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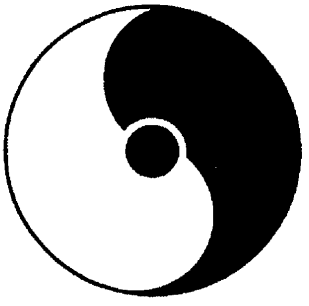
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 97

RBRC Scientific Review Committee Meeting

October 21-22, 2009



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 ~50 graduates of which 14 theorists and 6 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 ninety 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.

N. P. Samios, Director
March 2009

*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 21 – 22, 2009

Brookhaven National Laboratory, Upton, NY 11973

The tenth evaluation of the RIKEN BNL Research Center (RBRC) took place on October 21 – 22, 2009, at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC), present at the meeting, were Prof. Wit Busza (Chair), Prof. Ken Imai, Prof. Alfred Mueller, Prof. Charles Prescott, and Prof. Akira Ukawa. We are pleased that Dr. Hideto En'yo, the new 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 (Dr. Ryoji Noyori, RIKEN President) 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

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973 I

RBRC Scientific Review Committee (SRC) Meeting

Brookhaven National Laboratory, Upton, NY

Physics Department, Building 510,
October 21, 22, 2009

Committee Members

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Wednesday, October 21, 2009

8:00 AM - 9:00 AM ***SRC Executive Session (Room 2-160)***

New Director - Nishina Center

Director - RBRC

Open Sessions - Large Seminar Room

9:00 AM – 10:15 AM **EXPERIMENTAL GROUP PRESENTATIONS**

9:00 AM Yasuyuki Akiba: RBRC Experimental Group: Introduction and spin physics

9:15 AM Manabu Togawa: PHENIX local polarimetry using single transverse spin asymmetry for very forward neutron

9:30 AM Kieran Boyle: Improving the measurement of relative luminosity: Dealing with multiple collisions

9:45 AM David Kawall: Double longitudinal spin asymmetry and cross-section of non-identified charged hadrons $\sqrt{s}$ = 62.4 GeV/*c*

10:00 AM Kensuke Okada: First W signals in p+p collisions in PHENIX central arm

10:15 AM – 10:45 AM **Coffee Break**

Open Sessions - Large Seminar Room

10:45 AM – 12:00 PM **EXPERIMENTAL GROUP PRESENTATIONS**

10:45 AM Yasuyuki Akiba: RBRC Overview: Heavy ion and upgrades

11:00 AM Stefan Bathe: Parton energy loss in the quark-gluon plasma

11:15 AM Ralf Seidl: The PHENIX muon trigger upgrade

11:30 AM Atsushi Taketani: VTX pixel detector

11:45 AM Rachid Nouicer: Silicon vertex tracker "VTX" for PHENIX Upgrade: Silicon Stripixel Detector

12:00 - 1:30 PM ***SRC Executive Session - Working Lunch (Room 2-160)***

Open Sessions - Large Seminar Room

1:30 PM – 3:30 PM **THEORY GROUP PRESENTATIONS**

1:30 PM Larry McLerran: Theory Overview – Hot areas of interest In RBRC Theory

1:50 PM Feng Yuan: Theoretical study of nucleon structure

2:10 PM Cecilia Lunardini: Supernova neutrinos

2:30 PM Adrian Dumitru: The CGC and the Ridge

2:50 PM Denes Molnar: Two topics related to viscous hydrodynamics

3:10 PM Rainer Fries: Probing hot nuclear matter

3:30 PM – 4:00 PM **Break**

Open Sessions - Large Seminar Room

4:00 PM - 5:20 PM **THEORY GROUP PRESENTATIONS**

4:00 PM Anna Stasto: F_L structure function in DGLAP/BFKL approach

4:20 PM Derek Teaney: Viscosity in heavy ion collisions

4:40 PM Kirill Tuchin: Geometric effects in High Energy Electrodynamics

5:00 PM Toru Kojo: Quarkyonic Chiral Spiral

7:00 PM **DINNER**

Thursday, October 22, 2009

8:00 AM to 9:00 AM	***SRC Executive Session (Room 2-160)***
Open Session	**Large Seminar Room**
9:00 Am – 11:00 AM	**Lattice Gauge Theory Presentations**

9:00 AM	Norman Christ	Lattice QCD @ RBRC Physics Goals and the QCDCQ Project
9:30 AM	Taku Izubuchi:	RBRC Lattice activities
9:45 AM	Yasumichi Aoki:	Proton Decay Matrix Elements
10:00 AM	Thomas Blum:	Chiral Magnetic Effect in 2+1 flavor QCD
10:15 AM	Shigemi Ohta:	Nucleon structure functions from Dynamical (2+1)-flavor domain wall fermions
10:30 AM	Peter Petreczky:	Fluctuations of conserved charges in high-T QCD
10:45 AM	Tomomi Ishikawa:	$B^0 - \bar{B}^0$ mixing with domain-wall and static quarks
12:00 PM	Thomas Roser	eRHIC – the Future of RHIC

Break

11:30 AM - 12:30 PM	**INTERVIEWS - Meetings with Individual RBRC Staff (Rooms 2-160, Theory, and 2-78, Experimental)**
12:30 - 1:30 PM	***SRC Executive Session - Working Lunch (Room 2-160)***
1:30-3:00 PM	**INTERVIEWS - Meetings with Individual RBRC Staff (continued) (Rooms 2-160 and 2-78)**
3:00-4:15PM	**Executive Session**
4:15-5:00 PM	**Close Out**
5:00 PM	**Adjourn**

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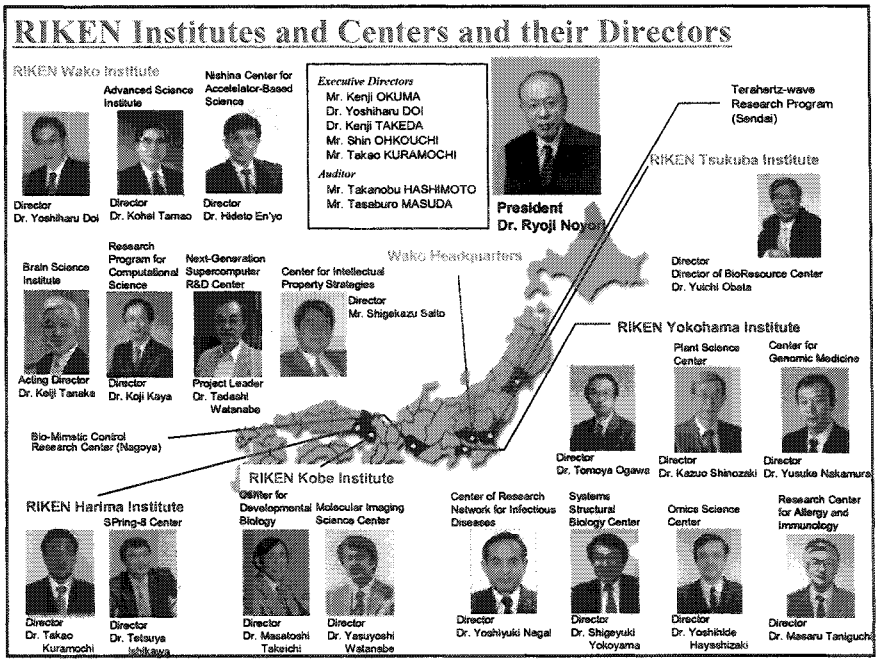
RIKEN NISHINA CENTER

Scientific Review Committee for RIKEN BNL Research Center (RBRC-SRC)

Hideto En'yo
Director, RIKEN Nishina Center (RNC)
November 17-18 2008
BNL, USA

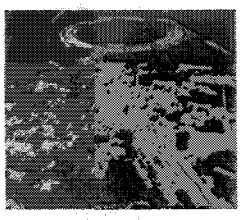
RIKEN Institutes and Centers and their Directors



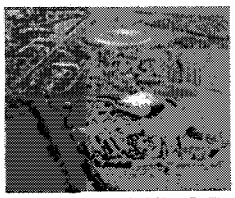
RIKEN NISHINA CENTER

RIKEN Nishina Center for Accelerator-Based Science

(established on April 1 2006)

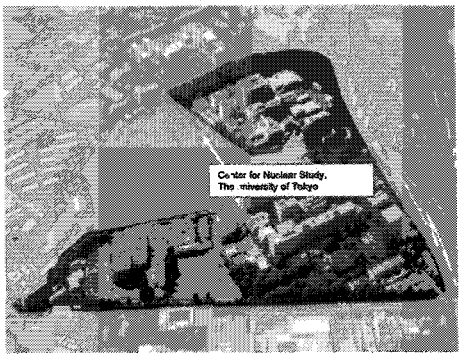


RIKEN BNL Research Center
World's first polarized proton beam colliding
High- speed lattice QCD computing

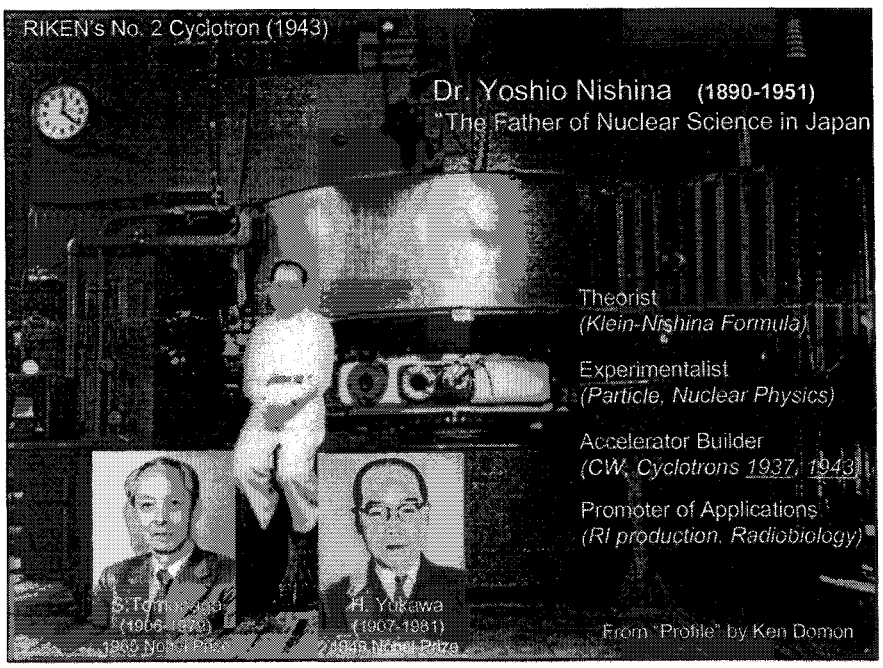


RIKEN RAL Muon Facility
World's most intense pulsed muon beam

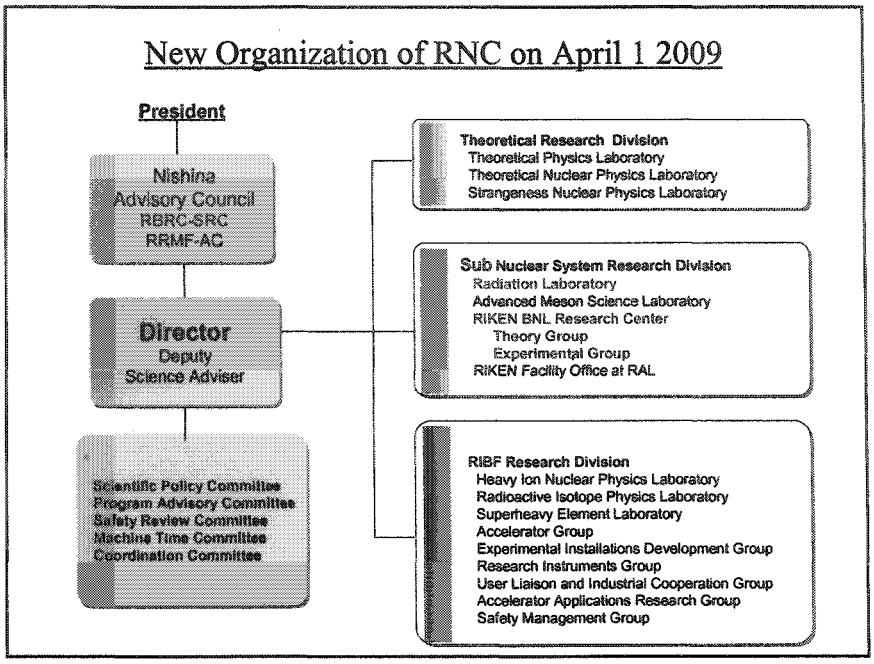
Research Locations



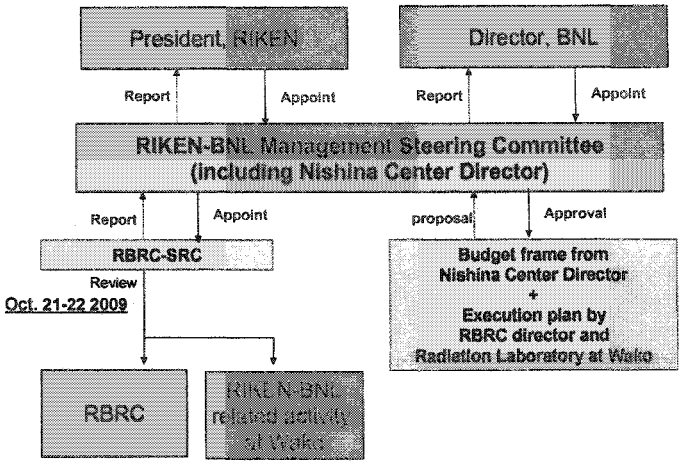
RI Beam Factory (Wako-city)
World's most intense exotic RI beam



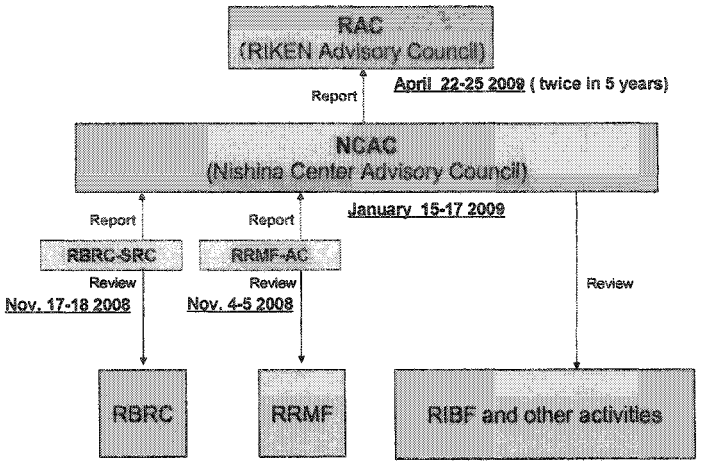
New Organization of RNC on April 1 2009



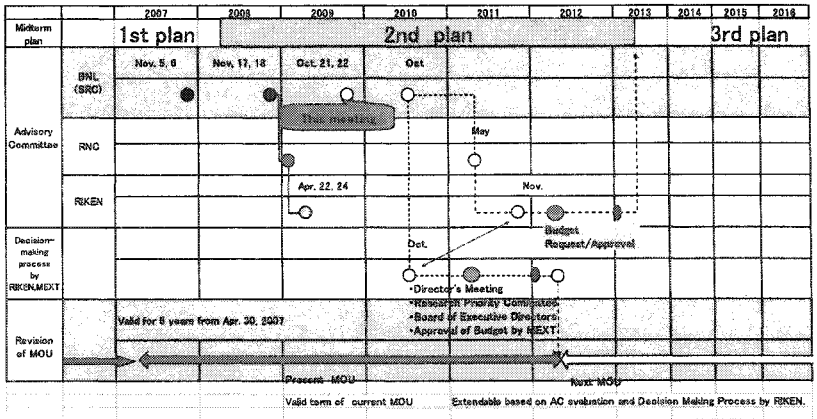
RIKEN Review System and Schedule (General)



RIKEN Review System and RBRC-SRC(when runs together)



Schedule of BNL-SRC,RNC-AC, RIKEN-AC and revision of the agreement with BNL



Next year's SRC will have an important sequence.
Please be prepare this time.

Nishina Center Advisory Council
January 15-17, 2009

Name	Affiliation
Sydney Gales (Chair)	GANIL
Shoji Nagamiya	**KEK, J-PARC Center**
Walter F.Henning	**ANL (Chair NP-PAC)**
Robert Kiefl	**University of British Columbia (Chair ML-PAC)**
Wit Busza	**MIT (Chair RBRC-SRC)**
Andrew Taylor	ISIS, RAL (Chair RRMF-AC)
Angela Bracco	**University of Milan**
Makoto Inoue	**Kyoto University (Prof. Emeritus)**
Alexey Korsheninnikov	**Kurchatov Institute**
Karlheinz Langanke	**GSI**
Hideyuki Sakai	**the University of Tokyo**
WenQing Shen	**SINAP, Chinese Academy of Science**
Bradley Sherrill	**NSCL, Michigan State University**
Hiroshi Toki	**RCNP, Osaka University**

List of members of the 7th RAC

	Name	Title and position	Specialized field	Country
Chairperson	Dr. Zach W. Hall	Emeritus Vice Chancellor, UCSF	Neuroscience	USA
Vice Chairperson	Dr. Yuan-Tseh Lee	President Emeritus, Academia Sinica	Chemistry	Taiwan
	Dr. Akira Inaba	Advisor, Japan Science and Technology Agency	Biotechnology	Japan
	Dr. Toshiaki Ikoma	Director, Center for Research and Development Strategy, Japan Science and Technology Agency	Engineering	Japan
	Prof. Mats L. H. Wahren	Professor, Department of Microbiology, Tumor and Cell Biology (MTC), Karolinska Institutet	Immunology	Sweden
	Prof. Howard Alper	Professor, Department of Chemistry, University of Ottawa	Chemistry	Canada
	Prof. Tomohiko Ohtsuki	Professor, Nihon University Graduate School	Environmental Sciences	Japan
	Prof. Colin Blakemore	Professor, Department of Physiology, Anatomy and Genetics, University of Oxford	Neurology	UK
	Prof. Rita R. Colwell	Distinguished University Professor, Center for Bioinformatics & Computational Biology, University of Maryland	Oceanography	USA
	Prof. Shuh Jiang	Director, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences	Chemistry	China
	Prof. Paul Kleiss	Professor Emeritus, Department of Physics, Munich University of Technology	Physics	Germany
	Prof. Karl B. Sharpless	Professor, Chemistry, University of Technology	Chemistry	Sweden
	Robert S. Matthews	Vice President of Basic Research	Pharmacy	USA

FOR LAST REVIEW !
NEXT ONE will be DIFFERENT

Terms of Reference from President to the Advisory Council (AC) of each Center

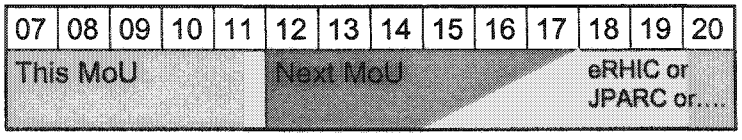
1) Are there achievements with major scientific significance or achievements with significant social impacts?
- Are there achievements which will be notable in the history of science?

2) How does the Center compare with similar research institutions abroad? Make recommendations for possible improvement based on this investigation.
- Where does RIKEN rank in the worldwide research community?

3) Evaluate the Center's collaborations within RIKEN and with outside institutions, and evaluate the Center's effort to promote international collaborations.
- Are the Center's collaborations resulting in better research achievements and more contribution to society?

Some remarks for this review

1) It is preferred to have Next MoU for 6 years, to match with RIKEN's mid term cycle.
2) Next MoU extension may not be so difficult, but we will certainly be asked what is happen at the end (from JFY2018). Although RIKEN Nishina Center will 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.



3) There glows significant Lattice QCD applications in 10 peta-flops Computer Center at Kobe. Please advice on the RBRC's standing point for that.

RBRC

Scientific Review Committee

RBRC Overview

Nicholas P. Samios

October 21, 2009

Brookhaven National Laboratory

RBRC Physics Interests

- Spin-Polarized Protons
  - Spin Structure of Proton
    - Gluon
    - Angular Momentum
  - W Production
    - Polarized anti-quark distributions
- Recent Results
  - Global next to leading order analysis of polarized parton distributions
  - Investigated relations between Sivers effect and twist three gluon correlations
  - First signals of W's in polarized p-p collisions

RBRC Physics Interests

Relativistic Heavy Ions
- Dense Nuclear matter
- sQGP
- Critical Point
- Color Glass condensate
- Topological Charge

Recent Results
- Topological Charge Fluctuations
- Quarkyonic Matter and the Phase Diagram at Finite Baryon Density and Temperature
- Color Glass Condensate
  - Two particle Angular Correlations seen in dA
- Ridge Structure in AA and flux tubes of colored fields

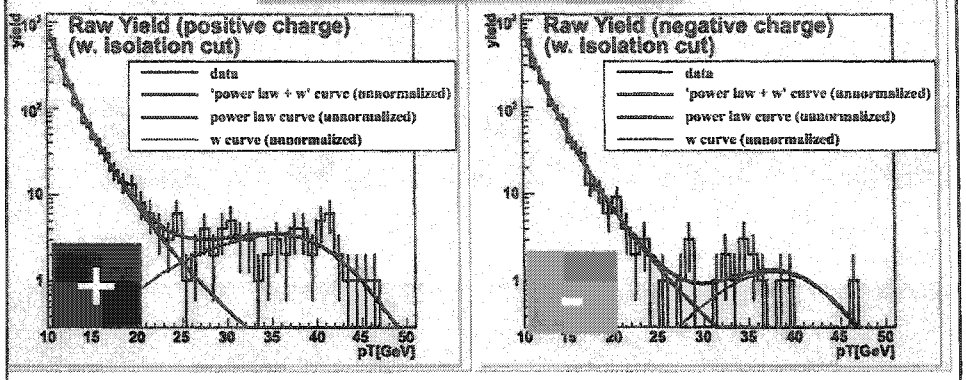
RBRC Physics Interests

Non-Perturbative QCD – Lattice Gauge
- Hadron Masses
- Heavy Quark and Nucleon Properties
- CKM Matrix
- Phase Transition – Equation of State
- CP violation

Recent Results
- 2+1 Flavor Dynamical Domain Wall Fermion Ensembles
  - Large volumes and smaller spacings
- Most accurate determination of B_K
- Determined V_{us} = .2249 (14)
- Physical Strange Quark Mass too large for chiral perturbation theory
- Most reliable result on axial charge

First W → e signals in p+p collisions

Shown in 2009 fall DNP/JPS at Hawaii



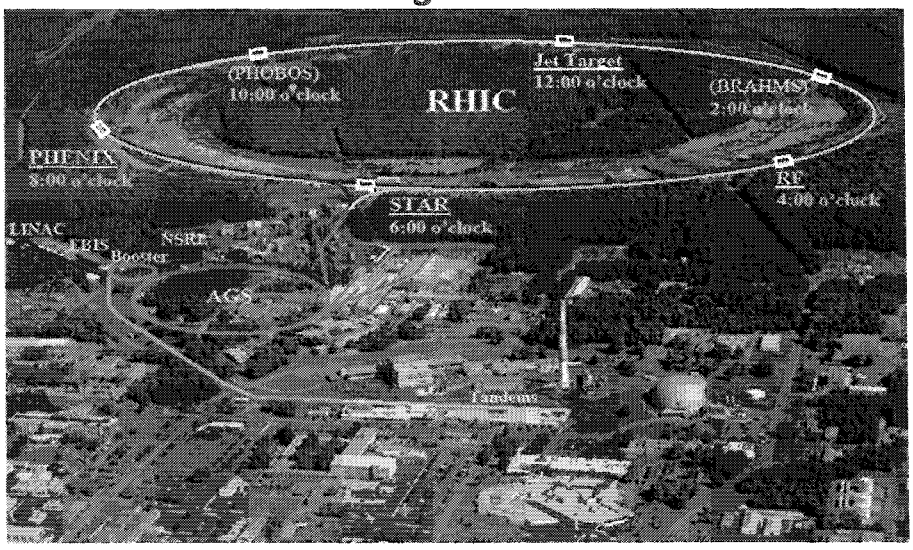
Raw yield with an isolation cut.

From the first 500 GeV p+p run at RHIC (RUN9)

W boson to electron decay signals are confirmed.
Cross section analysis is underway

Talk: K. Okada

RHIC – a High Luminosity (Polarized) Hadron Collider Entering Its Scientific Prime



RHIC Accelerator

Run 9 Polarized protons

200 GeV	10 weeks	
Luminosity	60 pb-1	(50% of goal)
Polarization	56%	(expected 60 -70%)
500 GeV	6 weeks	
Luminosity	60pb-1	(100% of goal)
Polarization	34%	(50% of goal)

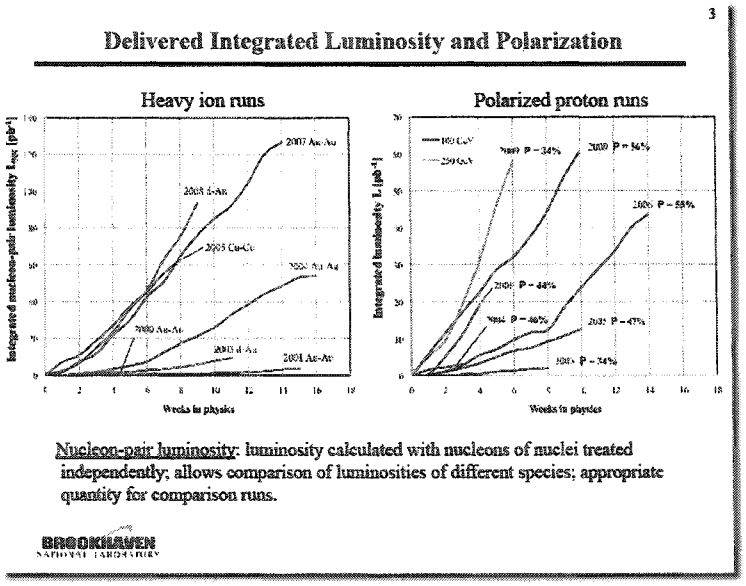
Expected Improvements

200 GeV

- Increase β^* .85
- Reduce Electron cloud – long bunch length
- Increase bunch intensity

500 GeV

- Run at a different vertical tune
- Improve AGS polarization



RHIC Accelerator

Run 10 25 – 30 weeks

Au x Au	200 GeV/Amu	10 weeks
	62.4 GeV/Amu	4 weeks
	7.7-39 GeV/Amu	6 – 11 weeks

Run 11 – 12

Au x Au	Low Energy
	200 GeV/Amu
Pol. p-p	500 GeV
U x U	200 GeV/Amu

2012 RHIC II Heavy Ion luminosity upgrade completed
Stochastic cooling
Polarized proton luminosity upgrade completed
Electron lenses
Low energy luminosity upgrade completed
Electron cooling

e-RHIC Joint BNL – Jeff Lab – International Advisory Committee
BNL EIC Task Force, E. Aschenauer, T. Ullrich
CAD – Phase I 4GeV e^- $L>10^{33}/cm^2/sec$
Phase II 10-20 GeV e^- $L>10^{33}/cm^2/sec$

Year	Likely Beam Species	Science Goals	New Detector Sub-systems	New Machine Upgrades	Gain from Machine Upgrades	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 completed; PHENIX HBD for heavy ions	Blue ring longitudinal + yellow & blue vertical stochastic cooling; yellow longitudinal cooling (μwave link) upgrade	Factor ~2 increase in average store luminosity for full energy Au+Au	Need 4-8 weeks early in run to (re)commission all 4 stoch. cooling systems, demonstrate gain in lumi. lifetime
FY11	Subinjection Au+Au; 500 GeV p+p; short 200 GeV U+U	Continue critical pt. search; gluon pol'n at low x + antiquark pol'n from W production; 1st characterization of deformation effects in U+U centrality distrib'n	PHENIX VTX; upgraded PHENIX trigger (t0) barrel	EBIS (tandem as backup); 9 MHz cavity; AGS tune jump quads (comm'd in Run 10); RHIC spin flipper	U beam capability; improved pp vertex distrib'n; improved pol'n from AGS; reduced syst. errors	9MHz requires upgrade to main PS + "bouncer" cavity for both rings + longitudinal damper or Landau cavity for each ring.
FY12	Au+Au at 200 GeV; 500 GeV p+p	RHIC-II heavy-ion goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations; antiquark polarizations in proton	PHENIX FVTX and μ trigger; STAR FGT + HFT prototype	Yellow + blue horiz. stoch. cooling (installed FY11); 56 MHz SRF; e-lenses; OPPIS solenoid + "proton cannon"; RHIC collimator upgrade	Full RHIC-II heavy-ion luminosity + improved vertex & store length; improved pp luminosity + polarization	Electron lens commissioning ⇒ Run 12 gains possible; detailed collimator upgrade plans still to be developed

Administration

Director Emeritus	T.D. Lee
Director	N.P. Samios
Associate Director	H. En'yo
Theory Group Leader	L. McLerran
Deputy Theory Group Leader	A. Baltz
Experimental Group Leader	Y. Akiba
Deputy Experimental Group Leader	A. Deshpande

Scientific Personnel

Theory

Fellows:		
Blum (1/2)	U. of Connecticut	Tenure
Fries	Texas A&M	NSF 5 year grant
Molnar	Purdue U.	
Tuchin	U. of Iowa	DOE Grant
Yuan	LBNL	
Lunardini	Arizona State	NSF Grant
Teaney	SUNY	DOE Grant (OJI)
Dumitru	CUNY	DOE Grant
Stasto	Penn State	OJI and Sloan Foundation

BNL

Aoki	
Izubuchi	
Ohta (Guest)	Vogelsang, W. - Tuebingen
Petreczky (1/2)	Qiu, Jianwei - (BNL)

Post-docs

Lichtl (1/2)	Goldman Sachs
Ishikawa	U. of Connecticut
Kojo	
Lehner FPD	
(Bin) FPD	

Scientific Personnel

Experiment

Fellows

Deshpande (1/4)	SUNY Tenure
Kawall	U. of Mass.
Bathe	CCNY

BNL

Okada	
Seidl	RIKEN, Tenure

Post-docs

Boyle	
Togawa (SPD)	Osaka U., Tenure
Shoji (SPD)	
Koster (FPD)	

RIKEN/RBRC @ BNL

Goto

Nakagawa

Visitor/Students

RIKEN/BNL

Takashi Ichihara	Atsushi Taketani	Yasushi Watanabe
Satoru Yokkaichi		

Students

Yoki Aramaki	Misaki Ouchida	Ken'ichi Karatsu
Yorito Yamaguchi	Jun Tamura	A. Takahara
Miki Kasai		
Takeshi Kanesue	Seishi Dairaku	Kohei Shoji

Visiting Scientist

Zheng Li	Kiyoshi Tanida	Akio Ogawa
Naohito Saito		

Collaborating Scientist

Masahiro Okamura	Kotaro Kondo	Rachid Nouicer

Theory Advisory Committee

L. McLerran (Chair)
A. Baltz
M. Creutz
F. Karsch
M. Gyulassy
R. Pisarski

Experimental Advisory Committee

A. Masaike
K. Imai
Y. Makdisi

QCDOC Advisory Committee

M. Creutz (Chair)
R. Pisarski
S. Aoki

International Meetings

Quark Matter 2009
Knoxville, TN April 2009
Lattice Gauge, Beijing, China July 2009
Significant RBRC Plenary Talks

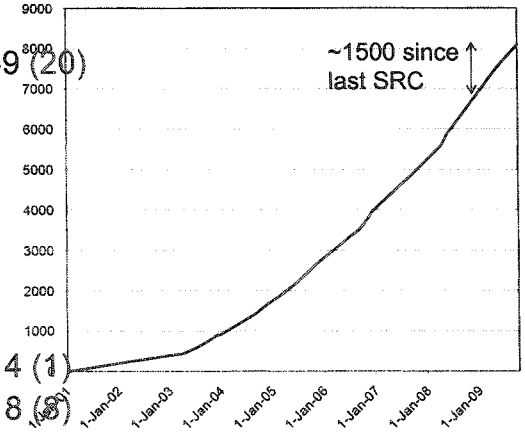
Publications

Theory – 54;

PHENIX publications and RBRC

- 83 (32)papers published since 2001
  - Phys. Rev. Lett. 49 (20)
  - Phys. Rev. C 23 (6)
  - Phys. Rev. D 6 (4)
  - Phys. Letter B 4 (1)
  - Nucl. Phys. A 1 (1)
- Total citation: ~8000
  - Topcite 500+ 2 (1)
  - 250-500 4 (1)
  - 100-250 18 (6)
  - 50-100 23(11)
- 9 (5) papers published since last SRC (Nov 2008)

published accepted



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

Workshops

PKU – RBRC Workshop on Transverse Spin Physics
June 30 – July 4, 2009
PHENIX Spin Fest School – 2009 at BNL
July 1 – July 30, 2009
(Critical Point – International Workshop
March 16 – 20, 2009)

Progress in High P_t Physics at RHIC
March 2010
P and CP Effects in Hot Dense Matter
April 2010
Saturation Physics Theory and Experiment
May 2010

Seminars:

Tuesday	RBRC/Spin
Wednesday	RBRC/BNL
Thursday	RBRC/Lunch
Friday	RBRC/BNL

Computing

QCDCQ
300 Tflops sustained speed

$5M cost	$1M ~ April 2010
	$4M ~ June 2010

Expectation

Installation	3rd Quarter 2010
	Complete 6/2011
$400K	commitment – T.D. Lee
$400K	commitment – S. Aronson
	BNL In kind contributions
$125K	in manpower to install/commission
$215K/yr	in operational expenses (power, cooling)

NCAC Meeting – January 15 – 17, 2009

"The Committee concurs with the review of the RBRC Scientific Review Committee that RBRC has been highly successful and cost effective. That it is doing forefront science and that it's strong support should be continued"

RBRC Exp. Group Introduction and Spin Physics

Y. Akiba

RBRC SRC review
2009/10/21

Exp. Group activities

Three major activities

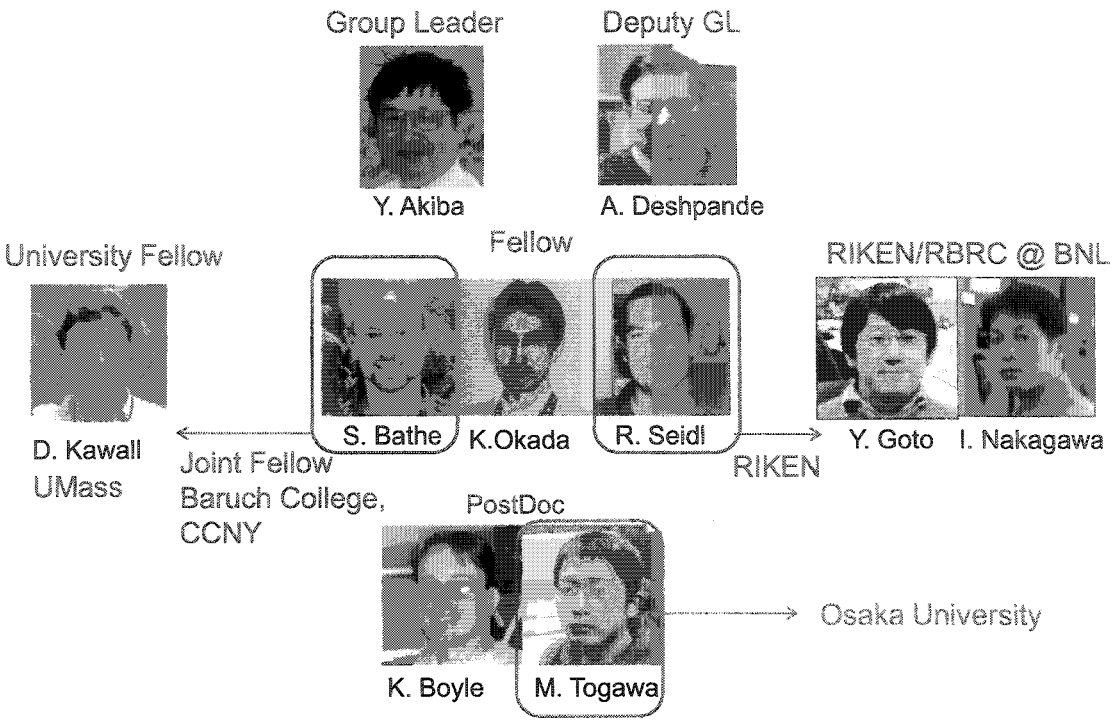
- Spin Physics
  - Study of spin structure of proton using the world only polarized p+p collider
  - Main activity of RBRC/RIKEN
  - RBRC/RIKEN are the leader of Spin Physics at RHIC/PHENIX

4 presentations in the 1st 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

4 presentations in the 2nd session

RBRC Experimental Group



- Plus Many Students and Visitors

Visitors/Collaborators/students

RIKEN/BNL

Takashi Ichihara Yasushi Watanabe Atsushi Taketani
talk: VTX pixel

Satoru Yokkaichi

Students

Yoki Aramaki	Misaki Ouchida	Ken'ichi Karatsu
Yorito Yamaguchi	Jun Tamura	A Takahara
Miki Kasai	Kohei Shoji	Seishi Dairaku
Katsuro Nakamura	Takeshi Kanesue	

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

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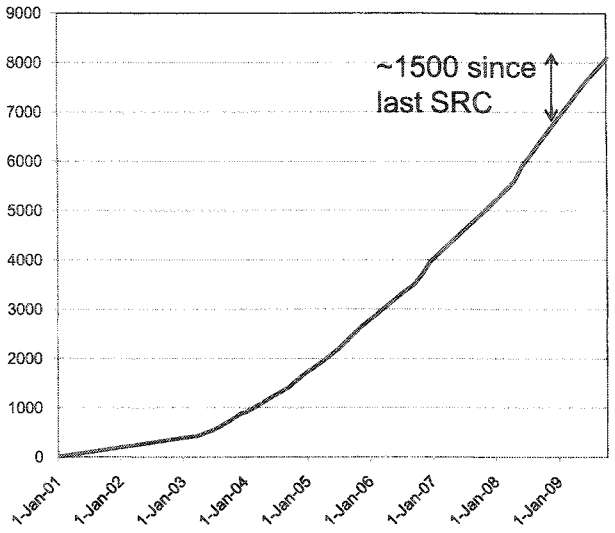
  - 50-100 23(11)
- 9 (5) papers published since last SRC (Nov 2008)

	published	accepted
– PRL	4 (3)	
– PRC	2	
– PRD	1 (1)	1
– PLB	2 (1)	

- 3 (1) papers in review



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

Exp Group Activities on Spin Physics

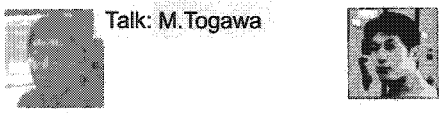
RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX

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

- W measurement (spin of sea quark) — W → e analysis; W→ μ Trigger

- Transverse Spin — Collins Function at Belle; A_N at RHIC

- Polarimeters — PHENIX Local Pol.; CNI Polarimeter

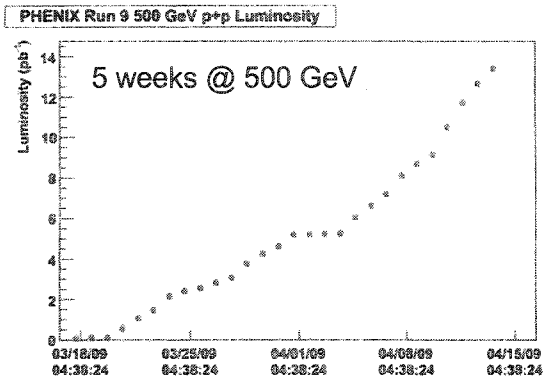


- Luminosity — Absolute Luminosity; Relative Luminosity

Essential for Spin physic.
Important RBRC contribution

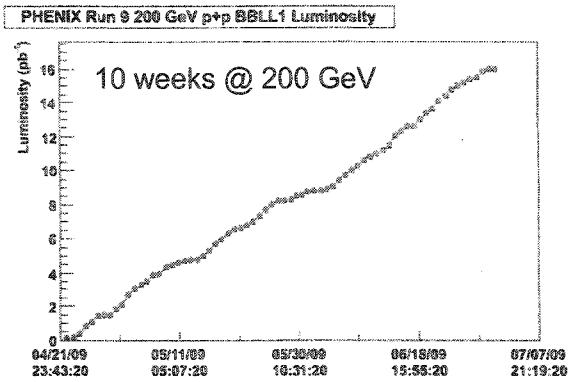
RHIC RUN9 is entirely for Spin Physics

First 500 GeV p+p run



- Polarization ~ 30%
  - Strong spin resonance
  - Tune studies for RUN11
- PHENIX recorded ~14/pb
- High rate (>1MHz)
- First W signal is seen!

Long 200 GeV p+p run



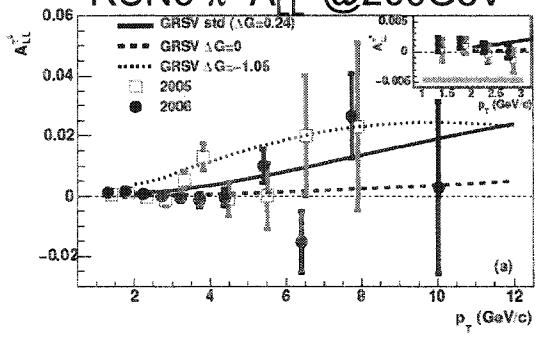
- Polarization ~ 55%
- PHENIX recorded ~16/pb
- ~2 times of P^4 L of RUN6 will improve DG measurements
  - π^0 A_{LL}
  - direct photon A_{LL}
  - single e A_{LL}

Recent PHENIX Spin results

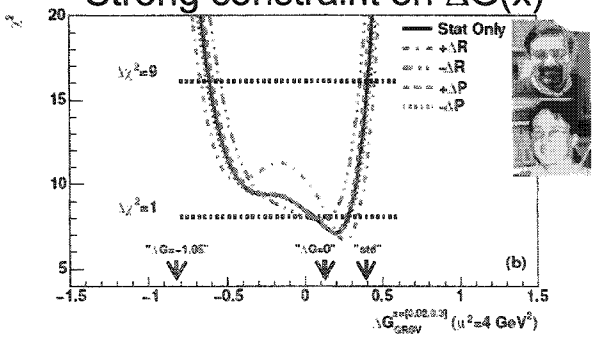
PRL103 (2009)

A. Deshpande
K. Boyle

RUN6 π^0 A_{LL} @200GeV



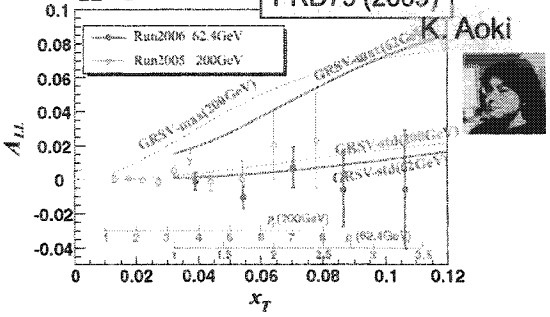
Strong constraint on $\Delta G(x)$



PRD79 (2009)

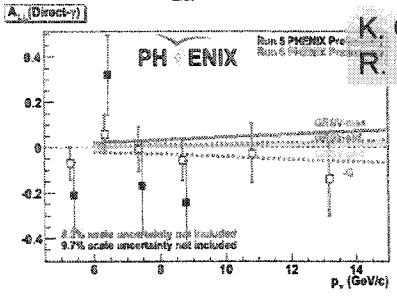
π^0 A_{LL} @ 62GeV

K. Aoki



Direct γ A_{LL}

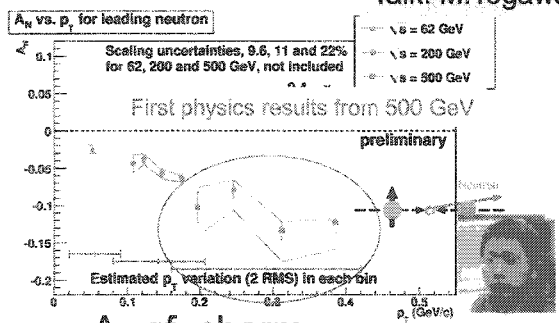
K. Okada
R. Bennett



Recent PHENIX Spin work by RBRC

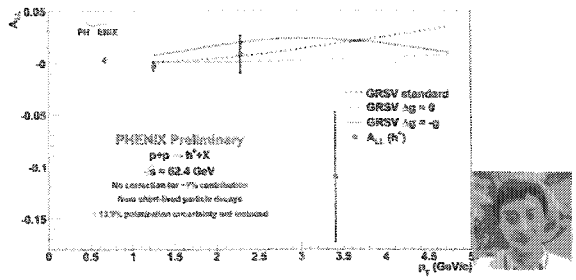
A_N of forward neutron

Talk: M.Togawa

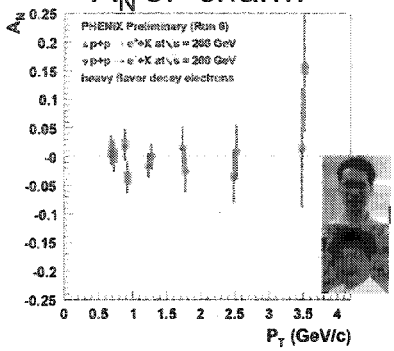


A_N of charged hadrons

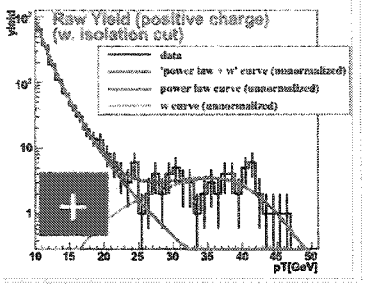
Talk: D. Kawall

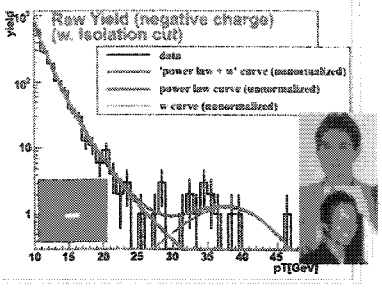


A_N of charm



W → e is seen! Talk: K. Okada





Exp Group Presentations

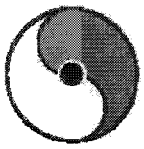
YA	"Exp. Group overview: Introduction and Spin Physics"
Manabu Togawa	"PHENIX local polarimetry using single transverse spin asymmetry for very forward neutron"
Kieran Boyle	"Improving the Measurement of Relative Luminosity"
Dave Kawall	"The Double Longitudinal Spin Asymmetry and Cross section of Non-identified Charged Hadrons at sqrt(s)=62.4 GeV"
Kensuke Okada	"First W signals in p+p collisions in PHENIX Central Arm"

10:15 AM-10:45 break

YA	"Exp. Group overview: HI Physics and PHENIX upgrades"
Stefan Bathe	"Parton Energy Loss in the Quark-Gluon Plasma"
Ralf Seidl	"The PHENIX Muon Trigger Upgrade"
Atsushi Taketani	"PHENIX VTX upgrade: Pixel detector"
Rachid Nouicer	"PHENIX VTX upgrade: Silicon Stripixel Detector"

PHENIX local polarimetry using single transverse spin asymmetry for very forward neutron

Manabu Togawa
RBRC review : Oct. 21th 2009



PHENIX

1

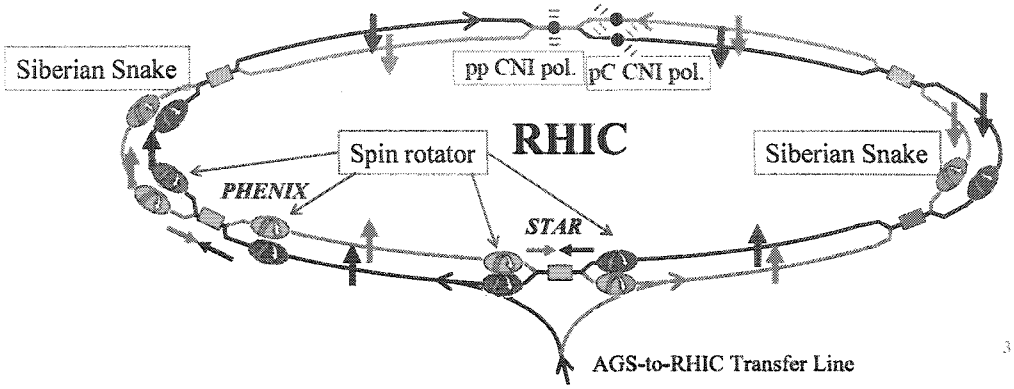
Outline

- Local polarimeter
  - Introduction
  - Detector setup
- 2009 year's operation
  - First polarized pp collision at $\sqrt{s}$ = 500 GeV
  - Newly-installed scaler mode
- Physics of neutron A_N
  - Comparison of various $\sqrt{s}$
- Summary

2

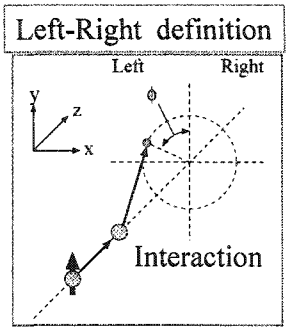
Polarized proton beams at RHIC

- Proton spin is kept by two Siberian snake magnets
  - Polarization direction is vertically transverse
  - Polarization is measured by *pC* and *pp* CNI polarimeters
- Spin is rotated to longitudinal at IP by Spin rotator magnets
  - Longitudinal spin is needed to be measured for precise A_{LL} or A_L.
    - → Local polarimeter measures proton spin direction at IP



3

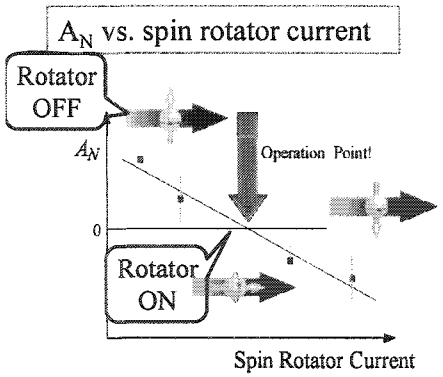
How to measure spin direction

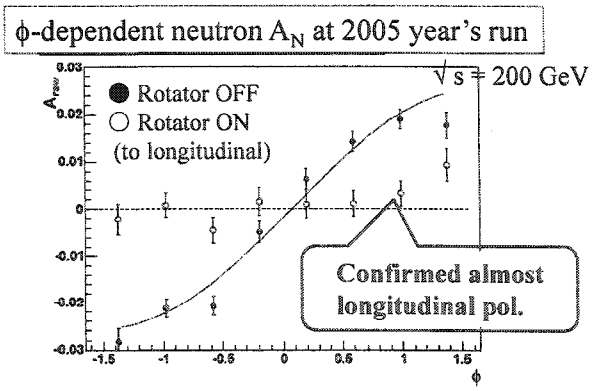


By measuring single transverse spin asymmetry, A_N

$$A_N \equiv \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}, \quad A_N = \frac{1}{P} \cdot \frac{N_L^{\uparrow} - N_R^{\uparrow}}{N_L^{\uparrow} + N_R^{\uparrow}} = \frac{1}{P} \cdot \varepsilon_N$$

in any produced particle from polarized proton collision,

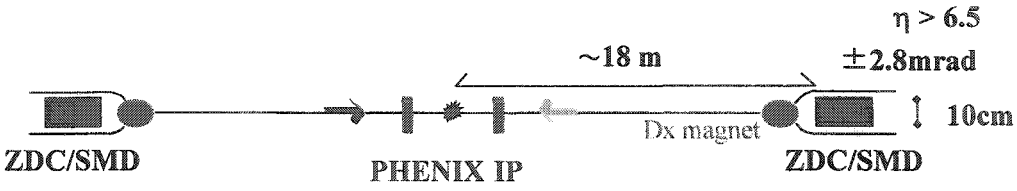




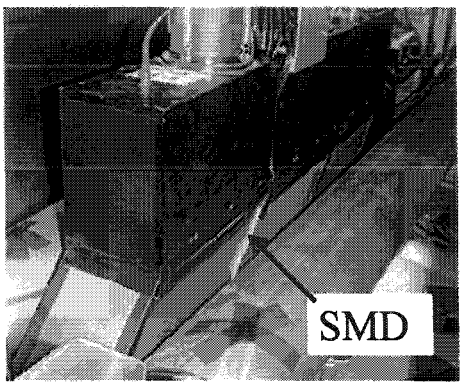
By measuring residual A_N, proton spin direction can be measured.

4

Local polarimeter by very forward neutron A_N



- ZDC (Zero Degree Calorimeter)
  - 3 modules : 5.1 λ_I
    (1.7 λ_I 50 X_0 for each module)
  - → Measure neutron energy
- SMD (Shower Max Detector)
  - Sintillator hodoscope in x and y
  - → Measure neutron position :
    Enable us to measure A_N
- Placed at very forward angle
  - No interference w/ other detectors.



5

Outline

- Local polarimeter
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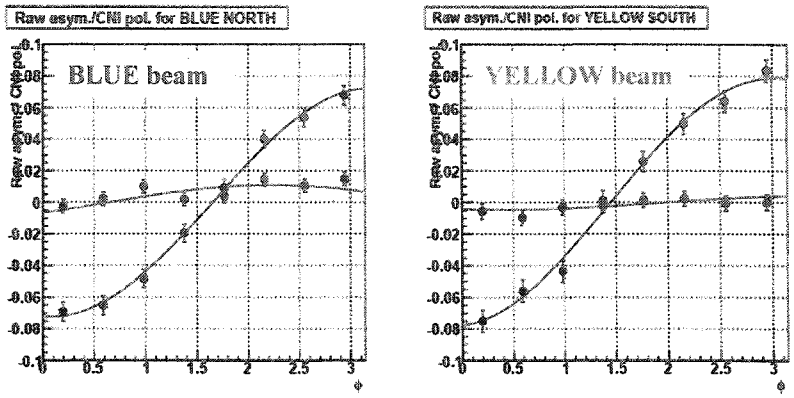
6

Polarized pp collision at $\sqrt{s}$ = 500 GeV

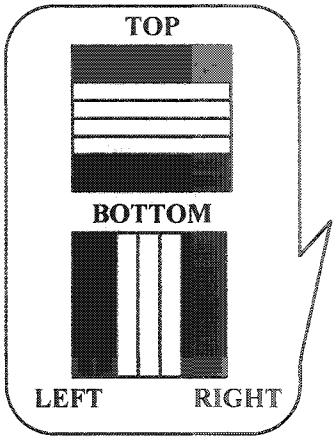
- Pol. beams were colliding at $\sqrt{s}$ = 500 GeV at the first time.
  - Average polarization ~ 35% (online value)
- Neutron asymmetry remains at this high energy !
  - **Local polarimetry can be performed by neutron at this energy.**



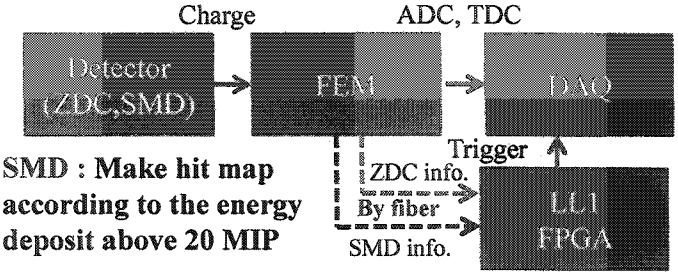
Red : Transverse run (Fill#10340)
Blue : Longitudinal run (Fill#10382)

Scaler mode for local polarimetry

- Newly-installed at 2009 run. Scaler mode improves,
  - ☺ No interference with PHENIX DAQ data band
    - ☺ Statistical uncertainty hugely improves
  - ☺ Fast analysis; analysis is performed by online monitor
    - ☺ Human resource



SMD : Make hit map according to the energy deposit above 20 MIP



Make scaler in LL1 board
4 * 2 (N or S) * 120 (bunch)
20 bits in each scaler

Results of scaler mode at $\sqrt{s}$ = 500 GeV

Statistical significance is HUGELY improved.

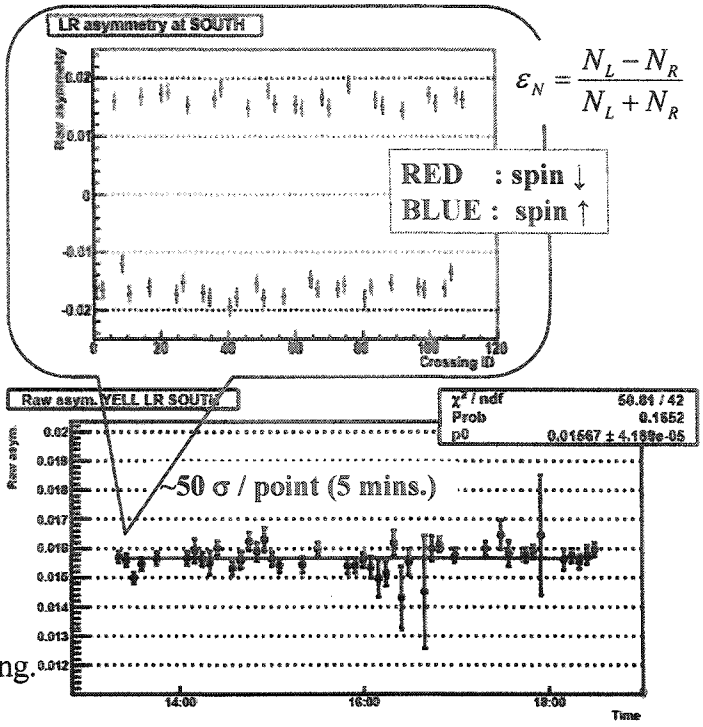
Bunch-by-bunch ε_N (5 minutes data)

→ Enable to monitor bunch-by-bunch.

Time dependent ε_N

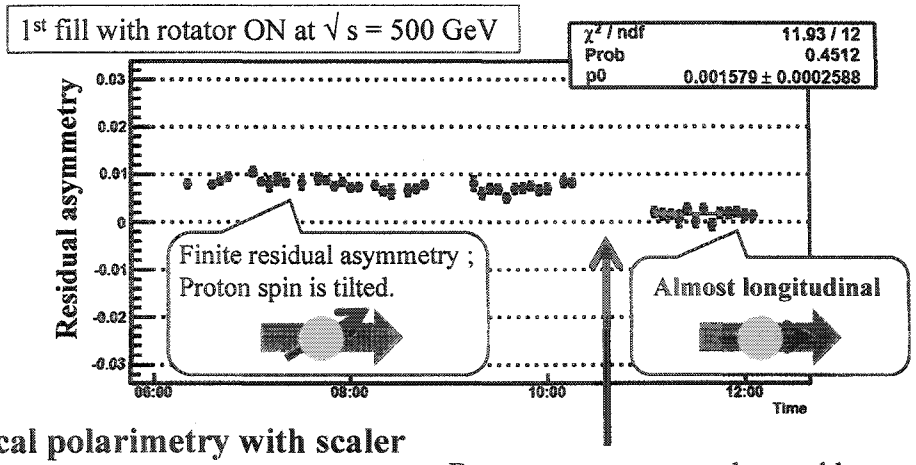
→ Enable to monitor spin stability during fill.

During 500 GeV, this high accurate polarimeter was used for spin commissioning.
→ **not "LOCAL" now.**



Rotator tune during fill

- Rotator feedback during fill was successful.
  - Enable to do quick feedback → Save time



Local polarimetry with scaler mode shows extraordinary performance !!

Rotator current was changed here
(No changes in CNI measurements)

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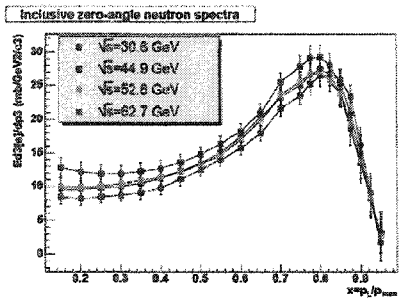
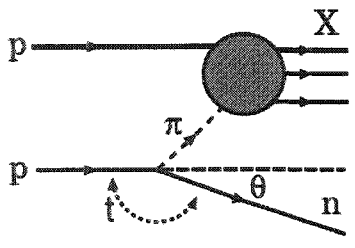
11

Physics : origin of neutron A_N

- Cross section measurements such very forward neutron production are performed at ISR.
  - Large cross section at high x_F region ($x_F \sim 0.8$)
  - No $\sqrt{s}$ dependence, scaled by x_F (31-63 GeV)
- These behaviors are explained by one pion exchange model.
  - A_N may be considered as this frame; Finite A_N needs interference btw spin flip and non-spin flip amplitudes. Pion exchange → spin flip



Nucl. Phys. B109 (1976) 347-356



One pion exchange model

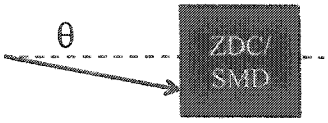
12

θ and p_T dependent neutron A_N

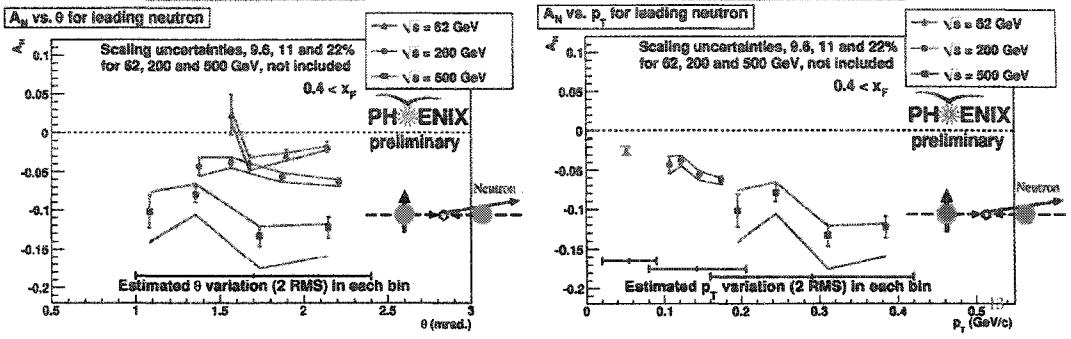
- Comparison of A_N using various $\sqrt{s}$
  - A_N grows with increasing θ
  - A_N grows with increasing $\sqrt{s}$
- Could change to p_T : $p_T \sim x_F * Ep * \theta$
  - A_N grows with increasing p_T

  → $\sqrt{s}$ dep. would come from p_T dependence.

* θ and p_T estimation assuming ISR p_T shape



θ dependence → p_T dependence



Summary

- Local polarimetry measures proton spin directions at IP using very forward neutron A_N at PHENIX
  - With first 500 GeV collision, we also measured significant A_N as well as 62 and 200 GeV.
- Scaler mode was implemented successfully.
  - We achieved : very high statistics result, fast analysis and independent operation to DAQ data band.
    - Can perform bunch-by-bunch monitoring
    - Online feedback during fill was success.
- Comparison of A_N with new $\sqrt{s}$ data provides new knowledge of production mechanism.
  - A_N grows with increasing $\sqrt{s}$.

    → It would come from p_T dependence.

Improving the Measurement of Relative Luminosity:

Dealing With Multiple Collisions

Kieran Boyle

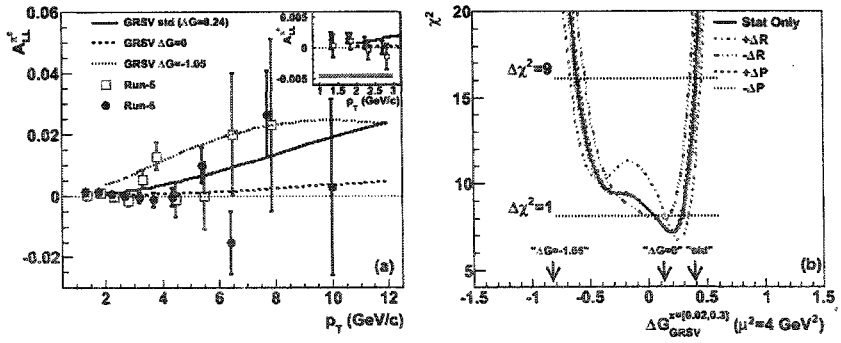
RBRC Review

October 21-22, 2009

Outline:

1. Constraint on ΔG from π^0 A_{LL}
2. Systematic Uncertainty from Relative Luminosity
3. New Method using Probability of Zero

π^0 A_{LL} Result

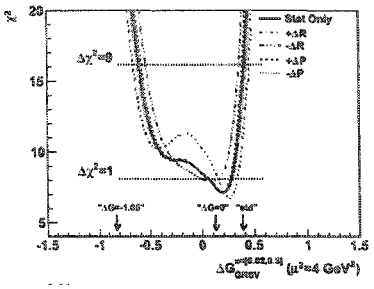


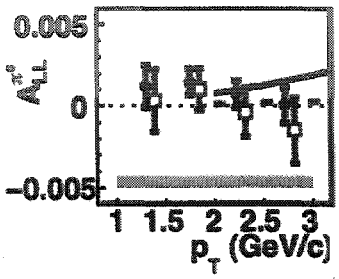
$$A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

- 2006 result published in **PRL** 103:012003, 2009
- *Highlighted Result* in Nature Physics (**Nature Physics** 5, 532 2009)
- Significant constraint on ΔG (DSSV, **PRL**101:072001, 2008)

Systematic Uncertainties

- Polarization:
  - Scaling uncertainty
  - In 2006, δP=8.4%
  - Limited impact on ΔG
- Relative Luminosity
  - In 2006, $\delta A_{LL}|_R = 7 \times 10^{-4}$.
  - Fully correlated between all p_T bins.
  - In 2006, comparable with statistical uncertainty
- 2009 data set
  - Expected statistical uncertainty will be ~1.4 times smaller.
  - Increased statistics comes from higher instantaneous luminosity.

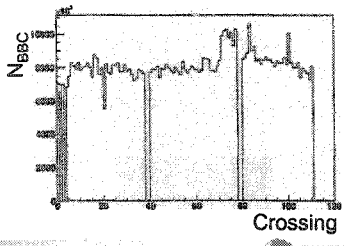




Systematic from Rel. Lumi.

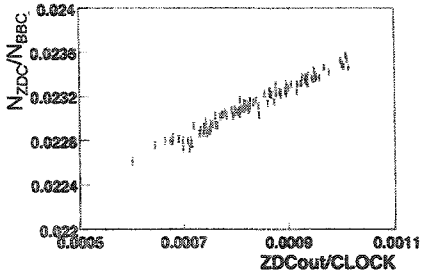
- Main source of uncertainty in Rel. Lumi. comes from miscounting.
  - Two main luminosity monitors
    - Beam Beam Counters (BBCs)
    - Zero Degree Calorimeters (ZDCs)
  - Event defined as coincidence between north and south detectors
  - Only Count 0 or 1.
- As (instantaneous) luminosity increases, events with more than one collision increase
  - Therefore, we undercount the luminosity

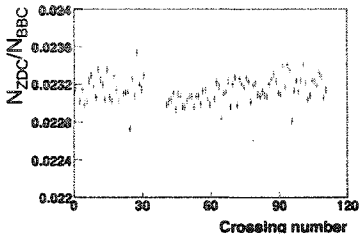
- At RHIC, each bunch has a different spin and luminosity lifetime
  - Can lead to false asymmetries



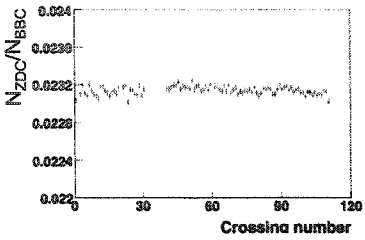
Clear Rate Dependence in Run6

- Estimate systematic uncertainty from A_{LL} of two lum. monitors.
- Look at
  - N_{ZDC}/N_{BBC}
- Sensitive to bunch to bunch fluctuations in beam dynamics
  - Rate effect





Rate Corr.



Luminosity Task Force

- In Run6
  - Unclear if effect was due to BBC or ZDC.
  - Rate correction was not used in Run6
- For Run9 and beyond
  - Higher Instantaneous Luminosity
  - Achieved 2.5 MHz BBCLL1 trigger rate
    - 15% of events contain more than 1 collision
  - In future runs, expect near 100% of events w/ multi. collisions
- Task force formed prior to Run9
  - Asked to be Chair
  - Many possible solutions were suggested
  - Here I focus on the most promising
    - Probability of Zero

NEW METHOD: Probability of Zero

- Probability of k events in a single crossing is

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

- Probability of seeing k events in a single detector with efficiency ε

$$P(k) = \frac{(\epsilon\lambda)^k e^{-(\epsilon\lambda)}}{k!}$$

- In the case of zero collisions, this is simply

$$P(0) = e^{-(\epsilon\lambda)}$$

Reality is a bit more complicated…

Getting to Relative Luminosity

$$P_N(0) = e^{-\epsilon_N(\lambda_2+\lambda_{1,N})-\lambda_{noise,N}} \quad P_S(0) = e^{-\epsilon_S(\lambda_2+\lambda_{1,S})-\lambda_{noise,S}}$$

$$P_{NS}(0,0) = e^{\epsilon_S\epsilon_N\lambda_2-\epsilon_S(\lambda_2+\lambda_{1,S})-\lambda_{noise,S}-\epsilon_N(\lambda_2+\lambda_{1,N})-\lambda_{noise,N}}$$

- Combining these three equations as

$$ln(P_{NS}(0,0)) - ln(P_N(0)) - ln(P_S(0)) = \epsilon_N\epsilon_S\lambda_2$$

- We record P(≠0) for the N, S and N|S detectors,
  - P(0) = 1 - P(≠0)

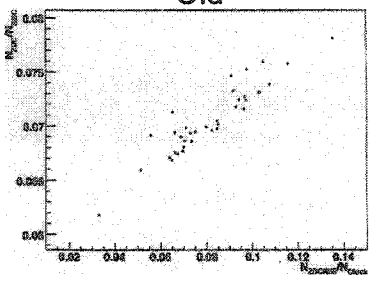
- To get relative luminosity, we simply take the ratio of ++ to +–, and efficiencies cancel, leaving

$$R' = \lambda_{++}/\lambda_{+-}$$

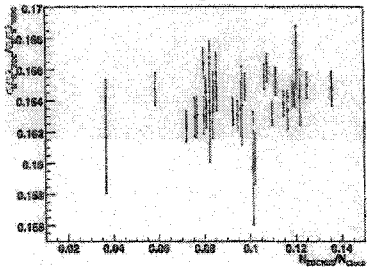
Rate independence of R'

- Rates highest in 500 GeV.
- While rate affect is clearly evident in old method (left), new method is independent of rate

Old



New



- Each data point corresponds to one fill.
- Right plot is from "Clock" data, left is from scalers.

Conclusions

- 2006 π^0 result significantly constrained ΔG
  - Result near systematic limit
  - Expected to be worse in Run9, due to greater number of multiple collision events.
- New Method is being developed based on the probability of measuring zero collisions
  - Removes a number of different backgrounds
  - Properly accounts for multiple collisions
  - Rate dependence is removed
  - Study ongoing

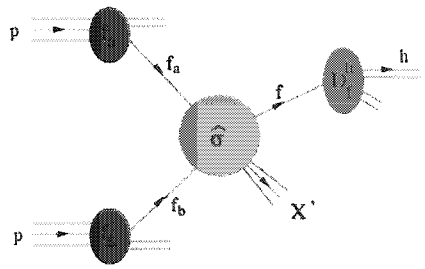
Double Longitudinal Spin Asymmetry and Cross-section of Non-identified Charged Hadrons at $\sqrt{s} = 62.4$ GeV

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

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

Motivation :

- PHENIX recorded $\approx$ 50 nb^{-1} of long. polarized pp collisions at $\sqrt{s}$=62.4 GeV in 2006
- Measured double spin asymmetry $A_{LL}^{pp\to h^{\pm}X}$ in new kinematic range
  - 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



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

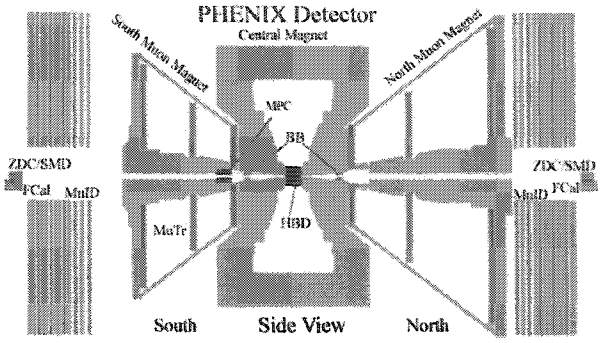
$\Rightarrow$ If $\Delta g > 0 : A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

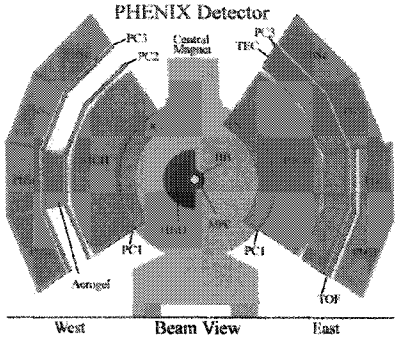
$\Rightarrow A_{LL}^{\pi^+}$ maximum analyzing power for Δg

- 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

Overview of the Asymmetry Analysis

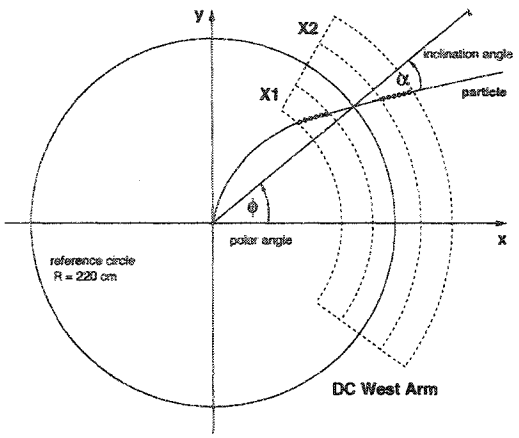
- Identify pp collisions by coincidence of hits in two Beam Beam Counters (BBCs) on either side of IR (minimum bias trigger)
- Select events with pp vertex within $\pm$ 30 cm of nominal center of IR (within acceptance of PHENIX central arms)
- Look for tracks with hits in Drift Chamber (DC) and Pad Chambers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

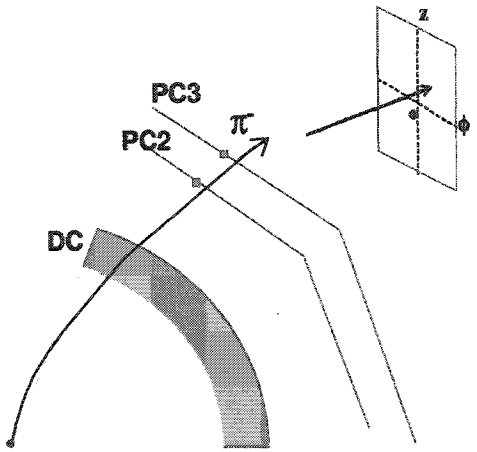




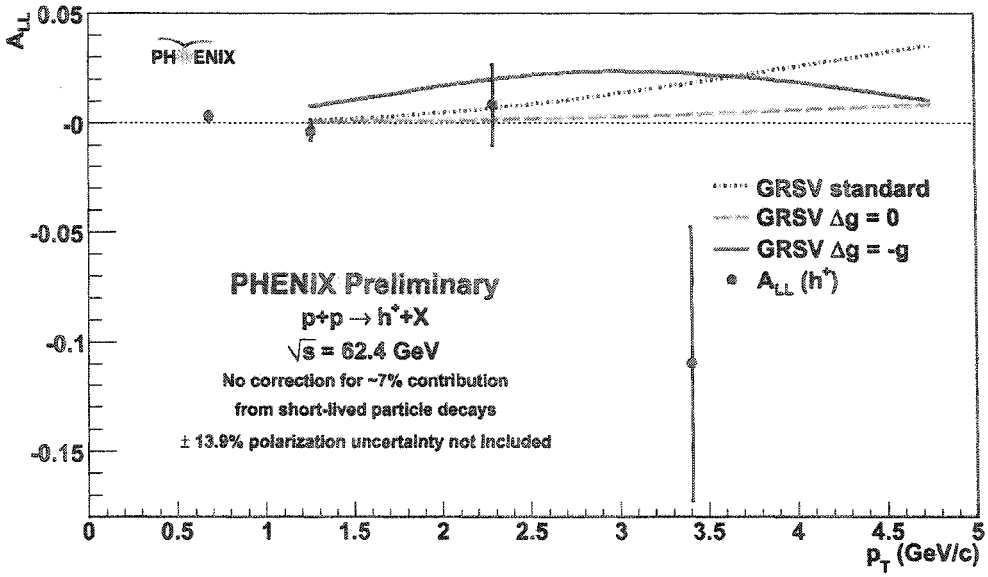
Overview of the Asymmetry Analysis

- Particle momentum determined by angle in DC with respect to infinite momentum track from origin : inclination angle $\alpha \approx 101$ mrad/ p_T [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



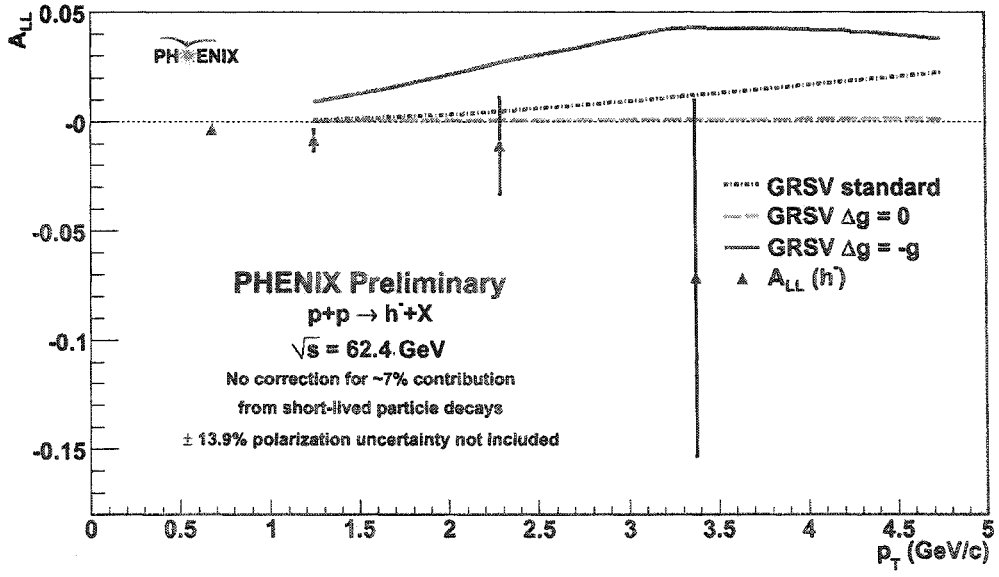


Results for A_{LL}^{h+} and Comparison with GRSV Model Predictions



- 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!

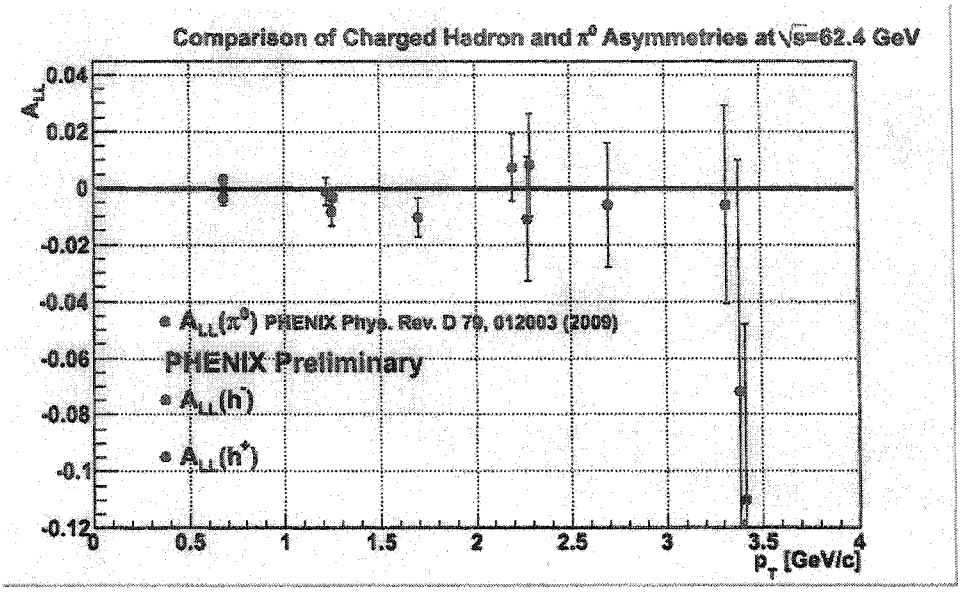
Results for A_{LL}^{h-} and Comparison with GRSV Model Predictions



- Asymmetries predicted for A_{LL}^{h-} smaller than those for A_{LL}^{h+}
- Measured A_{LL}^{h-} small, consistent with zero
- GRSV model $\Delta g(x) = g(x)$ (not shown on plot) clearly excluded by the data

Comparison of Charged Hadron A_{LL} with $A_{LL}^{\pi^0}$ results at $\sqrt{s} = 62.4$ GeV

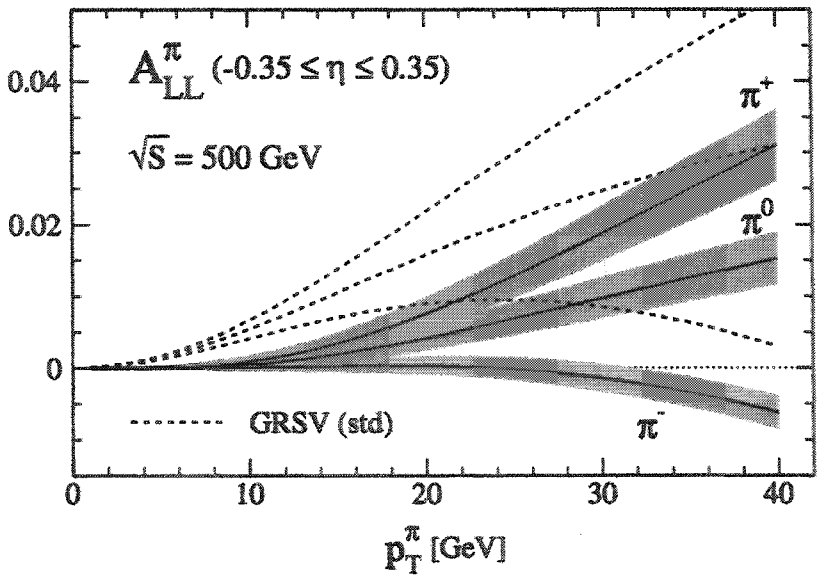
- Interesting to compare $A_{LL}^{\pi^0}$ with $A_{LL}^{h^\pm}$; latter dominated by charged pions
- If $\Delta g(x) > 0$: $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$



- No clear ordering apparent yet, need more data

Hint of Things to come : $A_{LL}^{\pi^+}$, $A_{LL}^{\pi^0}$, and $A_{LL}^{\pi^-}$ at $\sqrt{s} = 500$ GeV

- Predictions for A_{LL}^{π} from DSSV, Phys. Rev. D **80**, 034030 (2009)
- At high $p_T \Leftrightarrow$ high-x, predicted $\Delta g(x) > 0$, leads to ordering of asymmetries

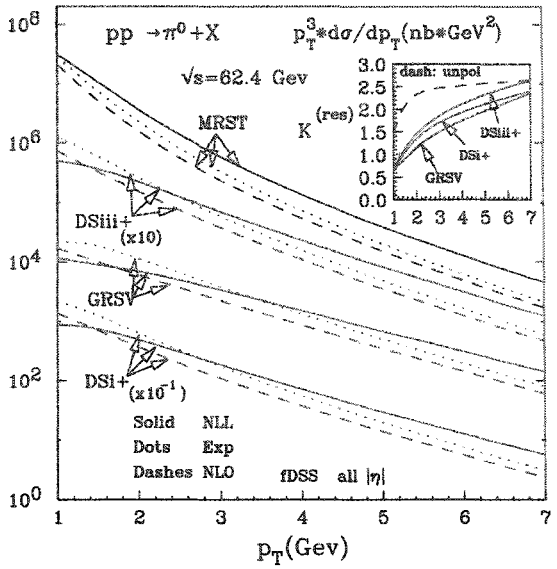


- Important to measure all three pion channels

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
- see de Florian, Vogelsang, Wagner, Phys. Rev. D 76, 094021 (2007)

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

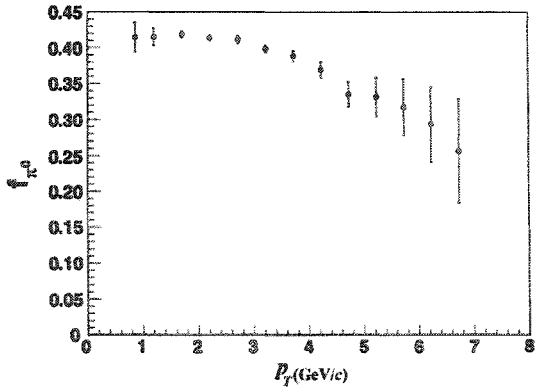
Non-identified charged hadron cross-section determination

- We determine the non-identified charged hadron cross-section at mid-rapidity for $(\pi^+ + K^+ + p)$ and $(\pi^- + K^- + \bar{p})$
- We go from particle yields to cross-section as follows :

$$\frac{E}{c}\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T dp_T dy d\phi}$$
$$= \frac{\sigma_{BBC}}{N_{MB}}\frac{1}{2\pi p_T}\frac{N_{yield}(p_T)}{dp_T dy}C_{smear}(p_T)C_{trig}(p_T)C_{eff}(p_T), \quad \text{where :}$$

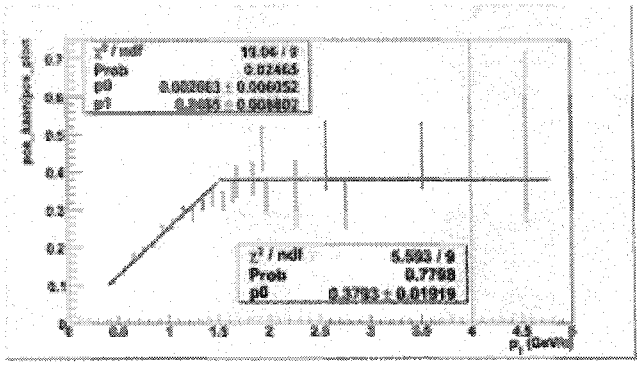
- σ_{BBC} : BBC effective cross-section $\approx$ 14 mb
- N_{MB} : Number of minimum bias triggers used in the analysis (140 million)
- p_T : Weighted mean transverse momentum in each bin
- N_{yield} : Number of charged hadrons detected in a p_T bin
- C_{smear} : Correction for migration of events into incorrect p_T bin due to finite momentum resolution
- C_{trig} : (Small) correction for the minimum bias trigger efficiency as function of p_T
- C_{eff} : Correction for the acceptance and efficiency of the detectors and cuts used in the analysis

BBC trigger efficiency, momentum smearing correction, and particle ratios



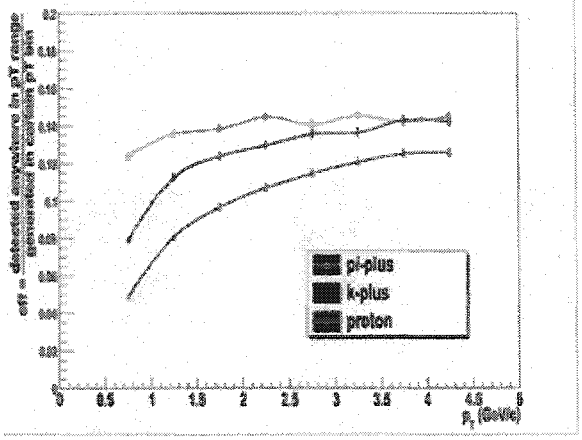
- BBC trigger efficiency measured as function of p_T (using π^0, PRD 79, 012003 (2009))
- Falling p_T spectrum coupled with uncertainty in momentum leads to false migration of events to higher p_T
  - $\Rightarrow$ corrected with detector simulation using measured particle composition, smaller than 5% effect

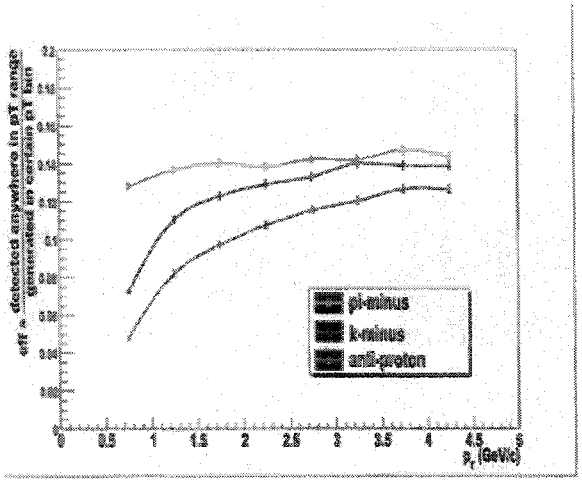
- Particles are non-identified, but mixture of (π^+, K^+, p) and $(\pi^-, K^-, \bar{p})$
- Particle ratios $K^+/\pi^+, p/\pi^+$, and $K^-/\pi^-, \bar{p}/\pi^+$ determined from PHENIX (M. Konno and T. Chujo) and ISR measurements



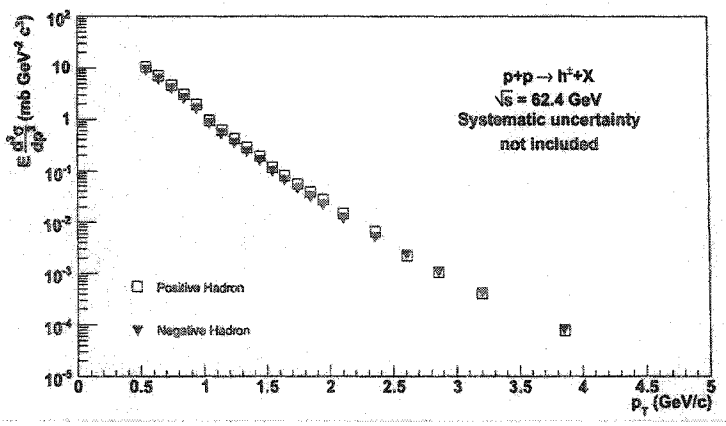
Single Particle Efficiencies

- 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





Cross-section Plot and Systematic Error Considerations



- $\sigma(h^+) > \sigma(h^-)$ for all p_T, ratio increases as p_T increases
- Analysis still underway, too early to make comparison plots with theory and other data sets (PHENIX,ISR)
- Uncertainty from BBC effective cross-section : $\approx$ 11%
- Background fraction uncertainty : $\approx$ 5%
- Smearing correction : 2% at maximum p_T
- Minimum bias trigger efficiency uncertainty : $2.5\% + (5 - 20)\%$ (p_T dependent)
- Acceptance and detector efficiency : $\approx$ 3%
- Species ratio uncertainty $20\% - 30\% \otimes$ species efficiency $\Rightarrow$ several % uncertainty on σ

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 nearly complete
  - Finishing background and feed-down estimates
  - Finishing treatment of uncertainties and correlations in uncertainties
  - Comparison of asymmetry and cross-section with theory (NLO and NLL) predictions

$\Rightarrow$ Prepare paper in next few months

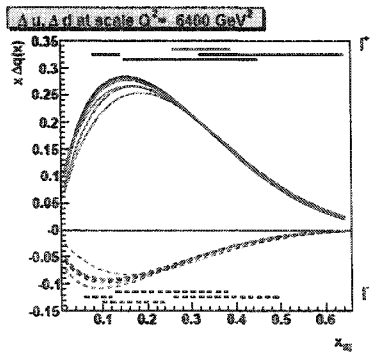
First W signals in p+p collisions in PHENIX Central arm

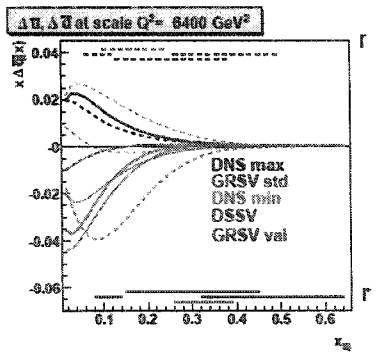
Kensuke Okada

RBRC review

October 21, 2009

(anti) quark components





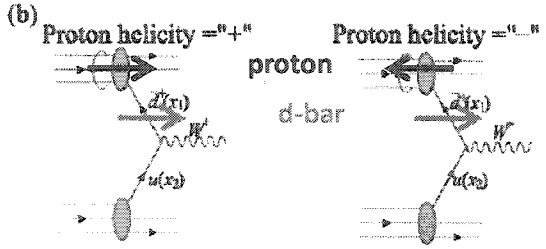
From SIDIS

W program at RHIC

d-bar+u →W+

u-bar+d →W-

d-bar, u-bar is always positive helicity



W^+ A_L: Longitudinal single spin asymmetry information of d-bar in the proton

No fragmentation function needed.

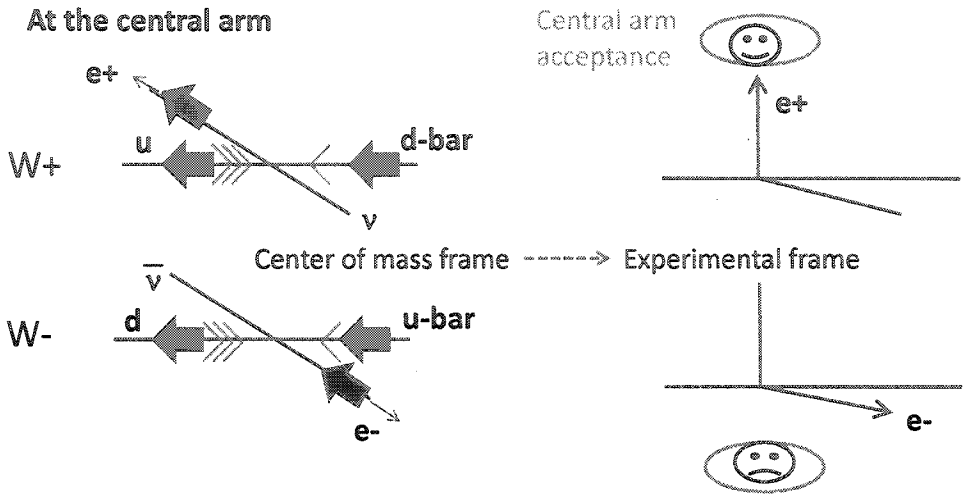
Test at very high Q^2 (M_W^2=6464GeV^2)

How to detect W at PHENIX

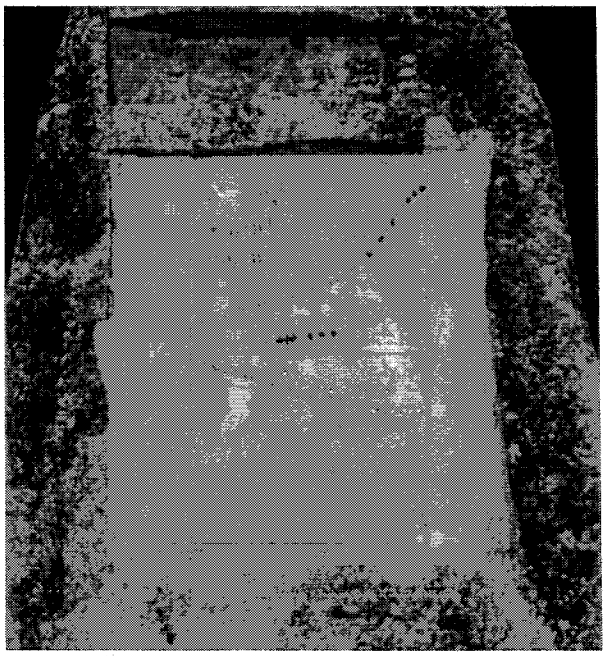
—PHENIX detector

Good for detecting electrons (central arm) and muons (muon arm).
(However) It doesn't have the 4pi coverage.

- ○ **Leptonic decay mode**
- × **Mass reconstruction**



A long time



Early 1990's,
this program is proposed.

Finally we took the first 500GeV polarized p+p run in 2009!

2009 (Run9) run

The first 500GeV pol p+p data

Period : February – July
Collision : pp500GeV and pp200GeV

~10 pb-1 is accumulated for the central arm W signal.
Polarization is preserved to the top energy.

- W to Electron channel :
  with the central arm, signal confirmation.
- W to Muon channel:
  with the muon arm, trigger upgrade commissioning.

Run9 data taking in the central arm

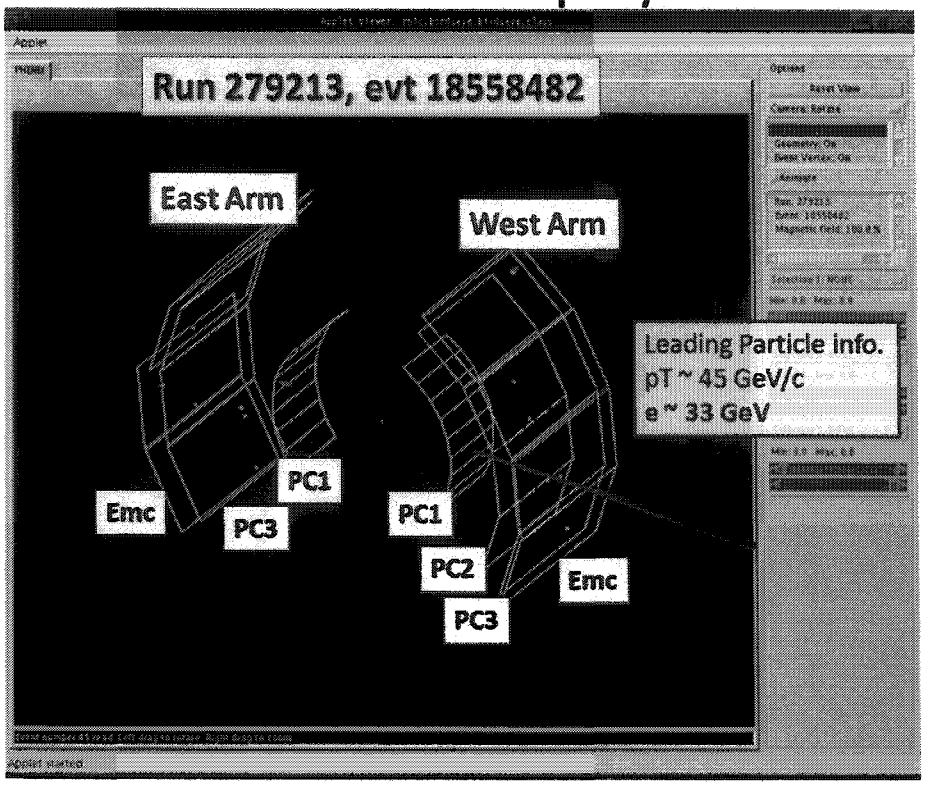
During the run, I mainly concentrated on

—EMCal
Gain change to increase the dynamic range.
Trigger
Online calibration for run by run variation
Calibration with pi0 peak position
(for the first time it's done before the run ends.)

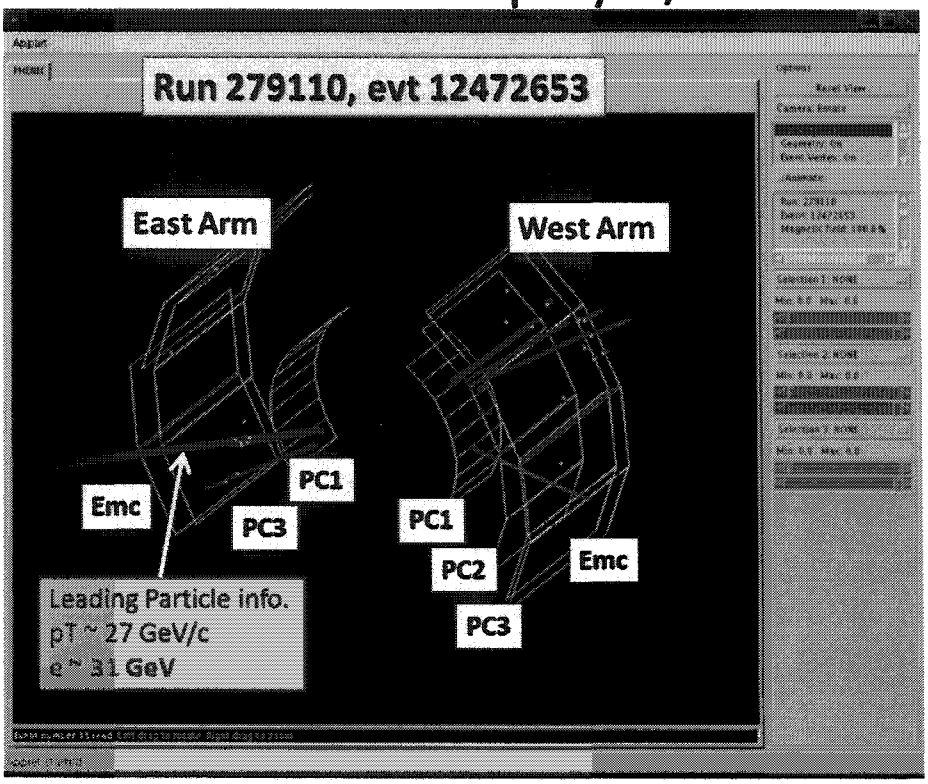
—Semi-online analysis using the W trigger striped data.

I worked with many students, especially thanks to
Kenichi Karatsu (Kyoto/RIKEN) : EMCal calibration and analysis
David Kleinjan (UCR) : EMCal trigger
Todd Kempel (ISU) : Data production

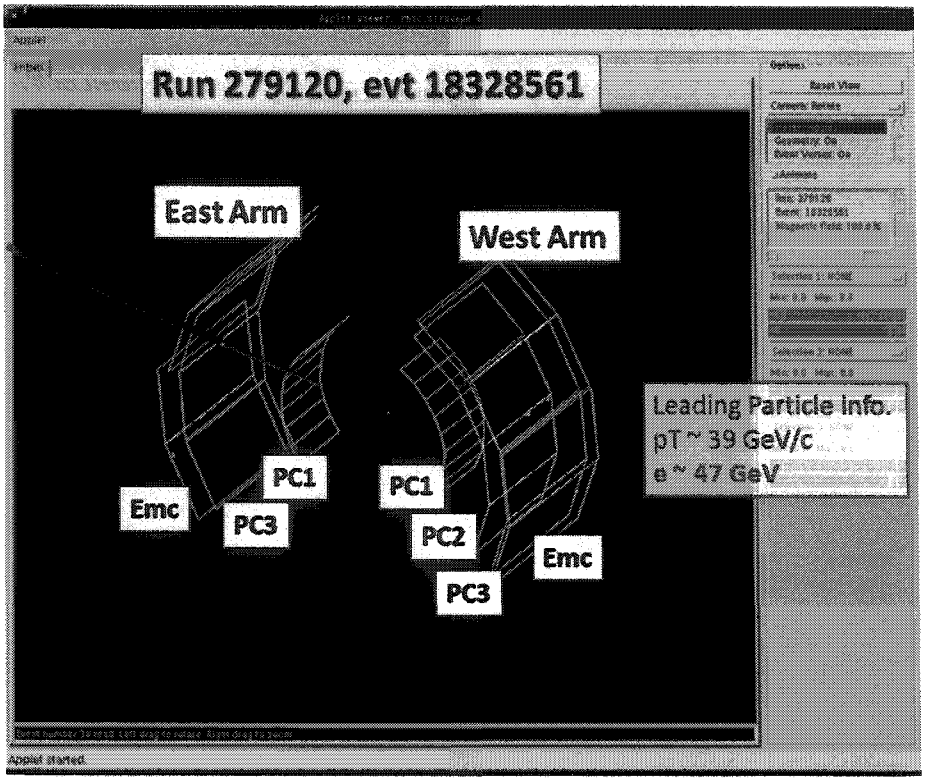
Event display



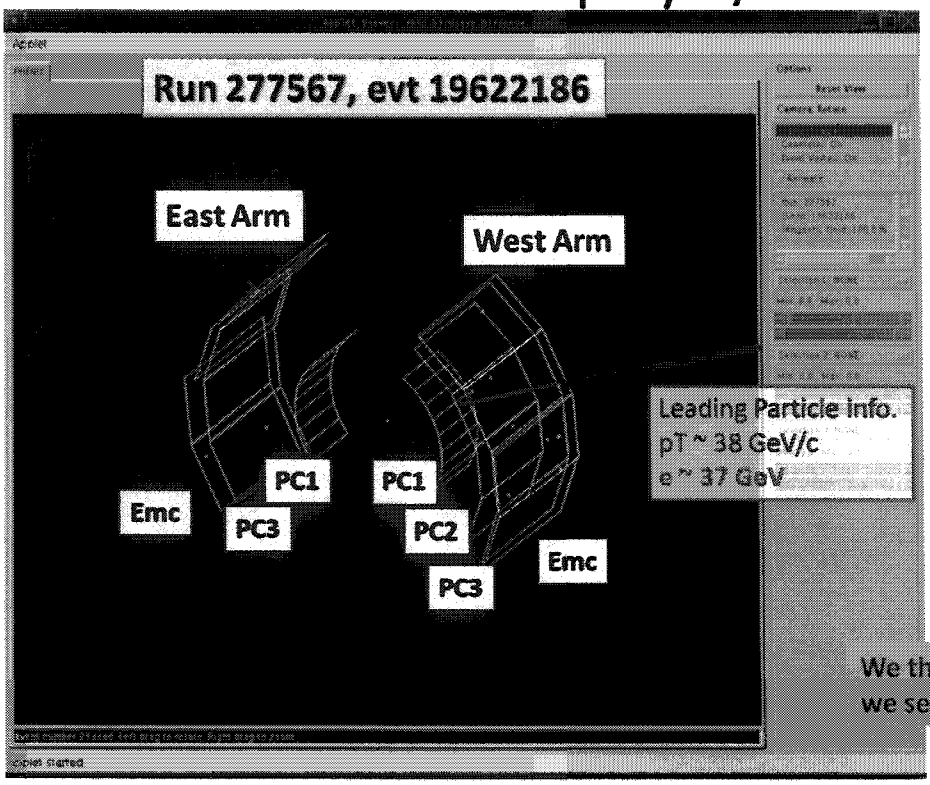
Event display 2/4



Event display 3/4

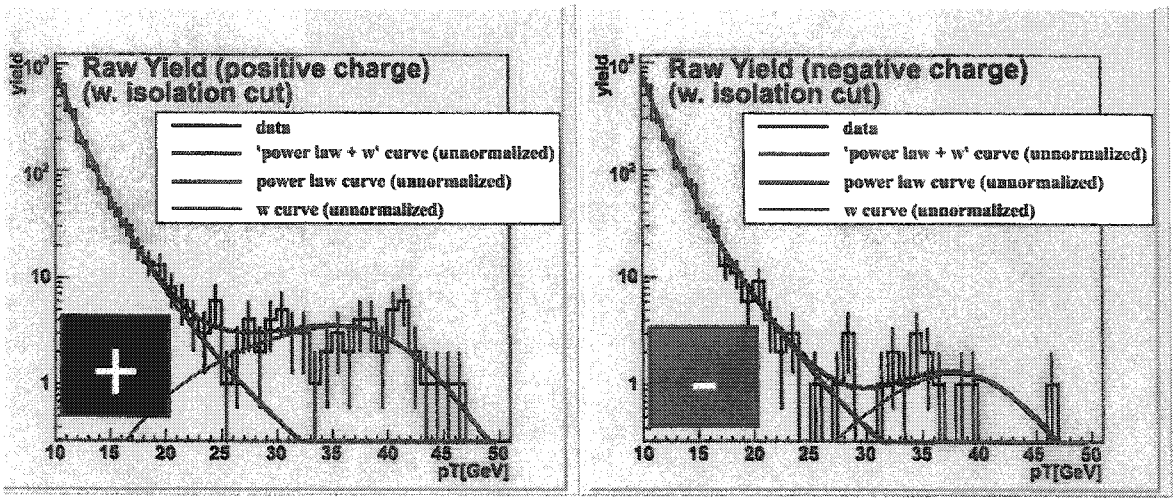


Event display 4/4



We think
we see W signals!

W→electron signal



Raw yield with an isolation cut.

W boson to electron decay signals are confirmed.

W signal is confirmed. What's next?

3 steps

1. Cross section measurement. (~∫L=10/pb)
2. Confirm non zero asymmetry from quark pol. (~∫L=100/pb)
3. Constrain anti quark polarization. (~∫L=300/pb)

- For the W-> electron channel, PHENIX is at step 1 with 2009 data.
- For the W->muon channel, new trigger system is required.

Summary

- In 2009, we took the first 500GeV p+p data.
  The W program has started.
- The W signal is observed.

- The next step is to calculate the cross section.
  Issues
    Background components.
      hadron response in the EMCal is the main question.
    Charge sign determination.
      It's at the edge of the DC resolution.
      We found some unexpected mis-identification.

- We hold weekly analysis subgroup meetings
  Stefan, Dave, Yasuyuki are regular members.

RBRC Overview
Heavy Ion and Upgrades

Y. Akiba

RBRC SRC review
2009/10/21

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

4 presentations in the 1st 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

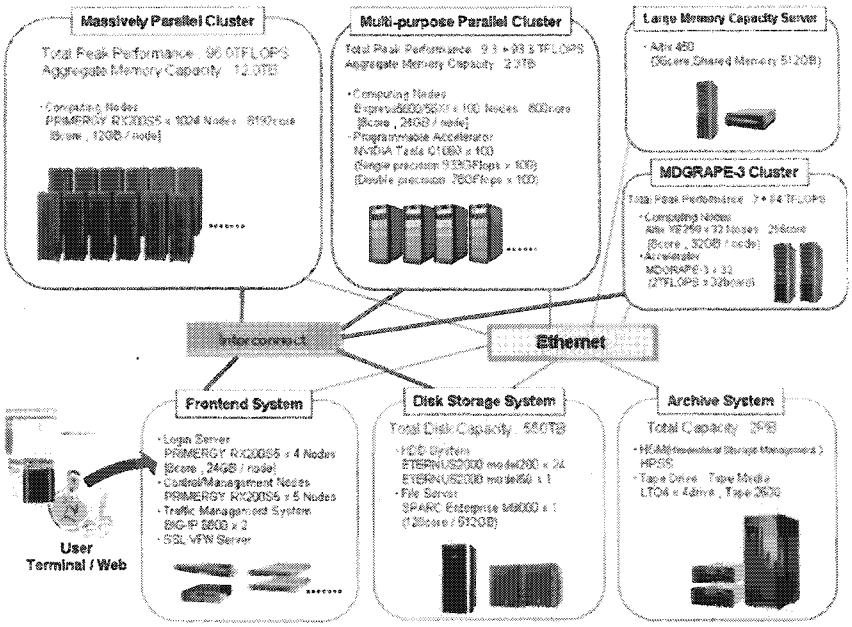
4 presentations in the 2nd session

Activities of CCJ at Wako

- 3 official projects
  - Data analysis for the muon trigger upgrade, K. Nakamura
  - Forward Muon Trigger Upgrade Y. Fukao
  - Analysis of Optical Alginment System for Muon Tracker, A. TaketaniSimulation
- 8 research plans
  - MPC Left/Right Asymmetry Measurement, J. Koster
  - Transverse single spin asymmetry of di-hadron production in pp, R. Yang
  - Reaction plane dependence of neutral pion production in Run7 Au+Au collisions, Y. Aramaki
  - Simulation of new type g-2 experiment by GEANT4, H. Okada
  - Low-mass vector mesons at PHENIX, Y. Tsuchimoto
  - Virtual photon measurement in p+p and d+Au collisions, Y. Yamaguchi
  - Open heavy flavor double helicity asymmetry measurement, K. Nakamura
  - Analysis of Jet Production A_LL with PHENIX Run6 data, S. Masuike
- A new analysis cluster was launched w/ 144 cores, 144 TB
  - 18 nodes/rack. Per node: 2 CPUs(8 cores), 16GB mem, 1TB disk x8
  - All pp-nDSTs of Run8,9 are always waiting you to be analyzed on the local disks.

RSCC -> RICC (RIKEN Integrated Cluster of Clusters)

12 Tflops -> 98 Tflops. Went online at Oct/1



- 97.94TF 34th of top500
- 2248CPU Xeon X5570 (Nehalem) = 8992 cores
- Disk: 550TB
- Tape: TS3500,LTO4 4 PB, 6 drives
- HPSS6.2 pFTP, HSI, VFS
- CCJ is exclusively possessing 40CPus (160 cores)

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

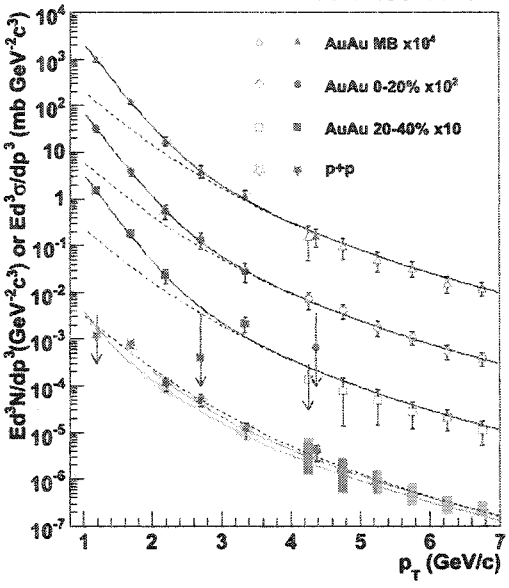
    + many more
  - Muon Trigger Upgrade strong support by RIKEN/RBRC

    + many more

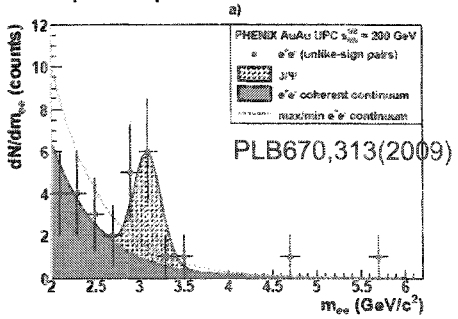
Recent PHENIX results with RBRC contribution

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

Arxiv:804.4168



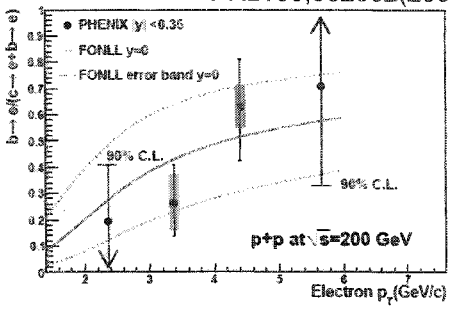
J/Ψ photo-production in Au+Au



PLB670,313(2009)

B→e/D→e measurement in p+p

PRL103,082002(2009)

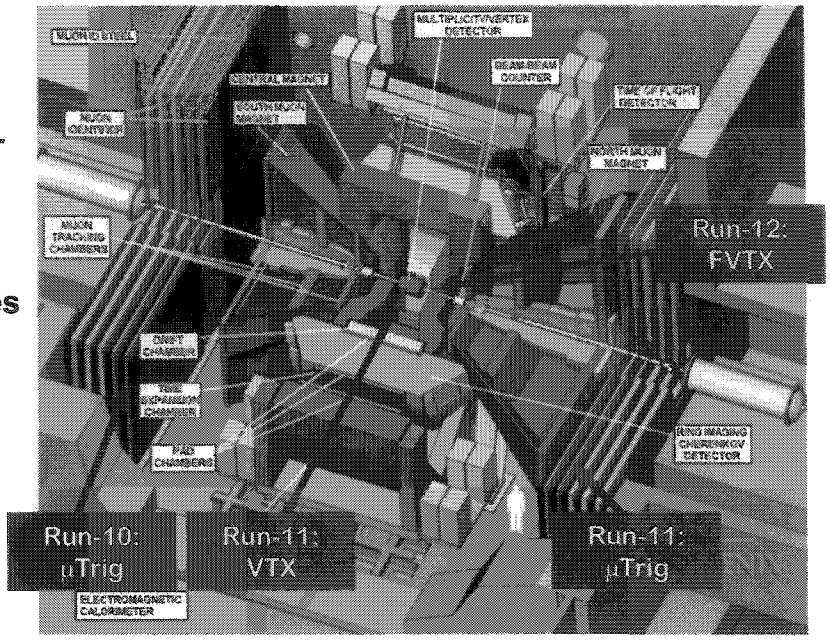


PHENIX detector upgrades

PHENIX detector was completed in 2002.

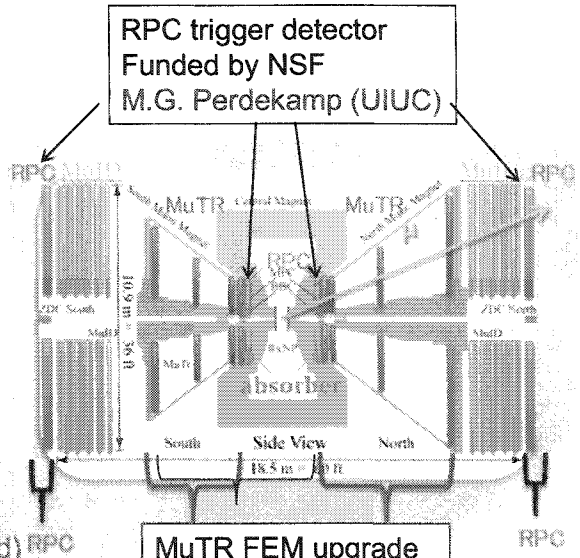
Many new detector were added and being constructed to improve the physics capabilities of PHENIX.

On going PHENIX upgrade by RIKEN/RBRC
- VTX
- μTrig



Muon trigger upgrade projects

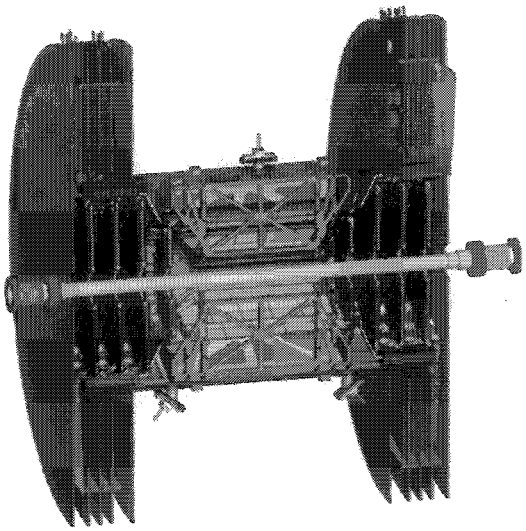
- W→μ measurment in the present PHENIX would be limited by the trigger. (Not enough trigger rejection)
- muTRIG upgrades will increase the trigger rejection factor by selecting high pT.
  - Essential for W measurement.
- Two projects:
  - RPC trigger (ready byRUN11)
    lead by M.G.Perdekamp
    (UIUC/former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



Large effort is ongoing for installation of both of muon trigger projects

Talk: Ralf Seidl

PHENIX VTX upgrade



- 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
- The US side of the project started
  - $4.7M from FY07 to FY10
- The second annual review of the VTX project (June 2-3, 2009)
- To be ready for RUN11

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

Summary

- Three pillars of RBRC Experimental Group Activity
  Spin Physics/HI Physics/PHENIX Upgrade
- Spin Physics
  - Main activity of the group
  - Strong constraint on DG(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: Spin Physics"
Manabu Togawa	"PHENIX local polarimetry using single transverse spin asymmetry for very forward neutron"
Kieran Boyle	"Improving the Measurement of Relative Luminosity"
Dave Kawall	"The Double Longitudinal Spin Asymmetry and Cross section of Non-identified Charged Hadrons at sqrt(s)=62.4 GeV"
Kensuke Okada	"First W signals in p+p collisions in PHENIX Central Arm"

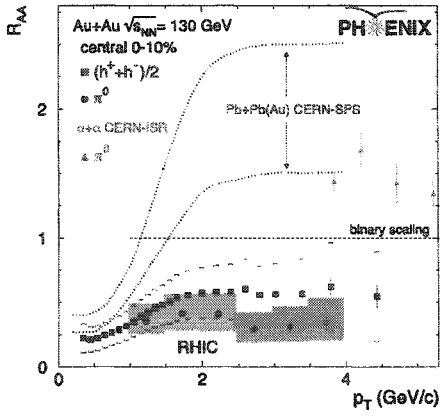
10:15 AM-10:45 break

YA	"Exp. Group overview: HI Physics and PHENIX upgrades"
Stefan Bathe	"Parton Energy Loss in the Quark-Gluon Plasma"
Ralf Seidl	"The PHENIX Muon Trigger Upgrade"
Atsushi Taketani	"PHENIX VTX upgrade: Pixel detector"
Rachid Nouicer	"PHENIX VTX upgrade: Silicon Stripixel Detector"

PARTON ENERGY LOSS IN THE QUARK-GLUON PLASMA

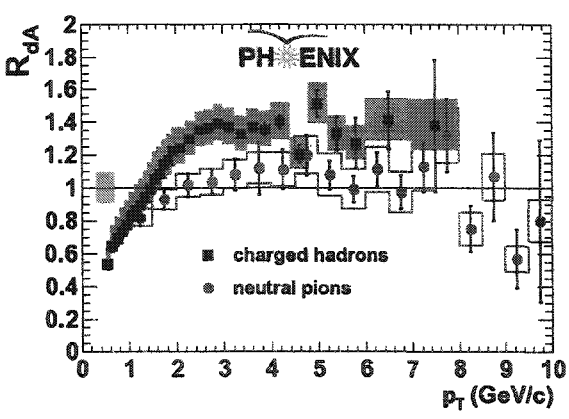
Stefan Bathe, RBRC Review, 21Oct2009

Hard Scattering Results in PHENIX



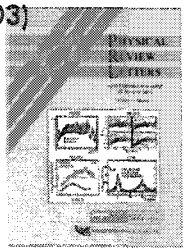
Phys.Rev.Lett. 88, 022301 (2002)

Most cited paper from RHIC
520 citations to date



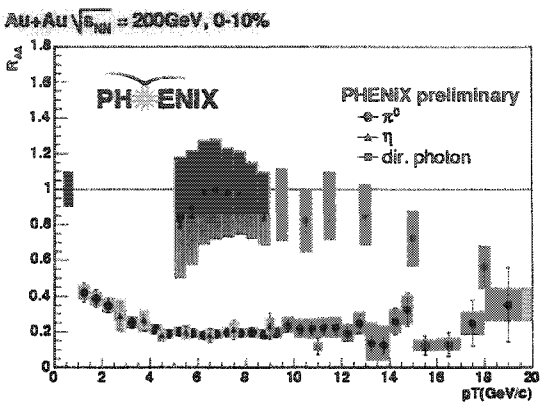
Phys. Rev. Lett. 91, 072303 (2003)

One of six 'famous' PHENIX papers with > 250 citations



High p_T π^0 And Direct Photons Today

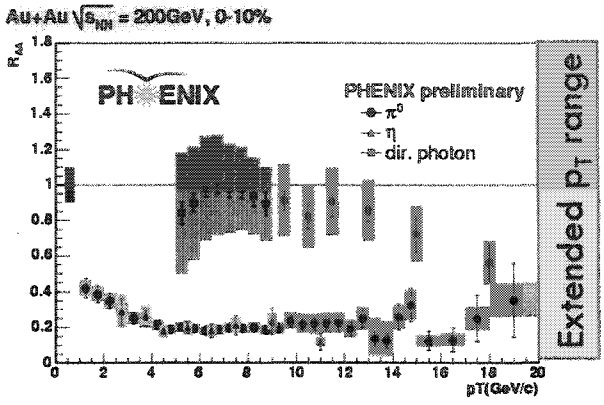
3



- Indication for same R_{AA} for direct γ and π^0 at high p_T
- If true, then no E loss at hight p_T
- LHC would have nothing to measure!
- In general interesting to quantify E loss at high p_T

High p_T π^0 And Direct Photons Today

4



Have high statistics (factor 3) data set (2007)
Also, have
high statistics (factor 30) d+Au data set (2008)

- Indication for same R_{AA} for direct γ and π^0 at high p_T
- If true, then no E loss at hight p_T
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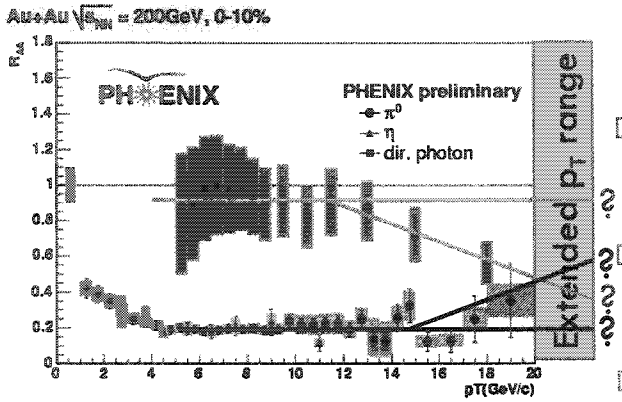
- In general interesting to quantify E loss at high p_T

High p_T π^0 And Direct Photons Today

5



- Indication for same R_{AA} for direct γ and π^0 at high p_T
- If true, then no E loss at hight p_T
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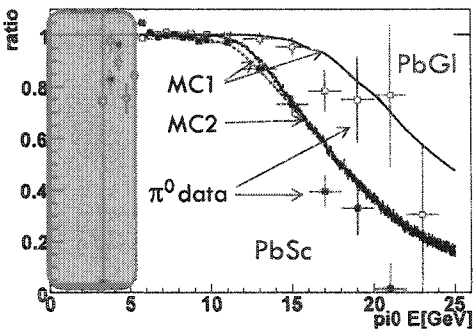
- In general interesting to quantify E loss at high p_T

Have high statistics (factor 3) data set (2007)
Also, have
high statistic[illegible] 30 d+Au data set (2008)

High p_T $\pi^0$and direct γ: Outlook

6



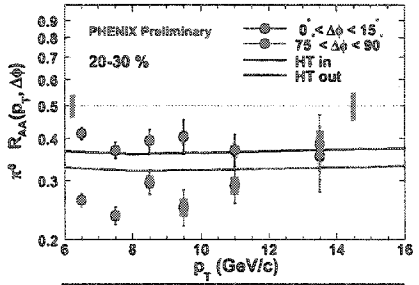
PHENIX Analysis Note 734

- EMCal calibration has been major preparation work
- Next analysis steps straightforward (largely repeat of previous analyses)
- Understanding merging systematics only challenge
- Simulations and previous studies provide guidance
- Goal: have result in spring 2010

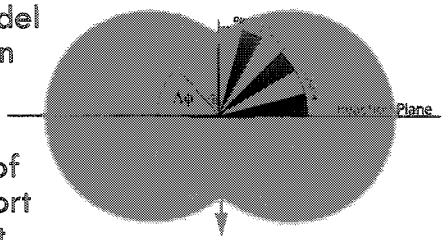
Progress since last year

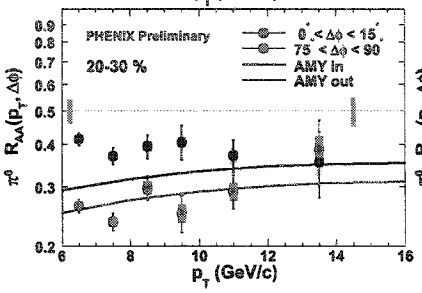
7

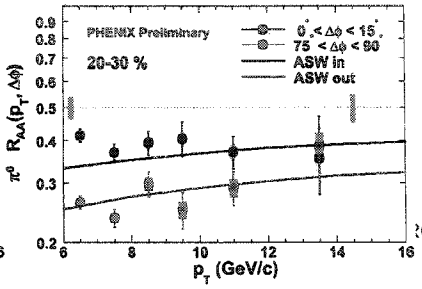
- Azimuthal anisotropy of RAA



- Provides more differential model comparison than RAA
- Allows determination of medium transport coefficient qhat





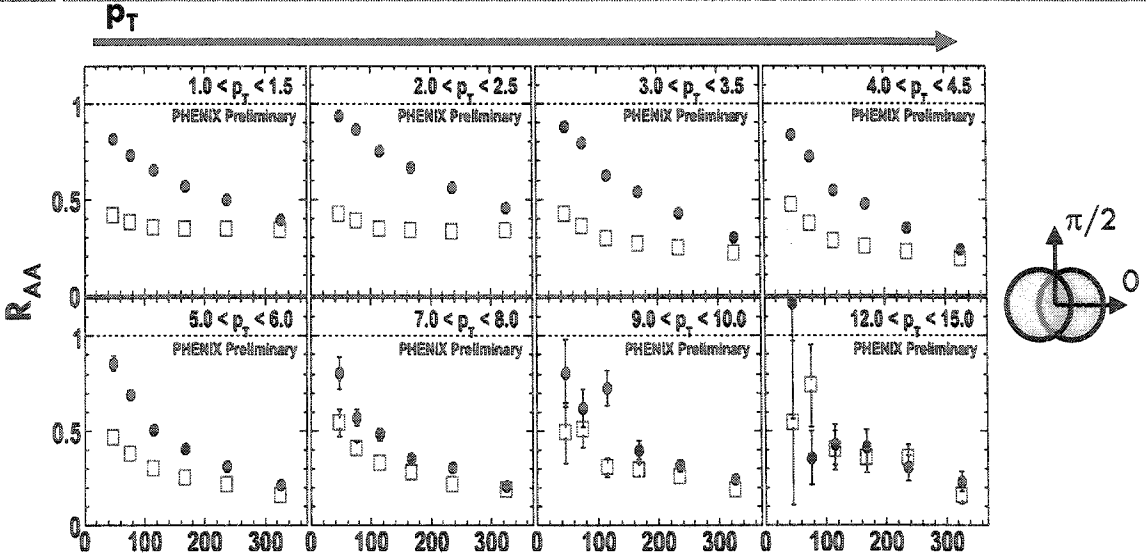


Calculation by S.Bass et al. arXiv:0808.0908

RBRC Review 2009

Centrality Dependence

8



- Indication for saturation of R_{AA} at certain path length

Stefan Bathe RBRC Review 2009

Use η instead of π^0 ?

9

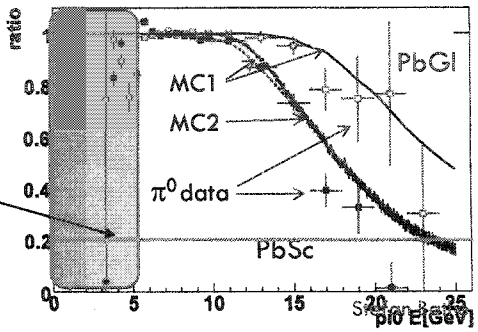
- η
- Mass: 0.5479 MeV/c^2
- $\Gamma(\eta \to \gamma\gamma)/\Gamma(\eta \to X)$: 0.393
- Wave function:
  - $(u\bar{u}+d\bar{d})/2+s\bar{s}/\sqrt{2}$

- π^0
- Mass: 0.1350 MeV/c^2
- $\Gamma(\pi \to \gamma\gamma)/\Gamma(\pi \to X)$: 0.988
- Wave function:
  - $(u\bar{u}-d\bar{d})/\sqrt{2}$

η/π^0 = ~0.5 (measured at high pT)

Probability of detecting two γ's from π^0

η probability
0.393*0.5=0.1965



- η yield exceeds π^0 yield above pT~23GeV/c.
- Systematic error on η yield should be much smaller for pT>12GeV/c
  - Because we don't need to take care of merging effect

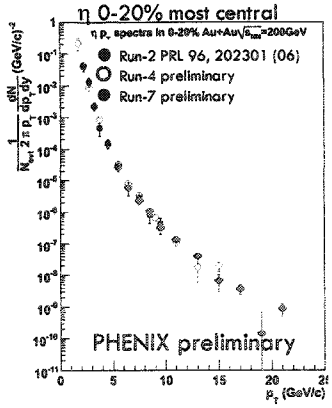
Stefan Bathe RBRC Review 2009

PHENIX Analysis Note 734

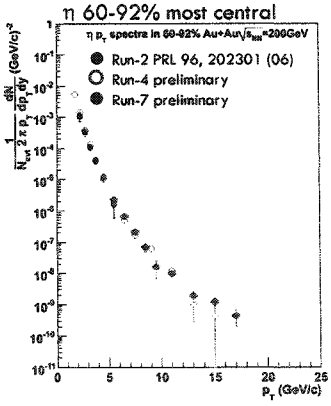
η invariant yield

10

η 0-20% most central



η 60-92% most central



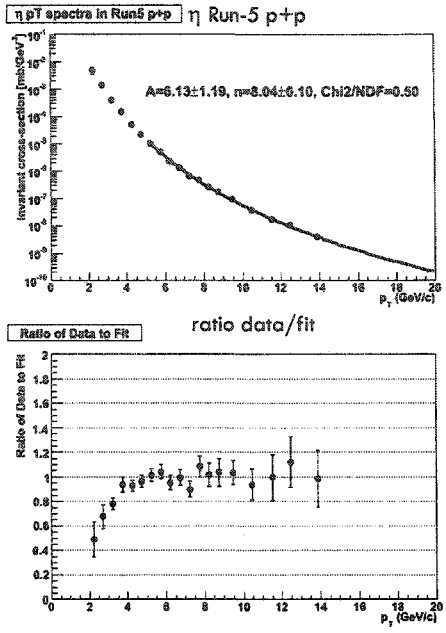
- Problem:
  - While η wins over π^0 (in terms of statistics) at 23 GeV, statistics runs out earlier

- However
  - η still provides cross check of π^0 with independent systematics for 13 GeV < p_T < 23 GeV, where merging effect is significant

Stefan Bathe RBRC Review 2009

p+p Reference

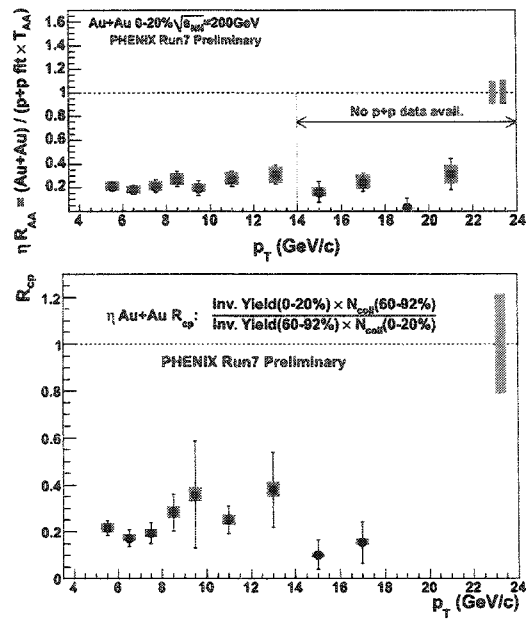
11



- Current p+p data (Run-5) run out at 14 GeV
- Relying on fit to extrapolate to higher p_T
- Alternative
  - Use π^0 as reference (correcting for η/π^0 ratio)
  - Problem: π^0 suffers from merging → introduces systematic uncertainty
- Also:
  - have ~7x p+p statistics in can from Runs 6,9

η R_{AA}, R_{cp}

12

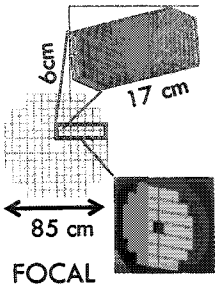


- Independently confirms π^0 R_{AA}
- Like π^0:
  - Use π^0 as reference (correcting for η/π^0 ratio)
  - consistent with constant p_T dependence
  - But rise with p_T cannot be excluded

The Future

- Joining faculty of Baruch College, CUNY, as tenure track professor in February 2010
  - Joint with RBRC fellowship for first 5 years
- Starting experimental nuclear physics group
  - Two nuclear theorists already there: Adrian Dumitru (RBRC fellow) and Jamal Jalilian-Marian
- Applying for research grant
- Looking for:
  - new hardware project in PHENIX
    - Possibly FOCAL
  - students and postdocs to work with

Baruch College, Manhattan



FOCAL

The PHENIX muon trigger upgrade:

RBRC review,
October 21/22

Ralf Seidl
(RIKEN BNL Research Center)

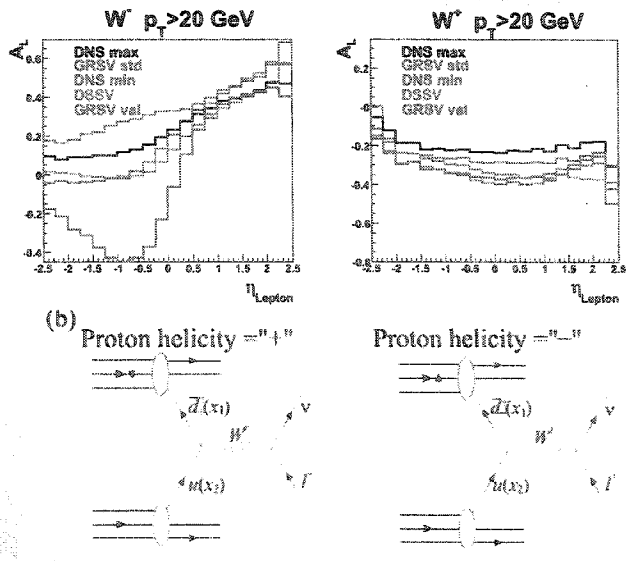
W production as access to quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔ Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

➔ Difference of the cross sections gives quark helicities $\Delta q(x)$

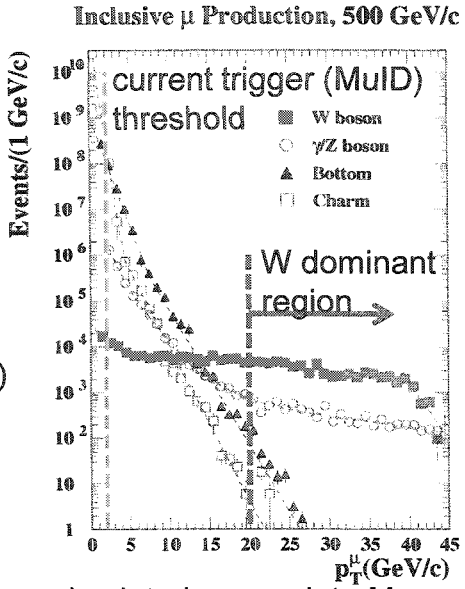
- Testing the spin structure at the W scale without fragmentation functions
- Large asymmetries to be expected



New muon trigger system necessary

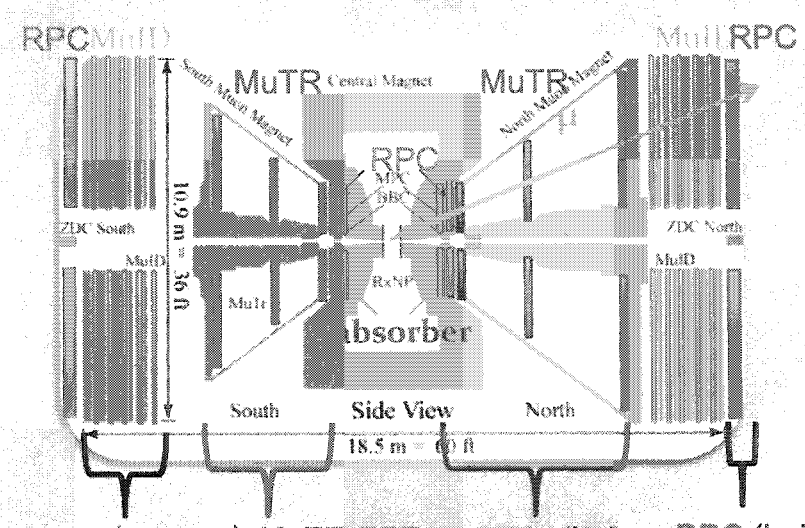
- σ(tot)=60mb, L=3x10^{32}cm^{-2}s^{-1} (500GeV)
  - collision rate = 18MHz
  - (after luminosity upgrade)
- DAQ rate limit < 2kHz (for muon Arm)
- Therefore, required rejection ratio
  - > 9000

- But, MuID-trigger rejection ratio (500GeV)
  - < 100
- *We need momentum dependent trigger*



simulated muons into Muon Arm
(2000pb-1, with PYTHIA5.7)

PHENIX Muon Trigger Upgrade Project



MuID trigger (existing) selecting muon momentum > 2GeV/c

MuTR FEE upgrade (being installed) fast selection of high-momentum-tracks

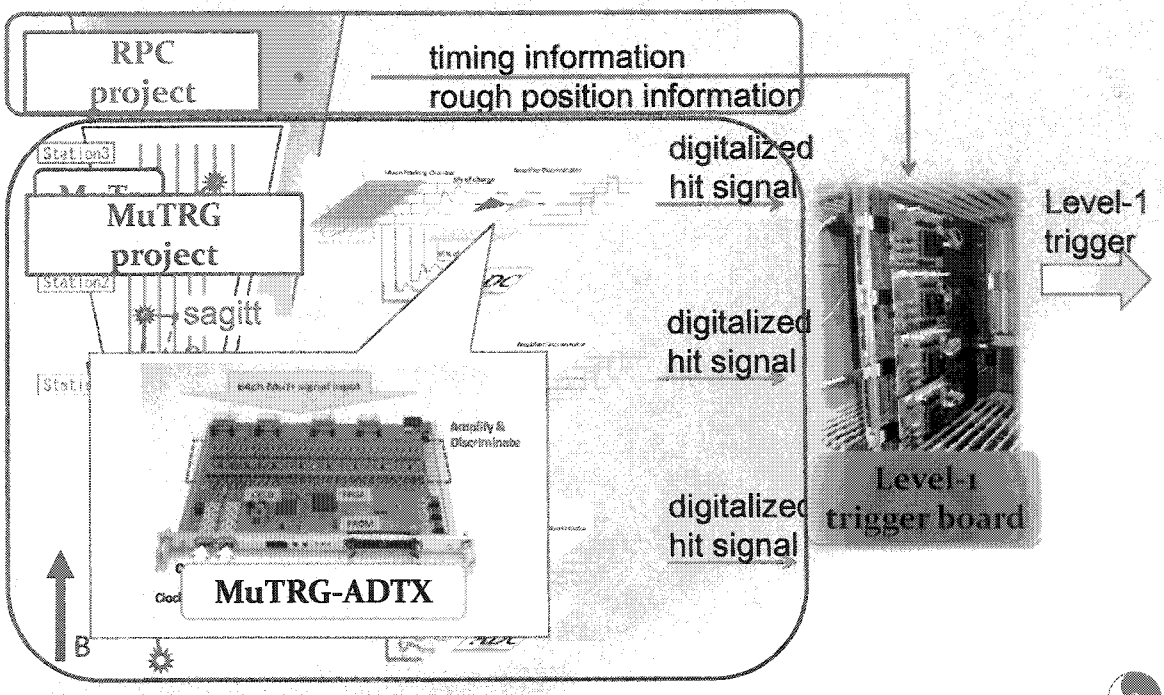
RPC (being installed) provide timing information and rough position information

Muon Trigger upgrade Collaboration

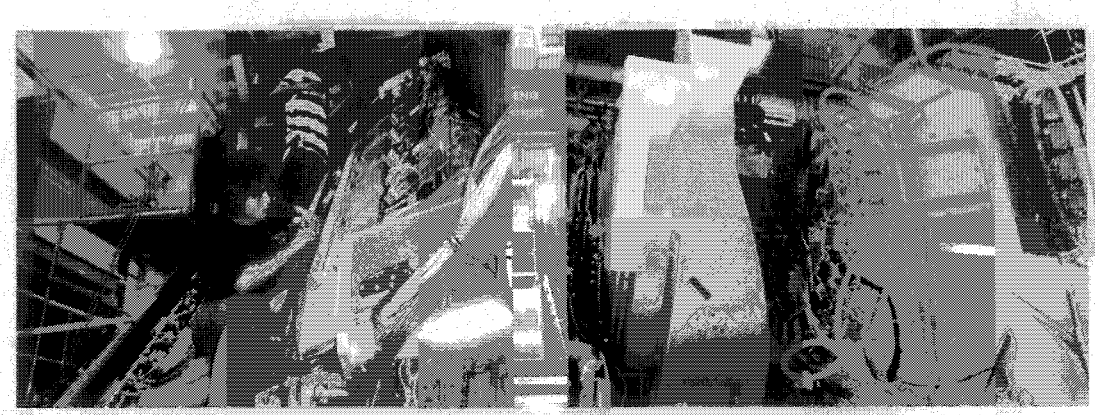
- Abilene Christian University
- University of California, Riverside
- CIAE, Beijing
- University of Colorado, Boulder
- Columbia University and Nevis Laboratory
- Georgia State University
- University of Illinois, Urbana
- Iowa State University
- KEK
- Korea University
- Kyoto University
- Los Alamos National Laboratory
- Muhlenberg College
- University of New Mexico
- Peking University, Beijing
- RIKEN Brookhaven Research Center
- RIKEN
- Rikkyo University

5

Upgraded Muon Trigger System



MuTRG installation status



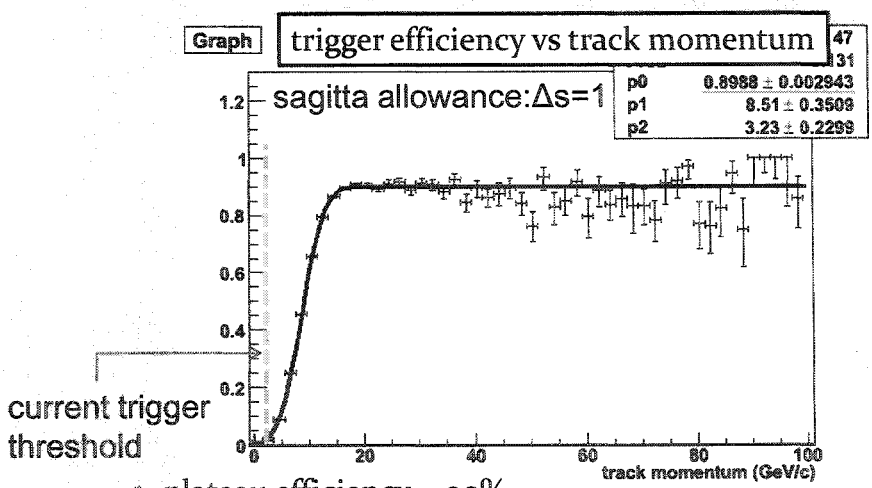
South Arm

- installation is ongoing
  - will be completed in this shutdown

North Arm

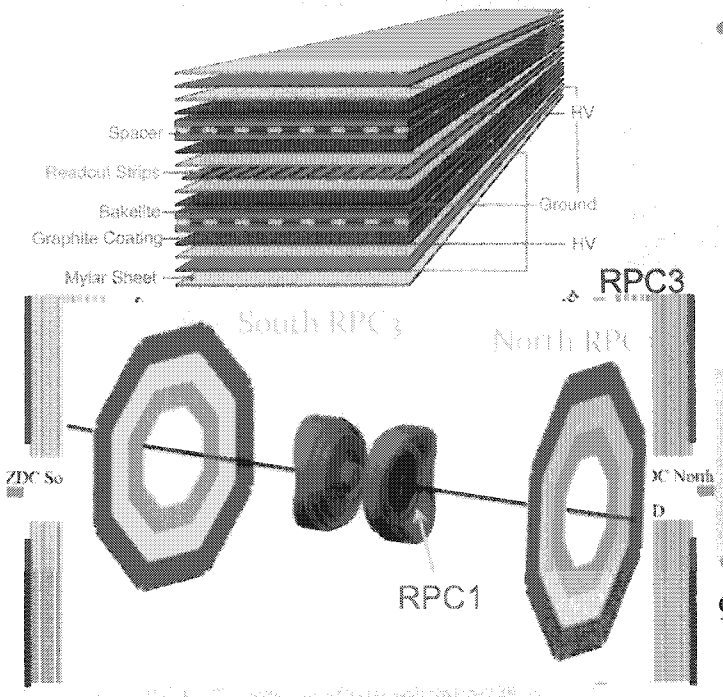
- already finished installation
  - Summer 2008
  - commissioning with run9 500GeV pp data

efficiency and threshold-momentum of MuTRG



- plateau efficiency ~ 90%
  - → (hit efficiency par station ~ 97%)^3 x (vertex cut efficiency)
  - higher threshold momentum than current trigger
- achieve expected efficiency and threshold momentum
- rejection ratio estimation is also on going

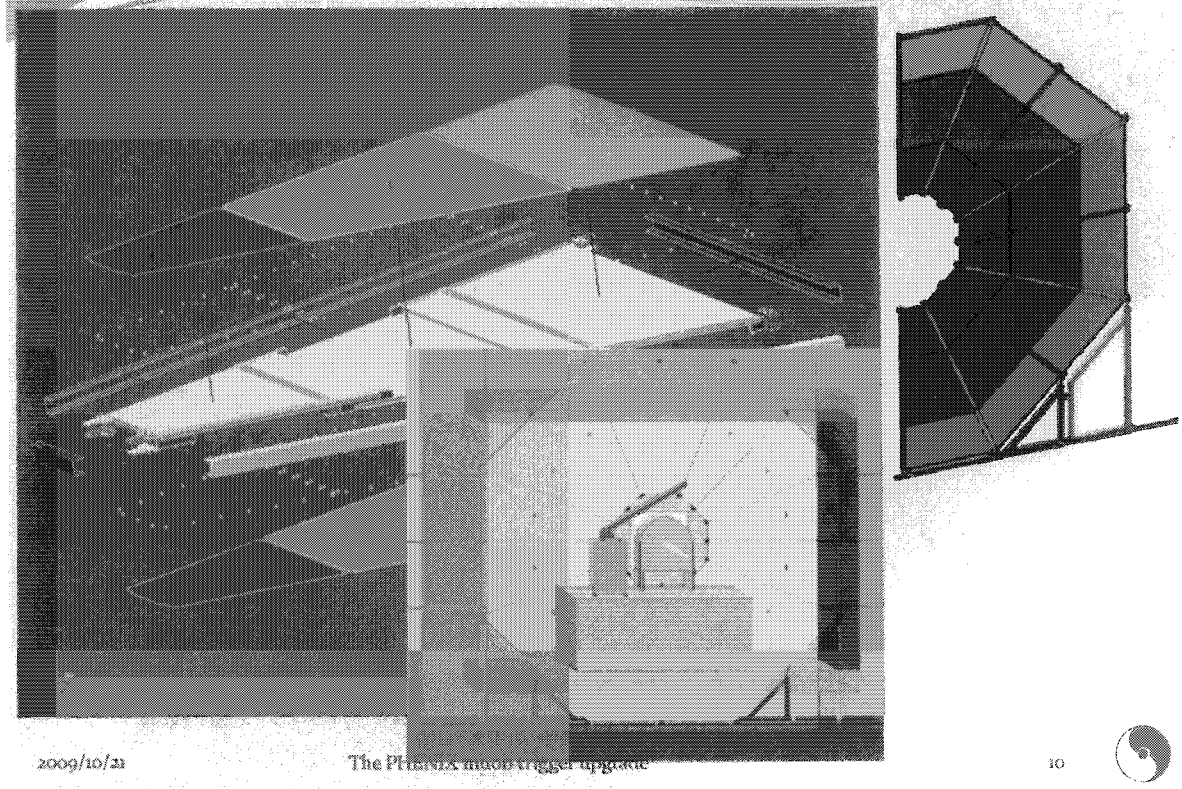
Resistive Plate Chamber (RPC)



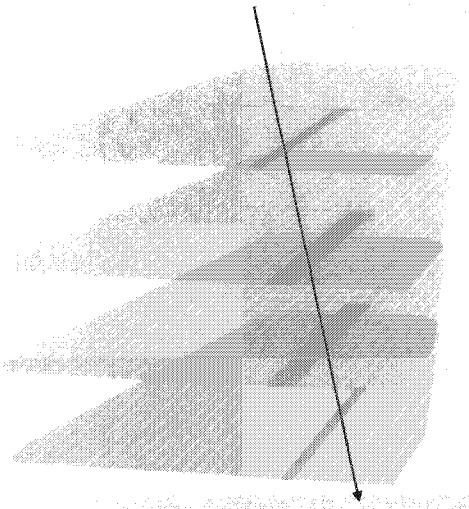
- Characteristics of RPC
  - Fast response
    - Suitable for as trigger device
  - ***Good intrinsic time resolution***
  - Good spatial resolution: ~ cm
    - Determined by the read-out strip width and cluster size
  - Low cost
- Typical gas mixture

95% $C_2H_2F_4$ + 4.5% i-C_4H_{10} + 0.5% SF_6

Half Octant assembly in tunnel

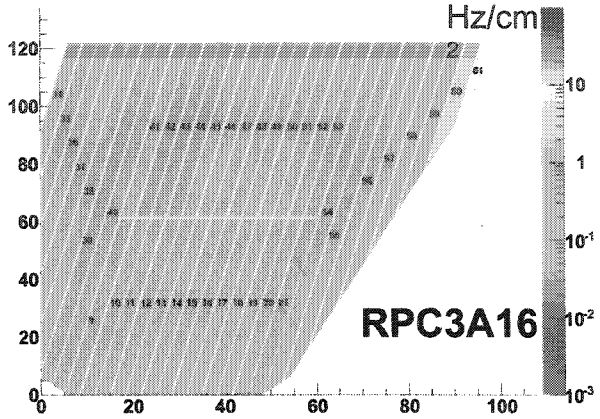


Module QA with cosmics

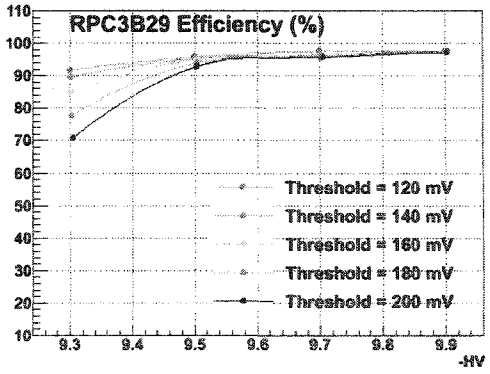


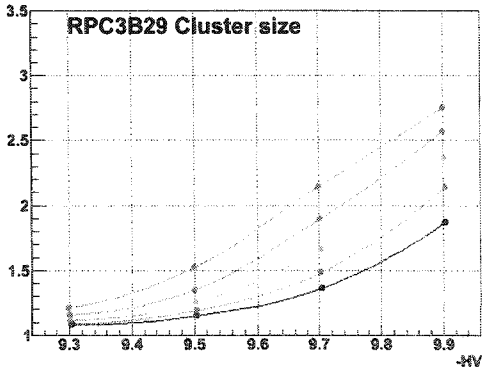
Event display

- Modules stay in cosmic test stand for at least several days
- Evaluate Efficiencies and cluster sizes as a function of HV and threshold
- Evaluate noise rates :



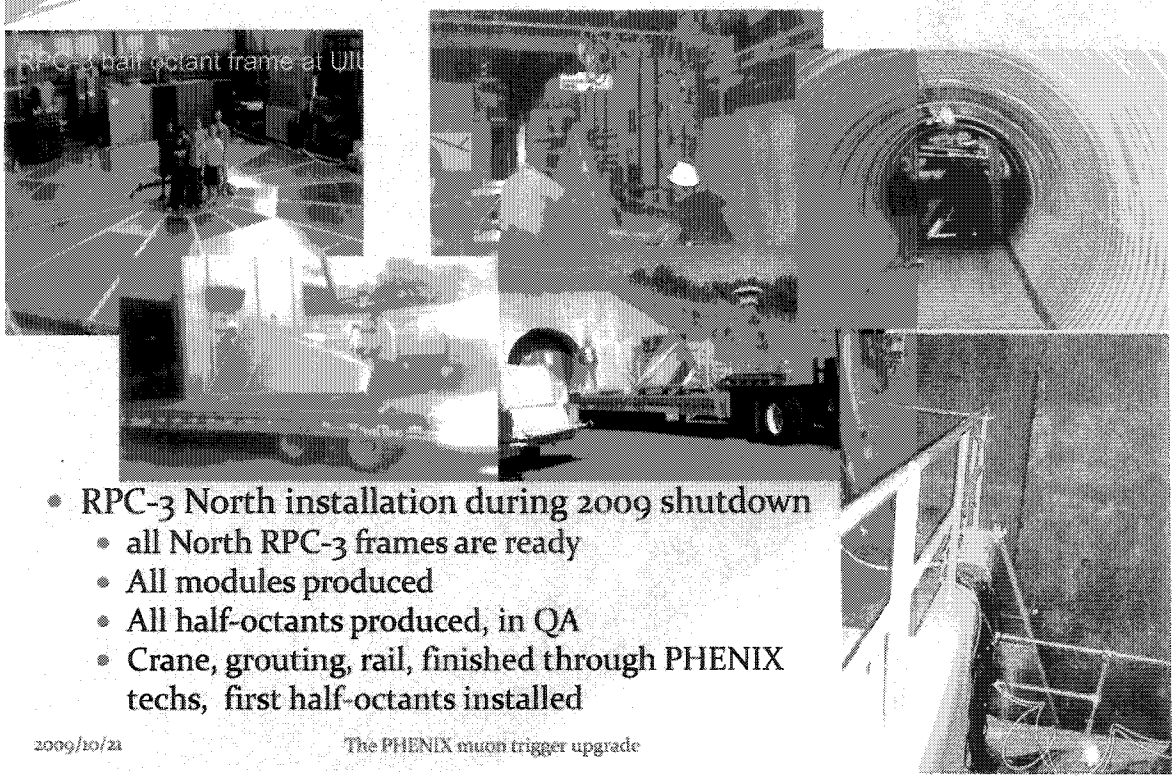
Module efficiencies and Cluster sizes





- High efficiencies from 9.5 kV at reasonably high thresholds
- Cluster sizes in the range 1-2 strips
- Typical operation mode: 9.7 kV and 140 mV

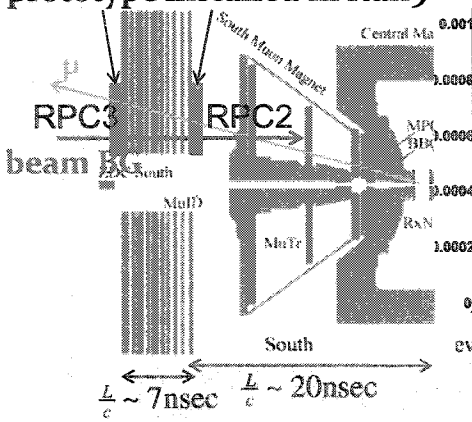
RPC3N installation status

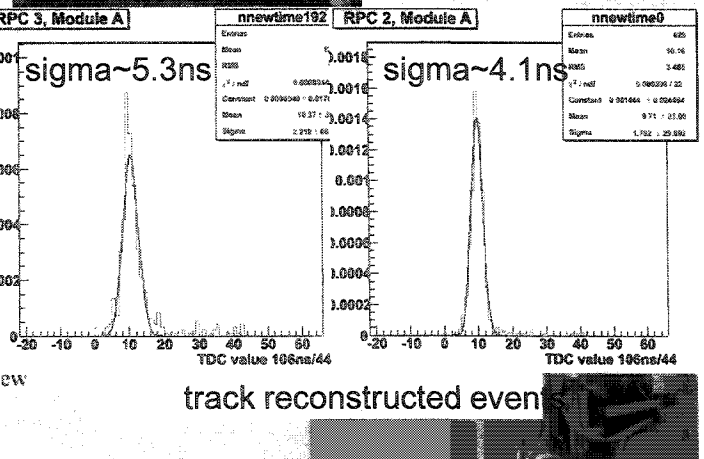


- RPC-3 North installation during 2009 shutdown
  - all North RPC-3 frames are ready
  - All modules produced
  - All half-octants produced, in QA
  - Crane, grouting, rail, finished through PHENIX techs, first half-octants installed

2009 beam data

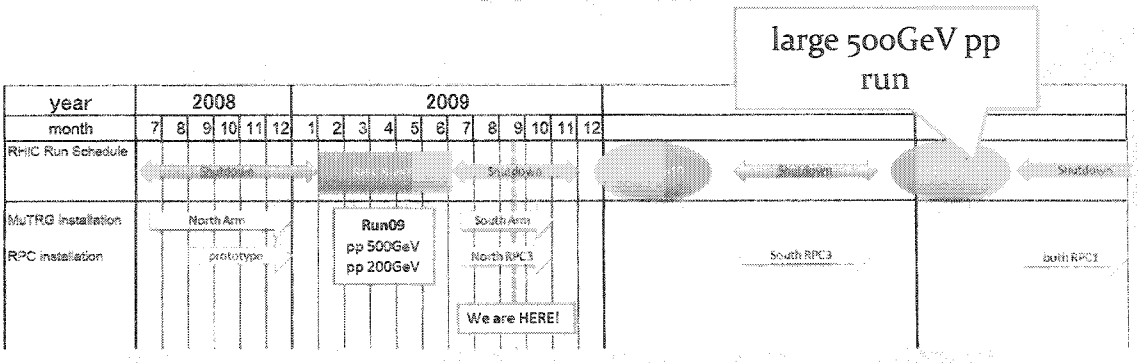
prototype installed in Run9





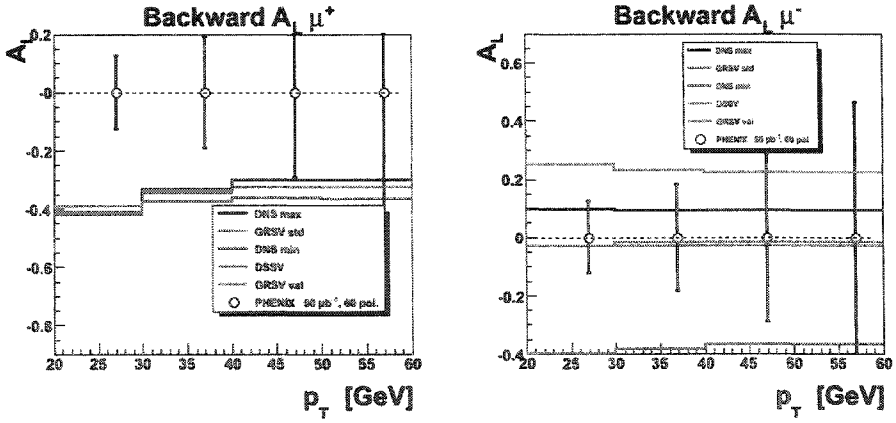
- **2 prototypes have been installed during 2009 run**
- **typical timing resolution 4 ~ 5 nsec**
  - **beam background can be separated**
  - **Bunch crossing can be identified → Spin pattern**

MuTRG and RPC installation schedule



- MuTRG + RPC3 (not including RPC1) can generate trigger signal
  - the main purpose of RPC1 is cosmic background rejection
- North MuTRG + RPC3 system will be completed in 2009
- South MuTRG + RPC3 system will be completed in 2010 shutdown
- Ready for run 11

Backward W asymmetries for run11 BUP values



- Full detector simulation including smearing, 3/1 Signal to background, 60% polarization

Summary

- Muon Trigger upgrade will be ready for run11
  - RPCs and MuTRG FEE worked as expected in run9
  - good efficiency and momentum-threshold
  - Readiness for forward/backward W physics
- RUN11: first long 500 GeV run with about 50 pb^{-1} and 50-60% polarization expected
  - W physics in forward/backward and central regions

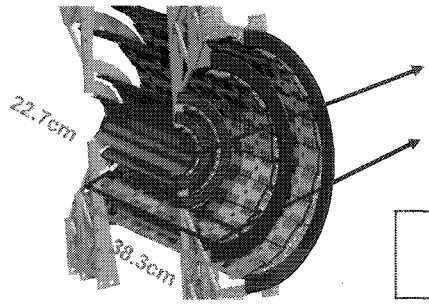
Backup slides

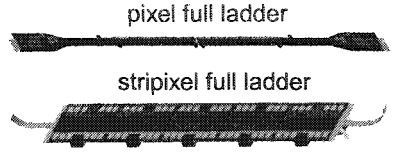
VTX Pixel detector

Atsushi Taketani
RIKEN Nishina Center Detector Team
RIKEN Brookhaven Research Center

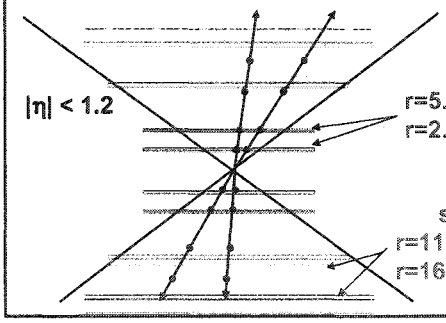
Silicon Vertex Tracker (VTX)

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



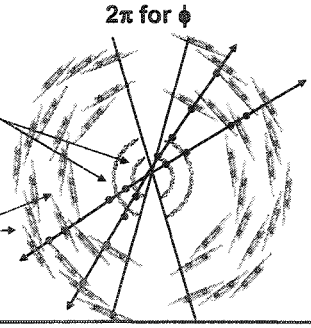


- High spatial resolution : σ_{DCA}~ 100 μm
- Large acceptance : $|\eta| < 1.2$, 2π for ϕ



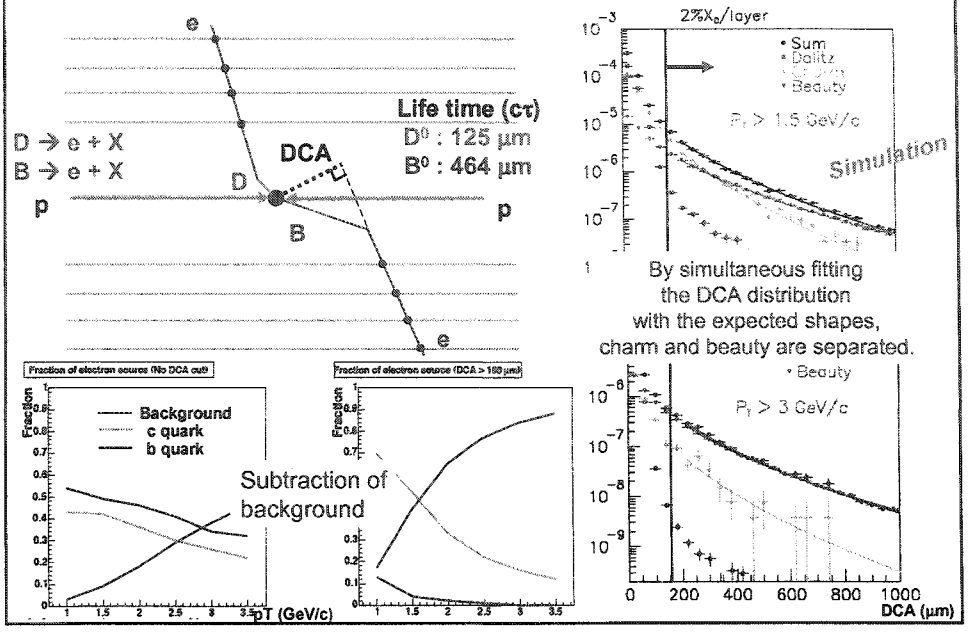
pixel layer
r=5.0cm Δz=±10cm
r=2.5cm Δz=±10cm

stripixel layer
r=11.5cm Δz=±16cm
r=16.5cm Δz=±19cm



Identifying heavy flavor production by VTX

charm and beauty separation with difference of their life time



Physics Goals

Open up new horizon!

Spin program

- gluon polarization by using beauty / charm final state by measuring decay length.
- gluon polarization by using γ + jet final state by identifying Jet with large acceptance detector.

Heavy Ion program

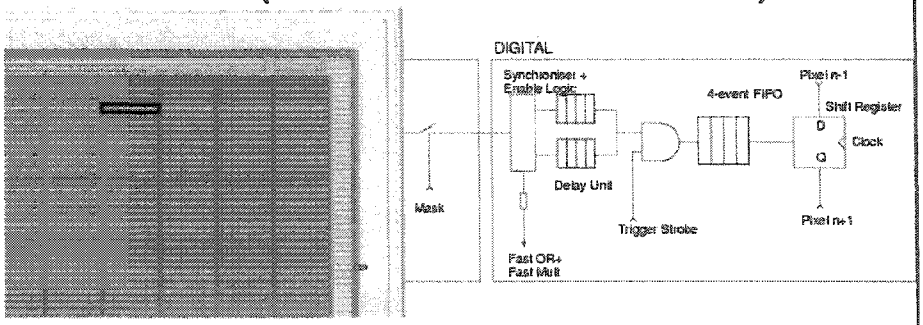
- Potential enhancement of charm production.
- Open beauty production.
- Flavor dependence of jet quenching and QCD energy loss.

Required specification

- •High spatial resolution for identifying bottom/charm quark by decay length
- •High rate trigger performance in polarized proton-proton collision
- •Working in high hit occupancy environment in heavy ion collision.
- •Large acceptance.

4

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

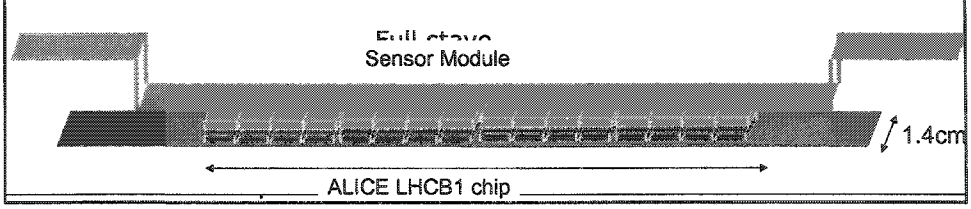
Readout by ALICE_LHCB1 chip

- 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

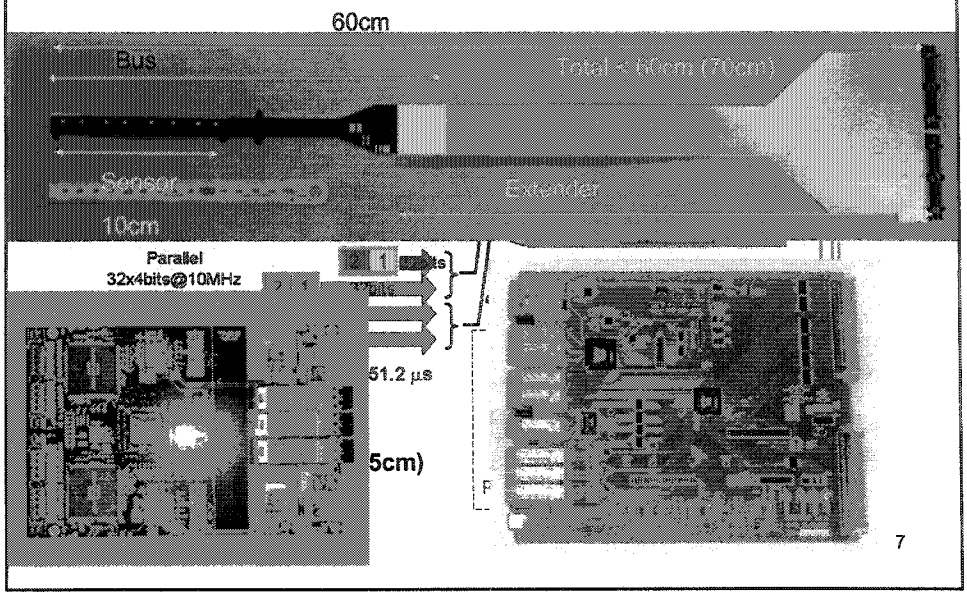
5

Pixel detector module

- 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

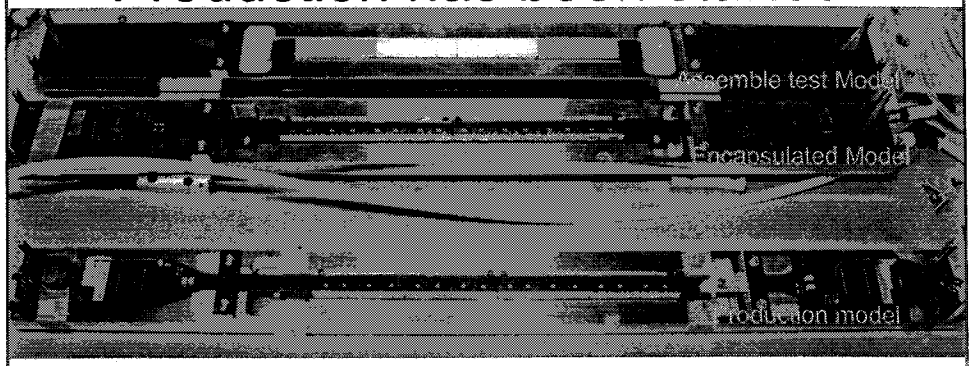


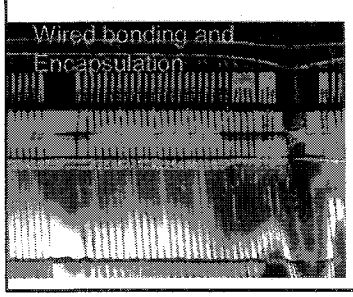
Pixel Readout Overview



7

Production has been started





We have all pieces of parts

- Sensor modules
- Carbon staves
- Readout bus

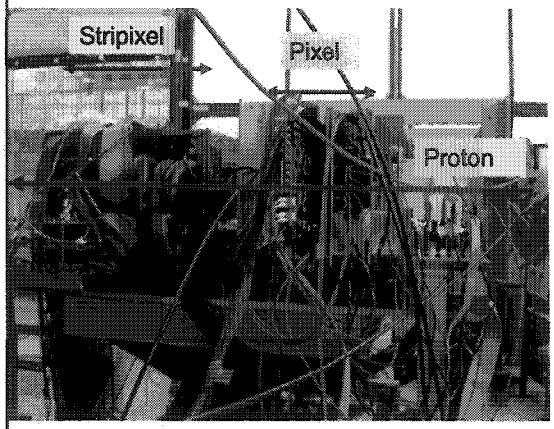
And Assembly technique.

4 ladder produced. Need 30 ladders.

Electrically working well.

8

Test beam at 120GeV Proton



FERMILAB Meson Test area

120 GeV Proton

5-30mm beam spot

4.5 sec spil per 1 min.

2×10^{10} proton / spil

Independent DAQ for Pixel and Stripixel.

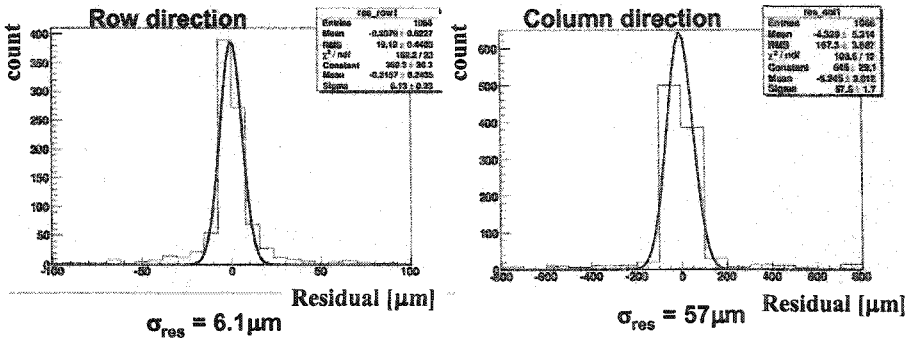
Using trigger scintillation counters

Stripixel	Pixel
3 Prototype ROC	3 Prototype pixel ladder
Trigger: Beam defining Scinti.	Trigger: Scinti * FAST_OR (3layer)
DAQ : SVX4+ ROC+RCC	DAQ: Prototype Readout + PHENIX DAQ

9

Pixel performance

$$\textbf{\textit{Residual}} = \sum_{i=1}^{3}(Fit - X_i)^2$$



Un-convolute

Fit include all 3 layers hit position

Multiple scattering effect

→

Intrinsic resolution

row : 14μm

column : 152μm

10

People at Wako Base Activity

RIKEN/RBRC VTX group as of 2009 Oct.

VTX Detector Council: Y. Akiba@RBRC

Pixel Subsystem Manager : A. Taketani

Post Doc: M. Kurosawa, S. Baumgart (Just arrived)

Technician: J. Kanaya

Rikkyo : K. Kruita(Prof), M.Kasai(Grad Stu.), Y.Haki(Grad. Stu.)

KEK : M. Sekimoto (A. Prof.)

People left since 2008 review

Post Doc: K. Fujiwara to Tokyo Met. Industry of Tech. Inst. as Tenure Track.

R. Ichimiya to KEK Detector Development group

Y. Onuki to Tohoku Univ. High Energy group

We also accepted 2 summer students from Technical college.
(since 2006 total 13 students worked with us)

11

Summary

- PHENIX Silicon VTX will be installed in 2010 and will extend Spin and Heavy Ion physics by identifying b and c separately.
- RIKEN Wako group has been in charge of development and construction of Pixel stave.
- Production has been started.

12

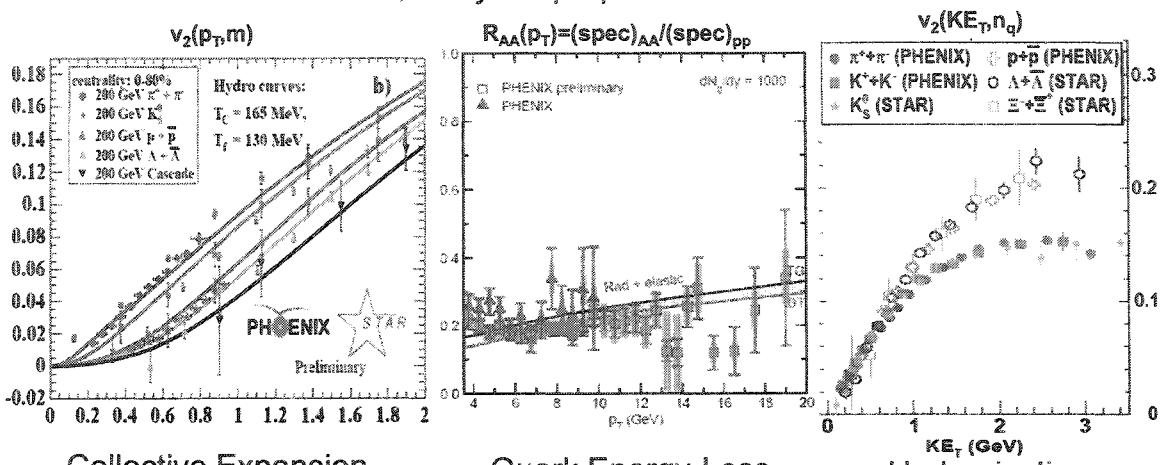
Silicon Vertex Tracker "VTX" for PHENIX Upgrade

Silicon Stripixel Detector

Rachid Nouicer, Annual RBRC Scientific Review, Oct. 21st 2009

What the main physics motivation for building VTX detector?

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

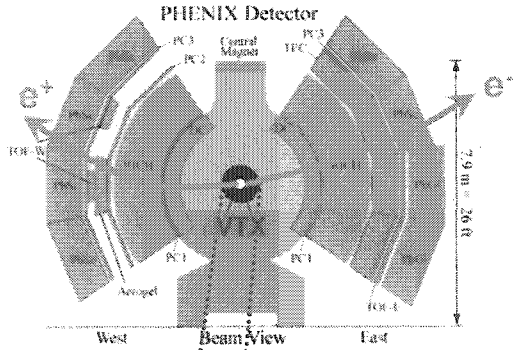


Collective Expansion | Quark Energy-Loss | Hadronization

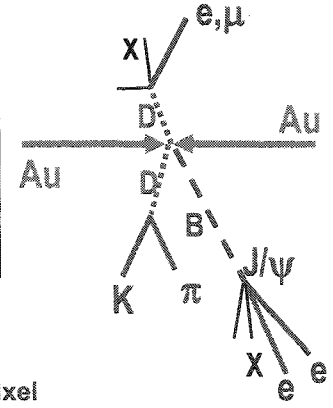
Strongly-interacting matter has been created in central Au+Au at 200 GeV

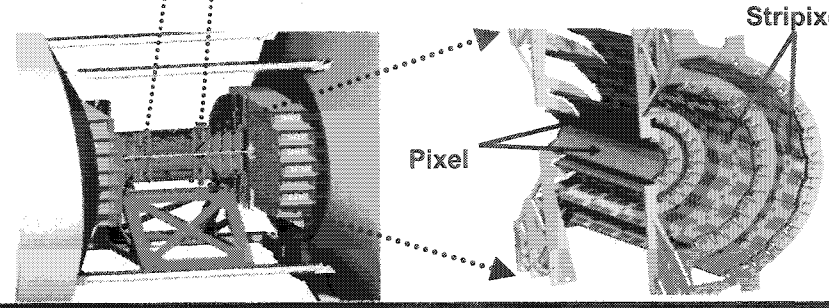
Physics Motivation

- 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





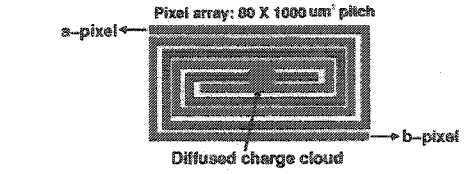
-Large acceptance
($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)

-Displaced vertex measurement
$\sigma < 40$ μm

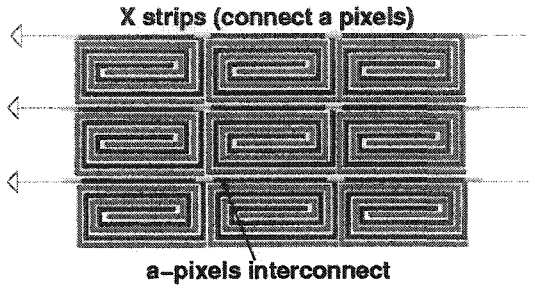
Silicon Stripixel Concept (Barrels 3 &4)

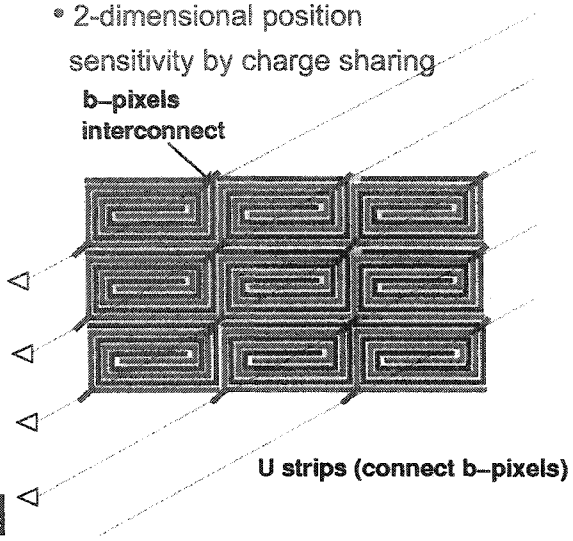
"New technology: unique to PHENIX"

- 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)



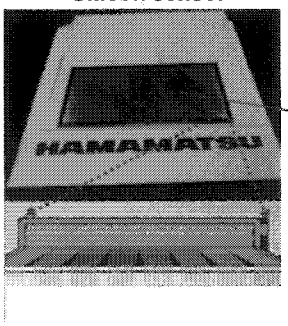
- DC-Coupled silicon sensor
- Sensor single-sided
- 2-dimensional position sensitivity by charge sharing



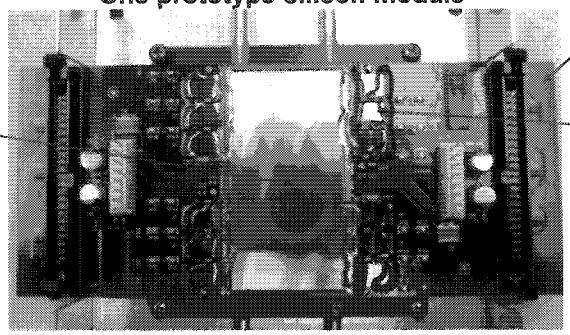


Stripixel Silicon Module: Pedestal Distribution

Silicon sensor

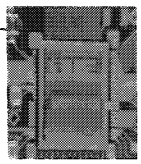


One prototype silicon module



ROC (readout silicon module)

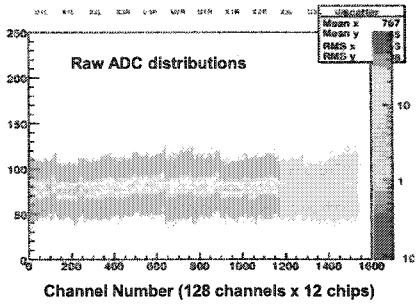
SVX4 chip



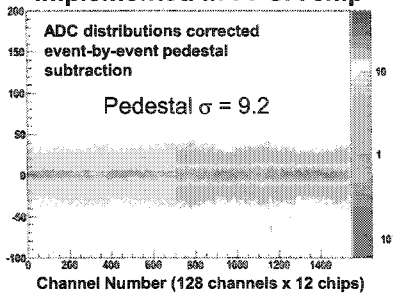
- 8 bit ADC
- 128 channel / chip
- 3 mW / channel

• Results:

• Online plot



• Offline analysis: implemented in FPGA chip



Silicon sensor+ prototype ROC+SVX4 chips were successfully tested

➪ Performance Results of Silicon Module Prototype ROC

- ❖ Response to electrons from ^{90}Sr beta source
- ❖ Response to muons from cosmic-rays
- ❖ Response to proton beam at 120 GeV (FNAL)

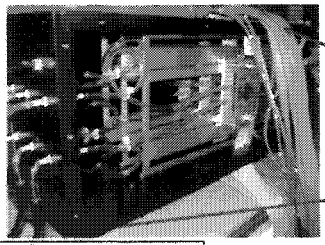
For details: R. Nouicer et al., Journal of Instrumentation (JINST), 4 P04011 (2009)

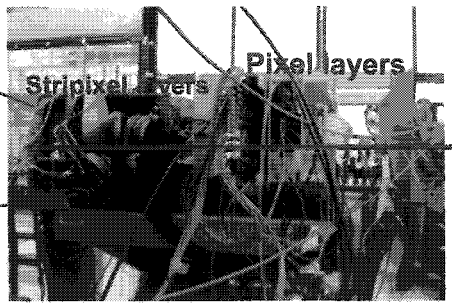
• Summary of the Performance Results

— **Good results from beta source, cosmic-ray and beam test (proton):**

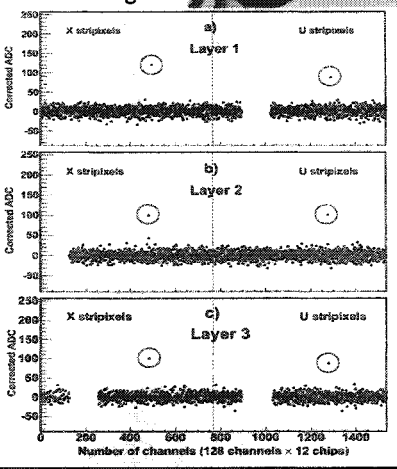
- — Hits have successfully detected
- — Good correlation between X and U strips has been observed
- — Signal/Noise has been measured: MIP/Noise = 10.4
- — Tracking efficiency: very good (more than 98%)

Highlight: Response to Proton Beam at 120 GeV (FNAL)

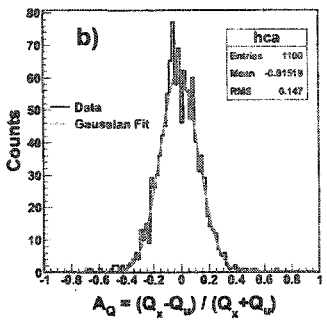




• Single Event Tracking



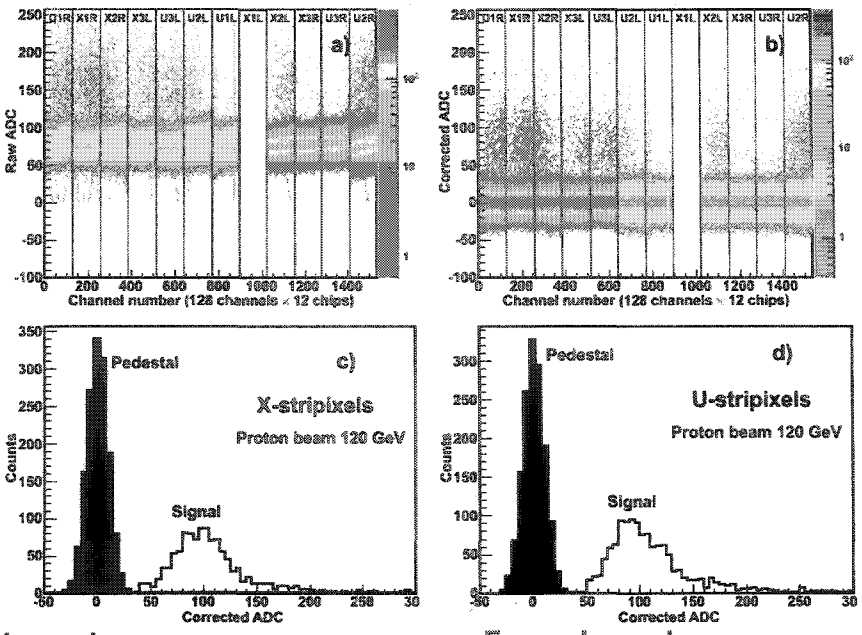
• Charged Sharing



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

Highlight: Response to Proton Beam at 120 GeV (FNAL)

- Signal-to-Noise Ratio



- For x channels

HV(V)	Pedestal 1σ	MPV	S/N
200	9.6	98.6	10.3

- For u channels

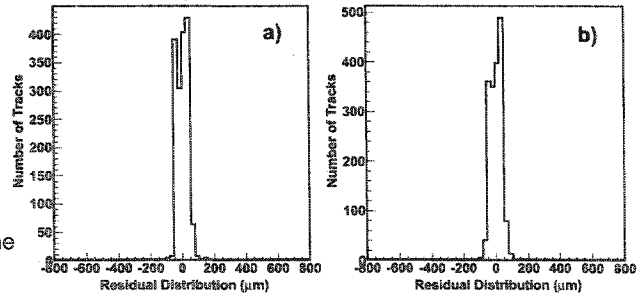
HV(V)	Pedestal 1σ	MPV	S/N
200	10.1	102.2	10.1

Highlight: Response to Proton Beam at 120 GeV (FNAL)

- 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).

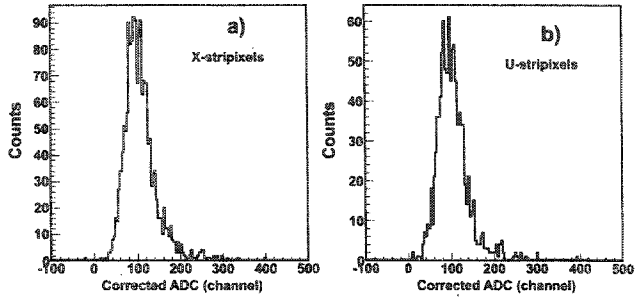
Note: Shape of the distribution is consequence of the three-plane-resolution with imperfect alignment



- Tracking efficiency (detection efficiency)

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

Tracking efficiency very good

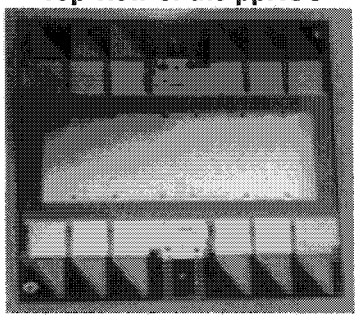


⇨ Performance Results of Silicon Module Using Pre-Production ROC

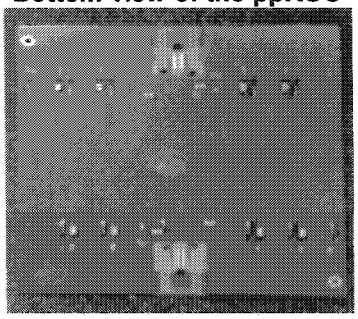
Performance Results of Silicon Module Using Pre-production ROC

❖ First Stripixel Ladder on Aluminum Stave

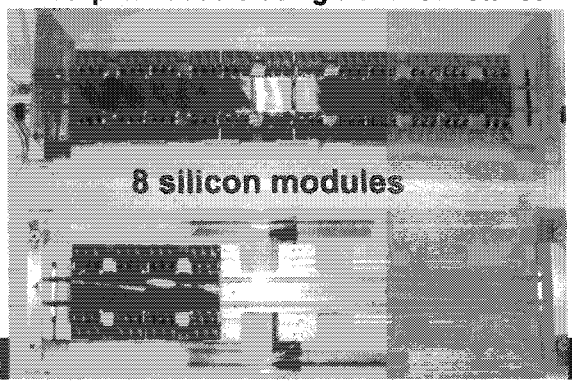
- Top view of the ppROC



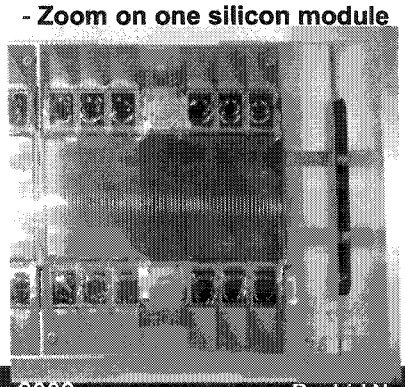
- Bottom view of the ppROC



- Stripixel ladders using aluminum staves

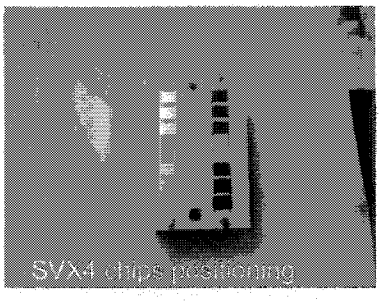


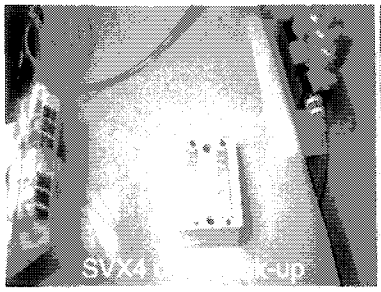
- Zoom on one silicon module

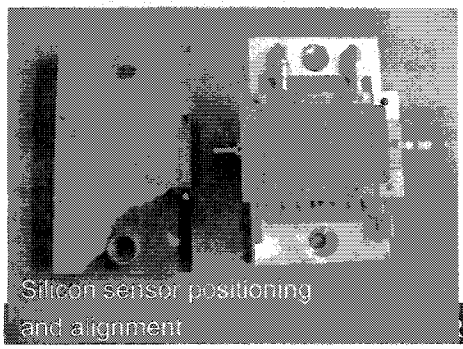


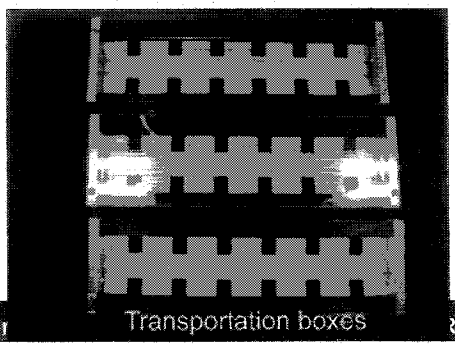
Preparation for Assembly of Silicon Module Mass production

- All fixtures for silicon module assembly are ready and there were used to build the silicon modules of ladder for electrical test: designed at BNL and fabrication by BNL/SBU shops





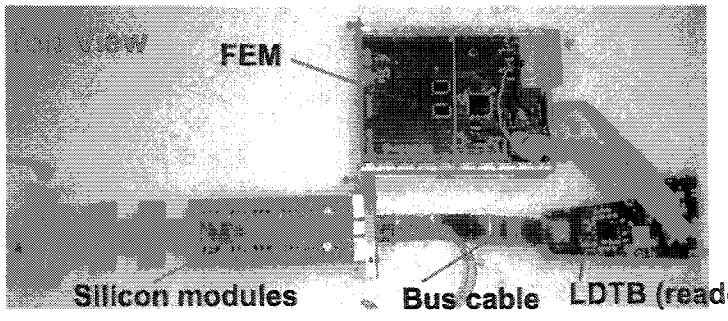


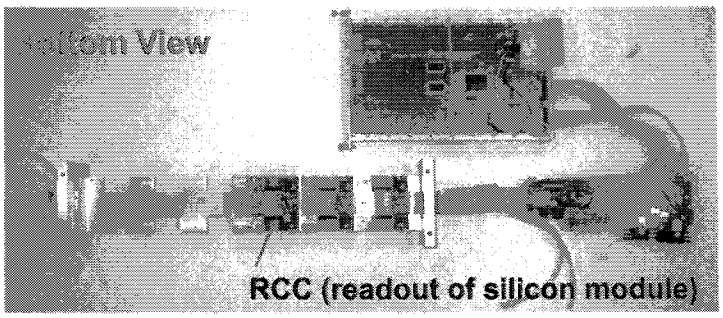


Performance Results of Silicon Module Using Pre-production ROC

❖ Stripixel ladder Readout Chain

- Photograph of the readout chain used for the ladder electrical tests

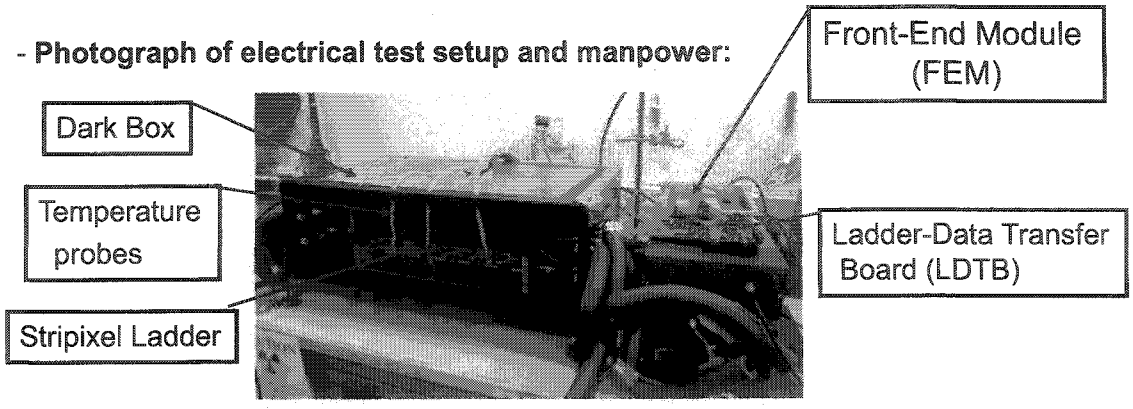




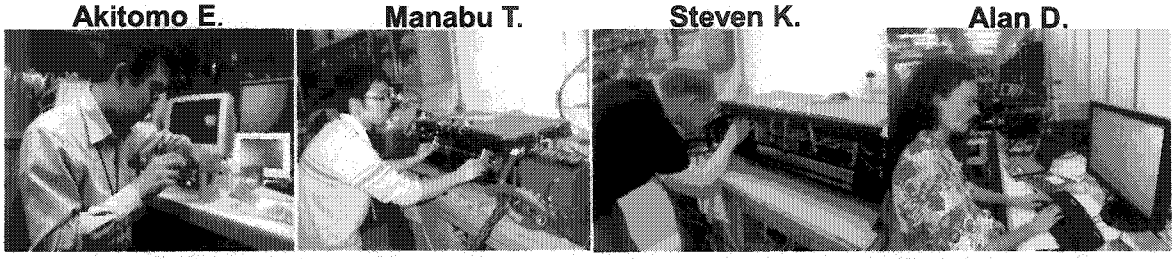
Performance Results of Silicon Module Using Pre-production ROC

❖ Electrical ladder tests

- **Photograph of electrical test setup and manpower:**



Akitomo E. **Manabu T.** **Steven K.** **Alan D.**

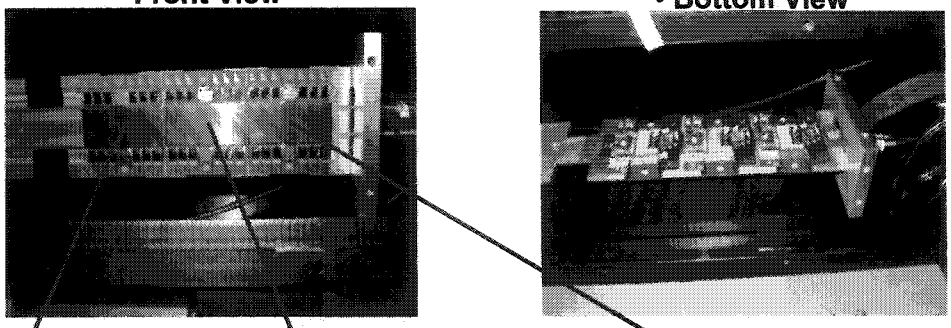


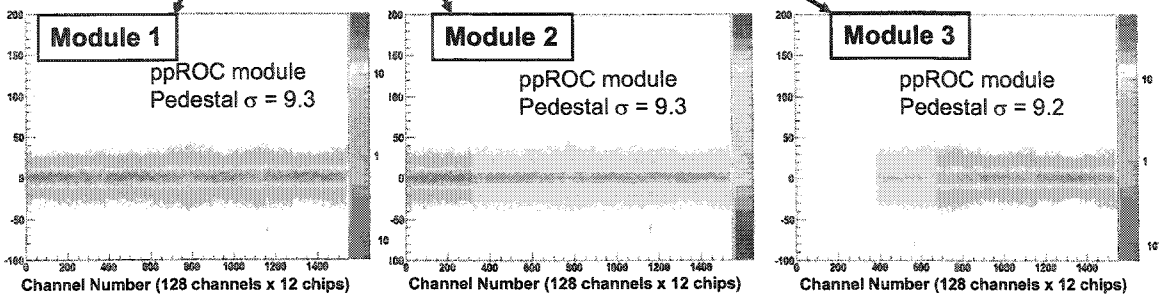
Performance Results of Silicon Module Using Pre-production ROC

❖ Electrical ladder tests: 3 modules readout simultaneously

With event-by-event pedestal subtraction

- **Front View**
- **Bottom View**





Preparation for Assembly of Silicon Module Mass production

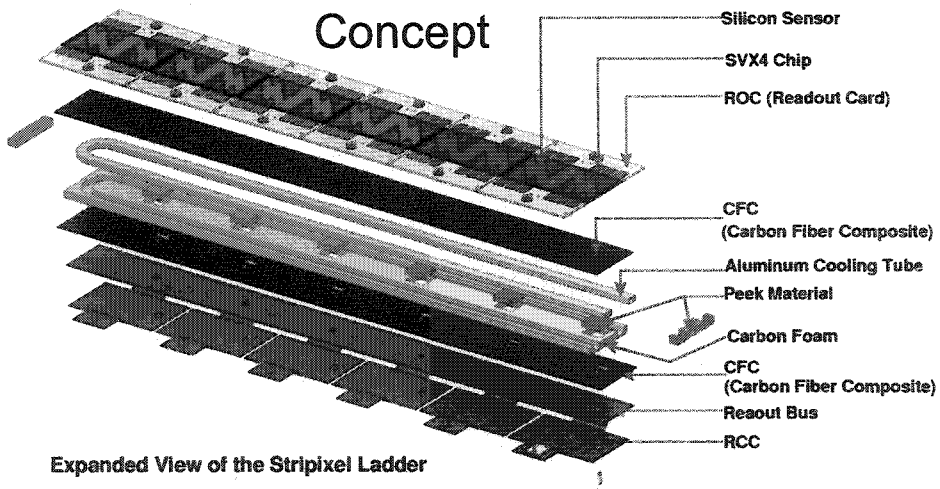
- **SOW with FNAL has been established**
  - wire-bonding, encapsulation of the ROC-SVX4-Sensor and precision placement of the silicon sensor (FNAL)
  - Mounting SVX4 on ROC (VTX manpower)
  - Testing (VTX manpower)
- **Team:** Tammy Hawke (FNAL, wire-bonding), Mike Herren (FNAL, encapsulation), Bert Gonzalez (FNAL, trained on sensor placement), Steve Kaneti (SBU, trained on SVX4 placement), Manabu Togawa (RBRC, testing) + Paul Kline (SBU) and Rachid Nouicer (training people and ensuring success).

Tammy H. **Mike H.** **Bert G.** **Steven K. & Rachid N.**

- The procedure of the silicon module mass production assembly has been implemented successfully. Yes, we are ready.

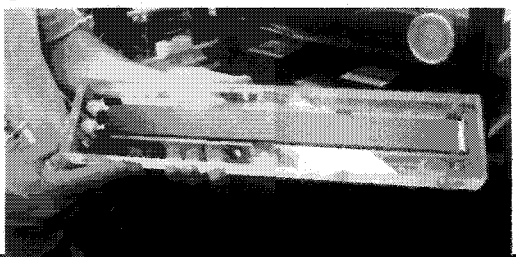
Stripixel Ladder

Concept



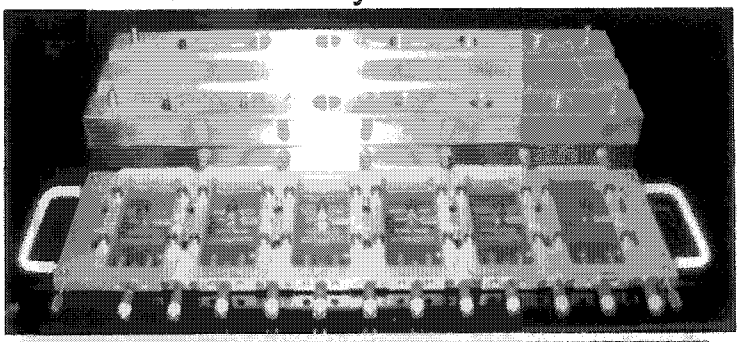
Expanded View of the Stripixel Ladder

Two prototype stripixel staves were delivered

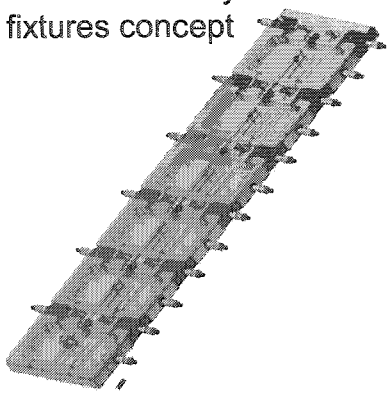


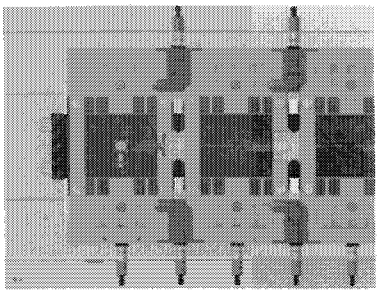
Stripixel Ladder: assembly fixtures and machine ready

- Ladder assembly fixtures delivered



- Ladder assembly fixtures concept

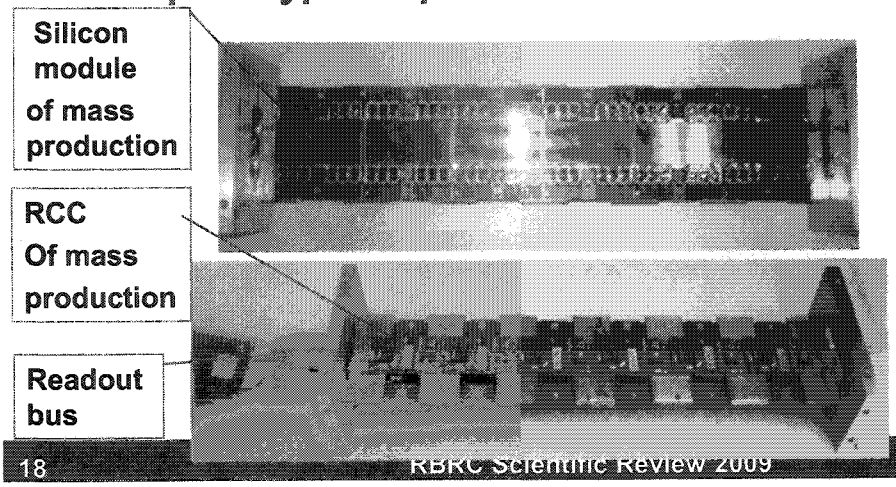




Stripixel Modules: 1st article from mass production

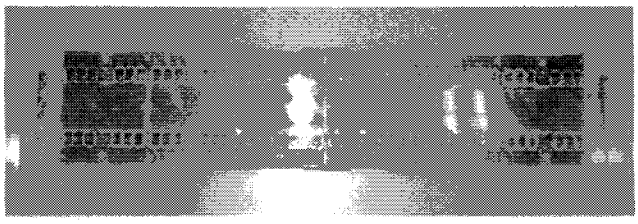
- Today, we have fully working:
  - 9 silicon modules from mass production (1st article)
  - 7 RCC from mass production (1st article)
  - 5 readout buses as mass production (28 inches)
  - 1 good prototype CFC stave

First prototype stripixel ladder will build in October 2009.



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

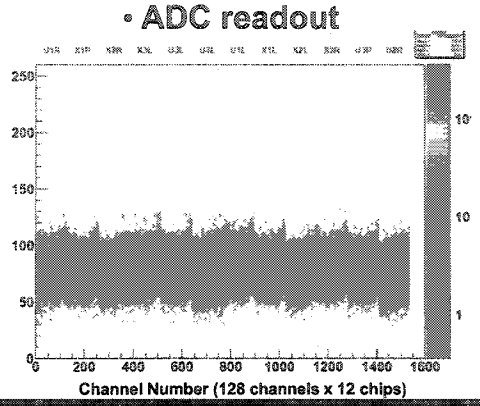
Stripixel Modules: 1st article from mass production



Performance Results:

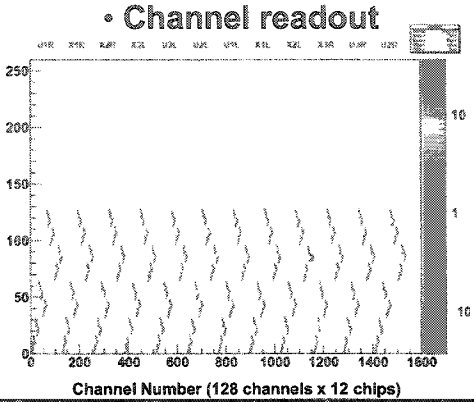
Online plot

- ADC readout



Channel Number (128 channels x 12 chips)

- Channel readout



Channel Number (128 channels x 12 chips)

Stripixel Detector Manpower of Assembly and Testing

Subsystem Manager
- **Abhay Deshpande (SBU/RBRC)**
- **Rachid Nouicer (BNL)**

Mass production assembly/tests silicon modules at FNAL:
- **Manabu Togawa (RBRC)**
- **Paul Klein (SBU)**
- **Andrew Manion (SBU)**
- **Steven Kaneti (SBU)**
- ❖ **Rachid Nouicer (BNL)**

Mass production testing: silicon modules/ladders/barrels in VTX-lab. at BNL
- **Swadhin Taneja (SBU)**
- **Andrew Manion (SBU)**
- **John Chen (SBU)**
- **Paul Klein (SBU)**
- ❖ **Rachid Nouicer (BNL)**

Mass production assembly of ladders/barrels in VTX-lab. at BNL
- **Stefan Bathe (RBRC)**
- **Kieran Boyle (RBRC)**
- **Sookhyun Lee (SBU)**
- ❖ **Rachid Nouicer (BNL)**

❖ Training people and ensuring success.

Summary

Stripixel Detector/VTX

- The physics motivation of VTX detector is well established and we still focusing on the target:
  "Study the properties of the strongly-interacting matter created at RHIC as well precise probing of the spin structure of the proton."

- Good performance results have been obtained using prototype/pre-production/mass production stripixel silicon modules

- The first prototype ladder: 5 silicon modules + 5 RCC (readout modules) + readout bus + good prototype stave will be achieved this month.

Complete installation at the PHENIX IR in the fall of 2010

Hot Areas of Interest in RBRC Theory [1]

Quark Gluon Plasma:

Viscosity

Hydrodynamics

Equation of State

Quarkyonic Matter

Color Glass Condensate and Glasma

Ridge

Two Particle Correlations

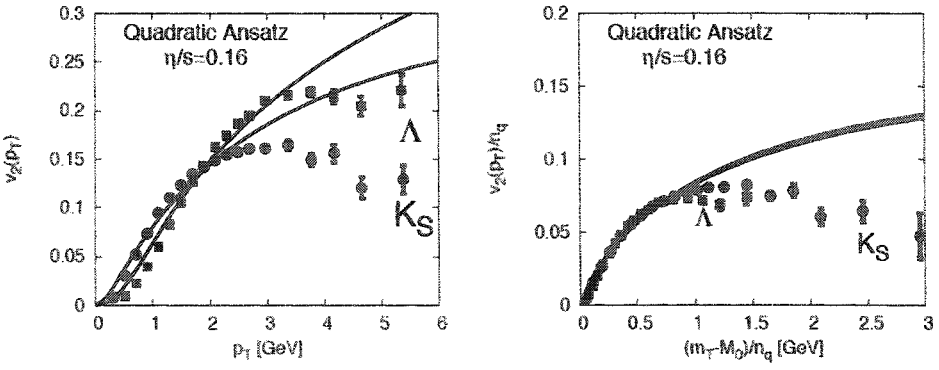
Perturbative QCD and Spin

eRHIC

Astrophysics and Neutrinos

1: Lattice gauge theory included in talk by Taku Izubuchi

V2 Provides Most Convincing Argument for Small Viscosity

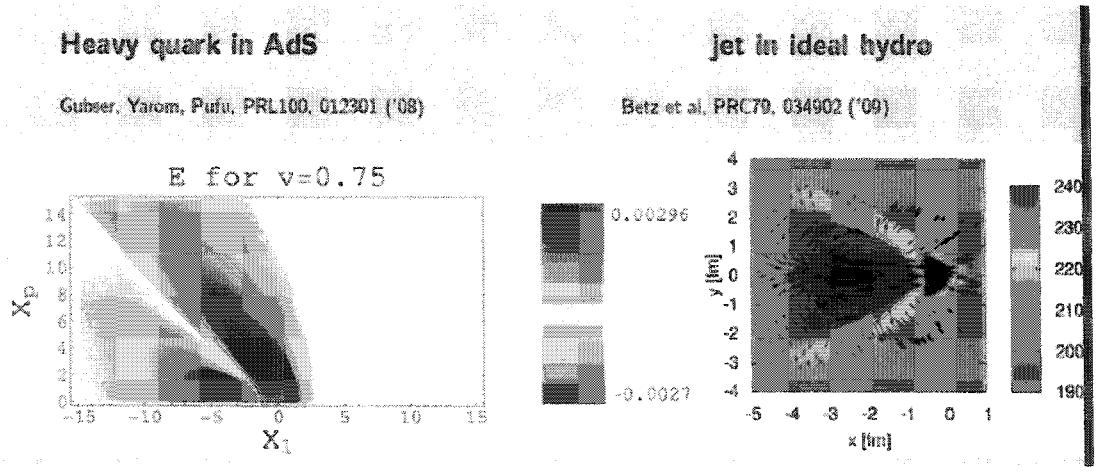


At intermediate pt, hydro breaks down

Quark number scaling (not theoretically justified)

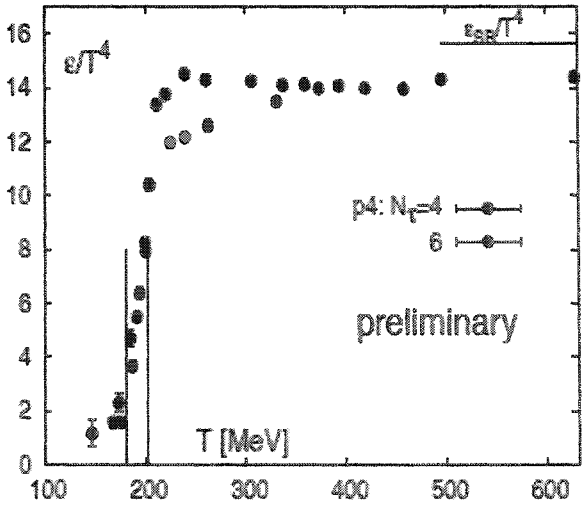
Result of more detailed computation (with theoretical justification, but not same underlying mechanism)

Hydrodynamics and the Mach Cone



Is there really a Mach cone seen in the data?

How to compute properties of a Mach cone?



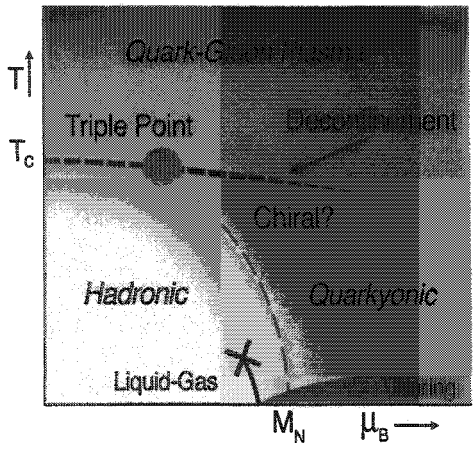
Equation of State for use in Hydrodynamics?

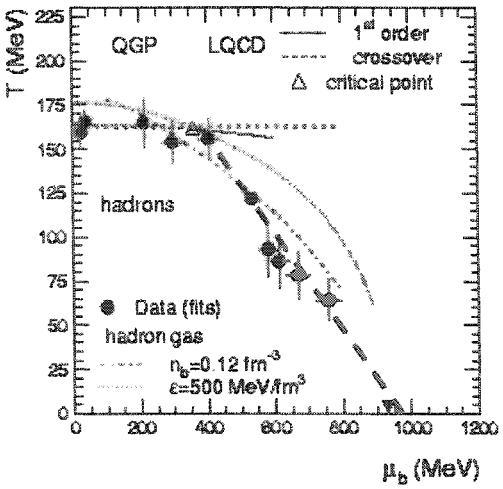
Need results in low density region.

Current data does not generate correct mass scale of resonances?

How to match together an acceptable resonance gas with the lattice, and then be useful for hydro computation

Quarkyonic Matter





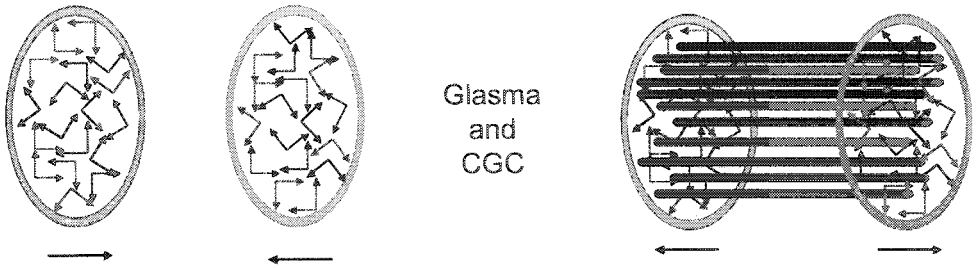
The nature of chiral symmetry breaking in Quarkyonic Matter?

Chiral Spiral?

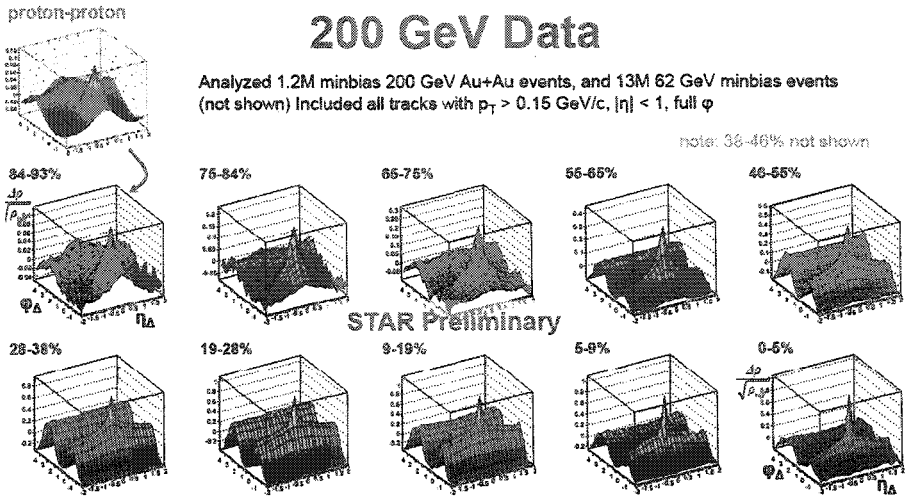
Crystalline?

Triple point?

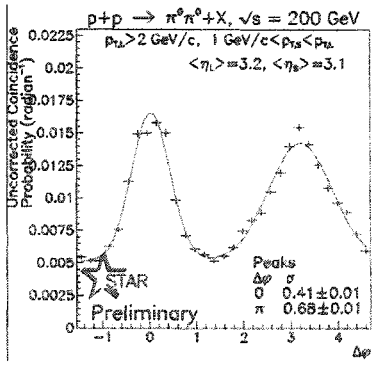
Peaks in abundance ratios?

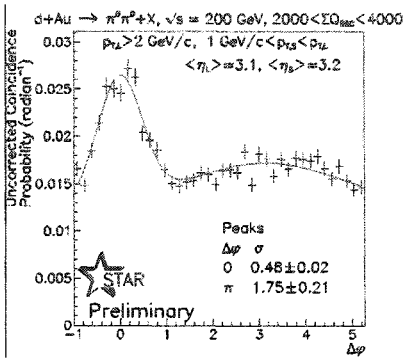


Glasma and CGC



Imaging lines of color flux

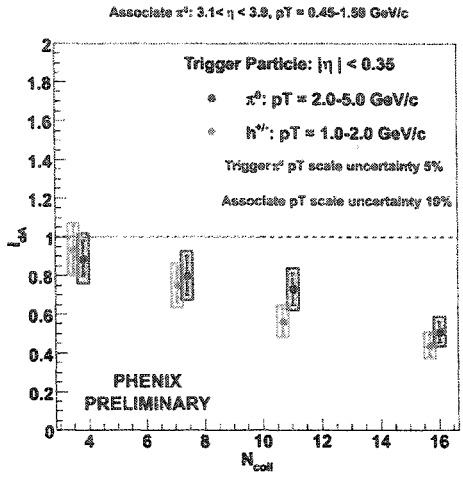




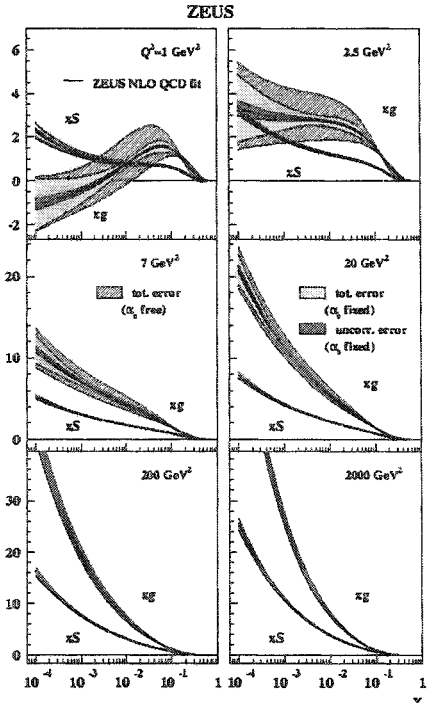
"Jet Quenching" in dA Collisions:

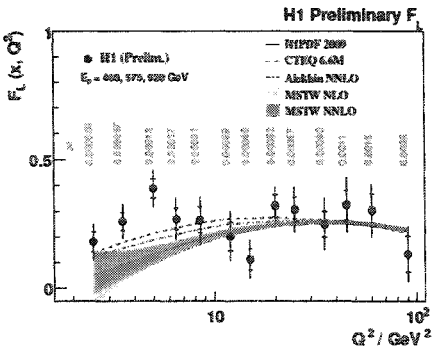
Forward backward angular correlation between forward produced, and forward-central produced particles

Conclusive evidence that the CGC is a media!



Perturbative QCD and Spin





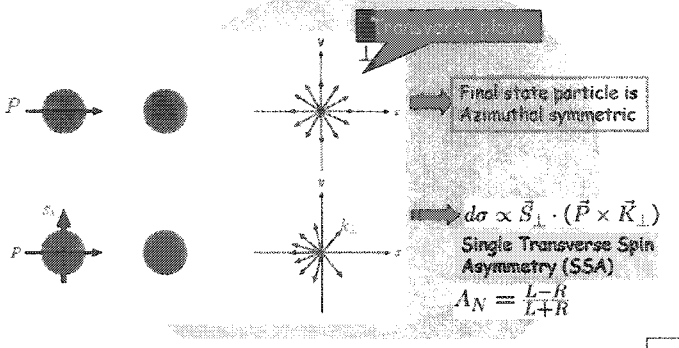
Is there "intrinsic glue" at small x?

Longitudinal structure function directly proportional to gluon

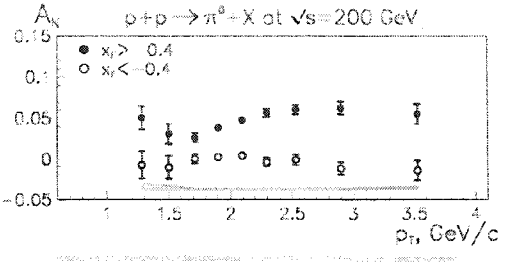
Alternatively, from DGLAP evolution and measurement of F2

Perturbative QCD and Spin

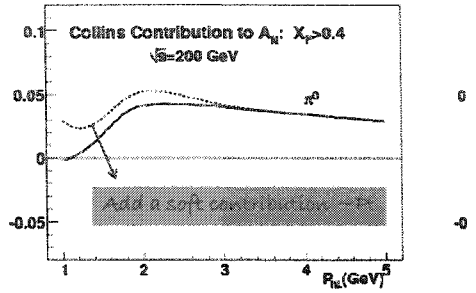
What's Single spin asymmetry?



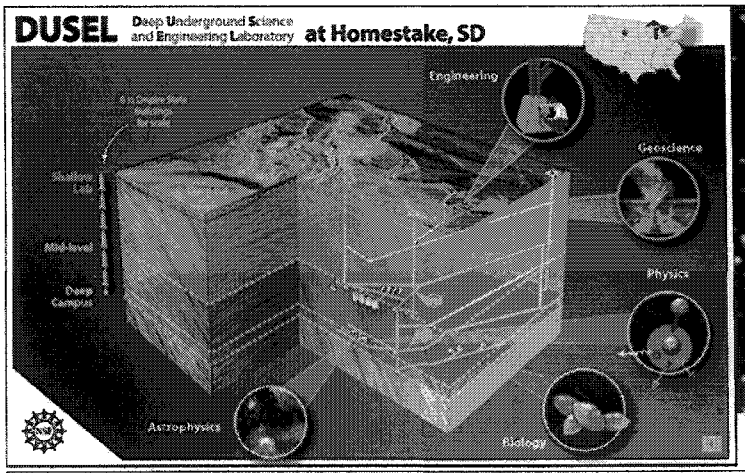
Involves intrinsic quark angular momentum

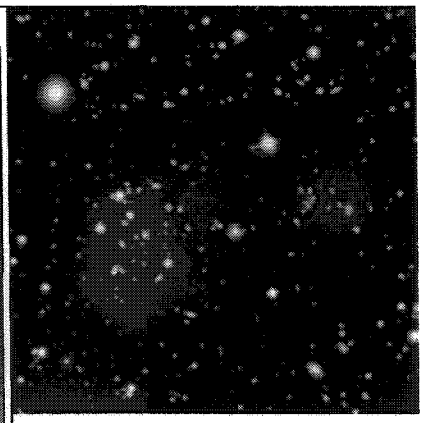


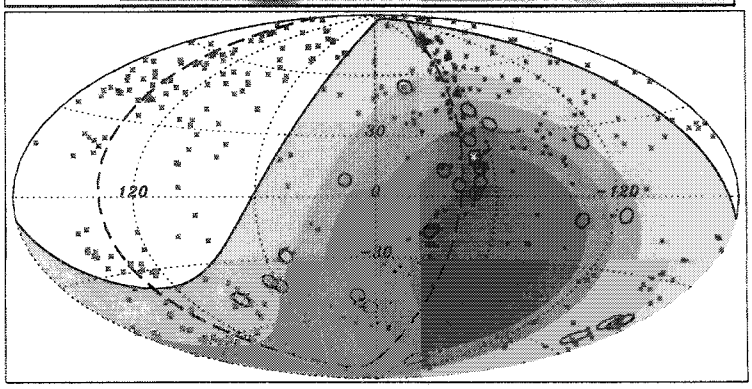
STAR



Yuan-Vogelsang







Neutrinos?

Dark Matter?

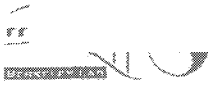
Proton Decay?

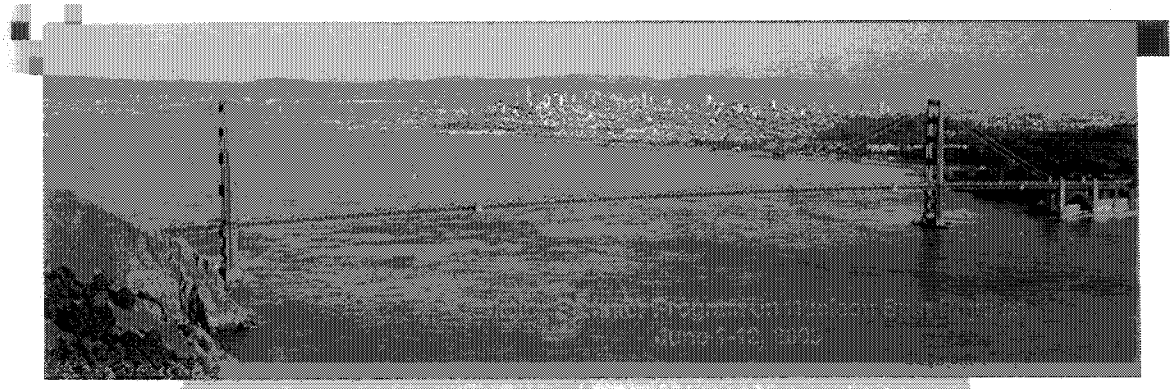
Highest Energy Cosmic Rays?

Feng Yuan
Lawrence Berkeley National Laboratory
RBRC, Brookhaven National Laboratory

Summary of publications in 2009

- **Collins contribution to SSA**
  - Collins Function and the Single Transverse Spin Asymmetry, F.Yuan, J. Zhou, **Phys.Rev.Lett.103:052001,2009**
- **QCD evolution and NLO calculation**
  - QCD Evolution of the Transverse Momentum Dependent Correlations, J. Zhou, F. Yuan, Z. Liang, **Phys. Rev. D79, 114022 (2009)**
  - Next-to-leading Order Calculation of the Single Transverse Spin Asymmetry in the Drell-Yan Process, W. Vogelsang, F. Yuan, **Phys. Rev. D79, 094010 (2009)**
- **Large transverse momentum quark distributions and Drell-Yan**
  - Drell-Yan Lepton Pair Azimuthal Asymmetry in Hadronic Processes, J. Zhou, F.Yuan, Z. Liang, **Phys.Lett.B678:264,2009**
  - Transverse momentum dependent quark distributions and polarized Drell-Yan processes, J. Zhou, F. Yuan, Z. Liang, e-Print: arXiv:0909.2238 [hep-ph]
- **Small-x saturation**
  - Semi-inclusive Deep Inelastic Scattering at Small-x, Cyrille Marquet, Bowen Xiao, Feng Yuan, e-Print: arXiv:0906.1454 [hep-ph]





- Organizers:
  - Ernst Sichtermann (Lawrence Berkeley Lab)
    Werner Vogelsang (Brookhaven Lab)
    Feng Yuan (LBNL/RBRC)
- Participants: ~28
- **We are grateful to RBRC Support!**

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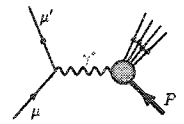
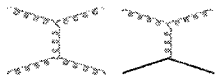
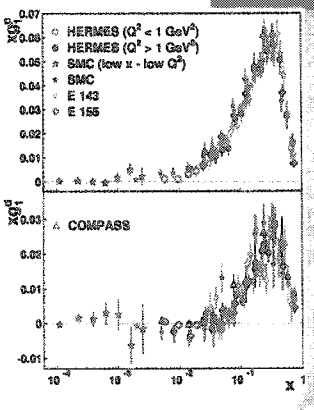
Proton Spin Sum

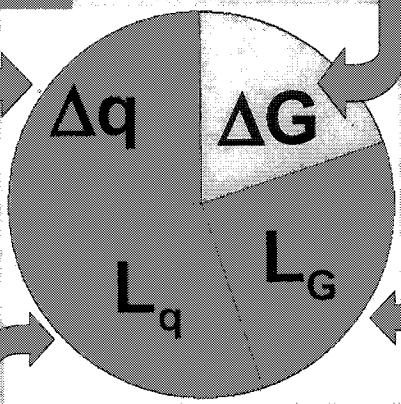


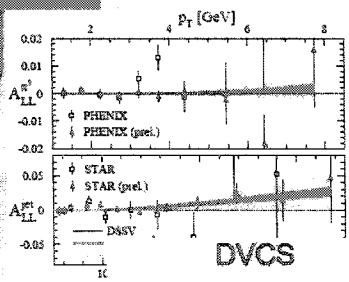
Quark spin ~30%
DIS, and pp coll.

Gluon spin~ 0-70%
RHIC, EIC, . . .

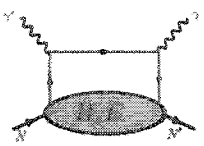




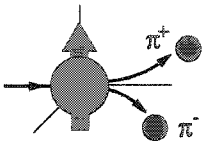




DVCS



Deeply Virtual Compton Scattering, FF,
Transverse spin physics, in DIS, pp coll.



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UNVEIL THE MYSTERIES FOR SingleSpinAsymmetry

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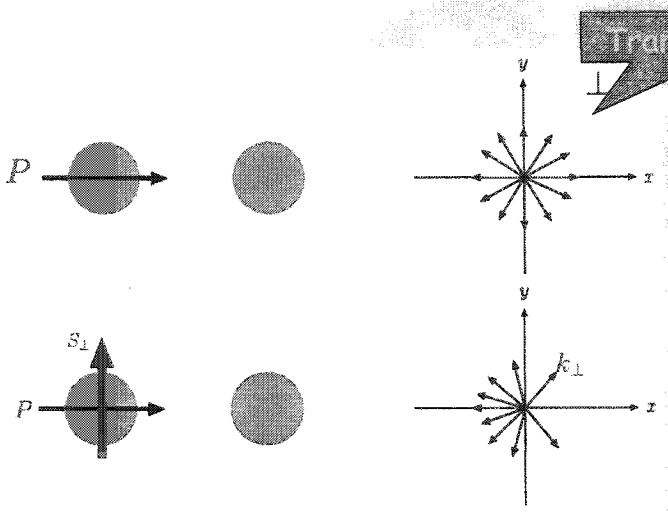
What's Single spin asymmetry?



Final state particle is Azimuthal symmetric

$d\sigma \propto \vec{S}_\perp \cdot (\vec{P} \times \vec{K}_\perp)$

Single Transverse Spin Asymmetry (SSA)

$A_N = \frac{L-R}{L+R}$

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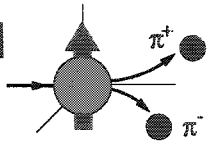
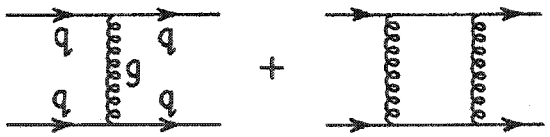
Single Spin Asymmetry

- Motivations:
  - It is hard to understand it in QCD
  - Its strong tied with the quark orbital angular momentum
  - We have beautiful data
  - Nontrivial QCD dynamics, and fundamental test of the factorization, and the universality of Parton Distribution Functions, Fragmentation Functions,...

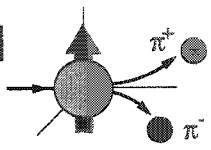


Naïve parton model fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, 1978),

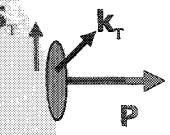


  - It is in general suppressed by $a_s m_q/Q$
    - See also, Ma-Sang, arXive: 0809.1791
- We have to go beyond this naïve picture

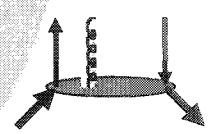


Two mechanisms in QCD

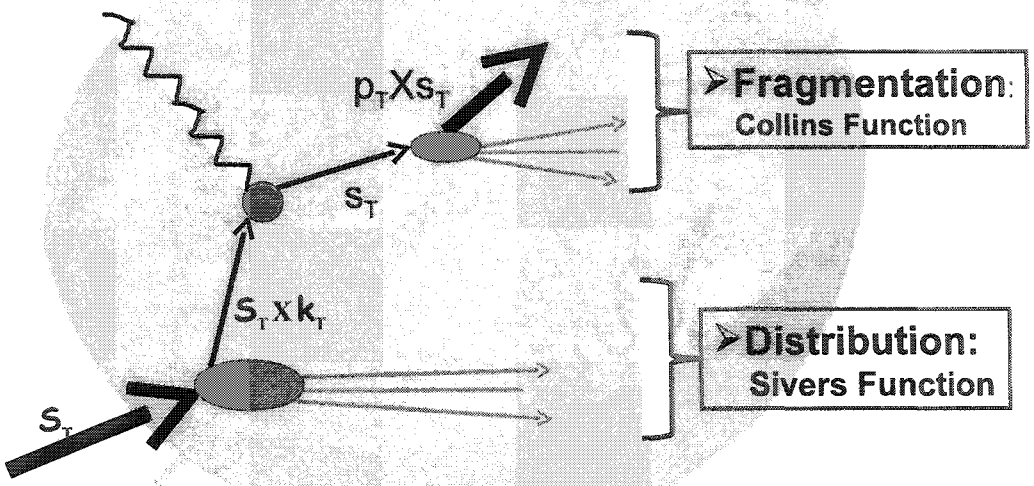
- Spin-dependent transverse momentum dependent (TMD) function
  - Sivers 90 Sivers function ~ $S_T \cdot (P \times k_T)$
  - Colllins 93



- Twist-3 quark-gluon correlations (coll.)
  - Efremov-Teryaev, 82, 84
  - Qiu-Sterman, 91,98



Two contributions, e.g., in DIS



QCD Dynamics
TRANSVERSE MOMENTUM DEPENDENCE

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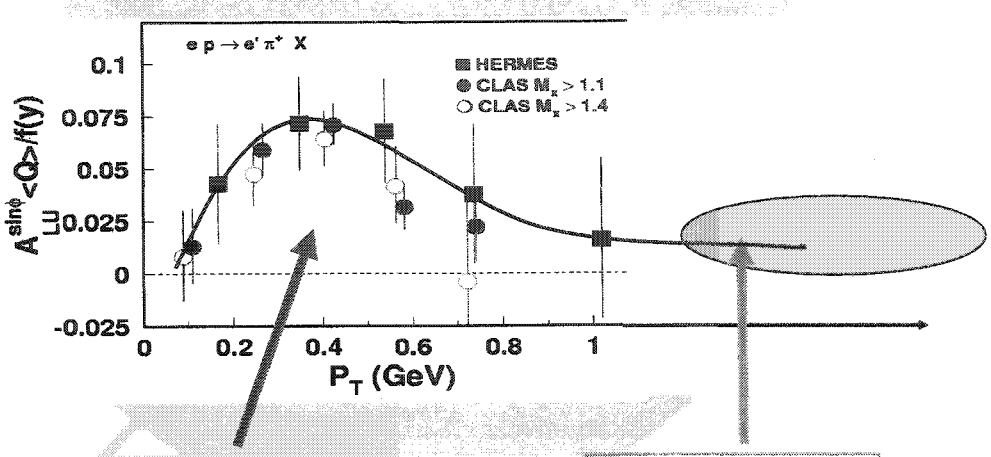
Transition from Perturbative region to Nonperturbative region

- Compare different region of P_T



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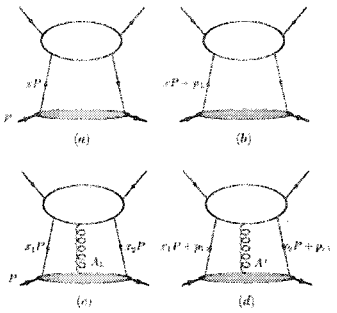
Perturbative tail is calculable

- Transverse momentum dependence

$$q(x,k_\perp)|_{k_\perp \gg \Lambda_{\rm QCD}} = \frac{1}{(k_\perp^2)^n}\int \frac{dx'}{x'} f_i(x') \times \mathcal{H}_{q/i}(x;x')$$

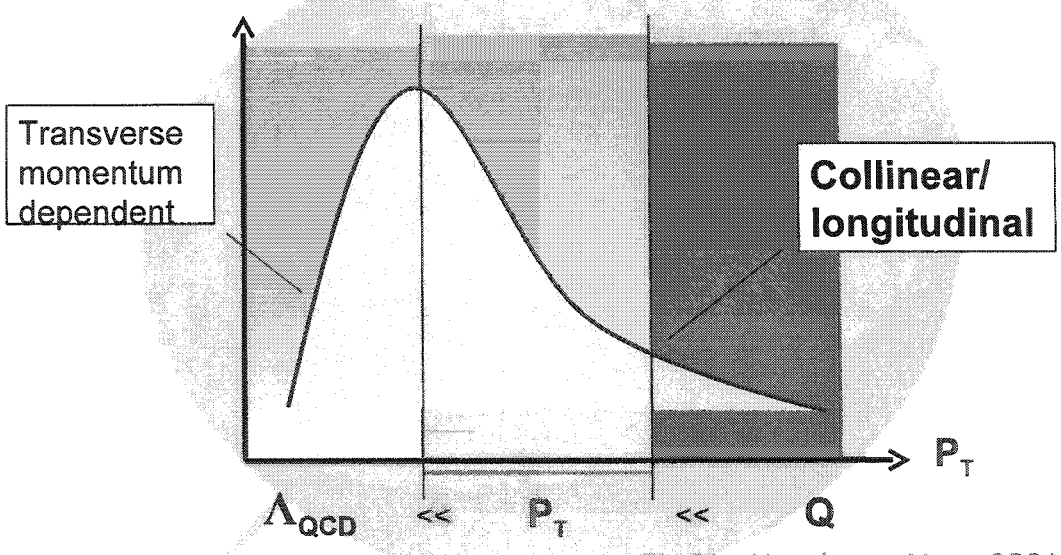
Power counting, Brodsky-Farrar, 1973

Integrated Parton Distributions Twist-three functions



Zhou,Yuan,Liang, 0909.2238

A unified picture (leading pt/Q)



Ji-Qiu-Vogelsang-Yuan, 2006
Yuan-Zhou, 2009

There has been difficulty to reconcile these two pictures

- In the twist-three approach, it has been thought that the soft (hard) gluonic poles contribute to the associated SSA (Koike 02-06)
  - Which however violates the universality found in the TMD approach
  - The soft gluonic matrix elements for the fragmentation have to vanish Meissner-Metz 2008
- To solve this problem, Let's start from the beginning...

Collins function: definition

$$\mathcal{M}_h(z,p_\perp) = \frac{n^+}{z}\int\frac{d\xi^-}{2\pi}\frac{d^2\xi_\perp}{(2\pi)^2}e^{-i(k^+\xi^- - \vec{k}_\perp\cdot\vec{\xi}_\perp)} \times\sum_X\frac{1}{3}\sum_a\langle 0|\mathcal{L}_0\psi_{\beta a}(0)|P_hX\rangle \times\langle P_hX|(\bar{\psi}_{\alpha a}(\xi^-,\vec{\xi}_\perp)\mathcal{L}^\dagger_\xi|0\rangle\ ,$$

$$\mathcal{M}_h = \frac{1}{2}\left[D(z,p_\perp)\,\not{n} + \frac{1}{M}H_1^\perp(z,p_\perp)\sigma^{\mu\nu}p_{\mu\perp}n_\nu\right]$$

- Kt-moment defines a twist-3 fragmentation function

$$\hat{H}(z) = \int d^2p_\perp\frac{p_\perp^2}{2M}H_1^\perp(z,p_\perp) = n^+z^2\int\frac{d\xi^-}{2\pi}e^{ik^+\xi^-}\frac{1}{2}\left\{\mathrm{Tr}\sigma^{\alpha+}\langle 0|\left[iD_\perp^\alpha + \int_{\xi^-}^{+\infty}d\zeta^- gF^{\alpha+}(\zeta^-)\right]\psi(\xi)|P_hX\rangle \times\langle P_hX|\bar{\psi}(0)|0\rangle + h.c.\right\}\ ,$$

which belongs to general twist-three fragmentation

Fragmentation function at twist-three
have been studied in the literature

$$\hat{M}^{\alpha}_{\rho\sigma}(z,z_1) = \int \frac{d\lambda}{2\pi}\frac{d\mu}{2\pi} e^{-i\lambda/z} e^{-i\mu(1/z_1-1/z)} \langle 0|i\overrightarrow{D}^{\alpha}_{\perp}(\mu n)\psi_{\rho}(0)|\pi(P)X\rangle\langle\pi(P)X|\bar{\psi}_{\sigma}(\lambda n)|0\rangle$$
$$+ \int \frac{d\lambda}{2\pi}\frac{d\mu}{2\pi} e^{i\lambda/z} e^{i\mu(1/z_1-1/z)} \langle 0|\psi_{\rho}(\lambda n)|\pi(P)X\rangle\langle\pi(P)X|\bar{\psi}_{\sigma}(0)i\overleftarrow{D}^{\alpha}_{\perp}(\mu n)|0\rangle$$

$$= M\gamma^{\alpha}\not{p}\frac{\hat{E}(z,z_1)}{z}$$

But they have nothing to do with the Collins function!

New construction

Yuan-Zhou, 08

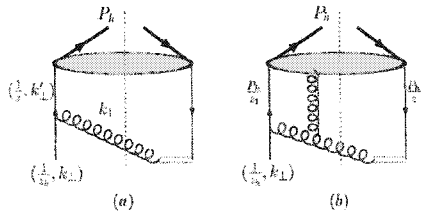
$$\hat{H}_D(z_1,z_2) = n^+ z_1 z_2 \int \frac{d\xi^- d\zeta^-}{(2\pi)^2} e^{ik_2^+\xi^-} e^{ik_B^+\zeta^-} \frac{1}{2}\left\{\mathrm{Tr}\sigma^{\alpha+}\langle 0|iD^{\alpha}_{\perp}(\zeta^-)\psi(\xi^-)|P_hX\rangle\right.$$
$$\left.\times\langle P_hX|\bar{\psi}(0)|0\rangle + h.c.\right\},$$

- H_D is the imaginary while E the real parts of the same twist-three matrix element in the fragmentation

Therefore

- It is H_D not E (previously used in the twist-three calculations) corresponding to the Collins effects
- These two are different from the first principle
  - If time-reversal invariance is valid for the fragmentation function, H_D would vanish
  - However, that's not the case!

Collins function at large kt

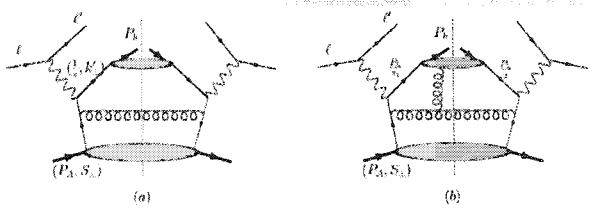


$$H_1^\perp(z_h, p_\perp) = \frac{\alpha_s}{2\pi^2}\frac{2M}{(p_\perp^2)^2}\int\frac{dz}{z}\left[A + \delta(\hat{\xi}-1)\hat{H}(z)C_F\ln\frac{\hat{\zeta}^2}{p_\perp^2}\right]$$

$$A = C_F\left[\left(z^3\frac{\partial}{\partial z}\frac{\hat{H}(z)}{z^2}\right)(-2\hat{\xi}) + \hat{H}(z)\frac{2\hat{\xi}^2}{(1-\hat{\xi})_+}\right] + \int\frac{dz_1}{z_1^2}PV\left(\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\right)\hat{H}_F(z,z_1)$$
$$\times\left[-C_F\frac{2z_h}{z}\left(1+\frac{z_h}{z_1}-\frac{z_h}{z}\right) - \frac{C_A}{2}\frac{2z_h}{z}\frac{zz_1(z+z_1)-z_h(z^2+z_1^2)}{z(z-z_1)(z_1-z_h)}\right].$$

- It is universal
  - The gauge link does not contribute a pole in these diagrams
  - The final result does not depend on the gauge link direction
  - This is different from the Sivers function, which is process dependent

Collins contribution in SIDIS



$$\left.\frac{d\sigma(S_\perp)}{dx_B dy dz_h d^2\vec{P}_{h\perp}}\right|^{V_4+V_9}_{P_{h\perp}\ll Q} = \frac{4\pi\alpha_{em}^2 s}{Q^4}x_B(1-y)\sin(\phi_h+\phi_s)\frac{1}{z_h^2}\frac{\alpha_s}{2\pi^2}\frac{1}{|\vec{q}_\perp|^3}$$
$$\int\frac{dxdz}{xz}h_1(x)\left\{A\delta(\xi-1)+B\delta(\hat{\xi}-1)\right\},$$
$$B = C_F\hat{H}(z_h)\left[\frac{2\xi}{(1-\xi)_+}+2\delta(\xi-1)\ln\frac{Q^2}{\vec{q}_\perp^{\,2}}\right]$$

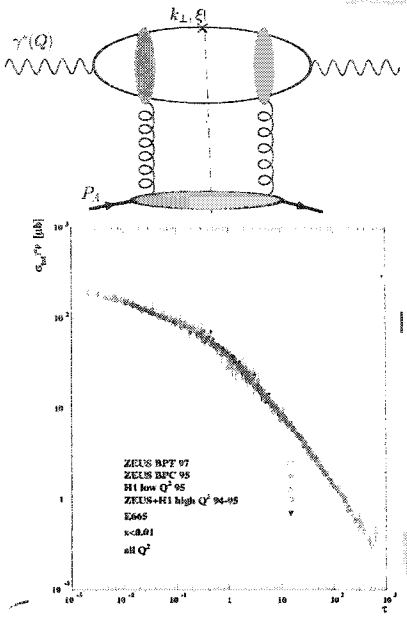
- This result can be reproduced by the TMD factorization with Collins function calculated, the quark transversity distribution
- This demonstrate that the TMD and collinear approaches are consistent in the intermediate transverse momentum region for the Collins effects

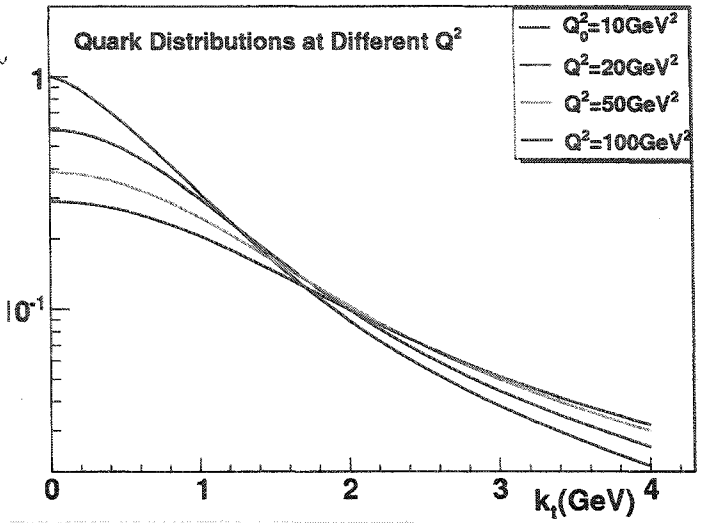
Summary

- We have identified the correspondent collinear twist-three fragmentation function for the Collins effects
- The Collins function calculated from this twist-three function is universal, does not dependent on the gauge link direction
- We have shown that the TMD and collinear approaches are consistent in the intermediate transverse momentum region.

Back-Up

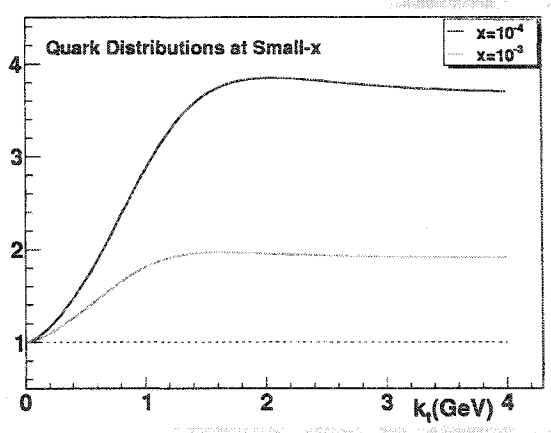
DIS can probe the quark distribution at small-x

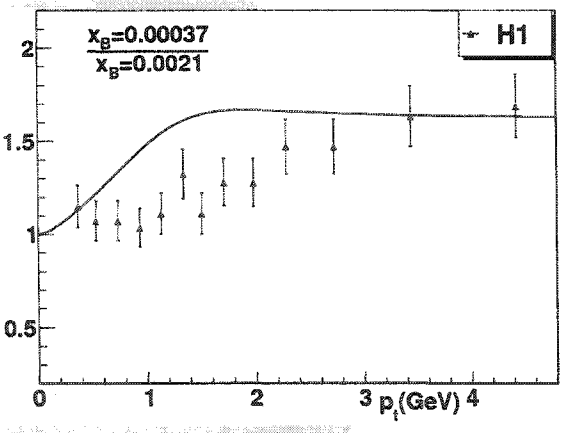




Marquet, Xiao, Yuan

Interesting ratios





- Quark distribution can be directly probed in DIS process
- These ratios shall provide crucial information about small-x physics

These physics together with many other interesting predictions from small-x saturation physics shall be rigorously studied in a future EIC collider

Supernova neutrinos

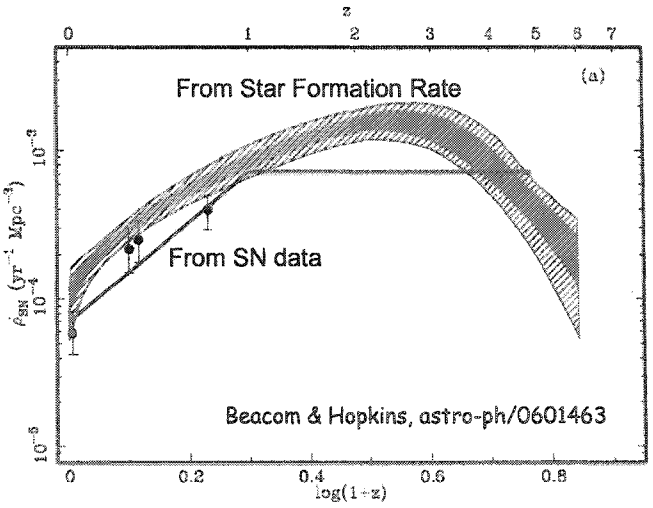
Cecilia Lunardini
Arizona State University
And RIKEN BNL Research Center

RBRC annual review, BNL, October 2009

Diffuse neutrinos from all SNe

- Integrated over whole universe
  - Alternative to a galactic supernova!
  - Already constrained by SuperKamiokande
- Scoping of next generation detectors (DUSEL)
  - done: SuperK limits, anti-nue flux in water detectors, neutrino oscillations
  - New: nue flux in Argon detectors, new SN types

Cosmological rate of SNe



- $R_{SN}(z) \sim R_{SN}(0)\ (1+z)^3$, $z<1$
  - Normalization uncertain; here $R_{SN}(0) = 10^{-4}$ Mpc^{-3} yr^{-1}

Neutrino production and propagation

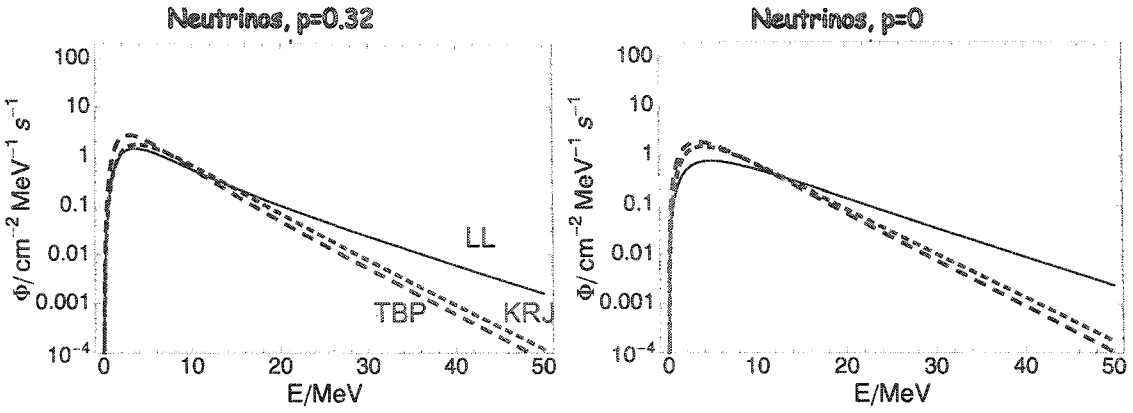
- *Fluxes at production*: numerical models
  - Lawrence Livermore
  - Thompson, Burrows, Pinto (Arizona)
  - Keil, Raffelt, Janka (Garching)

- *oscillations* depend on matter content, θ_{13} and sign of $\Delta m^2_{31} > 0$ ("hierarchy")
  - Permutation : p= 0 - 0.32 , $\overline{p}$ = 0 - 0.68

Chakraborty et al., hep-ph/08053131

DSNnF spectrum

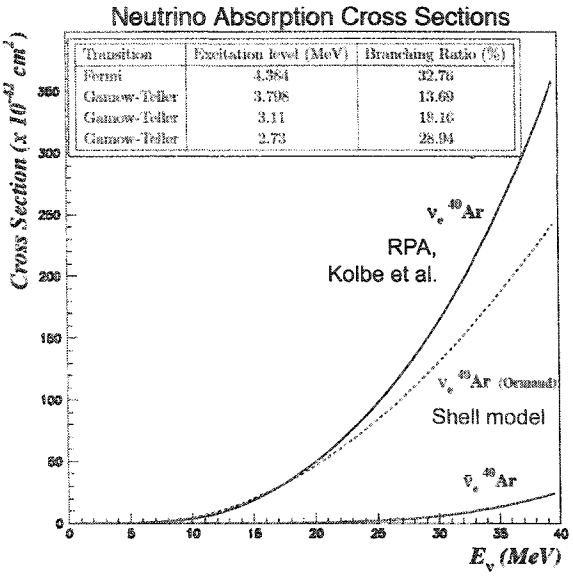
Exponential decay with E



C.L., in preparation

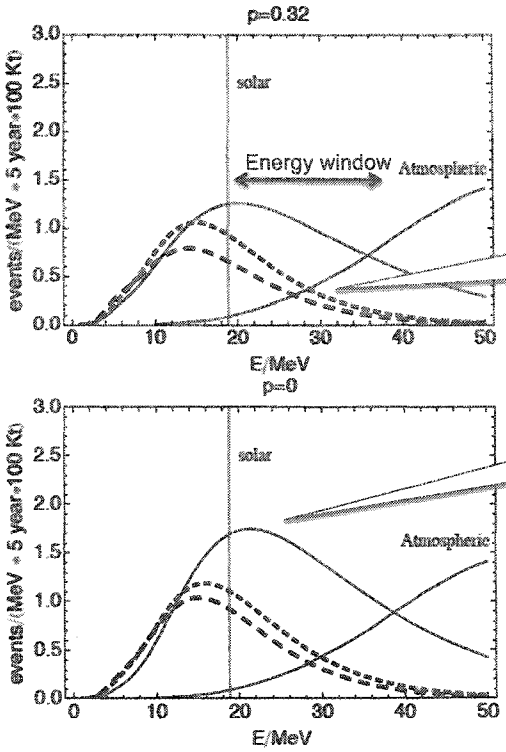
nue absorption on ^{40}Ar:

- Higher multipoles important in the energy window
- Energy/angle distribution of e^-?
  - nue energy used in plots of events



Bueno, Gil Botella and Rubbia, hep-ph/0307222

LAr, 100 kt



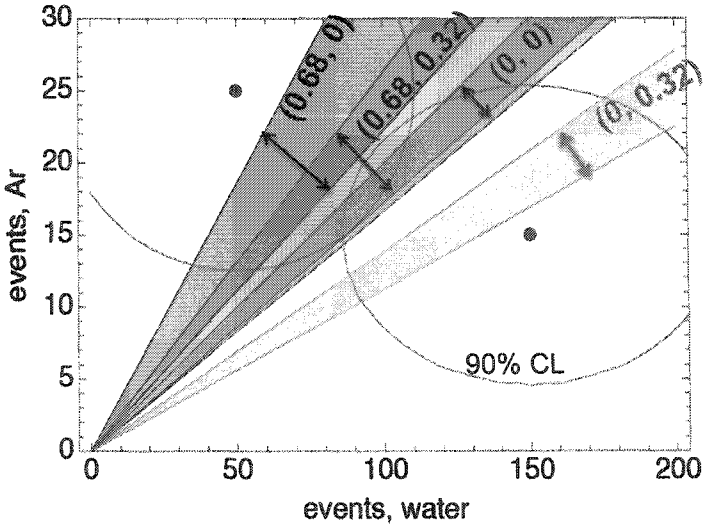
Background/signal ~ 0.2-0.3

Bulk of events may be captured!

~6 - 28 events in 5 years
Scaling?

C.L., in preparation

Probing oscillation scenarios



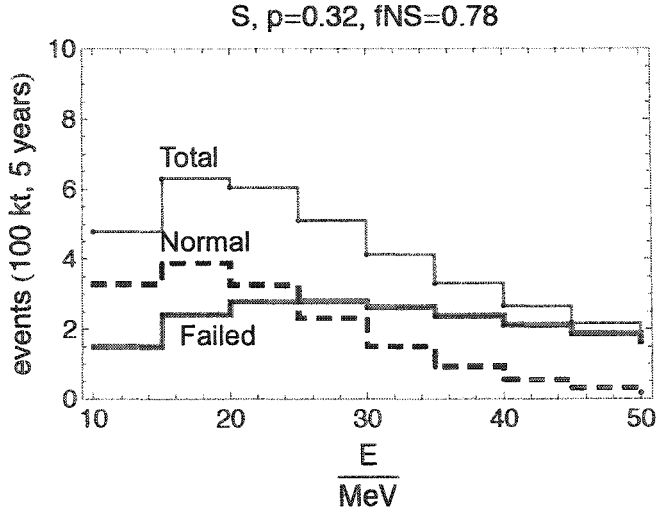
- Combinations ($\bar{p}$,p) distinguished by *joint* water + Ar analysis → test hierarchy and θ_{13}

New SN types: failed SNe

- M > 40 Msun, 9-22% of all collapses
- *Direct* BH-forming collapse (no explosion):
  - *Higher energies:* $E_0 \sim 20 - 24$ *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)

- Bulk of events from failed SNe captured
- Failed SN at least a 10% effect in energy window



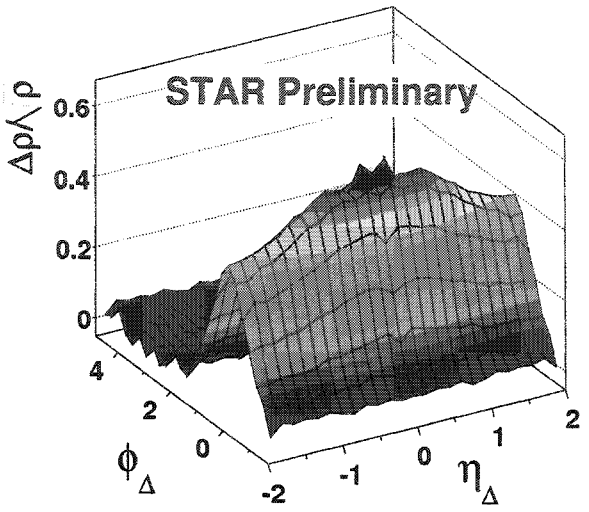
C.L., Phys. Rev. Lett., 2009, J. Keehn & C.L., in preparation

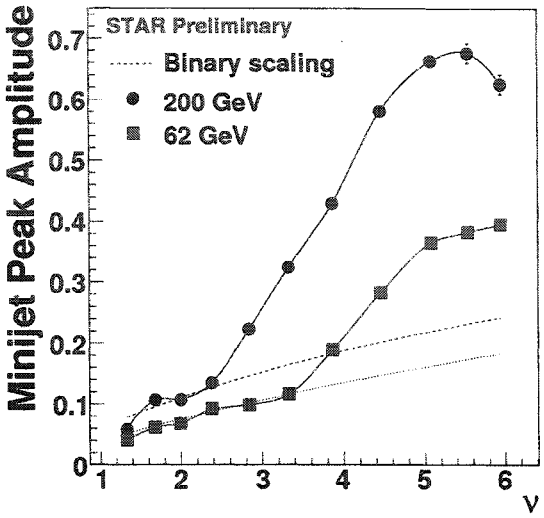
Branching out...

- More supernova diversity?
- Energy window: what else is there?
  - Other neutrino sources (BH, type Ia, ...)
  - new physics (nu from relic decay..)
- Supernova-GRB connection: high energy counterpart?

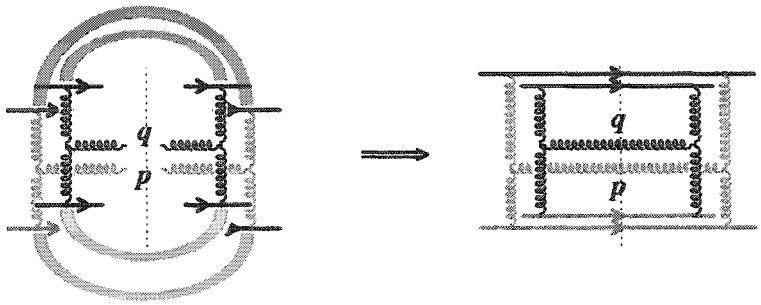
The GGC and the Ridge

Adrian Dumitru
RIKEN-BNL and Baruch College

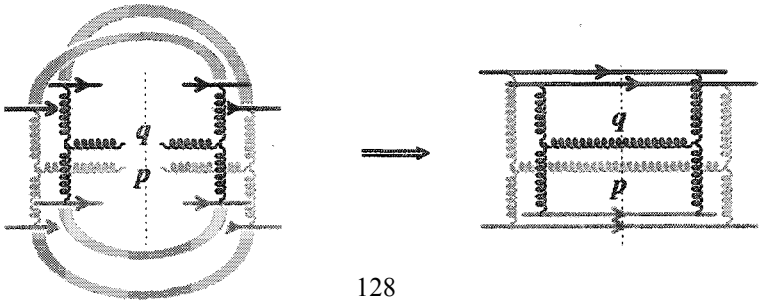




Independent production of two gluons: $\langle |A_\mu(\mathbf{p})|^2 \rangle \langle |A_\nu(\mathbf{q})|^2 \rangle$

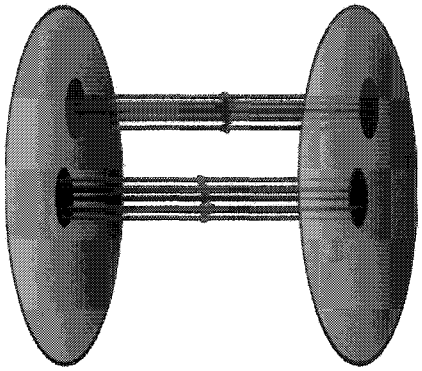


Genuine two-particle production graphs:



$$C(\mathbf{p},\mathbf{q}) \sim \frac{\pi R^2}{(2\pi)^6}\frac{Q_s^8}{g^4}\frac{\pi N^2(N^2-1)}{p_\perp^4 q_\perp^4}\int_{Q_s^2}^{\infty}\frac{dk_\perp^2}{k_\perp^4}$$

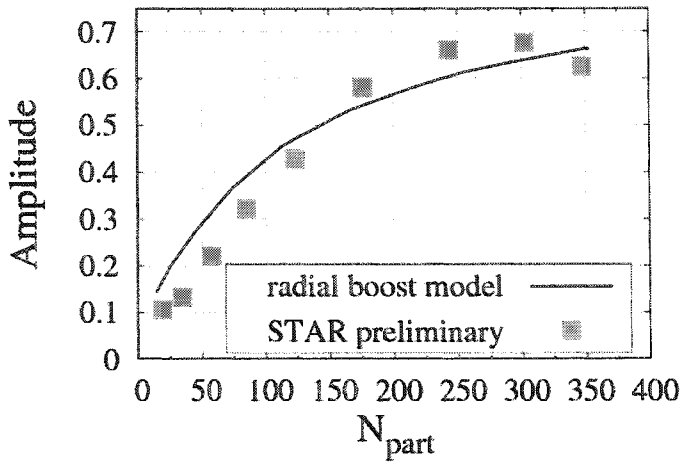
$$= \frac{\pi R^2}{(2\pi)^6}\frac{Q_s^8}{g^4 Q_s^2}\frac{\pi N^2(N^2-1)}{p_\perp^4 q_\perp^4}$$

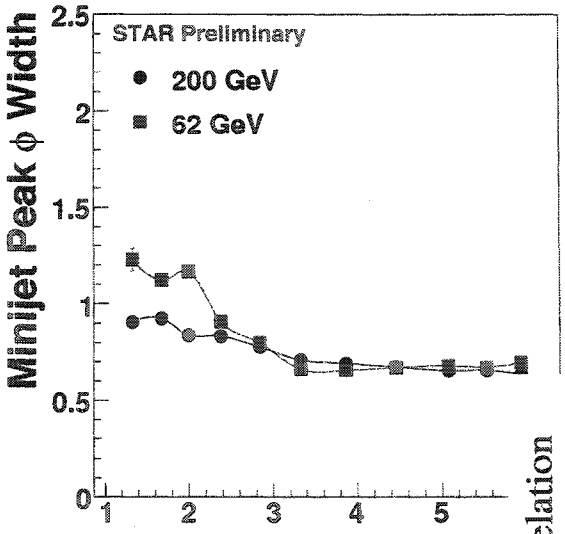


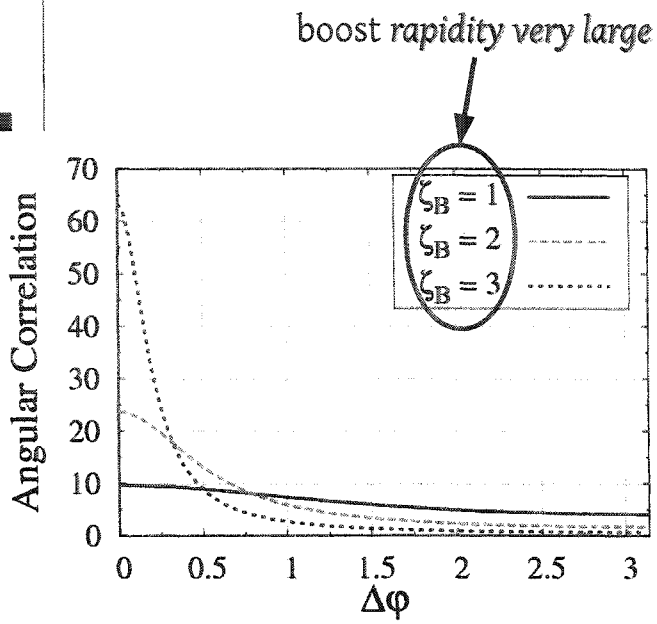
Distribution after radial boost (flow):

$$\sim K_R \frac{1}{\alpha_s(Q_s)}\frac{\cosh\zeta_B}{\cosh^2\zeta_B - \sinh^2\zeta_B\cos^2\Delta\Phi/2}$$

Amplitude: $\mathcal{A} = K_R\dfrac{\gamma_B - \gamma_B^{-1}}{\alpha_s(Q_s)}$



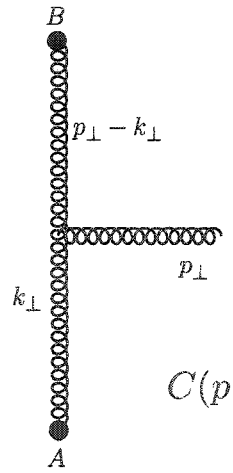




Main features:

- ✔ correlation flat in rapidity
- ✔ particles produced at same $x_\perp$
- ✔ ridge structure independent of transv. momentum
- ✔ radial boost reproduces amplitude

- ✗ angular width too large
- ✗ no evolution towards sources on the light-cone
- ✗ kinematics $x=x(y,p_\perp)$
- ✗ $k_\perp$ dependent uGD $\Phi(x,k_\perp)$



$$\mathcal{M}^a_\lambda = p^2 A^{\mu,a}(p)\,\epsilon^\lambda_\mu(p)$$

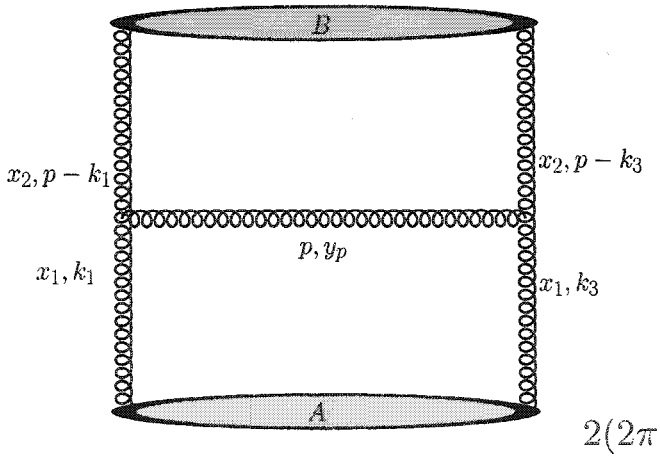
$$p^2 A^{\mu,a}(p) = -if^{abc}\frac{g^3}{2}\int\frac{d^2k_\perp}{(2\pi)^2}L^\mu(p_\perp,k_\perp)\frac{\rho^a_A(k_\perp)}{k_\perp^2}\frac{\rho^b_B(p_\perp-k_\perp)}{(p_\perp-k_\perp)^2}$$

$$C(p,q)\sim\sum_{a,a';\lambda,\lambda'}\left(\left\langle|\mathcal{M}^{aa'}_{\lambda\lambda'}(p,q)|^2\right\rangle-\left\langle|\mathcal{M}^a_\lambda(p)|^2\right\rangle\left\langle|\mathcal{M}^{a'}_{\lambda'}(q)|^2\right\rangle\right)$$

MV model: $\langle\rho^{*a}(k)\,\rho^b(q)\rangle(x)\sim\mu^2\delta^{ab}\,(2\pi)^2\delta(k-q)$

here: $\langle\rho^{*a}(k)\,\rho^b(q)\rangle(x)\sim\dfrac{1}{g^2}\delta^{ab}\,(2\pi)^2\delta(k-q)\,\Phi(x,k^2)$

unintegr. gluon distrib.

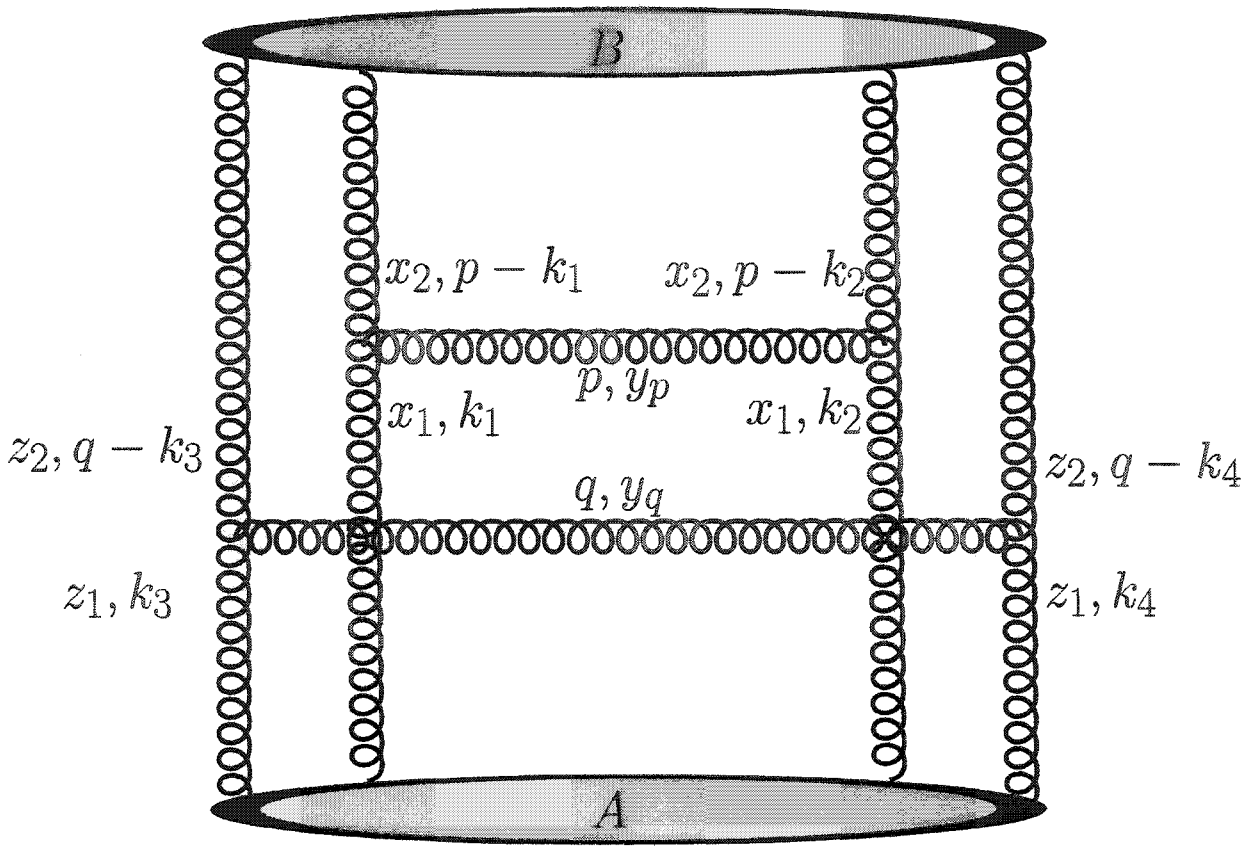


$$x_{1,2}=\frac{p_\perp}{\sqrt{s}}\,e^{\pm y}$$

$$2(2\pi)^3E\frac{dN}{d^3p}=\sum_{a;\lambda}\left\langle|\mathcal{M}^a_\lambda(p)|^2\right\rangle$$

$$\frac{dN}{d^2p_\perp dy}=\frac{4\alpha_s}{p_\perp^2}\frac{N}{N^2-1}\int d^2r_\perp\int^{p_\perp}d^2k_\perp\frac{\Phi_A(x_1,k_\perp^2)}{k_\perp^2}\frac{\Phi_B(x_2,(p_\perp-k_\perp)^2)}{(p_\perp-k_\perp)^2}$$

single-inclusive cross section



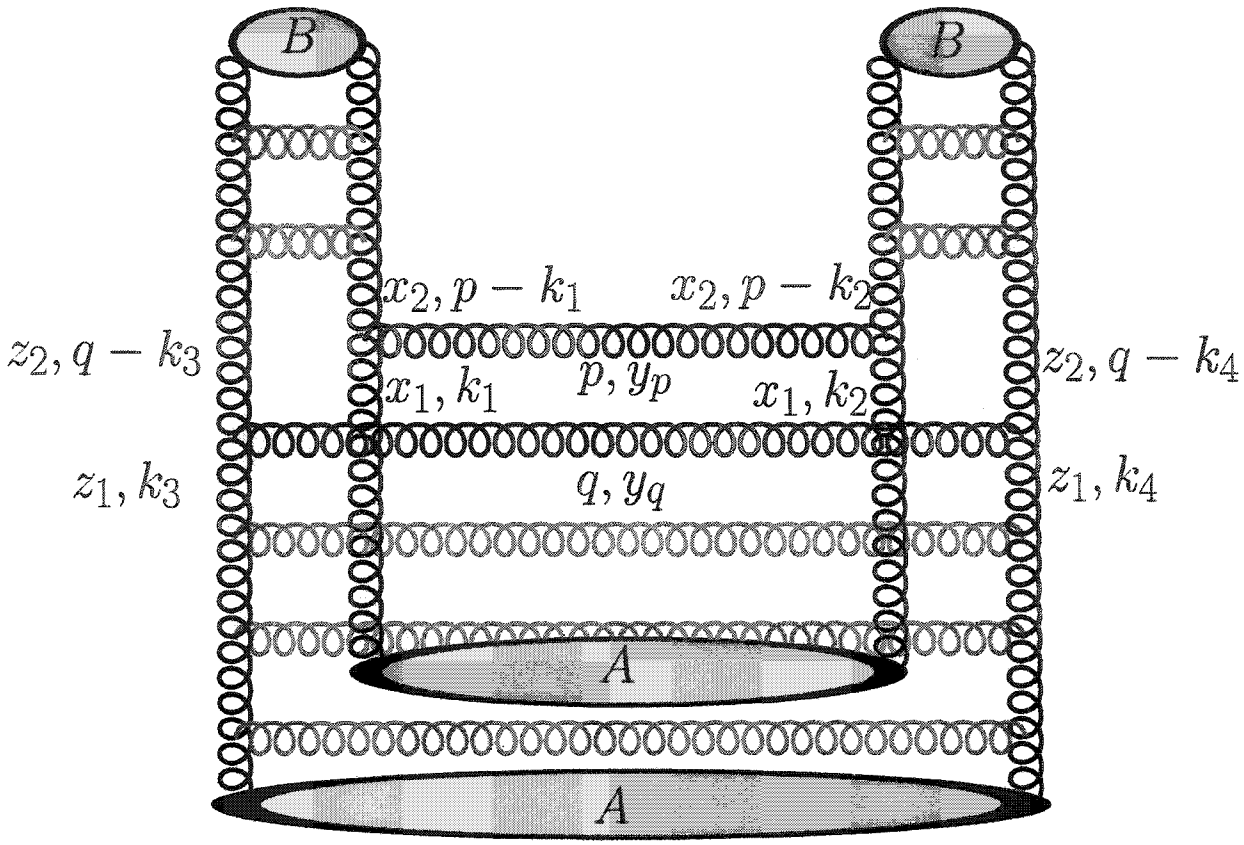
$$C(p_\perp, q_\perp) =$$

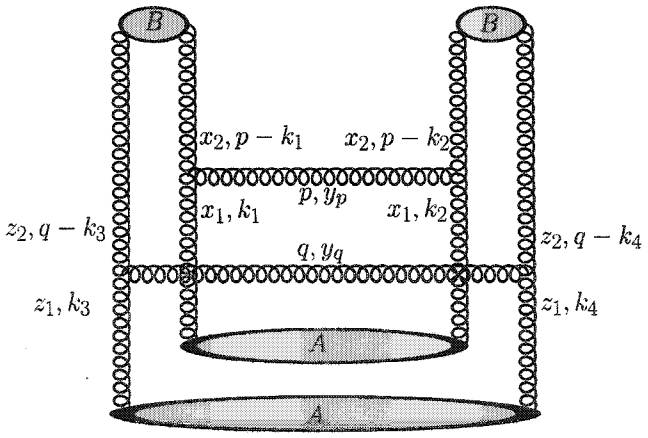
$$\frac{g^{12}}{64(2\pi)^6}\left(f_{abc}f_{a'\bar{b}\bar{c}}f_{a\hat{b}\hat{c}}f_{a'\tilde{b}\tilde{c}}\right)\int\prod_{i=1}^{4}\frac{d^2k_{i\perp}}{(2\pi)^2k_{i\perp}^2}$$

$$\times\frac{L_\mu(p_\perp,k_{1\perp})L^\mu(p_\perp,k_{2\perp})}{(p_\perp-k_{1\perp})^2(p_\perp-k_{2\perp})^2}\,\frac{L_\nu(q_\perp,k_{3\perp})L^\nu(q_\perp,k_{4\perp})}{(q_\perp-k_{3\perp})^2(q_\perp-k_{4\perp})^2}$$

$$\times\left\langle\rho^{*\hat{b}}{}_1(k_{2\perp})\rho^{*\tilde{b}}{}_1(k_{4\perp})\rho_1{}^{b}(k_{1\perp})\rho_1{}^{\bar{b}}(k_{3\perp})\right\rangle$$

$$\times\left\langle\rho^{*\hat{c}}{}_2(p_\perp-k_{2\perp})\rho^{*\tilde{c}}{}_2(q_\perp-k_{4\perp})\rho_2{}^{c}(p_\perp-k_{1\perp})\rho_2{}^{\bar{c}}(q_\perp-k_{3\perp})\right\rangle$$



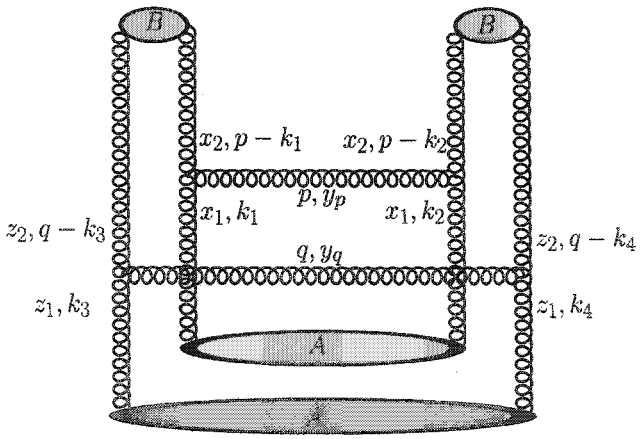


$$C(p,q) \sim \frac{g^{12}}{64(2\pi)^6} \int \prod_{i=1}^{4} \frac{d^2k_{i\perp}}{(2\pi)^2 k_{i\perp}^2}$$

$$\times \frac{L_\mu(p_\perp, k_{1\perp}) L^\mu(p_\perp, k_{2\perp})}{(p_\perp - k_{1\perp})^2 (p_\perp - k_{2\perp})^2} \frac{L_\nu(q_\perp, k_{3\perp}) L^\nu(q_\perp, k_{4\perp})}{(q_\perp - k_{3\perp})^2 (q_\perp - k_{4\perp})^2}$$

$$\times \langle {\rho^*}_1(k_{2\perp}) \rho_1(k_{1\perp}) \rangle \langle {\rho^*}_1(k_{4\perp}) \rho_1(k_{3\perp}) \rangle$$

$$\times \langle {\rho^*}_2(p_\perp - k_{2\perp}) {\rho^*}_2(q_\perp - k_{4\perp}) \rangle \langle \rho_2(p_\perp - k_{1\perp}) \rho_2(q_\perp - k_{3\perp}) \rangle$$



$$C(p,q) = 16(2\pi)^2\alpha_s^2\, S_\perp \frac{N^2}{(N^2-1)^3}\frac{1}{p_\perp^2}\frac{1}{q_\perp^2} \int d^2k_\perp \frac{\Phi_A(x_1,(p_\perp+k_\perp)^2)}{(p_\perp+k_\perp)^2}\frac{\Phi_A(x_1,(q_\perp-k_\perp)^2)}{(q_\perp-k_\perp)^2}\frac{\Phi_B^2(x_2,k_\perp^2)}{k_\perp^4}$$

Sum of all 4 dominant diagrams ($p \neq \pm q$, $p,q \gg Q_s$)

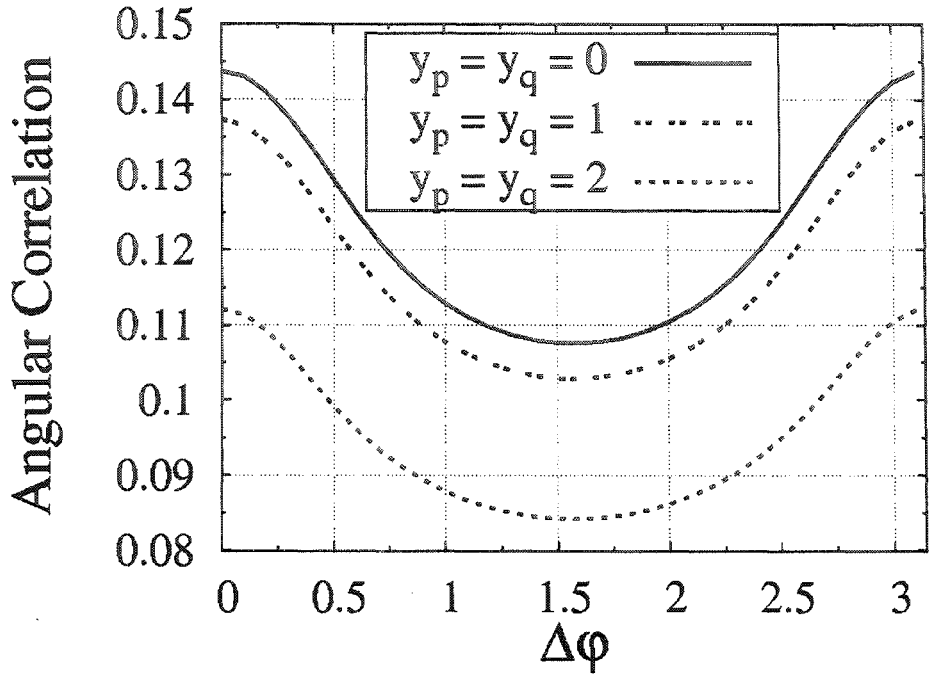
$$C(p,q) = 16(2\pi)^2\alpha_s^2\, S_\perp \frac{N^2}{(N^2-1)^3}\frac{1}{p_\perp^2}\frac{1}{q_\perp^2} \int^{p_\perp,q_\perp} d^2k$$
$$\left\{\frac{\Phi_A^2(x_1,k^2)}{k^4}\left[\frac{\Phi_B(x_2,(p+k)^2)}{(p+k)^2}+\frac{\Phi_B(x_2,(p-k)^2)}{(p-k)^2}\right]\frac{\Phi_B(x_2,(q-k)^2)}{(q-k)^2}\right\}$$
$$+\left\{\frac{\Phi_B^2(x_2,k^2)}{k^4}\left[\frac{\Phi_A(x_1,(q+k)^2)}{(q+k)^2}+\frac{\Phi_A(x_1,(q-k)^2)}{(q-k)^2}\right]\frac{\Phi_A(x_1,(p-k)^2)}{(p-k)^2}\right\}$$

for a first run, used $\Phi(x,k_\perp^2) \sim \dfrac{1}{\alpha_s}\dfrac{k_\perp^2 Q_s^2(x)}{\max(k_\perp^2, Q_s^2(x))}$

central Au+Au: $Q_s^2(x) = 2\ \mathrm{GeV}^2\left(\dfrac{0.01}{x}\right)^\lambda$

Numerical result:

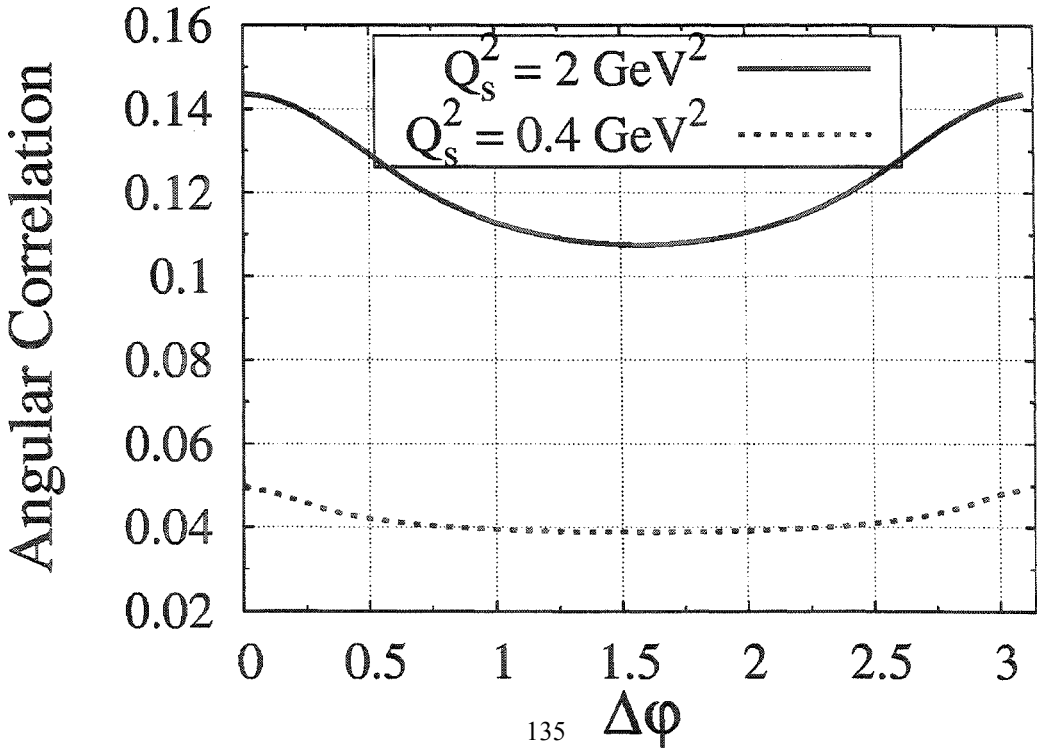
$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}}(\Delta\phi) = C(p,q)\frac{dN/dy}{dN/dy_p d^2p_\perp \; dN/dy_q d^2q_\perp}$$



$p_\perp$ = 5 GeV
$q_\perp$ = 4 GeV

AA versus pp :

$p_\perp$ = 5 GeV, $y_p = y_q = 0$
$q_\perp$ = 4 GeV



Summary:

- (partial) collimation in φ already at production
- effect disappears for small Qs

Two topics related to viscous hydrodynamics

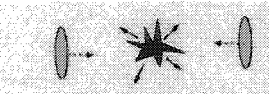
Denes Molnar
RIKEN/BNL Research Center & Purdue University

for RBRC Annual Review

Oct 21-22, 2009, RIKEN BNL Research Center, Upton, NY

- conical flow - arXiv:0908.0299
- viscous freezeout - work in progress

Thermalization at RHIC



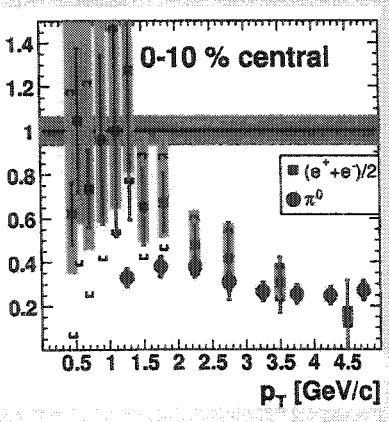
efficient conversion of spatial eccentricity to momentum anisotropy

"elliptic flow"

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

very opaque - large energy loss, even for heavy quarks

$$R_{AA} = \frac{measured\ yield}{expected\ yield\ for\ dilute\ system}$$



Main dynamical frameworks

• causal relativistic hydrodynamics Israel, Stewart; ... Muronga, Rischke, Teaney et al, Romatschke et al, Heinz et al, DM & Huovinen

$$\partial_\mu T^{\mu\nu} = 0 \qquad (\mu_B \to 0)$$

$$T^{\mu\nu} = (e+p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu}$$

$$\dot{\pi}^{\mu\nu} = F^{\mu\nu}(e,u,\pi,\Pi) \ , \qquad \dot{\Pi} = G(e,u,\pi,\Pi)$$

e.g. Israel-Stewart theory

• covariant transport Israel, de Groot,... Zhang, Gyulassy, DM, Pratt, Xu, Greiner...

$$p^\mu \partial_\mu f = C_{2\to 2}[f] + C_{2\leftrightarrow 3}[f] + \cdots$$

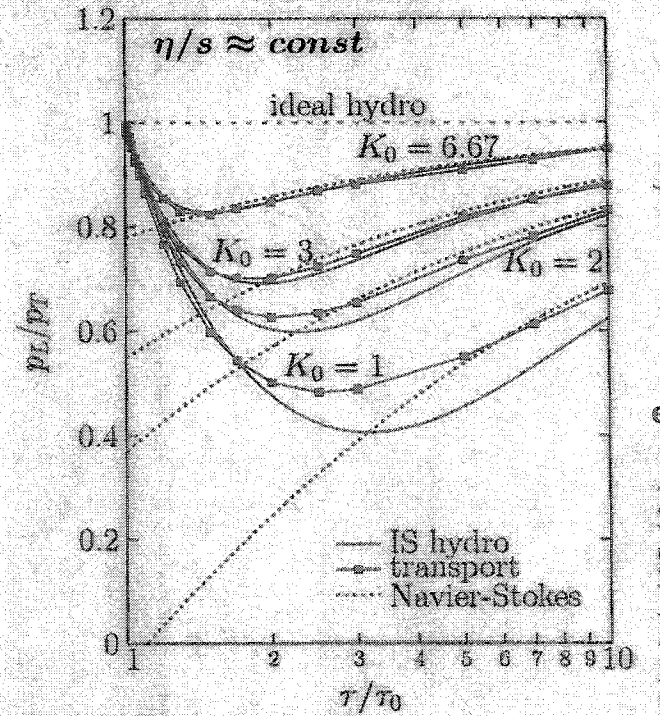
fully causal and stable

near hydrodynamic limit, transport coefficients and relaxation times:

$$\eta \approx 1.2T/\sigma_{tr}, \qquad \tau_\pi \approx 1.2\lambda_{tr}$$

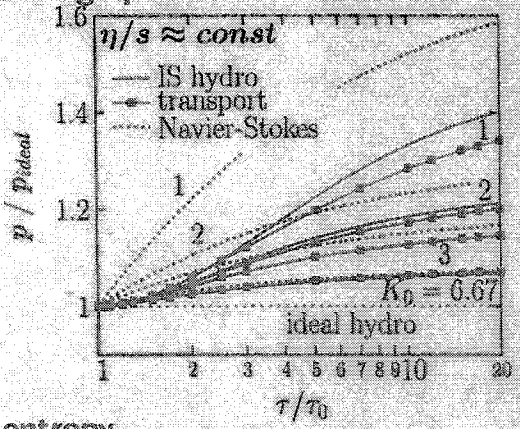
Validity of Israel-Stewart hydro (0+1D Bjorken)

pressure anisotropy T_{zz}/T_{xx}

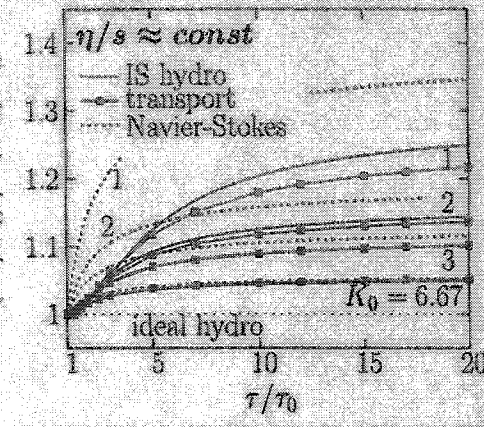


IS is 10% accurate when $K_0 \equiv \tau_0/\lambda_{tr,0} \gtrsim 2$

average pressure Huovinen & DM, PRC79



entropy



In terms of viscosity

$$K_0 \approx \frac{T_0 \tau_0}{5} \frac{s_0}{\eta_{s,0}} \approx 12.8 \times \left(\frac{T_0}{1\ \mathrm{GeV}}\right)\left(\frac{\tau_0}{1\ \mathrm{fm}}\right)\left(\frac{1/(4\pi)}{\eta_0/s_0}\right) \qquad (1)$$

for typical RHIC hydro initconds $T_0\tau_0 \sim 1$, therefore

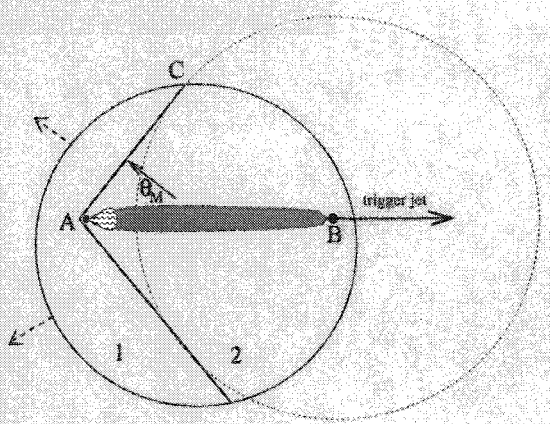
$$K_0 \gtrsim 2-3 \quad \Rightarrow \quad \frac{\eta}{s} \lesssim \frac{1-2}{4\pi} \qquad (2)$$

I.e., shear viscosity cannot be many times more than the conjectured bound, for IS hydro to be applicable.

When IS hydro is accurate, dissipative corrections to pressure and entropy do not exceed 20% significantly (a necessary condition).

IF matter is really equilibrated, natural to expect shock phenomena

Stocker et al, Rischke, Csernai, ... Shuryak, Cassalderrey-Solana, Teaney... Neufeld, Betz, Gyulassy et al...



if long-lived source, static medium: mach angle

$$\cos\theta_M = \frac{c_s}{v}$$

speed of sound $c_s^2 = \frac{\partial p}{\partial e}$

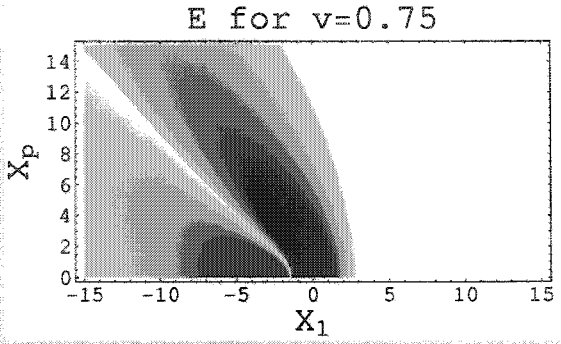
how realistic is this?

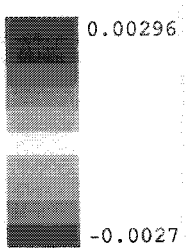
Conical flow from transport

Why transport? - includes dissipation
- can treat full 3+1D (jet breaks all symmetry)
- self-consistent jet+medium coupling
- it decouples, no Cooper-Frye prescription

Heavy quark in AdS

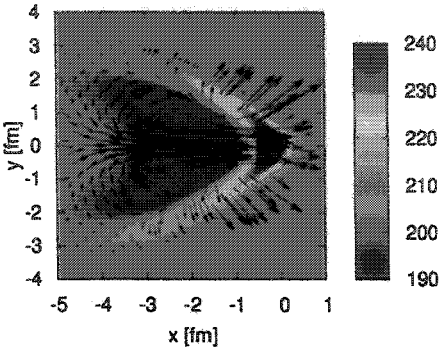
Gubser, Yarom, Pufu, PRL100, 012301 ('08)





jet in ideal hydro

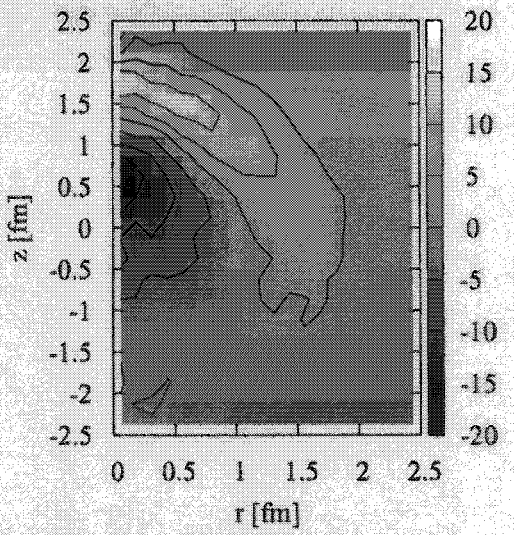
Betz et al, PRC79, 034902 ('09)



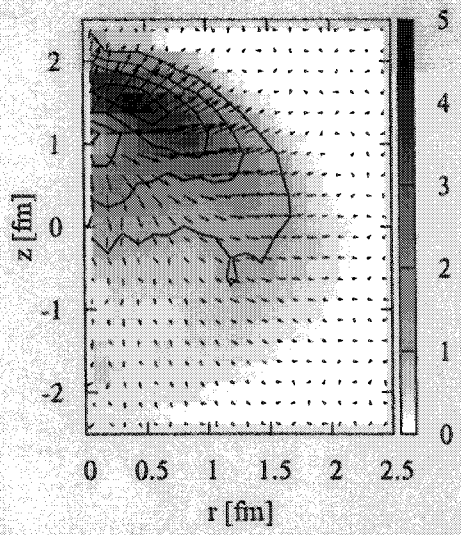
Textbook scenario: $\partial_\mu T^{\mu\nu} = j^\nu$ **- source moving in static thermal bath,** $z = vt$

$dE/dz = const$, $d\vec{p}/dz = 0$, **very low** $\eta/s \approx 0.075$

energy density

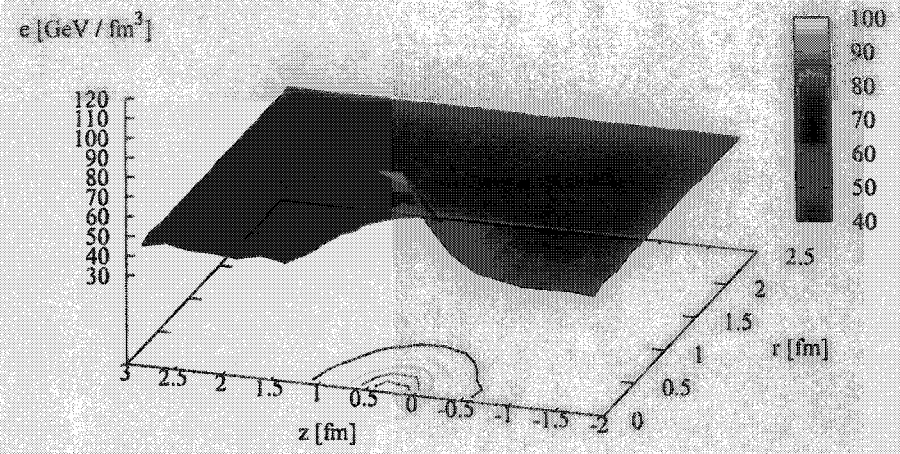


momentum density DM ('09)

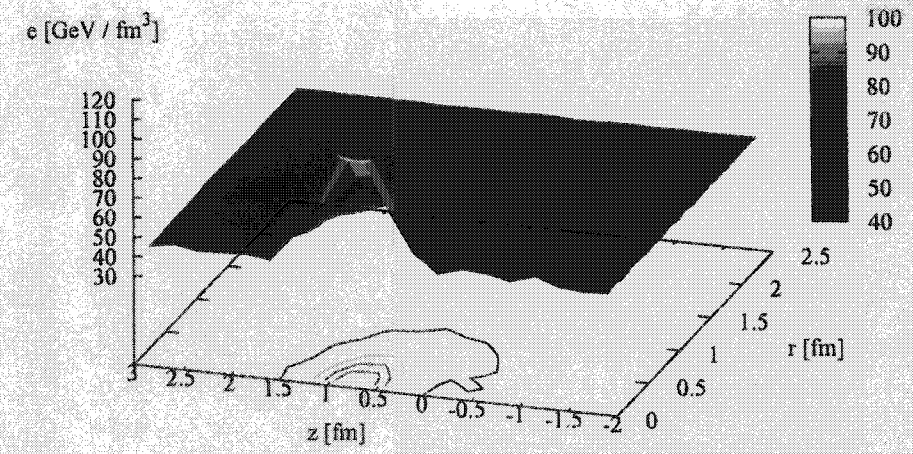


(isotropic $2 \to 2$ transport, $dE/dx = 68$ GeV/fm, $\lambda_{MFP} = 0.125$ fm, $T = 0.385$ GeV, $v = 0.9$)

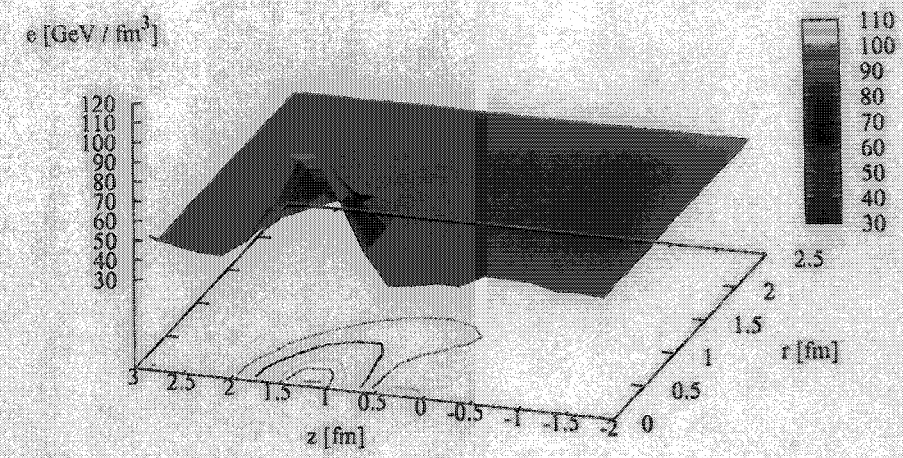
$t = 0.5$ fm


e [GeV / fm^3]
120
110
100
90
80
70
60
50
40
30
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
z [fm]
0
0.5
1
1.5
2
2.5
r [fm]
100
90
80
70
60
50
40

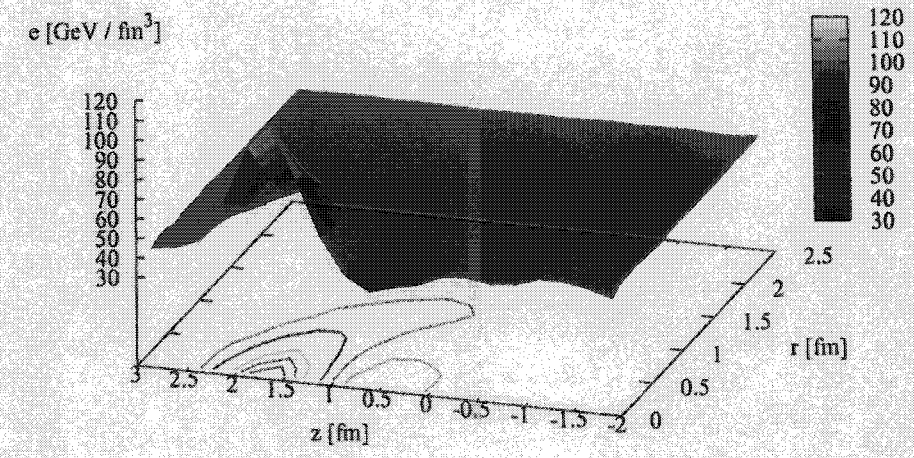
$t = 1$ fm


e [GeV / fm^3]
120
110
100
90
80
70
60
50
40
30
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
z [fm]
0
0.5
1
1.5
2
2.5
r [fm]
100
90
80
70
60
50
40

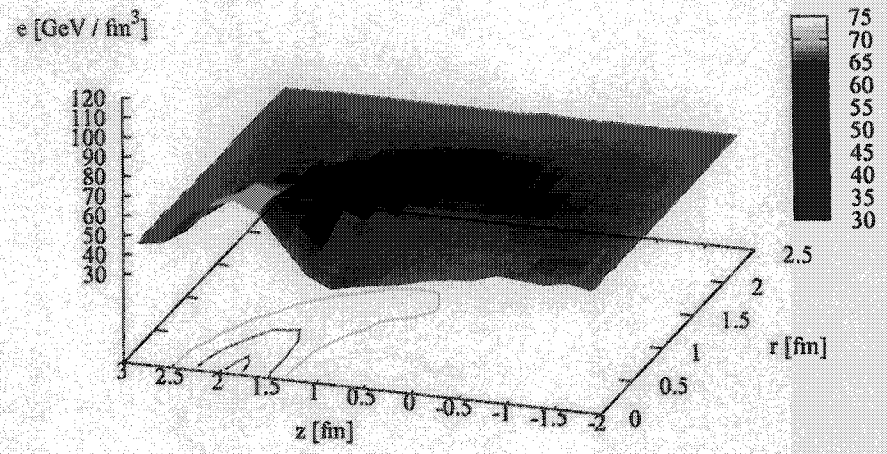
$t = 1.5$ fm



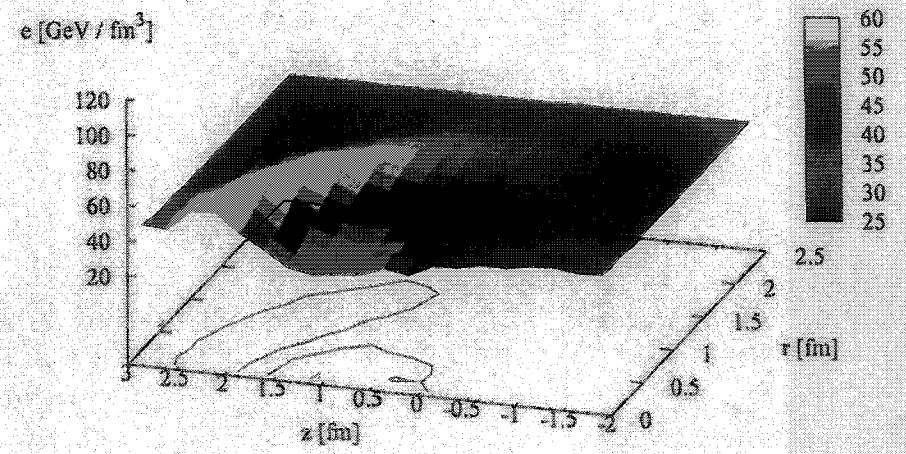
$t = 2$ fm (source switches off)



$t = 2.25$ fm



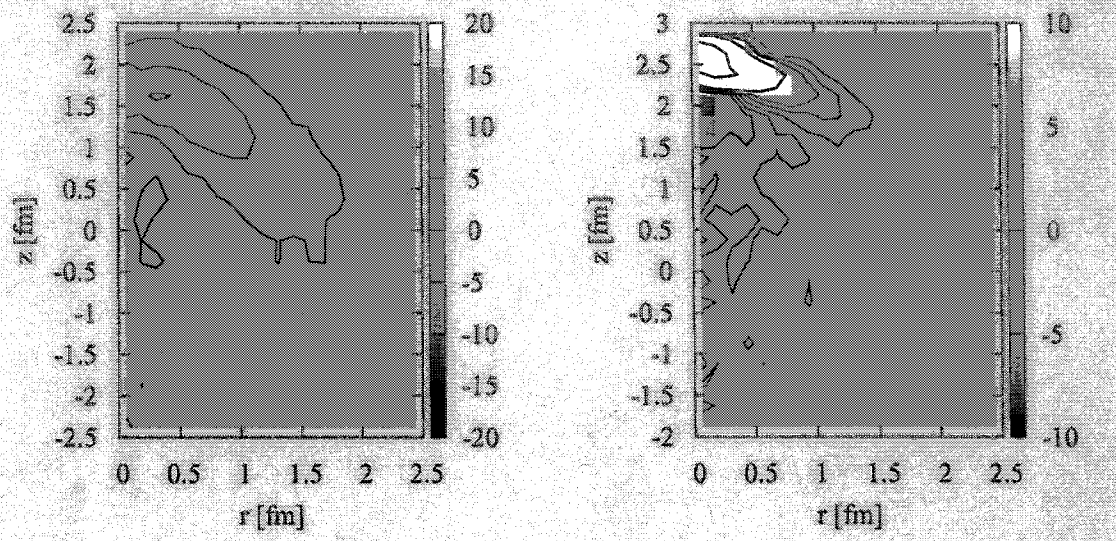
$t = 2.5$ fm



it will be interesting to see whether this survives in a realistic (expanding) scenario, including self-consistent feedback on the jet

one thing is clear, larger $\eta/s \approx 0.3$ washes it out

energy density for: $d\vec{p}/dz = 0$ $dE/dz \approx dp_z/dz$ DM ('09)



Freezeout and viscosity

heavy-ion applications in the end must match hydrodynamics to a particle description

- in local equilibrium

$$T^{\mu\nu}_{LR} = diag(e,p,p,p) \quad \Leftrightarrow \quad f_{eq} = \frac{g}{(2\pi)^3} e^{-p^\mu u_\mu / T}$$

- near local equilibrium

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \delta T^{\mu\nu} \quad \Leftrightarrow \quad f = f_{eq} + \delta f$$

correction δf crucially affects basic observables - spectra, elliptic flow, ...

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 was a starting point in deriving IS hydro from kinetic theory

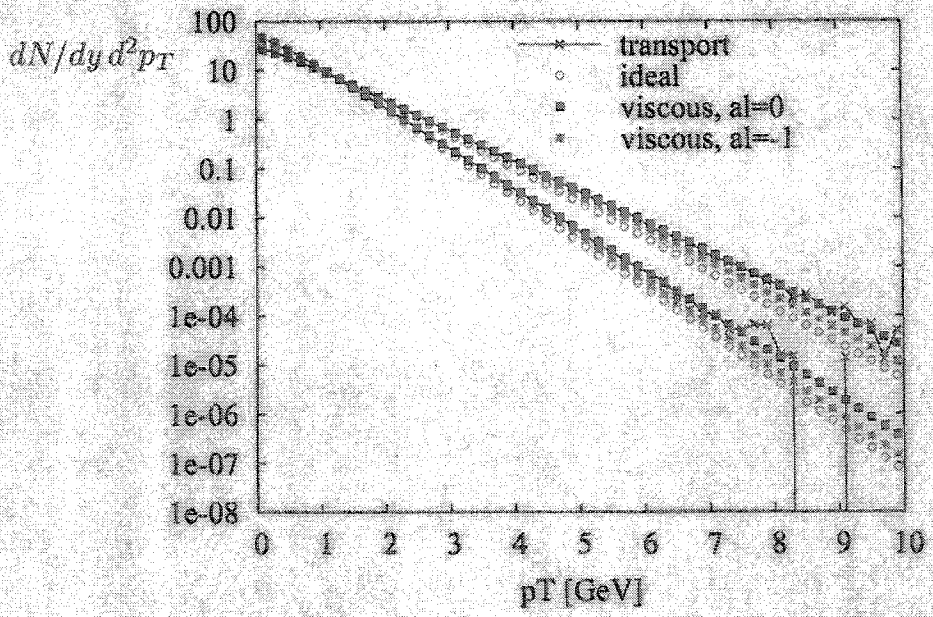
from linear response: $\chi(x) \sim x^\alpha$ **with** $-1 \lesssim \alpha \lesssim 0$ Dusling, Teaney, Moore, ('09)

δf **blows up at large momenta** $\Rightarrow$ **approximation breaks down**

transport can tell how far in momenta we can trust these...

DM ('09):

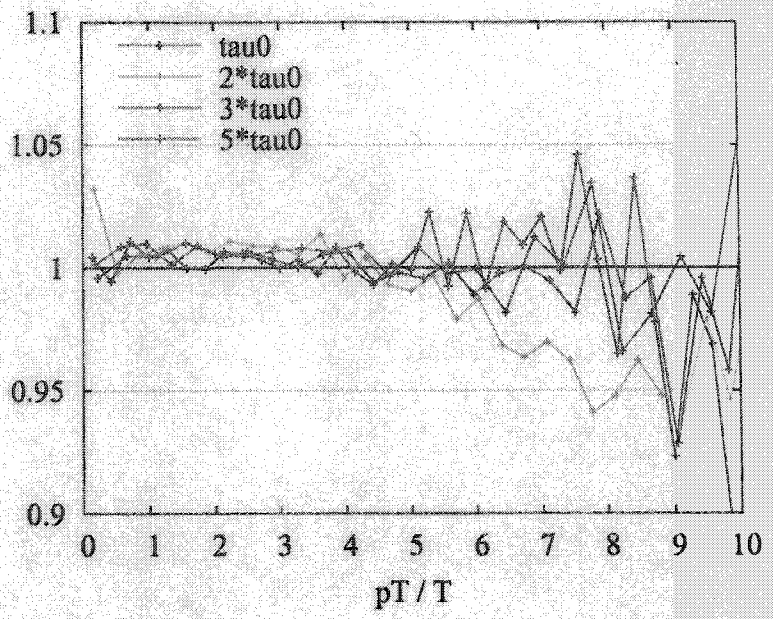
spectra in 0+1D Bjorken scenario at $\tau = 2\tau_0$ **and** $5\tau_0$
for $\eta/s \approx const$, $K_0 = 3$, **local equilibrium initconds** $\pi^{\mu\nu}(\tau_0) = 0$



Grad ansatz ($\alpha = 0$) **works surprisingly well - on a log plot at least**

ratio - transport spectra / Grad approximation

DM ('09):

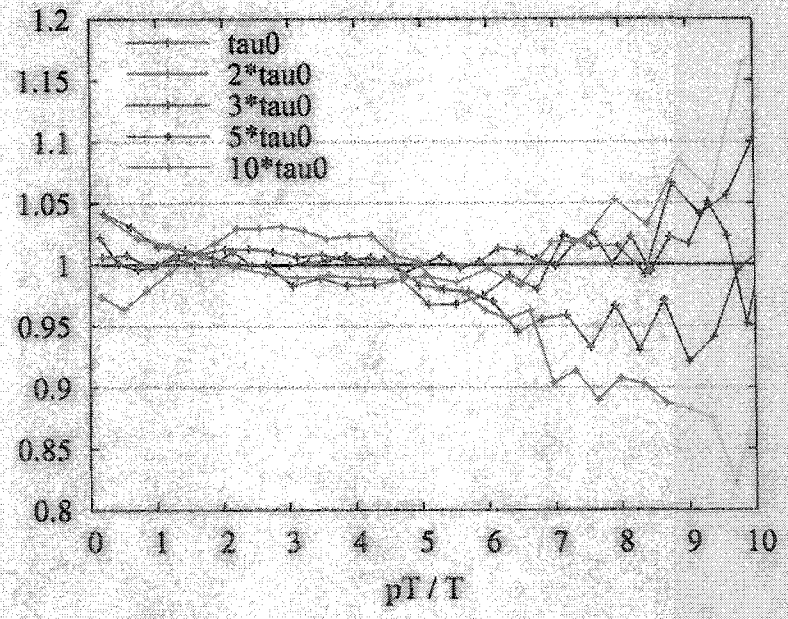


spectra are few-percent accurate even at $p_T/T = 6$(!)

for $K_0 = 1$, i.e., three times higher η/s

ratio - transport spectra / Grad approximation

DM ('09):



accuracy worsens - should be noticeable in other observables, e.g., v_2

Summary

We can use covariant transport to study viscous hydrodynamics in full 3+1D. Causality & stability - no problem. Bow shock formation demonstrated in idealized static medium scenario.

In the hydrodynamic regime of $2 \to 2$ transport, Grad's quadratic formula $\delta f \propto f_{eq} \pi^{\mu\nu} p_\mu p_\nu$ is surprisingly accurate, at least for p_T spectra in a 0+1D Bjorken scenario.

Of course, this ignored pQCD power-law tails, which will invalidate hydro at high pT, nevertheless.

+ some more work ahead, as usual.

Backup slides

Probing Hot Nuclear Matter

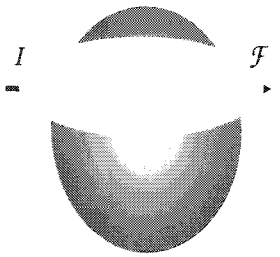
Rainer Fries

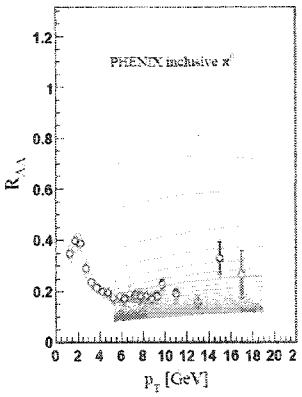
Texas A&M University & RIKEN BNL

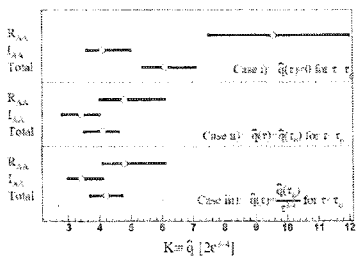
RBRCReview, Brookhaven National Lab
October 21-22, 2009

QCD Tomography

- What are the properties of the QCD state found at RHIC?
  - Equation of state, phase diagram, transport properties, ...
- Precision probes:
  - QCD jets interacting with the medium
  - Electromagnetic radiation
  - Many possible effects to understand: jet qenching, broadening, correlation measurements, hadro chemistry, ...
- Tomography of QCD matter? Getting closer ...



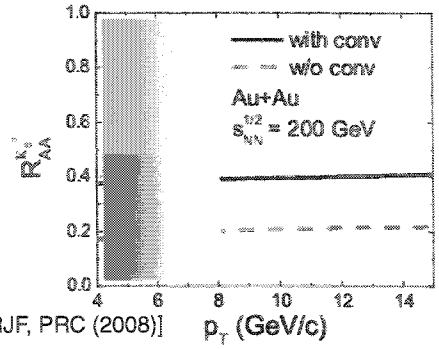




Armesto et al., arxiv:0907.0667

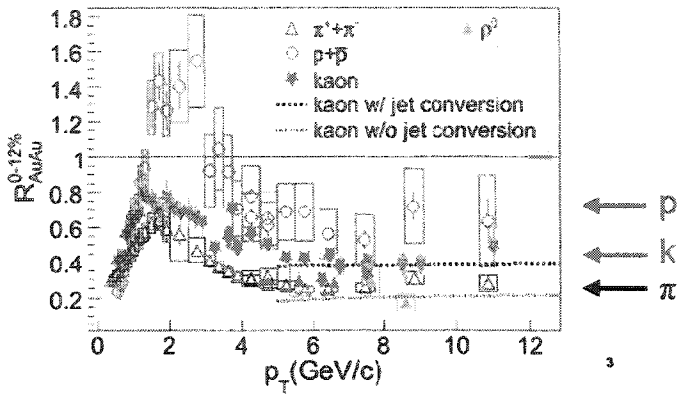
Update For Last Year: High-P_T Strangeness

- Predicted s-jet enhancement at RHIC through conversion of high momentum particles in a medium.
  - Translates into kaon enhancement at RHIC



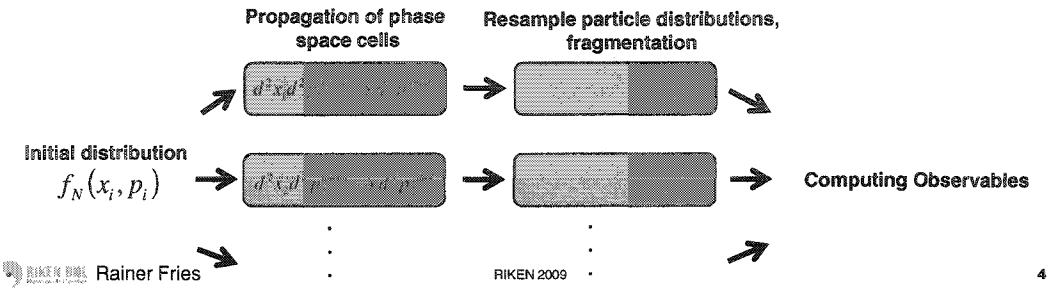
[Liu, RJF, PRC (2008)]

- New STAR result:
  - Kaon enhancement seen between 6 and 10 GeV/c.
  - A first unambiguous signal conversions?
  - Caution: p enhancement too big.



Propagating Particles in a Medium (PPM)

- Developing flexible code to simulate N jets in a fireball.
  - Part of a NSF project; authors: R. Rodriguez, R.J. Fries, E. Ramirez
- Input:
  - initial phase space distribution
  - background (aka fireball)
  - specifics of dynamics (energy loss model, fragmentation)
- What it should do:
  - Evolution of particle distributions; (modified) fragmentation and hadronization; analysis of results in terms of experimentally relevant observables
- E.g. leading particle energy loss + fragmentation:



Propagating Particles in a Medium (PPM)

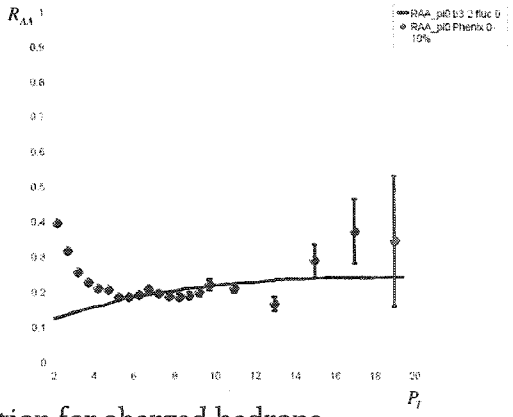
- Preliminary version up and running.
- First testing promising, more to be done.
- First physics project underway, see later.
- Implemented:
  - Leading particle propagation for up to N = 2; photons, quarks and gluons.
  - Single, vacuum fragmentation to pions,
  - Opacity expansion (GLV type) energy loss $\Delta E = \frac{C_R \alpha_s}{4} \frac{\mu^2}{\lambda} L^2 \log E$
  - Basic observables like single and double spectra, R_{AA}, triggered fragmentation functions, map function.
- To-do:
  - Different implementations of energy loss, ,modified fragmentation
  - Transverse dynamics (broadening, etc.)
  - Conversions, more hadron species, hadro chemistry
  - Tracking particle distributions / multi fragmentation
  - Canbe combined with: NLO initial input, hydro fireball maps

Propagating Particles in a Medium (PPM)

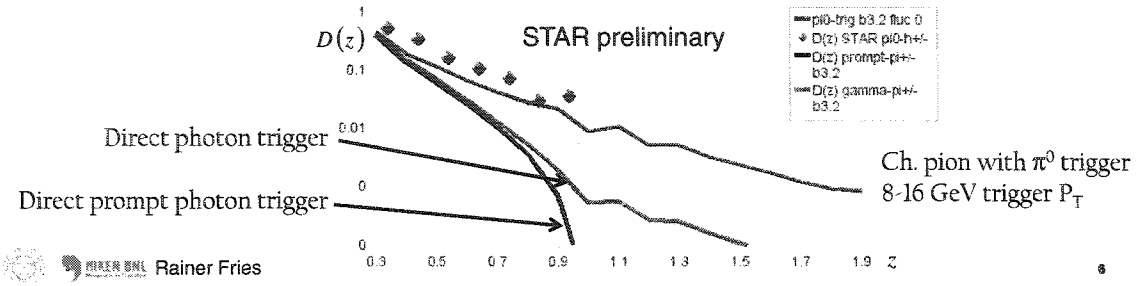
- Some results from the testing process.
- Neutral pion R_{AA} vs PHENIX data

$$R_{AA} = \frac{dN_{AA}/dP_T}{N_{\text{coll}} dN_{pp}/dP_T}$$

  - Estimate $\hat{q} = \frac{\mu^2}{\lambda} \approx 2.5\,\text{GeV/fm}^2$

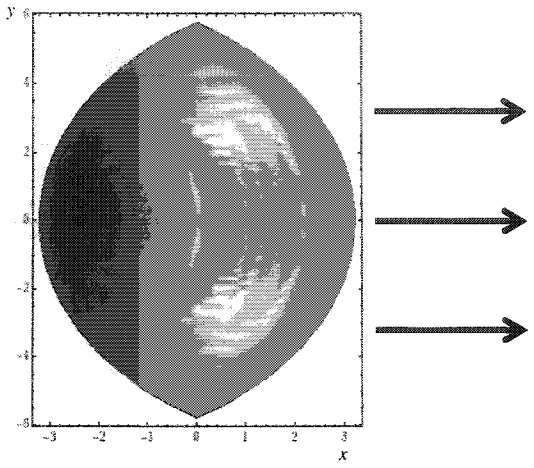


- Triggered away side fragmentation function for charged hadrons.



Propagating Particles in a Medium (PPM)

- Map functions
  - Emissivity for 8 GeV up-quarks going to the right, b=7.4 collision of Au ions.

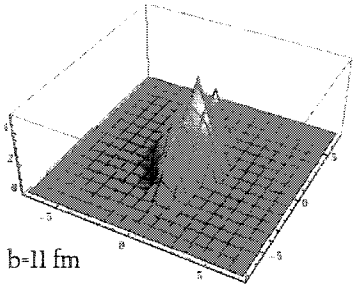


Propagating Particles in a Medium (PPM)

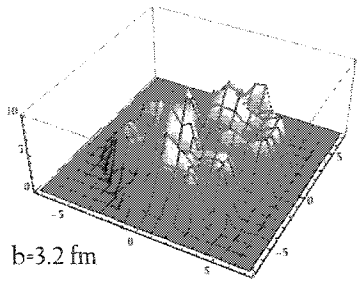
- Goals:
  - Near future: full vetting and testing of basic functions.
  - Build a flexible test bed for hard and electromagnetic probes.
  - Comprehensive, quantitative studies of observables.
  - photon/Z – jet/hadron correlations at NLO accuracy.
- Understanding photon/Z – jet/hadron correlations ↔ understanding electromagnetic sources and conversion processes.
- Eventually code can be made public and/or be made part of a larger effort (Techqm, JET)

Probing the Spatial Structure

- What can hard probes tell us about the spatial structure of the fireball?
  - Or: can we do true tomography?
  - Seemingly hopeless: we sum over many events and only see an average fireball.
- What is the effect of an inhomogenous fireball on hard probes?
  - Realistic initial conditions with fluctuations have been studied for hydrodynamics.
  - Applicability of hydro and elliptic flow seem to set some boundaries for times > 1 fm/c.
  - Hard probes from the surface layer and in peripheral collisions might be affected by fluctuations in the background.



b=11 fm



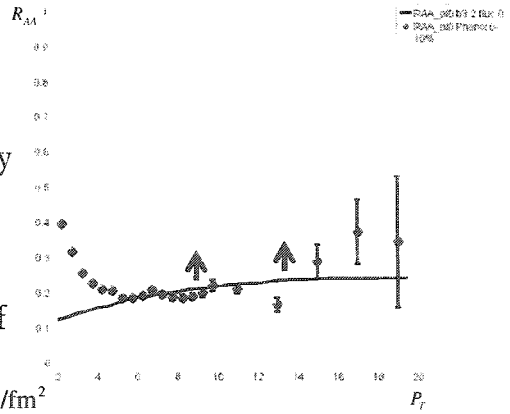
b=3.2 fm

Probing the Spatial Structure

- Use our PPM (pre-release) code for a study.
- Run events over ensembles of fluctuating transverse profiles of the energy density.
  - Have tried simple transverse profiles with Gaussian fluctuations.
  - Here: initial state Glauber estimates of the number of participants (i.e. no energy flow build-up taken into account that would wash out inhomogeneities);
  - Assume $\hat{q} \propto \varepsilon^{3/4}$.
  - Will run some existing initial state simulations (e.g. GLISSANDO)
- For every observable take average over events.

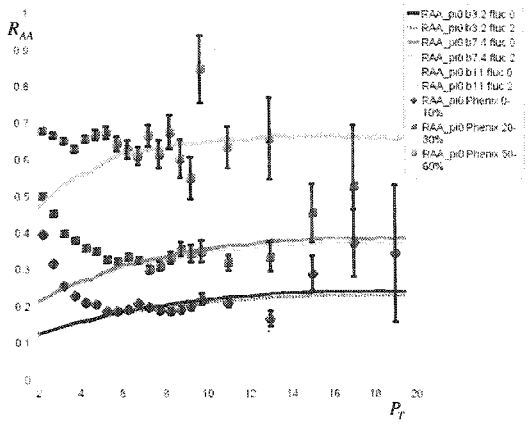
Probing the Spatial Structure

- Check single pion spectra:
- As expected: fluctuations lead to slightly less suppression.
- This can be absorbed in the definition of your favorite energy loss parameter.
  - Indeed, fit data well with a new $\hat{q} = 3.1\,\mathrm{GeV/fm}^2$
  - Nothing won, effect not observable.
  - But the extracted strength of energy loss changes by 25%. Add to the list of uncertainties.



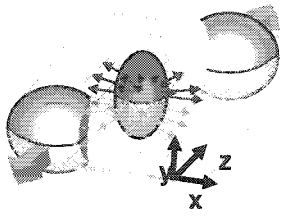
Probing the Spatial Structure

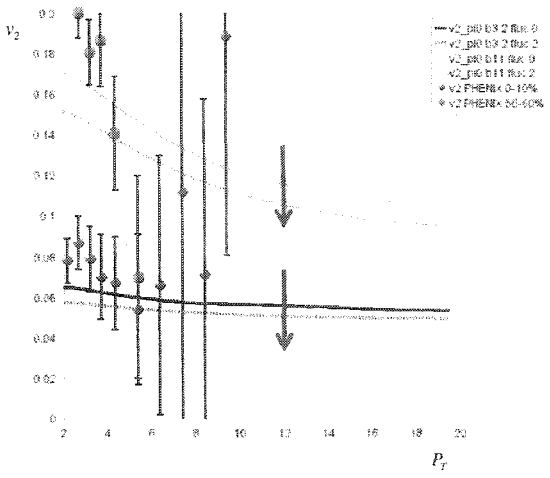
- Centrality dependence and P_T dependence:
- With inhomogeneities dependence stays the same after redefinition of $\hat{q}$.
  - Results fit PHENIX pion data.
- No signature.



Probing the Spatial Structure

- Elliptic Flow v_2:

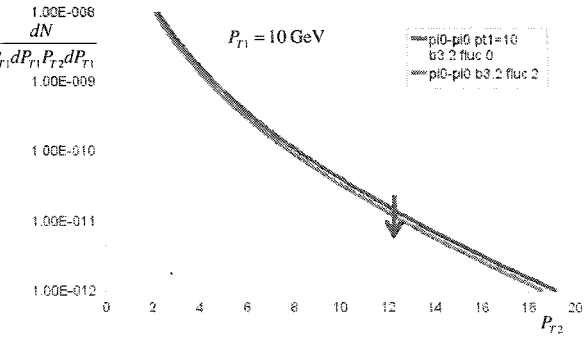




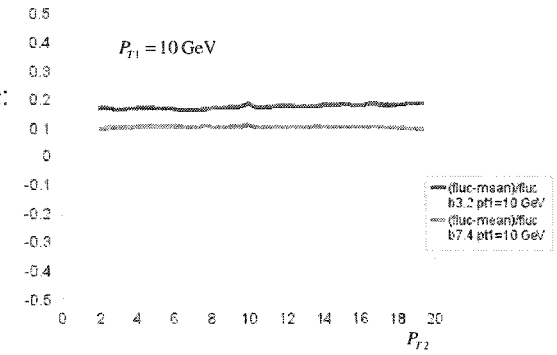
- 10-20% reduction in v_2 even after redefinition of $\hat{q}$.

Probing the Spatial Structure

- Dipion spectrum:
  - Visible deviation with inhomogeneities



- Relative deviation on linear scale:



- 10-20% reduction in correlation strength after redefinition of $\hat{q}$.

Summary & Outlook

- Work progressing on PPM framework for studies of hard and electromagnetic probes.
- Promising early results; new features ahead. Will start precision studies of photon-hadron and hadron-hadron correlations soon.
- Study of partons propagating in inhomogeneous backgrounds.
- Local fluctuations of the energy density deposited in the collision leads to 25% increase in the quenching strength needed to explain the data.
- Even after adjusting the quenching strength, up to 20% secondary effect visible in elliptic flow and dihadron correlations.

Backup

F_L structure function in DGLAP/BFKL approach

Anna Staśto
Penn State & RIKEN BNL

Work done in collaboration with Krzysztof Golec-Biernat

RBRC meeting, BNL, October 21st

Friday, October 16, 2009

Outline

Unified DGLAP/BFKL approach

High energy vs collinear factorization

Gluon kinematics

Comparison with the HERA data

Friday, October 16, 2009

Why F_L ?

- Vanishes in the parton model: quarks spin 1/2, transverse momentum limited.
- Should be non-zero in QCD: gluon radiative corrections, transverse momentum grows with Q^2
- Directly sensitive to the gluon density.
- Large higher twist effects (observed at large x).
  - Extremely important to see what happens at low x and low Q^2

Unified DGLAP/BFKL approach

- Simplest resummed model: set of two integral equations for the unintegrated gluon density and quark sea density.

J.Kwiecinski, A.D.Martin, A.S.

- Gluons:
  - BFKL with kinematical constraint
  - DGLAP splitting function
  - running coupling

$$f(x,k^2) = \tilde{f}^{(0)}(x,k^2) + \overline{\alpha}_S(k^2)\,k^2\int_x^1 \frac{dz}{z}\int_{k_0^2}\frac{dk'^2}{k'^2}\left\{\frac{f\left(\frac{x}{z},k'^2\right)\Theta\left(\frac{k^2}{z}-k'^2\right)-f\left(\frac{x}{z},k^2\right)}{|k'^2-k^2|}+\frac{f\left(\frac{x}{z},k^2\right)}{[4k'^4+k^4]^{\frac{1}{2}}}\right\}$$
$$+\ \overline{\alpha}_S(k^2)\int_x^1\frac{dz}{z}\left(\frac{z}{6}P_{gg}(z)-1\right)\int_{k_0^2}^{k^2}\frac{dk'^2}{k'^2}f\left(\frac{x}{z},k'^2\right)+\frac{\alpha_S(k^2)}{2\pi}\int_x^1 dz P_{gq}(z)\Sigma\left(\frac{x}{z},k^2\right).$$

non-perturbative input $\quad \tilde{f}^{(0)}(x,k^2) = \dfrac{\alpha_S(k^2)}{2\pi}\displaystyle\int_x^1 dz\,P_{gg}(z)\,\frac{x}{z}g\left(\frac{x}{z},k_0^2\right).$

Unified DGLAP/BFKL approach

- Quarks:
  - k_T factorization theorem
  - Three different regions for quark and gluon momenta
    - Non-perturbative (soft)
    - Strongly ordered (low gluon momenta)
    - Perturbative (high gluon momenta)
  - Momentum sum rule

$$\Sigma(x,k^2) = S^{(\mathrm{soft})}(x) + \sum_q \int_x^a \frac{dz}{z} S_q^{(\mathrm{box})}(z,k'^2=0,k^2;m_q^2)\frac{x}{z}g\left(\frac{x}{z},k_0^2\right) + V(x,k^2)$$
$$+ \sum_q \int_{k_0^2}^{\infty} \frac{dk'^2}{k'^2}\int_x^1 \frac{dz}{z} S_q^{(\mathrm{box})}(z,k'^2,k^2;m_q^2) f\left(\frac{x}{z},k'^2\right) + \int_{k_0^2}^{k^2}\frac{dk'^2}{k'^2}\frac{\alpha_S(k'^2)}{2\pi}\int_x^1 dz\, P_{qq}(z) S_{uds}\left(\frac{x}{z},k'^2\right),$$

non-perturbative, soft terms $\quad S^{(\mathrm{soft})}(x) = S_u^P + S_d^P + S_s^P\,, \quad S_u^P = S_d^P = 2S_s^P = C_P x^{-0.08}(1-x)^8\,.$

F_L calculated from k_T factorization

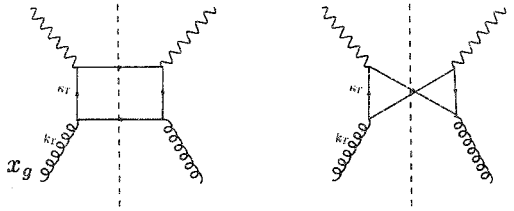
high momenta

$$F_L(x,Q^2) = \frac{Q^4}{\pi^2}\sum_q e_q^2 \int \frac{dk^2}{k^4}\theta(k^2>k_0^2)\int_0^1 d\beta \int d^2\kappa'\,\alpha_s(\mu^2)\,\beta^2(1-\beta)^2\left(\frac{1}{D_{1q}}-\frac{1}{D_{2q}}\right)^2 f(x_g,k^2)$$
$$+ \frac{\alpha_s(Q^2)}{\pi}\left\{\frac{4}{3}\int_x^1\frac{dy}{y}\left(\frac{x}{y}\right)^2 F_2(y,Q^2) + \sum_q e_q^2\int_x^1\frac{dy}{y}\left(\frac{x}{y}\right)^2\left(1-\frac{x}{y}\right) yg(y,k_0^2)\right\}.$$

quarks — non-perturbative

$$\frac{x}{z} \equiv x_g \equiv x\left(1+\frac{\kappa'^2+m_q^2}{\beta(1-\beta)Q^2}+\frac{k^2}{Q^2}\right).$$

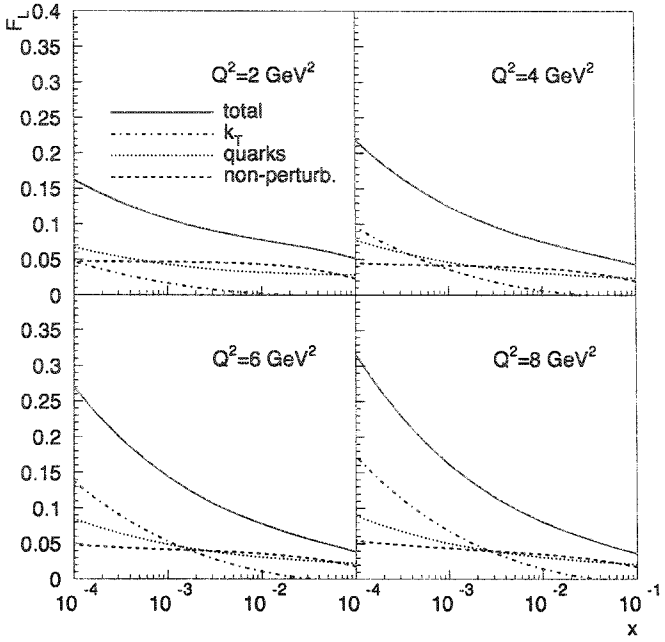
exact gluon kinematics



Charm quark density generated dynamically through the boson-gluon fusion with exact kinematics

non-perturbative gluon parametrization $\quad yg(y,k_0^2) = N(1-y)^\beta\,,$

Different contributions to F_L



Non-perturbative (low gluon momenta) term nearly constant.

Quark contribution non-negligible for lowest Q^2 and higher $x > 0.01$

Gluon contribution (high momenta) strongly suppressed for $x > 0.01$

Kinematics very important in this regime (and not only!)

k_T factorization vs collinear

$$F_L(x,Q^2) = 2\frac{Q^4}{\pi^2}\sum_q e_q^2 \int \frac{dk^2}{k^4}\int_0^1 d\beta \int d^2\boldsymbol{\kappa}'\,\alpha_s(\mu^2)\,\beta^2(1-\beta)^2\,\frac{1}{2}\left(\frac{1}{D_{1q}}-\frac{1}{D_{2q}}\right)^2 f\left(\frac{x}{z},k^2\right)$$

$$k^2 \ll Q^2$$

on-shell approximation

$$F_L^{(\mathrm{on-shell})}(x,Q^2) = 2\sum_q e_q^2\left[J_q^{(1)} - 2\frac{m_q^2}{Q^2}J_q^{(2)}\right]$$

Gluon kinematics crucial in obtaining the collinear approximation

$$J_q^{(1)} = \frac{\alpha_s}{\pi}\int_{\bar{x}_q}^1 \frac{dy}{y}\left(\frac{x}{y}\right)^2\left(1-\frac{x}{y}\right)\sqrt{1-\frac{4m_q^2x}{Q^2(y-x)}}\,yg(y,Q^2)$$

$$J_q^{(2)} = \frac{\alpha_s}{\pi}\int_{\bar{x}_q}^1 \frac{dy}{y}\left(\frac{x}{y}\right)^3 \ln\left[\frac{1+\sqrt{1-\frac{4m_q^2x}{Q^2(y-x)}}}{1-\sqrt{1-\frac{4m_q^2x}{Q^2(y-x)}}}\right] yg(y,Q^2)$$

$$\frac{x}{z} \equiv x_g \equiv x\left(1+\frac{\kappa'^2+m_q^2}{\beta(1-\beta)Q^2}+\frac{k^2}{Q^2}\right).$$

$$y \equiv x\left(1+\frac{\kappa'^2+m_q^2}{\beta(1-\beta)Q^2}\right)$$

k_T factorization vs dipole model

$$F_L(x,Q^2) = 2\frac{Q^4}{\pi^2}\sum_q e_q^2 \int \frac{dk^2}{k^4}\int_0^1 d\beta \int d^2\kappa'\,\alpha_s(\mu^2)\,\beta^2(1-\beta)^2\,\frac{1}{2}\left(\frac{1}{D_{1q}}-\frac{1}{D_{2q}}\right)^2 f\left(\frac{x}{z},k^2\right)$$

small x approximation replaces the argument of the gluon density: gluon is longitudinally soft

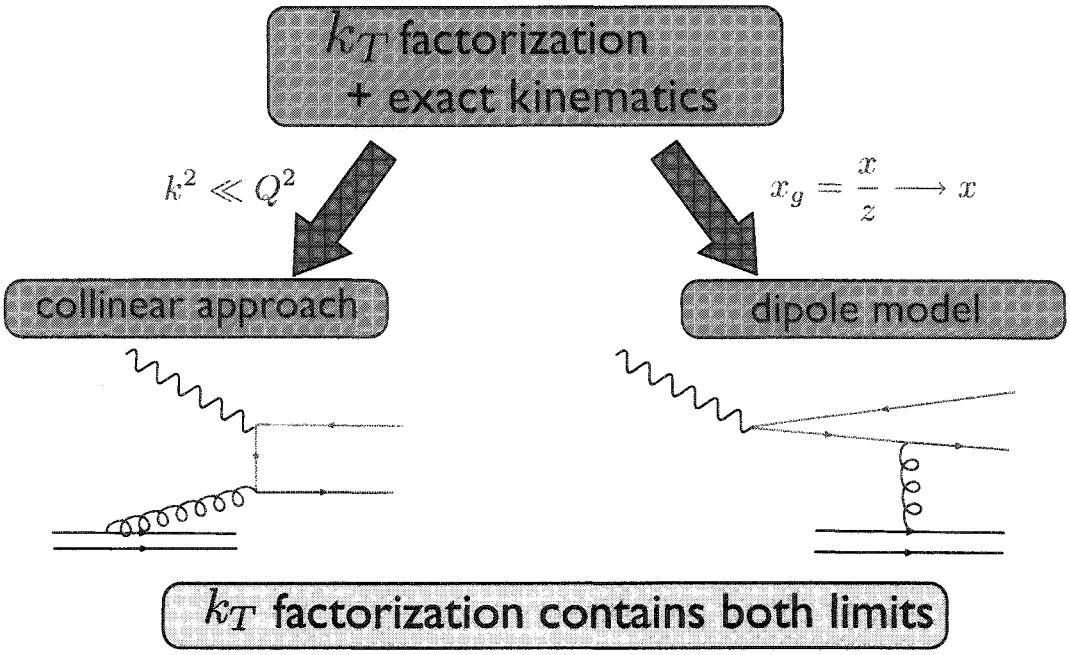
$$x_g = \frac{x}{z} \longrightarrow x$$

$$\sigma_L = \frac{\alpha_{em}}{\pi}\sum_q e_q^2 \int d^2r \int_0^1 d\beta\, 4Q^2\beta^2(1-\beta)^2 K_0^2(\overline{Q}r) \times \int \frac{d^2\boldsymbol{k}}{k^4}\,\alpha_s f(x,k^2)(1-e^{-i\boldsymbol{r}\cdot\boldsymbol{k}})(1-e^{i\boldsymbol{r}\cdot\boldsymbol{k}})\,.$$

dipole cross section $\quad \hat{\sigma}(x,r) \equiv \frac{2\pi}{3}\int \frac{d^2\boldsymbol{k}}{k^4}\alpha_s f(x,k^2)(1-e^{-i\boldsymbol{r}\cdot\boldsymbol{k}})(1-e^{i\boldsymbol{r}\cdot\boldsymbol{k}})$

Friday, October 16, 2009

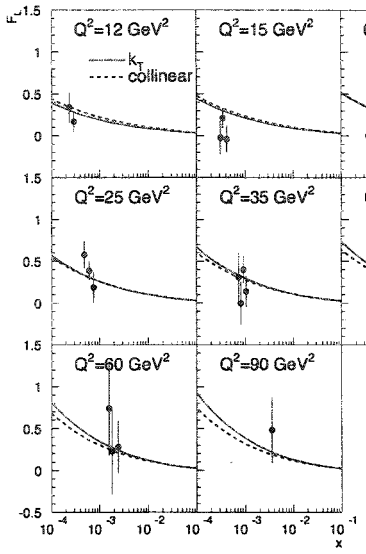
k_T factorization vs collinear approach and dipole model



Friday, October 16, 2009

k_T vs collinear

H1



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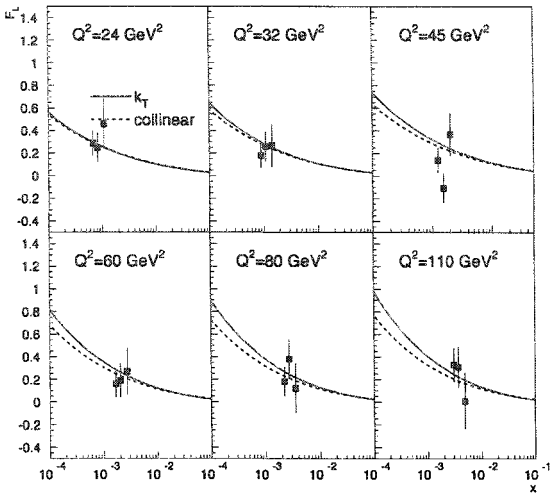


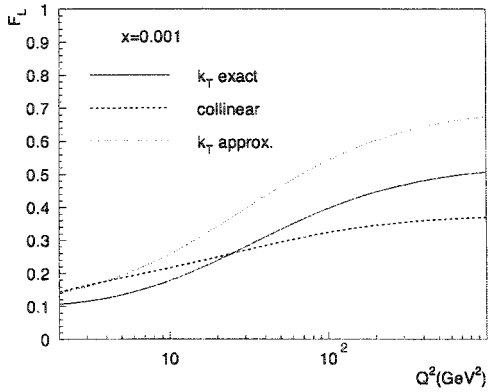
Collinear gluon also includes resummation at small x

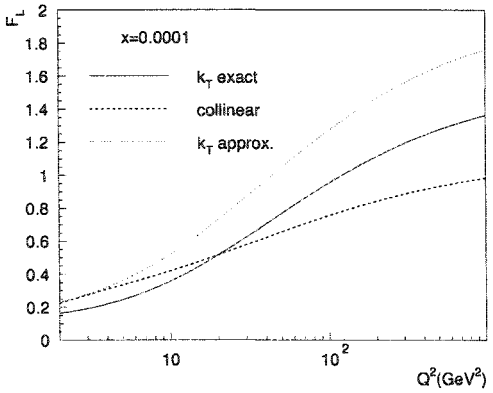
Differences between k_T and collinear approaches are small for F_L in this kinematic regime.

This is different than F_2, where differences are typically large.

k_T vs collinear

Q^2 dependence



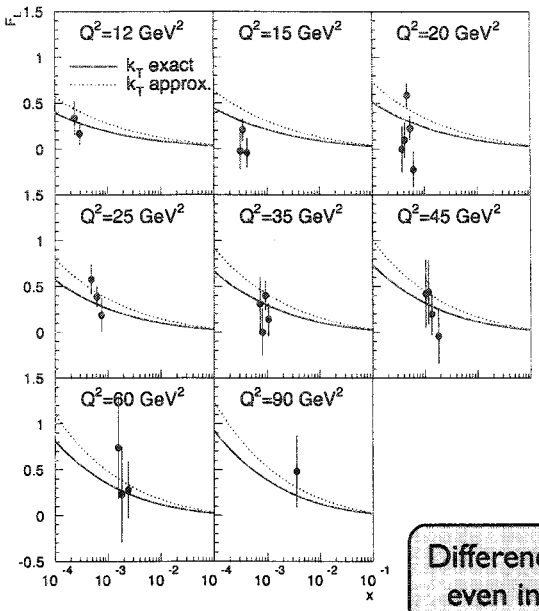


Differences between k_T and collinear approaches are small for F_L in this kinematic regime.

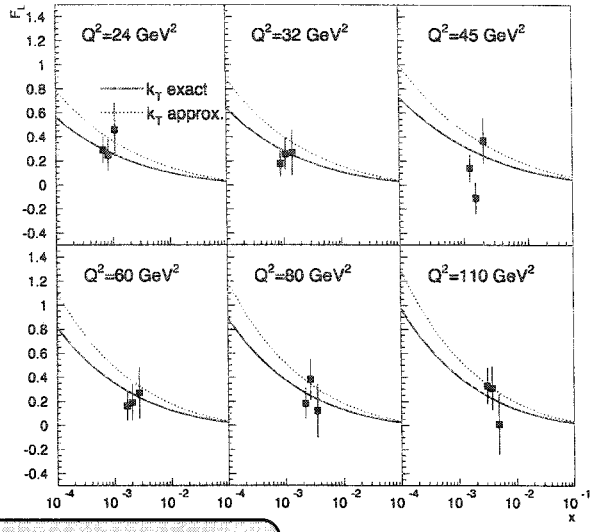
However, Q^2dependence different for the k_T factorization and collinear.

k_T vs dipole kinematics

H1



ZEUS



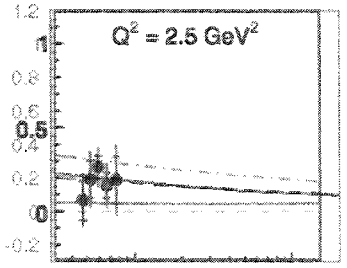
Differences are non-negligible even in the small x regime.

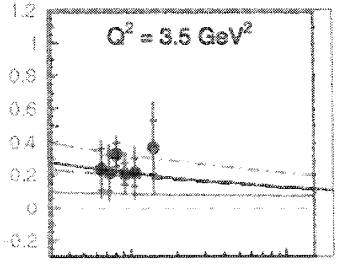
effective x of the gluon

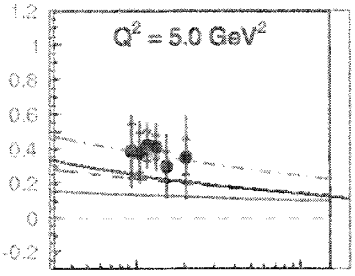
$$x_g \simeq 5.7\, x\,,$$

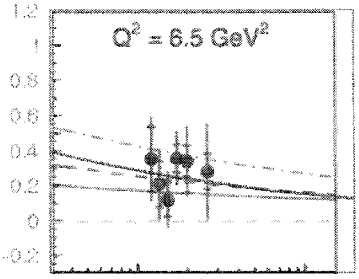
Low Q^2 region

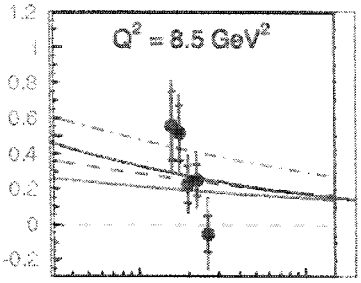
Comparison with the H1 preliminary low Q2 data





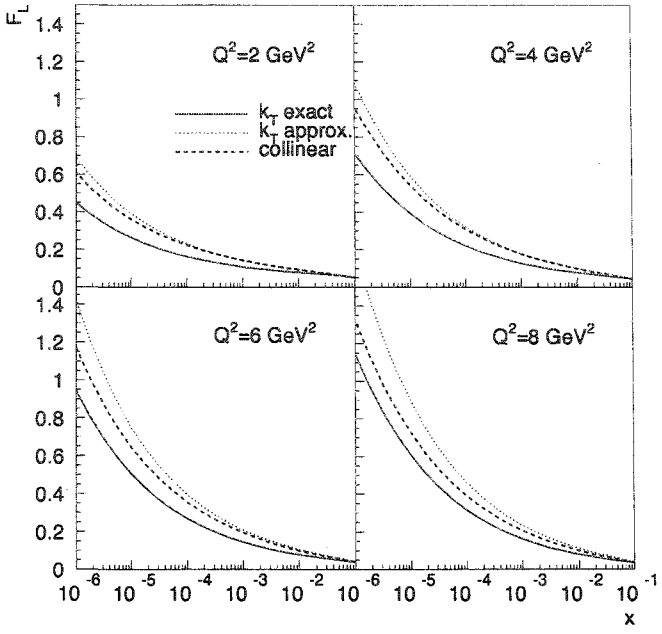






Good agreement with the data at low Q2 too.

Extrapolations to lower x: LHeC



Kinematic effects important even for lowest values of x.

Can compensate for the difference by changing the normalization of the gluon density.

Using approximate (dipole-like) kinematics, forces the gluon density to be smaller.

This is important if one wants to study saturation effects.

Summary:

- Unintegrated gluon distribution from unified DGLAP/BFKL.
- High energy factorization with exact gluon kinematics contains both collinear and dipole approach.
- In the HERA kinematics regime collinear and k_T factorization give similar results for F_L . Agreement with HERA data.
- Kinematic effects significant, dipole model underestimates the gluon density. Effective $x_g \simeq 5.7x$
- Predictions for EIC, LHeC

Outlook:

- Unified approach close to Ciafaloni-Colferai-Salam-Stasto resummation approach. Extend to obtain unintegrated gluon distribution function from CCSS resummation.
- Applications of unintegrated resummed densities at LHC.

Viscosity in Heavy Ion Collisions

Derek Teaney

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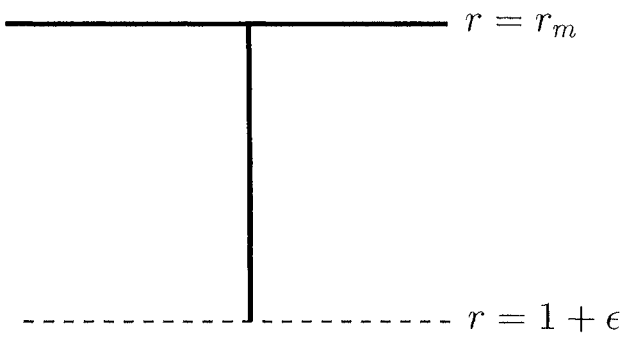
STONY BROOK
STATE UNIVERSITY OF NEW YORK

Summary

1. Stochastic Noise in AdS/CFT
   - D. T. Son and D. Teaney, JHEP **0907**, 021 (2009).
   - J. Casalderrey-Solana, K. Y. Kim and DT, arXiv:0908.1470.
2. Viscous Corrections – Rad E-loss, and Quark Number Scaling
   - K. Dusling, G. Moore and D. Teaney, arXiv:0909.0754 [nucl-th].
3. Two Reviews
   - D. Teaney, arXiv:0905.2433 for QGP4
   - T. Schaefer and D. Teaney, arXiv:0904.3107

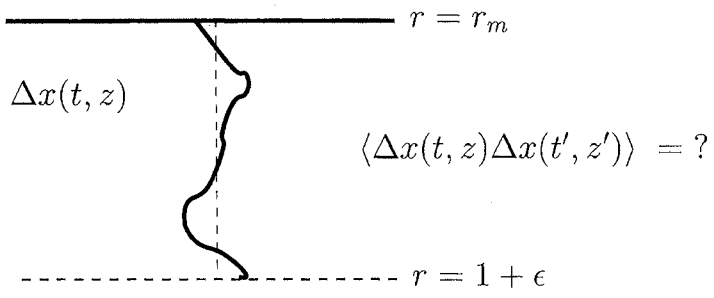
A heavy quark in AdS/CFT



Not the dual of an equilibrated quark!

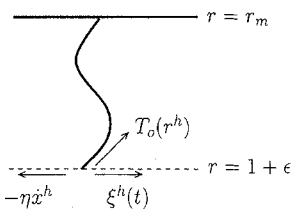
A heavy quark in AdS/CFT with noise

$$M\frac{d^2\mathbf{x}}{dt^2} = \underbrace{-\eta}_{\text{Drag}}\,\dot{x} + \underbrace{\xi}_{\text{Noise}} \qquad \langle \xi(t)\xi(t')\rangle = 2T\eta\,\delta(t-t')$$



Where is the noise? What are the dual statistics $\langle \Delta x(t,z)\Delta x(t,z')\rangle = ?$

Hawking radiation and the random force



- Overdamped horizon motion with a random force

$$\overbrace{T_o(r_h)\partial_r x(t, r_h)}^{\text{Tension}} + \overbrace{\xi^h(t)}^{\text{Random force}} = \overbrace{\eta\, \dot{x}^h(t)}^{\text{Drag}}$$

- Random force satisfies a horizon fluctuation dissipation theorem

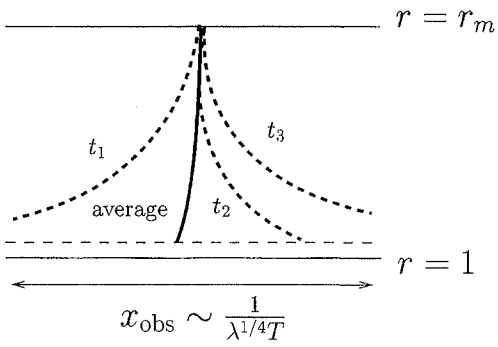
$$\left\langle \xi^h(t)\xi^h(t') \right\rangle = 2T\eta\delta(t - t')$$

- More Generally when times of order $1/\pi T$

$$\left\langle \xi^h(\omega)\xi^h(-\omega) \right\rangle = (1 + 2n)\omega\eta$$

Gives rise to random motion on the string

What happens when noise is included:



1. Every step t_1, t_2, t_3 fluctuates to a new trailing string –a random force!

$$\Delta x = \frac{-\xi^o(t)}{2\pi T\eta}\left[\tan^{-1}(z) - \tanh^{-1}(z)\right]$$

2. The *average* of the trailing strings gives the drag

$$x_{\text{ave}}(z) = vt + \frac{v}{2\pi T}\left[\tan^{-1}(z) - \tanh^{-1}(z)\right]$$

Horizon random force gives the correct boundary random force and drag

Hydro

Viscous Corrections

1. Viscous corrections to the equation of motion

$$\partial_\mu T^{\mu\nu} = 0 \qquad \text{with} \qquad T^{\mu\nu} = \underbrace{(e+p)u^\mu u^\nu + p g^{\mu\nu}}_{\text{ideal}} \underbrace{-2\eta \left\langle \partial^\mu u^\nu \right\rangle}_{\text{viscous } \pi^{\mu\nu}}$$

2. Viscous corrections to the distribution function

$$f \to f_o + \delta f$$

3. In a relaxation time approximation

$$\delta f = -\tau_R(p) \times f_o(p) \frac{p^i p^j}{p} \left\langle \partial_i u_j \right\rangle$$

   - All simulations have assumed $\tau_R(p) \propto p$
   - All simulations have assumed one relaxation time for mesons and baryons

We challenged both of these assumptions

Notation and Estimate

$$\delta f(p) = -\chi(p)\hat{p}^i\hat{p}^j \langle \partial_i u_j \rangle$$

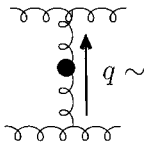
- Found by solving the linearized boltzman equaiton
- Order of magnitude estimate

$$\chi(p) \sim \underbrace{\tau_R(p)}_{\sim \frac{p}{\frac{dp}{dt}}} p \sim \frac{p^2}{\frac{dp}{dt}}$$

Three Models of Energy Loss

1. Soft Scattering

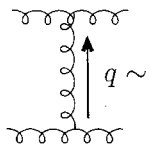
$$\frac{dp}{dt} \propto C_R\, \alpha_s^2 T^2 \log\left(\frac{T}{m_D}\right)$$



find $\chi(p) \propto p^2$

2. Collisional Energy Loss

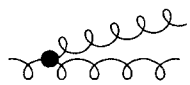
$$\frac{dp}{dt} \sim C_R\, \alpha_s^2 T^2 \log\left(\frac{p}{m_D}\right)$$



find $\chi(p) \propto \frac{p^2}{\log(p\mu)}$

3. Radiative + Collisional Energy Loss in Infinite medium

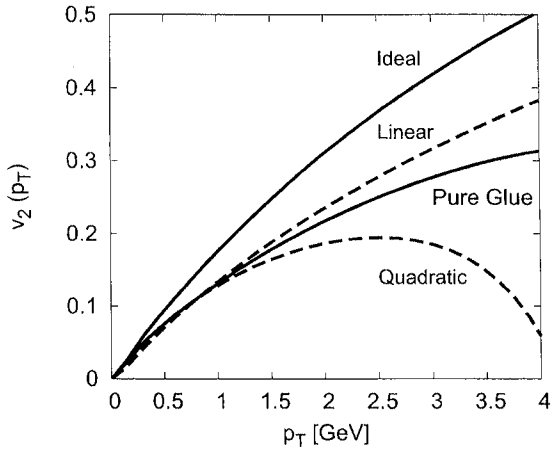
$$\frac{\Delta p}{\Delta t} \sim \alpha_s \sqrt{\hat{q} E_{\mathbf{p}}}$$



find $\chi \propto \sqrt{\hat{q}} p^{3/2}$

Phenomenological Summary

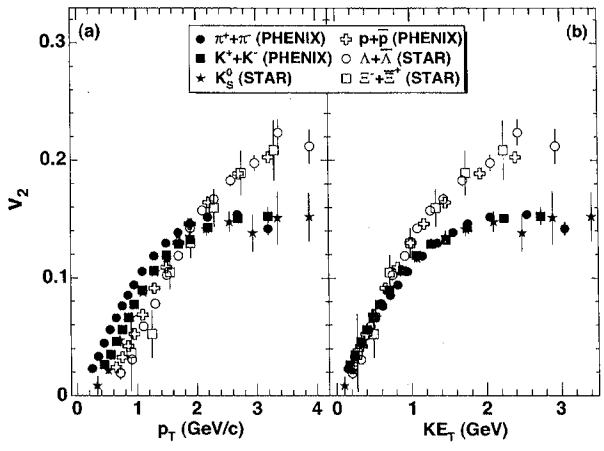
pure glue, $\eta/s = 0.08$, $e_{\rm frz} = 0.6\,{\rm GeV/fm}^3$



pQCD is closer to a linear ($\tau_R = $ const) rather than a quadratic ansatz

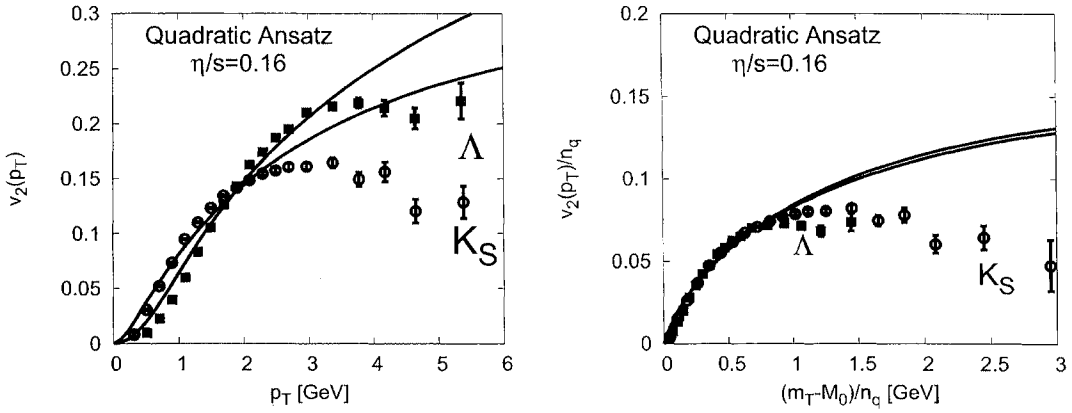
$\hat{q}$ loss sets the tail $p^{3/2}$ for hydro

Mesons and Baryons have different flows



Perhaps they have different relaxation times

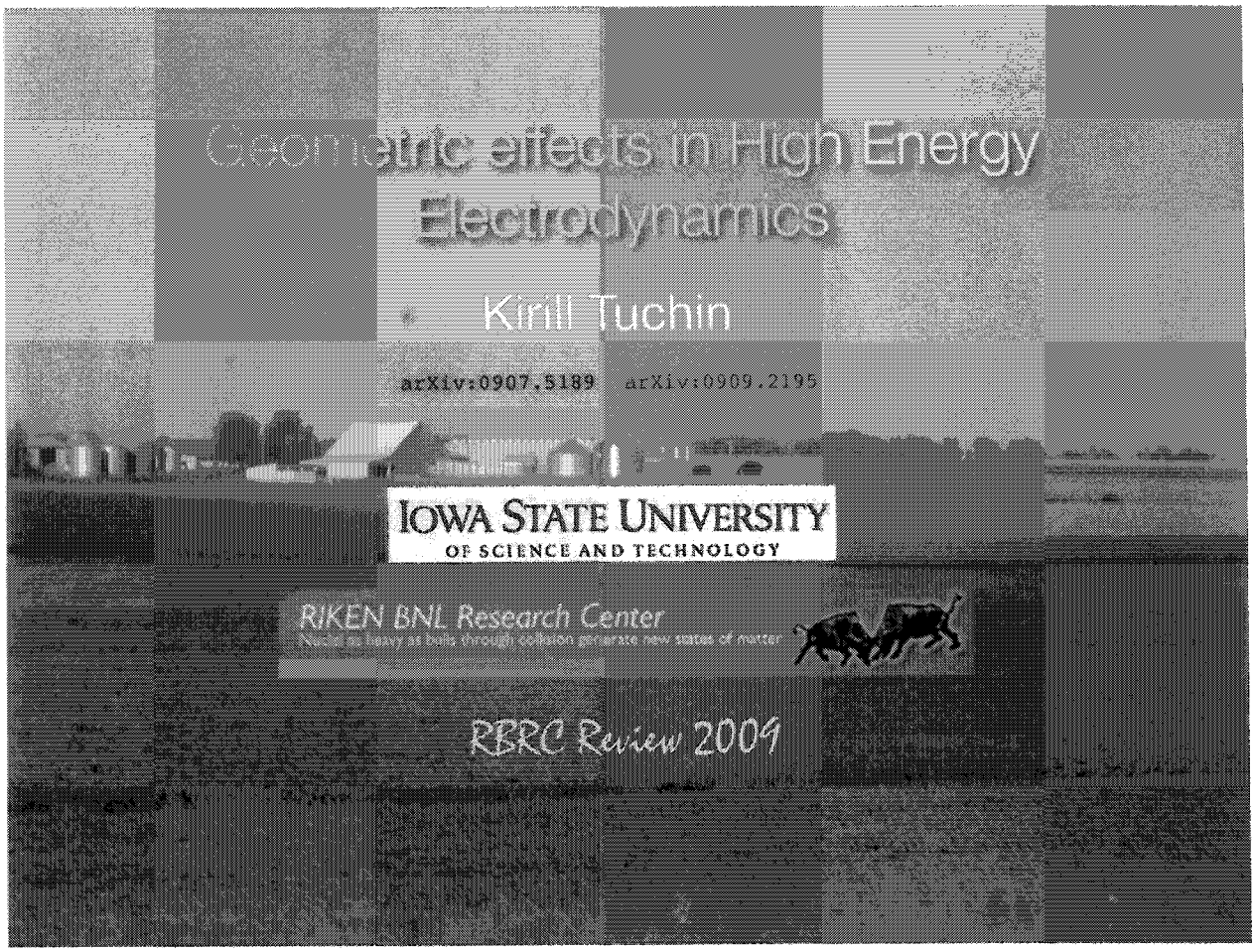
Scaling



Perhaps quark number scaling is simply *Relaxation Time Scaling* (RTS)

Future

- Hawking radiation out of equilibrium. With the $2PI$ formalism perhaps.
  - We in this field could contribute greatly!
- Further tests of viscous hydro
  - Much larger comparison with data
  - Putting in consistent η/s with $\hat{q}$
  - 2nd order kinetic theory.



Motivation

What is the main mechanism of particle production in hadron and nucleus collisions at high energies?

Is it perturbative bremsstrahlung?

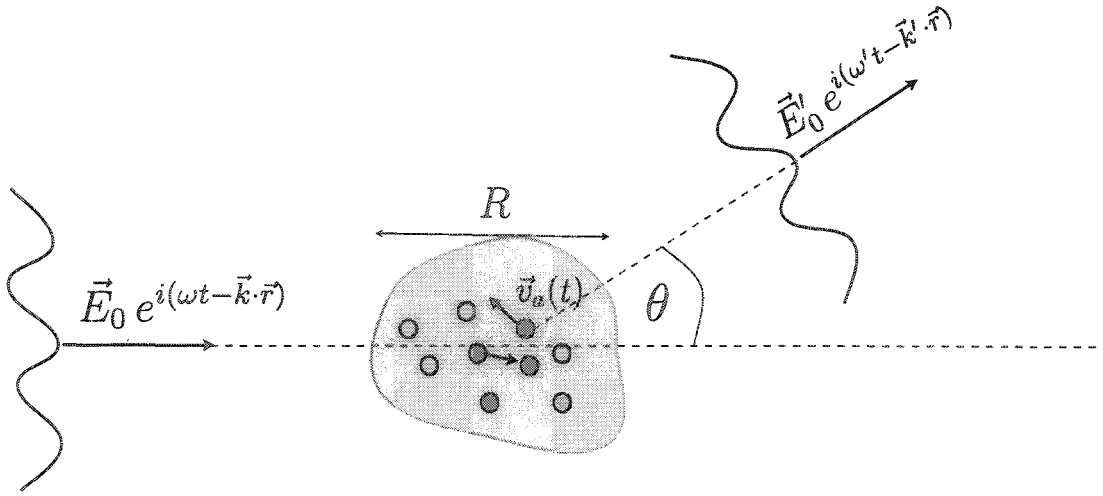
Or it is a non-perturbative pair production a la Schwinger effect?

It is hard to tell in QCD: these processes certainly occur since intensities are high and coupling is not very small, but confinement hides well the dynamics.

It is instructive to see what happens in QED.

Besides, non-linear QED is a research frontier by itself.

Classical E&M



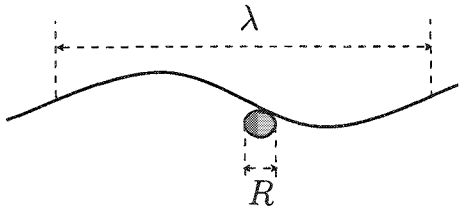
Cross section: $d\sigma = r_e^2 \left\langle \left| \sum_a e^{i\vec{q}\cdot\vec{r}_a} \right|^2 \right\rangle_t \sin^2\theta d\Omega$ $\qquad r_e = \dfrac{e^2}{mc^2}$

Momentum transfer: $\vec{q} = \vec{k}' - \vec{k}$ $\qquad q = \dfrac{2\omega}{c}\sin\dfrac{\theta}{2} \propto \dfrac{1}{\lambda}$

3

Long and short wavelengths

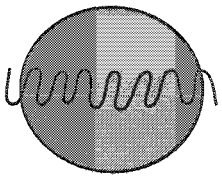
Long wavelength: $\lambda \gg R$



$|\vec{q}\cdot\vec{r}| \sim R/\lambda \ll 1 \quad \Rightarrow \quad e^{i\vec{q}\cdot\vec{r}} = 1$

$d\sigma = \boxed{N^2} r_e^2 \sin^2\theta\, d\Omega$ All charges radiate in-phase.

Short wavelength: $\lambda \ll R$

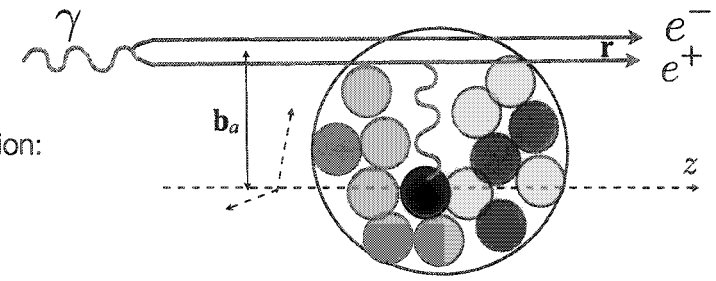


$|\vec{q}\cdot\vec{r}| \sim R/\lambda \gg 1 \quad \Rightarrow \quad \langle e^{i\vec{q}\cdot(\vec{r}_a - \vec{r}_b)}\rangle_t = \delta_{ab}$

$d\sigma = \boxed{N} r_e^2 \sin^2\theta\, d\Omega$ Charges are independent

Quantum Theory: Inelastic Scattering $\hbar = c = 1$

Pair production:



Condition for coherence (in the longitudinal direction): $q_z\, z_a \ll 1$

$$q_{z,\min} = \omega - \sqrt{E_+^2 - m^2} - \sqrt{E_-^2 - m^2} \approx \frac{m^2\omega}{2E_-E_+} \sim \frac{m^2}{\omega}$$

$$\omega \gg \frac{m^2}{R_A}$$

Consequence of coherence: photon can ***simultaneously*** interact with ***any*** number of protons in the nucleus.

5

Theory of multiple scattering

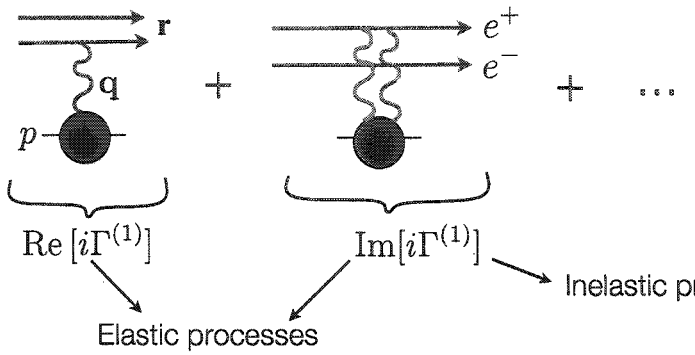
Glauber, Gribov

It is convenient to work in the configuration space because high energy particles travel along straight lines ⇒ scattering matrix is diagonal.

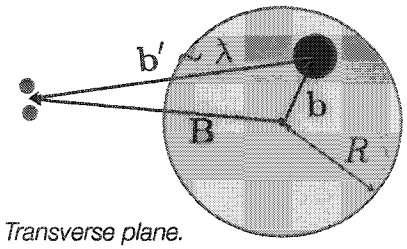
$$\sigma_{\rm tot}^{\gamma Z}(s) = \frac{\alpha\, m^2}{\pi} \int \frac{d^2r}{2\pi} \underbrace{\left\{ \frac{2}{3} K_1^2(rm) + K_0^2(rm) \right\}}_{\sim\sim\rightleftarrows} \sigma^{l\bar{l}Z}(\mathbf{r}, s)\,.$$

Assume that all Z protons are independent: $\langle \Gamma^{(Z)} \rangle = 1 - e^{-Z\langle \Gamma^{(1)} \rangle}$

$i\Gamma^{(1)} =$



Point-like nucleus



Transverse plane.

$$R \sim 6\,\text{fm} \quad \lambda = 100\,\text{fm}$$

$$l_c(\omega = 10\,\text{MeV}) = 10^4\,\text{fm}$$

$$\langle \Gamma^{(1)}(\mathbf{B}) \rangle = \Gamma^{(1)}(\mathbf{B})$$

$i\Gamma^{(1)}$ is real.

This an elastic process (A is intact)

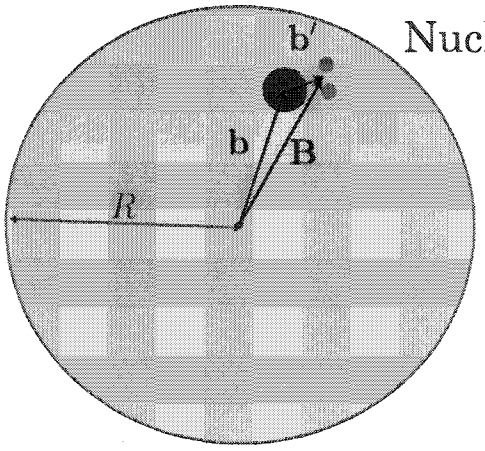
$$\sigma_{\text{tot}}^{\gamma Z}(s) = \underbrace{\frac{28}{9}\frac{\alpha^3 Z^2}{m_e^2}\left(\ln\frac{s}{M m_e} - \frac{109}{42}\right)}_{\text{Bethe-Heitler, 1934}} \underbrace{- \frac{28}{9m^2}\alpha^3 Z^2 \frac{1}{2}[\psi(1 - i\alpha Z) + \psi(1 + i\alpha Z) - 2\psi(1)]}_{\text{Bethe-Maximon, 1954}}$$

~Z^2 : classical effect of coherence

quantum effect of coherence

7

Nuclear medium



Case 2: b' << R

THIS IS ANALOGOUS TO QCD!

$i\Gamma^{(1)}$ is imaginary.

This an inelastic process (A is broken)

Due to coherence, dependence on nuclear density is non-linear!

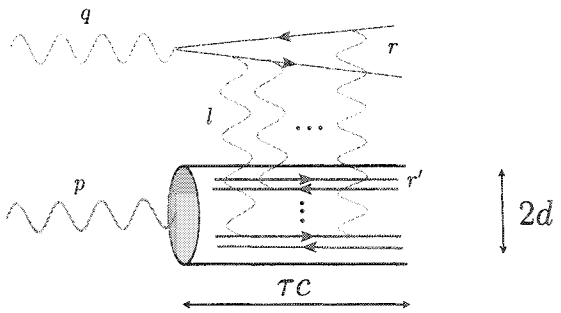
$$\sigma_{\text{tot}}^{\gamma Z}(s) = 2\alpha\, m^2\, R^2 \int \frac{d^2 r}{2\pi} \left\{\frac{2}{3}K_1^2(rm) + K_0^2(rm)\right\} \left[1 - e^{-\rho L\, 2\pi\alpha^2 r^2 \ln\omega}\right]$$

8

Applications to $\gamma\gamma$ scattering

Energetic photon ~100s GeV

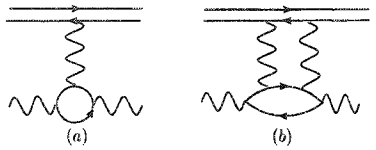
Attosecond laser pulse ~ 100 keV



For short laser pulses we can get $l_c >> \tau c$ and $b' << 2d \Rightarrow$ in medium scattering!

Characteristic parameter:

$$\kappa = N\langle \mathrm{Im}[i\Gamma^{e^-e^+\gamma}]\rangle = \frac{8\alpha^3\rho\tau}{m^2} = \frac{4I}{\pi\hbar c}\alpha^3\tau\lambda^2\lambda$$



=0 by CP

9

Applications to $\gamma\gamma$ scattering

Linear regime: $\kappa \ll 1$ Lipatov, Frolov; Cheng, Wu

$$\sigma_{\mathrm{tot}}^{\gamma\ell}(s) = \frac{\alpha^4 N}{m^2}\frac{1}{36\pi}[175\zeta(3) - 38] = \alpha\,\pi d^2\,\kappa\,\frac{1}{36\pi}[175\zeta(3) - 38]$$

Multiphoton regime $\kappa \gg 1$ K.T. 2009

$$\sigma_{\mathrm{tot}}^{\gamma\ell}(s) = \frac{1}{3}\,d^2\alpha\ln\kappa$$ dependence on intensity becomes logarithmic!

$\kappa = 1$ corresponds to $I_{\mathrm{mp}} = \dfrac{\pi\hbar c}{4\alpha^3\tau\lambda^2\lambda}$

$\hbar\omega$	$\hbar\Omega$	$\sqrt{s}$	$b'_{\max}/d$	τ	l_c/L	I_{mp}
100 GeV	100 eV	6.3 MeV	$6.3\cdot10^{-3}$	100 as	2.5	$7\cdot10^{-24}$ W/cm^2
10 GeV	1 keV	6.3 MeV	$6.3\cdot10^{-2}$	10 as	2.5	$7\cdot10^{-26}$ W/cm^2

10

Comparison with the Schwinger mechanism

Schwinger mechanism for pair production requires fields $E_c \sim \frac{m^2c^3}{e\hbar}$

Corresponding intensities $I_c = \frac{m^4c^6}{4\pi\alpha\hbar^2} = 10^{29}\,\mathrm{W/cm^2}$

$$\frac{I_{\mathrm{mp}}}{I_c} = \frac{\pi^2\lambda^2}{\alpha^2\lambda L}$$

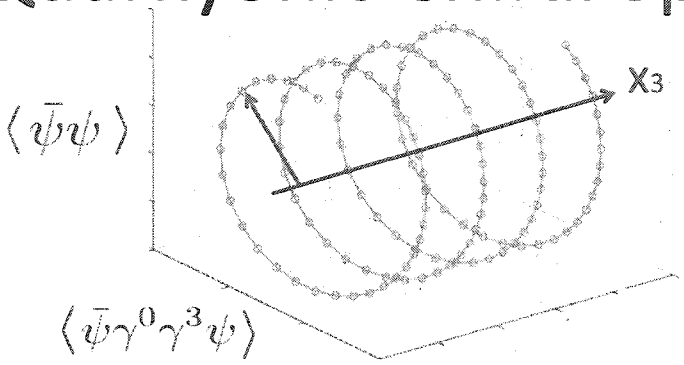
For a realistic parameters I_{mp} is much smaller!

11

Conclusion

With the rapid progress of laser technology we will soon be able to study fascinating non-linear processes in QED and learn a great deal about the perturbative and non-perturbative production mechanisms in QCD.

Quarkyonic Chiral Spiral

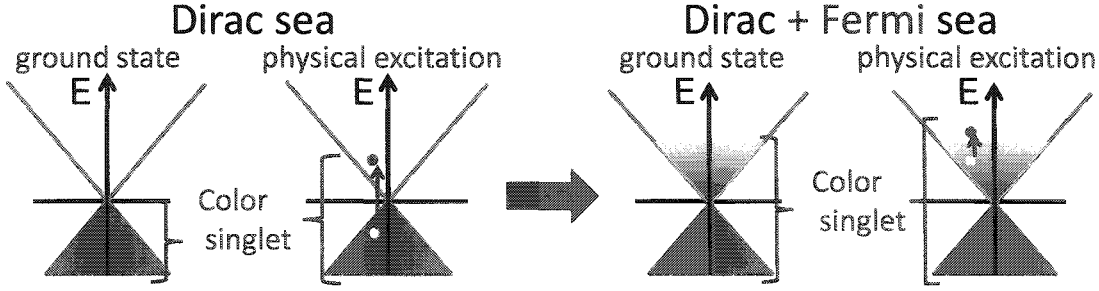


Toru Kojo (RBRC)

in collaboration with

L. McLerran (RBRC/BNL) & R. Pisarski(BNL)

Quarkyonic Matter at T=0 : Confining aspects



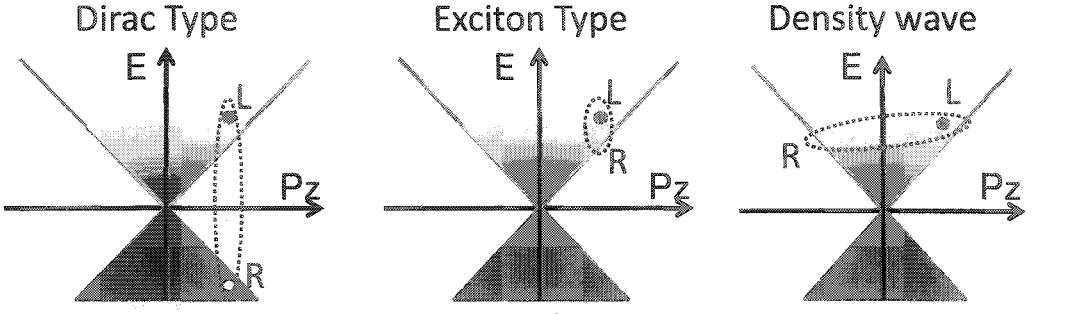
- Main difference: allowed phase space for pair creation
  → Color screening for low momentum gluons
- Quarkyonic regime: $m_D \ll \Lambda_{\rm QCD} \ll \mu$
  confining effects are strong enough; quark density is high enough
  → describe both residual hadronic & quark dynamics
- Large N_c: $m_D \to 0$, so we can use vacuum gluon propagator

$$D^{AB}_{\mu\nu}(k) = i\delta^{AB}\delta_{\mu 0}\delta_{\nu 0} \times \frac{2N_c}{N_c^2-1}\frac{\sigma}{(\mathbf{k}^2)^2}$$

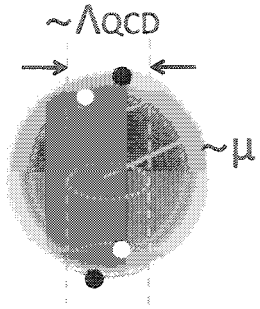
: leading part of Coulomb gauge (ref: e.g., Zwanziger)

Chiral Symmetry Breaking: Pairing Pattern

- Candidates which spontaneously break Chiral Symmetry



$P_{Tot}=0$ (uniform) $P_{Tot}=0$ (uniform) $P_{Tot}=2\mu$ (nonuniform)



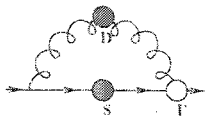
We will consider special solutions of particle & hole pairing within cylinder of Fermi sea

Both exiciton & Density wave solutions are included

4D → 2D reduction of Self-Consistent Eqs.

ex) Schwinger-Dyson eq. (in Rainbow sum) (conf. potential)

$$\not{\Sigma}(p)+\Sigma_m(p)=\int\frac{dk_4dk_zd^2\vec{k}_T}{(2\pi)^4}\gamma_4S(k)\gamma_4\frac{\sigma}{|\vec{p}-\vec{k}|^4}$$



1, $\mu \gg P_T \sim \Lambda_{QCD}$; conf. potential provides typical transverse cutoff

$$\Sigma_j(\vec{k})=\underline{k_j}\Sigma_s(\underline{\vec{k}^2}) \rightarrow \Sigma_i(\vec{k})/\Sigma_z(\vec{k})\sim\Lambda_{QCD}/\mu$$

(rotational inv.) (transverse/longitudinal)

2, Degeneracy of quark energy in P_T direction → Factorization

$$\text{RHS}\longrightarrow\int\frac{dk_4dk_z}{(2\pi)^2}\gamma_4S(k_4,k_z,\underline{\vec{0}_T})\gamma_4\int\frac{d^2\underline{k_T}}{(2\pi)^2}\frac{\sigma}{|\vec{p}-\vec{k}|^4}$$

(k_T –factorization) (→2D Smeared gluon propagator)

Non pert. self-consistent equations near the Fermi surface:

4D QCD in Coulomb gauge ⟷ 2D QCD in A_1=0 gauge

Two dictionaries & Chiral Spiral

- 4D spin sym. → 2D flavor sym. by suppression of transverse dynamics

2D spinor:

- 2D flavor multiplet: $\Psi = \begin{bmatrix} \varphi \\ \chi \end{bmatrix} \quad \varphi = \begin{bmatrix} \varphi_R \\ \varphi_L \end{bmatrix} = \begin{bmatrix} \psi_{R+} \\ \psi_{L-} \end{bmatrix} \quad \chi = \begin{bmatrix} \chi_R \\ \chi_L \end{bmatrix} = \begin{bmatrix} \psi_{L+} \\ \psi_{R-} \end{bmatrix}$

kin. part: $\left(\bar{\psi}\gamma^0\psi \ , \bar{\psi}\gamma^3\psi\right) \longleftrightarrow \left(\bar{\Psi}\Gamma^0\Psi \ , \bar{\Psi}\Gamma^3\Psi\right)$

SU(Nf) confining model ⟷ SU(2Nf) 'tHooft model

- 2D Chiral multiplet in baryon charge sector:

U(1) Chiral multiplet: $\left(\bar{\Psi}\Psi,\ \bar{\Psi}\Gamma^5\Psi\right) \longleftrightarrow \left(\bar{\psi}\psi,\ \bar{\psi}\gamma^0\gamma^3\psi\right)$

(Other channels will not show condensation)

- μ=0 & μ≠0 dictionary: $\Psi' = e^{i\mu z\Gamma_5}\Psi$ (chiral rotation or boost)

eliminates μ: $\bar{\Psi}\left[i\Gamma^\mu\partial_\mu + \mu\Gamma^0\right]\Psi \to \bar{\Psi}' i\Gamma^\mu\partial_\mu\Psi'$

μ = 0 results μ ≠ 0 results (Chiral Spiral)

$$\langle\bar{\Psi}'\Psi'\rangle = \cos(2\mu x_3)\langle\bar{\Psi}\Psi\rangle + \sin(2\mu x_3)\langle\bar{\Psi}i\Gamma^5\Psi\rangle$$

Specialities of 2D: Quasi-Long range order

- Non-Abelian Bosonization & Charge-Flavor-Color Separation

μ=0 'tHooft model → Bosonized WZW action with Separated quantum nums.

$$S = \underbrace{S_{U(1)}[\phi] + S^{flavor}_{k=N_c}[g]}_{\text{conformal inv.}} + \underbrace{S^{color}_{k=N_f}[h]}_{\text{dimensionful}} + \text{gauge int.}$$

- Two point function to detect chiral quasi-long range order:

$$\langle\bar{\Psi}_L\Psi_R(x)\bar{\Psi}_R\Psi_L(y)\rangle \quad \text{separation of each sector}$$

$$= \underbrace{\langle :e^{i\sqrt{4\pi}\phi(x)}::e^{-i\sqrt{4\pi}\phi(y)}:\rangle\langle \mathrm{tr}g(x)\mathrm{tr}g^\dagger(y)\rangle}_{\text{algebraicly computable using infinite conformal \& internal sym.}} \otimes \underbrace{M^2\langle \mathrm{tr}h(x)\mathrm{tr}h^\dagger(y)\rangle}_{\text{computable by matching 'tHooft solutions of meson spectra}}$$

Long range behavior

$$\boxed{|x-y|^{-\text{const.}/N_c}} \otimes \boxed{\langle\Phi\rangle^2} \xrightarrow{\text{large Nc}} \boxed{\langle\Phi\rangle^2}$$

(Very slow disociation) (Constant Amplitude)

Summary

- In Quarkyonic regime, Chiral Spiral pairing is favored.
  - Large Nc limit: Periodic long range order (Chiral Spiral)

Not conventional pion condensate

$$\langle \bar{\psi}\psi \rangle \sim |\langle \Phi \rangle| \cos(2\mu x_3)$$
$$\langle \bar{\psi}\gamma^0\gamma^3\psi \rangle \sim |\langle \Phi \rangle| \sin(2\mu x_3)$$

Chiral Sym. is restored globally, but violated locally.

  - Finite Nc: No long range order

Strong phase rotation

$$\langle \bar{\psi}\psi \rangle \sim |\langle \Phi \rangle| \cos(2\mu x_3) \otimes \langle e^{i\theta} \rangle \sim 0$$

But still shows anomalous slow damping in 2-point function (Quasi-long range order)

$$\langle \bar{\psi}\psi(x)\bar{\psi}\psi(y) \rangle \sim \cos|x-y| \otimes |x-y|^{-\text{const.}/N_c}$$

Lattice QCD @ RBRC
Physics Goals and the QCDCQ Project

October 22, 2009

Norman H. Christ

Outline

- Lattice QCD @ RBRC
  - Strengths
  - Strategy
  - Examples
- QCDCQ project
- Physics goals

Lattice QCD @ RBRC
Present Capabilities

Computers

- QCDOC
  - 4 Tflops sustained
  - Generate lattice ensembles $\leq 24^3 \times 64$
  - Current use
    - broad range of measurements
    - doubled $24^3 \times 64$ ensembles
    - QCD thermo
- NYBlue: Large QCD-thermo use, many smaller projects
- BG/P at Argonne
  - Create three $32^3 \times 64$, $1/a = 2.32$ GeV ensembles
  - Perform all light quark measurements
  - Use 140 M BG/P core hours (4 rack years).
- BG/L at LLNL: HotQCD, N_T=8, p4 and ASQTAD EOS.

People

- RBRC
  - Yasumichi Aoki
  - Taku Izubuchi (RBRC fellow)
  - Tomomi Ishikawa (→ UConn)
  - Shigemi Ohta (KEK)
- BNL
  - Mike Creutz
  - Chulwoo Jung
  - Shinji Ejiri
  - Frithjof Karsch
  - Chuan Miao
  - Peter Petreczky
  - Amarjit Soni
  - Ruth Van de Water (Goldhaber fellow)
  - Oliver Witzel
- Bielefeld University
- Columbia University
- University of Connecticut
- Edinburgh University
- GSI
- Southampton University
- University of Virginia

Physics
Long term strategy

- Develop and apply 2nd generation fermions:
  - Domain wall fermions
  - Accurate chiral symmetry
  - Allows accurate non-perturbative renormalization (off-shell O(a) improved)
- Target quantities that may show BSM physics:
  - Light quarks: B_K, $K13$, f_K, f_π,
  - Heavy quarks: f_D, f_{Ds}, f_B, f_{Bs}, B_B, B_{Bs}
  - $K \to \pi\pi$ decays: $\Delta I = 1/2$ and ε'/ε
- Study quantities sensitive to chiral symmetry
  - *LEC's*, η' mass
  - EM splittings
  - Nucleon properties: g_A, structure functions

Physics
Long term strategy

- QCD thermodynamics for RHIC and LHC
  - Exploit p4 and ASQTAD actions
    - Determine EOS
    - Locate T_c
    - Study non-zero μ
    - Examine continuum limit
    - Explore effects of charm and charmed states.
  - Develop staggered HISQ action
    - Reduce O(a^2) errors
    - Decrease taste breaking
  - Apply domain wall fermions
    - Explore the chiral transition with chiral fermions
    - Compare Wilson-based and staggered results.

New Results

- DWF results from two lattice spacings
  - Small, 1-2% , $O(a^2)$ errors.
  - Dominant errors: $m_l \rightarrow$ 3-5 MeV limit.
  - $B_K = 0.537(19)$ [preliminary].
- First results for N_t=12 QCD thermo.

Lattice 2009, Beijing
Plenary talks

- Yasumichi Aoki: *Non-perturbative renormalization*
- Chulwoo Jung: *Status of dynamical ensemble generation*
- Enno Scholz (recent BNL postdoc): *Light Hadron Masses and Decay Constants*
- Ruth Van de Water: *The CKM matrix and flavor physics from lattice QCD*

Heavy quark physics
(Hao Peng)

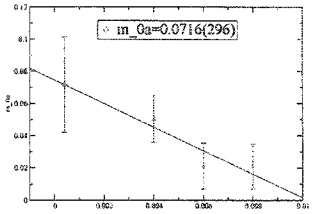
- Continue to develop relativistic heavy quark (RHQ) approach.
  - Remove all $(m_h a)^n$ errors.
  - Introduce two new parameters, c_P and ζ:

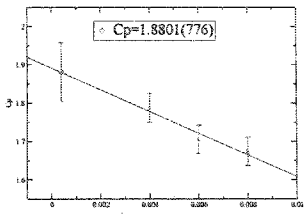
$$\mathcal{L}_{\text{Symanzik}} = \overline{\psi}\left(\gamma^0 D^0 + \zeta\vec{\gamma}\cdot\vec{D} + m_0 + \sum_{\mu,\nu}\frac{i}{4}c_P\sigma_{\mu\nu}F_{\mu\nu}\right)\psi$$

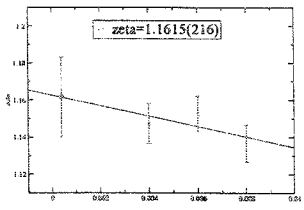
- Repeat charm and bottom study on 1/a=2.32 GeV ensembles
  - Examine scaling
  - Determine action to be used in $B - \overline{B}$ mixing calculation.

Heavy quark physics
(Hao Peng)

- Determine m_0, c_P and ζ on 32^3x64, $1/a = 2.32$ GeV ensemble:



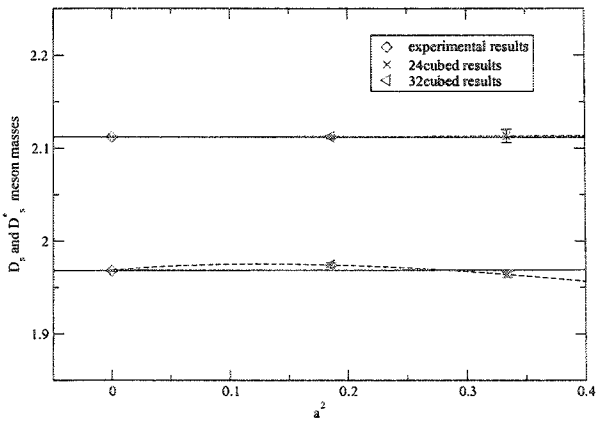




$m_0 = 0.072(30)$ $c_P = 1.88(8)$ $\zeta = 1.16(2)$

Heavy quark physics
(Hao Peng)

- Examine scaling of m_{Ds} and m_{Ds*}



	m_{Ds} MeV	m_{Ds*} MeV
$1/a$=1.73 GeV	1964(3)	2.113(7)
$1/a$=2.32 GeV	1974(2)	2.112(2)
Exp't	1968.2(5)	2.1120(6)

Preliminary!

$K \to \pi\pi$ decays
$\Delta I = 1/2$ rule and ε'/ε

- Challenges:
  - Quadratic divergent penguin diagrams
  - Operator normalization and mixing
  - Two particle π–π final state
  - Disconnected diagrams
- First I=2 ($\Delta I = 3/2$) and I=0 ($\Delta I = 1/2$) calculations started.

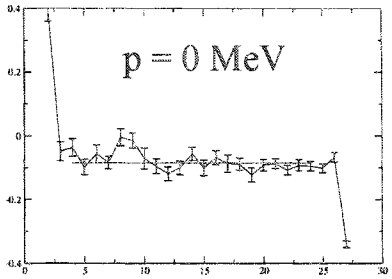
$K \to \pi\pi$ decays: $\Delta I = 3/2$ amplitudes

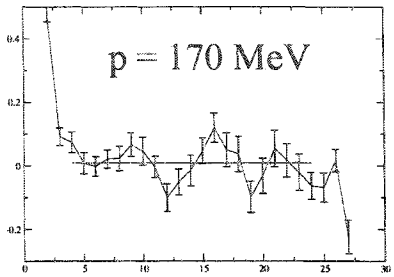
(Matthew Lightman)

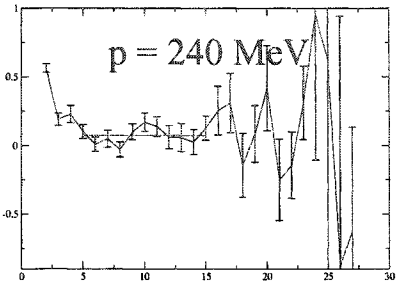
- Less demanding than $\Delta I = 1/2$.
- Non-zero $\pi^+ - \pi^+$ relative momentum
  - Impose anti-periodic B.C.'s on π^+'s
  - Anti-periodic u's, periodic d's
  - Only needed for valence quarks.
- First $1/a = 1.3$ GeV, $24^3 \times 64$ quenched study:
  - $m_\pi = 230$ MeV
  - Preliminary!
- Next step is 2+1 flavor, $32^3 \times 64$ at Argonne (begin in December).

$K \to \pi\pi$ decays: $\Delta I = 3/2$ amplitudes

(Matthew Lightman)







p (GeV)	0	170	240
O^{27}	0.0051(2)	0.0088(4)	0.0142(14)
O^{88}	0.087(3)	0.092(3)	0.102(10)
O^{88m}	0.302(10)	0.324(11)	0.373(28)

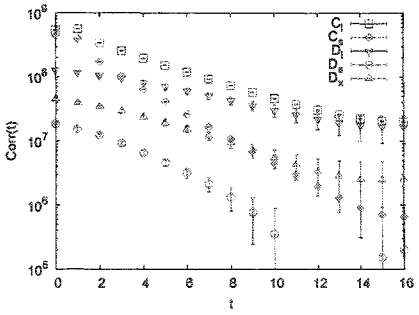
$K \to \pi\pi$ decays: $\Delta I = 1/2$ amplitudes

(Qi Liu)

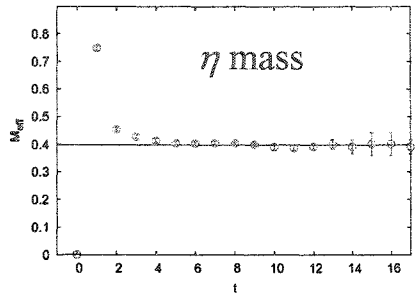
- Disconnected diagrams
- Code written and checked
- Use $p_K \sim 740$ MeV to achieve physical $\pi-\pi$ state
- Use G-parity in next phase?
- Preliminary $16^3 \times 32$, 2+1 flavor $K \to \pi\pi$ results being analyzed.
- High statistics strategy
  - Put K and $\pi-\pi$ sources on each of 32 time planes.
  - Use Ran Zhou's eigenvector accelerator code.
- Early results for η and η' states (arXiv:0910.2658 [hep-lat]).

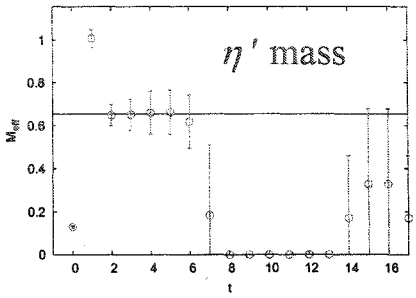
η and η' mixing and masses

(Qi Liu)



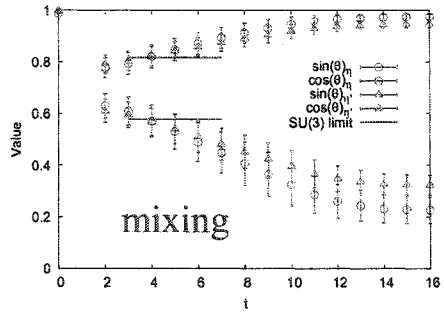
- See satisfactory signal: $3 \le t \le 7$.
- Time separation too small to avoid excited states?
- Multi-state variational calculation needed.

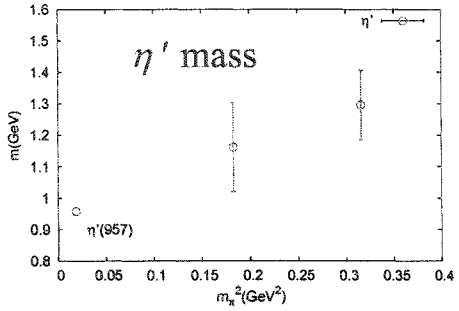




η and η' mixing and masses

(Qi Liu)





- With m_l/m_s=0.25 see anomaly-dominated mixing:
  - Eigenstates are octet and singlet, not $\bar{u}u+\bar{d}d$ and $\bar{s}s$
  - Masses obey Gell-Mann/Okubo: $m_\eta = 687(29)$ MeV

$$3\,m_\eta^2 + m_\pi^2 = m_K^2 \quad \rightarrow \quad m_\eta = 667(4)\ \text{MeV}$$

- Adding more statistics to check results.

QCDCQ Project
(QCD with Chiral Quarks)

QCDCQ

- Technology
  - QCDOC design now 10 years old.
  - Important opportunities:
    - 180 → 45 nm feature size
    - Enables multiple cores/chip and FPUs/core.
  - 50x boost in cost performance:
    $1/Mflops → < $0.02/Mflops
- Strategy
  - Joint RBRC/Columbia/Edinburgh/IBM project.
  - Follow-on to QCDOC and BlueGene projects.
  - Joint research project builds two 300 Tflops prototype computers:
    - RBRC
    - Edinburgh

QCDCQ

Single rack (1024-node) capability:

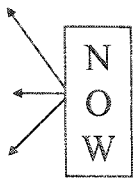
- BG/P rack (2 Tflops) → QCDCQ rack (60 Tflops)

  $32^3 \times 64$ → $64^3 \times 128$

- Consistent with 2^6 scaling of RHMC algorithm
- On 1024 nodes $64^3 \times 128 \Leftrightarrow 8 \times 16 \times 16 \times 16$ local volume
  - Gives efficient performance: memory and communications bandwidth/latency are adequate.
  - $48^3 \times 64 \Leftrightarrow 8 \times 6 \times 12 \times 12$ local volume works well too.

QCDCQ
Target Ensembles

Volume	$1/a$	L	m_π	Time units	$m_{quark}a$
$32^3 \times 64$	1.40 GeV	4.5 fm	180 MeV	200	0.001+0.0018
			250 MeV	1000	0.0042+0.0018
$24^3 \times 64$	1.73 GeV	2.7 fm	315 MeV	9000	0.005+0.0032
			402 MeV	9000	0.01+0.0032
$32^3 \times 64$	2.32 GeV	2.7 fm	300 MeV	7000	0.004+0.0006
			350 MeV	8000	0.006+0.0006
			410 MeV	6000	0.008+0.0006



Volume	$1/a$	L	m_π	Time units	$m_{quark}a$	QCDCQ Rack Yrs.
$48^3 \times 64$	1.40 GeV	6.7 fm	140 MeV	3000	0.0001+0.0018	0.5
$48^3 \times 64$	2.32 GeV	4.0 fm	180 MeV	6000	0.001+0.0006	0.25
$32^3 \times 8$	1.40 GeV	4.5 fm	140 MeV	200,000	0.0001+0.00018	0.6

QCDCQ
Target Ensembles

Volume	$1/a$	L	m_π	Time units	$m_{quark}a$	QCDCQ Rack Yrs.
$48^3 \times 64$	1.40 GeV	6.7 fm	140 MeV	3000	0.0001+0.0018	0.5
$48^3 \times 64$	2.32 GeV	4.0 fm	180 MeV	6000	0.001+0.0006	0.25
$64^3 \times 128$	2.32 GeV	5.4 fm	140 MeV	6000	0.0004+0.0006	2.5
$32^3 \times 8$	1.40 GeV	4.5 fm	140 MeV	200,000	0.0001+0.0018	0.6
$48^3 \times 8$	1.40 GeV	6.7 fm	140 MeV	200,000	0.0001+0.0018	2.8
$48^3 \times 12$	1.73 GeV	5.4 fm	140 MeV	200,000	0.0005+0.001	2.0

- Coarse lattice $K \rightarrow \pi\pi$ with physical kinematics.
- Fine lattice scaling study with $m_\pi \geq 180$ MeV.
- DWF thermo scaling with physical m_π.

Physics Goals

- The chiral limit: most important challenge for lattice QCD
  - Fermions with chiral symmetry
  - Pions and kaons with physical masses.
  - Nucleon structure at large volume, nearly physical masses.
- Include $\pi\pi$ states:
  - Decades old problems of $\Delta I = \frac{1}{2}$ rule and ε'/ε are likely soluble.
  - First steps underway on QCDOC, NYBlue and Argonne BG/P.
- Finite temperature studies: reach a new level of accuracy
  - Go from $N_T = 8$, to 12 and 16 (staggered), 5% EOS
  - Use chiral, DWF fermions, $N_T = 8$ & 12, $T < T_c$

Conclusion

- Lattice QCD methods and machines:
  - Highly developed after 3 decades
  - Now at the "chiral threshold"
- RBC-UKQCD Collaboration:
  - Very strong science
  - Broad research program
  - Excellent opportunities to learn
- QCDCQ exploits these strengths:
  - Accurately control of chiral limit
  - Treat 2-particle states ($K \rightarrow \pi\pi$)
  - Do nucleon physics in 6 Fermi box.
  - Explore the QCD phase transition and plasma using highly improved staggered and chiral fermions and at 2x smaller lattice spacings.

RBRC Lattice Activities

Taku Izubuchi

for RBC-UKQCD collaboration

RIKEN BNL Research Center

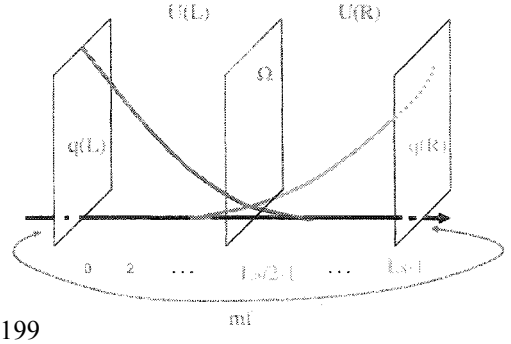
BROOKHAVEN NATIONAL LABORATORY

Domain Wall Fermions

- Almost perfect chiral symmetric lattice quarks
  - Automatic off-shell O(a) improvement.
  - Error from discretization is small $O(a^2\Lambda^2) \sim O(1\%)$
  - Best for QCD Matrix Elements
- Vacuum polarization effects from up, down, strange (Nf=2+1) quarks are fully incorporated.
- The second lattice spacing this year.
- Unitary theory

Volume	a^{-1} (GeV) m_{ss}	m_l, m_s	MD time units	Number of wall sources
$16^3 \times 32 \times 16$ (1.82 fm)^3	1.62(4) 0.00308(4)	(0.01, 0.04) (0.02, 0.04) (0.03,0.04)	4015 4045 7900	
$24^3 \times 64 \times 16$ (2.74 fm)^3	1.75(3) 0.00315(2)	(0.005,0.04) (0.01,0.04) (0.02,0.04) (0.03,0.04)	8980 8540 2850 2813	2×203 2×178
$32^3 \times 64 \times 16$ ($\approx$ 3 fm)^3	2.32(4) 0.000664	(0.004, 0.03) (0.006, 0.03) (0.008, 0.03)	6756 7220 5980	305 (P+A) 312 (P+A) 253 (P+A)
$32^3 \times 64 \times 32$ ($\approx$ 4.5 fm)^3	$\approx$ 1.4 $\approx$ 0.0018	(0.0042, 0.045)	3000	Being generated

[R. Mawhinney Lattice09]



RBC/UKQCD collaboration

RIKEN-BNL Research Center
Y. Aoki, T. Izubuchi, T. Ishikawa, S. Ohta

BNL
C. Jung, A. Soni, R. Van de Water, O. Witzel

Columbia Univ.
N. Christ, M. Endres, X-Y. Jin, C.Kim, M. Li, S. Li, M.Lightman, Q. Liu, R. Mawhinney, H. Peng, S. Takeda

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

Univ. Virginia C. Dawson

Univ. Regensburg E. Scholz

Harvard Univ. M. Clark

Yale Univ. M. Lin

Univ. Edinburgh
D. Antonio, P. Boyle, Paul Cooney, A. Hart, A. Kennedy, R. Kenway, C. Kelly, C. Maynard, B. Pendelton, J. Wennekers, J. Zanotti

Univ. Southampton
D. Brommel, M. Donnellan, J. Flynn, Elaine Goode, Patrick Fritzsch, C. Sachrajda

Univ. Swansea C. Allton

12 students, 16 PhD thesis,

3 new faculties

HAW09 work shop (2+2 talks)

1 talk @ LBV09

(4+2) plenary talks @ LATTICE09

3 plenary talks @ KAON09

(4.5+1) talks @ Tsukuba CCP Workshop 09

2 talks @ MORIOND QCD09

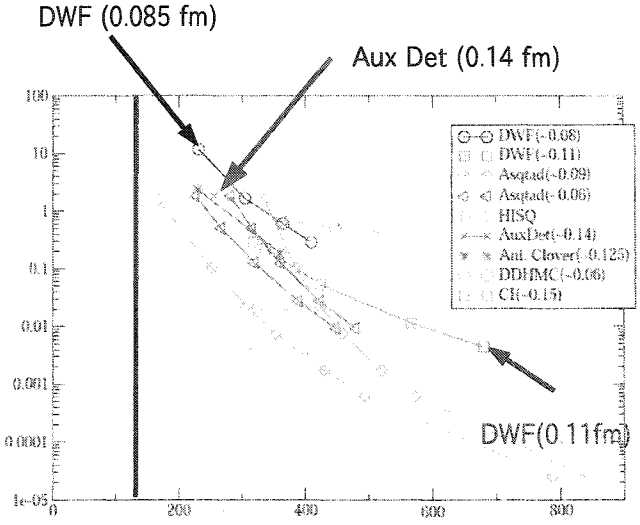
3

Menu of lattice QCD

- Nf=2+1 dynamical quark , two lattice spacings
- Chiral Perturbation Theory meson mass & decay constant
- Electro-Magnetic (QED) Effects & Quark masses
- Renormalization & Scheme matching
- Reweighting
  & Strange quark contents in Nucleon (Dark matter detection)
- Chiral magnetic effect
  [T. Blum's talk]
- Nucleon studies
  [Y. Aoki, S. Ohta's talks]
- Flavor Physics, CKM, Electro Weak Matrix Elements
  - f_K / f_π
  - $K \to \pi\, l\, \nu$ (K13)
  - K0-K0 mixing (B_K)
  - B, D physics
    [N. Christ's, T. Ishikawa's talks]
- Strong dynamics (Technicolor), SUSY

5

Cost vs quark mass [C. Jung lat 09]



TFlops-year vs. m_π(Mev)

10^4 MD units, $m_\pi L = 4$, $T/L = 2$

- Ukawa's Berlin Wall (lattice 2001) becomes less harsh

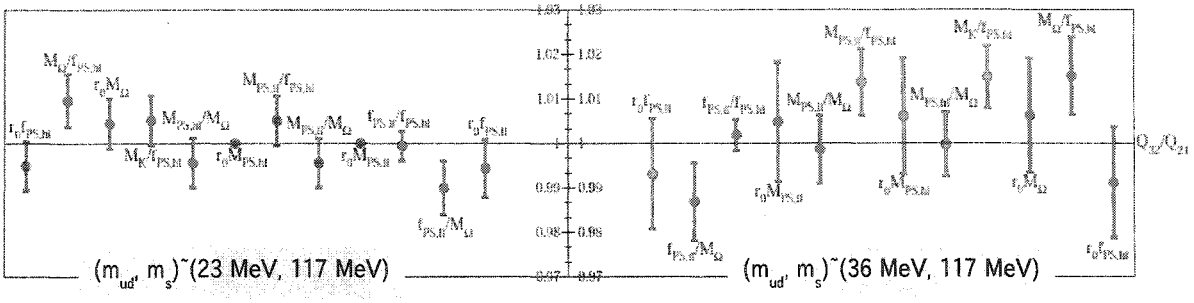
$$\left(\frac{L^3 \times T}{a^4}\right)^{5/4} \left(\frac{1}{m_\pi a}\right) \left[C_0 + C_1 \frac{1}{m_K^2 a} + C_2 \left(\frac{a}{m_\pi}\right)^2\right]$$

- But DWF on the physical point is still difficult.

DWF Needs chiral extrapolation from simulation points to the physical point m_π = 135 MeV (mu, md = 2 ~ 6 MeV)

Scaling check [C. Kelly lat09]

- Two lattice spacings 1/a = 1.72(2), 2.32(3) GeV
  (0.11 fm, 0.085 fm)
- To isolate the scaling (lattice spacing) error, we pick the similar simulation quark mass points from the two lattice spacing.
- Compare ratios of dimensionless quantities, made from r_0, M_{PS}, M_Ω, $f_{PS,}$ between the two lattices.
- Tuning for the quark mass points is done using $r_0 M_{PS,ll}$ and $r_0 M_{PS,hl}$
- Little dependence on which quantities were matched
- Less than about 2 % scaling error, consistent with $O((a\Lambda)^2)$

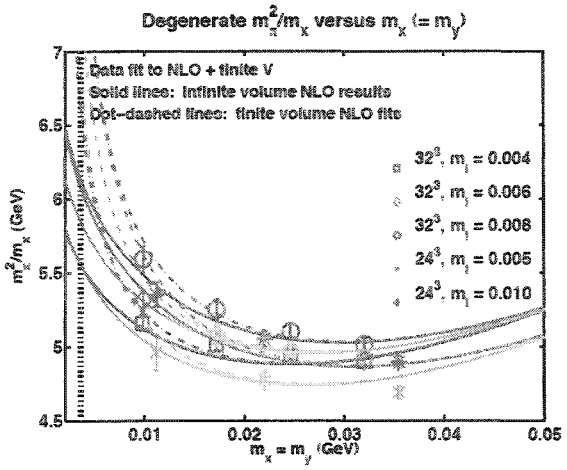


Chiral extrapolation

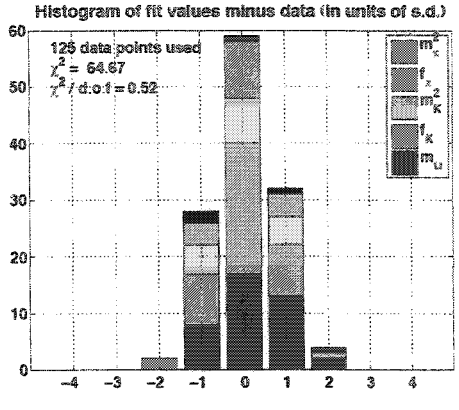
[B. Mawhinney lat09]

- Using Chiral Perturbation Theory (ChPT) at NLO(1-loop).
- Heavy Kaon + SU(2) Partially Quenched ChPT
- Global simultaneous fit for M^2_π, f_π, M^2_K, f_K, M_Ω using two lattice spacings.
- Counting m_q, $(a\Lambda)^2$ as small

  (Only Leading order Low Energy Constant B, f, has lattice spacing errors, a^2)

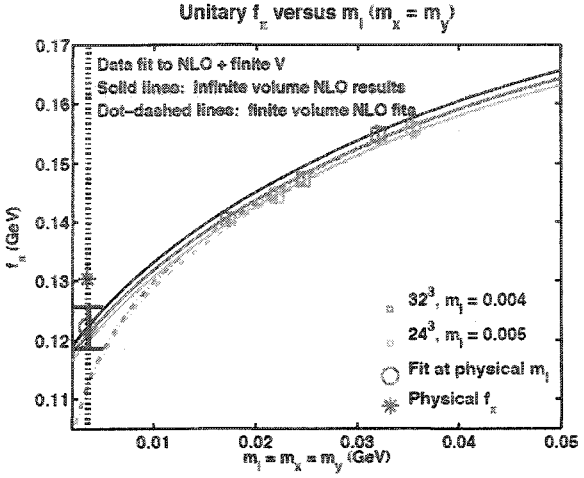


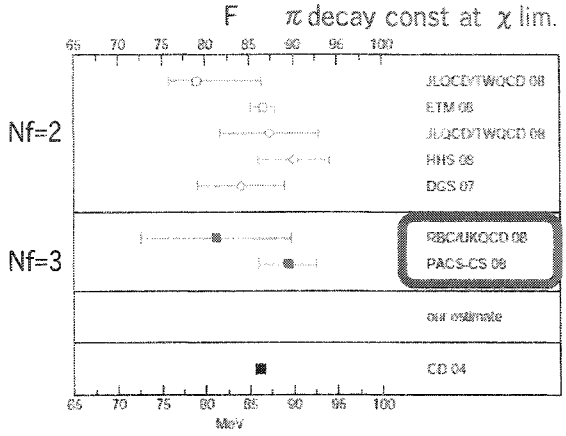
(125 data, ~20 parameters)



Chiral extrapolation

- SU(2) NLO Chiral extrapolation for f_π and f_K
- Extrapolated f_π, f_K at the physical point
  undershoot by 8 % [3σ], 5 % [2σ]
- NNLO (2-loop) fits on our data are not stable.
  (too heavy and/or small number of data points?)

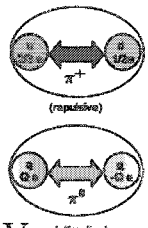




[FlaviA net 09]

QCD+QED simulation

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



- Up down quark has different electric charge and masses
  → Breaking of isospin symmetry
- Isospin breaking effects are accurately measured experimentally

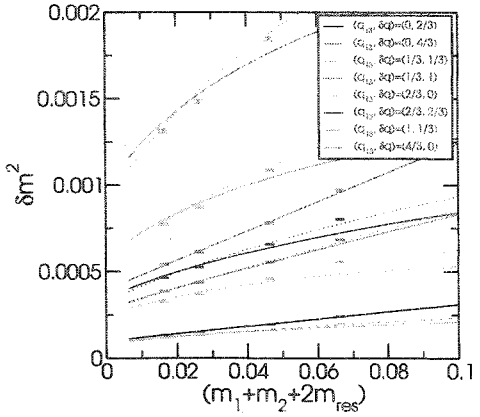
$$\Delta m_\pi = m_{\pi^\pm} - m_{\pi^0} = 4.5936(5)\text{MeV},\ m_N - m_P = 1.2933317(5)\text{MeV}$$

- Quark masses. Is up quark massless possible ?
  Can it explain the very small Neutron Electric Dipole Moment ? (Strong CP problem)

$$\delta m^2 = M_{\rm PS}^2(e^2) - M_{\rm PS}^2(e^2 = 0)$$

- 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

24^3 $m_l = 0.01$

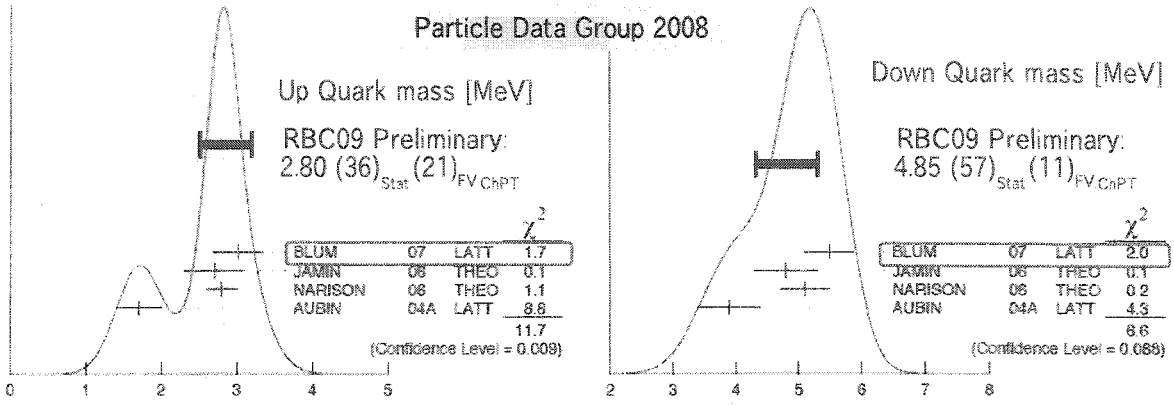


- Fit to chiral perturbation theory with EM (SU(3)+EM and SU(2)+Kaon+EM) to extract quark masses.
- Chiral symmetry is essential to define quark massless points unambiguously.
- Inputs:

$$M_{\rm PS}(m_{\rm up}, 2/3, m_{\rm dwn}, -1/3) = 139.57018(35)\text{MeV}$$
$$M_{\rm PS}(m_{\rm up}, 2/3, m_{\rm str}, -1/3) = 493.673(14)\text{MeV}$$
$$M_{\rm PS}(m_{\rm dwn}, -1/3, m_{\rm str}, -1/3) = 497.614(24)\text{MeV}$$

Quark mass results

- Just from PDG08, the world-averaging of each individual up and down quark mass were started. There are only 4 (2 lattice) results for up quark so far.
- PDG09 (PDGlive)'s world averages ($\overline{\rm MS}$, [NDR] 2 GeV)
  m(up) = 2.70 ± 0.18 MeV m(down) = 5.00 ± 0.23 MeV
- QCD+QED simulation new results (only 1/a ~ 1.72 GeV)



- Origins of charge splitting of Kaons

K+ : $(\bar{s}u)$ K0 : $(\bar{s}d)$

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

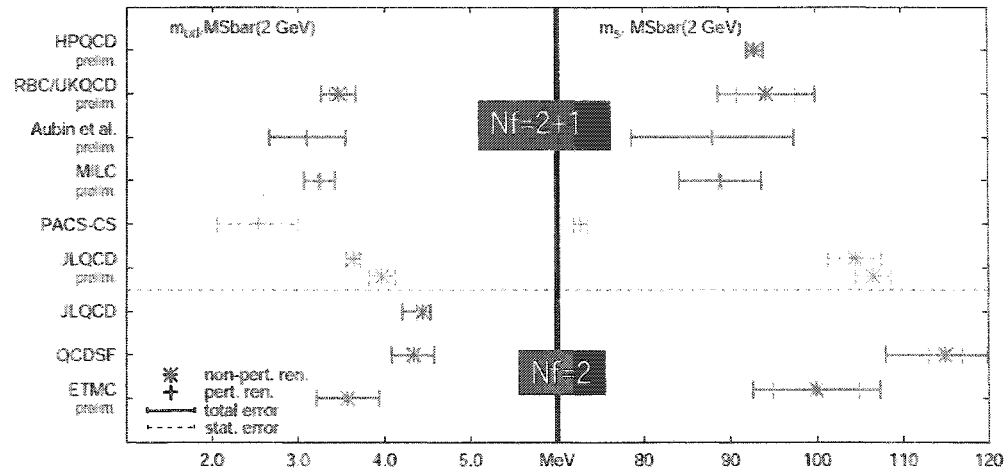
$$\Delta^{(e^2)} M_K = 1.20(10)\text{MeV}$$
$$\Delta^{(mq)} M_K = -5.13(11)\text{MeV}$$

Quark mass results

[Enno Scholz lat09]

- Status of quark mass determinations from lattice QCD
  (In this plot, QED effects are estimated by Dashen's theorem)

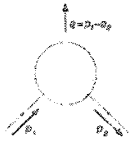
$\bar{m}(\overline{\rm MS}, 2\text{GeV}) = (m_u + m_d)/2$ $m_s(\overline{\rm MS}, 2\text{GeV})$



New Renormalization Scheme [Yasumichi Aoki lat09]

[C. Sturm, Y. Aoki, N. Christ, TI, C. Sachrajda, A. Soni]

- Match the normalization of operator on lattice and in continuum theory (MS) in RI/SMOM scheme $(q^2 = p_1^2 = p_2^2)$

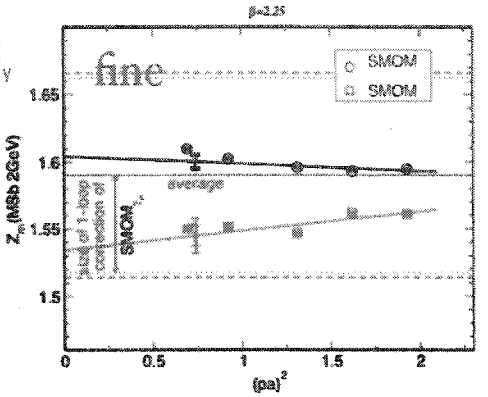


calculat the 3 pt amplitudes for {a momentum configuration on lattice non-perturbatively, same mom. Configuration in continuum, and in MS}

- We find symmetric momentum (SMOM) configuration is useful to reduce one of the dominant systematic error due to IR effects, ~10% → ~ 5% (PT dominant) , of central values for quark masses.

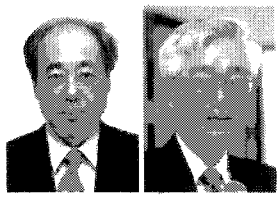
- Two intermediate schemes to check the systematical errors RI/SMOM & RI/SMOM$_\gamma$
- Writing a paper for the four quark operator for B_K
- Now the two loop matching calculation is in progress

[L. Almeida, C. Sturm, TI]



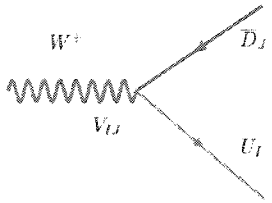
CKM physics on DWQCD

[Ruth Van de Water lat09]



- In 1963, N. Cabbibo, then M. Kobayashi and T. Maskawa in 1973 introduced a mixing between quark flavors.

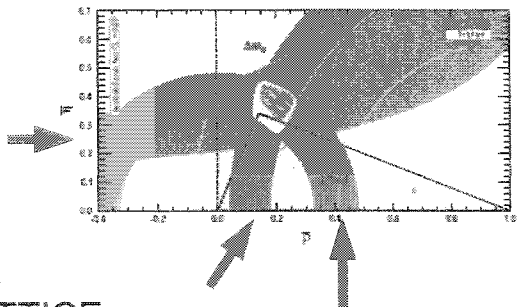
$$V_{CKM} = \begin{bmatrix} V_{ud}, V_{us}, V_{ub} \\ V_{cd}, V_{cs}, V_{cb} \\ V_{td}, V_{ts}, V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\lambda^2/2, & \lambda, & A\lambda^3(\rho - i\eta) \\ -\lambda, & 1-\lambda^2/2, & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta), & -A\lambda^2, & 1 \end{bmatrix}$$



- Unitary condition CKM matrix includes: the unitarity triangle

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

K_0-$\bar{K}_0$ B_K



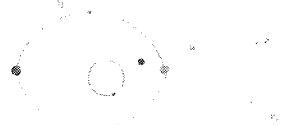
- To pin down the CKM, and to search for the new physics, the Hadron matrix elements is needed: EXPT. = CKM x LATTICE

B decay, B_0-$\bar{B}_0$ $B \to \pi$ l nu

V_{us} from K_{l2} and K_{l3}

- Taking ratio of the decay widths of K and π (W. Marciano 2004):

$$\frac{\Gamma(K^+ \to \bar{\mu}\nu(\gamma))}{\Gamma(\pi^+ \to \bar{\mu}\nu(\gamma))} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2}{f_\pi^2} \frac{m_K}{m_\pi} \left[\frac{1 - m_\mu^2/m_K^2}{1 - m_\mu^2/m_\pi^2}\right]^2 \times (1 + \delta_{em})$$



- Kaon's leptonic decay form factors
  - T. Kaneko 2005 RBC Nf=2,
  - +UKQCD (A. Juttner, C. Sachrajda et. al.) Nf=2+1

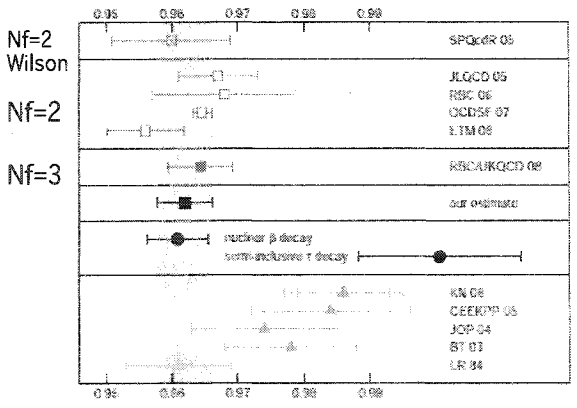
$$\Gamma(K \to \pi l \bar{\nu}) \propto \langle \pi(p)|\bar{s}\gamma_\mu u|K(p')\rangle |V_{us}|$$

$$\propto f_0(q^2)\frac{m_K^2 - m_\pi^2}{q^2} q_\mu + f_+(q^2)\left[(p+p')_\mu - \frac{m_K^2 - m_\pi^2}{q^2} q_\mu\right]$$

- "Future is in the hands of lattice : $f_+(0)$, f_K/f_π, m_s" (Marciano KAON07)

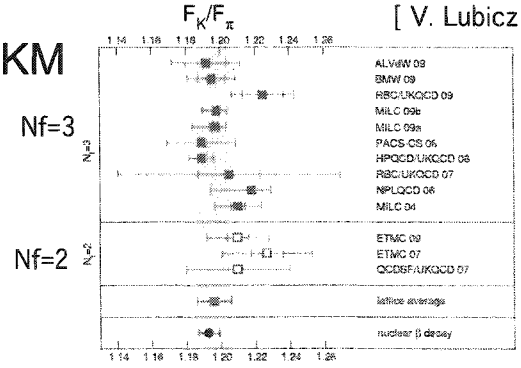
Lattice world averages for CKM

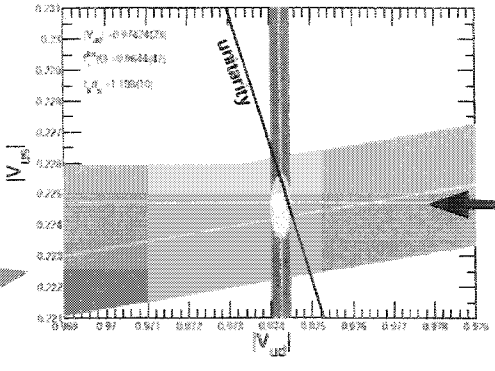
$f_+(0)$



[G. Colangelo KAON09]

F_K/F_π [V. Lubicz lat09]





- RBRC/UKQCD, Nf=2+1 , now taking continuum limit values
- Only one KI3 for Nf=3: the world best $|V_{us}|$
- f_K/f_π good agreements

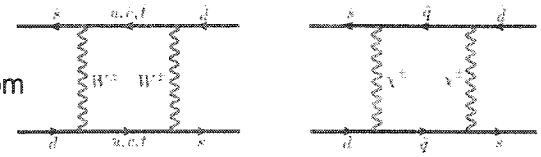
$$V_{ud} = 0.97424(23)$$

I.Towner and J.Hardy, CKM(2008)

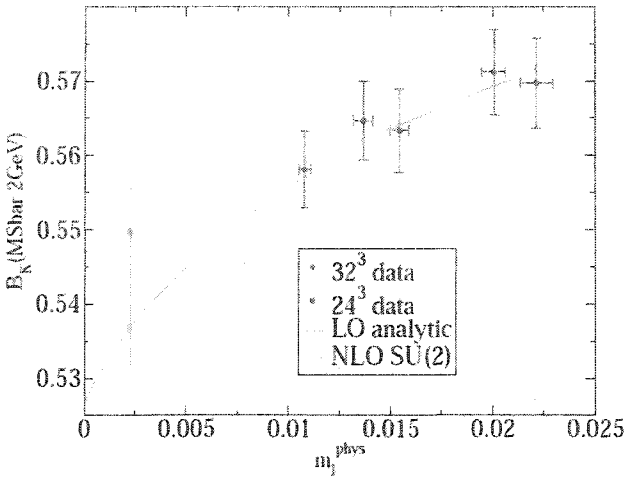
Courtesy of Flavianet Kaon WG and A.Juttner

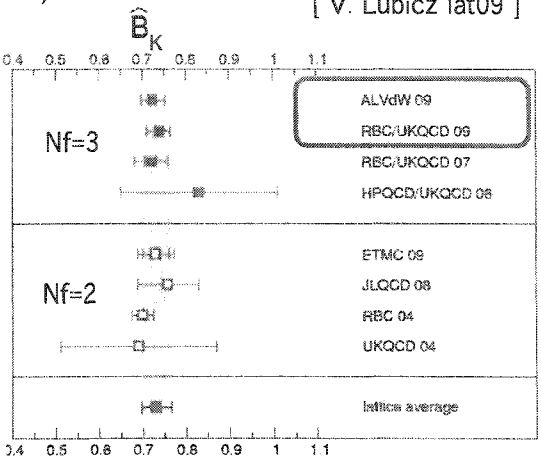
B_K [C. Kelly lat09]

- Taking continuum limit
- Non-perturbative renormalization. Systematics from four RI-(S)MOM schemes
- SU(2) ChPT fit (linear fit for systematical error)
- Preliminary value (without finite volume correction)
  B_K(2GeV) = 0.537(19)



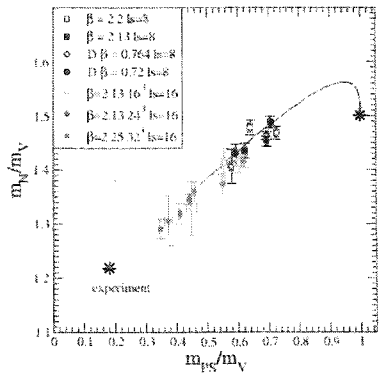
[V. Lubicz lat09]





Nucleon studies on DWF

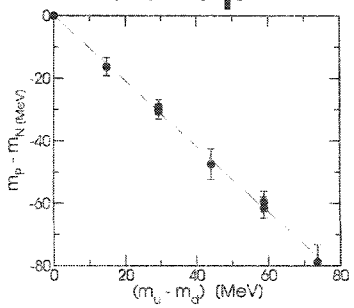
- Proton / Neutron mass and their splittings
- Proton Decay [Y. Aoki's talk]
- Structure functions [S. Ohta's talk]
- Proton / Neutron's Electric dipole moment



[DWF compilations by C. Maynard]

Nucleon mass splitting on Nf=2, 2+1

$m_n - m_p|_{\Delta m_q}$



a linear extrapolation to the physical point

$$m_{\text{down}} - m_{\text{up}} = 2.0(2)\ \text{MeV}$$

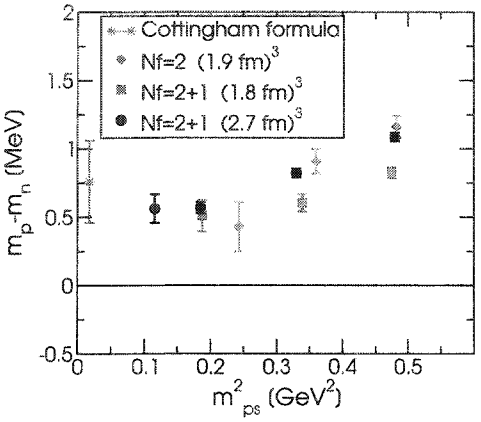
- Two origins of Proton Neutron mass difference

$$m_n - m_p = 1.29933317(5)\ \text{MeV}$$

- up down quark mass difference
  RBC 09 Preliminary

$$m_n - m_p|_{\Delta m_q} = 2.3(3)\ \text{MeV}$$

$m_n - m_p|_{\text{QED}}$

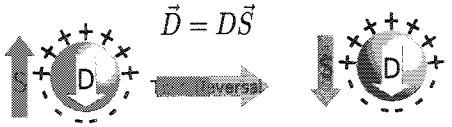


- Quark charges difference:

  a consistent results with ChPT prediction

$$m_n - m_p|^{\text{ChPT}}_{\text{QED}} = -0.76(30)\ \text{MeV}$$

- Electric Dipole Moment (EDM) of Nucleons (Strong CP problem)

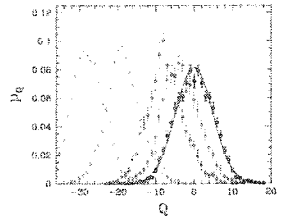


- vacuum angle θ , is implemented on lattice with analytical continuation:

$$\theta \rightarrow -i\theta$$

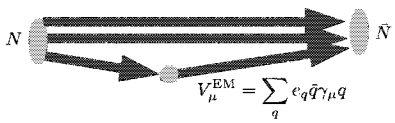
- Topological charge distribution & EDM

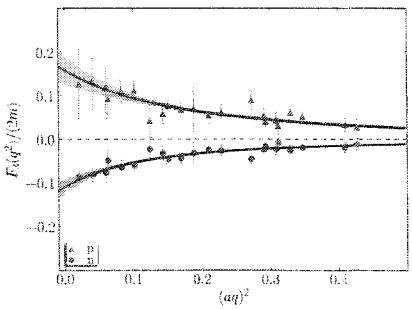
$\theta = 1.5, 1.0, 0.4, 0.2, 0.0$



$$D_n = \lim_{q^2 \to 0} \frac{e}{2m_N} F_3(q^2)$$

$$\left\langle N_s(p')|V_\mu^{EM}(q)|\overline{N}_s(p)\right\rangle_\theta = F_1(q^2)\gamma_\mu + F_2(q^2)\frac{q_\nu \sigma_{\mu\nu}}{2m_N} + i\theta F_3(q^2)\frac{q_\nu \sigma_{\mu\nu}\gamma_5}{2m_N} + \cdots, \qquad q = p' - p$$





- The non-zero signal may be dominated by systematical error due to the chiral symmetry violations of the clover fermions.
- Same calculation using DWF, which controls the chiral symmetry breaking, is proposed. [with T. Blum]
- A limiting factor will be a statistics (need algorithm / computational resources).

Summary

- Lattice QCD is becoming a practical tool for non-perturbative calculation for particle physics from the first principle (bridge b/w experiments and theories)
- DWF, preserves chiral symmetry, is optimal for (Weak) Matrix elements , which are necessary ingredients for precise check for the standard model of the particle physics and beyond.
- Chiral extrapolation is one of the remaining dominant sources of systematical errors: Lighter quark AuxDet is running.
- Complimentary to Wilson/staggered, by which one could get closer to the physical point, multi-handron systems etc.
- We need further developments on theories, algorithms, hardware.
- Samples of RBRC Lattice activities for zero temperature QCD :
  - spectrum, decays and quark masses from QCD(+QED) simulation.
  - New renormalization schemes (2 for bin.lin., 4 for B_K) RI/SMOM (=> Static, SF ?)
  - The most accurate ever results for Kaon sectors, B_K, K_{l3} and the new heavy quark programs B & D
  - Nucleon & Other new directions

Appendix

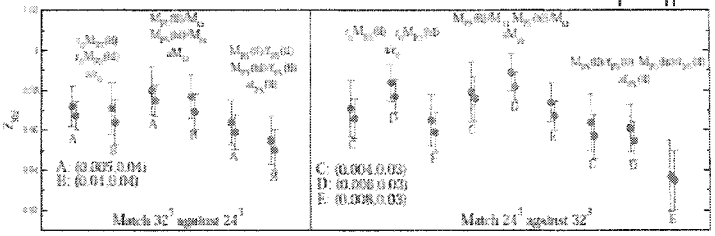
Ensemble generation performance

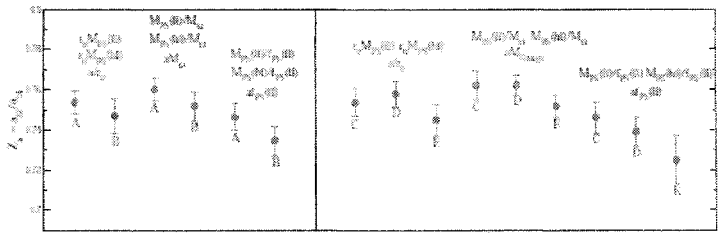
$32^3 \times 64 \times 16 (m_s = 0.03)$ BG/P					
	2048 × 4 core BG/P			4096 × 4 core BG/P	
m_l	0.008	0.006		0.004	
Local volume	$4^4 \times 16$			$4^4 \times 8$	
Routines	time(sec)		MFlops/s	time(sec)	MFlops/s
MInv	851	950	443	563	374
CG	320	433	464	342	391
GF	34	39	350	45	302
RF	142	162	83	306	23
HF	2	3	30	12	4
Total time(seconds)	1406	1646		1355	
Total flops ($\times 10^{12}$)	4450	5260		5868	

$48^3 \times 64 \times 16$ DWF			$32^3 \times 64 \times 32$ AuxDet DWF		
$m_s = 0.03, 8192 \times 4$ core BG/P			$m_s = 0.045, 2048 \times 4$ core BG/P		
m_l	0.002		0.0042	0.001	
Local volume	$6^3 \times 2 \times 8$		$4^4 \times 32$		
Routines	time(sec)	MFlops/s	time(sec)		MFlops/s
MInv	1672	477	4073	4112	488
CG	1155	517	3438	4839	538
CG(AuxDet)			199	196	503
GF	206	408	137	130	344
RF	479	50	643	642	71
HF	29	3	12	12	27
Total time(s)	4050		8888	10500	
Total flops ($\times 10^{12}$)	47857		33017	39439	

Scaling checks [C. Kelly lat09]

- Two lattice spacings 1/a = 1.72(2), 2.32(3) GeV (0.11 fm, 0.085 fm)
- Matching simulation quark mass points by dimensionless combinations of r_0, M_{PS}, M_Ω, f_{PS}
- Plots of Ratios for for lattice quantities, a, m_l m_h,

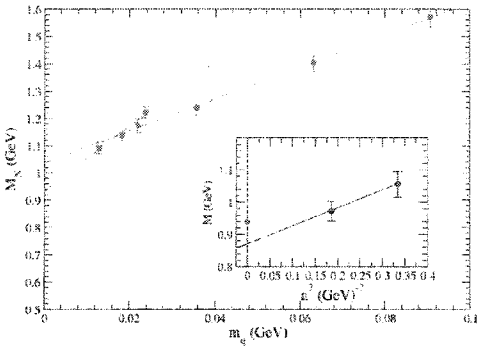


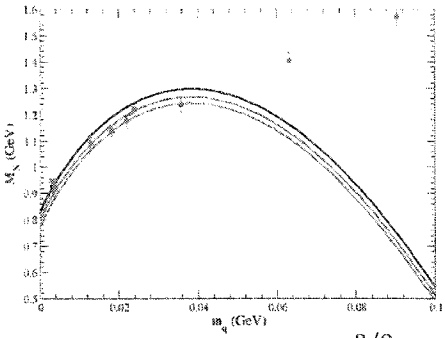


Nucleon mass spectrum

- Nucleon mass vs quark mass
- Two lattice spacings
- Linear fit (left) and the ChPT-inspired fit

[C. Maynard Lattice09]





$$M_N = c_0 + c_1 m_q + c_2 m_q^{3/2} + c_3 a^2$$

Lattice Gauge theories

- Non-perturbative computations from the truly first principle
- Indispensable bridge between experiments and theories to find new laws in elementary particle physics. Precision frontier.
- Also explores new theories
- Symmetries are key ingredients (gauge symmetry, chiral symmetry of quarks)

~1973 QCD, '74 Lattice formulation

'79 Lattice Gauge simulation (M. Creutz)

....Spectrum, Wilson Fermion, Kogut-Susskind fermion...

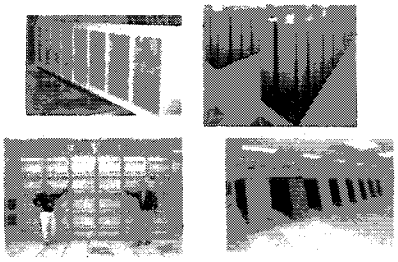
'97~ Domain-Wall Fermions (DWF) Nf=0 quenched
(Blum & Soni, CP-PACS,
'99~ Riken-BNL-Columbia (RBC))

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

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

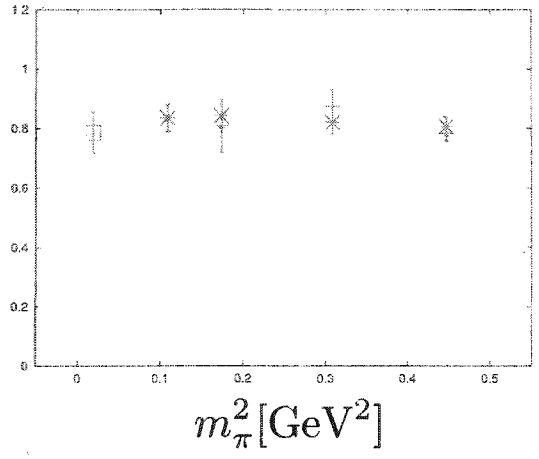
'08~ Graphene fermion (M. Creutz)

QCDSP CP-PACS ~1Tflops



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

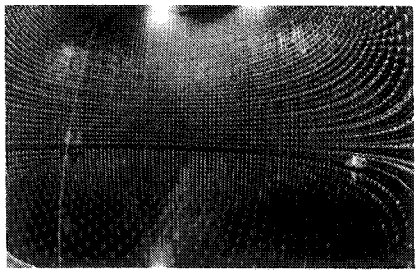
$$\frac{\langle x \rangle_{u-d}}{\langle x \rangle_{\Delta u - \Delta d}}$$



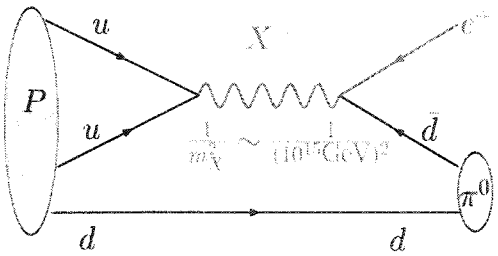
$m_\pi^2 [\mathrm{GeV}^2]$

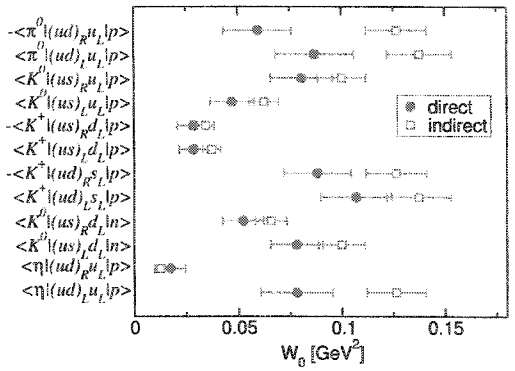
- The momentum of the isovector parton fraction $\langle x \rangle_{u-d}$
- The momentum of the isovector helicity fraction $\langle x \rangle_{\Delta u - \Delta d}$
- Transverse spin structure
- Twist-3 coefficient of the polarized structure function

- Non-perturbatively renormalized.
- Checked the finite volume effects on the two volumes $(2.7\mathrm{fm})^3$ (X) $(1.8\mathrm{fm})^3$ (+).
- Observe small dependence on quark mass.



$$\Gamma_P \propto \left| \overline{v_e^c} \langle \pi | (ud)_{R/L} u_L | P \rangle \right|^2$$





R&D for Algorithms

- Reweightings [C. Jung, T. Ishikawa]

- EigCG
- Four dimensional operator
- Smearings
- (Finite chemical potential)

PROTON DECAY MATRIX ELEMENTS

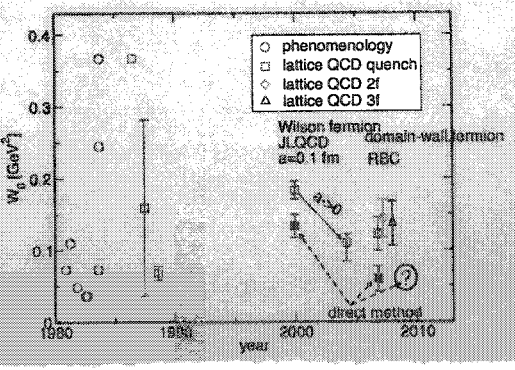
Yasumichi Aoki
RIKEN BNL Research Center

10/22/09 SRC Meeting 2009

motivation

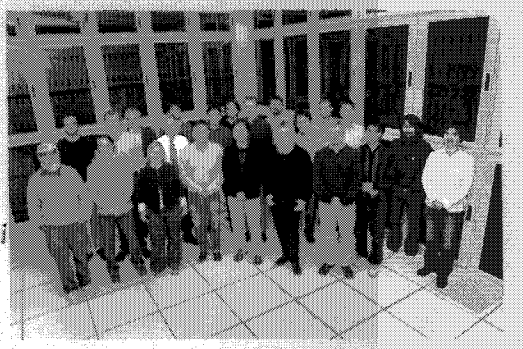
- Proton decay is a smoking gun of physics beyond the standard model
- Unique in searching for GUT scale physics → one of the main physics programs in next generation deep underground detectors (DUSEL, HyperKamiokande...)
- $p \to \pi^0 + e^+,\ p \to K^+ + \overline{\nu}, \cdots$ lifetime, Br,... needs low energy QCD matrix element
- Lattice QCD calculations have been improved by JLQCD, CP-PACS and RBC, RBC/UKQCD
- one (could be last) missing piece of element is W_0 with $N_f=3$ using direct method

$\langle \pi^0 | (ud)_R u_L | p \rangle$



collaboration in RBC/UKQCD effort

- RBC/UKQCD collaboration for gauge ensemble generation with domain-wall fermions
  - we use a^{-1}=1.73 GeV L=2.7, 1.8 fm lattices
- Scidac USQCD collaboration project
  - YA, C. Dawson, T. Izubuchi, A. Lichtl, A. Soni
- Partly supported by Japanese Kakenhi Grant
  - YA(PI), T. Izubuchi, T. Ishikawa
- UKQCD participation
  - P. Cooney, R. Tweedie et al.



some RBC people &
QCDOC super computer @BNL

$p \to \pi^0 + \bar{q}$ low energy matrix element

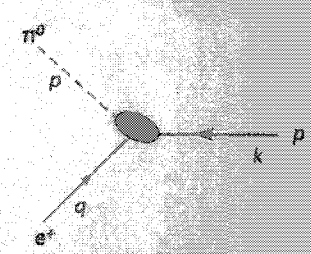
- $\mathcal{L}^{GUT} \to \mathcal{L}^{SM} + \sum_i C^i(\mu) \cdot O^i(\mu) + \cdots$

  $O^i(\mu) = (qq)_\Gamma (ql)_{\Gamma'}$ "i" labels chirality and flavor structure

- yields a decay: baryon → meson + anti-lepton

$$\langle \pi^0, e^+ | p \rangle_{GUT} = \sum_i C^i(\mu) \cdot \langle \pi^0, e^+ | O^i(\mu) | p \rangle_{SM}$$

$$\langle \pi^0, e^+ | (ud)(eu) | p \rangle = \overline{v_e^c} \cdot \langle \pi^0 | (ud) u | p \rangle$$



- a convenient parametrization using 2 form factors

$$\langle \pi^0 | (ud)_\Gamma u_L | p \rangle = P_L [W_0 - \frac{i\not{q}}{m_p} W_1] u_p$$

$$\begin{aligned} \langle \pi^0, e^+ | (ud)_\Gamma (eu)_L | p \rangle &= W_0 \cdot (v_e, u_p)_L + \frac{m_e}{m_p} W_1 \cdot (v_e, u_p)_R \\ &= W_0 \cdot (v_e, u_p)_L + O(m_e/m_p); \quad (\leftarrow W_0 \simeq W_1 \text{: ChPT, lattice}) \end{aligned}$$

- partial width

$$\Gamma(p \to \pi^0 + e^+) = \frac{m_p}{32\pi^2} \left[1 - \left(\frac{m_\pi}{m_p} \right)^2 \right]^2 \left| \sum_i C^i W_0^i (p \to \pi^0) \right|^2$$

constraining GUT

- partial width

$$1/\tau(p \to \pi^0 + e^+) = \frac{m_p}{32\pi^2}\left[1 - \left(\frac{m_\pi}{m_p}\right)^2\right]^2 \left|\sum_i C^i W_0^i(p \to \pi^0)\right|^2$$

- given GUT and W_0^i from lattice, $C^i(\mu)$ is constrained using experimental lower bound of proton lifetime
- $C^i(\mu)$ is function of $g(\mu)$ and
  - m_X,... for heavy boson mediated dim 6 nucleon decay
  - m_c and spectrum of sparticles for colored higgs mediated dim 5 nucleon decay
    - complement to LHC
- minimal SU(5) SUSY GUT already ruled out

QCD matrix element of nucleon decay

- $\langle \pi^0 | (ud)_\Gamma u_L | p \rangle = P_L [W_0 - \frac{i\not{q}}{m_p} W_1] u_p \qquad \Gamma = R, L$
- indirect method: approximation to lowest order in ChPT: Claudson, Wise, Hall, 1982

$$W_0[\langle \pi^0 | (ud)_R u_L | p \rangle] \simeq \frac{\alpha}{\sqrt{2} f}(1 + D + F)$$

$$W_0[\langle \pi^0 | (ud)_L u_L | p \rangle] \simeq \frac{\beta}{\sqrt{2} f}(1 + D + F)$$

f : pion decay constant

$D + F = g_A$: nucleon axial charge

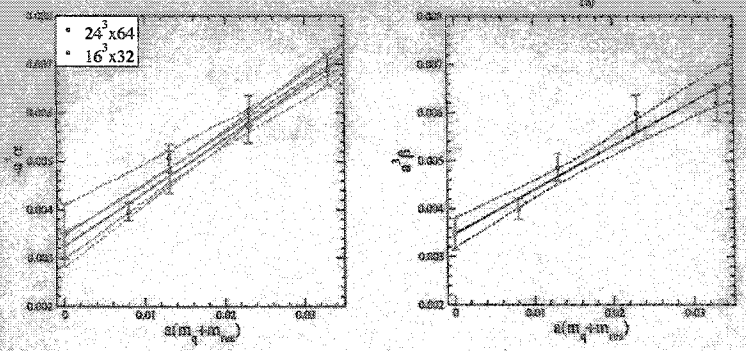
$\langle 0 | (ud)_R u_L | p \rangle = \alpha u_p$

$\langle 0 | (ud)_L u_L | p \rangle = \beta u_p$

- direct method: calculate the form factor W_0 through three-point functions
- renormalization: RI/MOM non-perturbative renormalization
- issues:
  - volume effect
  - chiral extrapolation: no 1-loop calculation in ChEFT available

low energy constants α and β

[RBC/UKQCD YA et al. 2010]

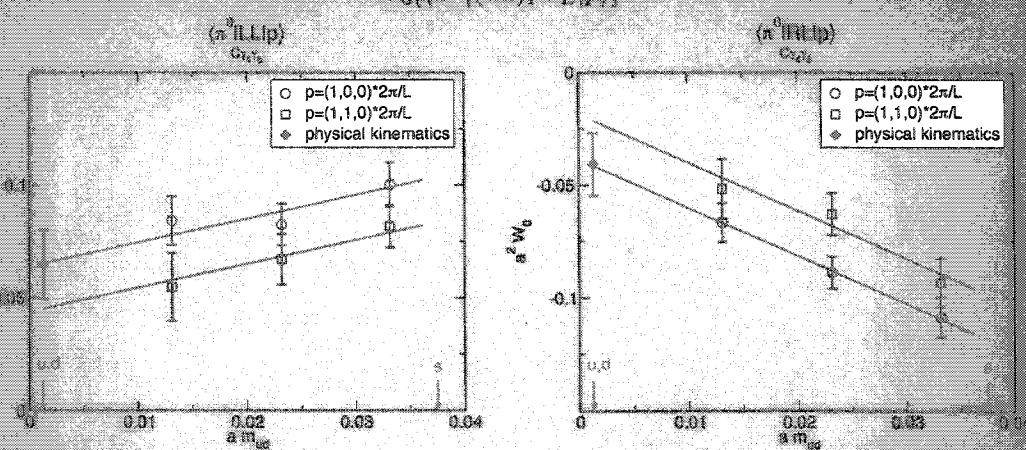


- α, β calculated by taking the chiral limit of values at simulated u,d quark mass
  - no volume dependence
  - chiral exrtrap. error is estimated through difference: lightest point [included/out]
    - ➡ gives largest contribution [18%] to total systematic error to final values

$$-\alpha = 0.0122 \pm 0.0012_{(\mathrm{stat})} \pm 0.0022_{(\mathrm{syst})}\,\mathrm{GeV}^3,$$
$$\beta = 0.0120 \pm 0.0013_{(\mathrm{stat})} \pm 0.0023_{(\mathrm{syst})}\,\mathrm{GeV}^3$$

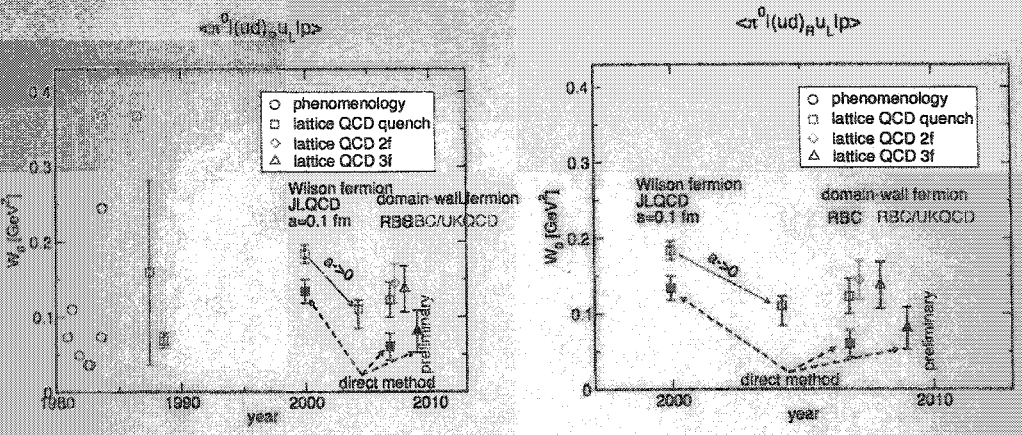
direct method (preliminary) on [illegible]

$$W_0[\langle\pi^0|(ud)_\Gamma u_L|p\rangle]$$



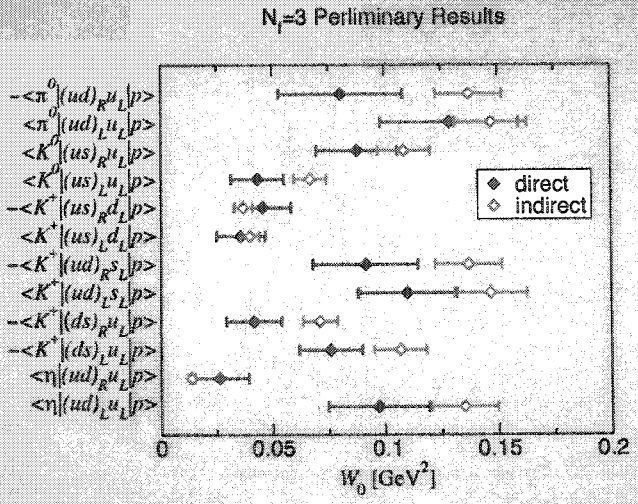
- statistical error will be reduced by more sophisticated analysis
- fit using linear in u,d mass & p^2 to extrapolate/interpolate to physical kinematics
- systematic error will be studied once even lighter mass (m_π=330 MeV) is analyzed
- it seems hard to beat 20% total → probably 30% is at best for current simulated masses
  - (indeed, 23% total error with unknown sys. error)

paring with other results



- 1st (preliminary) unquenched estimate of W_0 with direct method has been obtained!
- consistent with old quench result.
- smaller form factor for direct method than indirect
- caution!: indirect method underestimates proton lifetime

complete set of W_0 for p→PS transition



- statistical error only for comparison → will be improved for direct estimates
- indirect approx. tends to overestimate W_0, resulting in underestimate of lifetime

Summary

- 1st calculation of nucleon decay form factor for all possible N->PS transitions with
- still rooms for improvement with sophisticated analysis and additional quark mass
- direct estimate gives smaller form factor than indirect, which prolongs lifetime
- indirect approximations tend to overestimate W_0 -> underestimating lifetime
  - large difference is due to energetic pion/kaon in the final state, screwing up ChPT
  - no need to worry, as we have direct estimate of W_0 (everybody should use this)
- chiral extrapolation error could be ~20%, but that's not bad for the purpose
  - error propagation to τ~40%
- improving it requires smaller masses, serious 1-loop ChPT study...

The Chiral Magnetic Effect in 2+1 flavor QCD+QED

Michael Abramczyk, Tom Blum,
Gregory Petropoulos, and Ran Zhou

(University of Connecticut)

RBRC Review, October 22, 2009

Outline

1. Introduction
2. results
3. Summary/Outlook

Introduction

- **Kharzeev**[†]: In heavy-ion collisions **topological charge** fluctuations in the QGP, in the presence of large **magnetic** fields, will produce electric **charge separation** of particles.

- First direct observation of topological charge fluctuations!

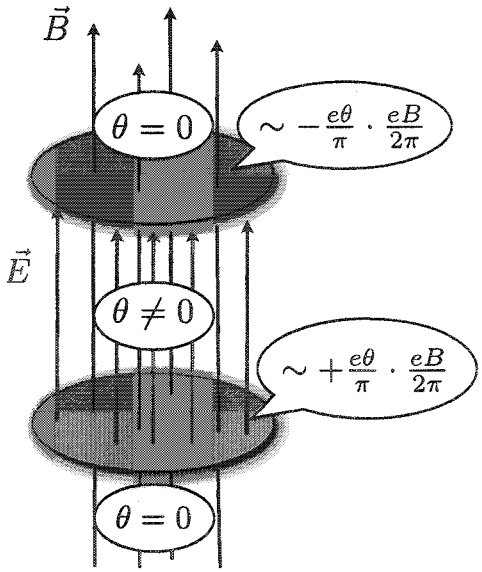
- STAR experiment at RHIC has observed a signal (nucl-ex/0510069; talk by S. Voloshin, Quark Matter 2009)

- Lattice calculation very interesting* and useful

[†] See (Kharzeev (2004); Kharzeev and Zhitnitsky (2006); Kharzeev, McLerran, Warringa (2007); Fukushima, Kharzeev, Warringa (2008),...

* See Polikarpov, *et al*, 2009

Charge separation (chiral magnetic effect)



Take θ static, non-zero only between domain-walls ("parallel-plate capacitor")

$$E = \theta \frac{q^2}{4\pi^2} B$$

"Plates" are charged, with charge density $\pm q^2 \theta B / 2\pi^2$

(Kharzeev, arXiv:0906:2808;

Kharzeev and Zhitnitsky, 2006)

Analogous to Witten's dyon, electrically charged magnetic monopole in presence of non-zero θ

Zero Modes of $\not{D}$

Physical picture: $\vec{B}$ polarizes the chiral zero-mode(s) associated with the instanton (equal quark and anti-quark components).

Useful to work with low modes of the Dirac operator.

Spectral decomposition of Dirac operator

$$\begin{aligned}(\not{D}+m)\psi_\lambda &= (i\lambda+m)\psi_\lambda \\ (\not{D}+m)^{-1} &= \sum_\lambda \frac{\psi_\lambda^\dagger \psi_\lambda}{i\lambda+m}\end{aligned}$$

(Calculate eigenvectors of hermitian operator instead, $\gamma_5(\not{D}+m)$)

Contribution to charge density

$$\begin{aligned}\rho &= \bar{\psi}\gamma_0\psi \\ &= \mathrm{tr}(\not{D}+m)^{-1}\gamma_0 \;=\; \mathrm{tr}\gamma_5\not{D}_H\gamma_0 \\ &= \sum_\lambda \frac{\psi_\lambda^\dagger\gamma_0\gamma_5\psi_\lambda}{\lambda+m}\end{aligned}$$

contribution to $\rho = 0$ for an *exact* chiral zero-mode, so in presence of $\vec{B}$, zero-mode $\rightarrow$ near-zero mode

Should probably use exactly conserved point-split current for DWF. Using "local" $\bar{\psi}\gamma_0\psi$ for now

Classical instanton (-like solution)

Put classical, topological charge = 1, instanton on lattice

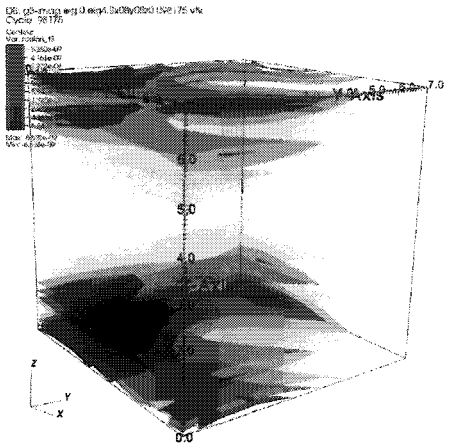
Chen, *et al*, PRD59, 1999 (CU group)

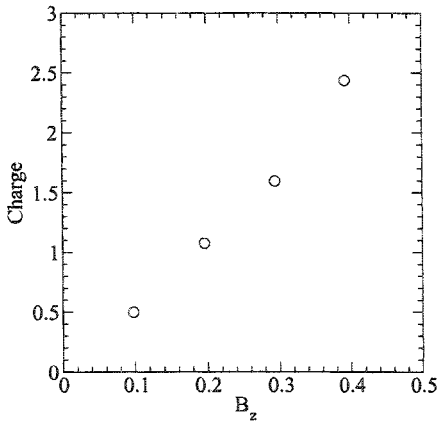
$$A_\mu = -i \sum_{j=1}^{3} \eta^{j\mu\nu} \lambda_j \frac{x_\nu}{x^2 + \rho^2}$$

$$\rho(r) = \rho_0 \left(1 - \frac{r}{r_{\text{max}}}\right) \Theta(r_{\text{max}} - r)$$

Charge separation (classical instanton-like solution)

8^4 lattice, $\rho_0 = 10$, $r_{max} = 3$





$B_z = 0.098175$. Total separated charge above mid-plane from "zero-modes" (chirality ≈ 1)

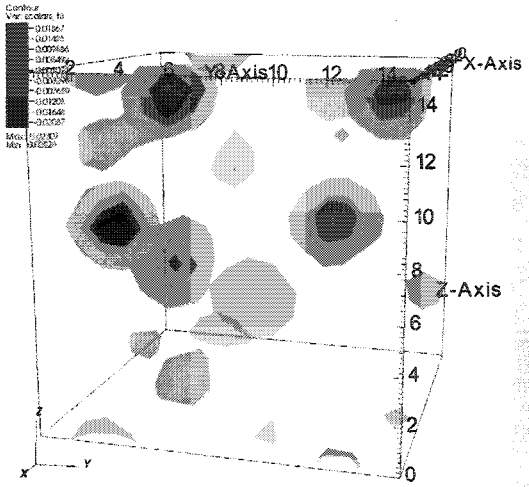
2+1 flavor QCD+QED lattice Simulations

- $N_\tau = 8$, N_f=2+1, DWF (RBC+LLNL). Eventually 1+1+1
- Couple sea quarks to QCD and QED (First!)
- Include external magnetic field $\vec{B}$ in dynamical evolution
- Work (evolve) in *fixed* topological sector(s)
  - use the auxiliary determinant method [Vranas, JLQCD, RBC]

2+1 flavor QCD+QED configuration

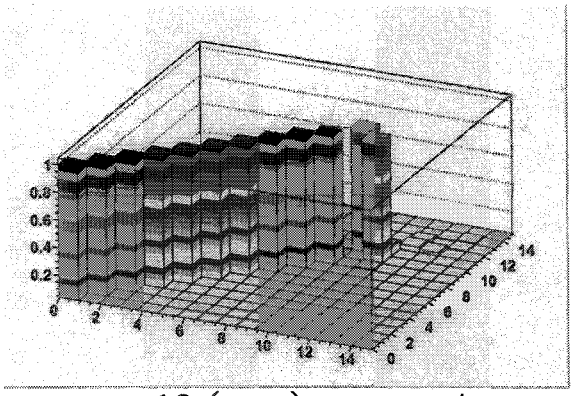
Topological charge density

DB: top.vtk

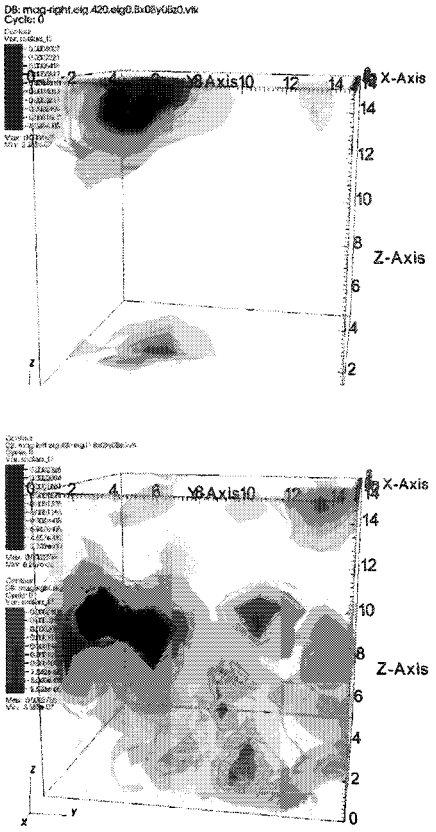


$Q = 9$ or 10

Chirality $\langle\psi_i|\Gamma_5|\psi_j\rangle$



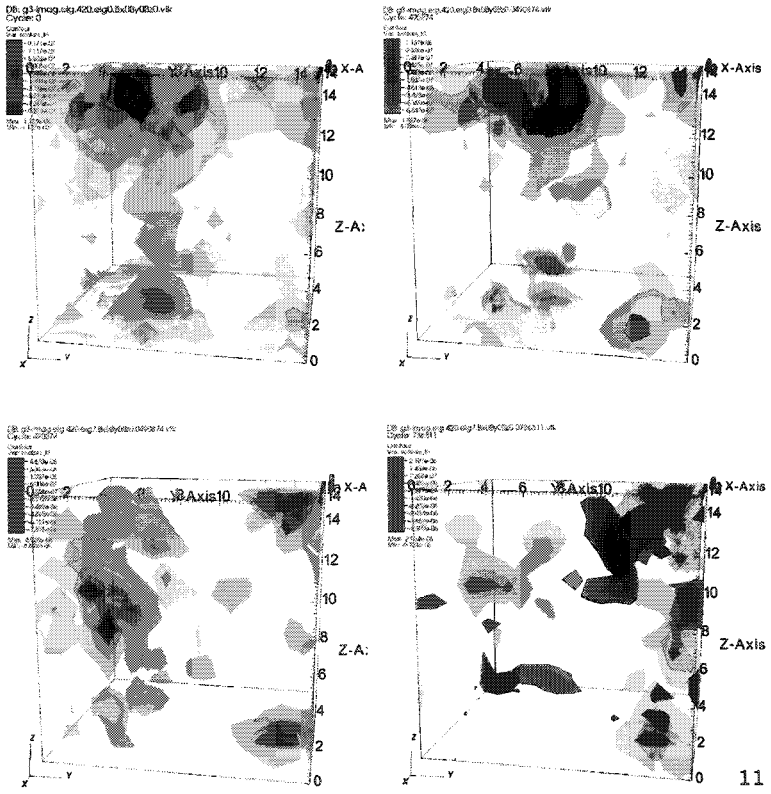
10 (near) zero modes



Right-handed eig 0,
Right-handed eig 7,
Right and Left-handed eig 11
($B_z = 0$)

10

Charge separation (charge density, Plus Minus)
$B_z = 0$
0.0490874,
0.0736311



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How to measure total charge separation?

- Find center of topological charge density
- Sum charge "above and below" this center in z direction (*c.f.* classical instanton)
- Not conclusive on above configuration
- Total charge not conserved $\longrightarrow$ conserved point-split current
- Magnetic field and Temperature dependence?

Summary/Plans

- Chiral magnetic effect new and exciting investigation of physics of topological charge
- Initial lattice results are interesting
- Need to implement conserved point-split current
- Study correlation of $(\vec{E}\cdot\vec{B})_{QCD}$ and $(\vec{E}\cdot\vec{B})_{QED}$
- Lattice calculations important to confirm/understand the recent RHIC results. (Scan in T and B)

Acknowledgements

Calculations done on NY Blue and QCDOC supercomputers at Brookhaven National Lab.

Thanks to Dima Kharzeev for useful discussions and Massimo Di Pierro for help with 3d plots

Nucleon structure functions from dynamical (2+1)-flavor domain wall fermions

Shigemi Ohta *†‡

RBRC Scientific Review, October 2009

RBC and UKQCD collaborations produced some dynamical DWF ensembles using QCDOC's:

- Iwasaki gauge action, $\beta = 2.13$, and Domain-Wall Fermions (DWF) quarks, $L_s = 16$ and $M_5 = 1.8$,
- $m_{\rm strange}a = 0.04$, $m_{\rm ud}a = 0.03$, 0.02, 0.01 and 0.005, $m_{\rm res} = 0.003$, with $a^{-1} \sim 1.7$ GeV.

Best ever hadron structure calculations: flavor and chiral symmetries and lattice volume, including isovector

- nucleon form factors where we saw large finite-size effects in the axial current,
- some low moments of structure functions which may be trending to the experiments.

Here we report a finite-size study on the latter with our two volumes, $24^3 \times 64$ (2.7fm) and $16^3 \times 32$ (1.8 fm)

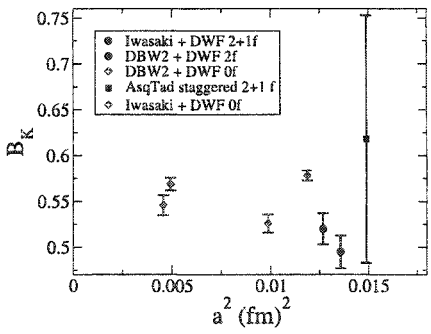
- by Takeshi Yamazaki, James Zanotti, Huey-Wen Lin, Shoichi Sasaki, Tom Blum, Robert Tweedie, ...

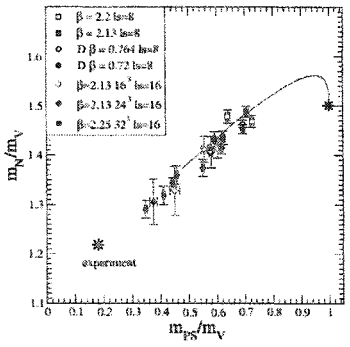
and are now almost final.

*Inst. Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan
†Physics Department, Sokendai Graduate University of Advanced Studies, Hayama, Kanagawa 240-0193, Japan
‡RIKEN BNL Research Center, Upton, NY 11973, USA

RBC/UKQCD $N_f = 2 + 1$ dynamical DWF ensemble: from Ω^- and K masses we estimate

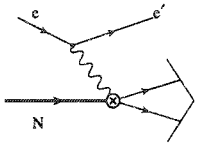
- Lattice cutoff $a^{-1} = 1.73(2)$ GeV, or physical volume is $(2.74(3)\text{fm})^3$,
- physical strange mass is 0.035(1)+0.003 in lattice units.





The best ever kaon and nucleon calculations in regard of good flavor and chiral symmetries.

- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV, $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV.
- Very accurate constraints on CKM matrix: $B_K^{\overline{\rm MS}}(2\text{GeV}) = 0.524(10)(28)$, K_{l3} $f_+(0) = 0.964(5)$, ...
- Beginning to tell where SU(3) chiral perturbation fails, e.g. NLO corrections $\sim 0.5\times$LO.

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:

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

- 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 $\langle 1\rangle_{\delta q}(\mu) = \langle P,S|\bar\psi i\gamma_5\sigma_{\mu\nu}\psi|P,S\rangle$ which may be measured by polarized Drell-Yang 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 $\vec P = 0$.

Our formulation follows the standard one:

- Two-point function: $G_N(t) = \mathrm{Tr}[(1+\gamma_t)\sum_{\vec{x}}\langle T B_1(x) B_1(0)\rangle]$, using $B_1 = \epsilon_{abc}(u_a^T C\gamma_5 d_b)u_c$ for proton.
- Three-point functions: appropriate operator inserted between source and sink.
- Source and sink are separated by 12 lattice spacings. 4 source positions.
- Gaussian smearing is employed to enhance ground-state signals.
- All the matrix elements except d_1 are iso-vector.

Number of configurations and pion mass

$m_f a$	# of config.'s	meas. interval	N_{sources}	m_π (GeV)	m_N (GeV)
0.005	646+286	10	4	0.3294(13)	1.154(7)
0.01	356	10	4	0.4164(12)	1.216(7)
0.02	98	20	4	0.5550(12)	1.381(12)
0.03	106	20	4	0.6681(15)	1.546(12)

Good chiral and flavor symmetries of DWF help:

- negligible unwanted mixings,
- straight-forward non-perturbative renormalization: RBC-standard RI-MOM (Rome-Southampton).

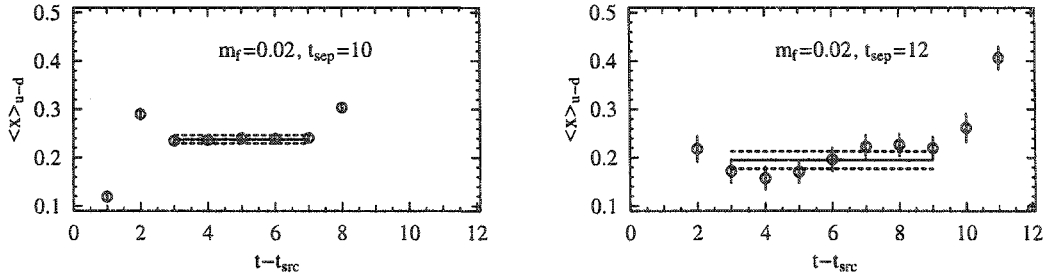
In particular, ratios such as g_A/g_V or $\langle x\rangle_{u-d}/\langle x\rangle_{\Delta u-\Delta d}$ are naturally renormalized.

Two possibly important sources of systematics:

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

Source/sink time separation:

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



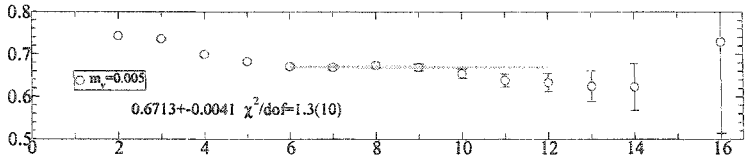
- In an earlier RBC 2-flavor DWF study at $a^{-1} \sim 1.7$ GeV, separation of 10 or 1.1 fm appeared too short.

In this study we choose separation 12 or 13 : ~1.4 fm: lighter quarks help maintaining the signal.

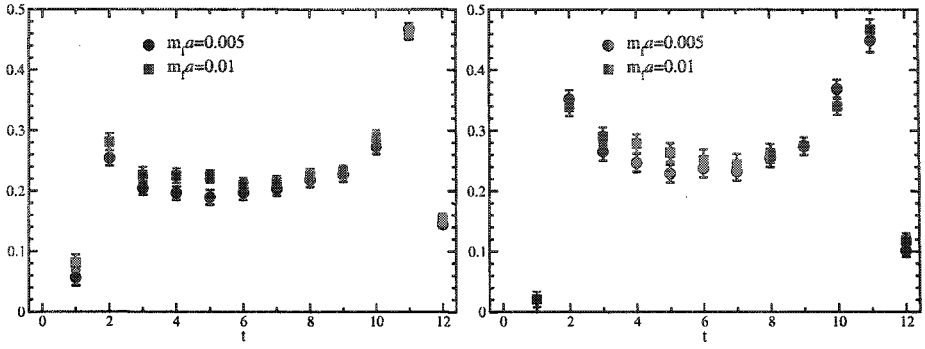
- We may need longer separations: future problem.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

Mass signal: $m_f = 0.005$



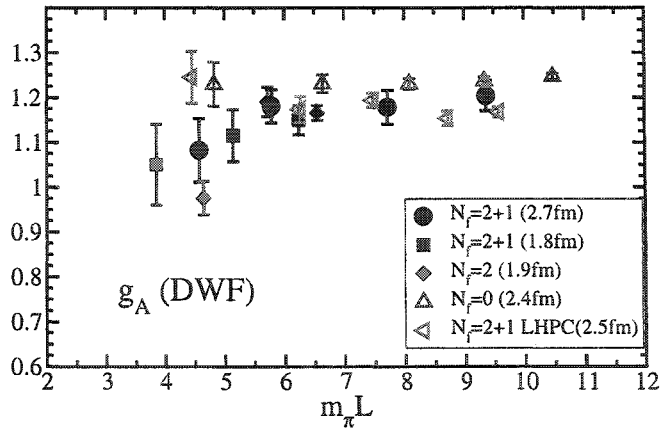
Bare three-point functions: $\langle x \rangle_{u-d}$ (left) and $\langle x \rangle_{\Delta u - \Delta d}$ (right), for $m_f = 0.005$ (red +) and 0.01 (blue ×):



Similar in quality with 2-flavor, time separation 12.

Spatial volume: in Lattice 2007 Takeshi Yamazaki reported significant finite-size effect in axial charge:

- measured in neutron β decay, $g_A/g_V = 1.2695(29)$, decides neutron life.



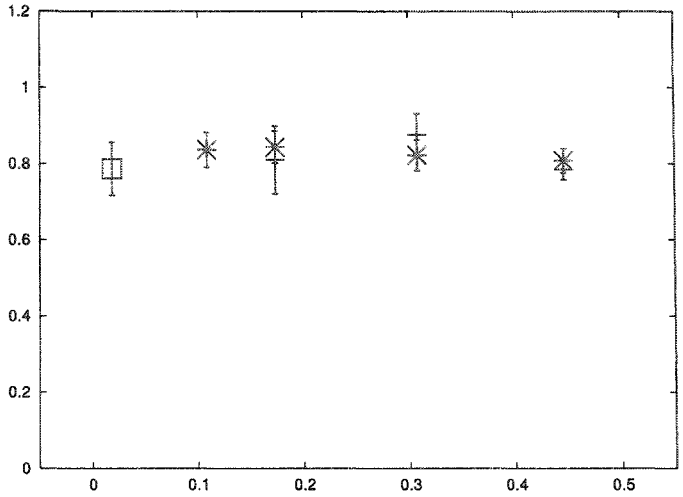
Our DWF on quenched and LHPC DWF on MILC calculations are presented for comparison.

- 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 $m_\pi L$:
  - elastic form factors demand big volumes.
- Does not necessarily mean inelastic structure functions do: need further investigation.

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

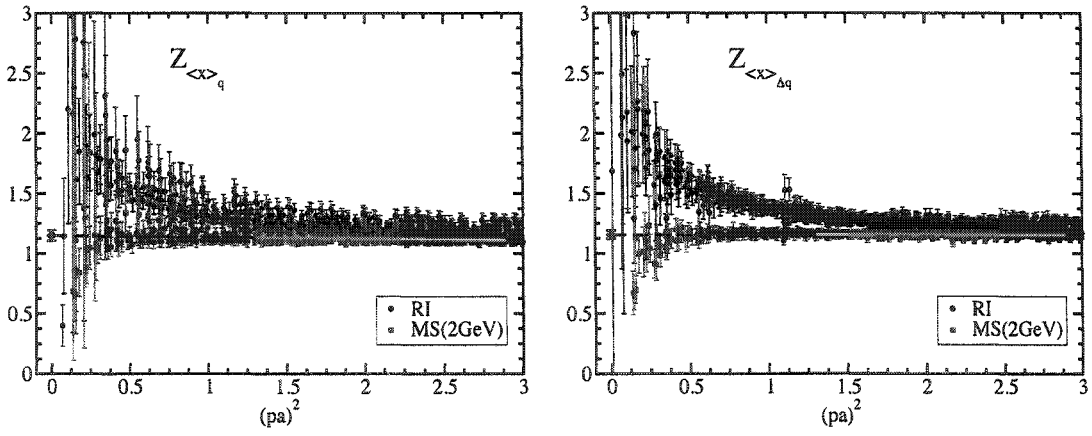
- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,

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.

To compare the absolute values of the moments such as the momentum and helicity fractions, $\langle x \rangle_{u-d}$ and $\langle x \rangle_{\Delta u - \Delta d}$, we non-perturbatively renormalize with RBC-standard RI-MOM (Rome-Southampton) scheme:

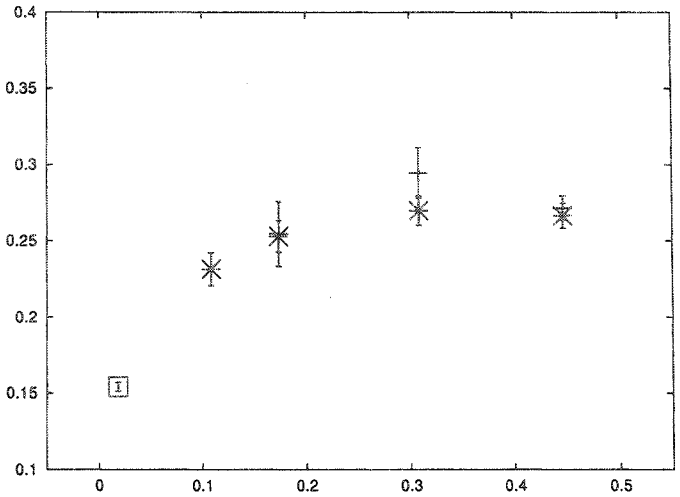


$Z^{\overline{\rm MS}}_{\langle x \rangle_q}(2{\rm GeV}) = 1.15(4)$ and $Z^{\overline{\rm MS}}_{\langle x \rangle_{\Delta q}}(2{\rm GeV}) = 1.15(3)$

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,

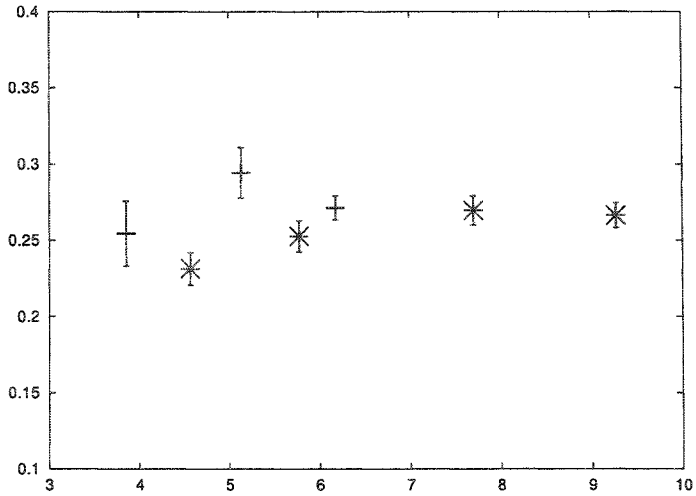


Absolute values have improved, trending to the experimental values, with NPR, $Z^{\overline{\rm MS}}(2{\rm GeV}) = 1.15(4)$.
No finite size effect seen (16^3 (+) and 24^3 (×) results agree): Likely physical light-quark effect.

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 $m_\pi L$,

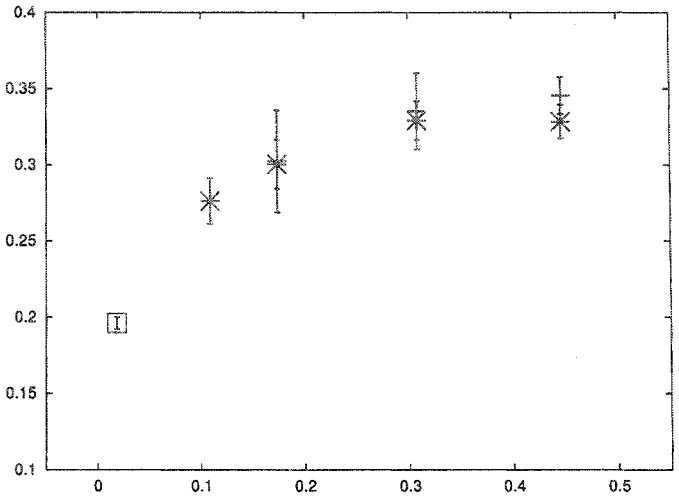


16^3 (+) calculations are carried out at smaller $m_\pi L$ than 24^3 (×): No finite size effect seen.
Likely physical light-quark effect.

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,

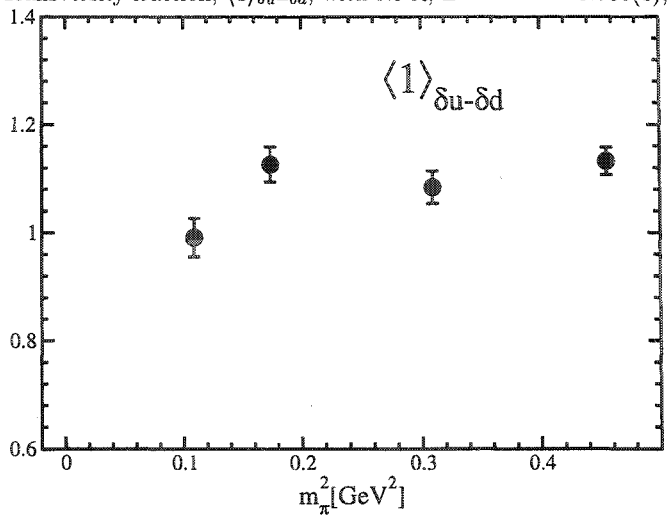


Absolute values have improved, trending to the experimental values. with NPR, $Z^{\overline{\rm MS}}(2{\rm GeV}) = 1.15(3)$.
No finite size effect seen (16^3 (+) and 24^3 (×) results agree): Likely physical light-quark effect.

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,

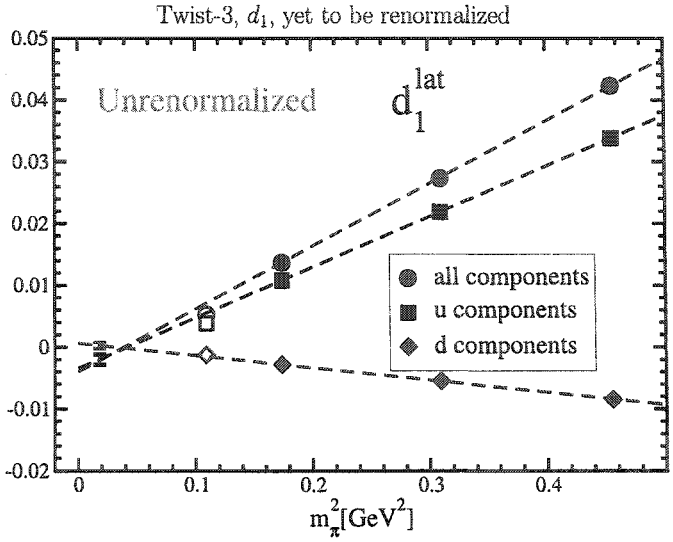
Transversity fraction, $\langle 1 \rangle_{\delta u - \delta d}$, with NPR, $Z^{\overline{\rm MS}(2{\rm GeV})} = 0.783(3)$,



NPR is $Z^{\overline{\rm MS}}(2{\rm GeV}) = 0.783(3)$.

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 in consistency with Wandzura-Wilczek relation.

Conclusions

RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical calculations with, $a^{-1} = 1.73(2)$ GeV, $(2.74(3)\text{fm})^3$ box, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$, $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV:

While elastic form factors such as, g_A/g_V, naturally renormalized on the lattice, suffer large finite-volume effect,

- a naturally renormalized ratio, $\langle x \rangle_{u-d}/\langle x \rangle_{\Delta u - \Delta d}$, does not show such effect.
  - It is consistent with experiment, and
  - does not show any discernible quark-mass dependence.
- Lightest points show an encouraging trend toward experiments in both momentum and helicity fractions.
  - No finite-size effect is seen (16^3 and 24^3 results agree): likely physical light-quark effect.
  - But they are different from corresponding LHPC/MILC results. NPR? Unitarity? Source/sink?
- Transversity moment is obtained.
- Non-perturbative renormalizations are now complete: typically 15-20 % effect.
- Twist-3 moment, d_1, is chirally well-behaved, small, and consistent with Wandzura-Wilczek relation.

Structure function may not suffer so severe finite-volume effect as form factors.

- Need optimizing source and sink and their separation.

Fluctuations of conserved charges in high-T QCD

Péter Petreczky

BROOKHAVEN NATIONAL LABORATORY

QCD for finite chemical potentials can be studied using Taylor expansion :

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{BQS}_{ijk} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$ hadronic

$$\frac{p(T,\mu_u,\mu_d,\mu_s)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{uds}_{ijk} \left(\frac{\mu_u}{T}\right)^i \left(\frac{\mu_d}{T}\right)^j \left(\frac{\mu_s}{T}\right)^k$$ quark

$$\chi^{abc}_{i,j,k} = \frac{\partial^i}{\partial \hat{\mu}_a^i} \frac{\partial^j}{\partial \hat{\mu}_b^j} \frac{\partial^k}{\partial \hat{\mu}_c^k} \frac{1}{VT^3} \ln Z(T,V,\mu_a,\mu_b,\mu_c)|_{\mu_a=\mu_b=\mu_c=0}$$

$$\hat{\mu}_X = \mu_X/T$$

Fluctuation of conserved quantum numbers at zero baryon density : probes of deconfinement and d.o.f at high T

Physics at non-zero baryon density:

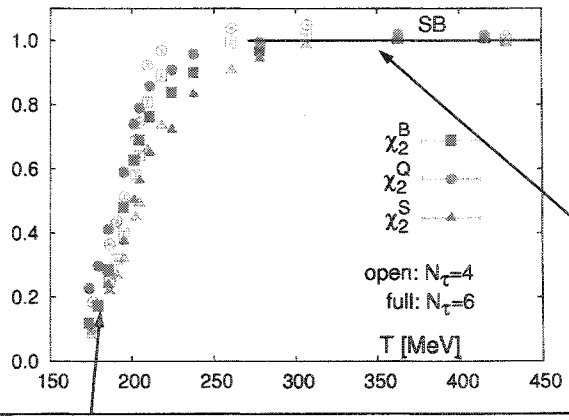
Deconfinement : fluctuations of conserved charges

$$\chi_2^B = \frac{1}{VT^3}(\langle B^2\rangle - \langle B\rangle^2)$$ baryon number

Cheng et al., PRD 79 (09) 074505

$$\chi_2^Q = \frac{1}{VT^3}(\langle Q^2\rangle - \langle Q\rangle^2)$$ electric charge

$$\chi_2^S = \frac{1}{VT^3}(\langle S^2\rangle - \langle S\rangle^2)$$ strange quark number



conserved charges are carried by massive hadrons

Ideal gas of quarks :

$$\chi_{2\ SB}^B = \frac{1}{3} \quad \chi_{2\ SB}^Q = \frac{2}{3}$$

$$\chi_{2\ SB}^S = 1$$

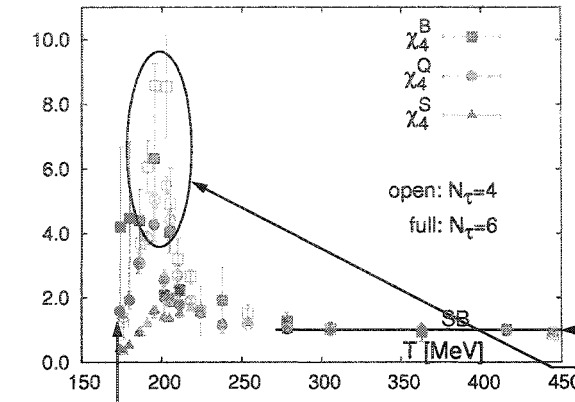
conserved charges carried by light quarks

Deconfinement : fluctuations of conserved charges

$$\chi_4^B = \frac{1}{VT^3}(\langle B^4\rangle - 2\langle B^2\rangle^2)$$ baryon number — Cheng et al., PRD 79 (09) 074505

$$\chi_4^Q = \frac{1}{VT^3}(\langle Q^2\rangle - 3\langle Q^2\rangle^2)$$ electric charge

$$\chi_4^S = \frac{1}{VT^3}(\langle S^2\rangle - 3\langle S^2\rangle^2)$$ strange quark number



Ideal gas of quarks :

$$\chi_4^B{}_{SB} = \frac{2}{9\pi^2} \qquad \chi_4^Q{}_{SB} = \frac{4}{3\pi^2}$$

$$\chi_4^S{}_{SB} = \frac{6}{\pi^2}$$

conserved charges carried by light quarks

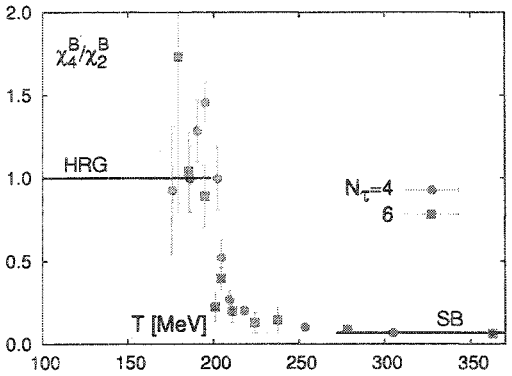
enhanced fluctuations due to nearby critical point $\chi_4^B \simeq |T - T_c|^{-\alpha}$

conserved charges are carried by massive hadrons

Fluctuations in the hadron resonance gas model

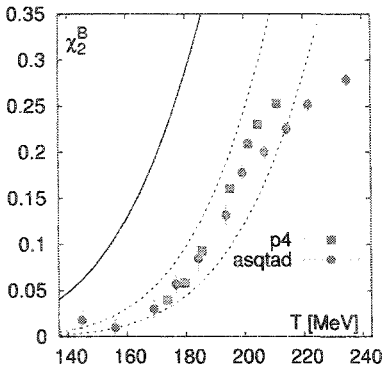
Hadron resonance gas (HRG) is expected to be a good reference at low temperatures

Kurtosis (the ratio of 4th order to 2nd order fluctuations) of baryon number shows good agreement with HRG for *T<200* MeV but rapidly drops to the value characteristic of a quark gas



Cheng et al., PRD 79 (09) 074505

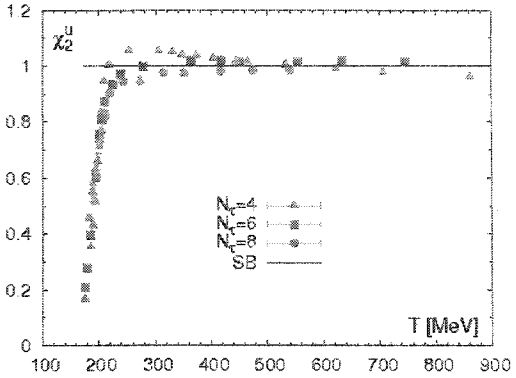
The agreement of the baryon number fluctuations with HRG is not good because of lattice artifacts but can be understood if lattice masses are used in the HRG

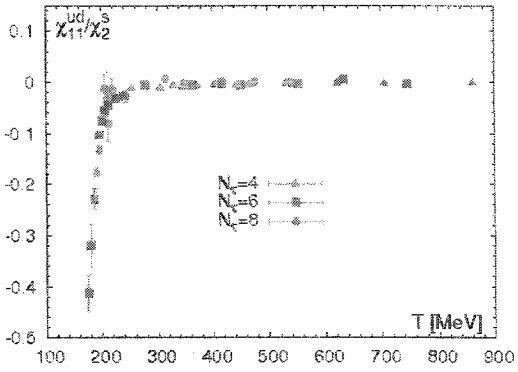


P. Huovinen, P.P., work in progress

Fluctuations of quark numbers at high T

RBC-Bielefeld, work in progress

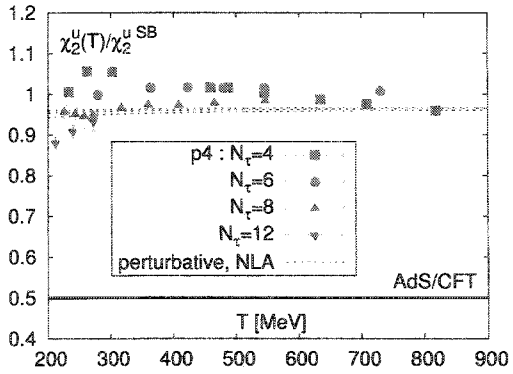


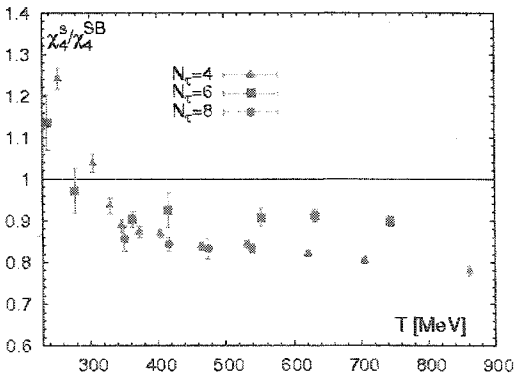


Rapid increase in quark number fluctuations at $T \sim 200$ MeV => deconfinement
Quark number fluctuations get close to the ideal gas limit for $T>300$ MeV and have reasonably small discretization effects

correlations between and u and s quark numbers is non-zero at low T due to hadronic bound states containing both type of quarks and rapidly vanish at high temperatures => constraints on models of sQGP
(e.g. PRD 73 (06) 014509)

Fluctuations of quark numbers at high T





The quark number susceptibilities for $T>300$MeV agree with resummed petrurbative predictions
A. Rebhan, arXiv:hep-ph/0301130
Blaizot et al, PLB 523 (01) 143
and are in contrrast with *AdS/CFT* expectations
Teaney, PRD 74 (06) 045025

4th order quark number fluctuations are also close to the ideal gas limit but not analytic calculations are available yet
(RBC-Bielefeld, work in progress)

Summary

• Fluctuations of conserved charges are sensitive probes of deconfinement and degrees of freedom at high temperatures.

• At low temperatures fluctuations can be understood within Hadron Resonance Gas model if lattice distortions of the hadron masses are taken into account

• Quark number fluctuations are close to the ideal gas limit and agree well with the results of resummed perturbative calculations for $T>300$MeV

• Future challenge : calculations of 2nd and 4th order fluctuations on $N_\tau = 8$ and 12 lattices and with highly improved staggered quark (HISQ) action

$B^0 - \bar{B}^0$ mixing with domain-wall and static quarks

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(University of Connecticut, Physics Department)

RBC/UKQCD Collaborations

RBRC Scientific Review Committee Meeting
October 21-22, 2009

1

Current members on this project

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- T. Dumitrescu
- T. I
- T. Izubuchi
- O. Loktik
- A. Soni
- R. S. Van de Water
- O. Witzel

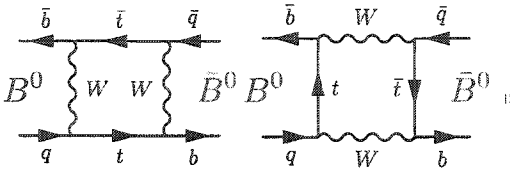
UKQCD Collaboration

- C. Albertus
- P. A. Boyle
- L. Del Debbio
- J. M. Flynn
- C. T. Sachrajda
- J. Wennekers

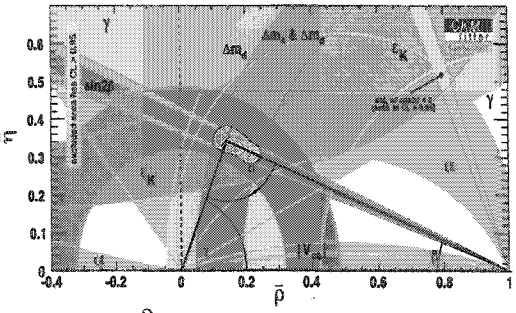
$B^0 - \bar{B}^0$ mixing and CKM

Constraints to CKM triangle

- Oscillation frequency



$q = \{d, s\}$



$$\Delta m_{B_q} = (\text{known factors}) \times \left|V_{tq}^* V_{tb}\right|^2 m_{B_q} f_{B_q}^2 B_{B_q}$$

$\Rightarrow$ constraints to V_{td}, V_{ts}

- Hadronic matrix elements

$$\mathcal{M}_{B_q} = \langle \overline{B}_q^0 | [\bar{b}\gamma_\mu P_L q][\bar{b}\gamma_\mu P_L q] | B_q^0 \rangle = \frac{8}{3} m_{B_q}^2 f_{B_q}^2 B_{B_q}$$

They can be calculated by the lattice simulation, in principle.

$B^0 - \bar{B}^0$ mixing on the lattice

Difficulty of heavy-light system

- Basically, multi-scale problem

  • Light quark is too light.

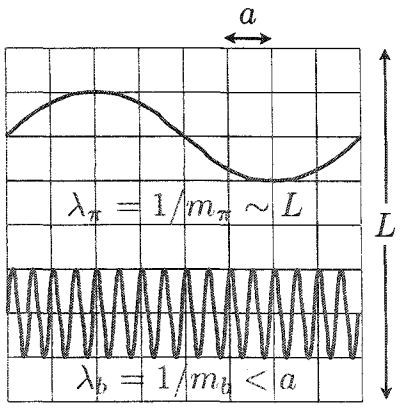
  Large volume is needed.

  $L > 2$ fm

  • b-quark is too heavy.

  Small lattice spacing is needed.

  $a \ll (5\ \text{GeV})^{-1} = 0.04$ fm



- Various framework to avoid the problem
  • Heavy Quark Effective Theory (HQET)
  • Non-relativistic QCD (NRQCD)
  • Relativistic Heavy Quark Formalism (RHQ)

Heavy Quark Effective Theory (HQET)

- $1/m_b$ expansion of QCD

$$\mathcal{L}_{\rm QCD} = -\frac{1}{2g_0^2}{\rm Tr}F_{\mu\nu}F_{\mu\nu} + \sum_f \bar{\Psi}_f\left(\gamma_\mu D_\mu + m_f\right)\Psi_f$$

  - HQET: formal $1/m_b$ expansion of QCD

$$\bar{b}\left(\gamma_\mu D_\mu + m_b\right)b \longrightarrow \mathcal{L}_{\rm stat} + O(1/m_b),$$
$$\mathcal{L}_{\rm stat} = \bar{h}\left(D_0 + \delta m\right)h$$

  - Expansion is accurate for heavy quark mass $m_h \gg \Lambda_{\rm QCD}$

- Operator matching

  - different renormalization ⟶ operator matching

Physics target in static approx.

- Static approximation (leading order of HQET)

  - Easy to implement

  - Symmetries (HQ spin symmetry + chiral symmetry)

⇨ reduced operator mixing

  - But, we always have the error coming from static approx.

$$O(\Lambda_{\rm QCD}/m_b) \sim 10\%$$

- SU(3) breaking ratio ξ

$$\frac{\Delta m_s}{\Delta m_d} = \frac{|V_{ts}|^2}{|V_{td}|^2}\frac{m_{B_s}}{m_{B_d}}\xi^2$$

  - Error coming from static approx. is reduced to:

$$O\left(\frac{m_s - m_d}{\Lambda_{\rm QCD}} \times \frac{\Lambda_{\rm QCD}}{m_b}\right) \sim 2\%$$

Test on $16^3 \times 32$ lattice

Gauge configurations

- Nf=2+1 DWF configurations (~300 config. at each parameter)
- $16^3 \times 32,\ (1.8\ \mathrm{fm})^3,\ L_s = 16$
- $\beta = 2.13,\ a^{-1} = 1.729(28)\ \mathrm{GeV},\ a \sim 0.11\ \mathrm{fm}$
- $m_\pi = 400 - 630\ \mathrm{MeV}$

Various implementations

- APE, HYP link smearing in the static action
- One-loop PT matching including O(a) discretization error

  (In this test, O(a) correction for ξ is not included.)

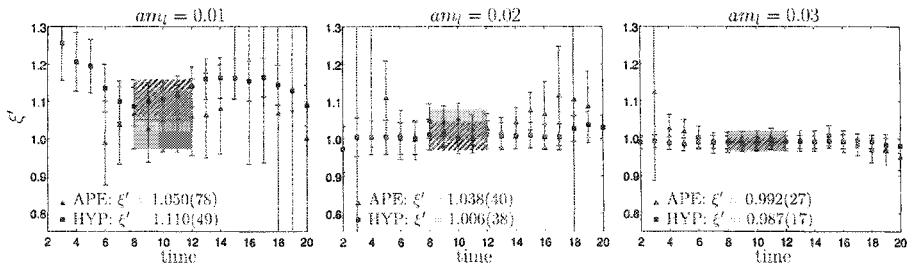
- ChPT for the chiral extrapolation

$$\xi - 1 \propto \text{"chiral logs"} + \frac{2\mu}{(4\pi f)^2} c_{\mathrm{val}}(m_s - m_d)$$

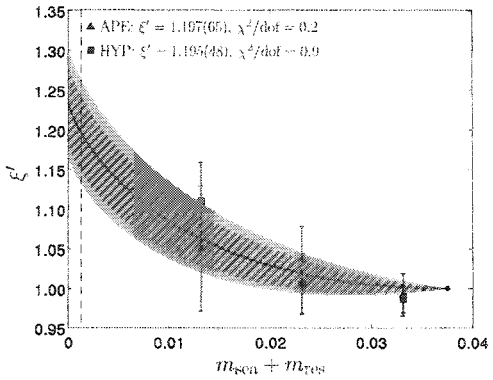
Test on $16^3 \times 32$ lattice

Preliminary results

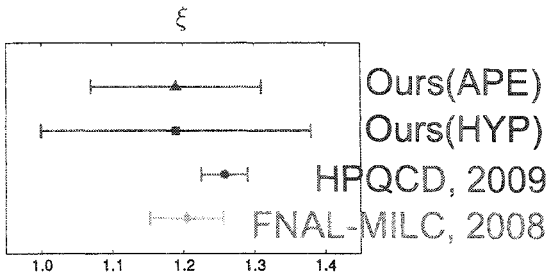
- Signal



- Chiral extrapolation



- Comparison



Future plans

- Gauge configurations (Nf=2+1 DWF)
  - $24^3 \times 64 \times 16$, $(2.7\ \mathrm{fm})^3$, $a \sim 0.11\ \mathrm{fm}$
    $m_\pi = 320 - 630\ \mathrm{MeV}$
  - $32^3 \times 64 \times 16$, $(2.7\ \mathrm{fm})^3$, $a \sim 0.085\ \mathrm{fm}$
    $m_\pi = 300 - 400\ \mathrm{MeV}$

  larger volume, lighter quark masses, better generation algorithm
- Simulating on partially quenched points
- $O(\alpha_s a)$ improvement for all operators
- Scaling study
- Finishing within 1-2 years
- We are also starting RHQ simulation.

9

eRHIC – the Future of RHIC

- RHIC performance
- Adding a polarized electron beam to RHIC
- R&D plans

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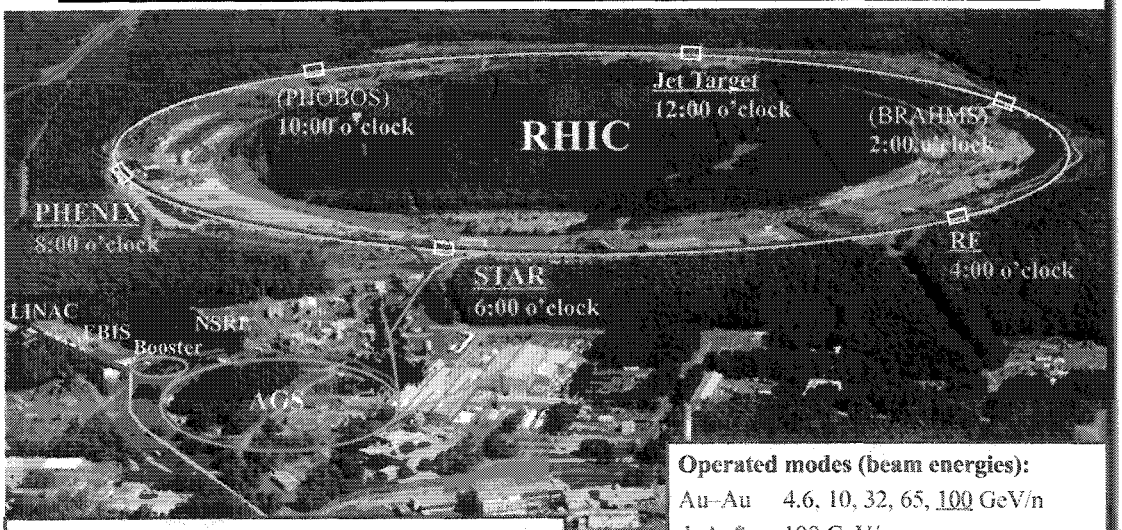
Thomas Roser
2009 RBRC review
October 22, 2009

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{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):

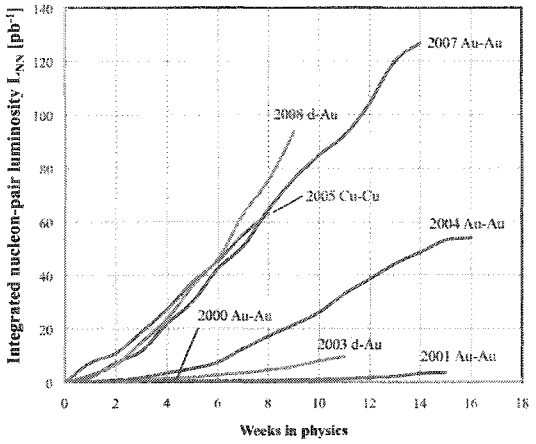
Au–Au	4.6, 10, 32, 65, 100 GeV/n
d–Au*	100 GeV/n
Cu–Cu	11, 31, 100 GeV/n
p↑–p↑	11, 31, 100, 250 GeV

Planned or possible future modes:

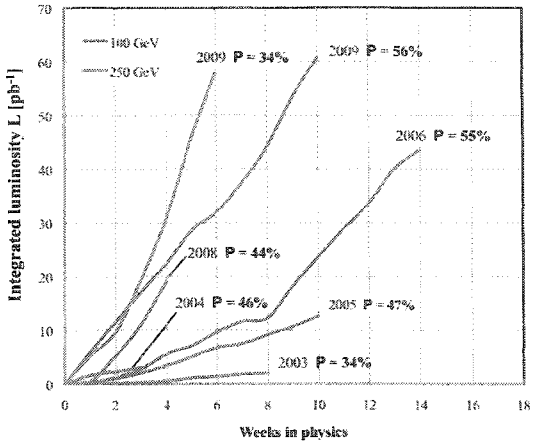
Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

Delivered Integrated Luminosity and Polarization

Heavy ion runs



Polarized proton runs



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	Enhanced Design	Next L upgrade
Au-Au operation		(2007)		(2012)
Energy	GeV/nucleon	100	100	100
No of bunches	…	103	111	111
Bunch intensity	10^9	1.1	1.0	1.0
Average L	$10^{26}cm^{-2}s^{-1}$	12	8	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 L	$10^{30}cm^{-2}s^{-1}$	28 / 55	30 / 150	300
Polarization P	%	56 / 35	70	70

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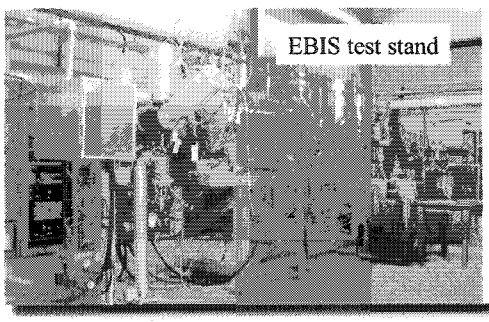
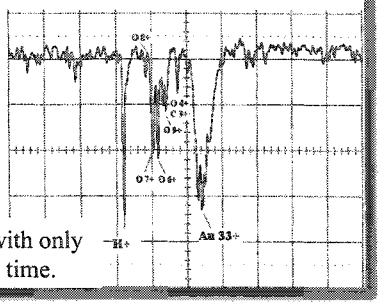
RHIC Facility Upgrade Plans

- 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}(× 4); 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)
- Low energy ($\sqrt{s}$=5…30 GeV) Au-Au collisions for critical point search
  - ~ 1…5 MeV electron cooling of Au beams at injection (~ 2014)
- eRHIC: high luminosity (≥ 1×10^{33} cm^{-2} s^{-1}) eA and pol. ep collider using 4 GeV and later 10 - 20 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (~ 2020)
  Exploring gluons at extreme density!

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, uranium (RHIC) and polarized He^3 (eRHIC)
- Achieved 1.7×10^9 Au^{33+} in 20 ms pulse with 8 A electron beam (60% neutralization)
- Start beam commissioning soon



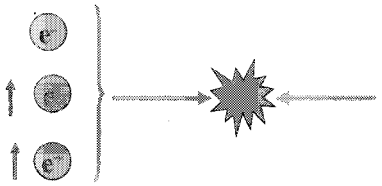


Gold charge state with only 40 ms confinement time.

eRHIC

Electron accelerator

Unpolarized and polarized leptons
3 - 10 (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 - 100 (200) GeV
Note: eA program for eRHIC needs as high an electron energy as possible even with a trade-off for the luminosity: up to 30 GeV would be possible.

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Staging of eRHIC (Based on Linac-Ring Option)

MeRHIC: Medium Energy eRHIC

- Both accelerator and detector are located in RHIC at 2 o'clock IR
- 90% reuse of components for eRHIC
- 4 GeV ↑e^- × 250 GeV ↑p (63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
- 4 GeV e^- × 100 GeV/n Au (40 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1}

eRHIC

- High energy and luminosity, possibly also inside RHIC tunnel
- 10 (20) GeV ↑e^- × 250 GeV ↑p (140 GeV c.m), L ~ 2.6 x 10^{33} cm^{-2} sec^{-1}
- 10 (20) GeV e^- × 100 GeV/n Au (89 GeV c.m.), L/n ~ 2.9 x 10^{33} cm^{-2} sec^{-1}

Possible eRHIC extensions and upgrades

Higher energy and/or higher luminosity. For example:

- 10 GeV ↑e^- × 325 GeV ↑p, L ~ 10^{35} cm^{-2} sec^{-1} (high energy proton cooling, high e-beam intensity)
- 30 GeV e^- × 120 GeV/n Au (120 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1} (extended linac, reduced e-beam intensity to limit synchrotron radiation power)

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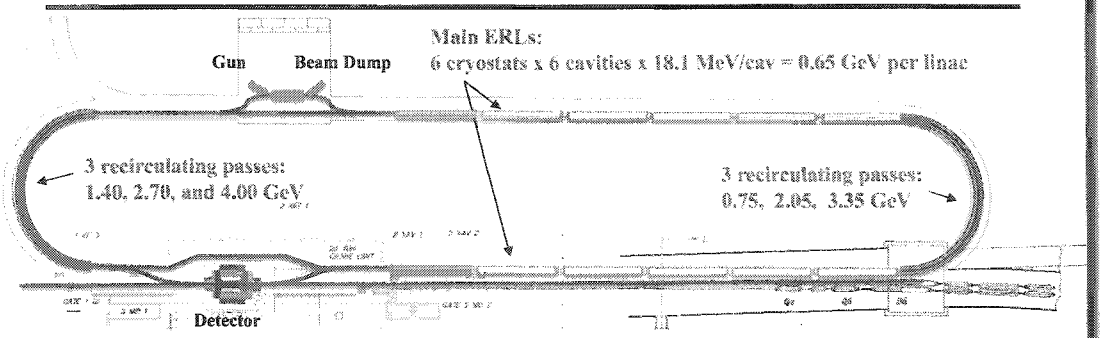
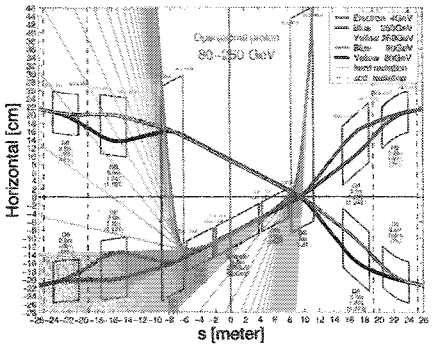
MeRHIC: 4 GeV ERL at 2 o'clock IR of RHIC



- 250 GeV p↑ × 4 GeV e ↑ or
  100 GeV Au × 4 GeV e
- Peak luminosity: 1×10^{32} cm^{-2} s^{-1}



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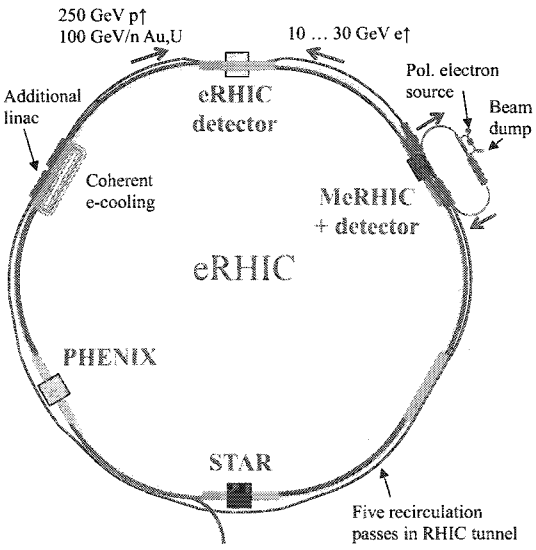
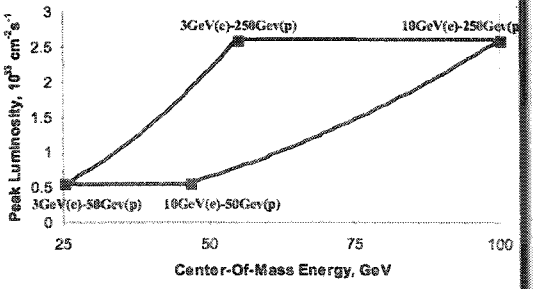
ERL-based Linac-Ring eRHIC





- Full use of MeRHIC
- 10 GeV electron design energy. Possible upgrade to 20 – 30 GeV.
- Peak luminosity: 3×10^{33} cm^{-2} s^{-1}
- 5 recirculation passes in the RHIC tunnel
- 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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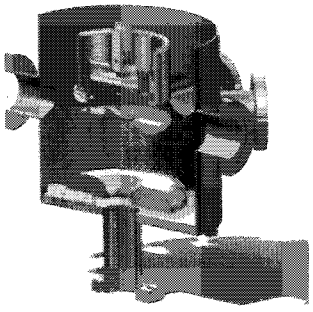
Medium Energy eRHIC parameters for e-p collisions

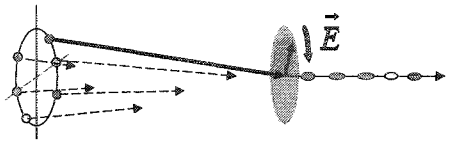
	no cooling of protons: parallel to RHIC ops		high energy cooling of proton beam		eRHIC with high energy cooling of proton beams	
	p	e	p	e	p	e
Energy, GeV	250	4	250	4	250	20
Number of bunches	111		111		166	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31	2.0	0.24
Beam current, mA	320	50	320	50	420	50
95% normalized emittance, $\pi\mu m$	15	440	1.5	44	1.2	150
Rms emittance, nm	9.4	9.4	0.94	0.94	0.75	0.75
β^*, cm	50	50	50	50	25	25
rms bunch length, cm	20	0.2	5	0.2	5	0.2
beam-beam parameter	0.002	0.44	0.015	0.69	0.015	0.49
disruption parameter		3.1		7.7		3.9
Peak Luminosity, 10^{33} cm^{-2}s^{-1}	**0.1**		**1.0**		**2.8**	

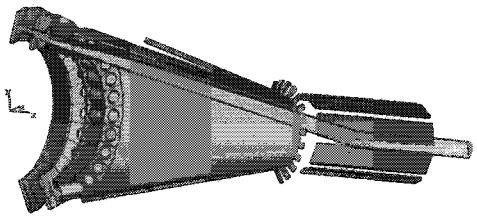
Polarized Electron Gun Development

- ERL eRHIC design needs 50 - 250 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 to reach 250 mA or 50 mA with 2 mA per cathode:





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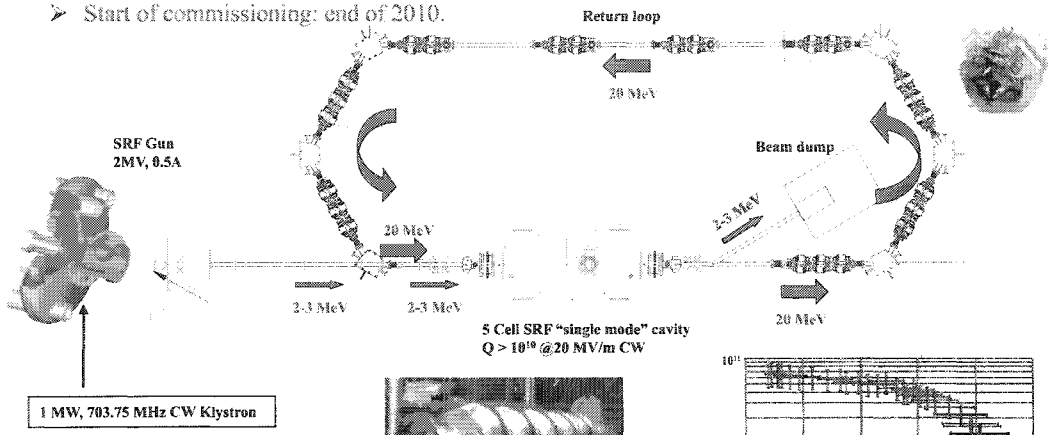
Energy Recovery Linac (ERL) Test Facility

- 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 10 – 20 GeV high intensity ERL for eRHIC
- Test of high current beam stability issues, highly flexible return loop lattice
- Allows for addition of a 2nd recirculation loop
- Start of commissioning: end of 2010.



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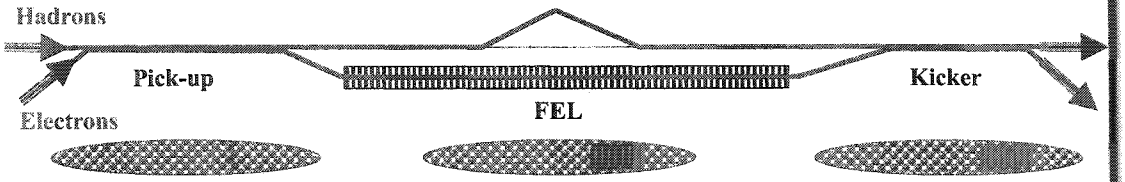
Coherent Electron Cooling

- 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 possible in RHIC using test ERL.

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}]
- Low energy ($\sqrt{s}$=5…30 GeV) RHIC collisions (~ 2014)
  Au-Au collisions for critical point search
- eRHIC: high luminosity ($\geq 1 \times 10^{33}$ cm^{-2} s^{-1}) eA and pol. ep collider (~ 2020)
  4 GeV and later 10 - 20 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams

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CURRICULA VITAE - SUMMARY
CURRENT RBRC FELLOWS/RESEARCH ASSOCIATES/RESEARCHERS

Yasuyuki Akiba **Birthplace:** Tokyo, Japan **DOB:** October 20, 1959
D.S. 1988, University of Tokyo
Experience: Research Associate, Institute for Nuclear Study, University of Tokyo, March 1988 – March 1997;
Research Associate, High Energy Accelerator Research Organization (KEK), April 1997 – March 2003;
Senior Research Scientist, RIKEN, April 2003 – July 2003;
Senior Researcher, RIKEN, August 2003 – present;
RIKEN Spin Program Researcher, RBRC-E, November 2003 – present
Deputy Spokesperson for PHENIX, 2004 - present.

Sinya Aoki **Birthplace:** Tokyo, Japan **DOB:** May 16, 1959
D.S. 1987, University of Tokyo
Experience: Research Associate, Brookhaven National Laboratory, 1987-1989
Post-Doctoral Fellow, SUNY at Stony Brook, 1989-1991
Assistant Professor, U. of Tsukuba, Japan
Lecturer, U. of Tsukuba, 1993-1994
Associate Professor, U. of Tsukuba, 1994-2001
Professor, U. of Tsukuba, April 2001 – present
Visiting Fellow, joint position with RBRC Theory Group and Tsukuba University, April 1, 2004 – present.

Awards and Honors: Fellowships of the Japan Society for the Promotion of Science for Japanes Junior Scientists, at Physics Department, U. of Tokyo, Japan;
First (FY 2004) JSPS Prize Award, Mathematics; Physical Sciences; Chemistry; Engineering Sciences.

Yasumichi Aoki **Birthplace:** Gunma, Japan **DOB:** January 7, 1968
Ph.D. 1996, University of Tsukuba, Japan
Experience: COE Research Fellow at the Center for Computational Physics University of Tsukuba;
Assistant (3 year research position) at the Center for Computational Physics, University of Tsukuba
Research Associate, RIKEN BNL Research Center, May 1, 2000 – April 30, 2003.
RBRC Visiting Scientist, with Columbia University, May 1 to July 31, 2003.
Research Associate, University of Wuppertal, Germany, August 2003-September 2006;
RIKEN Fellow, RIKEN BNL Research Center (Theory), October 1, 2006 - present.

Stefan Bathe Birthplace: Warstein, Germany **DOB:** May 12, 1971

Ph.D. October 28, 2002 Department of Physics, University of Muenster, Germany

Experience: PhD on WA98 and PHENIX
Postdoc at UC Riverside 2003-2007 work on PHENIX, high pT and photon physics co-convenor Photon Physics Working Group 2005-2008 RBRC fellow since 01/2008

Award and Honors:
02/99–08/99 DAAD Scholarship of the German Service for Foreign Academic Exchange.
12/97–11/01 Graduate Fellowship of the State Nordrhein-Westfalen, Germany.

Thomas C. Blum **Birthplace**: USA **DOB**: December 27, 1962

Ph.D. 1995, University of Arizona, Tucson, AZ

Experience: Postdoctoral Fellow, High Energy Theory Group, BNL
RIKEN BNL Fellow, October 1, 1998 – September 30, 2003;
Associate Physicist, Brookhaven National Laboratory, October 2003 – Dec. 2003.
•RHIC Physics Fellow/Assistant Professor—RBRC/U. of Connecticut, Storrs, January 1, 2004 - present.

Awards and Honors:
DOE-GANN Fellowship: August 1990 - May 1993;
Year 2005 Department of Energy Outstanding Junior Investigator Award, High Energy Physics.

Kieran Boyle **Birthplace: USA** **DOB: 06/14/79**

Ph.D. 2007, Stony Brook University, Stony Brook, NY
Graduate Student researcher, PHENIX at RHIC at BNL

Awards and Honors: *Graduate Student Researcher,* **SUNY Stony Brook Physics Dept.** Summer 2003
Nuclear Theory Research with Prof. Ismael Zahed. Studied chiral multiplets of heavy-light mesons with respect to results from the BABAR collaboration.

Research Assistant, **NASA Goddard Center,** Maryland Summer 2002
Climate Research with Dr. William Lau. Examined trends in rainfall data using Empirical Mode Decomposition to study non-linear series.

Research Assistant, **Vassar College Math Dept.** 2000 - 2001
Number Theory Research with Prof. John McCleary. Researched previous methods of attacking the odd perfect number problem and worked toward developing new ones.

Research Assistant, **Vassar College Physics Dept.** 1999 - 2000

Electronic device development with Prof. Mark Somerville. Studied Indium Arsenide transistors for optimization. Streamlined computer coding for device testing.

Adrian Dumitru **Birthplace**: Bucharest / Romania **DOB:** October 31, 1968

Ph.D. 1997, Institut fuer Theoretische Physik, Goethe University, Frankfurt, Germany

Experience: Baruch College, Associate Professor 09/08 - today
J.W. Goethe University, Junior Professor 01/03 - 08/08
Brookhaven Lab., Postdoctoral Fellow 10/01 - 12/2002
Columbia University, Postdoctoral Fellow, 09/99 - 09/2001
Yale University, Postdoc, 04/98 - 08/1999

Awards and Honors:

1. RIKEN-BNL Fellow, since Sept. 2008
2. Postdoctoral scholarship from the German Academic Exchange Service (DAAD), 1998 – 1999
3. Ph.D. scholarship from the Johann Wolfgang Goethe University, Frankfurt, 1994 – 1995
4. Diploma award from the "Heraeus Stiftung," July 1993 ad.

Abhay L. Deshpande **Birthplace**: Mumbai/Bombay, India **DOB**: March 21, 1965

Ph.D. 1994, Yale University

Experience: Visiting Scientist, BNL, 1989-1994 (Member of the BNL-E851 Collaboration)
Visiting Scientist, CERN, 1994-1999 (Member of the SMC Collaboration)
Visiting Scientist, DESY, 1998-Present (Member of the ZEUS Collaboration)
Associate Research Scientist, Yale University, 1994-2000
RIKEN BNL Fellow (Experimental Group), February 2000 – December 31, 2003.
•RHIC Physics Fellow/Assistant Professor-RBRC-E, SUNY, Stony Brook, January 1, 2004 – present.

Awards and Honors: Gibbs Prize in Physics, University of Bombay, 1985.

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Ph.D 2001, University of Regensburg

Experience: Assistant Professor, Texas A&M University 2006-
RHIC Fellow, RIKEN/BNL 2006-
Assistant Professor, University of Minnesota, 2005-2006
Research Associate, University of Minnesota, 2003-2005
Research Associate, Duke University, 2002-2003

Awards and Honors: Fellowship for Outstanding Students, Government of Bavaria, 1991-1996
Feodor Lynen Fellow, Alexander von Humboldt Foundation, 2002-2003
IUPAP Young Scientist Prize 2007

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B.S. 2001, Kyoto University, Kyoto, Japan
Master Course Student, 2002 – present
Experience: RBRC Young Researcher, Experimental Group, 2002 – 2003.
RIKEN Junior Research Associate, RBRC, Experimental Group, April 1, 2003 – present.

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Ph.D 1996, Kyoto University, Kyoto, Japan
Experience: Research Fellow of the Japan Society for the Promotion of Science, 1994-1996
Postdoctoral Fellow, RIKEN, Japan, 1996-1999
RIKEN BNL Fellow, November 1999 – March 31, 2002
Scientist, RIKEN, April 2002 to March 2003;
Senior Research Scientist, RIKEN, April 2003 – present.
RIKEN Spin Program Researcher, RBRC, April 1, 2002 – present.

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Ph.D. Now Student, Kyushu Univ., Fukuoka, Japan
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Award and Honors:

None

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Ph.D. 2002, Hiroshima University, Japan
Experience: Researcher, Hiroshima University, April 2002 to March 2003;
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Research Associate, RIKEN BNL Research Center (Theory), October 1, 2006 - present.

Taku Izubuchi **Birthplace**: Tokyo, Japan **DOB**: February 15, 1970
Ph.D. 1997, University of Tokyo

Experience: Postdoc, Tsukuba University, April 1997-November 1999.
Research Associate (with tenure), Department of Physics, Kanazawa University, December 1999 – February 2001
Brookhaven National Laboratory, High Energy Theory Group, March 2001 – February 2003
Research Associate (with tenure), Department of Physics, Kanazawa University, March 2003 – present.
RBRC Visiting Fellow with Kanazawa University, April 1, 2003 – present.

Awards and Honors:
Japan Society for the Promotion of Science (JSPS), Research Fellowship for Doctor Course, 1994-1997; André Lagarrigue Scholarship at the International School of Subnuclear Physics, Erice, Italy, 1995; JSPS Research Fellowship for Post Doctor, 1997-1999; JSPS Research Fellowship for Research Abroad, 2001-2003.

David M. Kawall **Birthplace**: Glasgow, UK **DOB**: April 13, 1965
Ph.D. 1996, Stanford University
Experience: Associate Research Scientist, Yale University, Physics Department, 1995-2004.
RIKEN BNL Fellow, RBRC Experimental Group, June 1, 2004 – January 2005.
RHIC Physics Fellow, RBRC Experimental Group/Assistant Professor, University of Massachusetts, Amherst, January 2005 - present
Awards and Honors: G. David Scott Scholarship in Physics, Trinity College Scholarship, Faculty Scholar, Varsity Fund National Admission Scholarship, William R. Hossack Memorial Scholarship in Mathematics and Physics

Adam Lichtl **Birthplace**: El Paso, TX USA **DOB**: July 29, 1981
Ph.D. 2006, Carnegie Mellon University, Pittsburgh, PA
Experience: Research Associate, RIKEN BNL Research Associate (Theory); October 2006 to present.

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Ph.D. 2001, SISSA-ISAS, Trieste, Italy
Experience: 2001 - 2004 Post-doctoral fellowship at the Institute for Advanced Study (IAS), School of Natural Sciences, Princeton. Funds from the National Science Foundation (NSF) and the Keck Foundation.
2004 - 2007 Five years fellow at the Institute for Nuclear Theory of Seattle and research assistant professor at the Physics Department of the University of Washington, Seattle.
2007 - Assistant professor at Arizona State University of Tempe, AZ and fellow at the RIKEN BNL Research Center (RBRC) October 2007 to present.

Awards and Honors:
2009: Grant from National Science Foundation, May 11, 2009-May 2011
December 2006: Selected as plenary speaker for the major conference "Neutrino 2006"(XXII International Conference on Neutrino Physics and Astrophysics) in Santa Fe, New Mexico from June 13-19, 2006.
January 2003: Prize "Giorgio Gamberini" issued by Scuola Normale in Pisa (Italy) for a PhD thesis in Theoretical Physics.

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Experience: Research Associate, RIKEN BNL Research Center (Theory)
October 2, 2006 - present

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Ph.D. 2002, Columbia University, New York
Experience: Postdoctoral Fellow, Nuclear Theory Group, The Ohio State University, Columbus, 2002-2003;
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Awards and Honors: Graduate Research Fellowship, Columbia University, 1997-2002;
Postdoctoral Fellowship, The Ohio State University, 2002-2003;
Klaus Kinder-Geiger Award for Best Talk at Hot Quarks 2004 Intl. Workshop, Taos, New Mexico, 2003

Itaru Nakagawa **Birthplace**: Japan **DOB**: October 5, 1969
Ph.D. 1999, Graduate School of Tohoku University, Sendai, Japan
Experience: Postdoctoral Associate of the Laboratory for Nuclear Science, Massachusetts Institute of Technology, Nov. 1999 to Nov. 2002; Postdoctoral Associate of Department of Physics and Astronomy, University of Kentucky, Dec. 2002 - Nov. 2003; Research Assistant Professor of the Department of Physics and Astronomy, University of Kentucky, December 2003-November 2004;
Scientist RIKEN, December 2004 - present;
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Awards and Honors:
Japan Ikueikai Scholarship, 1989-1994 and 1995-1999; The Peter T. Demos Award for the outstanding Ph.D. thesis in MIT-Bates Laboratory, 2000; Award for outstanding young physicists in Experimental Nuclear physics, Japanese Physics Society, 2003.

Akio Ogawa **Birthplace**: Japan **DOB**: September 6, 1969
Ph.D. 1997, Nagoya University, Japan
Experience: Research Associate, September 2002 and Assistant Scientist, April 2003, Brookhaven National Laboratory (BNL), STAR Experiment;
RIKEN Spin Program Visiting Scientist, Experimental Group, Belle Collaboration, KEK, January 1, 2002 - present.

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Ph.D. 2001, Nagoya University
Experience: Contract Researcher at RIKEN, Wako, Japan, June 2001-March 31, 2002
Research Associate, RIKEN BNL Research Center (Experiment),
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RIKEN Fellow, RIKEN BNL Research Center (Experiment),
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Peter Petreczky **Birthplace**: Uzsgorod (Ungvar), Ukraine **DOB**: February 17, 1973
Ph.D. 1999, Eötvös University, Budapest, Hungary
Experience: Research Fellow, Bielefeld University, Germany, 1999-2002
Goldhaber Fellow, Brookhaven National Laboratory, October 2002 – Sept. 2005;
RIKEN BNL Fellow, RBRC Theory Group joint with Nuclear Theory
October 1, 2003 – September 30, 2005; RIKEN BNL Fellow/Assistant Physicist joint with Lattice Gauge Group, October 1, 2005 to present.
Awards and Honors: Goldhaber Fellowship, 2002.

Ralf-Christian Seidl **Birthplace**: Nürnberg, Germany **DOB**: June 11, 1975
Ph.D. 2004, University of Erlangen-Nürnberg and DESY, Hamburg, Germany
Experience: Working Visit, Hermes Group at Tokyo Institute of Technology, Japan, granted by DFG/JSPS, October 2003; Hermes Experiment at DESY, Hamburg, Germany, 2002-2004; Postdoctoral Researcher, University of Illinois at Urbana-Champaign;
Visiting Scientist, RBRC Experimental Group, May 15, 2005 to present

Anna Stasto **Birthplace**: Kolobrzeg, Poland **DOB**: Feb. 12, 1973

PhD: 1999: Joint Ph.D. degree with distinction in theoretical high energy particle physics from the Polish Academy of Science, Institute of Nuclear Physics in Krakow, Poland, and the University of Durham, United Kingdom.
2005: Habilitation degree with distinction in theoretical physics
from the Polish Academy of Science, Institute of Nuclear Physics in Krakow, Poland.
1996: M.S. degree with distinction in theoretical physics from the Jagiellonian University, Krakow, Poland.

Experience: 2006 - 2008: Research Associate at the Department of Physics, Penn State University, University Park, 16802 PA.
2004 - 2006: Research Associate with the Nuclear Theory Group, Physics

Department, Brookhaven National Laboratory, Upton, NY, USA.
2002 - 2004: Postdoctoral Fellow with the Theory Group at DESY in Hamburg, Germany.
2000 - 2002: Postdoctoral Fellow at INFN in Florence, Italy.
1999 - 2000: Senior Research Associate at the Institute of Nuclear Physics, Polish Academy of Science in Krakow.
1996 - 1997: Research Assistant at the Institute of Nuclear Physics, Polish Academy of Sciences in Krakow.

Collaborations:

BNL (Upton, NY), CERN (Switzerland), DESY (Germany), Durham University (United Kingdom), INFN Florence (Italy),
Hamburg University, Jagiellonian University (Poland), Paris VI, and VII Universities (France), Warsaw University (Poland).

Other professional experience:

Convenor of the theory group for the Large Hadron Electron Collider (LHeC) project at CERN.
Referee for Acta Physica Polonica B, European Physical Journal C, Journal of High Energy Physics, Nuclear Physics A and B, Physical Review Letters, Physical Review C and D, and Physics Letters B.

Awards: 2009, DOE's Outstanding Junior Investigator Award for her research in nuclear physics
2009, Alfred P. Sloan Research Fellowship in recognition of her research as a young scientist engaged in cutting-edge research
H. Niewodniczanski Prize of Institute of Nuclear Physics, Polish Academy of Science, Krakow. Polish Science Foundation Fellow.
1999, PhD degree with distinction from the Institute of Nuclear Physics Krakow, Poland and University of Durham, UK.
Institute of Physics Prize for the most outstanding first year research student at the University of Durham, UK.
1996, M.S. degree with distinction from the Institute of Mathematics, Physics and Astronomy at the Jagiellonian University.

Atsushi Taketani **Birthplace**: Ako, Japan **DOB**: February 26, 1963
Ph.D. 1990, Hiroshima University, Japan
Experience: Research Associate, Fermi National Accelerator Laboratory, Batavia, IL, 1990-1994
Researcher, RIKEN, 1994-1999
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RIKEN Spin Program Researcher, April 1, 2001 – present.

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Ph.D. 2001, SUNY at Stony Brook

Experience: Postdoctoral Research Fellow, Brookhaven National Laboratory, October 2001 – 2004
Postdoctoral Research Fellow, SUNY at Stony Brook, July 2004 – July 2006
Assistant Professor, Arkansas State University, July 2006 – present
Awards and Honors: T.A. Pond Prize for Distinction on the Qualifying Exam, SUNY at Stony Brook, 1996
Anthony D. Stanley Memorial Prize for Excellence in Mathematics, Yale University, 1995

Kirill Tuchin **Birthplace:** Makeevka, Ukraine **DOB:** August 11, 1973
Ph.D. 2001, Tel-Aviv, Israel
Experience: Postdoctoral Research Associate, Institute for Nuclear Theory, University of Washington, 2001-2003; Postdoctoral Research Associate, Nuclear Theory Group, Brookhaven National Laboratory;
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Awards and Honors: Prize for research achievements from the School of Physics and Astronomy, Tel Aviv University, 2000.

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Ph.D. 1993, University of Tokyo, Japan
Experience: Scientific Researcher, RIKEN, 1991
Research Collaborator, PHENIX/RBRC
Scientific Researcher, RIKEN, RBRC, 1998-2001
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Ph.D. 2000, Kyoto University, Japan
Experience: Research Fellow of the Japan Society for the Promotion of Science, 1995-1997
Research Fellow of the Department of Physics, Kyoto University, 1998-2000; Special Postdoctoral Researcher, RIKEN, 2000-2001
RIKEN Spin Program Research Associate, April 1, 2001 – present
Awards and Honors: Fellowship: Japan Society for the Promotion of Science, 1995-1997

Feng Yuan **Birthplace**: Huangmei, China **DOB**: March 10, 1972
Ph.D. 2000, Peking University, P.R. China
Experience: Postdoctoral Research Associate, U. of Heidelberg, Germany, September 2000 to February 2002; Postdoctoral Research Associate, U. of Maryland, College Park, March 2002 to August 2004;
Research Associate, RIKEN BNL Research Center, Theory Group, September 1, 2004 – present.
Awards and Honors: National Outstanding Ph.D. Thesis, Chinese Ministry of Education, 2002.

Transverse momentum and centrality dependence of dihadron correlations in Au+Au collisions at s(NN) = 200-GeV: Jet-quenching and the response of partonic matter.
By PHENIX Collaboration (A. Adare *et al.*). May 2007. (Received May 2007). 6pp.
Published in **Phys.Rev.C77:011901,2008**.
e-Print: **arXiv:0705.3238** [nucl-ex]

Centrality dependence of charged hadron production in deuteron + gold and nucleon + gold collisions at s(NN)(1/2) = 200-GeV.**
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Published in **Phys.Rev.C77:014905,2008**.
e-Print: **arXiv:0708.2416** [nucl-ex]

Cold Nuclear Matter Effects on J/Psi as Constrained by Deuteron-Gold Measurements at s(NN)(1/2) = 200-GeV.**
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Published in **Phys.Rev.C77:024912,2008**
e-Print: **arXiv:0711.3917** [nucl-ex]

Particle-species dependent modification of jet-induced correlations in Au+Au collisions at s(NN)(1/2) = 200-GeV.**
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Published in **Phys.Rev.Lett.101:082301,2008**.
e-Print: **arXiv:0712.3033** [nucl-ex]

Source breakup dynamics in Au+Au Collisions at s(NN)(1/2) = 200-GeV via three-dimensional two-pion source imaging.**
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Published in **Phys.Rev.Lett.100:232301,2008**.
e-Print: **arXiv:0712.4372** [nucl-ex]

Experimental Study of Dense Matter at RHIC.
Y. Akiba, (Brookhaven) . 2008. 14pp.
Published in **Prog.Theor.Phys.Suppl.174:88-102,2008**.

J/psi Production in s(NN)(1/2) = 200-GeV Cu+Cu Collisions.**
By PHENIX Collaboration (A. Adare *et al.*). Jan 2008. (Received Sep 19, 2008). 6pp.
Published in **Phys.Rev.Lett.101:122301,2008**.
e-Print: **arXiv:0801.0220** [nucl-ex]

Quantitative Constraints on the Opacity of Hot Partonic Matter from Semi-Inclusive Single High Transverse Momentum Pion Suppression in Au+Au collisions at s(NN)(1/2) = 200-GeV.**
By PHENIX Collaboration (A. Adare *et al.*). Jan 2008. (Received Jan 2008). 13pp.
Published in **Phys.Rev.C77:064907,2008**.
e-Print: **arXiv:0801.1665** [nucl-ex]

Suppression pattern of neutral pions at high transverse momentum in Au + Au collisions at s(NN)(1/2) = 200-GeV and constraints on medium transport coefficients.**
By PHENIX Collaboration (A. Adare *et al.*). Jan 2008. (Received Dec 5, 2008). 6pp.
Published in **Phys.Rev.Lett.101:232301,2008**.
e-Print: **arXiv:0801.4020** [nucl-ex]

Dihadron azimuthal correlations in Au+Au collisions at s(NN)(1/2) = 200-GeV.**
By PHENIX Collaboration (A. Adare *et al.*). Jan 2008. (Received Jan 2008). 44pp.
Published in **Phys.Rev.C78:014901,2008**.
e-Print: **arXiv:0801.4545** [nucl-ex]

Onset of pi0 Suppression Studied in Cu+Cu Collisions at sNN=22.4, 62.4, and 200 GeV.
By PHENIX Collaboration (A. Adare *et al.*). Jan 2008. (Received Oct 17, 2008). 7pp.
Published in **Phys.Rev.Lett.101:162301,2008**.
e-Print: **arXiv:0801.4555** [nucl-ex]

Dilepton mass spectra in p+p collisions at s(1/2) = 200-GeV and the contribution from open charm.**
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Published in **Phys.Lett.B670:313-320,2009**.
e-Print: **arXiv:0802.0050** [hep-ex]

Enhanced production of direct photons in Au + Au collisions at s(NN)(1/2) = 200-GeV.**
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Submitted to Phys.Rev.Lett.
e-Print: **arXiv:0804.4168** [nucl-ex]

Charged hadron multiplicity fluctuations in Au+Au and Cu+Cu collisions from sqrt(s_NN) = 22.5 to 200 GeV.
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Published in **Phys.Rev.C78:044902,2008**.
e-Print: **arXiv:0805.1521** [nucl-ex]

The Polarized gluon contribution to the proton spin from the double helicity asymmetry in inclusive pi0 production in polarized p + p collisions at s(1/2) = 200-GeV.**
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Published in **Phys.Rev.Lett.103:012003,2009**.
e-Print: **arXiv:0810.0694** [hep-ex]

Inclusive cross section and double helicity asymmetry for pi^0 production in p+p collisions at sqrt(s) = 62.4 GeV.
By PHENIX Collaboration (A. Adare *et al.*). Oct 2008. (Received Oct 2008). 10pp.
Published in **Phys.Rev.D79:012003,2009**.
e-Print: **arXiv:0810.0701** [hep-ex]

Silicon Pixel Detector for the PHENIX experiment at the BNL RHIC.
Ryo Ichimiya *et al.* Dec 2008. 7pp.
e-Print: **arXiv:0812.2834** [nucl-ex]

Fine pitch and low material readout bus for the Silicon Pixel Detector in the PHENIX Vertex Tracker.
Kohei Fujiwara *et al.* 2009. 8pp.
Published in **IEEE Trans.Nucl.Sci.56:250-257,2009**.

Heavy ion physics at RHIC.
Yasuyuki Akiba, (Wako, RIKEN) . 2009. 6pp.
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Assembly procedure for the silicon pixel ladder for PHENIX silicon vertex tracker.
Y. Onuki *et al.* 2009. 9pp.
Published in **Nucl.Instrum.Meth.A606:395-403,2009**.

Status and Performance of New Silicon Stripixel Detector for the PHENIX Experiment at RHIC: Beta Source, Cosmic-rays and Proton Beam at 120-GeV.
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Invited talk at PIXEL 2008: International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, Batavia, Illinois, 23-26 Sep 2008.
Published in **JINST 4:P04011,2009**.
e-Print: **arXiv:0902.4223** [nucl-ex]

Photoproduction of J/psi and of high mass e+e- in ultra-peripheral Au+Au collisions at s(1/2) = 200-GeV.**
By PHENIX Collaboration (S. Afanasiev *et al.*). Mar 2009. 20pp.
Published in **Phys.Lett.B679:321-329,2009**.
e-Print: **arXiv:0903.2041** [nucl-ex]

Photon-Hadron Jet Correlations in p+p and Au+Au Collisions at s(1/2) = 200-GeV.**
By PHENIX Collaboration (A. Adare *et al.*). Mar 2009. (Received Mar 2009). 14pp.
Published in **Phys.Rev.C80:024908,2009**.
e-Print: **arXiv:0903.3399** [nucl-ex]

Measurement of Bottom versus Charm as a Function of Transverse Momentum with Electron-Hadron Correlations in p+p Collisions at sqrt(s)=200 GeV.
By PHENIX Collaboration (A. Adare *et al.*). Mar 2009. (Received Aug 21, 2009). 6pp.
Published in **Phys.Rev.Lett.103:082002,2009**.
e-Print: **arXiv:0903.4851** [hep-ex]

Kaon interferometric probes of space-time evolution in Au+Au collisions at s(NN)(1/2) = 200-GeV.**
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Published in **Phys.Rev.Lett.103:142301,2009**.
e-Print: **arXiv:0903.4863** [nucl-ex]

High-pT pi0 Production with Respect to the Reaction Plane in Au + Au Collisions at s(NN)(1/2) = 200-GeV.**
By PHENIX Collaboration (S. Afanasiev *et al.*). Mar 2009. 35pp.
Submitted to Phys.Rev.C
e-Print: **arXiv:0903.4886** [nucl-ex]

Systematic Studies of Elliptic Flow Measurements in Au+Au Collisions at s(1/2) = 200-GeV.**
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Published in **Phys.Rev.C80:024909,2009**.
e-Print: **arXiv:0905.1070** [nucl-ex]

Dilepton Radiation Measured in PHENIX probing the Strongly Interacting Matter Created at RHIC.
By PHENIX Collaboration (Y. Akiba *for the collaboration*). Jul 2009. 4pp.
To appear in the proceedings of Quark Matter 2009: 21st International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (QM2009),

Knoxville, Tennessee, 30 Mar - 4 Apr 2009.
e-Print: **arXiv:0907.4794** [nucl-ex]

BNL FY: October 1, 2008 to September 30, 2009

758. PACS-CS collaboration N. Ukita et. al. "SU(2) and SU(3) chiral perturbation theory analyses on meson and baryon masses in 2+1 flavor lattice QCD"

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760. PACS-CS collaboration Y. Namekawa et. al. "Charm quark system in 2+1 flavor lattice QCD using the PACS-CS configurations".

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768. Kojo, Toru; Jido, Daisuke;"QCD Sum Rules and $1/N_c$ expansion".

769. Yasumichi Aoki, "Quark mass renormalization with non-exceptional momenta to appear in: PoS(LATTICE2008)222"

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776. Yoshimas Hidaka, Kenji Fukushima "Two-gluon production and longitudinal correlations in the Color Glass Condensate", submitted to Nuclear Physics A, 2008.

777. Tomomi Ishikawa "Perturbative O(asa) matching in static heavy and domain-wall light quark system".

778. Denes Molnar, Pasi Hyovinen "Dissipatice effects form transport and viscous hydrodynamics"Journal of Phsyics G-Nuclear and Particle Physics, Vol 35, 10, 104125.

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781. Sinya Aoki, Oliver Baer, Benedikt Biedermann "Pion scattering in Wilson chiral perturbation theory". Submitted Phys. Rev D 78, 114501 (2008).

782. Yasumichi Aoki, "The QCD transition temperature: results wit physical masses in the contimuum limit II" submitted to JHEP, March 25, 2009.

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asymmetry in open charm production"

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791. Feng Yuan, Jian Zhou " Collins Function and the Single Transverse Spin Asymmetry".

792. Jian Zhou, Feng Yuan, Zuo-Tang Liang "Drell-Yan Lepton Pair Azimuthal Asymmetry in Hadronic Processes".

793. Feng Yuan "Recent Development in Proton Spin Physics"

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798. W. Liu, R.J. Fries "Heavy quark production from jet conversions in a quark-gluon plasma" Physical Review C 78, 037902 (2008).

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Through collision
Generate new states of matter.
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