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FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 101

RBRC Scientific Review Committee Meeting

October 27-29, 2010

Organizer:

N.P. Samios

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~100 graduates of which 27 theorists and 14 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are one hundred proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the summer of 2011.

N. P. Samios, Director
October 2010

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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RBRC Scientific Review Committee Meeting

October 27 -29, 2010

Brookhaven National Laboratory, Upton, NY 11973

The eleventh evaluation of the RIKEN BNL Research Center (RBRC) took place on October 27 – 29, 2010 at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC), present at the meeting, were: Prof. Wit Busza (Chair), Prof. Miklos Gyulassy, Prof. Ken Imai, Prof. Teiji Kunihiro, Prof. Richard Milner, Prof. Alfred Mueller, Prof. Charles Young Prescott, Prof. Horst Stoecker, Prof. Robert Sugar, and Prof. Akira Ukawa. We are pleased that Dr. Hideto En'yo, the Director of the Nishina Institute of RIKEN, Japan, participated in this meeting both in informing the committee of the activities of the RIKEN Nishina Center for Accelerator-Based Science and the role of RBRC and as an observer of this review.

In order to illustrate the breadth and scope of the RBRC program, each member of the Center made a presentation on his/her research efforts. This encompassed three major areas of investigation: theoretical, experimental and computational physics. In addition, the committee met privately with the fellows and postdocs to ascertain their opinions and concerns.

Although the main purpose of this review is a report to RIKEN management on the health, scientific value, management and future prospects of the Center, the RBRC management felt that a compendium of the scientific presentations are of sufficient quality and interest that they warrant a wider distribution. Therefore we have made this compilation and present it to the community for its information and enlightenment.

We thank Brookhaven National Laboratory and the U.S. Department of Energy for providing the facilities to hold this meeting.

N. P. Samios

RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510, Open Sessions – Large Seminar Room
October 27, 28 & 29, 2010
Agenda

Committee Members

Busza, Wit	busza@mit.edu (RBRC SRC Chair)
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Wednesday, October 27, 2010 – 2-160

8:00 AM to 9:20 AM ***SRC Executive Session & Working Breakfast*** ***(Room 2-160)***

8:00	Welcome	Samuel Aronson
8:10	RIKEN Overview	Hideto En'yo
8:40	RBRC Overview	Nicholas P. Samios
9:00	SRC Executive Session	

Open Session - Large Seminar Room

9:30 AM to 10:35 AM EXPERIMENTAL GROUP PRESENTATIONS –YASUYUKI AKIBA, CHAIR

9:30	Experiment Overview - HI and Upgrades	Yasuyuki Akiba
9:50	PHENIX Run-10	Stefan Bathe
10:05	Pixel detector at PHENIX Vertex Tracker	Atsushi Taketani
10:20	Overview of the Stripixel Detector for PHENIX Upgrade	Rachid Noucier

10:35 PM to 11:00 PM Break

11:00 AM to 12:35 PM EXPERIMENTAL GROUP PRESENTATIONS – ABHAY DESHPANDE, CHAIR

11:00	Overview of Spin	Abhay Deshpande
11:20	RUN9 ALL	Kieran Boyle
11:35	Measurement of transverse single spin asymmetries in polarized proton-proton collisions at PHENIX	John Koster
11:50	Measurement of Double Longitudinal Spin Asymmetries and Cross-Sections of Non-identified Charged Hadrons	David Kawall
12:05	Observation of W boson decay at PHENIX central arm	Kensuke Okada
12:20	Readiness of Forward Muon Arms for W Detection	Itaru Nakagawa

Wednesday, October 27, 2010 (Continued)

2-160

12:35 PM to 1:30 PM ***SRC Executive Session - Working Lunch (Room 2-160)***

1:30 PM to 3:20 PM THEORY GROUP PRESENTATIONS--LARRY MCLERRAN, CHAIR

1:30 PM	Theory Overview	Larry McLerran
1:50 PM	Spectral Densities and Hydrodynamics for RHIC	Derek Teaney
2:05	Probing Quark-Gluon Matter	Rainer Fries
2:20	JIMWLK evolution and two-particle correlations at RHIC and LHC	Adrian Dumitru

2:35 PM to 3:00 PM Break

3:00 PM to 4:05 PM THEORY GROUP PRESENTATIONS—TONY BALTZ, CHAIR

3:00	Understanding single transverse spin asymmetry	Zhongbo Kang
3:15	Neutrino astrophysics and cosmology	Cecilia Lunardi
3:30	The dichotomous nucleon and axial charge in large Nc	Toru Kojo
3:45	QCD Thermodynamics close to the chiral limit	Frithjof Karsch

4:05 PM to 5:30 PM ***SRC Executive Session (Room 2-160)***

6:30 PM Executive Dinner (Chachama Grill, East Patchogue) (See Invitation)

Thursday, October 28, 2010

8:00 AM to 9:00 AM ***SRC Executive Session and Continental Breakfast (Room 2-160)***

Large Seminar Room

9:00 AM to 10:40 AM Lattice Gauge Presentations – Taku Izubuchi, CHAIR

9:00	Physics of RBC and UKQCD I. overview of 2010 achievements	Taku Izubuchi
9:20	Nucleon structure from 2+1 flavor domain wall QCD at a nearly physical pion mass	Shigemi Ohta
9:35	Neutral B meson mixing --towards a precision test of the Standard Model--	Yasumichi Aoki
9:50	Challenges of small and large quark masses in lattice QCD.	Christoph Lehner
10:05	Domain-wall fermionwith low-mode projection	Eigo Shintani
10:20	Physics of RBC/UKQCD II. Present and Future	Thomas Blum
10:40	Viscous fluid and particles	Denes Molnar
10:55	Small x evolution in impact parameter space	Anna Stasto

11:00 AM to 11:30 AM Break

11:30 AM to 12:30 PM **Meetings with Individual RBRC Staff** (Possible Tours)

Theorists (Room 2-160)
Experimentalists (Room 2-78)

12:30 PM to 1:30 PM ***SRC Executive Session and Working Lunch (Room 2-160)***

Continued Next Page

1:30 PM to 2:30 PM	**Meetings with Individual RBRC Staff (Continued)**	
	Theorists (Room 2-160) Experimentalists (Room 2-78)	
2:30 PM to 3:30 PM	***SRC Executive Session (Room 2-160)***	
3:30 PM to 6:00 PM	**Organizational Meeting for Review of 6-year RBRC Renewal *(Room 2-160)***	
3:30 PM to 4:50 PM	**BNL Future Plan Presentations – Nicholas P. Samios, CHAIR**	
3:30	BNL , RHIC, e-RHIC Future Plan	Thomas Ludlam
3:50	Accelerator (Operation & Design) Future Plan	Thomas Roser
4:10	e-RHIC Theory Plan	Raju Venugopalan
4:30	Spin Theory Plan	Jianwei Qiu
4:50 PM to 6:00 PM	***SRC Executive Sessions (Room 2-160)***	
7:00 PM	Reception and Dinner (Three Village Inn, Stony Brook) (See Invitation)	

Friday, October 29, 2010

8:00 AM to 9:00 AM	***SRC Executive Session and Continental Breakfast (Room 2-160)***	
Room 2-160 **9:00 AM to 11:00AM**	**RBRC Proposal for a 6-year Extension of the RIKEN BNL Collaboration MOU Beyond 2012**	
9:00 AM	Overview	Nicholas P. Samios
9:20	Theory	Larry McLerran
9:40	Computer	Taku Izubuchi / Norman Christ
10:00	Experiment	Yasuyuki Akiba
10:20	e-RHIC	Abhay Deshpande
10:40 AM to 11:00 AM	Break	
11:00 AM to 3:30 PM	***SRC Executive Sessions and Working Lunch (Room 2-160)***	
3:30 PM to 4:30 PM	Closeout/Adjourn (Room 2-160)	

RBRC Scientific Review Committee Membership 2010

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RIKEN NISHINA CENTER

Scientific Review Committee for RIKEN BNL Research Center & Scientific Review for the extension of BNL-RIKEN collaboration

(Renewal of Memorandum of Understanding 2012-2018)

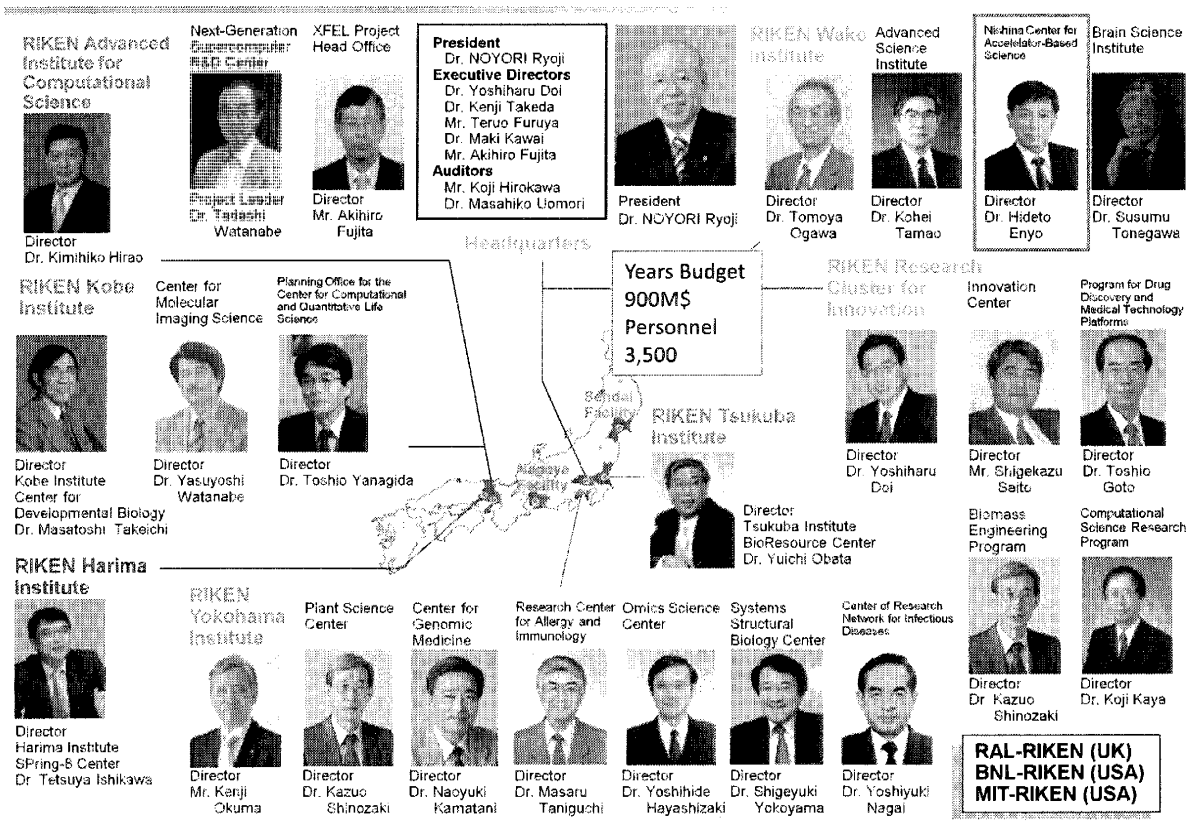
Hideto En'yo

Director, RIKEN Nishina Center (RNC)

October 27-29, 2010

BNL, USA

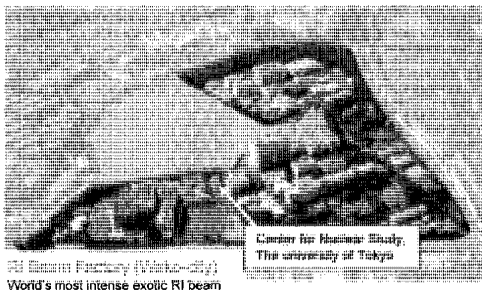
Nishina Center in RIKEN



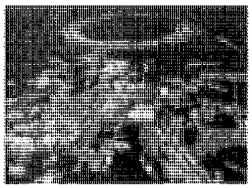
Organization of RIKEN Nishina Center, April 2010

(established on April 1 2006)

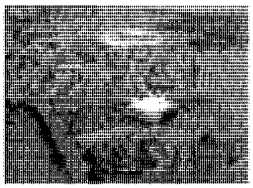
Research Locations



World's most intense exotic RI beam



RIKEN BNL Research Center
World's first polarized proton beam colliding
High- speed lattice QCD computing



RIKEN RAL Muon Facility
World's most intense pulsed muon beam

President

Advisory Council
RBRC-SRC
RRMF-AC

Director
Deputy
Coordinator
Science Adviser

Scientific Policy Committee
Program Advisory Committee
Safety Review Committee
Machine Time Committee
Coordination Committee

Theoretical Research Division
Theoretical Physics Laboratory
Theoretical Nuclear Physics Laboratory
Strangeness Nuclear Physics Laboratory
Mathematical Physics Laboratory

Sub Nuclear System Research Division
Radiation Laboratory
Advanced Meson Science Laboratory
RIKEN BNL Research Center
Theory Group
Experimental Group
RIKEN Facility Office at RAL

RIBF Research Division
Radioactive Isotope Physics Laboratory
Superheavy Element Laboratory
High Energy Astrophysics Laboratory
Accelerator Group
Experimental Installations Development Group
Research Instruments Group
User Liaison and Industrial Cooperation Group
Accelerator Applications Research Group
Safety Management Group

W. Henning
Deputy director for RIBF

H. Sakai for User Liaison for RIBF

T. Motobayashi for synergetic use coordinator

RIKEN Nishina Center in Size (FY2010)

Budget (MEXT approved, before overhead cut of 8.3%)

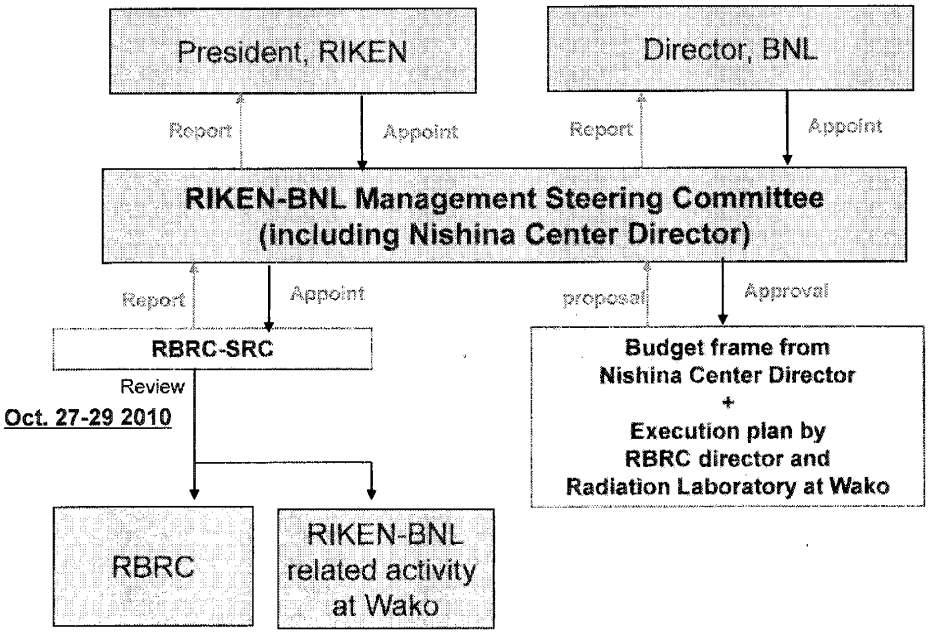
RIBF:	2,975MJY	(including 1,177MJY for electricity)
RAL:	175MJY	
BNL:	661MJY	
Personnel:	920MJY	(for permanent staff)
Supplemental:	82MJY	(Helium supply)
Total:	4,813MJY	

+ SAMURAI (Multi particle spectrometer) construction budget.

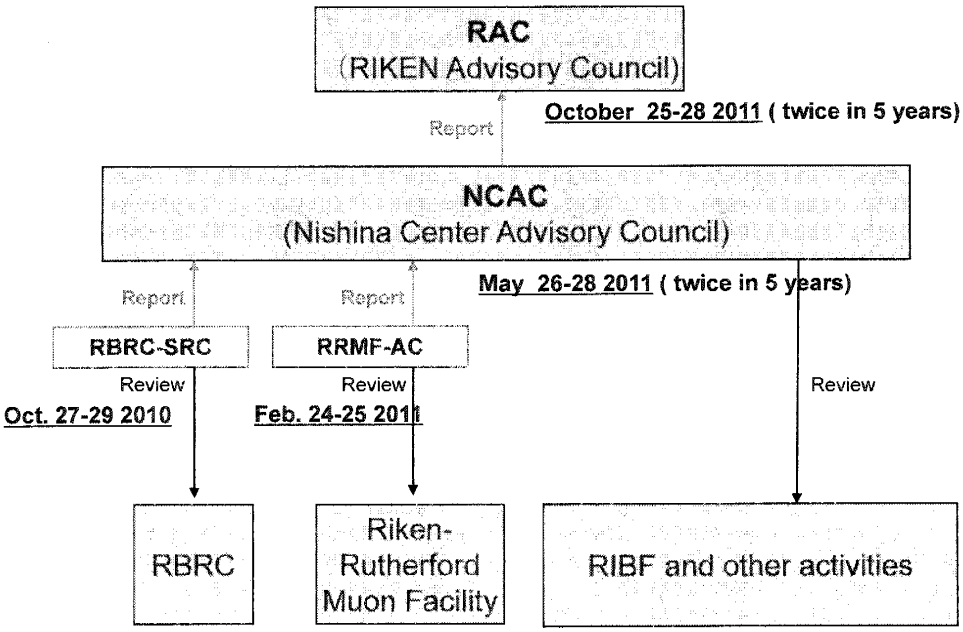
Man power (JFY2008)

Permanent staff:	
research	75
administration	7
Fixed term staff	170
Part-time staff	21
Company (operator)	46
Total:	319

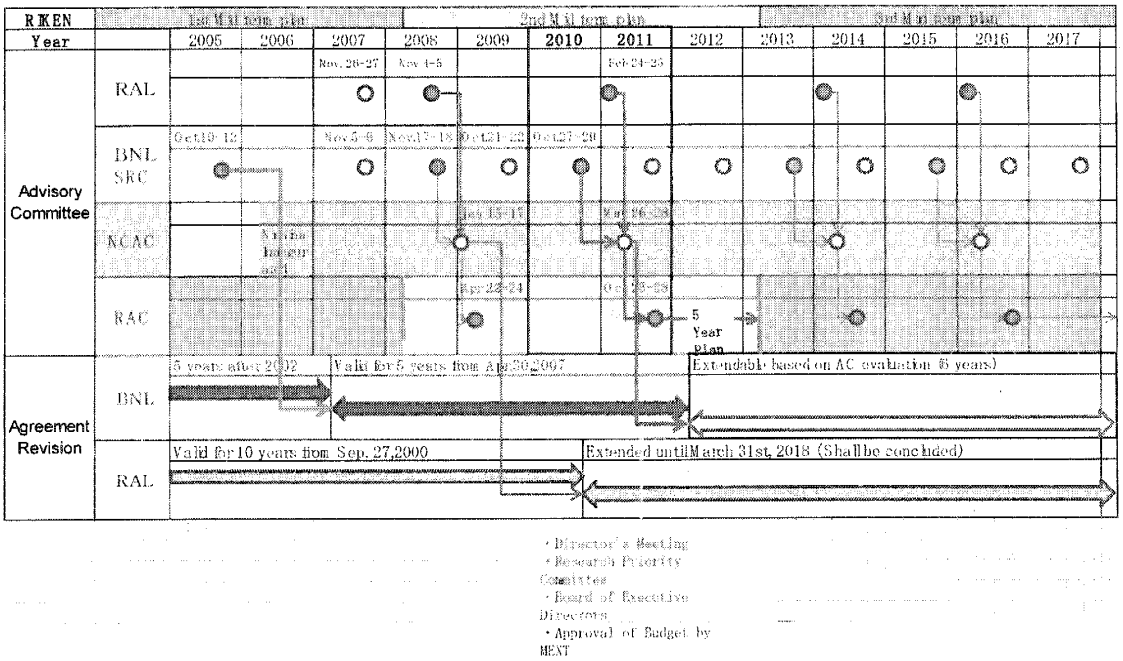
RBRC Review System and Schedule (General)



RIKEN Review System and Schedule
(when runs together)



Schedule of RNC-AC, revision of the agreement with BNL,RAL



The RBRC-SRC review report:

will be addressed to President of RIKEN
(through the NCAC)

and
may include confidentialities
to Director of Nishina Center and Director of RBRC.

- The review report will be the key material for the Director of Nishina Center to drive forward this project.
- The review report must include the answers to the terms of reference from President Noyori.
- And, please
  - •Evaluate the scientific activities through this MoU period.
  - •Evaluate the reactions to your last recommendations.

Your recommendation on the MoU extension is the starting point to realize the RIKEN-BNL collaboration in 2012-2017.

RAC members list (Core members)

Rita R. Colwell <Chair>	Distinguished University Professor, University of Maryland at College Park (11th Director, National Science Foundation)	Oceanography
Howard Alper <vice chiar>	Distinguished University Professor, University of Ottawa Chair, Government of Canada Science, Technology and Innovation Council	Chemistry
Colin Blakemore <vice chair>	Professor of Neuroscience, University of Oxford (former Chief Executive, UK Medical Research Council)	Neuroscience
Hiroo Imura <vice chair>	Chairman, Foundation for Biomedical Research and Innovation Principal Fellow (Chair), Center for Research Development Strategy, JST (Professor Emeritus, Kyoto University)	Medicine: Endocrinology
Hidetoshi Fukuyama	Professor, Tokyo University of Science (Professor Emeritus, University of Tokyo)	Basic Solid States Science
Paul Kienle	Professor Emeritus, Department of Physics, Munich University of Technology (former Director, GSI Darmstadt)	Physics
Karin Markides	President, Chalmers University of Technology	Chemistry
Chi-Huey Wong	President, Academia Sinica	Chemical Biology
Yuichiro Anzai	Executive Advisor for Academic Affairs and Professor, Faculty of Science and technology, Keio University	Informatics/Cognitive Science
Teruhiko Beppu	Professor, Advanced Research, Institute for the Sciences and Humanities, Nihon University (Professor Emeritus, University of Tokyo, former Chairman, Japan Bioindustry Association)	Applied Microbiology
Mitiko Go	Executive Director, Research Organization of Information and Systems (former President, Ochanomizu University)	Bioinfomatics
Zach W. Hall	Emeritus Vice Chancellor, University California, San Francisco (founding President, California Institute for Regenerative Medicine)	Neuroscience
Biao Jiang	Vice President, Shanghai Advanced Research Institute	Chemistry
Takehiko Sasazuki	President Emeritus, International Medical Center of Japan	Medicine: Immunology
Rainer Metternich	Former Vice President, Basic Research, and site head, West Point, Merck & Co., Inc	Drug Discovery

NCAC members (2011～2013)

NCAC members	institute	job title
Sydney Gales (Chair)	GRAND ACCELERATEUR NATIONAL D'IONS LOURDS (GANIL)	Director, GANIL
Shoji Nagamiya (Chair, Public Relation Committee)	J-PARC Center, Japan Atomic Energy Agency	Director, J-PARC Center, JAEA
Robert Tribble (Chair, RIBF-PAC)	Cyclotron Institute/Physics Department, Texas A & M University,	Distinguished Professor of Physics Director of Cyclotron Institute
Jean-Michel Poutissou (Chair, ML-PAC)	TRIUMF	Former Associate Director Head of Nuclear Medicine Division
Wit Busza (Chair, RBRC-SRC)	Department of Physics, MIT,	Francis L. Friedman Professor of Physics
Andrew Taylor (Chair, RIKEN-RAL AC)	ISIS Pulsed Neutron & Muon Source, Rutherford Appleton Laboratory,	Director, ISIS
Angela Bracco	Dipartimento di Fisica, Fisica del Nucleo, University of Milan	Professor
Makoto Inoue	Kyoto University Research Reactor Institute,	Professor Emeritus
Alexey Korsheninnikov	Russian Research Centre "Kurchatov Institute"	Deputy Director
Karlheinz Langanke	Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt in der Helmholtz-Gemeinschaft	Director of Research
WenQing Shen	Shanghai Institute of Applied Physics(SINAP),Chinese Academy of Science	Vice President(NSFC), Professor of Nuclear Physics
Bradley Sherrill	National Superconducting Cyclotron Laboratory, Michigan State University	University Distinguished Professor of Physics
Tadashi Shimoda	Graduate School of Science, Osaka University	Professor
Hiroshi Toki	Research Center for Nuclear Physics (RCNP), Osaka University	Professor

8th RAC Terms of Reference

■Evaluate RIKEN's responses to the recommendations made in the 7th RAC report, *RIKEN: Laying the Foundation for Creative Advancement.*

■Under its third 5-year plan from April 2013 to March 2018, RIKEN will continue to pursue its current mission and also use its full resources as a comprehensive scientific research institute to contribute to the gathering of knowledge essential for humanity's continued existence. The 8th RAC is asked to advise on the governance, strategies, research systems, and management policies necessary to achieve this goal.

■The 8th RAC is asked to evaluate RIKEN's cross-boundary research activities among its Centers and Institutes, as well as its domestic and international collaborative activities with universities, industry, and other external institutions. It is also asked to advise on how to maximize RIKEN's collective strengths.

President Noyori's suggested topics for deliberation by the Advisory Councils for RIKEN's Centers and Institutes

1. Does the Center/Institute have achievements of major scientific significance and/or social impact?
   - Evaluate Scientific impacts of "Spin physics", "Quark-gluon plasma physics", and "Lattice QCD computer physics"
2. Does the Center/Institute have a functioning Plan-Do-Check-Action (PDCA) cycle? In particular, are the mechanisms for reorganizing, improving or closing laboratories working effectively?
   - Evaluate the planning & achievements of each project under RIKEN-BNL
3. Are the personnel management practices (hiring and employment conditions) of the Center/Institute appropriate to its world-class standing? Are the quality and the diversity of researchers being maintained at a sufficiently high level? This is a major concern of President Noyori.
   - Evaluate RBRC personnel management
4. Evaluate the Center/Institute's collaborative activities within and outside RIKEN, as well as its efforts to promote international collaborations.
   - Naturally done well, but let other fields know

Some remarks in reviewing the MoU extension

1) The next MoU for 6 years, to match with RIKEN's mid term cycle.
2) Evaluate the scientific scope of the extension and expected outcomes, and give us a recommendation.
3) We will certainly be asked what is happen at the end (from JFY2018). Although RIKEN Nishina Center is willing to continue this project as long as RHIC runs, Nishina Center also planning to have RIKEN J-PARC collaboration Center. Please advice on RIKEN's standing point for eRHIC and possible other international activities.

07	08	09	10	11	12	13	14	15	16	17	18	19	20
This MoU					Next MoU						eRHIC or JPARC or....		

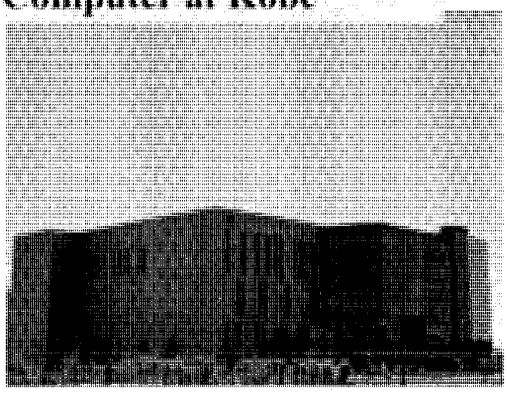
4) There glows significant Lattice QCD applications in 10 peta-flops Computer Center at Kobe. Please advice on the RBRC's standing point for that.
5) We have decided that RIKEN-RAL MoU shall be concluded Mar. 2018.

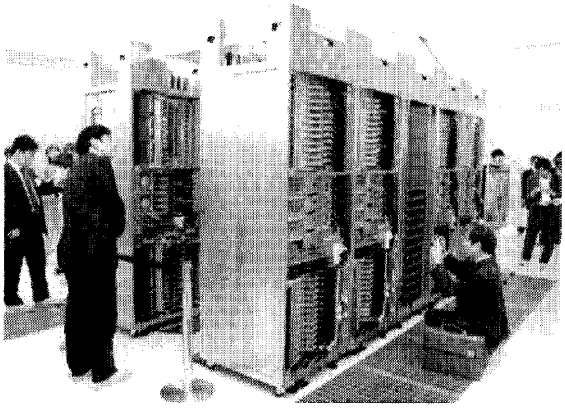
Related issue #1. RHIC decadal plan

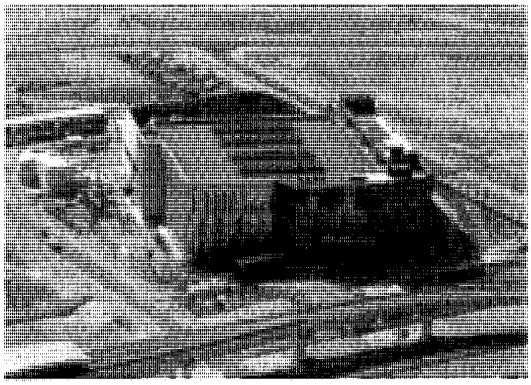
PHENIX Executive Summary (part)

- The suite of currently funded upgrades addresses key physics questions related to the sQGP (e.g. chiral symmetry restoration, heavy flavor flow), fundamental cold nuclear matter physics, and spin physics (e.g. quark flavor contributions to the proton spin via parity-violating W decays). Additionally, we see a need during this time frame for a new forward calorimeter (FOCAL) to address low-x gluon saturation physics (targeted for 2014) and an upgraded data acquisition referred to as Super-DAQ (targeted for 2013–2014) to fully utilize the increased luminosity of the collider. As demonstrated in the draft run, these key physics questions will be addressed on the five-year time scale.
- Beyond these five years, after the completion and full exploitation of the Midterm Upgrades and RHIC luminosity increases, and after the turn on of the LHC heavy ion program, we have identified new areas of investigation related to the fundamental properties of the sQGP, and to transverse spin physics, that require major new detector capabilities... Drell-Yan pair for T-odd transverse-momentum-dependent (TMD) distribution functions.
- The tools for answering these questions rely on a major evolution in the configuration of the PHENIX detector, while still building upon core detectors and data acquisition, infrastructure,
- and collaboration personnel strength. Studying the coupling of quarks to the medium and exploring the mechanisms of fast parton interactions demands precision over the next decade.
- The PHENIX upgrade plan is envisioned for the 2016–2018 time frame, and involves replacing the PHENIX central magnet with a new compact solenoid.
- The forward upgrade design is driven by nucleon structure physics, cold nuclear matter physics, and the capability to study first collisions at the EIC.
- Our plan is to carry out the Midterm Physics Plan while simultaneously aggressively pursuing a targeted R&D program and detailed physics simulations to move this new detector concept to the proposal stage.

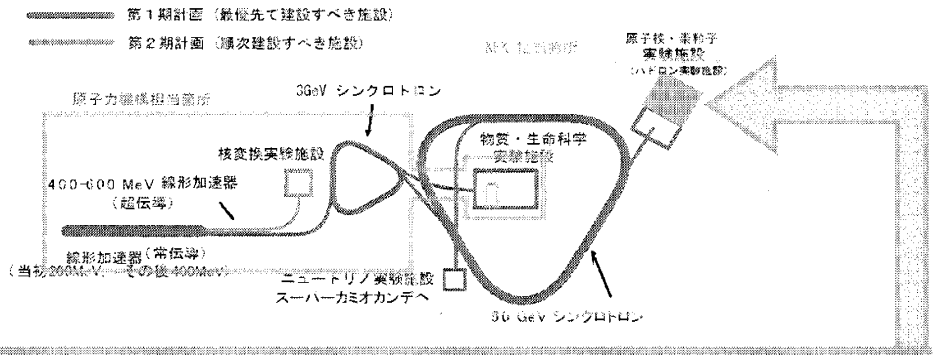
Related Issue #2. Peta-scale Computer at Kobe







Related Issue #3. RIKEN J-PARC Center Project



- In addition to the currently-going projects driven by KEK, such as hyper-nuclear physics and particle physics in the existing counting house, RIKEN wants to be the second driving force to promote hadron physics at J-PARC.
- To achieve the goal, RIKEN wants to extend the existing Hadron Hall, and construct a few spectrometer and the required beam lines.
- Although RIKEN's own interests are in the studies of "origin of mass" and "exotic hadron structure", the facilities must be for open use.

Nishina Center Advisory Council Jan. 2009

- The RIKEN-BNL Research Center (RBRC) is a role model for successful international collaboration. The physics issues addressed by the RBRC are among the most important in subnuclear physics, the results obtained to date are highly significant and of long term value. A major strength of the RBRC research program is its focus on one broad topic, QCD. Its experimental program and theory program including the lattice computation program are all aimed at understanding the structure and properties of QCD matter. There is good reason to believe that prospects are there for the RBRC to continue being a highly successful scientific enterprise with potential for major scientific discoveries. In the longer term, the focus of RHIC will be on realizing eRHIC. This will be a powerful, unique tool of the study of QCD. Its capabilities will dramatically extend the limits of existing machines to probe the spin structure of the nucleon and the role of partons in nuclei.

  - **NCAC concurs with the view of the RBRC Advisory Committee that RBRC has been highly successful and cost effective, that it is doing fore front science and that its strong support should be continued.**

Nishina Center Advisory Council Jan. 2009 (cont.)

Summary Assessment in Terms of Reference (RBRC related only)

1- Are there achievements with major scientific significance or achievements with significant social impacts?

- RIKEN's participation in the relativistic polarized-proton and heavy-ion programme at RHIC/Brookhaven has given the Center with comparatively modest investment a disproportionate involvement and, to a certain extent, leadership role in the study of QCD and partonic matter. The exploration of the new regimes and resulting science discoveries will be absolutely notable in the history of science.

2- How does the Center compare with similar research institutions abroad?

- RNC ranks now as the leader in rare-isotope research; forefront and leadership roles are also played by the Japanese groups in the RIKEN-RAL muon programme and the RIKEN-BNL relativistic beam program in QCD and quark-gluon matter.
- RIKEN should be considered in the top group of research institutions worldwide in the physical sciences.

3- Evaluate the Center's collaborations within RIKEN and with outside institutions, and evaluate the Center's effort to promote international collaborations.

- RIKEN has demonstrated its deep-rooted intent for international collaboration with the RIKEN-RAL and the RIKEN-BNL Centers. Also the RIBF facility at the RIKEN Nishina Center has already significant international collaborations. Additional opportunities exist for expanding on such collaborations with the completion of RIBF. A major advance could come from earlier and more involvement of the international community in the development of major instrumentation at RIBF which will determine future research programmes. Added international scope is expected to generate increased opportunities for scientific achievements and societal contributions.

RBRC
Scientific Review Committee

RBRC Overview

Nicholas P. Samios

October 27, 2010
Brookhaven National Laboratory

1

Administration

Director Emeritus:	T.D. Lee
Director:	N.P. Samios
Theory Group Leader:	L. Mc Lerran
Deputy Theory Group Leader:	A. Baltz
Experimental Group Leader:	Y. Akiba
Deputy Exp. Group Leader:	A. Deshpande

2

Recent Interesting Physics Results

- Direct Photons observed in Gold-Gold collisions at 200 Gev
  - -Effective Temperature 220 Mev; Extrapolated Temperature 300 Mev
- Measurement of Spin Asymmetry in leptonic W decays at 500 Gev
- Bubbles of Broken Symmetry in hot sQCD have been produced at RHIC
  - -Possible local violation of (P, CP)

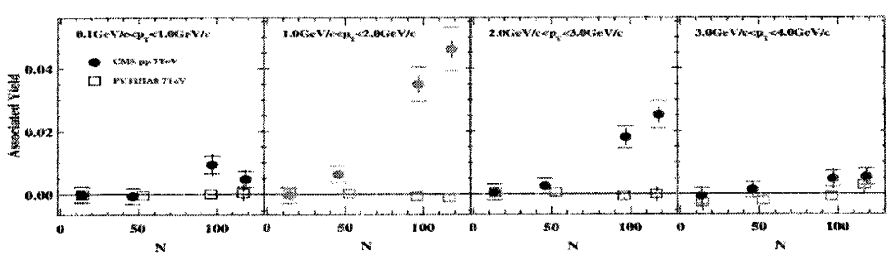
Glasma and Color Glass Condensate

- Ridge Structure Observed in Long Range Two Particle Correlations in Gold-Gold Collisions at 200 GEV at RHIC
- Ridge Structure Observed in pp Collisions at 7 TEV at CMS at LHC at CERN
- Disappearance of Away Side Peak in Two Particle Correlation in Deuterium Gold Collisions at 200 Gev at RHIC

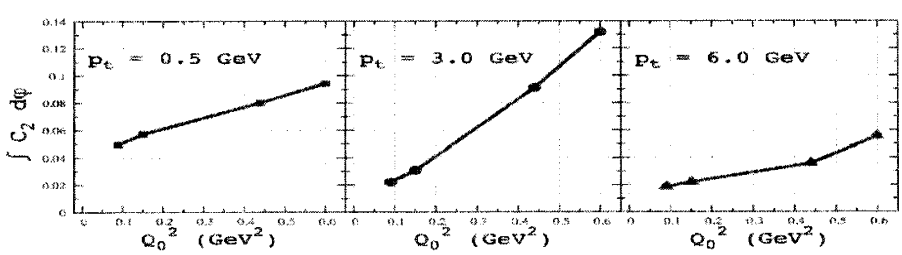
- Calculation of lattice QCD & QED with Dynamical Quark Effects
  Masses of u, d quarks and Eta prime meson

3

CERN CMS 7 TEV pp



Adrian Dumitru - Color Glass - pp 14 TEV



4

RHIC Accelerator

Run 10

Au x Au

200 Gev/Amu	11 Weeks	10 nb^{-1}
62 Gev/Amu	3 Weeks	.5 nb^{-1}
39 Gev/Amu	2 Weeks	.2 nb^{-1}
11 Gev/Amu	1 Weeks	4.7 μb^{-1}
7.7 Gev/Amu	4.5 Weeks	2.1 μb^{-1}

Excellent Run

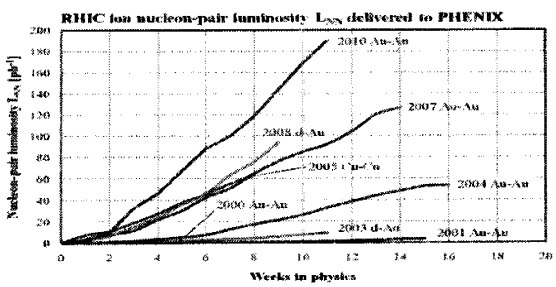
Polarized pp

500 Gev — Engineering Run - Encouraging Run Near $^2/_3$ Resonance

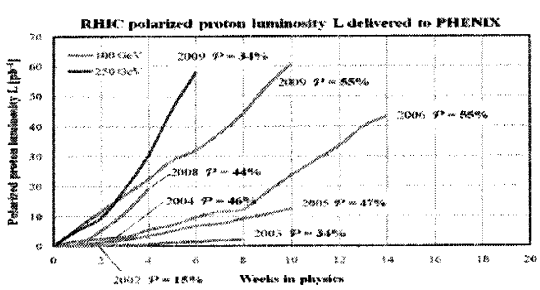
Run 11

Au x Au	200 Gev/Amu
	27, 18 Gev/Amu
U x U	200 Gev/Amu
Polarized pp	500 Gev

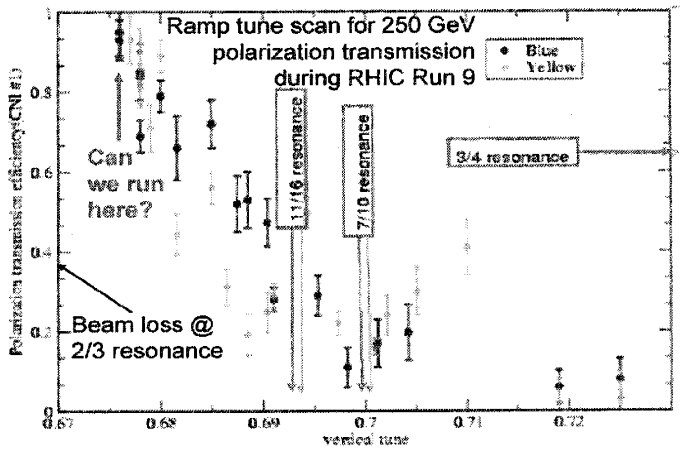
Year	2006	2007	2008	2009	2010	2011
Weeks	21	20	19	22	27	28-30



Note: The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where L is the luminosity, and A_1 and A_2 are the number of nucleons of the ions in the two beam respectively.



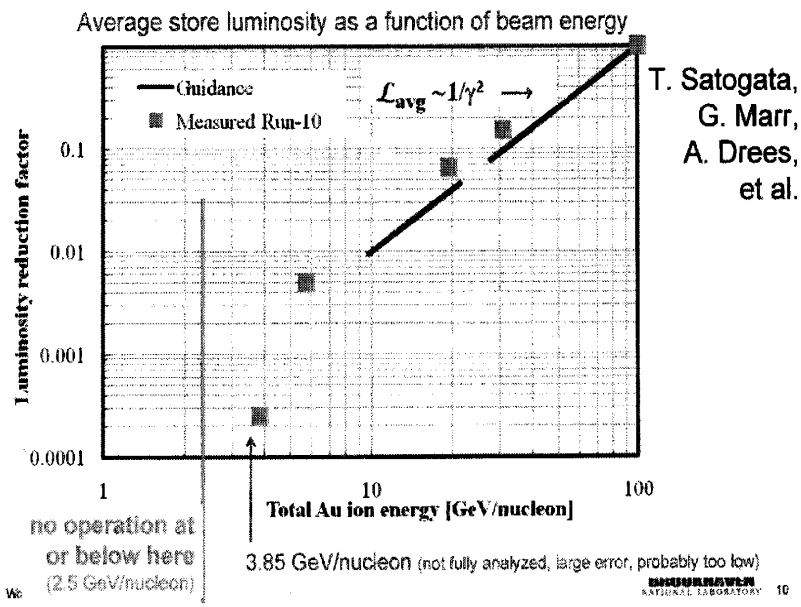
Improving Polarization Performance at 250 GeV Requires High Machine Stability



Power supply improvements during summer 2009 ⇒ improved stability in 2010. Tests with Au beams ⇒ very encouraging indications of ability to run sufficiently close to 2/3-integer machine resonance. Also working on polarized source and AGS improvements for higher polarization.

7

Run-10 Au-Au medium and low energies



T. Satogata, G. Marr, A. Drees, et al.

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Scientific Personnel (Theory)

Fellows:

Denes Molnar	Purdue University
Kirill Tuchin	Iowa State University
Feng Yuan	Lawrence Berkley National Laboratory
Rainer Fries	Texas A&M University
Cecilia Lunardini	Arizona State University
Derek Teaney	Stony Brook University (SUNY)
Adrian Dumitru	Baruch College (CUNY)
Anna Stasto	Pennsylvania State University
Yasumichi Aoki	Brookhaven National Laboratory
Taku Izubuchi	Brookhaven National Laboratory
Shigemi Ohta	Guest

Post docs:

Zhongbo Kang; Toru Kojo (SPD); Christoph Lehner (FPD); Eigo Shintani

Future Fellows:

Indiana University
City University of New York
University of Connecticut
(Wayne State)

Future Post Doc:

Adam Bzdak

Scientific Personnel (Experimental)

Fellows:

Ralf-Christian Seidl	Brookhaven National Laboratory
Stefan Bathe	Baruch College (CUNY)
David Kawall	University of Massachusetts
Kensuke Okada	Brookhaven National Laboratory

Post docs:

Kieran Boyle	Brookhaven National Laboratory
John Koster	FPD

RIKEN/RBRC at Brookhaven National Laboratory:

Yuji Goto
Itaru Nakagawa

Search:

1 Fellow
2 Post Docs

RBRC Personnel

Honors and Recent Grants:

Rainer Fries	NSF Career Award	5 years
Yasumichi Aoki	JSPS	3 years
Taku Izubuchi	JSPS	3 years
Feng Yuan	DOE Young Investigator	5 years
Denes Molnar	DOE Young Investigator	5 years
Larry Mc Lerran	J. Hans D. Jensen Prize	

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Committees

Theory Advisory Committee:

- Larry Mc Lerran
- Anthony Baltz
- Michael Creutz
- Frithjof Karsch
- Dmitri Kharzeev
- Miklos Gyulassy
- Robert Oswald-Pisarski
- Jianwei Qiu

Experimental Advisory Committee:

- Akira Masaike
- Kenichi Imai
- Yousef Makdisi

OCDOC Advisory Committee:

- Michael Creutz
- Robert Oswald-Pisarski
- Sinya Aoki

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Seminars

Tuesday – RBRC/Spin

Wednesday – RBRC/BNL/SUNY

Thursday – RBRC/Lunch

Friday – RBRC/BNL

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Workshops

- Progress in High-p_t Physics at RHIC March 17-19, 2010 – Vol. 95
- P- and CP-odd Effects in Hot and Dense Matter April 26-30, 2010 – Vol. 96
- EIC Meeting at Stony Brook January 10-12, 2010
- Saturation, the Color Glass Condensate and Glasma: What Have we Learned from RHIC? May 10-12, 2010 – Vol. 98
- The Physics of W and Z Bosons June 24-25, 2010 – Vol. 99
- BNL Summer Program on Nuclear Spin Physics July 14-27, 2010 – Vol. 100

Publications

Theory - 42

Experiment - 29

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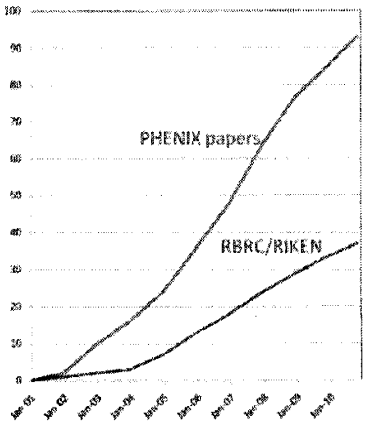

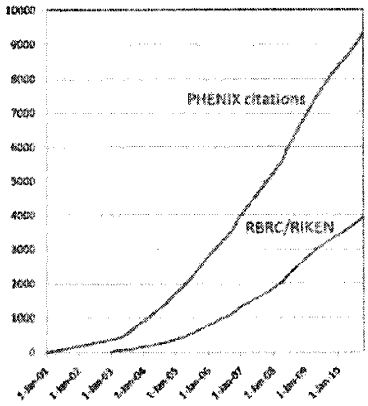

15

Computing:

QCDOC

10 Teraflops	- Running at greater than 95% efficiency
2005	- Low Maintenance

QCDCQ

200 Teraflops/Rack	- R&D Complete (RBRC post-doc 3 years)
2011	- Pre-production ½ Rack – Nov. 2010
	($400k Columbia University; $400k U.K.)
	- RIKEN/BNL - 2 Racks (400 Teraflops)
	Aug. 2011 – RIKEN $1M; BNL $1.5M
	- Location: BNL – QCDOC Room
	- Power: 20 Teraflops QCDOC
	400 Teraflops QCDCQ

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RBRC

Yearly Review

- Spin/Experiment
- Theory
- Lattice Gauge/Computing
- Interview Fellows and Post docs

Renewal – 6 year 2012-2018

- BNL Context
- Document
- Review of Highlights

17

RBRC Exp. Group
Introduction and Spin Physics

Y. Akiba

RBRC SRC review
2010/10/27

Exp. Group activities

Three major activities

- Spin Physics
  - Study of spin structure of proton using the world only polarized p+p collider
  - Main activity of RBRC/RIKEN
  - RBRC/RIKEN are the leader of Spin Physics at RHIC/PHENIX

  5 presentations in the 2nd session

- Heavy ion physics at RHIC/PHENIX
  - Study of the properties of the quark gluon plasma formed in heavy ion collisions at RHIC
  - RBRC/RIKEN are focusedon penetrating probes
- PHENIX detector upgrades
  - Extend the capabilities of PHENIX for spin and heavy ion physics
  - RBRC/RIKEN are leading major upgrade projects

  3 presentations in the 1st session

RBRC Experimental Group

Group Leader

Y. Akiba

Deputy GL

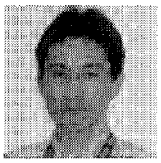
A. Deshpande

University Fellow

D. Kawall UMass

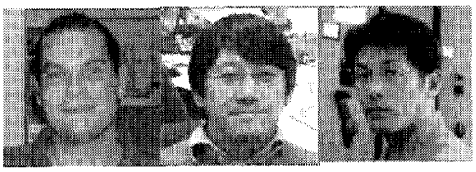
S. Bathe Baruch CCNY

Fellow



K.Okada

RIKEN/RBRC @ BNL

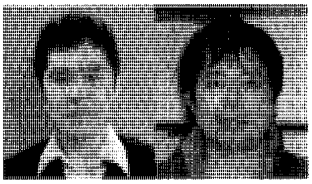


R. Seidl Y. Goto I. Nakagawa

PostDoc

K. Boyle

J. Koster



A. Taketani T. Hachiya

- Plus Many Students and Visitors
- In process of hiring 1 Fellow + 2 postDocs

Visitors/Collaborators/students

RIKEN/BNL

Takashi Ichihara, Yasushi Watanabe, Atsushi Taketani
Satoru Yokkaichi, Yuji Goto, Itaru Nakagawa
Ralf Seidl

Students

Yoki Aramaki, Yorito Yamaguhci, A Takahara
Kohei Shoji, Seishi Dairaku, Ken'ichi Karatsu
Katsuro Nakamura, Hidemitsu Asano, Ryoji Akimoto
Takeshi Kanesue, Masaya Nihashi, Takahiro Todoroki

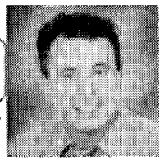
Visiting Scientist

Zheng Li, Kiyoshi Tanida, Akio Ogawa
Naohito Saito

Collaborating Scientist

Masahiro Okamura, Kotaro Kondo, Rachid Nouicer

talk: VTX strip

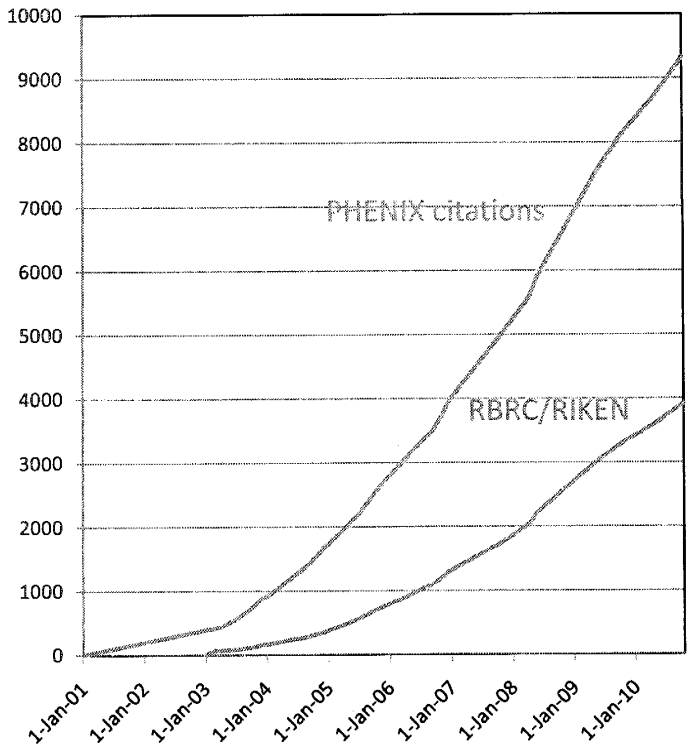


PHENIX publications and RBRC

- 93 (37)papers published since 2001
  - Phys. Rev. Lett. 53 (22)
  - Phys. Rev. C 26 (9)
  - Phys. Rev. D 9 (4)
  - Phys. Letter B 4 (1)
  - Nucl. Phys. A 1 (1)
- Total citation: ~9400
  - Topcite 500+ 2 (1)
  - 250-500 6 (2)
  - 100-250 19 (7)
  - 50-100 27(13)
- 10 (5) papers published since last SRC (Oct 2009)

  published
  - PRL 4 (2)
  - PRC 3 (3)
  - PRD 3

The number in () is the number of papers with significant RIKEN/RBRC contributions



Exp Group Activities

- Heavy Ion Physics at RHIC study of (s)QGP

  RBRC/RIKEN studies sQGP using penetrating probes
  - High p_T physics

  - J/Psi and Heavy quark

  - Low p_T direct photon and low mass dielectrons

- PHENIX detector Upgrade
  - Silicon Vertex Tracker (VTX) upgrade Lead by RIKEN/RBRC

+ many more

  - Muon Trigger Upgrade strong support by RIKEN/RBRC

+ many more

Exp Group Activities on Spin Physics

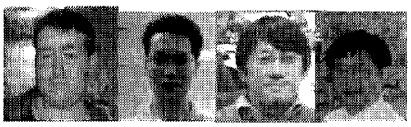
RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX

- ΔG measurement — A_{LL} of π^0, $\pi^{\pm}$, direct γ, jets, charm, etc…

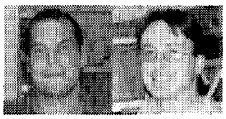
- W → e analysis

- J/Psi Polarization

- A_N at RHIC



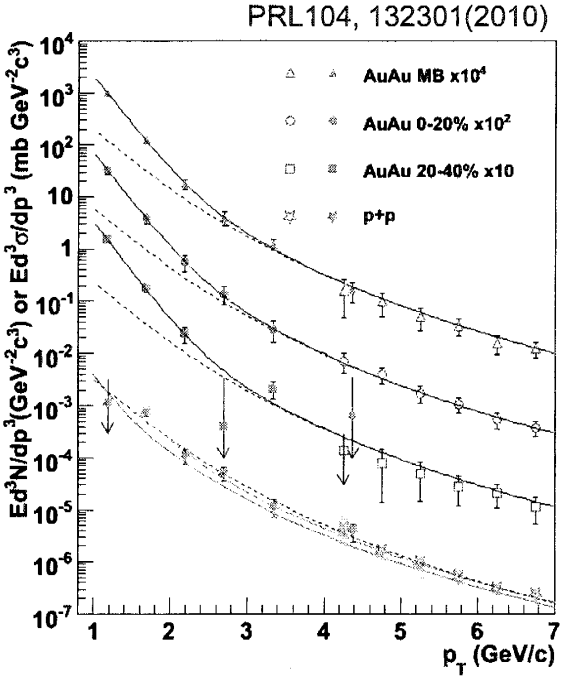
- Fragmentaion Function at Belle



Recent PHENIX H.I. result w. RBRC contribution

Low p_T direct photon in Au+Au
First measurement of thermal photon from QGP

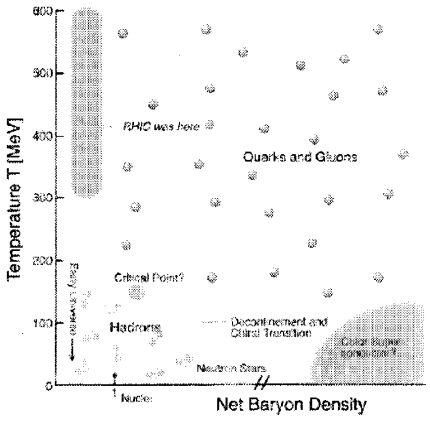
PRL104, 132301(2010)



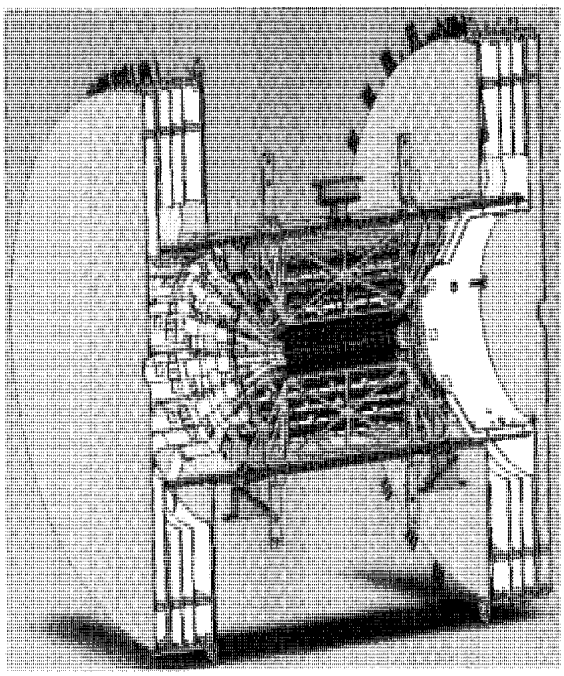
Large enhancement of direct photon over scaled p+p collisions observed

From theory comparison, initial temperature of 300 – 600 MeV is achieved at RHIC, well above the transition temperature to QGP

BNL press release on 2010/2/15 at APS in Washington DC.



PHENIX Upgrade: VTX

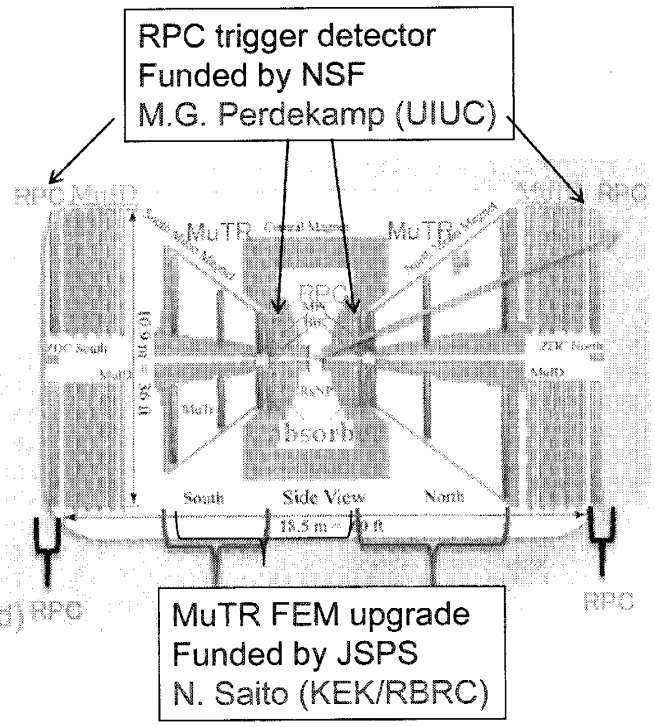


- Key device to improve heavy quark measurement at RHIC/PHENIX
  - Identify charm/bottom decay by precision tracking ($\sigma \sim 50\mu$)
  - Provides near 4π acceptance
- ~100 collaborators working on the project
- Project is lead by RIKEN/RBRC
  - Y. Akiba (RIKEN) : project manager
  - A. Taketani (RIKEN): pixel manager
  - A. Deshpande (StonyBrook/RBRC) strip manager
  - R. Nouicer (BNL/RBRC): strip detector
- The US side of the project
  - $4.7M from FY07 to FY10
- Detector near completion.
- To be ready for RUN11

Talks: A. Taketani (Pixel)
R. Nouicer (Strips)

PHENIX Uprade: W → mu

- W→μ measurment in the present PHENIX would be limited by the trigger. (Not enough trigger rejection)
- muTRIG upgrades will increase the trigger rejection factor by selecting high pT.
  - Essential for W measurement.
- Two trigger projects:
  - RPC trigger (ready byRUN11)
    lead by M.G.Perdekamp
    (UIUC/former RBRC fellow)
    R. Seidl (RBRC fellow)
  - Muon tracker FEE (almost completed)
    lead by N. Saito (KEK/RBRC)
    I. Nakagawa (RIKEN/RBRC)
- New muon absorbers
  - Reduce background by a factor of ~10



Talk: Itaru Nakagawa

Summary

- Three pillars of RBRC Experimental Group Activity
  Spin Physics/HI Physics/PHENIX Upgrade
- Spin Physics
  - Main activity of the group
  - Strong constraint on $\Delta G(x)$
  - First 500 GeV run → First signal of W
- Heavy Ion Physics
  - Study of QGP with penetrating probes
  - Important heavy ion results from RBRC
- Upgrade of PHENIX detector to explore the full physics opportunities at RHIC
  - Muon trigger upgrade for W measurements
  - Silicon Vertex Tracker Upgrade Project
- RBRC experimental group plays leading roles in Spin Physics, HI physics and PHENIX upgrades

Exp Group Presentations

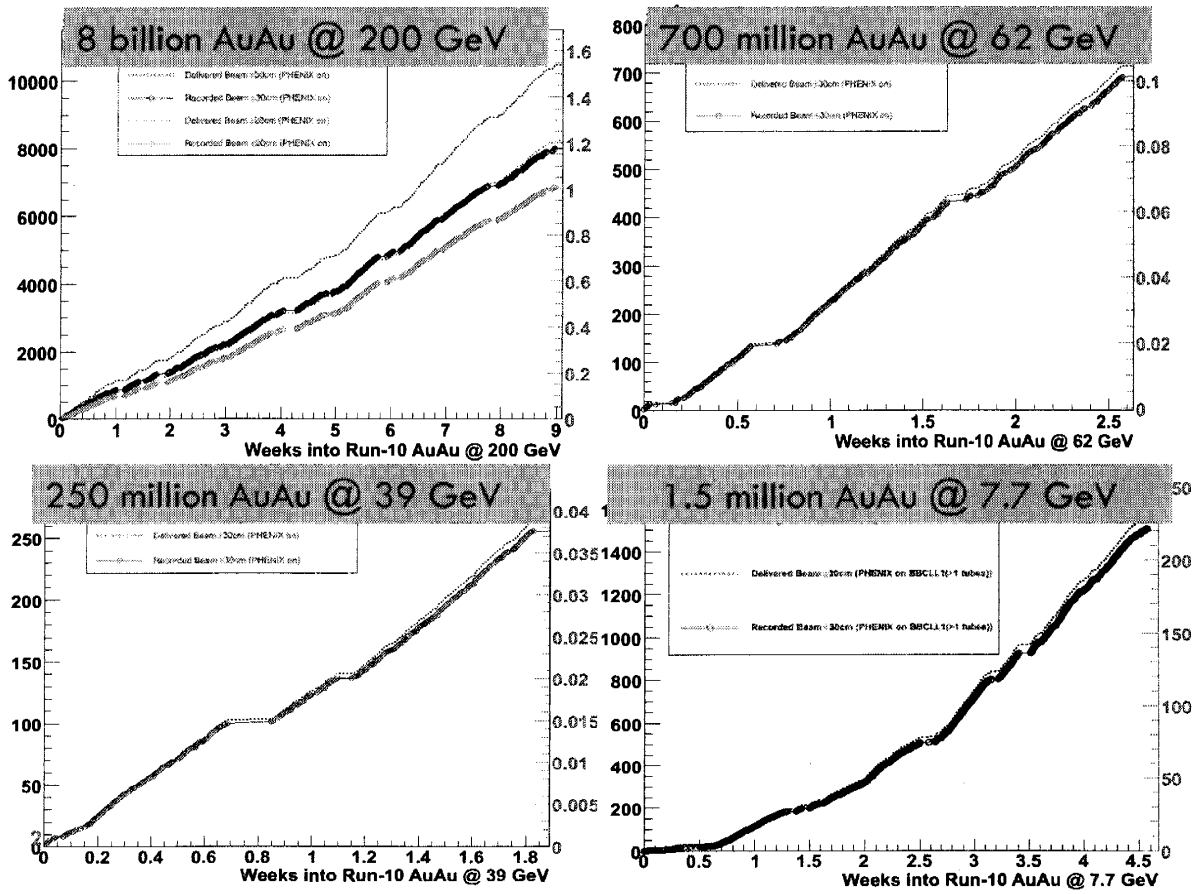
YA	"Exp. Group overview: HI Physics and PHENIX upgrades"
Stefan Bathe	"PHENIX RUN10"
Atsushi Taketani	"Pixel Detector at PHENIX Vertex Tracker"
Rachid Nouicer	"Overview of the Stripixel Detector for PHENIX Upgrade"

Break

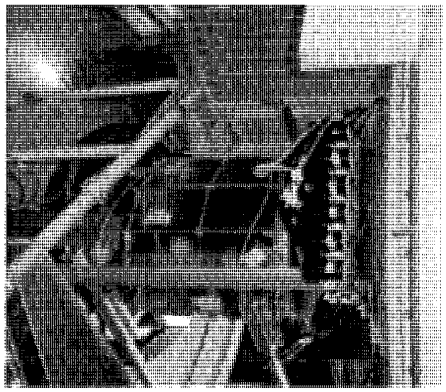
Abhay Deshpande	"Spin Physics at RBRC"
Kieran Boyle	"Measurement of Run9 π^0 ALL at sqrt(s)=200 GeV"
John Koster	"Measurement of Transverse Spin Asymmetry in Polarized proton-proton Collisions"
Dave Kawall	"The Double Longitudinal Spin Asymmetry and Cross section of Non-identified Charged Hadrons"
Kensuke Okada	"Observaton of W boson decay at PHENIX central arm"
Itaru Nakagawa	"Readiness of Forward Muon Arms for W Detection"

PHENIX RUN-10

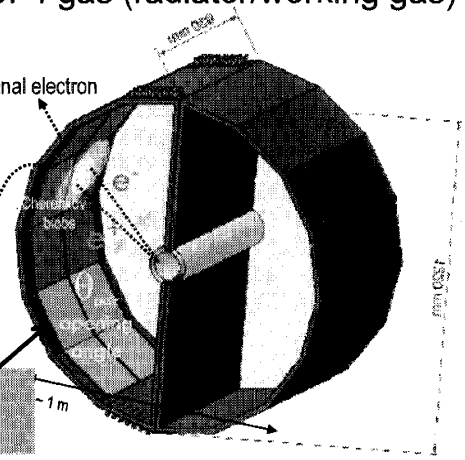
Stefan Bathe, RBRC Review, 27Oct2010



Hadron Blind Detector (HBD)



HBD: novel windowless Cerenkov detector with CF4 gas (radiator/working gas)

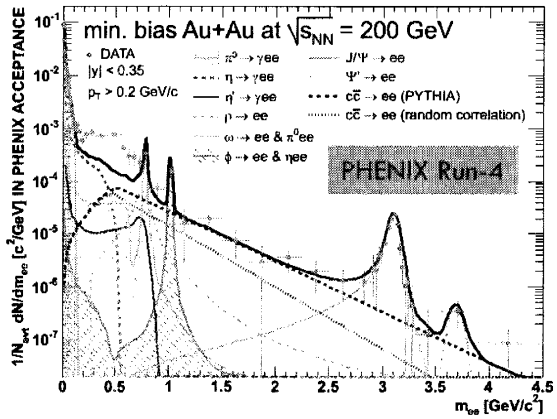


CsI photocathode covering triple GEMs

HBD will greatly improve e+e- pair measurements, including the virtual photon analysis.

Removes background e+e- pairs

200 GeV Au+Au Goal

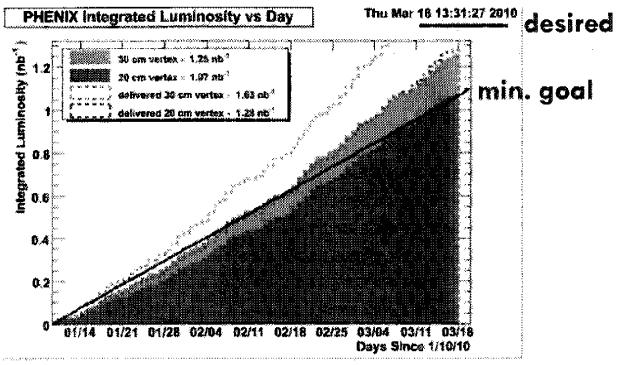


Phys. Rev. C 81, 034911 (2010)

- Study electron continuum in low M_{ee} region
- Measure in medium-modifications of ρ, ω, ϕ
- Chiral symmetry restoration
- Measure temperature (internal conversion of direct photons)

All with HBD

200 GeV: Jan 10 - Mar 18



Goal reached.
Success!

- Run-10 data set factor 1.5 larger than Run-7 data and has functioning HBD!

- BUP goal
  - record 1.4 nb^{-1} (± 30 cm)
    - realistically 1.1 nb^{-1} (± 30 cm) in 10 weeks
- Recorded
  - 8.2 B minimum bias events or 1.3 nb^{-1} (±30 cm)
  - 7.0 B minimum bias events or 1.1 nb^{-1} (± 20 cm)
  - Recorded 77 % (86 %) of min. bias evts. in ±30 cm (±20 cm)

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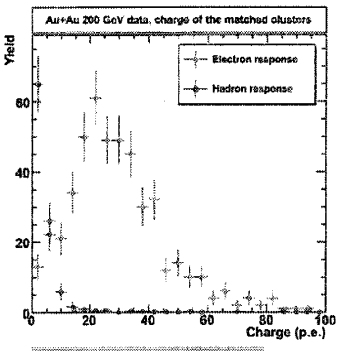
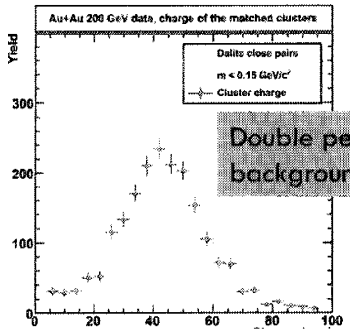
HBD Performance in 200 GeV Au+Au

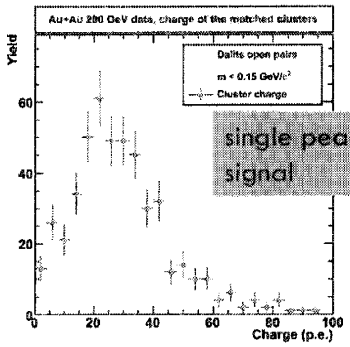


Hadron rejection

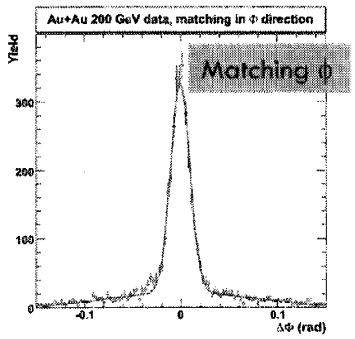
HBD worked as expected



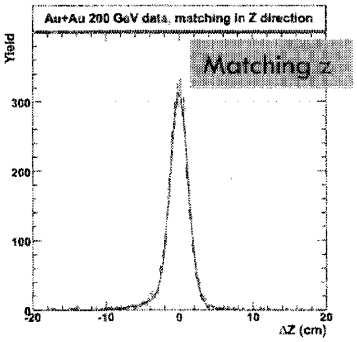
Double peak: background



single peak: signal



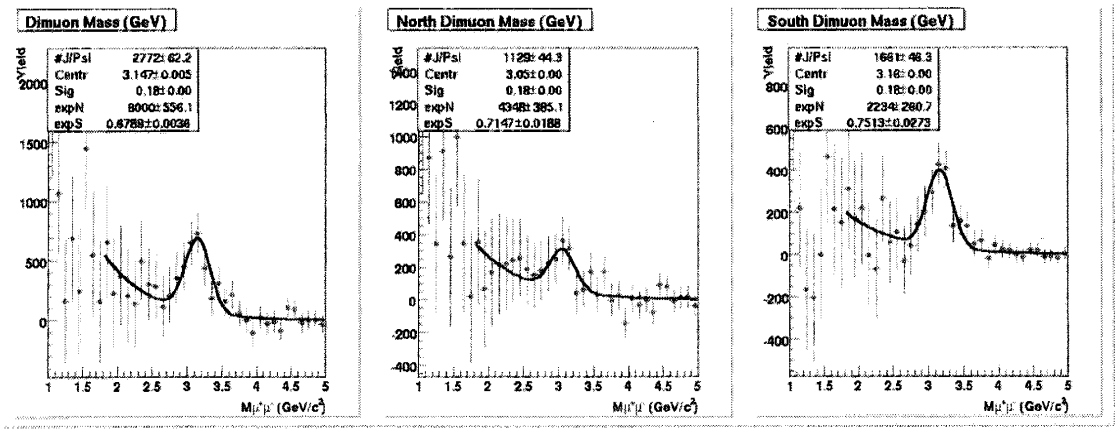
Matching Φ



Matching z

J/ψ in Muon Arms in 200 GeV Au+Au

7



Analyzed Luminosity (for mass plots):
147.7 μb^{-1} gives 18.8 +- 0.4 (stat) J/Ψ per μb^{-1}
Compared to Run7 Au+Au which had about 18.2 J/Ψ per μb^{-1}

J/ψ yield as expected

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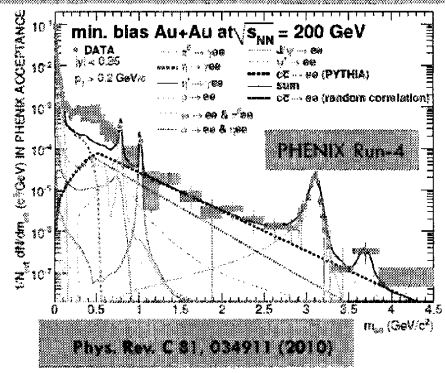
200 GeV success—Now on to 62.4 GeV

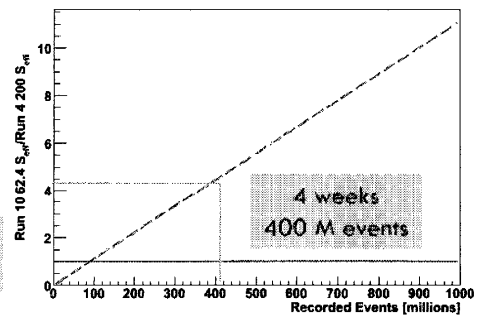
62 GeV goal: Dilepton physics

With 400 million recorded AuAu @ 62 GeV minimum bias events in PHENIX, if we assume a similar low mass enhancement to our published Run-04 AuAu @ 200 GeV result, we will have an increase in the statistical significance of 2.

The Run-04 @ 200 GeV low mass enhancement is a 2.6 sigma effect.

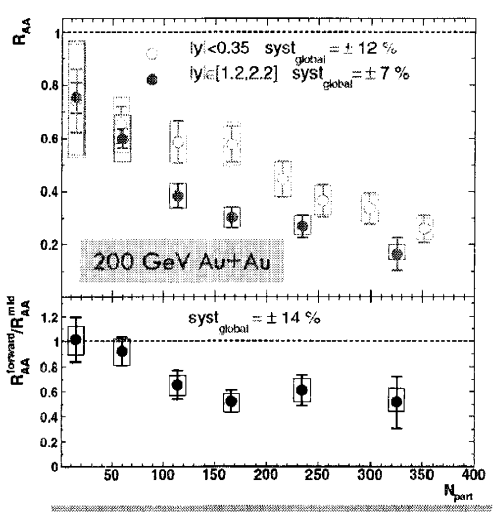
Thus, the Run-10 @ 62 GeV result would be a 5.2 sigma effect.





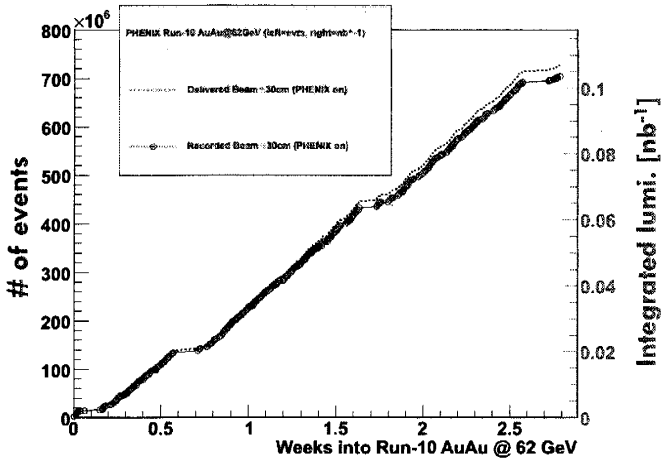
62.4 GeV improvement factor w.r.t. Run-4@200GeV as function of # of events

Enhanced goal: J/ψ Measurement at 62 GeV



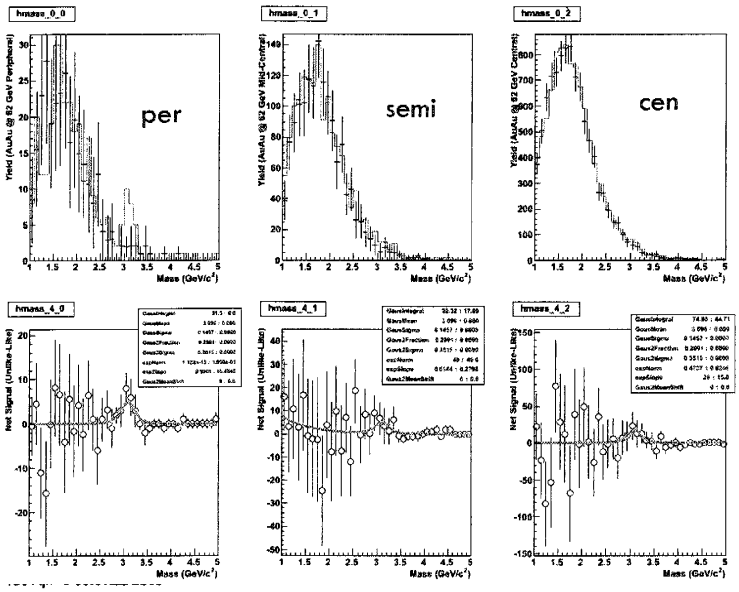
- Performance twice better than expected
- In three weeks of running
  - 600 M min. bias events (recorded)
  - 500 J/ψ
- Measure J/ψ suppression at 62.4 GeV
- Recombination models (Rapp et al.)
  - J/ψ yield at 200 GeV dominated by recombination
  - predict much larger suppression at 62 GeV than at 200 GeV
    - J/ψ yield down 1/3 at 62 GeV
    - Recombination down 1/10
- Extremely interesting test of recombination models

62 GeV: Mar 19 – Apr 8



Achieved: 700 M events in 3 weeks
Original HBD goal reached
New J/ψ goal reached also

First Glimpse at J/ψ from 62 GeV



Peak visible from about 25 % of statistics

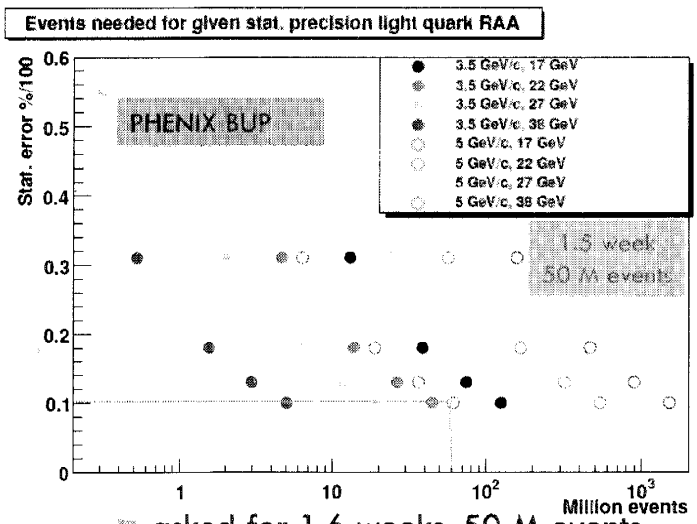
Encouraging!

13

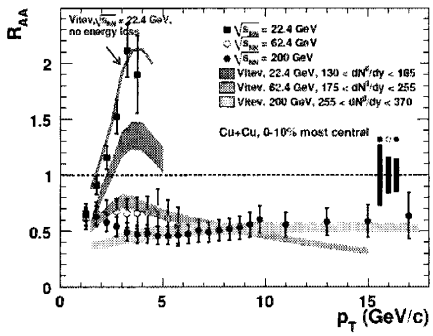
62.4 GeV success—Now on to 39 GeV

Goal: Light Quark R_{AA} at 39 GeV

14



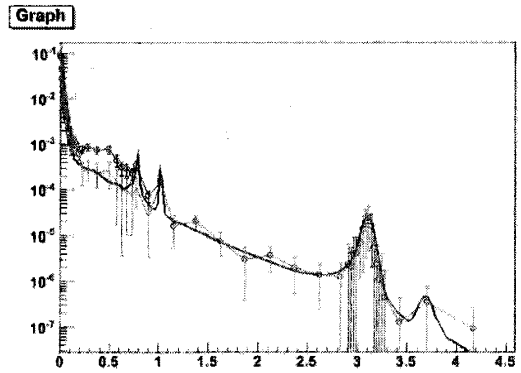
PHENIX Phys. Rev. Lett.101, 162301 (2008)



- asked for 1.6 weeks, 50 M events
  - to achieve 10% statistical uncertainty
  - pion R_{AA} at 5 GeV/c p_T

Onset of Jet Quenching

Enhanced Goal: Dilepton Measurement at 39 GeV

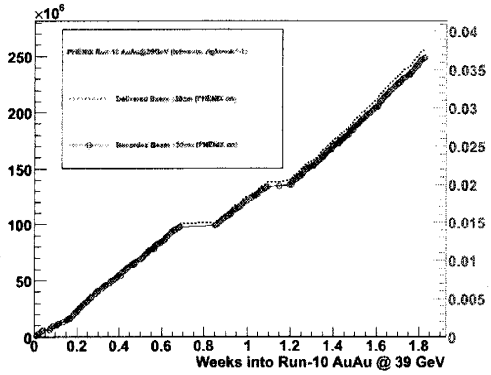


- Performance 2-3x better than expected
- With 200M events in ± 20cm vertex cut
  - If excess is unchanged at 39 GeV
  - Measured excess x4.7 ± 0.77(total); 6 σ result
  - If excess is 1/3 of that at 200 GeV
  - Measured excess x1.57 ± 0.77(total)

*NB: BUP request was 400M

How do dilepton excess and ρ modification at SPS evolve into the large low-mass excess at RHIC?

39 GeV: Apr 9 – Apr 22

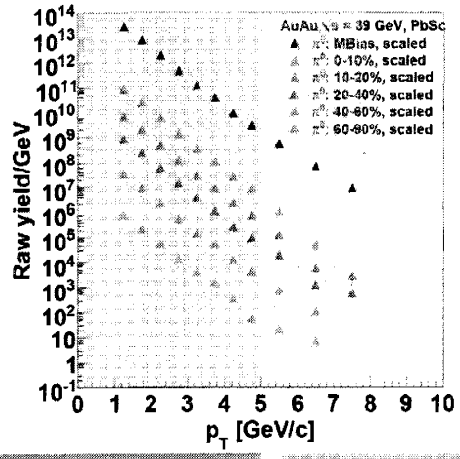


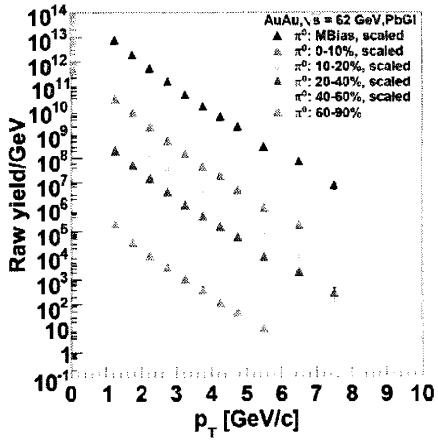
Achieved 250 M events in 1.9 weeks

Both light quark R_{AA} and dilepton measurement goals met

π^0 yields (uncorrected) at 39 GeV

17





desired p_T reach

Extra p_T reach

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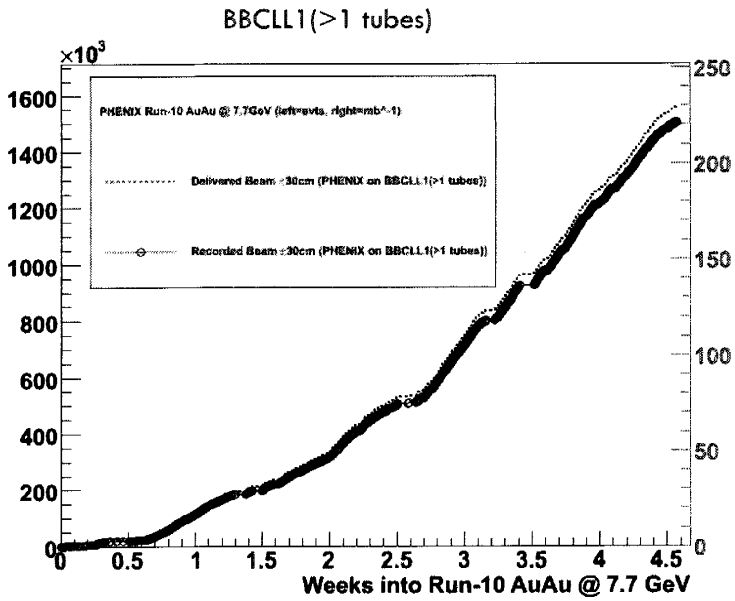
39 GeV success—Now on to 7.7 GeV

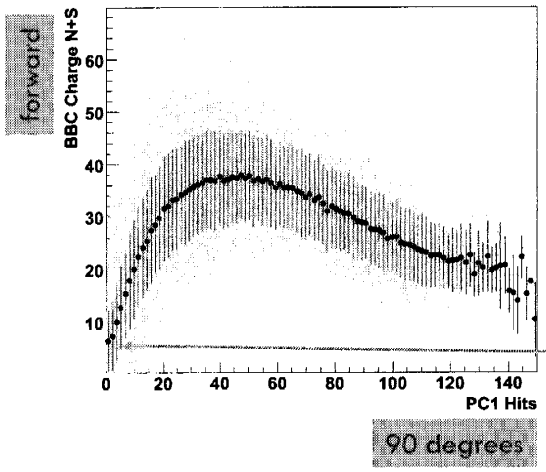
7.7 GeV: April 25—May 27



1.5 M minimum bias events recorded @ 7.7 GeV (twice better than expected)

$\sqrt{s_{NN}}$	Fluctuations in $\langle n \rangle$	Fluctuations in $\langle p_t \rangle$	PID spectra, identified particle ratios	longitudinal density correlations	critical exponent η	
5.5	0.01	0.03	0.03	2		M evts
7.7	0.01	0.03	0.02	2		

Particle production and fragmentation at 7.7 GeV



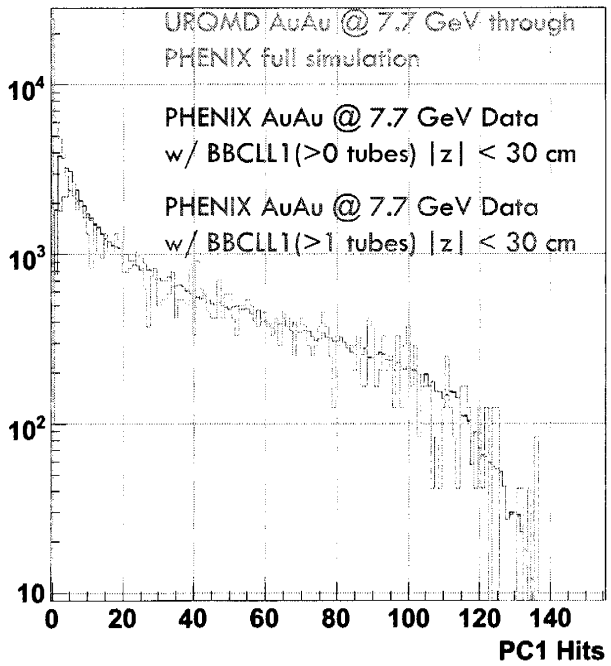
Run-10 AuAu @ 7.7 GeV

72,078 events total up to Run Number 315,999 passing BBCLL1(>1 tubes) and |z| < 30 cm.

Is there hidden background?

Very similar to what was seen at 9 GeV and expected from URQMD + fragmentation model

Background check: negative



URQMD normalized to match real data integral for PC1 hits > 40.

URQMD not matched to z distribution in real data. **<u>However, note that there is no rescaling of the x-axis.</u>**

Then comparing the integrals implies (as a first look) that the BBCLL1(>0 tubes) fires on 77% of the cross section and the BBCLL1(> 1 tubes) fires on 70% of the cross section.

No indication of deviation at low PC1 hits from background (at least by this particular check).

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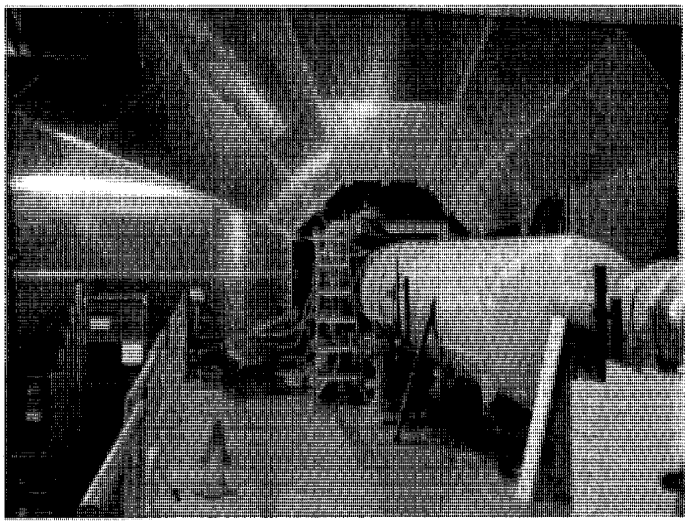
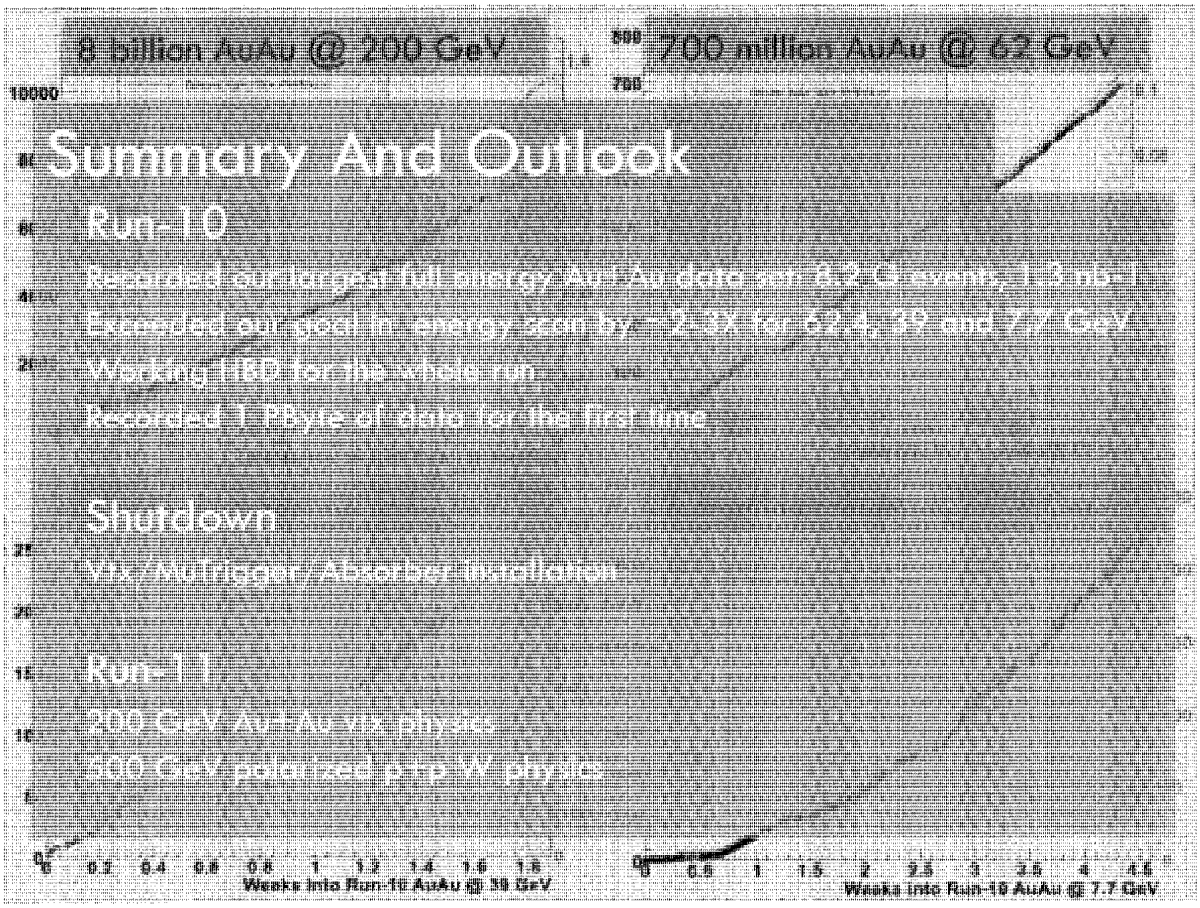
7.7 GeV success—Now on to 11.5, i.e. RPC commissioning

Muon Trigger Commissioning

- No collisions in PHENIX @ 11.5 GeV
- Commissioned new muon detectors with cosmic rays instead
- Crucial for next year's W physics program





Pixel detector
at
PHENIX Vertex Tracker
as of Now

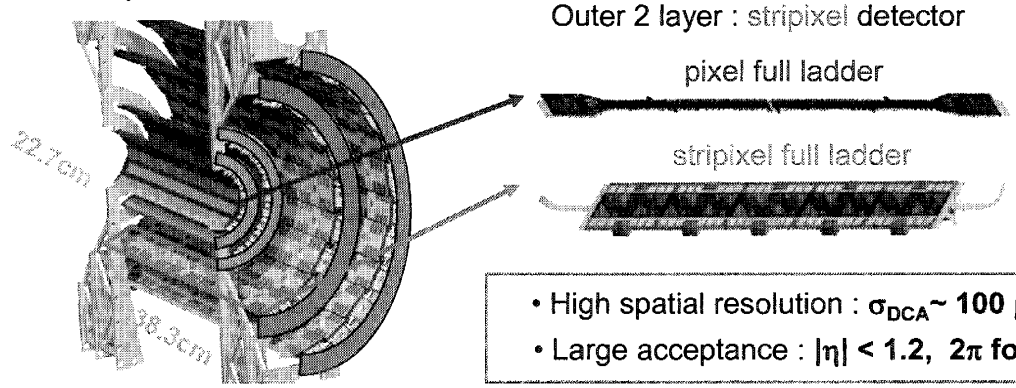
Atsushi Taketani

RIKEN Nishina Center Detector Team

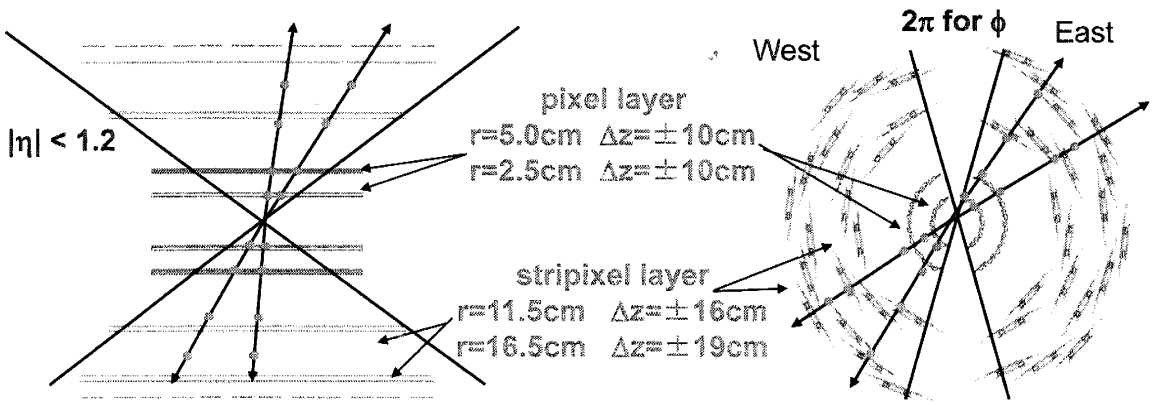
RIKEN Brookhaven Research Center

Silicon Vertex Tracker (VTX)

4 layers barrel structure → Inner 2 layer : pixel detector
Outer 2 layer : stripixel detector

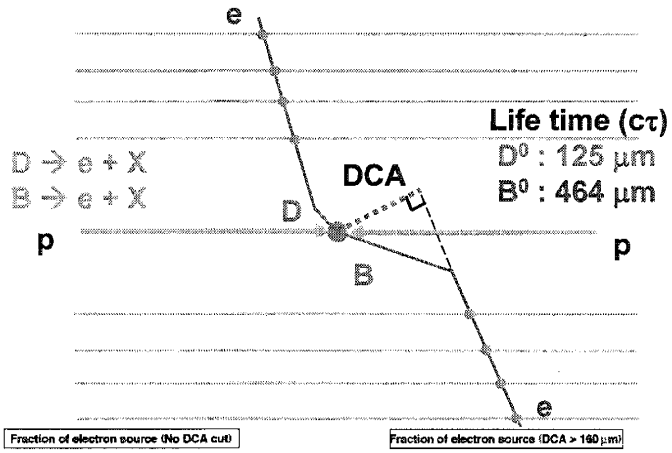


- High spatial resolution : σ_{DCA}~ 100 μm
- Large acceptance : $|\eta| < 1.2$, 2π for ϕ

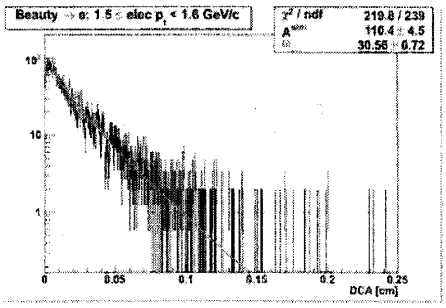


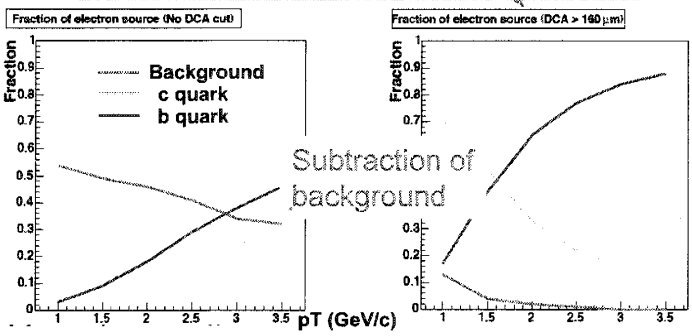
Identifying heavy flavor production by VTX

charm and beauty separation with difference of their life time



DCA by detailed simulation





SPIN

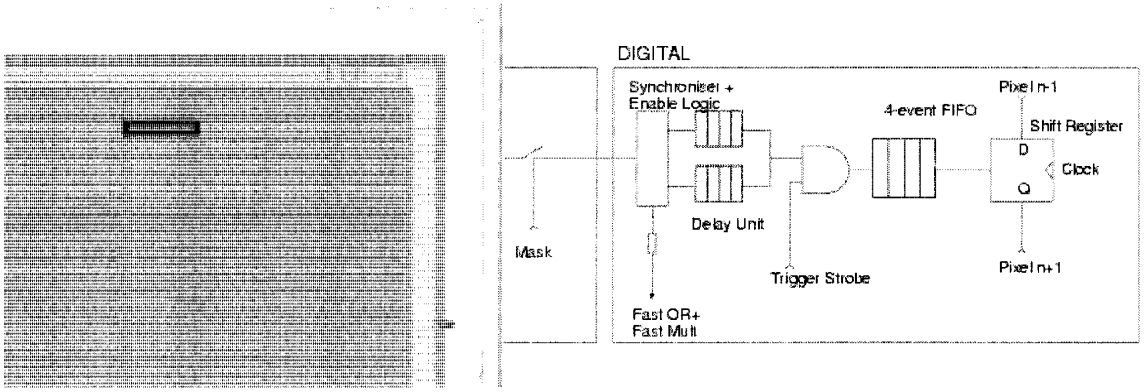
- Gluon polarization by heavy flavor production
- Gluon polarization sign by jet + Gamma event

Heavy Ion

- Enhancement charm
- Open beauty production
- Flavor dependent energy loss in QGP

3

PIXEL (Sensor and Readout)



Pixel size(Φ x z) 50 μm x 425 μm
Sensor Thickness 200μm
ΔrΦ = 1.28cm, Δz = 1.36 cm (Active area)
256 x 32 = 8192 channel / sensor
4 chip / sensor
4 sensor / stave

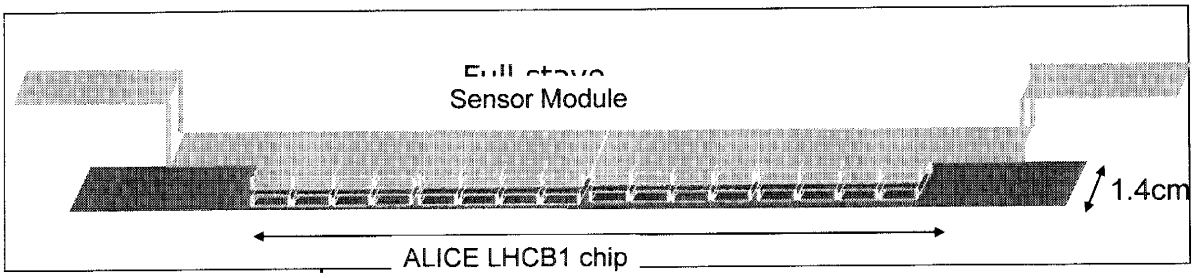
Readout by ALICE_LHCB1 chip

- Amp + Discriminator / channel
- Bump bonded to each pixel
- Running 10MHz clock (RHIC 106nsec)
- Digital buffer for each channel > 4μsec depth
- Trigger capability > FAST OR logic for each crossing
- 4 event buffer after L1 trigger

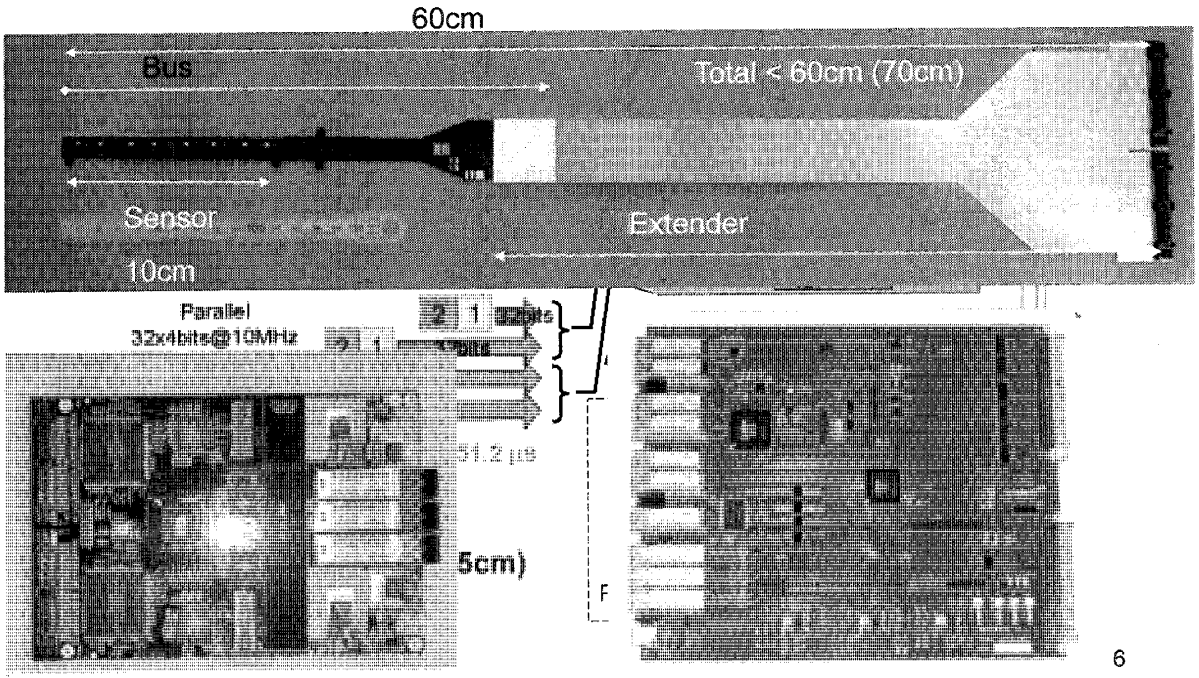
4

Pixel ladder structure

- Sensor module consists of 4 ALICE Pixel readout chips Bump-bonded to silicon sensor
- One readout unit, half stave, made from two sensor modules
- Half stave is mounted on the support structure
- Pixel BUS to bring data out and send control signal in to the readout chip is mounted on the half stave
- Each detector module is built of two half staves, read out on the barrel ends



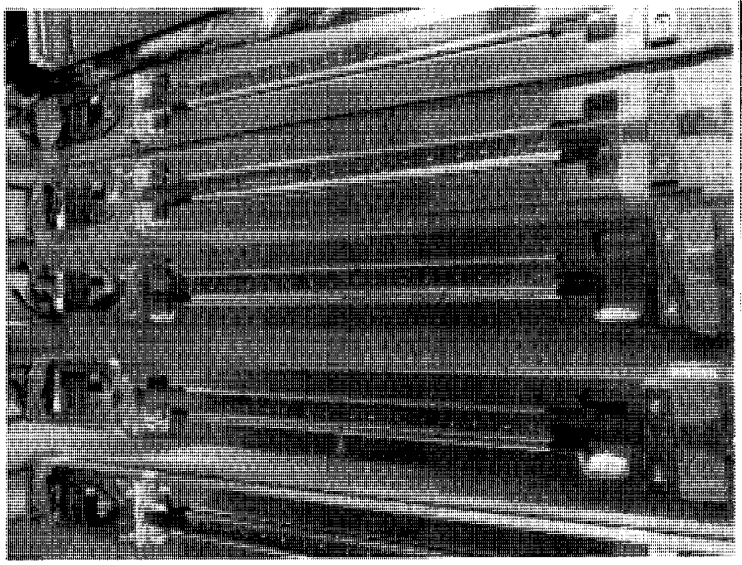
Pixel Readout Overview

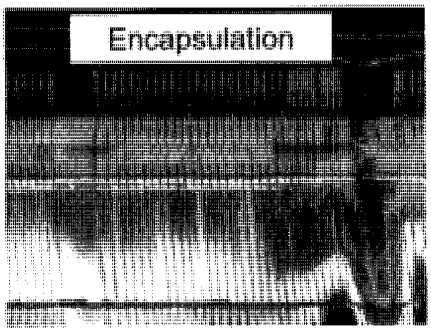


SPIRO: Ecole Polytechinque + RIKEN

Front End Module: Stony Brook

Pixel Ladder Production





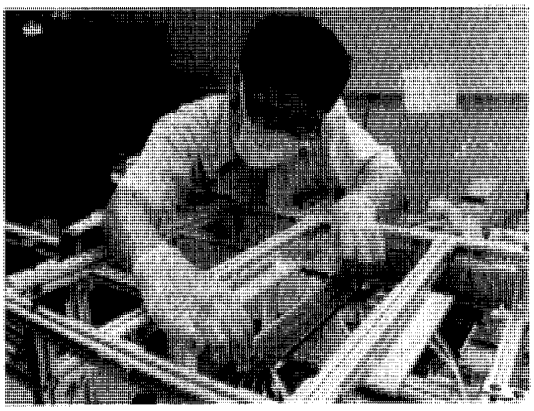
All parts Q.A.@RIKEN
↓
Assemble@REPIC Co.
↓
Q.A.@RIKEN
↓
Encapsulation@IDEA Co.
↓
Q.A.@RIKEN
↓
BNL for Detector Assembly

Parts : Sensor + Readout Chip by CERN
Carbon Stave by LBNL
Readout Bus by RIKEN

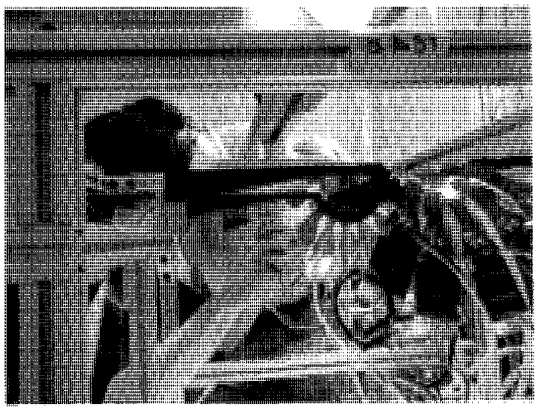
Necessary Ladders are produced and delivered to BNL.

Ladder on Barrel mount

Putting ladder

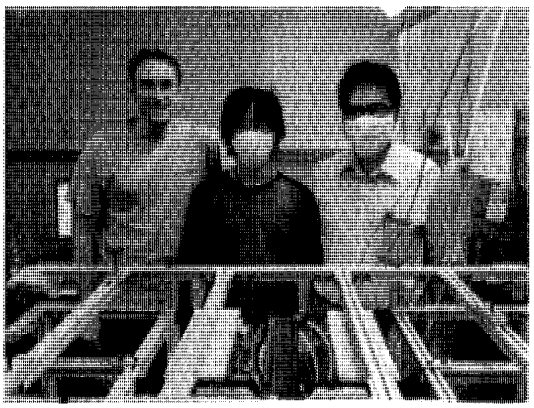


Screw up

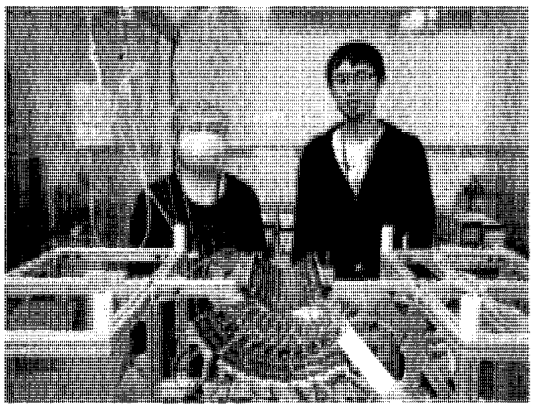


West Detector Assemble

West Layer 1 @Sep 1st.



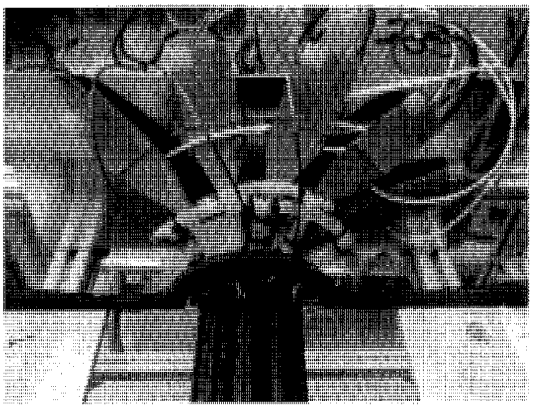
West Layer 2 @ Sep 22nd.



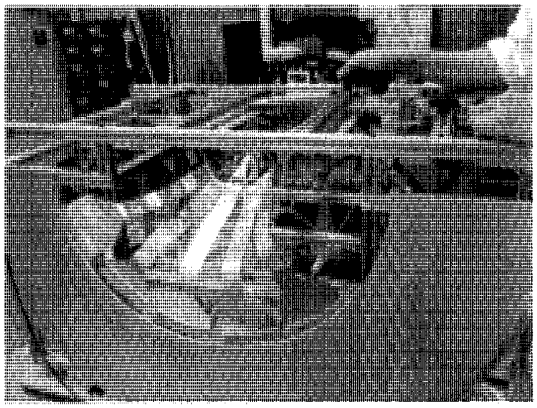
9

Service and Readout electronics

Cooling tubes and thermo couples



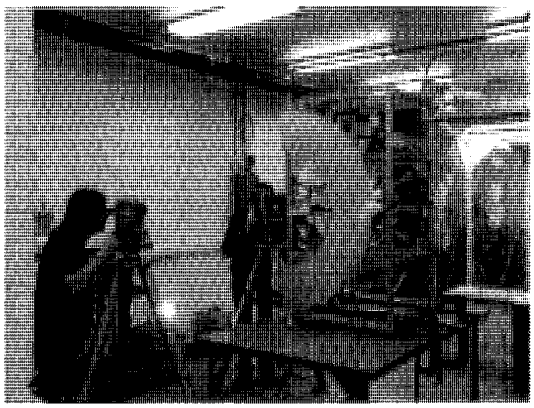
Extender and SPIRO



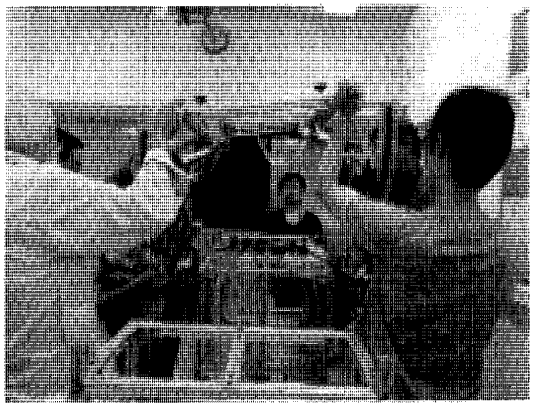
10

Survey and mating

Survey West L1

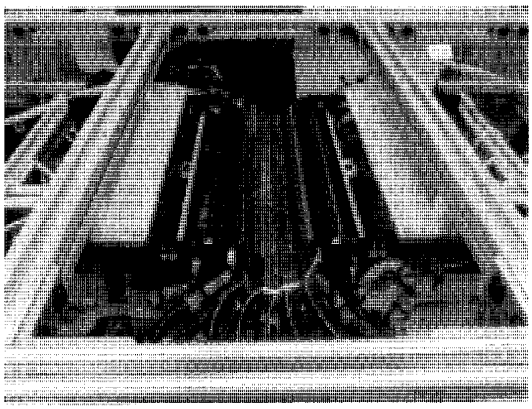


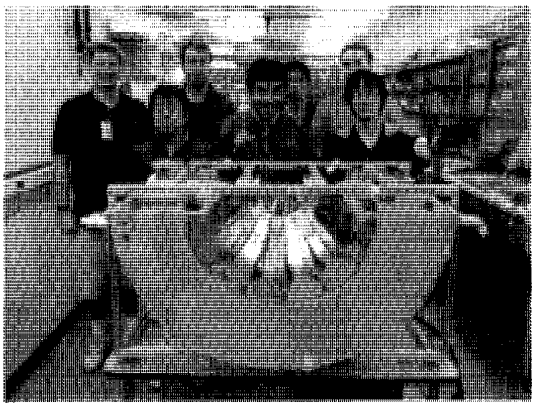
Mating West L1 and L2
Yesterday morining



11

As of Yesterday





- West 1st and 2nd layer are mated and confirmed working perfectly as of 18:11 yesterday.
- West Pixel and Stripixel will be mated in a few days.
- West arm of VTX will be completed in this week.
- East 1st and 2nd layer are ready to survey.
- East VTX will be completed in next week.
- VTX will be installed in Nov.

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Active Pixel people as of 2010/10

RIKEN/RBRC VTX group as of 2010 Oct.

VTX Detector Council: Y. Akiba

Pixel Subsystem Manager : A. Taketani

Post Doc: M. Kurosawa, S. Baumgart, T. Hachiya, J. Koster

Technician: J. Kanaya

JRA: H. Asano (Kyoto), R. Akimoto (Tokyo)

City University of New York *S. Bathe* + Grad. Student

University of Massachusetts *D. Kawall* + PosDoc

Columbia University

Iowa State University

Japan Atomic Energy Agency K. Imai's group.

KEK

Rikkyo University *Kazu Kurita* + Grad. Students

Stony Brook University

Tokyo metropolitan industrial technology research institute *K. Fujiwara*

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Summary

- RIKEN has been in charge of development and construction of Pixel detectors.
- As of Yesterday, West L1 and L2 were mated and East are ready to survey and mate.
- PHENIX Silicon VTX will be installed in Nov and will extend Spin and Heavy Ion physics by identifying b and c separately.

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BROOKHAVEN NATIONAL LABORATORY

RIKEN BNL Research Center

PHENIX

Upgrade with Silicon Vertex Tracker

Silicon Stripixel Detector Status

Rachid Nouicer
Brookhaven National Laboratory (BNL)
Research Affiliate of RIKEN-BNL Research Center

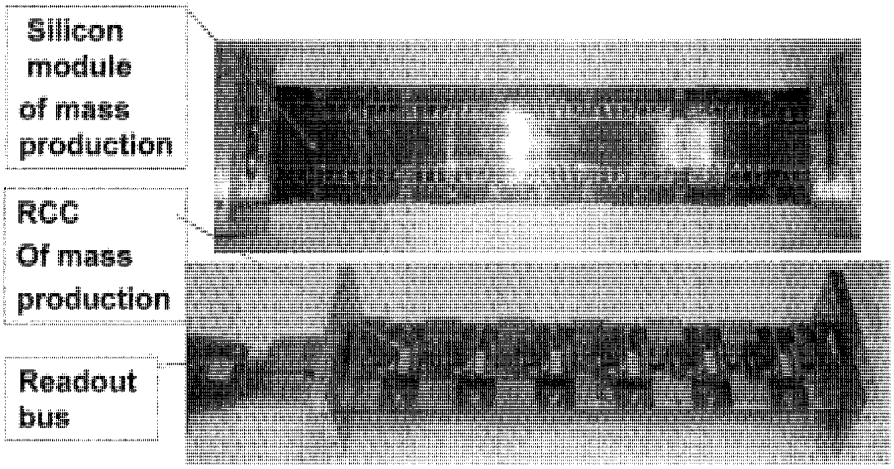
1. Executive Summary

2. Current Status

Annual RBRC Scientific Review, October 27th 2010

Executive Summary I:

- **October 2009: First prototype stripixel ladder**



- Top view (6 silicon modules)
- Bottom view (6 RCCs)

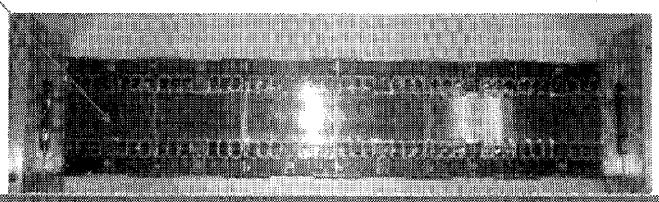
- 6 silicon modules from mass production (1st article)
- 6 RCC from mass production (1st article)
- 1 readout buses as mass production (28 inches)

Executive Summary I:

- **October 2009: First prototype stripixel ladder**

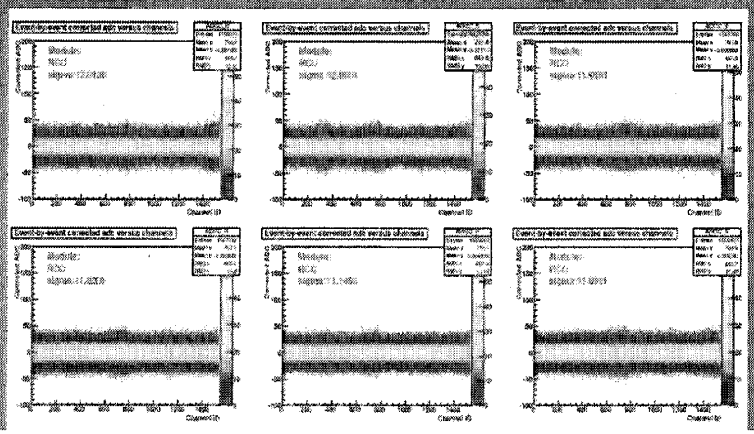
Silicon module of mass production

RCC



- Top view (6 silicon modules)

Pedestal distributions for each module (modules readout simultaneously)

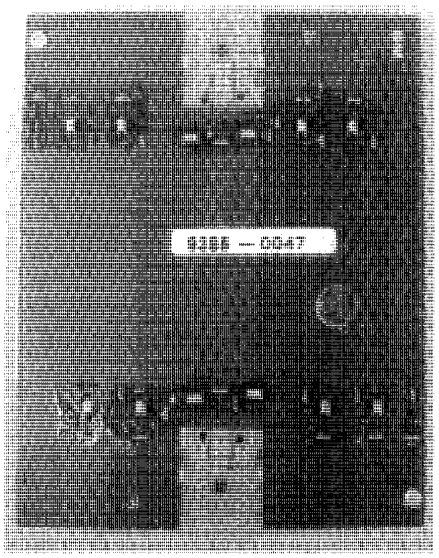


Executive Summary II:

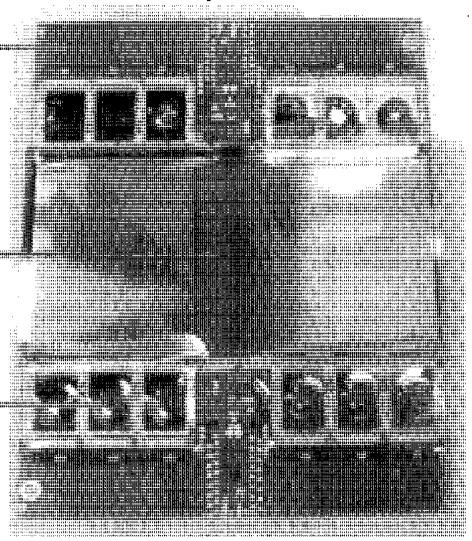
- **October 2010:**

Achievement #1: **we built and tested successfully 246 (224 needed) silicon modules for the stripixel Detector**

- Bottom view



- Top view



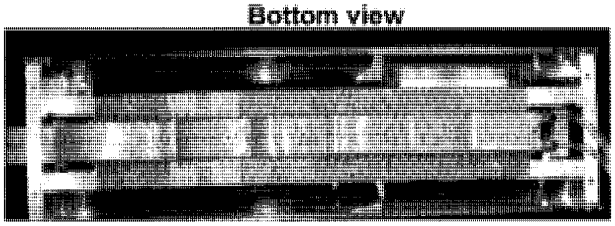
Executive Summary II: 5

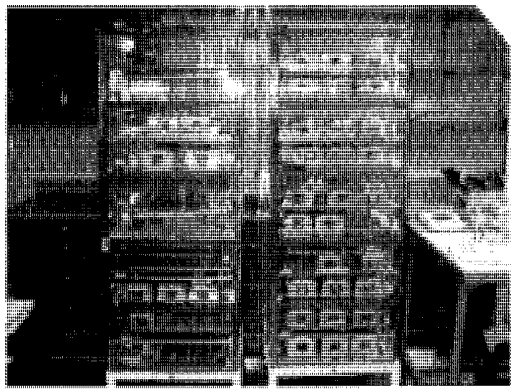
- October 2010:

Achievement #2: **we built and tested successfully 42 (40 needed) silicon ladders for the stripixel Detector**

Top view

Bottom view





42 ladders in desiccator cabinets

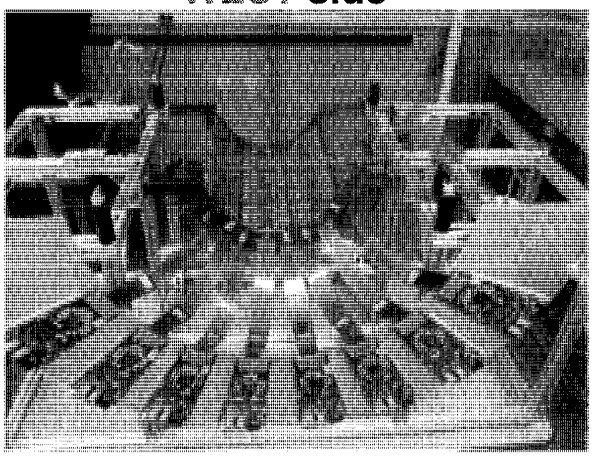
Executive Summary II: 6

- October 2010:

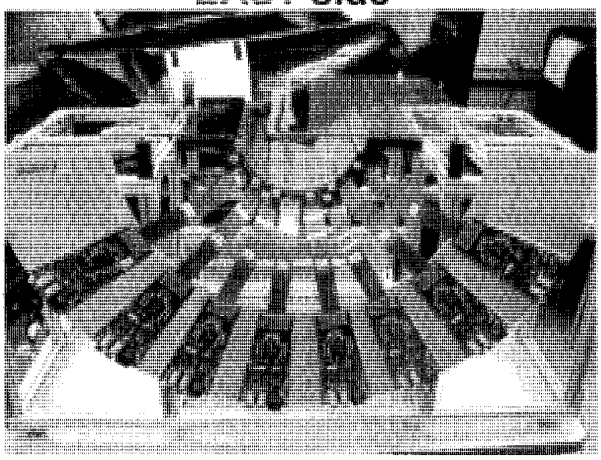
Achievement #3: **Stripixel detector was built and successfully tested at the lab. It's moving to PHENIX-IR to take data of RUN-11 and beyond**

Barrel 3: ready

WEST side



EAST side



Barrel #3 has 16 ladders (1 ladder has 5 silicon modules): 80 silicon modules

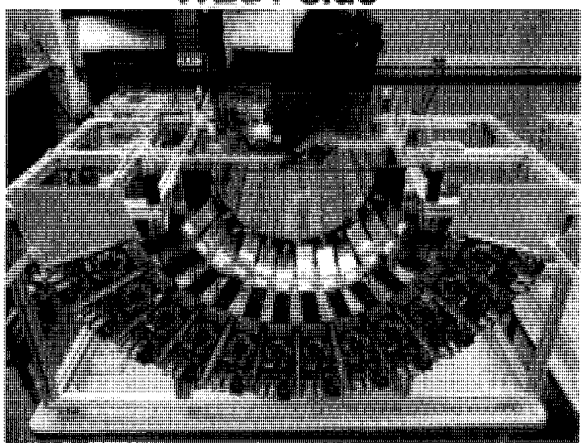
Executive Summary II:

- October 2010:

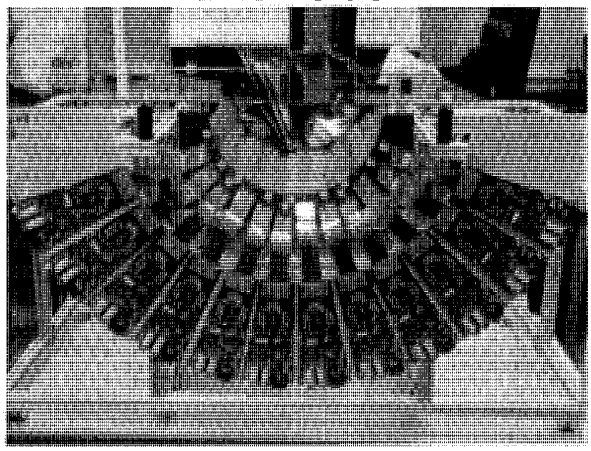
Achievement #3: **Stripixel detector was built and successfully tested at the lab. It's moving to PHENIX-IR to take data of RUN-11 and beyond**

Barrel 4: ready

WEST side



EAST side



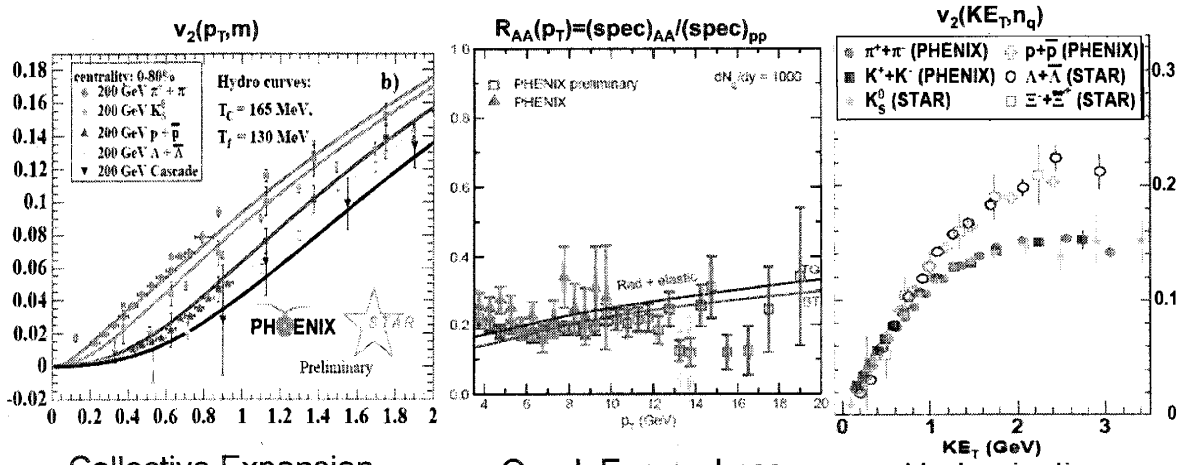
Barrel #4 has 24 ladders (1 ladder has 6 silicon modules): 144 silicon modules

Current Status

Motivation of the VTX Project

What the main physics motivation for building VTX detector?

Answer: Discoveries; study the properties of matter created at RHIC

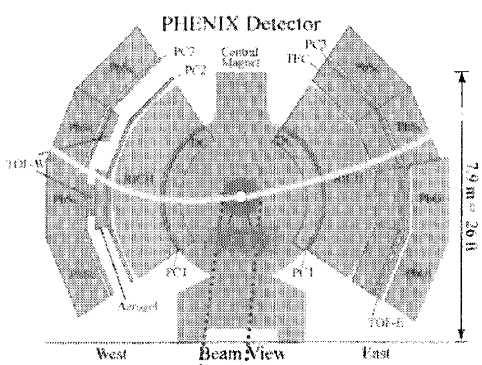


Collective Expansion | Quark Energy-Loss | Hadronization

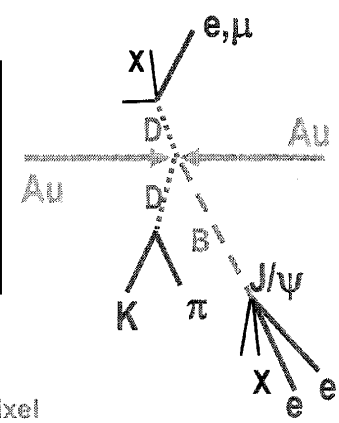
Strongly-interacting matter has been created in central Au+Au at 200 GeV

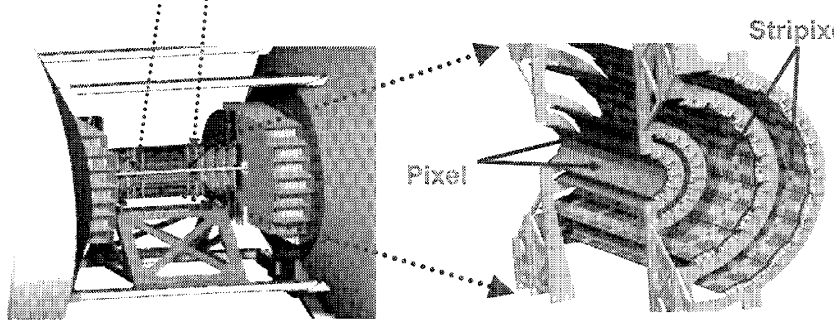
Physics Motivation

- Heavy flavor (c and b quarks) are produced in the early stages of heavy ion collision
- Experimentally easy to observe Semi-leptonic decays



	Mass (MeV)	cτ (μm)
D^0	1865	125
D	1869	317
B^0	5270	464
B	5279	496

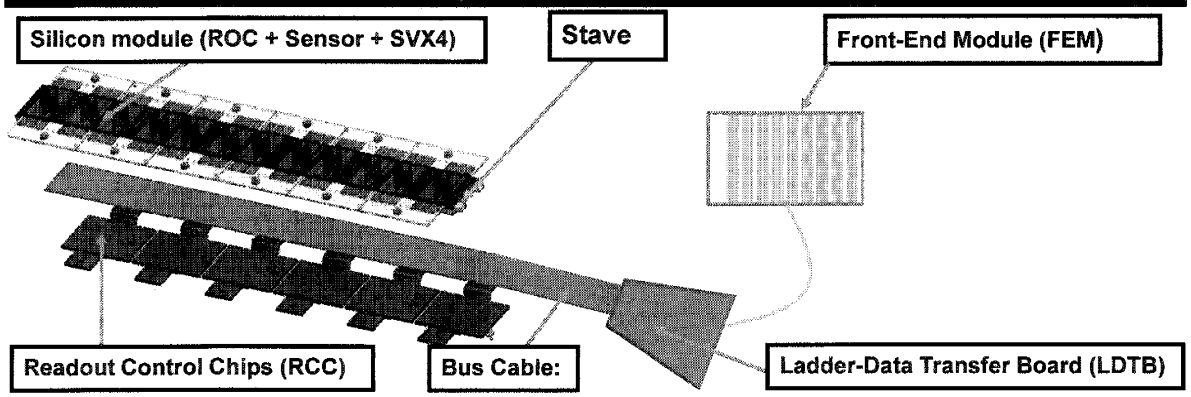




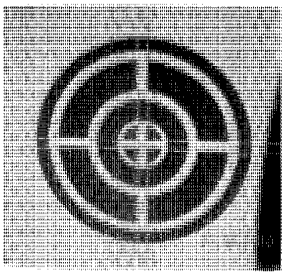
-Large acceptance ($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)

-Displaced vertex measurement $\sigma < 40\ \mu m$

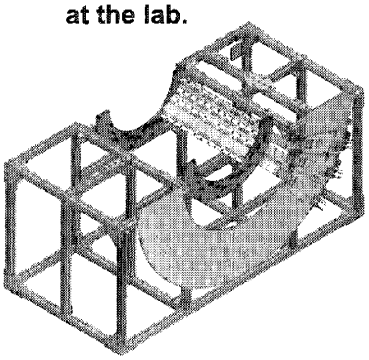
Outline (Progress Timeline)

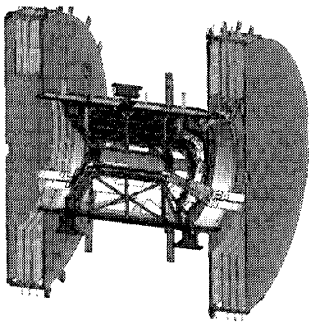


- Silicon modules survey on ladder at the lab.



- Assembly and testing of ladders and barrels at the lab.





October 27th, 2010

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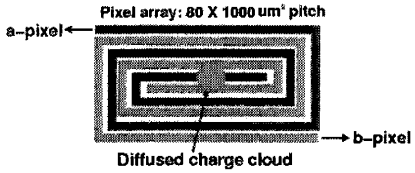
Status of Silicon Modules Mass Production:

- Assembly, alignment and testing

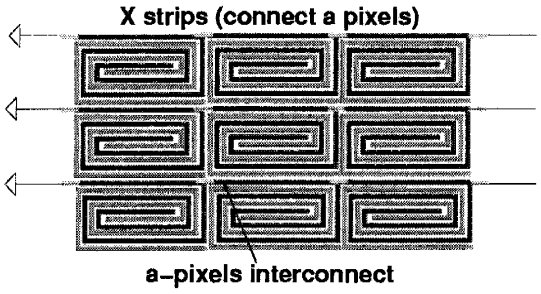
Silicon Stripixel Concept (Barrels 3 &4)

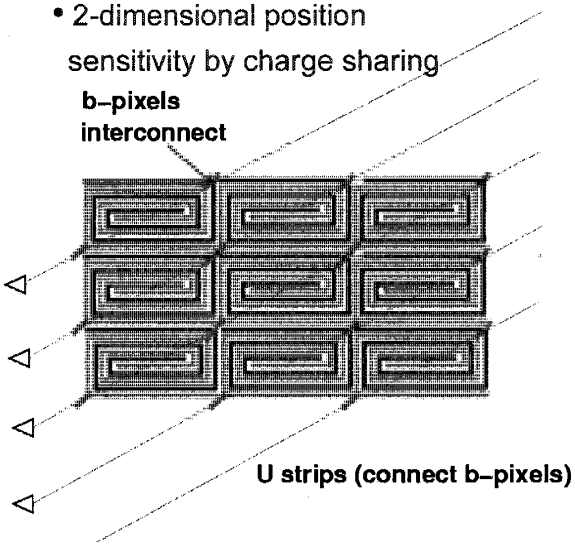
"New technology: unique to PHENIX"

- Innovative design by BNL Instr. Div. : Z. Li et al., NIM A518, 738 (2004);
- R. Nouicer et al., NIM B261, 1067 (2007);
- R. Nouicer et al., Journal of Instrumentation, 4, P04011 (2009)



- DC-Coupled silicon sensor
- Sensor single-sided
- 2-dimensional position sensitivity by charge sharing





October 27th, 2010

Status of Silicon Modules Mass Production

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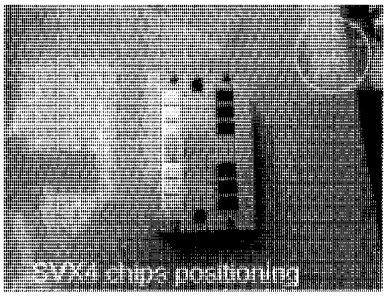
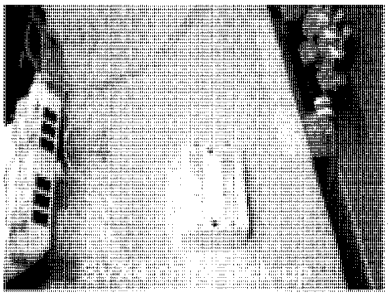
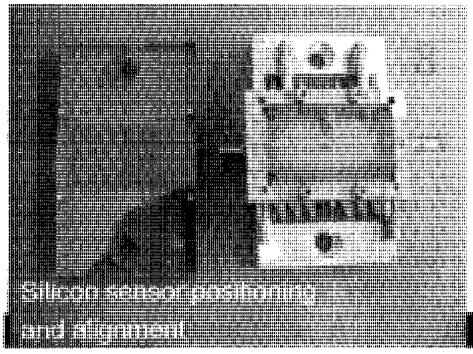
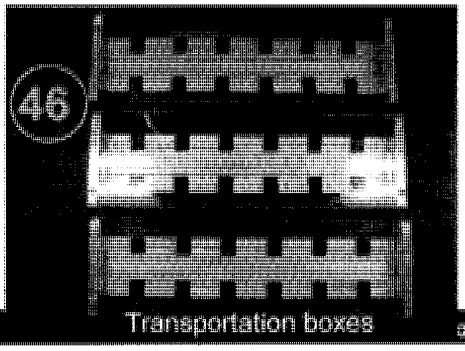
- Assembly fixtures for silicon module assembly were made at BNL









Status of Silicon Modules Mass production

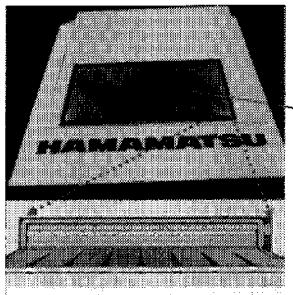
15

- **Achieved at FNAL using VTX and FNAL manpower**
  - wire-bonding, encapsulation of the ROC-SVX4-Sensor and precision placement of the silicon sensor (FNAL)
  - Mounting SVX4 on ROC (VTX manpower)
  - Testing (VTX manpower) and production manager (VTX)
- **Team:** Tammy Hawke (FNAL, wire-bonding), Mike Herren (FNAL, encapsulation), Bert Gonzalez (FNAL, sensor), Steve Kaneti (SBU),Paul Kline (SBU), Andrew Manion (SBU), Lei Ding (ISU) , Philippe Castera (BNL) and Rachid Nouicer (BNL, training people and ensuring success)

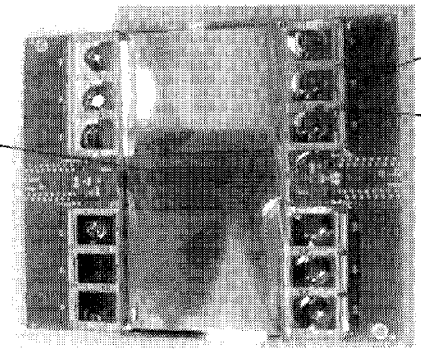
The silicon modules mass production assembly, testing and database were completed successfully: 246 silicon modules (224 needed)

Stripixel Silicon Module: Pedestal Distribution

Silicon sensor

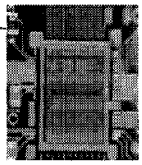


One silicon module



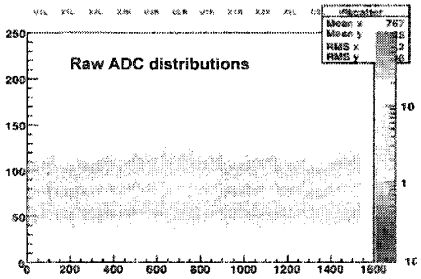
ROC (readout silicon module)

SVX4 chip

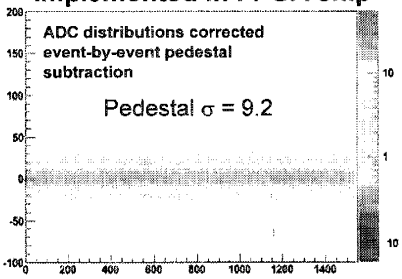


- 8 bit ADC
- 128 channel / chip
- 3 mW / channel

- **Results:**
  - **Online plot**



- **Offline analysis: implemented in FPGA chip**



Silicon sensor+ ROC+SVX4 chips were successfully tested

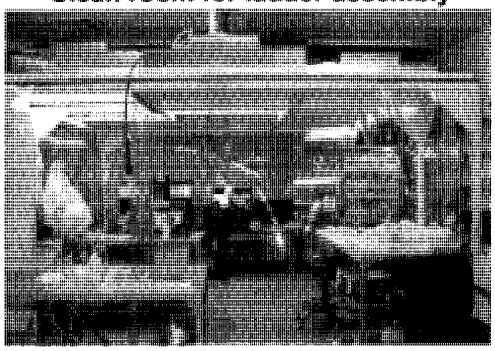
Status of Ladders Mass Production

- Assembly, survey and testing

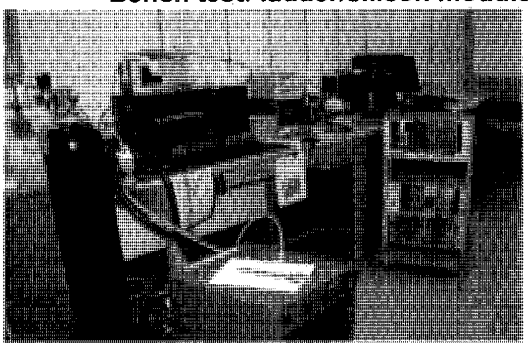
Status of Ladders Mass Production (started on June 3, 2010) 18

- The ladders assembly, testing and survey achieved at BNL using VTX manpower

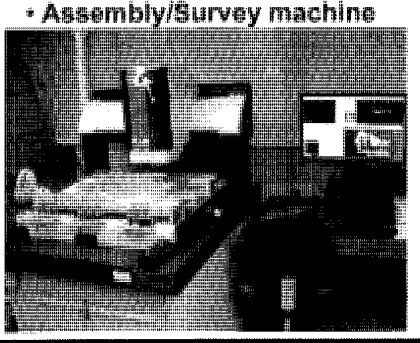
- Clean room for ladder assembly



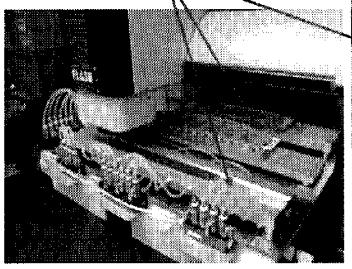
- Bench test: ladder/silicon modules

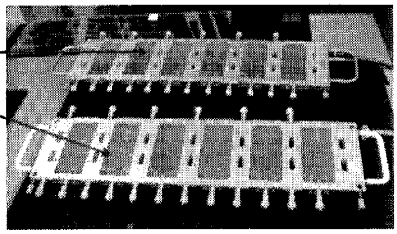


- Assembly/Survey machine



- Assembly fixtures





Status of Ladders Mass Production

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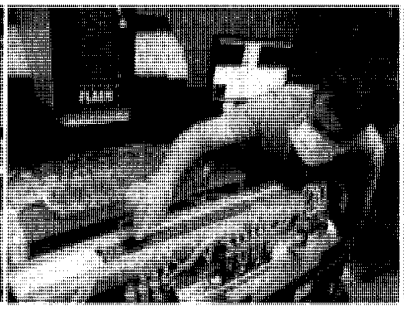
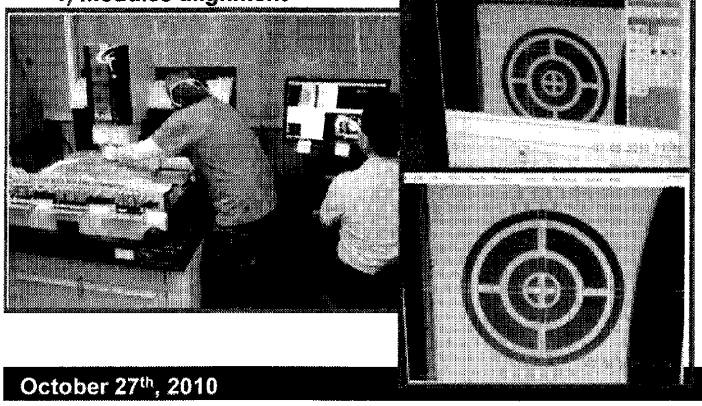
1) Laser scan of the stave (flatness)

2) Dow Corning glue: 150 [um]

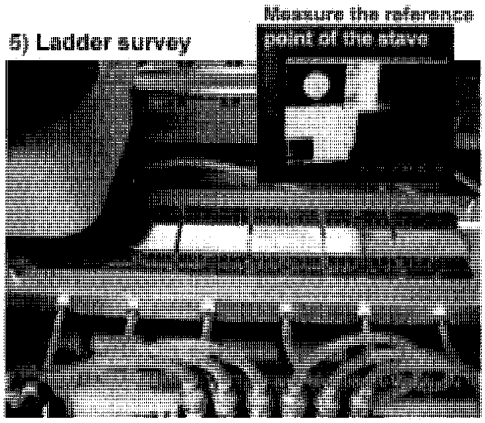


3) Placing modules on stave

4) Modules alignment



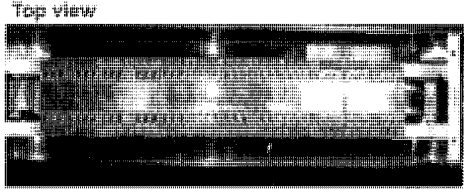
5) Ladder survey



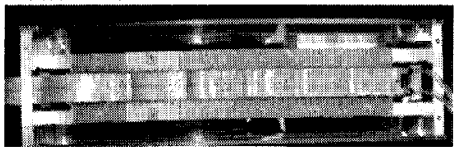
Status of Ladders Mass Production

20

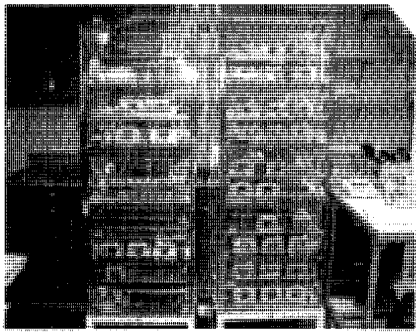
Top view



Bottom view

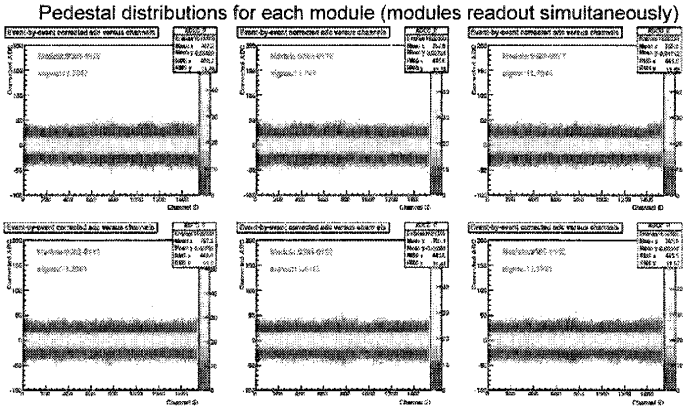


42 ladders in desiccator cabinets



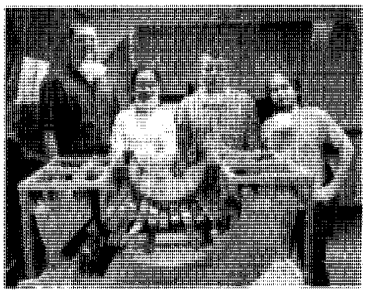
Testing team: Swadhin T., Paul K., Andrew M., Lei D., Philippe C., Brian V., Sookhyun L., Sankalpa K., and Ciprian G.

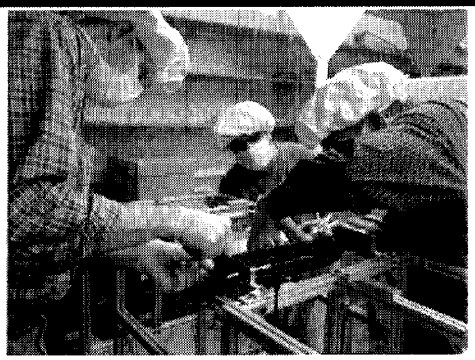
Pedestal distributions for each module (modules readout simultaneously)



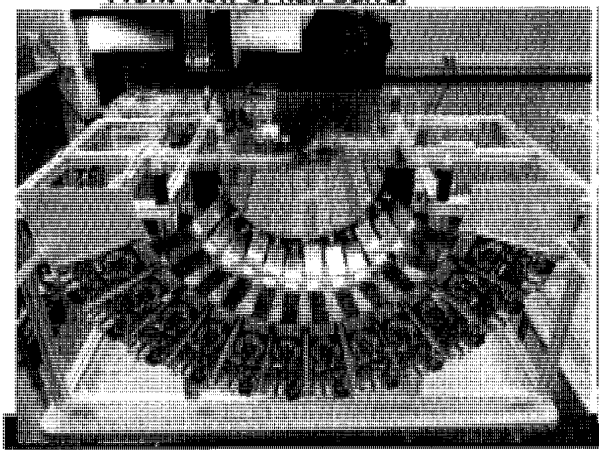
Barrels:
- Assembly and testing

Barrels Assembly and Testing at the Lab.

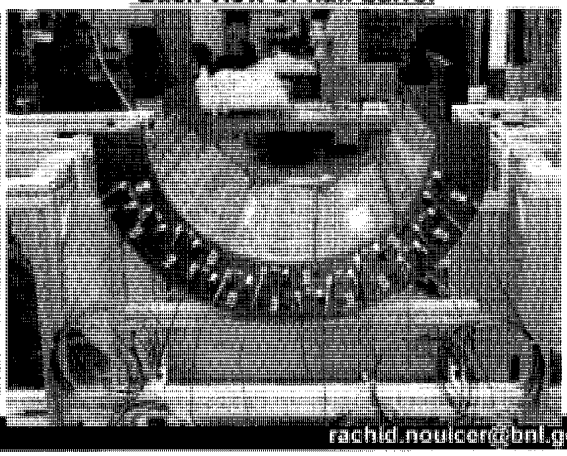




- Front view of half barrel



- Back view of half barrel

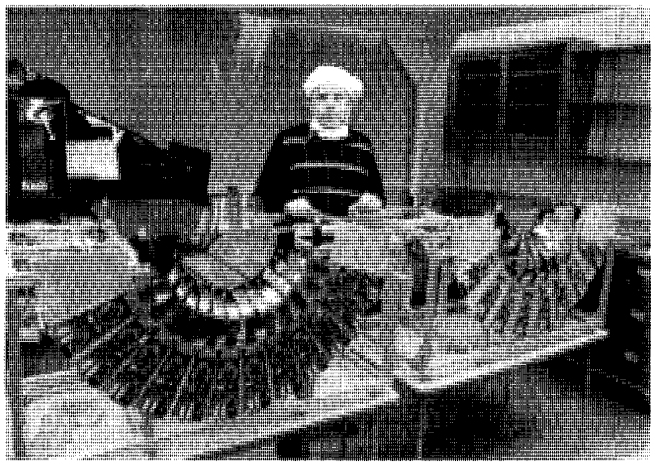


Barrels Assembly and Testing at the Lab.

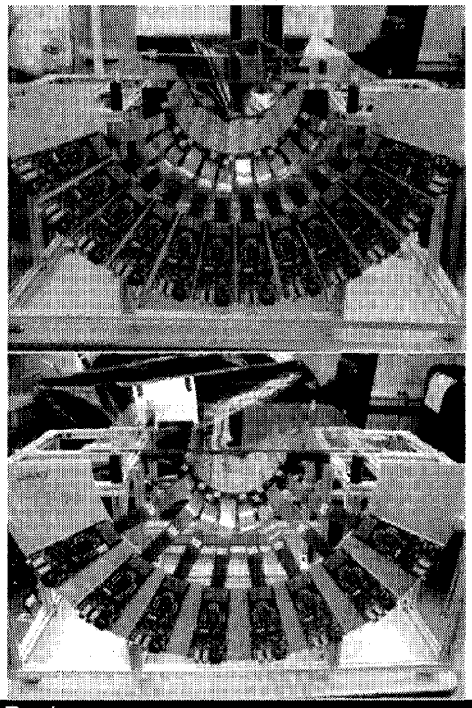
23

- All barrels completed and tested successfully: done

West

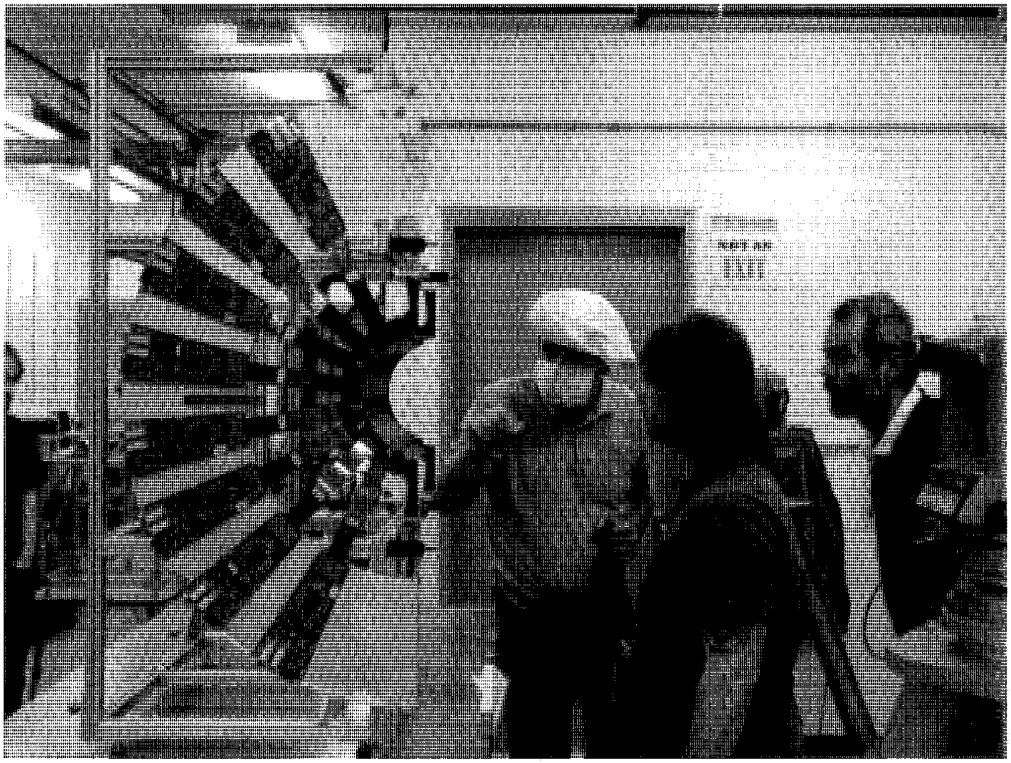


East



Survey

24



Manpower participating in the assembly, testing and survey 25

Summary 26

Achievement: Stripixel detector was built and successfully tested at the lab. It's moving to PHENIX-IR to take data of RUN-11 and beyond

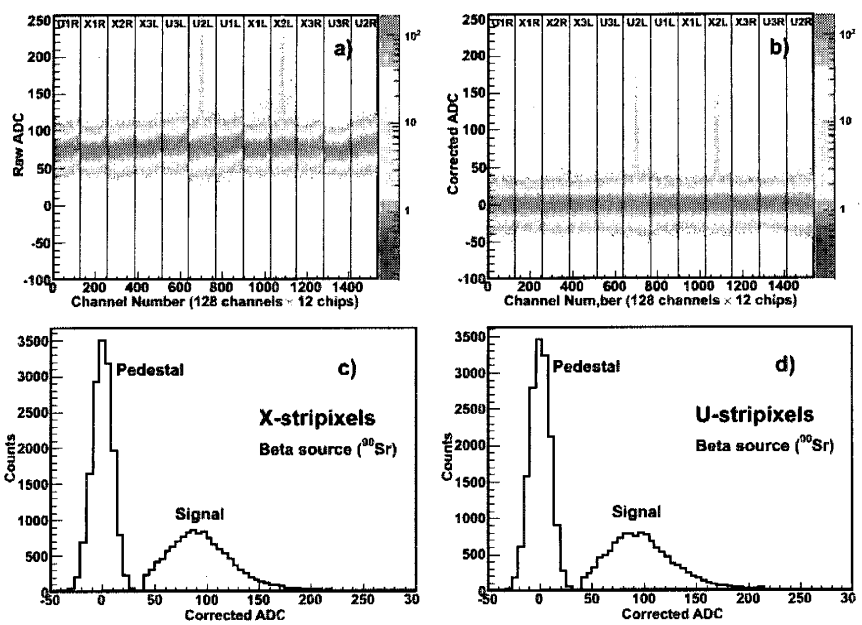
- Still to be done:
  - Installation in PHENIX-IR
  - Commissioning of the detector

- Manpower participating in the assembly, testing and survey: Lei Ding (ISU), Brian Vaos (ISU), Paul Kline (SBU), Andrew Manion (SBU), Ciprian Gal (SBU), Swadhin Taneja (SBU), Kieran Boyle (RBRC), John Chen (SBU), Yasuyuki Akiba (RIKEN), John Koster (RBRC), Akitomo Enokizono (ORNL), Yuri Efremenko (ORNL), Richard Ruggiero (BNL), Mike Lenz (BNL), and Rachid Nouicer (BNL).

Auxiliary Slides

Response to Electrons from ^{90}Sr Beta Source

- Silicon Module Using ROC-3: Excellent Charge Sharing



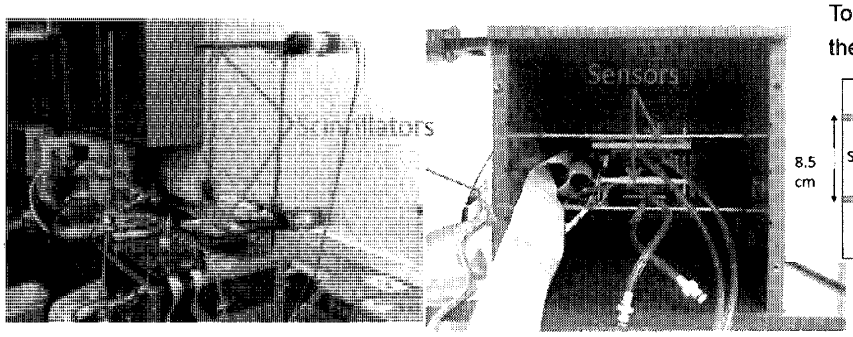
- For x channels

HV(V)	Pedestal [σ]	MPV	S/N
200	9.41	87.8	9.3

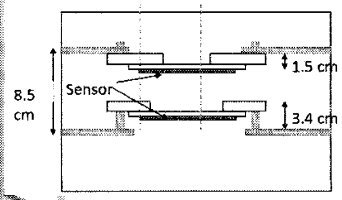
- For u channels

HV(V)	Pedestal [σ]	MPV	S/N
200	9.41	91.2	9.7

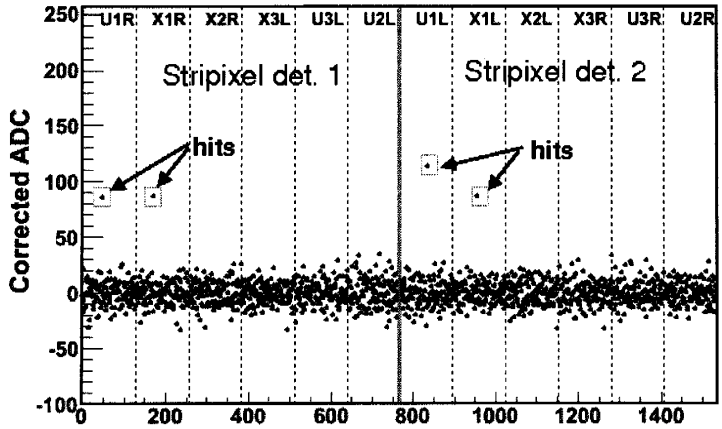
Response to Muons from cosmic-rays 29



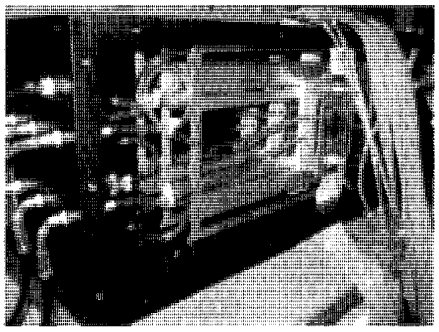
Top module is rotated so that the read-out region overlaps.

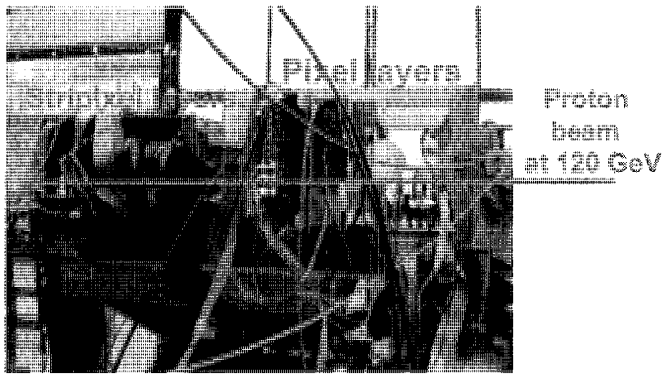


The tracks have been observed from cosmic-ray

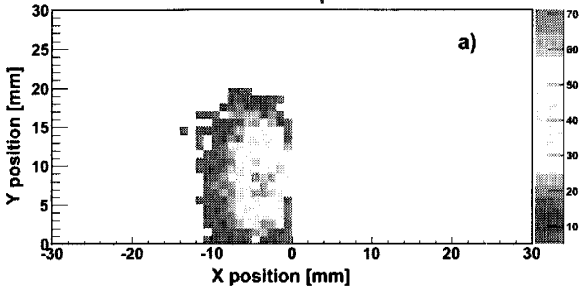


Response to Proton Beam at 120 GeV (FNAL) 30

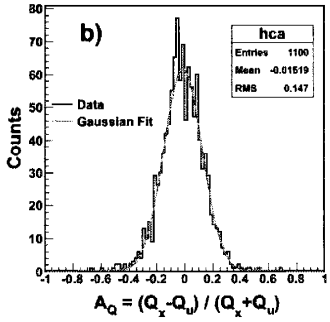




- Profile of the proton beam



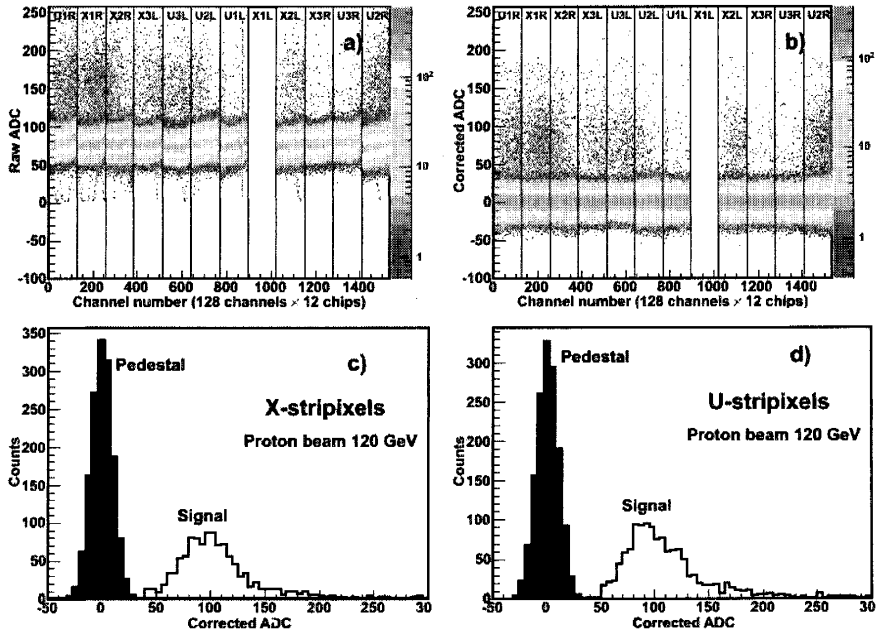
- Charged Sharing



Principal of two-dimensional position sensitivity based on charge sharing works

Response to Proton Beam at 120 GeV (FNAL) 31

- Signal-to-Noise Ratio



- For x channels

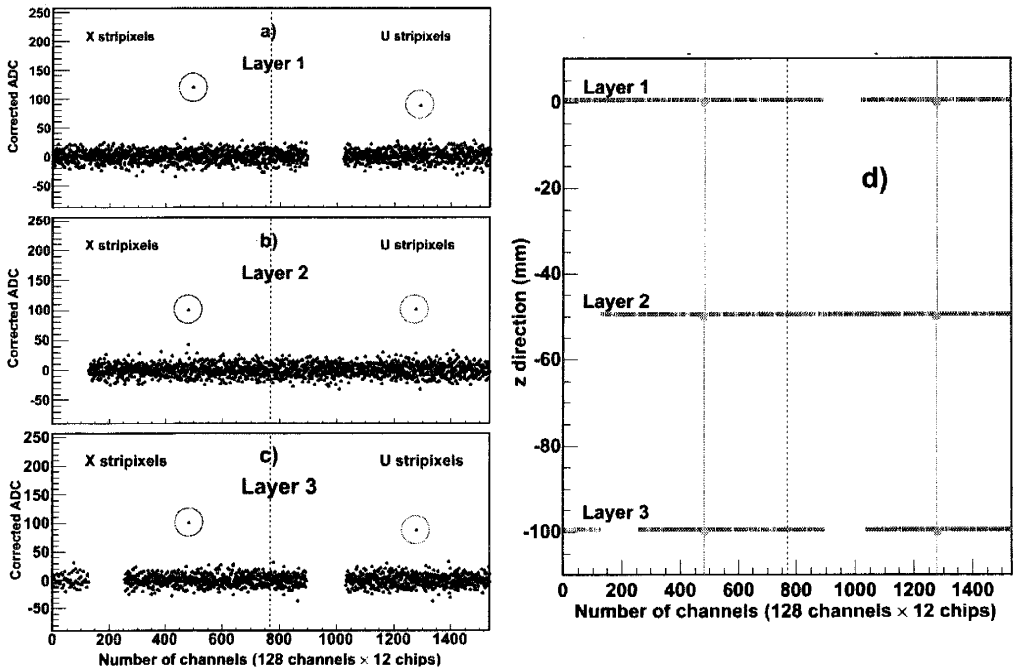
HV(V)	Pedestal (σ)	MPV	S/N
200	9.6	98.6	10.3

- For u channels

HV(V)	Pedestal (σ)	MPV	S/N
200	10.1	102.2	10.1

Response to Proton Beam at 120 GeV (FNAL) 32

- Single Event Tracking: Linear Fit Track

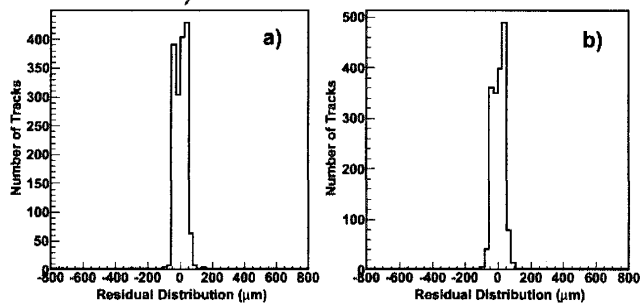


Response to Proton Beam at 120 GeV (FNAL)

33

- Residual distribution (position resolution)

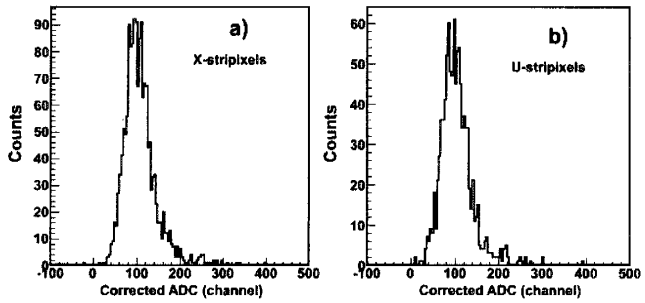
- X-stripixel 0.42 x 80 (μm) = 33.6 (μm)
- U-stripixel 0.44 x 80 (μm) = 35.2 (μm)
  - from the RMS values
  (tracks are defined by layers 1 and 3).



- Tracking efficiency (detection efficiency)

- X-stripixel: 99.5 +/- 0.2 %
- U-stripixel: 98.9 +/- 0.2 %

Tracking efficiency very good

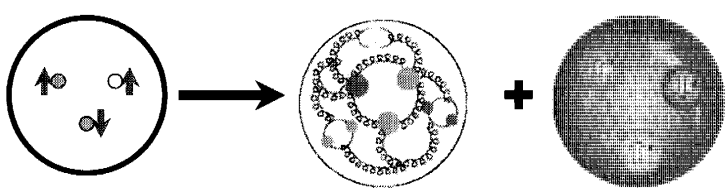


Spin Physics at RBRC

An overview of our current & near future activities

Abhay Deshpande
Stony Brook University
RIKEN BNL Research Center

Time evolution: Our Understanding of Nucleon Spin



1980s 1990/2000s

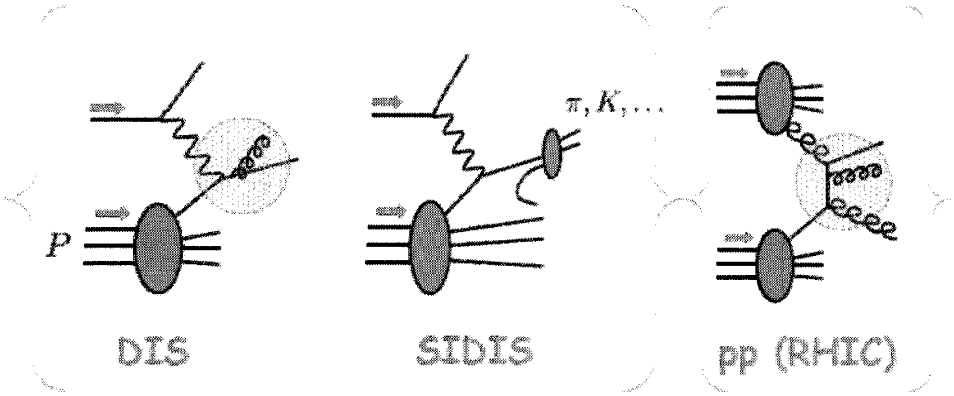
$$\frac{1}{2}\Delta\Sigma = \frac{1}{2}$$

$$\frac{1}{2}\Delta\Sigma + \Delta G = \frac{1}{2}$$

$$\frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G = \frac{1}{2}$$

$$J_Q + J_G = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G = \frac{1}{2}$$

Complementary probes of nucleon (spin) structure



DIS/SIDIS: virtual photon (colorless)

- Measures: only (ΔQ + ΔQbar), no LO interaction with gluons

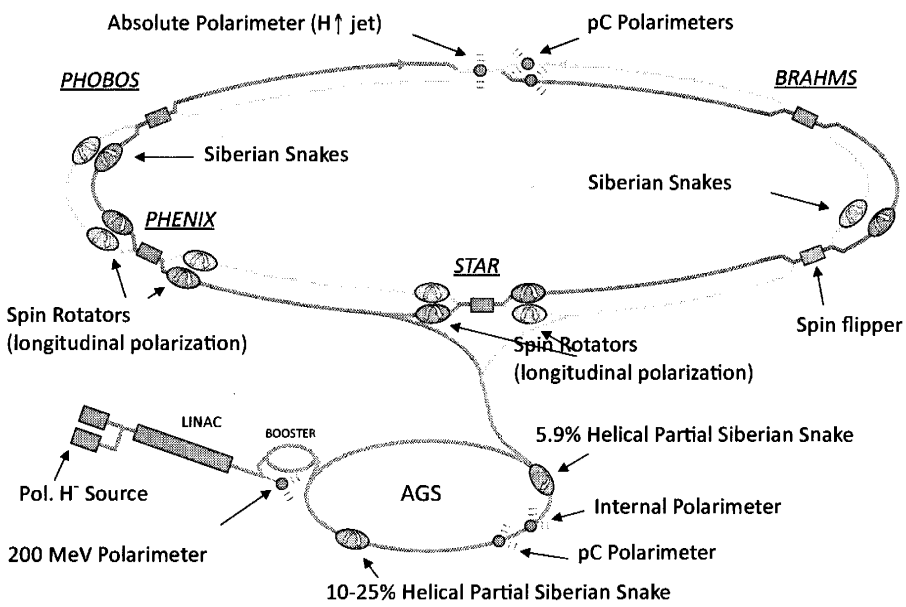
Hadron-hadron: → gluonic probe (color-full)

- Can explore gluons & quarks directly
- High energy has advantages in terms of reliability of PQCD

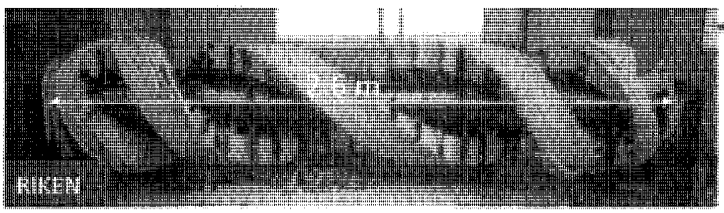
RHIC spin program

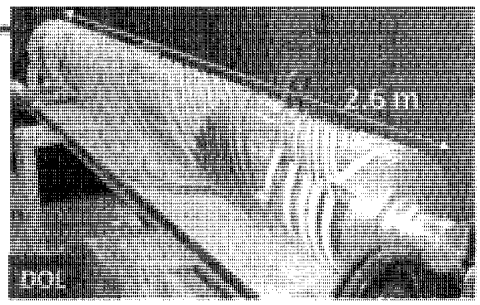
- Direct determination of the polarized gluon distribution ΔG(x) in the nucleon nucleon using multiple complementary measurements:
  - $\vec{p} + \vec{p} \rightarrow \left[\pi^{0,\pm},\ \eta,\ \gamma,\ \text{jet},\ q\bar{q}, ...\right] + X$
  - **Double longitudinal spin measurements**
- Direct determination of $\Delta\bar{q}$ using parity violating production and decay of $W^{+/-}$ at 500 GeV CM of collisions of polarized proton
  - $\bar{p} + p \rightarrow W^{\pm} \rightarrow (\mu/e)^{\pm} + \nu$
  - **Single longitudinal spin asymmetry measurements**
- Systematic study of transverse spin asymmetries to probe the transverse/spatial parton distributions & dynamics
  - **Multiple probes, different kinematics and their correlation to underlying physics**

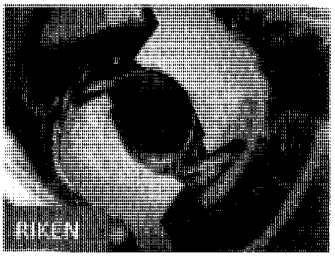
RHIC as a polarized proton collider



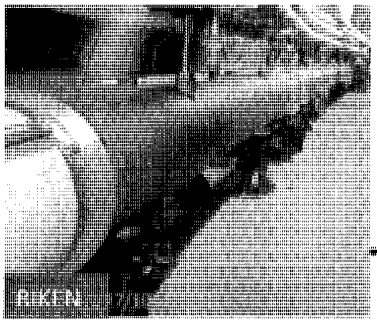
Siberian Snake Magnets

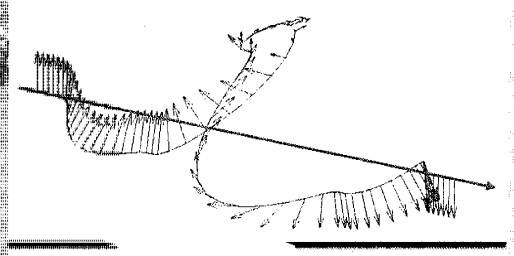


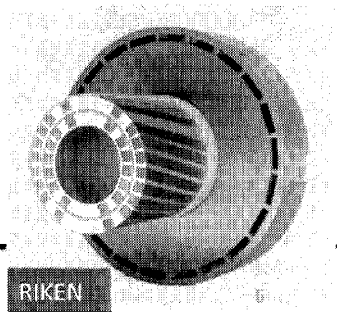




- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist







Courtesy of A. Luccio, T. Roser

PHENIX Detector

Central detectors:

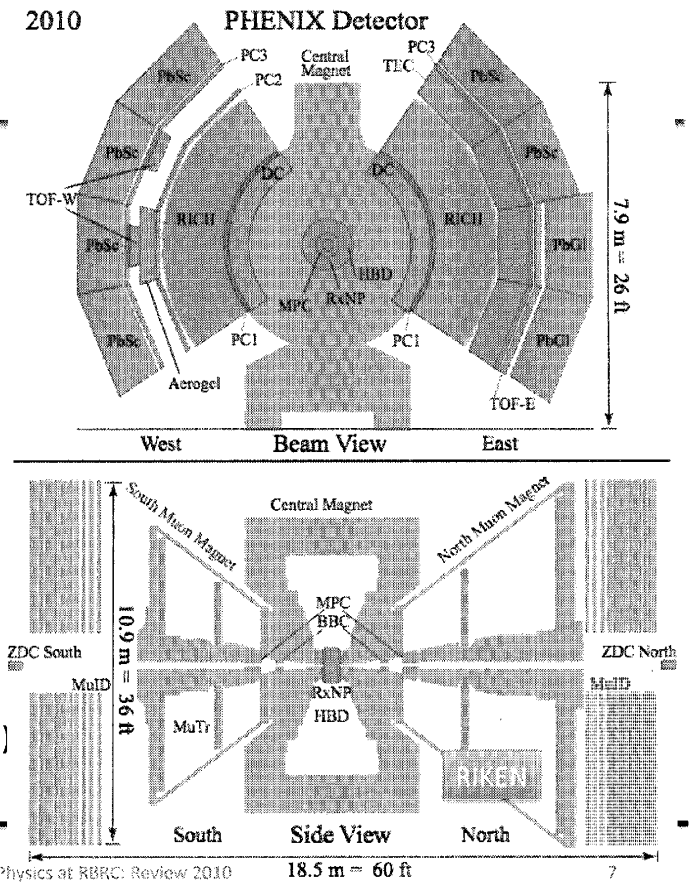
- EM Calorimetry
- Tracking
- Particle ID
- Time of Flight

Forward detectors:

- BBC, ZDC (collisions)
- Muon trackers & ID
- Muon Piston Cal.

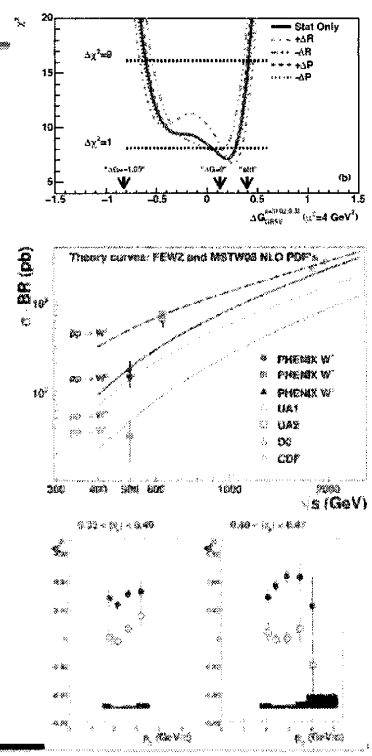
Near term Upgrades:

- Si VTX tracker (R. Nouicer)
- Mu Trig. Upgrade (I. Nakagawa)



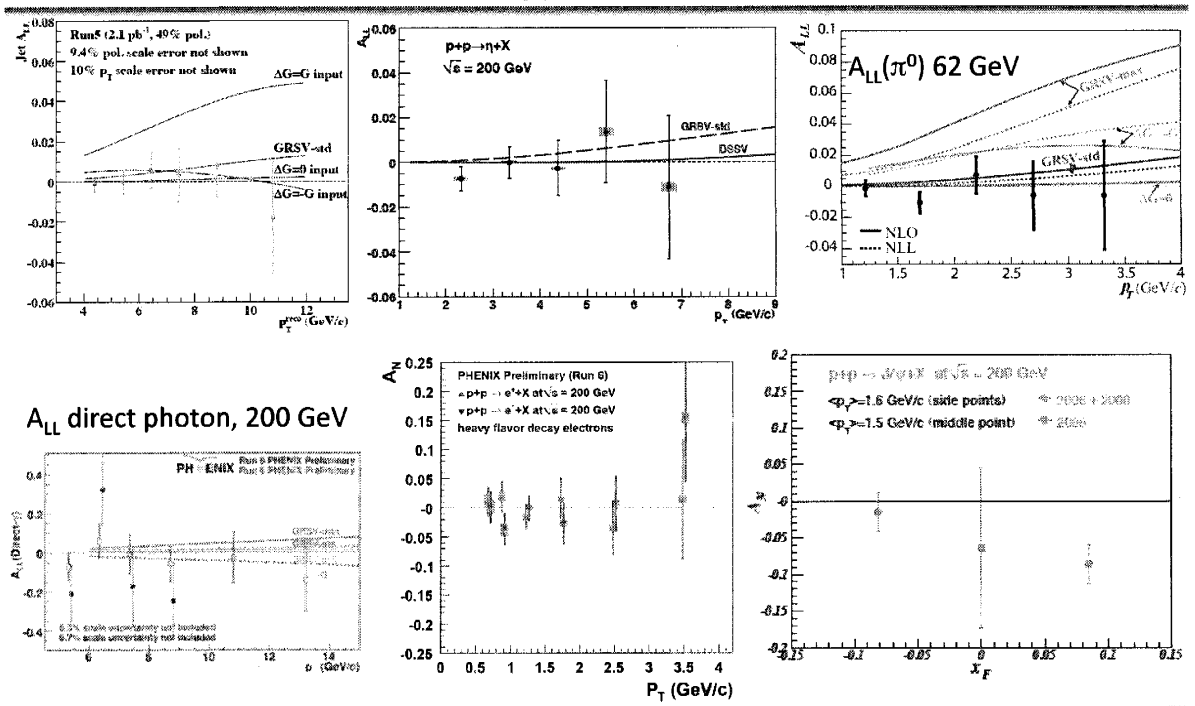
In this session:

- Polarized gluon distribution measurements
  - Kieran Boyle: Run-9 π^0 & global analysis
  - Dave Kawall: charged hadrons
- Beginning of the Anti-Quark polarization measurement program (W-Physics)
  - Kensuke Okada: (W→ e) hot new result
  - Itaru Nakagawa: (W→ μ) forward upgrade
- Transverse spin
  - John Koster: transverse spin, large x_F



Many more results by RBRC-*family*

(not being presented today….)



Future: 2011-2015 PHENIX Run Plan

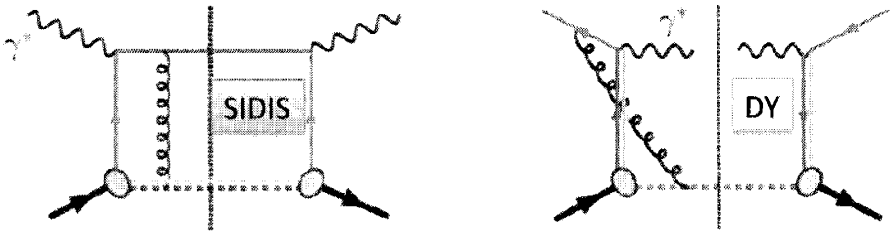
PHENIX Decadal plan

Submitted to BNL ALD October 1st, 2010

Plenty of good physics still to come…. & significant "spin running" in the PHENIX decadal plan.

run	Species	$\sqrt{s_{NN}}$	Wks	$\int L\,dt$ |z| < 30 cm	$\int L\,dt$ |z| < 10 cm	Pol.	Comments
11	$p+p$	500	10	50 pb^{-1}	20 pb^{-1}	50% (L)	W program + ΔG
	Au+Au	200	8		0.7 nb^{-1}		heavy flavor (VTX)
	Au+Au	18	1.5	5.5 μb^{-1}			energy scan
	U+U	192	1.5		0.03 nb^{-1}		explore geometry
12	$p+p$	500	8	100 pb^{-1}	35 pb^{-1}	50% (L)	W program + ΔG
	$p+p$	200	5	13.1 pb^{-1}	4.7 pb^{-1}	60% (T)	HI comparison
	Au+Au	200	7		0.8 nb^{-1}		heavy flavor (F/VTX)
	Au+Au	27	1	5.2 μb^{-1}			energy scan
13	$p+p$	500	10	200 pb^{-1}	74 pb^{-1}	60% (L)	W program
	U+U	200	5		0.57 nb^{-1}		geometry
	Cu+Au	200	5		2.4 nb^{-1}		geometry
14	$p+p$	200	10	34 pb^{-1}	12 pb^{-1}	65% (T)	CM/CNM/FOCAL
	$p+p$	62	3	0.6 pb^{-1}	0.2 pb^{-1}	60% (T/L)	CM/CNM/FOCAL
	$d+Au$	200	8	260 nb^{-1}	150 nb^{-1}		CNM/FOCAL
	$d+Au$	62	2	6.5 nb^{-1}	3.8 nb^{-1}		CNM/FOCAL
15	Au+Au	200	10		2.8 nb^{-1}		High Bandwidth
	Au+Au	62	4		0.13 nb^{-1}		HF vs $\sqrt{s_{NN}}$
	$p+^3He$	132	5			(T)	Test Run

Spin Physics Beyond 2015: Drell-Yan

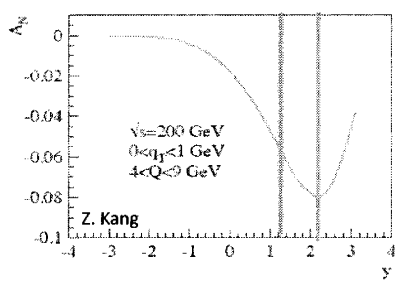


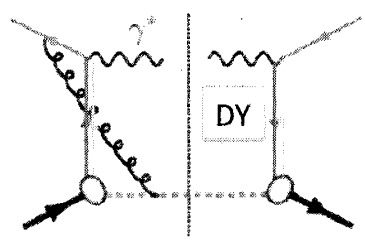
Fundamental test of k_T factorization

A_N in DY : Nonzero correlation between S_{proton} & k_T partons

- $A_N < 0$ in DY : k_T factorization robust
- $A_N > 0$ in DY : k_T factorization not applicable
- If $A_N = 0$ our present understanding of SIDIS & pion production and its interpretation is substantially incomplete

Spin Physics Beyond 2015: Drell-Yan





Fundamental test of k_T factorization

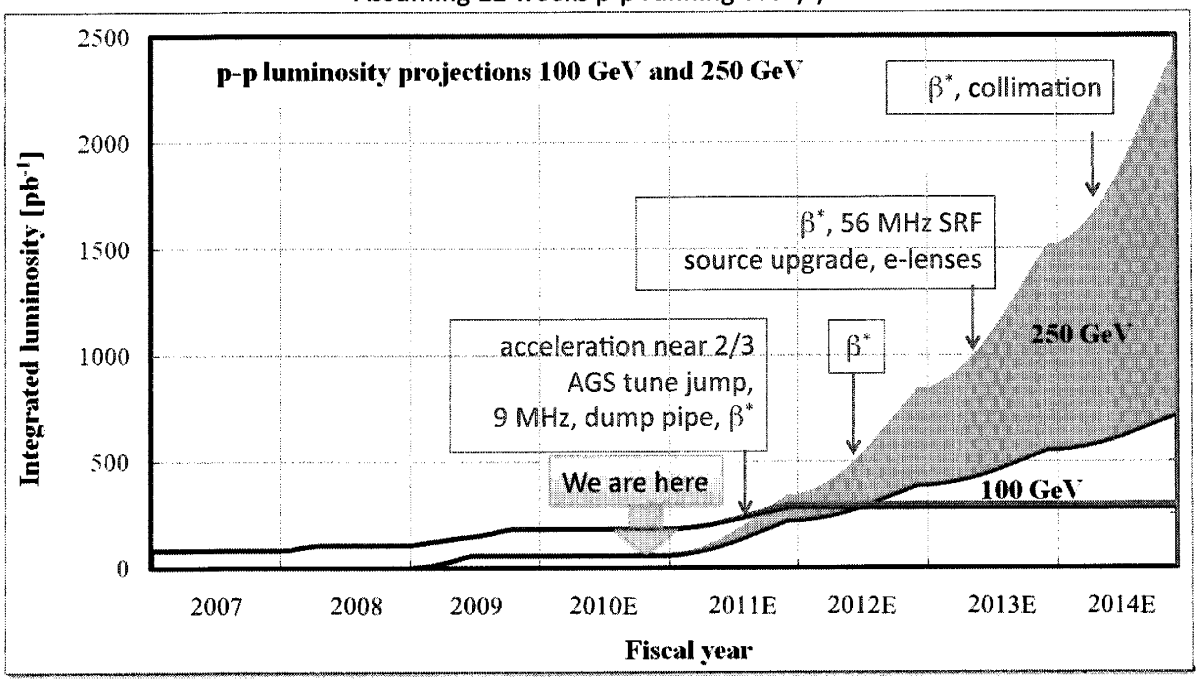
A_N in DY : Nonzero correlation between S_{proton} & k_T partons

- $A_N < 0$ in DY : k_T factorization robust
- $A_N > 0$ in DY : k_T factorization not applicable
- If $A_N = 0$ our present understanding of SIDIS & pion production and its interpretation is substantially incomplete
- Exploratory studies possible with PHENIX muon arms→ $1.2 < \eta < 2.2$
- Measurements :PHENIX decadal upgrade or one of two initiatives IP2 at RHIC

W. Fischer

RHIC 5 yr outlook with polarized protons

Assuming 12 weeks p-p running every year



Summary

- RHIC Spin program has reached a milestone:
  - having explored polarized gluon distribution with 200 GeV collisions
  - it is now moving on to the 500 GeV Collisions to explore anti-quark distributions via W production
  - transverse spin phenomena continue to perplex us…

  This session will give you a flavor of all these developments

- RIKEN BNL Research Center Fellows and post doctoral fellows have played critical role in the Spin Physics until now, and fully expect to do the same in near and long term future

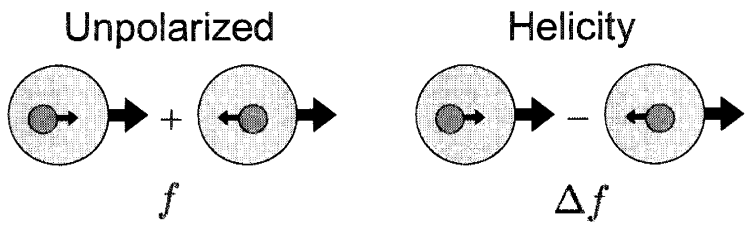
Measurement of Run9 π^0 A_{LL} at $\sqrt{s}$=200 GeV

Kieran Boyle (RIKEN BNL Research Center)

Outline:

1. Introduction: Why π^0 at PHENIX
2. Measurement and issues
3. Results at $\sqrt{s}$=200 GeV
4. Impact on Global Fit for ΔG

Spin Structure



- Spin Sum Rule

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{z,q} + L_{z,g}$$

  - $\Delta\Sigma$ (ΔG) is the quark (gluon) spin contribution,
  - Measurements from polarized DIS, SIDIS and pp allow access to ΔG and $\Delta\Sigma$.

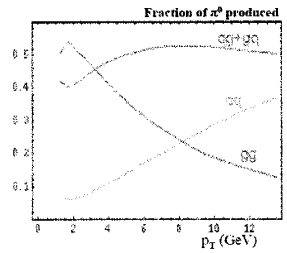
Accessing ΔG in p+p Collisions

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

From ep (&pp) (HERA mostly)

NLO pQCD

From e+e- (& SIDIS,pp)



- If $\Delta f = \Delta q$, then we have this from pDIS
- So roughly, we have

$$A_{LL} \cong a_{gg}\Delta g^2 + b_{gq}\Delta g \Delta q + c_{qq}\Delta q^2$$

- where the coefficients a, b and c are dependent on final state observable and event kinematics (η,p_T).

+- =

++ =

Why π^0 A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

+ - = Opposite helicity =

++ = Same helicity =

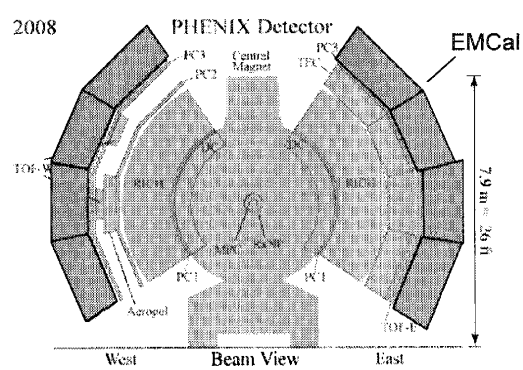
N = Yield
P = beam polarization
R = L_{++}/L_{--} = relative luminosity

Pions are produced abundantly in p+p collisions.

+ PHENIX EMCal has limited acceptance but fine resolution ($\Delta\eta\times\Delta\phi$=0.01×0.01)

+ High energy photon trigger with good efficiency

= Large π^0 yield allowing for precise measurement of A_{LL}



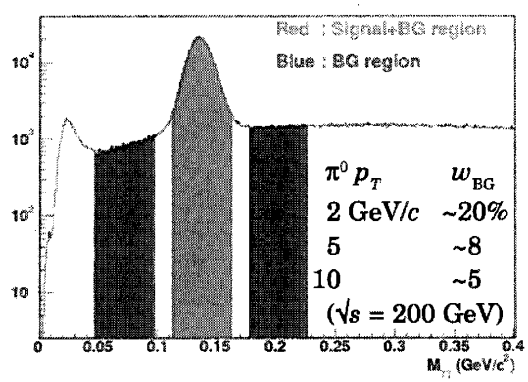
Run9 Data Sets

- Run9 200 GeV data
  - Analysis by Andrew Manion (SBU) and KB
  - More than twice larger statistics compared to Run6 with similar polarization.
  - Achieved with higher collision rates
  - Higher rate creates some problems
    - Rate effect in Relative luminosity (expected)
    - Rate effect in π^0 background (unexpected)

- Run9 500 GeV data
  - Significant luminosity
  - Low polarization meant statistical significance of data scaled by $1/(P_B{*}P_Y) \sim 6.25$
  - Therefore, minimal impact expected from Run9 500 GeV data set for A_{LL}
  - Expect P>50% in coming run.

Measurement

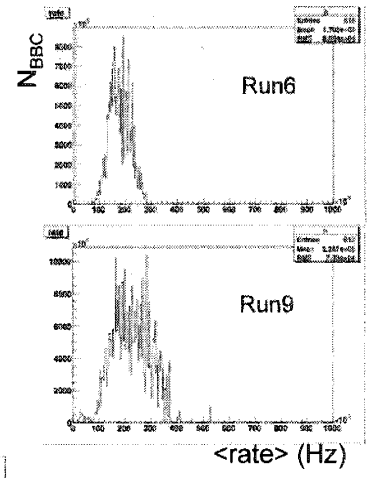
$$A_{LL}^{\pi 0} = \frac{A_{LL}^{\pi 0 + BG} - w_{BG} A_{LL}^{BG}}{1 - w_{BG}}$$

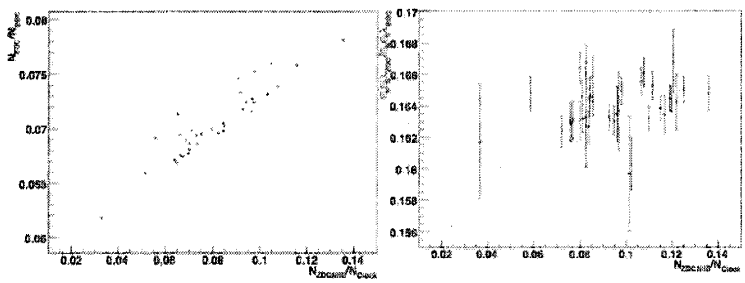


- Reconstruct π^0 via $\gamma\gamma$ decay
- Measure A_{LL} in signal and sideband regions of invariant mass plot
- Determine background fraction w_{BG} from fit
- Subtract background asymmetry to get π^0 A_{LL}.

Luminosity Rate Effects

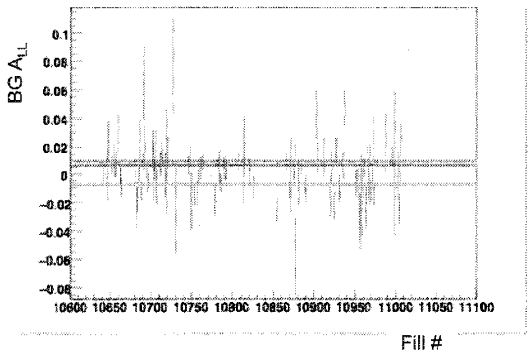
- Systematic uncertainty from Relative Luminosity
  - Determined from comparison of ZDC and BBC triggers
- Higher Luminosity in Run9
  - ➔ Larger fraction of multiple collisions
  - ➔ Increased uncertainty as the detectors do not respond in the same way
- New method in development
  - Uses probability of zero for each detector
  - Accounts for rate effects in data
  - Should reduce systematic uncertainty





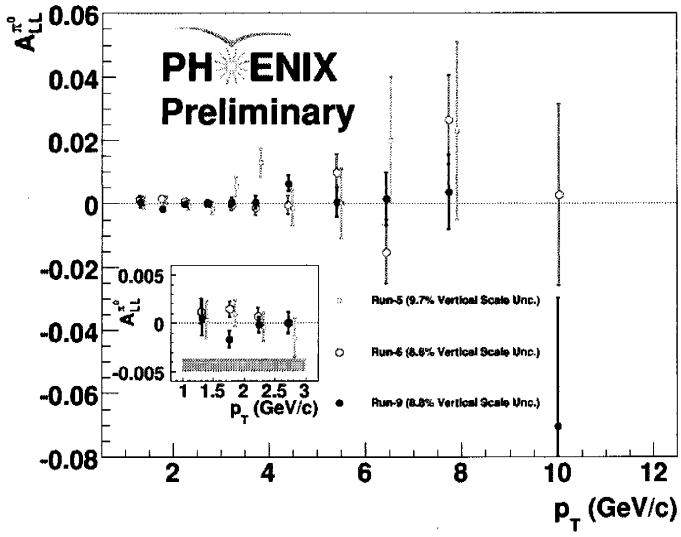
EMCal Rate Effect

- Rate effect also impacts π^0 yields
  - Determination of energy deposit in an event based on adc comparison with ~400ns earlier (~4 bunch crossings)
  - If energy deposit from one of previous 4 collisions, will be mistakenly counted in wrong event.
  - Luminosity variations from bunch to bunch ➔ bunch to bunch variation in π^0 backgrounds
  - Can create false asymmetry in combinatorial background
  - Worse at higher rates



- Solution:
  - Separately analyze each spin pattern
  - Use stricter cuts to reduce low energy background clusters and minimize effect
- Result: False asymmetries reduced significantly below statistical precision.

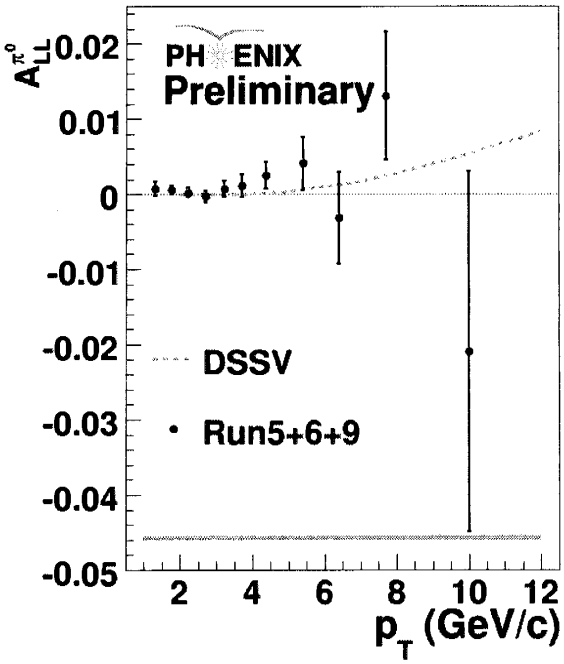
Results from Run9



- Results from Run 9 are consistent with previous years
- A_{LL} is small, but what about ΔG?

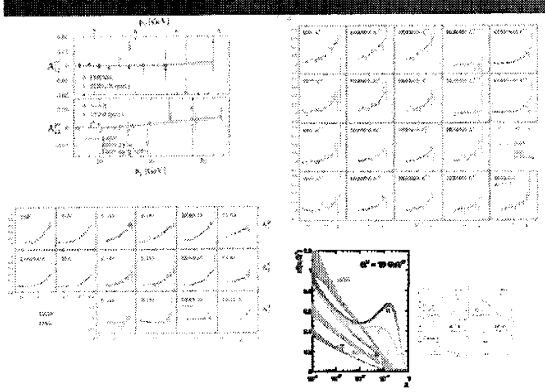
Results from Run9

- Combine data from 2005, 2006 and 2009
- Compare to DSSV global analysis
  - Not exactly prediction as 2005 and 2006 data included in fit



Impact on Global Analysis

Global Analysis Ingredients



- World Data
  - DIS
  - SIDIS
  - p+p
- Caveats
  - Functional Form of PDF
  - Positivity requirements
  - Validity of constraints from beta decay (within uncertainties)
- Other distributions
  - PDFs from MRST
  - FF from DSS

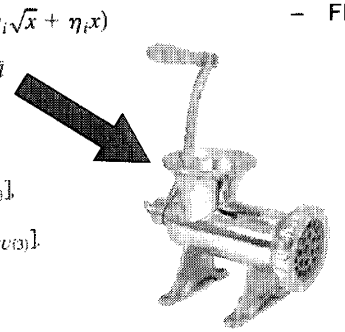
$$x\Delta f_i(x, \mu_0^2) = N_i x^{\alpha_i}(1-x)^{\beta_i}(1+\gamma_i\sqrt{x}+\eta_i x)$$

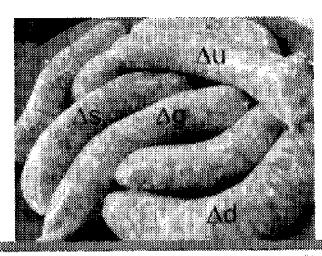
$$\alpha_{\bar{u}} = \alpha_{u+\bar{u}} \quad \alpha_{\bar{d}} = \alpha_{\bar{s}} = \alpha_{d+\bar{d}}$$

$$\Delta s = \Delta\bar{s}$$

$$\Delta\Sigma_u - \Delta\Sigma_d = (F+D)[1+\varepsilon_{SU(2)}],$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = (3F-D)[1+\varepsilon_{SU(3)}].$$



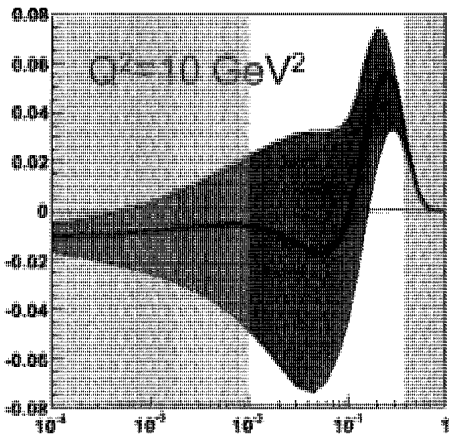


Extension of the Global Analysis

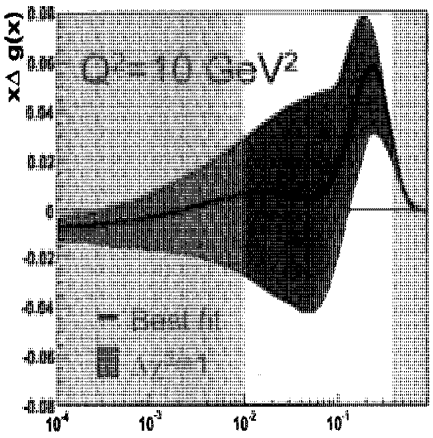
- Group of Theorists and Experimentalists
  - KB, D. DeFlorian, A. Deshpande, C. Gal, R. Sassot, M. Stratmann, S. Taneja, and W. Vogelsang
  - Based on work in :
    - Phys.Rev.Lett.101:072001,2008
    - Phys.Rev.D80:034030,2009
- Four goals:
  - Inclusion of systematic uncertainties (nearly complete)
  - Determination uncertainty as a function of x
  - Examination of theoretical uncertainties
  - Inclusion of new data

Inclusion of New 2009 PHENIX π^0 A_{LL}

- Run9 results from new PHENIX $\pi 0$ A_{LL} data now included in DSSV based fit.
- New data reduce uncertainties in RHIC region.



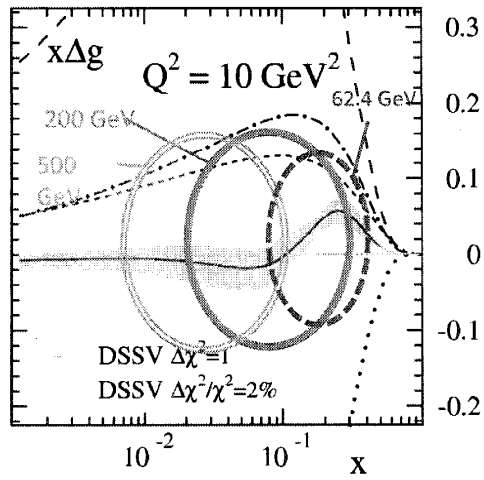
Before Run9

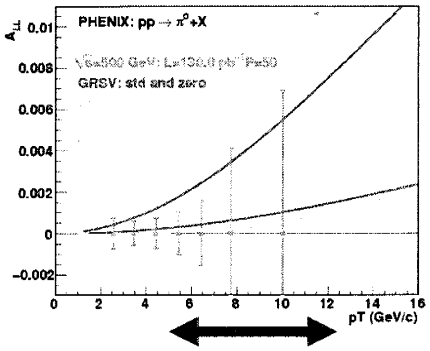


With Run9

Future Plans

- 500 GeV data set required for W physics also can be used for A_{LL}.
- This can allow us access to lower x, where current data does not constrain ΔG



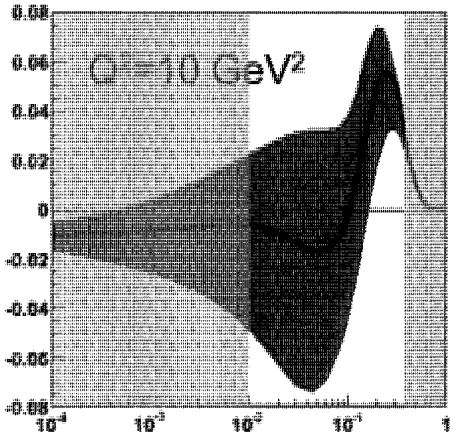


Equivalent x coverage at 200 GeV (p_T=2-5 GeV)

Conclusion

- Run9 had a significant luminosity
- Data from Run9 running at 200 GeV has been analyzed
  - Results are consistent with previous data.
  - Data are consistent with DSSV fit with uncertainties
- New results were included in DSSV based fit
  - Small shift in best fit value to positive value for DG
  - Uncertainties visibly reduced
  - Including uncertainties, result still consistent with gluon spin contributing remaining missing proton spin
- Preparations for coming 500 GeV run are ongoing

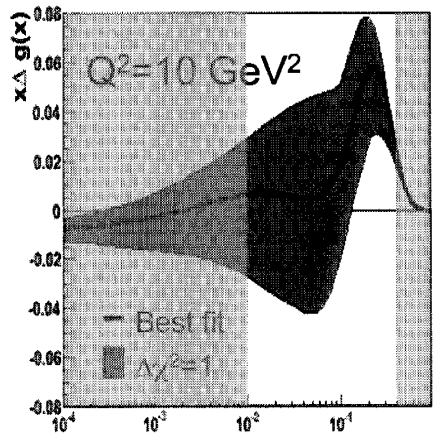
Impact of 2009 π^0 A_{LL}: Uncertainty



Before Run9

$\int_{0.001}^{1}\Delta G=0.01$ $^{+0.18}_{-0.22}$

$\int_{0.01}^{0.4}\Delta G=0.02$ $^{+0.15}_{-0.17}$

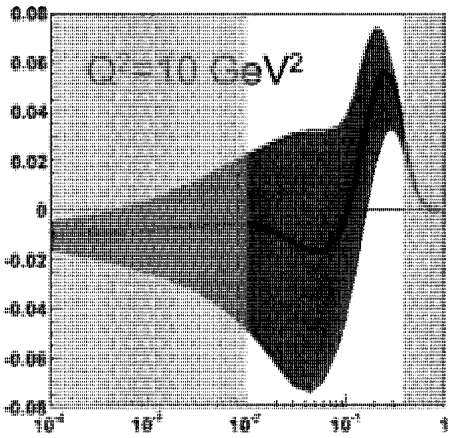


With Run9 x

$\int_{0.001}^{1}\Delta G=0.05$ $^{+0.16}_{-0.21}$

$\int_{0.01}^{0.4}\Delta G=0.08$ $^{+0.11}_{-0.15}$

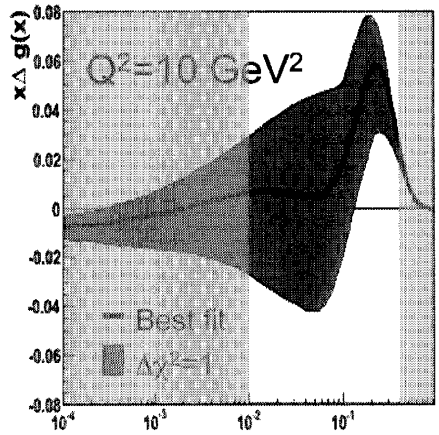
Impact of 2009 π^0 A_{LL}: Range of ΔG



Before Run9

$\int_{0.001}^{1}\Delta G=0.01$ (-0.21,0.19)

$\int_{0.01}^{0.4}\Delta G=0.02$ (-0.15,+0.17)

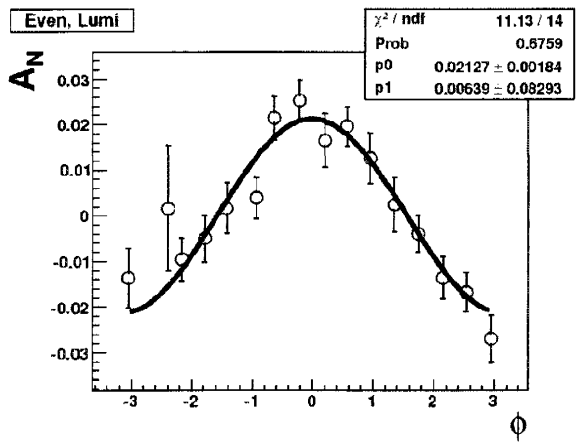


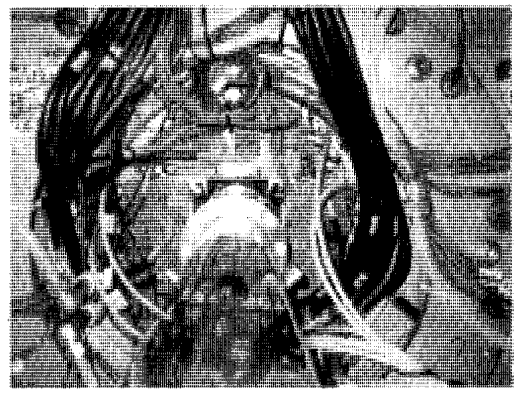
With Run9 x

$\int_{0.001}^{1}\Delta G=0.05$ (-0.16,+0.21)

$\int_{0.01}^{0.4}\Delta G=0.08$ (-0.07,+0.19)

Measurement of Transverse Spin Asymmetries in Polarized proton-proton Collisions

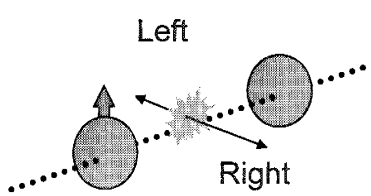


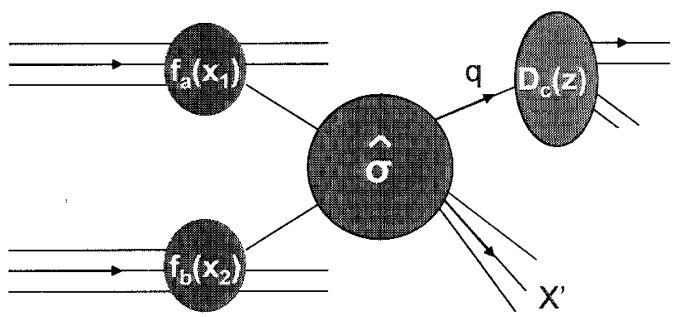


John Koster
RBRC

RBRC Scientific Review
2010/10/27

Experimental Observable: Cross-sections for hadrons





Factorize cross-section into 3 components:

Proton Structure — Fragmentation Function

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to \pi^0 X\right)}{dx_1 dx_2 dz} \propto f_a(x_1)\cdot f_b(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(ab \to cd)}{dx_1 dx_2} \times D_c(z)$$

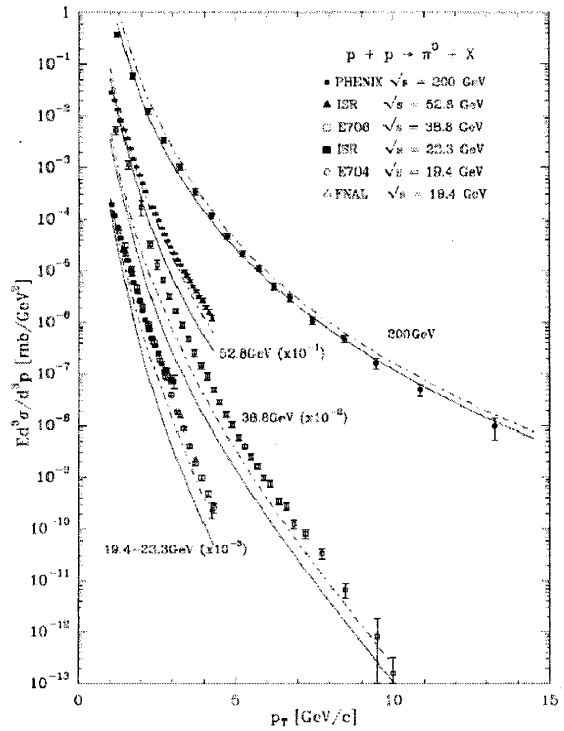
Calculable in pQCD

Spin Summed Cross-section: $\sigma^{\uparrow} + \sigma^{\downarrow}$

- Distribution functions: $f_a(x)$, $D_h(z)$ determined from DIS, Drell-Yan, e^+e^- experiments
- Used to predict hadron production from proton-proton collisions

- Good agreement between theory and exp.
- ✓ √s=200 GeV
- ✓ √s=62.4 GeV
- O √s=19.4 GeV – More work needed

- Theoretical tools successfully describe spin summed cross-sections for √s≥62 GeV



Eur.Phys.J.C36:371-374,2004

Spin Difference Cross-section: $\sigma^{\uparrow} - \sigma^{\downarrow}$

$$A_N = \frac{1}{P}\frac{\sigma_L^{\pi} - \sigma_R^{\pi}}{\sigma_L^{\pi} + \sigma_R^{\pi}}$$

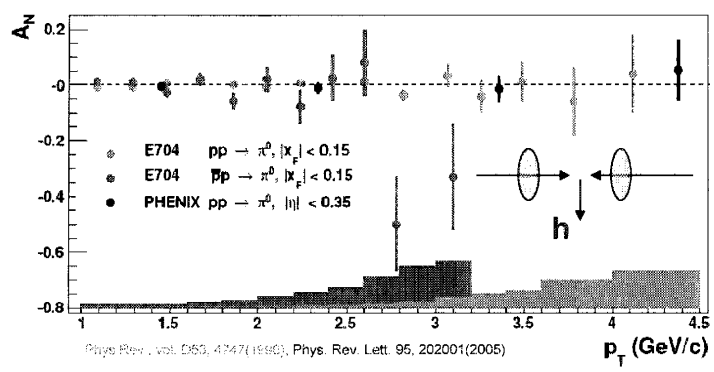
Early Theory Expectation:
Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

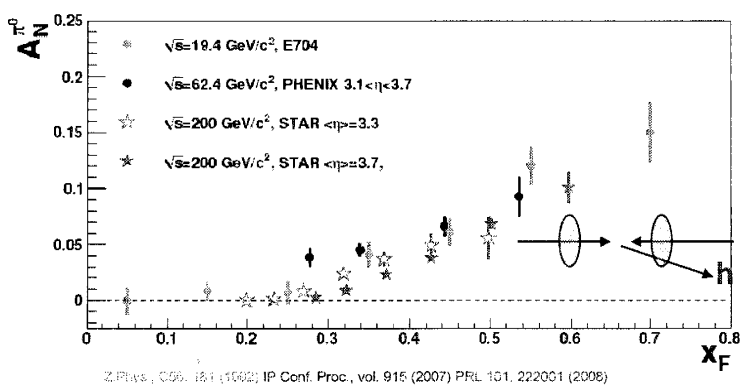
A_N O(10^{-4}) Theory

Experiment:

- **Consistent with zero at mid-rapidity**
- **O(10%) at Forward-rapidity ~independent of √s**



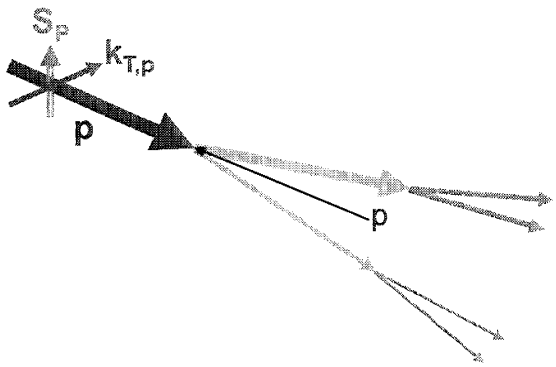
Phys.Rev., vol. D53, 4747(1996), Phys. Rev. Lett. 95, 202001(2005)



Z.Phys., C56, 161 (1992) IP Conf. Proc., vol. 915 (2007) PRL 101, 222001 (2008)

Possible A_N Explanations: Transverse Momentum Dep. Distributions

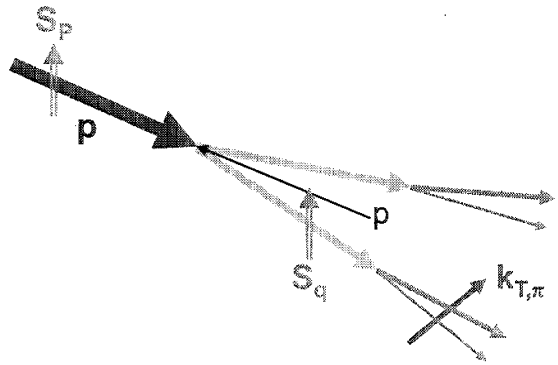
Sivers Effect:
Introduce transverse momentum of parton relative to proton.



Correlation between Proton spin (S_p) and parton transverse momentum $k_{T,p}$

$$\bar{f}_{1T}^{\perp q}(x, k_{T,P}^2) \cdot D_q^h(z)$$

Collins Effect:
Introduce transverse momentum of fragmenting hadron relative to parton.



Correlation between Proton spin (S_p) and quark spin (S_q) + spin dep. frag. function

$$\delta q(x) \cdot H_1^{\perp}(z_2, \bar{k}_{\perp}^2)$$

5

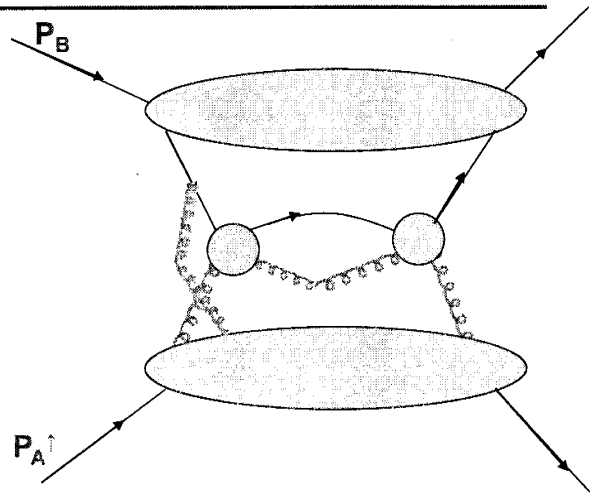
Graphics from L. Nogach (2006 RHIC AGS Users Meeting)

Possible A_N Explanations: Higher Twist Correlation Functions

- **No k_T (collinear partons)**
- **Additional interactions between proton and scattering partons**
- **Goes beyond leading twist (two free colliding quarks)**

Higher twist interaction contributions expected to drop like $1/p_T$

See this afternoon's talks by F. Yuan and Z. Kang for additional information.

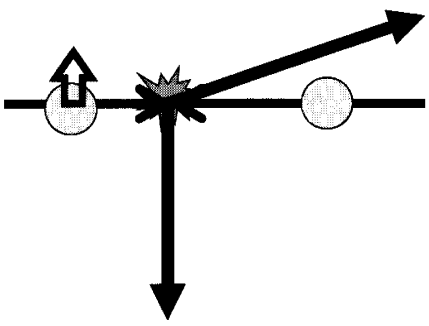


Graphic from Zhongbo Kang

6

Requirements for A_N Measurements

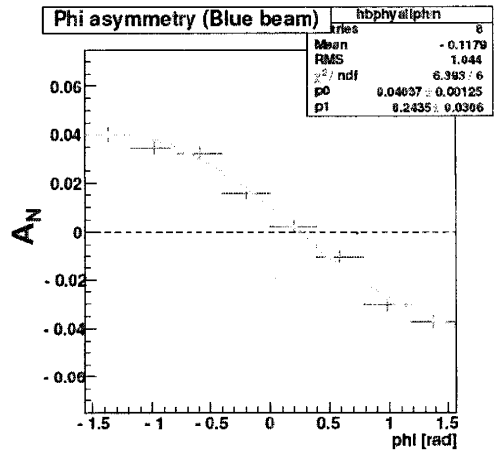
1. **Polarized Protons**
2. **Measure polarization:**
   Determined to be 15 degrees from vertical at PHENIX (unexpected result).
3. **Measure yields**



Forward-rapidity

Detector built as part of graduate work.

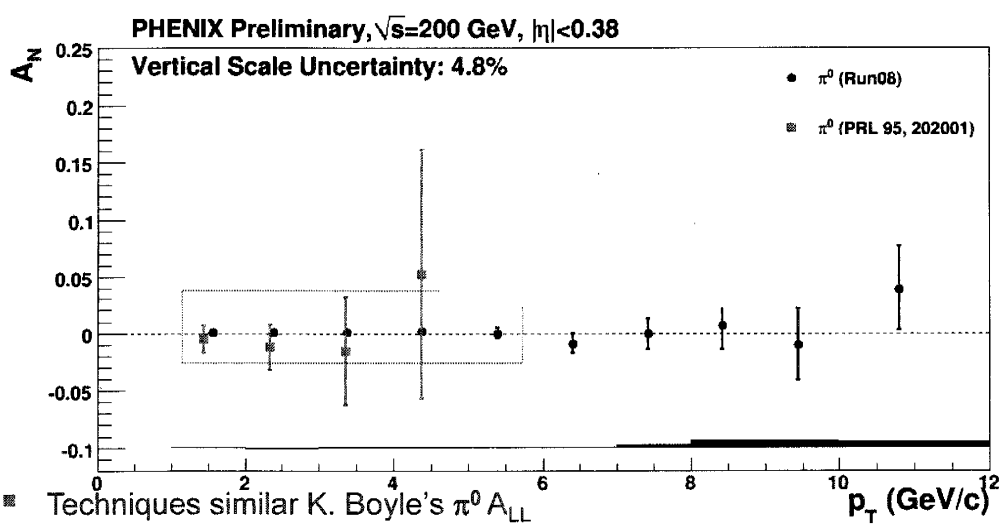
Mid-rapidity (same hardware used in Kieran's talk)



p0: ∝ Polarization
p1: Polarization Direction

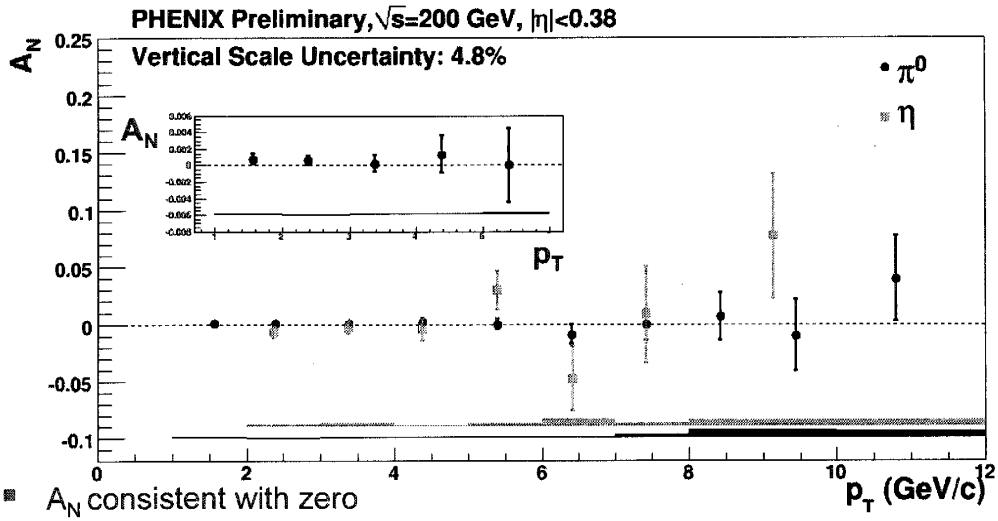
Mid-Rapidity Analysis: Comparison to previous result

2002 Published Result **2008 Preliminary Result**



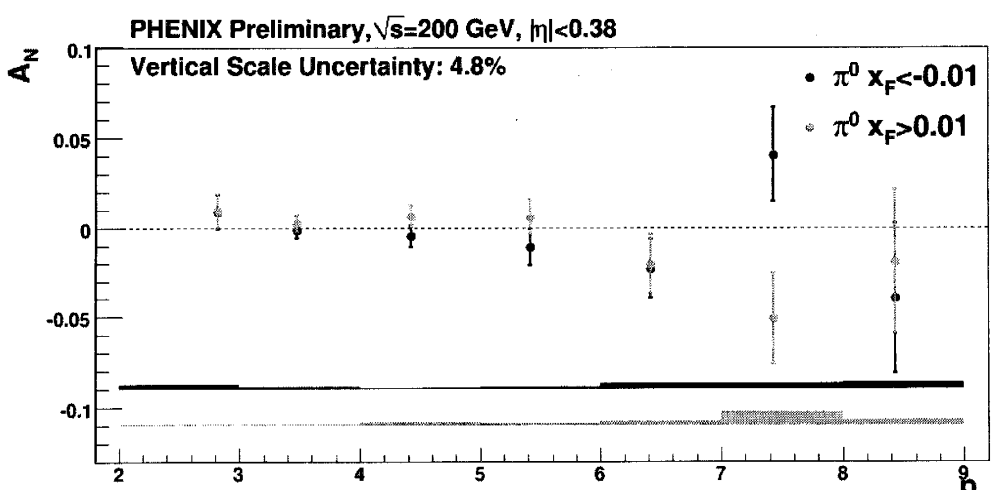
- Techniques similar K. Boyle's π^0 A_{LL}
- 20x smaller error bars than previous 2002 A_N results
- →Large improvement by BNL Collider/Accelerator department in both polarization and luminosity

Mid-rapidity π^0 and η A_N



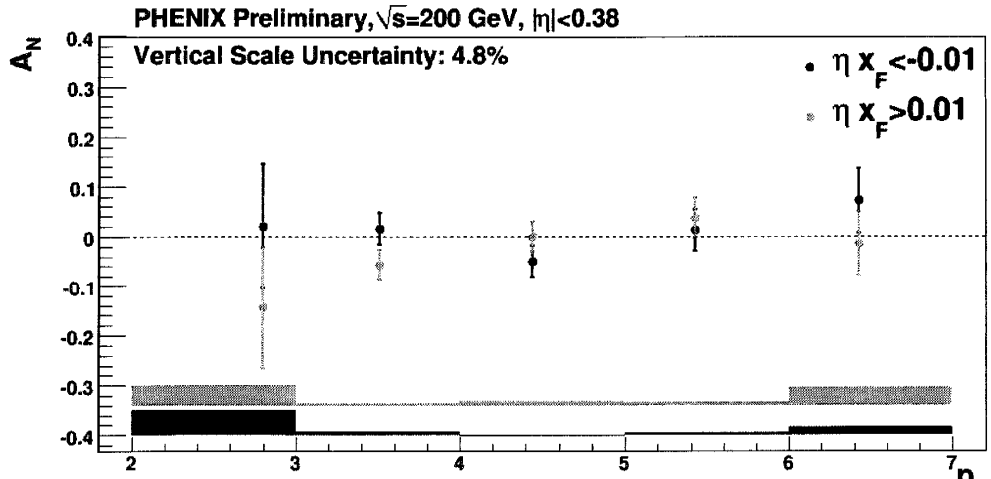
- A_N consistent with zero

Mid-rapidity π^0 A_N $|x_F|>0.01$



- A_N consistent with zero

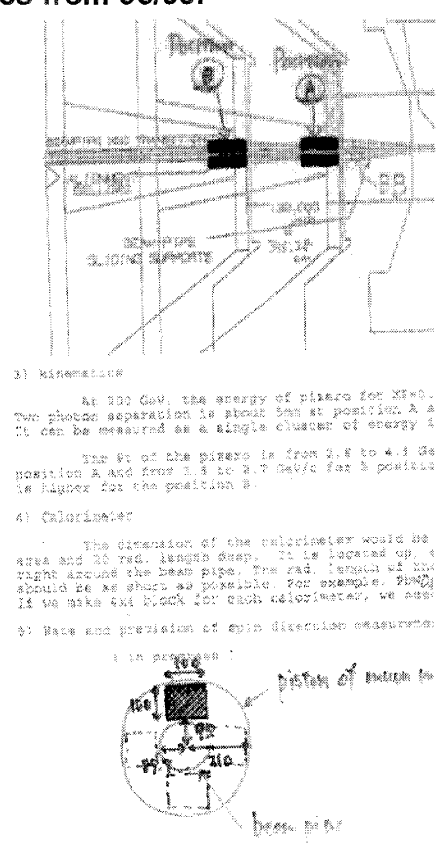
Mid-rapidity η A_N $|x_F|>0.01$



- A_N consistent with zero

11

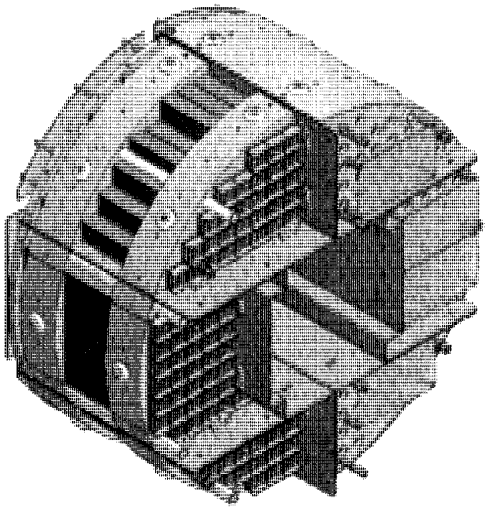
Idea from Y. Goto, K. Imai
Slides from 96/99.

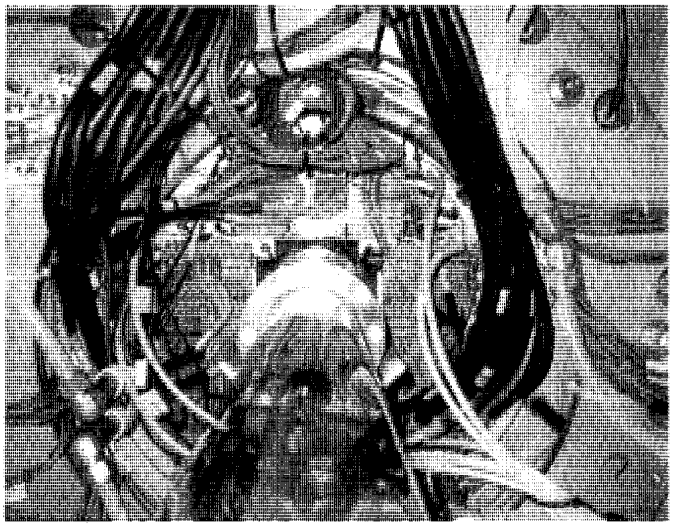


Muon Piston Calorimeter Upgrade

- **Tower: $PbWO_4$ scintillating crystals**
- **Readout: APD**
- **Covers: $3.1 < \eta < 3.7$ (North) and $-3.9 < \eta < -3.1$ (South)**
- **Installed: 2006/2007**

Hardware/software contributions from:
D. Kawall (UMass-Amherst/RBRC) and
A. Deshpande, N. Means (SBU/RBRC)





Muon Piston Calorimeter A_N

Photon merging effects prevent two-photon π^0 analysis for E>20 GeV (p_T>2 GeV/c)

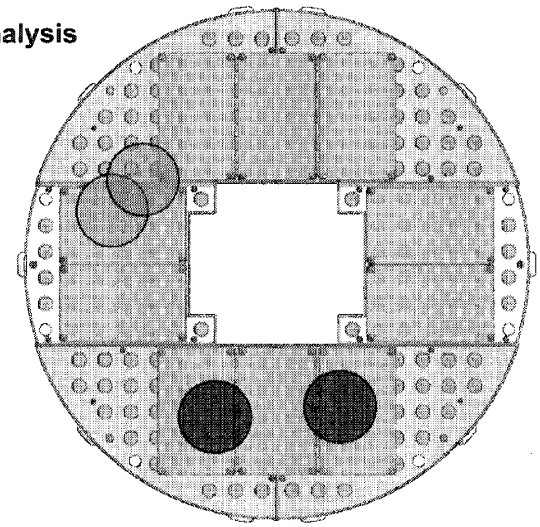
At 62 GeV:

20 GeV → 0.65 x_F:Two-photon π^0 analysis

At 200 GeV:

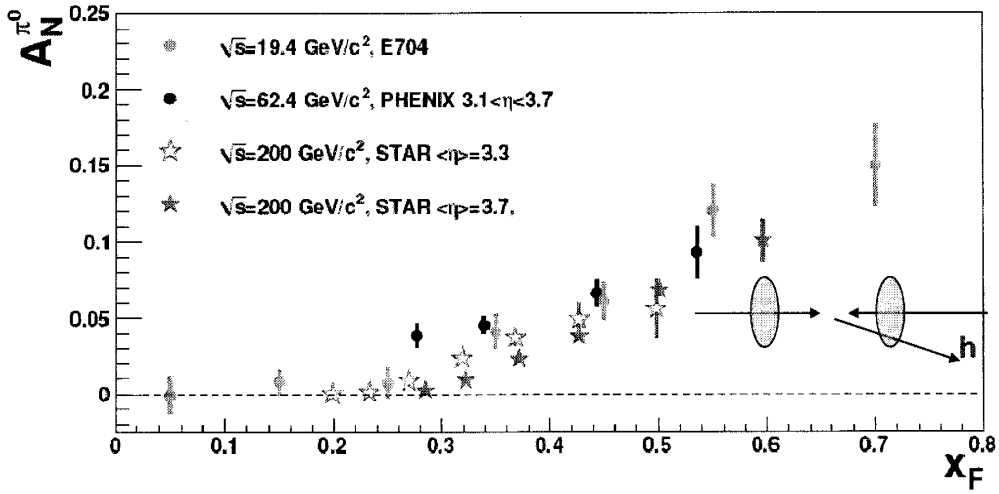
20 GeV → 0.20 x_F :
Switch to "Single clusters"
Yields dominated by merged π^0's but also get contributions from other sources (direct photon, eta meson, charged hadrons, etc.)

Contamination estimated using Monte-Carlo (GEANT3)



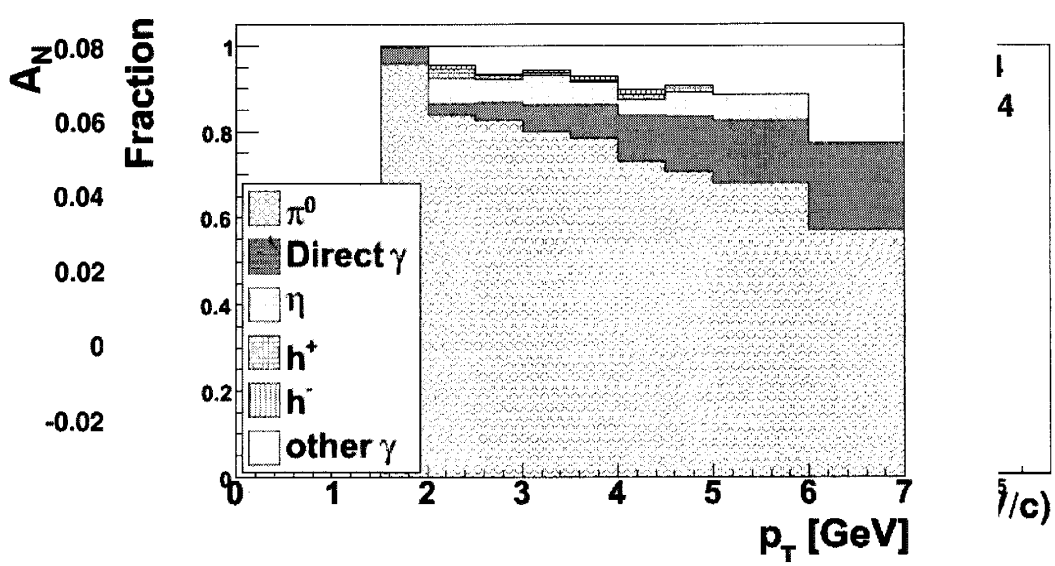
Decay photon impact positions for **low** and high energy π^0's

Transverse Single Spin Asymmetries with the MPC at 62 GeV



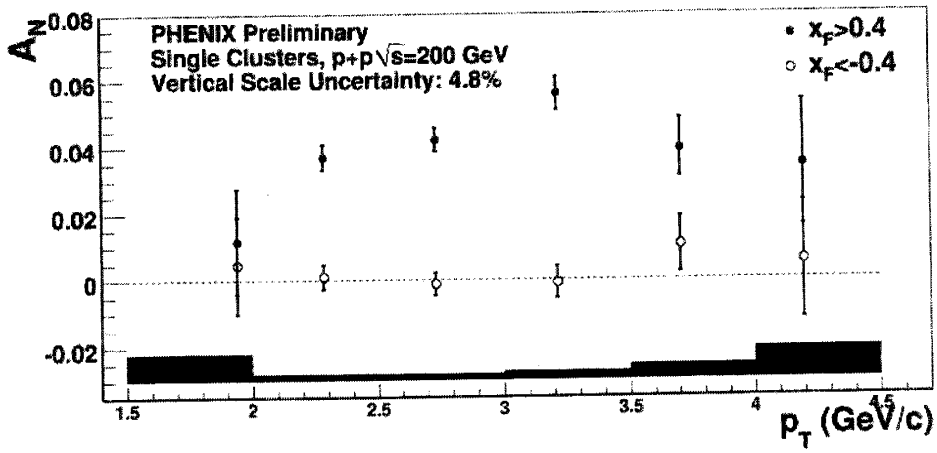
- **Two-photon π^0 reconstruction**
- **Asymmetries at 62 GeV similar to lower and higher energies.**

Transverse Single Spin Asymmetries with the MPC at 200 GeV



- **Merged cluster π^0 analysis.**
- **Cluster content receives contributions from other sources.**

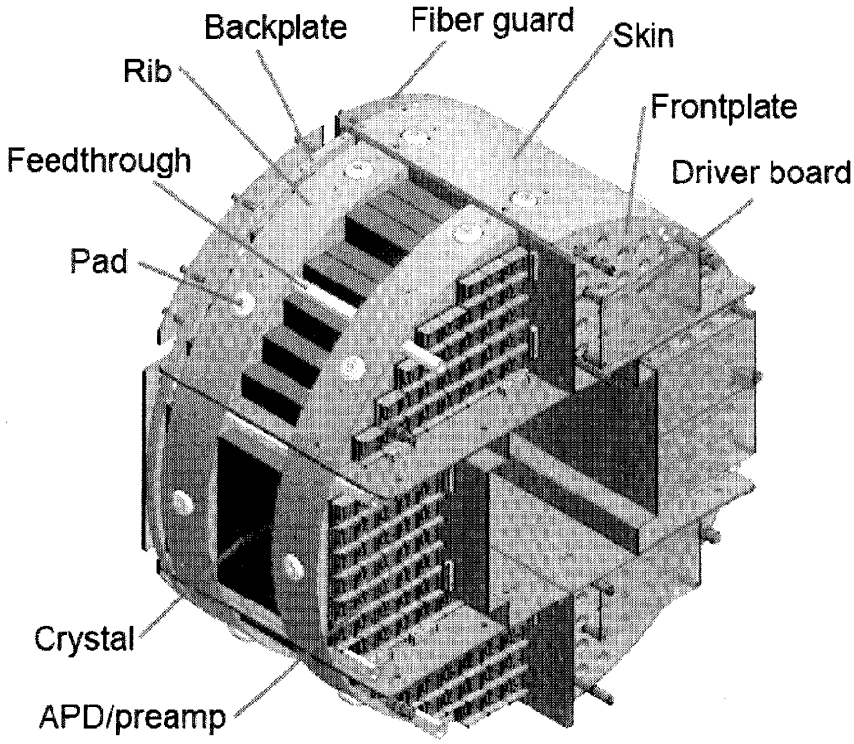
Transverse Single Spin Asymmetries with the MPC at 200 GeV



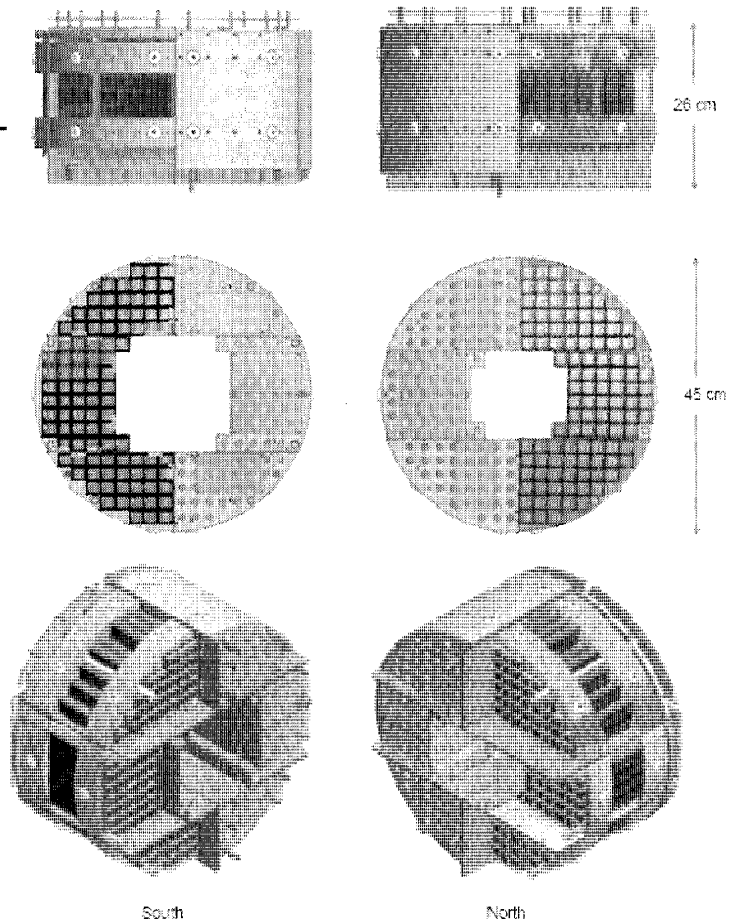
- **Merged cluster π^0 analysis.**
- **Cluster content receives contributions from other sources.**

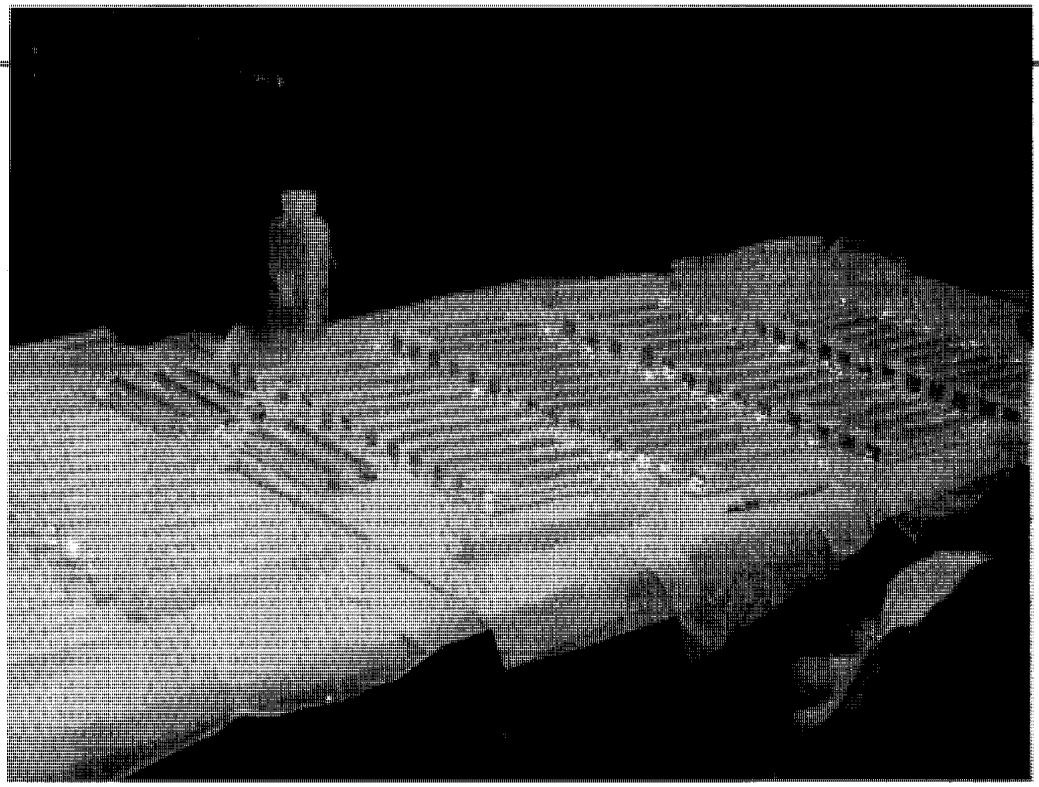
Ongoing MPC Analyses

- **Polarized pp:**
  - η meson A_N (confirm STAR preliminary results)
  - π^0 A_{LL} + di-hadron correlations
- **dA:** Search for new physics at high gluon densities
  - Di-hadron correlation widths (I_{dA})
  - Single hadron suppression at forward rapidity (R_{dA})


Backplate
Fiber guard
Skin
Rib
Frontplate
Feedthrough
Driver board
Pad
Crystal
APD/preamp

20

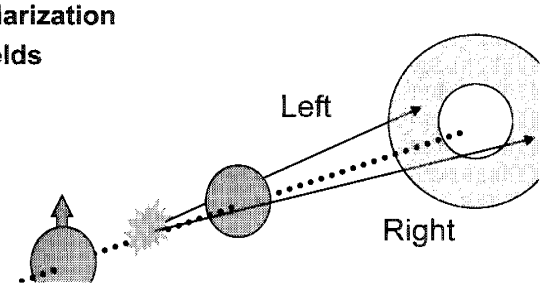

26 cm
45 cm
South
North

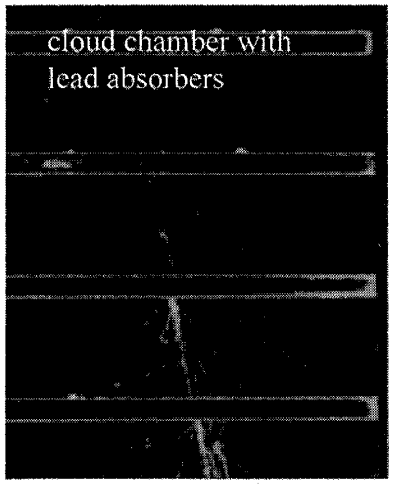


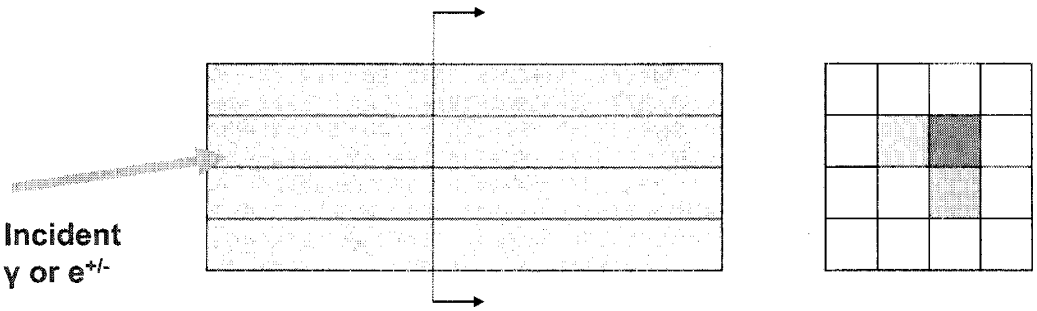
22

Requirements for Measurements

1. **Polarized Protons**
2. **Measure polarization**
3. **Measure Yields**

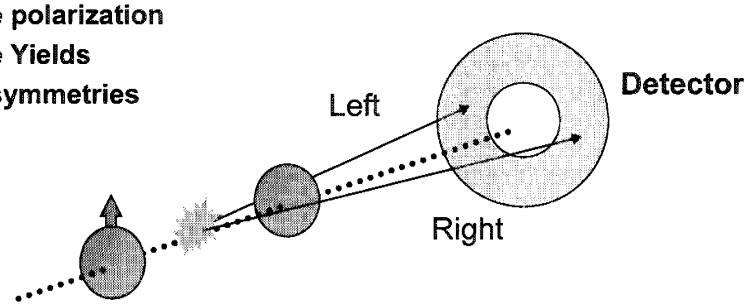






Requirements for Measurements

1. **Polarized Protons**
2. **Measure polarization**
3. **Measure Yields**
4. **Form Asymmetries**



a. Both beams are polarized (Blue and [illegible] beams). Spin direction (up or down) set in alternating patterns

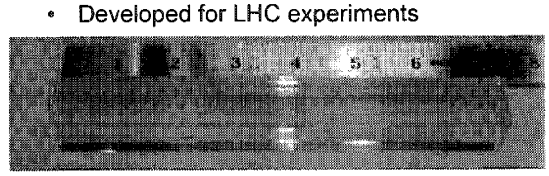
b. Spin sort detector left and right detector yields by
Blue beam spin up or down
Summing gives no net polarization in yellow beam

c. Repeat for yellow beam ("forward/backward direction" flipped)

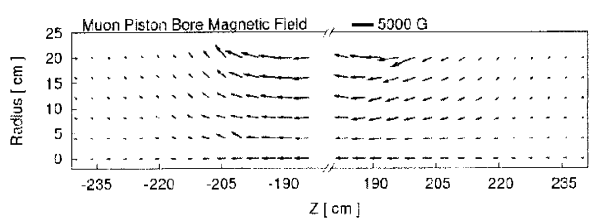
d. Calculate asymmetry
Detailed studies on azimuthal weighting, acceptance effects, numerical stability performed. Details in backup.

Detector Design

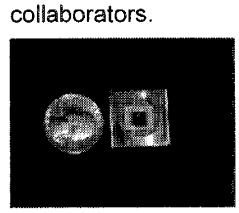
- **Muon Piston Hole Properties**
  - Small available space
    - Detector outer diameter determined by hole's 45 cm diameter
    - Detector inner diameter determined by the beam pipe (different between arms)
- **Calorimeter Tower**
  - $PbWO_4$ Scintillating Crystal
    - Smallest Moliere radius of any known scintillating crystal.
    - Developed for LHC experiments



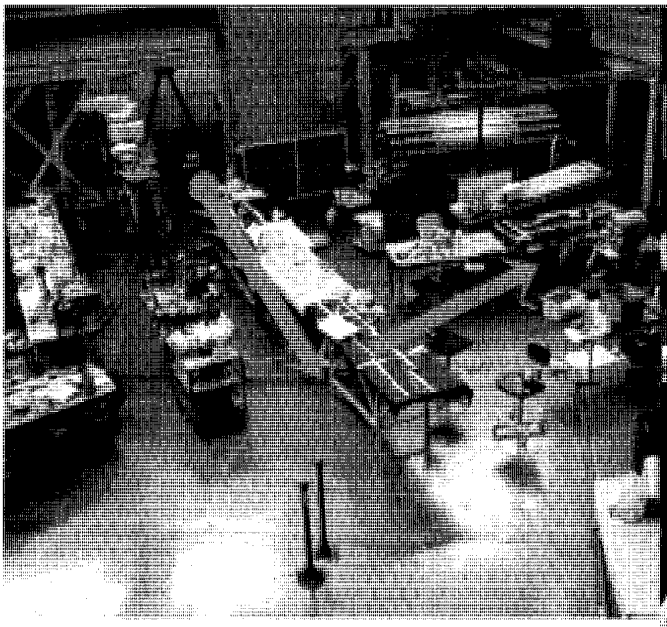
  - Magnetic Field



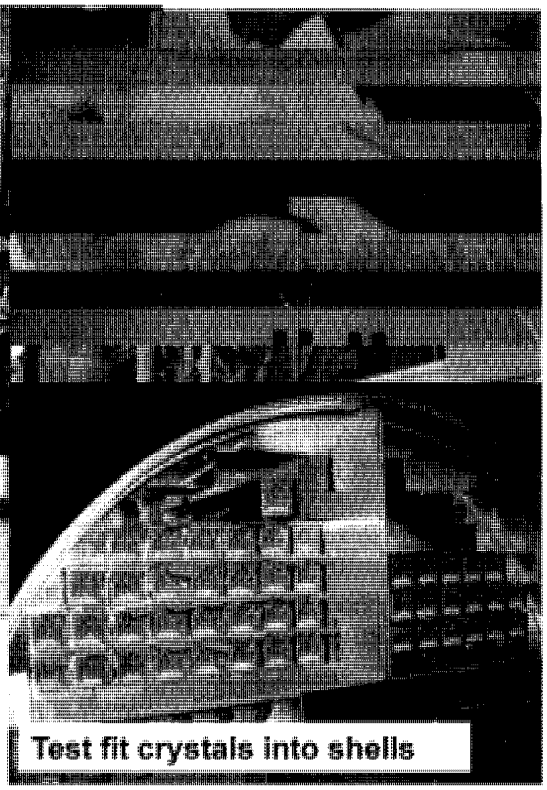
  - Avalanche Photodiode
    - Only expensive mesh dynode photomultiplier tubes can operate reliably in magnetic fields
    - Silicon based device. In use by LHC collaborators.



Crystal Wrapping at Urbana Nuclear Physics Laboratory



More than 400 crystals prepared



Test fit crystals into shells

Calibration Overview

Measure an uncalibrated charge (ADC) in ~400 calorimeter towers (i).
Therefore, must convert :

$$\text{Energy}_i = G_i * R_i(t) * \text{ADC}_i$$

Absolute Energy Scale
Minimum Ionizing Particle Peaks – utilizes Bethe Bloche formula.

Relative Gain Changes
LED based monitoring system.

Front End Electronics
Pedestals, various PHENIX-specific electronics calibrations

Confirmation

1) Stability checked with pi0 and eta meson invariant mass peaks over time
2) Monte-Carlo. Compare pi0 and eta peak positions and widths with full simulation of detector in realistic simulated pp collisions.

This work: developed general calibration scheme for all MPC analyses in PHENIX.

Measurement of Double Longitudinal Spin Asymmetries and Cross-sections of Non-identified Charged Hadrons

D. Kawall, RBRC and Univ. of Massachusetts; A. Datta and M. Stepanov, UMass; and C. Aidala, LANL

Double Longitudinal Spin Asymmetry of Non-identified Charged Hadrons at $\sqrt{s} = 62.4$ GeV

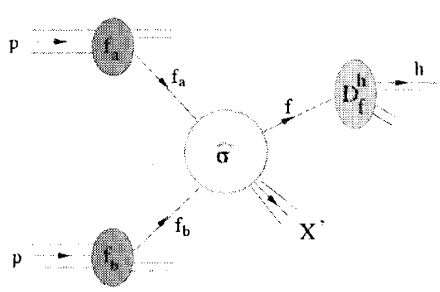
Motivation :

- PHENIX recorded $\approx$ 214 M minimum bias long. polarized pp collisions at $\sqrt{s}$=62.4 GeV in 2006 (11 nb^{-1})

  Can factorize pp scattering into $2 \Rightarrow 2$ scattering of partons composing proton

  Hadrons with $p_T \gtrsim 1.2$ GeV/c produced dominantly by quark-gluon scattering

  Asymmetry measurement important because it is sensitive to Δg



- $A_{LL}^{\pi} \propto \Delta g \otimes \sum_{q,q} \left(\Delta q \otimes D_q^{\pi}\right)$, where $\Delta u \approx 0.8$, $\Delta d \approx -0.40$
- $A_{LL}^{\pi+} \propto \Delta g \otimes \left(\Delta u \otimes D_u^{\pi+} + \Delta \bar{d} \otimes D_{\bar{d}}^{\pi+} \gg 0\right)$
- $A_{LL}^{\pi-} \propto \Delta g \otimes \left(\Delta \bar{u} \otimes D_{\bar{u}}^{\pi-} + \Delta d \otimes D_d^{\pi-} \lesssim 0\right)$

$\Rightarrow$ **If $\Delta g > 0$: $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$**

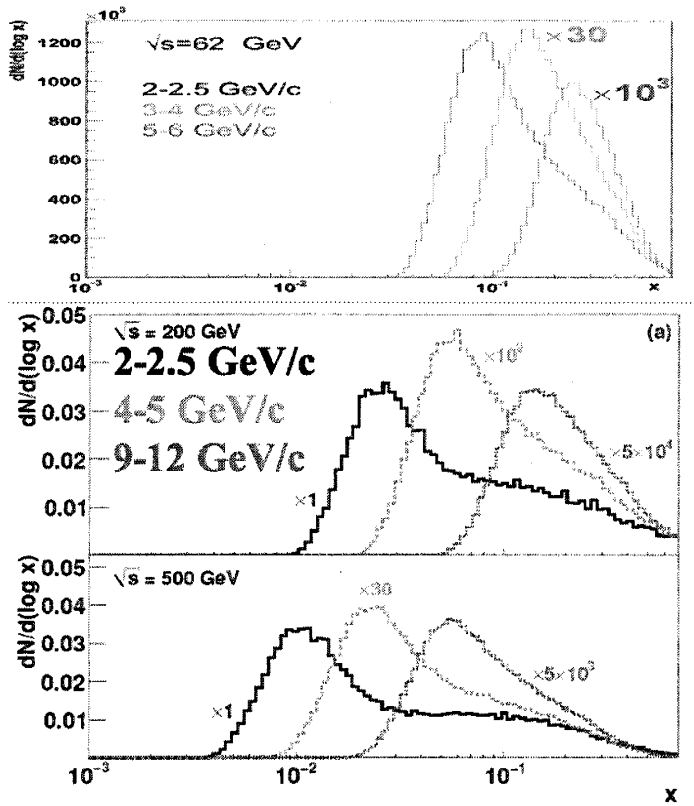
$\Rightarrow$ $A_{LL}^{\pi+}$ maximum analyzing power for Δg

Comparison of $A_{LL}^{\pi^0}$ versus $A_{LL}^{h^\pm}$ may be sensitive to sign of Δg

Probing Δg with different channels adds robustness to extraction of Δg

- Measured double spin asymmetry $A_{LL}^{pp \to h^\pm X}$ in new kinematic range

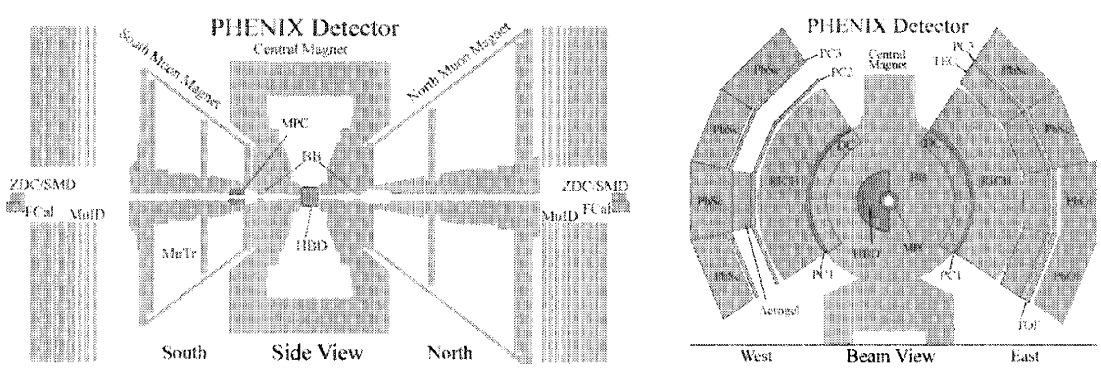
Probing Δg in a new kinematic range



- Bjorken x correlated with p_T of final state hadron in hard-scattering
- Changing $\sqrt{s}$ from 62.4-500 GeV changes range of x probed
- Changes x range over which we're sensitive to $\Delta g(x)$
- Low $\sqrt{s}$ good way to probe Δg at high x

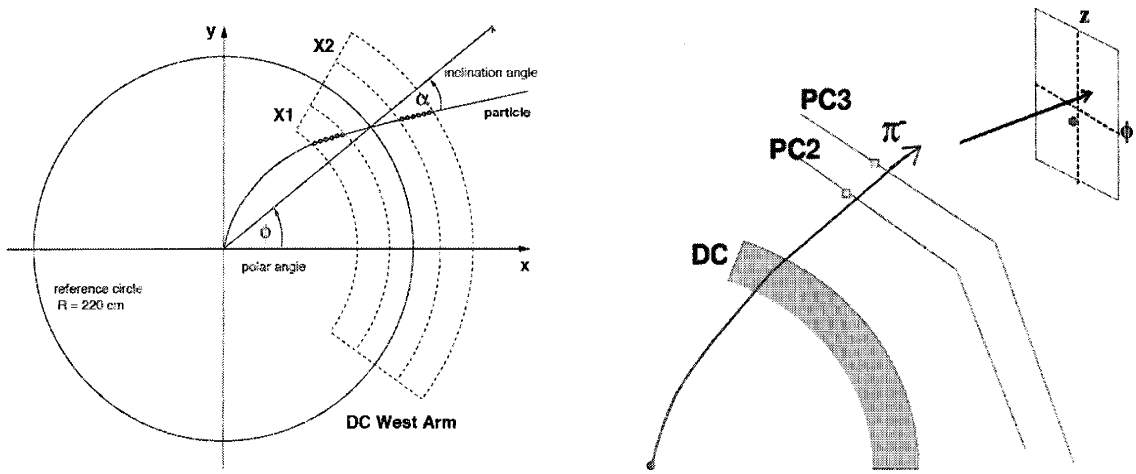
Overview of the Asymmetry Analysis

- Identify pp collisions by coincidence of hits in two Beam Beam Counters (BBCs) on either side of IR (minimum bias trigger)
- Select events with pp vertex within $\pm$ 30 cm of nominal center of IR (within acceptance of PHENIX central arms)
- Look for tracks with hits in Drift Chamber (DC) and Pad Chambers (PC), determine momentum, sort by beam helicity

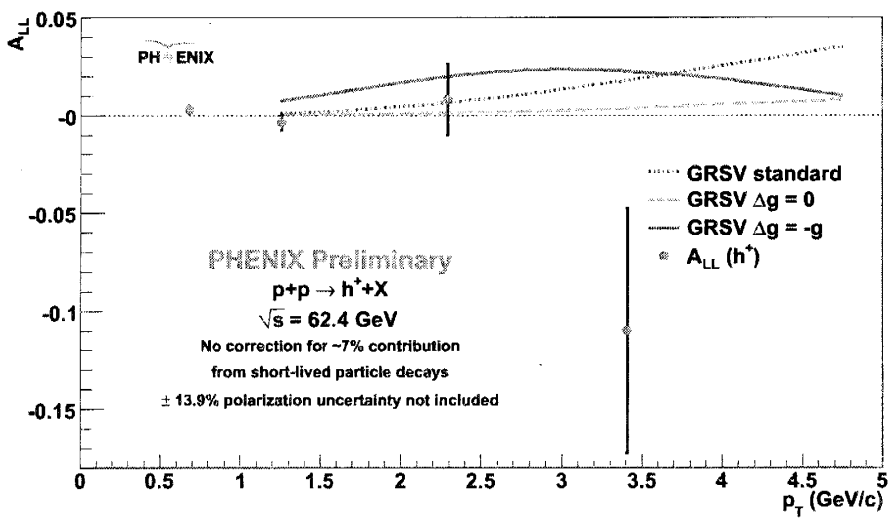


Overview of the Asymmetry Analysis

- Particle momentum determined by angle in DC with respect to infinite momentum track from origin : inclination angle $\alpha \approx 101\ \mathrm{mrad}/\ p_T\ [\mathrm{GeV}/c]$
- Impose fiducial cuts, restrict to transverse momenta to 0.5 GeV/c $< p_T <$ 4.5 GeV/c
- Require that projections of track segments from different detectors match up
- Correct for offsets of beam/detectors from nominal positions which affect determination of momentum, apply veto using Ring Imaging Čerenkov, to eliminate $e^{\pm}$ background

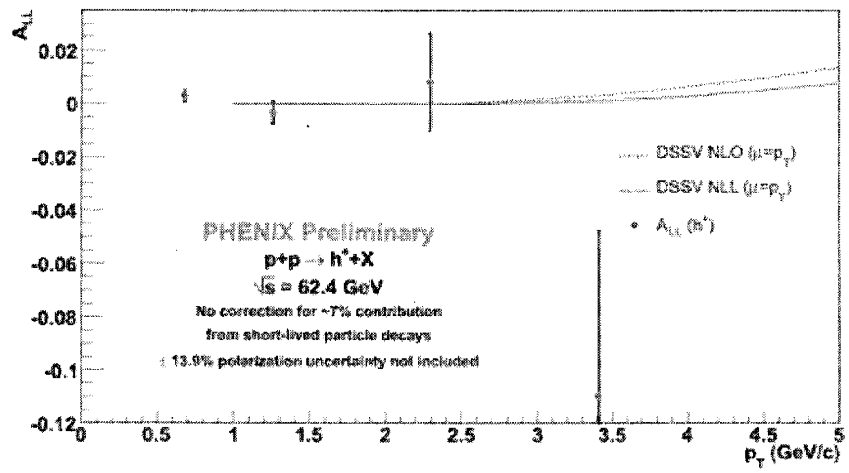


Results for $A_{LL}^{h^+}$ and Comparison with GRSV Model Predictions (pre-RHIC)



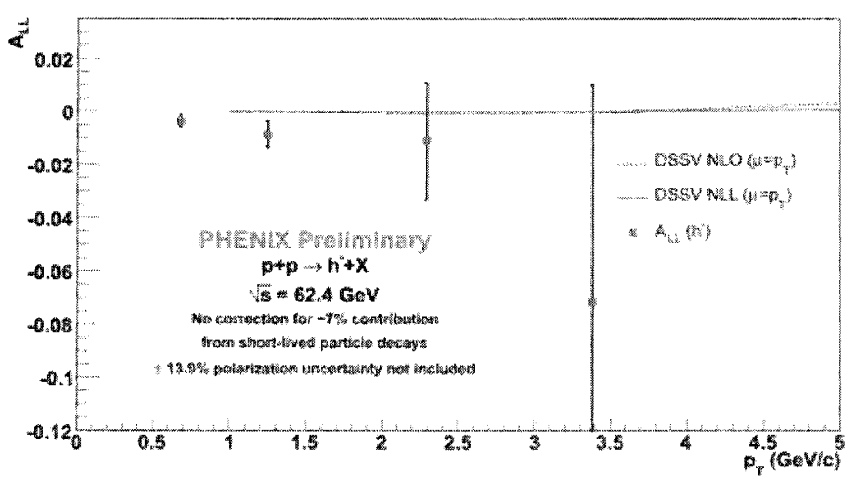
- Beam polarization roughly 48%, 13.9% scale uncertainty, δA_{LL}(Rel. Luminosity)$\approx 1.4 \times 10^{-3}$
- GRSV model $\Delta g(x) = g(x)$ (not shown on plot) is > 0.1 at $p_T = 3.75$ GeV/c
- $\Delta g(x) = g(x)$ clearly excluded by the data, which favor smaller $\Delta g(x)$
- Not bad for ≈ 1 week of data!

Results for $A_{LL}^{h^+}$ and Comparison with DSSV Model (Post-RHIC)



- Data from PHENIX $A_{LL}^{\pi^0}$ and STAR jets used in DSSV global analysis to constrain Δg
- DSSV : D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. D **80**, 034030 (2009))
- Extract much smaller Δg than GRSV models which preceded RHIC
- (For predictions : species-dependent asymmetries summed, weighted by detection efficiency)
- Will be challenging to constrain Δg further

Results for $A_{LL}^{h^-}$ and Comparison with DSSV Model (Post-RHIC)

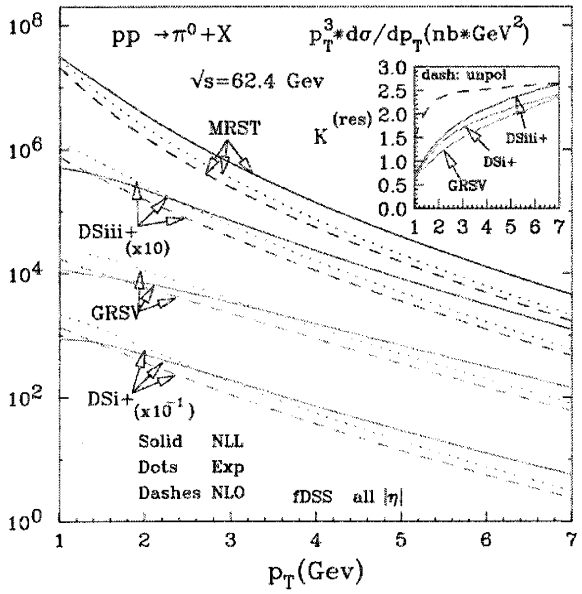


- Note : $A_{LL}(\mathrm{h}^-)$ predicted at high p_T smaller than $A_{LL}(\mathrm{h}^+)$
- These measurements alone could have ruled out pre-RHIC models of Δg

Cross-section Determination of Non-identified Charged Hadrons at $\sqrt{s} = 62.4$ GeV

Motivation :

- σ measurements of inclusive high p_T hadrons at low $\sqrt{s_{pp}}$ important baseline for heavy ion physics
  - Hadron yields in heavy ion collisions versus pp collisions, changes as $\sqrt{s}$ increases
  - Interesting to compare yields with ISR results from mid 1970s



- At large $x_T \equiv 2p_T/\sqrt{s} \gtrsim 0.1$, just enough energy to produce hadrons, "threshold" region
- Gluon-radiation inhibited, large logarithmic corrections to cross-section
- Comparison of NLO and NLL cross-section predictions with data are important test of our understanding
- Pushing/extending pQCD into new regions of applicability
- see de Florian, Vogelsang, Wagner, Phys. Rev. D **76**, 094021 (2007)

Consistency between predictions and data lead to confidence in extraction of Δg

Non-identified Charged Hadron Cross-section Determination

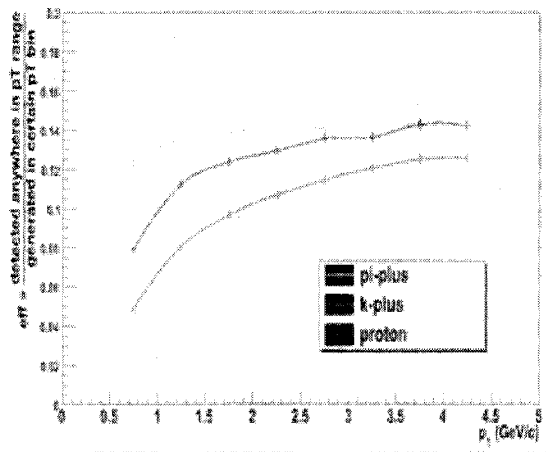
- We determine the non-identified charged hadron cross-section at mid-rapidity for : $(\pi^+ + K^+ + p)$ and $(\pi^- + K^- + \bar{p})$
- Use detector simulation to determine species-dependent detection efficiency : $\epsilon^{\pi}(p_T),\ \epsilon^{K}(p_T),\ \epsilon^{p}(p_T)$
- Particle species fractions $f_\pi,\ f_K,\ f_p$ from identified hadron analyses of PHENIX, ISR
- Weight species fraction and particle detection efficiencies to determine overall $\epsilon(p_T)$

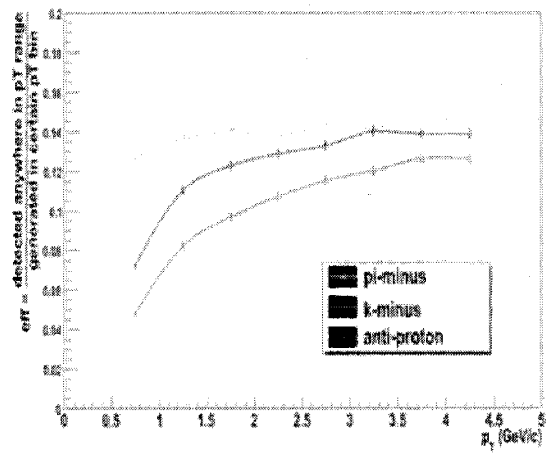
- Extract cross-section for non-identified hadrons, after corrections :
  - Correct for migration of events into incorrect p_T bin due to finite momentum resolution
  - (Small) correction for the minimum bias trigger efficiency as function of p_T
  - Correction for the acceptance and efficiency of the detectors and cuts used in the analysis

- Cross-section results had been held up by disagreement with identified hadron analysis
- Normalization error found in our analysis, p_T-dependent trigger bias found in other analysis
- Finally consistent, way cleared for publication (in preparation)

Single Particle Efficiencies

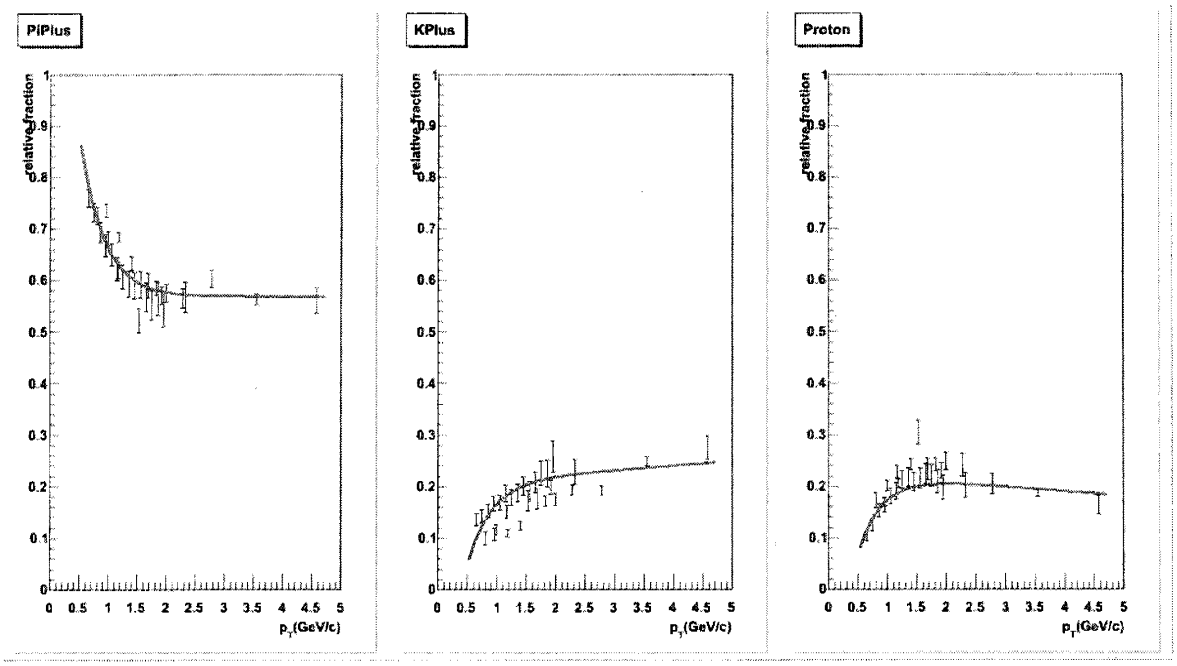
- Need to estimate detection efficiency as function of p_T for ± 0.5 units in rapidity, for different species ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$)
- Same rapidity and p_T corresponds to different θ for particles of different mass, $\Rightarrow$ hence different acceptance
- Single particle efficiencies determined using a full detector simulation
- Lower efficiency for kaons due to decay in flight





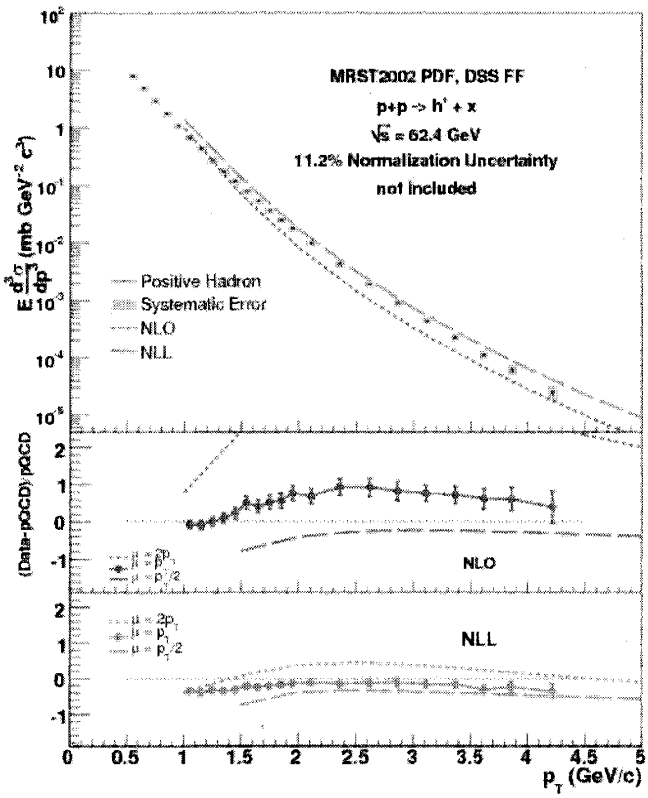
Particle Species Fractions

- Species fractions determined from PHENIX (M. Konno and T. Chujo, low p_T) and ISR measurements



π^+ K^+ p

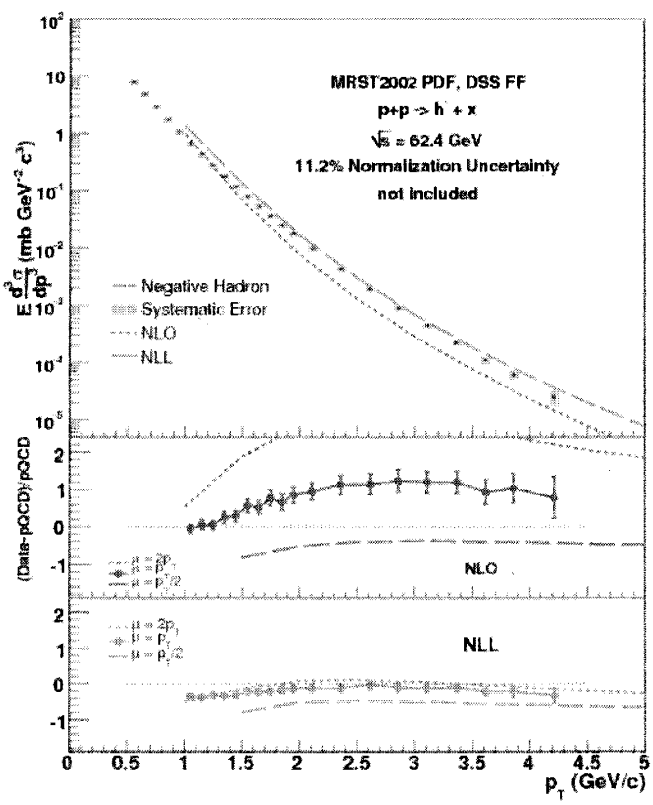
Cross-section for Positively Charge Hadrons and Comparison with Theory



Systematic uncertainties :

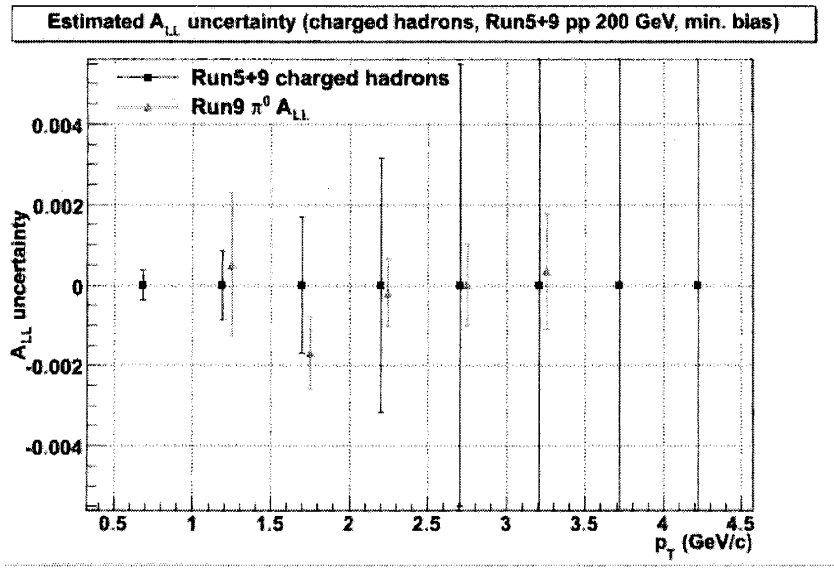
- 1%-5% from uncertainties in species fractions
- 0.6%-5% from background fraction
- 0.5%-1.5% from uncertainty in momentum smearing
- 11%-24% from uncertainty in acceptance and efficiency
- 11% uncertainty in normalization (integrated luminosity)
- NLL more consistent with data than NLO
- Interpret asymmetry data in NLL framework

Cross-section for Negatively Charge Hadrons and Comparison with Theory



Cross-section and Asymmetry Analysis of Non-identified Hadron at $\sqrt{s}$=200 GeV

- Can extend this analysis to minimum bias data set at $\sqrt{s} = 200$ GeV
- Very high statistical sensitivity at low p_T, competitive with π^0 $(\delta A_{LL} < 10^{-3}$!)
- Sensitivity to Δg at low x, analysis underway



Summary and Future Work

- Longitudinal double spin asymmetries of non-identified charged hadrons at $\sqrt{s} = 62.4$ GeV have been measured

  A week of data excludes GRSV model $\Delta g(x) = g(x)$!
- Cross-section measurement complete

  NLL gives good description of data, use to interpret A_{LL}

  Paper draft underway (finally!)

  Extending asymmetry and cross-section analysis to large $\sqrt{s} = 200$ GeV data set

  Competitive with $A_{LL}(\pi^0)$ in a few bins

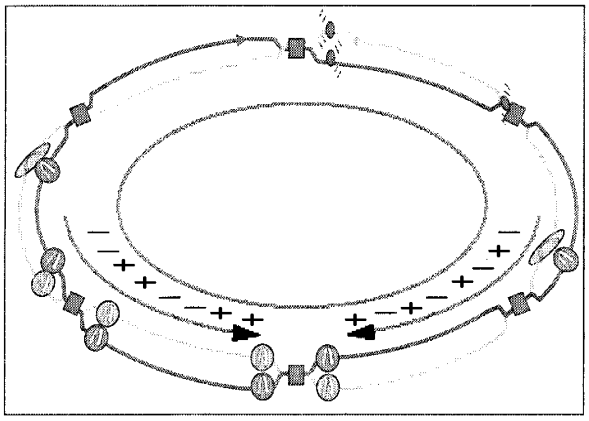
Observation of W boson decay at PHENIX central arm

Kensuke Okada

RBRC review

October 27, 2010

W bosons at RHIC



Polarized *p+p* collider

- An unique probe to access the flavor dependence of polarized sea quarks.
- Parity violating single spin asymmetry (A_L).

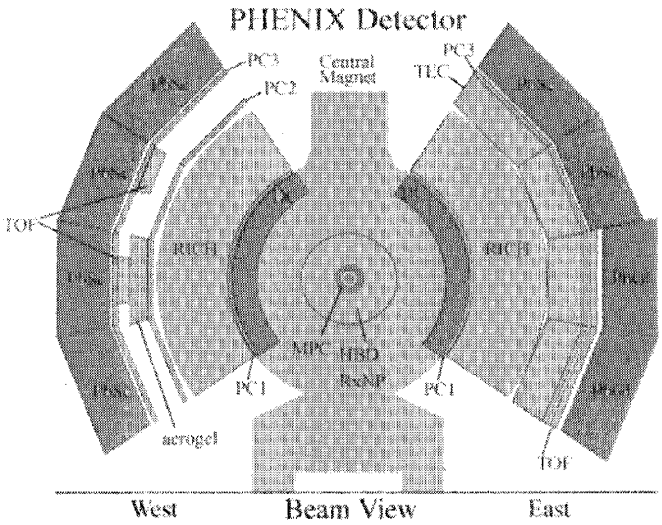
RHIC-PHENIX 2009 run

- The first 500GeV *p+p* run. (March to April, 2009)
- Beam Polarization : <P>=0.39±0.04
- Integrated luminosity (with vertex cut) : ∫Ldt=8.6/pb

Today's talk

$W^{\pm}$ electron decay channel

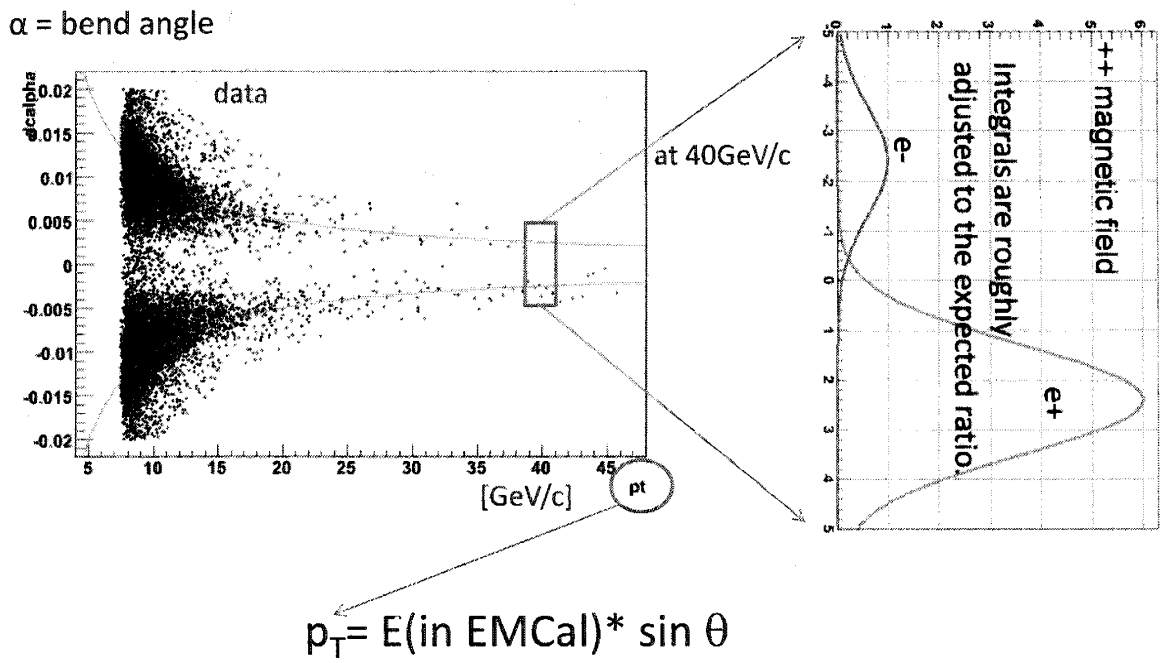
PHENIX Central arm: $W^{\pm} \rightarrow e$



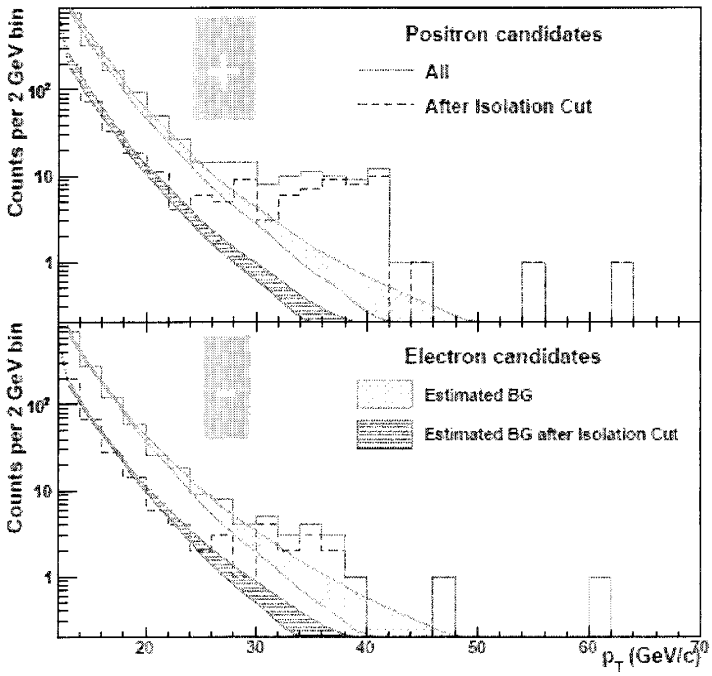
EMCal + DC/PC1 tracking
Acceptance :
±0.35 in rapidity
0.5π*2arms in ϕ

EMCal Trigger
Fully efficient at 12GeV

$e^{\pm}$ energy and charge



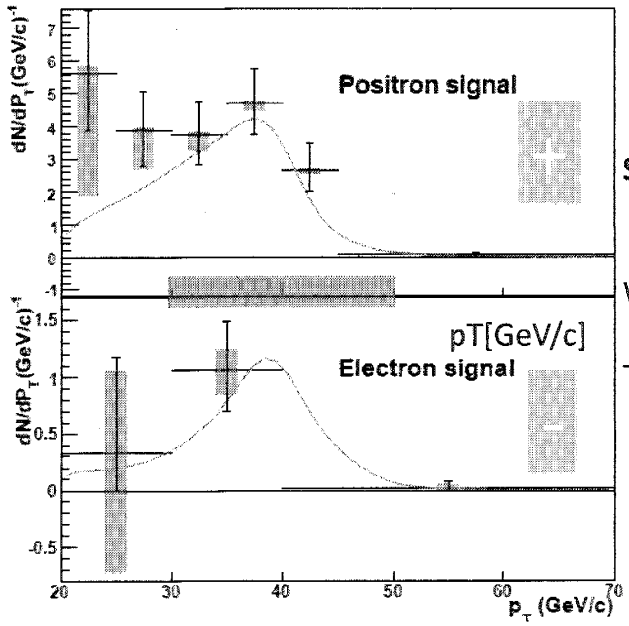
Jacobian peak is confirmed



p_T distribution of electron candidates

Red histogram:
with minimum track requirements
Blue histogram:
with an isolation cut

Consistent with the expectation



Signal shape after background subtraction
electrons from W, Z bosons.

With minimum track requirements

The red curve shows the expectation (NLO)

Consistent with the expectation (numbers)

W,Z decay electrons

		$\frac{d\sigma}{dy}(30 < p_T^e < 50\,\mathrm{GeV}/c)\|_{y=0}$ [pb]		
Lepton		Data	NLO	NNLO
e^+	positron	$50.2 \pm 7.2^{+1.2}_{-3.6} \pm 7.5$	43.2	46.8
e^-	electron	$9.7 \pm 3.7^{+2.1}_{-2.5} \pm 1.5$	11.3	13.5
e^+ and e^-		$59.9 \pm 8.1^{+3.1}_{-6.0} \pm 9.0$	54.5	60.3

uncertainties: Statistical

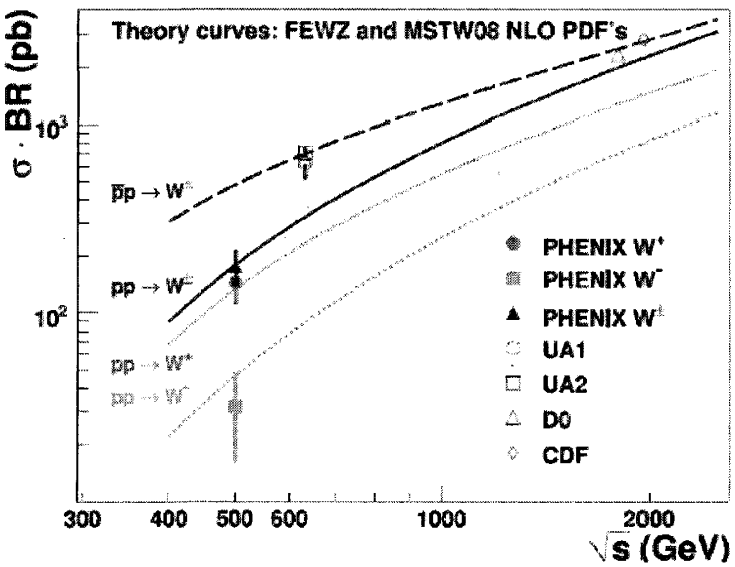
Systematic (Background assumptions)

Normalization (15%)

(acceptance, efficiency, luminosity)

Convert to the total W production

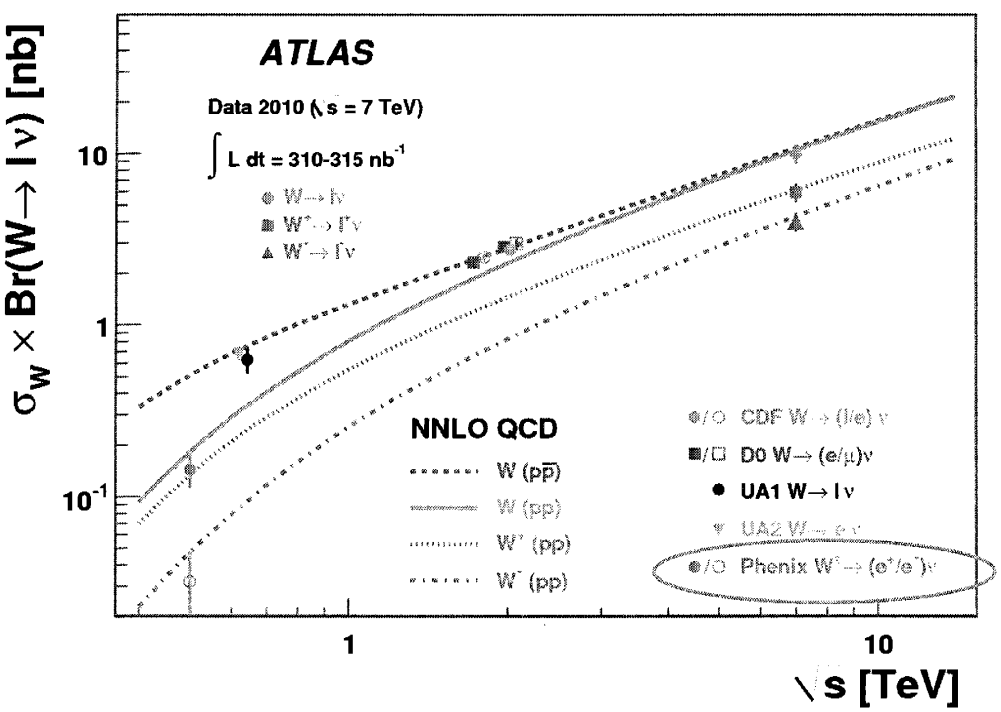
PHENIX acceptance ⟶ Total
(pT>30GeV, |y|<0.35)



Z boson contribution
+ : ~7%, -: ~30%
Fraction of the PHENIX
+ : ~22%, -: ~15%

The first measurement in *p+p* collisions.

RHIC recognized as a p+p collider



Parity violating single spin asymmetry

RHIC has 120 bunches polarized (every 106ns)
→ Reduces detector time dependence

Concept: 1-beam polarized

Raw asymmetry: $$\epsilon_L = \frac{N^+ - R \cdot N^-}{N^+ + R \cdot N^-}$$

N^+ : yields in helicity +
N^- : helicity –
normalized by $\int L$

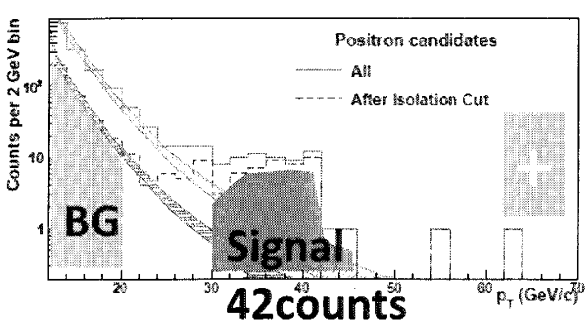
Physics asymmetry : $$A_L = \frac{\epsilon_L \cdot D}{P}$$

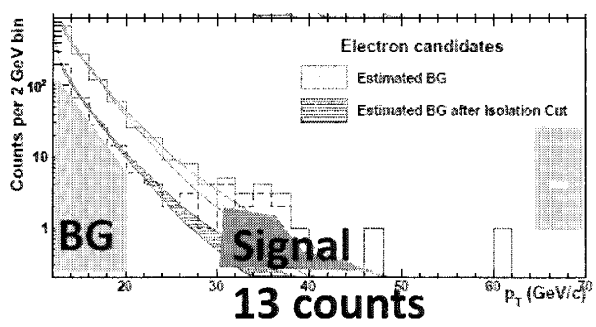
D: Dilution correction
P: Beam Polarization

Actual calculation

From 4 spin patterns (= 2 beams * 2 helicity patterns)

Parity violating raw asymmetries (ε_L)





Sample	ϵ_L
Bkgrnd +	-0.015 ± 0.04
Signal +	-0.31 ± 0.10
Bkgrnd −	-0.025 ± 0.04
Signal −	0.29 ± 0.20

ε_L=0 for Background (as expected)

Large ε_L for Signal (especially in e^+)

Physics asymmetries (A_L)

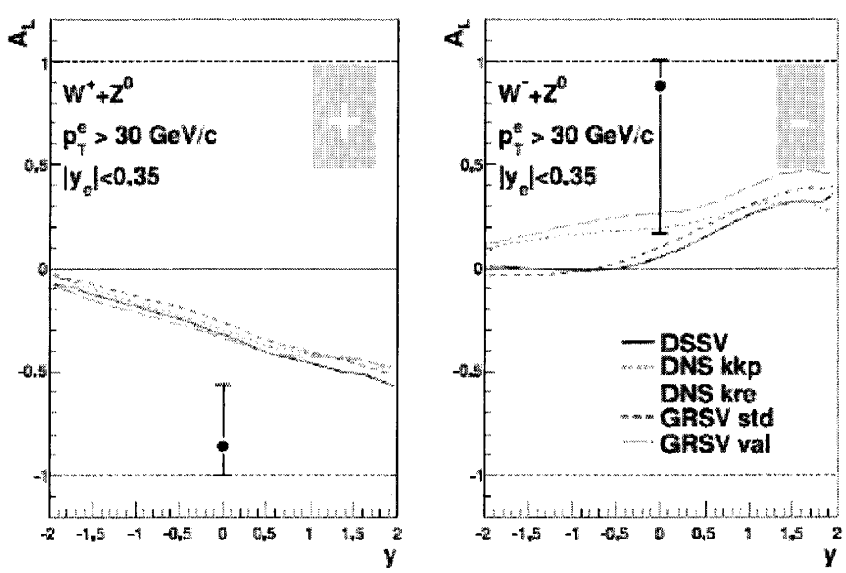
$$A_L = \frac{\epsilon_L \cdot D}{P}$$

D: 1.04±0.03 (+ signal)
1.14±0.10 (- signal)
P: 0.39±0.04 (2 beam average)

Sample	ϵ_L		$A_L^e(W+Z)$	68%CL	95%CL
Bkgrnd +	-0.015 ± 0.04				
Signal +	-0.31 ± 0.10	→	-0.86	$[-1, -0.56]$	$[-1, -0.16]$
Bkgrnd −	-0.025 ± 0.04				
Signal −	0.29 ± 0.20	→	$+0.88$	$[0.17, 1]$	$[-0.60, 1]$

Limited to the physical region [-1,1].

A_L (68%CL) and predictions



They are consistent with all models for now.
A non-zero asymmetry (98.4%CL) is observed in the positive candidates.

Summary

- PHENIX central arm detects electrons from W boson decay.
- The production cross section is as expected.
- Measured the parity violating single spin asymmetry (non zero A_L).
- Submitted to a journal. (arXiv:1009.0505)
- This is a start of RHIC W boson program.

W working group meetings

Regular member → paper preparation group (ppg)
(M.Chiu, K.Karatu(JRA), D.Kawall(Fellow), J.Haggerty, A.Bazilevsky, E.Kistenev, KO)

2008, Some preparation
Bazilevsky, Karatsu, KO
(2009-01-23)
(2009-02-05)
(2009-02-13)
(2009-02-27)
(2009-03-13)
(2009-03-27) Run9 500GeV
(2009-04-10)
(2009-05-07)
(2009-05-21)
(2009-06-12)
(2009-07-14)
(2009-07-21)
(2009-07-27)
(2009-08-04)
(2009-08-11)
(2009-08-18)
(2009-08-25)
(2009-09-01)
(2009-09-08)
(2009-09-15)
(2009-09-23)
(2009-09-29)

(2009-10-06)
(2009-10-20) DNP/JPS (10/13) Karatsu
(2009-10-27)
(2009-11-03)
(2009-11-09)
(2009-11-16)
(2009-11-30)
(2009-12-07)
(2009-12-14)
(2009-12-22)
(2009-12-29) WWND (1/2) Kawall
(2010-01-05)
(2010-01-12)
(2010-01-19)
(2010-01-26)
(2010-02-02)
(2010-02-24) APS (2/13) Haggerty
(2010-03-02) LLWI (2/14) Okada
(2010-03-09)
(2010-03-16) High PT2010 (3/17) Karatsu
(2010-03-23)
(2010-03-30)

(2010-04-07) DIS2010 (4/19) Chiu
(2010-04-13)
(2010-04-20)
(2010-04-27)
(2010-05-04)
(2010-05-11)
(2010-05-18)
(2010-05-25)
(2010-06-09)
(2010-06-16)
(2010-06-29) W-BNL (6/24) Kawall
(2010-07-07)
(2010-07-15)
(2010-07-20) ICHEP (7/21) Haggerty
(2010-07-27)
(2010-08-03)
(2010-08-06)
(2010-08-17)

8/17- 9/4 ppg meetings everyday.
arXiv:1009.0505

JPS,SPIN 9/11,27 Okada

Readiness of Forward Muon Arms for W Detection

Itaru Nakagawa

For the PHENIX Muon Trigger Upgrade Collaboration

Current Muon System

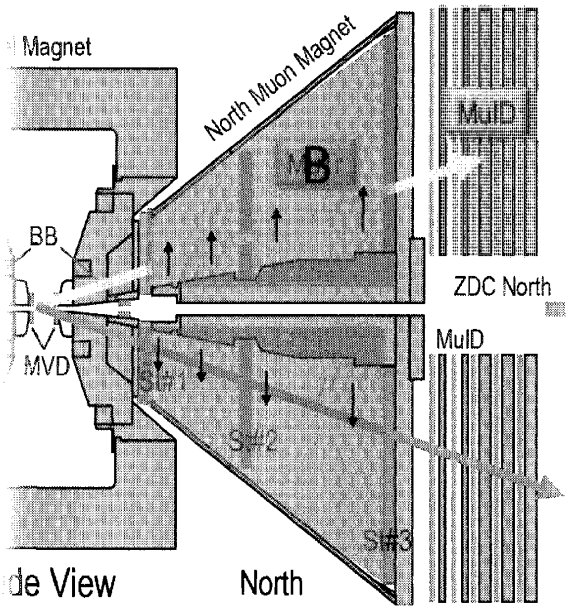
1. Muon Tracking Chambers

- 3 stations of [illegible] chambers
- Grid detection [illegible] for [illegible]
- View [illegible]

2. Muon Identifier

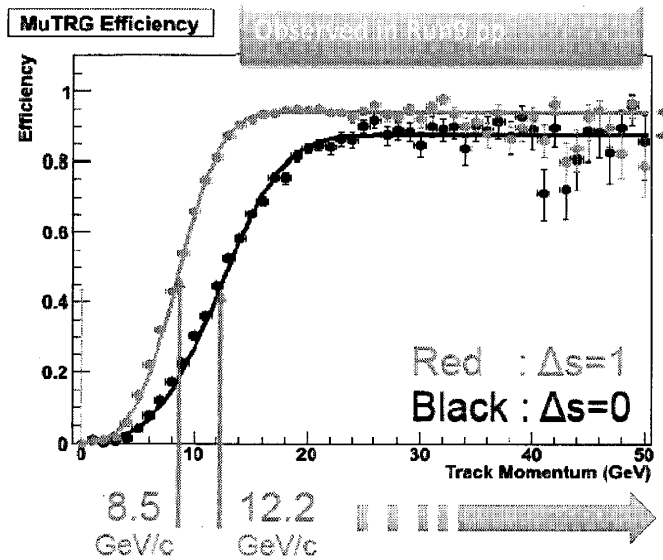
- 5 layers [illegible]
- 40 cm of steel [illegible] (total)

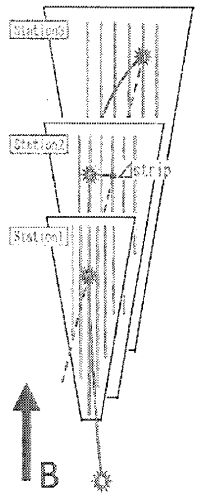
[illegible] trigger p_T > 2 GeV

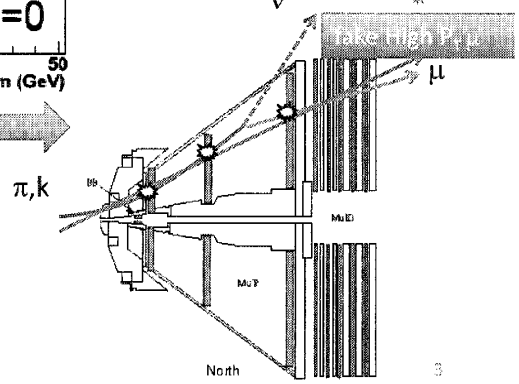


Same configuration in South

MuTRG Efficiency for Track

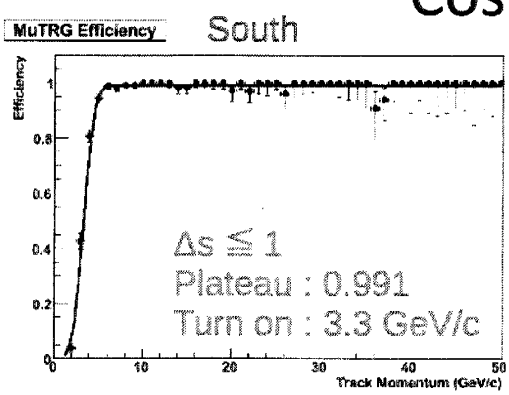


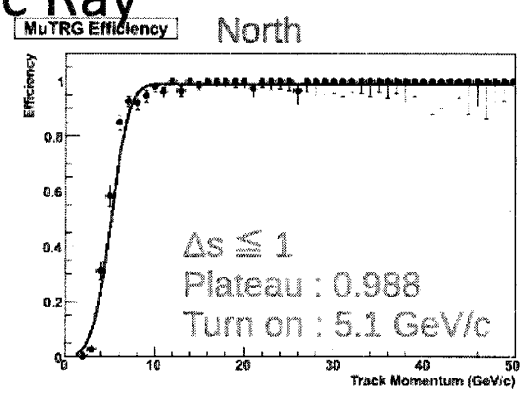


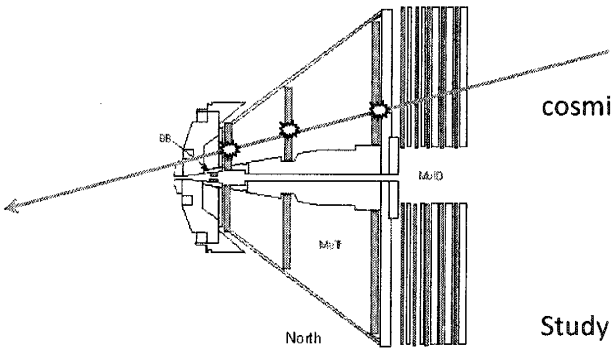


Study done by Yoshinori Fukao (RIKEN)

Efficiency Measurement with Cosmic Ray







cosmic

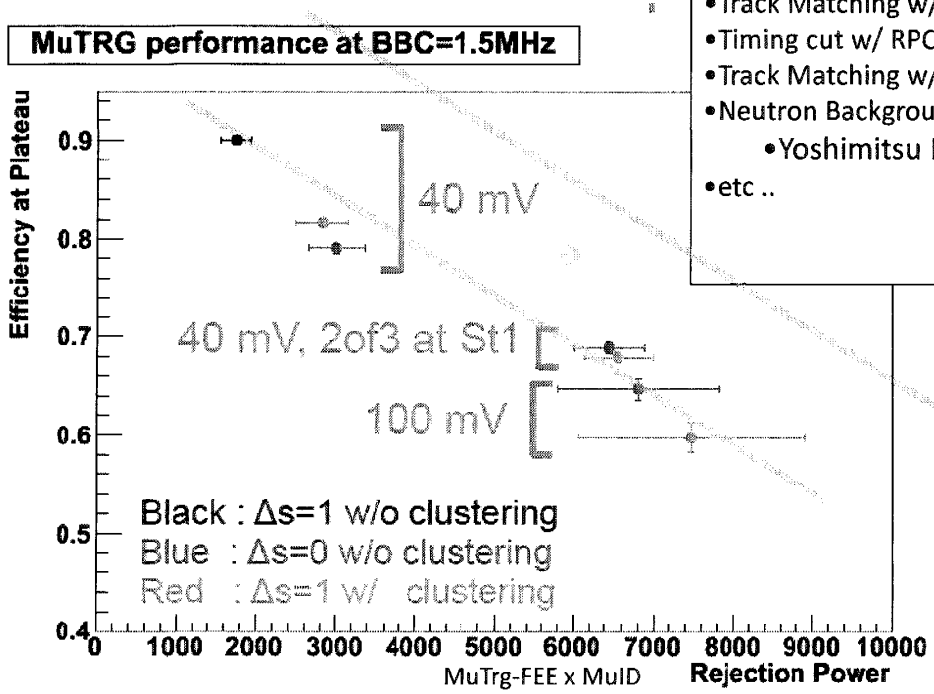
High Efficiency under Clean Circumstance!

Study done by Yoshinori Fukao (RIKEN)

MuTRG System Run09 performance

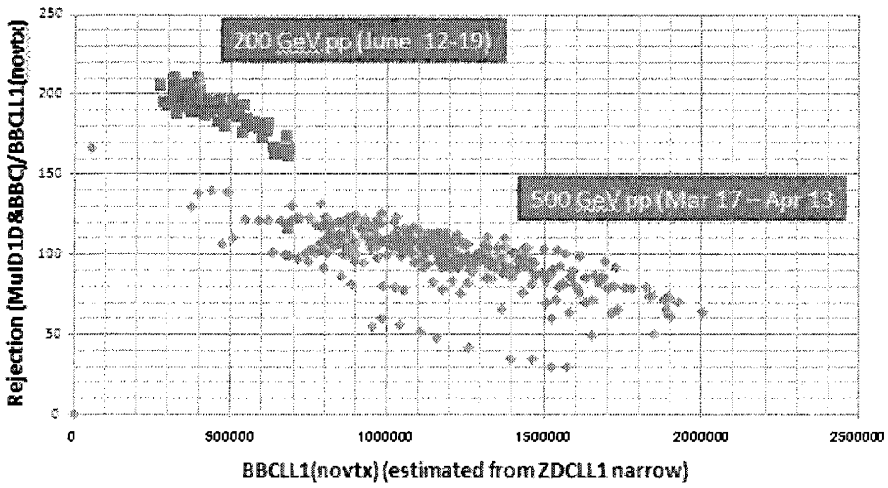
Study done by Yoshinori Fukao (RIKEN)

- MuID Algorithm
- Track Matching w/ MuID
- Timing cut w/ RPC
- Track Matching w/ RPC
- Neutron Backgrounds
  - Yoshimitsu Imazu's Talk
- etc ..



5

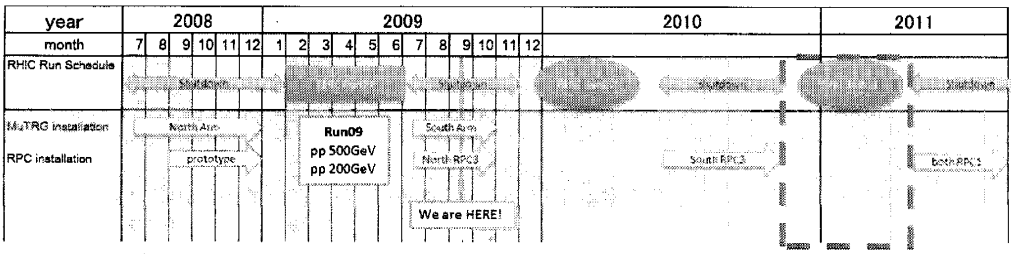
Rate Dependence of MuID Rejection Power

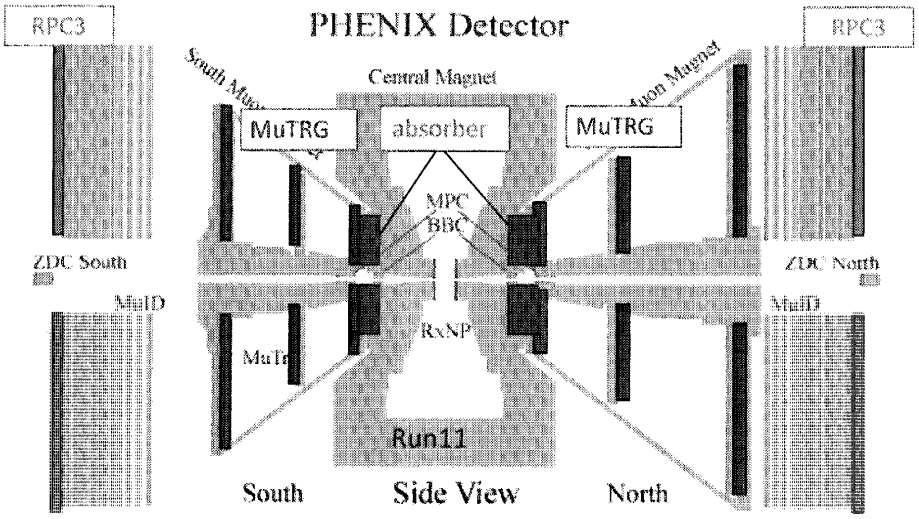


- Can RPC substitute MuID?
- Does RPC give better Rejection Power?

6

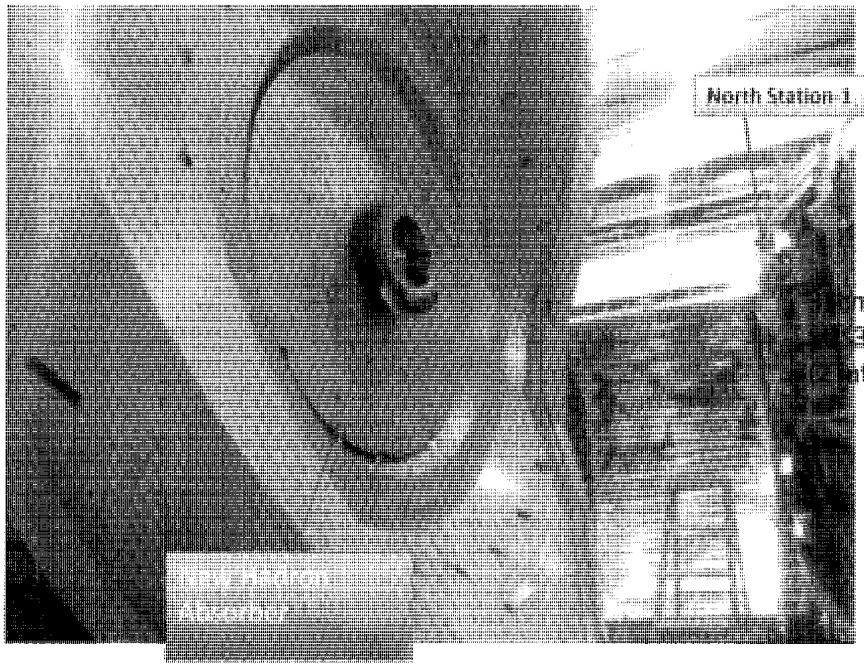
Road Map to Run11 Production Run





7

Completed Installation of Absorbers

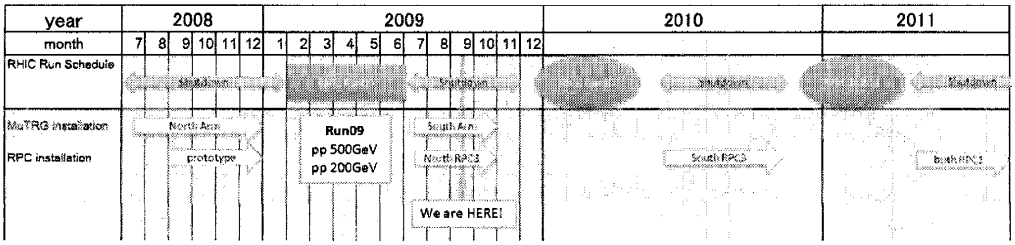


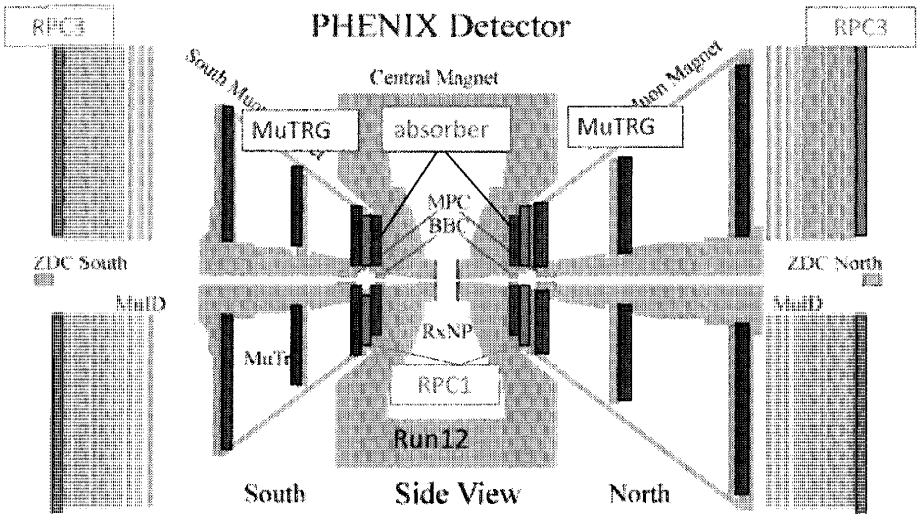
North
South

m thick
310
teraction Length)

8

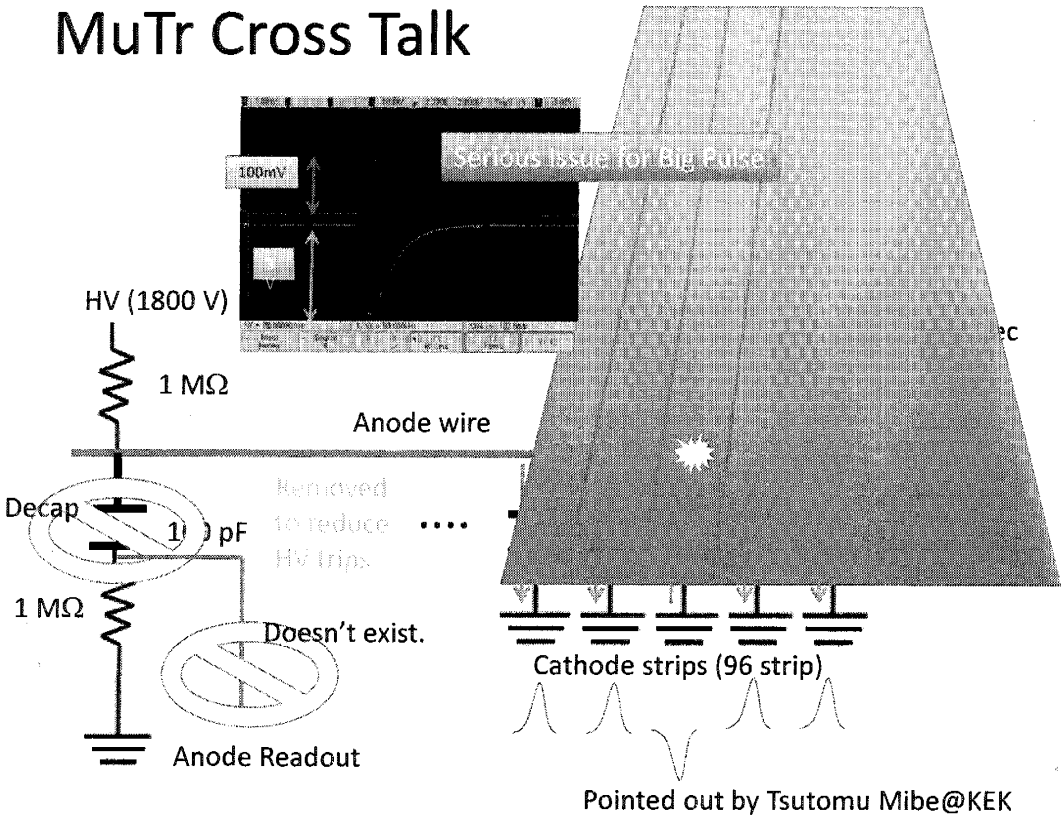
Final Muon Trigger Configuration





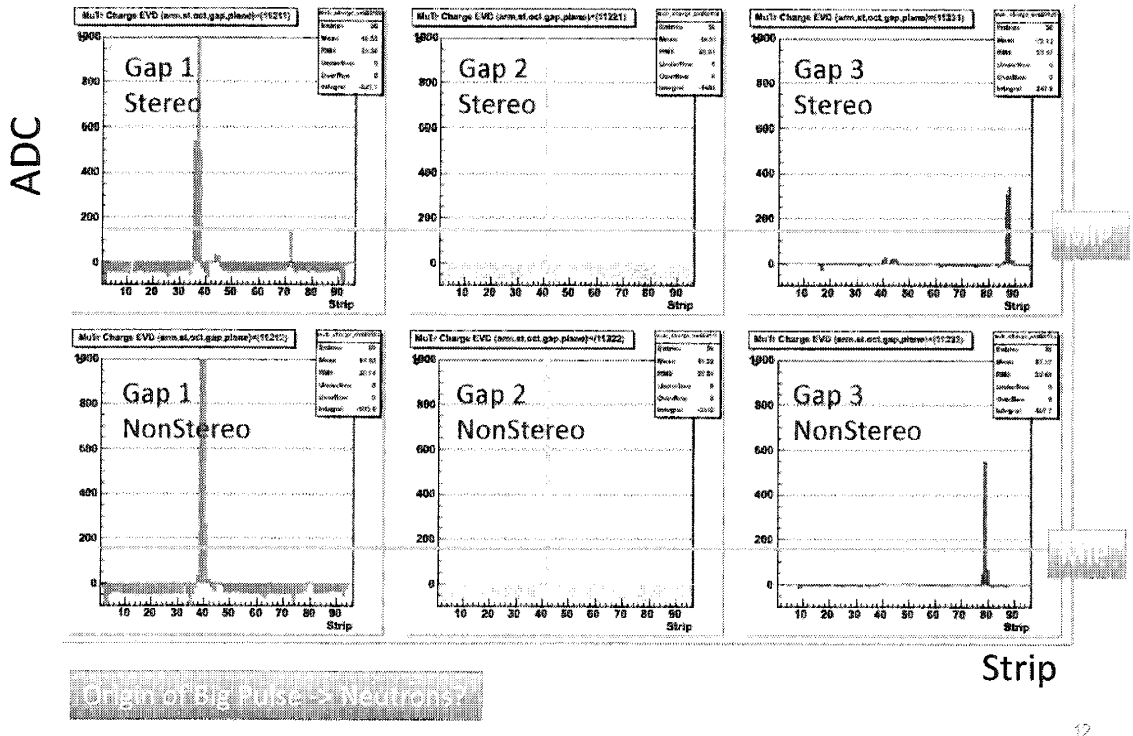
MuTr X-Talk

MuTr Cross Talk



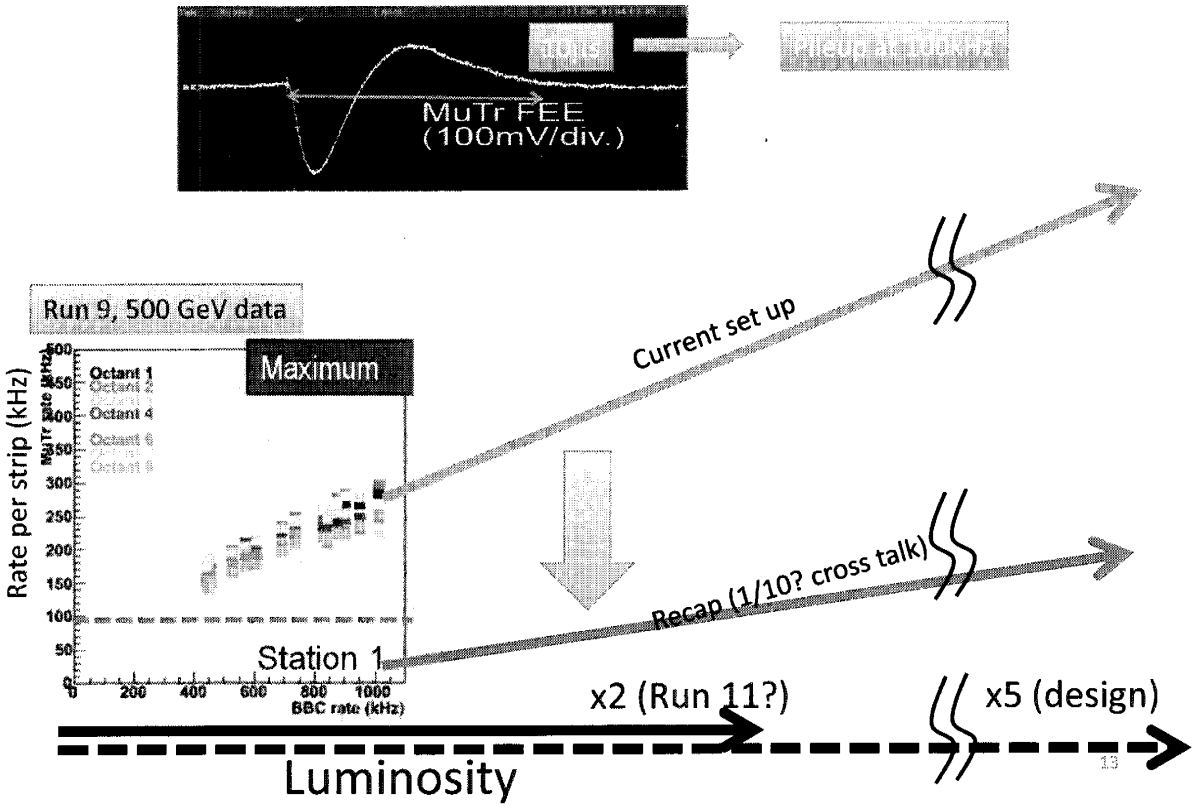
11

Event Display of ADC Distribution

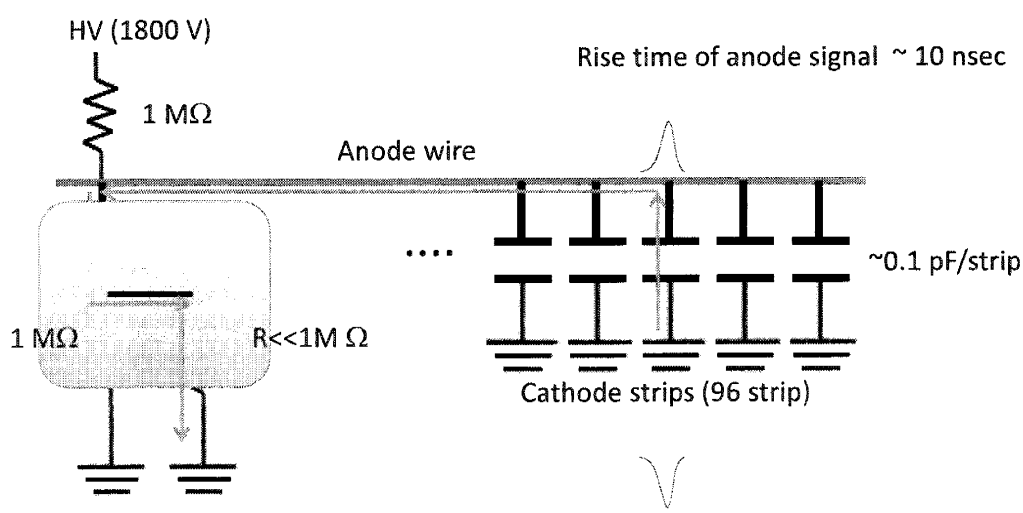


12

Can be serious issue at high rate

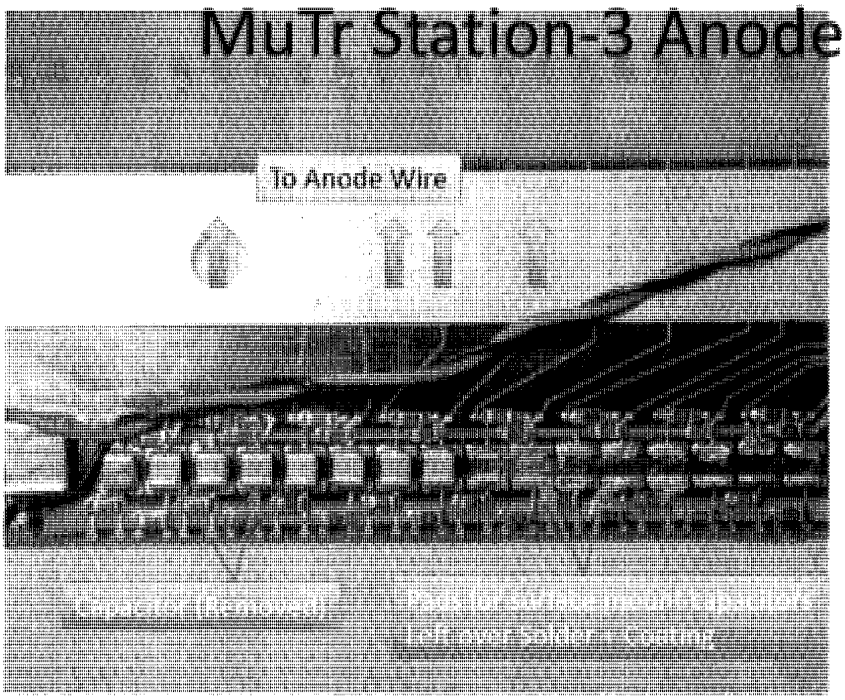


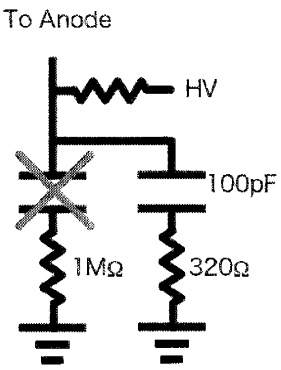
Solution



Additional Circuit to let anode current escape to ground.

MuTr Station-3 Anode Card

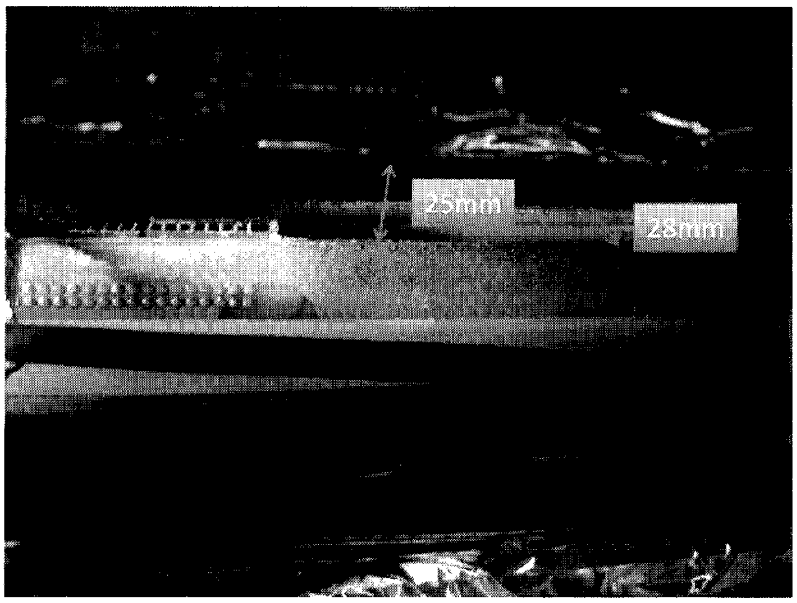




15

North Station-3 Anode Gap

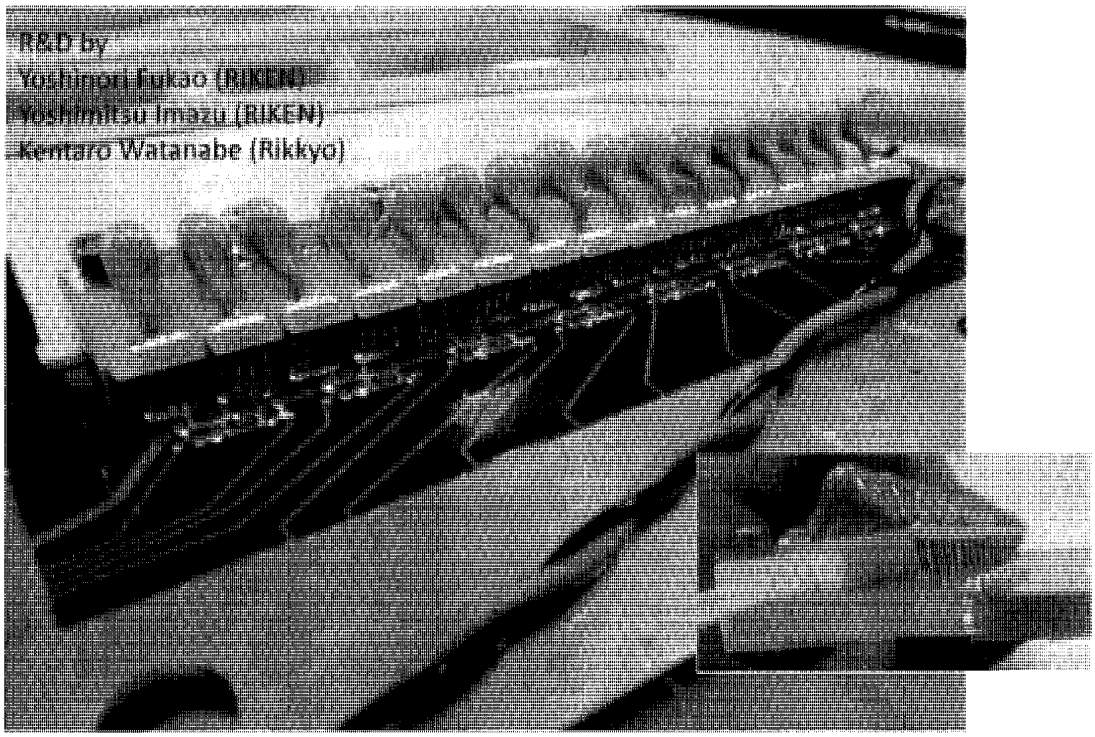
Geometrical Constraint



Anode cards are only accessible from their back.
Front pattern can only be visible using an inspection mirror.

16

Recap Clamp Prototypes

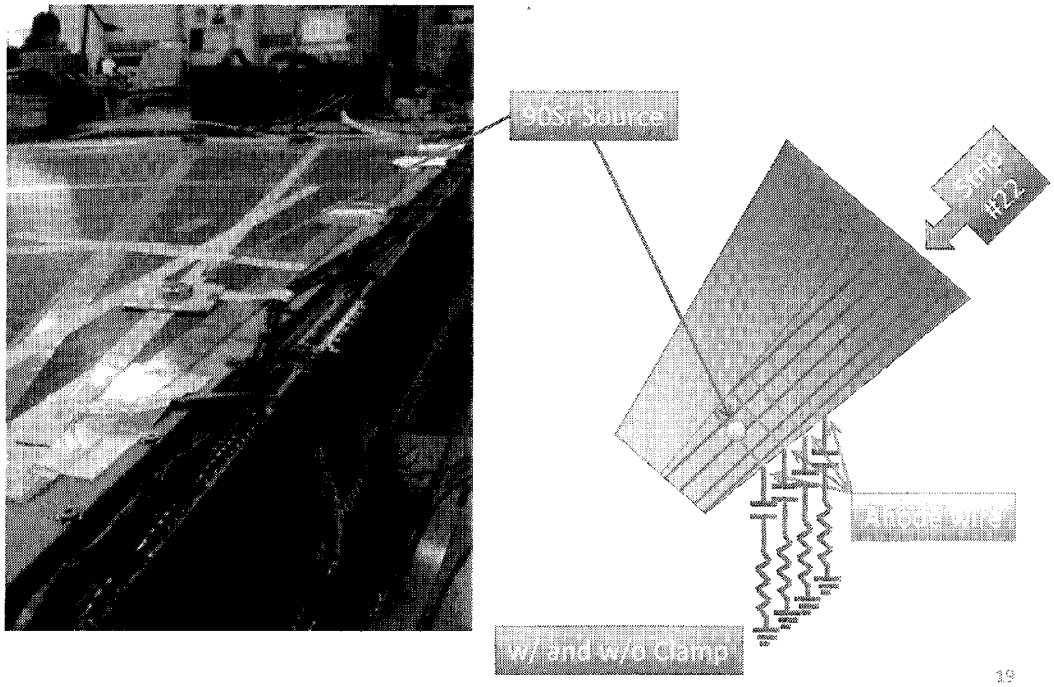


17

Effect of Recap

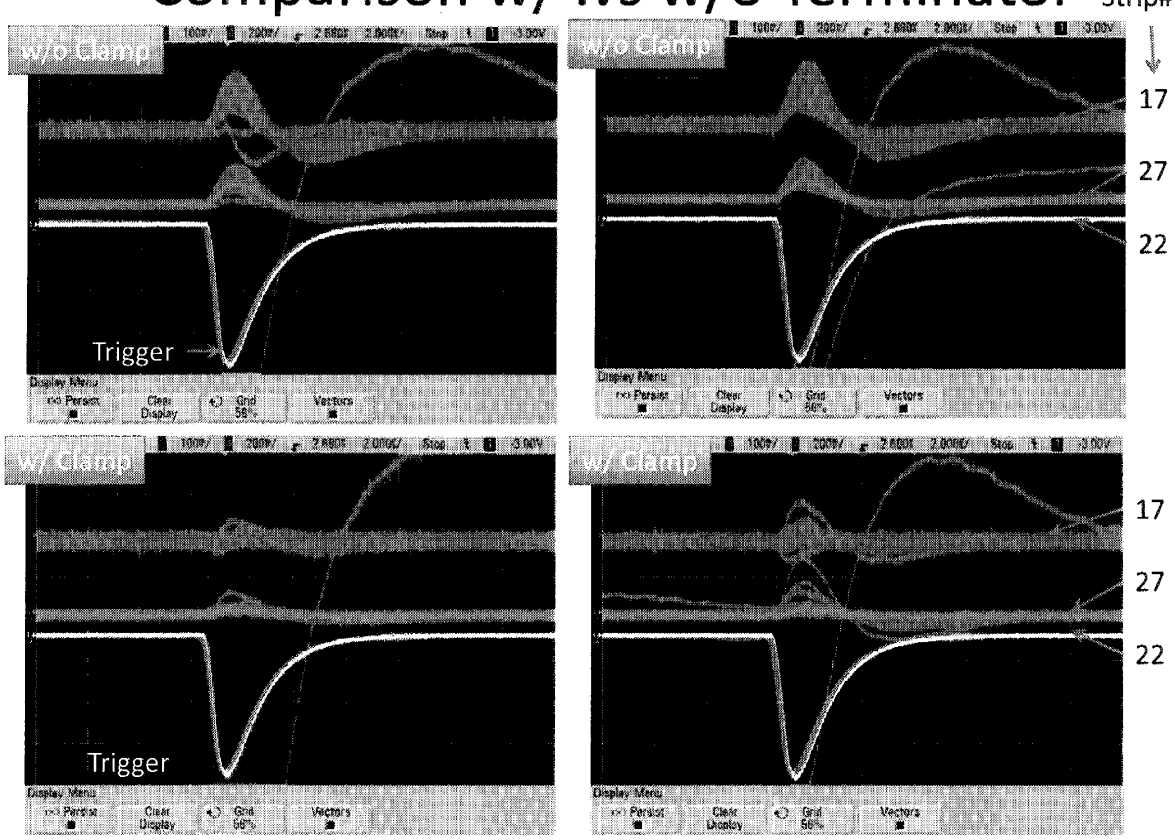
18

Test Bench Setup

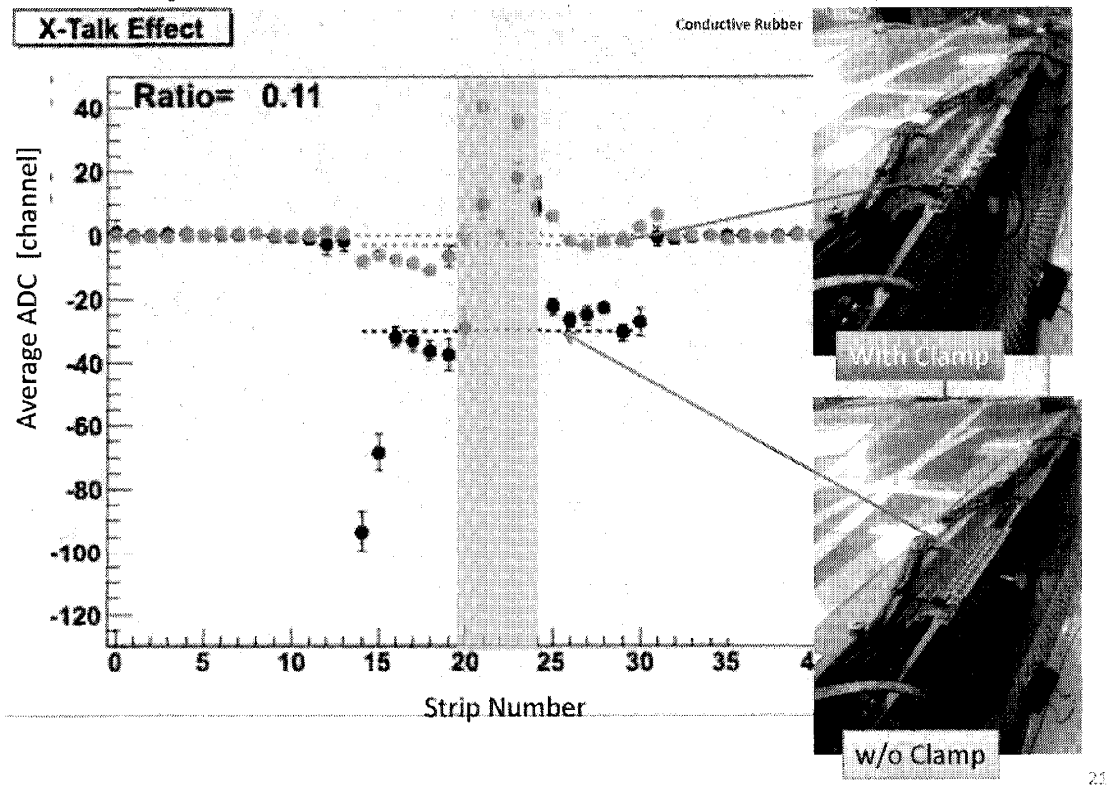


19

Comparison w/ .vs w/o Terminator



Comparison w/ .vs w/o Clamp



21

Neutron Absorber

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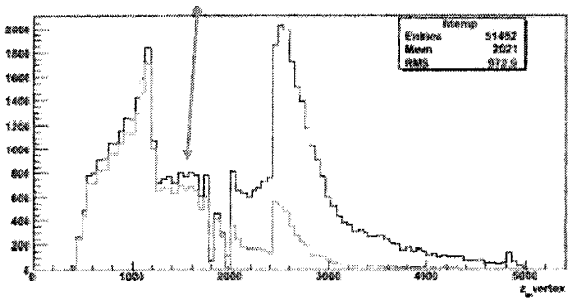
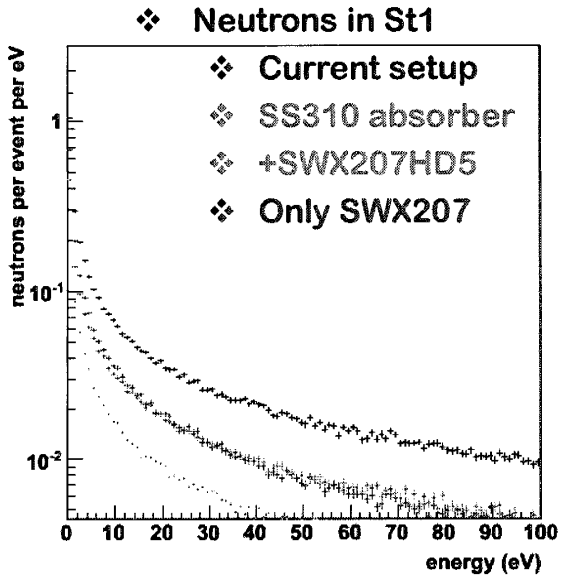
The full muon arm again

- Only 1/20 of all PYTHIA events
- Only MuTr St1
- Y-scale is from old macro
- Only neutrons from upstream of St1





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Thermal Neutron

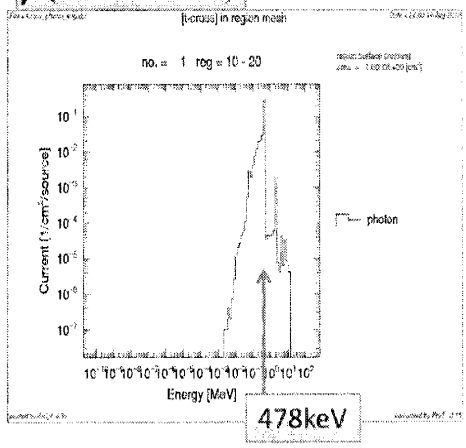
- Origin of Big Pulse

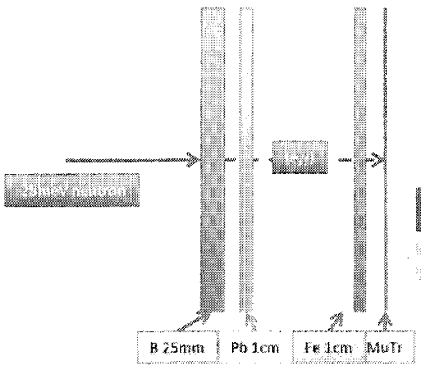
$$A + n(thermal) \rightarrow (A+1) + \gamma(\leq 8\,MeV)$$

- Thermal Neutron Absorber

$$^{11}B + n \rightarrow {}^{7}Li^{*} + \alpha$$

$$^{7}Li^{*} \rightarrow {}^{7}Li + \gamma(478keV)$$





	Thermal Neutron	photon
Absorber	Borated Poly 2.5cm	Pb 1cm + Fe 1cm
Attenuation	~10^{-2}	~5×10^{-2}

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Summary

- High Momentum Muon Trigger (MuTrig-FEE & RPC3) is to be commissioned in Run11
- Sufficient Rejection Power can be achieved, but trade off of efficiency.
- 99% Efficiency with Cosmic at High P_T
- Thermal Neutron is suspect degrades MuTr performance
  - Neutron Absorber Partial Install
  - Recapacitation Clamp Prototypes to be tested in Run11

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Backup Slides

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Towards Successful Installation

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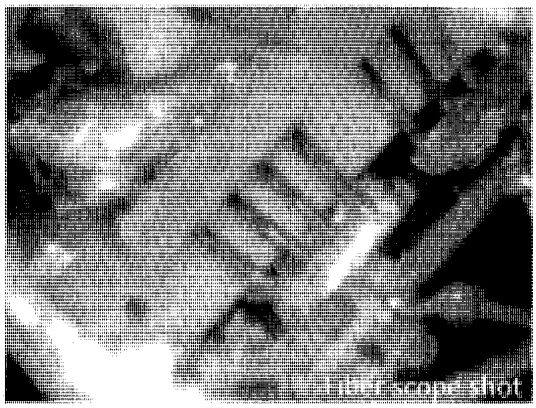
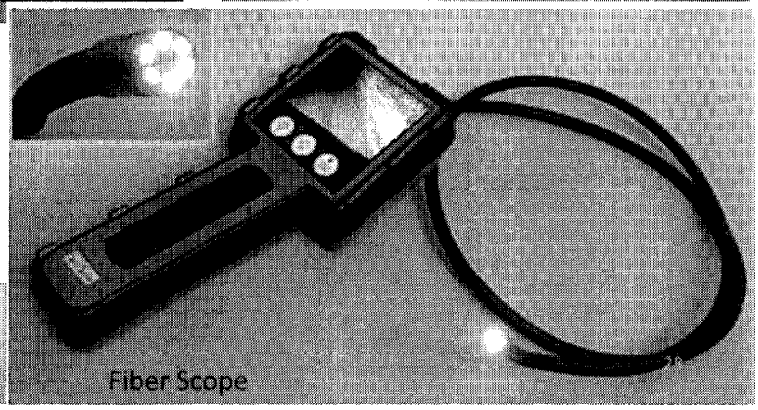
Alignment

Spacer determines transverse direction within ~ 300μm.



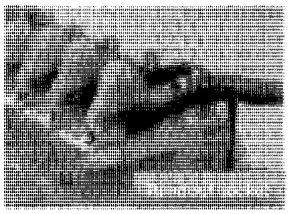
Fiber scope shot

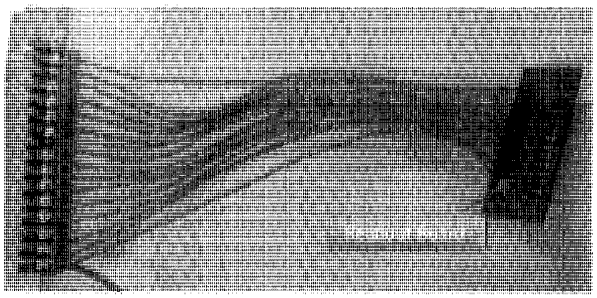


Fiber Scope

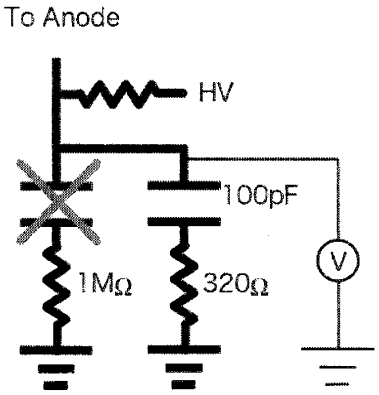
Possible misalignment can be found by visual inspection using a fiber scope

Electrical Contact



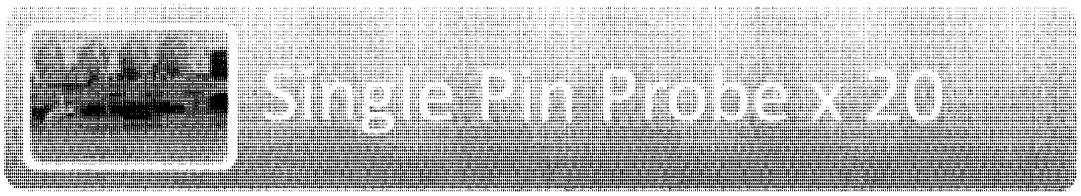


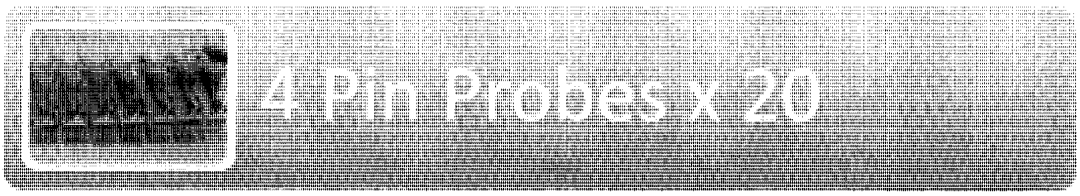
To be removed after the measurement.

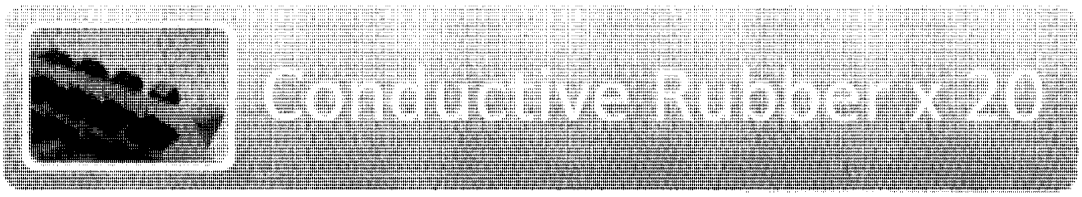


Electrical Contact will be confirmed by measuring voltage using temporary readout tool.

Installation Proposal



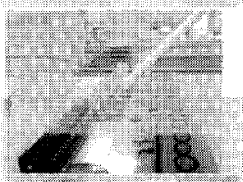




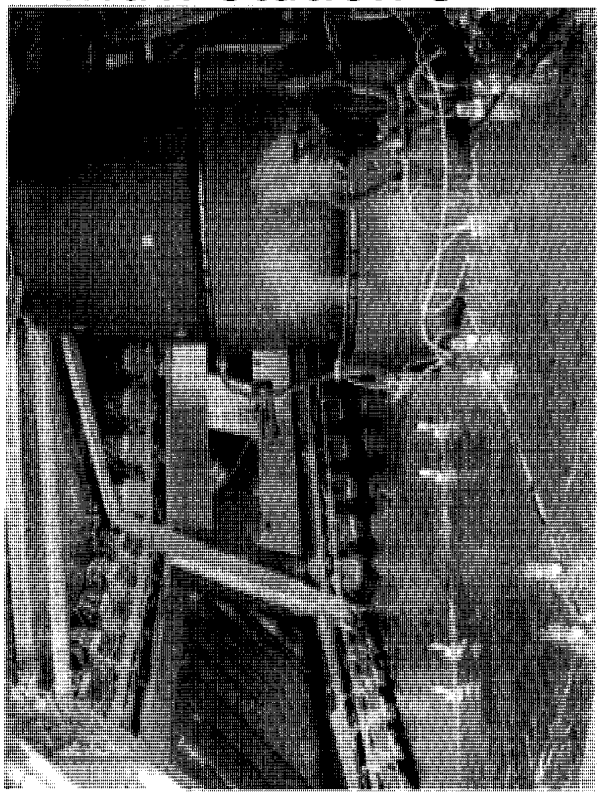
To be installed North Bottom Octants

Extreme Breathing Test

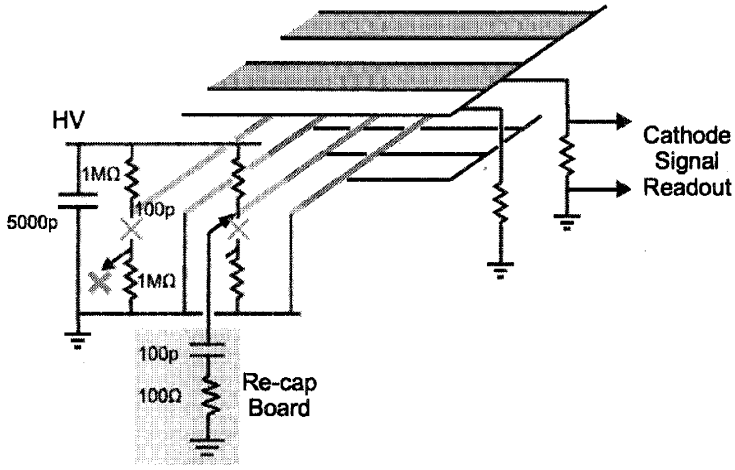
HV=1900V
Duration 2min

	Clamp	Coating	Max Current	Average Current
	w/o	w/	<1uA	<1uA
	w/	w/o	>100uA	Tripped after 2 min.
	w/	w/	1uA	1uA
	w/	w/o	>100uA	Tripped after 1min.
	w/	w/	2uA	2uA

MuTr Station-3



Recapacitation (Station-3)



Capacitorはすべて取り外し済み。
Station-3 Chamberを取り出すの実質的に難しい。
簡易的に取り付けられるクリップでグラウンドに落とす。

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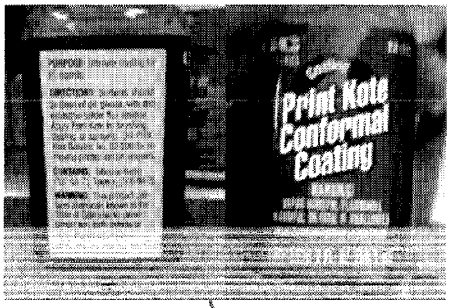
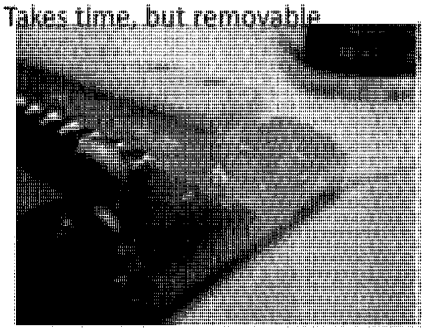
Coating

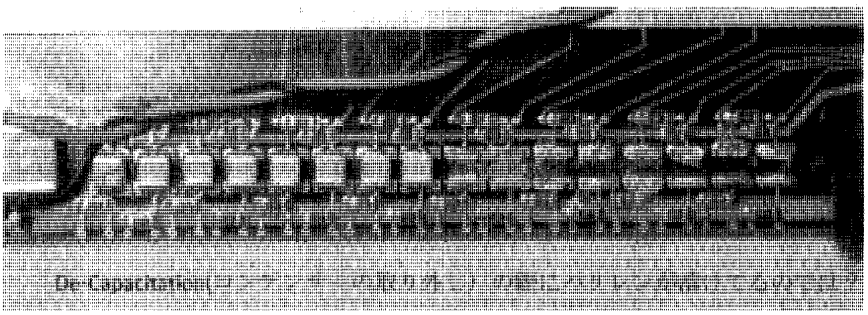


remover

Takes time, but removable



[illegible] 175℃ [illegible] ナフタレンに反応して溶解 [illegible] 時
事実上ムリ。



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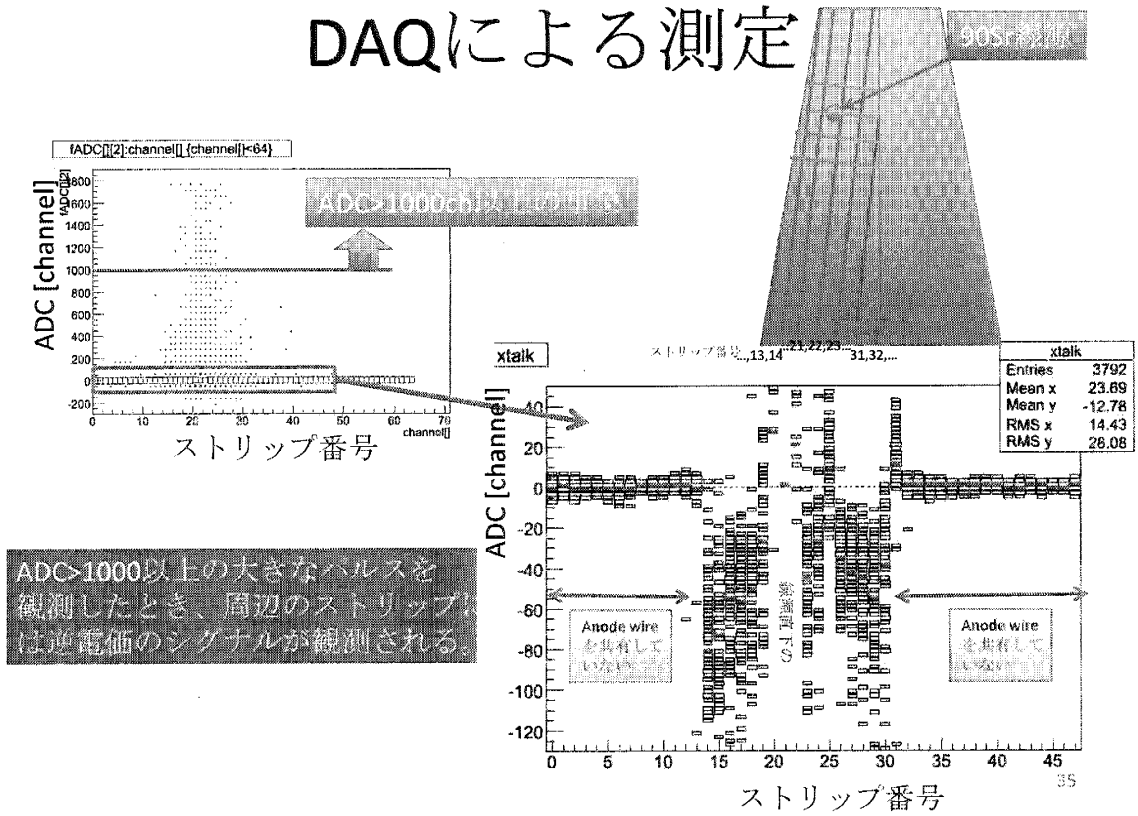
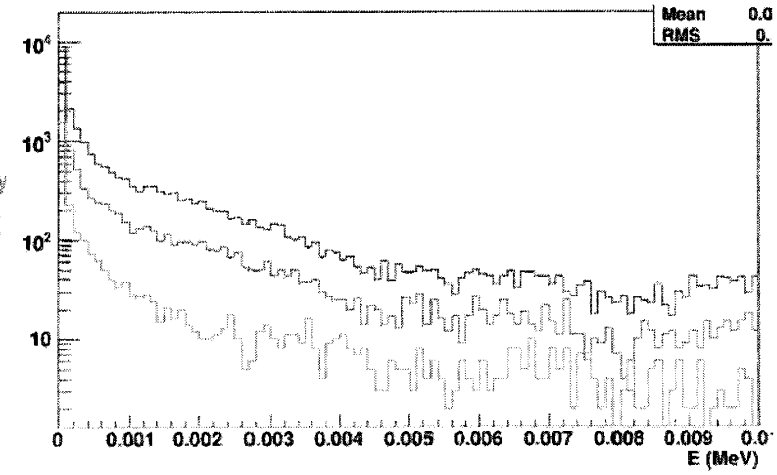
DAQによる測定



Low energy neutrons

- Low energies
- Fluctuation before SWX needs investigation
- Suppression of very low energies might depend on input neutrons



Overview of Topics Covered in Theory Presentations:

Five General Areas:

Phenomenology of CGC and Glasma
Dumitru, Kang and Yuan

Spin and Perturbative QCD
Kang and Yuan

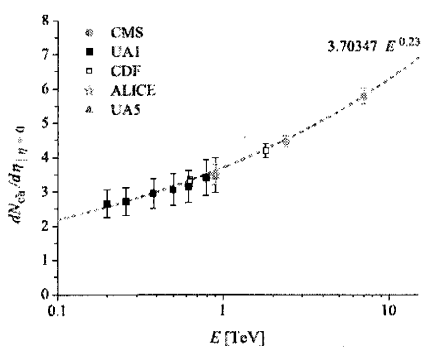
Phenomenology of the QGP
Fries, Molnar, and Teaney

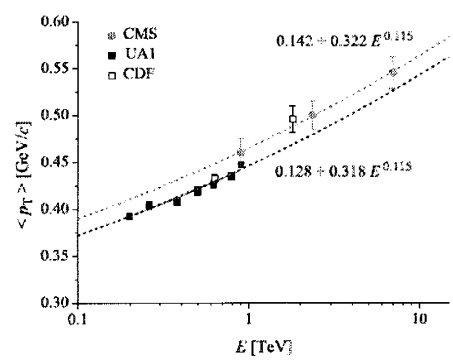
Properties QGP and Quarkyonic Matter
Karsch and Kojo

Astrophysics, Cosmology and Neutrino Physics
Lunardini

The CGC and Glasma:

Data from LHC Suggests CGC-Glasma in High Multiplicty pp





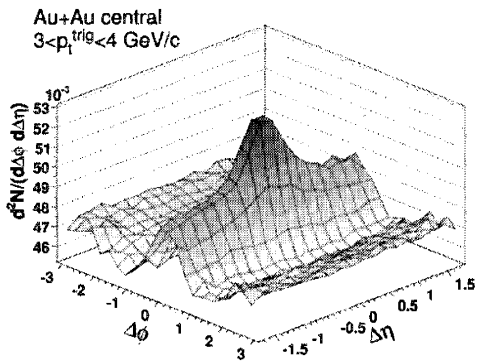
$$\frac{dN_{\rm ch}}{d\eta} = \kappa Q_{\rm sat}^2 = AE^{\lambda}$$

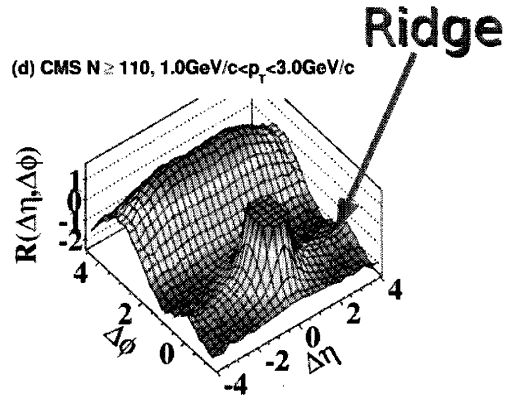
$$\langle p_{\rm T} \rangle = B + CE^{\lambda/2}$$

Geometric Scaling of pT distributions
Average pT grows with multiplicity as in CGC theory
Multiplicity fluctuations according to theory of Glasma fluctuations

The Ridge Seen at RHIC is seen at LHC in CMS

STAR (arXiv:0909.0191)

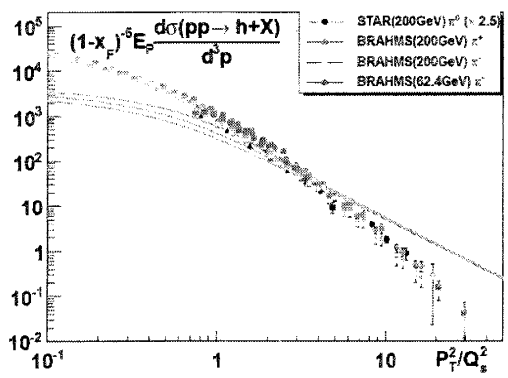




Long range rapidity structure is caused by longitudinal color field
Transverse extent in pp collisions is sub-nucleonic
Most prominent at high multiplicity
Glasma predicts this: Dumitru

Note that how the angular peaking develops may be:
Initial state effect (Dumitru)
Induced triangular flow (Teaney)
Radial Flow Effect (LM)
Opacity Effect (Shuryak)
But this is not the essential point!

Encouraging data from RHIC



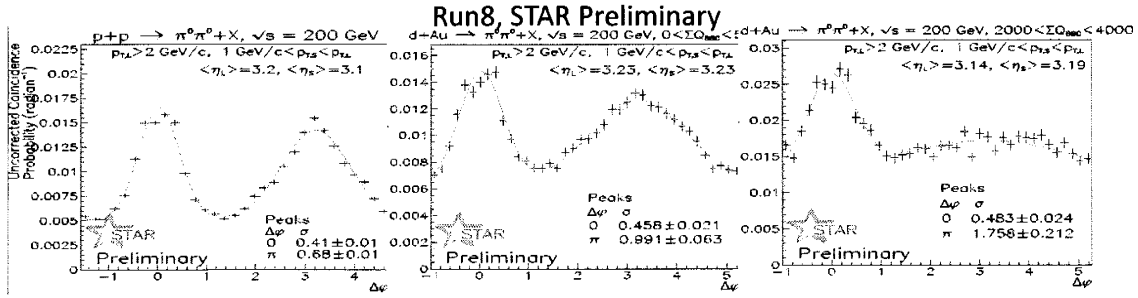
10/14/2010

Yuan's talk: Geometric scaling predicted by CGC as seen in LHC data is also seen in RHIC data

Backward angular correlation seen in dAu at RHIC can be described by CGC: Tuchin, Albacete and Marquet, Yuan

200 GeV *p+p* and *d + Au* Collisions

Run8, STAR Preliminary



pp *d+Au (peripheral)* *d+Au (central)*

Spin and Perturbative QCD

Transverse momentum dependent structure functions required for single spin asymmetries
Kang

Gauge invariance requires introduction of functions of gluon field that cannot be related to a universal gluon distribution function.
Kang and Yuan

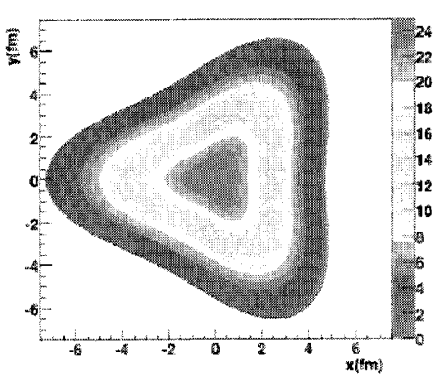
The CGC provides a universal way of computing such functions at small x
(The wavefunction of a hadron is universal and is independent of how it is measured)
Yuan

The CGC and perturbative QCD
Yuan

Phenomenology of the QGP:

"elliptic flow"

$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle} \qquad v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \equiv \langle \cos 2\phi_p \rangle$$



v_3

How well do hydrodynamic effects such as flow constrain the viscosity in the QGP? Molnar

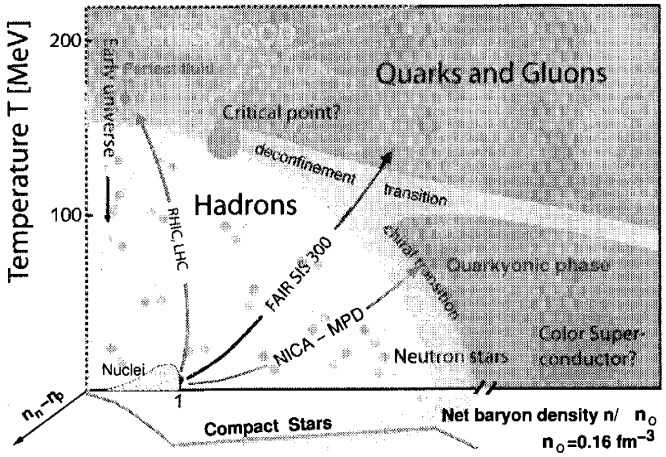
How do we extract information from ridge data relevant for triangular flow? Teaney, Fries

How do we compute the viscosity on the lattice?

Is there a reliable quantitative formalism for jet quenching? Fries

How to realistically infer properties of heavy ion collisions from jet quenching? Fries

Properties of QGP and Quarkyonic Matter



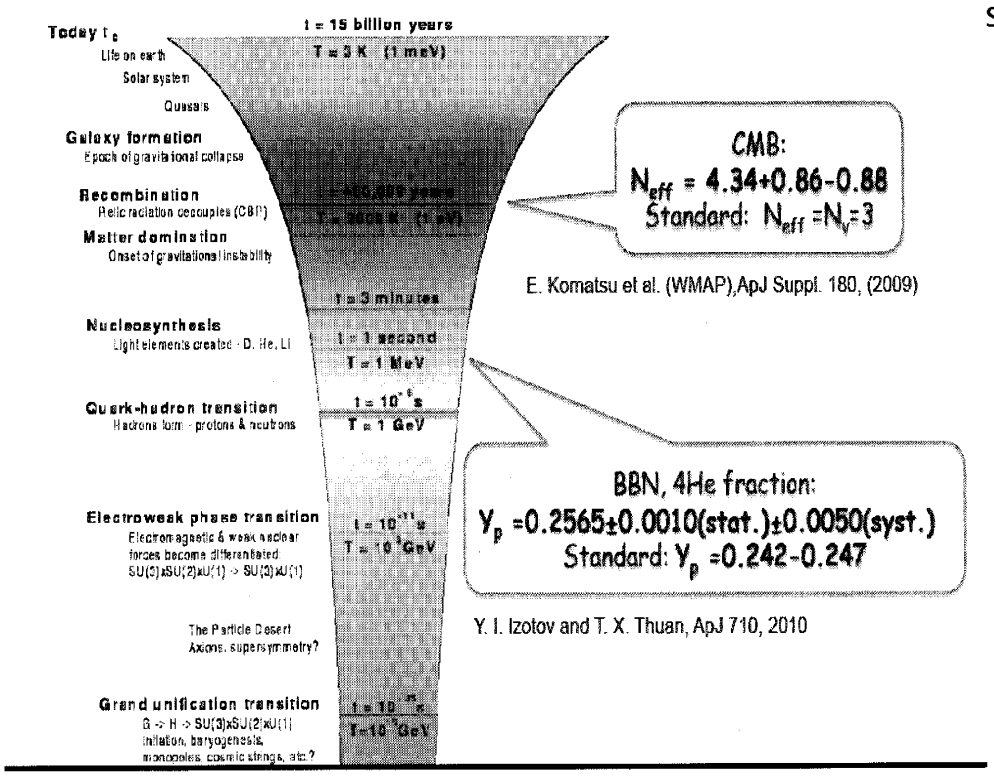
Realistic computations of pressure and energy density in low baryon density region.
Karsch

Quarkyonic matter breaks translational invariance and maybe parity:
Chiral spiral
Happy Island
Kojo

Extrapolations to high baryon density to find Happy Island
Karsch

Large Nc limit and the axial vector coupling:
Or How to have a reasonable phenomenology
Of nuclear matter and forces in the large NC limit.
Kojo

Non standard cosmology?



Sterile Neutrinos?

Large BBN asymmetries in neutrino-anti-neutrino abundances?

Lunardini

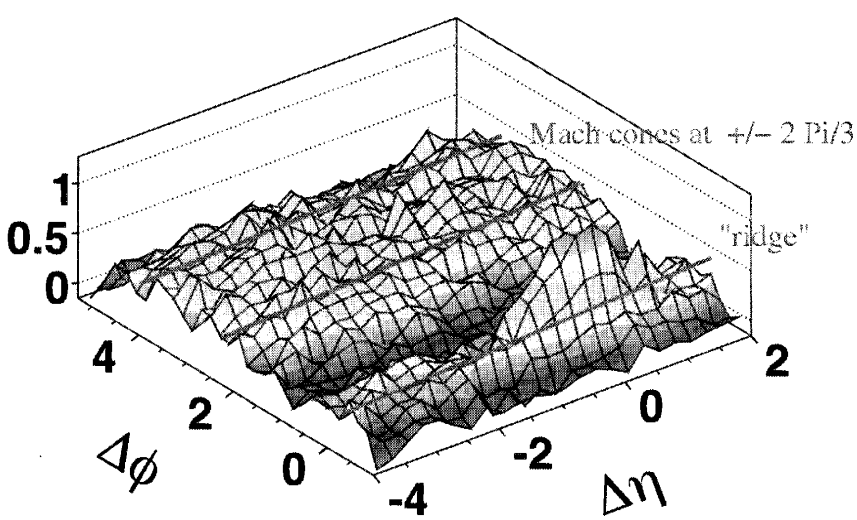
Fluctuating Hydrodynamics at RHIC

Derek Teaney
SUNY Stonybrook and RBRC Fellow

- In collaboration with Yan Li – http://arxiv.org/abs/1010.1876

Interesting Two Particle Correlations at RHIC

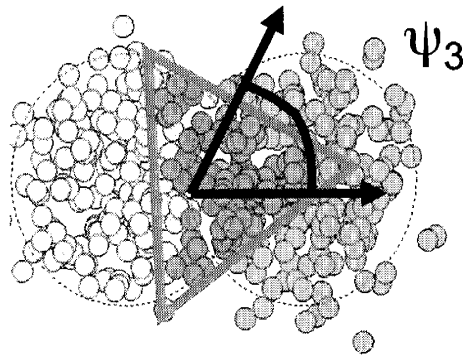
- After flow subtraction see additional structures $p_T^{\rm trig} > 2.5\,{\rm GeV}$
  - known as the "ridge" and the "shoulder" and the "mach cone" at $\pm 2\pi/3$



These structures are well described by $\cos(\Delta\phi)$ and $\cos(3\Delta\phi)$

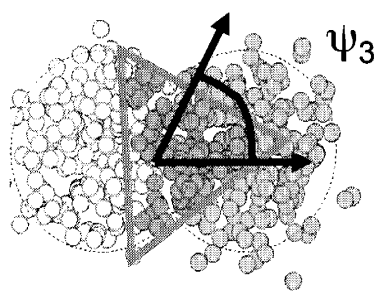
Triangularity explanation

- Many precursors – Takashi et al, Sorenson, AMPT predictions
- I will follow Alver & Roland
- On an event by event basis the initial energy density can be skewed



The triangular shape causes the distribution a triangular hydrodynamic response

Categorizing the fluctuating initial geometry



- The distribution of participants can be characterized by the third moment

$$\left\langle r^3 \cos(\phi - \psi_1) \right\rangle \qquad \left\langle r^3 \cos 3(\phi - \psi_3) \right\rangle$$

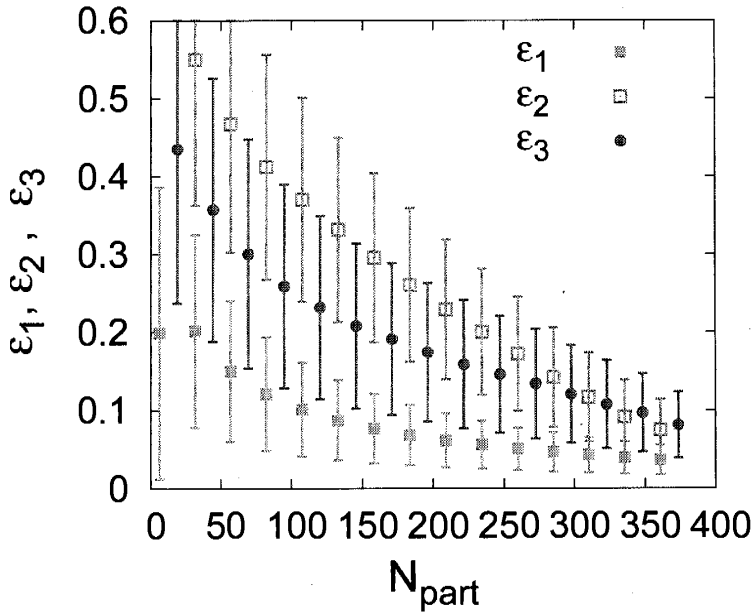
- This third rank tensor can be characterized the angle ψ_3 and

$$\frac{\left\langle r^3 \cos 3(\phi - \psi_3) \right\rangle}{\langle r^3 \rangle} \equiv \epsilon_3 \Rightarrow \text{ Triangularity}$$

$$\frac{\left\langle r^3 \cos(\phi - \psi_1) \right\rangle}{\langle r^3 \rangle} \equiv \epsilon_1 \Rightarrow \text{ Dipole Asymmetry}$$

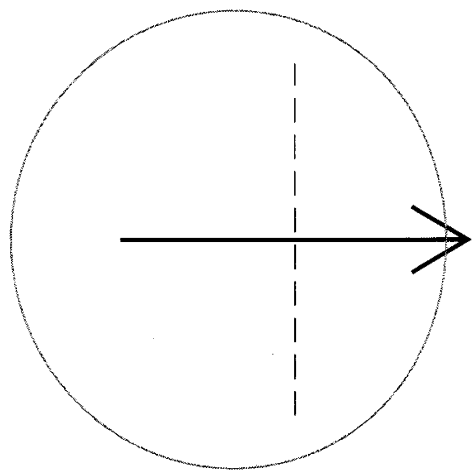
Formalized with Cummulant Expansion – this is all there is!

Distribution of eccentricity

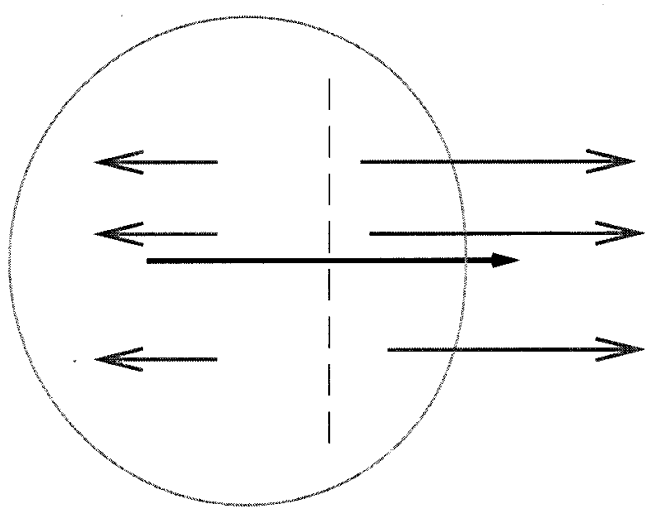


ϵ_3 is strikingly large! ϵ_1 is large enough!

Qualitative Description of Dipole Asymmetry

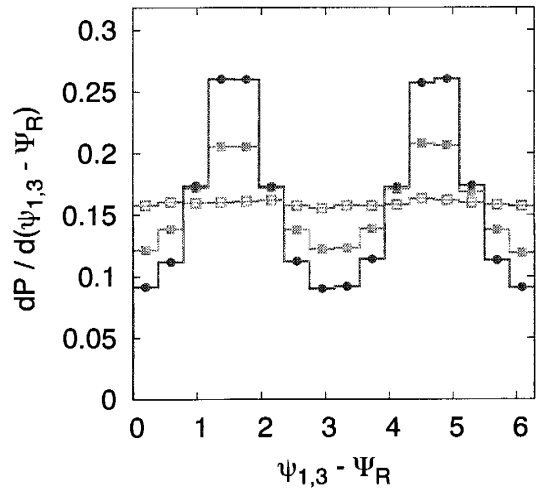


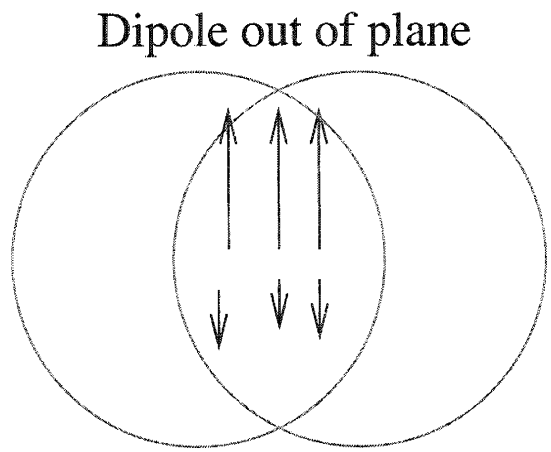
Qualitative Description of Dipole asymmetry



The dipole asymmetry gives rise to a net $v_1(p_T)$!

Dipole asymmetry and the reaction plane



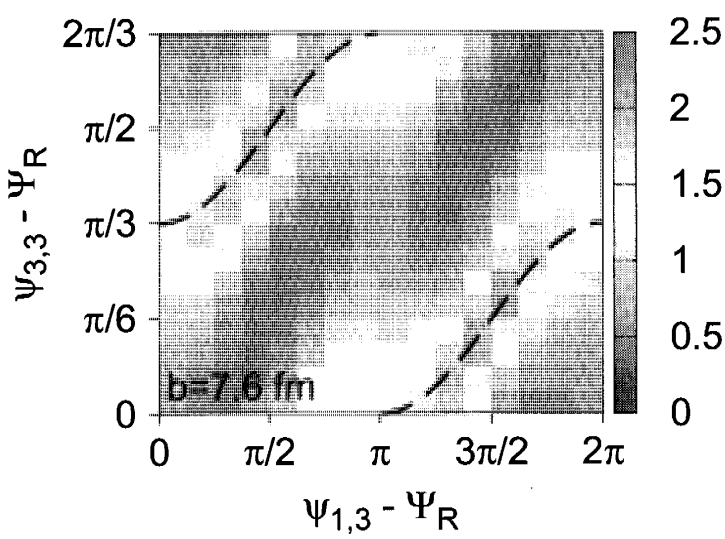


Dipole asymmetry has 20% preference out of plane

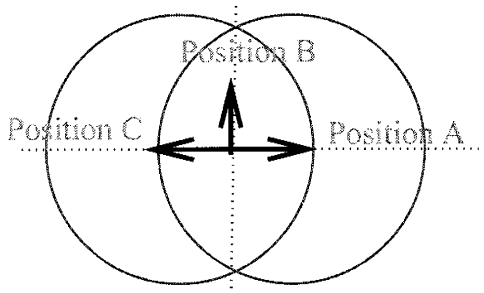
but ϵ_3 is uncorrelated with reaction plane

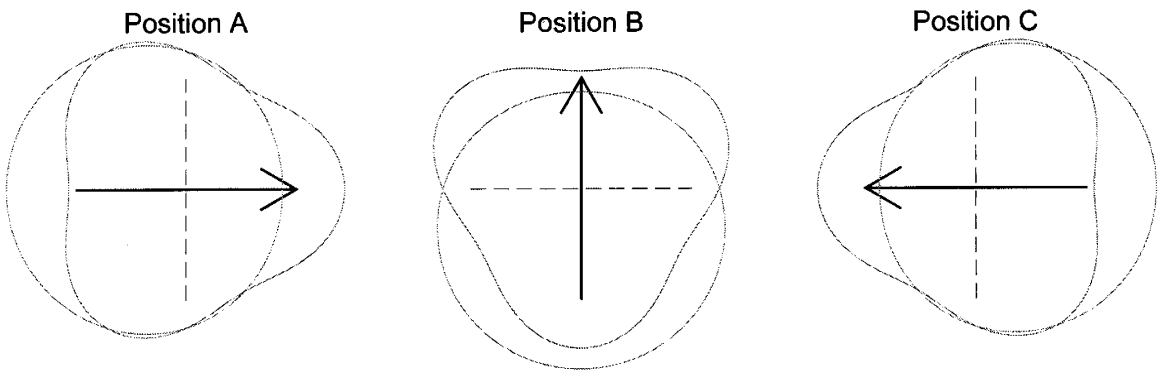
Dipole and Triangular Phases are strongly correlated

Plot shows probability of ψ_3 given ψ_1 or $P(\psi_3|\psi_1)$



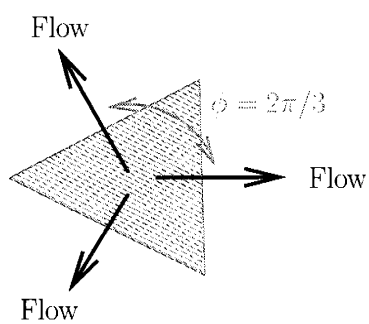
Geometric Fluctuations





More or less just a reflection of the almond shape!

Minimal initial conditions in hydrodynamics:



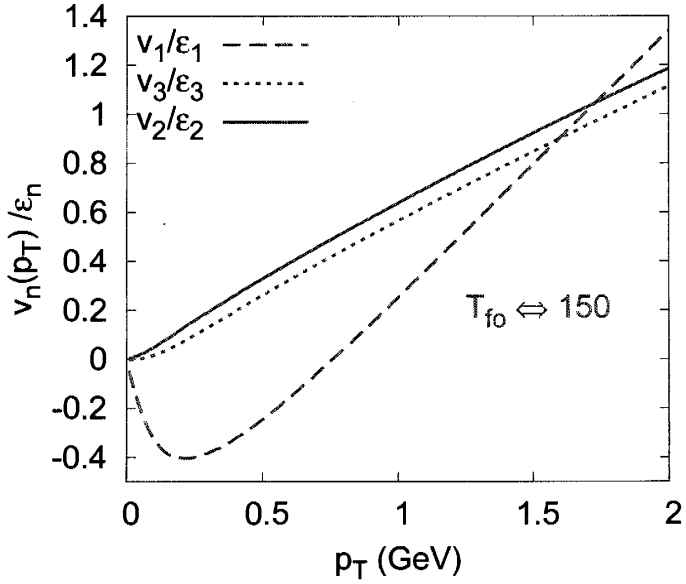
- Gaussian + third cummulant

$$s(\mathbf{x}, \tau_o) = \left[1 + \frac{\langle r^3 \rangle \epsilon_3}{24} \left(\left(\frac{\partial}{\partial x}\right)^3 - 3 \left(\frac{\partial}{\partial x}\right) \left(\frac{\partial}{\partial y}\right)^2 \right) \right] \exp\left(-\frac{x^2}{2R_x^2} - \frac{y^2}{2R_y^2} \right)$$

- Gaussian + first cummulant

$$s(\mathbf{x}, \tau_o) = \left[1 + \frac{\langle r^3 \rangle \epsilon_1}{8} \left(\left(\frac{\partial}{\partial x}\right)^3 + \left(\frac{\partial}{\partial x}\right) \left(\frac{\partial}{\partial y}\right)^2 \right) \right] \exp\left(-\frac{x^2}{2R_x^2} - \frac{y^2}{2R_y^2} \right)$$

Elliptic and triangular flow as a function of p_T



- $v_3(p_T)$ shows a characteristic rise $v_3(p_T) \propto p_T$
- $v_3/\epsilon_3 \simeq v_2/\epsilon_2$
- The dipole asymmetry is the same order of magnitude $v_1/\epsilon_1 \sim v_2/\epsilon_2$

Triangular interpretation of data — Following Alver & Roland

$$\frac{dN}{d\phi} = \frac{N_o}{2\pi}(1 + 2v_2\cos(2(\phi - \Psi_{RP})) + 2v_3\cos(3(\phi - \Psi_3)) + \ldots)$$

- The hydro prediction is linear with ϵ

$$v_3 = \left(\frac{v_3}{\epsilon_3}\right)\epsilon_3 \qquad v_2 = \left(\frac{v_2}{\epsilon_2}\right)\epsilon_2$$

- Then we get a definite prediction for the correlation function

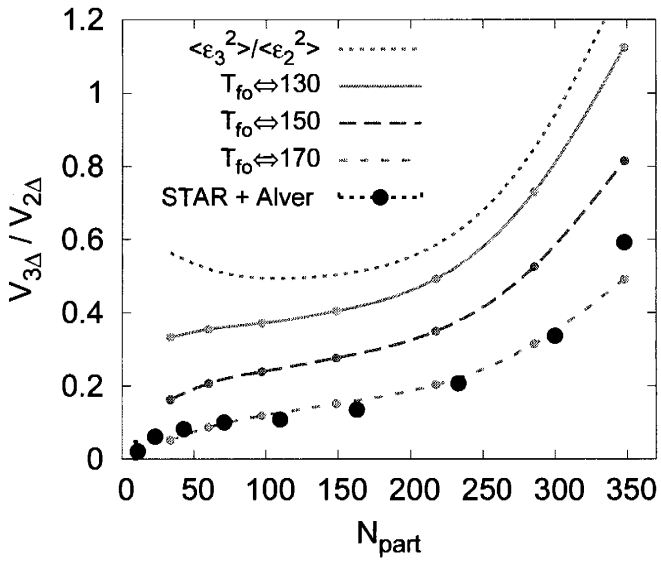
$$\begin{aligned}\frac{dN_{\text{pairs}}}{d\Delta\phi} &\simeq \int_{\phi_1}\left\langle\frac{dN}{d\phi_1}\frac{dN}{d(\phi_1+\Delta\phi)}\right\rangle_{\psi_2\psi_3} \\ &\propto (1 + 2\underbrace{\left(\frac{v_2}{\epsilon_2}\right)^2\langle\epsilon_2{}^2\rangle}_{\equiv V_{2\Delta}}\cos(2\Delta\phi) + 2\underbrace{\left(\frac{v_3}{\epsilon_3}\right)^2\langle\epsilon_3{}^2\rangle}_{\equiv V_{3\Delta}}\cos(3\Delta\phi) + \ldots\end{aligned}$$

- So comparing the two terms we have the prediction

$$\frac{V_{3\Delta}}{V_{2\Delta}} = \frac{\left(\frac{v_3}{\epsilon_3}\right)^2\langle\epsilon_3{}^2\rangle}{\left(\frac{v_2}{\epsilon_2}\right)^2\langle\epsilon_2{}^2\rangle}$$

Comparison with data

$$\frac{V_{3\Delta}}{V_{2\Delta}} = \underbrace{\frac{\left(\frac{v_3}{\epsilon_3}\right)^2}{\left(\frac{v_2}{\epsilon_2}\right)^2}}_{\simeq 1} \frac{\langle {\epsilon_3}^2 \rangle}{\langle {\epsilon_2}^2 \rangle}$$



General two particle correlation with respect to reaction plane

$$\left\langle\!\!\left\langle \frac{\mathrm{d}N_{\mathrm{pairs},\alpha\beta}}{\mathrm{d}\phi_\alpha \mathrm{d}\phi_\beta} \right\rangle\!\!\right\rangle \simeq \frac{N_\alpha N_\beta}{(2\pi)^2} \Big[1$$

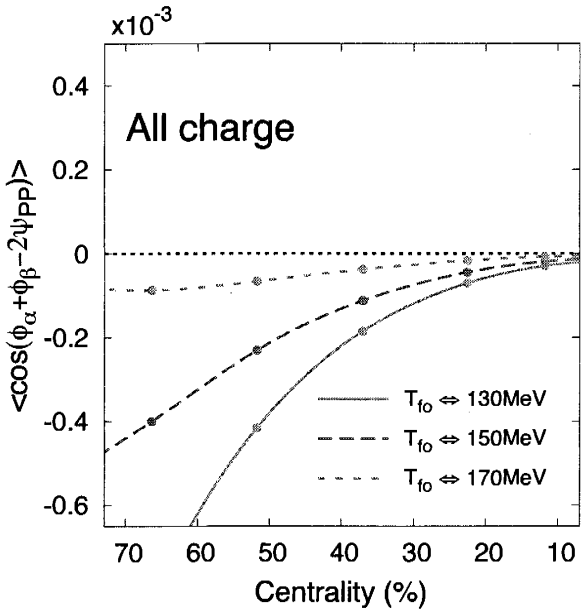
$$+ \underbrace{\cdots}_{\text{boring}}$$

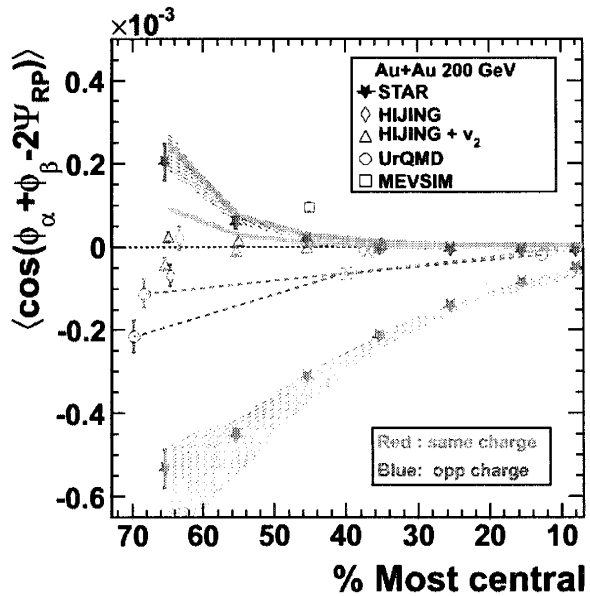
$$+ 2\frac{v_{1\alpha} v_{1\beta}}{\epsilon_1^2} \langle\!\langle \epsilon_1^2 \cos(2\psi_{1,3} - 2\Psi_{PP}) \rangle\!\rangle \underbrace{\cos(\phi_\alpha + \phi_\beta - 2\Psi_{PP})}_{v_1 \text{ out of plane}}$$

$$+ 2\frac{v_{1\alpha} v_{3\beta}}{\epsilon_1 \epsilon_3} \langle\!\langle \epsilon_1 \epsilon_3 \cos(\psi_{1,3} - 3\psi_{3,3} + 2\Psi_{PP}) \rangle\!\rangle \underbrace{\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_{PP})}_{v_1 \text{ and } v_3 \text{ term}}$$

$$\Big]$$

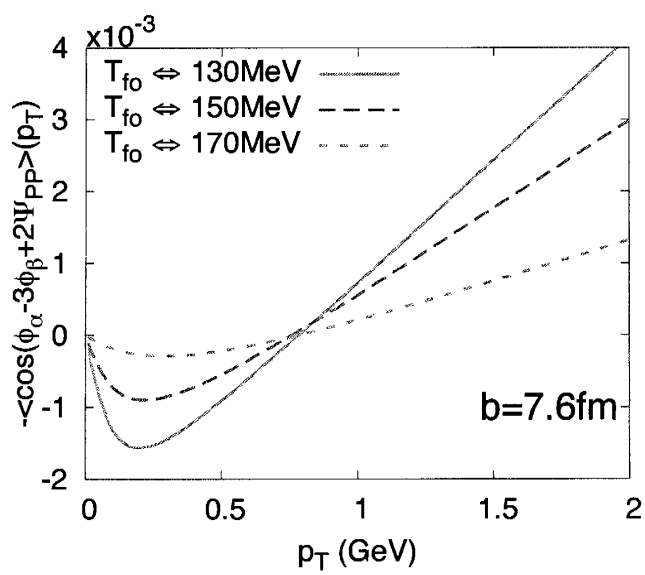
v_1 out of plane $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{PP}) \rangle$





Can't explain the charge asymmetry!

Change the one to a three: $\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_{PP})$



This is v_1 for particle α measured with respect to a plane determined by the reaction plane and the triangular plane

Conclusions

- Fluctuations are fun – a new testing ground for hydro.
  - Once we understand we can use it to constrain η/s
  - Viscosity . . . you bet I'm working on it !!!!!!
- Other things:
  - Viscous corrections to δf: Phys. Rev. C, more on this coming
  - Spectral Densities in weakly coupled plasmas: Accepted Phys. Rev C
  - Hawking radiation in non-equil AdS_5: In progress S. Caron-Huot, P. Chesler

I hope to tell you about some of these other things next year!

Probing Quark-Gluon Matter

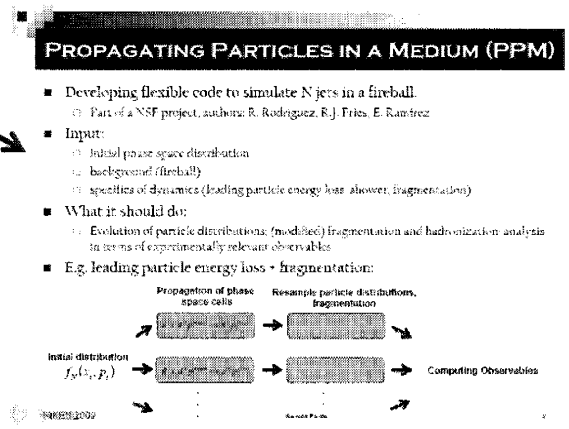
Rainer J. Fries
Texas A&M University & RIKEN BNL

RIKEN BNL Research Center

RBRC Review, Brookhaven National Lab
October 27, 2010

Simulations for Hard Probes

- Project started last year:
- v1.x now up and running.
- Currently 3 different ways of calculating leading particle energy loss:
  - Schematic LPM
  - ASW/BDMPS
  - ASW/GLV



- First results and projects under way:
  - Uncertainties from unknown fluctuations in the fireball + tomography of inhomogeneities
    [R. Rodriguez, RJF, E. Ramirez, Phys. Lett. B 693 (2010)]
  - Higher Fourier moments at high P_T.
    [R. Rodriguez, RJF, in preparation]
  - Density scaling of energy loss.
    [A. Delgado, R. Rodriguez, RJF, in preparation]

Precision Hard Probes?

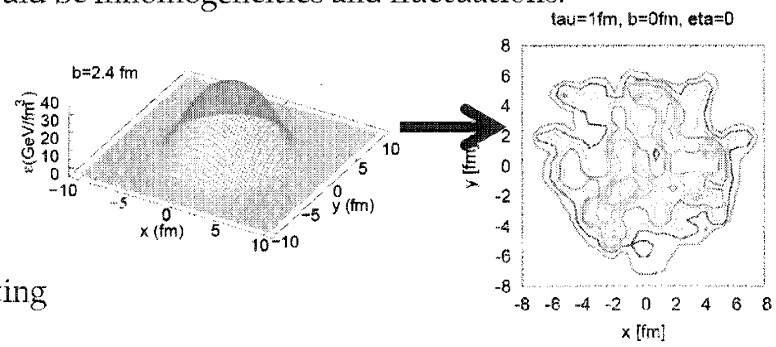
$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 $\mathrm{GeV}^2/\mathrm{fm}$	4.5 $\mathrm{GeV}^2/\mathrm{fm}$	
$s(\vec{r},\tau)$		4.3 $\mathrm{GeV}^2/\mathrm{fm}$	

[S. A. Bass et al., PRC 79, 024901 (2009)]

- On the surface a successful picture:
  - 1-parameter fits or RHIC data work for R_{AA}.
- On second thought not so much:
  - Uncertainties in $\hat{q}$ too large.
  - Wide range of different approximations made in different energy loss calculations.
  - Details of phenomenological modeling matter!
- Needed:
  - Clean-up & generalization of different calculations (→ TECHQM, JET)
  - Benchmark tests (brick problem, standardized hydro)
  - Honest assessment of all uncertainties going into hard probes calculation and the comparsion with data.

Background Geometry

- How well do we know the space-time structure of the fireball?
- On average/long wave length: probably ok (blastwave, hydro)
- Short distances: there could be inhomogeneities and fluctuations!
- Strong indications:
  - Eccentricity fluctuations
  - Triangularity



[Y. Hama et al., Acta Phys. Polon. B 40, 931 (2009)]

- Must check effects of inhomogeneous, fluctuating backgrounds on jet quenching observables!
  - Calculate jet quenching event by event!
- Can we can use hard probes to constrain the spatial structure → true tomography?

Emission-Propagation Correlation

- Density integral along the path of a parton created at point **r**.

$$h(\vec{r},\psi) = \int d\tau\, \tau^{\beta} \rho(\vec{r} + \tau \vec{e}_{\psi})$$

- For effect of energy loss on spectrum: weighted with emission probability:

$$n(\vec{r}) h(\vec{r},\psi)$$

- Fluctuating densities: take event average

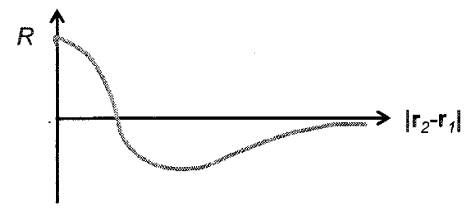
$$\langle n(\vec{r}) h(\vec{r},\psi) \rangle = \underbrace{\bar{n}(\vec{r}) \int d\tau\, \tau^{\beta} \bar{\rho}(\vec{r} + \tau \vec{e}_{\psi})}_{\text{average}} + \underbrace{\int d\tau\, \tau^{\beta} \langle \delta n(\vec{r}) \delta\rho(\vec{r} + \tau \vec{e}_{\psi}) \rangle}_{\text{correction due to fluctuations}}$$

- Relevant information contained in the correlation function

$$R(\vec{r}_1,\vec{r}_2) = \langle \delta n(\vec{r}_1) \delta\rho(\vec{r}_2) \rangle$$

density of jets emerging — density of QGP

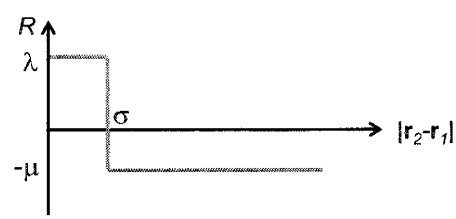
between emission and background densities.



Corrections From Fluctuations

- Simple 2-component model for *R*:

$$R(\vec{r}_1,\vec{r}_2) = \lambda \Theta(\sigma - |\Delta r|) - \mu \Theta(|\Delta r| - \sigma)$$



- Fluctuation signal on energy loss:

$$\delta(nh) \approx \lambda \sigma^{\beta+1} - \mu\left(l^{\beta+1}(\vec{r},\psi) - \sigma^{\beta+1}\right)$$

Path length

  - Shows potential cancellation between stronger quenching in regions of stronger emission and less quenching around those regions.
  - Sign depends on details of *R*.

- Elliptic flow signal in a fireball with short and long axes *X* and Y resp.

$$\delta v_2 \sim -\int d^2 r \left[\delta(nh)(\vec{r},0) - \delta(nh)\left(\vec{r},\frac{\pi}{2}\right) \right] \approx \mu \int d^2 r \left[l^{\beta+1}(\vec{r},0) - l^{\beta+1}\left(\vec{r},\frac{\pi}{2}\right) \right]$$

$$\sim X^{\beta+1} Y - Y^{\beta+1} X < 0$$

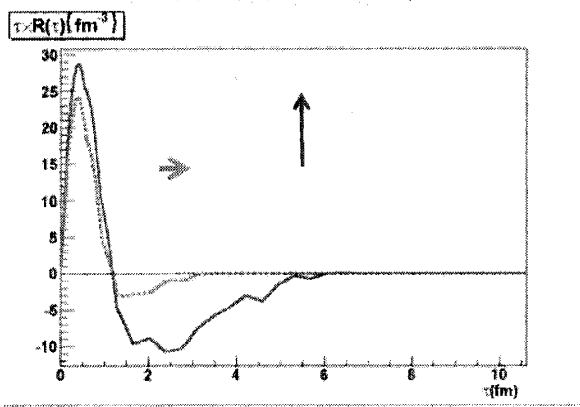
Tomography Of Glauber Events

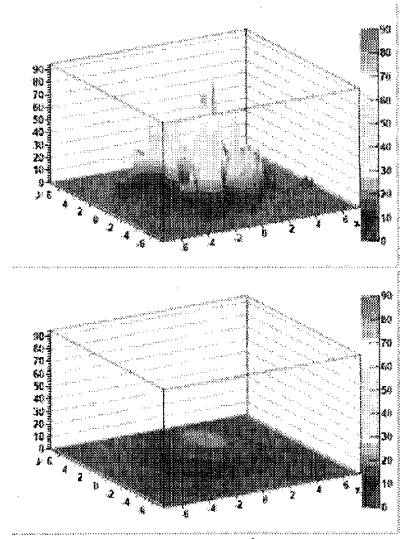
- Use Glauber MC GLISSANDO.

  [W. Broniowski, M. Rybczynski, P. Bozek, Comput.Phys.Commun.180, 69 (2009)]

- Correlation function R:
  - Along the long and short axes from the center

$$R(\tau) = \left\langle \delta n(\vec{0}) \delta\rho(\tau\vec{e}_\psi) \right\rangle$$





Typical event vs 500k averaged events, ⟨b⟩ = 3.2 fm

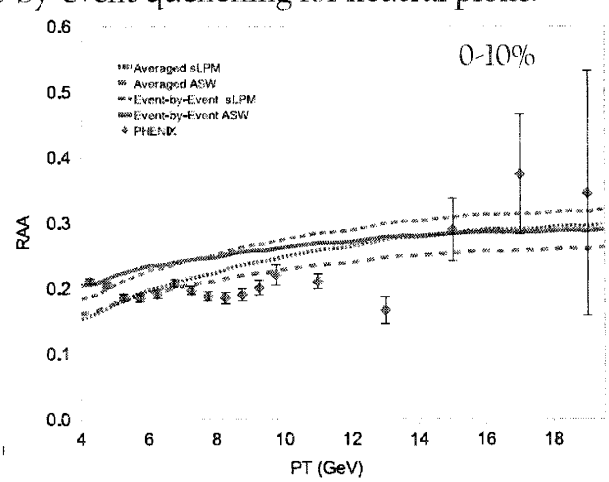
[R. Rodriguez, RJF, E. Ramirez, Phys. Lett. B 693 (2010)]

Numerical Study: Quenching

- Propagating leading partons through fireballs using two quenching models:
  - simple ~L^2 deterministic energy loss [sLPM] $\Delta E = -\int d\tau\, \tau\, c_{\mathrm{sLPM}} \rho(\vec{r} + \tau\vec{e}_\psi)$
  - Armesto-Salgado-Wiedemann/BDMPS [ASW]

- Compare averaged event with event-by-event quenching for neutral pions:

- Both models give *less* quenching at all centralities and momenta.

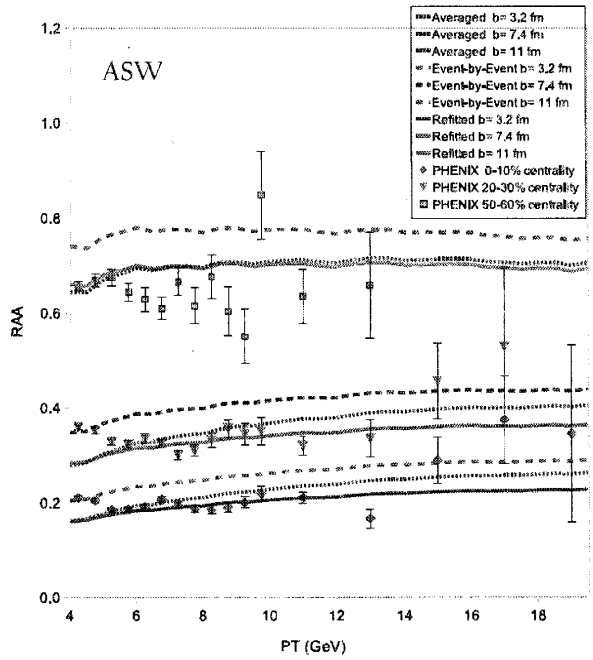


R_{AA} AND REFIT

- R_{AA} can be refitted across all centralities and momenta after adjusting the quenching strength.

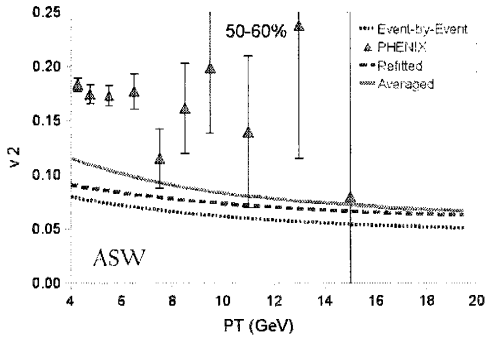
	smooth	Event-by-event
c_{sLPM} [GeV]	0.055	0.085
c_{ASW} [GeV]	1.6	2.8

- Additional uncertainty for the extraction of $\hat{q}$!

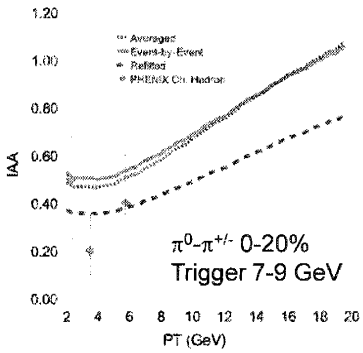


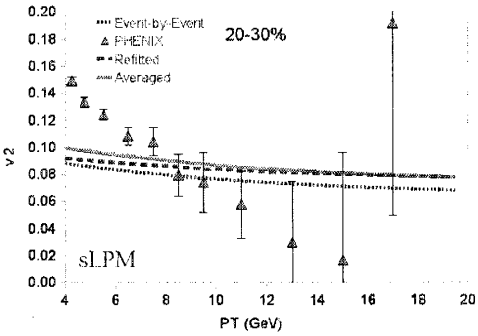
RESIDUAL SIGNATURES

- Event-by-event: v_2 reduced.
- After refitting: small residual suppression, up to 30% for peripheral events.



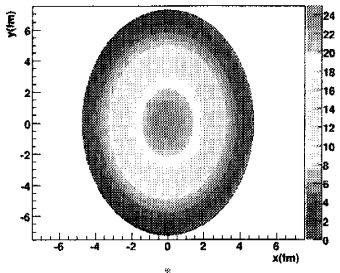
- Event-by-event: di-hadron suppression I_{AA} tends to be less affected than R_{AA}.
- After refitting: larger suppression.





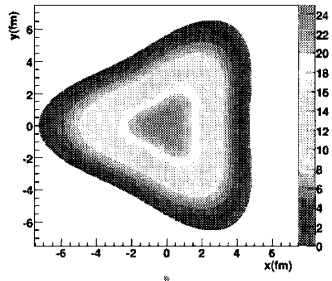
Asymmetries From Fluctuations

- What about azimuthal asymmetries v_n?
- We know: fluctuations lead to additional, "spontaneous" moments.
- Study v_n as a function of generalized eccentricity ε_n (spatial cos $n\phi$ moments)
- Hydro/bulk transport with engineered "events":

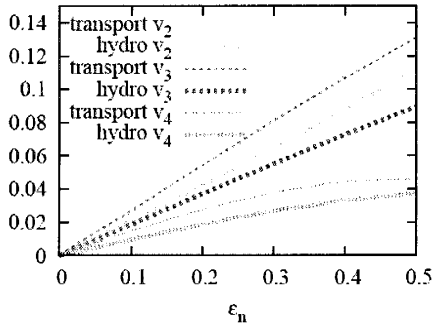


$$\rho(\vec{r}) = \rho_0 \exp\left[-\frac{r^2}{2r_0^2}(1 + e\cos n\phi)\right]$$

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos n\phi\rangle^2 + \langle r^n \sin n\phi\rangle^2}}{\langle r^n\rangle}$$



v_2

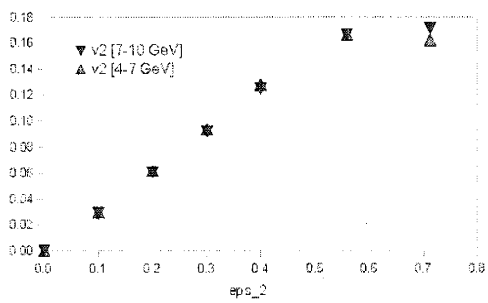


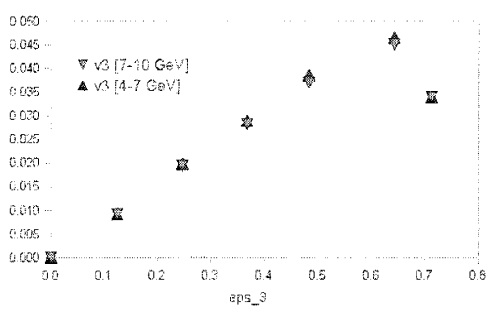
v_3

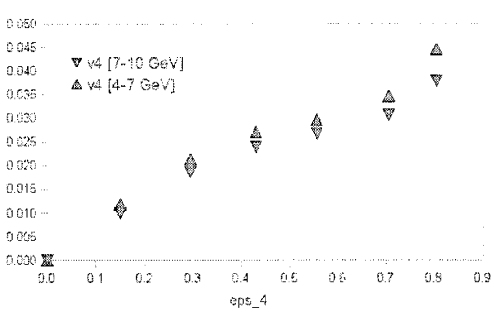
[B. H. Alver et al., PRC 82, 034913 (2010)]

Momentum vs Spatial Asymmetry

- We run a similar test for high P_T.
- Engineered events with n=2, 3, 4:
- Monotonous scaling of v_n with ε_n, very much linear.
- No dependence on P_T!

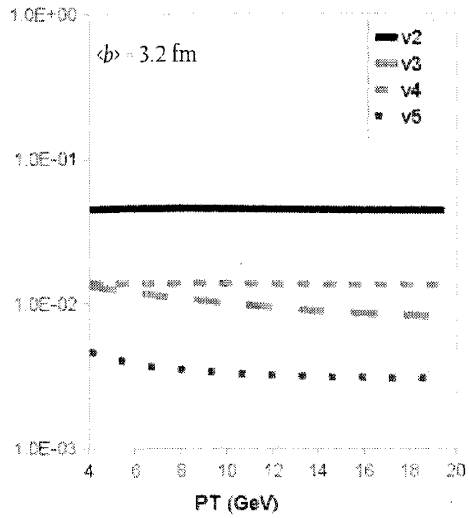


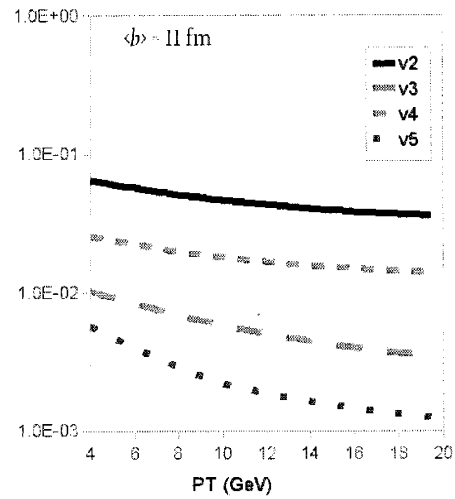




Higher Fourier Moments

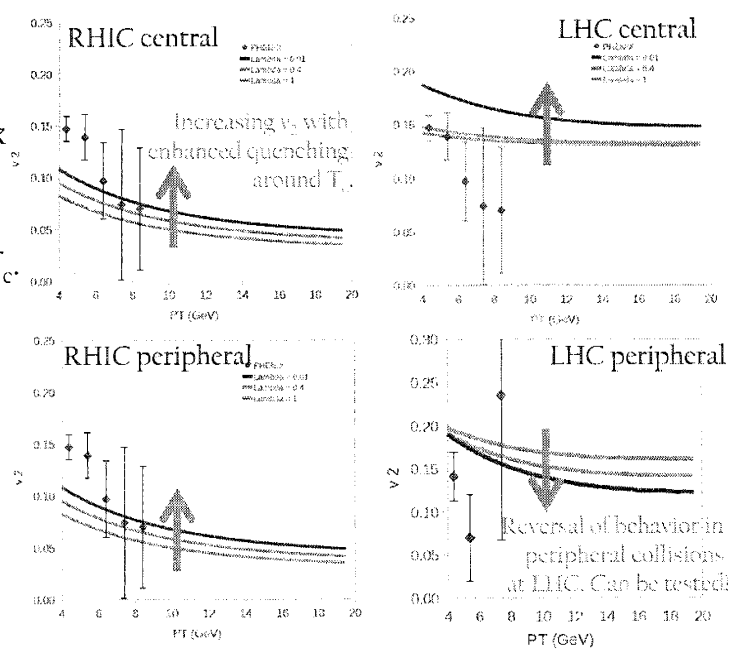
- Calculate moments v_n from GLISSANDO event sample.
- All moments are there!
- v_3 on the level of 1%.





Density Dependence of Quenching

- Novel ideas on non-trivial dependence of quenching strength on medium density
- E.g. magnetic quenching scenario by Liao and Shuryak
- RHIC v_2 data seem to favor stronger quenching around T_c.
- Can be tested by changing system size and energy.
- Systematic study under way.



Future

- JET = Jet and Electromagnetic Tomography of Extreme Phases of Matter (http://jet.lbl.gov/)
- Continued phenomenological studies (NSF+JET)
- JET Recombination working group (with Ch-Ming Ko and others): hadronization of modified jet showers in heavy ion environments.

Summary

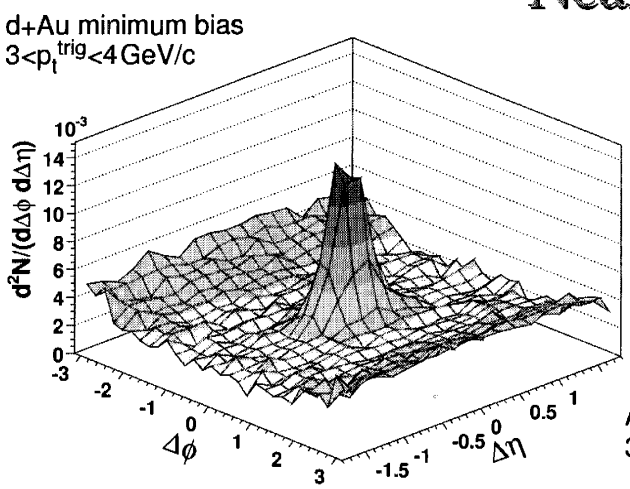
- Fluctuations are important for hard probes, as they are for the bulk!
- With no a priori knowledge of inhomogeneities additional uncertainty on $\hat{q}$ is up to 50%.
- This can be reduced using additional observables: v_2, dihadrons, ...
- Spatial granularity leaves an imprint on hard probe observables and could be estimated from data.
- Higher Fourier terms are present at high P_T. They scale linearly with eccentricities.

JIMWLK evolution and two-particle correlations at RHIC and LHC

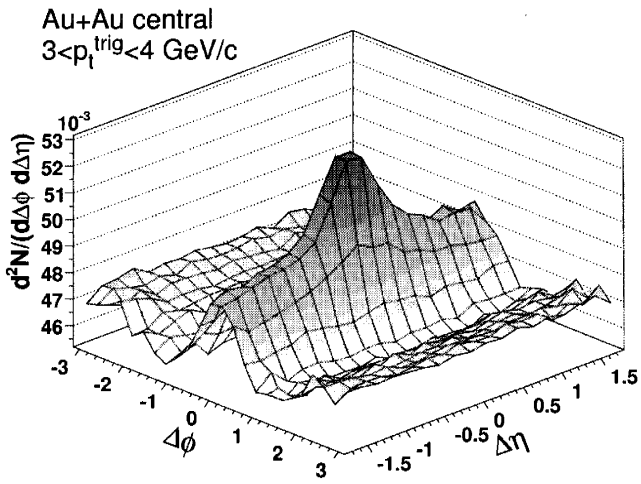
Adrian Dumitru
RIKEN-BNL and Baruch College

RBRC Scientific Review
Oct. 27th - 29th 2010

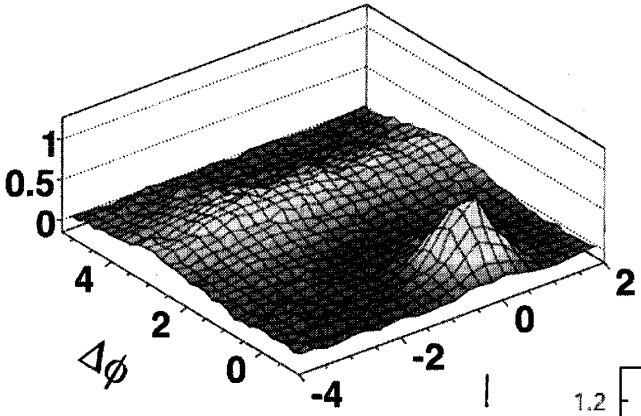
Near-side correlations, $\Phi<1$
(the "ridge")



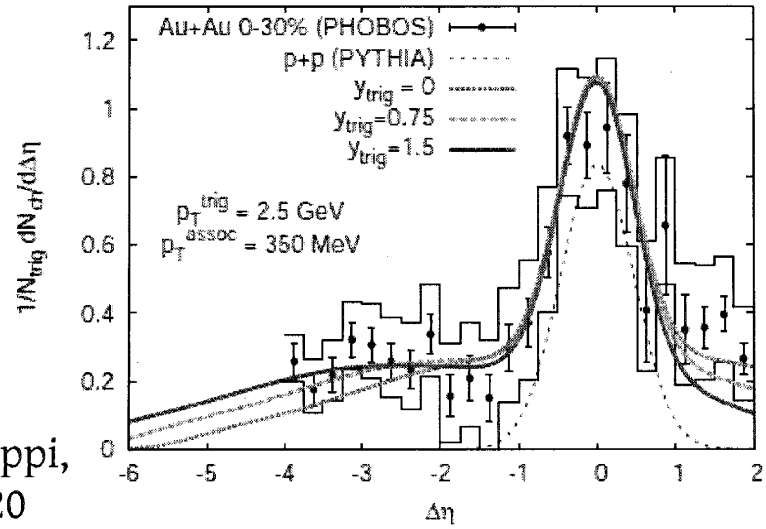
STAR (arXiv:0909.0191)



PHOBOS (arXiv:0903.2811):

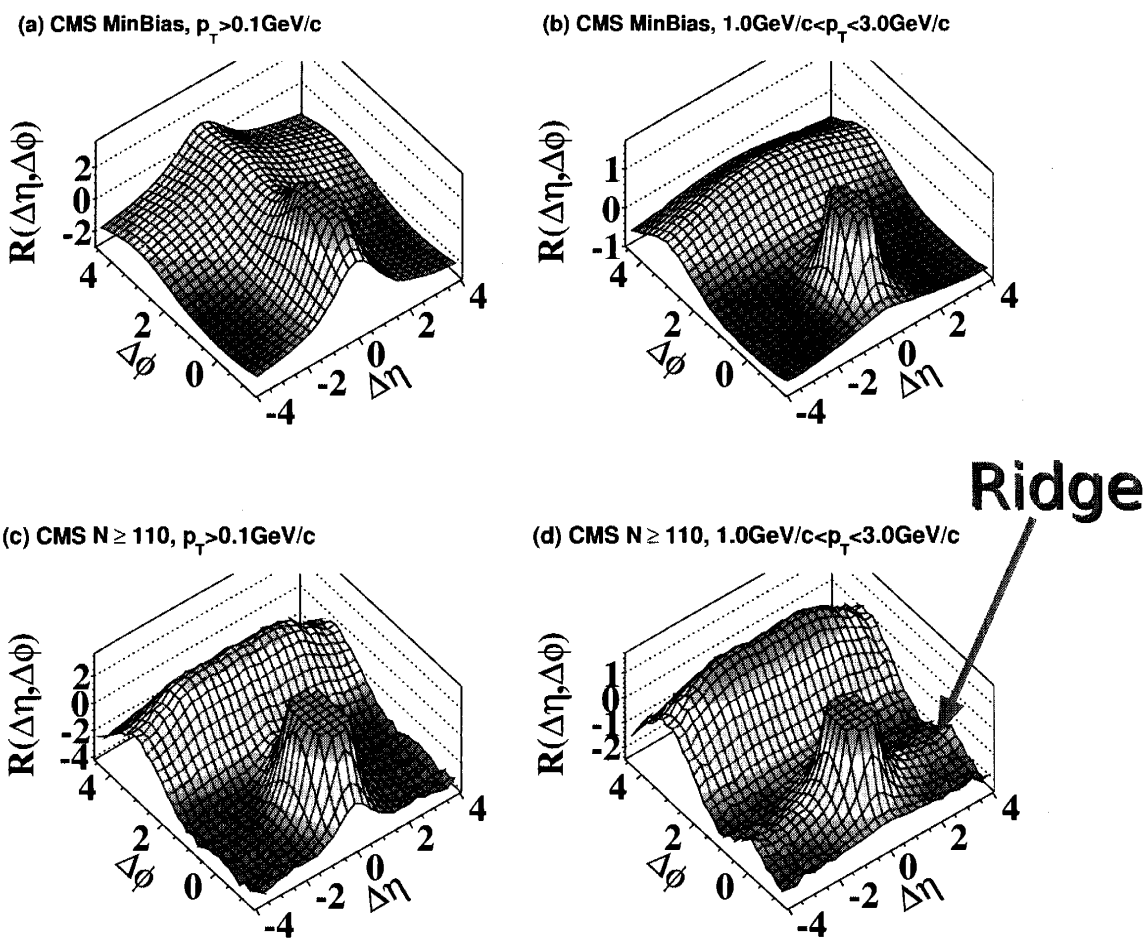


PYTHIA pp, p_T^{trig} > 2.5 GeV

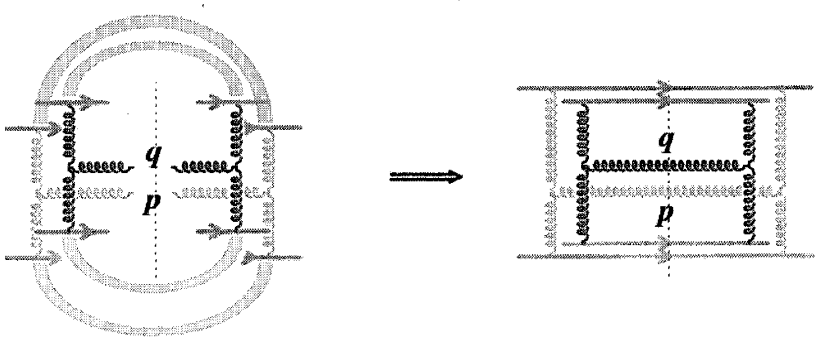


PHOBOS Au+Au, 0-30%
p_T^{trig} > 2.5 GeV

Dusling, Gelis, Lappi, Venug.: 0911.2720



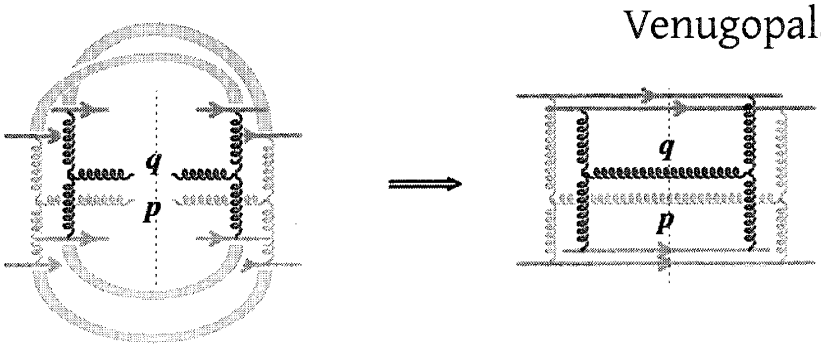
Independent production of two gluons:



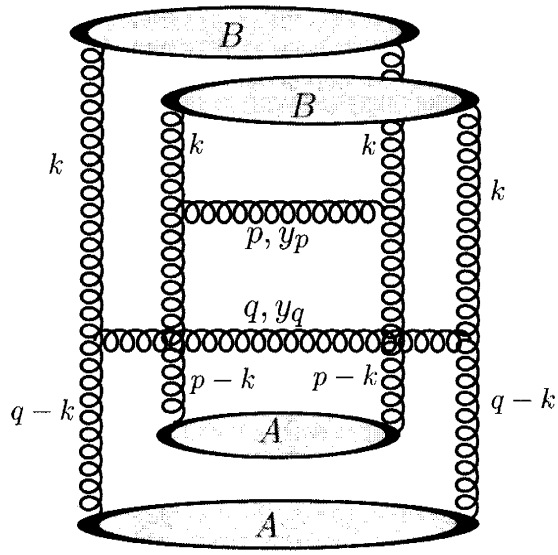
PYTHIA: "independent multi-parton interactions"

Correlated two-gluon production:

A.D., Gelis, McLerran, Venugopalan: 0804.3858



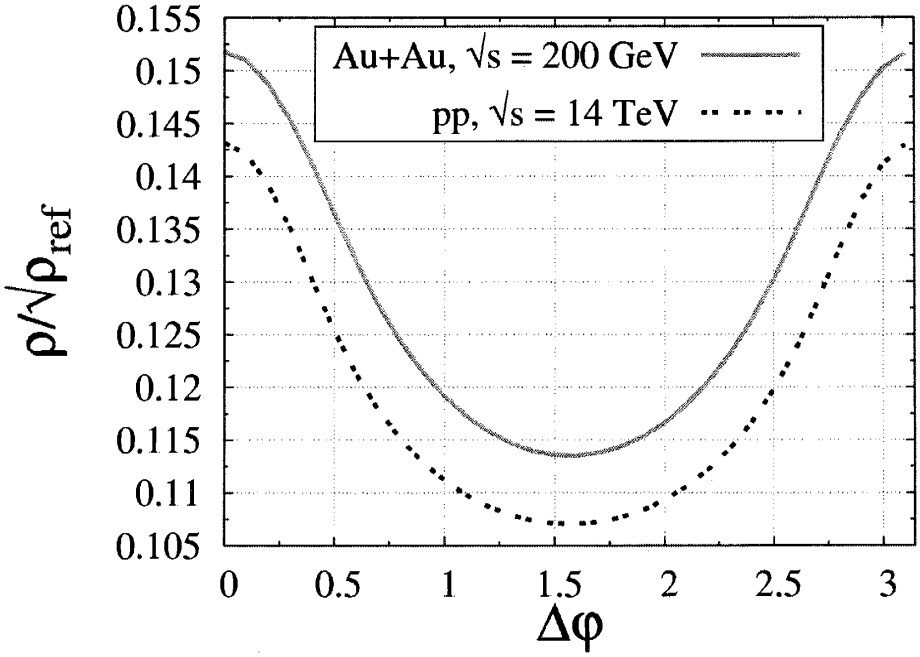
one single loop momentum k !



$$C(p,q) = 16(2\pi)^2\alpha_s^2\,\sigma_0\,\frac{N_c^2}{(N_c^2-1)^3}\,\frac{1}{p^2\,q^2}$$
$$\times\int d^2k\;\Phi_A(x_1,(p-k)^2)\,\Phi_A(x_1,(q-k)^2)\,\Phi_B^2(x_2,k^2)$$

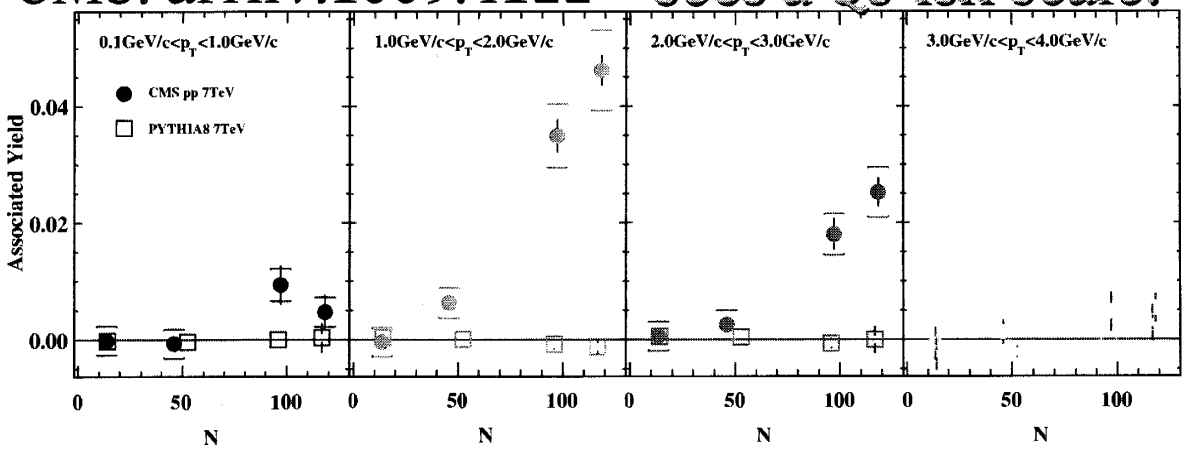
Depends on angle $\angle(p_\perp,q_\perp)$, not flat in ϕ !

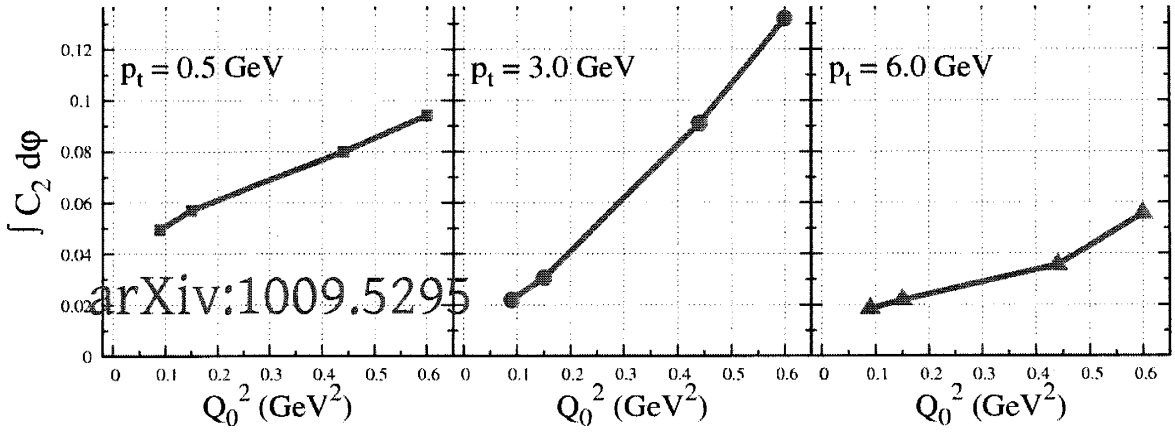
RHIC(Au+Au) versus LHC(pp) :



ridge in pp @ LHC ?!

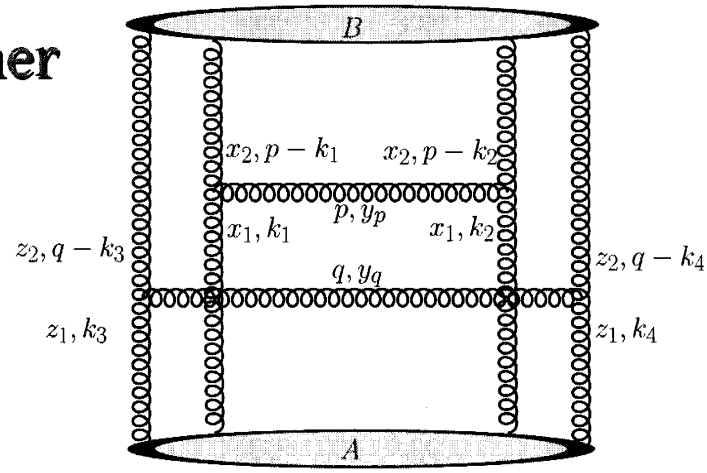
CMS: arXiv:1009.4122 sees a Qs-ish scale!





arXiv:1009.5295

however, we should rather compute THIS diagram:



$$C(p_\perp, q_\perp) = \frac{g^{12}}{64(2\pi)^6}\left(f_{abc}f_{a'\bar{b}\bar{c}}f_{a\hat{b}\hat{c}}f_{a'\tilde{b}\tilde{c}}\right)\int\prod_{i=1}^{4}\frac{d^2k_{i\perp}}{(2\pi)^2k_{i\perp}^2}$$
$$\times\frac{L_\mu(p_\perp,k_{1\perp})L^\mu(p_\perp,k_{2\perp})}{(p_\perp-k_{1\perp})^2(p_\perp-k_{2\perp})^2}\frac{L_\nu(q_\perp,k_{3\perp})L^\nu(q_\perp,k_{4\perp})}{(q_\perp-k_{3\perp})^2(q_\perp-k_{4\perp})^2}$$
$$\times\left\langle\rho^{*\hat{b}}_1(k_{2\perp})\rho^{*\tilde{b}}_1(k_{4\perp})\rho_1{}^b(k_{1\perp})\rho_1{}^{\bar{b}}(k_{3\perp})\right\rangle$$
$$\times\left\langle\rho^{*\hat{c}}_2(p_\perp-k_{2\perp})\rho^{*\tilde{c}}_2(q_\perp-k_{4\perp})\rho_2{}^c(p_\perp-k_{1\perp})\rho_2{}^{\bar{c}}(q_\perp-k_{3\perp})\right\rangle$$

however, "subleading-Nc" piece contributes at the same order to C(p,q)

Complete Balitsky/JIMWLK four-point function:
(in Gaussian approximation) A.D.+JJM: arXiv:1001.4820

$$\left\langle\rho^a\rho^b\rho^c\rho^d\right\rangle = \delta^{ab}\delta^{cd}\left\langle\rho^2\right\rangle^2 + \frac{1}{N_c}f^{ab\kappa}f^{cd\kappa}\left\langle\rho^2\right\rangle^2 + \cdots$$

$$f_{gaa'}f_{g'bb'}f_{gcc'}f_{g'dd'} \qquad \delta^{ac}\delta^{bd} \quad \delta^{a'b'}\delta^{c'd'} = N_c^2(N_c^2-1)$$

$$f_{gaa'}f_{g'bb'}f_{gcc'}f_{g'dd'} \quad \frac{1}{N_c}f^{ab\kappa}f^{cd\kappa}\,\delta^{a'c'}\delta^{b'd'} = N_c^2(N_c^2-1)$$

Projectile Target

[Note: independent/uncorrel. production

$$f_{gaa'}f_{g'bb'}f_{gcc'}f_{g'dd'}\,\delta^{ac}\delta^{bd}\,\delta^{a'c'}\delta^{b'd'} = N_c^2(N_c^2-1)^2$$

]

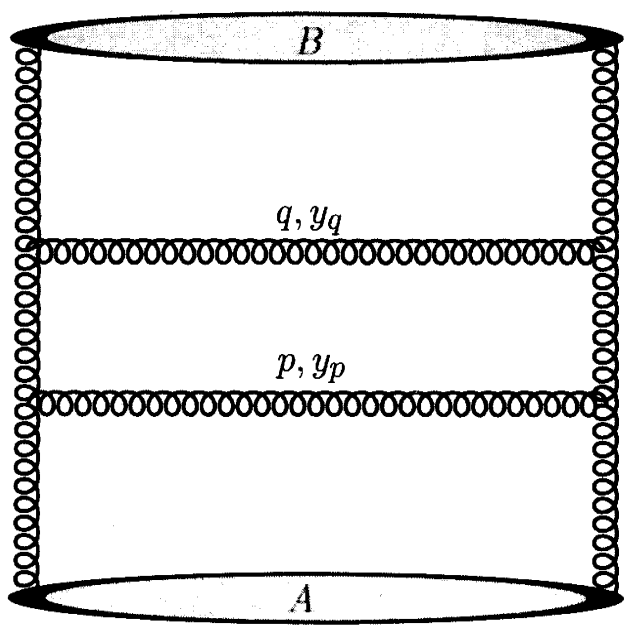
Summary:

- we might have seen Qs directly for the first time !
- particle correlations probe complete B-JIMWLK evolution of higher n-point fcts (unlike single-inclusive cross-section !)

- interesting future for pp @ LHC, eRHIC: beyond the uGD

(Correlated) two-particle production: the DGLAP way

~ δ(p+q) (at leading order, back-to-back dijet)



Understanding single transverse spin asymmetry

– On universality property of kt-dependent functions

Zhong-Bo Kang

RIKEN BNL Research Center
Brookhaven National Laboratory

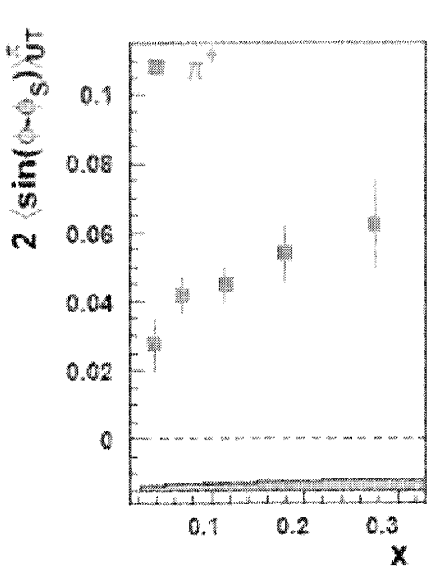
RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory
Upton, NY, Oct 27 - 29, 2010

Kang, Qiu, arXiv: 0912.1319, PRD81: 054020 (2010)
Boer, Kang, Vogelsang, Yuan, arXiv:1008.3543, PRL in press

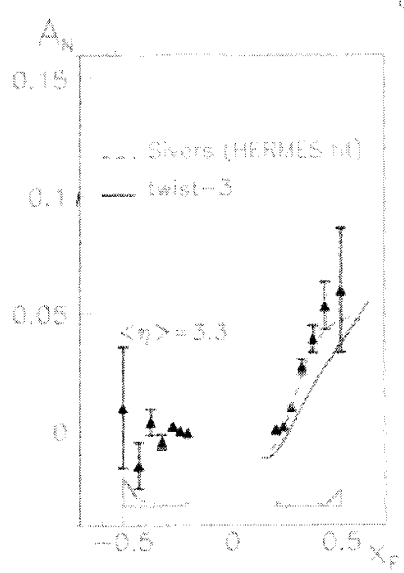
Experimental data on single transverse spin asymmetry

- Single transverse spin asymmetries (SSAs) have been observed in various experiments at different CM energies

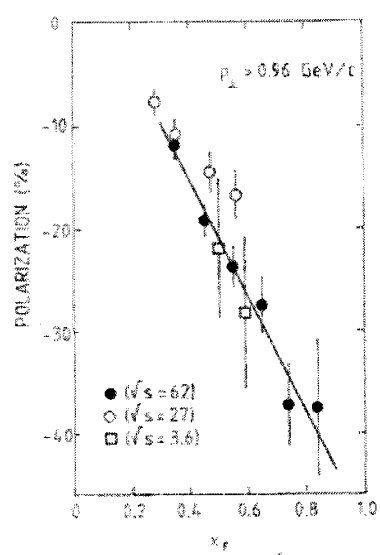
$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$



$\ell + p^\uparrow \to \ell' + \pi + X$
HERMES



$p + p^\uparrow \to \pi + X$
STAR

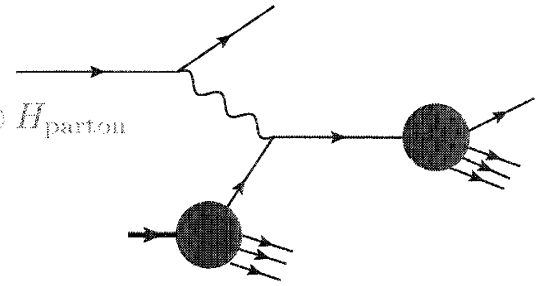


$p + p \to \Lambda^\uparrow + X$
E704

SSAs: kt-dependent functions in pQCD factorization

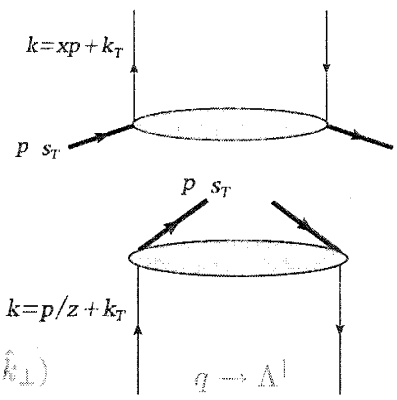
- pQCD kt-factorization

$$\sigma(p_h, s_\perp) \propto f_{a/A}(x, k_\perp) \otimes D_{c\to h}(z, p_\perp) \otimes H_{\text{parton}}$$



- SSAs come from spin-correlation in
  - either parton distribution functions (PDFs)
  - or fragmentation functions (FFs)
- Spin correlations
  - Sivers functions
    - **Asymmetric distribution of an unpolarized quarks inside a transversely polarized hadron**

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/h}(x, k_\perp)\, \vec{S}\cdot \hat{p} \times \hat{\mathbf{k}}_\perp$$



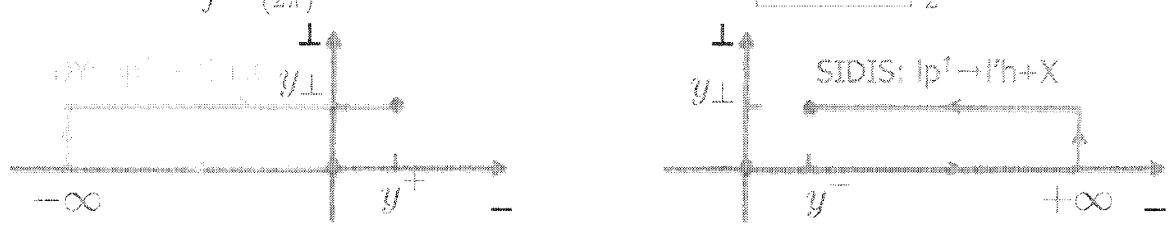
  - Polarizing fragmentation functions (PFFs)
    - **Asymmetric fragmentation from an unpolarized quark to a transversely polarized hadron**

$$D_{h^\uparrow/q}(z, \vec{k}_\perp) = \frac{1}{2} D_{h/q}(z, k_\perp) + \frac{1}{2}\Delta^N D_{h/q}(z, k_\perp)\, \vec{S}_\perp \cdot (\hat{p}_q \times \hat{k}_\perp)$$

K_T-dependent PDFs and FFs

- Gauge link is needed for gauge invariant definition of the PDFs and FFs
  - For collinear PDFs and FFs, the gauge link is only along light-cone, unitarity could be applied, thus they are usually universal (process independent)
  - For TMD PDFs and FFs, the gauge link lies along both light-cone, and transverse direction, unitarity is not easy to apply, thus gauge link in many cases are complicated and process dependent, thus the associated PDFs and FFs are generally not universal
- Sivers function is not universal because of different gauge links

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) = \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} e^{ixp^+ y^- - i\mathbf{k}_\perp \cdot \mathbf{y}_\perp} \langle p, \vec{S}|\bar{\psi}(0^-, \mathbf{0}_\perp) \boxed{\text{Gauge link}} \frac{\gamma^+}{2} \psi(y^-, \mathbf{y}_\perp)|p, \vec{S}\rangle$$



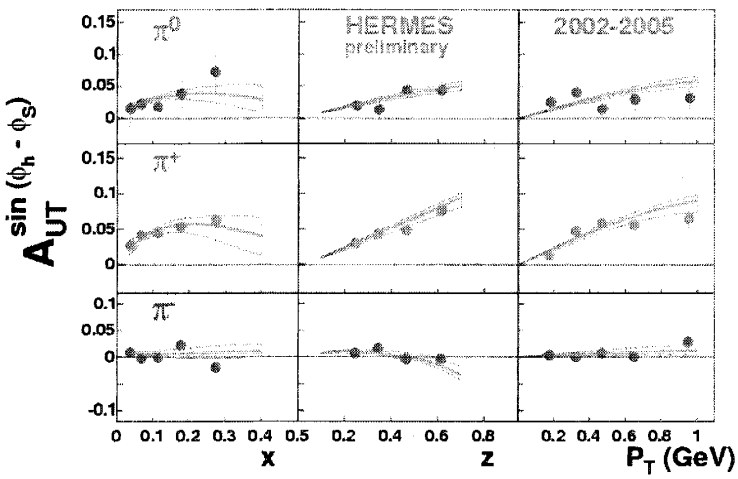
$$\Delta^N f^{\text{SIDIS}}_{q/h^\uparrow}(x, k_\perp) = -\Delta^N f^{\text{DY}}_{q/h^\uparrow}(x, k_\perp)$$

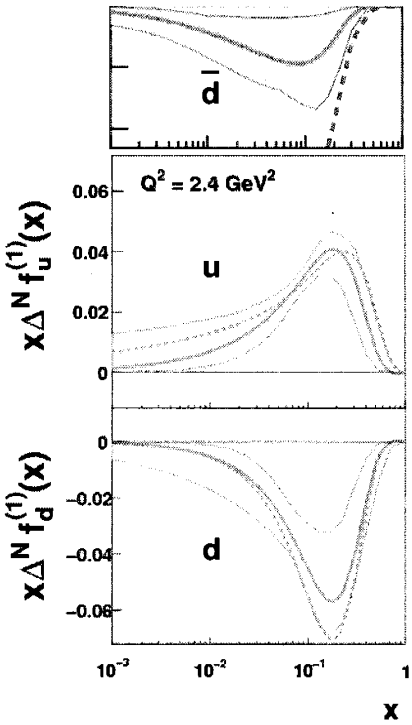
Collins 2002, Boer, Mulders, Pijlman 03, Metz, Collins 04, Kang, Qiu 09, ...

- Most critical test for understanding the SSAs: sign change

Sivers function from SIDIS

- Extract Sivers function from SIDIS

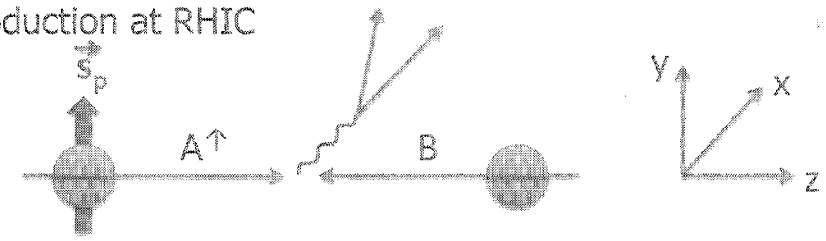




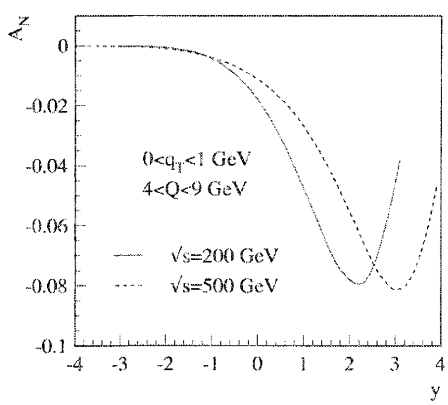
- u and d almost equal size, different sign
- d-Sivers is slightly larger
- d-bar Sivers is negative

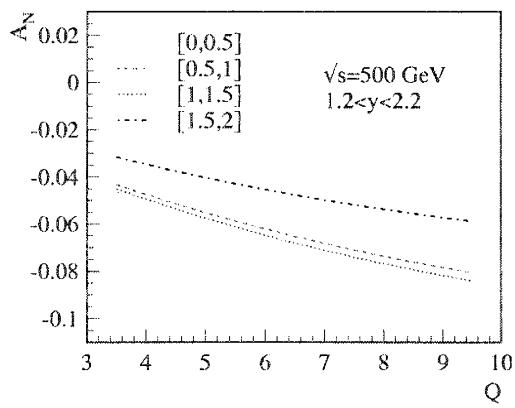
Predictions for Drell-Yan process at RHIC

- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC



$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, k_{\perp 1}) f_{q/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d \quad \Rightarrow \quad A_N < 0$$

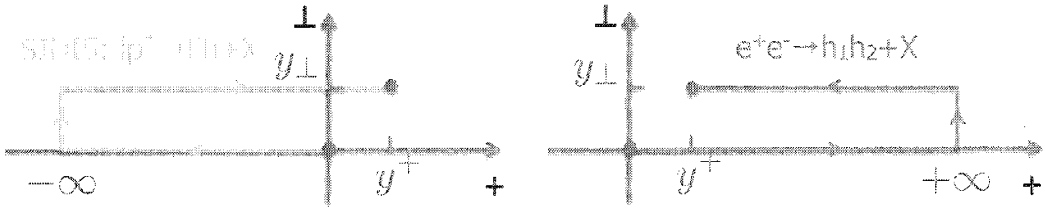




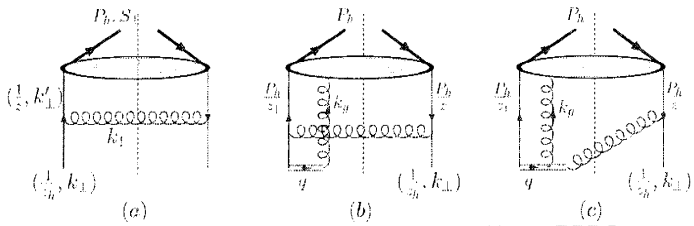
Universality for polarizing fragmentation functions

- Gauge link for polarizing fragmentation functions Boer, Mulders, Pijlman, 2003

$$\Delta(z,k_\perp) = \frac{1}{z}\int \frac{dy^+ d^2y_\perp}{(2\pi)^3} e^{-ik\cdot y}\langle 0|U_{[\pm\infty;0]}\psi(0)|P_h S_\perp X\rangle\langle P_h S_\perp X|\bar\psi(y)U_{[y;\pm\infty]}|0\rangle|$$



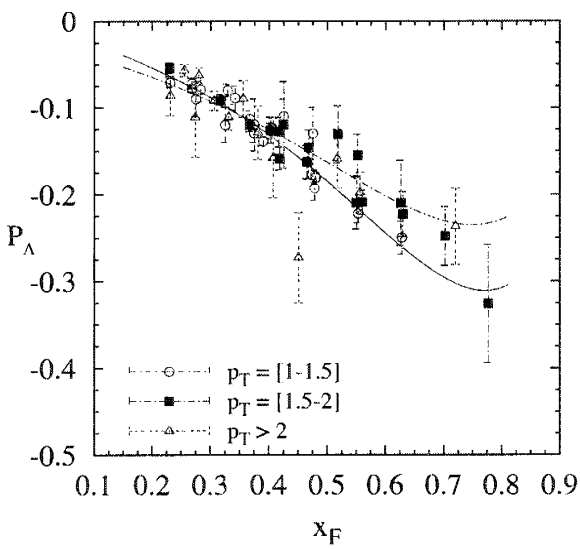
- However, they are universal: no sign change Metz 02, Metz, Collins 04, Yuan 08, ...
  - Time reversal change in-state to out-state, do not directly give the relation
  - Different theoretical approach lead to the conclusion for their universality
  - Expansion in terms of universal collinear correlators, verify their universality in perturbative region: contributions associated with gauge links vanish



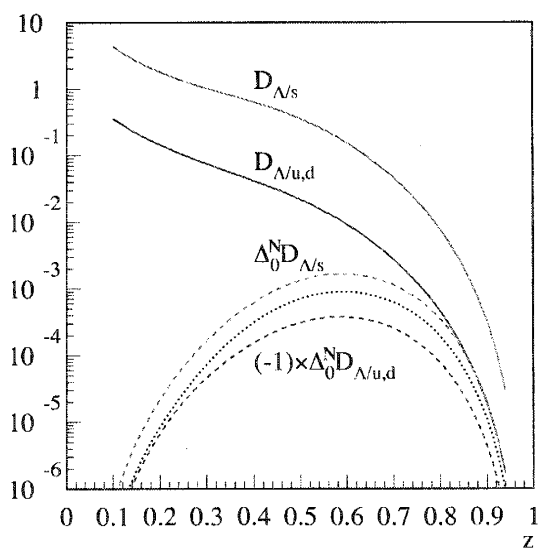
PFFs extracted from pp collisions

- Extract polarizing fragmentation functions from $pp \to \Lambda^\uparrow + X$

Anselmino, Boer, D'Alesio, Murgia, 2001



Example: fit with the data, $\sqrt{s}$ ~ 80 GeV

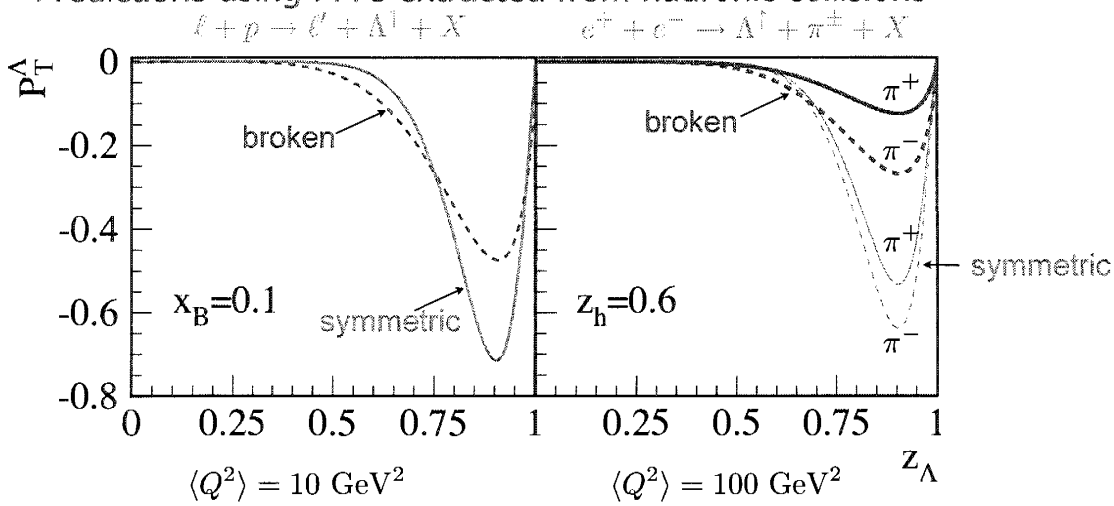


Extracted PFFs: for u, d quarks, negative for s quarks, positive

Predictions for SIDIS and e^+e^- annihilation

Duc Kang, Yuge Kang, Yu-A, Feb. 2013

- Predictions using PFFs extracted from hadronic collisions



- PFFs do NOT change sign, necessary condition for universality
  - SIDIS: u quark dominant, PFF for u-quark is negative, thus negative Λ polarization
  - e^+e^-: for pi-, ubar to pi- and u to Λ, leads to negative polarization
    for pi+, dbar to pi+ and d to Λ, leads again to negative polarization

Summary

- Gauge link dependence in Sivers functions leads to the modified universality for Sivers function in SIDIS and DY
  - Sign change is the necessary condition
  - DY measurement is expected at RHIC
- The counterpart in fragmentation functions is universal
  - Sign not change is also the necessary condition
  - Λ polarization measurement is expected at BELLE, COMPASS, and/or EIC
- Future measurements will help understand the mechanism of single transverse spin asymmetry, and the associated pQCD kt-factorization

Summary

- Gauge link dependence in Sivers functions leads to the modified universality for Sivers function in SIDIS and DY
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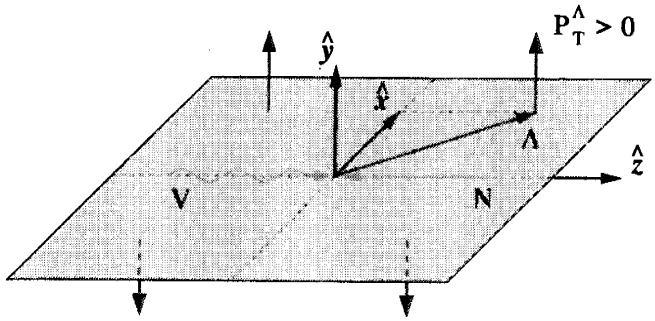
- Future measurements will help understand the mechanism of single transverse spin asymmetry, and the associated pQCD kt-factorization

Thank you!

Frame for SIDIS

- Polarization is defined in the following frame: virtual photon is in +z direction
  - SIDIS: proton is in -z direction
  - e^+e^-: accompanying hadron is in -z direction



- Outlook: Λ polarization might also help to study gluon saturation

Neutrino astrophysics and cosmology

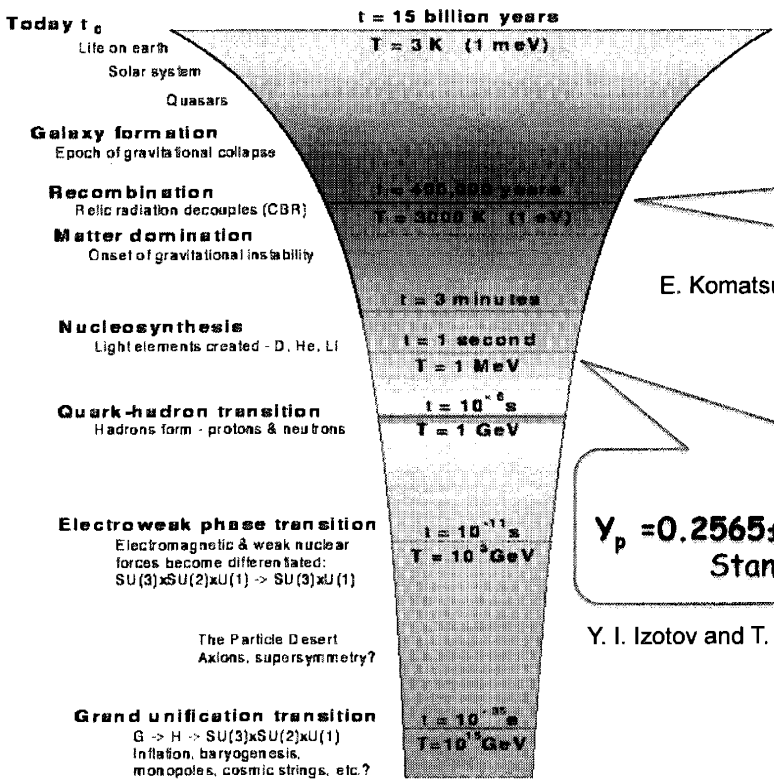
Cecilia Lunardini
Arizona State University
And RIKEN BNL Research Center

RBRC annual review, BNL, October 2010

Neutrinos, WMAP7, and BBN

L. M. Krauss, C.L. and C. J. Smith, arXiv: 1009.4666, submitted to Phys. Rev. D

Non standard cosmology?



CMB:
N_{eff} = 4.34+0.86-0.88
Standard: $N_{eff} = N_\nu = 3$

E. Komatsu et al. (WMAP),ApJ Suppl. 180, (2009)

BBN, 4He fraction:
Y_p =0.2565±0.0010(stat.)±0.0050(syst.)
Standard: Y_p =0.242-0.247

Y. I. Izotov and T. X. Thuan, ApJ 710, 2010

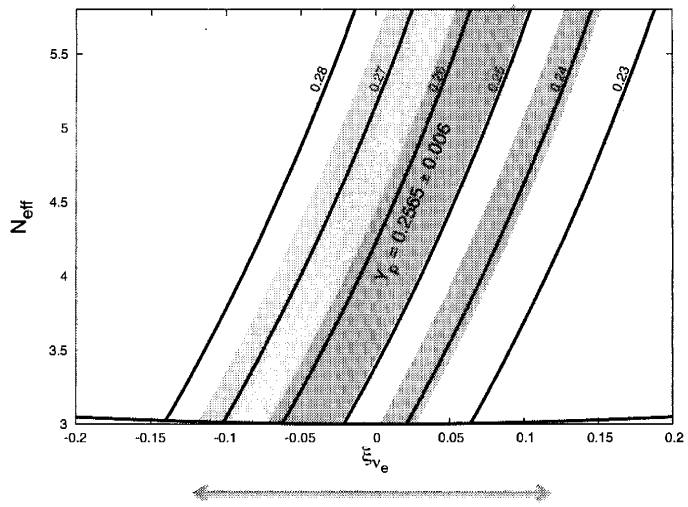
New neutrino physics?

- *Extra light d.o.f.* → larger N_{eff}, larger Y_p (earlier weak freezeout)
  - Sterile ν?
  - Large pre-BBN neutrino asymmetries

- *Modified reaction rates*
  - ν-anti-ν asymmetry at BBN time ($\xi=\mu/T$)

- Model-independent scan of parameter space:

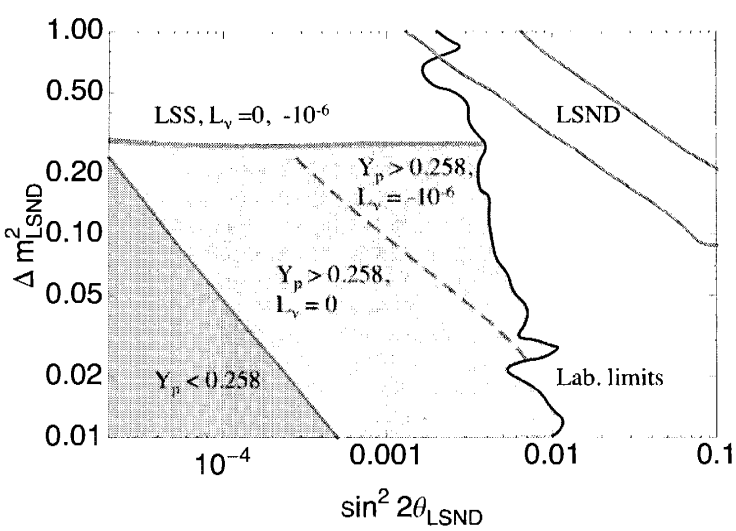
BBN code: C. J. Smith, G. M. Fuller and M.S. Smith, PRD79, 2009



Relaxed BBN bound: -0.14 < ξe <0.12,

Natural realization: sterile ν

- Produced via oscillations/ collisions
  - N_{eff} = 4 if thermalized
- Previously disfavored region back on!
  - Testable experimentally



Neutrinos from failed supernovae

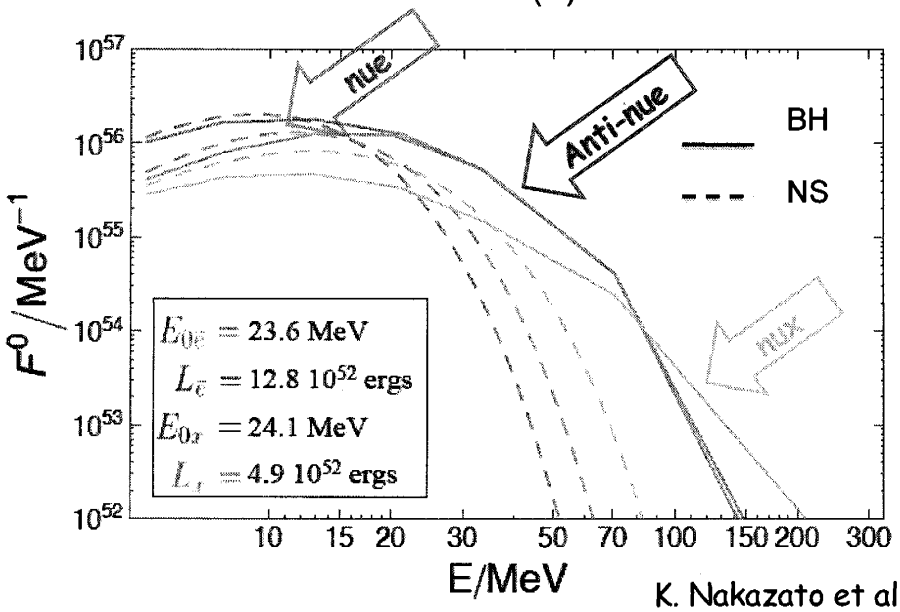
J.G. Keehn and C.L., to appear soon
C.L. and L. Yang, work in progress

New SN types: failed SNe

- M > 40 Msun, 9-22% of all collapses
- *Direct* BH-forming collapse (no explosion):
  - *Higher energies: E_0 ~ 20 - 24 MeV*
    - For all flavors
    - Due to rapid contraction of protoneutron star before BH formation
  - *Electron flavors especially luminous*
    - (e^- and e^+ captures)

Liebendörfer et al., ApJS, 150, 263, K. Sumiyoshi et al., PRL97, 091101 (2006), T. Fischer et al., (2008), 0809.5129, K. Nakazato et al., PRD78, 083014 (2008)

Shen et al. (S) EoS



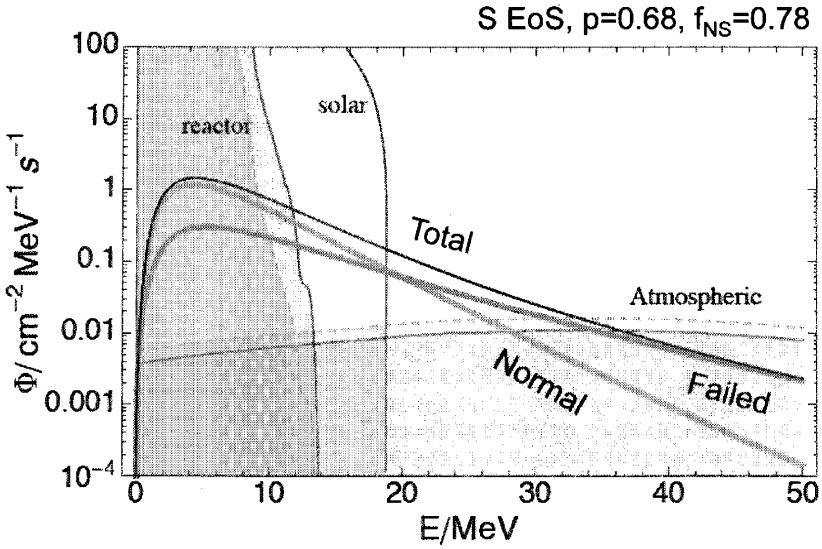
K. Nakazato et al., PRD78, 083014 (2008)

- Progenitor: M=40 M_{sun}, from Woosley & Weaver, 1995
- "stiffer" eq. of state (EoS) → more energetic neutrinos

Diffuse flux

- 10-100% effect!

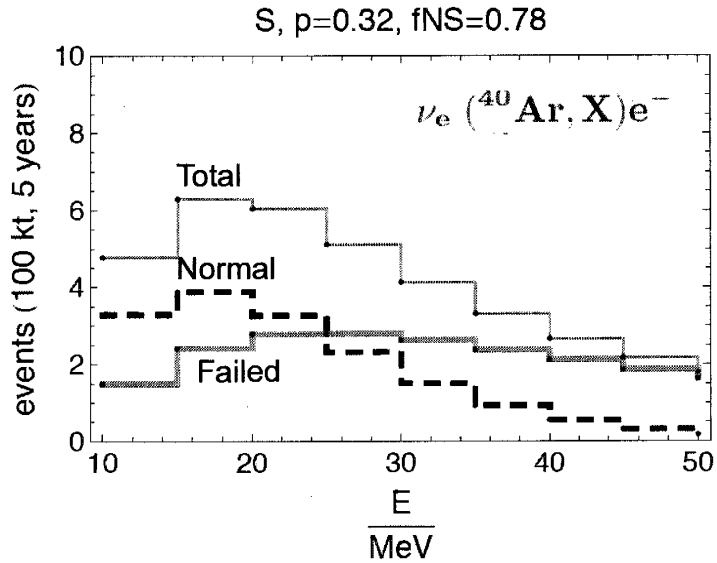
S EoS, p=0.68, f_{NS}=0.78



C.L., Phys. Rev. Lett., 2009, J. Keehn & C.L., in preparation

Signal in liquid argon

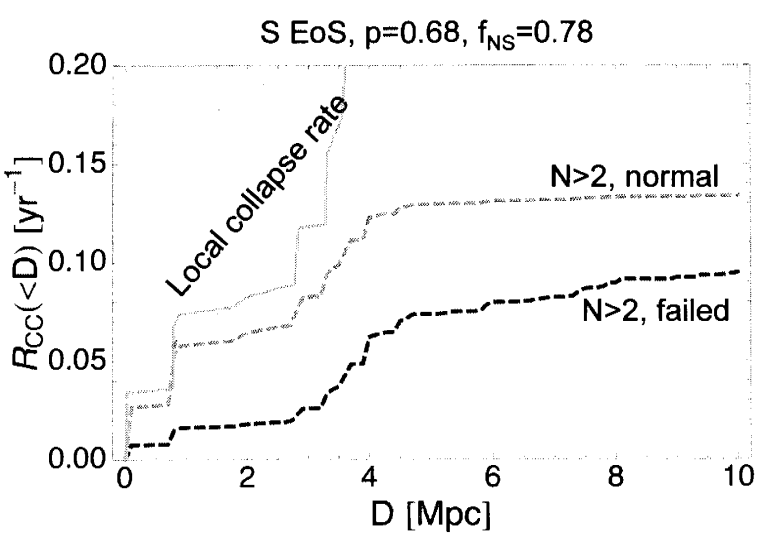
- Bulk of events from failed SNe captured



J. Keehn & C.L., in preparation

Nearby failed Sne detectable

- N>2 events up to ~6.5 Mpc
  - Compensates for rarity
- ~0.1/yr in Mt detector



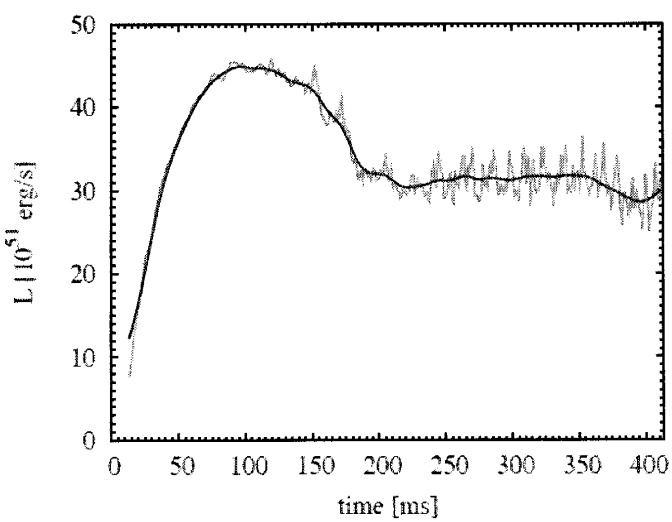
C.L. and L. Yang, work in progress

Local rate from Ando, Beacom & Yuksel, PRL 95 (2005)

Supernova neutrinos: timing

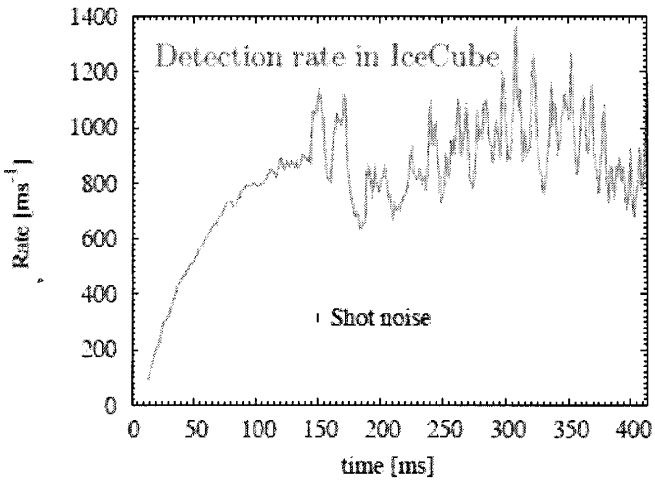
T. Lund, A. Marek. C.L., H.T. Janka & G. Raffelt,
arXiv:1006.188, accepted in Phys. Rev. D

- SASI (Standing Accretion Shock Instability)
  - Oscillations of shock front modulates neutrino luminosity
  - Probes large scale convection



Blondin, Mezzacappa & DeMarino, ApJ 584
Marek, Janka & Mueller, Astron. Astrophys. 496, 475 (2009)

- Detectable above noise at Km^3 detectors
- Frequencies up to 100-200 Hz measurable
- possibility to *test SASI vs non-SASI models!*



T. Lund, A. Marek. C.L., H.T. Janka & G. Raffelt, arXiv:1006.1889

Final remarks

- Neutrinos are becoming an increasingly powerful probe of astrophysics and cosmology!

The Dichotomous Nucleon:

- Some Radical Conjectures in large Nc

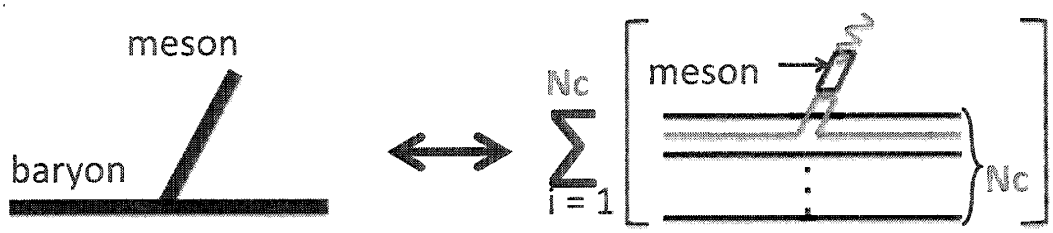
Toru Kojo (RBRC)

based on work

Y. Hidaka (Kyoto), T.K., L. McLerran, R. D. Pisarski (BNL)

arXiv:1004.2261 [hep-ph]

Meson-baryon interactions in 1/Nc (Witten, 79)



	meson - **quark** int.		**weight**		meson - baryon int.	
naive :	$N_c^{-1/2}$	×	N_c	→	$N_c^{1/2}$	(Max)
With Cancellations :	$N_c^{-1/2}$	×	1	→	$N_c^{-1/2}$	(Min)

e.g.) vector exchange $\qquad V \propto (\text{coupling})^2$

charge (weight)		**exchange potential**		**phen. potential**
quark number	~ Nc	ω -meson	~ Nc	7 ~ 10
isospin	~ 1	ρ -meson	~ 1/Nc	0.7 ~ 0.9

How about long range Pion part?

Conventional Nc counting: $\longrightarrow$ $g_A \sim N_c$

(Skyrmion, quark model, etc.) (**pion** exchange $\sim (g_A/f_\pi)^2 \sim N_c$)

Typical potential $\rightarrow \sim -N_c \Lambda_{QCD} \sim -$ **600** MeV

However

Exp. : $-$**2.2** (deuteron B.E.) , $-$**16** MeV (normal nuclear matter)

Therefore

It is much more **natural** to pursue the **possiblity**:

$$g_A \sim 1 \rightarrow \langle V \rangle \sim -\Lambda_{QCD}/N_c \sim -60 \text{ MeV.}$$

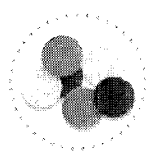
$$\langle p^2 \rangle / 2M_N \sim +\Lambda_{QCD}/N_c$$

cancellation

Small binding energy

O(Nc) gA v.s. O(1) gA Nucleons

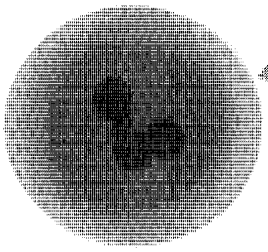
Nc valence quarks
(~ bare nucleon)



short distance region
$\sim 1/\Lambda_{QCD}$

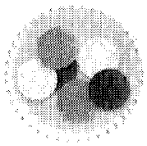
conventional

unconventional



$g_A \sim N_c$

$g_A \sim 1$

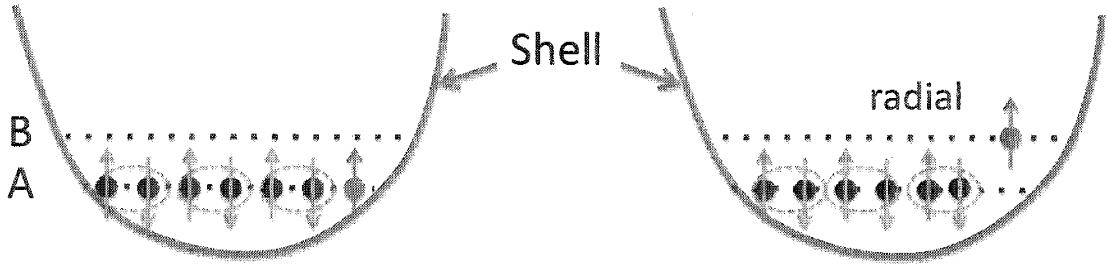


coherent	pion clouds	quantum
O(Nc) (coherent overlap)	NN potential (long distance)	O(1) (one pion exchange)
$\langle K \rangle \ll \langle V \rangle$ (solid - like)	low density regime	$\langle K \rangle \sim \langle V \rangle \sim 1/N_c$ (liquid - like)

Dichotomous spatial wavefunction

overlap: $x \equiv |\langle A|B\rangle| = \left| \int d\vec{r} A^*(\vec{r}) B(\vec{r}) \right|$

Conventional (x=1) Dichotomous (x=0)



$gA = \dfrac{Nc + 2}{3}$ (exp. 1.25) $gA = 1$

(1.66 for Nc = 3) carried by solitary quark

(No contributions from diquarks)

For Nc = 3, w.f. would be superposition of these two.

Energetic arguments : valence and field

Conventional (x=1) Dichotomous (x=0)

Valence quark part ($r < 1/\Lambda_{QCD}$) :

$E_{val}(x=1)$ $\sim E_{val}(x=1) + \underbrace{O(\Lambda_{QCD})}_{\text{energy cost}}$

Field energy ($r > 1/\Lambda_{QCD}$) :

e.g.) pion clouds energy: $\sim \underline{g_A^2 / f_\pi^2}$

$E_{field}(x=1) = O(Nc)$ $E_{field}(x=0) = O(1/Nc)$

Our expectation:

$$\boxed{\frac{d}{dx}\left(E_{val}(x) + E_{field}(x) \right) = 0 \longrightarrow \underset{\text{large Nc}}{x = 0}}$$

Summary

The baryon axial charge is:

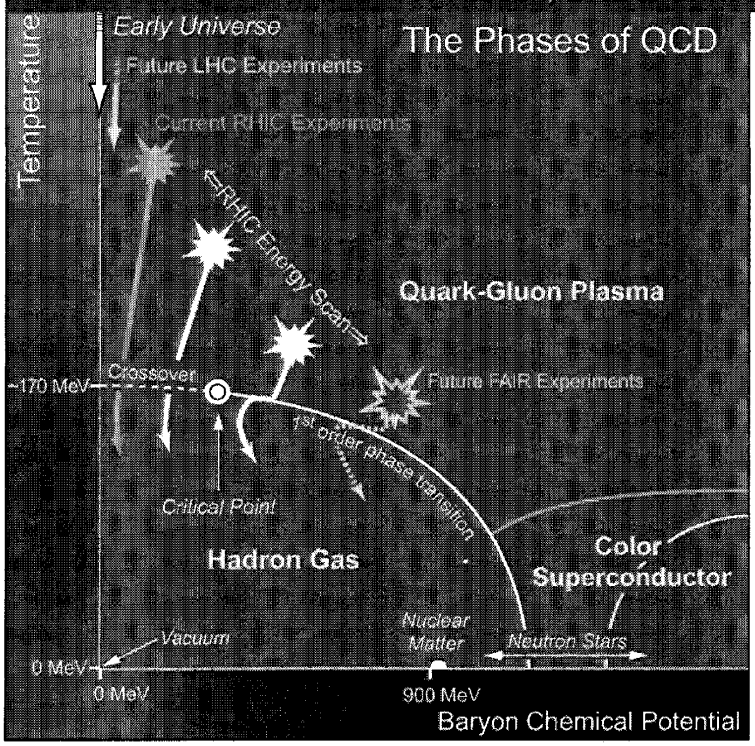
- a key quantity in Nuclear Physics.
- a quantity to qualify the nature of pion clouds.
  (Coherent v.s. Quantum)
- a good probe to see **quark dynamics inside baryons**.

If dichotomous nucleons are large Nc ground state:

- Nucleons smoothly change from Nc=3 to ∞.
  (controlled by a spatial overlap of **paired** and **unpaired** w.f.s)
- 1/Nc expansion is applicable to Nc=3 nuclear dynamics.

QCD Thermodynamics close to the chiral limit

F. Karsch, BNL & Univ. Bielefeld



Outline

- The QCD phase diagram
- Universality close to the chiral limit
- Equation of state and transition temperature
- curvature of the critical line and charge fluctuations

F. Karsch, RBRC review, October 27, 2010

Collaborations

BNL: Alexei Bazavov, HengTong Ding, Prasad Hegde, FK, Swagato Mukherjee, Peter Petreczky, Chulwoo Jung

RBC-Bielefeld-GSI: subset of above +

M. Cheng, N. H. Christ, A. Francis, O.Kaczmarek, E. Laermann, R. D. Mawhinney, C. Miao, C. Schmidt, W. Soeldner

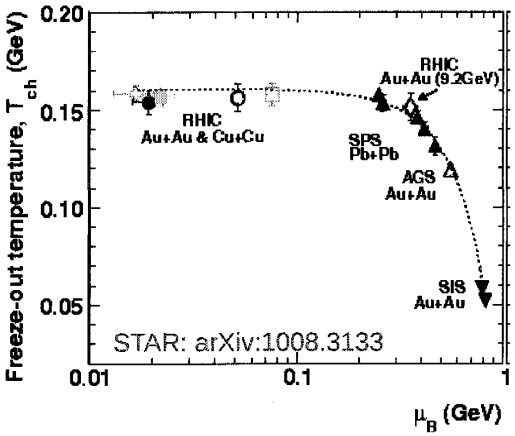
HotQCD: subset of above +

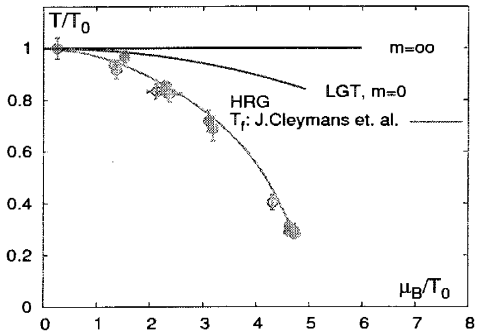
T. Bhattacharya, C. DeTar, Steven Gottlieb, R.Gupta, U.M. Heller, L. Levkova, D. Renfrew, R.A. Soltz, R. Sugar, D. Toussaint, W. Unger and P. Vranas

+ S. Ejiri (Niigata), M. Kitazawa (Osaka), K. Redlich (Wroczlaw),....

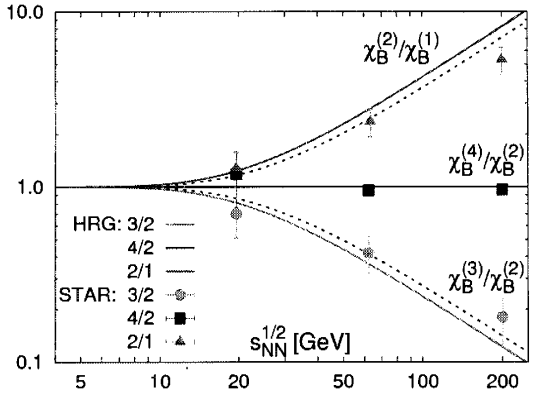
F. Karsch, RBRC review, October 27, 2010

The RHIC low energy runs





Moments of charge fluctuations



FK, K Redlich, arXiv:1007.2581
data from STAR: arXiv:1004.4959

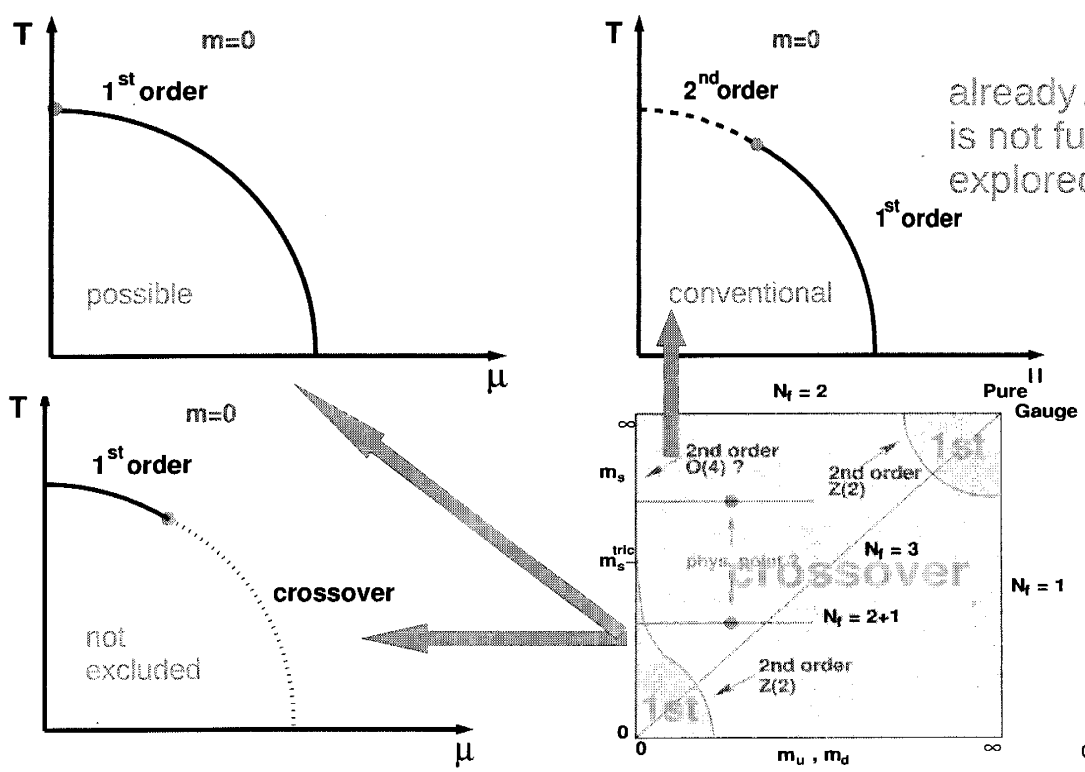
charge fluctuations at freeze-out agree with HRG model predictions

freeze-out line and chiral phase transition

BNL-Bielefeld-GSI, in preparation

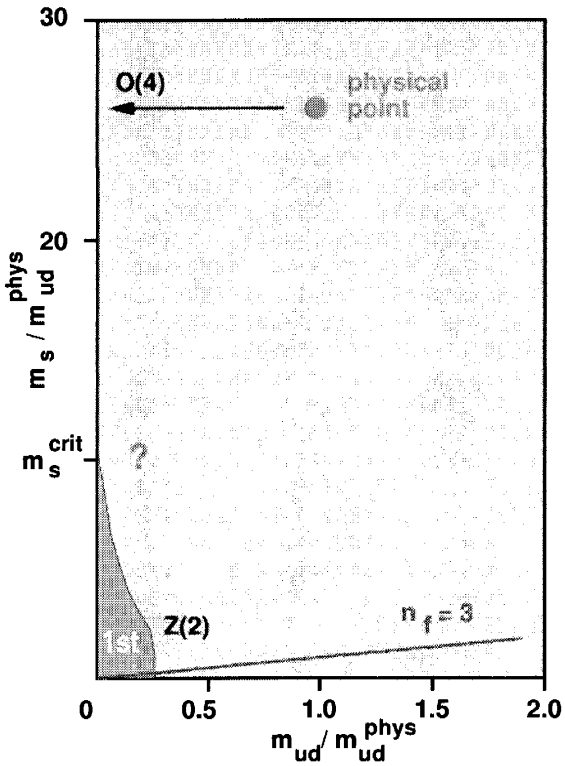
F. Karsch, RBRC review, October 27, 2010

Critical behavior in hot and dense matter QCD phase diagram & chiral limit



already $\mu_B = 0$ is not fully explored

Phase diagram for $\mu_B = 0$



- drawn to scale

Is physics at the physical quark mass point sensitive to (universal) properties of the chiral phase transition?

physical point may be above $\mathbf{m_s^{crit}}$

$$n_f = 3 : \ \mathbf{m_\pi^{crit} \lesssim 70\ MeV}$$

first order region starts below physical pion mass value

F. Karsch, RBRC review, October 27, 2010

O(N) scaling and the chiral transition

- thermodynamics in the vicinity of a critical point:

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V,T) = h^{1+1/\delta} f_s(t/h^{1/\beta\delta}) + f_r(V,T)$$

with scaling fields $\quad t \equiv \frac{1}{t_0}\left(\frac{T}{T_c} - 1\right) \quad , \quad h \equiv \frac{1}{h_0}\frac{m_l}{m_s}$

- In the vicinity of (t,h)=(0,0) the chiral order parameter and its susceptibility are given in terms of scaling functions

$$M = h^{1/\delta} f_G(z) \quad , \quad \chi_M = \partial M / \partial h = h^{1/\delta - 1} f_\chi(z)$$

$$\chi_{m,t} = \partial M / \partial T = \frac{1}{t_0 T_c} h^{(\beta-1)/\delta\beta} f'(z)$$

$$f_\chi(z) = \frac{1}{\delta}\left(f_G(z) - \frac{z}{\beta} f_G'(z)\right)$$ known from 3d O(N) spin model

F. Karsch, RBRC review, October 27, 2010

Scaling analysis in (2+1)-flavor QCD

RBC-Bielefeld-GSI arXiv:0909.5122; hotQCD in preparation

QCD with 2 light and a "physical" strange quark mass:

- improved staggered fermions; most detailed: p4-action extended to asqtad and hisq
- calculations have been performed on $N_\sigma^3 \times N_\tau$ lattices
  $N_\sigma = 32,\ 48\ ,\ N_\tau = 4,\ 6,\ 8$
- calculations with p4-action cover a wide quark mass range:
  $N_\tau = 4: \quad 1/80 \leq m_l/m_s \leq 2/5$
  $\Rightarrow \quad 75\ \mathrm{MeV} \leq m_\pi \leq 320\ \mathrm{MeV}$

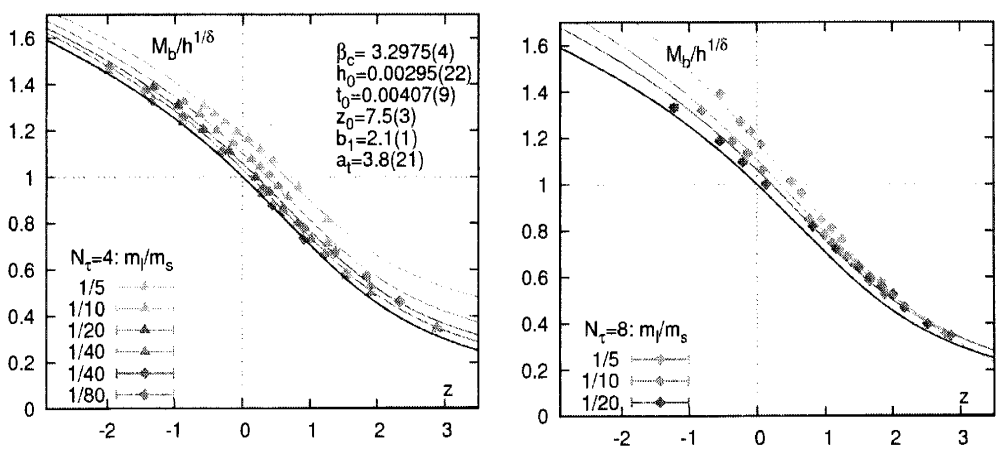
➡ evidence for O(N) scaling
expect O(2) rather than O(4) scaling with staggered fermions at non-zero lattice spacing

F. Karsch, RBRC review, October 27, 2010

Scaling analysis in (2+1)-flavor QCD

RBC-Bielefeld-GSI arXiv:0909.5122; hotQCD in preparation

$$M_b \equiv \frac{m_s \langle \bar{\psi}\psi \rangle}{T^4} \qquad z \equiv t/h^{1/\beta\delta}$$



$$\Rightarrow \quad T_c,\ t_0,\ h_0 \rightarrow z_0 = h_0^{1/\beta\delta}/t_0$$

W. Unger, PhD thesis, Bielefeld, September 2010

⬇ chiral phase transition

➡ controls $T_c(m_l/m_s)$

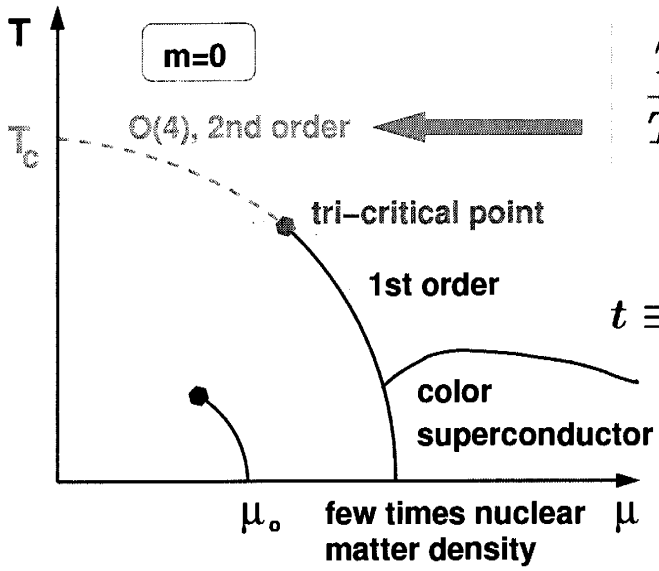
F. Karsch, RBRC review, October 27, 2010

The curvature of the critical line

BNL-Bielefeld-GSI in preparation

- QCD, chiral limit (u,d quarks only)

$$\mu_u = \mu_d > 0, \ \mu_Q = \mu_s = 0$$



$$\frac{T}{T_c} = 1 - \kappa_q \left(\frac{\mu_q}{T}\right)^2$$

$$t \equiv \frac{1}{t_0}\left(\left(\frac{T}{T_c} - 1\right) - \kappa_q \left(\frac{\mu_q}{T}\right)^2\right)$$

scaling laws control curvature of chiral transition line for small μ_q/T

F. Karsch, RBRC review, October 27, 2010

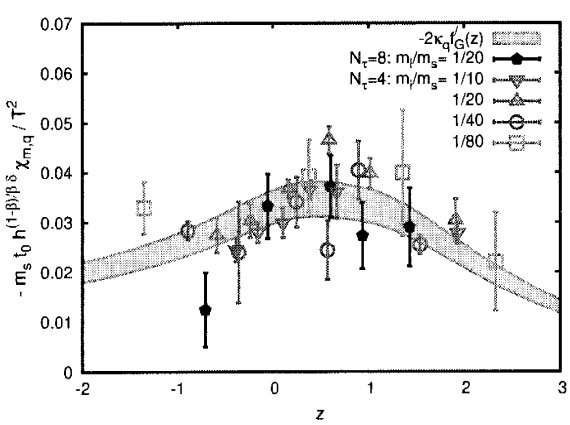
The curvature of the critical line

BNL-Bielefeld-GSI in preparation

- "thermal" fluctuations of the order parameter

$$t \equiv \frac{1}{t_0}\left(\left(\frac{T}{T_c} - 1\right) - \kappa_q \left(\frac{\mu_q}{T}\right)^2\right) \ , \ z = t/h^{1/\beta\delta}$$

$$M_b = h^{1/\delta} f_G(z) \ , \ \chi_{m,q} = \partial^2 M_b / \partial(\mu_q/T)^2 = \frac{2\kappa_q}{t_0 T_c} h^{(\beta-1)/\delta\beta} f'(z)$$

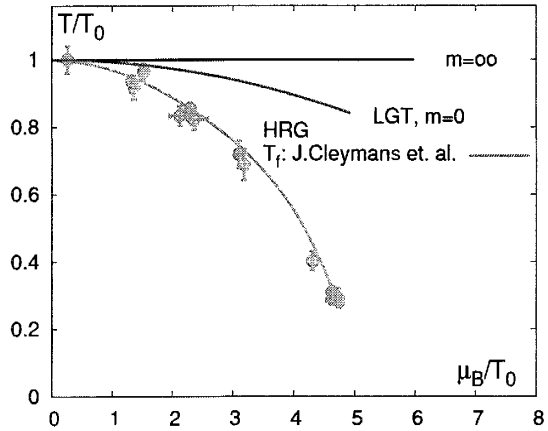


$$\kappa_q = 0.059 \pm 0.006$$

compare to freeze-out curve:

F. Karsch, RBRC review, October 27, 2010

Chiral Transition and Freeze-out



chiral phase transition curve:

$$\frac{T(\mu_B)}{T_c} = 1 - 0.0066(7)\left(\frac{\mu_B}{T}\right)^2 + \mathcal{O}(\mu_B^4)$$

open issues:
- continuum limit
- strangeness conservation
- non zero charge

freeze-out curve in heavy ion collisions:

$$\frac{T(\mu_B)}{T_c} = 1 - 0.023\left(\frac{\mu_B}{T}\right)^2 - c\left(\frac{\mu_B}{T}\right)^4$$

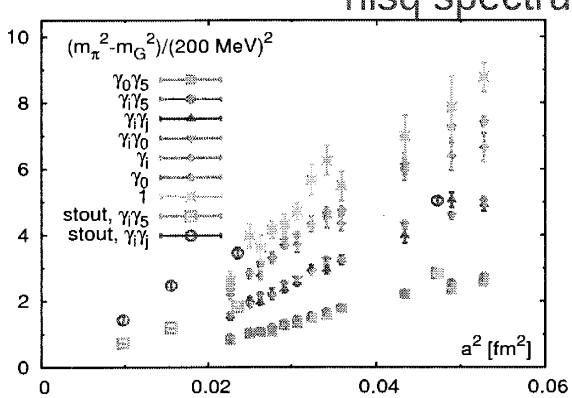
$$\mu_B(\sqrt{s_{NN}}) = \frac{d}{1 + e\sqrt{s_{NN}}}$$

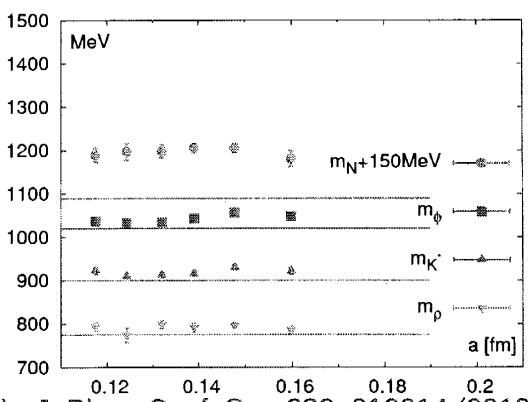
J. Cleymans et al., Phys.Rev. C73, 034905 (2006)

The chiral transition
hotQCD preliminary

- closer to the continuum limit with the asqtad staggered fermion action:
- reduced taste symmetry violation with the highly improved staggered action (hisq):

hisq spectrum calculation





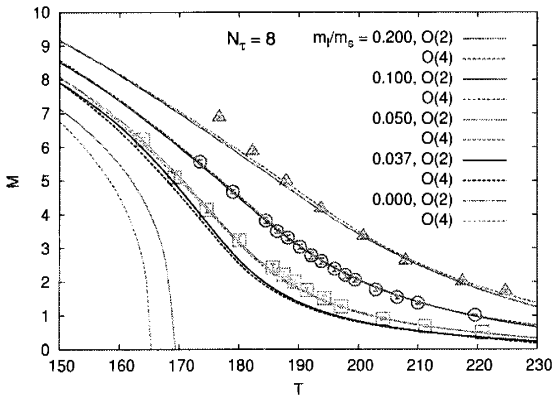
A. Bazavov,P. Petreczky (HotQCD collaboration), J. Phys. Conf. Ser. 230, 012014 (2010)

Chiral Phase Transition and Pseudo-critical temperature

- scaling ansatz can be used to extract transition temperatures from chiral condensates ;
- yields parameter free predictions for chiral susceptibilities
- yields predictions for quark mass dependence of pseudo-critical temperatures

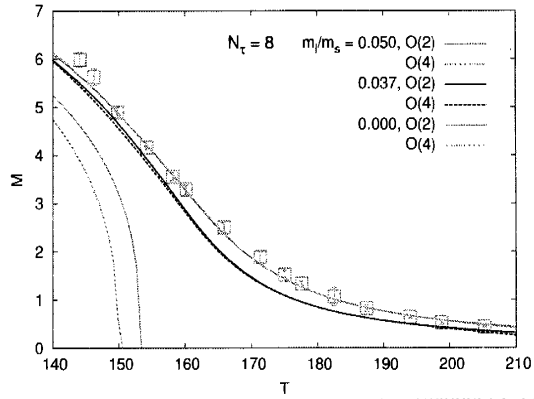
asqtad action

chiral condensate



hisq action

chiral condensate



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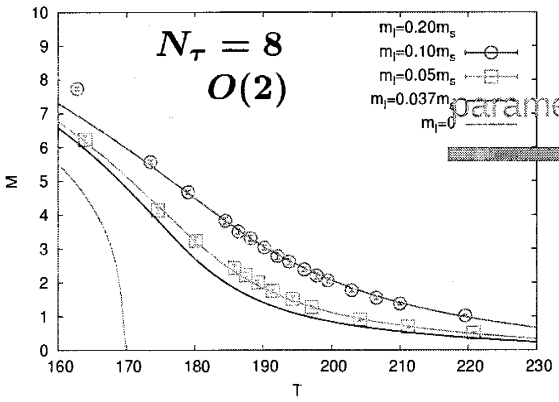
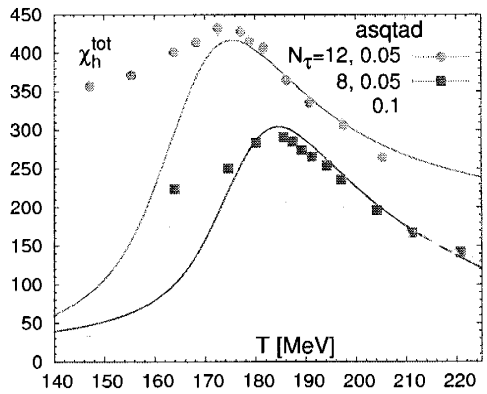


parameter free

chiral susceptibility



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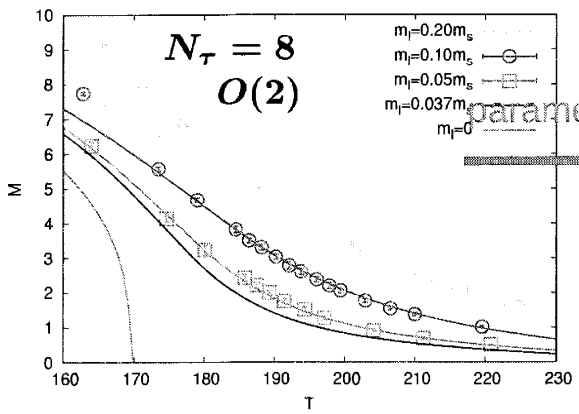
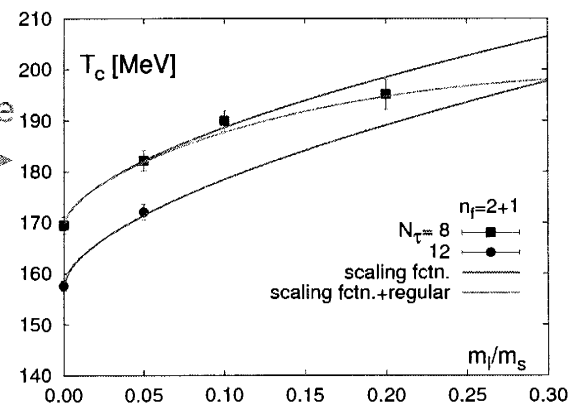
asqtad action

chiral condensate



parameter free

pseudo-critical temperatures



Chiral Phase Transition and Pseudo-critical temperature

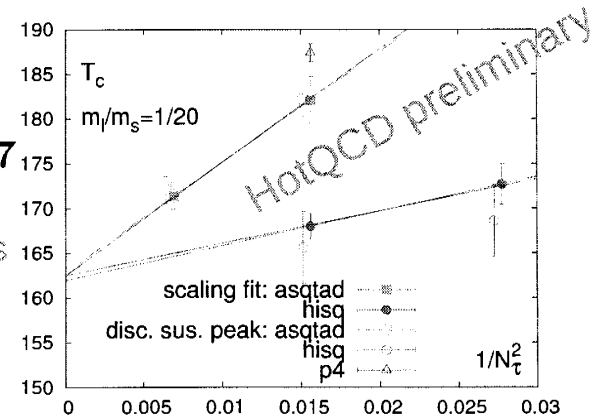
- scaling ansatz can be used to extract transition temperatures from chiral condensates;
- yields parameter free predictions for chiral susceptibilities
- yields predictions for quark mass dependence of pseudo-critical temperatures
- joint continuum extrapolation of pseudo-critical temperatures calculated with the asqtad and HISQ actions

(2+1)-flavor QCD: $m_l/m_s = 1/27$

$T_p = (164 \pm 6)$ MeV error: stat+sys

chiral limit:

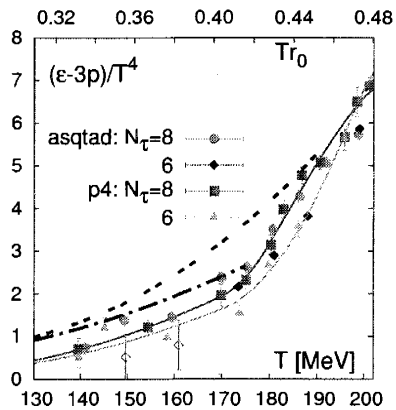
$T_c \simeq 150$ MeV



Equation of State

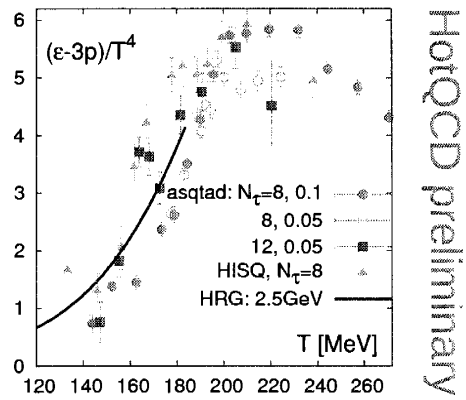
HotQCD ongoing research project

EoS in the transition region;
hadron resonance gas vs.
O(N) critical behavior



A. Bazavov et al (HotQCD collaboration), Phys. Rev. D80, 014504 (2009)

trace anomaly: NEW
asqtad Nt=12, hisq Nt=8

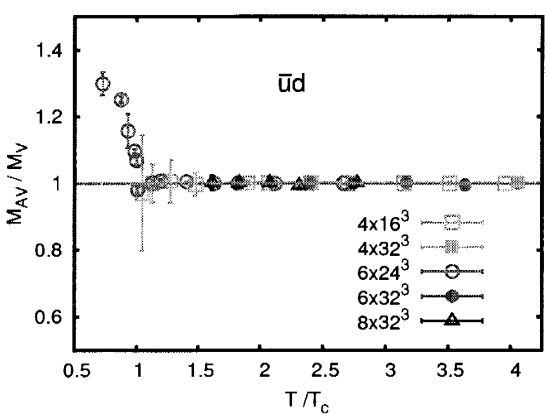


W, Soeldner, Lattice 2010, Viillasimius
A. Bazavov, xQCD 2010, Bad Honnef

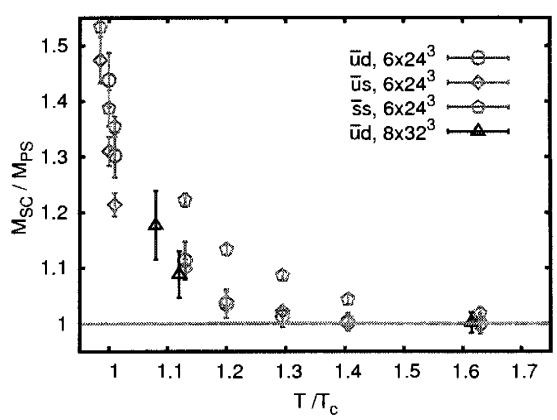
Chiral Transition and $U_A(1)$

RBC-Bielefeld-GSI arXiv:1010.1216

axial-vector/vector
screening mass



scalar/pseudo-scalar
screening mass



- screening masses in (2+1)-flavor QCD using staggered fermions: substantial $U_A(1)$ breaking also above T_c
- quest for thermodynamics with chiral actions

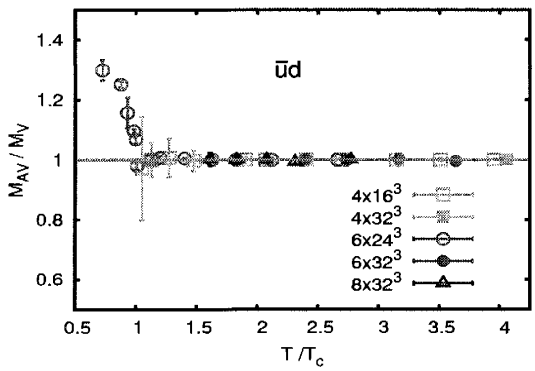
Chiral Transition and $U_A(1)$

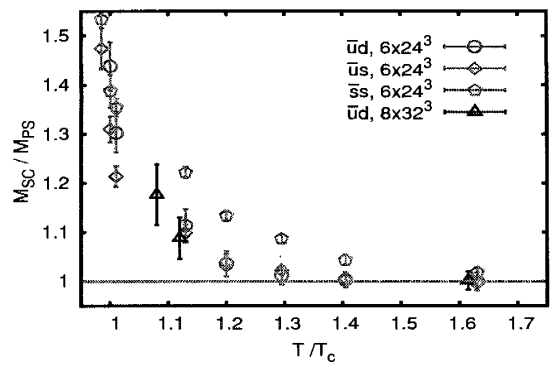
RBC and hotQCD

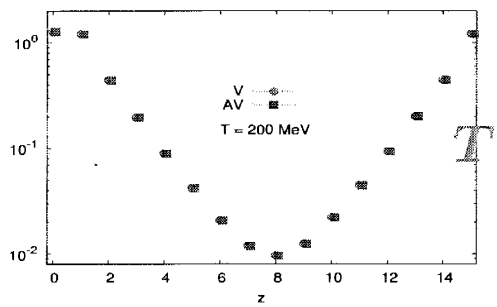
axial-vector/vector screening mass

staggered

scalar/pseudo-scalar screening mass

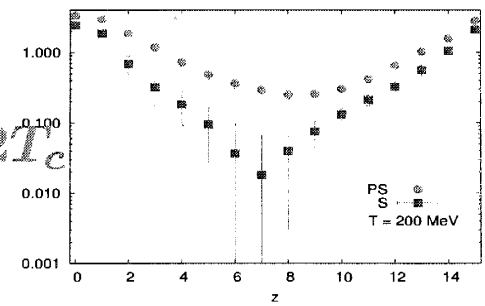






DWF

$T \simeq 1.2T_c$



:7, 2010

Thermodynamics with chiral fermions Domain Wall Fermions

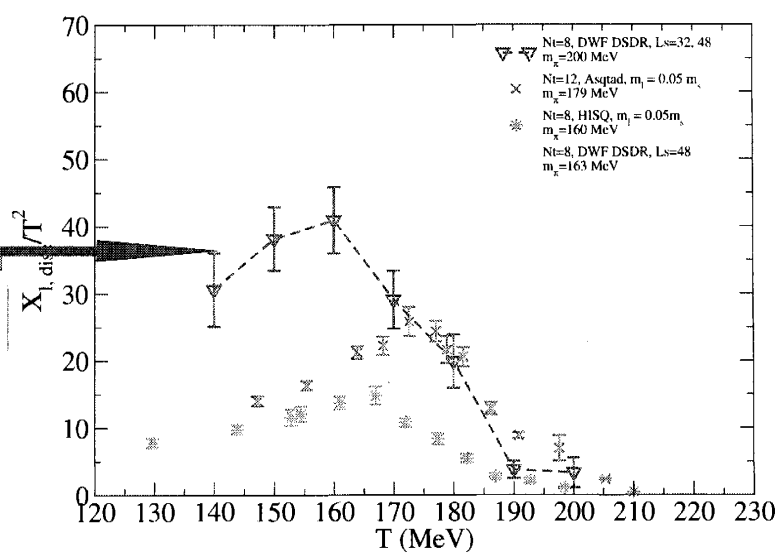
- HotQCD started calculations of chiral susceptibilities and other thermodynamic quantities using DWF

$$N_\sigma^3 \times 8 \times L_s$$

$$N_\sigma = 16,\ 32$$

$$L_s = 32,\ 48$$

$$m_\pi \simeq 200\ \text{MeV}$$



F. Karsch, RBRC review, October 27, 2010

Conclusions

- The BNL lattice group is involved in a broad spectrum of QCD thermodynamics calculations
- The group participates in several national and international collaborations

- How sensitive is the QCD transition with physical quark masses to universal properties at the chiral phase transition?
- How does the phase transition vary with chemical potentials?

- Use staggered fermion action with reduced taste violation (HISQ) with physical quark masses close to the cont. limit
- Use chiral fermion formulations (DWF) in thermodynamic calculations

F. Karsch, RBRC review, October 27, 2010

Physics of RBC and UKQCD
I. Overview of 2010 achievements

Taku Izubuchi

RIKEN BNL Research Center

BROOKHAVEN NATIONAL LABORATORY

Lattice Gauge theories

True first-principles non-perturbative computations

Indispensable bridge between experiment and theory, allowing new physics to be discovered. A part of precision frontier.

Also explores theories other than QCD.

Symmetries are key ingredients
(gauge symmetry, chiral symmetry of quarks)

QCDSP ~1Tflops

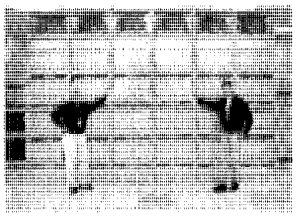
LGT @ BNL

'79 Lattice Gauge simulation (M. Creutz)

'97~ Domain-Wall Fermions (DWF) Nf=0 quenched
Blum & Soni

'99~ Riken-BNL-Columbia (RBC)

'02~ DWF Nf=2 up, down quarks RBC



QCDOC ~10Tflop BlueGene/L,P ~ 10-100 Tflops

'05~ DWF Nf=2+1 up, down, strange quarks (all light quarks) RBC/UKQCD

RBC/UKQCD collaboration

RIKEN-BNL Research Center (RBRC)

Y. Aoki, T.Izubuchi, C. Lehner,
S. Ohta, E. Shintani

BNL
M. Creutz, S. Ejiri, P. Hegde, C. Jung,
TI, F. Karsch, S. Mukherjee,
C. Miao, P. Petreczky, C. Sturm,
A. Soni, R. Van de Water,
A. Velytsky, O. Witzel

Columbia Univ.
N. Christ, M. Endres, X-Y. Jin,
C. Kelly, M. Lightman, J-Z. Lin,
Q. Liu, R. Mawhinney, H. Peng,
D. Renfrew, H. Yin

Univ. Connecticut
T.Blum, S. Chowdhury,
T. Ishikawa, R. Zhou

Univ. Virginia C. Dawson

Harvard Univ. M. Clark

Yale Univ. M. Lin

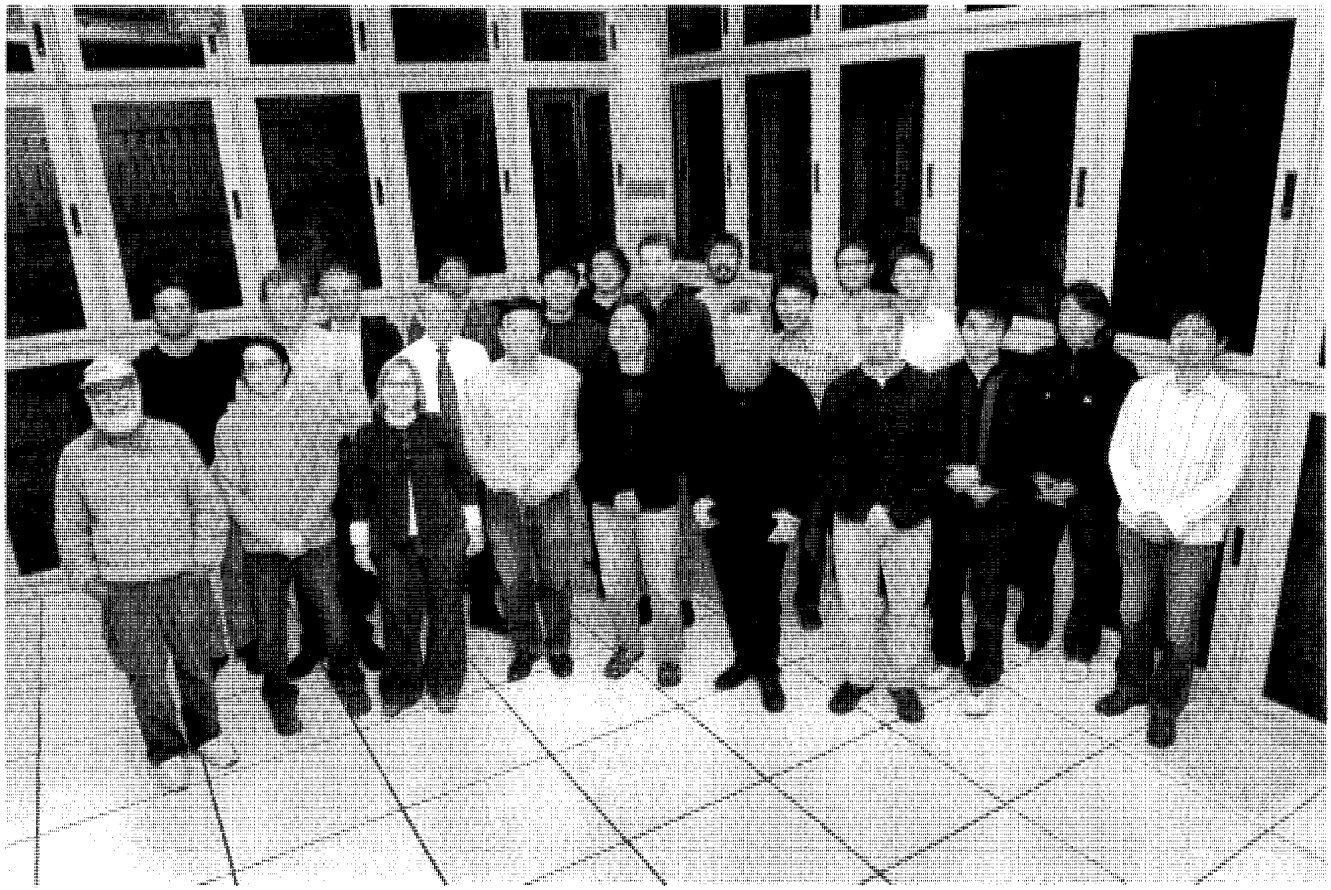
Univ. Edinburgh
R.Arthur, P. Boyle, L. del Debbio,
N. Garron, A. Kennedy, R. Kenway,
C. Maynard, B. Pendelton,
J. Wennekers, J. Zanotti

Univ. Southampton
D. Brommel, J. Flynn, P. Fritzsch,
E. Goode, C. Sachrajda

Univ. Regensburg E. Scholz

CERN A. Juttner

11 students, 18 PhD theses



Domain Wall Fermions

4D lattice quark utilizing an extra dimension

Almost perfect chiral symmetry

→ Small unphysical mixing for the Weak Matrix Elements

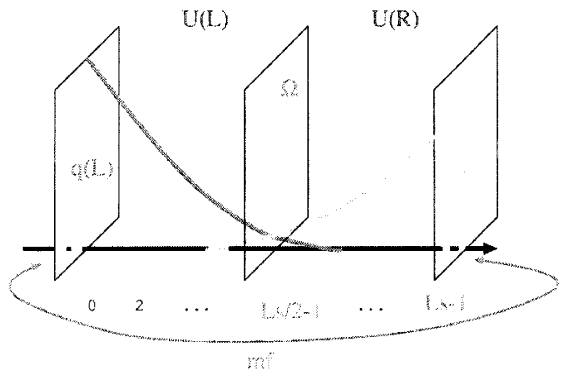
→ Error from discretization is small $O(a^2)$ ~ a few %

→ Chiral extrapolation is simpler

→ Flavor sensitive chiral transition in finite temperature/density

Vacuum polarization effects from up, down, and strange (Nf=2+1) quarks are fully incorporated.

Unitary theory at long distance



2010 lattice QCD @ RBRC

Hadron spectrum

2nd lattice spacings
η-η' masses & mixing

Quark masses
continuum limit

Isospin breaking & EM effects

QED reweighting

CKM, Flavor Physics

f_π/f_K
Neutral Kaon mixing B_K
$K\to\pi\pi$, $\Delta I = 3/2, 1/2$, ε'/ε
[T. Blum & N. Christ's talks]

B, D physics [Y. Aoki's talk]

Nucleon Physics
[S. Ohta & T. Blum's talks]

closer to the physical u,d mass
Form factors & Structure functions

Strange quark contents in Nucleon

Renormalization/Scheme matching

B_K & $\Delta S = 1$ EW operators
f_B & B_B [Y. Aoki & C. Lehner's talks]

QCD Thermodynamics
[F. Karsch, T. Blum, N. Christ's talks]

DWF Algorithm developments
[E. Shintani's talk]

QCDCQ & RICC R & D
[TI & N. Christ's talk on Fri.]

Nf= 2+1 DWF + Iwasaki & Nf=2+1 DWF+ Iwasaki-DSDR lattices [C. Jung lat10]

$m_s a$	$m_l a$	$\tilde{m}_s/\tilde{m}_l$	Δt_{light}	τ(MD)	Acceptance	m_π [MeV]
$24^3 \times 64 \sim (2.73\text{fm})^3$, $L_s = 16$, $\beta = 2.13$, $a^{-1} = 1.73(3)$ GeV, $m_{res}a = 0.003152(43), \tau/\text{traj} = 1$						
0.04	0.005	5.3	1/6	8980	73%	328
	0.01	3.3	1/5	8540	70%	417
$32^3 \times 64 \sim (2.76\text{fm})^3$, $L_s = 16$, $\beta = 2.25$, $a^{-1} = 2.28(3)$ GeV, $m_{res}a = 0.0006664(76), \tau/\text{traj} = 2$						
0.03	0.004	6.6	1/8	6856	72%	287
	0.006	4.6	1/8	7650	76%	344
	0.008	3.5	1/7	5930	73%	393

Two lattice spacings for Iwasaki action allows us to take the continuum limit.
Statistics for 24^3 lattices are doubled from previous publications.

Additional coarse, light ensemble for Iwasaki + DSDR action [T. Blum's talk]

Continuum / Chiral extrapolations

[C. Kelly, R. Mawhinney lat10]

Scaling trajectory : determine $m_{ud}(\beta)$, $m_s(\beta)$, and $a(\beta)$, for each β

m_π, m_K, m_Ω are defined to be constants.

Chiral ansatz :

* Linear Ansatz (Taylor expansion at a finite quark mass)

* SU(2) + Kaon ChPT [RBC / UKQCD 08]

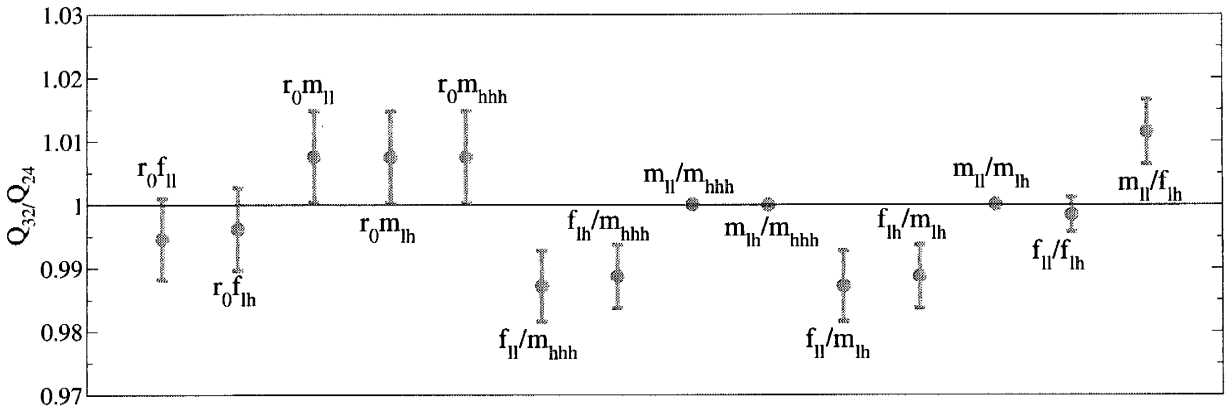
$$X = X0\,(1 + C\,a2 + D\,mq + mq\log(mq)) + O(m\,a^2, a\,m_{res}, m^2),$$

Ignore the NNLOs. (C and D are universal)
Finite Volume corrections.

Strange quark mass is corrected to physical value using reweighting method [C. Jung, T. Ishikawa]

Scaling test a^{-1} = 1.73 GeV and 2.28 GeV

[C. Kelly lat09]

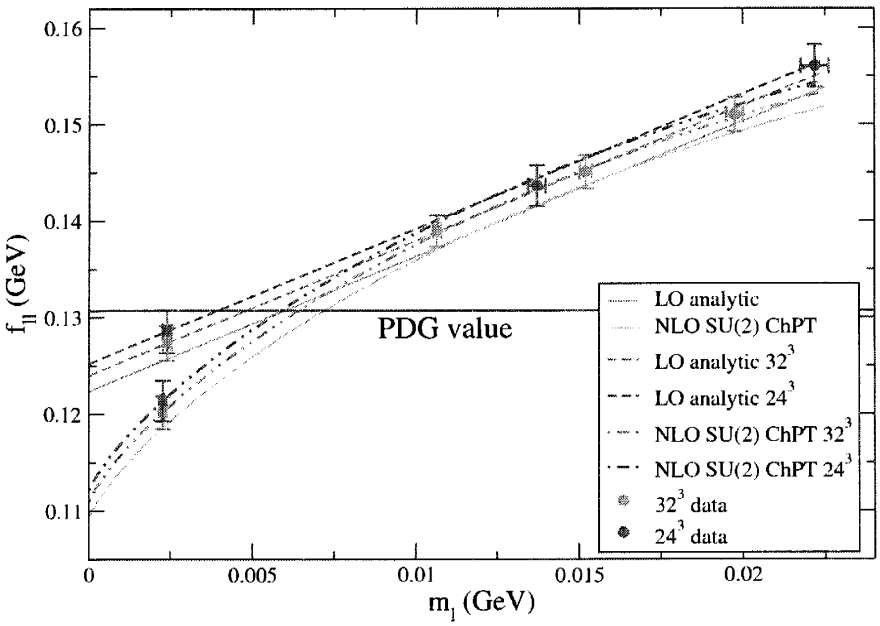


Ratios of dimensionless lattice quantities Q at simulation points.
Sommer's scale r_0, "pion" m_{ll}, f_{ll} "Kaon" m_{lh}, f_{lh}, and "Omega" m_{hhh}

(By construction, m_{ll}, m_{lh}, m_{hhh} are discretization error free.)

Only 1-2 % error, consistent with $O(a^2)$ scaling, which is removed.

Pion decay constants



SU(2)+Kaon ChPT and analytic ansatze

Scaling error is small.

Chiral extrapolations likely have significant systematic errors

Physical results

[125 pages paper to appear on arXiv ~ next Monday]

By averaging NLO SU(2)+Kaon (FV) and analytic fit :

f_π = 123(2)(5) MeV (130.7(4) MeV [expt])
f_K = 148(3)(3) MeV (159.8(1.5) MeV [expt])
f_K/f_π = 1.204(7)(20) (1.223 (12) [expt])

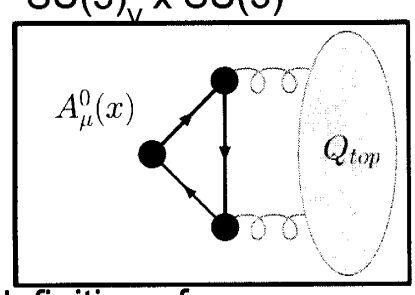
r0 = 0.4864(81)(3) fm (0.462(11)(4) fm [MILC])
r1 = 0.3331(59)(3) fm (0.317(7)(3) fm [MILC])

Quark masses in MS at 2GeV via RI/SMOM :

m_{ud} = 3.61 (13) (16) MeV (3.39(15) MeV [HPQCD])
m_s = 96.6 (1.7) (2.1)MeV (92.2(1.3) MeV [HPQCD])
m_s / m_{ud} = 26.8 (8)(1.1) (27.2 (1.2) [HPQCD])

η-η' and the strong $U(1)_A$ puzzle

Flavor singlet pseudoscalar (PS) meson, η', is heavier than non-singlet PS mesons , Nambu-Goldston bosons of $SU(3)_V$ x $SU(3)_A \to SU(3)_V$, due to the quantum anomaly



$$\partial_\mu \langle A^0_\mu(x)\rangle = 2m\langle J^0_5\rangle + \frac{N_f}{16\pi^2}\langle Q_{top}(x)\rangle$$

$$Q_{top}(x) = F_{\mu\nu}(x)\widetilde{F}_{\mu\nu}(x)$$

DWF, thanks to chiral symmetry, has an integer definition of topological charge a la Atiya-Singer's index theorem, thus optimal to study this meson.

$$\int d^4x Q_{top}(x) = \mathrm{Tr}[\gamma_5 D^{-1}_{\mathrm{DWF}}] = n_R - n_L \in Z$$

c.f.) Witten-Veneziano formula in large Nc

$$m^2_{\eta'} - m^2_\pi = \frac{4N_f}{f^2_\pi}\frac{\langle Q^2_{top}\rangle}{V}$$

For Nf = 2+1, one could also study mixing between η and η' due to SU(3) breaking

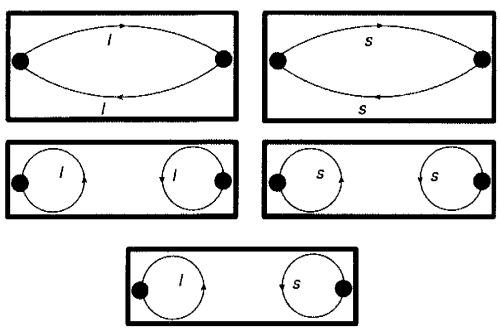
~16 years of challenges since Kuramashi-Fukugita-Mino-Okawa-Ukawa PRL 72, 3448 (1994)

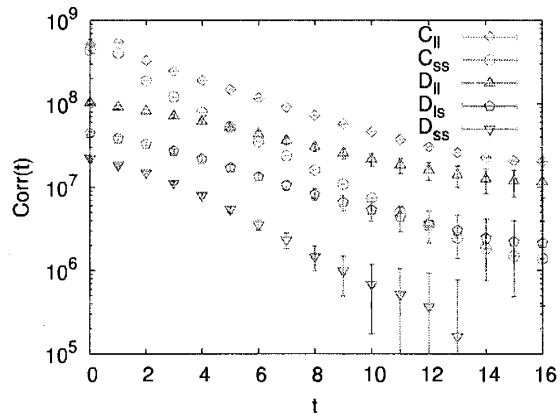
Nf=2+1, η' mass & η- η' mixing angle

In this year, Qi Liu published the first Nf=2+1 η' mass and η-η' mixing angle using chiral quarks. For Nf =2, Koichi Hashimoto carried out η_2 spectrum.

Wall source/sink at every time slice on 150 or 300 16^3 x 32 lattices (Recycled propagators of ΔI=1/2 K → ππ) M_{PS} are 421, 561, 672 MeV with the low eigenmode projection speed up (Ran Zhou, Eigo Shintani's talk).

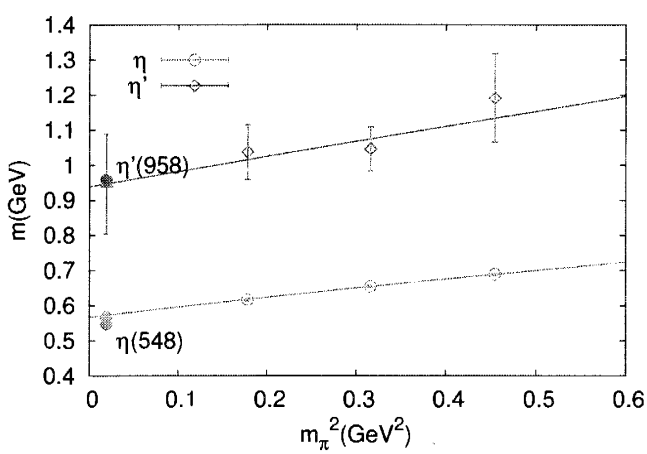
2x2 propagator made of the five co
CII, Css, DII, DIs, Dss.

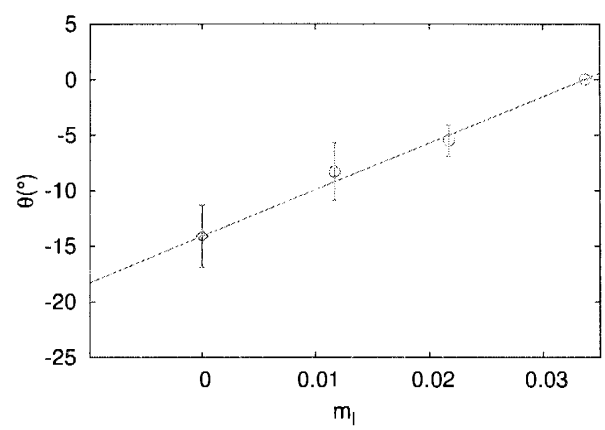




Mixing between the SU(3) octet O_8 and the singlet O_1 PS operators are solved by diagonalizing 2x2 propagators. Transformation matrix A has the information of the mixing angle between O_8 and O_1

$$\begin{pmatrix} C_{88} & C_{81} \\ C_{18} & C_{11} \end{pmatrix} \sim A^{-1} \begin{pmatrix} e^{-m_\eta t} & \\ & e^{-m_{\eta'} t} \end{pmatrix} A, \quad A = \begin{pmatrix} Z_8^{\frac{1}{2}} \cos(\theta) & -Z_1^{\frac{1}{2}} \sin(\theta) \\ Z_8^{\frac{1}{2}} \sin(\theta) & Z_1^{\frac{1}{2}} \cos(\theta) \end{pmatrix}$$

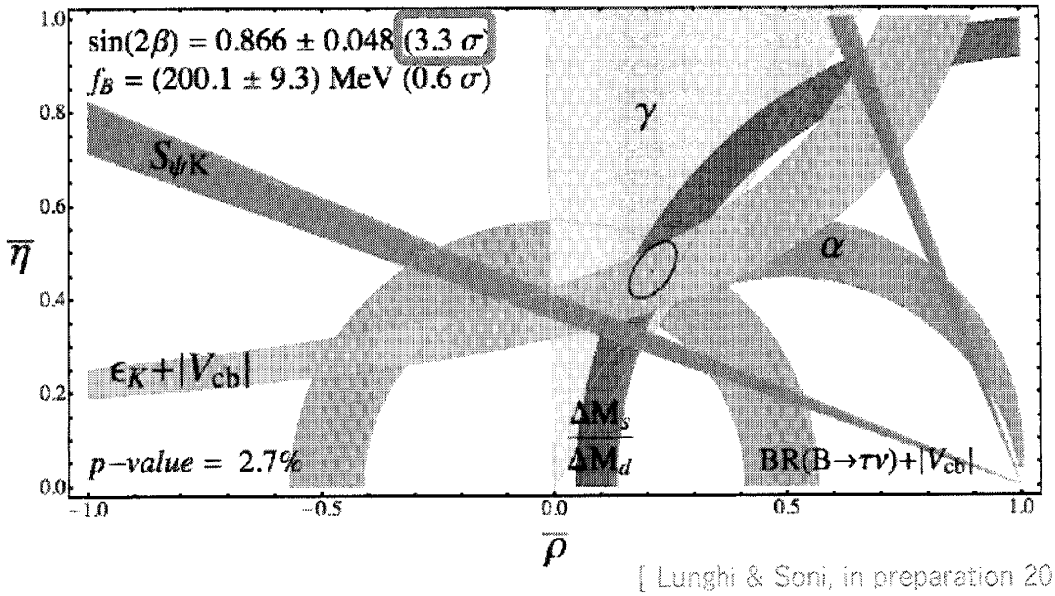




M_η = 573(6) MeV, $M_{\eta'}$=947(42) MeV, θ = - 14.1(2.8) degrees.
[to appear in Phys. Rev. Lett.]

CKM & Flavor Physics

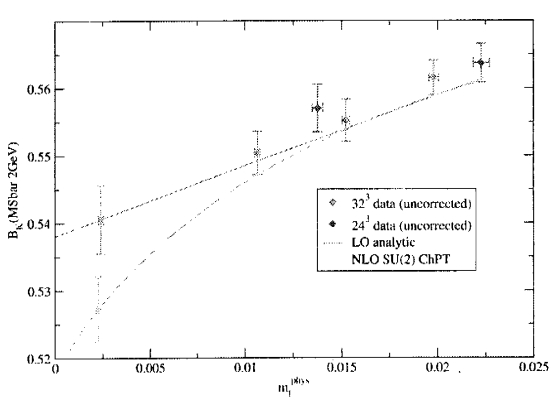
Lattice calculation for EW matrix elements,
B_K, B_{Bd}, B_{Bs}, f_B, f_{Bs}, semi-leptonic form-factors used in conjunction with experimental information on (indirect) CP violation in $K_L \to \pi\pi$, B, B_s mixing etc allow us unique tests of the CKM-paradigm of CP violation.

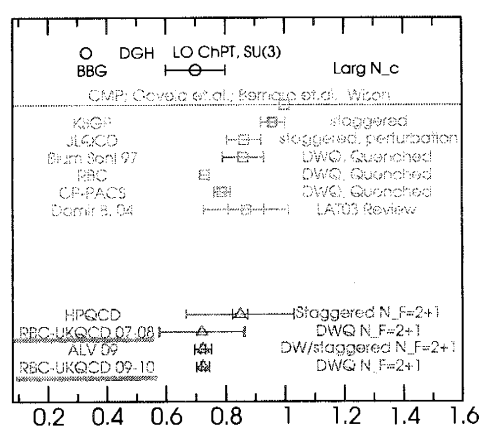


[Lunghi & Soni, in preparation 2010]

Continuum limit of B_K

[in preparation RBC / UQCD]





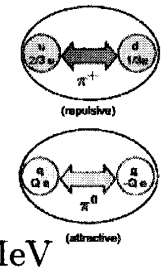
Error is significantly decreased from previous publication

Continuum limit B_K

κ_ε, V_cb, and B physics needs to be improved [Y. Aoki's talk]

QCD+QED simulation

[R. Zhou, S. Uno, T. Blum, T. Doi, M. Hayakawa. TI, N. Yamada, to appear in PRD]



Up down quark has different electric charge and masses
→ Breaking of isospin symmetry

Isospin breaking effects are accurately measured experimentally

$$\Delta m_\pi = m_{\pi^\pm} - m_{\pi^0} = 4.5936(5)\mathrm{MeV}, \quad m_N - m_P = 1.2933317(5)\mathrm{MeV}$$

Quark masses. (Strong CP problem)
[MILC 09 mu/md = 0.42(0)(1)(4)]

Compute Pion/Kaon using Nf=2+1 DWF QCD + QED

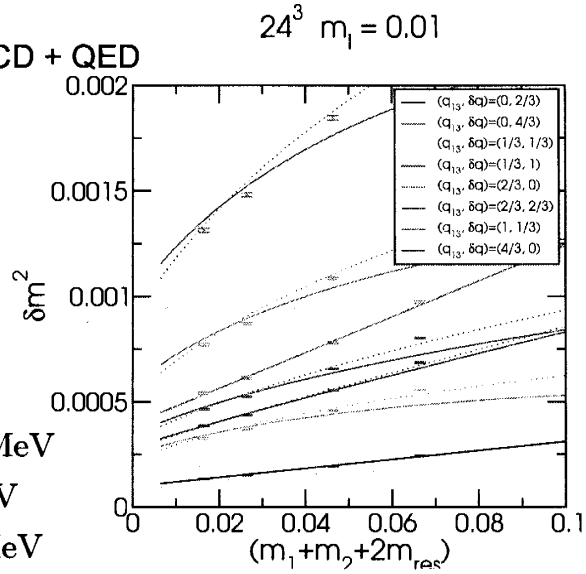
Requiring m_q < 40 MeV (70MeV), 48 (120) partially quenched data points for PS meson survive

Fit to chiral perturbation theory with EM (SU(3)+EM and SU(2)+Kaon+EM) to extract quark masses.

Chiral symmetry is essential to define quark massless points.

Inputs (no neutral pion)

$$M_{\mathrm{PS}}(m_u, 2/3, m_d, -1/3) = 139.57018(35)\mathrm{MeV}$$
$$M_{\mathrm{PS}}(m_u, 2/3, m_s, -1/3) = 493.673(14)\mathrm{MeV}$$
$$M_{\mathrm{PS}}(m_d, -1/3, m_s, -1/3) = 493.673(14)\mathrm{MeV}$$



Quark mass results

MS at 2 GeV, using NPR RI-SMOMγ

m_1, m_3 ≦ 40 MeV or M_{PS} ≦ 250 MeV

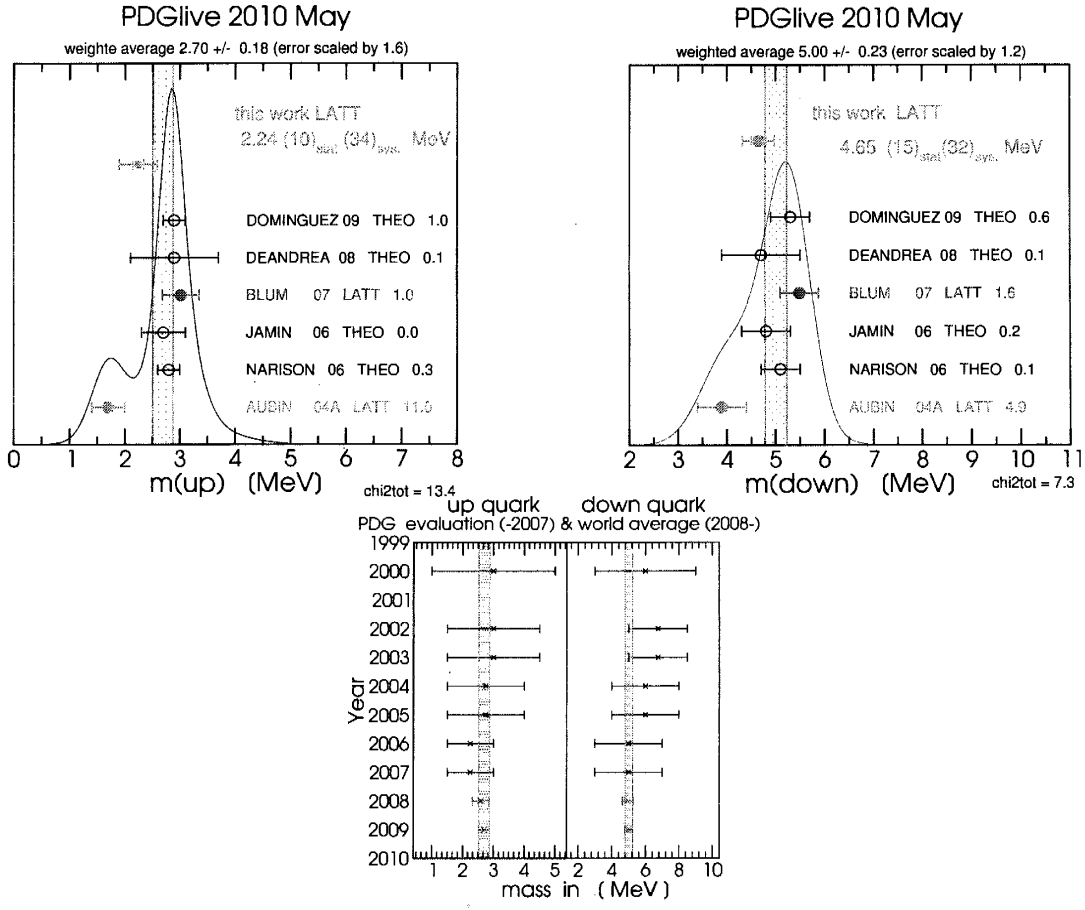
a^{-1} = 1.73 GeV, two volumes $(1.9\ \mathrm{fm})^3$ and $(2.7\ \mathrm{fm})^3$

SU(3) or SU(2) +Kaon+EM ChPT in infinite or finite volume.

Uncertainties in QED LEC have small effect to quark mass determinations.

	value (stat. error)	fit	FV	lat. discret.	QED quench.	m_s error	renorm of m
m_u	2.24(10)	+4.02	+13.50	4	2	-	2.8
m_d	4.65(15)	+3.55	-2.48	4	2	-	2.8
m_s	97.6(2.9)	+0.23	+0.07	4	2	2	2.8
$m_d - m_u$	2.411(65)	+7.77	-17.35	4	2	-	2.8
m_{ud}	3.44(12)	+2.75	+2.71	4	2	-	2.8
m_u/m_d	0.4818(96)	+5.45	+16.40	4	-		-
m_s/m_{ud}	28.31(29)	+2.91	-2.56	4	2	2	-

Quark mass results from lattice QED+QCD



Origins of Isospin breakings

Pion mass splitting, by neglect disconnected loop :

$\Delta M|_{QED} = 4.50\ (23)$ MeV

4.5936(5) MeV [expt.]

(m_u-m_d) effects may be small, consistent with phenomenological predictions, 0.17(3) or 0.32(20) MeV.

Kaon mass splitting: (breaking of Dashen's theorem)

$$\Delta M|_{\text{q. mass}} = -5.840(96)\text{MeV}$$
$$\Delta M|_{\text{QED}} = 1.87(10)\ \text{MeV}$$

$$M_{K^\pm} - M_{K^0} = -3.937(29)\text{MeV}$$

Proton / Neutron mass splitting :

$M_N - M_P|_{QED} = -0.383(68)$ MeV

$M_N - M_P|_{qmass} = 2.51(14)$ MeV

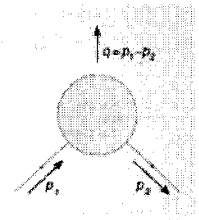
$\rightarrow M_N - M_P|_{pred} = 2.13(16)(70)$ MeV

1.2933321(4) MeV [expt]

SMOM Renormalization Schemes

[09 C. Sturm, Y. Aoki, N. Christ, TI, C. Sachrajda, A. Soni]
[10 L. Almeida, C. Sturm]

Match the normalization of operator on lattice and in continuum theory (MS) via RI/SMOM schemes



$(q^2 = p_1^2 = p_2^2)$

We find symmetric momentum (SMOM) configuration is useful to reduce one of the dominant systematic errors due to IR effects.

Quark mass renormalization error

~10% (MOM) → ~ 5% (SMOM) → ~ 2% (SMOM 2loop).

Z(BK) is calculated using 4+1 RI-(S)MOM schemes.

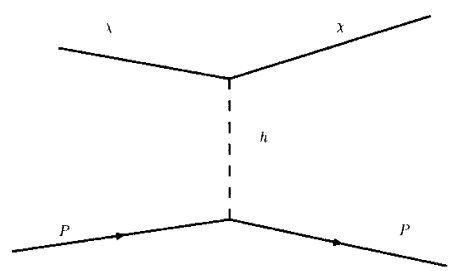
$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 2.31\mathrm{GeV}) = 0.964(25)[2.6\%]$$

Christoph Lehner & Christian Sturm carried out Δs = 1 EW four quark operators' matching between MS and RI/SMOM schemes.
Q_i' i=1,2,..., 7.

Strangeness in Nucleon [C. Jung lat10]

Scalar coupling of Nucleon

$$\sigma_{\pi N} \equiv m_{ud}(\langle N|\overline{u}u + \overline{d}d|N\rangle - \langle 0|\overline{u}u + \overline{d}d|0\rangle),$$
$$\sigma_{KN} \equiv m_s(\langle N|\overline{s}s|N\rangle - \langle 0|\overline{s}s|0\rangle)$$



sea quark mass dependece of Nucleon mass

$$\sigma_{KN} = m_s \frac{dm_N}{dm_s}$$

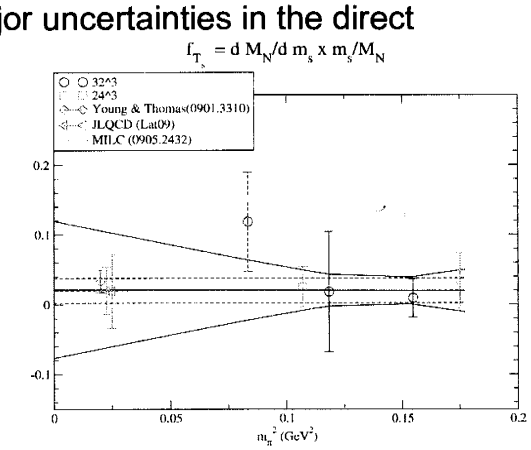
← Strange mass reweighting

(Heavy SUSY) Higgs coupling to proton is a major uncertainties in the direct search for the dark matter and WIMP.

$$\lambda_{H_{pp}} = \frac{m_P}{250\mathrm{GeV}}\left[\frac{2}{27} + \frac{25}{27} f_{T_s}\right]\tan\beta + \cdots$$

$$f_{T_s} = \frac{\sigma_{KN}}{m_N} = \frac{dm_N}{dm_s} \times \frac{m_s}{m_N}$$

F_{Ts} ~ 0.019(17) [linear fit]



QCDCQ softwares, Algorithm developments & External computational resources

CPS is ported for PC cluster (RICC, USQCD machines)
Dirac DP 57 % of peak using SSE.

CPS is being ported for QCDCQ
Dirac DP ~60 %, inverter works on multi node [P. Boyle]
RHMC code [C. Jung]

Improving DWF solver using eigen mode calculated by Lanczos.
[E. Shintani's talk , R. Zhou]

Inexact deflation & eig-CG [Q. Liu]

Force gradient integrator [H. Yin, J-Z. Lin]

4D effective DWF

Proposals for external computers :

About a factor of 8 larger proposals listed in the next page.
2007 → 2010 (USQCD , RIKEN Cluster)

Computational resources

QCDOC (DOE + RBRC) 2005-present 10 + 10 TFLOPS peak

2005-2007: 13 TFLOPS (peak) year 1 or 2 proposals to USQCD
Nf=2, 2+1 QCD vacuum, WME, B_K, EM, ...

2008: 80 TFLOPS (peak) year 2 proposals
QCD vacuum + pi,K INCITE ALCF 180 M BG/P core hours (70 TFLOPS year)

2009: 50 TFLOPS (peak) year 4 proposals
QCD vacuum + pi, K INCITE ALCF 78 M BG/P core hours (30+3 TFLOPS year)
Static-B, CPV 10 M QCD node hours (0.93 TFLOPS year)
Relativistic-B 2.6 M 6n-node hours (5.9 TFLOPS year)

2010: 97 TFLOPS (peak) year 7 proposals
QCD vacuum + pi, K INCITE ALCF 75 M BG/P core hour (30+2 TFLOPS year)
EM, Nucleon, Static-B RICC(RIKEN/Japan) 9.15 M RICC core hours
(12 TFLOPS year)
EM, Nucleon RICC 17.4 M RICC core hours (under review) (42 TFLOPS year)

Relativistic-B 4 M Jpsi core hours (4 TFLOPS year)

EM 7 M Jpsi core hours (7 TFLOPS year)

QCDCQ (QCD with Chiral Quarks) status

Prototype of IBM BlueGene/Q

Designed and developed by Columbia Univ, Edinburgh, IBM Watson, RIKEN-BNL
(synergy b/w national lab, universities and industry)

200 TFLOPS peak / rack , ~2.5 racks @ BNL
(QCDOC 0.8 TFLOPS / rack, 10 TFLOPS total)

75 K Watts / rack

Dirac operator efficiency on the first chip ~ 60 % peak

First 512 node (100 TFLOPS peak) operational in 2010 fall

Full machine will be available in June 2011

4 rack UK machine (800 TFLOPS peak) now funded

Summary

* Lattice QCD is becoming a practical tool for non-perturbative calculation from first principles in particle physics.
(bridge between experiment and theory)
* DWF, preserves chiral symmetry, is optimal for fundamental constants (Quark masses, EM spectrum, etc.) and (Weak) Matrix elements (B_K, K_{l3}, $K\to\pi\pi\pi$, f_B, B_B, etc). [Y. Aoki's, T. Blum & N. Christ's talks] , which are necessary ingredients for precise checks of the Standard Model of particle physics and beyond.

* Further calculations using DWF Nf=2+1 are being carried out thanks to many developments in theory, hardware, and algorithms.

* Current bottleneck of DWF is the unphysically heavy simulation quark masses that cause systematic error from chiral extrapolation

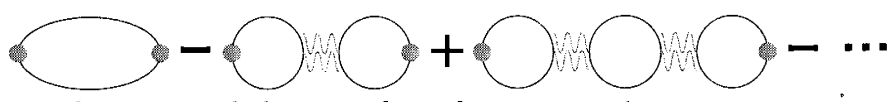
→ On physical point simulation using
Iwasaki + DSDR QCD ensemble [T. Blum's talk]

→ New hardwares QCDCQ (BG/Q), ...

Appendix

η' in dynamical simulation

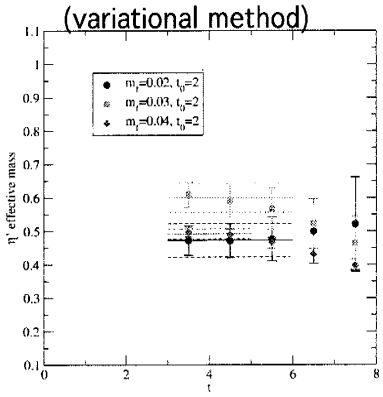
Flavor singlet meson has contributions both from connected quark loops and disconnected quark loops:

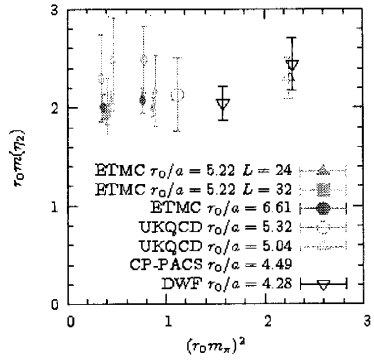
$C(x) - N_f D(x) =$ 

the dynamical quark loop is essential to make η' propagator as an unitary particle $\propto e^{-m_{\eta'} t}$

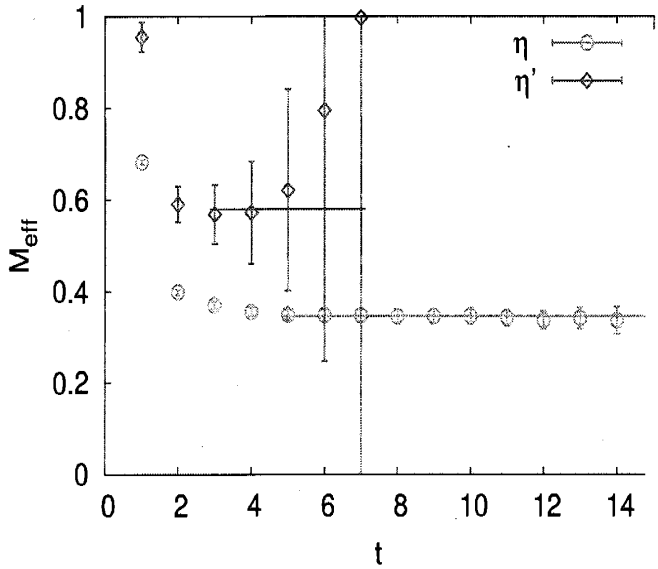
For Nf =2, Koichi Hashimoto carried out η_2 spectrum calculation using Gauge invariant Gaussian smearing & stochastic estimator (complex Z_2 noise) on 500-1,000 configurations.

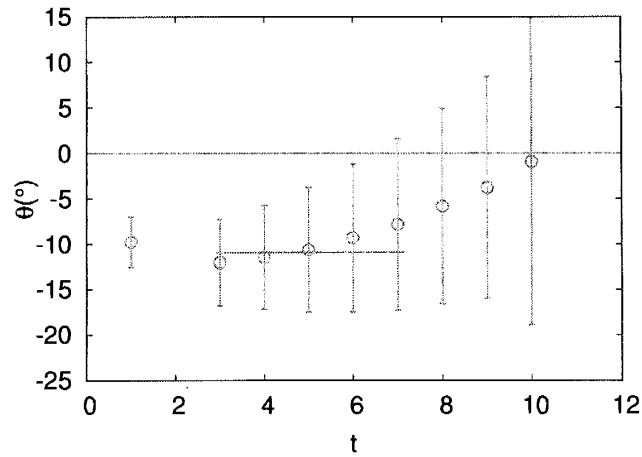
(variational method)



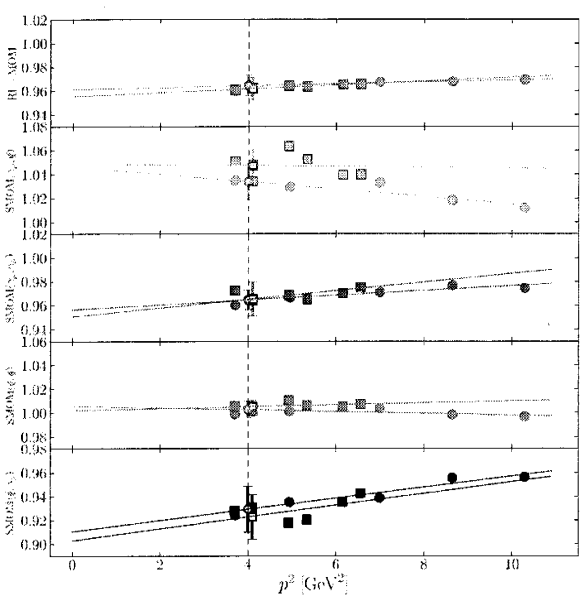


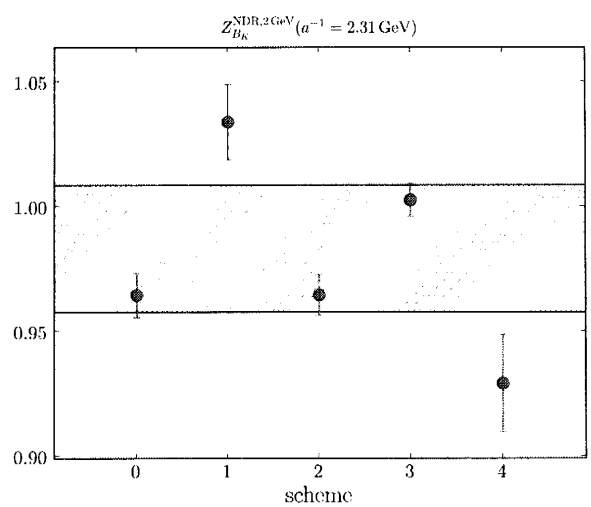
Effective masses and angle of η-η'





Z(BK) systematic errors





$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 2.31\mathrm{GeV}) = 0.964(25)[2.6\%]$$

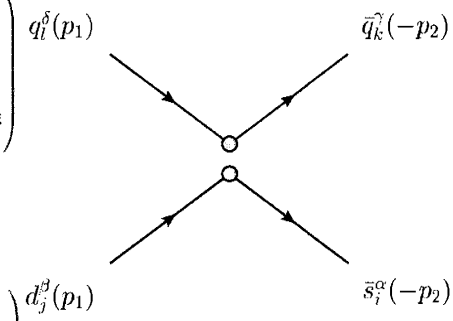
$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 1.73\mathrm{GeV}) = 0.936(30)$$

SMOM to Msbar matching for Δs = 1 EW operators

RI-SMOM(γ_μ, γ_μ)

$$p_1^2 = p_2^2 = (p_1 - p_2)^2$$

$$R = \begin{pmatrix} 0.212-0.734\xi & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.106-0.367\xi & 0.318+1.10\xi & 0 & 0 & 0 & 0 \\ 0 & 0.318+1.10\xi & -0.106-0.367\xi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0432-0.238\xi & -0.130+0.714\xi & 0 & 0 \\ 0 & 0 & 0 & -1.61+0.214\xi & 4.50+1.26\xi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0432-0.238\xi & -0.130+0.714\xi \\ 0 & 0 & 0 & 0 & 0 & -1.61+0.214\xi & 4.50+1.26\xi \end{pmatrix}$$



RI-SMOM$(\not{q}, \not{q})$

$$R = \begin{pmatrix} -0.455+0.286\xi & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.63+1.47\xi & 4.92+4.19\xi & 0 & 0 & 0 & 0 \\ 0 & -4.28-1.99\xi & -8.17-6.79\xi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0432-0.238\xi & -0.130+0.714\xi & 0 & 0 \\ 0 & 0 & 0 & -0.614+0.886\xi & 1.56-0.754\xi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0432-0.238\xi & -0.130+0.714\xi \\ 0 & 0 & 0 & 0 & 0 & -0.614+0.886\xi & 1.56-0.754\xi \end{pmatrix}$$

Nucleon structure from 2+1 flavor domain wall QCD at a nearly physical pion mass

Shigemi Ohta [*†‡] for RBC and UKQCD Collaborations

Talk at Tropical QCD 2010, Cairns, QLD, September 30, 2010

RBC and UKQCD collaborations are generating new dynamical DWF ensembles:

- Iwasaki + dislocation suppressing determinant ratio (DSDR) gauge action, $\beta = 1.75$, and
- Domain-Wall Fermions (DWF) quarks, $L_s = 32$ and $M_5 = 1.8$,
- $a^{-1} \sim 1.368(7)$ GeV, $m_{\rm res} \sim 0.002$: $m_{\rm strange}a = 0.045$, $m_{\rm ud}a = 0.0042$ and 0.001.

Much closer to physical pion mass than the previous set of Iwasaki+DWF ensembles:

- $m_\pi \sim 180$ and 250 MeV, with large volume, $(\sim 4.6{\rm fm})^3$ $(32^3 \times 64)$.

Here we report the current status of our nucleon calculations, by

- Meifeng Liu, Yasumichi Aoki, Tom Blum, Chris Dawson, Taku Izubuchi, Chulwoo Jung, SO, Shoichi Sasaki, Takeshi Yamazaki, James Zanotti ...

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‡RIKEN BNL Research Center, Upton, NY 11973, USA

Nucleon form factors, measured in elastic scatterings or β decay or muon capture:

$$\langle p|V_\mu^+(x)|n\rangle = \bar{u}_p\left[\gamma_\mu F_V(q^2) + \frac{\sigma_{\mu\lambda}q_\lambda}{2m_N}F_T(q^2)\right]u_n e^{iq\cdot x},$$

$$\langle p|A_\mu^+(x)|n\rangle = \bar{u}_p\left[\gamma_\mu\gamma_5 F_A(q^2) + iq_\mu\gamma_5 F_P(q^2)\right]u_n e^{iq\cdot x}.$$

$$F_V = F_1, F_T = F_2; G_E(q^2) = F_1 - \frac{q^2}{4m_N^2}F_2, G_M = F_1 + F_2.$$

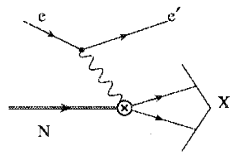
Related to mean-squared charge radius, magnetic moment, $g_V = F_V(0) = G_{\rm Fermi}\cos\theta_{\rm Cabibbo}$, $g_A = F_A(0) = 1.2694(28)g_V$, Goldberger-Treiman relation, $m_N g_A \propto f_\pi g_{\pi NN}$, ... determine much of nuclear physics.

On the lattice, with appropriate nucleon operator, for example, $N = \epsilon_{abc}(u_a^T C\gamma_5 d_b)u_c$, ratio of two- and three-point correlators such as $\dfrac{C_{\rm 3pt}^{\Gamma,O}(t_{\rm sink},t)}{C_{\rm 2pt}(t_{\rm sink})}$ with

$$C_{\rm 2pt}(t_{\rm sink}) = \sum_{\alpha,\beta}\left(\frac{1+\gamma_t}{2}\right)_{\alpha\beta}\langle N_\beta(t_{\rm sink})\bar{N}_\alpha(0)\rangle,$$

$$C_{\rm 3pt}^{\Gamma,O}(t_{\rm sink},t) = \sum_{\alpha,\beta}\Gamma_{\alpha\beta}\langle N_\beta(t_{\rm sink})O(t)\bar{N}_\alpha(0)\rangle,$$

give a plateau in t for a lattice bare value $\langle O\rangle$ for the relevant observable, with appropriate spin ($\Gamma = (1+\gamma_t)/2$ or $(1+\gamma_t)i\gamma_5\gamma_k/2$) or momentum-transfer (if any) projections.

Deep inelastic scatterings 

$: \left|\frac{\mathcal{A}}{4\pi}\right|^2 = \frac{\alpha^2}{Q^4} l^{\mu\nu} W_{\mu\nu},\ W^{\mu\nu} = W^{[\mu\nu]} + W^{\{\mu\nu\}}$

- unpolarized: $W^{\{\mu\nu\}}(x,Q^2) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_1(x,Q^2) + \left(P^\mu - \frac{\nu}{q^2} q^\mu\right)\left(P^\nu - \frac{\nu}{q^2} q^\nu\right) \frac{F_2(x,Q^2)}{\nu},$
- polarized: $W^{[\mu\nu]}(x,Q^2) = i\epsilon^{\mu\nu\rho\sigma} q_\rho \left(\frac{S_\sigma}{\nu}(g_1(x,Q^2) + g_2(x,Q^2)) - \frac{q\cdot S P_\sigma}{\nu^2} g_2(x,Q^2)\right),$

with $\nu = q\cdot P$, $S^2 = -M^2$, $x = Q^2/2\nu$.

Moments of the structure functions are accessible on the lattice:

$$
\begin{aligned}
2\int_0^1 dx x^{n-1} F_1(x,Q^2) &= \sum_{q=u,d} c_{1,n}^{(q)}(\mu^2/Q^2, g(\mu))\, \langle x^n\rangle_q(\mu) + \mathcal{O}(1/Q^2),\\
\int_0^1 dx x^{n-2} F_2(x,Q^2) &= \sum_{f=u,d} c_{2,n}^{(q)}(\mu^2/Q^2, g(\mu))\, \langle x^n\rangle_q(\mu) + \mathcal{O}(1/Q^2),\\
2\int_0^1 dx x^{n} g_1(x,Q^2) &= \sum_{q=u,d} e_{1,n}^{(q)}(\mu^2/Q^2, g(\mu))\, \langle x^n\rangle_{\Delta q}(\mu) + \mathcal{O}(1/Q^2),\\
2\int_0^1 dx x^{n} g_2(x,Q^2) &= \frac{1}{2}\frac{n}{n+1} \sum_{q=u,d} [e_{2,n}^q(\mu^2/Q^2, g(\mu))\, d_n^q(\mu) - 2e_{1,n}^q(\mu^2/Q^2, g(\mu))\, \langle x^n\rangle_{\Delta q}(\mu)] + \mathcal{O}(1/Q^2)
\end{aligned}
$$

- c_1, c_2, e_1, and e_2 are the Wilson coefficients (perturbative),
- $\langle x^n\rangle_q(\mu)$, $\langle x^n\rangle_{\Delta q}(\mu)$ and $d_n(\mu)$ are forward nucleon matrix elements of certain local operators,
- so is $\langle 1\rangle_{\delta q}(\mu) = \langle P,S|\psi\bar{\psi}\gamma_5\sigma_{\mu\nu}\psi|P,S\rangle$ which may be measured by polarized Drell-Yan and RHIC Spin.

Unpolarized (F_1/F_2): on the lattice we can measure: $\langle x\rangle_q$, $\langle x^2\rangle_q$ and $\langle x^3\rangle_q$.

$$\frac{1}{2}\sum_s \langle P,S|\mathcal{O}^q_{\{\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = 2\langle x^{n-1}\rangle_q(\mu)[P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{trace})]$$

$$\mathcal{O}^q_{\mu_1\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n-1} \gamma_{\mu_1} \overleftrightarrow{D}_{\mu_2}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{trace})\right] q$$

Polarized (g_1/g_2): on the lattice we can measure: $\langle 1\rangle_{\Delta q}$ (g_A), $\langle x\rangle_{\Delta q}$, $\langle x^2\rangle_{\Delta q}$, d_1, d_2, $\langle 1\rangle_{\delta q}$ and $\langle x\rangle_{\delta q}$.

$$-\langle P,S|\mathcal{O}^{5q}_{\{\sigma\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{2}{n+1}\langle x^n\rangle_{\Delta q}(\mu)[S_\sigma P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{5q}_{\sigma\mu_1\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n} \gamma_5\gamma_\sigma \overleftrightarrow{D}_{\mu_1}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})\right] q$$

$$\langle P,S|\mathcal{O}^{[5]q}_{[\sigma\{\mu_1]\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{1}{n+1} d_n^q(\mu)[(S_\sigma P_{\mu_1} - S_{\mu_1}P_\sigma)P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{[5]q}_{[\sigma\mu_1]\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n} \gamma_5\gamma_{[\sigma} \overleftrightarrow{D}_{\mu_1]}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})\right] q$$

and transversity (h_1):

$$\langle P,S|\mathcal{O}^{\sigma q}_{\rho\nu\{\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{2}{m_N}\langle x^n\rangle_{\delta q}[(S_\rho P_\nu - S_\nu P_\rho)P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{\sigma q}_{\rho\nu\mu_1\mu_2\cdots\mu_n} = \bar{q}[\left(\frac{i}{2}\right)^{n} \gamma_5\sigma_{\rho\nu} \overleftrightarrow{D}_{\mu_1}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})]q$$

Higher moment operators mix with lower dimensional ones: Only $\langle x\rangle_q$, $\langle 1\rangle_{\Delta q}$, $\langle x\rangle_{\Delta q}$, d_1, and $\langle 1\rangle_{\delta q}$ can be measured with $\vec{P} = 0$.

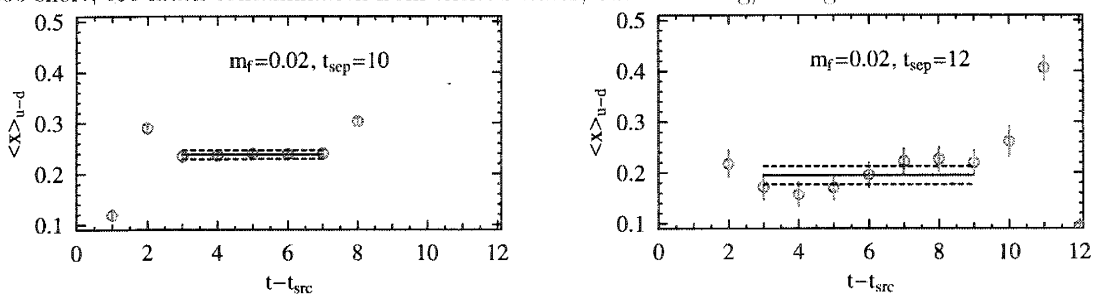
Previous RBC and RBC+UKQCD calculations addressed two important sources of systematics:

- Time separation between nucleon source and sink.
- Spatial volume.

And though not explicitly addressed yet, a better understanding of quark mass dependence is necessary.

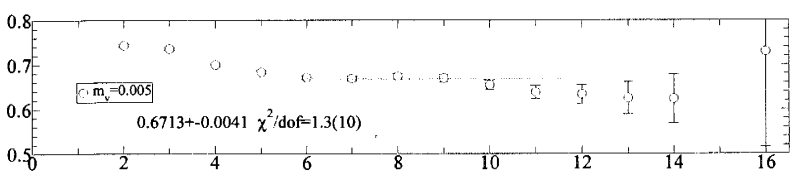
Source/sink time separation:

- If too short, too much contamination from excited states, but if too long, the signal is lost.

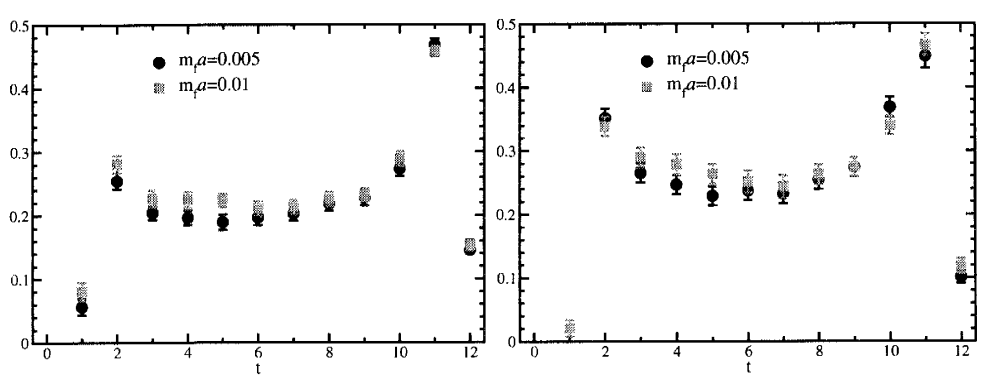


- In an earlier RBC 2-flavor DWF study at $a^{-1} \sim 1.7$ GeV, separation of 10 or 1.1 fm appeared too short.

In the RBC+UKQCD (2+1)-flavor study we choose separation 12 or 13 : ~1.4 fm:
Mass signal: $m_f = 0.005$

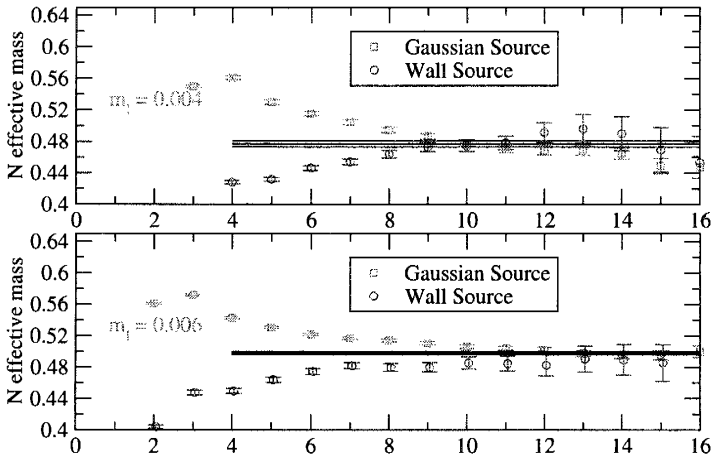


Bare three-point functions: $\langle x \rangle_{u-d}$ (left) and $\langle x \rangle_{\Delta u - \Delta d}$ (right), for $m_f = 0.005$ (red +) and 0.01 (blue ×):



In this study we like to do at least as good, hopefully better: separation of 10 lattice units or longer.

On the other hand, with RBC+UKQCD 2.2-GeV (2+1)-flavor dynamical DWF ensemble:



2-state fits suggest excited-state survives $t_{sink} \geq 9$.

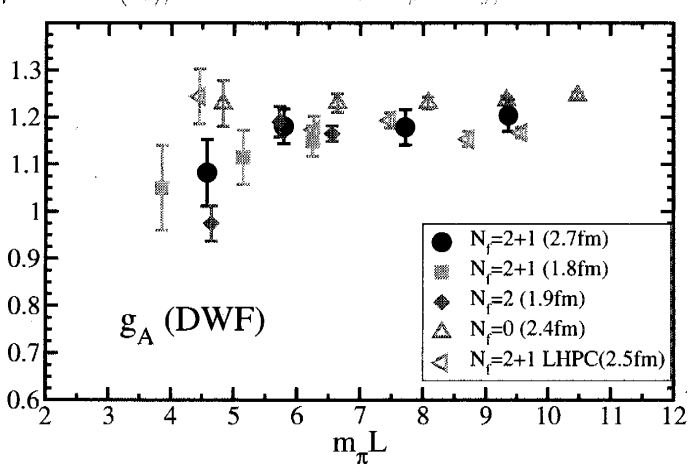
LHP analysis of vector form factors with $t_{sep} = 12$ or 1 fm agree with RBC+UKQCD 1.7-GeV results. Vector current is less sensitive: conserved charge cannot tell excited-state contamination, for example.

Can we go shorter, ~1 fm, separation, in spite of our lighter masses?

- Perhaps with better tuned source and sink smearing?
- Would be good as we have to fight growing error, $\sim \exp(-3m_\pi t)$.

Spatial volume. In Lattice 2007 Takeshi Yamazaki reported unexpectedly large finite-size effect:

- in axial charge, $g_A/g_V = 1.2694(28)$, measured in neutron β decay, decides neutron life.



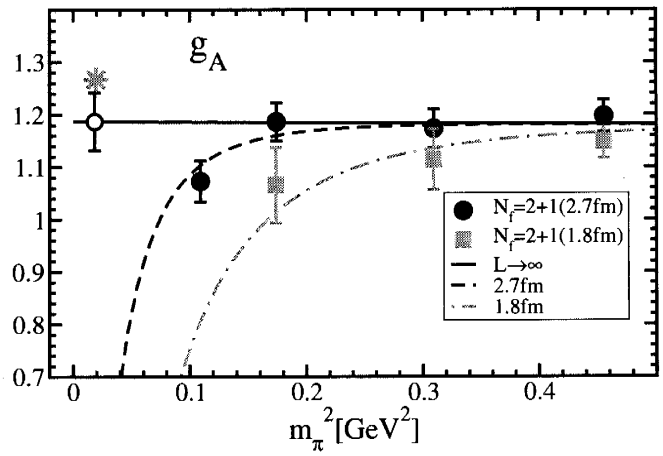
Our DWF on quenched and LHPC DWF on MILC calculations are presented for comparison.

- Heavier quarks: consistent with experiment, no discernible quark-mass dependence.
- Lighter quarks: finite-size sets in as early as $m_\pi L \sim 5$, appear to scale in $m_\pi L$:
  - confirmation of "pion cloud."
  - nucleon structure calculation demands big volumes.

present $(\sim 1.6\text{fm})^3$ volume is a good start.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

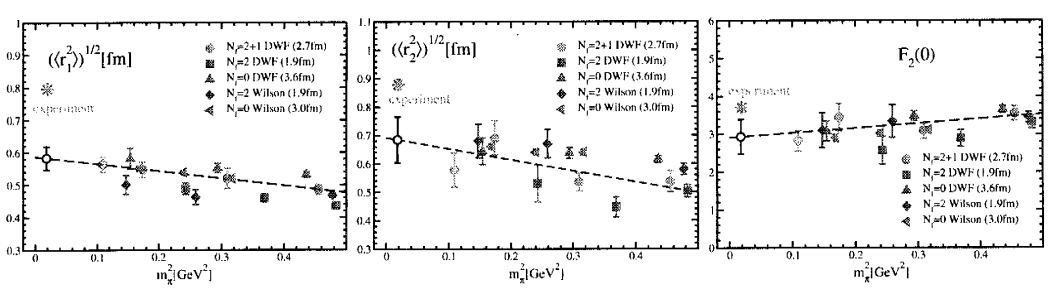
- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,
- chiral extrapolation of g_A/g_V and comparison with experiment β decay, $g_A/g_V = 1.2695(29)$.



- A value $1.20(6)_{\rm stat}(4)_{\rm syst}$ is obtained, the systematics from forms such as x^{-3} and $e^{-x}/\sqrt{x}$, $x = m_\pi L$.
- $m_\pi L$ of 6-8 seems necessary to drive the systematics below 1 %.
- 5 fm for the current lightest mass, or 10 for 140 MeV.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,
- Vector-current form factors: accommodate dipole fit, allow extraction of mean-squared radii.

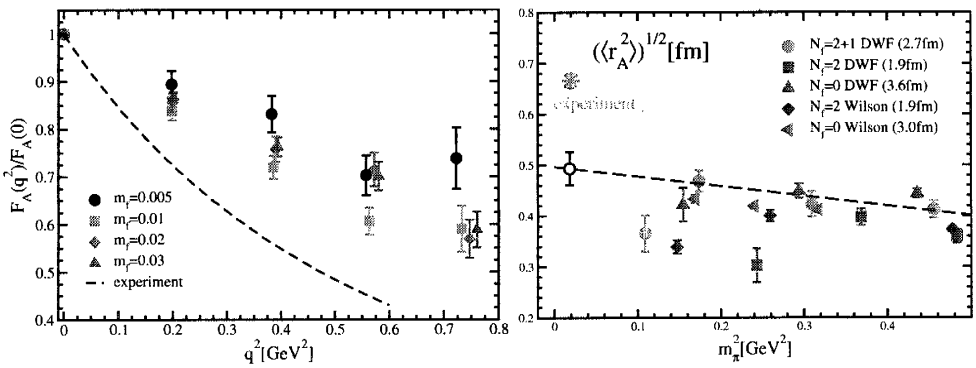


- No singular behavior in m_π^2 seen yet: still too heavy quark mass.
- Anomalous magnetic moment almost consistent with experiment.
- No clear finite-size effect is seen: probably because conserved vector current is too well-behaved.

LHP vector-current calculations on 2.2-GeV RBC/UKQCD ensembles confirm these results.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

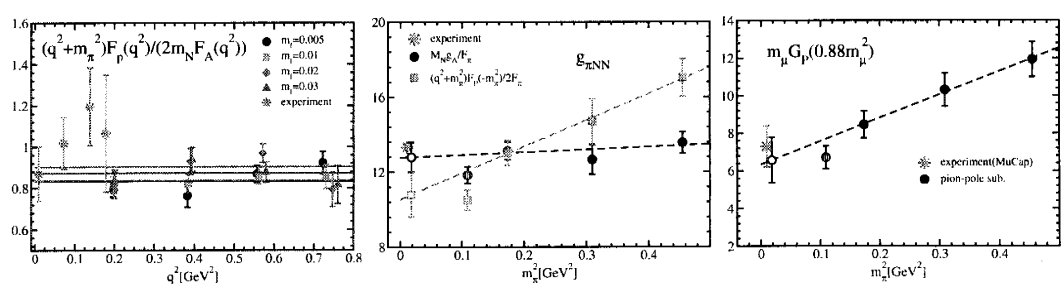
- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,
- Axial-current form factor: note $F_A(0)$ normalization has strong finite-size effect.



- Needs larger volume.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,
- Induced pseudoscalar form factor:

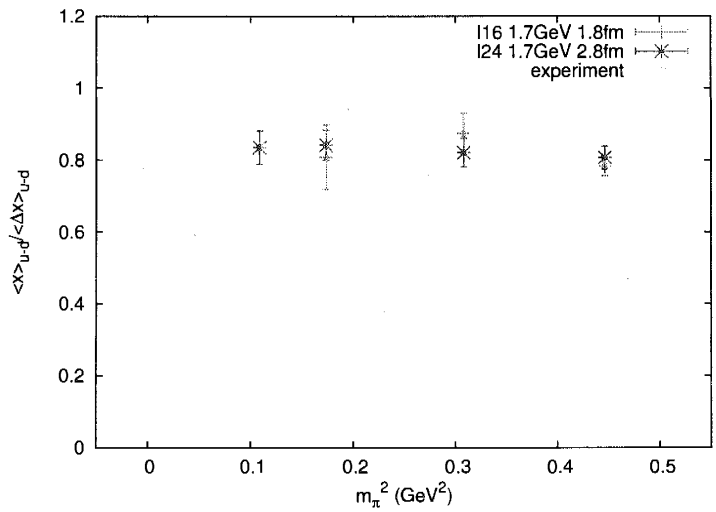


- "Goldberger-Treiman" relation at high momentum transfer?
- $g_{\pi NN}$ from GT and pion pole.
- Muon capture G_P with pion-pole assumption.
- All show finite-size effects at the lightest pion mass.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,

Ratio, $\langle x\rangle_{u-d}/\langle x\rangle_{\Delta u-\Delta d}$, of momentum and helicity fractions (naturally renormalized on the lattice),

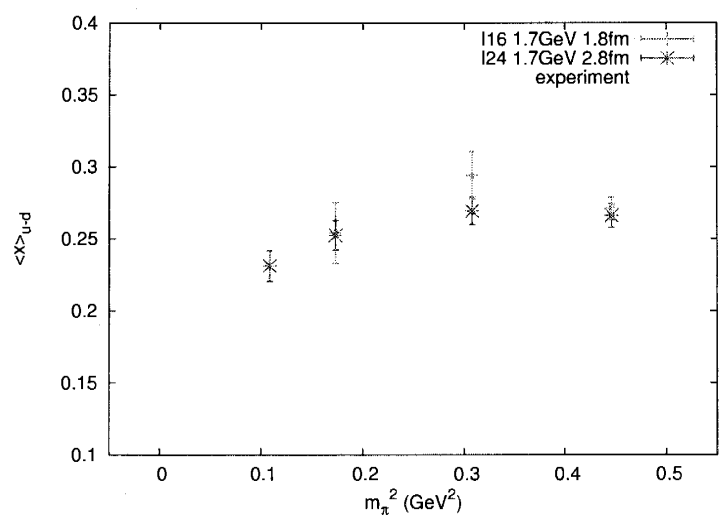


consistent with experiment, no discernible quark-mass dependence.
No finite-size effect seen, in contrast to g_A/g_V which is also naturally renormalized on the lattice.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,

Momentum fraction, $\langle x\rangle_{u-d}$, with NPR, $Z^{\overline{\rm MS}}(2{\rm GeV}) = 1.15(4)$, plotted against m_π^2,

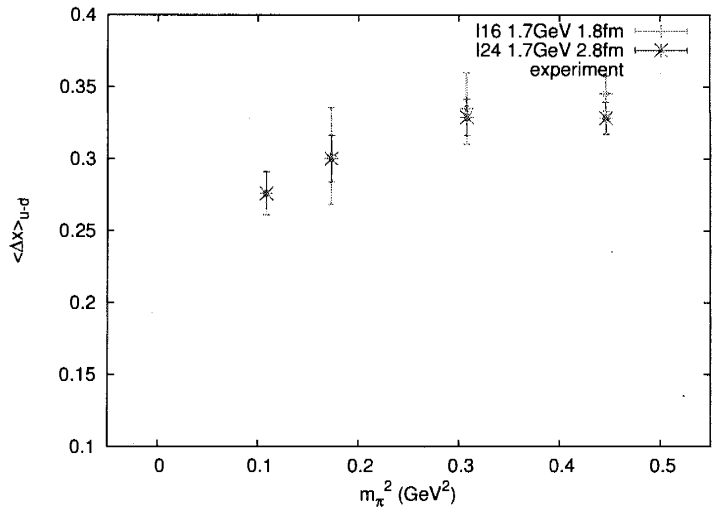


Absolute values have improved, trending to the experimental values, with NPR, $Z^{\overline{\rm MS}}(2{\rm GeV}) = 1.15(4)$.
No finite size effect seen (16^3 (+) and 24^3 ($\times$) results agree): Likely physical light-quark effect.
A better understanding of quark mass dependence is necessary.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,

Helicity fraction, $\langle x \rangle_{\Delta u - \Delta d}$, with NPR, $Z^{\overline{\rm MS}(2{\rm GeV})} = 1.15(3)$, plotted against m_π^2,

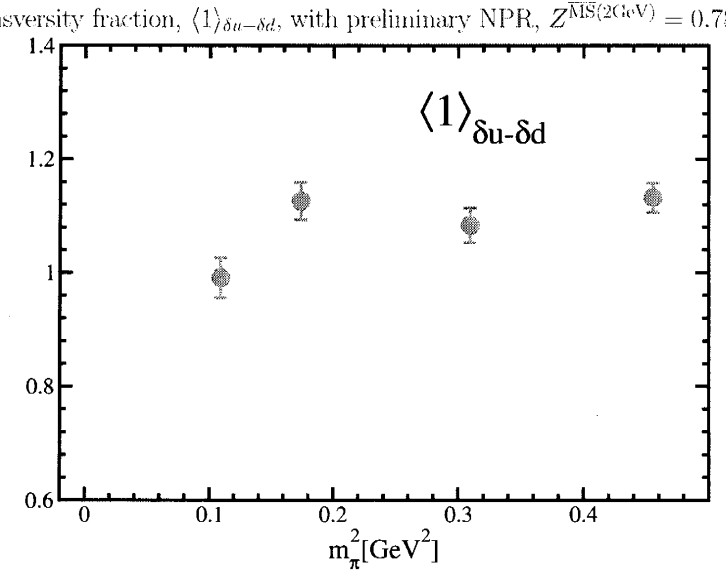


Absolute values have improved, trending to the experimental values, with NPR, $Z^{\overline{\rm MS}}(2{\rm GeV}) = 1.15(3)$.
No finite size effect seen (16^3 (+) and 24^3 (×) results agree): Likely physical light-quark effect.
A better understanding of quark mass dependence is necessary.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,

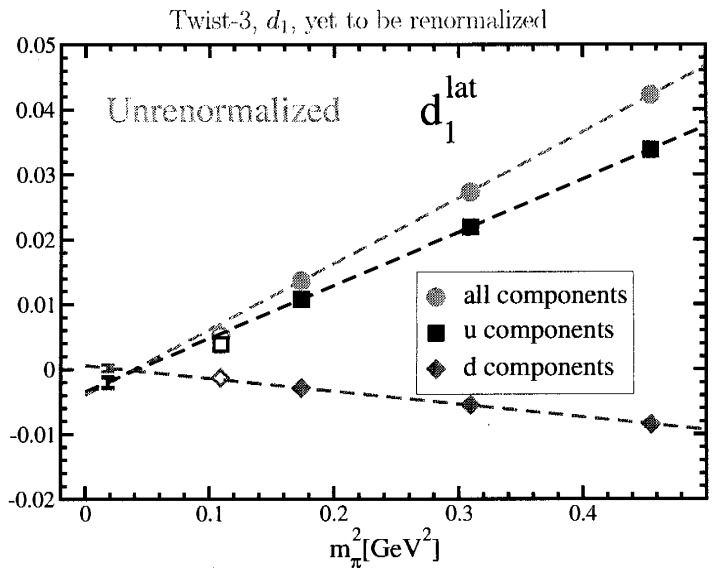
Transversity fraction, $\langle 1 \rangle_{\delta u - \delta d}$, with preliminary NPR, $Z^{\overline{\rm MS}(2{\rm GeV})} = 0.783(3)$,



Likely physical light-quark effect.
A better understanding of quark mass dependence is necessary.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,



Chirally well-behaved, small, and consistent with Wandzura-Wilczek relation.

Given the severe finite-size effect in axial-current form factors, such as g_A, we abandoned nucleon-structure calculations on the finer, 2.2-GeV, Iwasaki+DWF ensembles.

- LHP reports their analyses on our ensembles: encouraging confirmaiton of our vector-current form factors.

RBC and UKQCD collaborations are jointly generating new (2+1)-flavor DWF ensembles

- with Iwasaki and dislocation-suppressing-determinant-ratio (DSDR) gauge action, $\beta = 1.75$,
- and DWF fermion action, $L_s = 32$ and $M_5 = 1.8$, with $m_{\rm strange} = 0.045$, $m_{\rm ud} = 0.0042$ and 0.001,

aiming at lighter mass in a sufficiently large volume: We have reasonable topology distribution while maintaining small residual mass, $m_{\rm res} \sim 0.002$:

- lattice scale from Ω^-: $a^{-1} = 1.368(7)$ GeV,
- $m_\pi = 0.1816(8)$ and 0.1267(8), or ~ 250 and 180 MeV.

$32^3 \times 64$ volume is about 4.6 fm across in space, 9.2 fm in time.

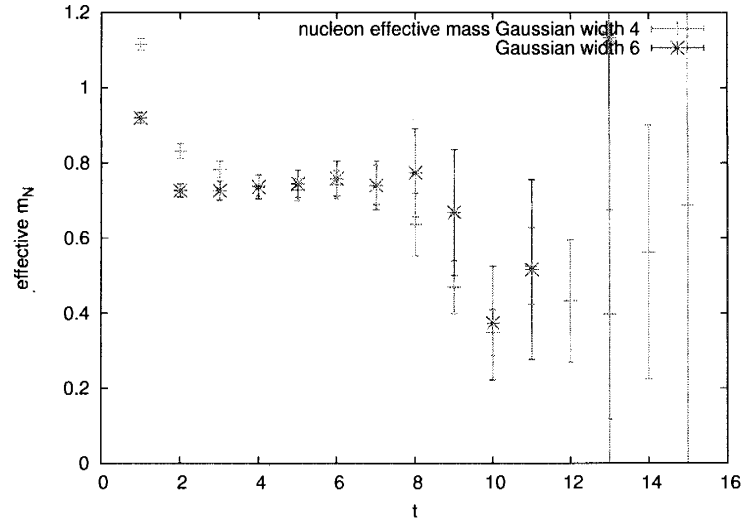
We started nucleon structure calculations using the RICC supercomputing facility at RIKEN, Wako, Japan.

- tuning Gaussian smearing with width 4 and 6,

at this 100-TFlops peak-speed facility.

RBC/UKQCD (2+1)-flavor, ID+DWF dynamical, $a^{-1} = 1.368(7)$ GeV, $m_{\rm strange} = 0.045$,

Nucleon mass signal from the light ($m_{\rm ud} = 0.001$ or $m_\pi = 180$ MeV) ensemble, with ~30 configurations,



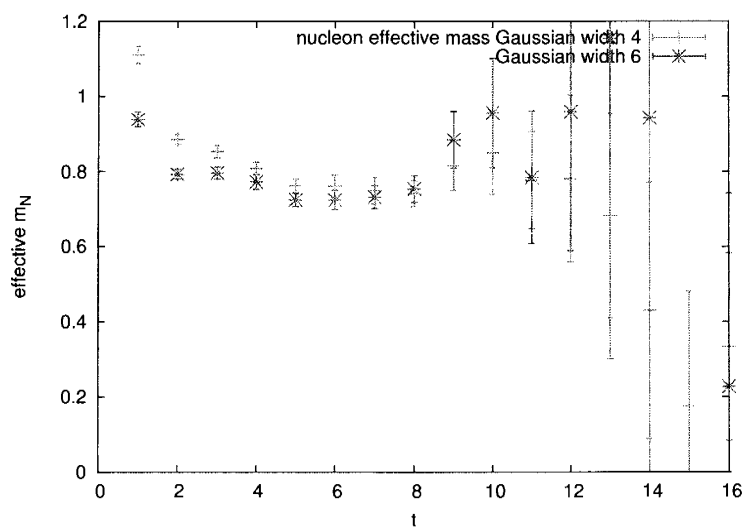
$m_N = 0.721(13)$ or ~ 0.98 GeV,

but probably needs a longer plateau for structure calculation to be free of excited-state contamination,

presently increasing the statistics.

RBC/UKQCD (2+1)-flavor, ID+DWF dynamical, $a^{-1} = 1.368(7)$ GeV, $m_{\rm strange} = 0.045$,

Nucleon mass signal from the heavy ($m_{\rm ud} = 0.0042$ or $m_\pi = 250$ MeV) ensemble, with ~40–50 configurations

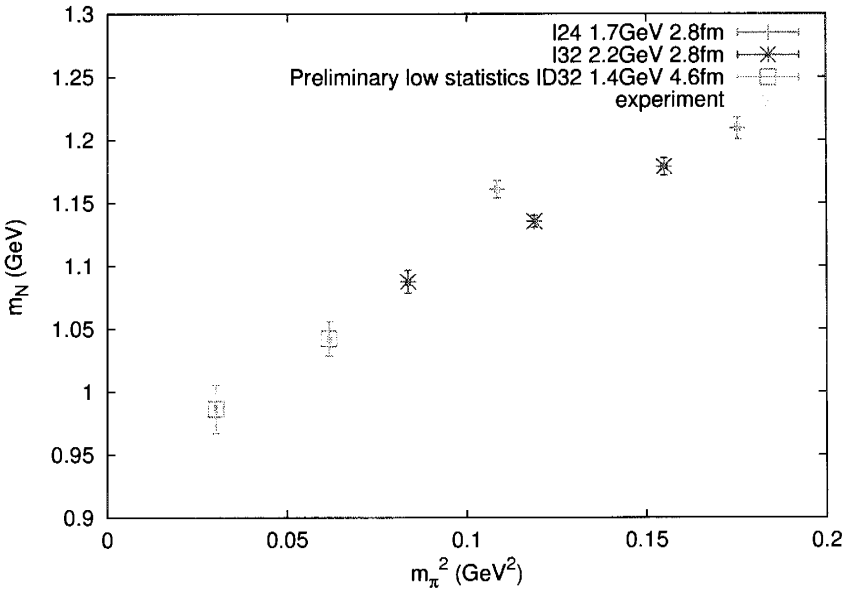


$m_N = 0.763(10)$ or ~ 1.05 GeV,

but needs a better plateau for structure calculation to be free of excited-state contamination,

presently increasing the statistics.

Conclusions: RBC/UKQCD (2+1)-flavor, ID+DWF ensembles are being analyzed for nucleon physics.



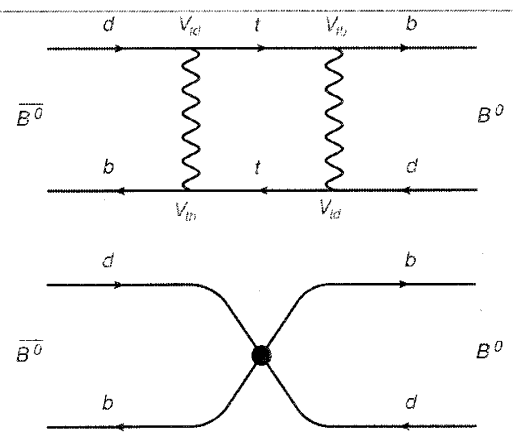
with $a^{-1} = 1.3068(7)$ GeV, $(\sim 4.6\text{fm})^3$ spatial volume.
Closer to physical mass, $m_\pi = 180$ and 250 MeV, $m_N < 1.0$ GeV,
Isovector form factors and structure function moments will be reported in the near future.

Neutral B meson mixing

– towards a precision test of the Standard Model –

Yasumichi Aoki (RBRC)
10/28/2010 @ RBRC SRC meeting

B^0 - anti B^0 mixing



- Induced at 1-loop from Box Diagram
- Effective Hamiltonian at low energy

$$\propto S_0 |V_{td}|^2 [\bar{b}\gamma_\mu(1-\gamma_5)d]^2$$

- mixing matrix elements

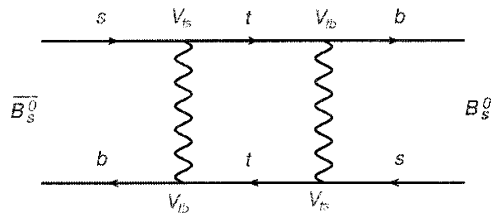
$$\mathcal{M}_d = \langle \overline{B}^0 | [\bar{b}\gamma_\mu(1-\gamma_5)d]^2 | B^0 \rangle$$

- oscillation frequency

$$\Delta m_q = (\text{known factor}) \cdot S_0 |V_{td}|^2 \mathcal{M}_q$$

- precisely known from experiment: Δm_d=0.507(5) ps^{-1} (PDG)
- stringent test for standard model through CKM possible
- Inami-Lim function: $S_0 \sim m_t^2/m_W^2$ enhances for larger mass
- high sensitivity to new physics: could lead to a discovery

B^0_s - anti B^0_s mixing



- Induced at 1-loop from Box Diagram
- Effective Hamiltonian at low energy

$$\propto S_0|V_{ts}|^2[\overline{b}\gamma_\mu(1-\gamma_5)s]^2$$

- mixing matrix elements

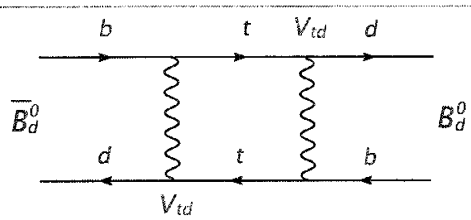
$$\mathcal{M}_s = \langle\overline{B}^0_s|[\overline{b}\gamma_\mu(1-\gamma_5)s]^2|B^0_s\rangle$$

- oscillation frequency

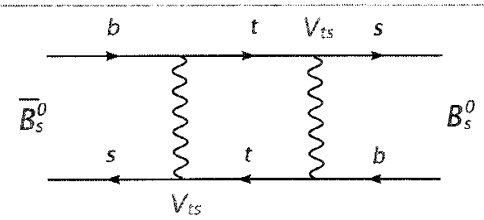
$$\Delta m_s = (\text{known factor}) \cdot S_0|V_{ts}|^2\mathcal{M}_s$$

- precisely known from experiment: Δm_s=17.77(12) ps^{-1} (CDF)
- stringent test for standard model through CKM possible
- Inami-Lim function: $S_0 \sim m_t^2/m_W^2$ enhances for larger mass
- high sensitivity to new physics: could lead to a discovery

SU(3) breaking ratio of B^0 - anti B^0 mixing



Δm_d=0.507(5) ps^{-1} (PDG)



Δm_s=17.77(12) ps^{-1} (CDF)

- $B^0 - \overline{B}^0$ oscillation frequency (q=d, s)

$$\Delta m_q = (\text{known factor}) \cdot |V_{tq}|^2\mathcal{M}_q$$

- $B^0 - \overline{B}^0$ mixing matrix elements

$$\mathcal{M}_q = \langle\overline{B}^0_q|[\overline{b}\gamma_\mu(1-\gamma_5)q]^2|B^0_q\rangle$$

- $SU(3)_f$ breaking ratio $\leftrightarrow$ CKM

$$\xi \equiv \frac{m_{B_d}}{m_{B_s}}\sqrt{\frac{\mathcal{M}_s}{\mathcal{M}_d}} \rightarrow \frac{\Delta m_s}{\Delta m_d} = \xi^2\frac{m_{B_s}}{m_{B_d}}\left|\frac{V_{ts}}{V_{td}}\right|^2$$

  - large fraction of statistical and systematic error cancel in the ratio

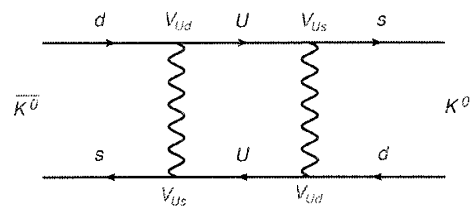
K^0 - anti K^0 mixing

- $K^0 \leftrightarrow \overline{K}^0$ mixing: indirect CP violation

$$|\epsilon_K| = \kappa_\epsilon C_\epsilon B_K A^2 \lambda^6 \bar{\eta}\{-\eta_1 S_0(x_c)(1-\lambda^2/2) + \eta_3 S_0(x_c, x_t) + \eta_2 S_0(x_t) A^2 \lambda^4 (1-\bar{\rho})\}$$

$$B_K = \frac{\langle K^0 | O_{VV+AA} | \overline{K}^0 \rangle}{\frac{8}{3} f_K^2 M_K^2}$$

$$O_{VV+AA} = (\overline{s}\gamma_\mu\gamma_5 d)^2 + (\overline{s}\gamma_\mu d)^2$$



- induced only from 1 loop of EW theory:
  - internal fermion: U=u, c, t
  - integration of the loop → Inami-Lim function ~ $(m_U/m_W)^2$
  - effect enhances for heavier mass: large sensitivity to new physics
- replacing s→b: similar process $B^0 \leftrightarrow \overline{B}^0$
- and further d→s: $B_s^0 \leftrightarrow \overline{B}_s^0$

difficulty in b quark simulation

- conventional light quark approach: m_b ~5 GeV > 1/a ~ 2 GeV
  - $(m_b a)^n$ error large : impossible to take continuum limit
- needs help from Effective Field Theory
  - on the lattice or
  - in continuum
- EFTs
  - on the lattice
    - NRQCD, HQET, RHQ
  - in continuum
    - HQET: static limit + 1/m expansion

B^0 - anti B^0 mixing: RBC/UKQCD's works

- 1st feasibility study on 2+1 flavor Iwasaki-DWF ensemble with static b quark

  "Neutral B-meson mixing from unquenched lattice QCD with domain-wall light quarks and static b-quarks", PRD82 (2010) 014505,

  RBC/UKQCD: C. Albertus, YA, P. A. Boyle, N. H. Christ, T. T. Dumitrescu, J. M. Flynn T. Ishikawa, T. Izubuch O. Loktik, C. T. Sachrajda, A. Soni, R. S. Van de Water, J. Wennekers, and O. Witzel

  - $V \sim (1.8\ \mathrm{fm})^3$, $a^{-1}=1.7$.
- 2nd study aiming precision
  - RBC/UKQCD under USQCD collaboration project on QCDOC: $24^3 \times 64$
  - RBC/UKQCD under RIKEN RICC project: $32^3 \times 64$
  - both: $V \sim (2.7\ \mathrm{fm})^3$, $a^{-1}=1.7$ and 2.3 GeV.
- All done on the RBC/UKQCD's Nf=2+1, DWF gauge ensembles

B^0 - anti B^0 mixing: RBC/UKQCD's works

- 1st feasibility study on 2+1 flavor Iwasaki-DWF ensemble with static b quark

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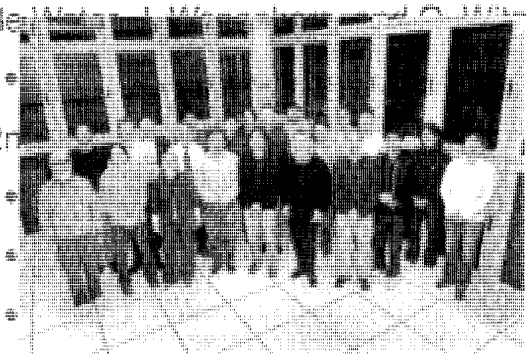
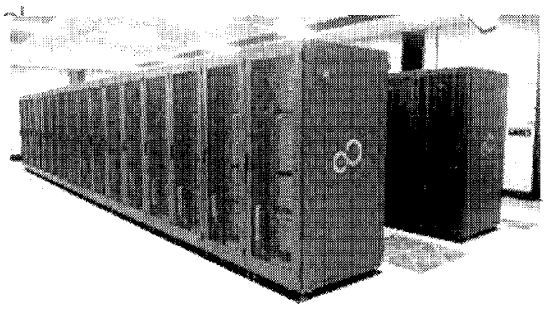
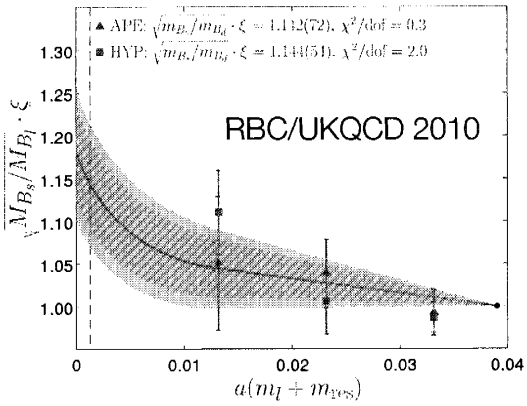


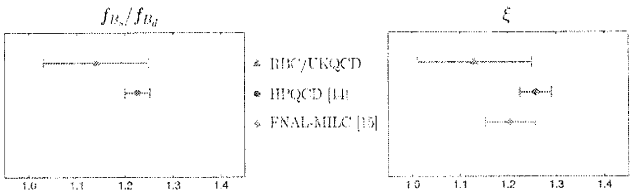


超並列PCクラスタ

- All done on the RBC/UKQCD's Nf=2+1, DWF gauge ensembles

ξ: DWF for light quarks
Static approximation on b quark





- RBC/UKQCD is still in feasibility study.
- Error is large compared to HPQCD or FNAL-MILC
- But, significant improvements expected....

error reduction strategy

RBC/UKQCD 2010

uncertainty	f_{B_s}/f_{B_d} APE	f_{B_s}/f_{B_d} HYP	ξ APE	ξ HYP
statistics	8%	4%	6%	5%
chiral extrapolation	7%	7%	7%	7%
uncertainty in $g_{B^*B\pi}$	3%	3%	2%	2%
discretization error	3%	3%	4%	4%
renormalization factors	0%	0%	2%	2%
scale and quark mass uncertainties	1%	1%	1%	1%
finite volume error	1%	1%	1%	1%
$1/m_b$ corrections	2%	2%	2%	2%
total systematics	9%	9%	9%	9%

small due to cancelation in the ratio

- main errors for ξ
  - statistical
  - chiral extrapolation
  - discretization

- method
  - source/sink optimization
  - smaller mass
  - O(a) improvement & 2nd (finer) lattice spacing

error reduction strategy

RBC/UKQCD 2010

uncertainty	f_{B_u}/f_{B_d} APE	f_{B_u}/f_{B_d} HYP	ξ APE	ξ HYP
statistics	8%	4%	6%	5%
chiral extrapolation	7%	7%	7%	7%
uncertainty in $g_{B^*B\pi}$	3%	3%	2%	2%
discretization error	3%	3%	4%	4%
renormalization factors	0%	0%	2%	2%
scale and quark mass uncertainties	1%	1%	1%	1%
finite volume error	1%	1%	1%	1%
$1/m_b$ corrections	2%	2%	2%	2%
total systematics	9%	9%	9%	9%

small due to cancelation in the ratio

- main errors for ξ
  - statistical
  - chiral extrapolation
  - discretization

✳method

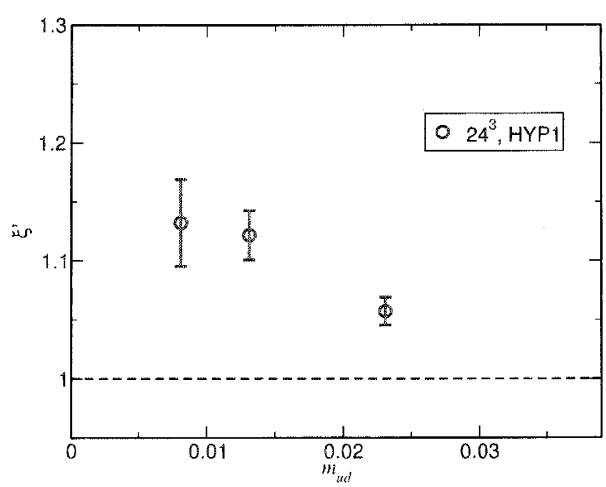
✓source/sink optimization

✓smaller mass

✳O(a) improvement & 2nd (finer) lattice spacing

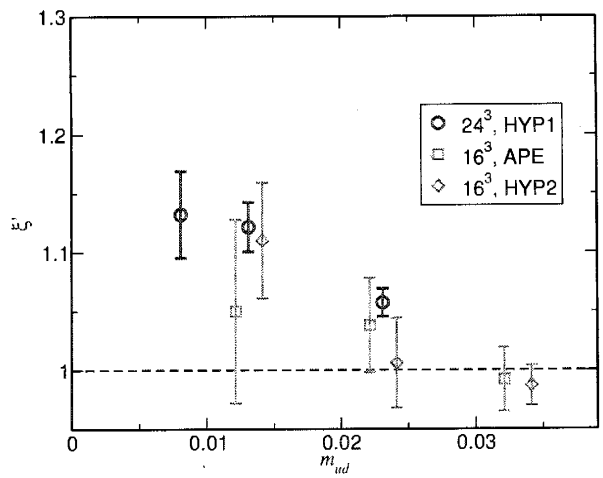
Monday, October 25, 2010

ξ vs m_{ud}



Monday, October 25, 2010

ξ vs m_{ud}



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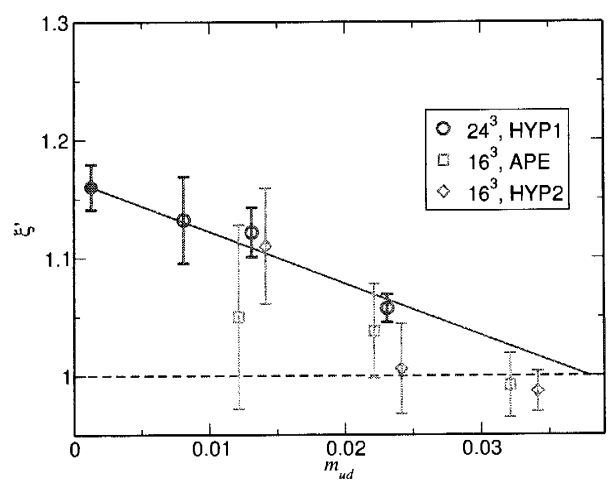

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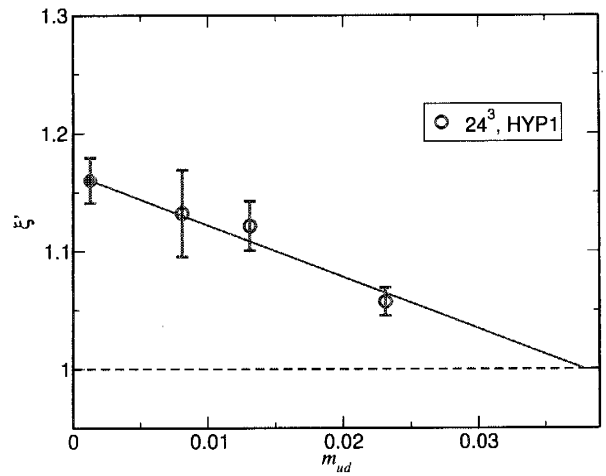

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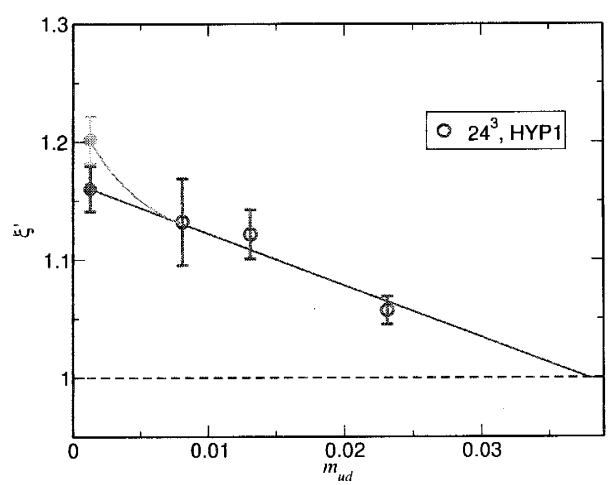

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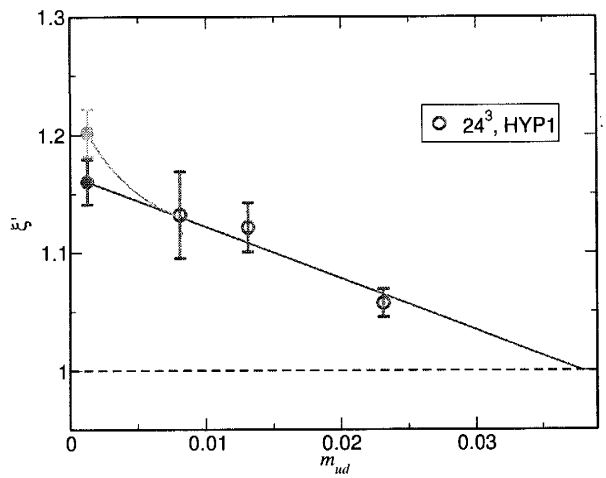
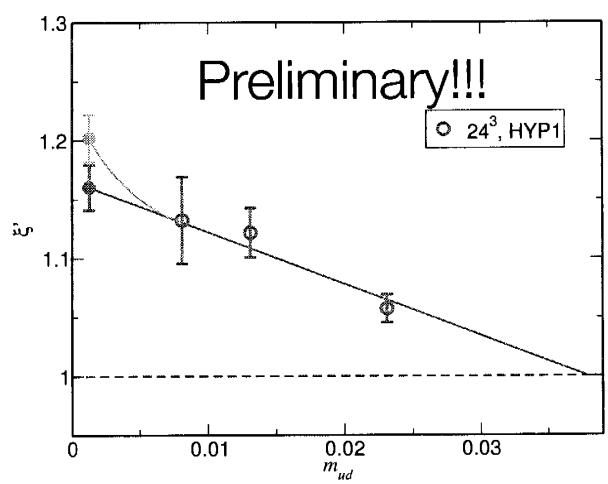
ξ vs m_{ud}



- O(a) yet to be improved

ξ vs m_{ud}



- O(a) yet to be improved

error budget in ξ

	ξ (16^3) APE HYP2	ξ (24^3) HYP1 preliminary!!!
statistics	6% 5%	2%
chiral extrapolation	7%	4%
uncertainty in $g_{B^*B\pi}$	2%	
discretization error	4%	
renormalization factors	2%	
scale and quark mass uncertainties	1%	
finite volume error	1%	
$1/m_b$ corrections	2%	
total systematics	9%	

Monday, October 25, 2010

error budget in ξ

	ξ (16^3) APE HYP2	ξ (24^3) HYP1 preliminary!!!	ξ (24^3) HYP2 being generated	ξ (32^3) HYP1 in preparation	ξ (32^3) HYP2 in preparation
statistics	6% 5%	2%			
chiral extrapolation	7%	4%	make use of partially quenched points		
uncertainty in $g_{B^*B\pi}$	2%	calculate it or use $g_{B^*B\pi}$ from DWF+RHQ [RBC/UKQCD: P. Fritzsch et al]			
discretization error	4%	O(a) improvement and continuum limit			
renormalization factors	2%				
scale and quark mass uncertainties	1%				
finite volume error	1%	1.5 x physical size: much smaller			
$1/m_b$ corrections	2%				
total systematics	9%	5% within our reach			

Monday, October 25, 2010

renormalization and O(a)

- all one loop renormalization factors and the coefficients of O(a) operators have been worked out
  - by matching matrix elements with on-shell light and heavy quark states
  - O(a): g^2pa, g^2ma: both had contribution of same order for ξ
  - T. Ishilawa @ Lattice 2008, T. Izubuchi @ Lattice 2009
  - will be incorporated in the analysis
- non-perturbative renormalization: RI/MOM type
  - T. Izubuchi @ Lattice 2009
  - will be investigated further
  - more important for individual matrix elements

B^0 - anti B^0 mixing: Summary and Outlook

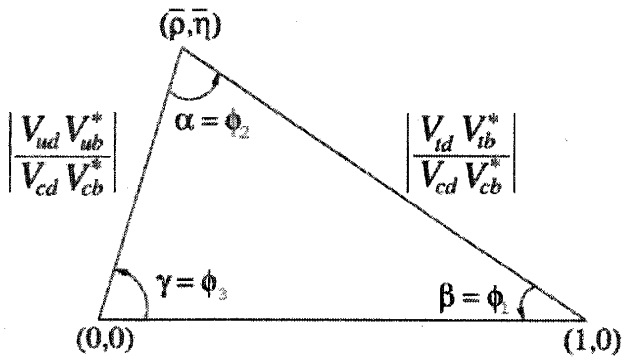
- Summary
  - 2+1 flavor Iwasaki+DWF and static quarks were used for B mesons
  - tuning of the smearing and source-sink separation brought a dramatic improvement in the statistical error
  - lighter ud mass is helping reduce the systematic error of chiral extrapolation
- Outlook
  - partially quenched points will be incorporated in the chiral fits
    - various fits should be tested: SU(3), SU(2), analytic,..
  - $O(g^2a)$ improvement / 2 different heavy quark actions / continuum limit will help reduce the discretization errors.
  - total error of ξ= 5% is within reach
  - NPR will be investigated

unitarity triangle

$$\mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}} W_\mu^+ \overline{U}_L \gamma_\mu V D_L + \frac{g_2}{\sqrt{2}} W_\mu^- \overline{D}_L \gamma_\mu V^\dagger U_L$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \simeq 0.22$$

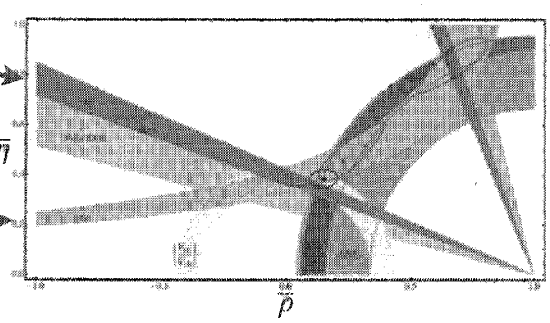


- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- divide by $|V_{cd}V_{cb}^*| = A\lambda^3$
- $(\bar\rho + i\bar\eta) - 1 + (1 - \bar\rho - i\bar\eta) = 0$
- $|1 - \bar\rho - i\bar\eta| = |V_{td}/V_{ts}|/|V_{us}|$
- $|V_{td}/V_{ts}|$ ←ξ and $\Delta m_d/\Delta m_s$
- V_{us} from f_K/f_π or $K \to \pi l \nu$
  <1% accuracy RBC/UKQCD

B^0 - anti B^0 mixing & B_K ⇒ CKM unitarity triangle

$B_0 \to \psi K_s$ (no need of Lattice QCD)

B_K



ξ

(our ξ not included yet)

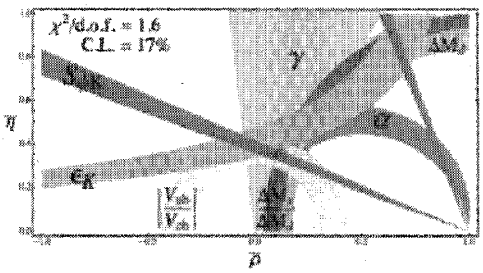
[Lunghi & Soni 08]

- 2-3 σ tension in sin2β → possible hint of new physics
- Similar analysis
  - Laiho, Lunghi, Van de Water, 2009; CKMfitter ICHEP2010;
- UTfit group 2010: 3σ+
- Lunghi & Soni 2010 in preparation: 3σ+

B_K, ξ perspective

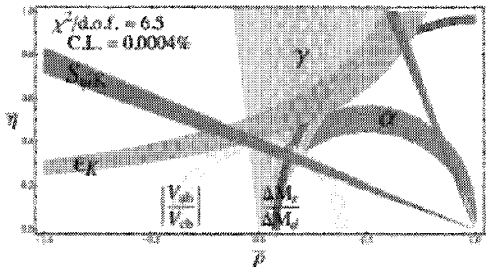
[Laiho, Van de Water, Lunghi 09]

- with current lattice results



[Van de Water, Lattice 2009]

- if lattice error reduced to 1%
  - ➡new physics
- effect: $\xi >> B_K$
  - ➡improving ξ is important



B^0 - anti B^0 mixing: Further Outlook

- use Columbia type relativistic heavy quark [$(m\ a)^n$] improvement for b quark
- RHQ parameters are being tuned (H. Peng/O. Witzel/R. Van de Water)
- use Iwasaki + DWF for 2 lattice spacings
- tree-level O(a) improvement for operators
- operator renormalization with perturbation theory (underway by C. Lehner)
- Individual matrix elements are calculated more precise than static approximation
  - a different constraint to CKM apex possible
- planned to be concluded in 1-2 year
  - USQCD project (led by O. Witzel/R. Van de Water) using FNAL cluster

Challenges of small and large quark masses in lattice QCD

Christoph Lehner

RIKEN BNL
Research Center

RBRC SRC Meeting, BNL, October 28 2010

Outline

1. Motivation
1.1 Small quark masses in a finite volume
1.2 Large quark masses at finite lattice spacing

2. The epsilon regime of QCD

3. Relativistic Heavy Quarks

Motivation

Consider

- quarks with mass m
- in a finite volume $V = L^4$
- at nonzero lattice spacing a .

Then we naturally have two limiting domains of quark mass:

1. Quark mass small compared to infrared scale L: $mV\Sigma < 1$
2. Quark mass large compared to ultraviolet scale a: $am > 1$

In both cases interesting challenges occur

1. The epsilon regime of QCD (Shoji Hashimoto, C.L., Tilo Wettig)
2. The Relativistic Heavy Quark action (Tomomi Ishikawa, Taku Izubuchi, C.L., ...)

The epsilon regime of QCD

We consider

- Lattice QCD: Euclidean QCD at finite volume V
- Small temperatures: Theory dominated by pions
- Small quark masses

Compton wavelength of pions large compared to volume V, i.e.,

$$\sqrt{V} m_\pi^2 < 1 \, .$$

QCD described by χPT in the ε expansion

The ε expansion

The ε expansion (systematic expansion in $1/F^2\sqrt{V}$)

Leading order:

- Described by random matrix theory (RMT)
- Dirac eigenvalue distributions in RMT known
- Fit Dirac eigenvalue distributions: Extract LECs of χPT

NLO:

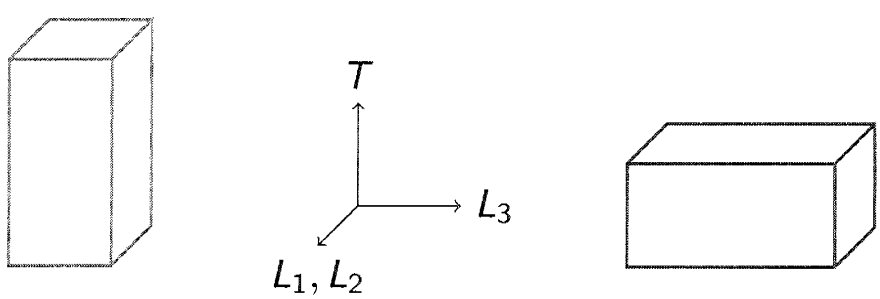
- Finite-volume corrections to LECs

NNLO:

- Systematic deviations from RMT
- Challenge: Minimizing systematic deviations from RMT

The ε expansion at NNLO

NNLO calculation in χPT (C.L., Hashimoto, Wettig 2010):



$$(a_x) \qquad T = xL\,, \qquad L_1 = L_2 = L_3 = L\,,$$
$$(b_x) \qquad L_3 = xT\,, \qquad T = L_1 = L_2\,.$$

Geometry (b_2) minimizes systematic deviations

Check against JLQCD epsilon-regime run

Two-flavor epsilon-regime run of JLQCD:

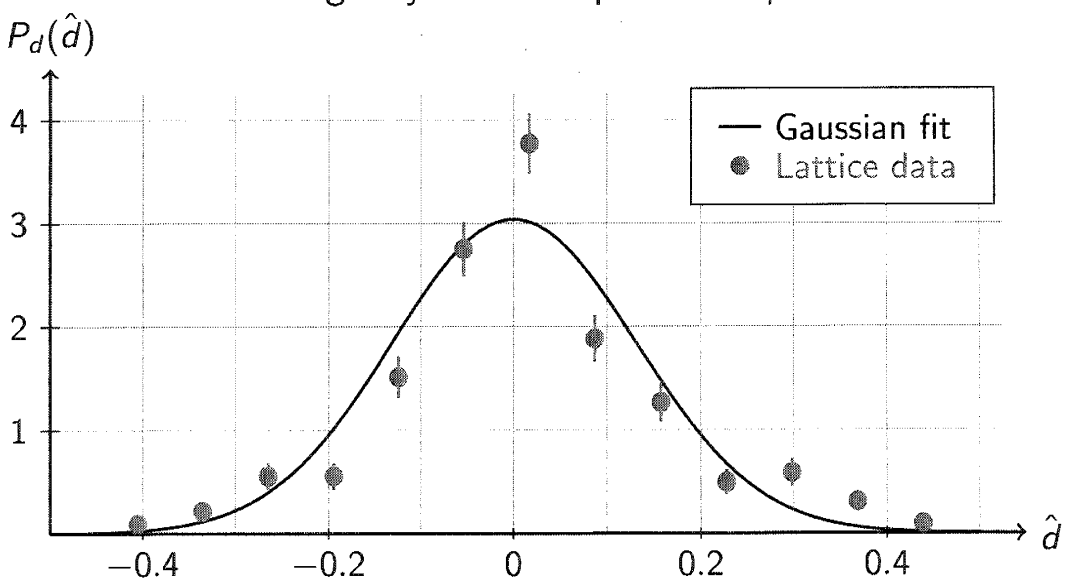
- Two-flavor dynamical Overlap fermions
- on a 32×16^3 lattice
- with $m_\pi^2 \sqrt{V} \approx 1$.

F from meson correlators (Fukaya et. al. 2008):

- $F^{\text{meson}} = 87(6)$ MeV
- Normalization: $F_{\text{experiment}} \approx 90$ MeV

Fit for F

Geometry (a_2): Shift of lowest Dirac eigenvalue due to small imaginary chemical potential $i\mu$:

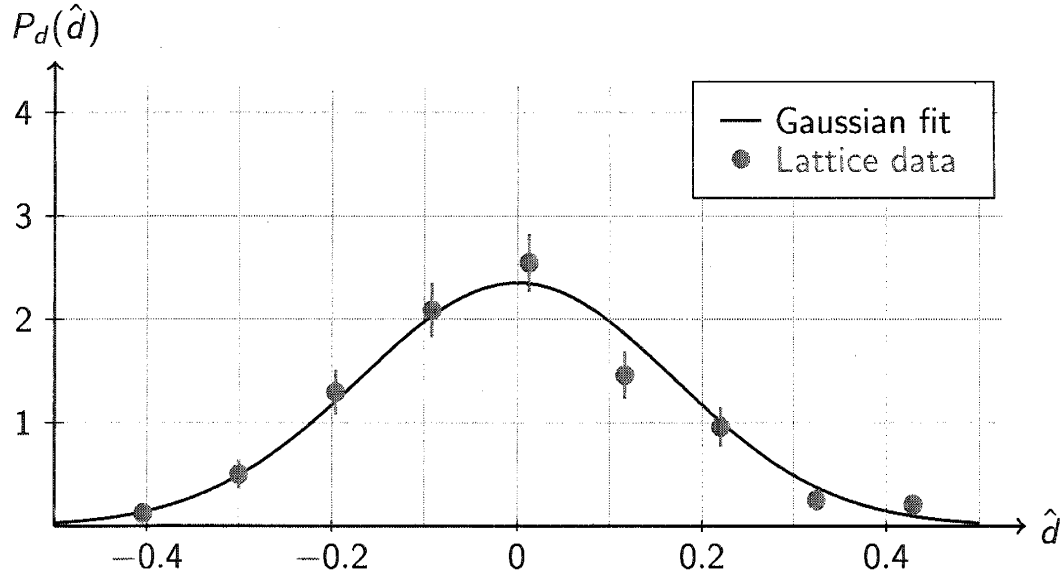


RMT prediction: Gaussian distribution, $\sigma^2 = \mu^2 F^2 V$

$\chi^2/\text{dof} = 4.2\,, \quad F = 51(4)$ MeV$\,, \quad F^{\text{meson}} = 87(6)$ MeV$\,.$

Fit for F

Geometry (b_2): Shift of lowest Dirac eigenvalue due to small imaginary chemical potential $i\mu$:



RMT prediction: Gaussian distribution, $\sigma^2 = \mu^2 F^2 V$

$\chi^2/\text{dof} = 0.91\,, \quad F = 80(5)\ \text{MeV}\,, \quad F^{\text{meson}} = 87(6)\ \text{MeV}\,.$

Summary of epsilon-regime efforts

- Can minimize systematic deviations from RMT by a suitable choice of lattice geometry (JHEP06(2010)028)
- Pion decay constant from JLQCD lattice configurations:

$$\boxed{\begin{aligned} F^{\text{RMT}} &= 80(5)\ \text{MeV}\,, \\ F^{\text{meson}} &= 87(6)\ \text{MeV}\,. \end{aligned}}$$

Outlook (in preparation):

- Calculation of spectral density in epsilon expansion beyond RMT

Relativistic Heavy Quarks (RHQ)

Consider quarks with mass $am \geq 1$:

- Problem: $(am)^n$ corrections are significant

Idea of RHQ to control these corrections:

- break Lorentz-symmetry
- add higher-dimensional operators to the quark action:

$$S_{\text{lat}} = \sum_{n,n'} \bar{\psi}_{n'} \Big(\gamma^0 D^0 + \zeta \gamma^i D^i + m_0 - \frac{r_t a}{2} D_0^2 - \frac{r_s a}{2} D_i^2 + \frac{i a c_B}{4} \sigma_{ij} F_{ij} + \frac{i a c_E}{2} \sigma_{0i} F_{0i} \Big)_{n'n} \psi_n \qquad (1)$$

Tune additional parameters

Relativistic Heavy Quarks (RHQ)

Formulations:

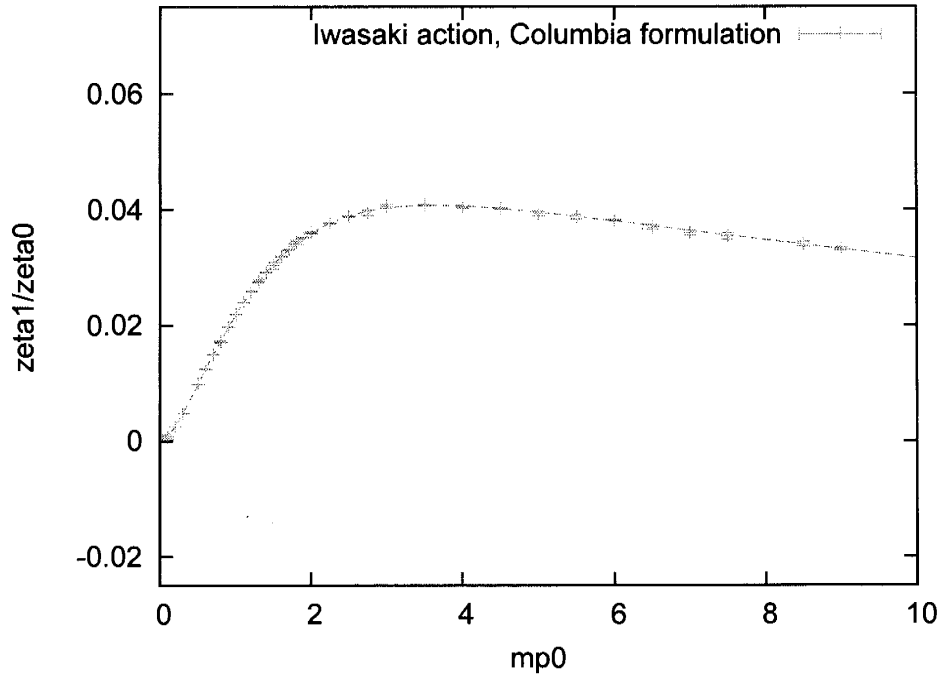
- Columbia: Three free parameters ($\zeta = r_s$, $c_P = c_E = c_B$, m_0)
- Fermilab: Four free parameters (ζ, c_E, c_B, m_0)
- Tsukuba: Five free parameters (ζ, r_s, c_E, c_B, m_0)

Tuning for Columbia action:

- Non-perturbative (Li,Peng,Van de Water,Witzel)
- Perturbative on-shell improvement (Ishikawa,Izubuchi,C.L.)

Relativistic Heavy Quarks (RHQ)

Perturbative result for $\zeta = \zeta^{(0)} + g^2\zeta^{(1)}$ (C.L.):



with $m_p^{(0)} = \log(1 + m_0)$.

Summary of RHQ efforts

Perturbative parameter-tuning (one-loop, MF-improved):

- Determine ζ, m_0, c_P from on-shell tuning
- Determine wavefunction renormalization

Outlook (in preparation):

- Perturbative matching factors (Lattice / $\overline{\mathrm{MS}}$) for vector/axial currents and four-quark operators.

Domain-wall fermion with low-mode projection

Eigo Shintani (RIKEN-BNL)

Plan of this talk

1. Introduction
   DWF operator
   How to calculate DW operator
2. Preconditioning of DWF operator
3. Physics

Introduction

- Lattice QCD

  Non-perturbative calculation of quark dynamics from the first principles

  Monte Carlo integral

  – Theoretical accuracy depends on quantity and quality of sampling
  – Large statistics
  – Large lattice size, small lattice spacing:
    reduce the systematic ambiguities
  – Chiral symmetry :
    Ginsperg-Wilson relation, Nilsen-Ninomiya no-go theorem,
    which depends on computational cost

  → high speed algorithm has the advantage of physics

DWF operator

- Domain-wall fermion (DWF)

  5D operator, approximate chiral symmetry, whose order depends on L_s

  Preconditioning (even-odd) works well, but cost is high

- DWF Action

$$S_F = \sum_{x,y} \sum_{s,t} \bar{\psi}_s(x) D_{m\,st}(x,y) \psi_t(y)$$

$$D_{m\,st}(x,y) = \begin{pmatrix} D_W(x,y) & P_R & 0 & \cdots & 0 & -mP_L \\ P_L & D_W(x,y) & P_R & 0 & \cdots & 0 \\ 0 & P_L & \ddots & & \cdots & \\ & \cdots & & & & \\ 0 & \cdots & & & \ddots & P_R \\ -mP_R & 0 & \cdots & & P_L & D_W(x,y) \end{pmatrix}$$

$$D_W(x,y) = \sum_{\mu} \left[(1-\gamma_\mu) U_\mu(x) \delta_{x+\hat{\mu},y} + (1+\gamma_\mu) U_\mu^\dagger(y) \delta_{x,y+\hat{\mu}} \right] + (5-M)\delta_{x,y}$$

How to calculate DWF propagator

DWF matrix has ($N_x^3 \times N_t \times N_5$) $\times$ 12 (spinor $\times$ color) ~ $O(10^8)$ cost

Iterative solver, e.g. CG (Conjugate Gradient) method

Algorithm : Conjugate Gradient for solve, b = Ax

Set x_0 ; $r = b - A x_0$; $p = r$;
while $|r|^2 < \varepsilon$; do ;
  $v = A p$; ← demand many flops
  $\alpha = (r, r)/(p,v)$;
  $x = x + \alpha p$;
  $r' = r - \alpha v$;
  $\beta = (r',r')/(r,r)$;
  $p = r' + \beta p$;
  $r = r'$;
done

where we set $\varepsilon = 10^{-20}$, #iteration ~ $O(10^5)$ cost

Preconditioning of DWF

- Even-odd preconditioning

divide the matrix size to ½ site, solve even site (e.g. mod(x_i,2)=0) only:

$$D_{m\,st}(x,y) = (5-M)\begin{pmatrix} 1_{ee} & -KM_{eo} \\ -KM_{oe} & 1_{oo} \end{pmatrix}, \; K = \frac{1}{2(5-M)}$$

Using

$$D'_m = \begin{pmatrix} 1_{ee} & KM_{eo} \\ KM_{oe} & 1_{oo} \end{pmatrix}, \quad D_m D'_m = \begin{pmatrix} 1_{ee} - K^2 M_{eo} M_{oe} & 0 \\ 0 & 1_{oo} - K^2 M_{oe} M_{eo} \end{pmatrix}$$

Algorithm : even-odd preconditioning

Set $b' = b_e - KM_{eo}\, b_o$;
define as $A = 1_{ee} - K^2\, M_{eo}\, M_{oe}$;
solve $A\, x' = b'$ with CG ;
$x_e = x'$, $x_o = b_o + KM_{oe}\, x'$

#iteration naively reduce to ½, because of reduction of condition number

Preconditioning of DWF

- Low-mode projection

  Low eigenmode (near zero mode) is significant to condition number

  → if we project out low-mode, #iteration of CG suppresses

  – Before CG

    calculate low-mode:

    $$H\psi_k = \lambda_k \psi_k, \quad H = (1_{ee} - M_{eo}M_{oe})^\dagger (1_{ee} - M_{eo}M_{oe})$$

  – In CG

    project out ψ_k from source vector

    $$b' = b - \sum_k \psi_k (\psi_k, b)$$

    obtain $x' = H^{-1} b'$

  – After CG

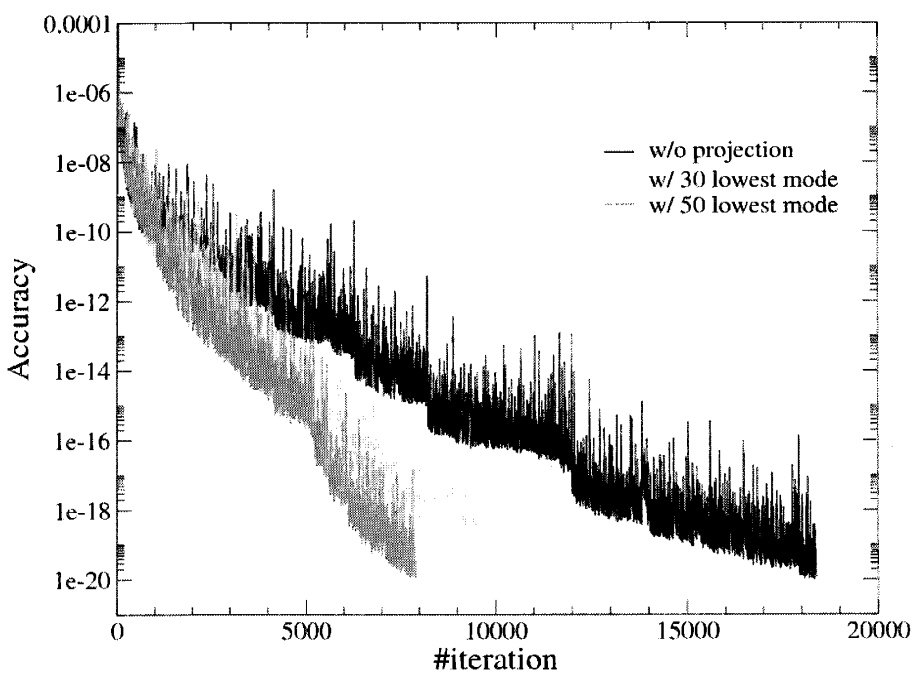
    add low-mode part:

    $$x = x' + \sum_k \frac{1}{\lambda_k} \psi_k (\psi_k, b)$$

Preconditioning of DWF

- Convergence test

  $24^3 \times 64 \times 16$ DWF $N_f = 2+1$, m = 0.005, M = - 1.8

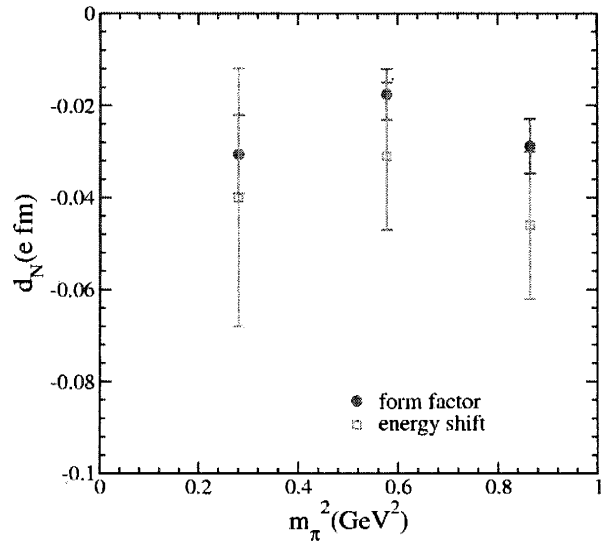


Using #low = 50,
#iteration:
18,000 → 8,000
2.2 times gain

Physics

- Neutron and Proton EDM
  - Strong CP violation from ϑ term
  - Chiral symmetry is important, especially near chiral limit
  - Need large statistics
    → require large costs
  - Update:
    Chiral symmetry
    Wilson → DWF
    Large volume
    2.5 fm^3 → 3.0 fm^3
    Light mass
    m_π : 0.5 GeV → 0.2 GeV
    Strange qaurk effect
    N_f : 2 → 2+1

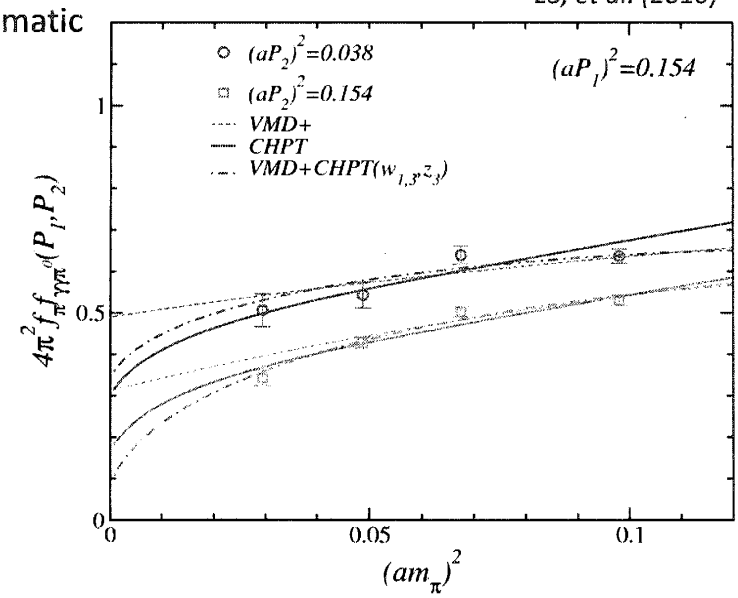
ES, et al. (2006)



Physics

- $\pi^0 \to \gamma\gamma$
  - Need small momentum for two photon
  - Must satisfy axial Ward-Takahashi identity
  - Need to reduce the systematic error in chiral fit
  - Update:
    Large momentum
    Q^2 = 0.3 GeV^2
    → 0.1 GeV^2
    Small quark mass
    m_π = 0.3 GeV
    → 0.2 GeV
    Strange quark effect
    N_f : 2 → 2+1

ES, et al. (2010)



Lattice action

- Path integral → sampling sum

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int [d\mu] \mathcal{O} e^{-S_E(\mu)} \Rightarrow \frac{1}{N} \sum_n \mathcal{O}_n$$

Gauge field randomly generates in Boltzmann weight e^{-S_E}

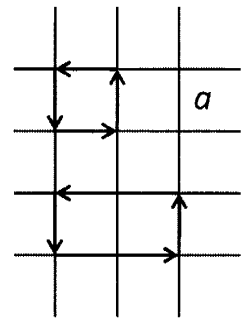
  - Set ultra cut-off *a* (lattice spacing), infra cut-off *V* (lattice volume)
  - <u>Gauge invariant, finite and unique solution</u>

- Gauge action

$$S_g = \beta \sum_x \sum_{\mu \neq \nu} \Big[c_0 \big(1 - \frac{1}{N_c} \mathrm{Tr}\, \mathrm{Re} U_{\mu\nu}(x)\big) + \cdots \Big] = a^4 \Big[-\frac{1}{4} F^2 + \mathcal{O}(a^2) \Big],$$

$$U_{\mu\nu}(x) = U_\mu(x) U_\nu(x+\hat{\mu}) U_\mu^\dagger(x+\hat{\nu}) U_\nu^\dagger(x), \quad \beta = \frac{2N_c}{g^2}$$

$$U_\mu(x) = \exp[iagA_\mu(x)]$$



c_n : the improved parameter to remove lattice aritifact

Lattice fermion

- Dynamical simulation (sea quark)

$$\begin{aligned} \langle PP \rangle &= \frac{1}{Z} \int [dU] (\det D_m)^{N_f} [D_m^\dagger(U) D_m(U)]^{-1} e^{-S_G} \\ &= \frac{1}{Z} \int [dU][d\phi] [D_m^\dagger(U) D_m(U)]^{-1} e^{-S_G - \left| D_m^{-N_f/2} \phi \right|^2} \end{aligned}$$

  - Pseudo-fermion is scalar
  - N_f = 2n : Gaussian distribution
  - generate U_μ, ϕ simultaneously, "Hybrid" Monte Carlo
  - require many time of D_m^{-1}
    ($det\, D = 0$: "quench approximation")

Lattice fermion

- Wilson fermion

  naively violates chiral symmetry by Wilson term, which is O(a)

  Cheap computational cost, preconditioning (even-odd, ...) works well

- Staggered fermion

  Chiral symmetry is defined as mixed with spinor and flavor space

  → need root trick for 2+1 flavor

  Much cheap cost, preconditioning (even-odd, ...) works well

- <u>Domain-wall fermion (DWF)</u>

  5D operator, approximate chiral symmetry, whose order depends on L_s

  Preconditioning (even-odd) works well, cost is high

- Overlap fermion

  Exact chiral symmetry, satisfied with GW relation

  Preconditioning works not well, cost is much high

Physics of RBC/UKQCD

II. Present and Future

Tom Blum
(University of Connecticut)

(RBC/UKQCD Collaboration)

RBRC Review, BNL, October 28, 2010

Outline

1. Introduction/motivation

2. Some preliminary results

   - Topology, m_{res}
   - Pseudoscalar masses and decay constants
   - $K \to \pi\pi$ matrix elements
   - QCD at non-zero temperature

3. Summary

RBC / UKQCD Collaboration

RBC			UKQCD	
RBRC	BNL	Columbia	Edinburgh	Southampton
Y. Aoki T. Blum (UConn) C. Dawson (Google) T. Ishikawa (UConn) T. Izubuchi (BNL) C. Lehner S. Ohta (KEK) E. Shintani	M. Creutz S. Ejiri P. Hegde C. Kelly F. Karsch S. Mukherjee C. Miao P. Petreczky A. Soni R. Van de Water A. Velytsky	N. Christ M. Endres (RIKEN) X.Y. Jin C. Jung (BNL) M. Lin (Yale) M. Lightmann (WU) Qi Liu R. Mawhinney H. Peng D. Renfrew H. Yin O. Witzel	R. Arthur P. Boyle L. del Debbio N. Garron R. Kenway J. Zanotti	D. Brommel J. Flynn P. Fritzsch E. Goode C. Sachrajda

Motivation Need light quarks and big boxes because

Chiral pert. theory slowly convergent

Direct $K \to \pi\pi$ decay calculations require large volume

Longstanding problems in nucleon structure calculations (g_A, momentum fraction, helicity fraction, form factors, ...)

EM properties of hadrons in QCD+QED

Hadronic corrections to muon $g-2$

...

Iwasaki-Dislocation Suppressing Determinant Ratio

(I-DSDR)

Take advantage of good chiral properties of DWF

Small quark mass, so large volume

Large lattice spacing (OK for DWF)

But residual mass gets big for conventional gauge actions

DWF and residual χ SB

The residual mass m_{res} [Furman and Shamir (1995), Blum (1998)]

A small additive shift to the bare quark mass due to finite size of the extra dimension of DWF, L_s

$$m_{\text{res}} \equiv \sum_{t \gg a} \frac{\langle J_{5q} J_5(t) \rangle}{\langle J_5 J_5(t) \rangle}$$

Falls off exponentially with L_s if gauge fields are smooth enough

[Shamir (1993); Hernandez, Jansen, Lüscher (1999); Neuberger (2000)]

$$T = \frac{1-H}{1+H}$$

$$H = \frac{1}{2 + D_W(-M_5)} \gamma_5 D_W(-M_5)$$

unless T has a unit eigenvalue

Low modes of D_W and explicit χ SB in DWF

Low modes of Wilson (DWF) Dirac operator near $(+) - M_5$ responsible for χ symmetry breaking in DWF Edwards, Heller, Narayanan (1999); Hernandez, Jansen, Lüscher (2000); Orginos (RBC Collaboration) (2002); Hernandez, Jansen, Nagai (2002); A. Aoki, *et al* (RBC Collaboration) (2004);

Low modes$\rightarrow$ $m_{\text{res}} \sim 1/L_s$ [Golterman and Shamir (2003); RBC/UKQCD (2007)]

Low modes supported by "dislocations", or small lattice artifact "instantons"

Suppress dislocations $\rightarrow$ reduce χ SB

These dislocations, with large topological charge density, are topology-changing gauge configurations, and cause a complete reordering of the (Dirac) spectrum: χ SB

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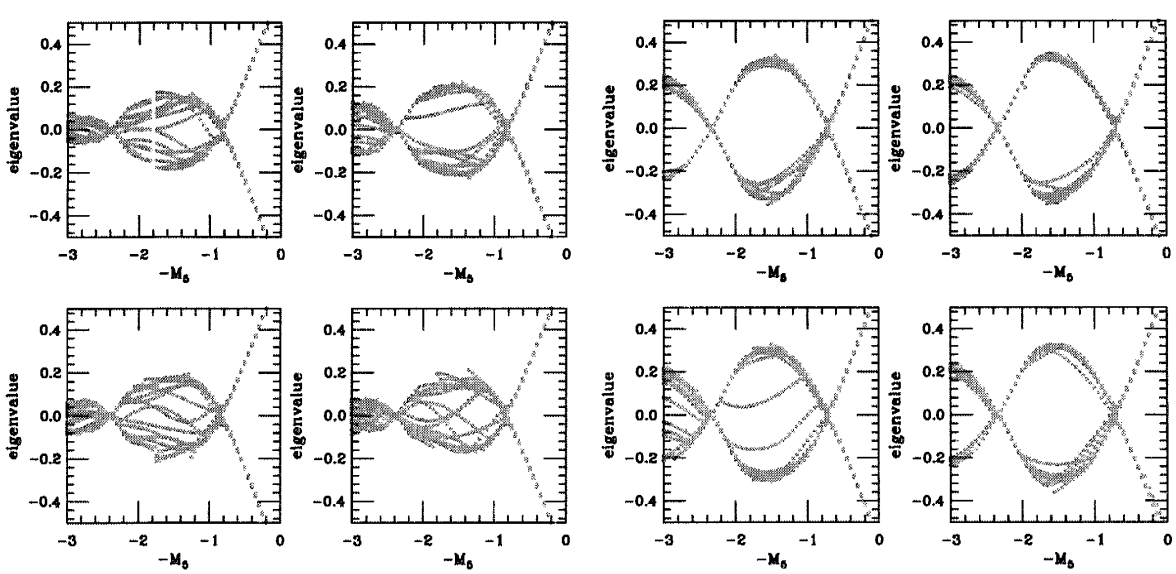
Low modes of D_W (Quenched, $a^{-1} \approx 2$ GeV)

Iwasaki suppresses low modes in the gap. Gap is also larger.
At strong coupling gap closes: Aoki phase [Aoki (1980)]



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Suppression of low modes: quenched case

Suppression is easy to understand. Modification of the gauge action of order $O(a^2/\rho^2)$ is positive for Iwasaki (and DBW2), so small instantons are suppressed. [Garcia Perez, Gonzalez-Arroyo, Snippe, van Baal (1994)].

Towards the continuum limit, tunneling of topological charge is suppressed, and it is worse for improved actions

Have to be careful: χ symmetry is better, but should not sacrifice correct average over topological sectors

In dynamical simulations, already use Iwasaki action, how can we suppress further?

Dislocation Suppressing Determinant Ratio

Add Wilson determinant(s) evaluated at $-M_5$ explicity to (rational) hybrid monte-carlo evolution:

$$\det \frac{\left(\not{D}_W(-M_5) + i\epsilon_f\gamma_5\right)\left(\not{D}_W(-M_5) + i\epsilon_f\gamma_5\right)^\dagger}{\left(\not{D}_W(-M_5) + i\epsilon_b\gamma_5\right)\left(\not{D}_W(-M_5) + i\epsilon_b\gamma_5\right)^\dagger} = \Pi \frac{\lambda^2 + \epsilon_f^2}{\lambda^2 + \epsilon_b^2}$$

$\det \not{D}_W(-M_5)$ - [Vranas (2000,2006) (GapDWF)]
suppresses zeroes at $-M_5$

$\det\left(\not{D}_W(-M_5) + i\epsilon_b\gamma_5\right)$ [JLQCD (2006) (fixed topology/overlap)]
Moderates the large shift in β caused by numerator

$\det\left(\not{D}_W(-M_5) + i\epsilon_f\gamma_5\right)$ [D. Renfrew, *et al.* (RBC) (2008)(unfix topology)]
allows for topology change

RBC/UKQCD I-DSDR Ensembles

After significant parameter searching, chose

$\epsilon_f = 0.02$

$\epsilon_b = 0.50$

$\beta_{\mathrm{I}} = 1.75$

$L_s = 32$

and find $a^{-1} \approx 1.34$ GeV and $m_{\mathrm{res}} \approx 0.0018$

Compare to 1.73 GeV and 0.003 (2 times reduction in m_{res} physical units)

RBC/UKQCD DWF Gauge Ensembles

Volume	$1/a$	L	m_π	Time units	$m_{\mathrm{quark}}a$	Gauge Action
$24^3 \times 64$	1.73 GeV	2.7 fm	315 MeV	9000	0.005+0.0032	Iwasaki
			402 MeV	9000	0.01+0.0032	
$32^3 \times 64$	2.28 GeV	2.7 fm	290 MeV	7000	0.004+0.0006	
			350 MeV	8000	0.006+0.0006	
			410 MeV	6000	0.008+0.0006	
$32^3 \times 64$	1.4 GeV	4.5 fm	180 MeV	1000	0.001+0.0018	Iwasaki + DSDR
			250 MeV	1800	0.004+0.0018	

Compare Iwasaki+DWF to I-DSDR+DWF
(latter is **preliminary**)

Topological Charge

Continuum:

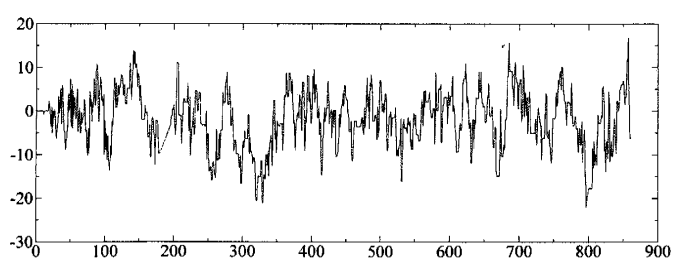
$$Q = \frac{g^2}{16\pi^2} \int d^4x \, G_{\mu\nu}(x) \tilde{G}_{\mu\nu}(x) \quad \text{and} \quad \chi_Q = \langle Q^2 \rangle / V$$

Define lattice Q using the "5 loop Improved" operator, linear combination of 5 loops: 1x1, 1x2, 1x3, 2x2, and 3x3.
[de Forcrand, *et al.* (1997)], after

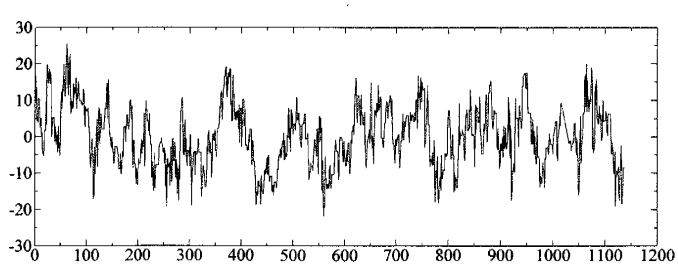
APE smearing the links 60 times with $\alpha_{\text{smear}} = 0.45$

Topological Charge

I-DSDR gauge action, $m_l = 0.0042$ (upper) and 0.001 (lower)



$m_l =$
0.001



0.0042

Topological Susceptibility

Lowest order [DiVecchia, Veneziano (1980); Leutwyler, Smilga (1992)]

$$\chi_Q = \Sigma\left(\frac{1}{m_u}+\frac{1}{m_d}\right)^{-1} = \Sigma\frac{m_u m_d}{m_u+m_d},$$

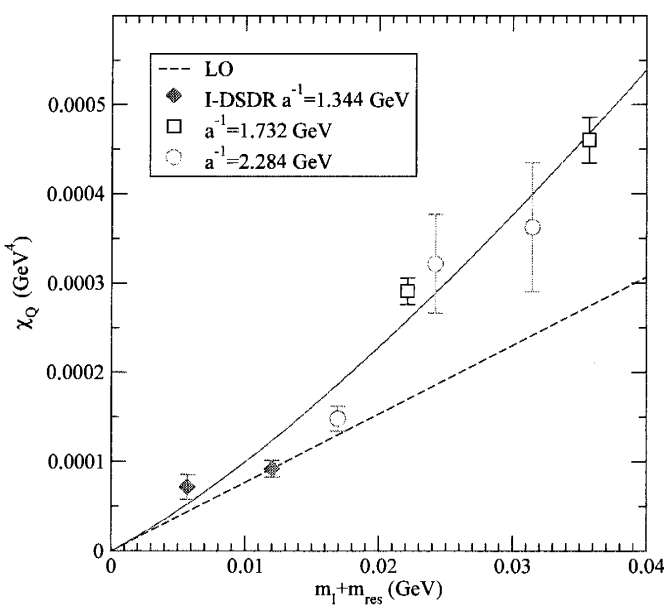
where $(\Sigma)^{1/3} = (Bf^2/2)^{1/3} = 251(4)(2)$ MeV.

At one-loop in chiral perturbation theory [Chiu and Mao (2009)],

$$\begin{aligned}\chi_Q &= \Sigma\left(\frac{1}{m_u}+\frac{1}{m_d}\right)^{-1}\times \\ &\quad\left(1-\frac{3}{(4\pi f)^2}m_\pi^2\log\frac{m_\pi^2}{\Lambda^2}+K_6(m_u+m_d)+2(2K_7+K_8)\frac{m_u m_d}{m_u+m_d}\right) \\ &= \Sigma\frac{m_l}{2}\left(1-\frac{3}{(4\pi f)^2}m_{ll}^2\log\frac{m_{ll}^2}{\Lambda^2}+(2K_6+2K_7+K_8)m_l\right),\end{aligned}$$

where $K_i = 128\,\Sigma L_i/f^4$

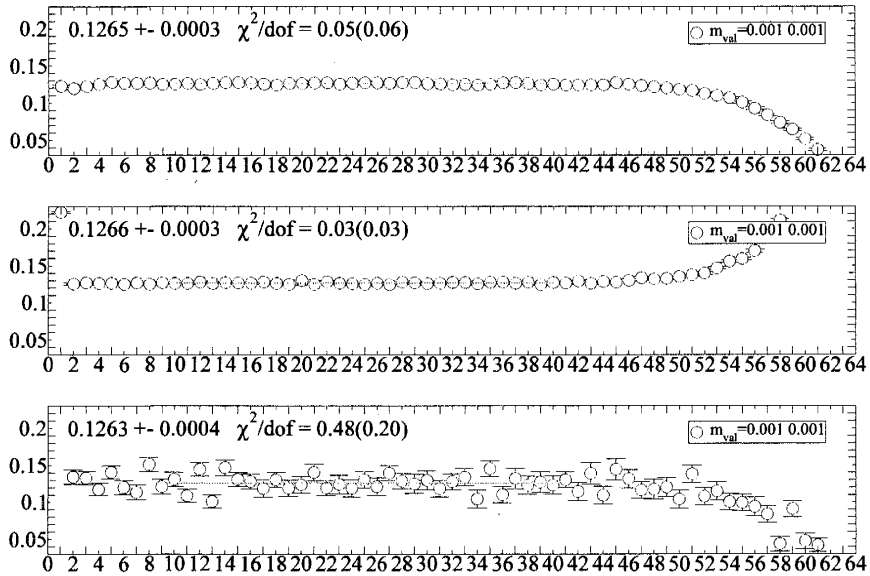
Topological Susceptibility



I-DSDR points preliminary (not included in fit)

Meson mass and decay constant fits (effective masses)

Simultaneously fit wall-point, wall-wall, PS and Axial Vector 2-pt functions: 1 mass, 3 amplitudes → decay constants



(0.001)

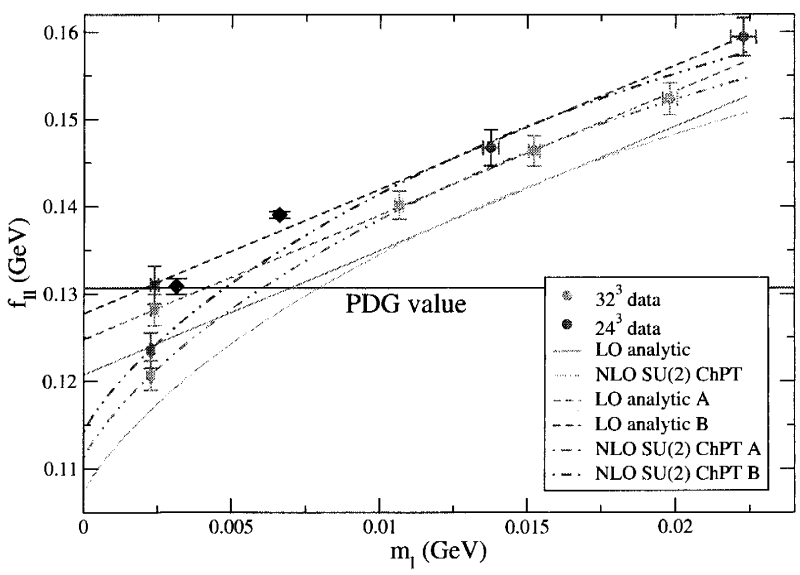
PS (p)

A_0 (p)

PS (W)

$(m_\pi L \gtrsim 4)$

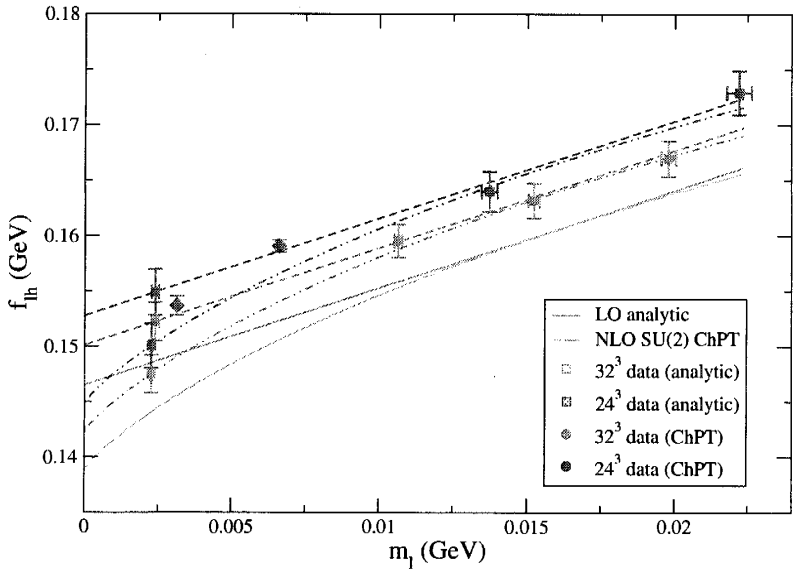
Pion Decay Constant Iwasaki+DWF, I-DSDR+DWF



$f_\pi = 122(2)(5)$ MeV (avgerage of NLO/FV and analytic fits)

I-DSDR points are Preliminary

Kaon Decay Constant Iwasaki+DWF, I-DSDR+DWF



$f_K = 147(2)(4)$ MeV **I-DSDR points Preliminary**

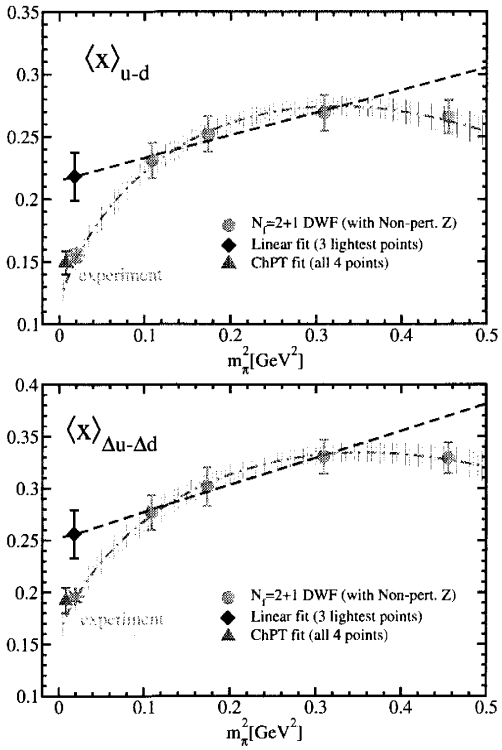
Nucleon Structure ($\langle x \rangle_q$, $\langle x \rangle_{\Delta q}$, axial charge g_A)

- Long standing "puzzles" (lack of agreement with exp.!)

- Heavy Baryon Chiral Perturbation Theory

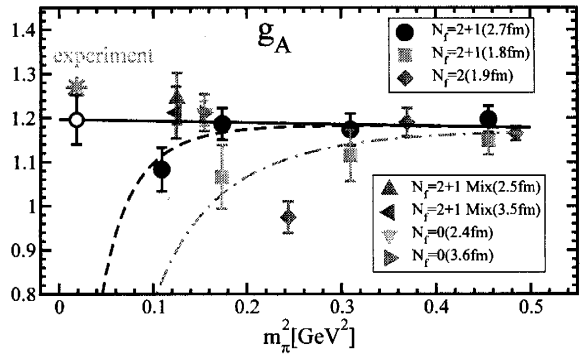
$$\langle x \rangle_{u-d} = C\left[1 - \frac{3g_A^2+1}{(4\pi F_\pi)^2} m_\pi^2 \ln\left(\frac{m_\pi^2}{\Lambda^2}\right)\right] + e(\Lambda^2)\frac{m_\pi^2}{(4\pi F_\pi)^2}$$

$$\langle x \rangle_{\Delta u - \Delta d} = \tilde{C}\left[1 - \frac{2g_A^2+1}{(4\pi F_\pi)^2} m_\pi^2 \ln\left(\frac{m_\pi^2}{\Lambda^2}\right)\right] + \tilde{e}(\Lambda^2)\frac{m_\pi^2}{(4\pi F_\pi)^2}$$



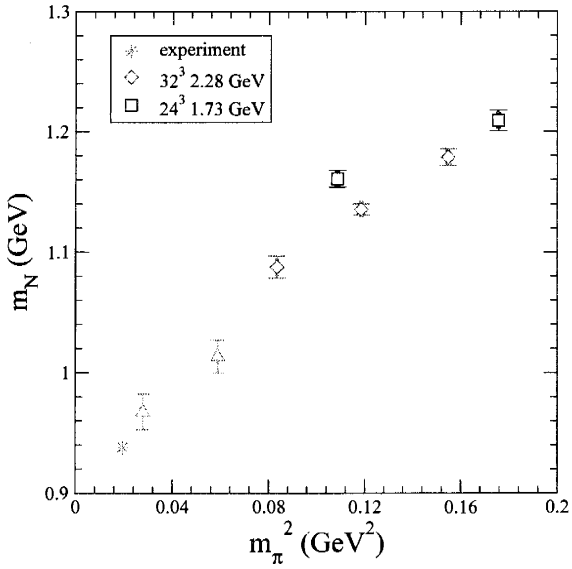
[Aoki, *et al.* (RBC/UKQCD) (2009)]

Iwasaki+DWF
24^3, 1.73 GeV ensembles



[Yamazaki, *et al.* (RBC/UKQCD) (2008)]

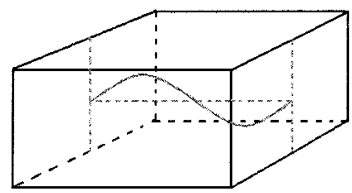
Nucleon Mass DWF+ I-DSDR/Iwasaki



I-DSDR points Preliminary [RICC project]

Calculate π- π final state directly

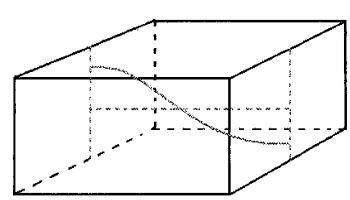
- SU(3) ChPT failure:
  Abandon $\langle K|H_W|\pi\rangle$ & $\langle K|H_W|0\rangle$ → $\langle K|H_W|\pi\pi\rangle$
- Maiani-Testa theorem (1990):
  - Euclidean space methods use e^{-Ht} to project onto lowest energy state
  - For π- π state this state will have zero relative momentum
- Lellouch-Luscher method (2000):
  - Use finite-volume quantization
  - Adjust volume so 1st or 2nd excited state has correct p
  - Correctly include π- π interactions
  - Extra finite-volume normalization factor.



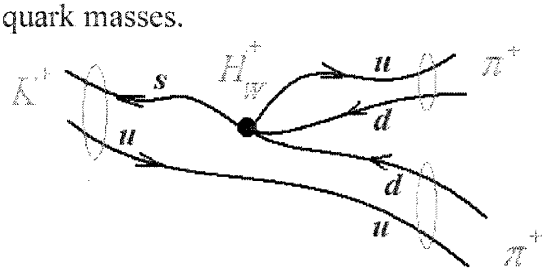
$p = 2\pi/L$

Δ I = 3/2 $K \to \pi\pi$

- $I = 2$ final state has no vacuum overlap.
- Use twisted boundary conditions (Changhoan Kim, hep-lat/0210003).
- $I = 2$ quantum number must be carried by four I=1/2 valence quarks.
  - Twist only valence quarks Sachrajda and Villadoro (hep-lat/0411033).
  - Safe to use slightly different valence and sea quark masses.



$p = \pi/L$



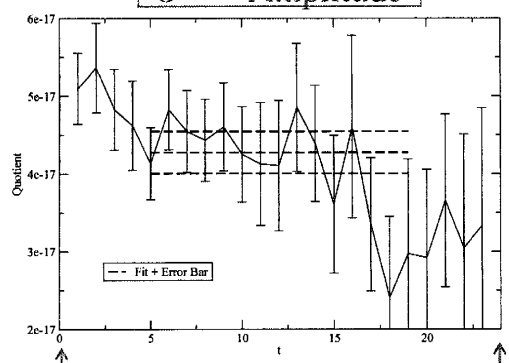
$< \pi\,\pi \,|\, O^{(27,1)} \,|\, K >$ from 47 configurations

(Matthew Lightman and Elaine Goode)

Quantity	This Calculation	Physical
m_π	145.6(5) MeV	139.6 MeV
m_K	519(2) MeV	493.7 MeV
$E_{\pi\pi}(p_\pi \approx 0)$	294(1) MeV	-
$E_{\pi\pi}(p_\pi \approx \sqrt{2}\pi/L)$	516(9) MeV	493.7 MeV
$E_{\pi\pi}(p_\pi \approx \sqrt{2}\pi/L) - m_K$	-2.7(8.3) MeV	0 MeV

$O^{(27,1)}$	0.000945(56)
$O^{(8,8)}$	0.0192(11)
$O^{(8,8)\mathrm{Im}}$	0.0641(38)

$O^{(27,1)}$ Amplitude



$\pi\,\pi$ Kaon

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Determine physical A_2

(Matthew Lightman and Elaine Goode)

- Recall $\langle \pi\pi(I=2)|\mathcal{L}_W(0)|K\rangle = A_2 e^{i\delta_2}$

$$A_2 = \frac{\sqrt{3}}{2\sqrt{2}} \frac{1}{\pi q_\pi} \sqrt{\frac{\partial\phi}{\partial q_\pi} + \frac{\partial\delta}{\partial q_\pi}} L^{3/2} a^{-3} G_F V_{ud} V_{us} \sqrt{m_K} E_{\pi\pi} \times \sum_{i,j} C_i(\mu) Z_{ij}(\mu) \langle \pi\pi | Q_j | K \rangle$$

- Re(A_2) dominated by single operator $O^{(27,1)}$.
- Determine Lellouch-Luscher factor.

$$\frac{\partial\phi}{\partial q_\pi} = 5.141 \qquad \frac{\partial\delta}{\partial q_\pi} = 0.305$$

- Re(A_2) = $1.56(7)_{\mathrm{stat}}(25)_{\mathrm{sys}}$ 10^{-8} GeV [Expt: 1.5 10^{-8} GeV]
- Im(A_2) equally easy, awaits NPR Z factors.

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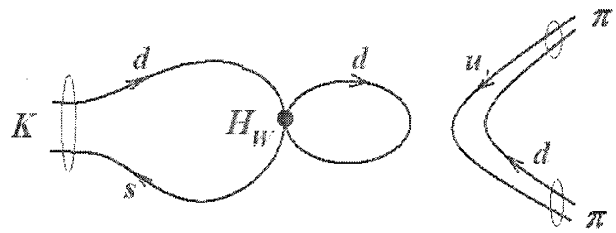
$\Delta I = 1/2 \;\; K \rightarrow \pi\pi$
(Qi Liu)

- Made much more difficult by disconnected diagrams:



- Experiment on $16^3 \times 32$ ensembles.
- $1/a = 1.73$ GeV, $m_\pi = 420$ MeV, $L = 1.8$ fm
- Start with 4000 time units, measure on every 10.
- Adjust valence strange mass for on-shell, threshold kinematics ($\pi\pi$ state is unitary)

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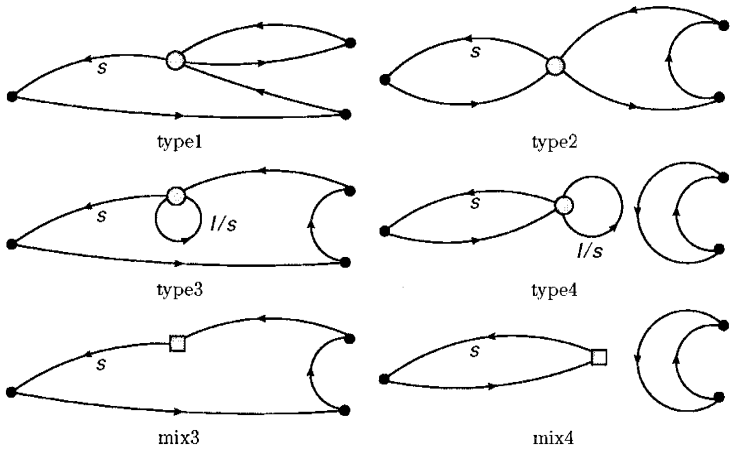
$\Delta I = 1/2 \;\; K \rightarrow \pi\pi$
(Qi Liu)

- Code 48 different contractions
- For each of 400 configurations invert with source at each of 32 times.
- Use Ran Zhou's deflation code



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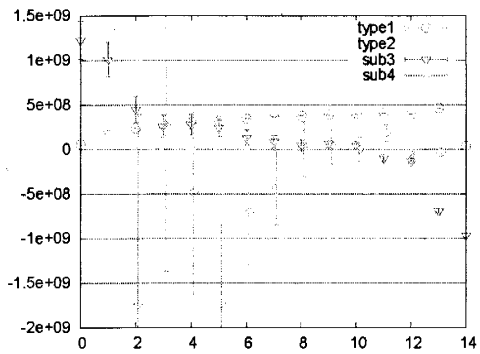
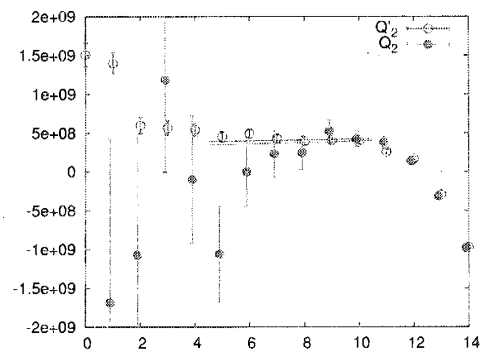
$\Delta I = 1/2$ $K \rightarrow \pi\pi$

(Qi Liu)

- Results for Q2, largest part of Re (A_0):





- Re (A_0) = 43(7) 10^{-8}
- Recall, $p = 0$, $m_\pi = 420$ MeV!

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Future Prospects/Plans $K \rightarrow \pi\pi$

- Re (A_2) and Im (A_2) known soon to 10%
  - 48^3 x 64 will allow unitary pions
  - Second lattice spacing → 2-3% error

  } 1 Tf yr → 10 Tf yr
- Re (A_0) and Im (A_0) with physical kinematics

ΔI=½ rule: Re(A_0)/Re(A_2) $\quad \epsilon' = \frac{ie^{i(\delta_2-\delta_0)}}{\sqrt{2}} \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]$

	Factor	Pflops yr
2000 configurations	1	1.40
$5^2 \cdot 3$ statistics for p != 0	75	105
Benefit of 2x time slices	0.5	52.50
Benefit of split sources	0.25	13.13
Gain from lighter kaon mass	0.53	3.69
Reduced precision	0.75	2.77
Benefit of large volume $16^3 \rightarrow 32^3$	0.13	0.35
Deflation	0.3	0.10

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QCD Thermodynamics [RBC/HotQCD]

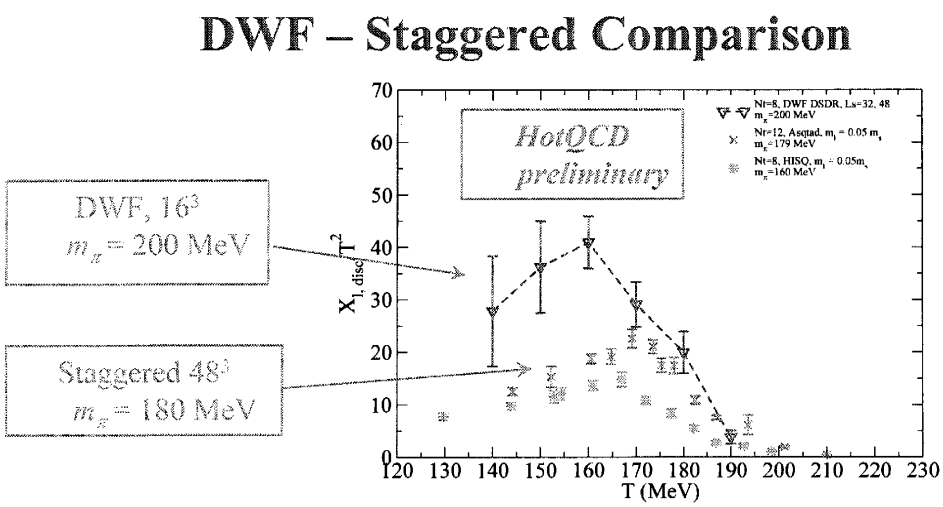
Longstanding goal: study chiral phase transition with DWF

Possible with I-DSDR action: m_{res} under control

Interesting results from initial $16^3 \times 8$ study

(see talk yesterday by F. Karsch)

Disconnected chiral susceptibility



- 2x higher peak.
- Lower peak temperature, may drop further at physical m_π.
- Important challenge for the next generation of machines!

Scaling: Iwasaki+DWF

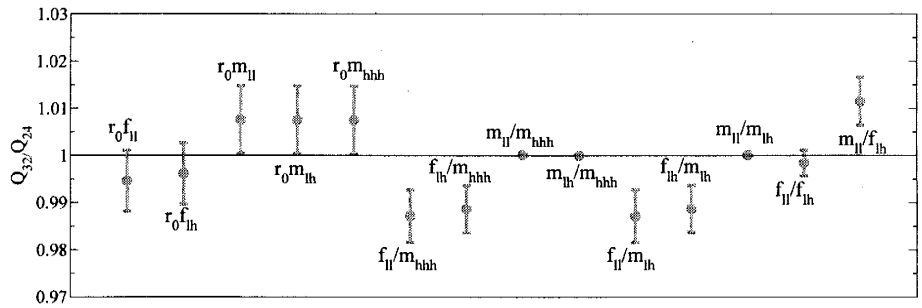


FIG. 1: Ratios of dimensionless combinations of lattice quantities Q (listed in the figure) between the 32^3 and 24^3 lattices at the match point corresponding to $m_l = 0.006$, $m_h = 0.03$ on the 32^3 lattice. A value of unity indicates perfect scaling. The ratios m_{ll}/m_{hhh} and m_{lh}/m_{hhh} (and consequently m_{ll}/m_{lh}) are defined to scale perfectly at these quark masses through our choice of scaling trajectory.

A wide range of *ratios* of physical observables scale very well between 1.73 and 2.28 GeV ensembles when matched at mass points where we have done simulations.

Scaling: I-DSDR+DWF

Only one lattice spacing so far

But, can still match at unphysical point with Iwasaki ensembles

Using 2.28 GeV ensemble, decay constants f_π and f_K scale within 3% and 2% respectively at the (0.001) match point

Both Iwasaki+DWF and I-DSDR+DWF appear to have modest lattice artifacts

Another I-DSDR at smaller a needed to confirm

Summary

- generation of new I-DSDR ensembles well underway
- residual χ SB small, even at large a ($m_{\text{res}} \approx 2.5$ MeV @ $a = 0.14$ fm)
- Unitary pion masses roughly 170 and 240 MeV
- Partially quenched physical pion/kaon masses (*c.f.*, $K \to \pi\pi(I = 2)$)
- Large volume $\gtrsim 4.5$ fm
- Scaling errors appear modest
- Physics prospects look bright ($K \to \pi\pi$, Nucleons, QCD thermo, ...)

Calculations done on NY Blue and QCDOC supercomputers at Brookhaven National Lab, Argonne National Lab Bluegene P, and the RICC cluster at RIKEN. Thanks to BNL, RBRC, RIKEN, and USQCD for computational resources.

Viscous fluid and particles

Denes Molnar

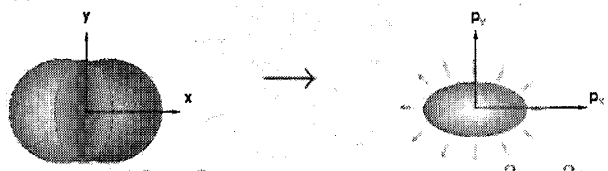
Purdue University and RIKEN BNL Research Center (recent graduate)

for RBRC Annual Review

Oct 27-29, 2010, RIKEN BNL Research Center, Upton, NY

RHIC collisions look largely thermalized → should be able to measure equation of state and viscosity

e.g., efficient conversion of spatial eccentricity to momentum anisotropy

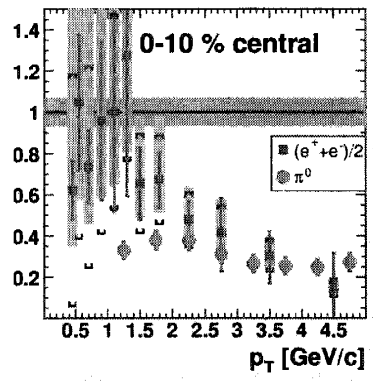


"elliptic flow"

$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle} \qquad v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \equiv \langle \cos 2\phi_p \rangle$$

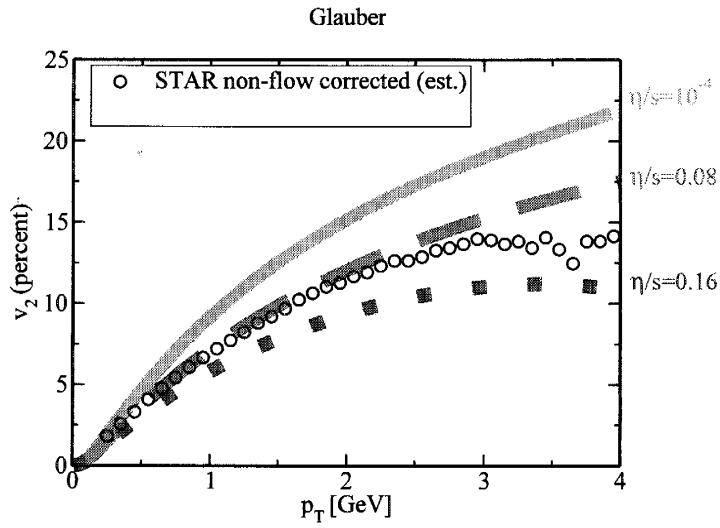
large energy loss, even for heavy quarks

$$R_{AA} = \frac{measured\ yield}{expected\ yield\ for\ dilute\ system}$$



Shear viscosity from RHIC data

Romatschke & Luzum, PRC78 ('08): **data vs 2+1D viscous hydrodynamics**



great, but in the end gave only conservative estimate $\eta/s \lesssim 0.5$

many uncertainties: hydro validity, $\eta/s(T)$**, initial conditions, decoupling, ...**

Main dynamical frameworks

- **causal relativistic hydrodynamics** Israel, Stewart; ... Muronga, Rischke; Teaney et al; Romatschke et al; Heinz et al, DM & Huovinen

$$\partial_\mu T^{\mu\nu} = 0 \qquad (\mu_B \to 0)$$

$$T^{\mu\nu} = (e+p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu}$$

$$\dot{\pi}^{\mu\nu} = F^{\mu\nu}(e,u,\pi,\Pi) \quad , \qquad \dot{\Pi} = G(e,u,\pi,\Pi)$$

e.g. Israel-Stewart theory

- **covariant transport** Israel, de Groot,... Zhang, Gyulassy, DM, Pratt, Xu, Greiner...

$$p^\mu \partial_\mu f = C_{2\to 2}[f] + C_{2\leftrightarrow 3}[f] + \cdots$$

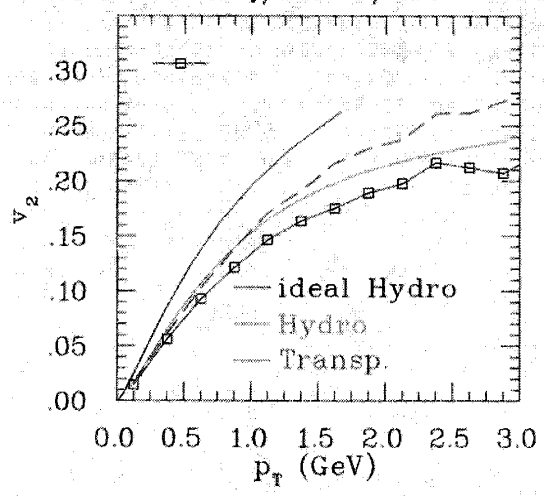
fully causal and stable

near hydrodynamic limit, transport coefficients and relaxation times:

$$\eta \approx 1.2T/\sigma_{tr}, \qquad \tau_\pi \approx 1.2\lambda_{tr}$$

Validity of hydrodynamics

IS hydro accurate for $\eta/s \approx 1/4\pi$ DM & Huovinen, JPG35 ('08)



relevant condition: high-enough inverse Knudsen number Huovinen & DM, PRC79 ('08)

$$K_0 \equiv \frac{\tau}{\lambda_{tr}} = \frac{\tau_{exp}}{\tau_{scatt}} \approx \frac{6\tau_{exp}}{\tau_\pi} > \sim 2-3$$

in terms of shear viscosity

$$\frac{\eta}{s} \sim \frac{2.6}{4\pi K_0} \lesssim 2 \times \frac{1}{4\pi}$$

Hydro → particles

heavy-ion applications in the end must match hydrodynamics to a particle description

- **in local equilibrium - one-to-one maping**

$$T^{\mu\nu}_{LR} = diag(e,p,p,p) \qquad \Leftrightarrow \qquad f_{eq,i} = \frac{g_i}{(2\pi)^3} e^{-p_i^\mu u_\mu / T}$$

- **near local equilibrium - one-to-many**

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \delta T^{\mu\nu} \qquad \Leftarrow \qquad f_i = f_{eq,i} + \delta f_i$$

corrections crucially affect basic observables - spectra, elliptic flow, ...

issue arises both in pure hydro and hydro + transport calculations

for massless gas, with viscous shear only

$$\delta f \equiv f_{eq} \times C(\chi)\, \pi^{\mu\nu} \frac{p_\mu p_\nu}{T^2}\, \chi(\frac{p}{T})$$

from Grad's ansatz: $\chi \equiv 1$

this is a starting point in deriving IS hydro from kinetic theory

from linear response: $\chi(x) \sim x^\alpha$ with $-1 \lesssim \alpha \lesssim 0$ Dusling, Teaney, Moore, ('09)

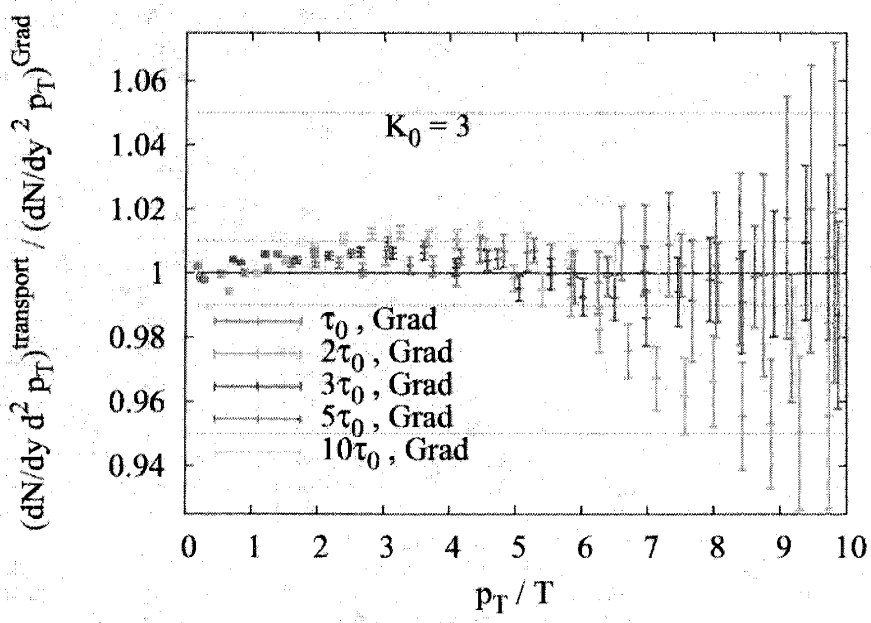
but δf blows up at large momenta $\Rightarrow$ approximation breaks down

check from nonlinear transport how far we can trust these...

Grad ansatz vs $2 \to 2$ transport

ratio - transport spectra / Grad approximation, $\eta/s \sim 0.1$

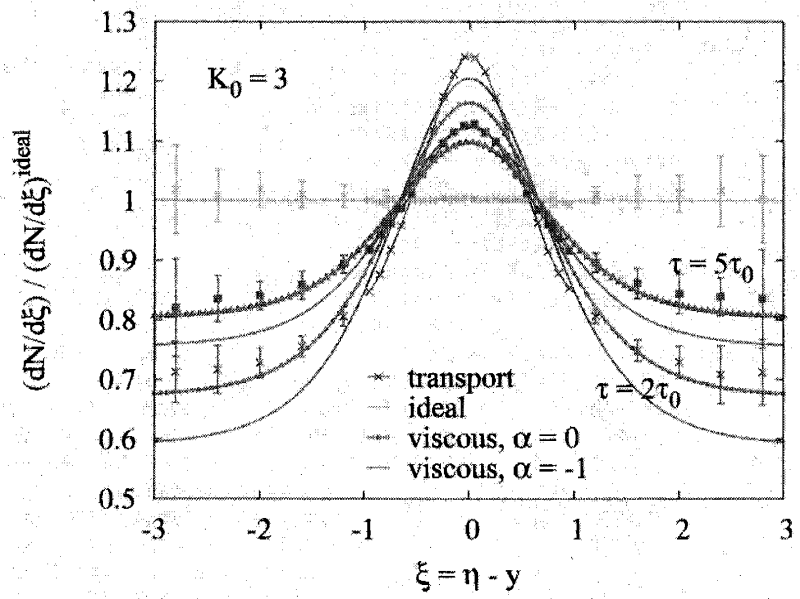
DM ('09):



Grad spectra are $\approx 1\%$ accurate even at $p_T/T = 6$(!)

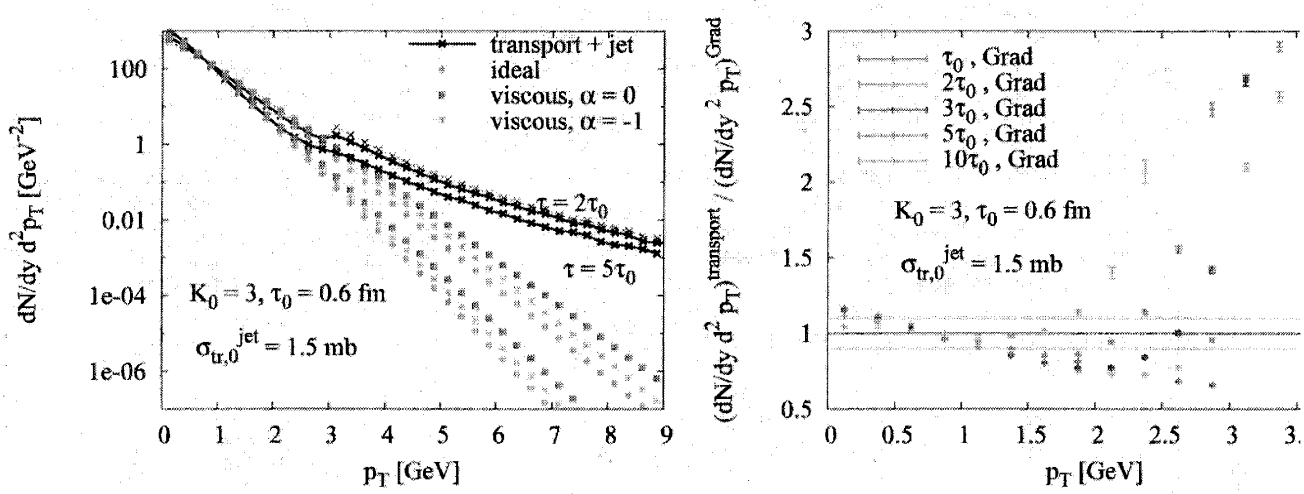
although Grad ansatz not as good for rapidity $\xi = \eta - y$ correlation

$\frac{dN/d\xi}{dN^{ideal}/d\xi}$ **distributions relative to IDEAL hydro,** $\eta/s \sim 0.1$ DM ('09-'10)



in practice, though, accuracy is limited by pQCD power-law tails DM ('09)-('10)

spectra **transport spectra / Grad approximation**



$[\text{bulk: } \eta/s \sim 0.1, \quad \text{jets: } \sigma_{tr} = T_0^2/T^2 \cdot 1.5 \text{ mb}, \quad T_0 = 385 GeV]$

with Grad, even $\approx 10\%$ accuracy extends only up to $p_T \sim 1.5$ GeV

Hydro $\longrightarrow$ gas mixture

must be tackled to address IDENTIFIED particle data

(!) from ONE set of viscous fields we need to obtain δf_i for EVERY species

commonly used "democratic" prescription:

$$\delta f_i \equiv f_i^{eq} \times \frac{\pi^{\mu\nu}}{2(\epsilon + p)} \frac{p_{\mu,i} p_{\nu,i}}{T^2} \qquad (i = \pi, K, p, \Lambda, ...)$$

ignores equilibration dynamics

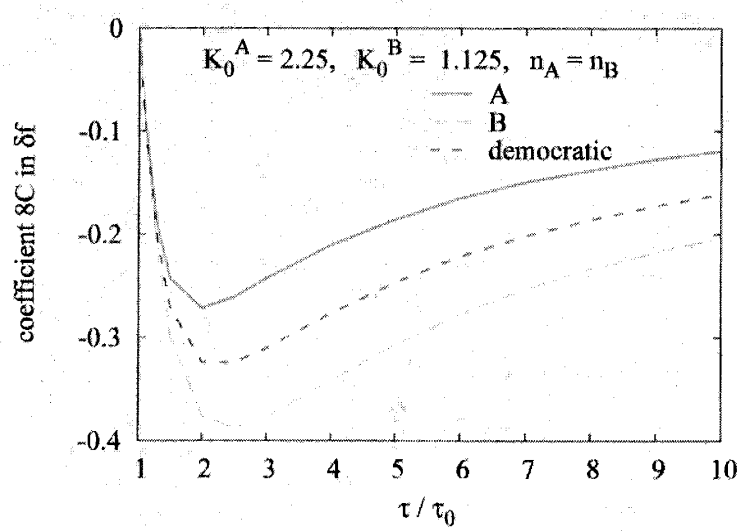
$$K_i \sim \frac{\tau}{\lambda_i} \sim \tau \sum_j n_j \sigma_{ij}$$

key drivers: <u>relative</u> Knudsen numbers between species K_j/K_i

Democratic vs $2 \longrightarrow 2$ transport

2-component 0+1D Bjorken test DM ('10) - A equilibrates twice as fast as B

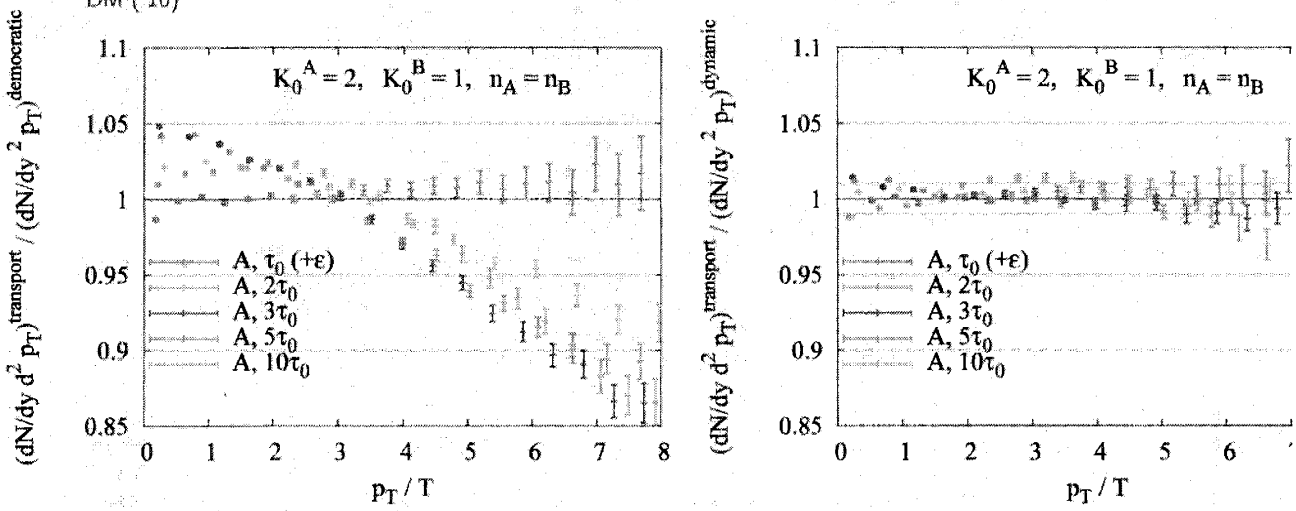
$$\delta f_i = C_i \, (p_T/T)^2 (\mathrm{sh}^2 y - 1/2) f_i^{eq} \qquad \pi_{L,i}/p_i = 8C_i$$



"democratic" ansatz misses viscous effects by $\sim 25 - 30\%$

transport spectra / "democratic" Grad vs transport / dynamical Grad

DM ('10)



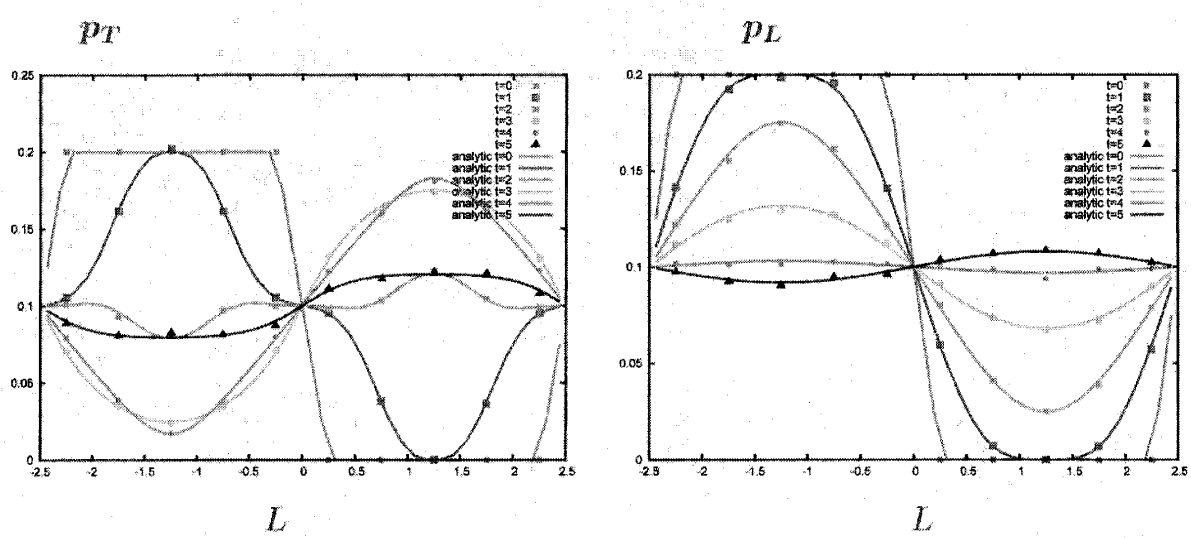
"democratic" Grad prescription not accurate

we must include dynamically determined partial shear stresses

⇒ will a one-component viscous hydro be sufficient?

progress also on another front...

D. Hemphill & DM, ('10): **pressure evolution in a box from grid transport algorithm**



everything in place for adding collisions, eventually radiative $3 \leftrightarrow 2$

Summary

Accurate determination of bulk properties from RHIC heavy-ion data will require assessment of theoretical uncertainties.

Based on comparison againts $2 \to 2$ covariant transport, prospects for application of viscous hydrodynamics at RHIC conditions look promising:

- **IS hydrodynamics was accurate to within 10%, if $\eta/s \lesssim 0.2$**
- **the Grad ansatz was ~ 1% accurate for spectra up to $p_T/T \sim 6$, if $\eta/s \lesssim 0.1$, even for two-component systems**

An open challenge is obtaining per-species dissipative corrections from one-component viscous hydrodynamics. "Democratic" sharing, though commonly assumed, is inaccurate.

And of course, the caveats: massless particles, Boltzmann limit, $2 \to 2$ transport, Bjorken expansion, (often) ignored pQCD power-law tails, ...

Complete set of Israel-Stewart equations of motion

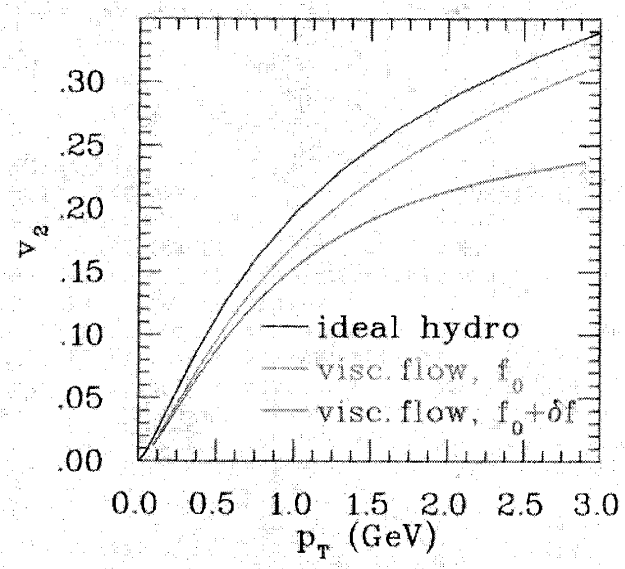
$$
\begin{aligned}
D\Pi &= -\frac{1}{\tau_\Pi}\left(\Pi + \zeta \nabla_\mu u^\mu\right) \\
&\quad -\frac{1}{2}\Pi\left(\nabla_\mu u^\mu + D\ln\frac{\beta_0}{T}\right) \\
&\quad +\frac{\alpha_0}{\beta_0}\partial_\mu q^\mu - \frac{a_0'}{\beta_0} q^\mu D u_\mu \qquad (1)\\
Dq^\mu &= -\frac{1}{\tau_q}\left[q^\mu + \kappa_q \frac{T^2 n}{\varepsilon + p}\nabla^\mu\left(\frac{\mu}{T}\right)\right] - u^\mu q_\nu D u^\nu \\
&\quad -\frac{1}{2} q^\mu\left(\nabla_\lambda u^\lambda + D\ln\frac{\beta_1}{T}\right) - \omega^{\mu\lambda} q_\lambda \\
&\quad -\frac{\alpha_0}{\beta_1}\nabla^\mu \Pi + \frac{\alpha_1}{\beta_1}(\partial_\lambda \pi^{\lambda\mu} + u^\mu \pi^{\lambda\nu}\partial_\lambda u_\nu) + \frac{a_0}{\beta_1}\Pi D u^\mu - \frac{a_1}{\beta_1}\pi^{\lambda\mu} D u_\lambda \qquad (2)\\
D\pi^{\mu\nu} &= -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu} u^{\nu\rangle}\right) - (\pi^{\lambda\mu}u^\nu + \pi^{\lambda\nu}u^\mu) D u_\lambda \\
&\quad -\frac{1}{2}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda + D\ln\frac{\beta_2}{T}\right) - 2\pi_\lambda{}^{\langle\mu}\omega^{\nu\rangle\lambda} \\
&\quad -\frac{\alpha_1}{\beta_2}\nabla^{\langle\mu} q^{\nu\rangle} + \frac{a_1'}{\beta_2} q^{\langle\mu} D u^{\nu\rangle} \,. \qquad (3)
\end{aligned}
$$

where $A^{\langle\mu\nu\rangle} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(A_{\alpha\beta} + A_{\beta\alpha}) - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta}A^{\alpha\beta}, \qquad \omega^{\mu\nu} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(\partial_\beta u_\alpha - \partial_\alpha u_\beta)$

Viscous hydro elliptic flow

TWO effects: - **dissipative corrections to hydro fields** u^μ, T, n
- **dissipative corrections to thermal distributions** $f \to f_0 + \delta f$

$\eta/s \approx 1/(4\pi) \qquad (\sigma \propto \tau^{2/3})$



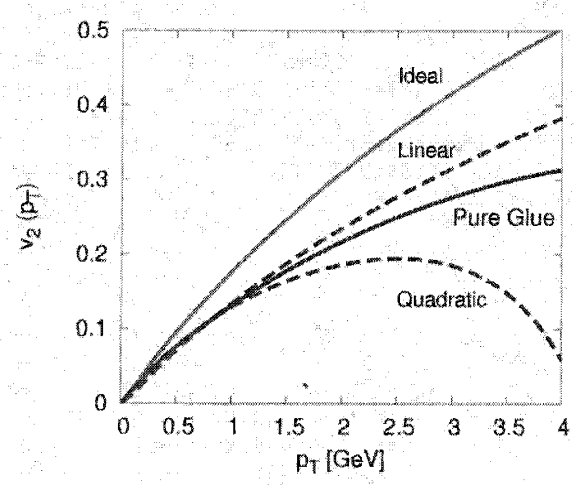
$\delta f = f_0 \left[1 + \frac{p^\mu p^\nu \pi_{\mu\nu}}{8nT^6}\right]$

calculation for $\sigma_{tr} = const \sim 15mb$ **shows similar behavior**

D. Teaney @ CATHIE-TECHQM WS (Dec '09):

Phenomenological Summary

pure glue, $\eta/s = 0.08$, $\epsilon_{\rm hyd} = 0.6\ {\rm GeV/fm}^3$



pQCD is closer to a linear (τ_R = const) rather than a quadratic ansatz

Teaney

Small x evolution in impact parameter space

Anna Stasto
Penn State & RIKEN BNL

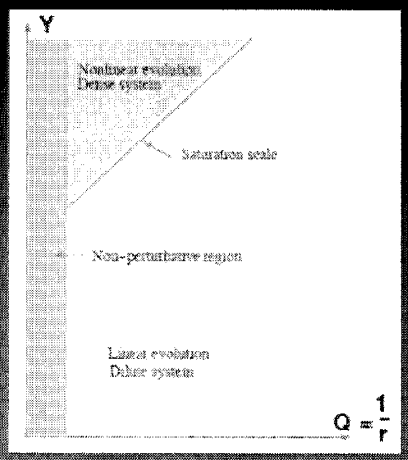
RBRC Review Meeting, October 28, 2010

Introduction

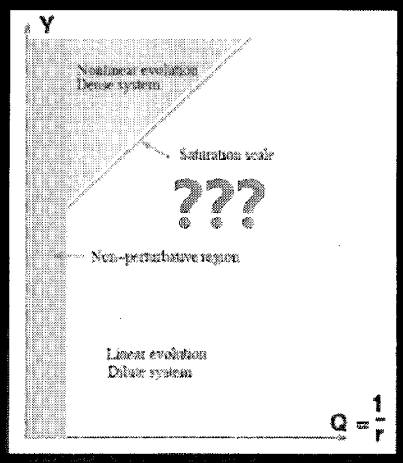
- With decreasing x (increasing energy) the gluon density rises very fast.
- Need to include parton saturation corrections.
- Dipole approach to saturation: BK evolution equation for the dipole scattering amplitude (dipoles: qqbar dipoles, good degrees of freedom at small x)

$$\frac{\partial N_{\mathbf{x}_0\mathbf{x}_1}}{\partial Y} = \bar{\alpha}_s \int \frac{d^2\mathbf{x}_2}{2\pi} \frac{(\mathbf{x}_0-\mathbf{x}_1)^2}{(\mathbf{x}_0-\mathbf{x}_2)^2(\mathbf{x}_1-\mathbf{x}_2)^2} \left[N_{\mathbf{x}_0\mathbf{x}_2} + N_{\mathbf{x}_1\mathbf{x}_2} - N_{\mathbf{x}_0\mathbf{x}_1} - N_{\mathbf{x}_0\mathbf{x}_2} N_{\mathbf{x}_1\mathbf{x}_2}\right]$$

- Typically BK solved in a local approximation: without impact parameter dependence.
- Can be solved (at least numerically) relatively easily.
- Generates the saturation scale that divides the dense and dilute regime.



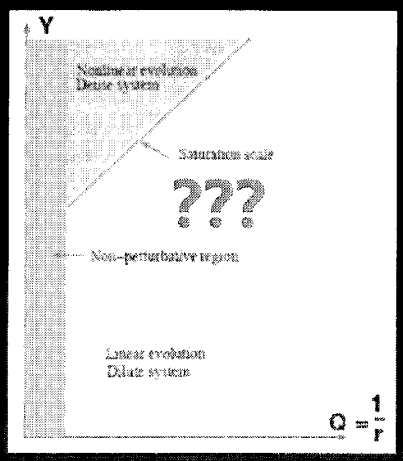
What about spatial distribution?



- Local approximation suggests that the system becomes more and more perturbative as the energy grows.
- But this cannot be true, for example in conformal theory there should be symmetry between IR and UV regions.
- In QCD, much increased sensitivity to IR.
- Need to take into account details of spatial distribution.
- Nonlinear evolution is nonlocal by construction (i.e. properties of the triple pomeron vertex).

Impact parameter profile

What about spatial distribution?



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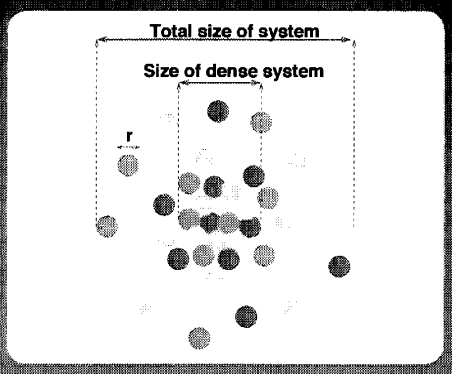

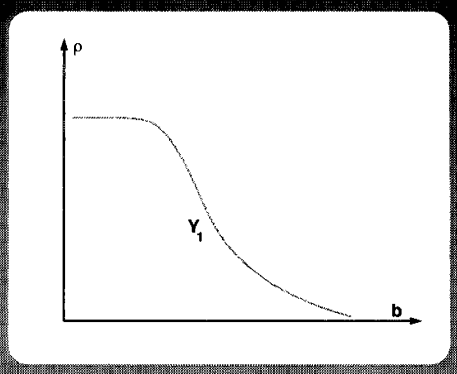

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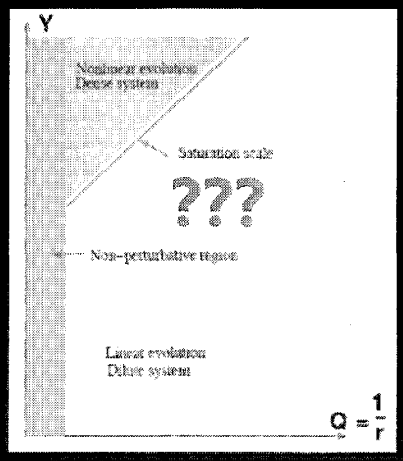

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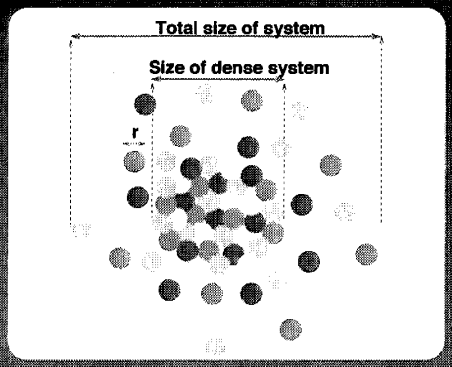
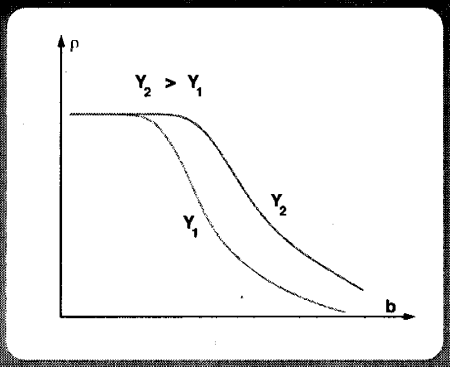


Impact parameter profile



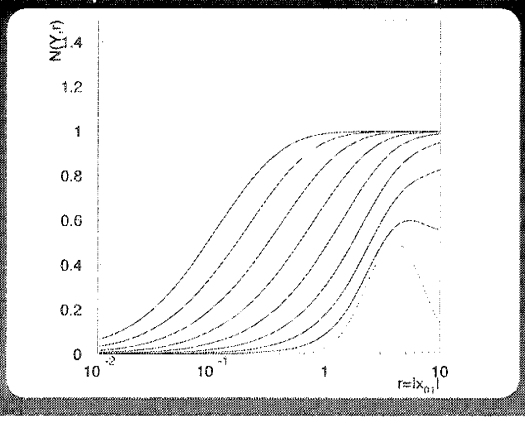
Including impact parameter dependence

- Apart from the x and transverse momentum (or the size of the probe) one needs to take into account the spatial distribution and the angular dependencies.
- Instead of 1 degree of freedom (single transverse momentum/size), there are now have 4 degrees of freedom
- Assumed cylindrical symmetry of the interaction region and calculated numerically (parallel computing on a cluster of 32 machines; 2-3 days to evaluate to rapidities maximum of 60 or so.)

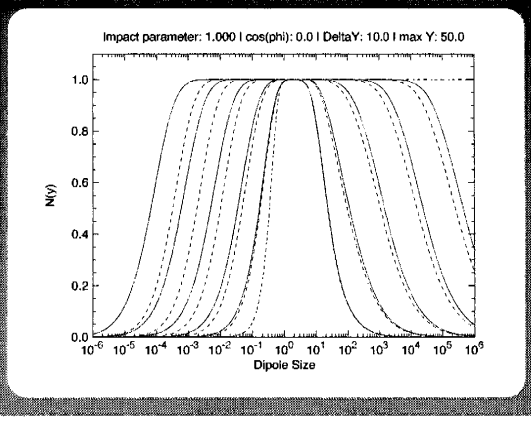
K.Golec-Biernat, A.Stasto 2003;
J.Berger, A.Stasto, 2010

Without impact parameter dependence

Dipole amplitude as a function of dipole size

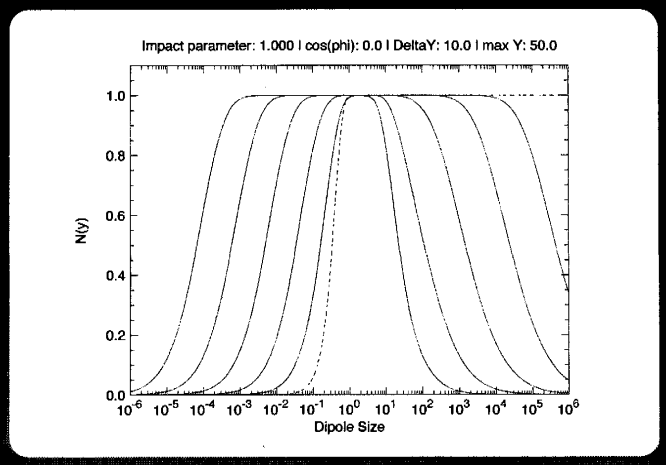


With impact parameter dependence



Impact parameter dependence

Amplitude as a function of the dipole size for fixed impact parameter



Probability of interaction is symmetric with respect to small and large dipoles (almost)

Now there are two saturation scales: for small and large sizes; UV and IR regions.

Slight asymmetry due to the assumption of the cylindrical symmetry of the interaction. This assumption can be relaxed.

Conformal symmetry at LO

$$\frac{d^2\mathbf{z}\,(\mathbf{x}-\mathbf{y})^2}{(\mathbf{y}-\mathbf{z})^2\,(\mathbf{x}-\mathbf{z})^2}$$

integral kernel of the evolution is invariant under Moebius transformations

$$x \to \frac{a\,x+b}{c\,x+d}$$

where $x = x_1 + i x_2, \quad \mathbf{x} = (x_1, x_2)$

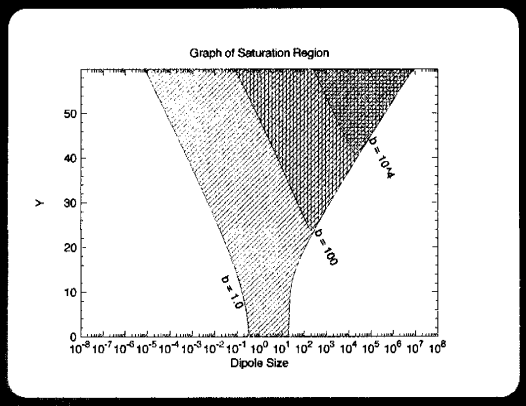
$$N\left(\frac{r_0^2}{r^2}\right) \quad \text{when} \quad r \gg b, r_0$$

$$N\left(\frac{r^2 r_0^2}{b^4}\right) \quad \text{when} \quad r, r_0 \ll b$$

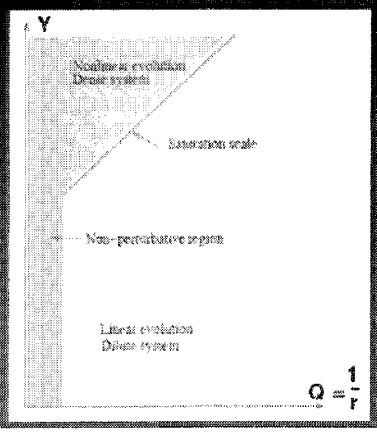
These properties stem from conformal invariance of the evolution (when the coupling is fixed)

How does the saturation picture change?

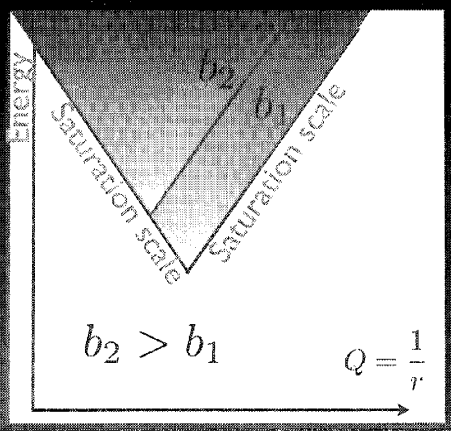
Infrared region no longer completely cutoff by saturation



'V' shape of saturation

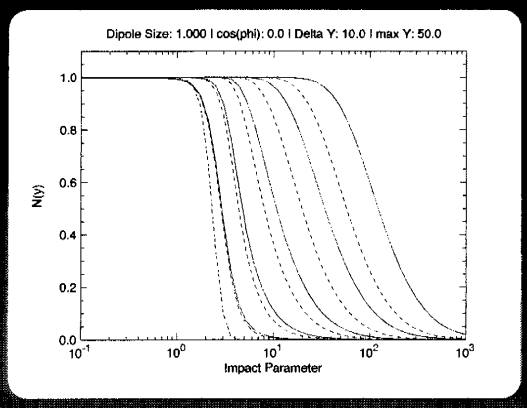


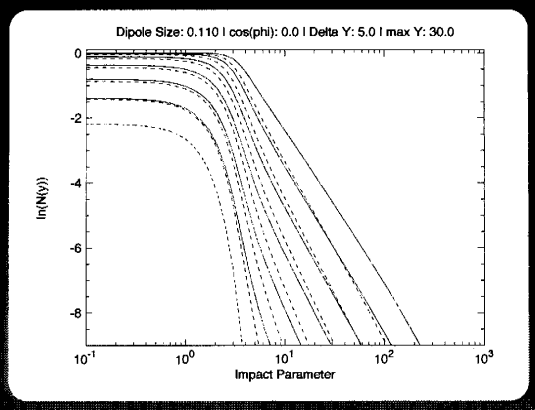
Including b dependence →



Nonlinear evolution with impact parameter dependence

Impact parameter profile of the interaction region





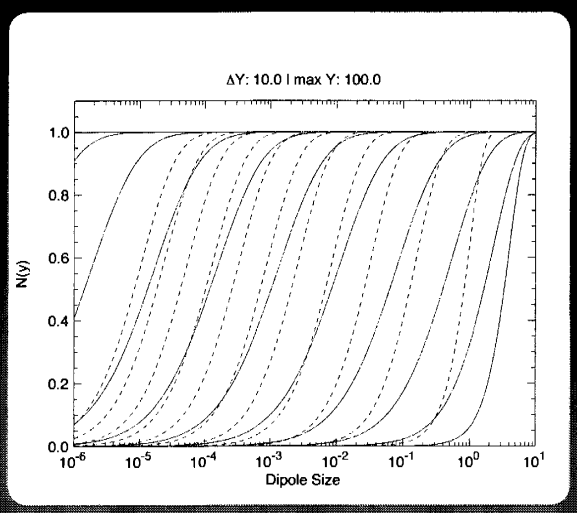
- Saturation for small impact parameters
- No saturation for large impact parameters (system is still dilute)
- Initial impact parameter profile is not preserved
- Power tail in b is generated, this is due to perturbative evolution and lack of confinement effect.

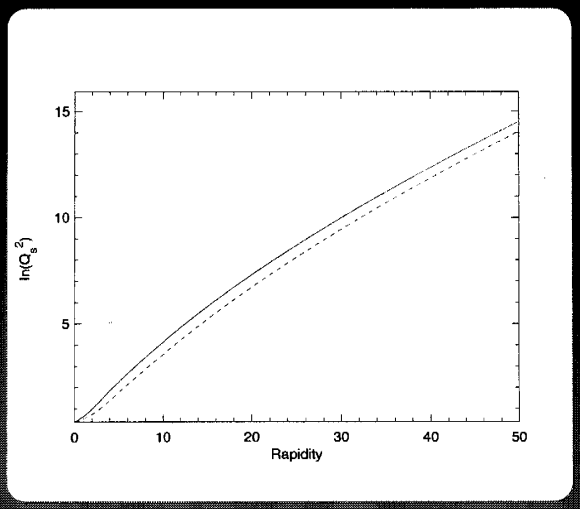
Beyond LL

- It is known that NLL corrections to BFKL are large.
- How does that affect nonlinear evolution?
- Full NLL difficult to solve with impact parameter (additional integrals).
- Investigate running coupling and kinematical constraints (partial NLL).
- Very different results for approximate and full case (with impact parameter).

Including NLO: running coupling

Without impact parameter:





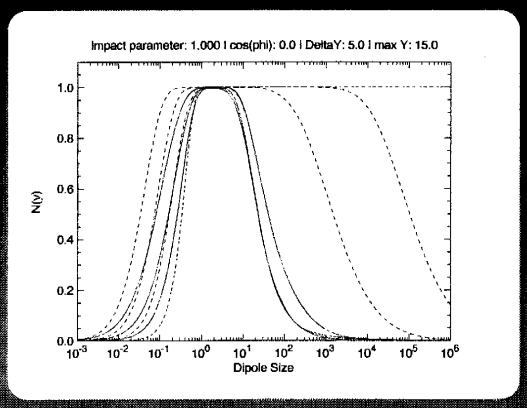
$$Q_s \sim \exp(c\sqrt{Y + Y_0})$$

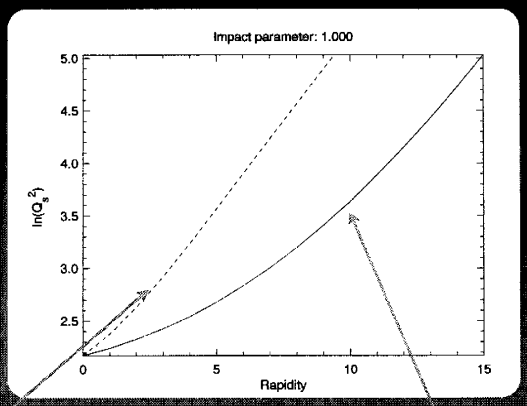
Evolution slowed down, saturation cuts off infrared regime hence there is no sensitivity to infrared regularization

Including NLO: running coupling

With impact parameter:

Now the saturation does not help, the solution is completely dominated by the IR region. Consistent with previous solutions to NLO BFKL (G. Salam et al., tunneling scenario, observed by Avsar et al in MC approach)





running coupling $\alpha_s(r_{cut}) = 0.3$

fixed coupling $\alpha_s = 0.1$

Kinematical cutoffs

Include (partially) effects of kinematics.
Modified kernel

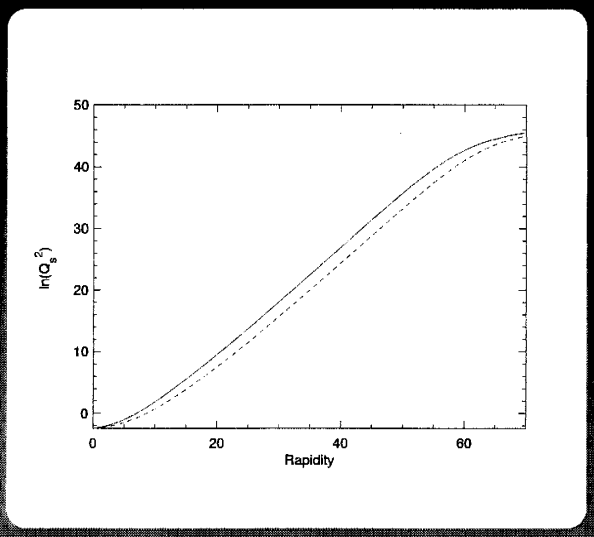
$$\frac{dz}{z}\, z\, \frac{d^2\mathbf{x}_2}{x_{01}^2}\left[K_1^2\left(\frac{x_{02}}{x_{01}}\sqrt{z}\right) + K_1^2\left(\frac{x_{12}}{x_{01}}\sqrt{z}\right) - 2\,K_1\left(\frac{x_{02}}{x_{01}}\sqrt{z}\right) K_1\left(\frac{x_{12}}{x_{01}}\sqrt{z}\right)\frac{\mathbf{x}_{02}\cdot\mathbf{x}_{12}}{x_{02}x_{12}}\right]$$

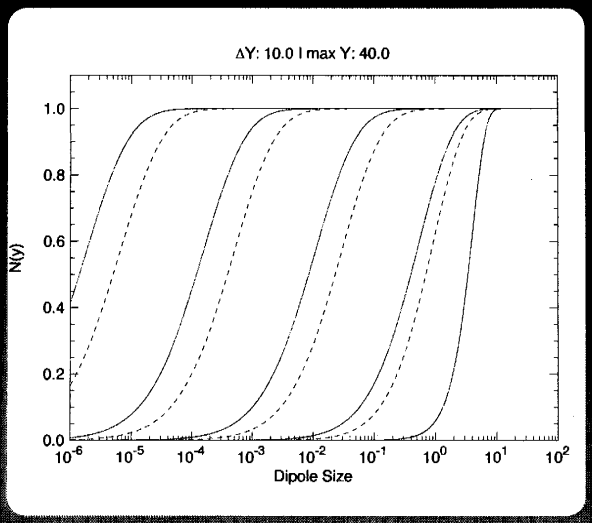
Similar to previous work, (Kwiecinski; Salam et al; Avsar, Loonblad, Gustafson)

Does not exhaust all the corrections, likely <u>underestimate</u> the effect of the NLO or resummed case.

Kinematical cutoffs

No impact parameter dependence

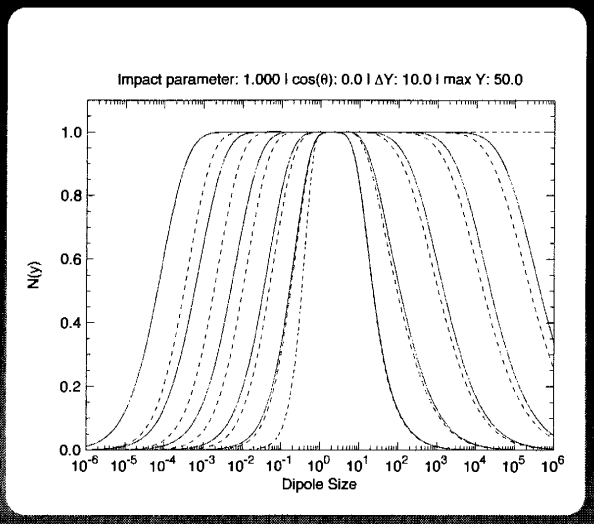


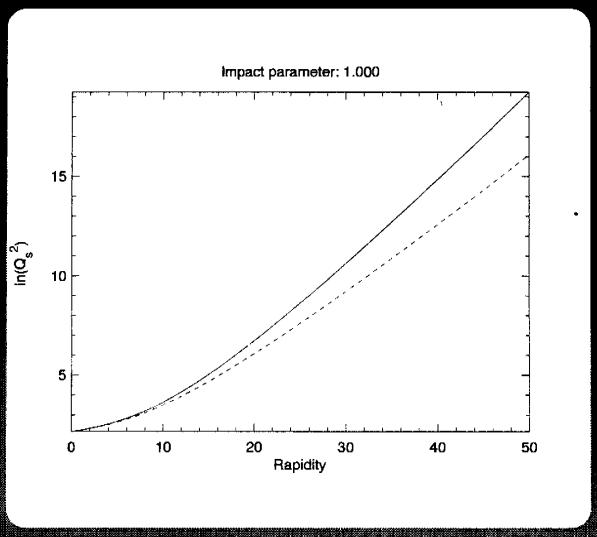


Only change in normalization, the exponent of the saturation scale is not affected (?!)

Kinematical constraint

With impact parameter is rather different...





Evolution slowed down significantly.Reduction of the exponent by 18% to 43% for coupling constant

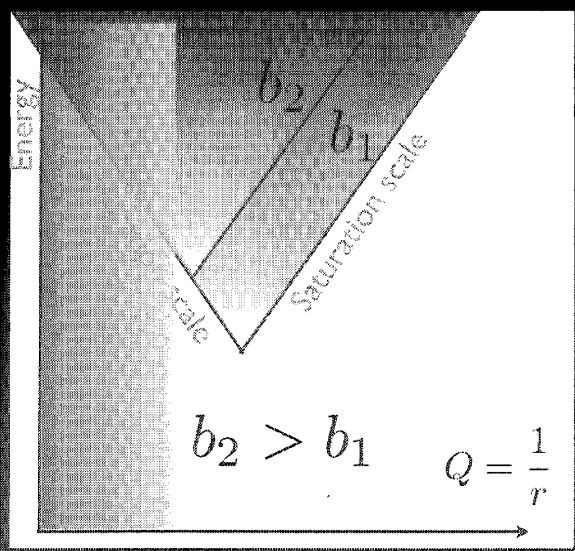
$$0.1 \leq \bar{\alpha}_s \leq 0.2$$

$$Q_s^2 \sim \exp(\alpha_s \lambda_s(\alpha_s) Y)$$

	λ_s
LO Kernel (1) $\bar{\alpha}_s = 0.1$	4.4
LO Kernel (2) $\bar{\alpha}_s = 0.1$	4.4
Modified Kernel $\bar{\alpha}_s = 0.1$	3.6
LO Kernel $\bar{\alpha}_s = 0.2$	4.4
Modified Kernel $\bar{\alpha}_s = 0.2$	2.5

Again consistent with previous results on NLL BFKL

Modified picture



Confinement

Extreme sensitivity to IR (ex. running coupling). Need to include confinement effects. Will effect the expansion of the interaction region and the total cross section. Correlations will modify the picture even more.

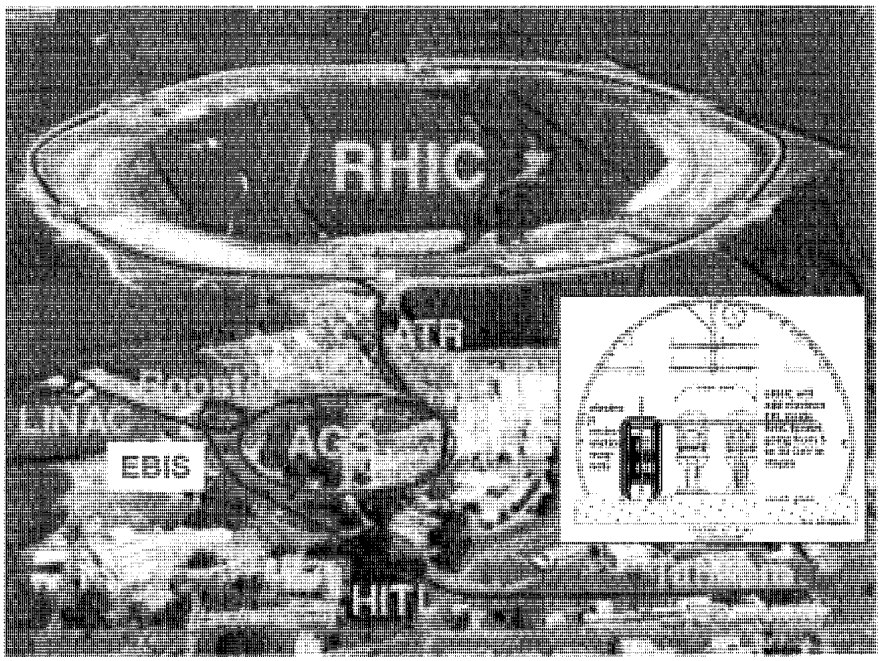
Summary and outlook

- Numerical simulations with impact parameter dependence. New methods allow to evaluate the solution relatively fast.
- Large qualitative and quantitative differences between b dependent and approximated case when NLL is included.
- NLL much more important in b dependent case (similarly to correlations). Consistent with previous investigations of NLL in linear case.
- Increased sensitivity to IR region.
- Expansion of the black disk radius and effects of confinement mass also investigated (not presented here).
- <u>Outlook:</u>
- Include the additional angle. Technically possible, need to optimize the computation.
- Full NLL and/or resummed case + correlations needed.

BNL Future Plans for RHIC and eRHIC

October 27, 2010 RBRC Meeting

T. Ludlam



RHIC So Far (2000 – 2010)

200 GeV Au-Au, d-Au:

- **Jet quenching, Flow...** Perfect Liquid
- **Long range near-side rapidity correlations...** "Ridge"
- **Forward supression in d-Au...** Gluon saturation

} CGC; Glasma

Energy scan in Au-Au collisions:

- **Search for QCD tri-critical point...** Begin mapping the QCD phase diagram

Proton spin measurements at 200 GeV:

- **A_{LL} measurements vs. x...** Constrain gluon spin contribution near zero
- **Discovery of large transverse asymmetries...** New window on QCD and spin structure
- **First measurements at 500 GeV...** $W^{\pm}$ production and asymmetry

Detector upgrades:

- **PHENIX...** HBD, VTX, FVTX, Muon trigger...
- **STAR...** EEMC, DAQ 1000, TOF, HFT started...

NSAC Performance Measures ("Milestones") evaluation August 2008:
The RHIC HI results were the only nuclear physics subfield where progress toward accomplishing original performance milestones received the highest rating.

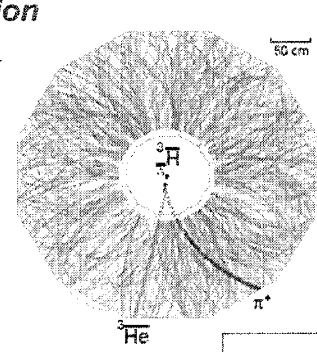
Future NSAC Milestones

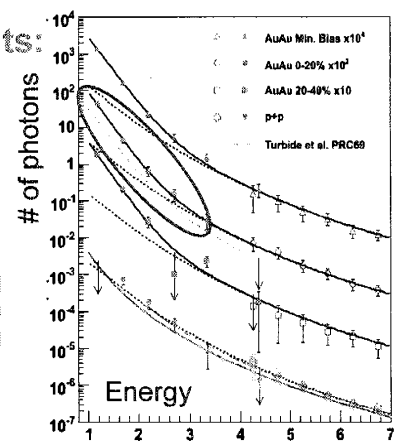
	Year	#	Milestone
Spin	2013	HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
Spin	2013	HP12 (update of HP1)	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
Spin	2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
Heavy Ion	2014	DM9 (new)	Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.
Heavy Ion	2014	DM10 (new)	Measure jet and photon production and their correlations in A≈200 ion+ion collisions at energies from medium RHIC energies to the highest achievable energies at LHC.
Heavy Ion	2015	DM11 (new)	Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at √sNN between 5 and 60 GeV to search for evidence of a critical point in the QCD matter phase diagram.
Heavy Ion	2016	DM12 (new)	Measure production rates, high pT spectra, and correlations in heavy-ion collisions at √sNN = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.
Heavy Ion	2018	DM13 (new)	Measure real and virtual thermal photon production in p + p, d + Au and Au + Au collisions at energies up to √sNN = 200 GeV.

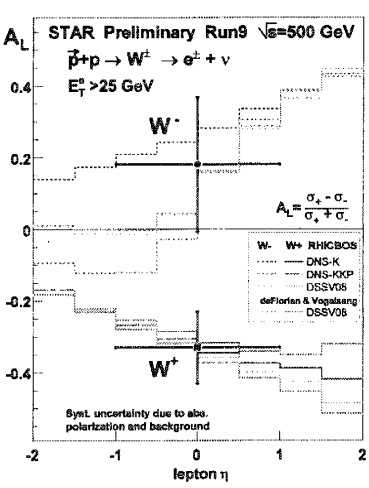
RHIC's 10th Year: Quite Possibly the Best Yet

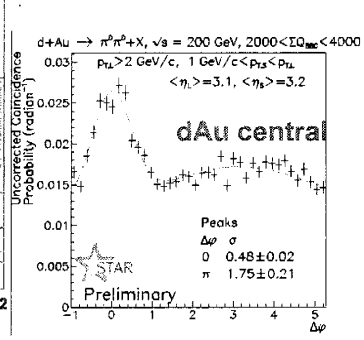
Steady stream of high-impact new science results:

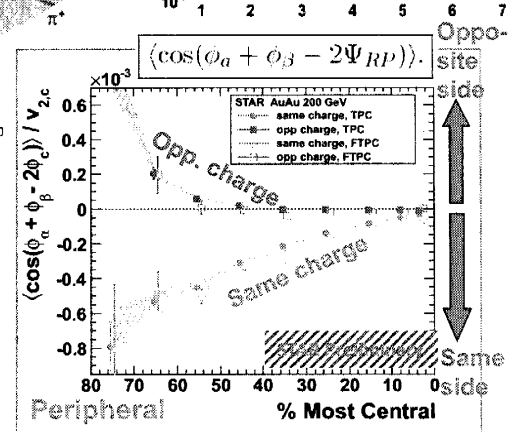
1) $T_{init} \gtrsim 300\ MeV \sim 4 \times 10^{12} K > T_{crit}$, $T_{Hagedorn}$
2) *Hints of local parity violation*
3) *Anti-hypertriton discovery*
4) *d+Au "mono-jet" signal for gluon saturation*
5) *First W prod'n spin asym.*











Near-term Plans

Luminosity upgrade in Au-Au: RHIC II... Stochastic Cooling
EBIS turn-on... Uranium collisions accessible
500 GeV spin physics running
Feasibility study for a new Drell Yan experiment

Updated RHIC 5-year Run Plan: **Assumes funding for annual 2-species runs**

Year	Likely Beam Species	Science Goals	Comments
FY10 ✓	Au+Au at 200, 62.4 GeV + assorted lower E	Low-mass dilepton spectrum; early collision temp.; improved jet quenching studies (especially e^- from heavy quarks); begin energy scan for critical pt.	STAR TOF, PHENIX HBD fully operational. Commission stochastic cooling
FY11	200 GeV Au+Au; 500 GeV p+p; short 200 GeV U+U; continue low-E Au+Au scan	Bottom vs. charm suppression, flow; antiquark pol'n from W production; 1st characterization of deformation effects in U+U centrality distrib'ns; continue critical pt. search	PHENIX VTX engineering run. p-p luminosity improvements.
FY12	Au+Au at 200 GeV; 500 GeV p+p	RHIC-II HI goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations; anti-quark and low-x gluon polarizations in proton	PHENIX FVTX and μ trigger; PHENIX DAQ/trigger upgrades; STAR FGT
FY13	200 GeV p+p; further heavy-ion running to comple-ment earlier runs	Continue RHIC-II heavy-ion goals; transverse spin asymmetry for γ + jet, start on Drell-Yan? (2015 spin milestone); pp reference data for new subsystems	Electron lens commissioning ⇒ Run 13 pp luminosity gains possible; STAR HFT prototype.
FY14	200 GeV Au+Au; low-E Au+ Au dictated by Run 10+ 11 results	Continue pursuit of γ + jet, energy scan and identified heavy flavor (DM10-12) milestones.	Full STAR HFT installed. e-cooling for lowest energy Au-Au running.

New Developments in RHIC Spin

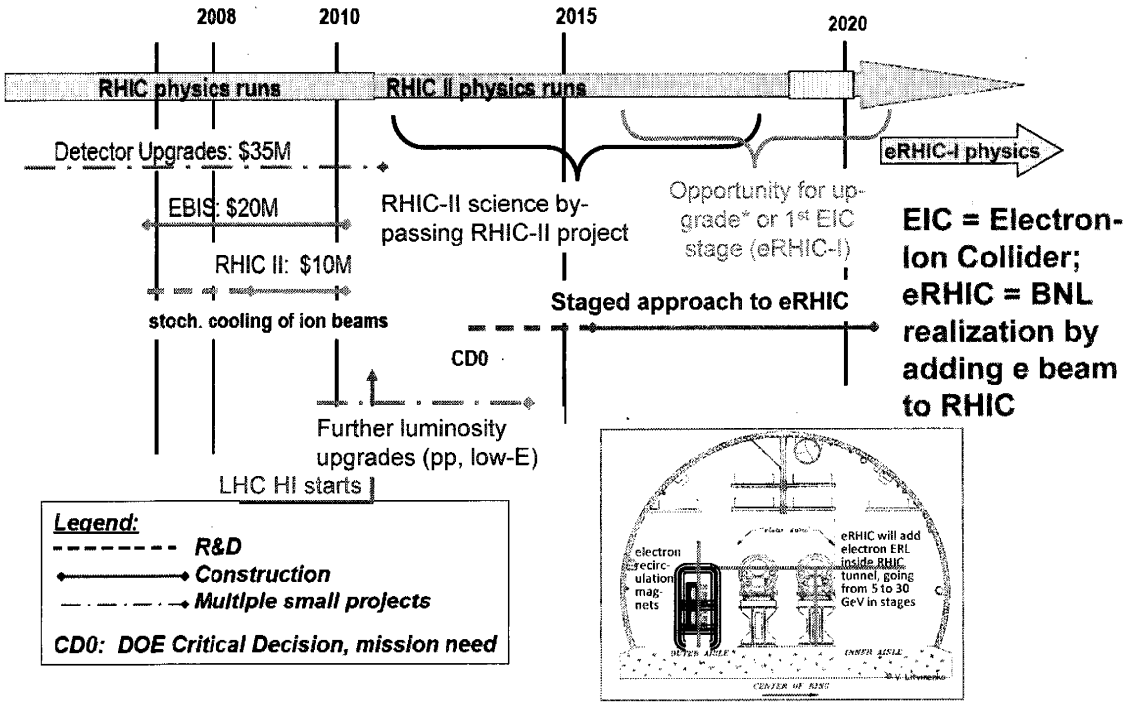
- **Elke Aschenauer has replaced Gerry Bunce as leader of the RHIC Spin group at BNL**
- **Jianwei Qiu and Marco Stratmann have joined BNL, and are now leading the spin theory effort.**
- **Elke has assumed leadership of the C-AD/Physics Dept. RHIC Polarimetry effort...**
  The rate-dependent effects found in Run 9 have been identified, and new DAQ hardware installed.

From Elke's presentation to the May 2010 DOE Medium Energy Physics review:

Next 5 (++) years:
- will concentrate on
  - core program of RHIC spin program in PheniX and STAR
    - Δg and Δq (HP8 and HP12)
  - develop a spin program for RHIC beyond the current spin plan
    - DY program for RHIC
      - to measure the sign change for the Sivers fct. in SIDIS and DY (HP-13)
      - evaluate the possibility of quark distributions in dAu
      - determine the requirements for discussed future forward upgrades in STAR & PheniX
        → next decadal plan
    - the gain of higher p-beam energies and running with polarized He-3
  - work on the physics case for eRHIC
    - transition of the RHIC spin collaboration into eRHIC spin collaboration
    - possibilities for ep/eA collisions in PheniX and STAR
  - RHIC Polarimetry
    - continuous improvements and developing polarimetry for eRHIC

These plans well received by DOE: FY 2011 funding allows growth of the group to 10 FTE

A Long Term (Evolving) Strategic View for RHIC



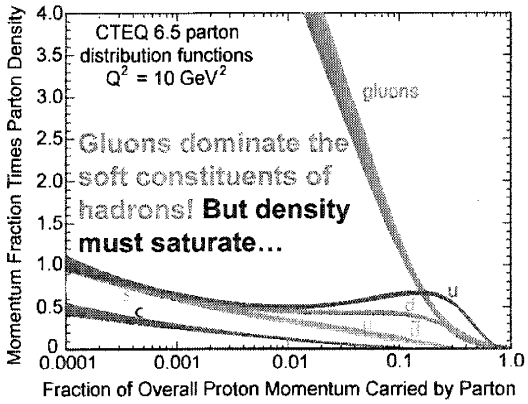
* New decadal plan charges given to STAR and PHENIX, reports due 10/1/10. Dedicated storage ring for novel charged-particle EDM measurements another option.

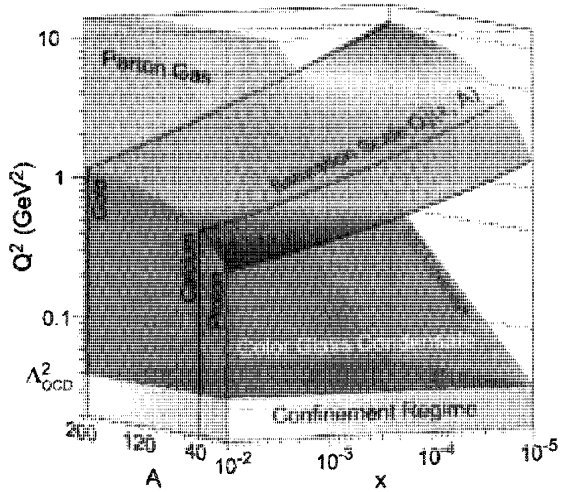
EIC Science: Gluon-Dominated Cold Matter in e+A

Search for supersymmetry @ LHC, ILC (?): *seeking to unify matter and forces*

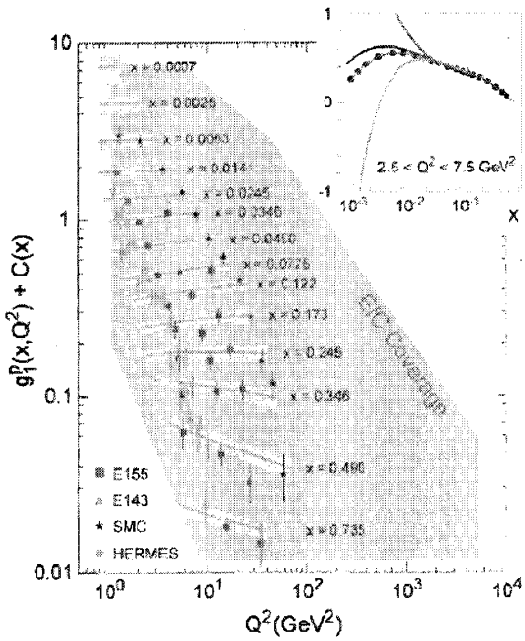
Electron-Ion Collider: *reveal that Nature blurs the distinction*

Deep inelastic scattering @ HERA ⇒





EIC probes *weak* coupling regime of very high gluon density, where gauge boson occupancy >> 1. ***All ordinary matter has at its heart an intense, semi-classical force field*** -- can we demonstrate its universal behavior? Track the transition from dilute parton gas to CGC? "See" confinement reflected in soft-gluon spatial distributions inside nuclei?

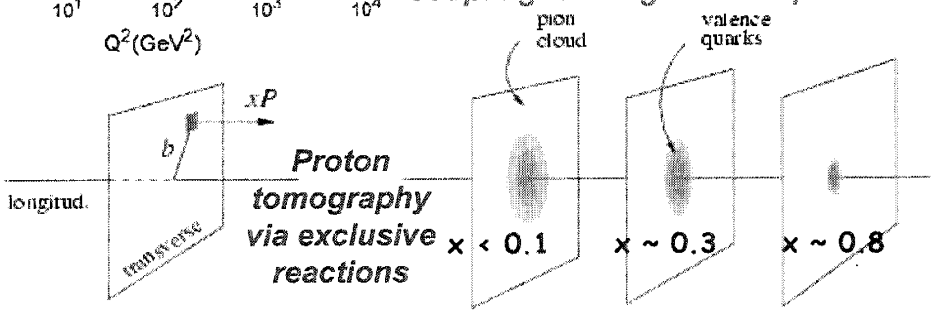


EIC $\vec{e} + \vec{p} \Rightarrow$ Important Extension of Nucleon Structure Studies at HERA, RHIC, JLab....

- *$\vec{DIS}$, γ-gluon fusion $\Rightarrow \Delta G(x >$ few $\times 10^{-4})$*
- *Bjorken sum rule test to $\lesssim \pm 2\%$*
- *SIDIS for low-x sea-quark polarization and transverse spin studies*

More luminosity-hungry:

- *Polarized DVCS, exclusive reactions + LQCD $\Rightarrow$ GPD's $\Rightarrow$ map low-x transverse position-dep. PDF's; J_q from Ji sum rule; J_g?*
- *High-Q^2 $\vec{e}+\vec{p,d}$ parity viol'n $\Rightarrow$ weak coupling running below Z-pole*



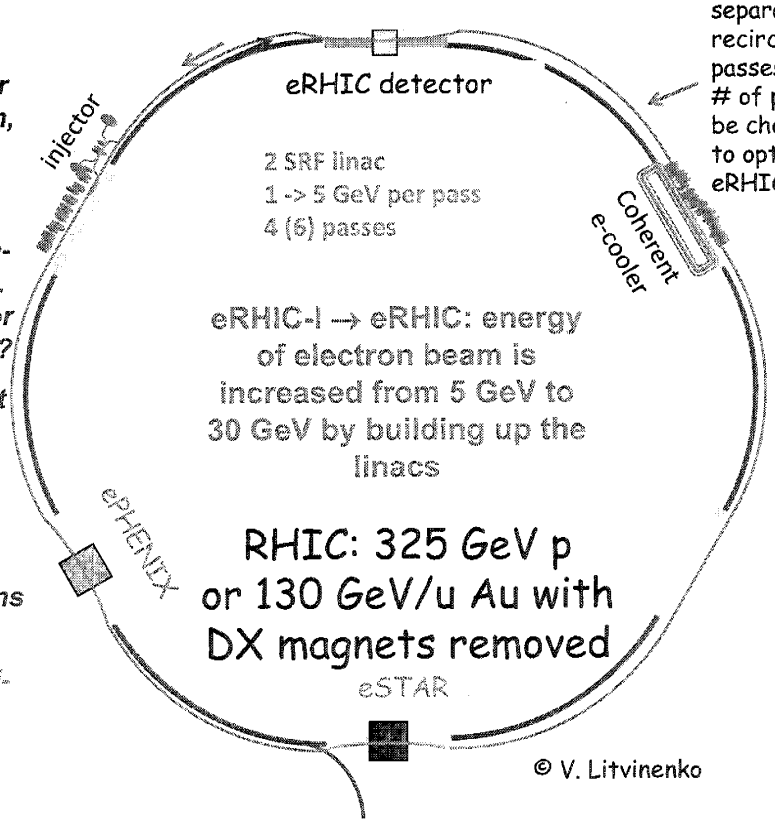
Proton tomography via exclusive reactions

eRHIC Design Currently Under Consideration

V. Litvinenko et al.

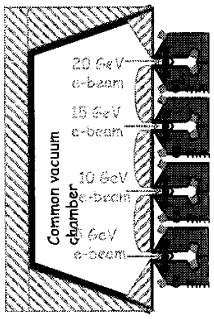
Vis-à-vis earlier MeRHIC design, this allows for:

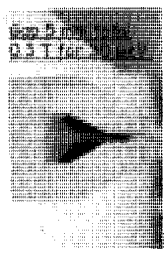
- *more IP's*
- *reusing infra-structure + det. components for STAR, PHENIX?*
- *reduced cost*
- *easier up-grade path*
- *minimal environmental impact concerns*
- *IR design to reach 10^{34} lumi-nosity*



eRHIC-I → eRHIC: energy of electron beam is increased from 5 GeV to 30 GeV by building up the linacs

Vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost





© V. Litvinenko

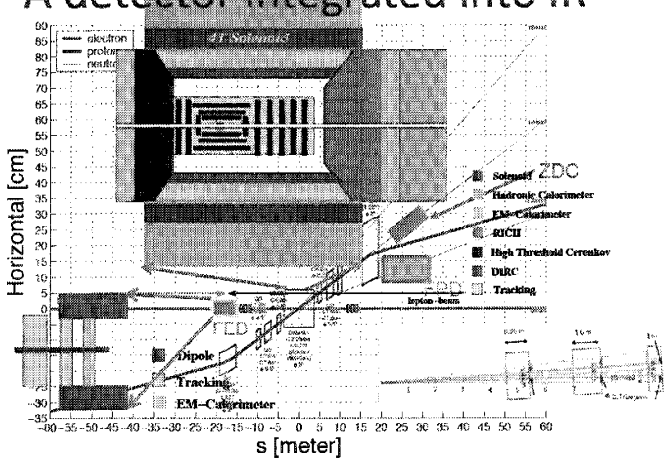
BNL's EIC Science Task Force

Led by Elke Aschenauer and Thomas Ullrich:

- **Develop the science case; "golden measurements"**
- **Develop detector & interaction region requirements; simulation tools**

Close interaction with accelerator group **(Vladimir Litvinenko)**; theory **(Raju Venugopalan, Jianwei Qiu, Marco Stratmann)**; international EIC collaboration **(Abhay Deshpande)**

A detector integrated into IR



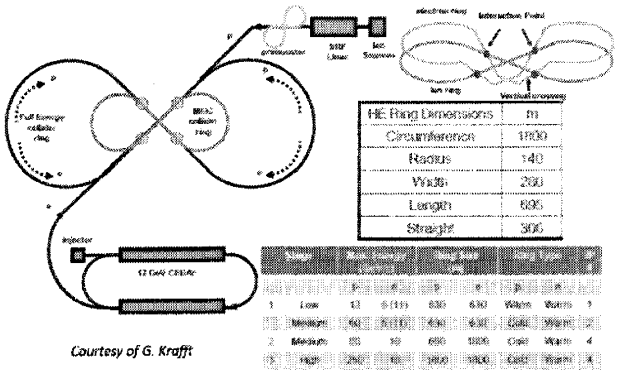
- Dipoles needed to have good forward momentum resolution
  - Solenoid no magnetic field @ r ~ 0
- DIRC, RICH hadron identification → π, K, p
- high-threshold Cerenkov → fast trigger for scattered lepton
- radiation length very critical → low lepton energies

DOE has funded an accelerator R&D program for EIC.

DOE & BNL are preparing an announcement of a detector R&D program for EIC.

BNL has funded a suite of LDRD projects targeted at accelerator, detector, and science development for eRHIC.

The national discussion for a U.S. Electron Ion Collider



Courtesy of G. Krafft

Competing design at Jlab: ELIC/MEIC

Focus on light ions, very high luminosity.
MEIC: $\sqrt{s}$ ~ 30 Gev; L ~ 10^{34}
ELIC: $\sqrt{s}$ ~ 100GeV; L ~ 10^{35}

EIC Advisory Committee appointed by BNL and JLab directors: how to proceed to a single proposal at next Nuclelar Physics Long Range Plan exercise.

- Ten-week workshop now on-going (thru Nov. 19) at Institute for Nuclear Theory (Seattle): EIC Science.
- Expect a follow-up "white paper" as input to Long Range Plan:
  Realizable EIC design, cost range, performance goals, science deliverables and upgrade paths.
- Timeline for down-select?
- Expect Long Range Plan resolution meeting ~2013
  Will there be a strong, unified user community for EIC?

BNL Planning Assumptions for eRHIC

S. Vigdor presentation to INT Workshop

- *Work on plan to allow straightforward upgrade path from 1st stage, but to incorporate starts on as much of the science program as possible in 1st stage* ***(needed to keep strong user community engaged ⇒ recent design advances)***

- ***Fully utilize RHIC A, p beams and infrastructure***

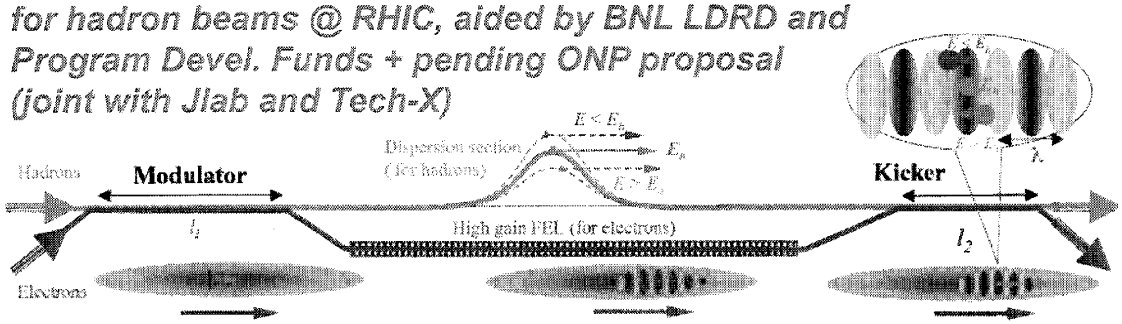
- *Utilize RHIC detector infrastructure, halls, subsystems as possible to control costs*

- ***Utilize BNL LDRD funds plus RHIC R&D funds to jump-start accelerator and detector R&D where possible***

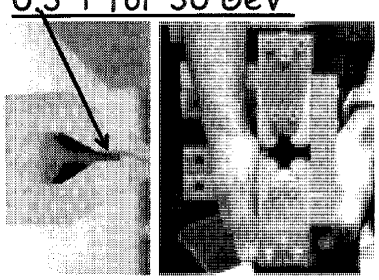
- *Work with JLab as possible to arrange collaborative approach to LRP*

Pursuing Aggressive R&D on Critical Technologies

- *Aiming for ~2014 proof-of-principle demo of Coherent e Cooling for hadron beams @ RHIC, aided by BNL LDRD and Program Devel. Funds + pending ONP proposal (joint with Jlab and Tech-X)*



Gap 5 mm total
0.3 T for 30 GeV



- ***Prototyping small-gap dipole and quadrupole magnets and vacuum chambers for compact recirculation arcs on electron beam, with BNL LDRD funds.***

- *Also exploring relevance of CeC for improving RHIC p+p luminosities and ERL-driven options for X-ray FEL (LDRD).*

All in addition to ongoing work on lattice, IR and detector design, plus beam & spin dynamics and beam-beam simulations.

EIC Advisory Committee (to JLab and BNL)

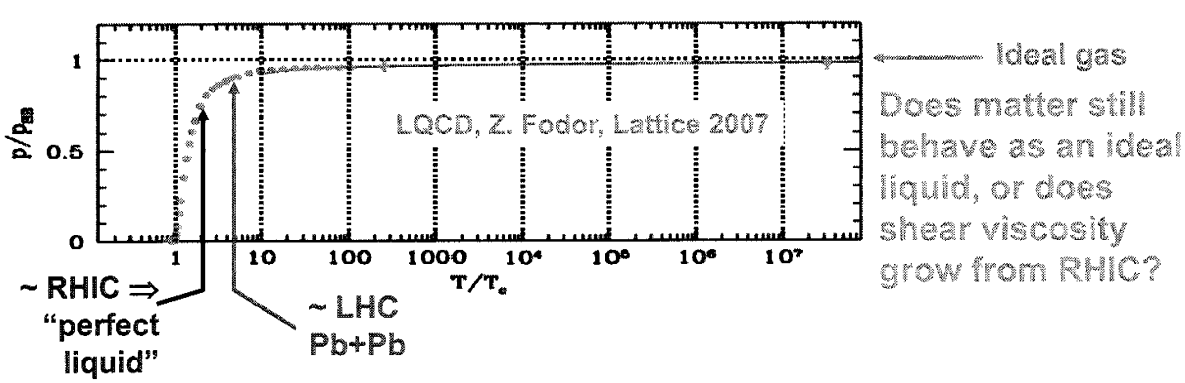
Joachim Bartels (Universitait Hamburg, DESY)
Allen Caldwell (Max-Planck Institute for Physics, Munich)
Albert De Roeck (CERN)
Walter Henning (ANL, Chair)
David Hertzog (University of Illinois)
Xiangdong Ji (University of Maryland)
Robert Klanner (DESY)
Al Mueller (University of Columbia)
Katsunobu Oide (KEK)
Naohito Saito (JPARC)
Uli Wienands (SLAC)

1st meeting 2/16/09. 2nd meeting 11/02/09.

Complementarity of LHC HI and RHIC-II

Steve Vigdor, RHIC Ops Review July 2010

LHC and RHIC-II HI results should be complementary & mutually stimulating: similar matter produced? How do properties evolve with temperature? Thermalization consistent?



A few tools (e.g., full jet reconstruction) may be sharper at LHC, but the focus on hot QCD matter will continue to be sharper at RHIC.

RHIC Status, Upgrades and Future Plans

- Towards higher luminosity and polarization
- Adding a polarized electron beam to RHIC: eRHIC

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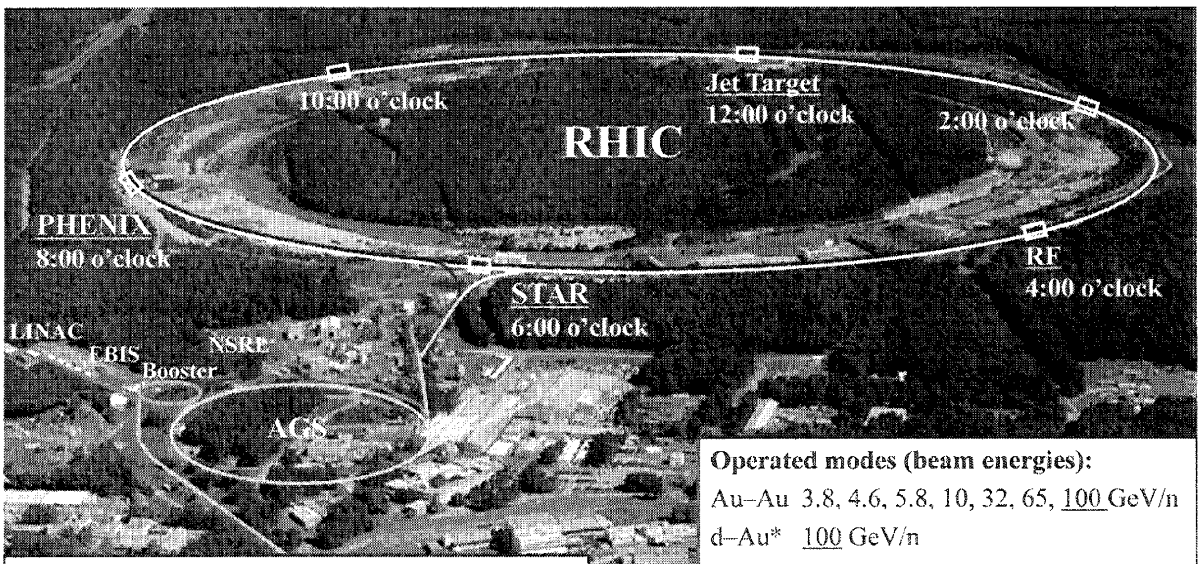
Thomas Roser
RBRC Review
October 28, 2010

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	155×10^{30} cm^{-2} s^{-1}
p↑–p↑	50×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	35×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

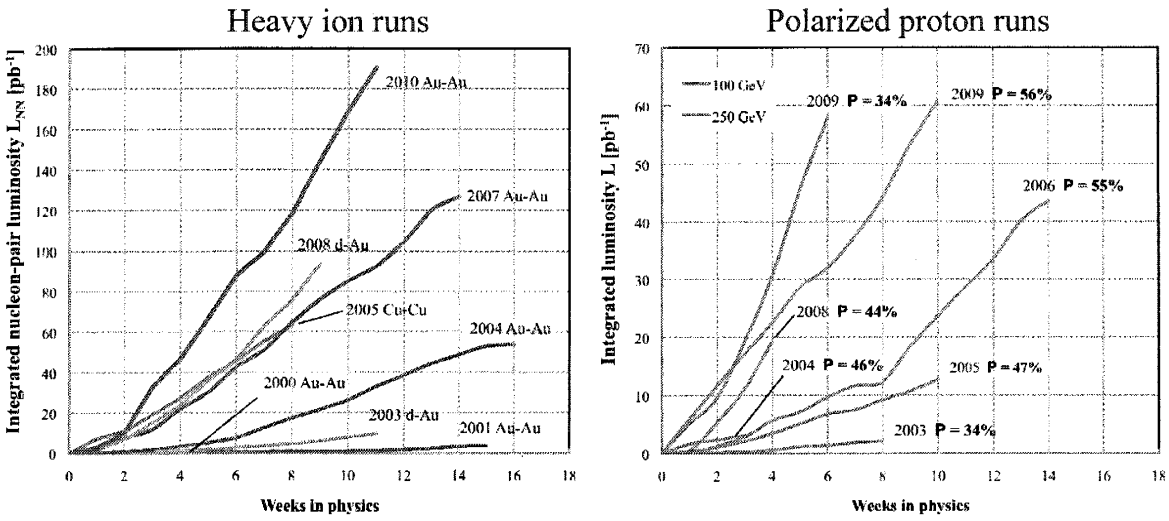
Operated modes (beam energies):

Au–Au	3.8, 4.6, 5.8, 10, 32, 65, 100 GeV/n
d–Au*	100 GeV/n
Cu–Cu	11, 31, 100 GeV/n
p↑–p↑	11, 31, 100, 250 GeV

Planned or possible future modes:

U – U	100 GeV/n
Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

Delivered Integrated Luminosity and Polarization



Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

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Luminosity and Polarization Goals

Parameter	unit	Achieved	With full stoch. cooling	
Au-Au operation		2010	≥ 2012	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.1	1.0	
Average Luminosity	10^{26} cm^{-2} s^{-1}	20	40	
p↑- p↑ operation		2009	≥ 2011/12	≥ 2014
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.1	1.3 / 1.5	2.0
Average Luminosity	10^{30} cm^{-2} s^{-1}	24 / 55	30 / 150	300
Polarization	%	56 / 34	70	70

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RHIC Facility Upgrade Plans

- EBIS (≥ 2011) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)
- RHIC luminosity upgrade (≥ 2012):
  [Au-Au: 40×10^{26} cm^{-2} s^{-1}; 500 GeV p-p: 1.5×10^{32} cm^{-2} s^{-1}]
  - 0.5 m β^* for Au – Au and p↑ – p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage rf system in RHIC
- Further luminosity upgrade for p↑ – p↑ operation (≥ 2014):
  [500 GeV p-p: ~ 3×10^{32} cm^{-2} s^{-1}]
  - 0.3 m β^* for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for head-on beam-beam compensation (× 2)
- eRHIC: high luminosity (10^{33} – 10^{34} cm^{-2} s^{-1}) eA and pol. ep collider using 5 GeV and later 10 - 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (~ 2020)
  Exploring gluons at extreme density!

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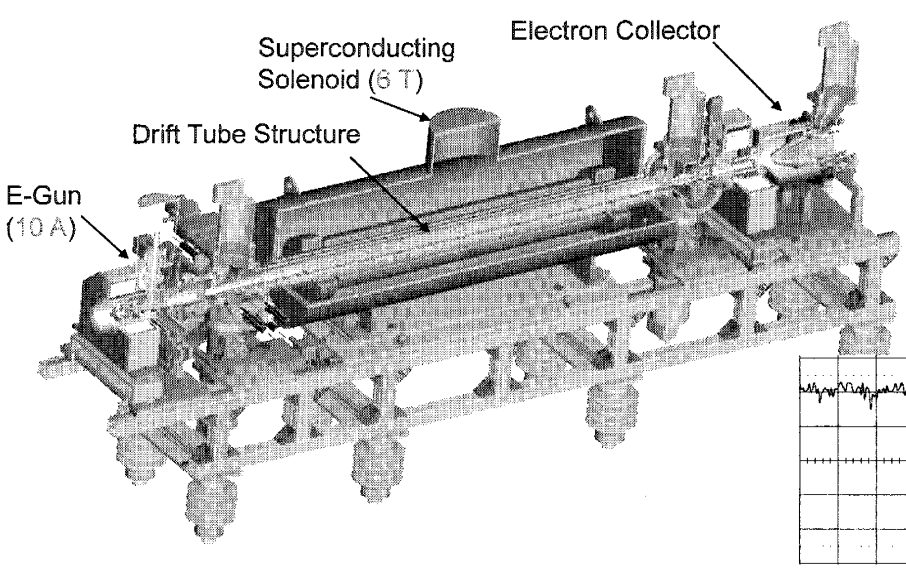
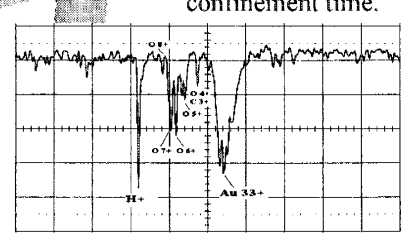
Electron Beam Ion Source (EBIS)

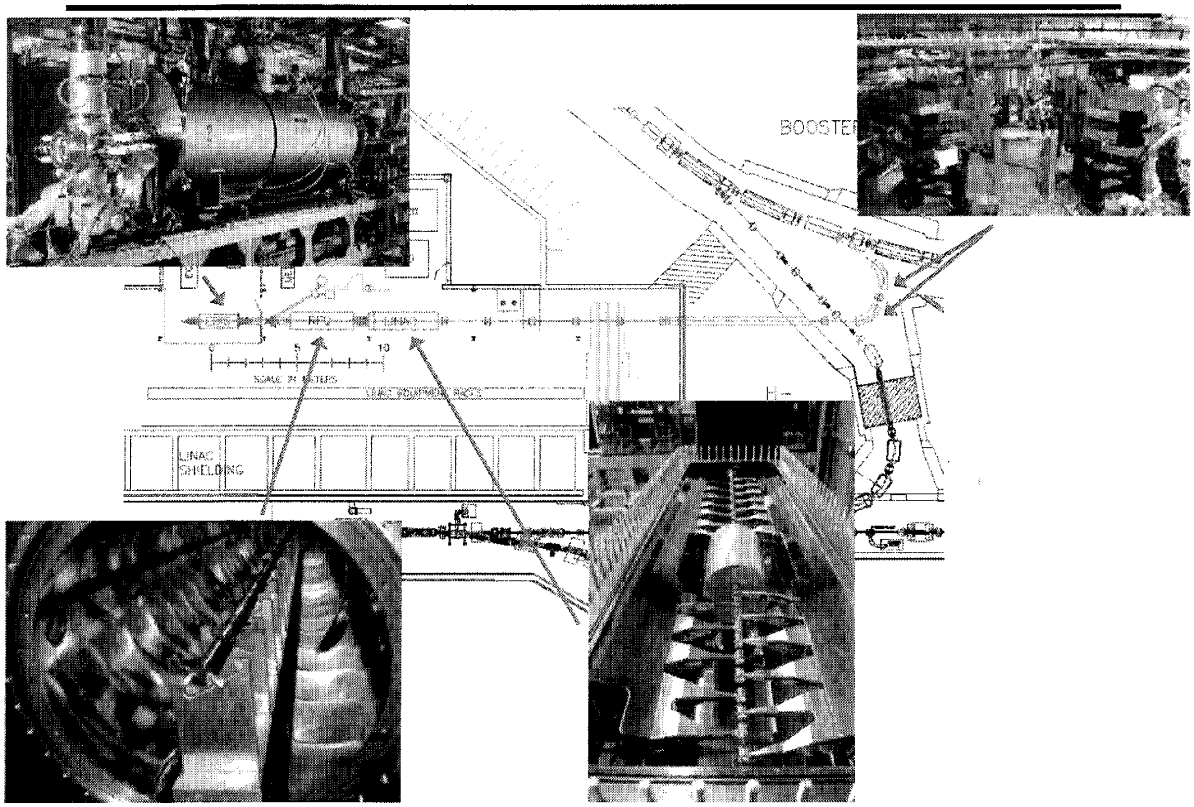
- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions (NSRL), uranium (RHIC) and polarized He^3 (eRHIC) (~ 1-2 × 10^{11} charges/bunch with $\varepsilon_{N,rms}$ = 1-2 μm)
- Construction of EBIS, RFQ and IH Linac completed on schedule and budget



Gold charge state with only 40 ms confinement time.

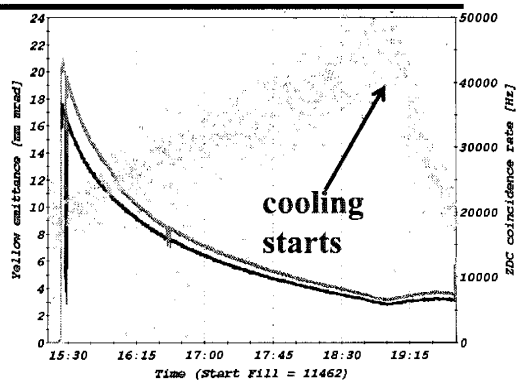


EBIS Pre-injector Construction



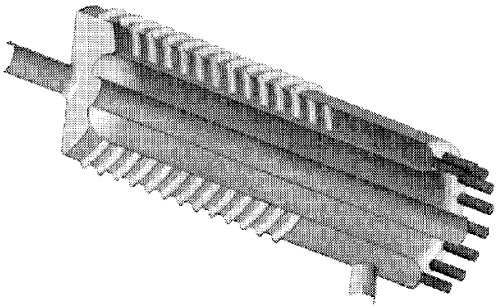
Stochastic Cooling and 56 MHz SRF cavity

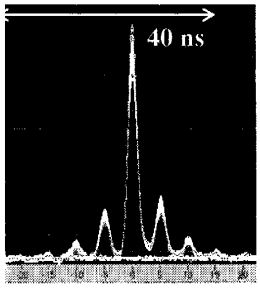
- Longitudinal and transverse cooling demonstrated at 100 GeV/nucleon in RHIC, counteracting IBS.
- Longitudinal and vertical cooling installed in both rings. Horizontal cooling under construction, to be completed for Run-12.



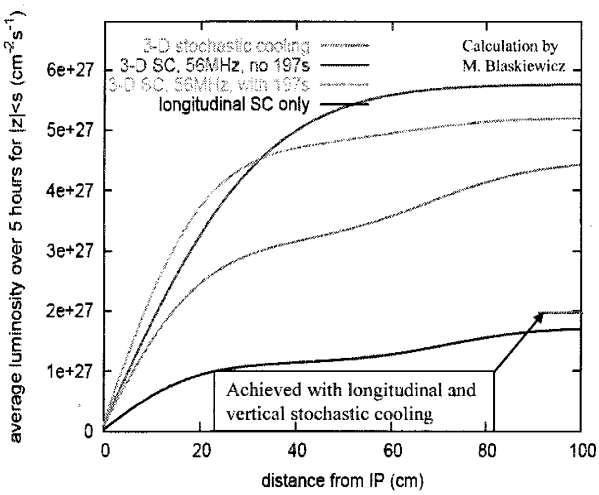
56 MHz, 2 MV SRF storage cavity:

- Greatly reduces satellite bunches
- Re-entrant quarter wave resonator
- Under construction, to be completed for Run-13

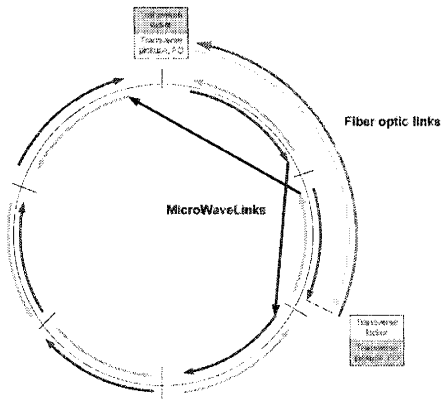


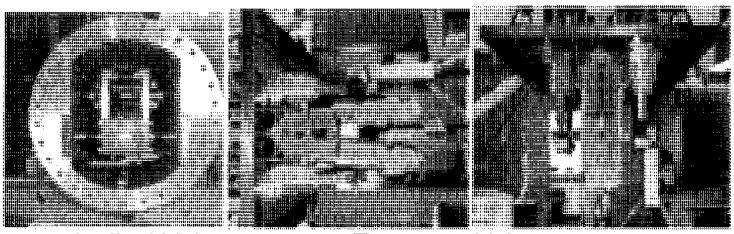


Luminosity Increase with Stochastic Cooling



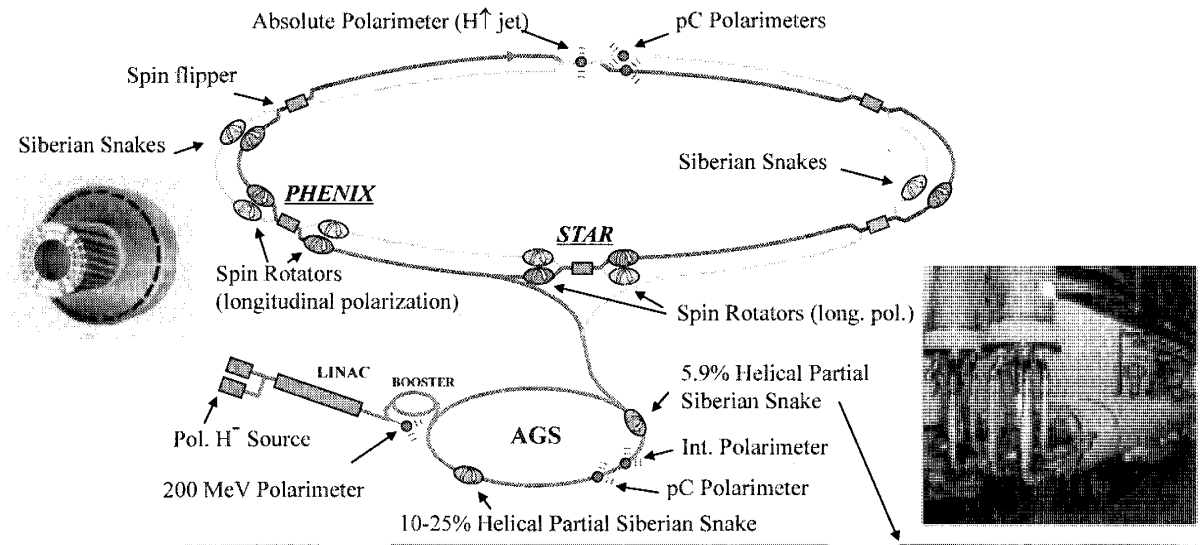
- 5 – 8 GHz bandwidth split up into 16 frequency bands with each frequency having its own cavity kicker
- 6 – 9 GHz bandwidth for longitudinal stochastic cooling using microwave link

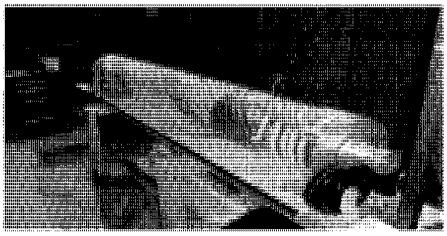


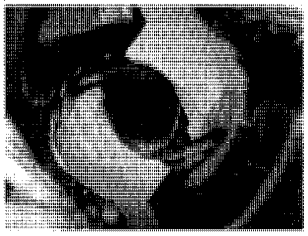


Longitudinal kickers Transverse kickers

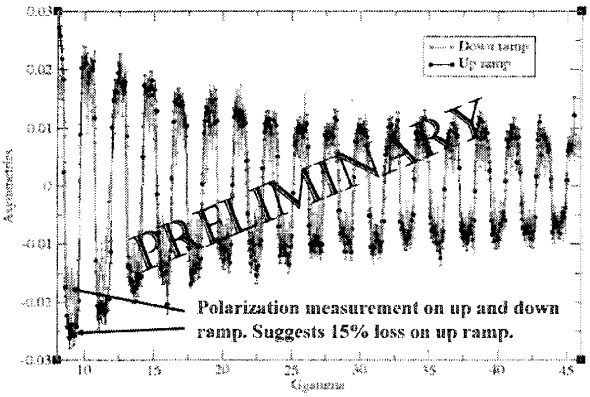
RHIC – First Polarized Hadron Collider

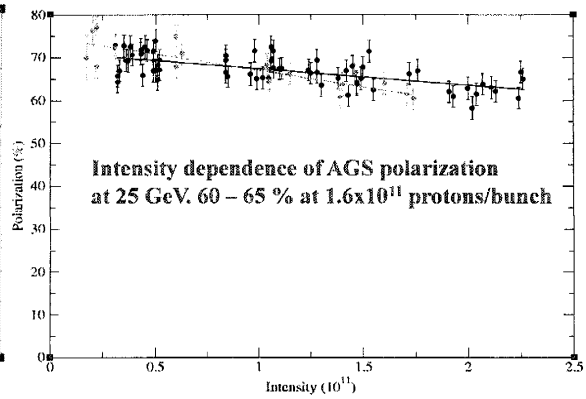




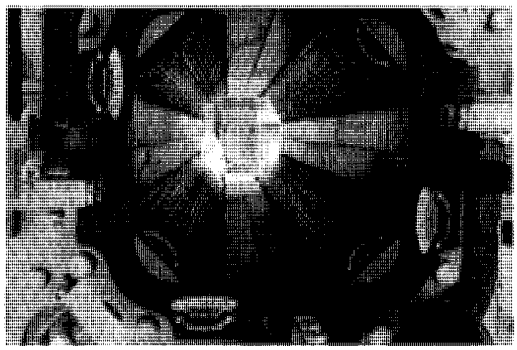


AGS Polarization Performance





- Two strong helical partial snakes overcome all vertical spin resonances
- New horizontal tune jump quadrupoles used for 82 weak horizontal resonances (+ 10%)
- New high intensity polarized source (+ 5%)



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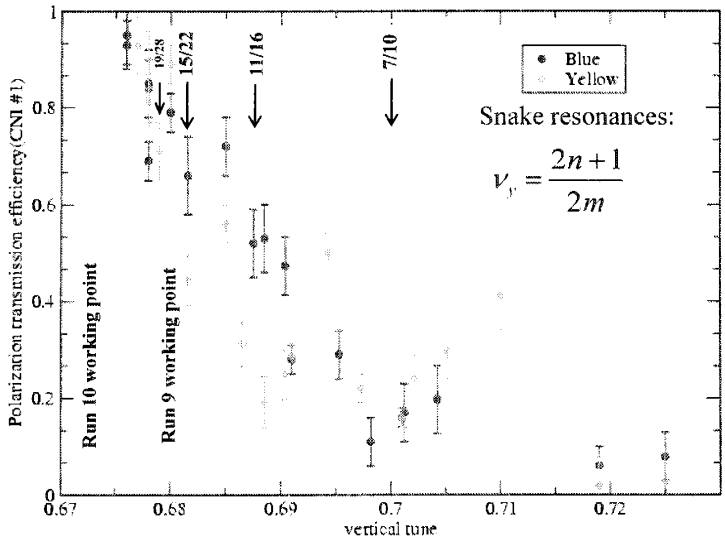
RHIC Polarization Performance

- 100 GeV polarization ~ 55 %, no loss between injection (25 GeV) and 100 GeV
- 250 GeV polarization ~ 35 %, loss is strongly tune dependent, as expected.
- Operating at 0.675 should give good polarization transmission to 250 GeV



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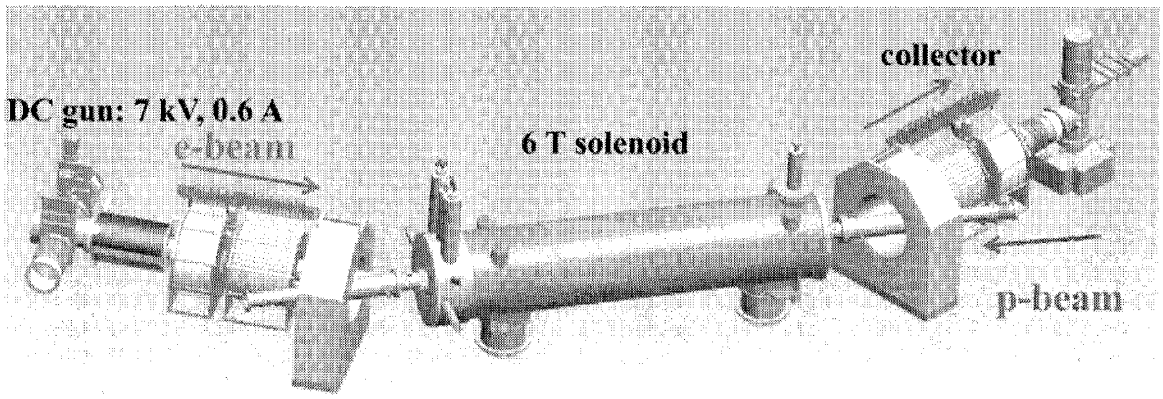
Electron Lenses for pp Beam-Beam Compensation

- Polarized proton luminosity is limited by effect of beam-beam interaction
- Two beam-beam collisions with positively charged (proton) beam are partially compensated by an additional collision with a **negatively** charged (electron) beam with the same amplitude dependence.
- Possible to double the maximum luminosity



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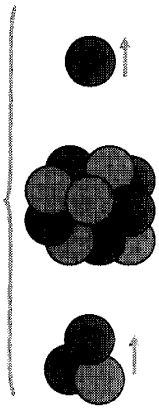
eRHIC

Electron accelerator

Unpolarized and polarized leptons 5 – 30 GeV

70% beam polarization goal
Positrons at low intensities

RHIC



Polarized protons 25 – 250 (325) GeV

Heavy ions (Au, U) 20 – 100 (130) GeV/n

Polarized light ions d,He^3: 125,167 GeV/n

Center mass energy range: 15 – 200 GeV

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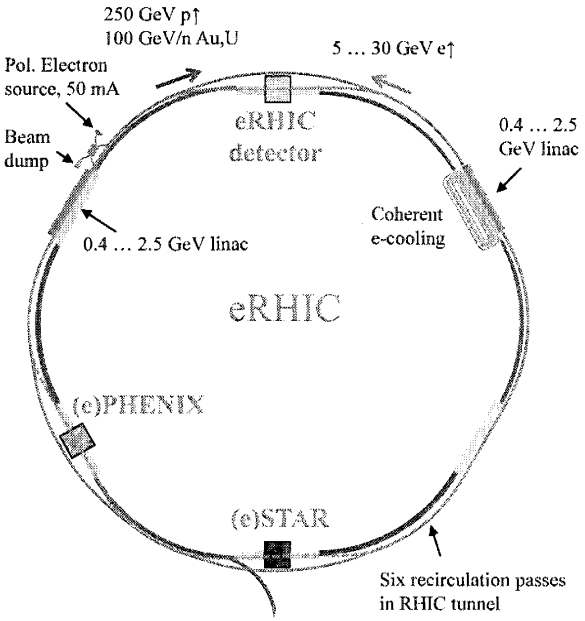
ERL-based Linac-Ring eRHIC



- 5 - 30 GeV electron energy. Upgradable by extending Linacs
- Peak luminosity: 1.5×10^{34} cm^{-2} s^{-1} in high luminosity IR
- 6 recirculation passes in the RHIC tunnel
- Requires 50 mA polarized electron gun
- Multiple electron-hadron interaction points and detectors possible
- Full polarization transparency at all energies for the electron beam
- Ability to take full advantage of transverse cooling of the hadron beams
- Possible options to include polarized positrons at lower luminosity: compact storage ring or ILC-type polarized positron source

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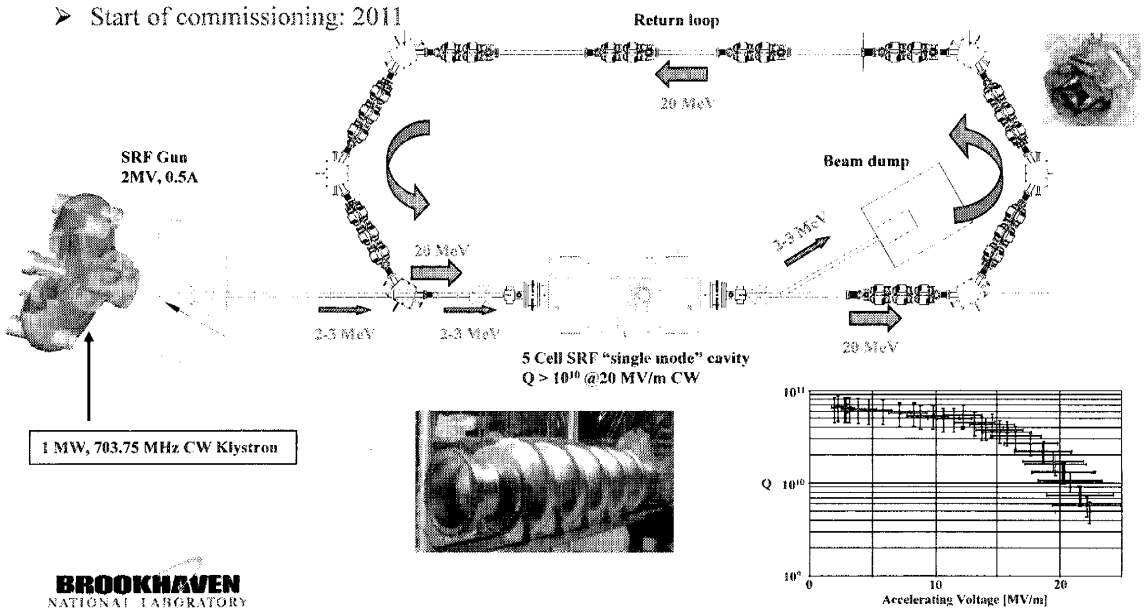
Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 5 – 30 GeV high intensity ERL of eRHIC
- Test of high current beam stability issues, highly flexible return loop lattice
- Allows for addition of a 2nd recirculation loop
- Start of commissioning: 2011



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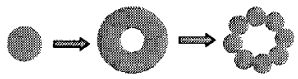
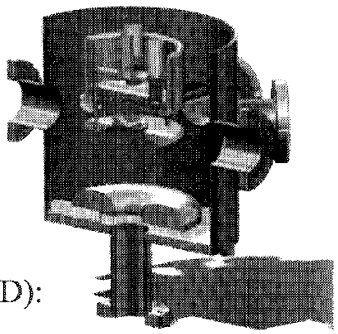
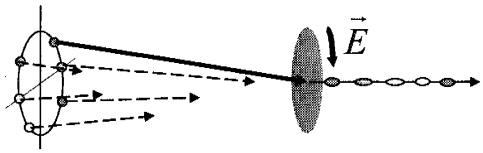
Polarized Electron Gun Development

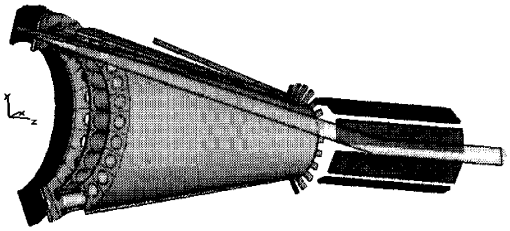
- ERL eRHIC design needs 50 mA
- 50 mA from large cathode (diameter > 1cm) with ~ 50 mA/cm^2
- Development of a source with large (ring like) cathode area (MIT-Bates, E.Tsentalovich) to minimize ion bombardment damage.





- Multiple guns with rf-combiner (Gatling gun) (LDRD):





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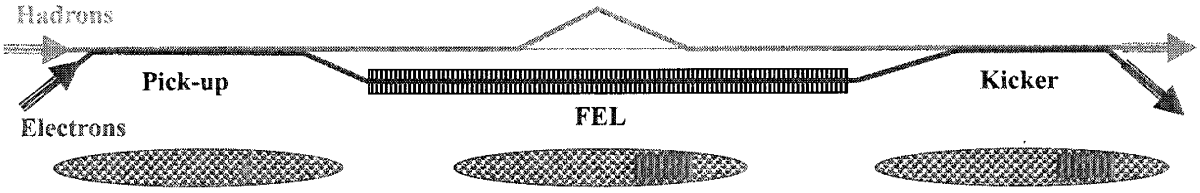
Coherent Electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration in RHIC at 40 GeV/n approved

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



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Summary

- EBIS (~ 2011)
  low maintenance linac-based pre-injector; all species including U and polarized ^{3}He
- RHIC luminosity upgrade (~ 2012)
  [Au-Au: 40×10^{26} cm^{-2} s^{-1}($\times$ 4); 500 GeV p-p: 1.5×10^{32} cm^{-2} s^{-1}]
- Further luminosity upgrade for p↑ – p↑ operation (~ 2014)
  [500 GeV p-p: ~ 3×10^{32} cm^{-2} s^{-1}]
- eRHIC: high luminosity (~ 1×10^{34} cm^{-2} s^{-1}) eA and pol. ep collider (~ 2020)
  5 - 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams

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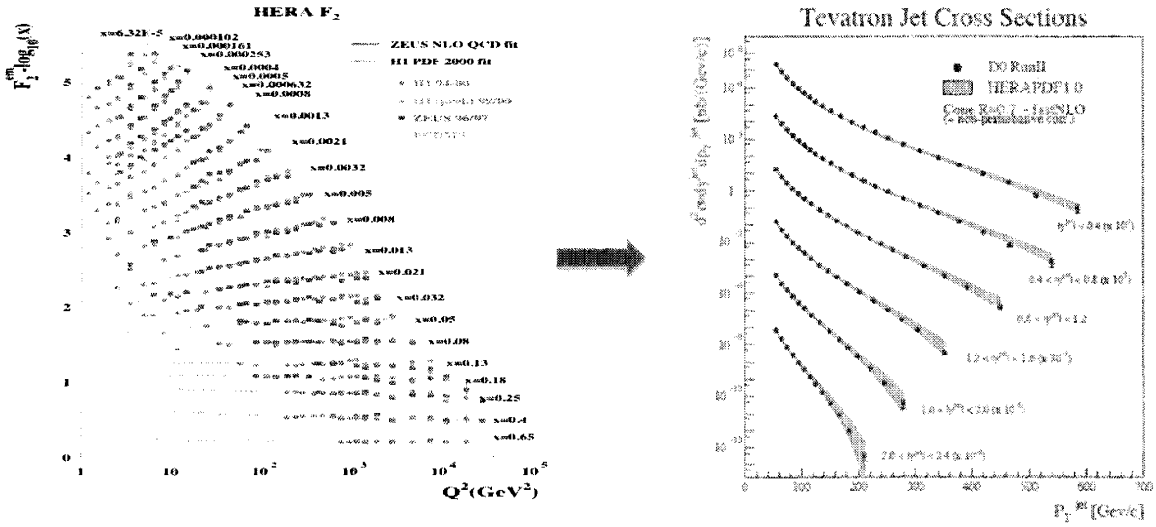
eRHIC Theory

Raju Venugopalan

Brookhaven National Laboratory

RBRC review, October 27-29, 2010

The big picture

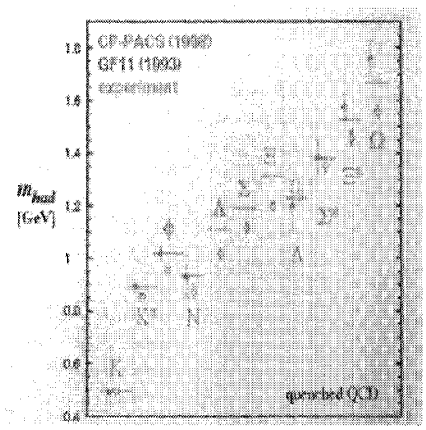


We believe QCD is the correct (nearly perfect) theory of the strong interactions

The big picture

How do the fundamental constituents of the theory form matter (hadrons) ?

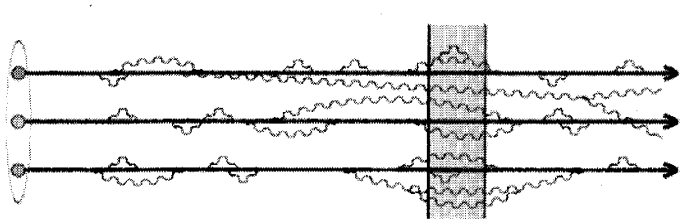
One answer: lattice QCD

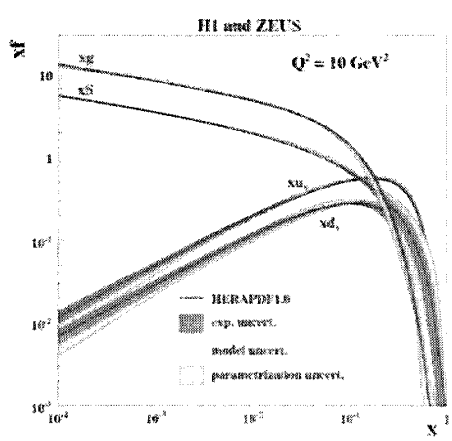


Absolutely essential but also far from the full story…

The big picture

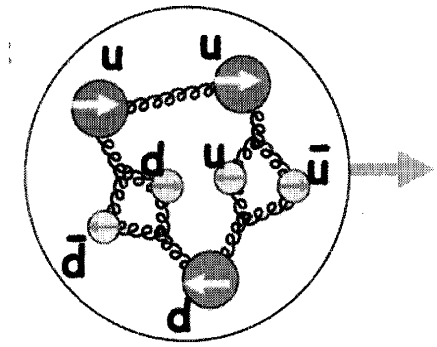
Lattice QCD cannot explain the nature of the hadron when probed at short "time" scales





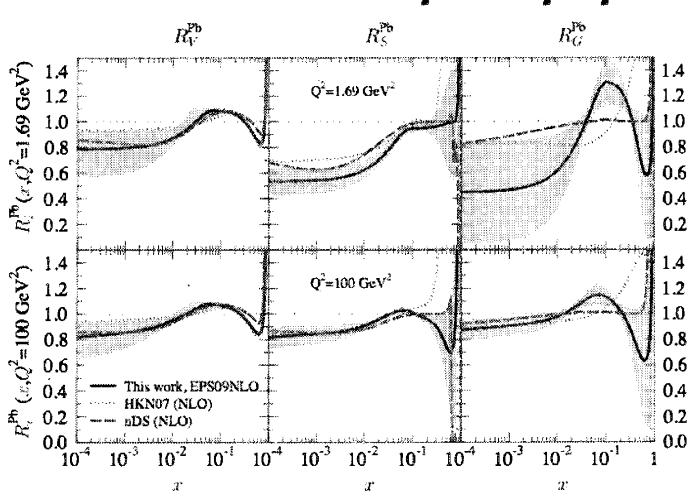
But these configurations are also "the proton"…
- they are the relevant configurations for high energy hadron/nuclear scattering

The hadron as a many body system



How do these many body quark and gluon fluctuations constitute the Mass, Spin, Flavor of the hadron ?

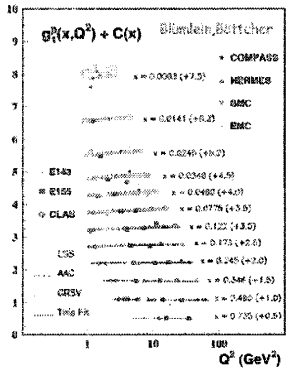
The hadron as a many body system

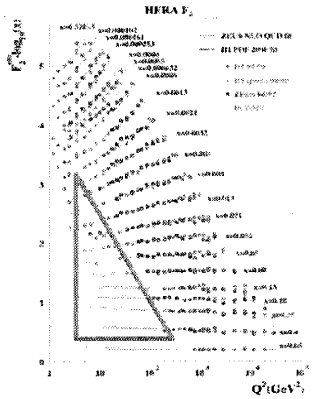


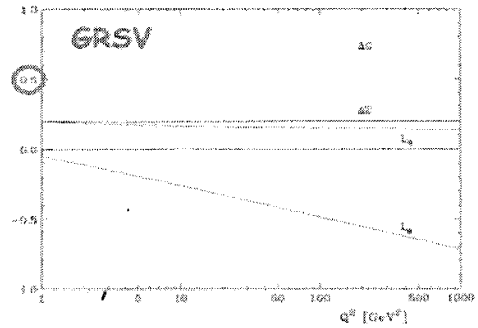
- **How do quarks and gluons constitute the momentum of the hadron ?**

Pretty good idea for the proton but no info on glue in nuclei for x < 0.01

The hadron as a many body system



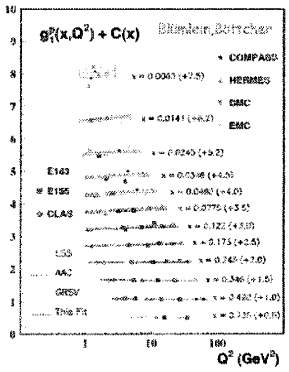


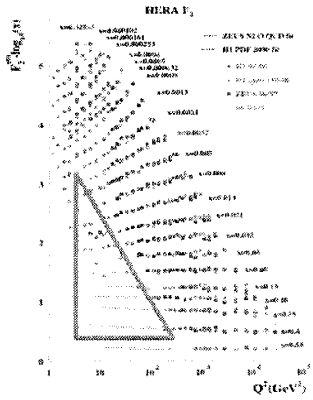


- How do quarks and glue make up hadron spin ?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

The hadron as a many body system





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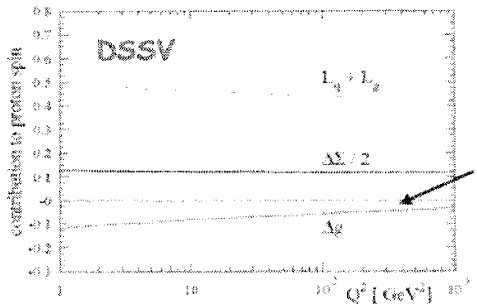
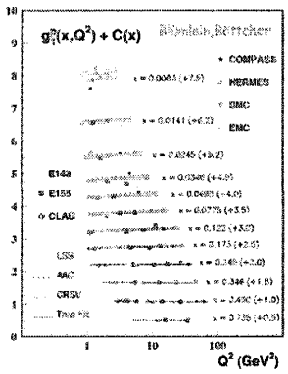
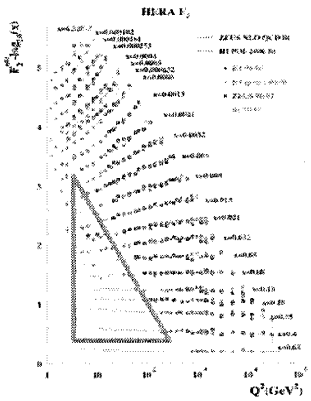


Polarized protons from RHIC deepen the mystery

The hadron as a many body system





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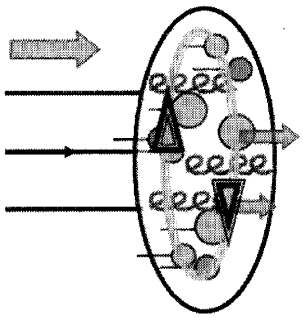
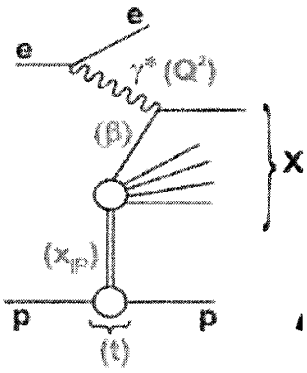


Orbital momentum: correlation of spatial position X spin

(Jianwei Qiu's talk)

The hadron as a many body system

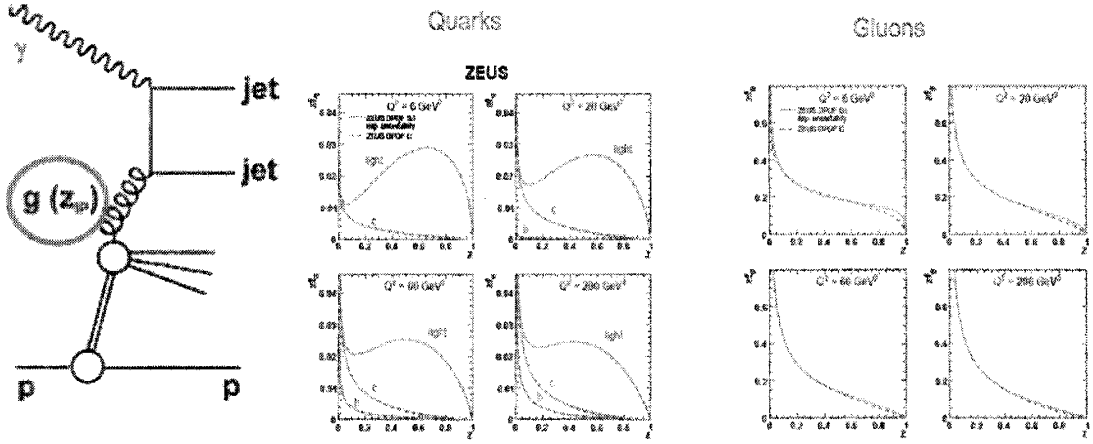


~ 15% of cross-section at HERA

Hard diffractive scattering: microscopic probe of color singlet "pomeron" exchanges

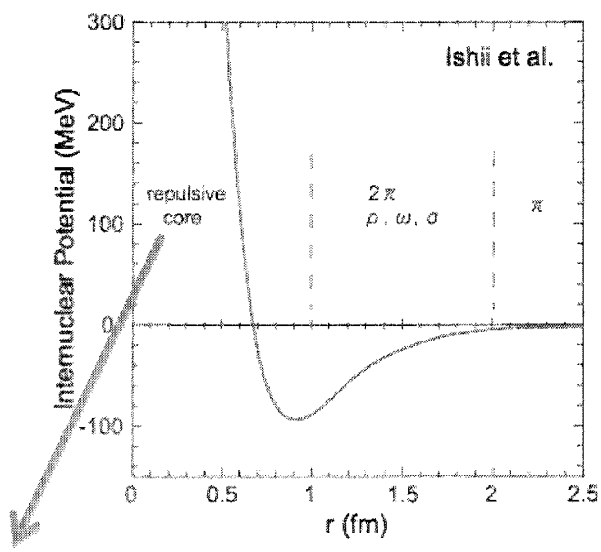
How do quarks and gluons in hadrons combine to produce such striking final states ?
-- probe role of confining/color screening dynamics in hadrons

The hadron as a many body system



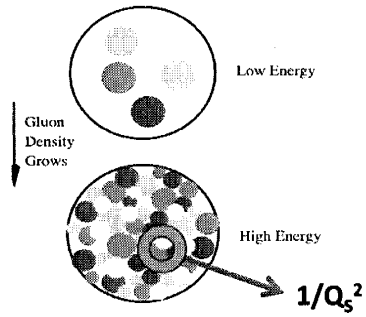
What is the nature of such color singlet exchanges in nuclei ?

The hadron as a many body system



What is the glue and sea-quark description of short-range nucleon-nucleon interaction ?

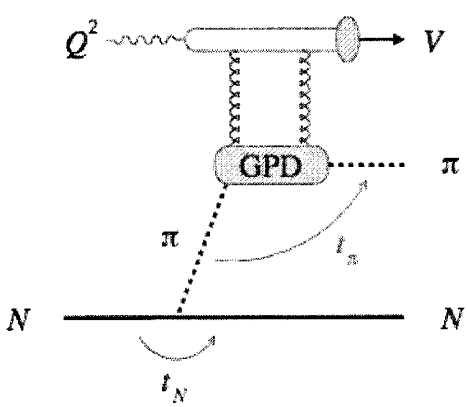
The hadron as a many body system

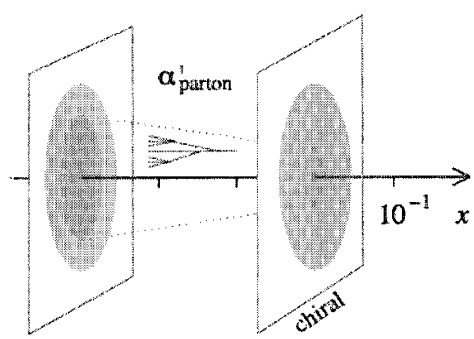


Are there universal many body states of saturated gluonic matter in hadrons and nuclei ?

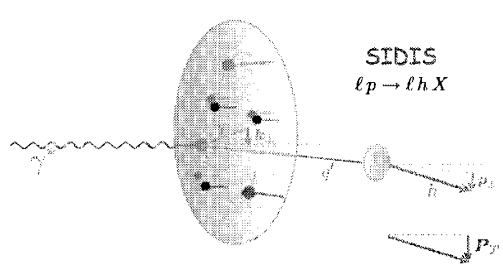
The hadron as a many body system

What is the role of chiral dynamics ?

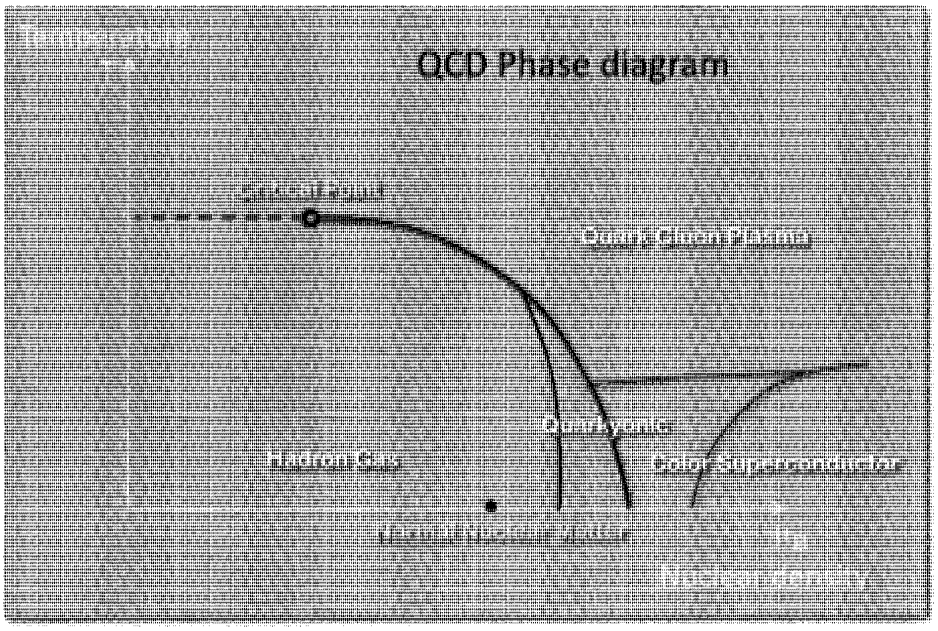




And topological effects…?



The hadron as a many body system

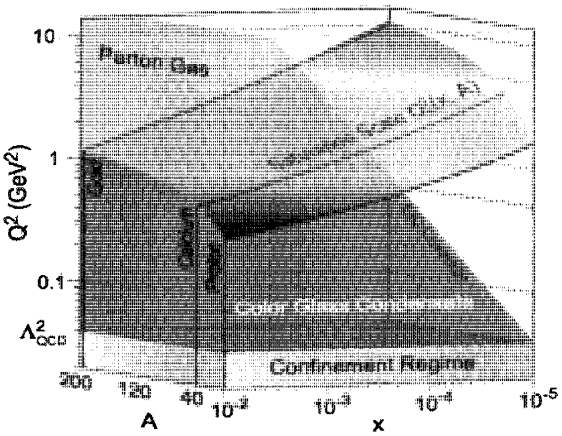


How does a deeper understanding of partonic structure of hadrons and nuclei lead to a deeper understanding of extreme states of QCD matter

EIC: über-microscope of hadron sub-structure

- **World's first e+A collider**
- **World's first pol.e-pol.p collider**
- $10^2 - 10^3$ **the luminosity of HERA (**highest energy eRHIC is factor of 2 less c.m. energy**)**

Why Physics at an e+A collider is interesting



Not your grand dad's e+A: world's first such collider, first measurements of a range of final states... eg. rapidity gaps, jets, impact parameter dependent distributions

Terra Incognita

- **Large x and Q^2 : Precision study of propagation of colored probes in extended QCD medium. QCD showering and fragmentation in nuclei. Heavy quark energy loss.**

- **Small x: Explore physics of strong, non-linear color fields**

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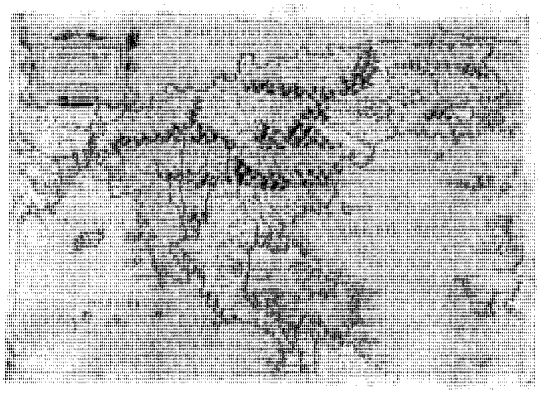
Why Physics at an e+A collider is interesting



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What are the measurements?

- **Precision inclusive measurements of structure functions**

$$eA \longrightarrow eX \;:\; F_2 \;,\; F_{\rm L}$$
$$eA \longrightarrow eX + {\rm gap}: \;\; F_2^{\rm D(3)} \;,\; F_{\rm L}^{\rm D(3)}$$ (Inclusive diffraction)

- **Semi-inclusive measurements of final state distributions**

$$eA \longrightarrow e\,\{\pi, K, \phi, D, J/\psi\}\,X$$

- **Exclusive final states**

$$eA \longrightarrow eA\,\{\rho, \phi, J/\psi, \Upsilon, \gamma\}$$

Multiple handles: x, Q^2, t, M_X^2 for light and heavy nuclei

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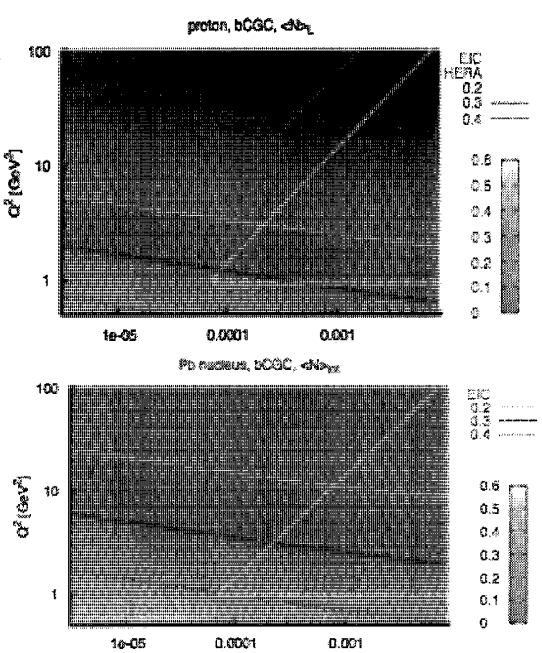
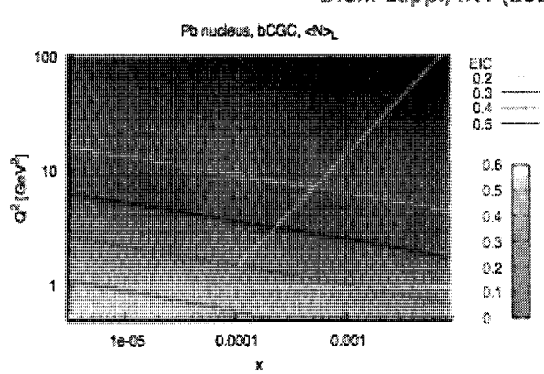
Non-linear QCD: F_L

$$F_L^A(x, Q^2) \propto x\, G_A(x, Q^2)$$ **F_L^A is sensitive to higher twist (non-linear) effects**



Diehl-Lappi, INT (2010)



First such measurements for nuclei for x < 0.01

A staged EIC is essential for F_L

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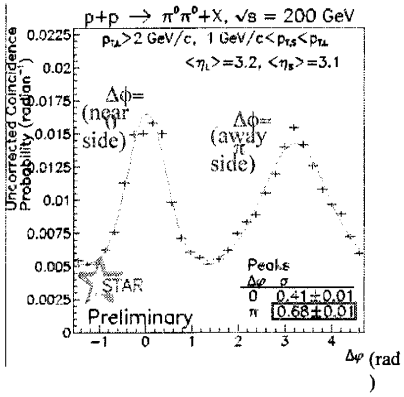
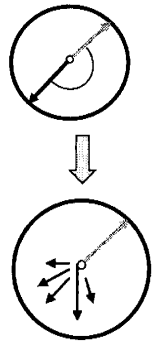
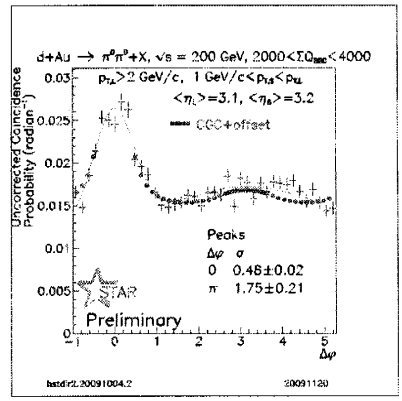
Semi-inclusive final states: golden channel?

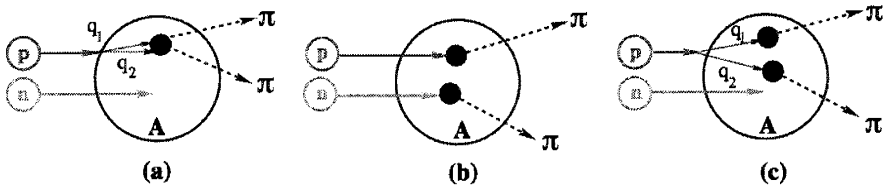


Away side parton randomized by strong color field





Recent suggestion: there could be a contribution from the pedestal generated by double parton scattering Strikman, Vogelsang:1009.6123



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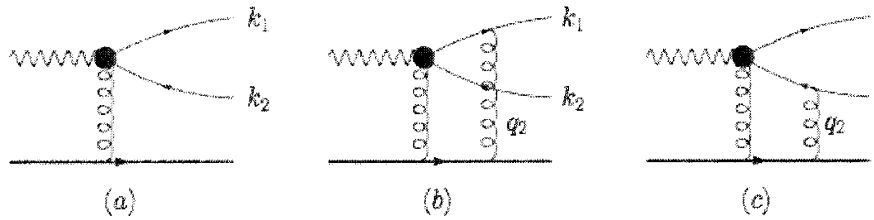
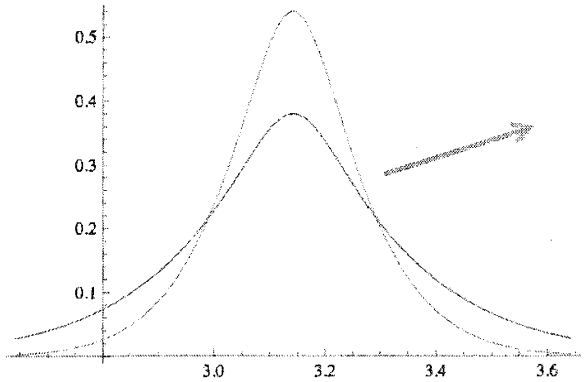
Semi-inclusive final states: golden channel?

Dominguez,Xiao,Yuan (2010)





Systematic depletion of away-side peak seen with increasing nuclear size/energy

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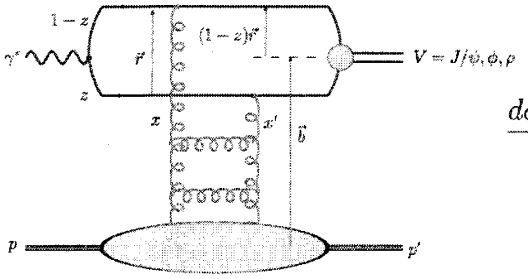
Exclusive final states in DIS



$$\frac{d\sigma_L^{\gamma^* A \to VA}}{dt}\Big|_{t=0} \propto \frac{\alpha_S^2(Q^2)}{Q^6}\left[xG_A(x,Q^2)\right]^2$$

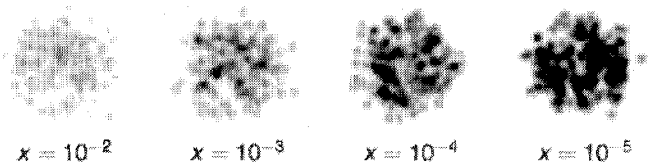
Brodsky et al.
Frankfurt,Koepf,Strikman

In the dipole model:

Kowalski,Motyka,Watt

$$\frac{d\sigma_{T,L}^{\gamma^* A \to VA}}{dt} = \frac{1}{16\pi}\Big|\int d^2r \int_0^1 \frac{dz}{4\pi}\int d^2b (\Psi_V^\star \Psi)_{T,L} \exp\left(-i|b-(1-z)r|\cdot\Delta\right)\frac{d\sigma_{q\bar{q}}}{d^2b}\Big|^2$$

$\sqrt{-t}$



Extract b dist. of glue In nuclei?

Caldwell-Kowalski

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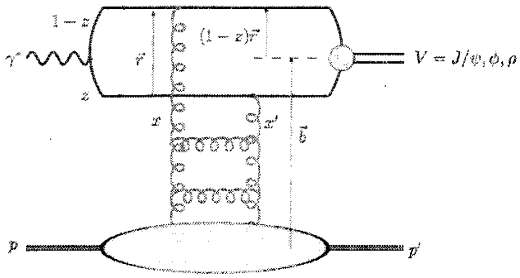
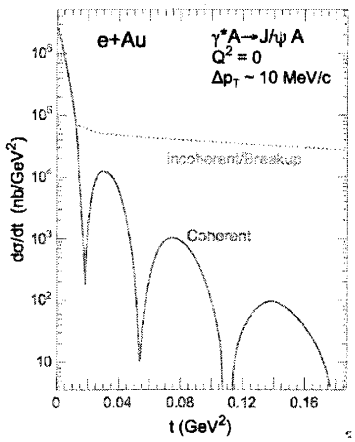
Exclusive final states in DIS

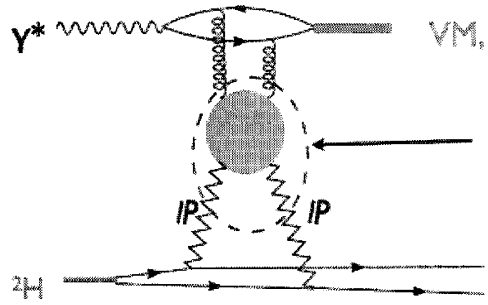


Exclusive photo-production of J/Ψ sensitive to spatial correlations of glue in nucleus

Caldwell,Kowalski



May be easier to learn about nucleon-nucleion short range correlations from light nuclei



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Theory effort

- **BNL theorists with active interest in EIC:**
  Baltz, Beuf, Kang, Kharzeev, Marciano, McLerran, Qiu, Stratmann, Venugopalan

- **LDRDs:**
  Electroweak studies: Marciano et al. (post-doc hired, Y. Li)
  Small x: Venugopalan et al. (post-doc hired, B. Schenke)
  eA event generator studies: Ullrich et al. (post-doc hired, T. Toll)
  Spin studies for EIC: Qiu (post-doc to be hired)

- **Close interaction of theorists with EIC BNL Taskforce (Aschenauer & Ullrich)**

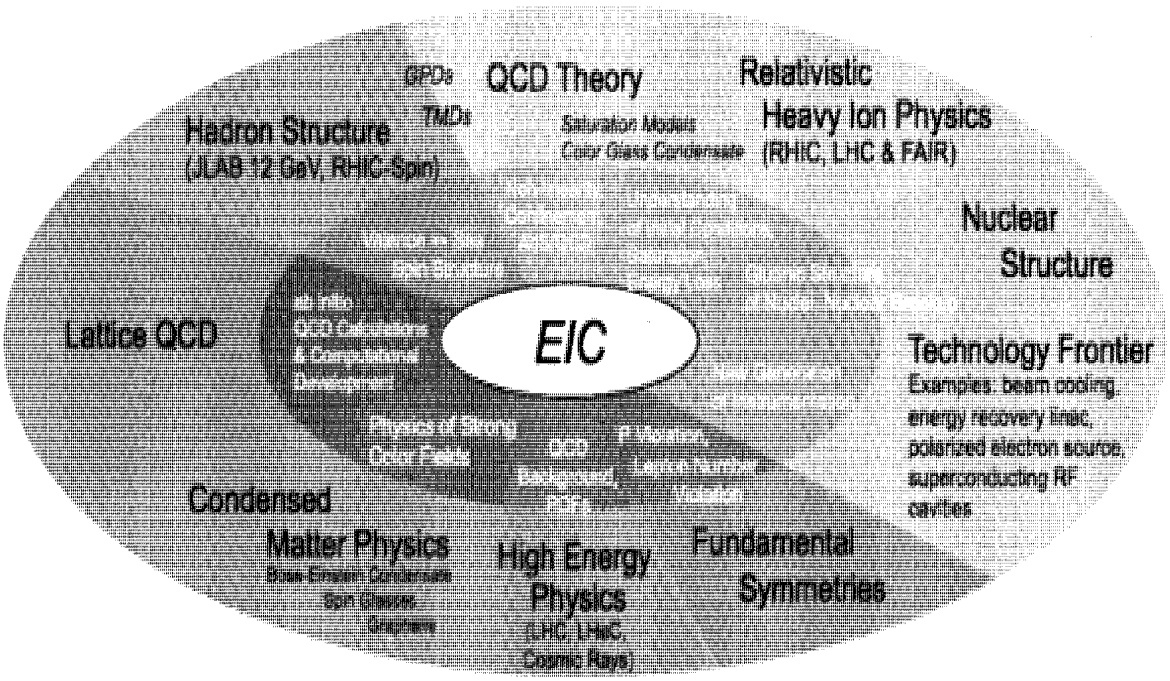
Theory effort

INT Seattle Fall program dedicated to EIC
(Organizers: Boer, Diehl, Milner, Venugopalan, Vogelsang)
http://www.int.washington.edu/PROGRAMS/10-3/

A document (along the lines of a CERN yellow report) on the "Science case for an EIC" is planned for early next year

Four themes:

a) Origin of nucleon spin (Covenors: Hasch, Stratmann, Yuan)
b) Spatial structure of QCD matter (Convenors: Burkardt, Guzey, Sabatie)
c) QCD matter under extreme conditions (Convenors: Accardi, Lamont, Marquet)
d) Electroweak/BSM studies (Convenors: Kumar, Li, Marciano)


GPDs
TMDs
QCD Theory
Saturation Models
Color Glass Condensate
Relativistic
Heavy Ion Physics
(RHIC, LHC & FAIR)
Hadron Structure
(JLAB 12 GeV, RHIC-Spin)
Nuclear
Structure
Lattice QCD
EIC
Technology Frontier
Examples: beam cooling, energy recovery linac, polarized electron source, superconducting RF cavities
Condensed
Matter Physics
Bose-Einstein Condensate
Spin Glasses
Graphene
High Energy
Physics
(LHC, LHeC,
Cosmic Rays)
Fundamental
Symmetries

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Spin Physics Theory Plan

Jianwei Qiu
Brookhaven National Laboratory

RBRC Scientific Review Committee Meeting
October 27-29, 2010
Physics Department, Brookhaven National Laboratory, Upton, New York

Outline of my talk

- Why spin?
- RHIC spin program
- Future opportunities:
  - PHENIX/STAR decadal plan
  - Electron-Ion Collider
- Summary

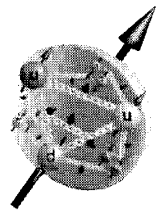
Why spin?

- Spin of an elementary particle:

  An intrinsic quantum property of the particle

- Spin of a composite particle:

  Angular momentum when the particle is at rest

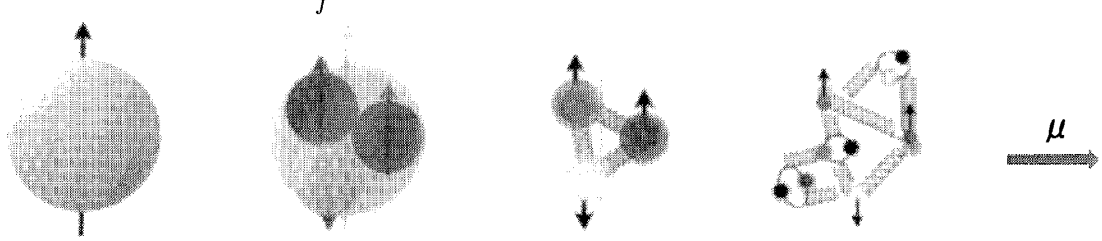


Elementary particles' spin
(intrinsic quantum effect)
+
Motion of the particles
(dynamical – fundamental interaction)

Proton spin

- in QCD:

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$



- Asymptotic limit:

JI, 2005

$$J_q(\mu \to \infty) \Rightarrow \frac{1}{2}\frac{3N_f}{16+3N_f} \sim \frac{1}{4} \qquad J_g(\mu \to \infty) \Rightarrow \frac{1}{2}\frac{16}{16+3N_f} \sim \frac{1}{4}$$

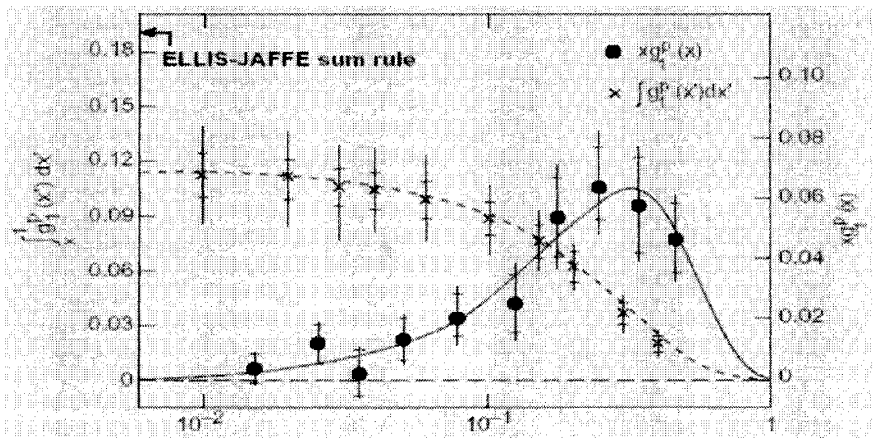
- Proton spin structure:

Role of the intrinsic parton's spin vs. the dynamical parton's motion

⟹ Test QCD dynamics and search for the clues of QCD confinement

The role of quark's spin

- EMC experiment in 1988/1989 – "the plot":



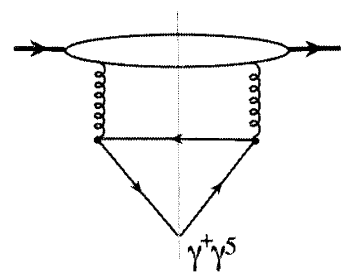
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right] + \mathcal{O}(\alpha_s) + \mathcal{O}(1/Q)$$

$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_\parallel | \overline{\psi}_q(0)\gamma^+\gamma_5\psi_q(0) | P, s_\parallel \rangle$$

- "Spin crisis" or puzzle: $\Delta\Sigma = \sum_q \left[\Delta q + \Delta\bar{q}\right] = 0.12 \pm 0.17$

Early "solution" to the "crisis"

- Large ΔG to cancel the "true" Δq:



$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_\parallel | \overline{\psi}_q(0)\gamma^+\gamma_5\psi_q(0) | P, s_\parallel \rangle$$

$$\Delta\Sigma \to \Delta\Sigma - \frac{n_f \alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$

Need $\Delta G(Q^2) \sim 2$ at Q ~ 1 GeV

- Role of gluon's spin:

$$J_g(\mu^2 \to \infty) \to \frac{1}{2}\frac{16}{16+3N_f} \sim \frac{1}{4}$$

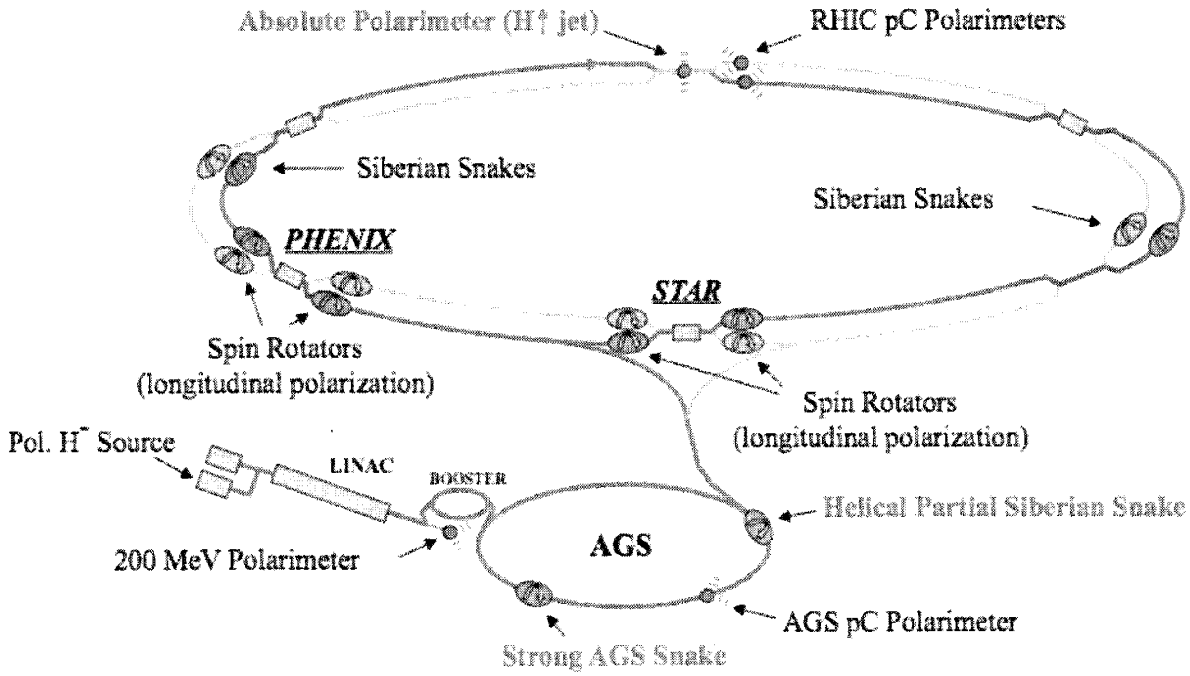
It is not a large number!

Need a large negative gluon orbital angular momentum if ΔG ~ 2?

- Question: How to measure ΔG independently?
  - ✧ Precision inclusive DIS
  - ✧ Jets in SIDIS
  - ✧ Hadronic collisions – RHIC spin
  - ✧ ...

RHIC spin program

- The machine:



Collider of two 100 GeV (250 GeV) polarized proton beams

The goals of RHIC spin program

- Determination of polarized gluon distribution (ΔG) over a large range of momentum fraction x, using multiple probes

- Determination of flavor identified quark and anti-quark polarization using parity violating production of $W^{\pm}$

- Transverse spin phenomena in QCD: transversity (δq), parton orbital angular momentum (L_q), and etc.

Challenges to the theorists

Experiments measure cross sections,

Not ΔG, Δq and $\Delta\bar{q}$!

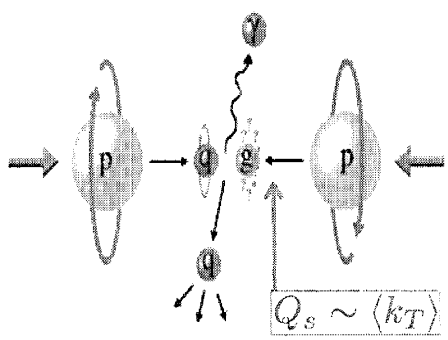
How reliable we can extract these quantities

from

the measured cross sections/asymmetries?

QCD factorization – approximation

- Collinear factorization – single hard scale:



$$\frac{d\sigma}{dy dp_T^2} = \int \frac{dx}{x} q(x) \int \frac{dx'}{x'} g(x') \frac{d\hat{\sigma}_{qg\to\gamma q}}{dy dp_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{Q_s}{P_T}\right)^n$$

Convoluted with a fragmentation function for inclusive single particle production

- Transverse momentum dependent (TMD) factorization:

$$\frac{d\sigma}{dp_T^2 dq_T^2} = \int \frac{dx}{x} \int d^2k_T\, q(x,k_T) \int \frac{dx'}{x'} \int d^2k'_T\, g(x',k'_T) \frac{d\hat{\sigma}}{dp_T^2 dq_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{q_T}{p_T}\right)$$

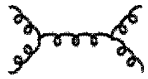
✧ Two very different physics scales: $p_T \gg q_T \gg \Lambda_{\rm QCD} \sim 1/{\rm fm}$

✧ Advantage: direct information on parton's transverse motion

✧ Challenges: theory effort needed to prove the factorization!

Determination of ΔG

- Physical channels sensitive to ΔG:

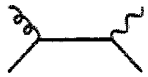
$\vec{p}+\vec{p}\rightarrow\pi+X$ $\quad \vec{g}\vec{g}\rightarrow gg$ 

$\vec{p}+\vec{p}\rightarrow \text{jet}+X$ $\quad \vec{q}\vec{g}\rightarrow qg$

Pion or jet production

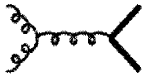
high rates

$\vec{p}+\vec{p}\rightarrow\gamma+X$

$\vec{p}+\vec{p}\rightarrow\gamma+\text{jet}+X$ $\quad \vec{q}\vec{g}\rightarrow\gamma q$ 

Direct photon production

low rates

$\vec{p}+\vec{p}\rightarrow D+X$ $\quad \vec{g}\vec{g}\rightarrow c\bar{c}$ 

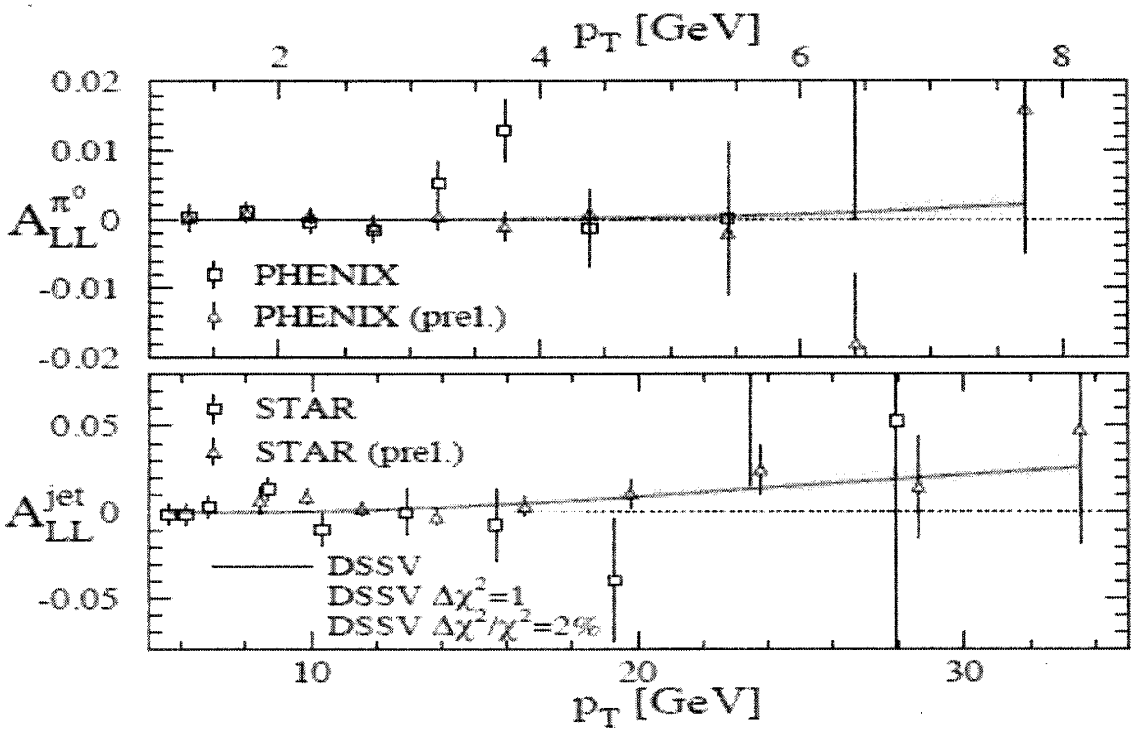
$\vec{p}+\vec{p}\rightarrow B+X$ $\quad \vec{g}\vec{g}\rightarrow b\bar{b}$

Heavy-flavour production

separated vertex detection required

Many NLO pQCD calculations are available

RHIC Measurements on ΔG

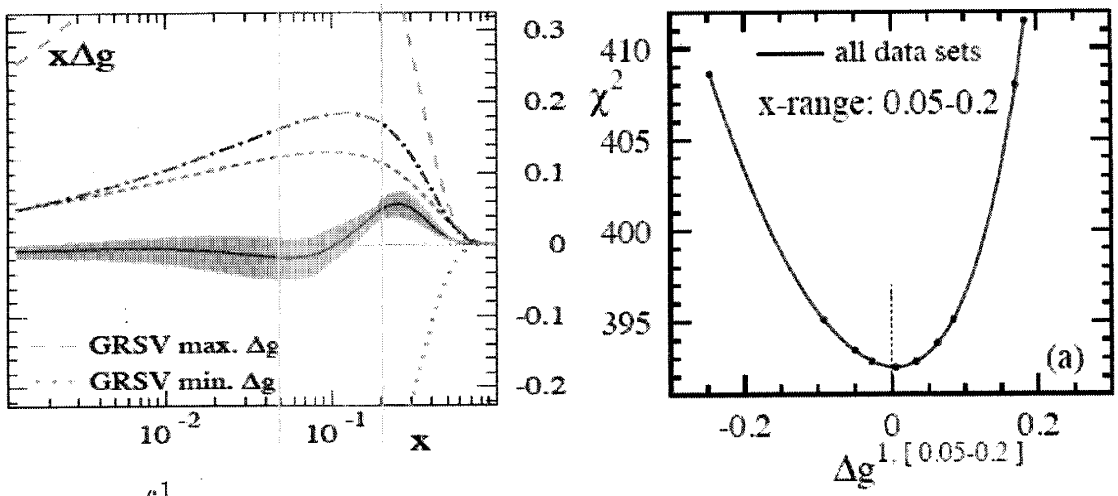


Small asymmetry leads to small gluon "helicity" distribution

Current status on ΔG

- Definition: $$\Delta G = \int_0^1 dx\, \Delta G(x)$$

- NLO QCD global fit - DSSV: **PRL101,072001(2008)**

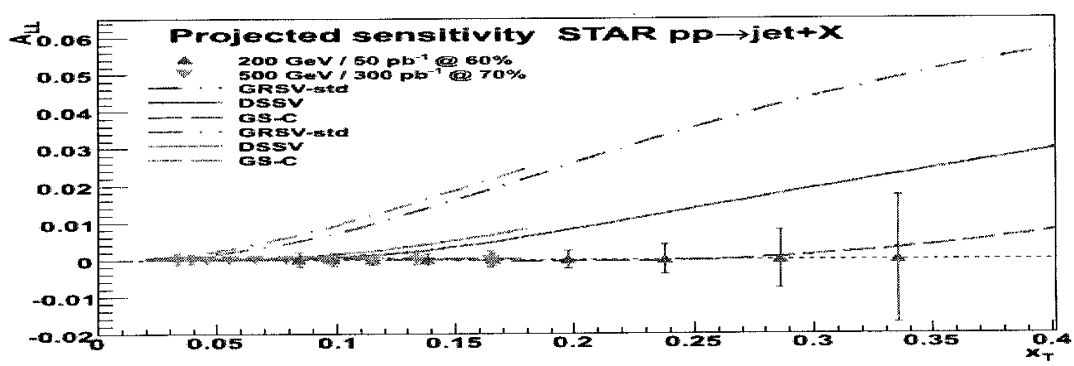


$$\Delta G \approx \int_{0.001}^1 dx\, \Delta G(x) = -0.084$$

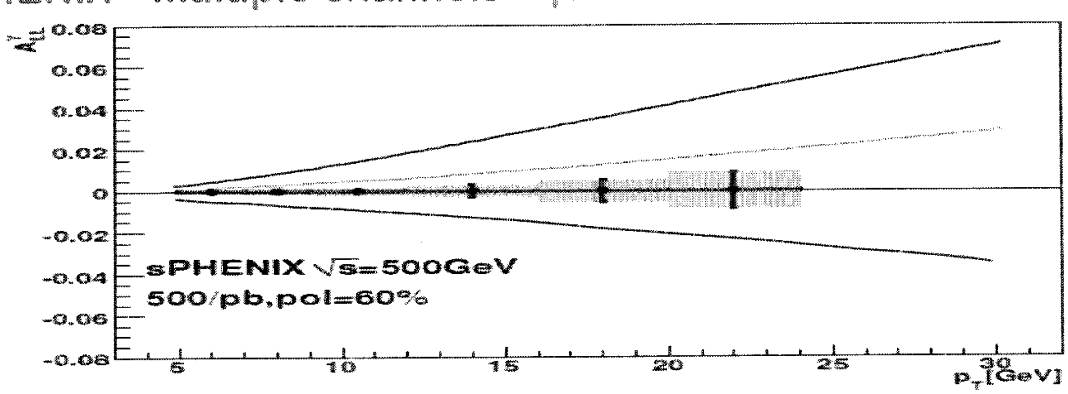
Strong constraint on ΔG from $0.05 \lesssim x \lesssim 0.2$

Future measurement on ΔG

- STAR – multiple channels – inclusive jet:



- PHENIX – multiple channels – γ:



Improvement to ΔG

- NNLO? Probably not yet
- Key: Extrapolation to low x and high x
  - ✧ Large x: total contribution might be small due to the steep falling phase space
  - ✧ Small x: larger phase space for shower and smaller Q for a fixed collision energy $\Rightarrow$ Large $\langle k_T^2 \rangle$ $\ln(s/Q^2) \sim \ln(1/x)$
- Collinear factorization does not work when $Q \sim Q_s(x) \sim \langle k_T \rangle$

$$G(x) = G^+(x) + G^-(x) \propto \frac{1}{x^{1+\alpha}}$$ at small x

$$\Delta G(x) = G^+(x) - G^-(x)$$ Could be proportional to $\frac{1}{x^\alpha}$

Not positive definite!

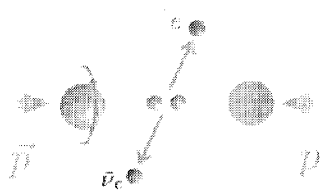
- Current understanding of ΔG :

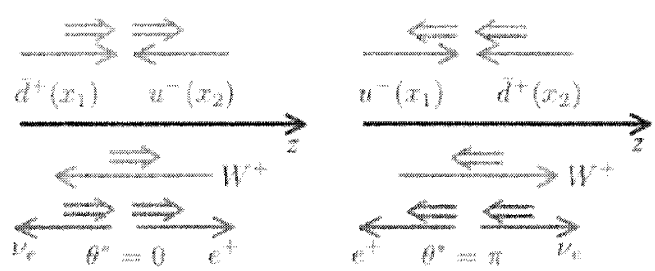
ΔG ~ 2 is unlikely, but, ΔG ~ ¼ or ½ (¼) is still possible

Theory effort is needed for understanding small-x behavior of ΔG!

Determination of Δq and Δq̄

- W's are left-handed:





- Flavor separation:

Lowest order:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

Forward W^+ (backward e^+):

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)} < 0$$

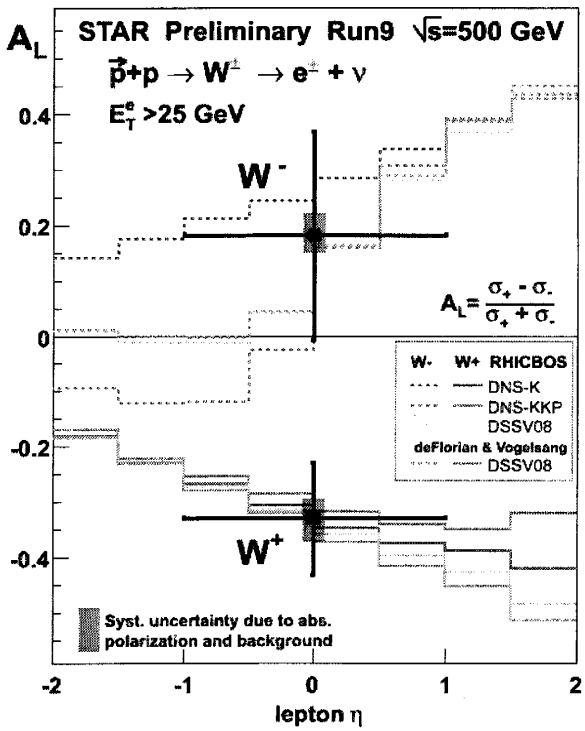
Backward W^+ (forward e^+):

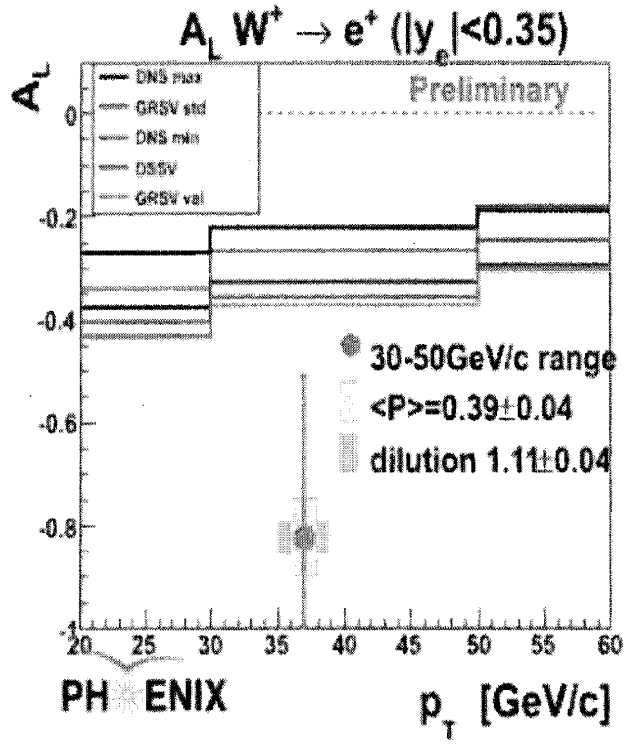
$$A_L^{W^+} \approx -\frac{\Delta\bar{d}(x_2)}{\bar{d}(x_2)} < 0$$

- Complications:

High order, W's p_T-distribution at low p_T

Measured W asymmetry – RHIC Run 9





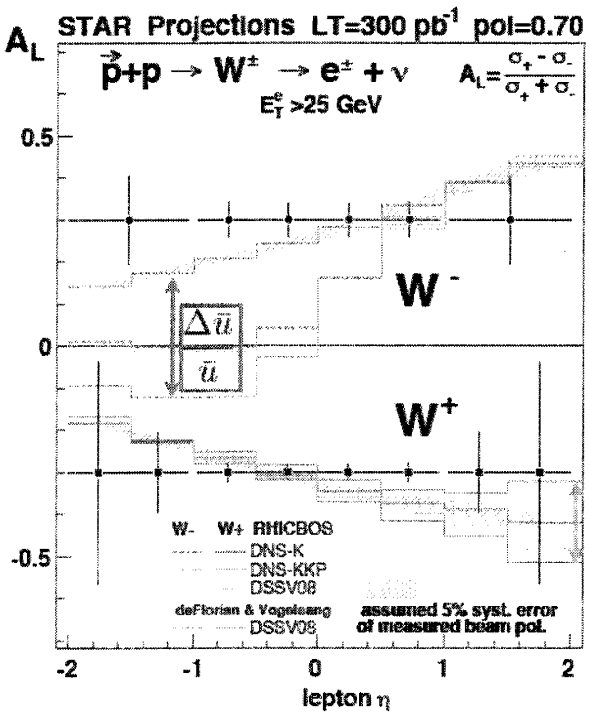
$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \ \pm 0.04(\text{syst.})$$

$$A_L(W^-) = \ 0.18 \pm 0.19(\text{stat.}) \ ^{+0.04}_{-0.03}(\text{syst.})$$

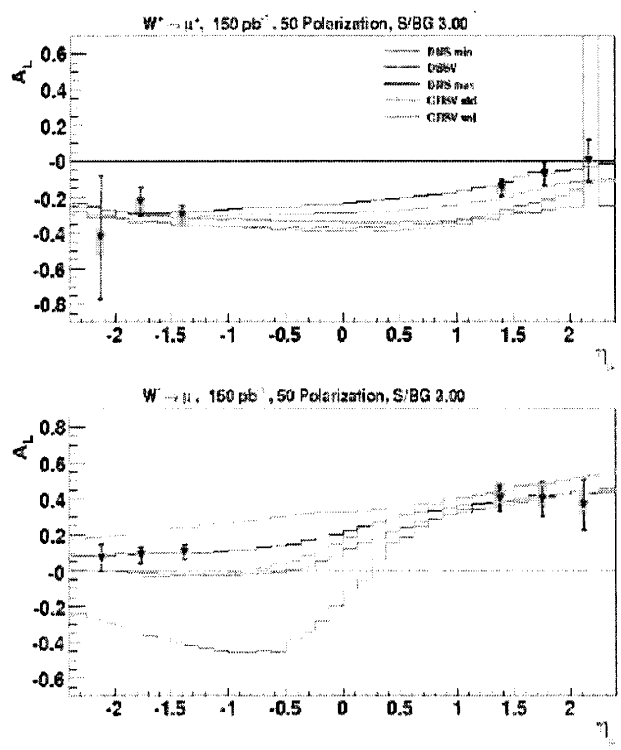
$$A_L(\bar{p}p \to W^+ \to e^+) = -0.83 \pm 0.31$$

Future on W asymmetry

STAR



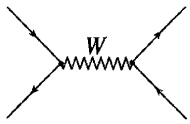
PHENIX



Challenges: high order + resummation

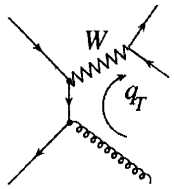
- Fixed order pQCD calculation:

LO:



$$\propto \delta^2(q_T)$$

NLO:



$$\propto \frac{1}{q_T^2} \quad \Rightarrow \infty \quad \text{as} \quad q_T^2 \to 0$$

- All order resummation is needed:

  CSS formalism – implemented in RHICBOS

- RHIC experiments measure the decay lepton not the W's:

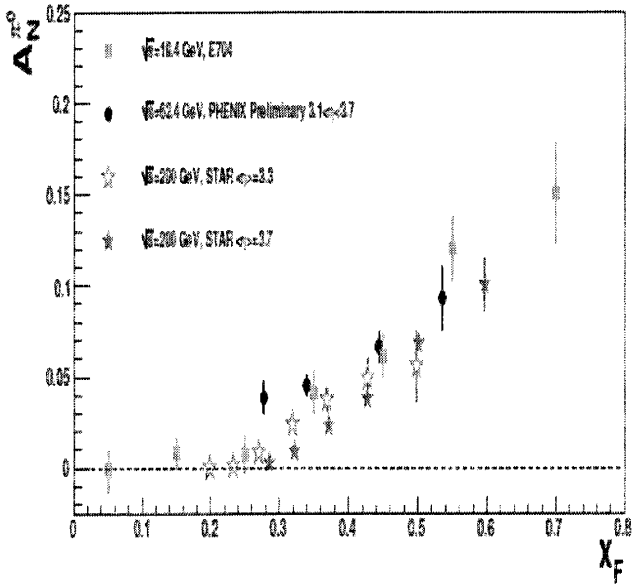
  Resummation for the lepton angular distribution needed!

- Test the precision scale dependence:

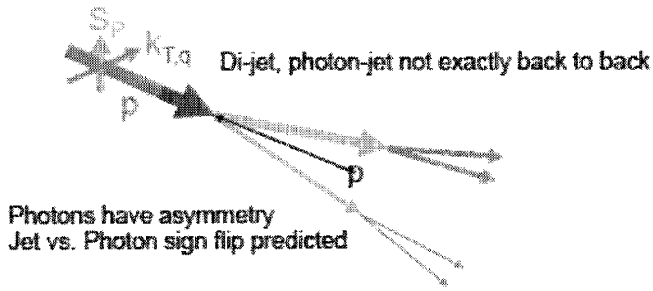
$$\Delta\bar{q}(\mu = M_W) \Longrightarrow \Delta\bar{q}(\mu = Q \sim \mathrm{GeV's})_{\mathrm{SIDIS}}$$

Transverse spin phenomena in QCD

- Left-right asymmetry:

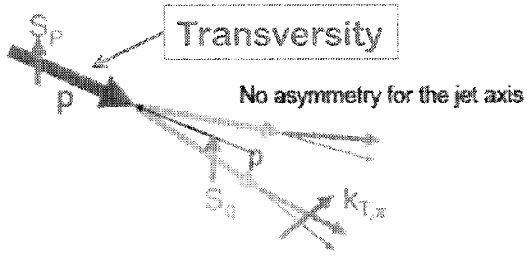


✧ Sivers effect:



Hadron spin influences parton's transverse motion

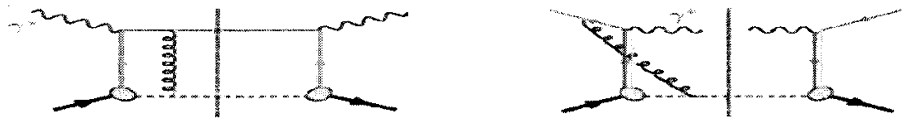
✧ Collins effect:



Parton's spin affects hadronization

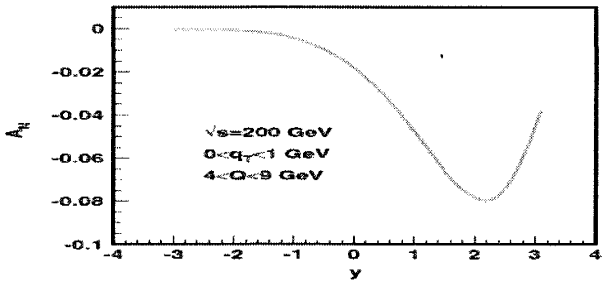
Critical test of TMD factorization

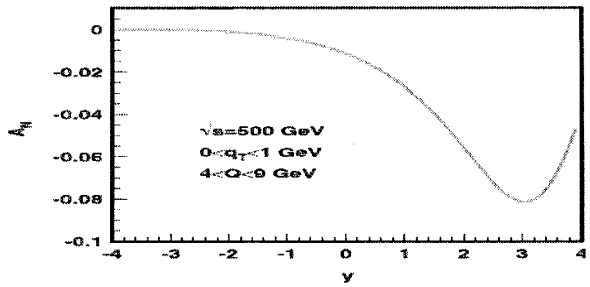
- Sign change:



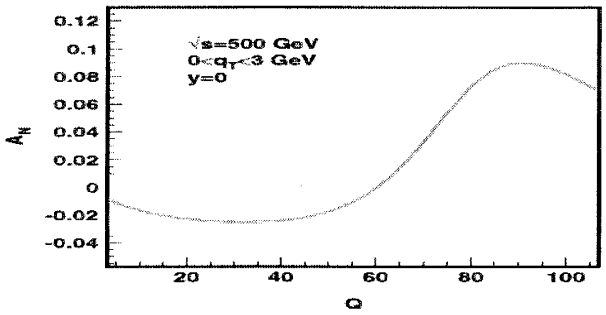
- Drell-Yan:

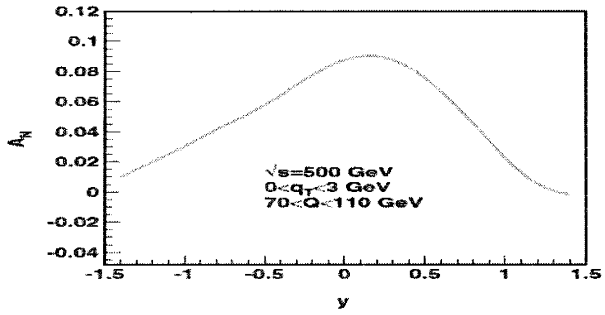
$$A_N^{\sin(\phi-\phi_s)} = -A_N$$





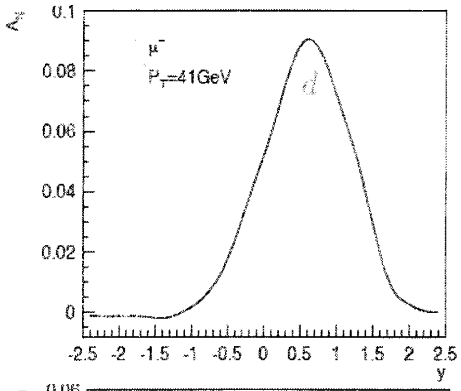
- Z^0:

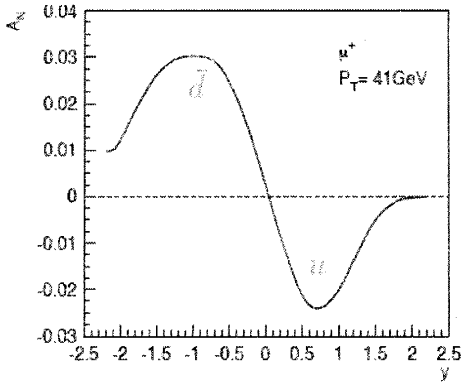


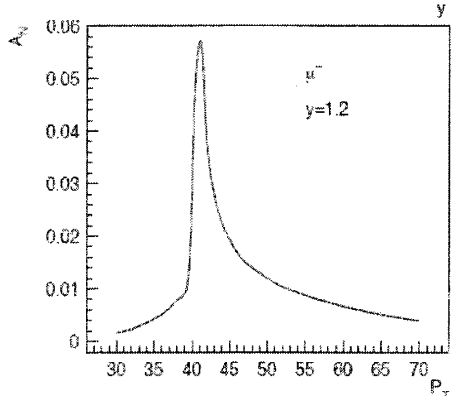


SSA of lepton from W-decay

- Flavor separation:





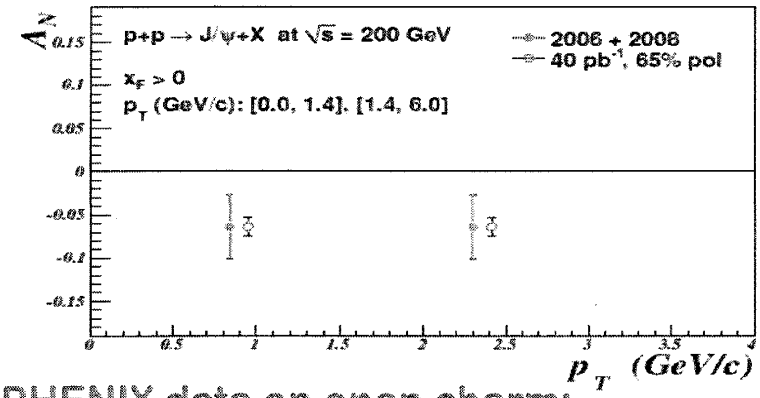


- flavor separation
- asymmetry gets smaller due to dilution should still be measurable by current RHIC sensitivity

Complimentary to Drell-Yan/Z^0 production

SSA of charm production

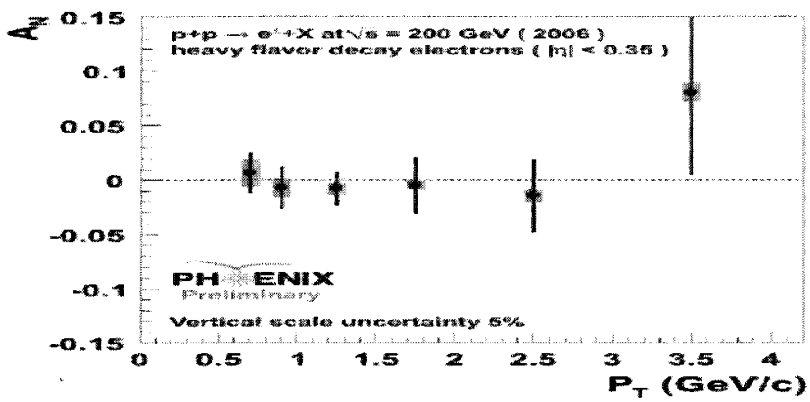
- PHENIX data on J/psi:



TMD factorization:

- ✧ Gluon Sivers function
- ✧ Initial-state vs final-state

- PHENIX data on open charm:



Challenges:

- ✧ J/psi production mechanism
- ✧ TMD factorization for hadornic coll.

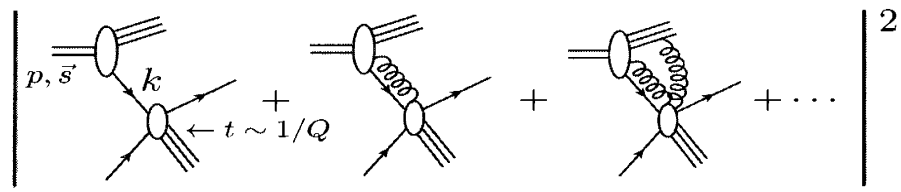
Collins, Qiu, Vogelsang, Yuan, Rogers, Mulder, ...

Cross section with ONE large scale

Efremov, Teryaev, 82; Qiu, Sterman, 91, etc.

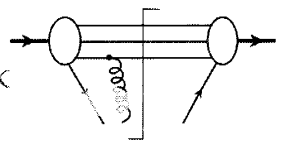
- A_N – twist-3 effect:

$\sigma(Q,\vec{s}) \propto$

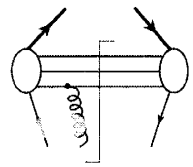


$$\Delta(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D_f(z) + \delta q_f(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z)$$

$T^{(3)}(x,x) \propto$



$D^{(3)}(z,z) \propto$



Qiu, Sterman, 1991, ...

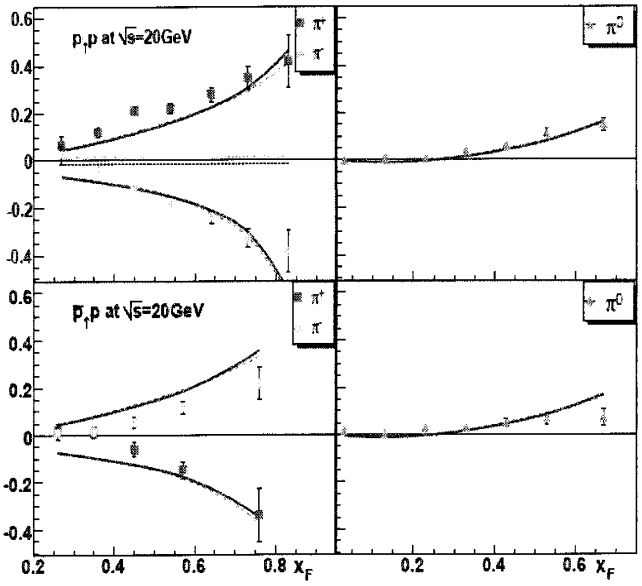
Kang, Yuan, Zhou, 2010

- Spin flip:
  - Interference of single parton and a two-parton composite state
- The phase:
  - Interference of Real and Imaginary part of scattering amplitude
  - gluonic pole: $\propto T^{(3)}(x,x)$
  - fermionic pole contribution: $\propto T^{(3)}(x,0)$ or $T^{(3)}(0,x)$

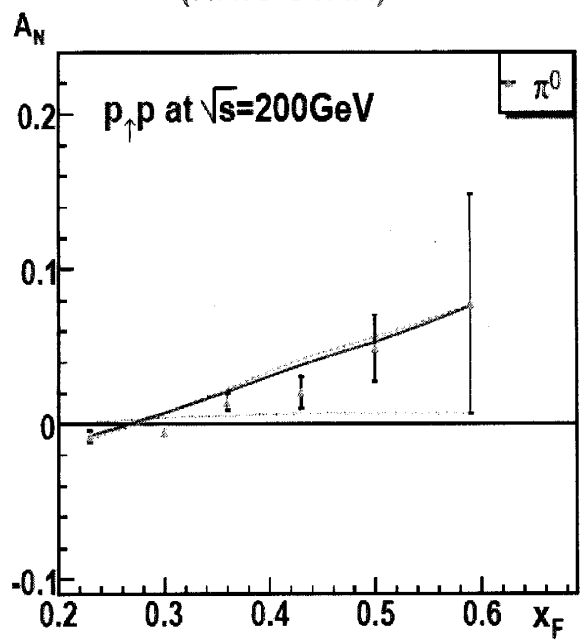
⟹ Integrated information on parton's transverse motion!

LO asymmetries from the $T_F(x,x)$

(FermiLab E704)



(RHIC STAR)



Kouvaris,Qiu,Vogelsang,Yuan, 2006

Nonvanish twist-3 function ⟶ Nonvanish transverse motion

Global QCD analysis for SSA

- Universality of correlation functions:

$$\langle P,s|\overline{\psi}(0)\gamma^+\psi(y^-)|P,s\rangle \longrightarrow \langle P,s|\overline{\psi}(0)\gamma^+\left[\epsilon_\perp^{\alpha\beta}s_{T\alpha}\int dy_2^-\,F_\beta^+(y_2^-)\right]\psi(y^-)|P,s\rangle$$

$$\langle P,s|\overline{\psi}(0)\gamma^+\gamma_5\psi(y^-)|P,s\rangle \longrightarrow \langle P,s|\overline{\psi}(0)\gamma^+\left[i\,g_\perp^{\alpha\beta}s_{T\alpha}\int dy_2^-\,F_\beta^+(y_2^-)\right]\psi(y^-)|P,s\rangle$$

Kang, Qiu, 2009

Same replacement for the gluons

- Scaling violation of correction functions:

Leading order evolution kernels for all channels have been derived!

Kang, Qiu, 2009
Yuan, Zhou, 2009
Braun et al, 2009

- What are urgently needed:

NLO partonic contributions to SSA of all measureable observables!

Vogelsang, Yuan, 2009

- NLO calculations are necessary for any precision pQCD test

To systematically reduce the artificial scale dependence!

Collinear vs TMD factorization

- Relation between TMD and collinear parton distributions:

spin-averaged: $$\int d^2k_T f_a^{\text{SIDIS}}(x,k_T) + \text{UVCT}(\mu^2) = q_a(x,\mu^2)$$

Transverse-spin: $$\frac{1}{M_P}\int d^2\vec{k}_\perp\ \vec{k}_\perp^2\ q_T(x,k_\perp) + \text{UVCT}(\mu^2) = T_F(x,x,\mu^2)$$

- Relation between two factorization schemes

They are valid for different kinematical regions:

Collinear: $Q_1 \ldots Q_n \gg \Lambda_{QCD}$

TMD: $Q_1 \gg Q_2 > \Lambda_{QCD}$

Common region – perturbative region:

$Q_1 \gg Q_2 \gg \Lambda_{QCD}$

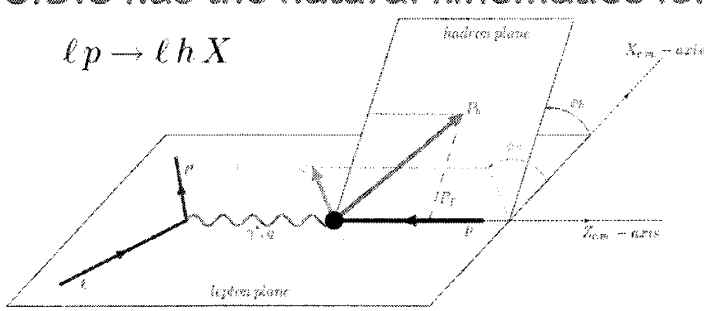
where both schemes are expected to be valid

Ji, Qiu, Vogelsang, Yuan.
Koike, Vogelsang, Yuan

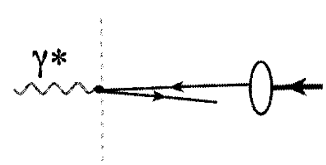
Future: Electron-Ion Collider

- SIDIS has the natural kinematics for TMD factorization:

$\ell p \to \ell h X$

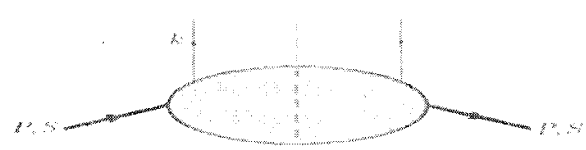


Large Q and small q_T



- Other TMD distributions:

$$\Phi(x,\boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \Big(S_L g_{1L} + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M} g_{1T}^\perp\Big)\gamma^5 \not{n}_+ + h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \Big(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_T}{M} h_{1T}^\perp\Big)\frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M} + h_1^\perp \frac{\sigma_{\mu\nu}k_\perp^\mu n_+^\nu}{M}\Big]$$



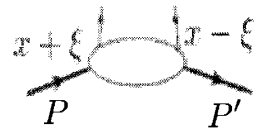
Total 8 TMD quark distributions

Similar decomposition for gluon TMD distribtutions

Generalized parton distribution (GPD)

- Generalized quark distribution:

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\lambda/2) | P \rangle$$
$$\equiv H_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$
$$+ E_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M} \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$



with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \to 0$

- Parton's orbital motion:

$$J_q = \frac{1}{2} \lim_{t\to 0} \int dx\, x \left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$
$$= \frac{1}{2}\Delta q + L_q$$

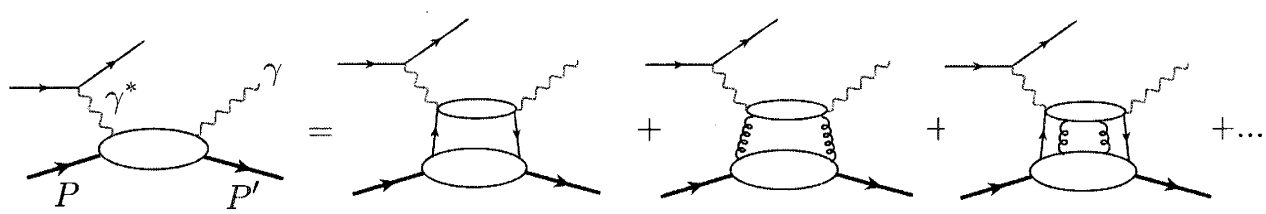
Ji, PRL78, 1997

- Connection to normal quark distribution:

$$H_q(x,0,0,\mu^2) = q(x,\mu^2)$$

EIC is ideal for probing GPD's

- DVCS – exchange vacuum quantum number:



- DVCS – Factorization is ok if $Q^2 \gg -t^2$
- Evolution from color singlet ladder diagrams:

ξ – Does not evolve

x – convolution

- DVCS – meson production:

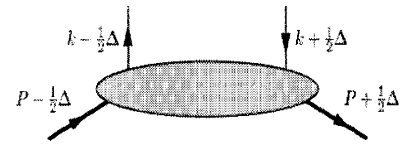
Factorization requires a sufficient separation between the meson and scattered proton: $Q^2 \gg -t^2 \gg \Lambda_{\rm QCD}^2$

Partonic motion seen by a hard probe

- Fully unintegrated distribution: Meissner, Metz, Schlegel, 2009

$$W^{[\Gamma]}_{\lambda\lambda'}(P,k,\Delta,N;\eta) = \frac{1}{2}\int \frac{d^4z}{(2\pi)^4}\, e^{ik\cdot z}\, \langle p',\lambda'|\,\bar{\psi}(-\tfrac{1}{2}z)\,\Gamma\,\mathcal{W}(-\tfrac{1}{2}z,\tfrac{1}{2}z\,|\,n)\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle$$

– not factorizable in general



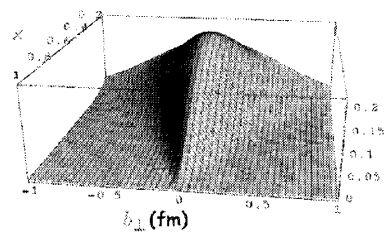
- Generalized TMDs:

$$\mathcal{W}(x,k_T,\Delta)_\Gamma = \int dk^2\, W(P,k,\Delta)_\Gamma$$

– could be factorized assuming on-shell parton for the hard probe

- Wigner function: Belitsky, Ji, Yuan

$$W(x,k_T,b) \propto \int d^3\Delta\, e^{i\vec{b}\cdot\vec{\Delta}}\, \mathcal{W}(x,k_T,\Delta)_{\Gamma=\gamma^+}$$



Burkardt, 2002

- Connection to all other known distributions:

$W(x,k_T,b)$ $\Rightarrow$ Tomographic image of nucleon

$$q(x,b_\perp) = \int d^2k_T db^-\, W(x,k_T,b)_{\gamma^+}$$

$\mathcal{W}(x,k_T,\Delta)_\Gamma$ $\Rightarrow$ TMDs $(\Delta=0)$, GPDs $(\int d^2k_T)$, PDFs $(\Delta=0, \int d^2k_T)$

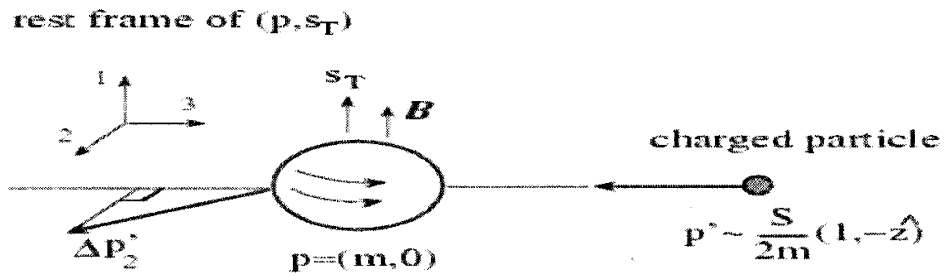
Summary

- Understanding proton spin could provide the first complete example to describe the fundamental properties of hadrons
- RHIC is the only polarized hadron collider in the world
- It has produced interesting and surprise results, and will continue producing new excitements in next decade
- Future EIC could be an ideal and complementary machine for studying the spin structure of hadrons
- With other spin programs around the world, the combination of RHIC and EIC spin program could provide many new opportunities to learn fundamental properties of hadrons in terms of QCD dynamics

Thank you!

What the twist-3 distribution can tell us?

- The operator in Red – a classical Abelian case:



- Change of transverse momentum:

$$\frac{d}{dt}p_2' = e(\vec{v}' \times \vec{B})_2 = -ev_3 B_1 = ev_3 F_{23}$$

- In the c.m. frame:

$$(m,\vec{0}) \to n = (1,0,0_T), \quad (1,-\hat{z}) \to n = (0,1,0_T)$$
$$\Longrightarrow \frac{d}{dt}p_2' = e\,\epsilon^{s_T \sigma n \bar{n}}\, F_\sigma{}^+$$

- The total change: $\Delta p_2' = e\int dy^-\, \epsilon^{s_T \sigma n \bar{n}}\, F_\sigma{}^+(y^-)$

Net quark transverse momentum imbalance caused by color Lorentz force inside a transversely polarized proton

Critical test of TMD factorization

- Factorization in terms of k_T-dependent PDFs:

$$\sigma(Q_1, Q_2, s_{1T}, s_{2T}) = H_0 \otimes \mathcal{F}_2(k_T, s_{1T}) \otimes \mathcal{F}_2(k_T, s_{2T}) + \mathcal{O}(Q_2/Q_1, Q_2/M, M/Q_1)$$

Unlike the collinear factorization, we should include the scale of hadron mass when $Q_2 \sim \Lambda_{QCD}$

- Sivers function:

$$\mathcal{F}_{q/h}(x, k_T, s_T) \equiv \mathcal{F}_{q/h}(x, k_T) + f_{q/h}^{\rm Sivers}(x, k_T)\, \vec{s}_T \cdot (\hat{p} \times \hat{k}_T)$$

- Parity and Time-reversal invariance of matrix element:

$$\langle P, s_T|\hat{\mathcal{O}}(\psi, A_\mu)|P, s_T\rangle = \langle P, -s_T|\mathcal{P}\mathcal{T}\hat{\mathcal{O}}(\psi, A_\mu)^\dagger \mathcal{T}^{-1}\mathcal{T}^{-1}|P, -s_T\rangle$$

$$\Longrightarrow \quad \mathcal{F}_{q/h}^{\rm SIDIS}(x, k_T, s_T) = \mathcal{F}_{q/h}^{DY}(x, k_T, -s_T)$$

$$\Longrightarrow \quad f_{q/h^\uparrow}^{\rm Sivers}(x, k_\perp)^{\rm SIDIS} = -f_{q/h^\uparrow}^{\rm Sivers}(x, k_\perp)^{\rm DY}$$

Time-reversal modified universality

- Collins function: $\sigma(Q_1, Q_2, s_T) = H_0 \otimes \delta q(x, s_T) \otimes \mathcal{D}_2(k_T, Q_1) + \ldots$

Probing the kt-dependent gluon distributions

Feng Yuan
Lawrence Berkeley National Laboratory
RBRC, Brookhaven National Laboratory

Kt-dependent gluon distributions

- Important concepts, objects, elements in small-x physics
- Resummation, evolution, unique feature of CGC
- QCD dynamics at small-x
  - Factorization, universality

Two different definitions in CGC

- Weizsacker-Williams gluon distribution
- Dipole gluon distribution
  - They have the same perturbative behavior
    - $1/qt^2$
  - They differ quite a lot in low pt region
    - $Ln(Qs/qt)$ vs. qt^2
- They were both used in CGC at early time; only the dipole gluon distribution is used now

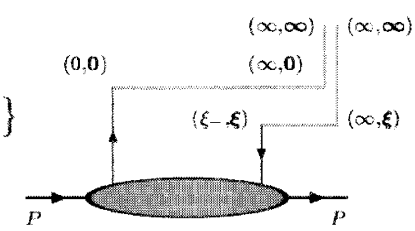
Conventional gluon distribution

- Collins-Soper, 1981

$$xG^{(1)}(x,k_\perp) = \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \times \langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{L}_\xi^\dagger \mathcal{L}_0 F^{+i}(0)|P\rangle$$

  - Gauge link in the adjoint representation

$$\mathcal{L}_\xi = \mathcal{P}\exp\{-ig\int_{\xi^-}^{\infty} d\zeta^- A^+(\zeta,\xi_\perp)\}$$
$$\mathcal{P}\exp\{-ig\int_{\xi_\perp}^{\infty} d\zeta_\perp\cdot A_\perp(\zeta^-=\infty,\zeta_\perp)\}$$



Classic YM theory

- McLerran-Venugopalan

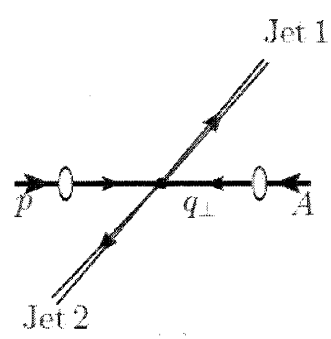
$$xG^{(1)}(x,k_\perp) = \frac{S_\perp}{\pi^2\alpha_s}\frac{N_c^2-1}{N_c}\int\frac{d^2r_\perp}{(2\pi)^2}\frac{e^{-ik_\perp\cdot r_\perp}}{r_\perp^2}\left(1-e^{-\frac{r_\perp^2 Q_s^2}{4}}\right)$$

  - See also, Kovchegov-Mueller
  - We can reproduce this gluon distribution using the TMD definition with gauge link contribution, following BJY 02, BHPS 02
  - WW gluon distribution is the conventional one

Two particle correlations as probe to the gluon distributions

- Dilute + Dense scattering

$$B + A \to H_1(k_1) + H_2(k_2) + X$$

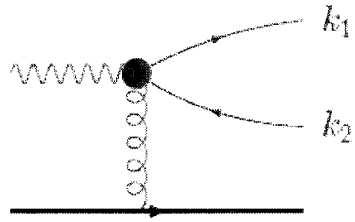


- Correlation limit:

$$|\vec{k}_{1\perp} + \vec{k}_{2\perp}| \ll P_\perp \rightarrow (\vec{k}_{1\perp} - \vec{k}_{2\perp})/2$$

DIS dijet probes **WW** gluons

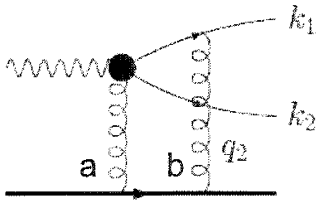
$$\gamma_T^* A \to q(k_1) + \bar{q}(k_2) + X$$



- Hard interaction includes the gluon attachments to both quark and antiquark
- The q_t dependence is the gluon distribution w/o gauge link contribution at this order

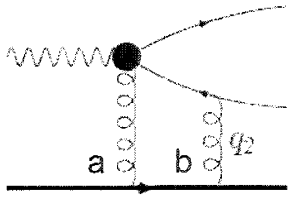
Final state interaction → gauge link

Belitsky-Ji-Yuan, 02
Bomhof-Mulders-Pijlman, 06



(b)

$$\frac{g}{-q_2^+ + i\epsilon} T^b \Gamma^a$$



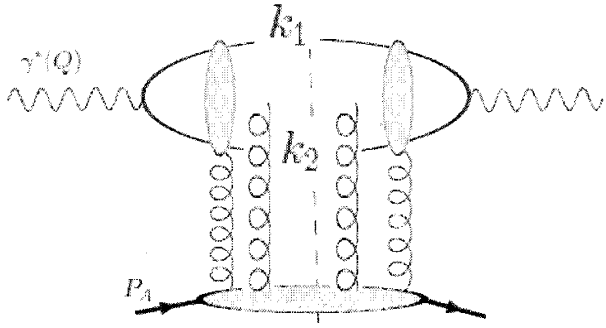
(c)

$$\frac{-g}{-q_2^+ + i\epsilon} \Gamma^a T^b$$

$$\frac{i}{-q_2^+ + i\epsilon}(-ig)(-if_{bca})T^c$$

This is exactly the leading order expansion of the gauge link contribution, checked at three-gluon exchange order

CGC/color-dipole calculations



$$|\mathcal{A}|^2 = N_c \alpha_{em} e_q^2 \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2b}{(2\pi)^2}\frac{d^2b'}{(2\pi)^2} e^{-ik_{1\perp}\cdot(x-x')}$$
$$\times e^{-ik_{2\perp}\cdot(b-b')} \sum \psi_T^*(x-b)\psi_T(x'-b')$$
$$\times \left[1 + S^{(4)}_{x_g}(x,b;b',x') - S^{(2)}_{x_g}(x,b) - S^{(2)}_{x_g}(b',x')\right]$$
$$S^{(2)}_{x_g}(x,b) = \frac{1}{N_c}\left\langle \mathrm{Tr}U(x)U^\dagger(b)\right\rangle_{x_g}$$
$$S^{(4)}_{x_g}(x,b;b',x') = \frac{1}{N_c}\left\langle \mathrm{Tr}U(x)U^\dagger(x')U(b')U^\dagger(b)\right\rangle_{x_g}$$

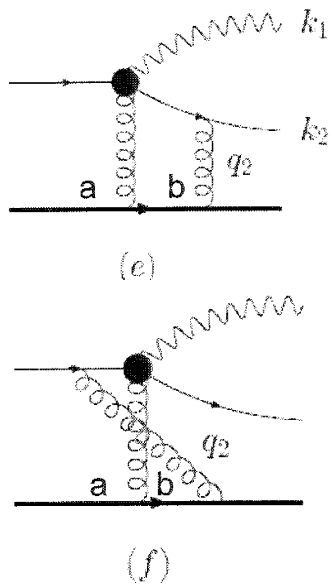
Expansion in the correlation limit, $q_\dagger \ll P_\dagger$

- There is cancellation between two-point and four-point functions
- final result

$$\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{d\mathcal{P}.\mathcal{S}.} = \alpha_{em}\epsilon_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right) z(1-z)\left(z^2+(1-z)^2\right)\frac{P_\perp^4+\epsilon_f^4}{(P_\perp^2+\epsilon_f^2)^4}$$
$$\times(16\pi^3)\int \frac{d^3v d^3v'}{(2\pi)^6} e^{-iq_\perp\cdot(v-v')} 2\left\langle \mathrm{Tr}F^{i+}(v)\mathcal{U}^{[+]\dagger}F^{i+}(v')\mathcal{U}^{[+]}\right\rangle_{x_g}$$

- Agrees with the TMD result

Photon-jet correlation probes the dipole gluon distribution



$$\frac{g}{-q_2^+ + i\epsilon} T^b \Gamma^a$$

$$\frac{g}{-q_2^+ + i\epsilon} \Gamma^a T^b$$

$$\frac{i}{-q_2^+ + i\epsilon}(-ig)\left(T^b\Gamma^a + \Gamma^a T^b\right)$$

There is no color structure corresponding to this, We have to express the gluon Distribution in the Fundamental representation

- Differential cross section

$$\frac{d\sigma^{(pA\to\gamma q+X)}}{d\mathcal{P}.\mathcal{S}.} = \sum_f x_1 q(x_1) x_g G^{(2)}(x_g, q_\perp) H_{qg\to\gamma q}$$

$$xG^{(2)}(x, k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp}$$

$$\langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle$$

Bomhof-Mulders-Pijlman 06

- This is the dipole gluon distribution, also called unintegrated gluon distribution

$$xG^{(2)}(x, q_\perp) \simeq \frac{q_\perp^2 N_c}{2\pi^2\alpha_s} S_\perp \int \frac{d^2 r_\perp}{(2\pi)^2} e^{-iq_\perp\cdot r_\perp} S^{(2)}_{x_g}(0, r_\perp)$$

  - Agrees with CGC calculation, e.g.,

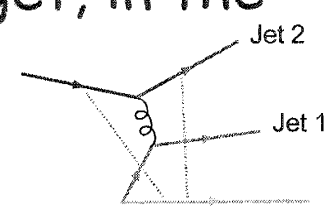
Gelis-Jalilian-Marian 02

Intuitive explanations

- Final state interactions in DIS can be eliminated by choosing the light-cone gauge → number density interpretation
- Photon-jet correlation have both initial/final state interactions, can not be eliminated by choosing LC gauge → there is no number density interpretation → dipole gluon distribution

Dijet-correlation at RHIC

- Dilute system on a dense target, in the large Nc limit,



$$\frac{d\sigma^{(pA\to\text{Dijet}+X)}}{d\mathcal{P}.\mathcal{S}.}$$
$$= \sum_q x_1 q(x_1) \frac{\alpha_s^2}{\hat{s}^2} \left[\mathcal{F}_{qg}^{(1)} H_{qg\to qg}^{(1)} + \mathcal{F}_{qg}^{(2)} H_{qg\to qg}^{(2)}\right]$$
$$+ x_1 g(x_1) \frac{\alpha_s^2}{\hat{s}^2} \left[\mathcal{F}_{gg}^{(1)} \left(H_{gg\to q\bar{q}}^{(1)} + H_{gg\to gg}^{(1)}\right)\right.$$
$$\left. + \mathcal{F}_{gg}^{(2)} \left(H_{gg\to q\bar{q}}^{(2)} + H_{gg\to gg}^{(2)}\right) + \mathcal{F}_{gg}^{(3)} H_{gg\to gg}^{(3)}\right] .$$

- Kt-dependent gluon distributions

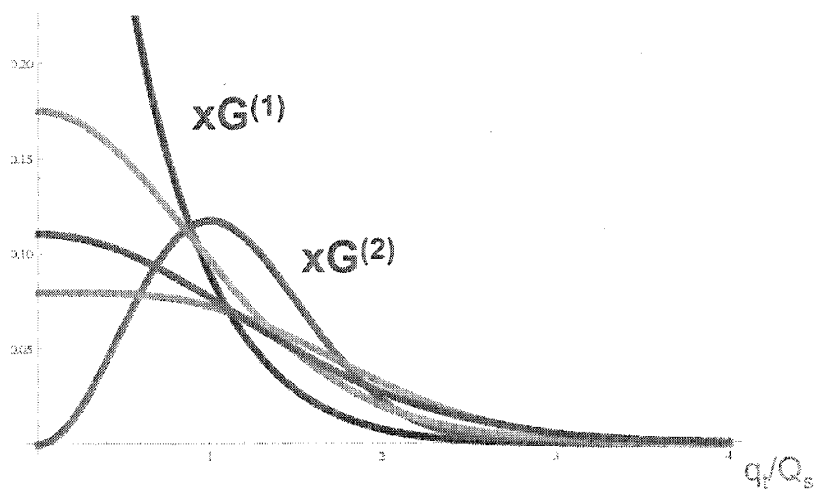
$$\mathcal{F}_{gg}^{(1)} = xG^{(2)}(x, q_\perp), \quad \mathcal{F}_{gg}^{(2)} = \int xG^{(1)}(q_1) \otimes F(q_2) \ ,$$

$$\mathcal{F}_{gg}^{(1)} = \int xG^{(2)}(q_1) \otimes F(q_2), \quad \mathcal{F}_{gg}^{(2)} = \int \frac{q_{1\perp} \cdot q_{2\perp}}{q_{1\perp}^2} xG^{(2)}(q_1) \otimes F(q_2)$$

$$\mathcal{F}_{gg}^{(3)} = \int xG^{(1)}(q_1) \otimes F(q_2) \otimes F(q_3) \ ,$$

- Color-dipole/CGC agrees with the above results

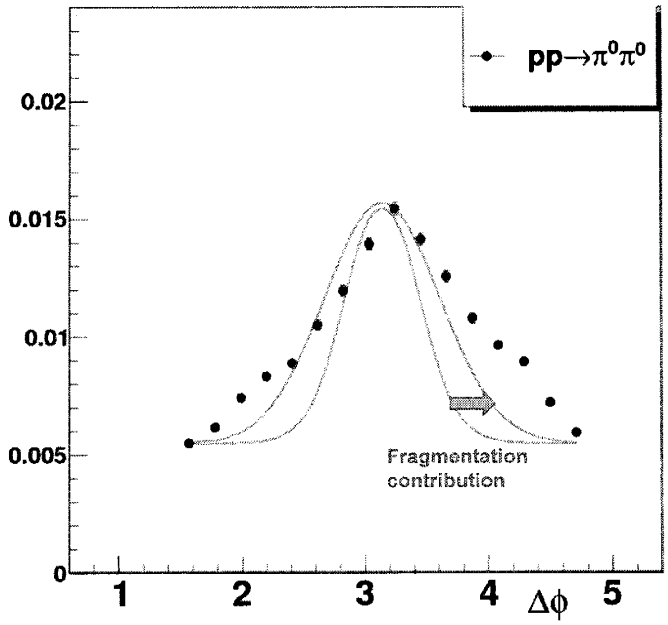
Kt-dependent gluon distributions



- Naïve kt-factorization breaks down, violation effect is 100%
- Integrate out $q_\perp$, recover the inclusive dijet cross section
- At large $q_\perp$: $P_\perp >> q_\perp >> Q_s, \Lambda_{QCD}$, collinear factorization result for the correlation,
  - Qiu-Vogelsang-Yuan 2007

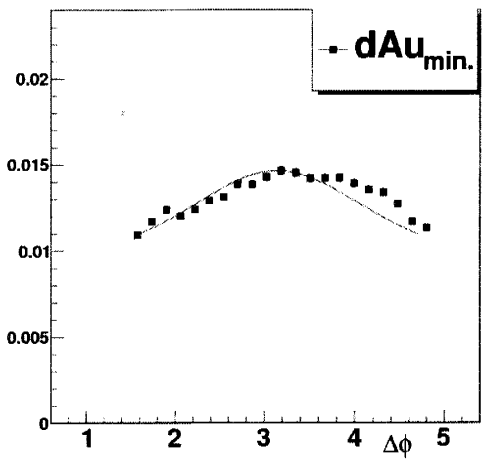
Compare to the STAR data

- $\eta_1 \sim \eta_2 \sim 3.1$
- GBW model for UGDs
- $Q_s^2 \sim (3.10^{-4}/x)^{0.28} GeV^2$
- Include Fragmentation contribution
- No-BK evolution

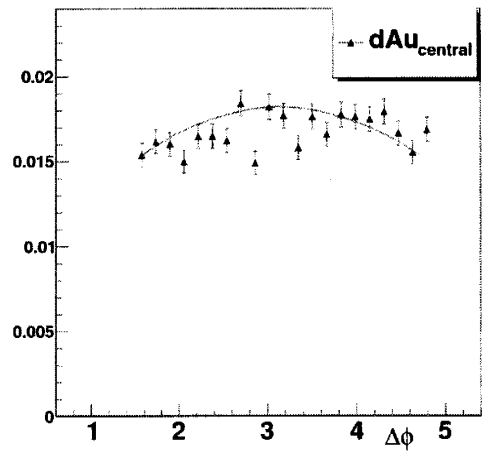


dAu collisions

- $\eta_1 \sim \eta_2 \sim 3.2$
- $Q^2_{sA} \sim 0.8 A^{(1/3)} Q_{sp}^2$

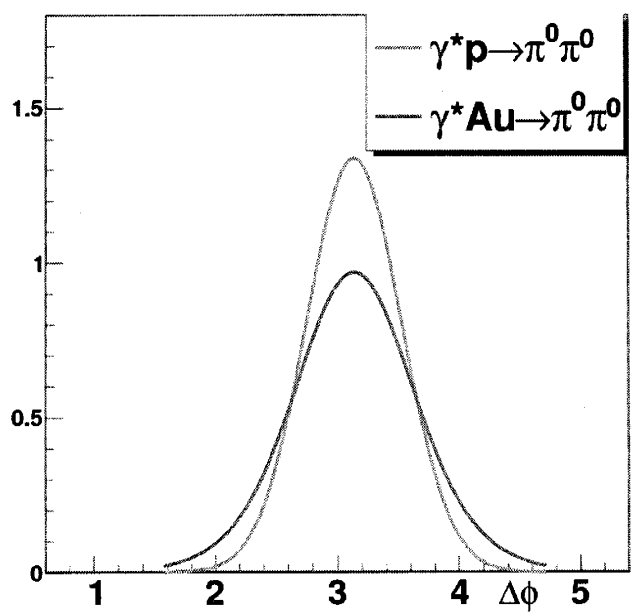


- $\eta_1 \sim \eta_2 \sim 3.1$
- $Q^2_{sA} \sim 1.7\ 0.8 A^{(1/3)} Q_{sp}^2$



EIC Predictions

- $\sqrt{s_{\gamma p}}$=100GeV
- $z_1 \sim z_2 \sim 0.3$ for two hadrons
- $Q^2_{sA} \sim 0.8 A^{(1/3)} Q_{sp}^2$
- Include Fragmentation contribution



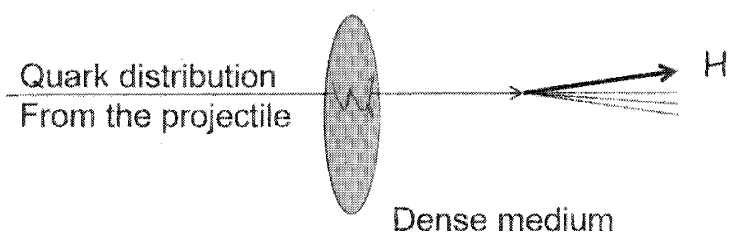
Conclusions

- Two particle correlations probe the kt-dependent gluon distributions

	DIS	SIDIS	Hadron in pA	Photon-jet in pA	DIS dijet	Dijet in pA
$G^{(1)}$ (WW)	×	×	×	×	√	√
$G^{(2)}$ (dipole)	√	√	√	√	×	√

(Leading order)

Forward hadron production



$$\frac{d\sigma}{dyd^2P_{h\perp}} = \int \frac{dz}{z^2} x_1 q(x_1) D(z) x_2 G^{(2)}(x_2, q_\perp = P_{h\perp}/z)$$

Dumitru-Jalilian-Marian, 02
Dumitru-Hayashigaki-Jalilian-Marian, 06

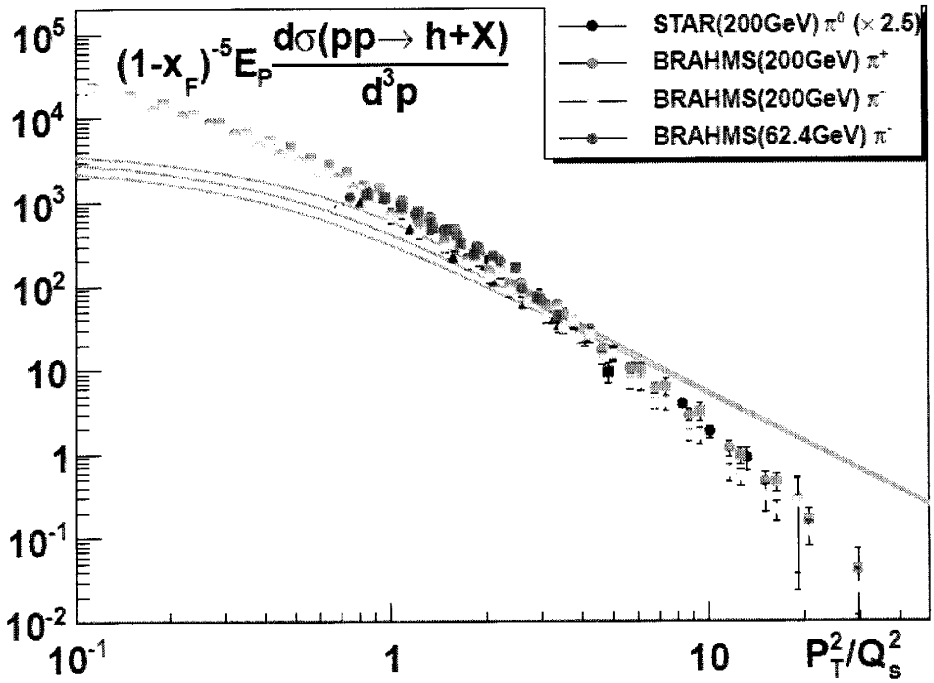
Simple power counting

- Forward region is dominated by the valence quark distribution $(1-x)^3$
- Similar power behavior for the fragmentation function, $(1-z)^{1\sim2}$, 1009.2481
- Pt-dependent-Geometric scaling,

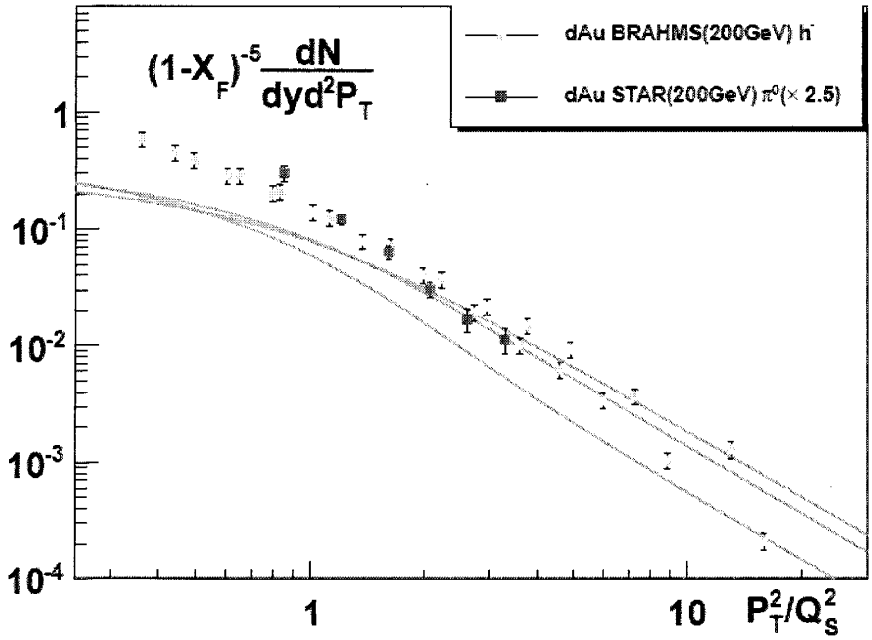
$$\frac{d\sigma}{dyd^2P_{h\perp}} = (1-X_F)^{5-6}\mathcal{F}\left(\frac{P_{h\perp}}{Q_s(x_2)}\right)$$

Similar study by McLerran- Praszalowicz, 10

Encouraging data from RHIC



dAu collisions



Report for RBRC review meeting by Kirill Tuchin

Publications

1. K.~Tuchin,
``Photon decay in strong magnetic field in heavy-ion collisions,"
[arXiv:1008.1604 [nucl-th]].

2. K.~Tuchin,
``Synchrotron radiation by fast fermions in heavy-ion collisions,"
Phys.\ Rev.\ {\bf C82}, 034904 (2010).
[arXiv:1006.3051 [nucl-th]].

3. K.~Tuchin,
``Rapidity and centrality dependence of azimuthal correlations in
Deuteron-Gold collisions at RHIC,"
Nucl.\ Phys.\ {\bf A846}, 83-94 (2010).
[arXiv:0912.5479 [hep-ph]].

4. K.~Tuchin,
``Nonlinear pair production in scattering of photons on ultra-short laser
pulses at high energy,"
Phys.\ Lett.\ B {\bf 686}, 29 (2010)
[arXiv:0911.4964 [hep-ph]].

Talks

1. ``Azimuthal correlations in dA collisions", The 25th Nishinomiya-Yukawa Memorial International Workshop, Yukawa Institute for Theoretical Physics, Kyoto, Japan, Aug 11th, 2010 (invited talk).

2. ``Gluon saturation and initial conditions", PHENIX collaboration meeting, Iowa State University, Ames, IA, July 12th, 2010 (invited talk).

3. ``J/ψ production and saturation effects, INT program "Quantifying the properties of hot QCD matter", July 6th, 2010 (invited talk).

4. ``Probing the low-x QCD with Diffraction on nuclei", LBNL, May 26th, 2010 (seminar).

5. ``Charmonium and open charm production and saturation", at the RIKEN-BNL workshop ``Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC?", BNL, May 10-12, 2010 (invited talk).

6. ``Cold nuclear matter effects on J/ψ production in AA and dA",
26th Winter Workshop on Nuclear Dynamics, Ocho Rios, Jamaica, January 2-9, 2010 (talk).

Scientific Meetings Organized

``An International Symposium in Celebration of Genya Levin's 70th Birthday", Tel Aviv, October 7-8, 2010.

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RIKEN BNL RESEARCH CENTER

RBRC Scientific Review Committee Meeting

October 27-29, 2010

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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D. Kawall
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I. Nakagawa
R. Nouicer
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K. Okada
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T. Roser
N.P. Samios
E. Shintani
A. Stasto
A. Taketani
D. Teaney
K. Tuchin
R. Venugopalan
F. Yuan

Session Chairs: Y. Akiba, A. Baltz, A. Deshpande, T. Izubuchi, L. McLerran, N.P. Samios
Organizer: N.P. Samios