BNL-81556-2008
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 91

RBRC Scientific Review Committee Meeting

November 17-18, 2008

Organizer:

N.P. Samios

RIKEN BNL Research Center

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

DISCLAIMER

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 2008

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

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Theory Presentations

QCDSP Project

RBRC Scientific Review Committee Meeting

November 17-18, 2008

Brookhaven National Laboratory, Upton, NY 11973

The ninth evaluation of the RIKEN BNL Research Center (RBRC) took place on Nov. 17-18, 2008, at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC) were Dr. Dr. Wit Busza (Chair), Dr. Miklos Gyulassy, Dr. Akira Masaike, Dr. Richard Milner, Dr. Alfred Mueller, and Dr. Akira Ukawa. We are pleased that Dr. Yasushige Yano, the Director of the Nishina Institute of RIKEN, Japan participated in this meeting both in informing the committee of the activities of the Nishina Institute 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,

November 17 and 18 Agenda

Committee Members

Busza, Wit (Chair)	**busza@mit.edu**
Gyulassy, Miklos	**gyulassy@phys.columbia.edu**
Masaike, Akira	**masaike@mvb.biglobe.ne.jp**
Milner, Richard	**milner@mit.edu**
Mueller, Alfred	**amh@phys.columbia.edu**
Ukawa, Akira	**ukawa@ccs.tsukuba.ac.jp**

Monday, November 17, 2008

8:00 AM - 9:00 AM *SRC Executive Session (Room 2-160)*
{Presentations by RIKEN/RBRC Adminstration}

Open Sessions - Large Seminar Room

EXPERIMENTAL GROUP PRESENTATIONS
Hideto En'yo, Chair

9:00	Exp. Group overview: HI Physics and PHENIX upgrade projects	Yasuyuki Akiba
9:15	Direct photon measurements at PHENIX	Kensuke Okada
9:30	Hard Scattering Physics in PHENIX And ATLAS	Stefan Bathe
9:45	PHENIX Muon Trigger FEE Upgrades for Sea Quark Polarization Measurement via W-Boson	Itaru Nakagawa
10:00	PHENIX VTX upgrade: Overview and Pixel detector	Atsushi Taketani
10:15	PHENIX VTX upgrade: Strip detector and software development	Manabu Togawa

10:30 AM **Break**

EXPERIMENTAL GROUP PRESENTATIONS
Yasuyuki Akiba, Chair

11:00	Exp. Group overview: Spin Physics	Abhay Deshpande
11:15	Constraining Delta G by Measuring Double Helicity Asymmetry in Neutral Pion Production	Kieran Boyle
11:30	The Double Longitudinal Spin Asymmetry in Unidentified	Dave Kawall

	Charged Hadrons from pp collisions at sqrt(s)=62.4 GeV	
11:45	Fragmentation Functions from Belle	Ralf Seidl
12:00	Drell -Yan measurement with polarized proton beams	Yuji Goto
12:15	RHIC Data Analysis at CCJ	Yasushi Watanabe

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

1:30 PM - 3:30 PM **THEORY GROUP PRESENTATIONS (<u>Large Seminar Room</u>)**
Larry Mc Lerran, Chair

1:30	QCD thermodynamics on the lattice	Peter Petreczky
1:50	The quark and gluon propagators at finite temperature	Masatoshi Hamada
2:00	Nucleon Structure on the Lattice	Shigemi Ohta
2:10	Study of eta' meson using domain-wall QCD	Taku Izubuchi
2:20	Improved Non-perturbative Renormalization	Yasumichi Aoki
2:30	Dynamical QCD+QED lattice simulations	Thomas Blum
2:40	Perturbative O(a) matching in static heavy and domain-wall light quark system	Tomomi Ishikawa
2:50	Drell-Yan Lepton Pair Azimuthal Correlation: Lam-Tung Relation Revisited	Feng Yuan
3:10	Neutrinos from core collapse supernovae	Cecilia Lunardini
3:20	A Beam Cooling Scheme for a Muon Collider	Adam Lichtl

3:30 PM – 4:00 PM **Break**

4:00 PM - 5:30 PM **THEORY GROUP PRESENTATIONS (<u>Large Seminar Room</u>)**
Tony Baltz, chair

4:00	Probing Hot and Cold Nuclear Matter	R. Fries
4:10	Medium-induced energy loss at weak and strong coupling	C. Marquet
4:20	Viscous hydrodynamics and RHIC	D. Molnar
4:30	Progress on Hydrodynamics and AdS/CFT	D. Teaney
4:40	Suppression of the Shear Viscosity in a "semi" Quark. Gluon Plasma	Y. Hidaka
4:50	Resummation in the high energy limit	A. Stasto
5:00	Coherent and incoherent diffractive hadron production in pA collisions	K. Tuchin
5:10	The gluon propagator and the heavy-quark potential in anisotropic QCD	A. Dumitru
5:20	Dynamical study of bare sigma pole with 1/Nc classifications	T. Kojo
5:30	RHIC Luminosity Upgrade	T.Roser

7:00 PM **DINNER**

<u>Tuesday, November 18, 2008</u>

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

	INTRODUCTORY TALKS (<u>Large Seminar Room</u>) **Nicholas P. Samios, Chair**
9:00 AM – 11:00 AM	**RBC Collaboration Research Highlights (Robert Mawhinney)** **Lattice Gauge Computing (Norman Christ) (QCDOC, QCDX)** **Physics at RHIC with Upgrades (Yasuyuki Akiba)** **e-RHIC (Abhay Deshpande)** **BNL – Strategic Plan (S. Vigdor)**
12:00 - 1:30 PM	***SRC Executive Session - Working Lunch (Room 2-160)***
1:30-3:00 PM	**INTERVIEWS - Meetings with Individual RBRC Staff (Rooms 2-160 and 2-78)**
3:00-4:15PM	**Executive Session**
4:15-5:00 PM	**Close Out**
5:00 PM	**Adjourn**

RBRC Scientific Review Committee Membership 2008

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E-mail: ukawa@ccs.tsukuba.ac.jp

RIKEN NISHINA CENTER

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

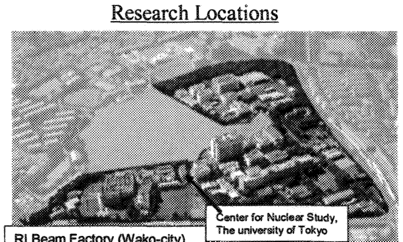
Yasushige Yano
Director, RIKEN Nishina Center (RNC)
November 17-18 2008
BNL, USA

RIKEN NISHINA CENTER

Organization of RIKEN Nishina Center

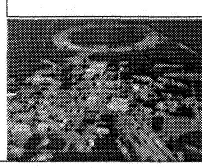
(established on April 1 2006)

Research Locations

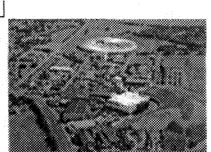


Center for Nuclear Study, The university of Tokyo

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



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



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

President

Advisory Council
RBRC-SRC
RRMF-AC

Director
Deputy
Science Adviser

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

Accelerator Division
- Accelerator Development Group
- Accelerator Operation Group

Nuclear Physics Research Division
- Heavy Ion Nuclear Physics Laboratory
- Theoretical Nuclear Physics Laboratory
- Radioactive Isotope Physics Laboratory
- Superheavy Element Laboratory
- Experimental Installations Development Group
- Experimental Installations Operation Group

User Liaison and Support Division
- User Liaison and Support Group

Sub Nuclear System Research Division
- Radiation Laboratory
- Advanced Meson Science Laboratory
- Theoretical Physics Laboratory
- Strangeness Nuclear Physics Laboratory

Accelerator Applications Research Division
- Accelerator Applications Research Group

Safety Management Group

RIKEN BNL Research Center
- Theory Group
- Experimental Group

RIKEN Facility Office at RAL

Terms and 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?

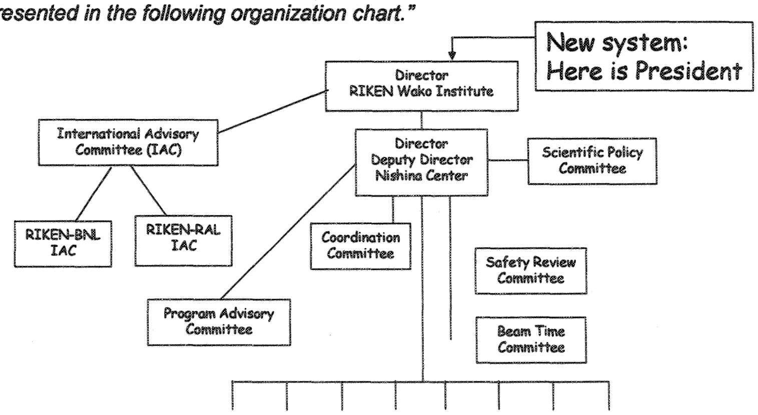
2) How does the Center compare with similar research institutions abroad? Make recommendations for possible improvement based on this investigation.
- Where does RIKEN rank in the worldwide research community?

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?

The last AC (Feb 23-25, 2006)'s recommendations included:

"The committee recommends that subcommittees be appointed, of a few people with the required expertise, to review activities at the Center such as the RIKEN BNL Research Center and the RIKEN RAL Muon Facility, and any other activities that are not an integral part of RIBF operations and research programs."

"The Committee believes that the proposed committee structure would be better represented in the following organization chart."



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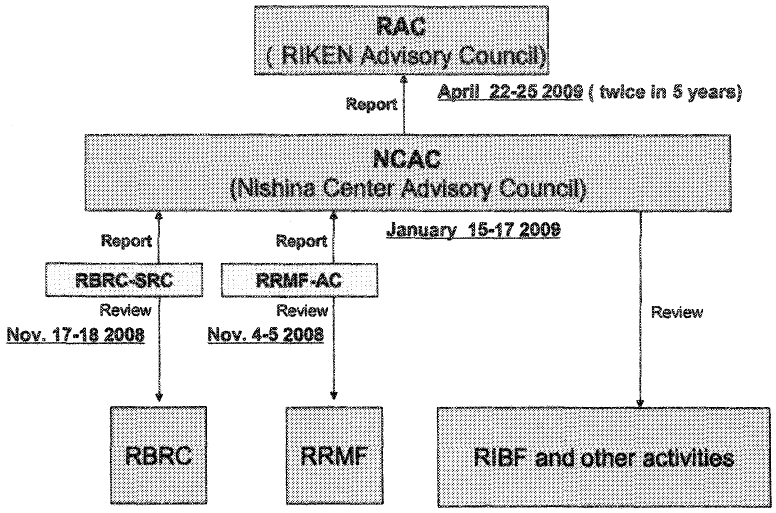
RIKEN Review System and Schedule



Nishina Center Advisory Council
January 15-17, 2009

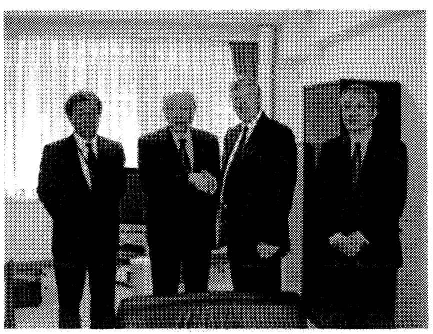
Name	Affiliation
Sydney Gales (Chair)	GANIL
Shoji Nagamiya	KEK, J-PARC Center
Walter F.Henning	ANL (Chair NP-PAC)
Robert Kiefl	University of British Columbia (Chair ML-PAC)
Wit Busza	MIT (Chair RBRC-SRC)
Andrew Taylor	ISIS, RAL (Chair RRMF-AC)
Angela Bracco	University of Milan
Makoto Inoue	Kyoto University (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

The RBRC-ACSRC review report:

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

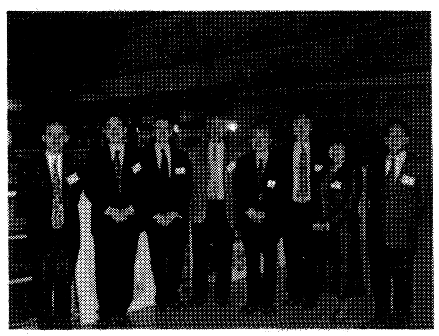
and
may include confidentialities
to Director of Nishina Center
and Director of RBRC.

RRMF-AC Nov. 4-5 Wako Japan



Courtesy visit to RIKEN President

R. Noyori
A. Taylor (Chairperson)

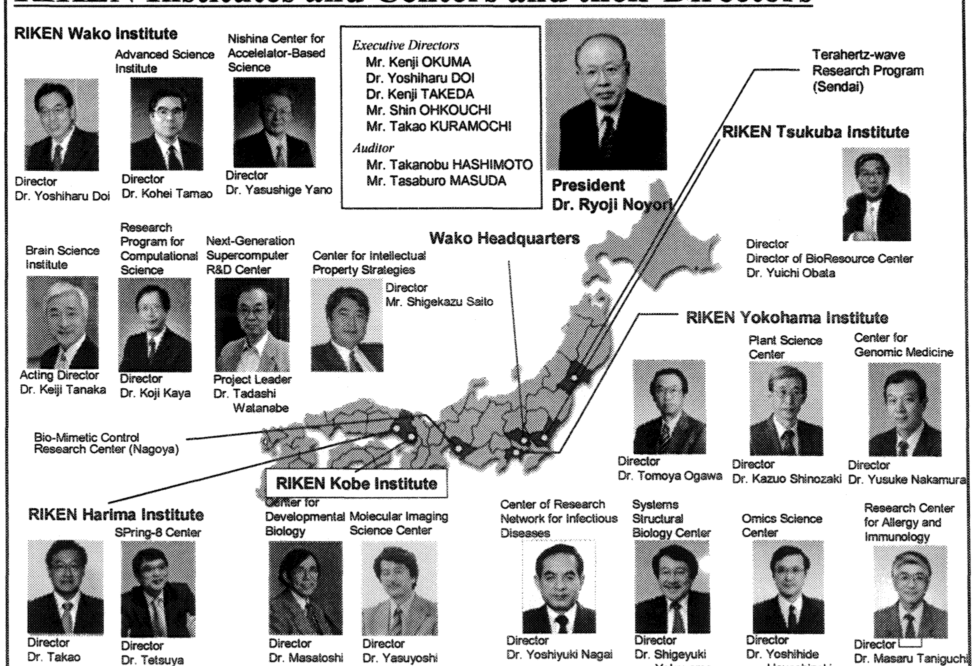


S. Blundell (Univ. of Oxford)
P. King (Secretary, ISIS)
K. Clausen (PSI)
J.M. Poutissou (TRIUMF)
Y. Yano (RIKEN)
A. Taylor (Chairperson, ISIS)
E. Torikai (Yamanashi Univ.)
J. Yamazato (KEK)

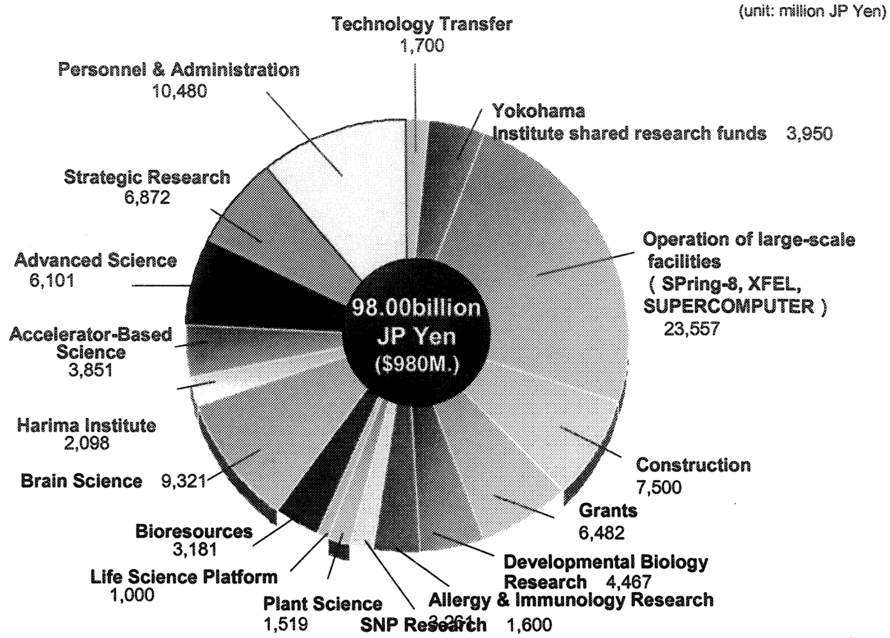
List of members of the 7th RAC

	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. Hiroo Imura	Advisor, Japan Science and Technology Agency	Endocrinology	Japan
	Dr. Toshiaki Ikoma	Director, Center for Research and Development Strategy, Japan Science and Technology Agency	Engineering	Japan
	Prof. Hans L. R. Wigzell	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. Teruhiko Beppu	Professor, Nihon University Graduate School	Bioresource 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. Biao Jiang	Director, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences	Chemistry	China
	Prof. Paul Kienle	Professor Emeritus, Department of Physics, Munich University of Technology	Physics	Germany
	Prof. Karin E. Markides	President, Chalmers University of Technology	Chemistry	Sweden
	Rainer E. Metternich	Vice President of Basic Research	Pharmacy	USA

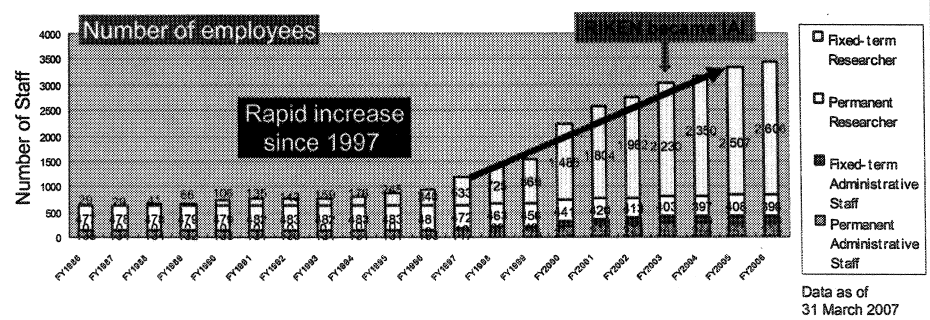
RIKEN Institutes and Centers and their Directors

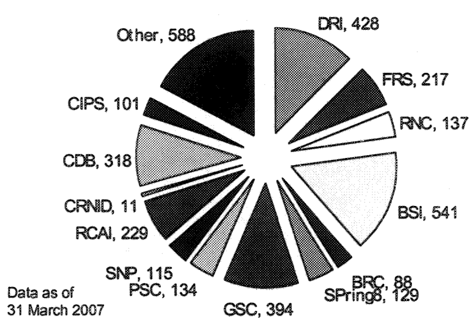


Budget for 2008 Fiscal Year



Recent Expansion





New research centers

1997	SPring-8
	Brain Science Institute
1998	Genomic Sciences Center
2000	Plant Science Center
	SNP Research Center
	Center for Developmental Biology
	BioResource Center
2001	Center for Allergy and Immunology
2006	Nishina Center for Accelerator-Based Science

Data as of 31 March 2008

RIKEN Nishina Center (FY2008)

Budget

RIBF:	2,921MJY	(including 1,149MJY for electricity)
RAL:	195MJY	
BNL:	735MJY	
Total:	3,851MJY	

(excluding salary for permanent staff, construction and external budget)

Man power

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

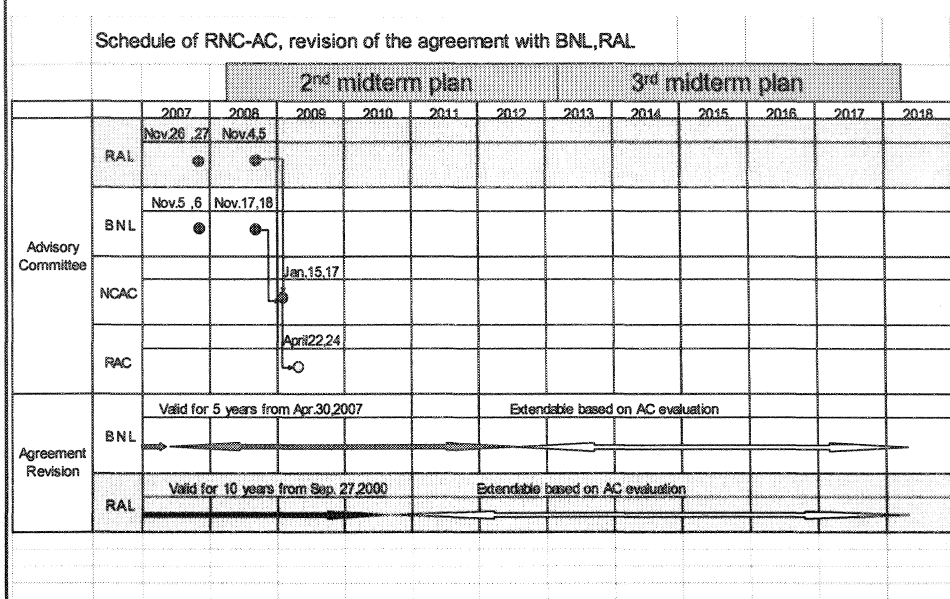
For your reference:

Terms and Reference from President to the 7th RIKEN Advisory Council (RAC)

Evaluate RIKEN's responses to the 6th RAC's proposal:
"RIKEN: Leading Japanese Science to Global Pre-Eminence."

Propose to the RIKEN Executive Board a management policy to realize the three pillars of the 2nd Five Year Plan:
"RIKEN that brings about dramatic progress in science and technology," "RIKEN that contributes to society and is worthy of society's trust," and "RIKEN that has a globally recognized brand image."

Evaluate RIKEN's collaborations within its own Centers and Institutes and with outside institutions, and propose to the RIKEN Executive Board means to further promote these collaborative efforts.



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For 1) & 2) :

- **General: impacts of "Spin physics", "Quark-gluon plasma physics", and "Lattice QCD computer physics" on Physics**

- **Characteristic feature of RBRC**

  among CERN, DESY, JLAB, SLAC, J-PARC (KEK) etc.

For 2) possible improvements:

- **Extension Period** : **6 years**

  road map to solve the problems
  matching with RIKEN's midterm cycle

For 2) possible improvements:

What condition or situation will make us conclude to terminate RIKEN-BNL collaboration.

If such condition or situation does not come out, this collaboration should continue, because its cost performance is quite high and the shutdown cost (budget) is not cheap. (Current running cost is nearly 8 M$/year. Initial cost was 30M$ and more)

- ✓ Overall quality of outcome (publication) is lowering as compared with the world standard. No outstanding outcome.
- ✓ No ambitious, unique research project.
- ✓ Number of researchers is decreasing, and as a result cost performance is lowering.
- ✓ No leader, No leadership.
- ✓ Unwillingness of BNL.

新しい経済対策「生活対策」における世界最先端の

研究開発促進施策について

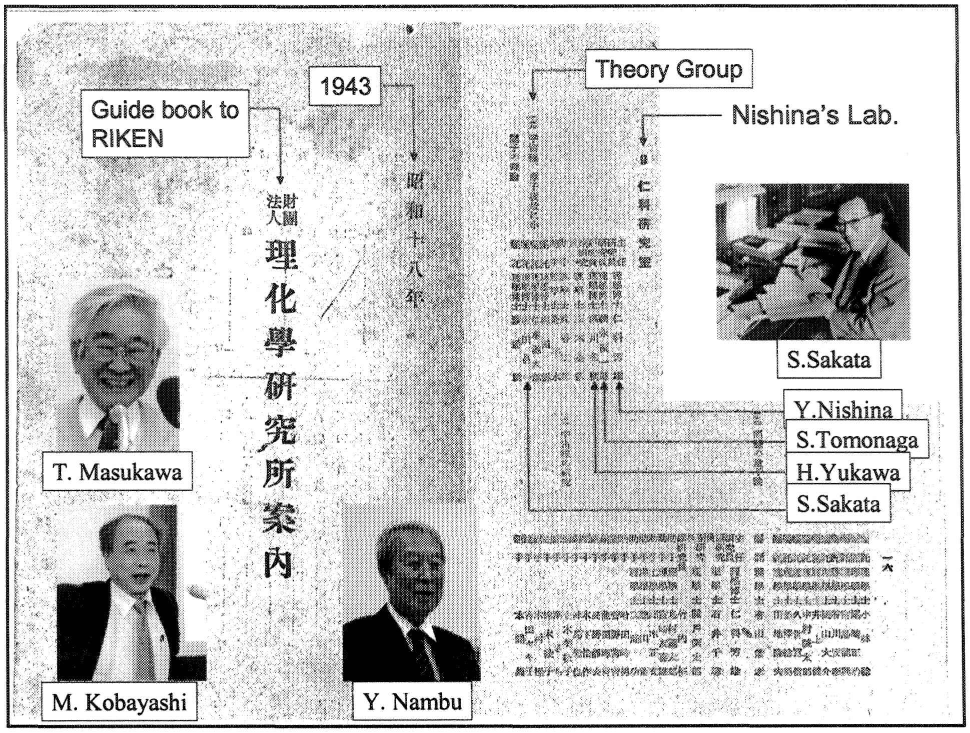
（研究振興局分）

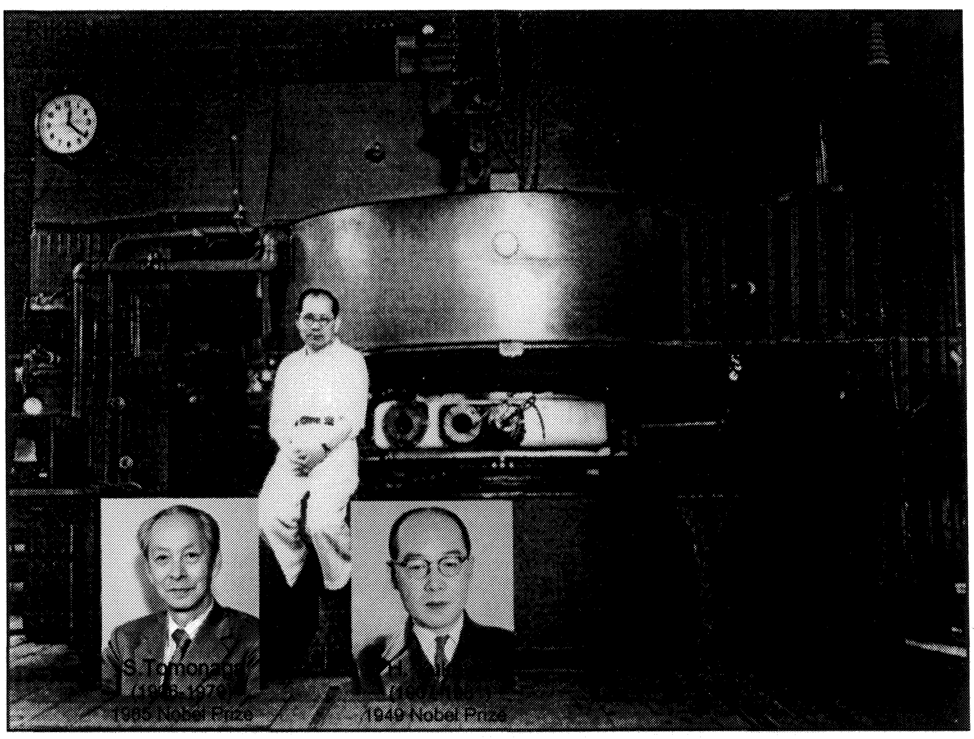
Approval of Second Supplement Budget

○ ノーベル賞を受賞するような世界最先端の研究開発促進

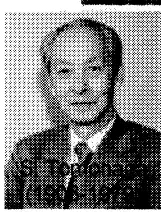
To promote Nobel prize researches

・RIビームファクトリー（理化学研究所）	15億円
RI beam factory (RIKEN)	1.5B JYen
・脳科学研究（理化学研究所）	30億円
Brain Science (RIKEN)	3.0B JYen
合 計	45億円


Guide book to RIKEN
1943
Theory Group
Nishina's Lab.
財團法人
理化學研究所案內
昭和十八年
S.Sakata
Y.Nishina
S.Tomonaga
H.Yukawa
S.Sakata
T. Masukawa
M. Kobayashi
Y. Nambu


1949 Nobel Prize

About Dr. Yoshio Nishina



Nobel Prize in 1965

Nobel Prize in 1949

Theorist
(Klein-Nishina Formula)
- RBRC Theory Group
- Theoretical Physics Laboratory
- Theoretical Nuclear Physics laboratory
- Strangeness Nuclear Physics Laboratory

Experimentalist
(Particle, Nuclear, Cosmic-ray Physics)
- Heavy ion Nuclear Physics Laboratory
- Radioactive Isotope Physics Laboratory
- Superheavy Element Laboratory
- Experimental Installations Development Group
- Experimental Installations Operation Group
- RBRC Experimental Group
- Radiation Laboratory
- Advanced Meson Science Laboratory

Accelerator Builder
(CW, Cyclotrons 1937, 1943)
- Accelerator Development Group
- Accelerator Operation Group

Promoter of Applications
(RI production. Radiobiology)
- RIKEN RAL Muon Facility (UK)
- Accelerator Applications Research Group

RIKEN's Old Cyclotrons (1937 ~ 1990)

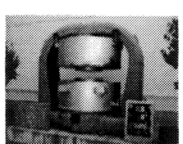
Multi-disciplinary Utilization

50th Anniversary of RI production (1990)

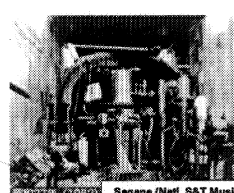
第1号サイクロトロン
磁極直径65cm
わが国最初のサイクロトロン
1st cyclotron
Magnet diameter 65cm
The first cyclotron in Japan

第2号60インチサイクロトロン
磁極直径150cm
2nd 60inch cyclotron
Magnet diameter 150cm

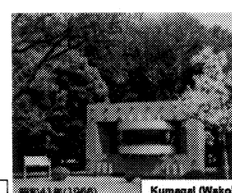
Old Campus



(Old RIKEN)



第3号サイクロトロン
磁極直径65cm
3rd cyclotron
Magnet diameter 65cm



第4号160cmサイクロトロン
磁極直径210cm
わが国初の重イオン加速器
4th 160cm cyclotron
Magnet diameter 210cm

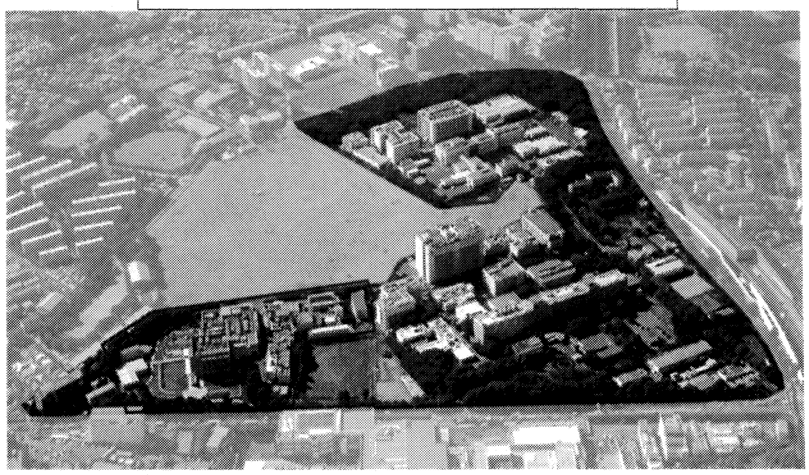
The Japan first Heavy Ion Accelerator (1967 ~ 1990)

New Campus

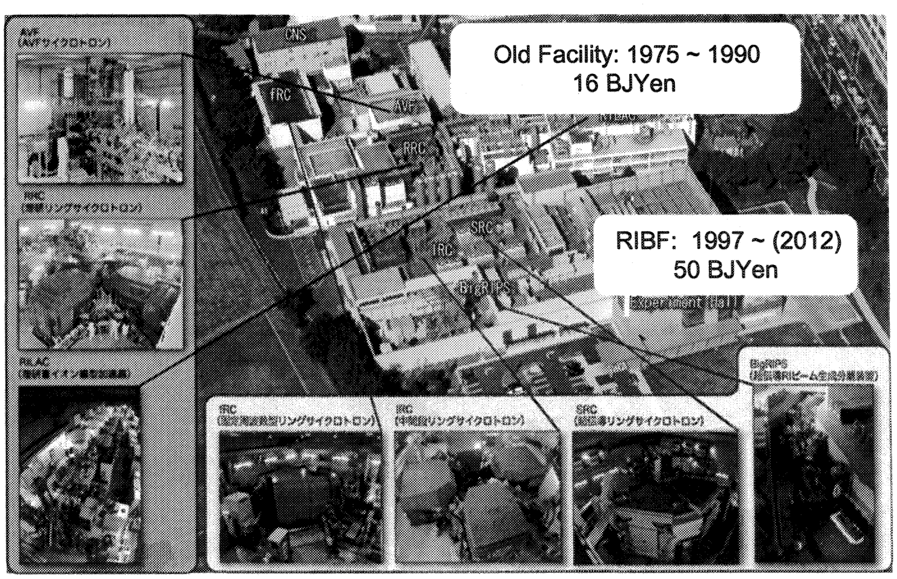
RI Beam Factory

(newly operational in March 2007)

World's most intense exotic RI beam



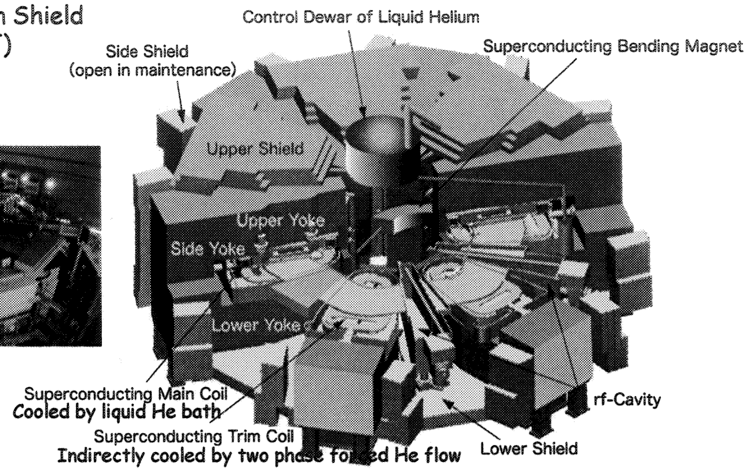
RI Beam Factory (RIBF), RIKEN Nishina Center, Wako-city

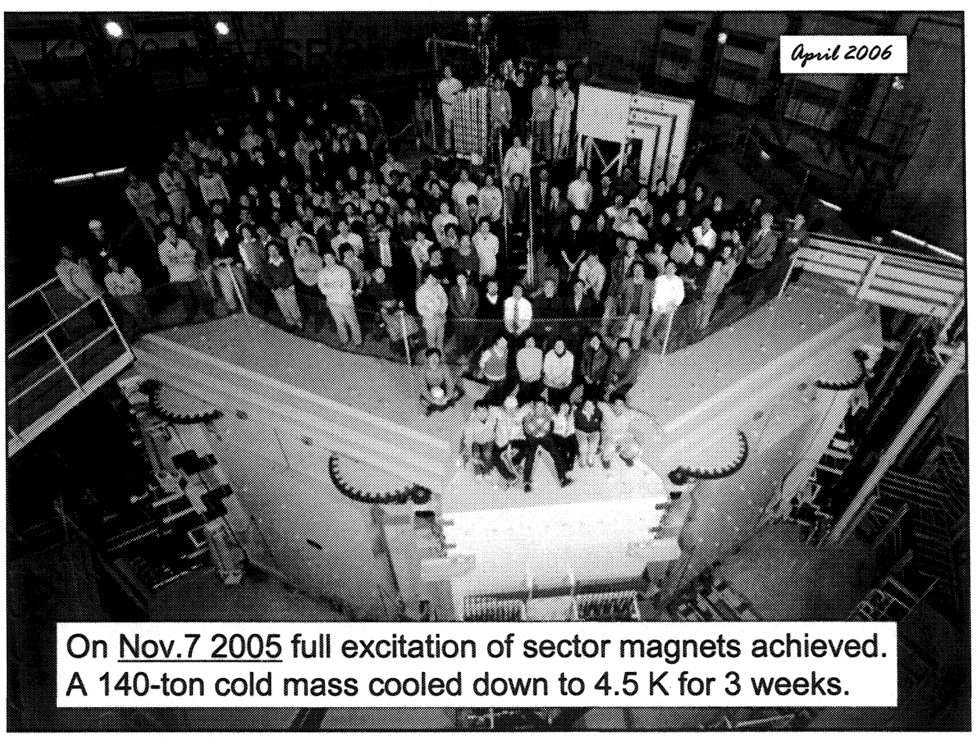


Superconducting Ring Cyclotron (SRC)

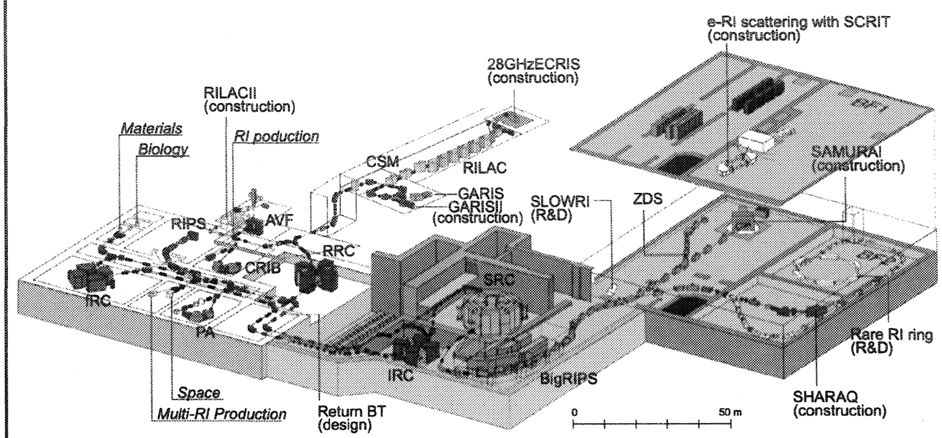
World's First, World's Strongest, World's Heaviest

K = 2,600 MeV
Self Magnetic Shield
Self Radiation Shield
3.8T (240 MJ)
18-38 MHz
8,300 tons



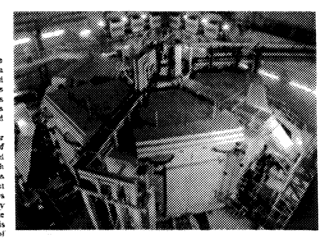


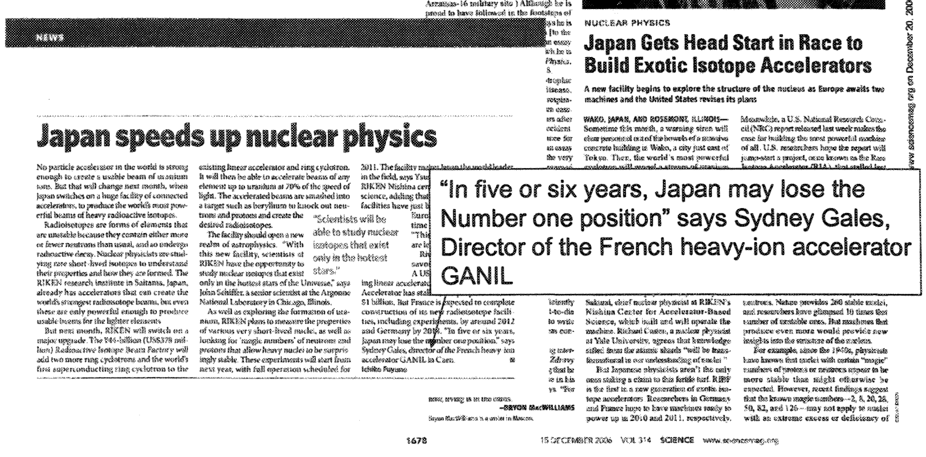
Major Experimental Installations



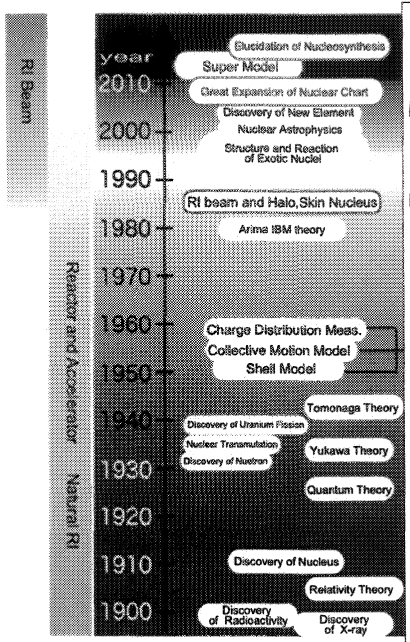
"Science" : Dec. 2006

"Nature" : Dec. 2006



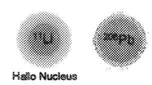


"In five or six years, Japan may lose the Number one position" says Sydney Gales, Director of the French heavy-ion accelerator GANIL



Development
of Nuclear Physics

Mystery of Nucleus?	Mystery of superconductivity?
Discovery of Halo Nucleus	Discovery of high Tc Superconductivity -Nobel Prize-
Understanding of Nucleus -3 Nobel Prizes-	Understanding of superconductivity (BCS theory) -Nobel Prize-
Discovery of Nucleus	Discovery of superconductivity -Nobel Prize-



BCS and IBM

MADHUSREE MUKERJEE AND YOICHIRO NAMBU

Department of Physics and The Enrico Fermi Institute, University of Chicago, 5640 S. Ellis Avenue, Chicago, Illinois 60637

Received December 5, 1988

The BCS theory of fermionic pairing and condensation is used to understand the interacting boson model. Results from BCS are incorporated into an effective Hamiltonian that after symmetry-breaking and second-order corrections yields an IBM-type Hamiltonian with coefficients determined by well-known nuclear constants. The $O(6)$ and $O(5)$ chains are shown to be largely of spontaneous origin. Supersymmetry aspects of the model are also discussed.

1. INTRODUCTION

The interacting boson model [1–7] is well established as a unified description of collective levels of heavy nuclei. The BCS theory of fermionic pairing and condensation [8] is likewise a tour-de-force with wide-ranging applications, not the least of which is to the nucleus [9]. Th

ANNALS OF PHYSICS 191,143-162 (1989)

paradigms of modern nuclear physics so that the former becomes the inevitable

References

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2. A. Arima and F. Iachello, *Phys. Rev. Lett.* **40** (1978), 385.
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15. P. B. Littlewood and C. M. Varma, *Phys. Rev. B* **26**, No. 9 (1982), 4883.
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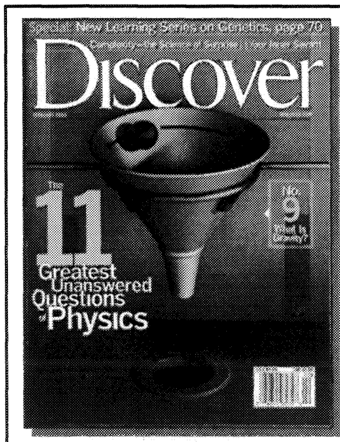
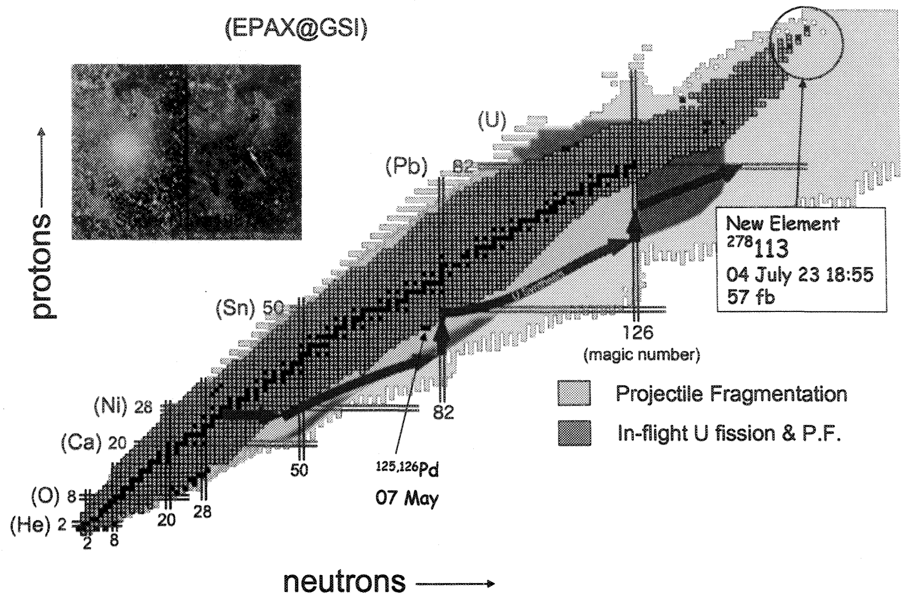


Report of the National Academy of Science
"The 11 Greatest
Unanswered Questions of Physics"

Discover Vol.23 No. 02
February 2002

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

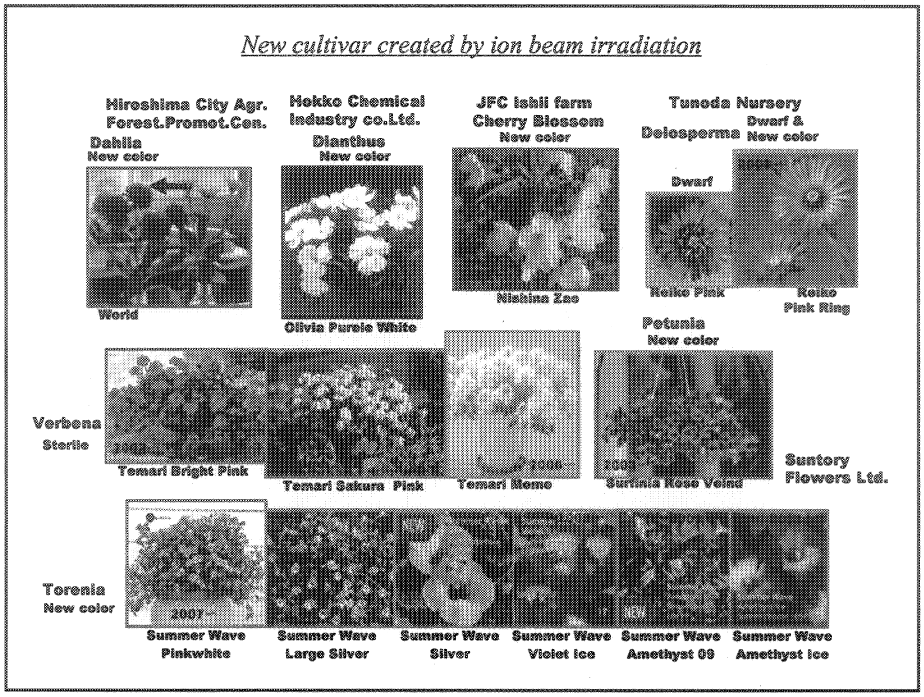
Great expansion of nuclear world by RIBF
Intensity > 1 particle/day
(EPAX@GSI)

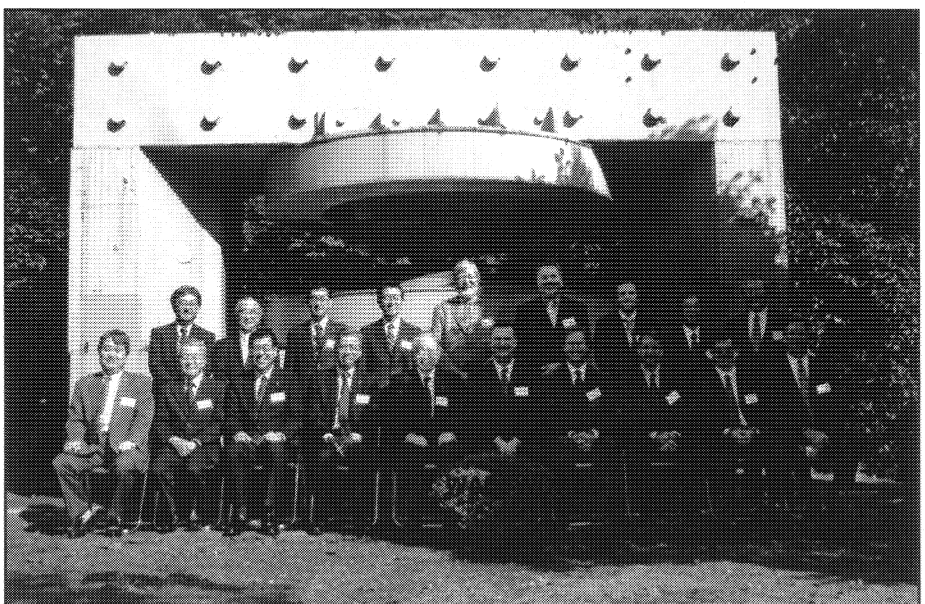


Missions of the RIKEN RI Beam Factory Project

Greatly expanding our knowledge of the nuclear world into presently unreachable regions on the nuclear chart, We will challenge:

1) To establish a New "Unified Picture of the Nucleus",
2) To elucidate the "Genesis of Elements", and
3) To open up New Applications of the RIB technology.





RIKEN-Battelle Collaboration Contract Oct. 30 2008

19

RBRC Scientific Review
Committee Meeting

RBRC Overview

Nicholas P. Samios

Nov. 17, 2008

Brookhaven National Laboratory

RBRC Major Physics Interests

Spin Structure of the Proton

High Energy Density Matter

- sQGP

Color Glass Condensate

Glasma

Critical Point

- RHIC

Lattice Gauge Calculations

- QCDOC (>95% Efficiency)

RHIC – Luminosity of Upgrade

eRHIC – Electron Capability

QCDX - 300 Tflop

Physics

Nuclear Spin

Global Analysis

Vogelsang *et al.*

Gluon Contribution

Small

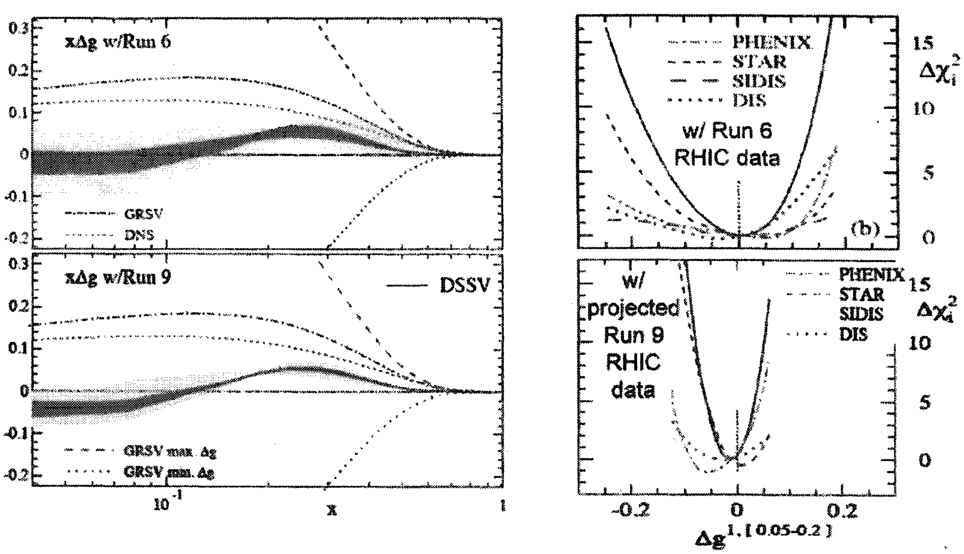
Consistent with zero

Run 8

d-Au 100 GeV/A_{mu} 100 GeV/A_{mu}
220 nb^{-1} (~10 × Run 3)

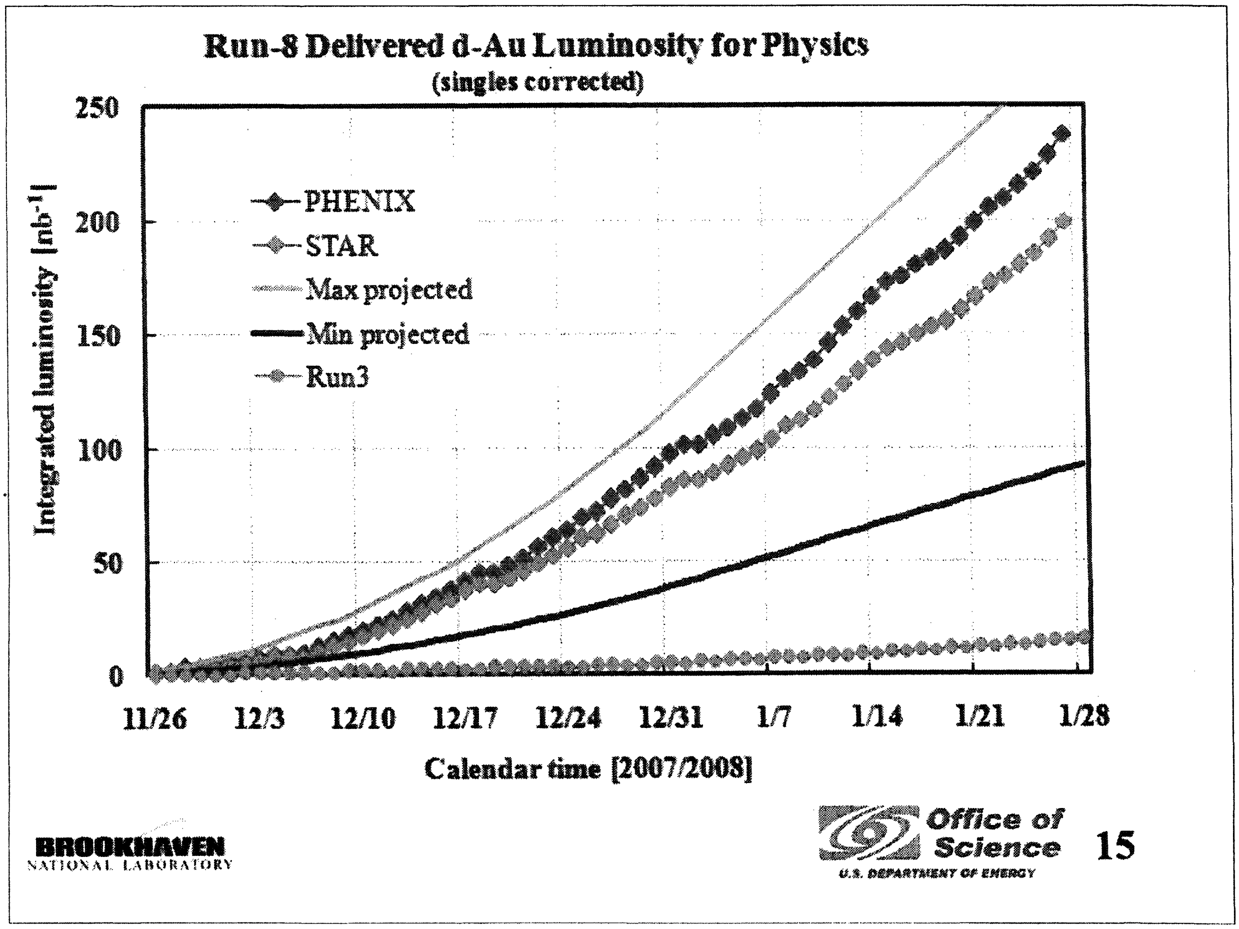
Polarized pp 100 GeV × 100 GeV
20 pb^{-1} (~3× Run 6)

Recent RHIC Research Highlights VI: Can $\vec{p}$-$\vec{p}$ Collisions Compete with DIS to Probe Nucleon Spin?

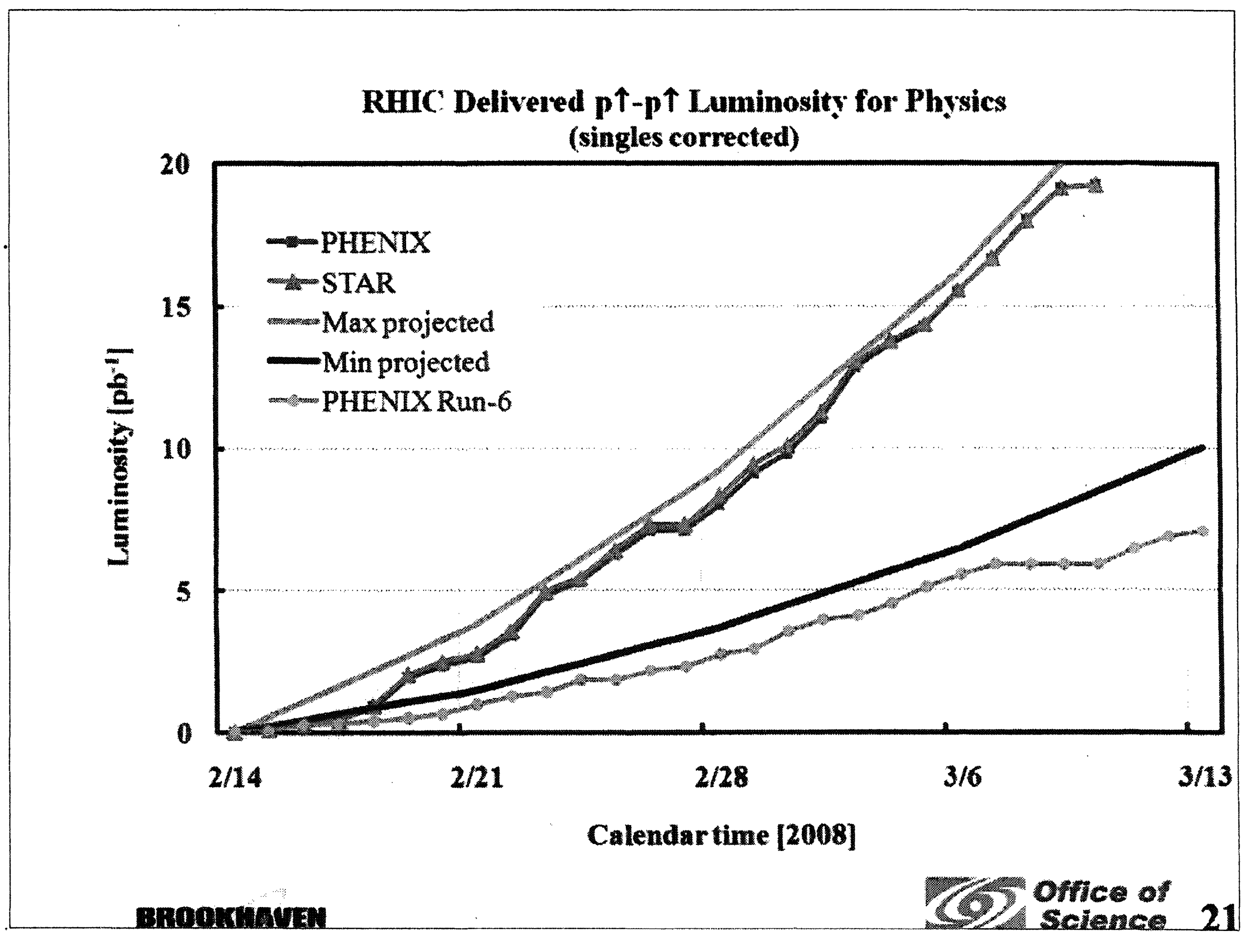


➢ *1st NLO pQCD analysis incorporating RHIC spin inclusive jet and π^0 A_{LL} (2006) data (arXiv:0804.0422) by de Florian, Sassot, Stratmann & Vogelsang*

➢ *DIS and RHIC spin impose comparable constraints to date on shape & magnitude of gluon polarization vs. x; RHIC spin data should dominate after next long 200 GeV p+p run*



Run-8 Delivered d-Au Luminosity for Physics
(singles corrected)
Integrated luminosity [nb-1]
250
200
150
100
50
0
PHENIX
STAR
Max projected
Min projected
Run3
11/26
12/3
12/10
12/17
12/24
12/31
1/7
1/14
1/21
1/28
Calendar time [2007/2008]
BROOKHAVEN
NATIONAL LABORATORY
Office of Science
U.S. DEPARTMENT OF ENERGY
15



RHIC Delivered p↑-p↑ Luminosity for Physics
(singles corrected)
Luminosity [pb-1]
20
15
10
5
0
PHENIX
STAR
Max projected
Min projected
PHENIX Run-6
2/14
2/21
2/28
3/6
3/13
Calendar time [2008]
BROOKHAVEN
Office of Science
21

Preparation for Future Runs

Low Energy $\sqrt{s}_{NN} = 9.2$ GeV.

Critical Point
3,000 Events – Star.

Measured particle yields
v_1, v_2, m_T..

All look good

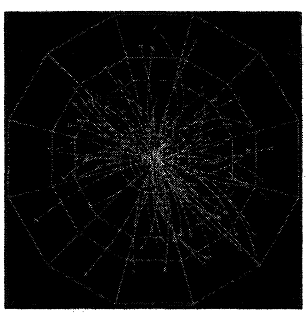
Polarized 250×250 GeV protons.

Anti-quark distributions

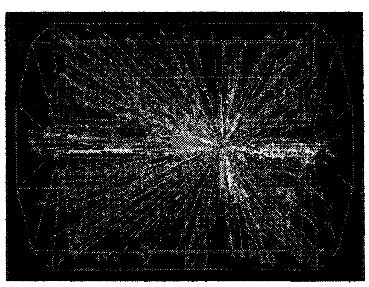
Achieved ~50% polarization
In Blue Ring

STAR Experiment and Collisions at $\sqrt{s}_{NN} = 9.2$ GeV

Collisions recorded in STAR
Time Projection Chamber

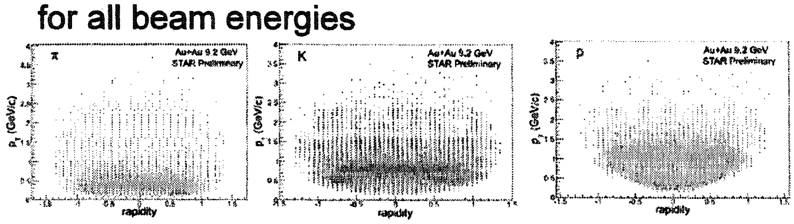


Non-central Collision

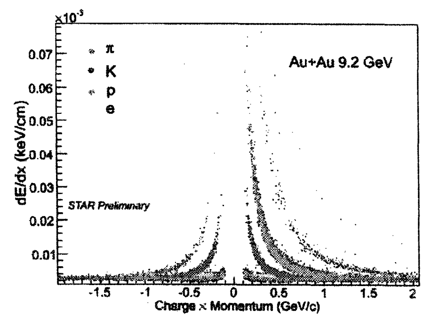


Central Collision

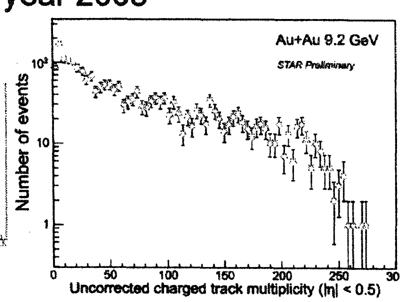
Collider experiment : Uniform Acceptance for all beam energies



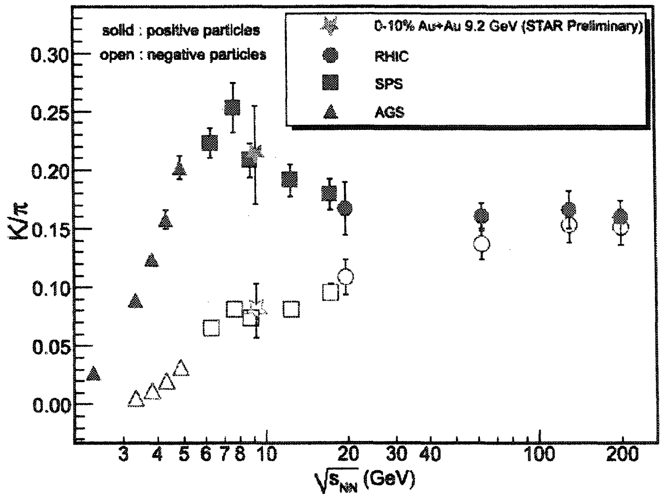
Excellent Particle Identification



Analysis based on ~ 3000 good events collected at ~ 0.7 Hz in year 2008



Beam Energy Dependence of Particle Ratios

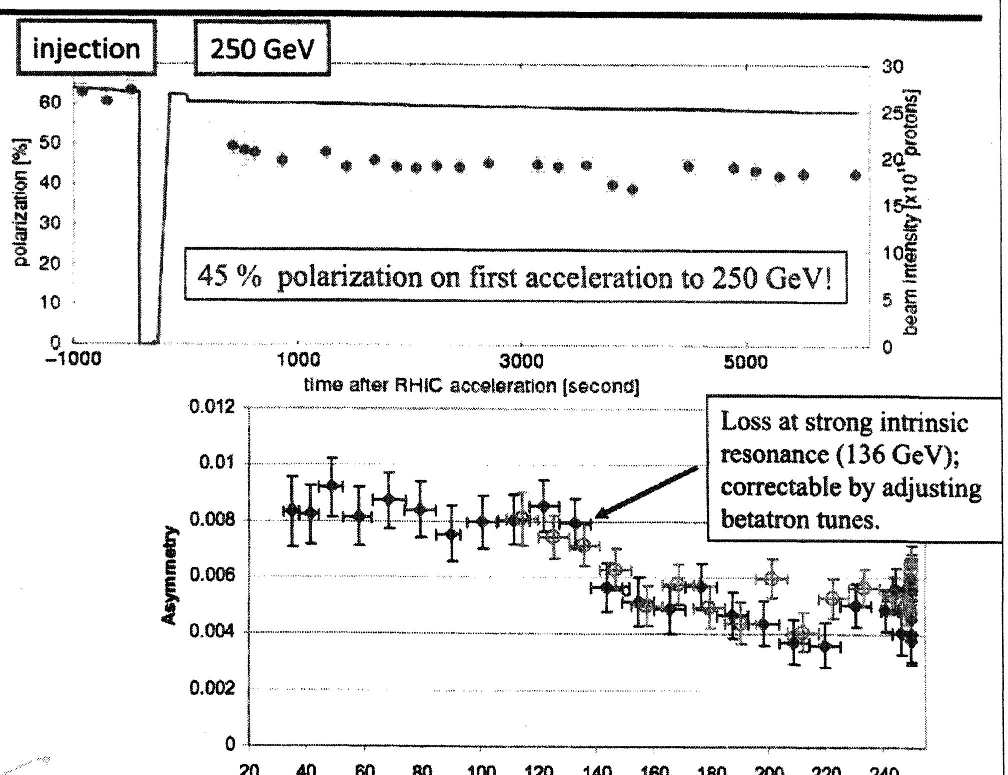


Total number of events for Au+Au 9.2 GeV ~ 3000

These ratios follow the observed beam energy dependence
K/π ratios reflect strangeness production in heavy ion collisions

NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910
STAR : ArXiv : 0808.2041, QM2008; E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904, 064901, PRC 62 (2000) 024901,
E895(AGS) : PRC 68 (2003) 054903

Test of Polarized Proton Acceleration to 250 GeV



BROOKHAVEN

Tentative RHIC Run Plan Following 2008 PAC Recommendations

(assumes 6-month FY09 CR, 2-species runs in FY10-14 & best info on detector upgrade schedules)

Fiscal Year	Colliding Beam Species/Energy	Comments
2009	200 GeV p+p	~12 physics weeks to complete 200 GeV A_{LL} measurements – could be swapped with 500 GeV Run 10 if >6-month FY09 CR likely; STAR DAQ1000 fully operational
2010	500 GeV p+p	~5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet 2011 RIKEN milestone
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st HI collision test of transverse stochastic cooling (one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed: focus on RHIC-II goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production
	200 GeV Au+Au or 2nd low-E scan	To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling.
	200 GeV p+p	Address 2015 DOE performance milestone on transverse SSA for γ-jet; reference data with new detector subsystems; test e-lenses for p+p beam-beam tune spread reduction

RBRC Organization

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

Theory Advisory Committee
- L. Mc Lerran (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

Theory		Experimental	
Fellows		Fellows	
Aoki, S.	Tsukuba	Deshpande	SUNY
Blum	U. of Conn.	Kawall	U. of Mass
Fries	Texas A&M	Okada	BNL
Molner	Purdue U.		
Tuchin	U. of Iowa		
'07			
Yuan	LBNL		
Lunardini	Arizona State		
Teaney	SUNY		
Dumitru	CUNY		
'08		'08	
Izibuchi	BNL	Seidl	BNL
Stasto	Penn State	Bathe	BNL
Aoki, Y.	BNL		
Petreczky	BNL		
Post Docs			
Marquet	BNL/Columbia	Boyle	BNL
Lichtl	BNL		
Ishikawa	BNL		

Major Conference Participation

RBRC & Alumni & Advisors

Quark Matter 2008

Jaipur, India, Feb. 4-10, 2008

Dominated by RHIC Physics

Plenary	Parallel
K. Fukushima	T. Hirano
T. Hatsuda	K. Itakura
L. Mc Lerran	D. Kharzeev
E. Shuryak	C. Marquet
R. Venugopalan	A. Mocsy
	D. Molnar
	Y. Nara
	P. Petreczky

Panic 08

Elat, Israel, Nov. 9-14, 2008

Plenary	Parallel
S. Aoki	A. Basilevsky
T. Hatsuda	A. Deshpande
D. Kharzeev	Y. Hidaka
D. Son	K. Imai
W. Vogelsang	H. Stoecker

Workshops

April 21-22, 2008

Hydrodynamics in Heavy Ion Collisions and QCD Equation of State

Karsch, Kharzeev, Molnár, Petreczky, Teaney

April 23-25, 2008

Understanding QGP through Spectral Functions and Euclidean Correlators

Mócsy, Petreczky

June 30-July 4, 2008

PKU-RBRC Workshop on Transverse Spin Physics

Avakarian, Bunce, Yuan

August 4-8, 2008

PHENIX Spinfest School 2008 at BNL

Aidala, Goto, Okada

September 2008

The Ridge

Longacre, Mc Lerran

Looking Ahead

Proton Spin
- More Complex & Exciting
- Quarks, Gluons, Orbital Angular Momentum
- 500 GeV Polarized Protons

High Energy Dense Matter
- sQGP – Ridge etc.
- Color Glass Condensate
- Critical Point
- A-A-
  - Heavy Flavors
  - Direct Photons

Lattice Gauge Computing
- Phase Transition
- Equation of State
- CKM
- Spectroscopy – Matrix Elements
- QCDOC , QCDX

Opportunity for young people – cutting edge of physics

Detector Upgrades	PHENIX, Star	
Accelerator Upgrades	Stochastic Cooling	cheaper
	Coherent Electron Cooling	faster
e-RHIC	Phased Approach	

Theoretical Physics at RIKEN-BNL Center

Strong Interactions and QCD

How do quarks and gluons compose strongly interacting particles?

How do fundamental interactions of QCD produce mass and confinement?

What is the behavior of strongly interacting matter in bulk?
Nuclear Matter ⟶ Quark Gluon Plasma
Color Glass Condensate, Glasma
Quarkyonic Matter

What is the physics beyond the standard model?
Tests of CKM matrix.
Hadron corrections to weak matrix elements

All issues intertwined!
Require understanding and computation.

1

Activities in Pursuit of These Questions

Lattice Gauge Theory

Masses and matrix elements of hadrons
CKM matrix
Properties of QGP and hadronic matter

Structure of Hadrons

Origin of spin
Quark and gluon distribution functions
Perturbative QCD at RHIC and LHC

Color Glass Condensate and Quark Gluon Plasma

RHIC Phenomenology
Everything for
$x \leq 10^{-2}$

New Phenomena:

Quarkyonic Matter (Unexpected new state of matter at high density)

Chiral Magnetic Effect (Event by event P and CP Violation)

Ridge (Imaging color flux tubes)

2

Accomplishments and Goals of Lattice Gauge Theory at RBRC

Have built and are now operating QCDOC. (Two other machine built and operating: DOE and Edinburgh)

New computer?

The weak interactions in strongly interacting particles

CP violation in kaon decays

Spectra of exotic hadronic states, such as the scalar nonet.

Low energy matrix elements

The nucleon force.

QCD Thermodynamics

3

Accomplishments and Goals in Study of Spin and Perturbative QCD

Achievements:

Developed GRSV Spin Structure Functions

Developed one set of standard structure functions used in heavy ion, dA and pp

Used GRSV for analysis at RHIC

NLO spin asymmetry in pp and gamma p->pion X (gluon spin measurement)

QCD soft gluon resummations

Single spin asymmetries in DIS and polarized pp

Goals

Extract gluon spin from RHIC experiments

Understand hard processes in larger program

4

Accomplishments and Goals in Study of High Energy Density Matter

Accomplishments:

Complete 3-d computations of distributions of particle produced in heavy ion collisions and relation to QGP

Developed a theory of matter at small x: Color Glass Condensate

Understood initial conditions in heavy ion collisions and early stages of evolution: Glasma

Quarkyonic matter as a possible new phase of high energy density matter

The chiral magnetic effect and event by event P and CP violation

The ridge phenomena and imaging of colored flux tubes

Goals:

Understand the nature of matter at highest energy densities

Understand from first principles in QCD, the high energy limit

5

BNL is a Good Place to Study QCD?

RHIC
QCDOC

Strong theory groups:
BNL, Columbia, Stony Brook

In both HEP and NP at BNL strong interest in theory and experiment
New BNL lattice gauge theory group under Karsch

Supportive atmosphere for young people
YOUNG PEOPLE FROM RBRC ARE SUCCESSFUL!

6

Relations

QCDOC and Lattice Gauge Theory

Joint Columbia-RBRC Project
NT has Jung as Junior Faculty
Karsch is head of lattice group
Soni and Creutz
SCIDAC project

Spin and pQCD

Vogelsang was RBRC
Larry Trueman in HEP

RHIC Physics

Strong collaboration with NT group
Kharzeev and Venugopalan were RBRC
Participation in Theory Advisory Committee

7

RBRC-BNL University Fellows Program (Theory)

University pays 1/2 of academic year salary

University selects candidates

Must be approved by Theory Advisory Committee

Current Theory Fellows:

- S. Aoki (Tsukuba)
- Y. Aoki, (BNL)
- T. Izubuchi (BNL)
- R. Fries, Texas A&M
- D. Molnar, Purdue
- P. Petreczky, BNL
- K. Tuchin, Iowa State
- C. Lunardini, Arizona State
- D. Teaney, Stony Brook
- F. Yuan, LBNL

New Theory Fellows:

- A. Dumitru (Baruch)
- A. Stasto (Penn State)
- T. Izubichi to BNL

Tenured Graduates:

- S. Bass, Duke
- T. Blum, Connecticut
- D. Bodeker, Bielefeld
- K. Iida, Kochi
- S. Jeon, McGill
- D. Kharzeev, BNL
- A. Kusenko, UCLA
- D. Rischke, Frankfurt
- S. Sasaki, Tokyo
- T. Schaefer, N. Carolina
- M. Stephanov, Illinois
- D. Son, Washington
- R. Venugopalan, BNL
- U. Van Kolck, Arizona
- W. Vogelsang, BNL
- U. Weidemann, CERN
- T. Wettig, Regensburg

8

Workshops:

Broad based coverage of topics related to areas of interest.

Must have an RBRC members as one of the proposers

Spin and Pert. QCD 41

Lattice and Computing 12

Quark Gluon Plasma 8

High Energy QCD 3

Jets and Hard Processes at RHIC 4

Flow, Hydrodynamics and Event Simulation 5

Hadron Physics and QCD 4

Color Glass Condensate 3

New Discoveries at RHIC 1

9

RBRC Theory Postdocs who have received faculty Faculty Jobs:

Recent Examples:

K. Itakura (KEK) (CGC)

T. Hirano (Tokyo) (RHIC Phenomenology)

K. Fukushima (Yukawa) (Color Superconductivity, CGC)

Yoshi Hatta (Tsukuba) (CGC)

S. Sasaki (Tokyo U.) (Lattice)

Y. Nara (Akita U.) (RHIC Phenomenology, CGC)

H. Fuji (Tokyo U.) (RHIC Phenomenology, CGC)

M. Kitazawa (Osaka) (QGP)

N. Yamada (KEK) (Lattice)

C. Orginos (William and Mary) (Lattice)

M. Wingate (Cambridge) (Lattice)

D. Boer (Spin) (Free U, Amsterdam)

10

RBRC Experimental Group

Y. Akiba

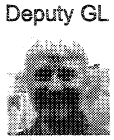
RBRC Scientific Review Committee
2008/11/17

RBRC Experimental Group (Jan 2008)

Group Leader

H. En'yo

Deputy GL



G. Bunce

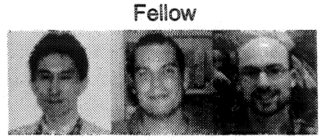
RBRC deputy director
RIKEN Chief Scientist

H. En'yo

University Fellow

D. Kawall A. Deshpande

Fellow

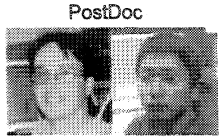


K.Okada R. Seidl S. Bathe

RIKEN/RBRC @ BNL

Y. Akiba Y. Goto I. Nakagawa

PostDoc



K. Boyle M. Togawa

- Plus Many Students and Visitors

RBRC Experimental Group (SRC 08)

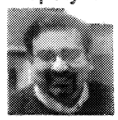
RBRC deputy director
RIKEN Chief Scientist

H. En'yo

Group Leader

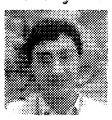
Y. Akiba

Deputy GL



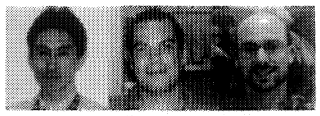
A. Deshpande

University Fellow



D. Kawall

Fellow



K.Okada R. Seidl S. Bathe

RIKEN/RBRC @ BNL

Y. Goto I. Nakagawa

PostDoc

K. Boyle M. Togawa

- Plus Many Students and Visitors

RIKEN/RBRC in PHENIX

RIKEN/RBRC personnel have important roles and positions in PHENIX

Deputy Spokesperson (2 out of 3)

Y. Akiba	(RIKEN/RBRC)
M. G-Perdekamp	(U. Illinois/former RBRC fellow)

Executive Council Members (4 out of 14)

Y. Akiba	
M. G-Perdekamp	
A. Deshpande	(StonyBrook/RBRC)
N. Saito	(KEK/RBRC)

Physics Working Group Conveners (1 out of 16)

K. Okada	(RBRC)

PHENIX VTX Upgrade Project

Y. Akiba	project manager
A. Taketani(RIKEN)	pixel subsystem manager
A. Deshpande	strip subsystem manager

PHENIX muon trigger upgrades

M. G-Perdekamp	PRC project leader
N. Saito	MuTR FEE project leadere

Large role in PHENIX operations and data analysis

Local Polarimeter	RICH	RICH-EMCAL trigger
EMCal	Muon arms	

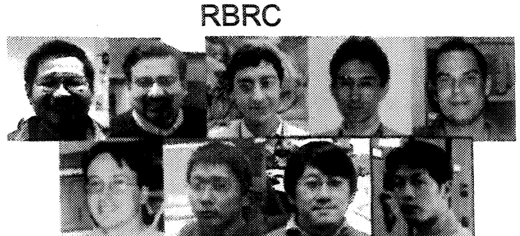
Exp Group Activities

- Spin Physics: study of spin structure of proton
  RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX
  - ΔG measurement — A_{LL} of π^0, $\pi^{\pm}$, direct γ, charm, etc…
  - Spin of sea quark — W measurement at 500 GeV
  - Fragmentation Function at Belle → Spin Physics at RHIC
  - Polarimeters — CNI polarimeter, jet polarimeter, PHENIX local pol
- 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 photon
- PHENIX detector Upgrade
  - Silicon Vertex Tracker (VTX) upgrade — Lead by RIKEN/RBRC
  - Muon Trigger Upgrade — strong support by RIKEN/RBRC

Spin Physics

- Measurement of Gluon Polarization DG(x)
  - π^0 A_{LL}
    K. Boyle, Y. Fukao, A. Deshpande
  - $\pi^{\pm}$ A_{LL}
    D.Kawall, A. Dutta
  - Cluster (Jet) A_{LL}
    K. Nakano, Y. Goto, YA
  - Direct γ A_{LL}
    R. Bennett, K. Okada
- Transverse Spin
  - Forward n A_N
    M. Togawa
  - Charm A_N
    S.Dairaku, YA
- Fragmentation Function
  R. Seidl, K. Boyle

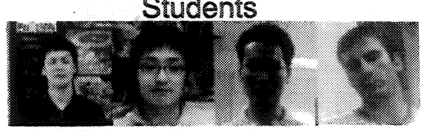
RBRC



PostDocs @ Wako

Y. Fukao K Aoki K. Nakano

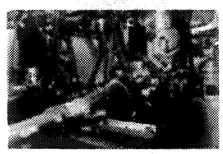
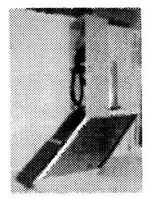
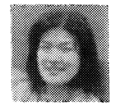
Students



K. Sakashita TITech | K. Shoji Kyoto | S. Dairaku Kyoto | R. Bennett StonyBrook

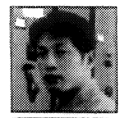
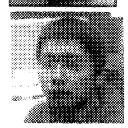
RHIC polarimeters

- RBRC has been working for RHIC polarimeters
  - Gas Jet absolute polarimeter
    First 2004 data is analyzed by H. Okada, a RBRC student.
  - pC CNI polarimeter
    I. Nakagawa worked for RUN5 polarization
  - PHENIX Local polarimeter
    M. Togawa has been working on it.

H. Okada
Now KEK

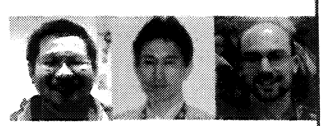
RBRC

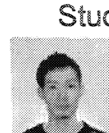
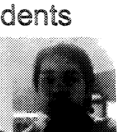
Heavy Ion and p+p (unpolarized)

- Study of sQGPformed in HI collisions
- RBRC/RIKEN have been working on the study of sQGP using penetrating probes
  - Heavy quark measurement via single e F. Kajihara(JRA), YA
  - J/Psi measurements Xie Wei, YA
  - High pT pi0 in Au+Au T. Isobe (JRA)
  - Direct photon in pp K. Okada
  - Low pT direct photons YA
- On-going work
  - Low pT direct photon via internal conversion in p+p and d+Au (Y. Yamaguchi)
  - Photon v2 (K. Miki)
  - High pT pi0 v2 (Y. Aramaki)
  - High pT omega (M. Ouchida)

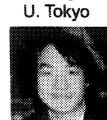
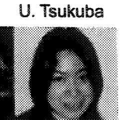
RBRC



Students

Y. Yamaguchi U. Tokyo — K.Miki U. Tsukuba

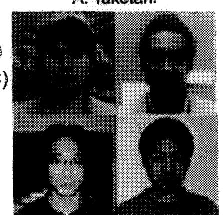
Y. Aramaki U. Tokyo — M. Ouchida Hiroshima U

VTX Upgrades

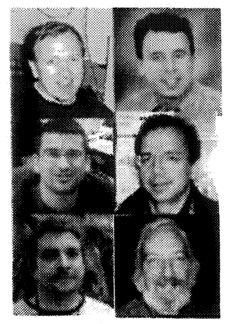
- The first major upgrade of PHENIX
- Large solid angle silicon tracker
  - 2 layers of Pixel Detector
  - 2 layers of Strip Detector
- Funded by RIKEN and DOE
  - RIKEN ~$3M
  - DOE $4.7 M
- Project is lead by RIKEN/RBRC
  - Project Manager: Y. Akiba (RIKEN/RBRC)
  - Deputy PM: C. Ogilvie (ISU)
  - Pixel Manager: A. Taketani (RIKEN/RBRC)
  - Strip Manager: A. Deshpande (SBU/RBRC)
- Ready for Physics in RUN11
  - Heavy quark (b, c) measurements in p+p, d+Au, and Au+Au
  - Photon+Jet measurement in p+p
  - And more

VTX@RBRC

Pixel Group @ Wako



VTX Collaborators



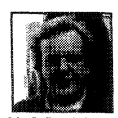
+ many more

~90 collaborators, 20 institutes

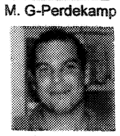
Muon Trigger Upgrades

- Two projects for Muon Trigger

1) RPC Trigger Chamber Project
   Funded by NSF (~$2M)
   Project Leader:M. Grosse-Perdekamp (UIUC, former RBRC fellow)
   R. Seidl and many students and postocs from UIUC and other institutes
2) Muon Tracker FEE Trigger Project
   Funded by JSPS (~$2M)
   Project leader: N. Saito (KEK/RBRC)
   I. Nakagawa, Y.Fukao and many students and postdocs



M. G-Perdekamp



RBRC Overview
Heavy Ion and Upgrades

Y. Akiba

RBRC SRC review
2008/11/17

Exp Group Presentations

YA	"Exp. Group overview: HI Physics and PHENIX upgrade projects"
Kensuke Okada	"Direct photon measurements at PHENIX"
Stefan Bathe	"Hard Scattering Physics in PHENIX And ATLAS"
Itaru Nakagawa	"PHENIX Muon Trigger FEE Upgrades for Sea Quark Polarization Measurement via W-Boson"
Atsushi Taketani	"PHENIX VTX upgrade: Overview and Pixel detector"
Manabu Togawa	"PHENIX VTX upgrade: Strip detector and software development"

10:30 AM-11:00 break

Abhay Deshpande	"Exp. Group overview: Spin Physics"
Kieran Boyle	"Constraining Delta G by Measuring Double Helicity Asymmetry in Neutral Pion Production"
Dave Kawall	"The Double Longitudinal Spin Asymmetry in Unidentified Charged Hadrons from pp collisions at sqrt(s)=62.4 GeV"
Ralf Seidl	"Fragmentation functions from Belle"
Yuji Goto	"Drell-Yan measurement with polarized proton beams"
Yasushi Watanabe	"RHIC Data Analysis at CCJ"

Exp Group Activities

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  - ΔG measurement — A_{LL} of π^0, $\pi^{\pm}$, direct γ, charm, etc…
  - Spin of sea quark — W measurement at 500 GeV
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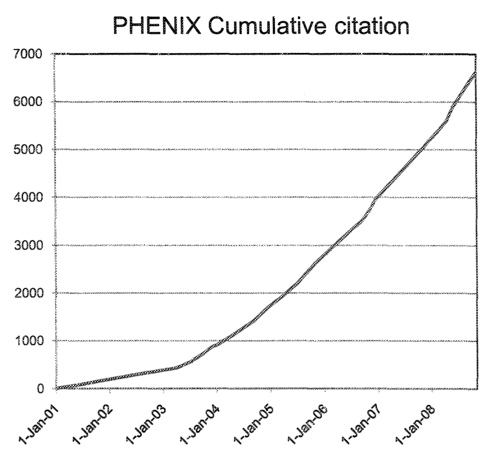
- Heavy Ion Physics at RHIC — study of (s)QGP
  RBRC/RIKEN studies sQGP using penetrating probes
  - High p_T physics
  - J/Psi and Heavy quark
  - Low p_T photon
- PHENIX detector Upgrade
  - Silicon Vertex Tracker (VTX) upgrade — Lead by RIKEN/RBRC
  - Muon Trigger Upgrade — strong support by RIKEN/RBRC

PHENIX publications

- 74 papers published since 2001
  - Phys. Rev. Lett. 45 (17)
  - Phys. Rev. C 21 (6)
  - Phys. Rev. D 5 (3)
  - Phys. Letter B 2
  - Nucl. Phys. A 1 (1) (white paper)
- Total citation: ~6600 (10/31/08)
  - Topcite 500+ 1 (1)
  - 250-499 5 (1)
  - 100-249 15 (6)
  - 50-99 18 (7)
- 13 (4) papers published/accepted since last SRC (Nov 2007)

	published	accepted
– PRL	4 (1)	1(1)
– PRC	6 (2)	
– PRD	1	
– PLB		1

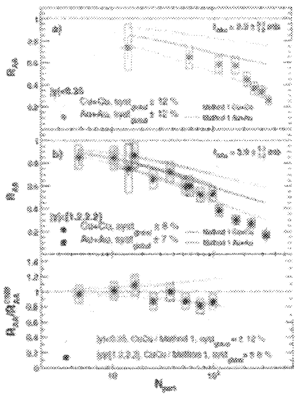
- 4 (3) papers in review, including RUN6 ΔG paper



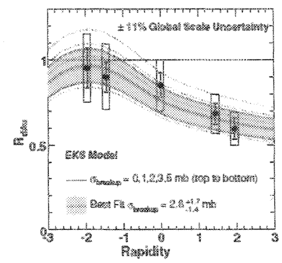
The number in () is the number of papers with significant RIKEN/RBRC contributions

Recent PHENIX HI publications with RBRC/RIKEN contributions

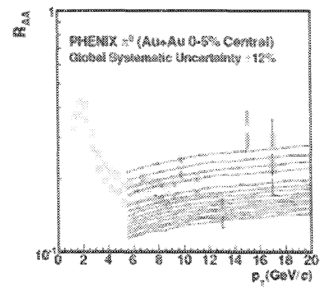
J/ψ in Cu+Cu
PRL101,122301



J/ψ in d+Au
PRC77,024912



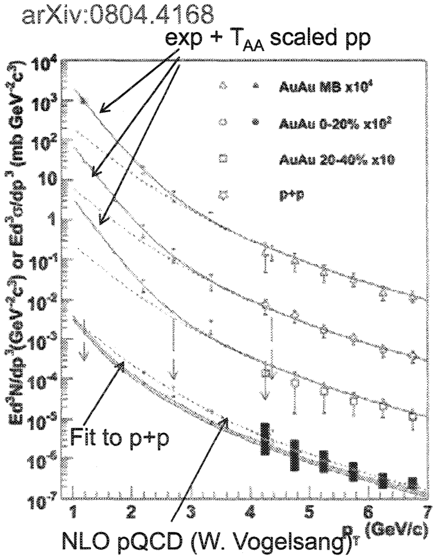
π^0 R_{AA} in Au+Au
PRL accepted
arXiv:0801.4020



- Spin physics results → Abhay's talk and 2[nd] session
- These are most important results in the study of dense matter formed at RHIC

Hot results: low p_T direct photon

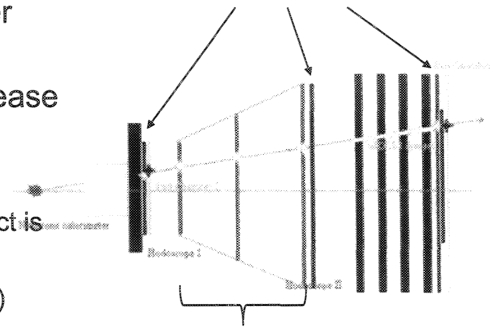
arXiv:0804.4168



- The p+p data agrees with NLO pQCD predictions
- For Au+Au there is a significant low p_T excess above scaled p+p expectations
- Excess is exponential in shape with inverse slope T~ 220MeV
- Thermal photons from hydrodynamical models with T_{init}=300 – 600MeV at τ_0=0.6-0.15fm/c are qualitative agreement with the data

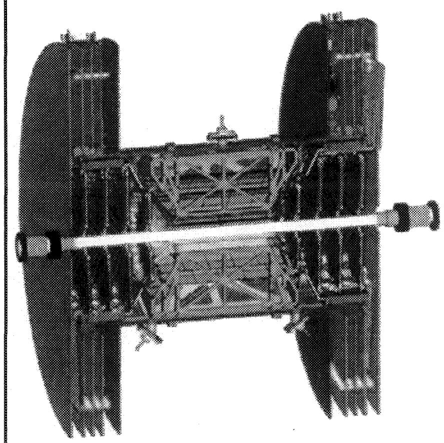
PHENIX Upgrade (1) muTRIG

- W→μ measurment in the present PHENIX would be limited by the trigger. (Not enough trigger rejection)
- muTRIG upgrade will increase the trigger rejection factor.
- Two projects:
  - RPC trigger chamber project is lead by M.G.Perdekamp (UIUC/former RBRC fellow) R. Seidl (RBRC fellow)
  - Muon tracker FEE project is lead by N. Saito (KEK/RBRC) I. Nakagawa (RIKEN/RBRC)



Presentation: I. Nakagawa

PHENIX Upgrade (2) VTX



- Key device to improve heavy quark measurement at RHIC/PHENIX
  - Identify charm/bottom decay by precision tracking ($\sigma \sim 50\mu$)
  - Provides near 4π acceptance
- ~100 collaborators working on the project
- Project is lead by RIKEN/RBRC
  - Y. Akiba (RIKEN) : project manager
  - A. Taketani (RIKEN): pixel manager
  - A. Deshpande (StonyBrook/RBRC) strip manager
- The US side of the project started
  - $4.7M from FY07 to FY10
- The first annual review of the VTX project (June 9-10, 2008)

Presentations: A. Taketani (Pixel) M. Togawa (Strips)

Summary

- Three pillars of RBRC Experimental Group Activity
  Spin Physics/HI Physics/PHENIX Upgrade
- RBRC/RIKEN have large role in PHENIX
  - PHENIX have been very productive in physics output
  - RBRC have a large share in physics output of PHENIX
- Recent HI Physics results
  - High p_T pion suppression
  - J/ψ suppression
  - Low p_T direct photons (thermal photons?)
- 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

Direct photon measurements at PHENIX

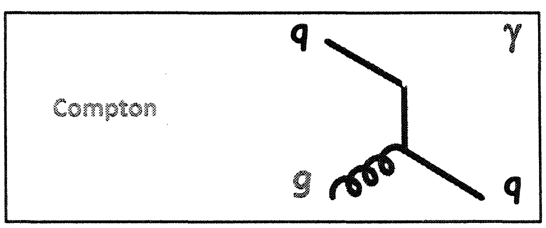
RBRC review

November 17, 2008

Kensuke Okada

Motivations

—**Direct photon production**



—**One of the simplest process**

QCD test

→Baseline for HI physics

→ pol PDF measurement

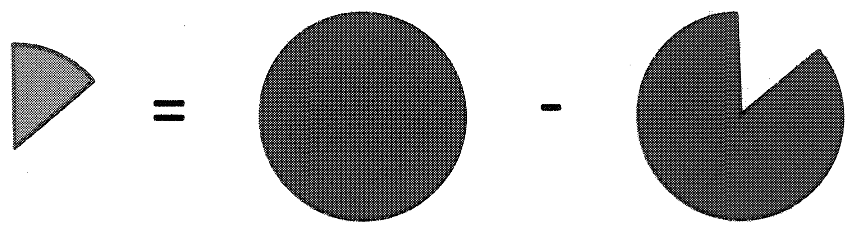
Measurements at PHENIX

1. subtraction method
2. (internal) conversion method

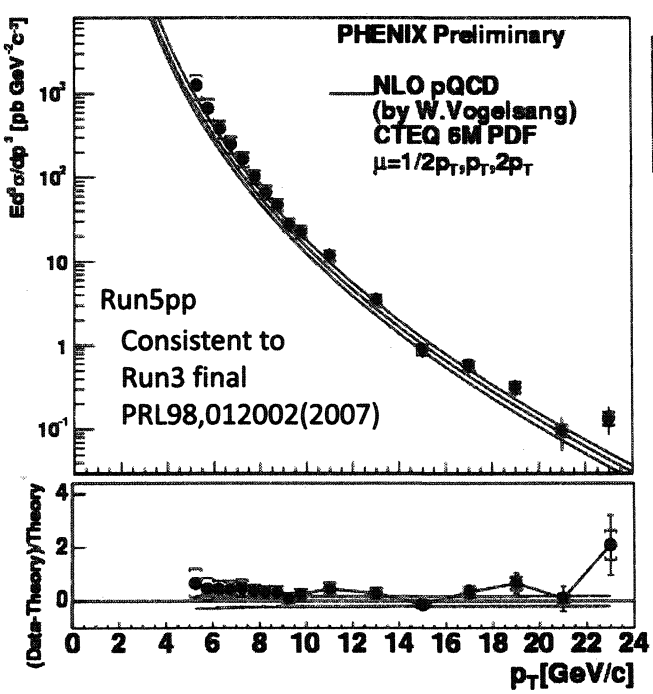
1.

(signal) = (all photons) – (background photons)

(isolated signal) = (all isolated photons) – (background isolated photons)



Cross section measurement

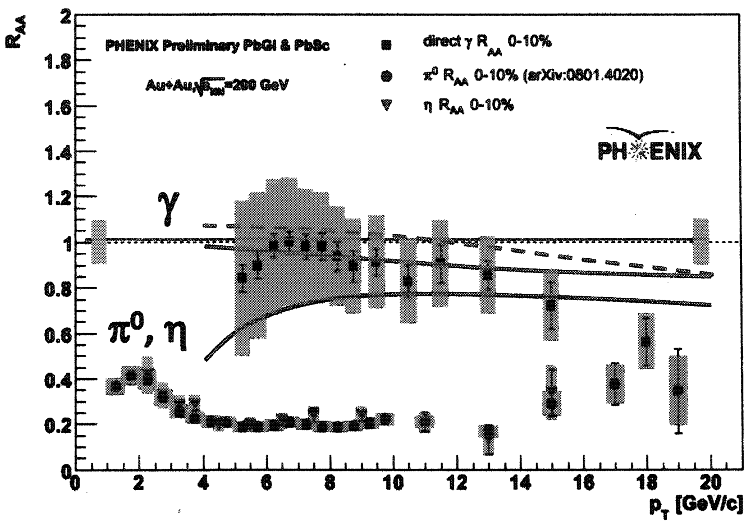


p+p 200GeV
Good agreement with pQCD

Run3 : 0.24pb-1
Run5: 2.8 pb-1

Direct photon R_{AA}

R_{AA} (since QM06)



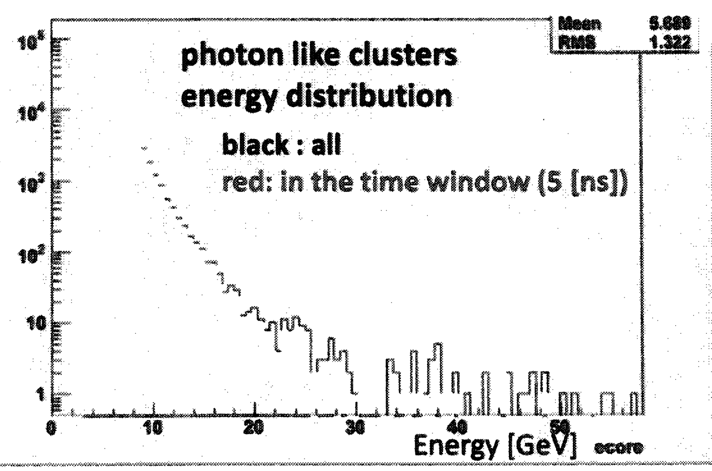
This plot is already shown many times as a preliminary.

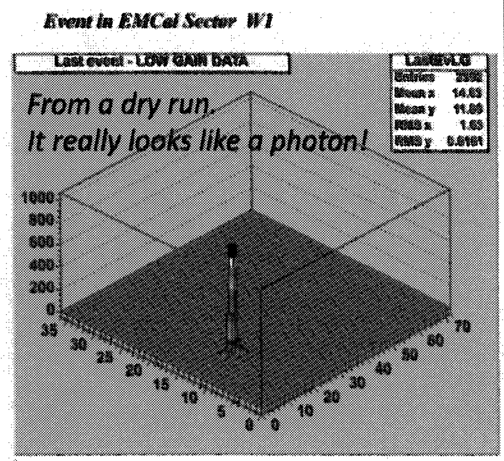
Comments
A difficulty in high pT region.
(=pi0 merging, very rare.)
We need to be careful.

Curves : F.Arleo JHEP09(2006)015
——— Isospin effect
- - - +cold nuclear effect (EKS)
——— +energy loss 20<ω_c <25GeV

Issues in high pT region

There is a chance to pick up cosmic events.
We needed the EMCal ToF calibration.



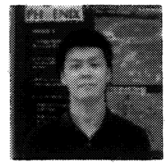


A study of the dry run shows the probability of non beam events is about right for 150kHz BBC trigger rate.

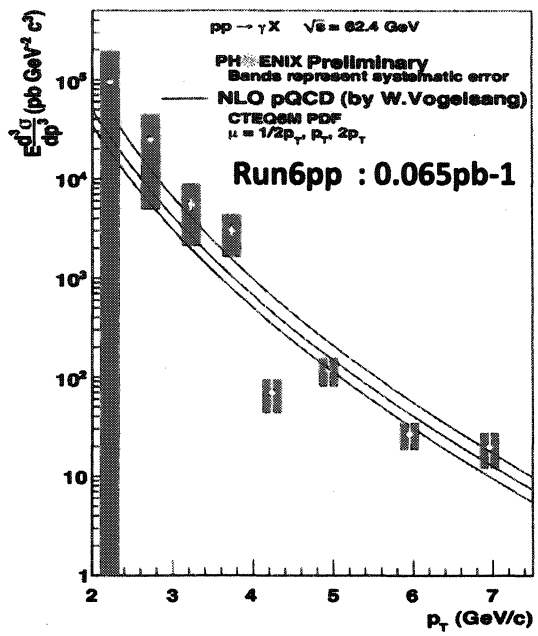
The RAA will go up a little.

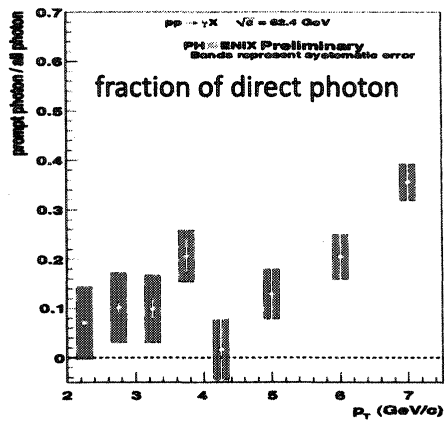
To the lower collision energy

The isospin effect should appear at lower pT.
We are free from the experimental issues
(cosmic ray event, pi0 photon merging.)



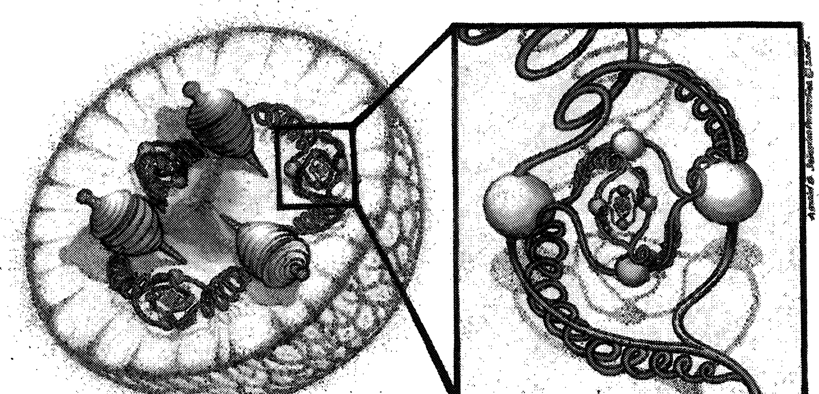
The analysis is done
by K.Sakashita (Tokyo Tech)





We see the direct photon signal.
The statistics is limited.

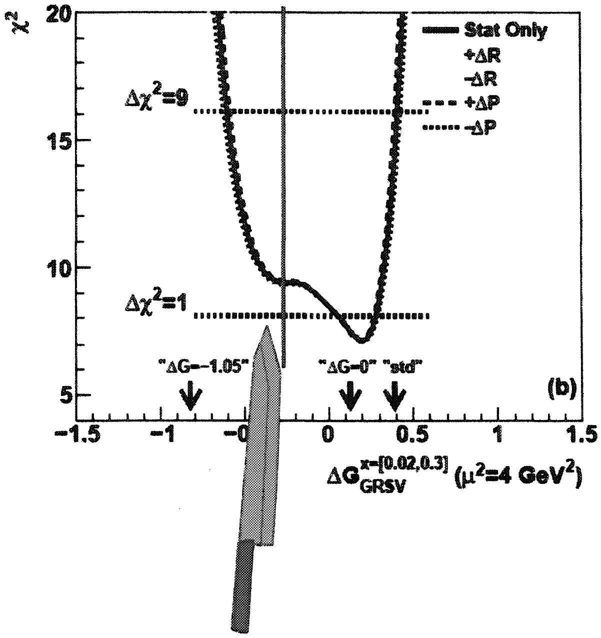
Measurement of the polarized PDF



The QCD picture of the Proton Color Pencil and pen Drawing by Sebastien Parmentier and Astrid Morreale

The polarized PDF

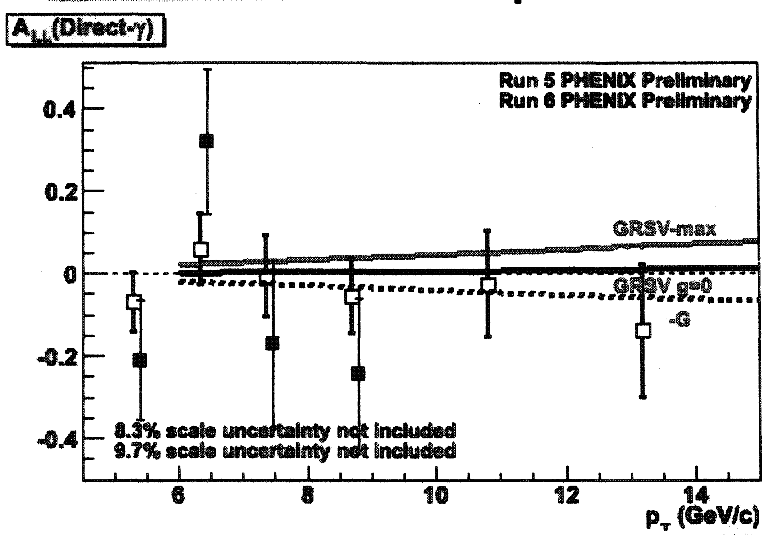
ΔG measurement with pi0 A_{LL}
arXive: 0810.0694

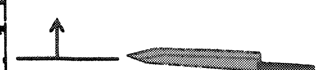


Direct photon

It's sensitive to the sign of ΔG

Direct photon A_{LL}

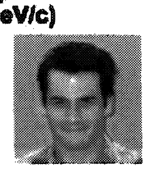




We hope to set a limit
in the end of the program.

Run5: $2.5pb^{-1}$, $p=47\% \rightarrow P^4L=0.12pb^{-1}$
Run6: $7pb^{-1}$, $p=57\% \rightarrow P^4L=0.74pb^{-1}$

Current goal: $50pb^{-1}$, $P=60\% \rightarrow P^4L=6.5pb^{-1}$



The analysis is done
by R. Bennett (SUNY)

They are important first measurements.

Summary

—Direct photon is a clean probe in QCD.

—Production cross section

We understood the backgrounds of non-beam origin.

→ It is more important for the high pT rare signal.

We saw the signal in lower √s collisions (62.4GeV).

→ It is statistically limited. We may come back to this energy depends on the run plan.

—Measurement of the polarized PDF

It is sensitive to the sign of ΔG unlike pi0/Jet probes.

It is a rare process.
The purity is not good where we have statistics.
We have first measurements.

→ We need more luminosity and polarization to accomplish the mission.

HARD SCATTERING IN PHENIX AND ATLAS

Stefan Bathe, RBRC Review 2008

Introduction

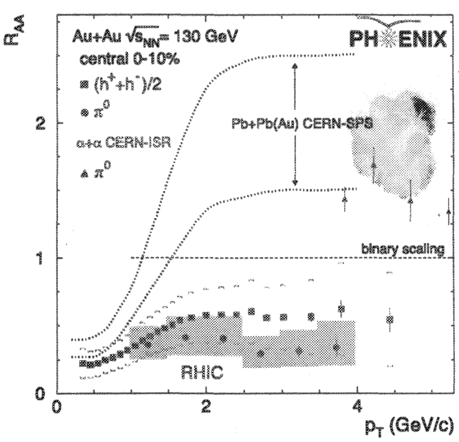
2

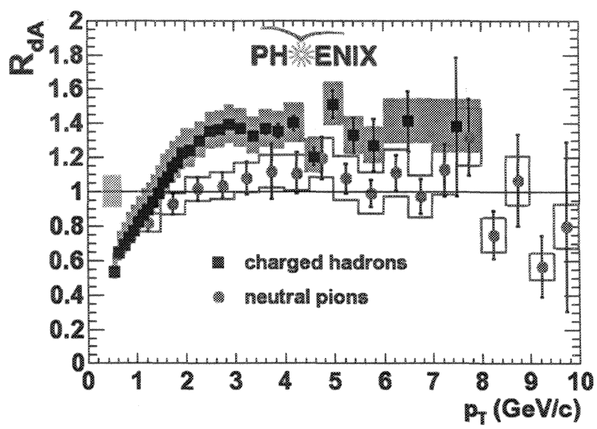
- RBRC fellow since 01/2008
- PHENIX member since 1998
- ATLAS member since 03/2008
- Main interests:
  - Hard scattering in A+A, p+p, p+A (neutral hadrons, direct photons, heavy quarks) to understand energy loss and pQCD
  - Thermal radiation (direct photons) to measure QGP initial temperature

Stefan Bathe, RBRC Review 2008 11/17/2008

Hard Scattering Results in PHENIX

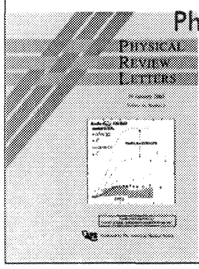
3





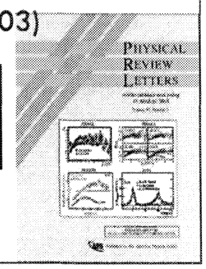
Phys.Rev.Lett. 88, 022301 (2002)

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



Most cited paper from RHIC
465 citations to date

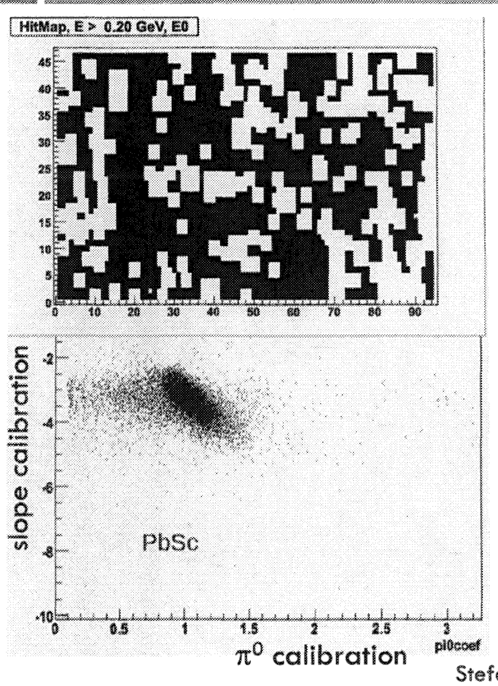
One of four 'famous' PHENIX papers with > 250 citations



Stefan Bathe, RBRC Review 2008 11/17/2008

EMCal Calibration Run-7

4

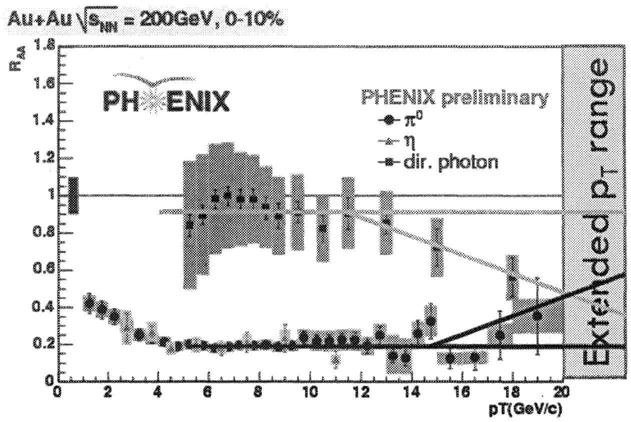


- EMCal acceptance had many holes due to mis-calibrated towers that had to be switched off
- Have led calibration effort by group of ~six people
- Will be completed in ~ one week

Stefan Bathe, RBRC Review 2008 11/17/2008

High p_T π^0 And Direct Photons Run7

5

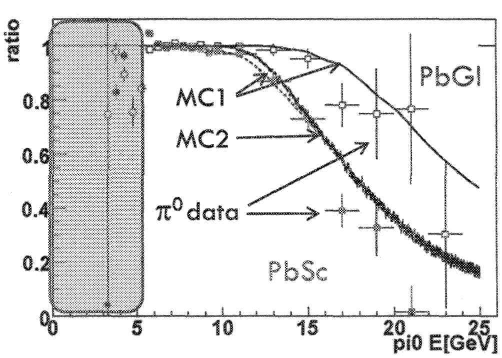


- Indication for same R_{AA} for direct γ and π^0 at high p_T
- If true, then no E loss at hight p_T
- LHC would have nothing to measure!
- In general interesting to quantify E loss at high p_T

Stefan Bathe, RBRC Review 2008 11/17/2008

High p_T π^0 . . . Outlook

6



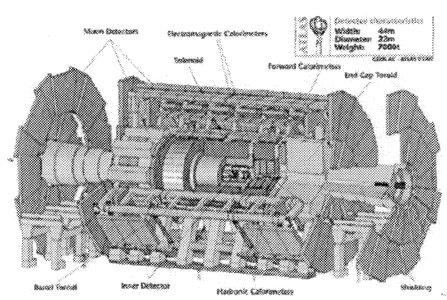
PHENIX Analysis Note 734

- EMCal calibration has been major preparation work
- Next analysis steps straightforward (largely repeat of previous analyses)
- Understanding merging systematics only challenge
- But here previous studies available to provide guidance
- Goal to have result for QM2009 conference in April

Stefan Bathe, RBRC Review 2008 11/17/2008

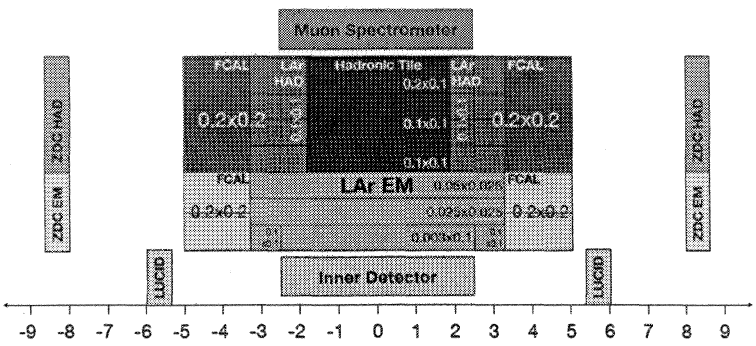
The ATLAS Detector

7



- Inner tracking
- EM and Hadronic calorimeters
- External muon spectrometers
- Full azimuthal acceptance in all detectors
- Large pseudorapidity coverage

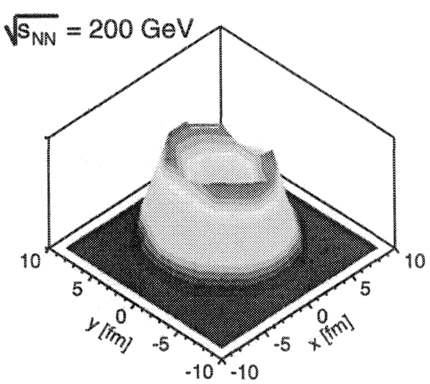
Capabilities
High-precision tracking |η| < 2.5
Muon identification |η| < 2.5
Highly segmented calorimetry |η| < 5
Forward coverage
Large bandwidth: DAQ + Trigger



Why Jets, γ-Jet?

8

Origin of partons that produce 5 GeV hadrons in central Au+Au



Dainese et al., Eur. Phys. J. C 38, 461 (2005)

- 2-particle correlations suffer from trigger bias (fragmentation) and surface bias (energy loss)
- Jets
  - overcome trigger bias
  - buy rate
- γ-jets
  - overcome surface bias
  - Calibrate jet energy

Jets in Heavy Ion Collisions

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Challenge: background!

In cone of $R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$

there is $E=\pi R^2 dE_T/(d\phi d\eta)$

$= R^2/2 * dE_T/d\eta$

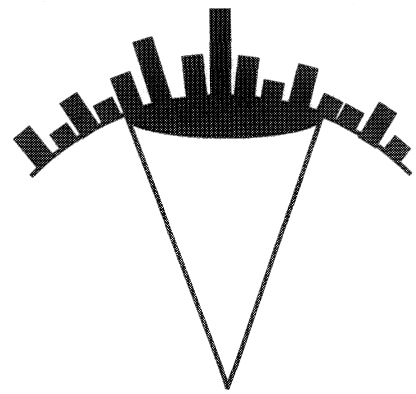
$dE_T/d\eta$ in central Au+Au at RHIC is 600 GeV*

* Phys. Rev. C 71, 034908 (2005)

$\rightarrow$E= 300 GeV in cone with R=1

75 GeV in cone with R=0.5

Compare to maximum jet energy: 100 GeV

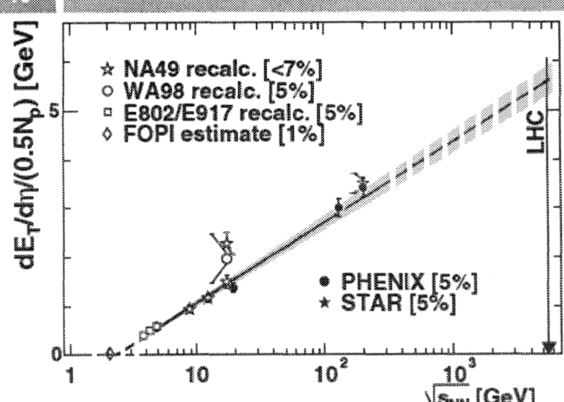


Jet measurement in HI at RHIC difficult!

Stefan Bathe, RBRC Review 2008 11/17/2008

Jets at the LHC

10

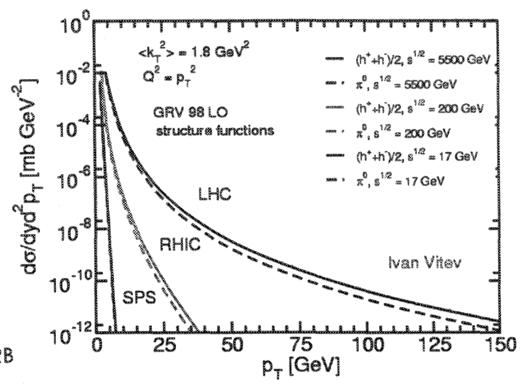


S. Milov, Jour.Phy.: Conf.Ser. 5 (2005) 17

soft background increases by ~ factor 2

- **Jet measurement in HI at LHC feasible, but still challenging**
- **Key: beat fluctuations**

jet cross section increases by orders of magnitude

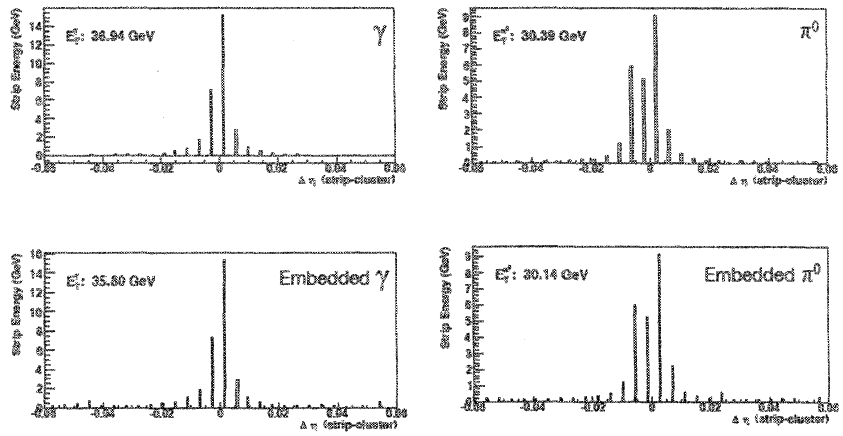


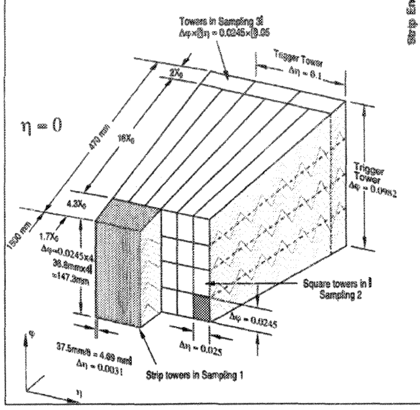
Stefan Bathe, RB

Lateral Segmentation

11

- Measurement of medium induced and fragmentation photons





- First EMCal layer has high separation in η
- Low occupancy even in central Pb+Pb
- π^0 rejection for $E_T \leq 70$ GeV

Summary

12

- Have been working on hard scattering physics in heavy ion collisions in PHENIX
  - leading role in key results such as discovery of high p_T hadron suppression and and d+Au reference measurement
- Currently working on quantifying medium modifications of hard scattering at highest p_T
- Natural extension of physics interest are jet measurements at LHC
- Started involvement in ATLAS, focusing on γ-jet

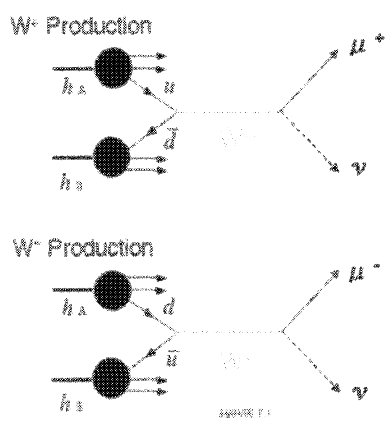
PHENIX Muon Trigger Upgrade for Sea Quark Polarization Measurement via W-boson

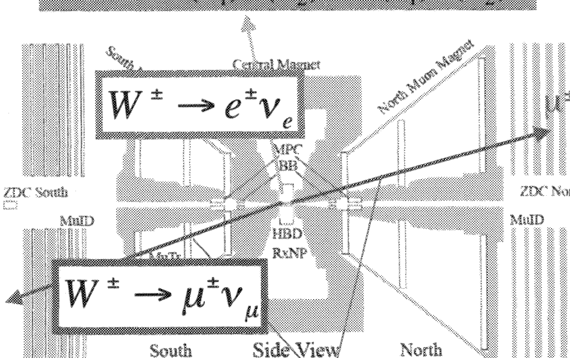
Itaru Nakagawa
RIKEN/RBRC
On behalf of RPC/MuTrig-FEE Collaboration

1

sqrt(s)=500 GeV @ RHIC

$$A_L^{W^+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$





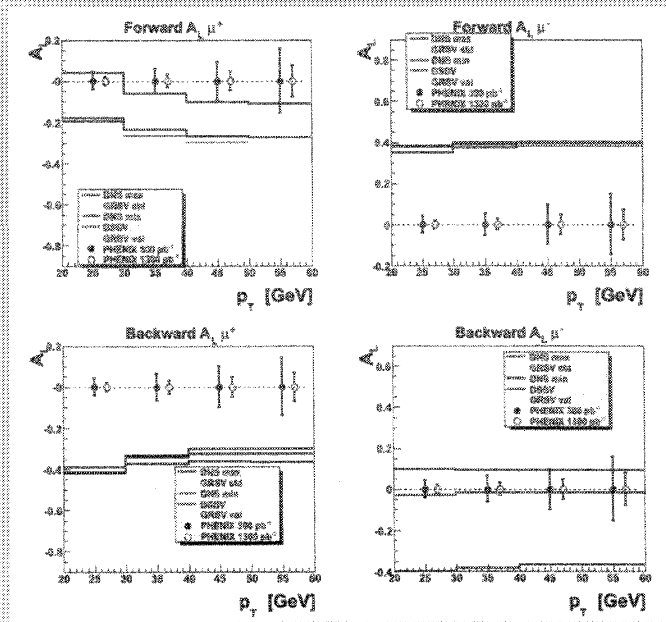
Parity Violation Asymmetry
Clean flavor separation
w/o fragmentation uncertainty

$$A_L^{W^+} \approx \frac{\Delta u(x_1, M_W^2)}{u(x_1, M_W^2)}, \quad x_1 > x_2 \ (y_W >> 0)$$

$$A_L^{W^+} \approx -\frac{\Delta\bar{d}(x_1, M_W^2)}{\bar{d}(x_1, M_W^2)}, \quad x_1 < x_2 \ (y_W << 0)$$

Expected precision for W->μ single spin asymmetries

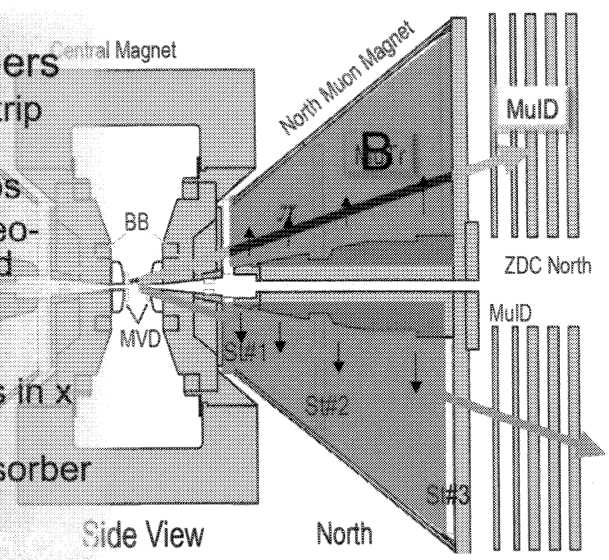
- Data points:
  - Events from RHICBOS + full detector simulation + reconstruction
  - $1.2 < \eta < 2.2$ both arms combined
  - Efficiencies of acceptance and reconstruction (70-80%)
  - Smearing of the reconstructed momentum (through simulation and reconstruction)
  - Fixed 3 / 1 Signal to background ratio (requires absorber + tighter cuts)
  - 70 % beam polarization
  - 300 (1300) pb^{-1} on tape corresponding roughly to RHIC projections until 2013 (and RHIC-II)
- Generated asymmetries
  - Events RHICBOS, $1.2 < \eta < 2.2$
  - Smearing of the reconstructed momentum (performed accd. to smearing matrix in finer binning on polarized and unpolarized yields separately)



08.11.13 R.Seidl: RPC design 3

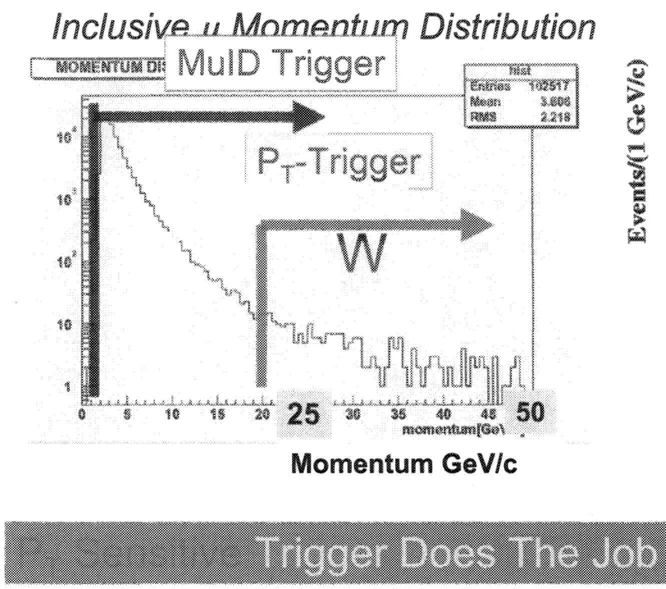
Current Muon System

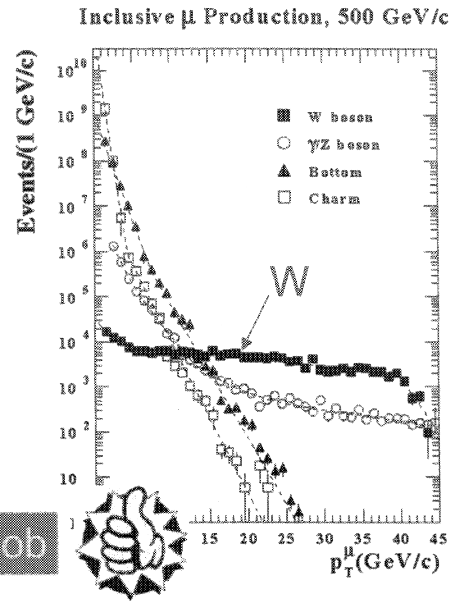
- Muon Tracking Chambers
  - 3 stations of Cathode strip chambers
  - 3 gaps + 3gaps + 2 gaps
  - Each gap has non-stereo-plane, stereo-plane, and anode plane
- Muon Identifier
  - 5 layers of Iarocci tubes in x and y directions
  - 80 cm of steel plate absorber (total)
  - Provides trigger $p_x > 1.5$ G



Same configuration in South 4

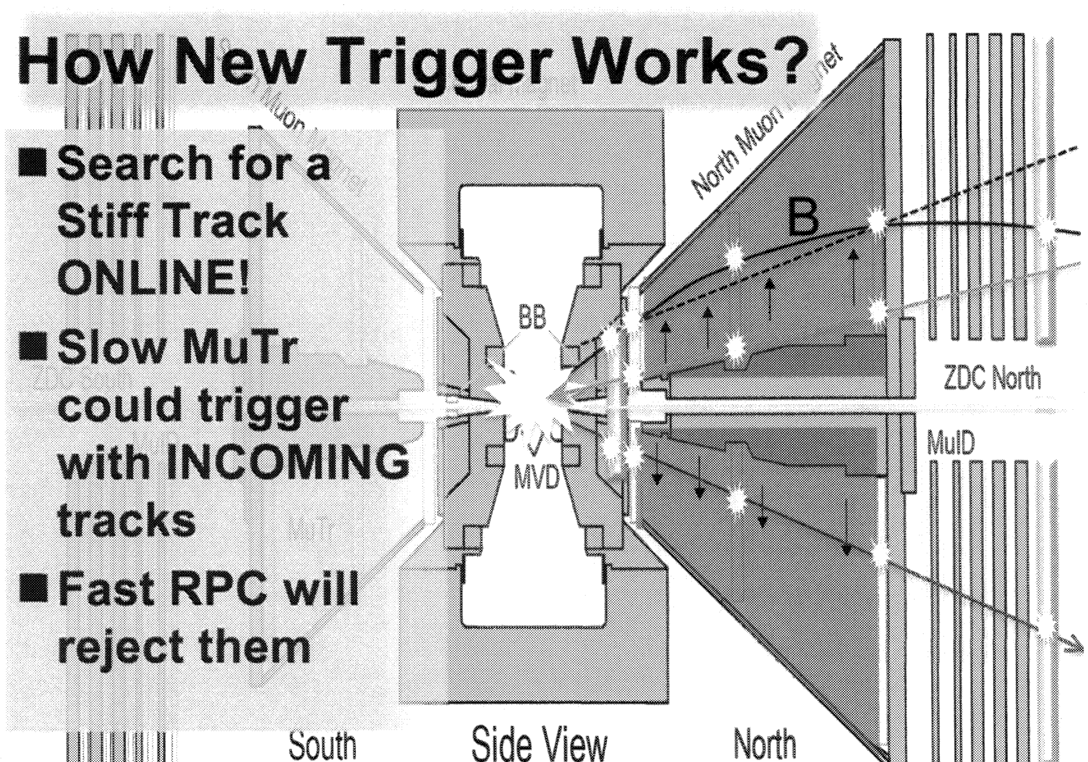
Rejection Power : Approach





How New Trigger Works?

- Search for a Stiff Track ONLINE!
- Slow MuTr could trigger with INCOMING tracks
- Fast RPC will reject them



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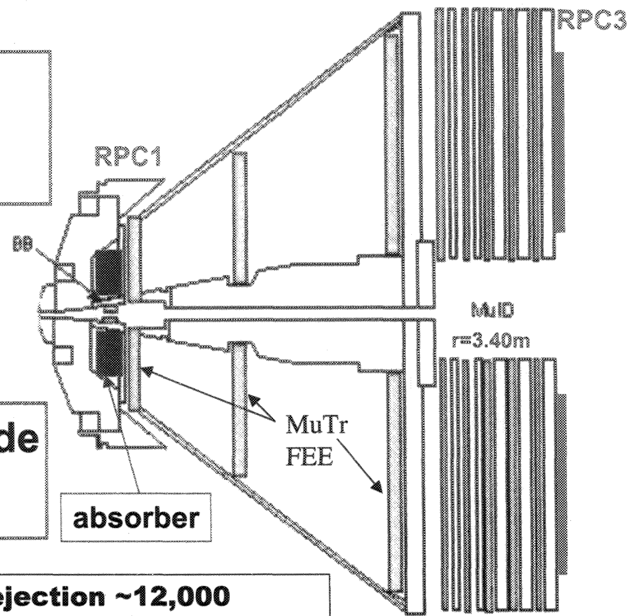
PHENIX Muon Trigger Upgrade

(I) RPC

(Resistive Plate Chambers)

NSF (Funded)



(II)MuTr FEE Upgrade

JSPS (Funded)

Combined Trigger Rejection ~12,000

7

RPC Collaboration

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Columbia University and Nevis Laboratory, New York

C. Butler, K. Dayana, X. He, C. Oakley and J. Ying
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J. Blackburn, M. Grosse Perdekamp, C. Lee, Y.-J. Kim, B. Meredith, T. Natoli, N. Mucia,
D. Northacker, J.-C. Peng, E. Thorsland, A. Veicht, A. Vossen and R. Yang
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Y. Mao and R. Han
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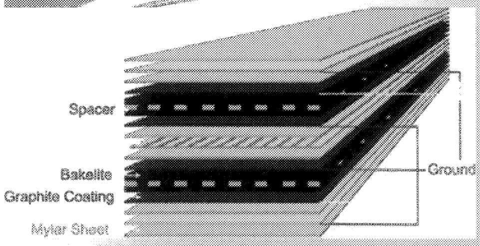
G. Bunce and R. Seidl
RIKEN BNL Research Center

8

8

General Ideas for using RPCs



Operation requirements

Efficiency	> 95%
Time resolution	≤ 3 ns
Average cluster size	≤ 2 strips
Rate capability	0.5 kHz/cm²
Number of streamers	< 10 %

Requirements

- Need fast detector for TRIGGER and bunch-crossing information (SPIN)
- Muon momentum has to be resolved to suppress low-Pt backgrounds
- Large area has to be covered
- Detectors have to be thin to fit into existing gaps

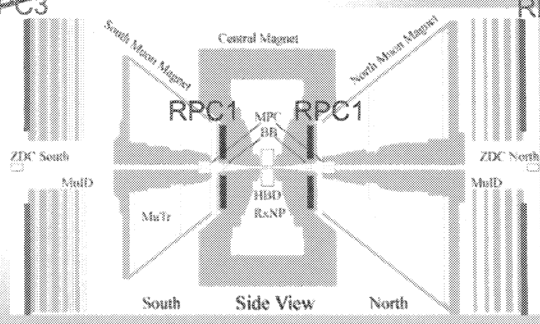
Solution

- RPCs have responses within ns
- Pseudo-radial readout segmentation at different planes around muon magnets
- Bakelite RPCs are relatively cheap, large plates available
- Gaps still very thin

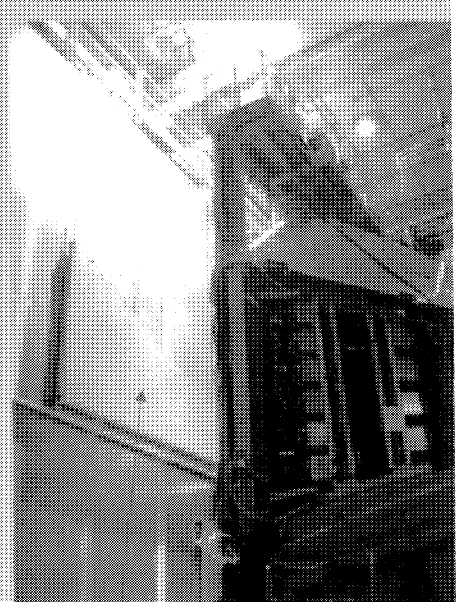
Use already established CMS Bakelite RPC technology and expertise

08.11.13 9

Status of RPC part of muon Trigger upgrade



- Successfully reviewed Sep'08 by BNL with DOE and NSF presence
- prototype installed in IR for run 9



RPC Prototype

08.11.13 R.Seidl: RPC design 10

MuTrig-FEE Collaboration

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KEK, Tsukuba, Ibaraki, 305-08011, Japan

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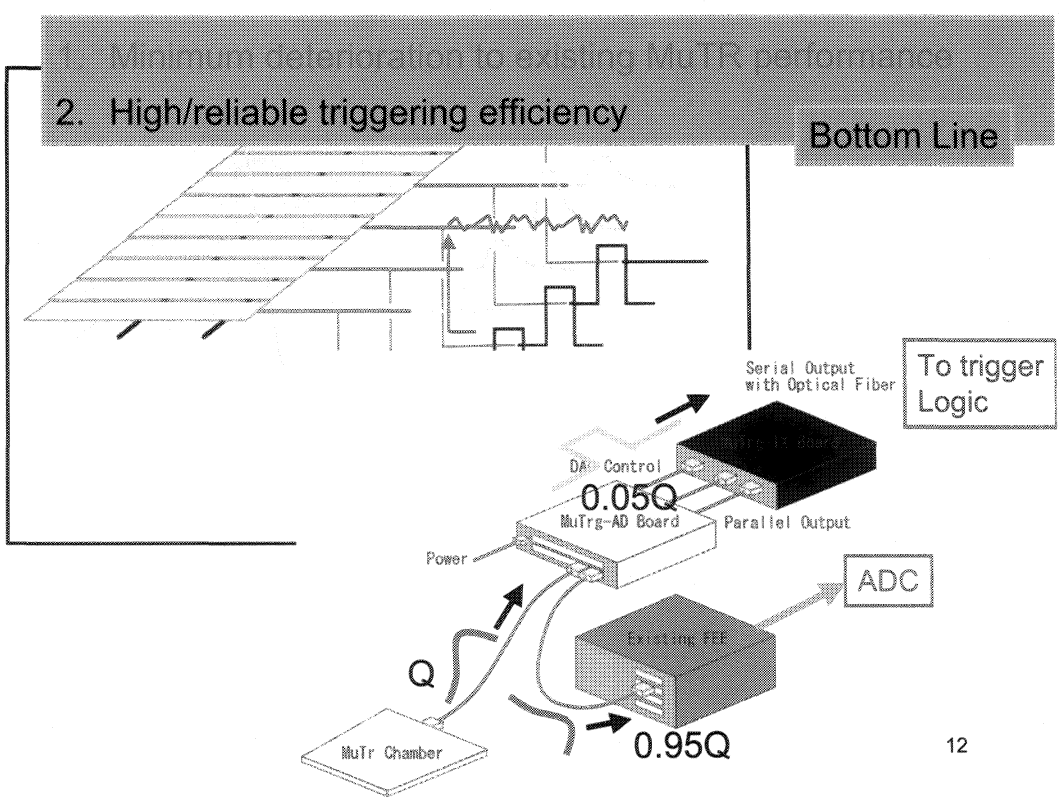
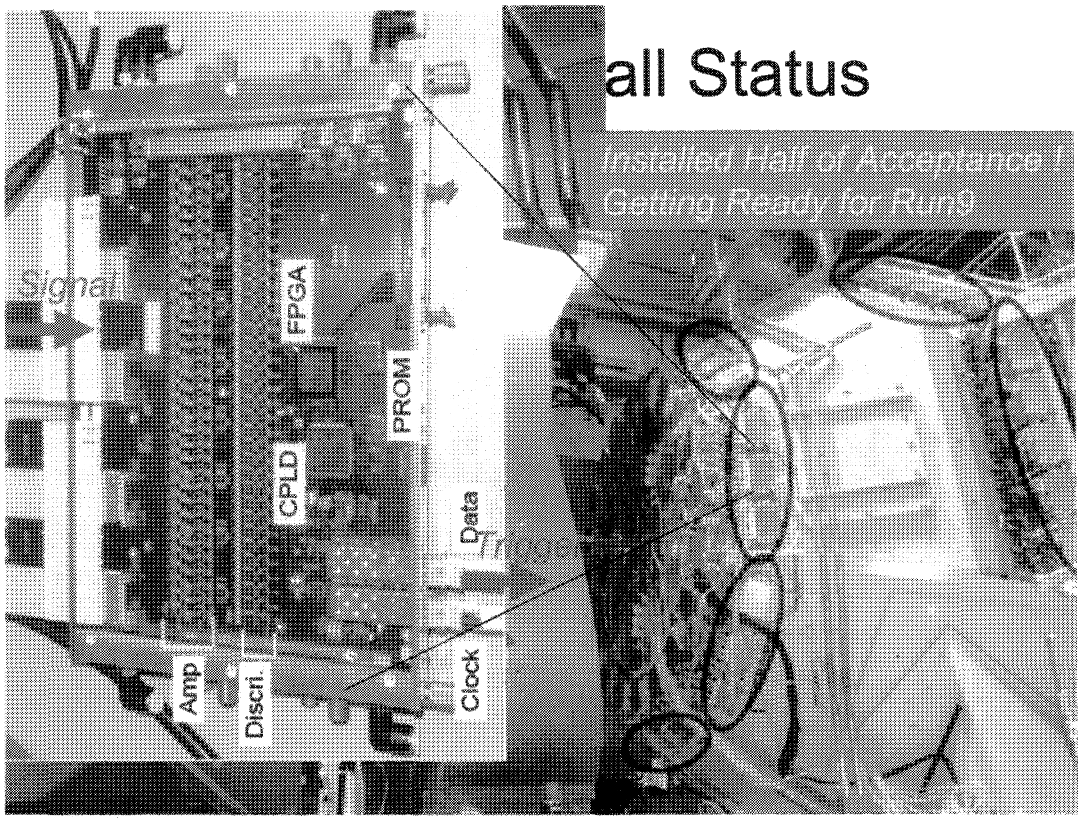
E. Kim, J. Park
Seoul National University, Seoul, South Korea





Summary

- W Single Spin Assymmetries as Quark/Antiquark helicities
- μ-Trigger Upgrade Necessary for W Detection
- P_T Sensitive Trigger → Factor 10000 Rejection
- RPC(NSF) and FEE-Upgrades (JSPS) Funded
- Installation is now underway

	North	South
MuTrig-FEE	Run09	Run10
RPC	Run10	Run11

Upgrade Projects are on schedule for comming exciting physics!

Backup Slides

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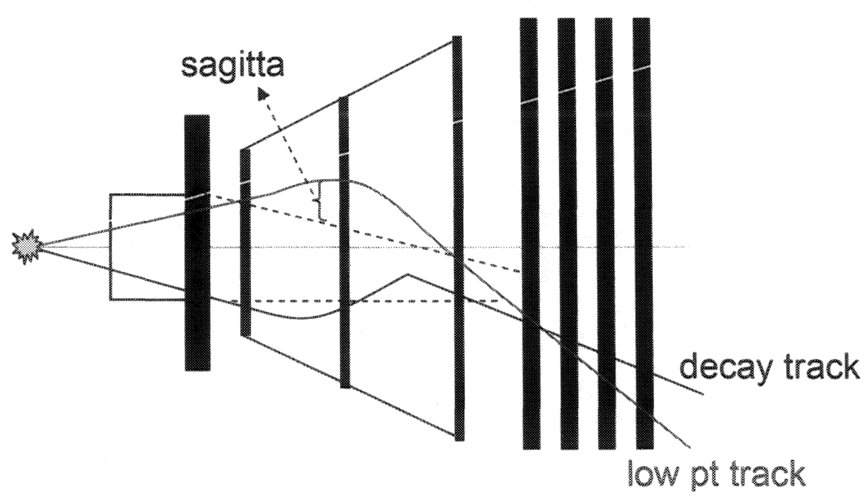
However, not yet the end of story…



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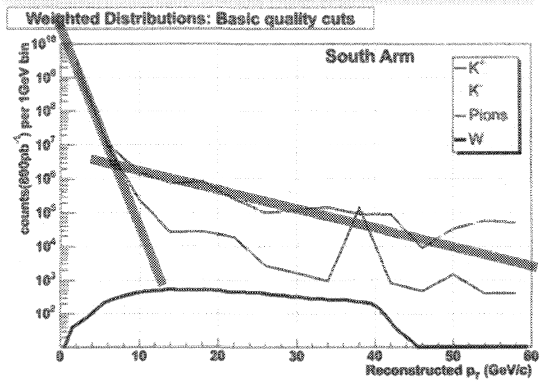
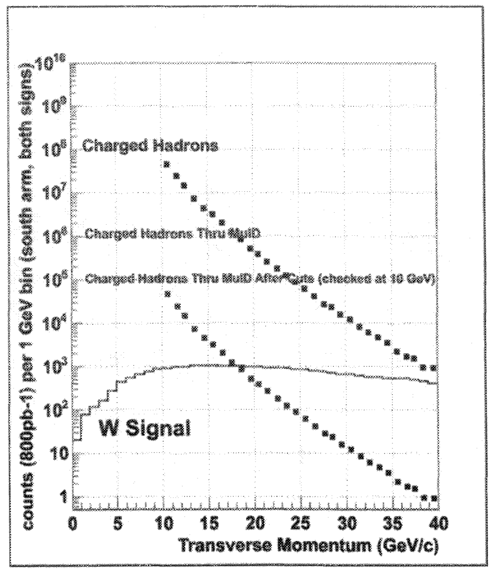
Backgrounds

1. Low PT π,K Decay in Flight



Primar
- *Tracker Alignment*
- *Absober*
- *EM Calorimeter*
- *Etc..*

2. Hi P_T π,K punch through

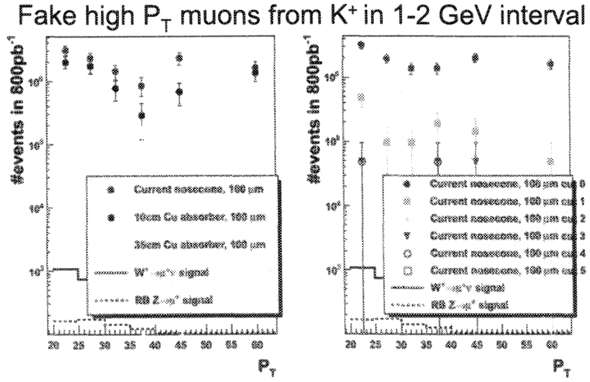


Absorber and cuts

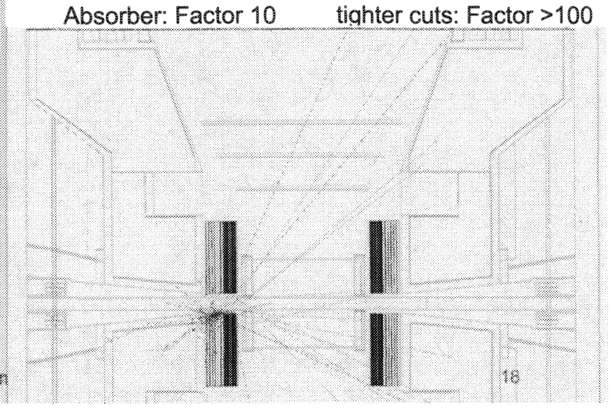
- Fake high P_T background can be reduced by absorber and tighter cuts in
- Full detector simulation of backgrounds using several absorber settings (large impact) and detector resolutions (little impact)

➔ Signal to background can be increased to 3/1

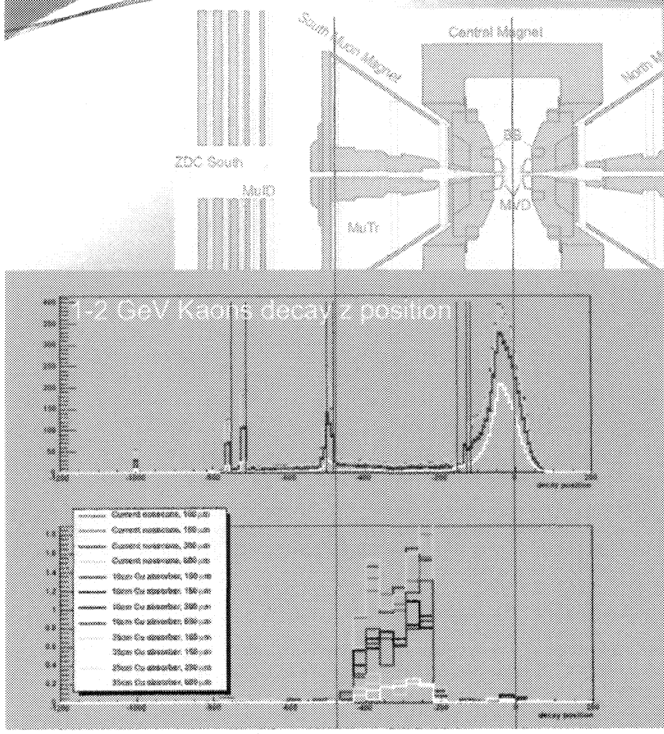
Fake high P_T muons from K^+ in 1-2 GeV interval



Absorber: Factor 10 tighter cuts: Factor >100



Backgrounds for high P_T muons in offline analysis:



- Most hadrons decay in central region or first absorbers
- Those surviving basic cuts decay within MuTr volume to fake a high momentum track
- Overall and cut decay muons in Muon arms reduced by possible absorber additions (no → 10cm →)
- Other backgrounds (small contributions):
  - Real high P_T muons from hadron decays
  - Cosmic muons
  - Z-decays

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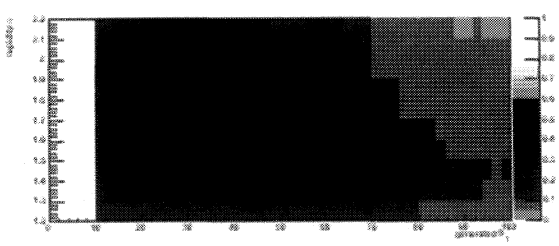
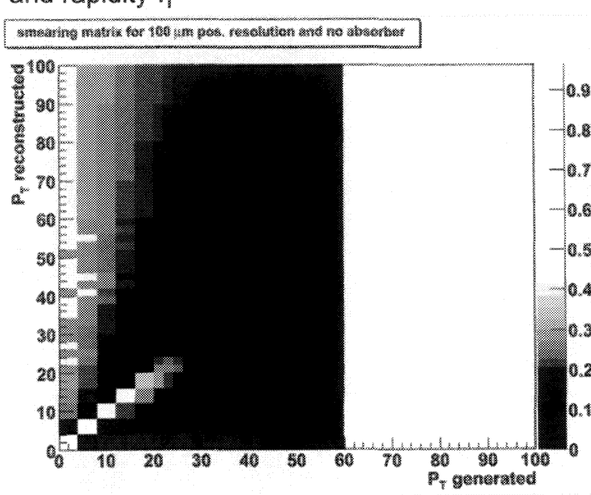


Efficiencies using tight cuts as function of P_T and rapidity η



W→μ signal simulations

- Testing single high P_T muon reconstruction in the muons system
- Optimizing cuts for background rejection and high efficiencies
- Understand detector smearing to be able to unfold final results
- Test possible offline improvements with MuTr Fee and RPC information

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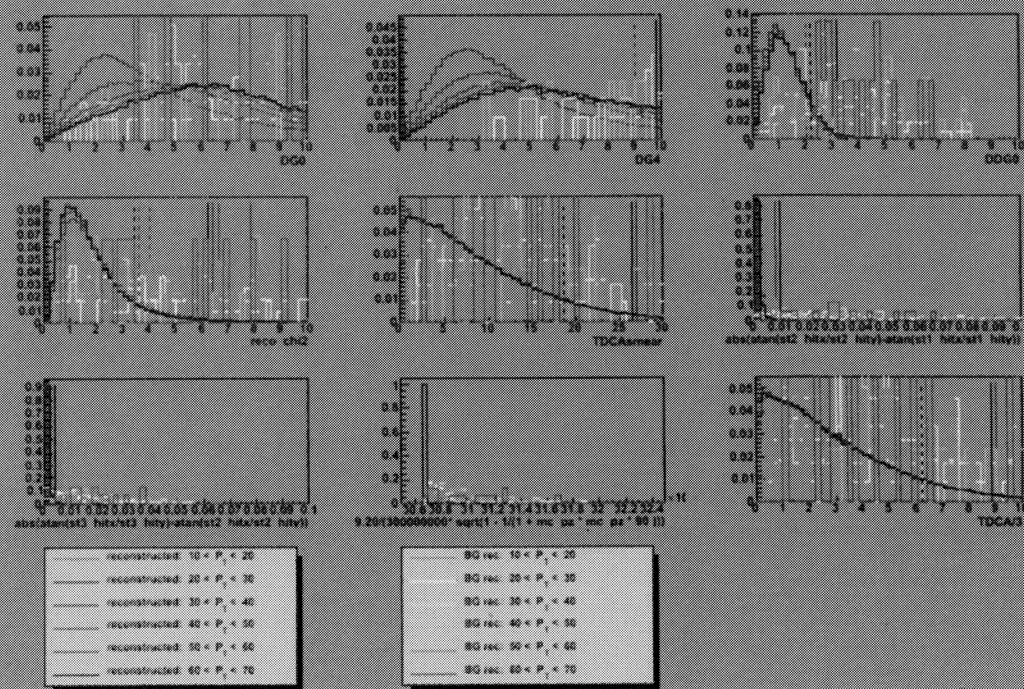
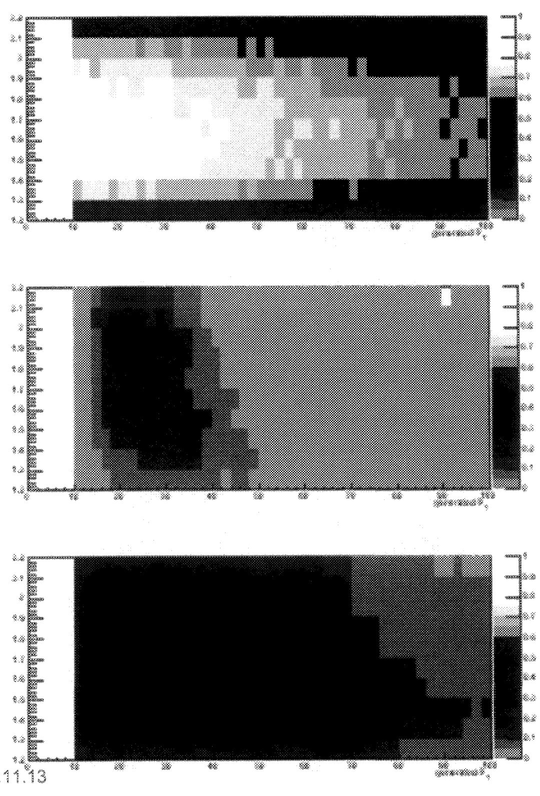
distribution



08.11.13 21

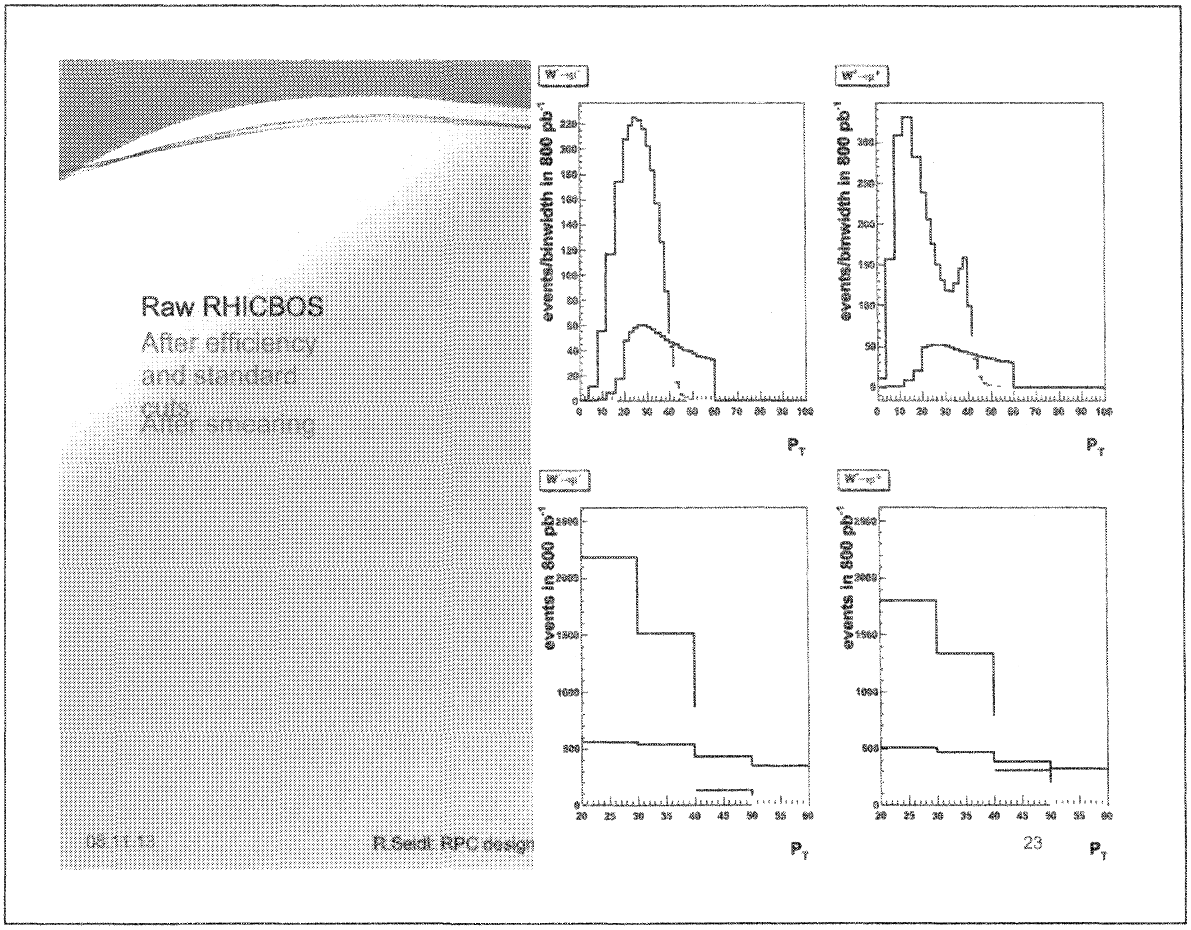


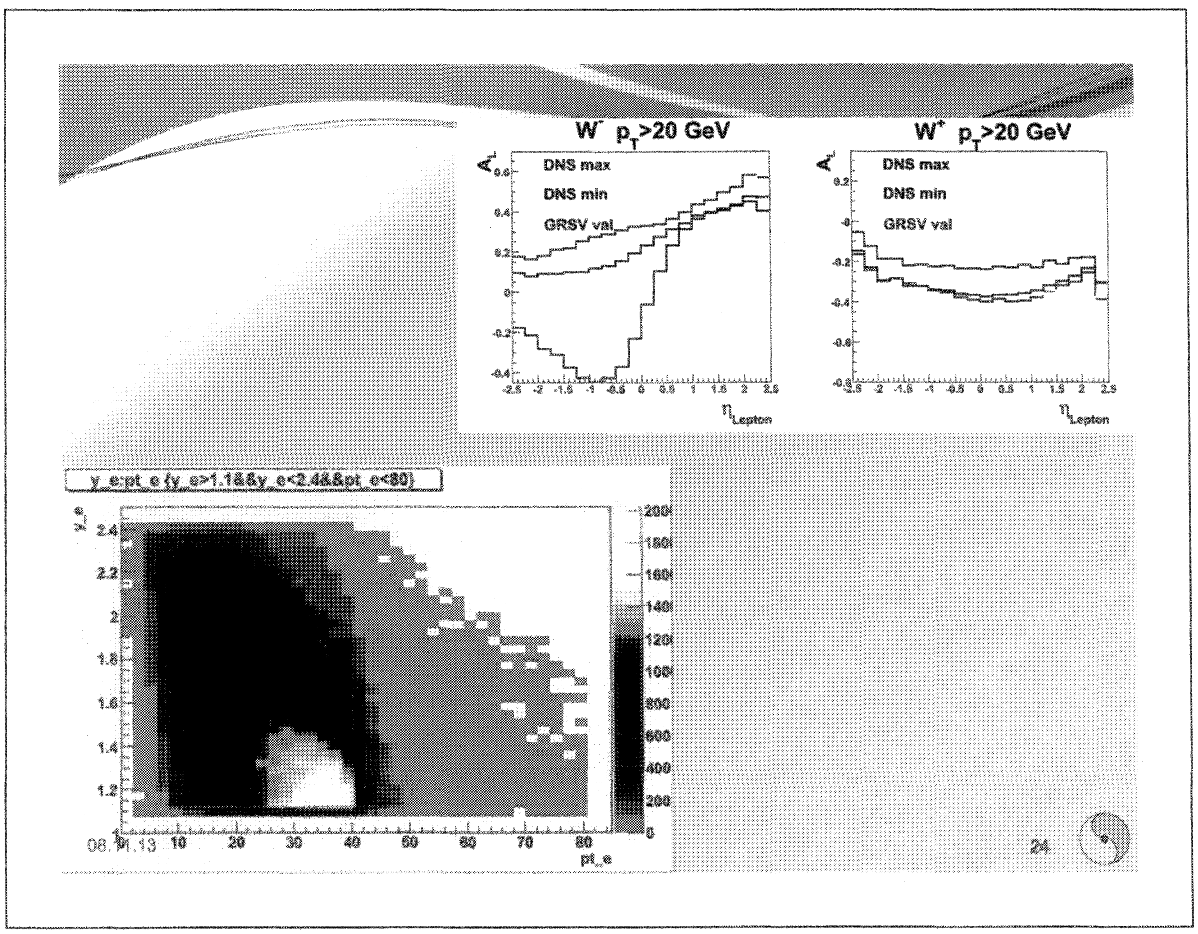
Absolute efficiencies 2d

- TOP: basic cuts
- Middle: old Tight cuts
- Bottom: new, optimized cuts

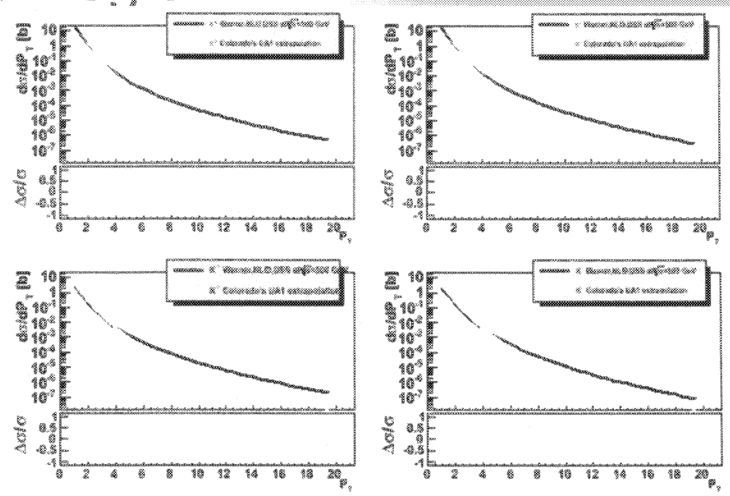
- Optimized cuts nearly 40 % efficient everywhere

08.11.13 22


Raw RHICBOS
After efficiency and standard cuts
After smearing
events/binwidth in 800 pb^{-1}
events in 800 pb^{-1}
P_T
08.11.13
R.Seidl: RPC design
23


W^- p_T>20 GeV
W^+ p_T>20 GeV
DNS max
DNS min
GRSV val
η_{Lepton}
y_e:pt_e {y_e>1.1&&y_e<2.4&&pt_e<80}
y_e
pt_e
08.11.13
24

Hadronic cross sections for forward region



- Colorado's assumption based on mid-rapidity UA1 data and 32%π,12%K (each charge) is close to NLO DSS cross section from Werner

RPC Detector Production Assembly and Installation

Bakelite

- **Pan-Pla, Italy** **Bakelite manufacture** (CMS bakelite vendor)
- **Riva, Italy** **Bakelite cutting** (CMS bakelite cutting company)
- **General Tecnica, Italy** **Bakelite cleaning** (CMS bakelite cleaning company)

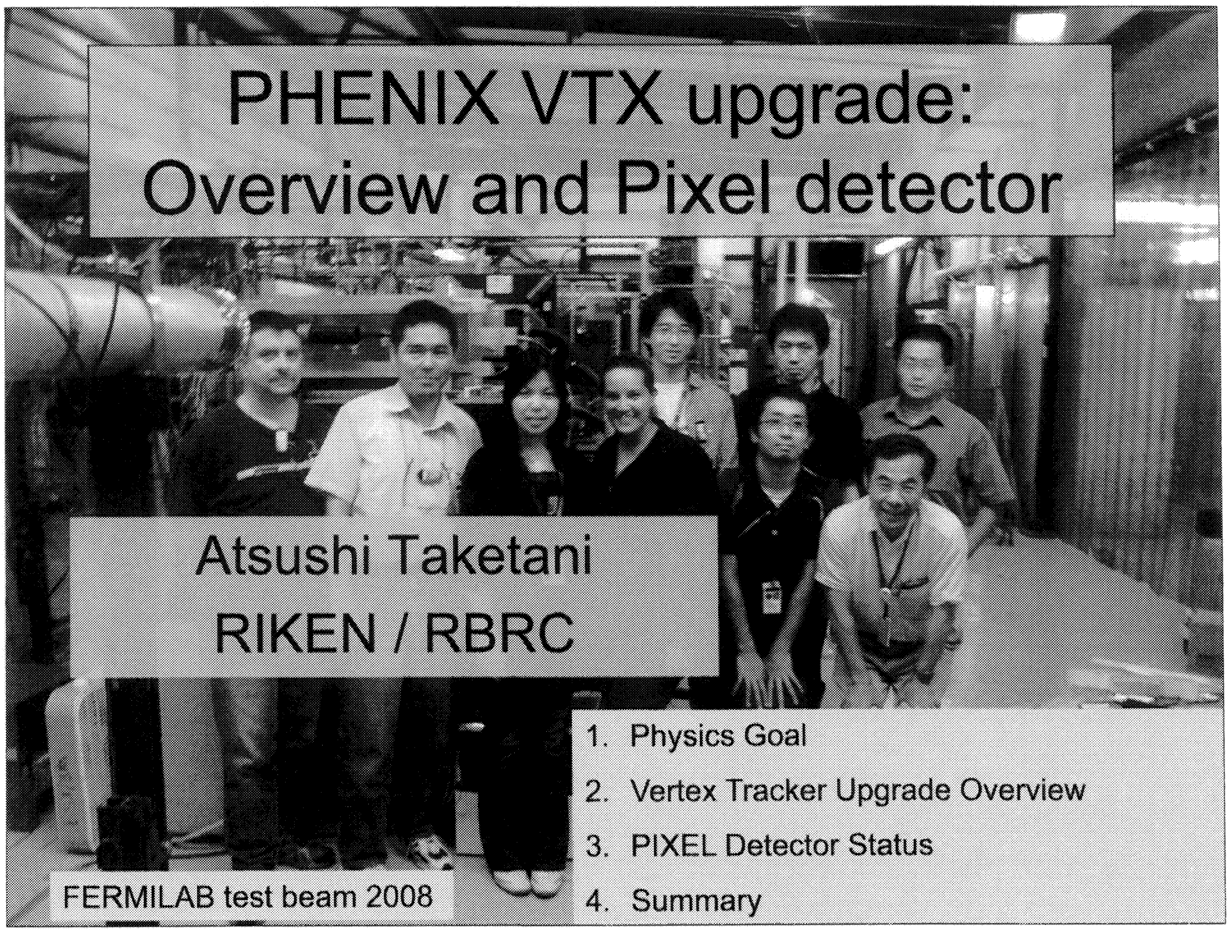
RPC Detector Parts

- **Korea University, Korea** **RPC gap** (CMS Endcap RPC gap vendor)
- **CIAE, China** **RPC module frame and readout strip plane** (CIAE has access to CMS frame/readout strip vendors)
- **Hi-Tech Manufacturing, US** **RPC half octant frame**
- **Nevis Lab. at Columbia University, US** **Electronics** (use CMS RPC discriminator chip)

RPC Detector

- **RPC factory, BNL, US** **Assemble & Test RPC modules** **Assemble & Test RPC half octants**
- **PHENIX, BNL, US** **RPC group:**
  - **Installation (help from PHENIX technicians)**
  - **Commissioning**
  - **Operation monitoring of RPCs**

PHENIX VTX upgrade: Overview and Pixel detector



Atsushi Taketani
RIKEN / RBRC

1. Physics Goal
2. Vertex Tracker Upgrade Overview
3. PIXEL Detector Status
4. Summary

Proposal for a Silicon Vertex Tracker (VTX) for the PHENIX Experiment

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J.S. Haggerty, J.T. Mitchell, C.L. Woody

As of May 2006 Proposal to DOE, 92 authors from 20 institutions

RIKEN VTX group as of 2008 Nov.

VTX Detector Council :Y. Akiba@BNL

Pixel Subsystem Manager :A. Taketani

Post Doc: Y.Onuki, R.Ichimiya, M. Kurosawa, K.Fujiwara, M. Togawa@BNL

Technician: J. Kanaya

Rikkyo : K. Kruita, K. Hashimoto, M.Kasai, Y.Haki

KEK : M. Sekimoto

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B. Bassalleck, D.E. Fields, M. Malik
University of New Mexico, Albuquerque, NM, USA

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Physics Goals

Open up new horizon!

Spin program

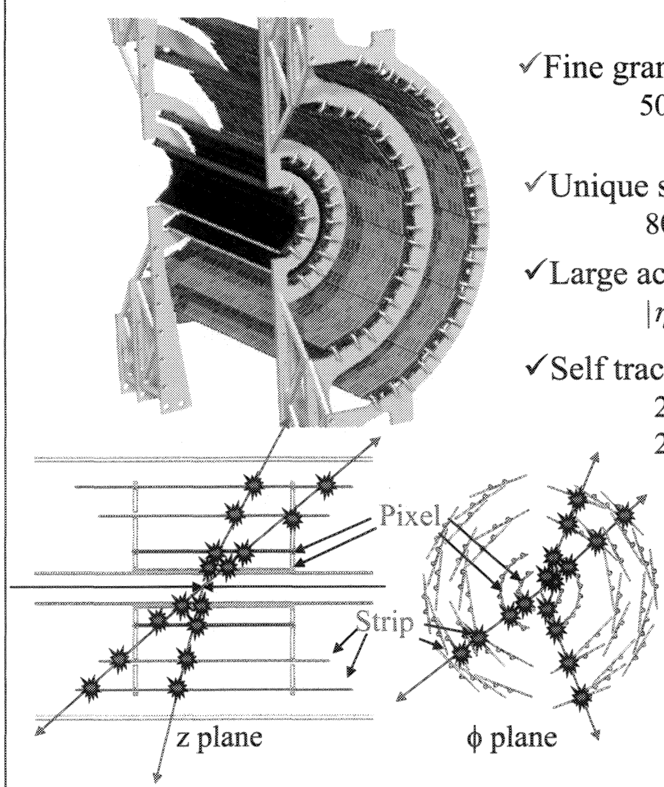
- Investigating nucleon spin structure by polarized proton-proton collider to utilize quark/gluon as probe, instead of DIS lepton.
- gluon polarization by using beauty / charm final state.
- gluon polarization by using γ + jet final state.
- Flavor decomposition by using W->e channel.

Heavy Ion program

- Potential enhancement of charm production.
- Open beauty production.
- Flavor dependence of jet quenching and QCD energy loss.
- Beauty and charm separation
- Accurate charm reference for quarkonium.
- Thermal dilepton radiation.
- Upsilon spectroscopy, e^+e^- decay channel
- γ -Jet correlation

3

Overview of Silicon Vertex Tracker



✓Fine granularity, low occupancy
50μm×450μm pixel sensor at inner 2 layers.

✓Unique strip sensor
80μm×1000μm pixel pitch

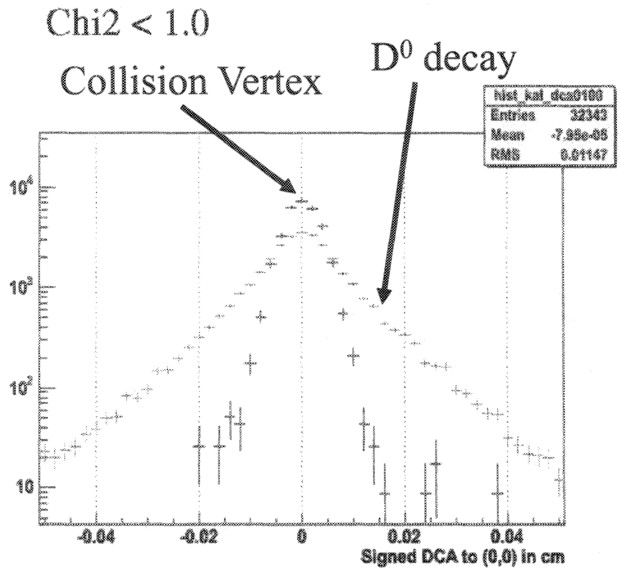
✓Large acceptance
$|\eta|<1.2$, almost 2π in ϕ plane

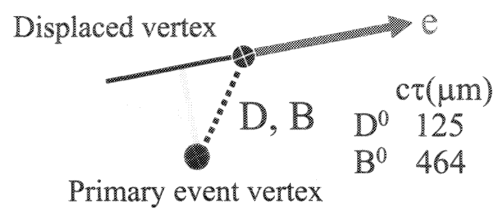
✓Self tracking capability
2 pixel sensor layers (r = 2.5, 5.0cm)
2 strip sensor layers (r = 10.0, 14.0cm)

VTX will be installed in 2010.

4

b/c flavor separation with VTX





Distance to the Closest Approach [cm]

Au-Au central event

VTX will have DCA resolution ~ 50 μm
We can separate b->e and c->e component with VTX.
A DCA resolution (~100μm) is sufficient for b/c separation 5

Requirements for Vertex Tracker

Physics side

- High precision tracking for displaced vertex measurement. 50μm displaced vertex resolution, cτ ~ 100μm(D), ~400μm(B)
- Large coverage tracking capability with momentum resolution (|η|<1.2 , and full azimuthally with σ/P ~ 5%P)

Environment side

- High charged particle density 'dN/dη' ~ 700 @η=0
- High Radiation Dose ~100KRad@10Years
- High Luminosity $2*10^{32}$ cm^{-2} s^{-1}@PP -> High rate readout
- Low Material Budget <- avoid multiple scattering and photon conversion for electron measurement by outer detectors.

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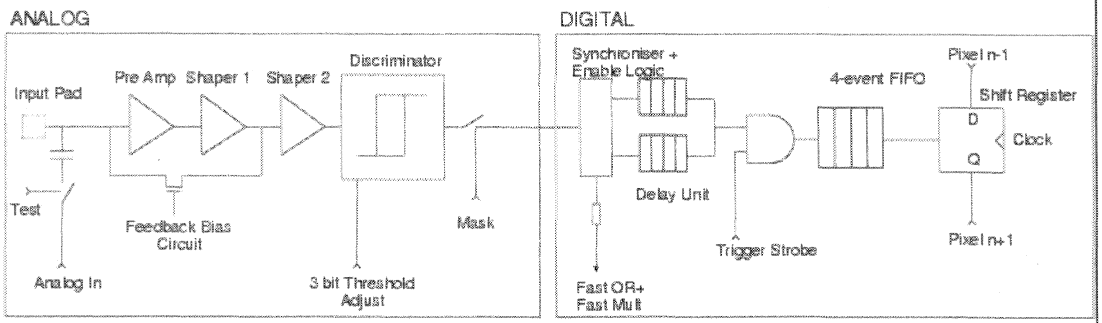
PIXEL (Sensor and Readout)



Pixel size(Φ x z)	50 µm x 425 µm
Sensor Thickness	200μm

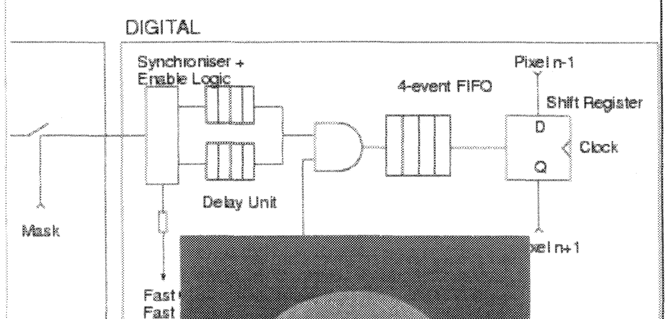
$\Delta r\Phi$ = 1.28cm, Δz = 1.36 cm (Active area)
256 x 32 = 8192 channel / sensor
4 chip / sensor
4 sensor / stave

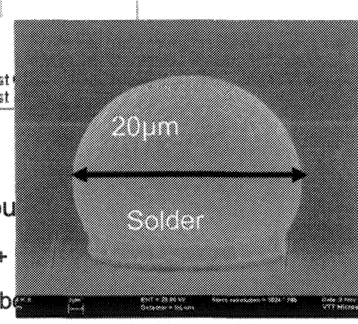
Readout by ALICE_LHCB1 chip

- 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

7

PIXEL (Sensor and Readout)





Pixel size(Φ x z)	50 µm x 425 µm
Sensor Thickness	200μm

$\Delta r\Phi$ = 1.28cm, Δz = 1.36 cm (Active area)
256 x 32 = 8192 channel / sensor
4 chip / sensor
4 sensor / stave

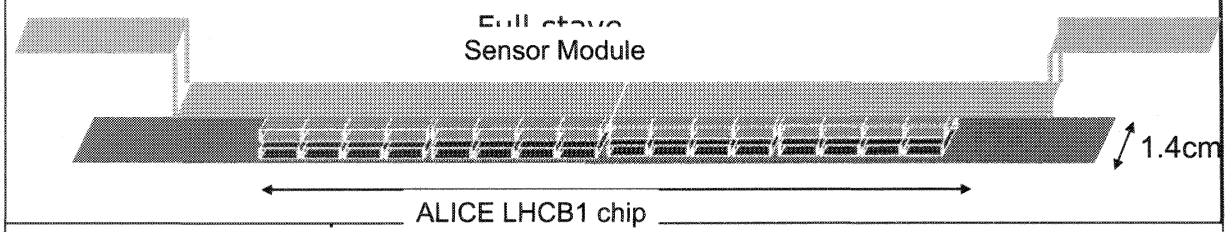
Readou

- Amp +
- Bump b
- 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

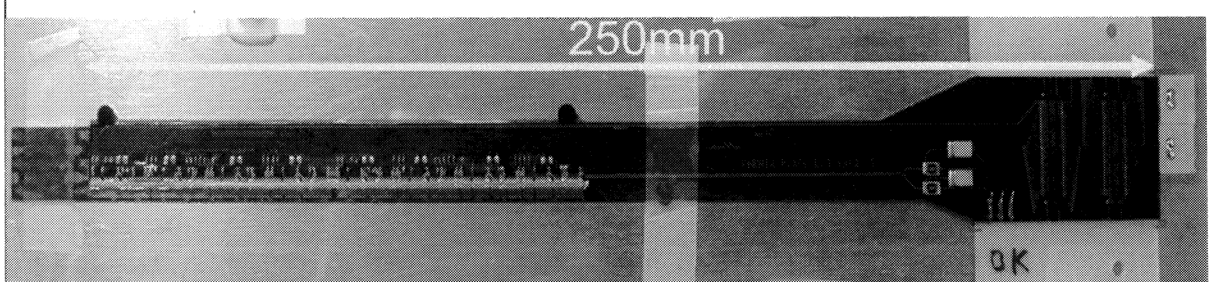
8

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

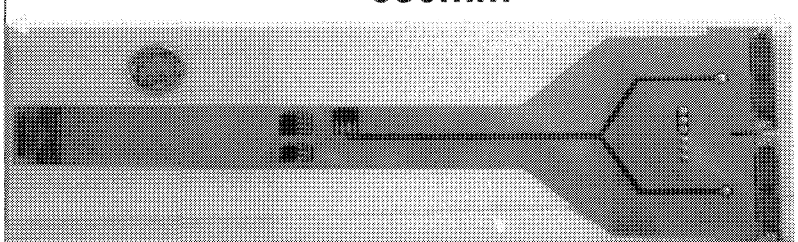


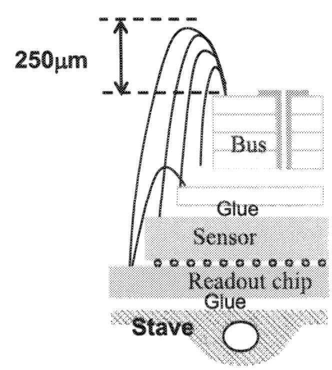
Readout Bus



Extender Ver. 5

350mm

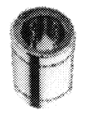




Ladder Crosse section

10

Alignment and Assembly

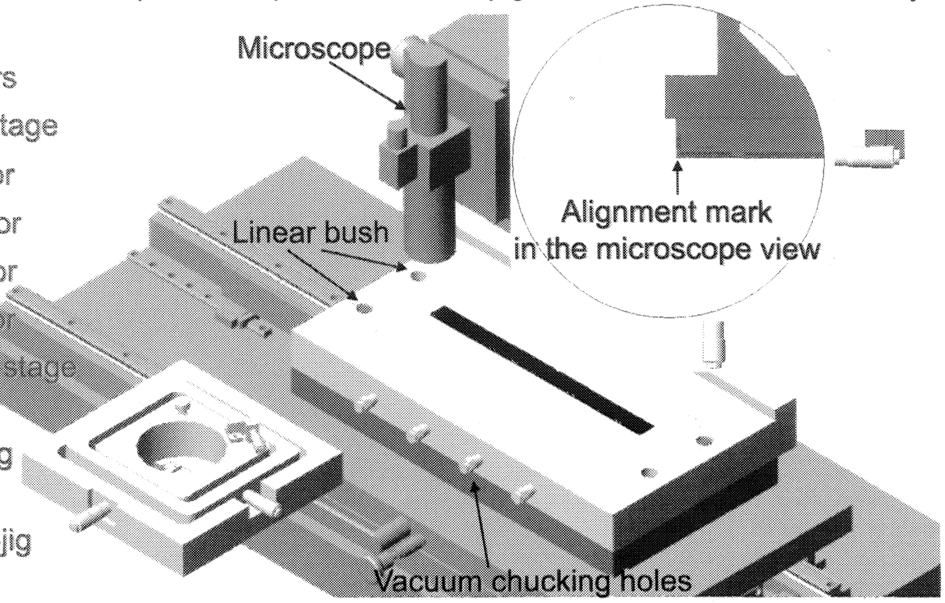


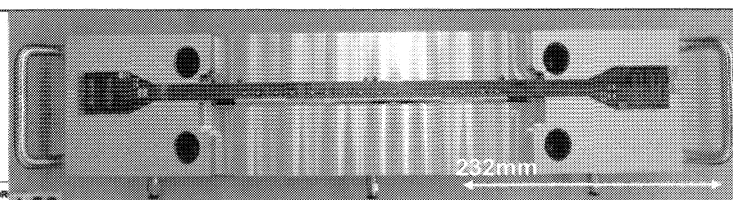
Linear bush:

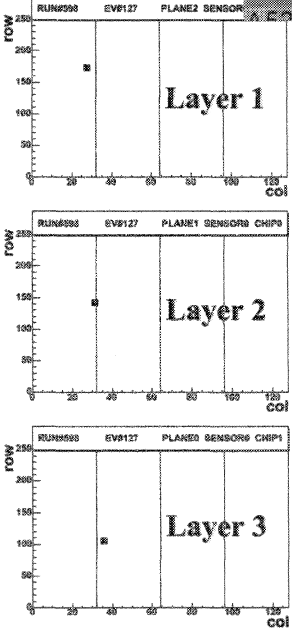
Linear ball bearing inside in the shell structure

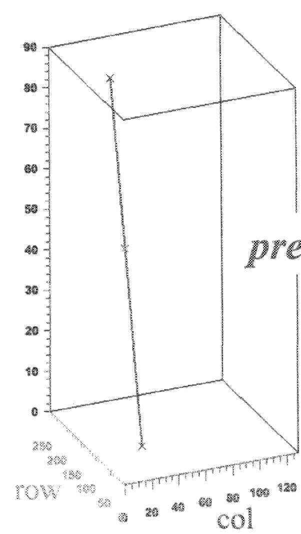
- Relative position between jigs is determined by linear bush and pin at <5μm accuracy in order to assemble stave at <25μm precision.
- Jigs have a flexibility for modification of the component.
- Detailed and quantitative procedures to keep good uniformity and reproducibility

1. Set the sensors
2. Set the XYθ–stage
3. Align 1st sensor
4. Align 2nd sensor
5. Align 3rd sensor
6. Align 4th sensor
7. Take out XYθ–stage and slide
8. Set the Turn-jig and chucking
9. Take out Turn-jig

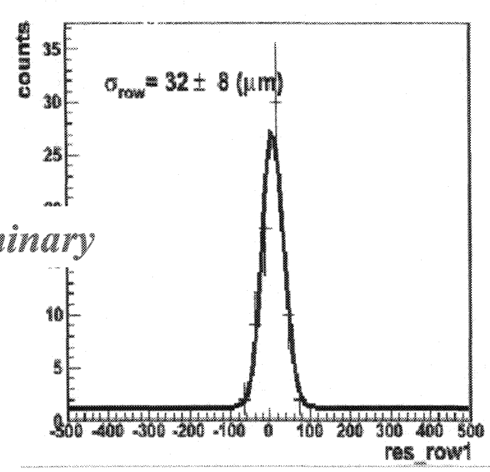








<Residual Distribution (row)>



Proton 120GeV@FERMILAB Test beam

Readout by PHENIX DAQ and confirmed functionality

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Summary

- Most of the pixel ladder design is finalized for production.
- Test beam confirms pixel performance.
- VTX will be installed partially on 2009 summer and fully implemented on 2010.

- At Wako, we have accepted 8 summer students in total from Tokyo Metropolitan College Aeronautical Engineering since 2006.

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Backup

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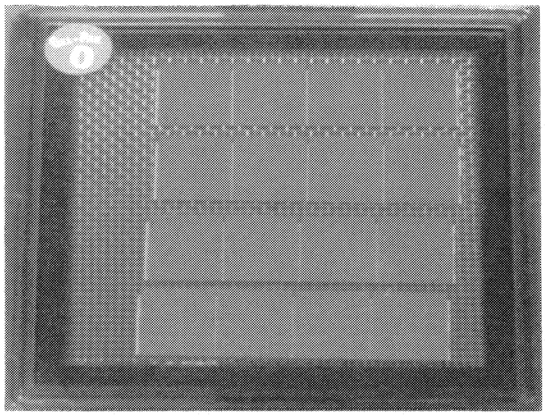
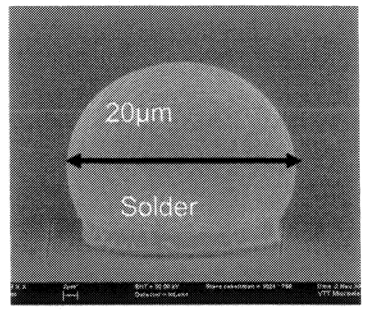
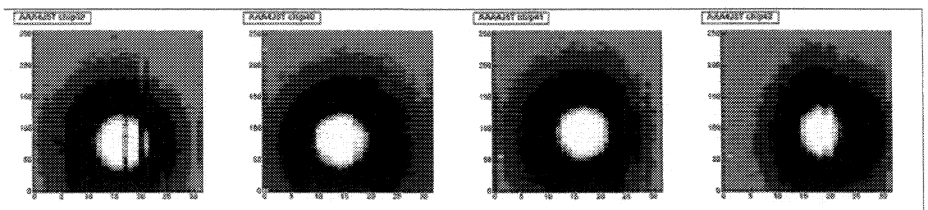
Bump bonding



Bump bond to
silicon pixel sensor





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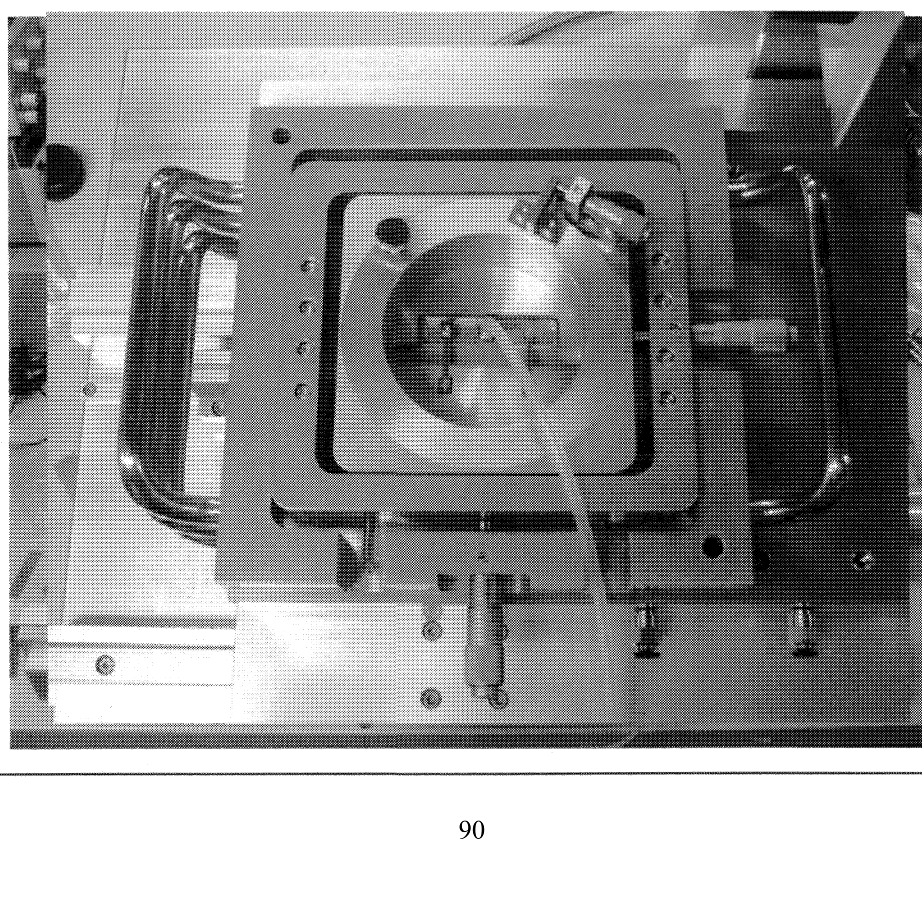
Assembly with 10μm accuracy



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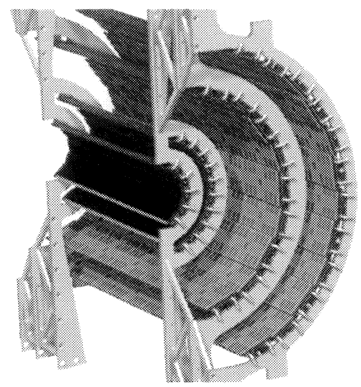
PHENIX VTX upgrade : Strip detector and software development

Manabu Togawa
RBRC review : November 17th 2008

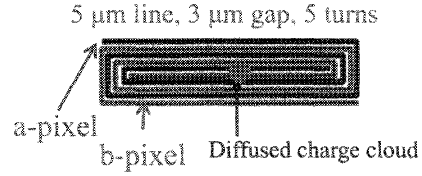


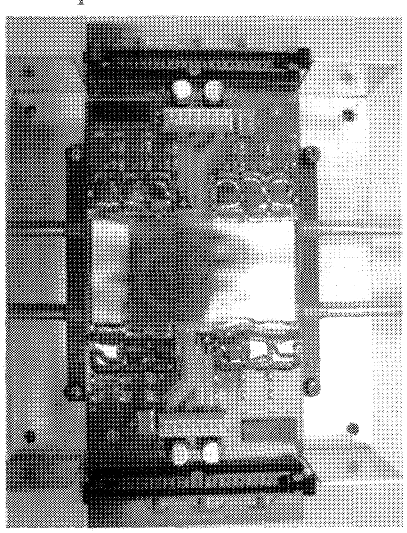
- Strip detector for the PHENIX VTX
  - Introduction
  - Performance study with beta source
  - Performance study with 120 GeV proton beam
- Software
  - Full Monte Carlo Simulation

1

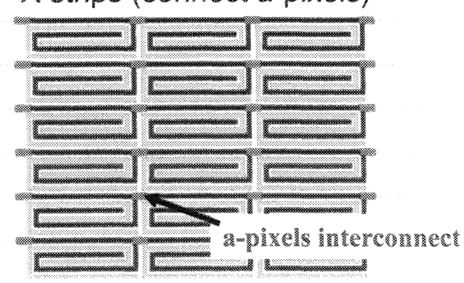
Strip detector : world's first 2-dimensional readout from 1 side

pixel array: 80×1000 μm^2 pitch
Reading by p-side
5 μm line, 3 μm gap, 5 turns





X strips (connect a-pixels)



- Pixel array: 80×1000 μm^2 pitch
  - so called "stripixel"
- Single sided (p-side), 2-dim. readout
  - Double metal structure
  - Charge sharing during x and u strip
- Detector size : 3.5×6.2 cm^2 ×625mm
  - 1536 channel / 1 sensor

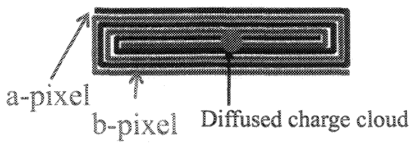
2

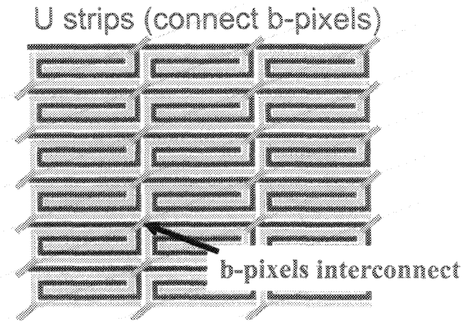
Strip detector : world's first 2-dimensional readout from 1 side

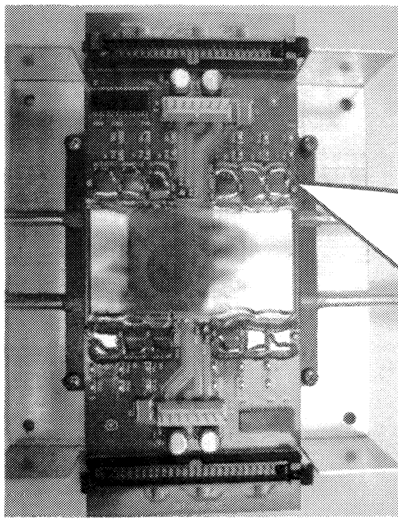
pixel array: 80 × 1000 μm² pitch

Reading by p-side

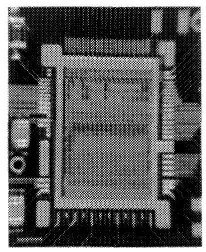
5 μm line, 3 μm gap, 5 turns





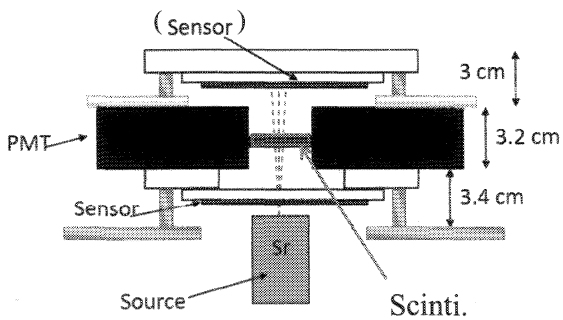


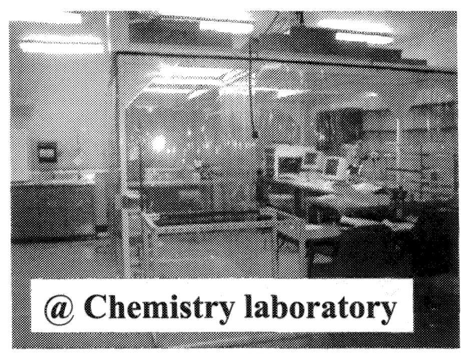
SVX4 chip



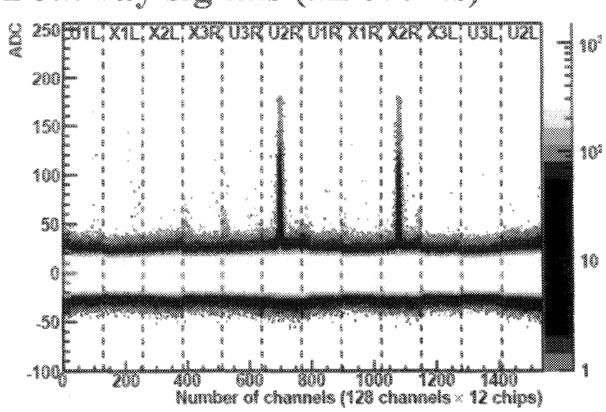
- 8 bit ADC
- 128 channel / chip
- Dead time less readout
- 3 mW / channel

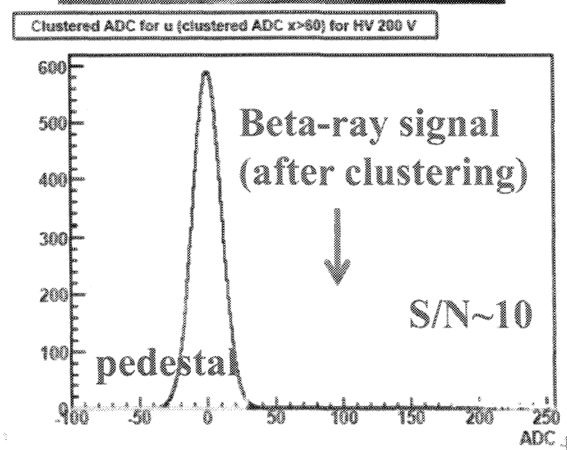
Test with beta source



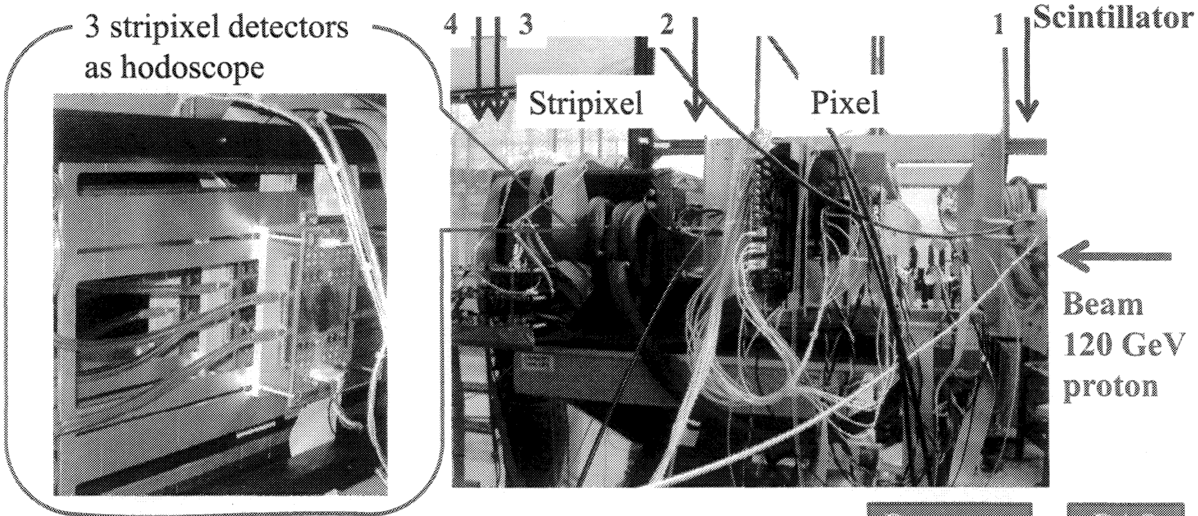


Beta-ray signals (all events)

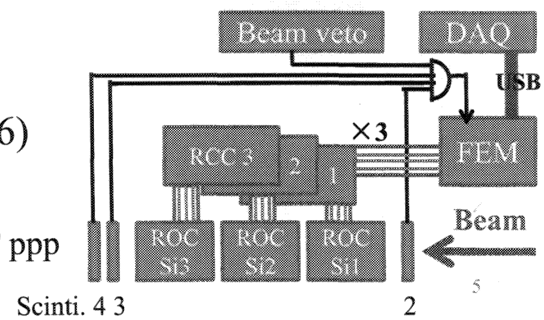




Performance study with 120 GeV proton beam



- Test beam at Fermi Lab.
  - T986 at MTBF (2008/Aug./20-26)
  - 120 GeV proton beam
    - 1 spill 4.5 s in each 1 min. 2×10^{10} ppp
    - Beam size : 5 ~ 30 mm

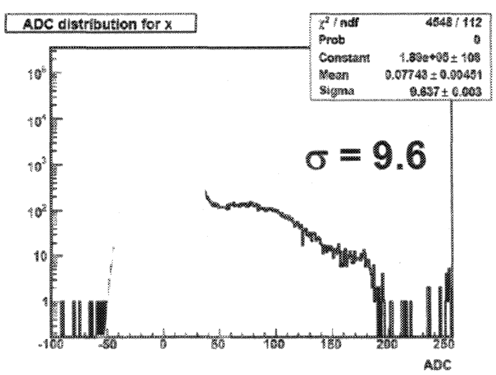


5

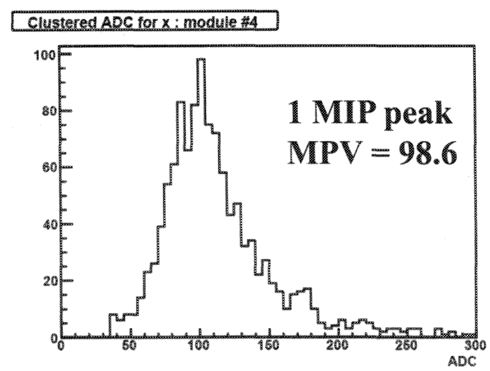
S/N ratio

preliminary

Raw ADC distribution



Clustered ADC distribution



Channels "Stripixel"	Pedestal σ	MIP MPV	S/N
x	**9.6**	**98.6**	**10.3**
u	**10.1**	**102.2**	**10.1**

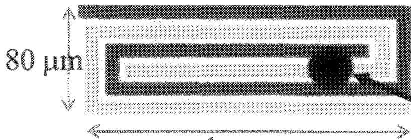
S/N ratio ~10 : consistent with the result of beta-ray

→ Evaluation of the position resolution and detection efficiency with this S/N ration

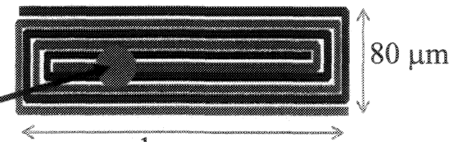
6

Charge sharing in x and u for 0 Degree

Prototype (3 turns)



Current production (5 turns)

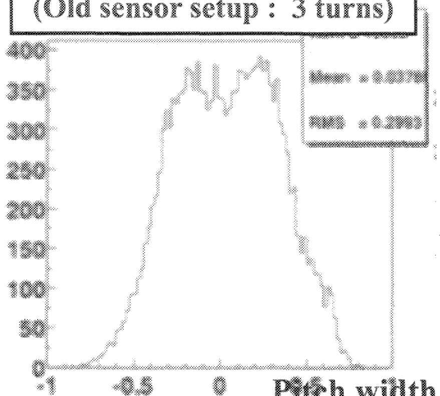


Diffused charge cloud

| Important parameter ↓

$$A_Q \equiv \frac{Q_x - Q_u}{Q_x + Q_u}$$

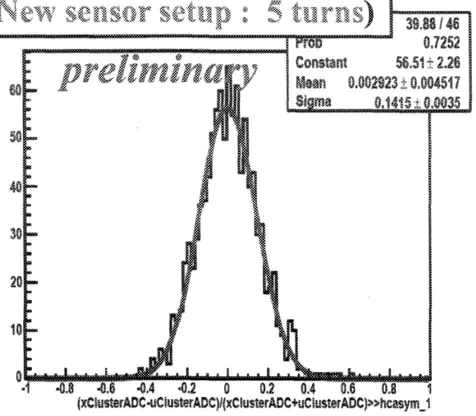
From KEK test (Old sensor setup : 3 turns)



A_Q

Pitch width is not enough narrow for charge diffusion

From Beam Test (FNAL): (New sensor setup : 5 turns)

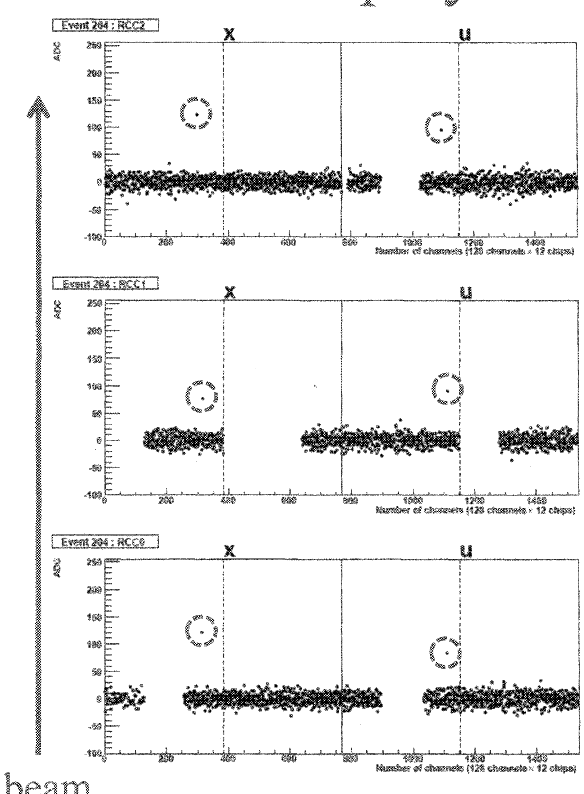


Good charge sharing in x and u

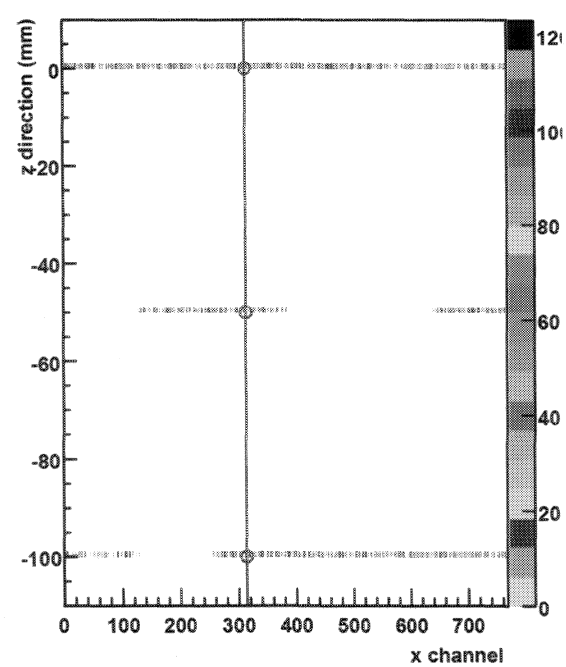
7

Event display & Tracking

preliminary



1 event display

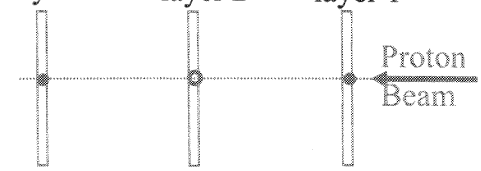


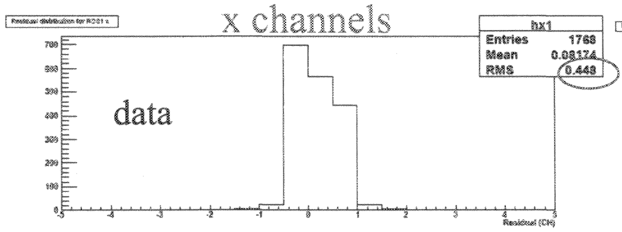
Tracking using 3 sensors

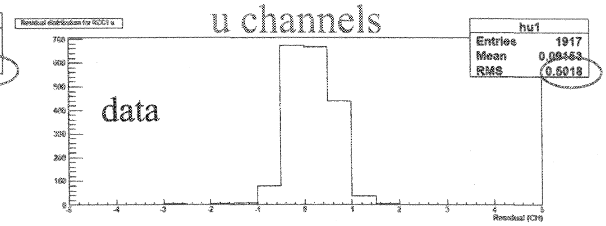
8

Residual distribution *preliminary*

- Difference btw hit position in layer 2 and expected position by tracking using layer 1 and 3







Residual RMS in layer2 :

for channels x: 0.45 (RMS) x 80 μm (pixel size) = 36 μm

for channels u: 0.50 (RMS) x 80 μm (pixel size) = 40 μm

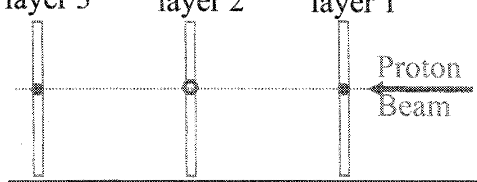
Shape of the distribution is consequence of the three-plane-resolution with imperfect alignment

9

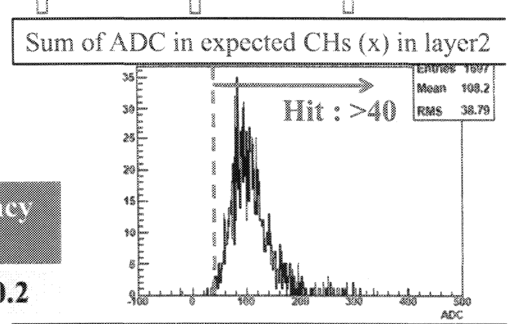
Detection efficiency *preliminary*

10

- Energy deposit in expected CH in layer 2 from the tracking using layer 1 and 3.



$$Eff \equiv \frac{(\text{All count}) - (\text{Count in ADC} < 40)}{\text{All count}}$$

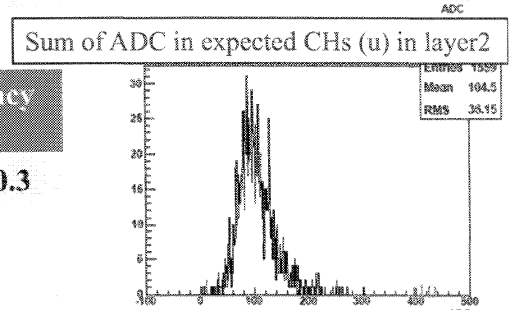


By tracking (x)

Layer #	All count	Count in ADC < 40	Efficiency (%)
2	**1697**	**9**	**99.5±0.2**

By tracking (u)

Layer #	All count	Count in ADC < 40	Efficiency (%)
2	**1559**	**18**	**98.9±0.3**

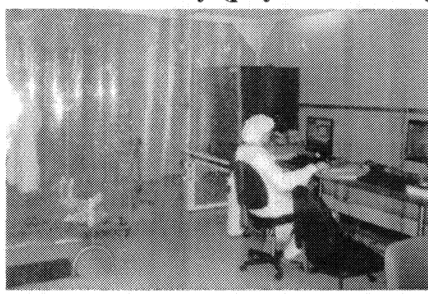


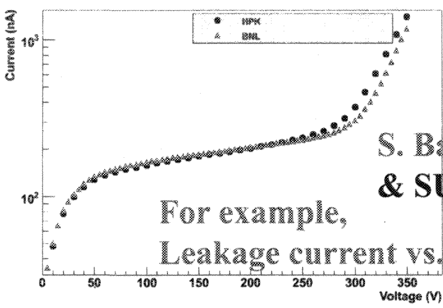
Results satisfy performance demand
→ Preparing for mass production

Sequence of mass production (Plan)

Silicon sensor QA
(RBRC room)

RBRC laboratory (physics building)





For example,
Leakage current vs. HV

S. Bathe, K. Boyle,
& SUNY group

ROC
(made by Hughes company)

↓

Mounting svx4 chips → test
(private company or FNAL)

↓

Mounting sensor → wire bonding → test
→ encapsulation (VTX people @ FNAL)

↓

Testing & ladder assembly
(BNL : chemistry lab.)

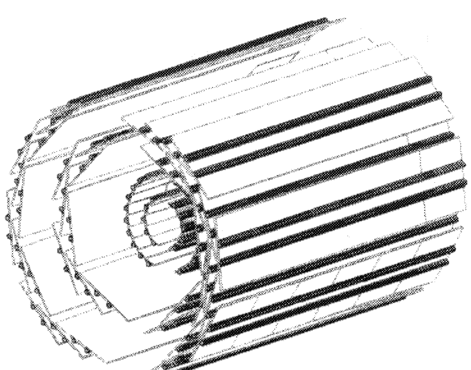
↓

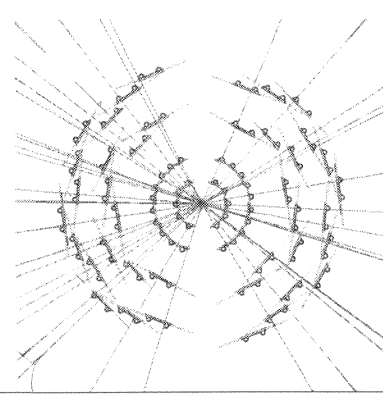
Barrel assembly
(BNL : chemistry lab.)

11

Full Monte Carlo Simulation

- Constructed based on the results of performance test
  - Configuration, material
    - Pixel : 1.3% / layer, Stripixel : 3.6% / layer
    - Total : ~10%
  - Charge sharing, S/N ratio
  - Data format is same as actual format we will take via DAQ.
    - Developing analysis code and perform blind analysis.
- We are preparing large amount of simulation data





12

Summary

- We are developing the silicon strip detector for the PHENIX VTX tracker
  - This is world's first 2-dimensional readout from 1 side (p-side).
- Performance study for the strip pixel detector were done with beta-ray and 120 GeV proton beam.
  - S/N ratio : 10
  - Residual : 36μm
  - Detection efficiency : >98% *preliminary*
  - Good charge sharing btw x and u strips.

  These performances satisfy a need for VTX tracker. Final adjustment for mass production is ongoing toward 2010 install.
- Full Monte Carlo simulation has been constructed based on these results.
  - Development of analysis code and blind analysis are ongoing

13

Physics with polarized beams at RHIC

An overview of RBRC's activities

Abhay Deshpande
Stony Brook University
RIKEN BNL Research Center

RHIC Spin program

- Direct measurement of polarized gluon distribution using multiple probes: Measure double spin asymmetry A_{LL} in:

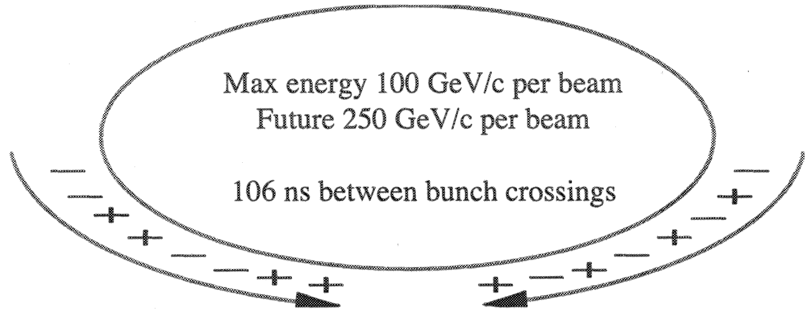
$$gg, gq \rightarrow \pi^{0,\pm} + X$$
$$gg \rightarrow c - \bar{c}, b - \bar{b} + X$$
$$gq \rightarrow \gamma + X$$

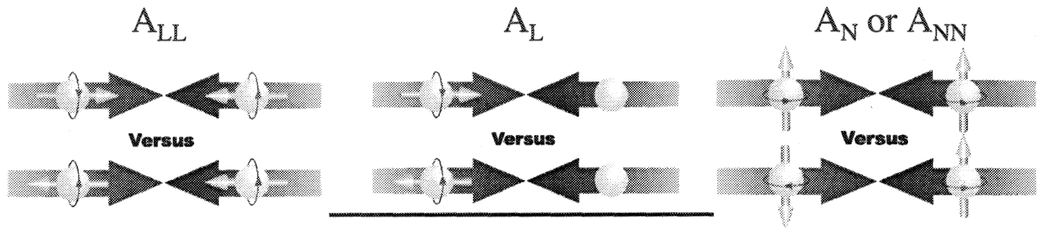
- Direct measurement of anti-quark polarization using parity violating production of $W^{+/-}$ in single spin A_L

$$u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu_l$$
$$\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu}_l$$

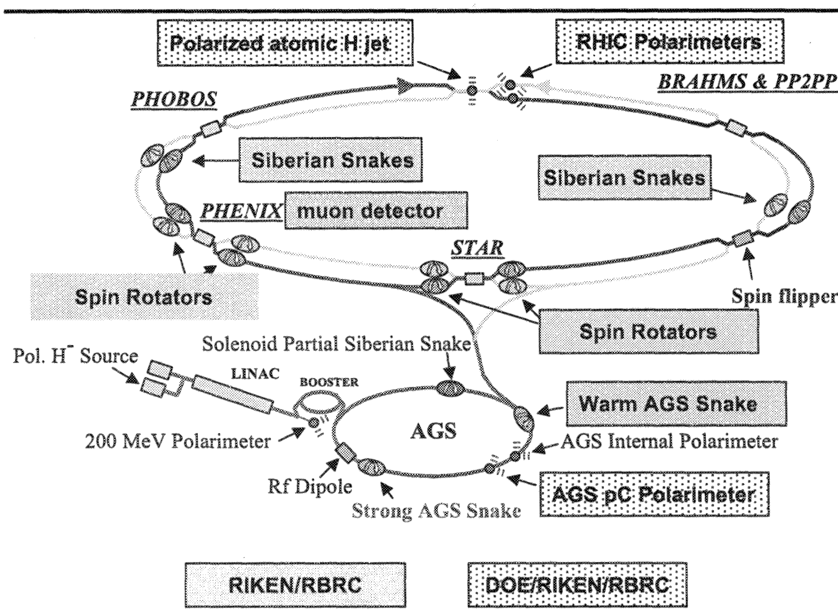
- Transverse spin: Transversity and transverse spin effects: possible connections to orbital motion of quarks(?)

Exquisite Control of Systematics



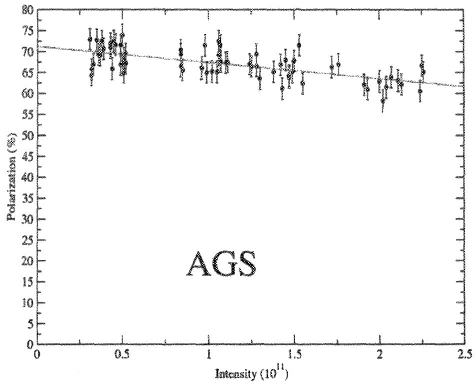


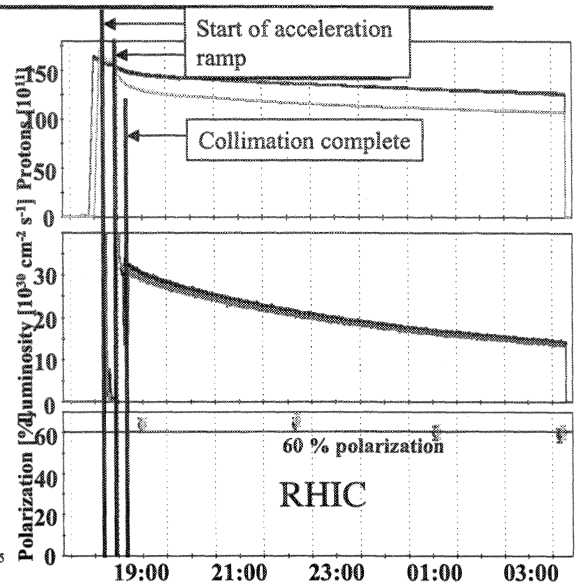
RHIC Polarized Collider



Polarization in AGS & RHIC

- Duel partial snakes largely eliminate luminosity dependence of beam polarization





Polarized Collider Evolution Center of Mass: 200 GeV

Year	Polarization	Luminosity (pb^{-1})	Comment
2002	15%	0.15	First polarized run, polarimetry commissioned
2003	30%	1.6	First $A_{LL}(\pi^0)$ measurement
2004	40%	3.0	Add absolute polarimetry
2005	50%	13	Large gluon spin ruled out
2006	60%	46	Precision gluon spin measurement initiated
2007			No p-p run
2008	50%	--	No p-p spin physics run
2009	**60-65% (?)**	**~120**	**500 GeV spin run(?)**

Beam polarimetry

STONY BROOK
STATE UNIVERSITY OF NEW YORK

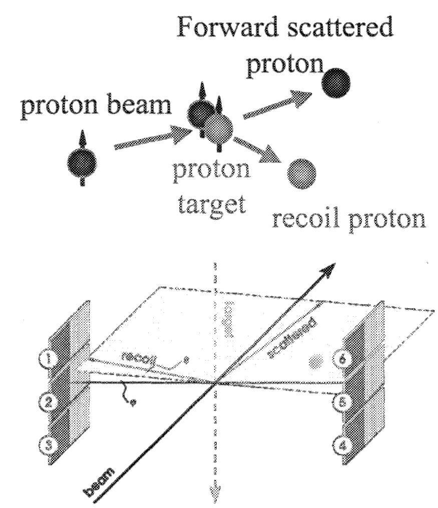
- RHIC polarimetry has three major components:
  - Proton-Jet CNI polarimeter: slow, absolute polarization
  - Proton-Carbon CNI: fast, polarization monitor

- Combination of p-Carbon and p-Jet CNI polarimetry has recently demonstrated < 5% absolute polarization measurement uncertainty (including systematics)

Details in Roser's talk

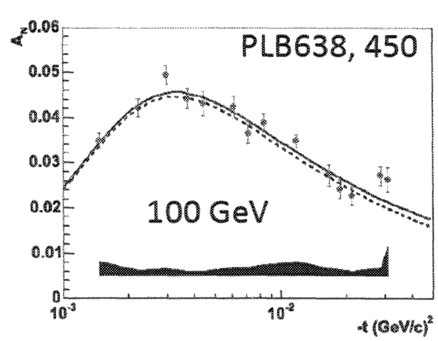
RHIC p-Jet Polarimetry

STONY BROOK
STATE UNIVERSITY OF NEW YORK



Target polarization measured using
A Breit-Rabbi polarimeter δP < 2%

- Beam & target are protons



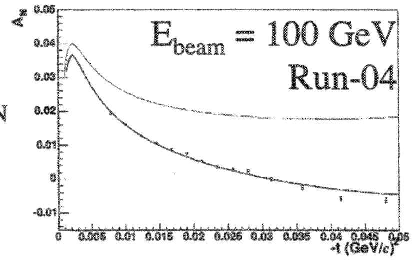
$$A_N(t) = -\frac{\varepsilon_{\text{target}}}{P_{\text{target}}} = \frac{\varepsilon_{beam}}{P_{beam}}$$

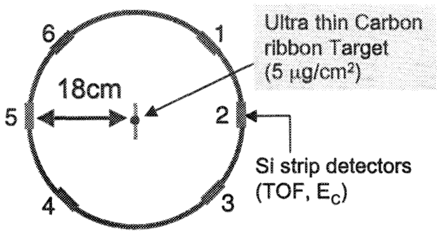
RHIC pC Polarimeter

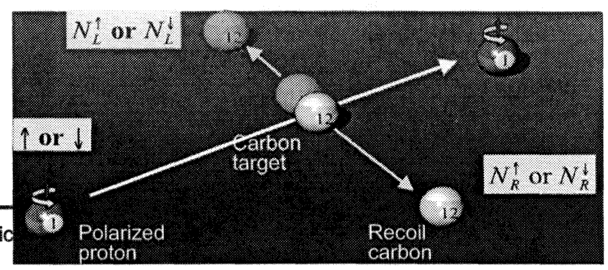
- L-R asymmetry in elastic pC scattering: interference between EM and hadronic amplitude in Coulomb Nuclear Interference (CNI) region:

$$P_{beam} = -\frac{\varepsilon_N}{A_N^{pC}}$$

$$\varepsilon_N = \frac{N_L - N_R}{N_L + N_R}$$

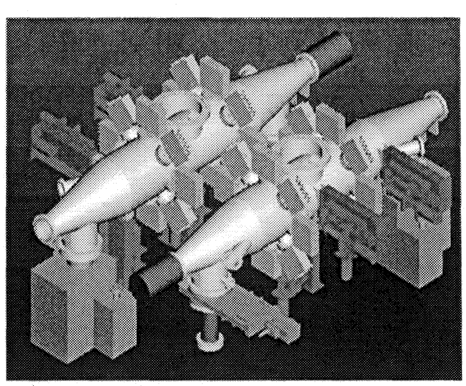






pC Upgrade

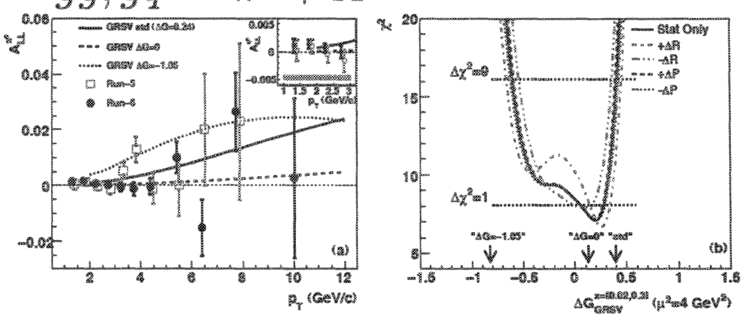
Proposed pC polarimeters



- Detector Upgrade: Photo-Diodes instead of Si Strips
- Target Upgrade: Carbon nano-tubes instead of filaments of carbon fibers
- Vacuum Chamber Upgrade:
  - Two polarimeters per ring
  - One of them can be a test bed for new detectors for high rate capability
  - Reduce the times for profile measurements (x&y)
- RBRC has been involved in many ways in the past. Will continue to do so in future

New result on ΔG

$gg, gq \longrightarrow \pi^0 + X$



PHENIX
200 GeV CM
Run-6 (+5)
submitted to PRL
Kieran Boyle's* Ph.D. thesis
Kieran now our Post Doc

Other analyses:

Neutral pion production at 62.4 GeV CM
- higher x-range (see Kieran Boyle's talk)

Charged hadron (pion) cross section and A_{LL}
- Sign of ΔG (See Dave Kawall's talk)

Direct photon, the golden channel for ΔG
- Luminosity starved process (See Kensuke Okada's talk)

A significant constraint on the global analysis of DIS and p-p data. See recent paper by DeFlorian, Sassot, Stratmann & Vogelsang

Transverse Spin Physics

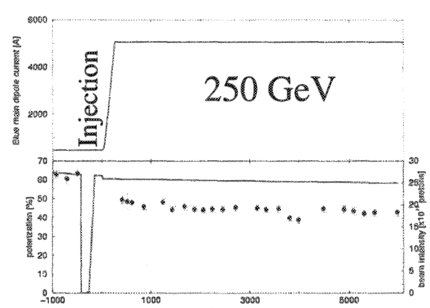
- Measurements of transversity, Final State (Collins), Initial State (Siver's) interactions in hadronic collisions
- Several PHENIX analyses published or now underway
  - Charged & neutral pion/hadron single spin asym. in central rapidity
  - Neutron single spin asymmetry in forward rapidity (ZDC)
- Disentangling the Final State vs. Ininitial State & Transversity requires a global analysis of DIS (SMC, HERMES, COMPASS, Jlab) and p-p (RHIC, E704…) transverse spin data
  - Difficulty: poorly known fragmentation functions
  - RBRC (Seidl, Grosse-Perdehamp) launched an effort at BELLE
  - Extremely significant result: Has been quoted and used in global analyses now to unfold all facets of the transverse spin effects
  - Ralf Seidl leads this effort now and will describe it in detail today

PAC 2008 Run Plan (updated)

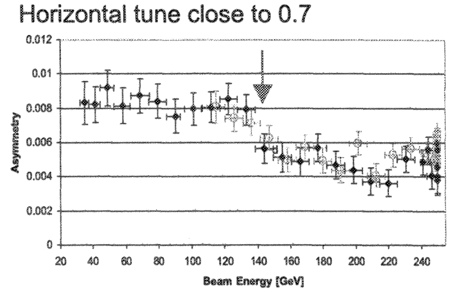
Fiscal Year	Colliding Beam Species/Energy	Comments
2009	**500 GeV p+p**	~5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet 2011 RIKEN milestone
2010	**200 GeV p+p**	~12 physics weeks to complete 200 GeV A_{LL} measurements –STAR DAQ1000 fully operational
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st HI collision test of transverse stochastic cooling (one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production
	200 GeV Au+Au or 2nd low-E scan	To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling.
	200 GeV p+p	Address 2015 DOE milestone on transverse SSA for γ-jet; reference data with new detector subsystems; test e-lenses for p+p beam-beam tune spread reduction

Physics with W production at RHIC

- Anti-Quark distribution measurements
  - Through W production and decay
  - Needs trigger rejections, upgrades on the way (Itaru's talk)
  - First 500 GeV (Engineering) run February 2009
  - First accelerator tests successful in 2006: No fundamental show-stoppers anticipated (details in Roser's talk)



Loss at strong intrinsic resonance (136 GeV)
Horizontal tune close to 0.7



RBRC crucial for spin physics at PHENIX and RHIC

- RBRC has a significant impact on the Spin Physics Results
  - The group not only contributes to analyses, but most often they lead the physics analysis (Boyle, Okada, Kawall, Togawa, Akiba, Deshpande)
- PHENIX operations: Most critical spin related tasks are taken over by RBRC members or recent graduates
  - Spin bit matching, relative luminosity studies, polarization measurement and "local" polarimetry, online monitoring of spin-related issues....
  - Data taking shifts, period coordinator ships, run-coordinator-ships (Okada, Deshpande)
- Leadership position in detector upgrade projects
  - VTX tracker (Akiba, Taketani, Deshpande)
  - W-physics trigger upgrade (Seidl, Nakagawa)
- RHIC beam polarimetry: members, students of Fellows

11/17/2008 Spin Physics with RHIC & RBRC 15

Concluding remarks

- RBRC Spin group is extremely active and vibrant
  - Each member contributes and leads a very significant analysis or an upgrade project within PHENIX
  - Excellent internal and external collaboration
- Significant recent results on polarized gluons, transverse spin and fragmentation functions
  - Anticipate demonstration of W-physics capability soon
- So far all RBRC experimental Fellows: excellent tenure record: UNM, UIUC, Stony Brook, Rikyo

11/17/2008 Spin Physics with RHIC & RBRC 16

Constraining ΔG by Measuring Double Helicity Asymmetry in Neutral Pion Production

Kieran Boyle

Research Center Review

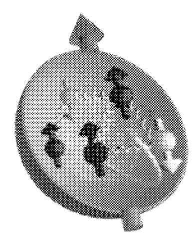
November 17-18, 2008

Outline:

1. Physics introduction
2. Measurement of π^0 A_{LL}
3. Extracting ΔG
4. ΔG Constraint
5. FF @ BELLE

1

Spin Puzzle

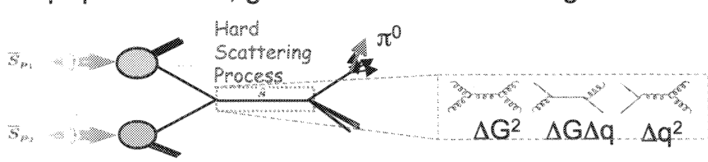


- Proton is a complicated structure
- Properties should arise from constituents:
  - Charge
  - Momentum
  - Spin

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

- Polarized DIS indicates quark spin ($\Delta\Sigma$) only is ~25% of proton spin
- Gluon spin (ΔG) and Orbital Angular Momentum from quarks and gluons must give the rest

- In p+p collisions, gluons interact at leading order



$\rightarrow A_{LL} \sim a_{gg} * \Delta G^2 + b_{gq} * \Delta G\, \Delta q + c_{qq} \Delta q^2$

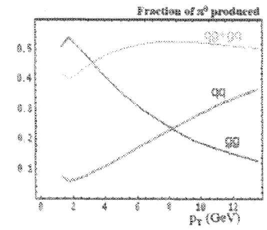
ΔG from p+p: Measure A_{LL}

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

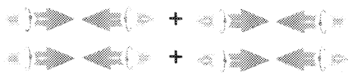
DIS (&pp) | pQCD NLO | e+e-,SIDIS,pp

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

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



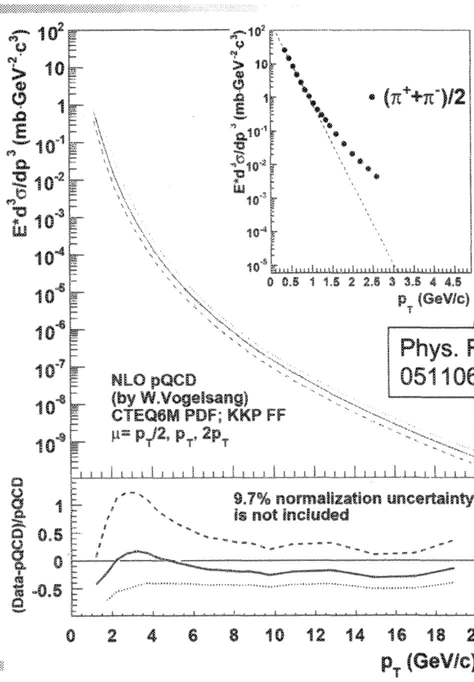
- The partonic fractions are p_T, process, rapidity and $\sqrt{s}$ dependent.



Applicability of NLO pQCD

Strategy:
1. Measure Cross Section to confirm that pQCD is applicable to data
2. Measure A_{LL} to extract ΔG

- Data is well described by NLO pQCD over 7 orders of magnitude.
- Therefore NLO pQCD is applicable for extracting DG.
- Estimated from Run5 result that soft physics contribution at p_T=2 GeV is ~10%, and quite negligible at high p_T [PRD 76, 051106 (2007)].



Phys. Rev. D 76, 051106 (2007)

Measuring A_{LL}

$$A_{LL} = \frac{-}{+} = \frac{1}{P_b P_y} \frac{-R}{+R}$$

+ - = Opposite helicity = +

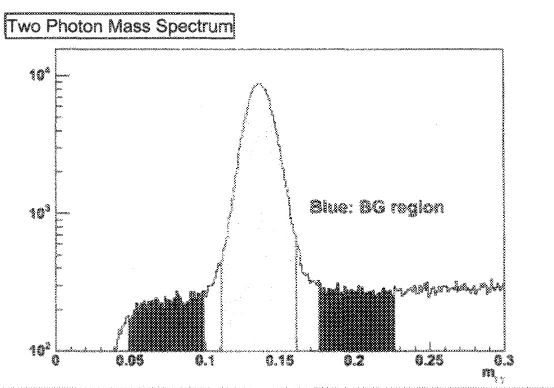
++ = Same helicity = +

- Helicity Dependent π^0 Yields
- (Local) Polarimetry
- Relative Luminosity ($R=L_{++}/L_{+-}$)
- A_{LL}

Calculating π^0 A_{LL}

1. Calculate $A_{LL}(\pi^\circ+BG)$ and $A_{LL}(BG)$ separately.
2. Get background ratio (w_{BG}) from fit of all data.
3. Subtract $A_{LL}(BG)$ from $A_{LL}(\pi^\circ+BG)$:

$$A_{LL}(\pi^\circ+BG) = w\pi^\circ \cdot \boxed{A_{LL}(\pi^\circ)} + w_{BG} \cdot A_{LL}(BG)$$



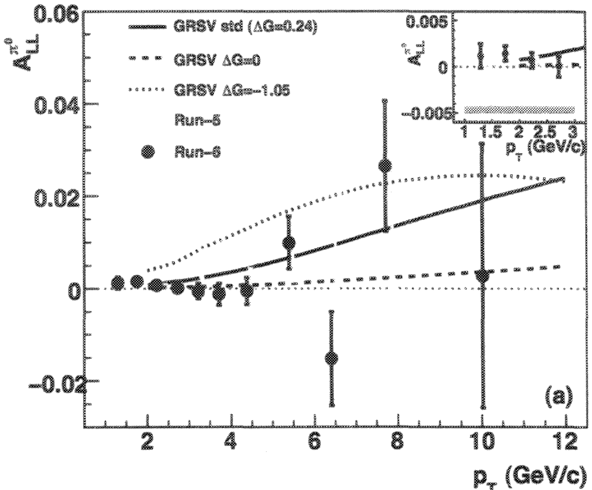
π^0+BG region :
±25 MeV around π^0 peak

BG region :
two 50 MeV regions around peak

π^0 p_T (GeV/c)	BG (%)
2.2	18
4.4	8
10.0	6

Neutral Pion A_{LL} Results

- Run6 result is about a factor 2 better statistical precision and extends the p_T range to 12 GeV.
- Statistical Uncertainty of lowest p_T bins of same order as systematic uncertainty from Relative Luminosity (grey band).
- Data is compared with three curves calculated (by W. Vogelsang) in the GRSV pDIS fit, with different input values of ΔG.

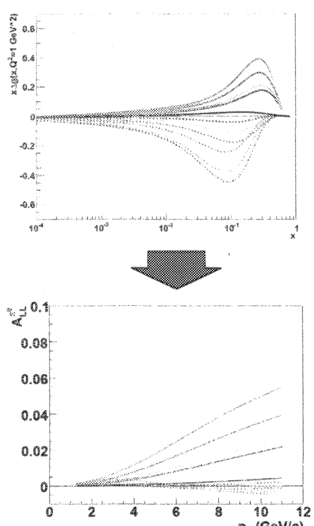
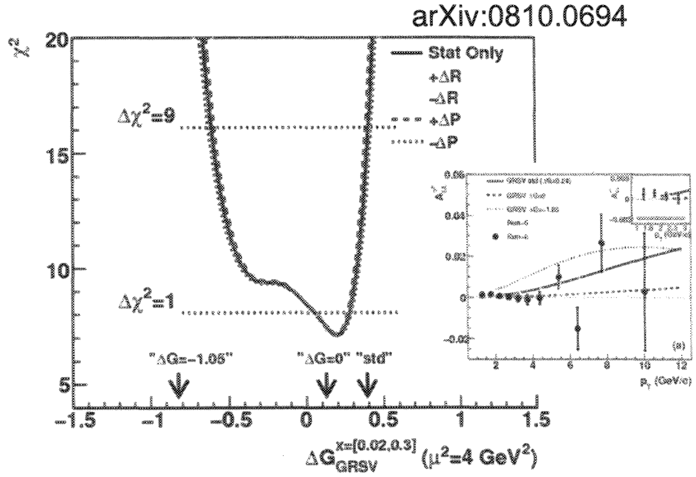


- 2005: PRD76, 051106
- 2006: arXiv:0810.0694
- GRSV: PRD63, 094005(2001)

A_{LL} → ΔG

- Vary ΔG in GRSV fit, and then generate A_{LL}.
- Calculate χ^2 for each expectation curve, and plot profile

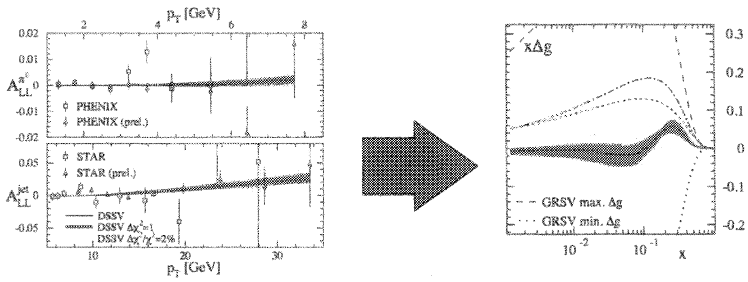
arXiv:0810.0694

Use combined Run5 and Run6 results

Recent Global Fit: DSSV

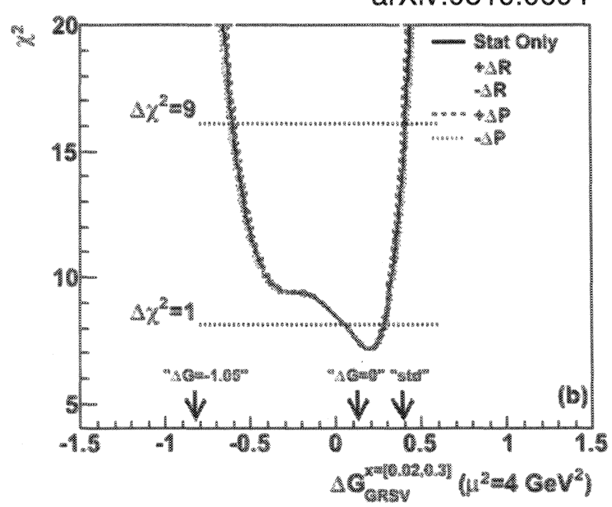
- PRL **101**, 072001(2008)
- First truly global analysis of polarized DIS, SIDIS and pp results
- PHENIX $\sqrt{s}$ = 200 and 62 GeV data used
- RHIC data significantly constrain ΔG in range $0.05<x<0.3$



- Experimental systematic uncertainties must be included taking into account correlations.
- Theoretical uncertainties must be considered.

Systematic Uncertainty Impact

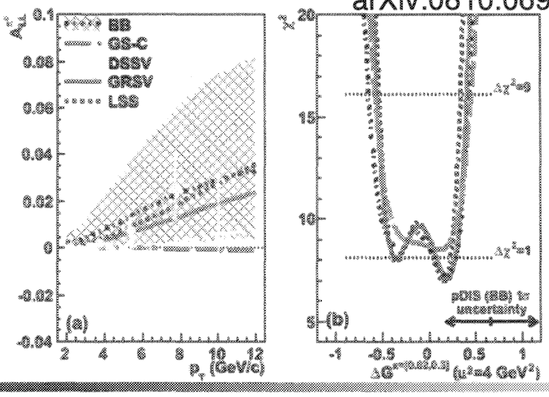
arXiv:0810.0694



- Consider impact of dominant uncertainties:
  - Polarization
  - Relative luminosity
- Polarization has negligible impact on ΔG constraint
- Relative luminosity uncertainty, though small (4.6×10^{-4}), is not neglible
- $\sigma_{\Delta G}$(syst) = 0.1

Theoretical uncertainties

arXiv:0810.0694



Parameterization choice

- Starting with best fit result for several fits to pDIS data, vary $\Delta g'(x) = \lambda \Delta g(x)$ and generate many A_{LL} expectations (using code supplied by M. Stratmann).
- Get χ^2 profile.
- At $\Delta\chi^2$=9 (~3σ), we find consistent constraint:
  -0.7 < $\Delta G^{[0.02,0.3]}$ < 0.5

→ Our data are primarily sensitive to the size of $\Delta G^{[0.02,0.3]}$.

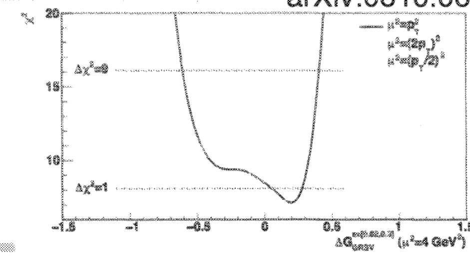
arXiv:0810.0694

Theoretical Scale Uncertainty:

- π^0 cross section is described by NLO pQCD within sizable uncertainty in theoretical scale μ
- How does this affect ΔG constraint?
- Vary scale in A_{LL} calc.

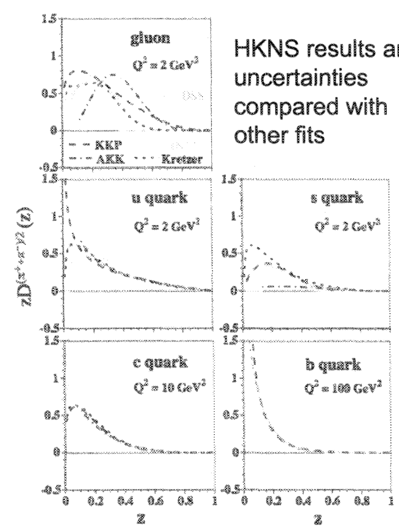
→ 0.1 uncertainty for positive constraint

→ Larger uncert. for negative constraint



Fragmentation Functions @ BELLE

- Recall that the calculation of π^0 A_{LL} requires the use of a fragmentation function (FF)
- Uncertainty on FF propagate to ΔG. As the majority of data used to determine FF come from LEP, uncertainty in the FF (particularly for the gluon) is large.
- BELLE offers very high precision data at a lower $\sqrt{s}$ (10.5 GeV) which will allow better precision.
- Beginning work on π^0 (and η) FF.



HKNS results and uncertainties compared with other fits

Fig. 2. Fragmentation functions for $(\pi^+ + \pi^-)/2$ are compared with other NLO analysis results.

Conclusions

- NLO pQCD is applicable at $\sqrt{s}$ = 200 for π^0 production for p_T>2 GeV, and can be used to extract ΔG from A_{LL}.
- PHENIX π^0 A_{LL} measurement from Run5 and 6 offer a significant constraint on ΔG, as found by both our own analysis and the DSSV global fit.
- Correct inclusion of experimental systematic uncertainties, as well as estimating theoretical uncertainties, are necessary for any final result for ΔG.
- We find for the Run5 and 6 results combined:

$$\Delta G^{[0.02,0.3]}_{\mathrm{GRSV}} = 0.2 \pm 0.1(\mathrm{stat}) \pm 0.1(\mathrm{sys}) {}^{+0.0}_{-0.4}(\mathrm{shape}) \pm 0.1(\mathrm{scale})$$

- Further theoretical uncertainties must be studied.
  - Fragmentation functions from BELLE will reduce these uncertainties.
- Global fit must include all uncertainties:
  - Collaboration with DSSV on handling of uncertainties in a global fit has started.

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

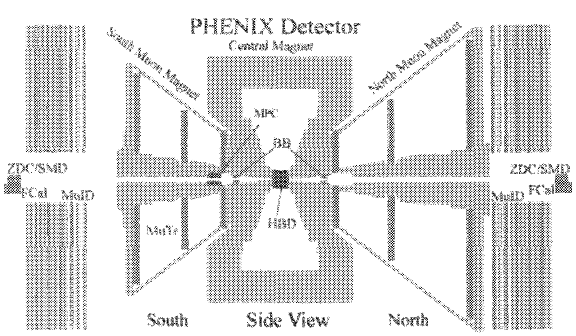
D. Kawall, RBRC and Univ. of Massachusetts; A. Datta and C. Aidala, Univ. of Massachusetts

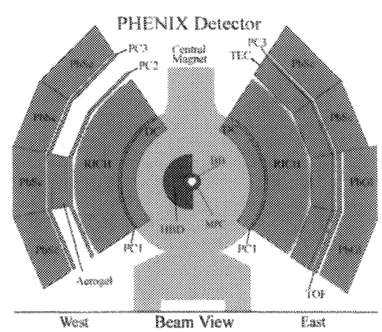
Motivation

- PHENIX recorded $\approx$ 50 nb^{-1} of long. polarized pp collisions at $\sqrt{s}$=62.4 GeV in 2006
- Cross-section 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
  - Compare yields with ISR results
- Measure double spin asymmetry $A_{LL}^{pp\rightarrow h^\pm X}$ in new kinematic range
  - Still probing qg scattering predominantly, sensitive to Δg at slightly higher x
- Charged hadron A_{LL} complementary to that of $A_{LL}^{\pi^0}$
  - Charged hadrons have different 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
- Comparison of inclusive hadron cross-sections at $\sqrt{s} = 62.4,\ 200$ GeV can be compared with predictions based on x_T scaling

Overview of the Analysis

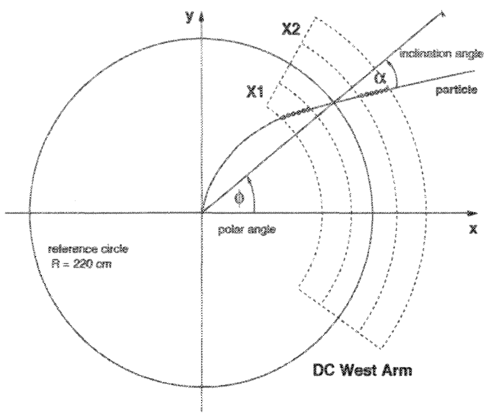
- Identify pp collisions by coincidence of hits in two Beam Beam Counters (BBCs) on either side of IR (minimum bias trigger)
- Select events with pp vertex within $\pm$ 30 cm of nominal center of IR (within acceptance of PHENIX central arms)
- Look for tracks with hits in Drift Chamber (DC) and Pad Chambers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

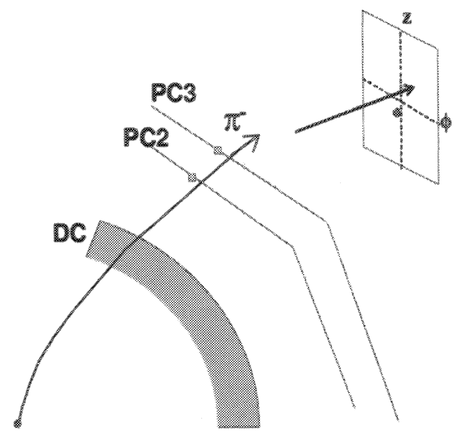




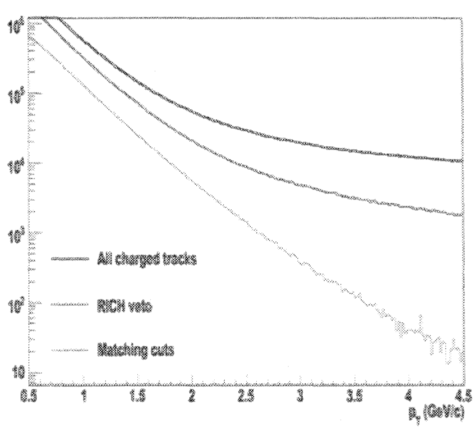
Overview of the Analysis

- Particle momentum determined by angle in DC with respect to infinite momentum track from origin : inclination angle $\alpha \approx 87\ \mathrm{mrad}/\ p_T\ [\mathrm{GeV/c}]$
- Impose fiducial cuts, restrict to transverse momenta to 0.5 GeV/c $< p_T <$ 4.5 GeV/c
- Require that projections of track segments from different detectors match up ("matching distribution cuts")
- Correct for offsets of beam/detectors from nominal positions which affect determination of momentum





Backgrounds



- Upper (black) curve is nominal p_T spectrum of all charged particle tracks
- Red curve has RICH veto, removes $e^{\pm}$ from photon conversion
- High p_T region contains tracks which don't originate at pp vertex, reconstructed incorrectly as having high p_T
- Requirement that projections of track segments from different detectors match reduces background

- A_{LL} corrected for contribution from long-lived ($c\tau \approx 1 - 10$ m) particles, estimated from tails in matching cut distributions
- Contribution from short-lived ($c\tau << 1$ m) particles estimated $\approx 7 \pm 7\%$, no correction to A_{LL} yet

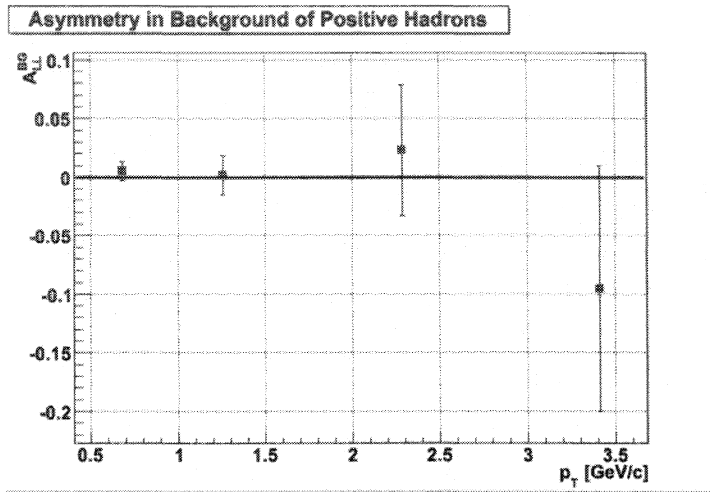
Background Fractions and Asymmetries

- The fraction f of long-lived backgrounds is estimated from the tails of the matching distributions
- The asymmetry of this background is measured in the tails of the matching distributions
- The measured asymmetry is corrected for the asymmetry in the background :

$$A_{LL}^{\text{Signal}} = \frac{A_{LL}^{\text{Signal+BG}} - f \times A_{LL}^{\text{BG}}}{1-f}$$

Background Fractions

p_T (GeV/c)	$f(h^+)$	$f(h^-)$
0.5-1.0	0.03	0.02
1.0-2.0	0.03	0.02
2.0-3.0	0.03	0.04
3.0-4.5	0.09	0.11

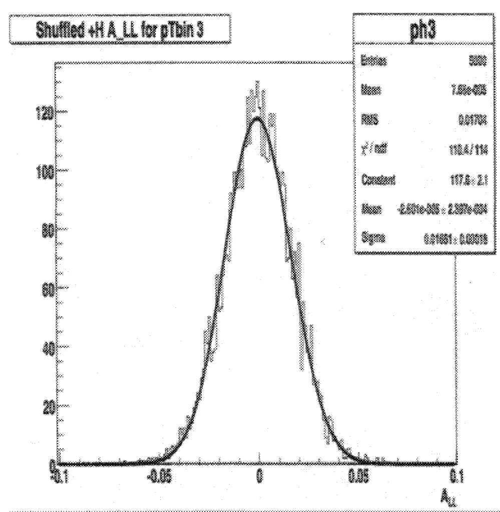


Cross-Checks for Systematic Effects

- Perform several tests for the presence of systematic errors in asymmetry determination
- Double spin asymmetries $A_{LL}^{pp\rightarrow h^{\pm}X}$ measured in each detector arm should be consistent
- Double spin asymmetries $A_{LL}^{pp\rightarrow h^{\pm}X}$ extracted from different RHIC fills should be consistent
- Bunch Shuffling : extract asymmetries using randomized beam helicities, look for increased width of resulting A_{LL} distribution

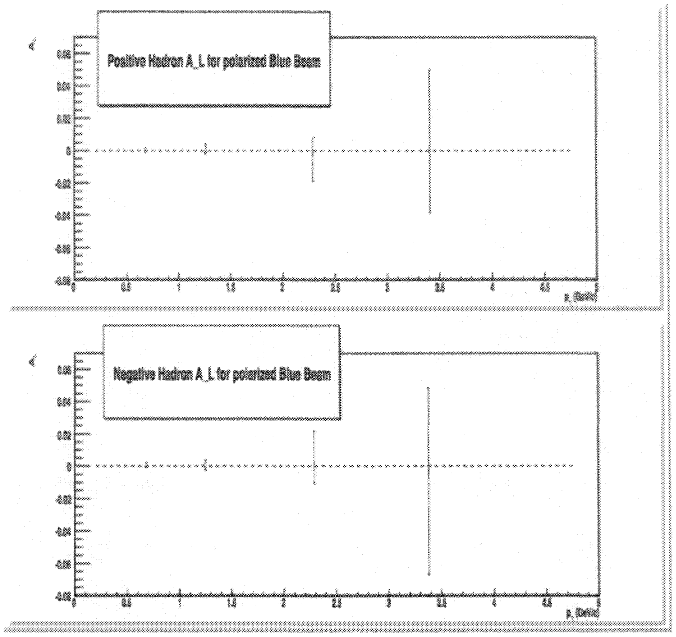
Bunch Shuffling Results

p_T (GeV/c)	δA_{LL}^{h+}	Shuffled Width h^+	δA_{LL}^{h-}	Shuffled Width h^-
0.5-1.0	0.0020	0.0021	0.0022	0.0023
1.0-2.0	0.0041	0.0040	0.0047	0.0047
2.0-3.0	0.018	0.017	0.021	0.022
3.0-4.5	0.056	0.054	0.072	0.067



Cross-Checks for Systematic Effects

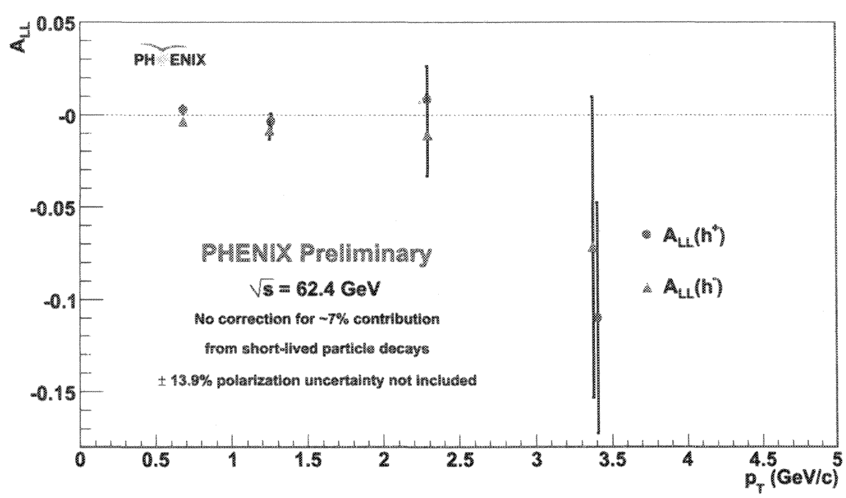
- Construct single-spin asymmetries, A_L from the data : $A_L = \frac{1}{P_{\text{beam}}} \frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$
- Non-zero A_L violates parity; experimental A_L results consistent with zero in both beams



Charged Hadron Asymmetry Results at $\sqrt{s} = 62.4$ GeV

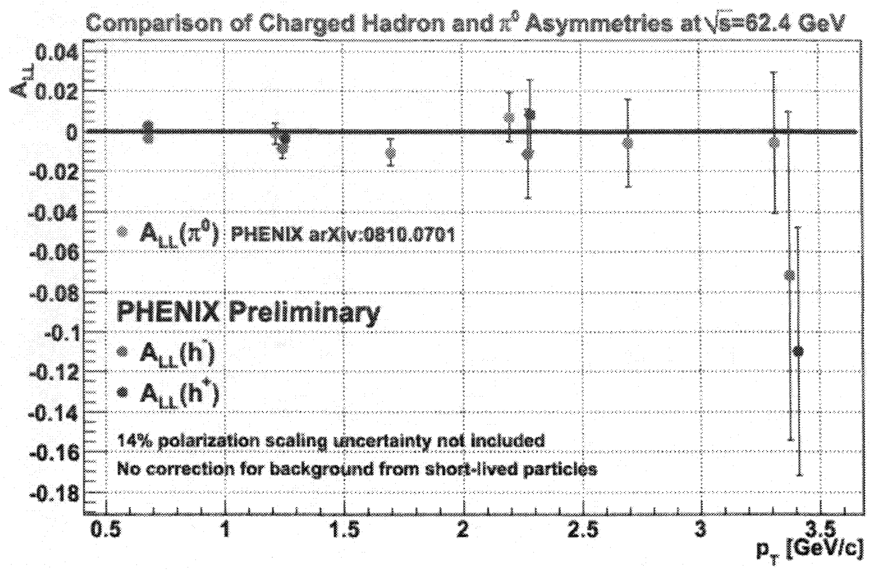
PHENIX Preliminary Charged Hadron Asymmetries, Corrected for Long-lived Backgrounds

p_T (GeV/c)	$A_{LL}(h+)$	$\delta A_{LL}(h+)$	$A_{LL}(h-)$	$\delta A_{LL}(h+)$
0.5-1.0	+0.0028	0.0021	-0.0036	0.0023
1.0-2.0	-0.0036	0.0042	-0.0086	0.0048
2.0-3.0	+0.0081	0.018	-0.011	0.022
3.0-4.5	-0.110	0.062	-0.072	0.082



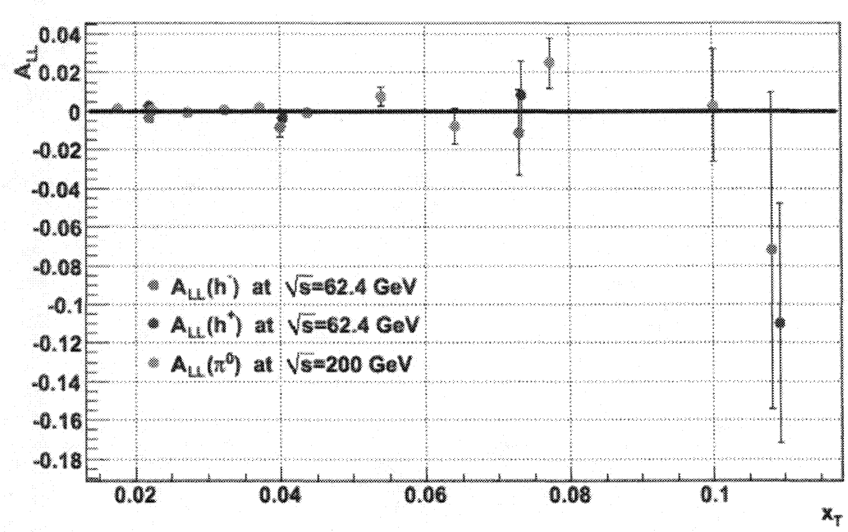
Comparison of Charged Hadron A_{LL} with $A_{LL}^{\pi^0}$ results at $\sqrt{s} = 62.4$ GeV

- Interesting to compare $A_{LL}^{\pi^0}$ with $A_{LL}^{h^\pm}$; latter dominated by charged pions
- When quark-gluon scattering dominates, expect $A_{LL}^{\pi} \propto \Delta g \, (\Delta u \, D_u^\pi + \Delta d \, D_d^\pi)$
- If $\Delta g(x) > 0 \, : \, A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$



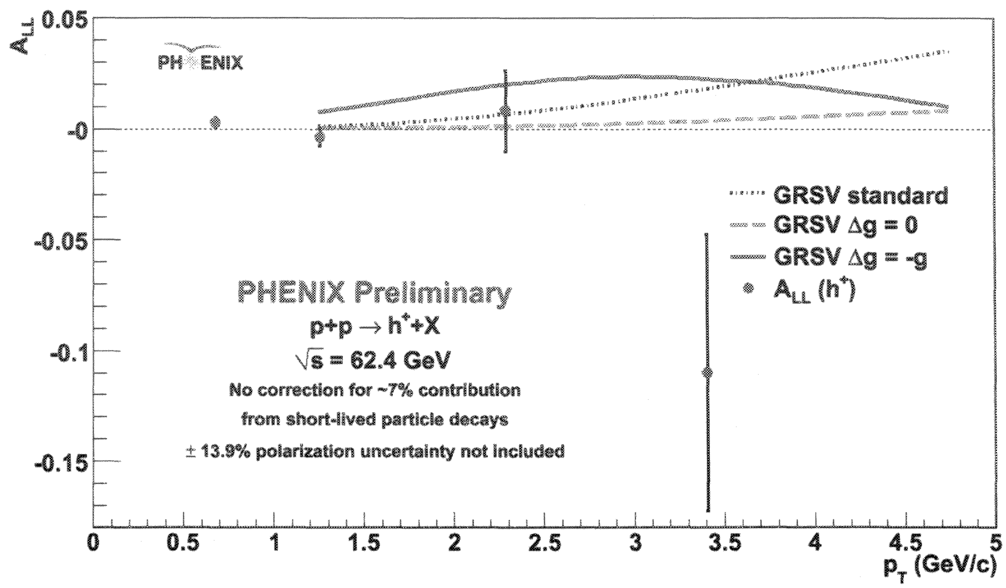
Comparison of Charged Hadron A_{LL} at $\sqrt{s} = 62.4$ GeV with $A_{LL}^{\pi^0}$ results at $\sqrt{s} = 200$ GeV

- Comparison of inclusive hadron cross-sections at $\sqrt{s} = 62.4, \; 200$ GeV can be compared with predictions based on x_T scaling : $\frac{Ed^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^n} \, G(x_T)$, where $x_T = p_T/\sqrt{s}/2$
- Cross-sections can be compared with NLO and NLL QCD predictions, determine importance of threshold effects as $x_T \to 1$
- Data at lower $\sqrt{s}$ access higher $x_T = p_T/\sqrt{s}/2$



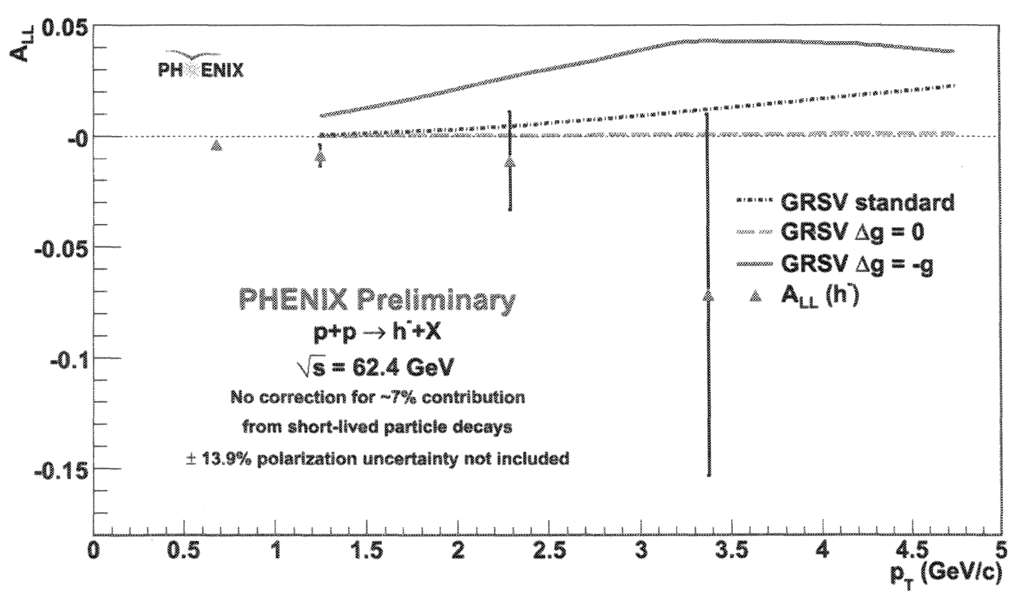
Comparison of Positively Charged Hadron Asymmetries with GRSV Model Predictions

- 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 $\Delta g(x)$



Comparison of Negatively Charged Hadron Asymmetries with GRSV Model Predictions

- GRSV model $\Delta g(x) = g(x)$ (not shown on plot) clearly excluded by the data, which favor smaller $\Delta g(x)$



Summary and Future Work

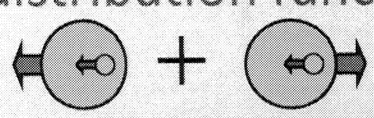
- Longitudinal double spin asymmetries of non-identified charged hadrons at $\sqrt{s} = 62.4$ GeV have been measured
- Fewer than 10 days of data excludes GRSV model $\Delta g(x) = g(x)$
- Careful treatment of backgrounds still required and consultation with theorists, before inclusion in global fit
- Si vertex detectors will be a very helpful addition to PHENIX tracking abilities, and for this analysis
- Expect to do cross-section analysis as well

Fragmentation function measurements at Belle

RBRC Review,
November 17

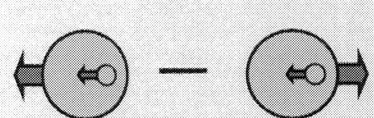
Ralf Seidl (RBRC)

Main Goal: Quark and Gluon distribution functions



Unpolarized distribution function q(x)

Sum of quarks with parallel and antiparallel polarization relative to proton spin (well known from Collider DIS experiments)

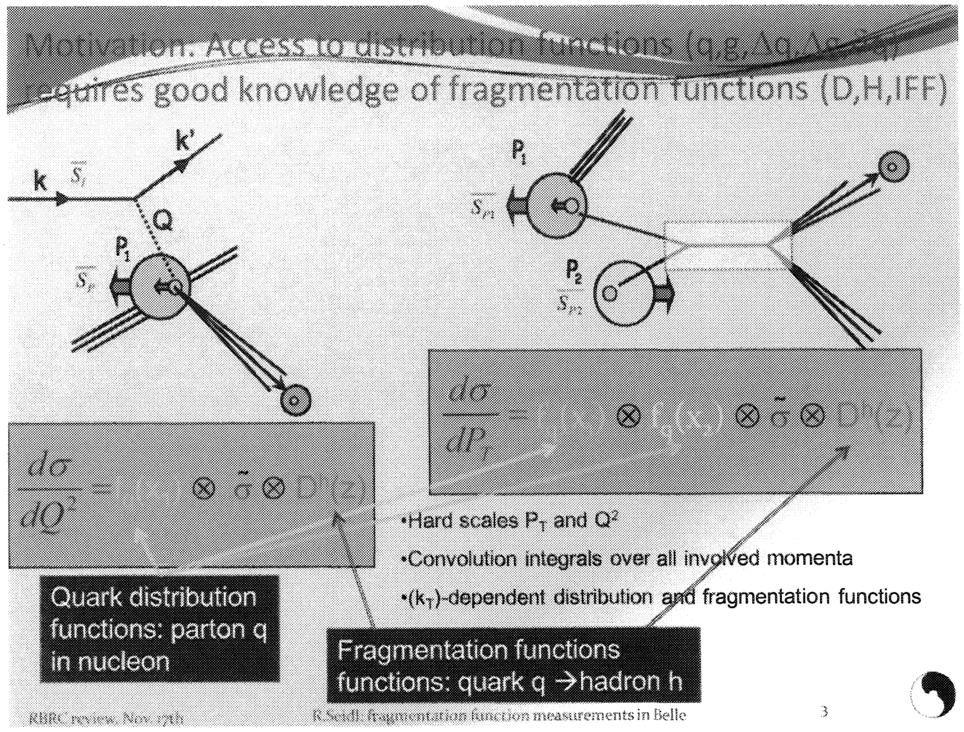


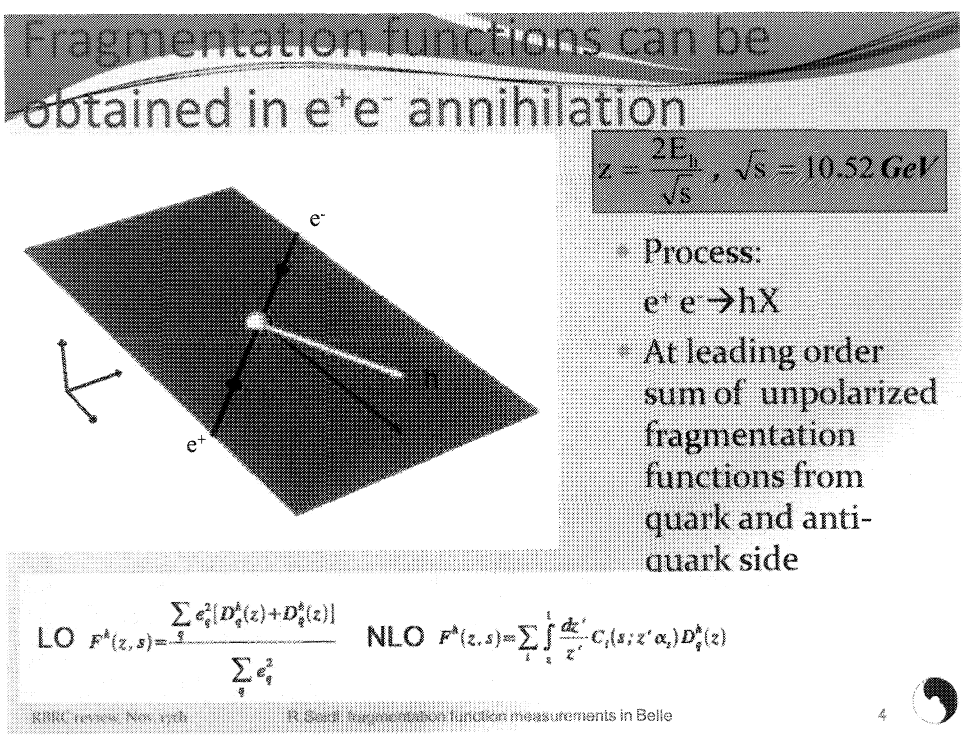
Helicity distribution function Δq(x)

Difference of quarks with parallel and antiparallel polarization relative to longitudinally polarized proton (known from fixed target (SI)DIS experiments)

Difference of quarks with parallel and antiparallel polarization relative to transversely polarized proton (first results from HERMES and COMPASS – with the help of Belle)

Transversity distribution function δq(x)

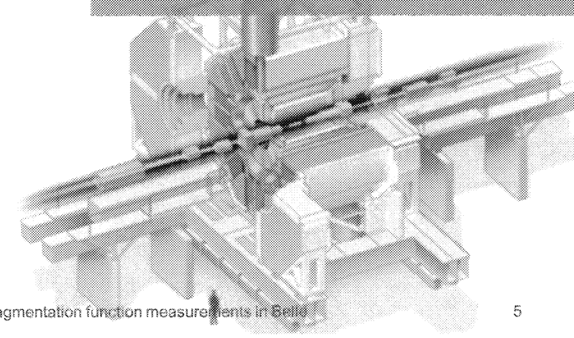

Motivation: Access to distribution functions (q,g,Δq,Δg,δq) requires good knowledge of fragmentation functions (D,H,IFF)
k
k'
Q
P1
P2
•Hard scales P_T and Q^2
•Convolution integrals over all involved momenta
•(k_T)-dependent distribution and fragmentation functions
Quark distribution functions: parton q in nucleon
Fragmentation functions functions: quark q →hadron h
RBRC review, Nov. 17th
R.Seidl: fragmentation function measurements in Belle
3


Fragmentation functions can be obtained in e+e- annihilation
z = 2E_h/√s , √s = 10.52 GeV
e-
e+
h
Process:
e+ e-→hX
At leading order sum of unpolarized fragmentation functions from quark and anti-quark side
LO
NLO
RBRC review, Nov. 17th
R.Seidl: fragmentation function measurements in Belle
4

KEKB: Record Luminosities to study fragmentation functions

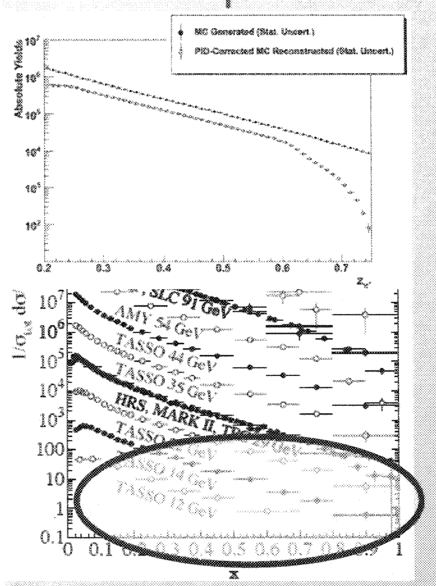
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c)
- Integrated Luminosity: >700 fb^{-1} >60fb^{-1} => continuum

Main research at Belle: CP violation and determination of Cabbibo Kobayashi Maskawa (CKM) matrix



World fragmentation data and need for precise FFs

M. Leitgab (UIUC)



- Low Q^2 and high z data not available
- Large uncertainty on gluon fragmentation
- → Very important input for RHIC Δg measurements
- Status:
  - Particle identification nearly finished
  - Smearing understood
  - Acceptance correction finished

Further unpol. FF measurements

- Additional FF measurements planned:
  - π^0 (cross check with completely different systematics)
  - η (PHENIX A_{LL} measurement available, higher strange content??, STAR A_N)
  - Other decaying particles (K_S,f^0,γ...?)
  - **k_t** dependent FFs

K. Boyle (RBRC)

RBRC review, Nov. 17th R.Seidl: fragmentation function measurements in Belle 7

Towards a global transversity analysis: Chiral-odd Fragmentation functions from Belle

RHIC and SIDIS experiments measure:

Transversity $\delta q(x)$ X

Collins Fragmentation function $H_1^{\perp}(z)$

or Interference Fragmentation function (IFF)

2 Unknown Functions measured together

·Universality understood

·Evolution ?

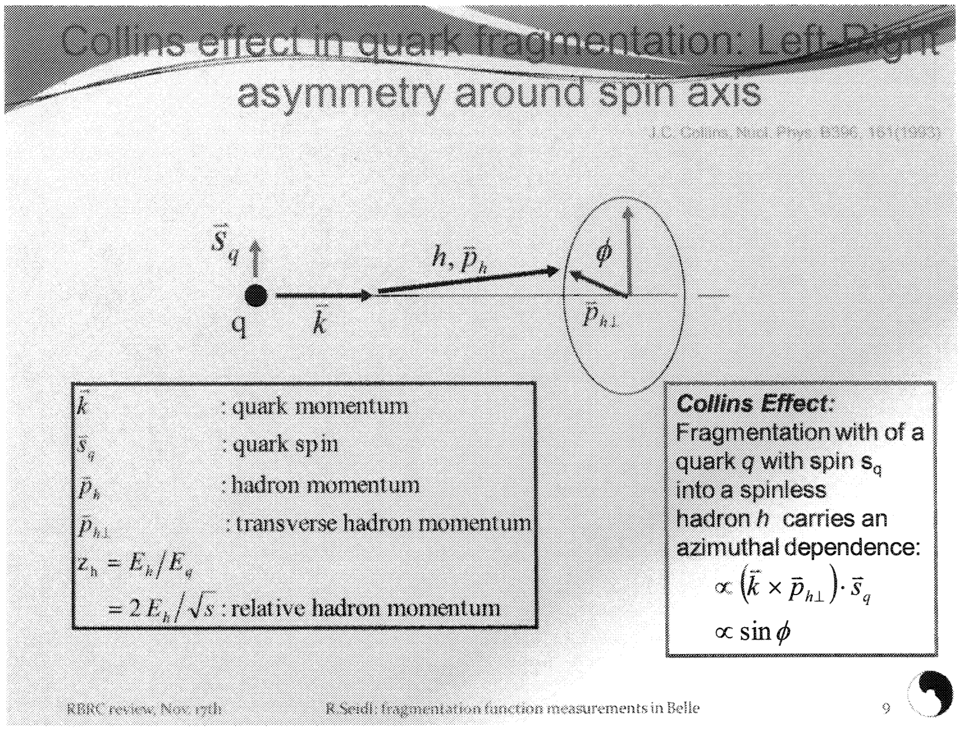
Transversity

Belle measures:

Collins X Collins

or IFF X IFF

RBRC review, Nov. 17th R.Seidl: fragmentation function measurements in Belle 8


Collins effect in quark fragmentation: Left-Right asymmetry around spin axis
J.C. Collins, Nucl. Phys. B396, 161(1993)
$\vec{s}_q$
$h, \vec{p}_h$
ϕ
q
$\vec{k}$
$\vec{p}_{h\perp}$
$\vec{k}$: quark momentum
$\vec{s}_q$: quark spin
$\vec{p}_h$: hadron momentum
$\vec{p}_{h\perp}$: transverse hadron momentum
$z_h = E_h/E_q$
$= 2E_h/\sqrt{s}$: relative hadron momentum
Collins Effect:
Fragmentation with of a quark q with spin s_q into a spinless hadron h carries an azimuthal dependence:
$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$
$\propto \sin\phi$
RBRC review, Nov. 17th
R.Seidl: fragmentation function measurements in Belle
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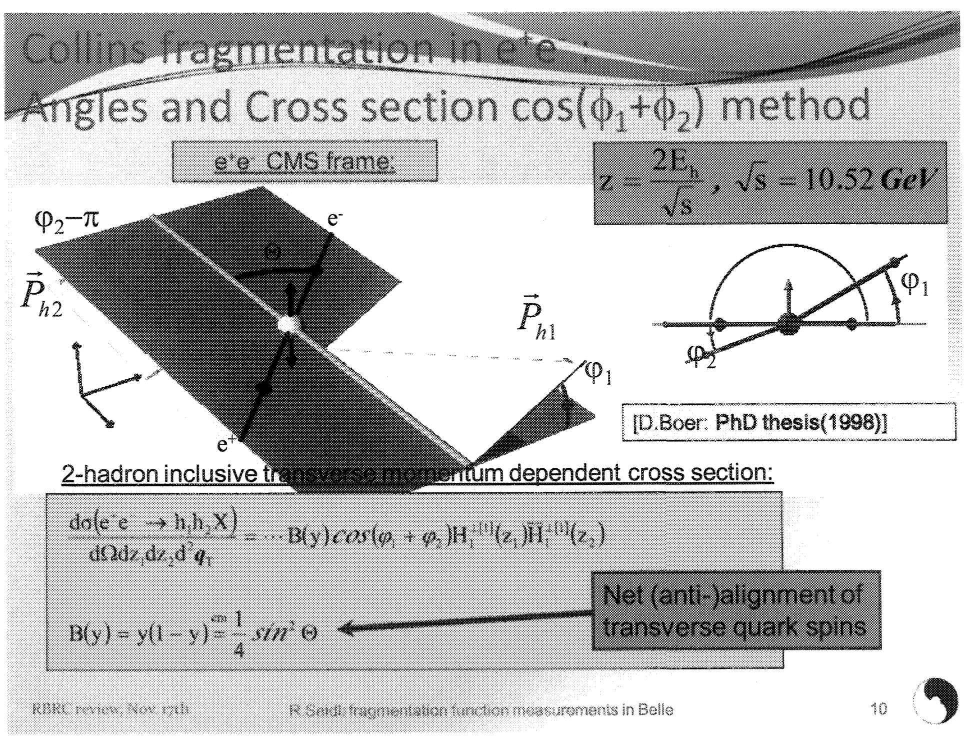
Collins fragmentation in e^+e^- :
Angles and Cross section $\cos(\phi_1+\phi_2)$ method
e^+e^- CMS frame:
$z = \frac{2E_h}{\sqrt{s}}, \sqrt{s} = 10.52\,GeV$
$\varphi_2 - \pi$
e^-
Θ
$\vec{P}_{h2}$
$\vec{P}_{h1}$
φ_1
e^+
φ_1
φ_2
[D.Boer: PhD thesis(1998)]
2-hadron inclusive transverse momentum dependent cross section:
$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2q_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)$
$B(y) = y(1-y) \stackrel{cm}{=} \frac{1}{4}\sin^2\Theta$
Net (anti-)alignment of transverse quark spins
RBRC review, Nov. 17th
R.Seidl: fragmentation function measurements in Belle
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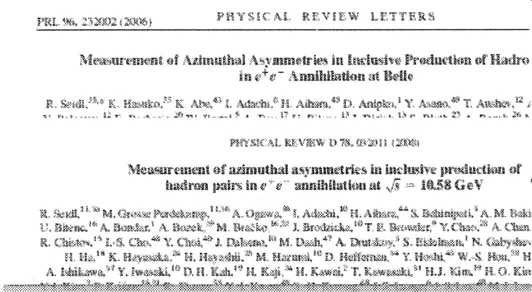
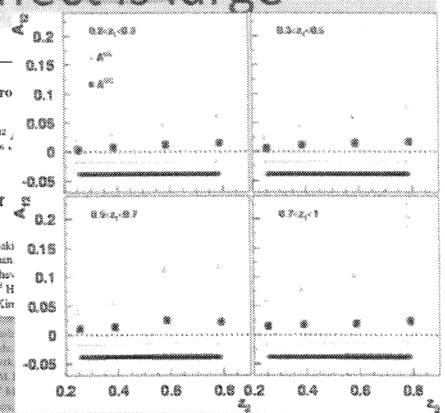
Collins FF analysis: Effect is large


PRL 96, 232002 (2006) PHYSICAL REVIEW LETTERS

Measurement of Azimuthal Asymmetries in Inclusive Production of Hadro[n Pairs] in e^+e^- Annihilation at Belle

PHYSICAL REVIEW D 78, 032011 (2008)

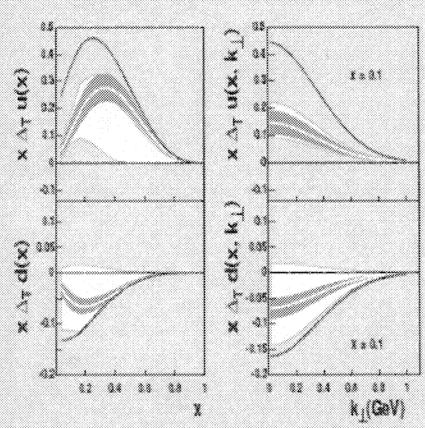
Measurement of azimuthal asymmetries in inclusive production of hadron pairs in e^+e^- annihilation at $\sqrt{s} = 10.58$ GeV



- First direct measurement of the Collins effect:
- Nonzero asymmetries
- Long paper: Inclusion of Resonance data 29 → 547 pb^{-1}
- 10% asymmtry ~ 30 % effect

Global transversity analysis

Alexei Prokudin, DIS2008, update of Anselmino et al: hep-ex 0701006



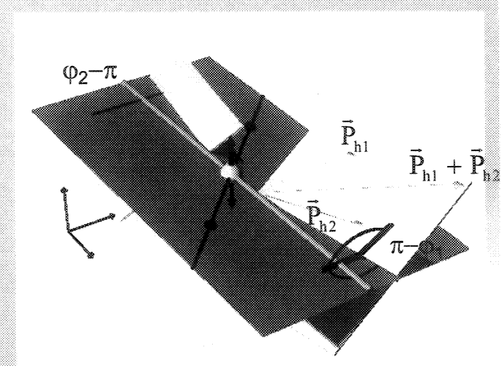
- First global analsys of the HERMES data, the COMPASS deuteron data and the final Belle data
- tensor charge slightly smaller than model and lattice predictions
- Open questions: evolution of Collins fragmentation function
- New Compass (proton) data not yet included

Interference Fragmentation analysis – thrust method

A. Vossen (UIUC),RS

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Similar to Collins analysis
- directly applicable to semi-inclusive DIS and pp)

- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]
- Evolution by Cecciopieri et.al. [PLB650(2007)]



Model predictions by:

•Jaffe et al. [PRL 80,(1998)]

•Radici et al. [PRD 65,(2002)]

$$A \propto H_1^{\angle}(z_1, m_1)\bar{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

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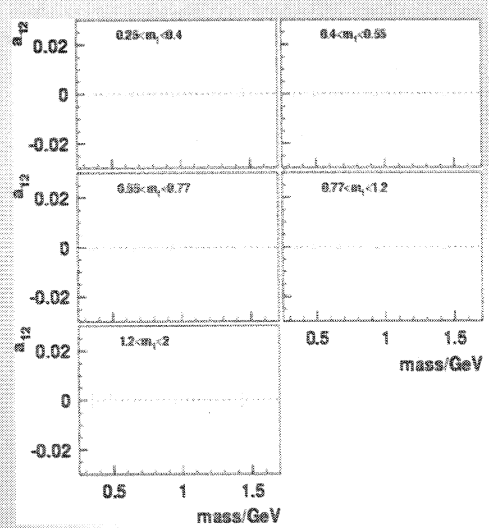
Expected sensitivities for 60 fb^{-1}

A. Vossen (UIUC),RS

- $(\pi^+\pi^-)$ $(\pi^+\pi^-)$ pairs as a function of the invariant mass $m_{\pi\pi,1}$ x $m_{\pi\pi,2}$
- Similar distributions to be shown as a function of $z_{\pi\pi,1}$ x $z_{\pi\pi,2}$
- Other hadron combinations (π^0,K,)

- Global analysis possible as well: HERMES, COMPASS and PHENIX data already available, more to come



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Summary and outlook

- Measure precise unpolarized fragmentation functions of many final states
- → Important input for general QCD physics and helicity structure measurements
- Analysis progressing:
  - PID studies
  - Acceptance correction
- Belle Collins data largely improved from 29 → 547 fb^{-1}
- Significant, nonzero asymmetries → Collins function is large
- Long Collins paper published
- Data used already in Global analysis

- Continue to measure precise spin dependent fragmentation functions at Belle
  - kT dependence of Collins function
  - Artru model test with Vector meson Collins
  - Interference Fragmentation function measurements (started)
- Measure other interesting QCD-related quantities at Belle:
  - Chiral-odd Λ-fragmentation function
  - Λ single spin asymmetry
  - Event shapes
  - R-ratio with ISR

Drell-Yan Measurement with Polarized Beams

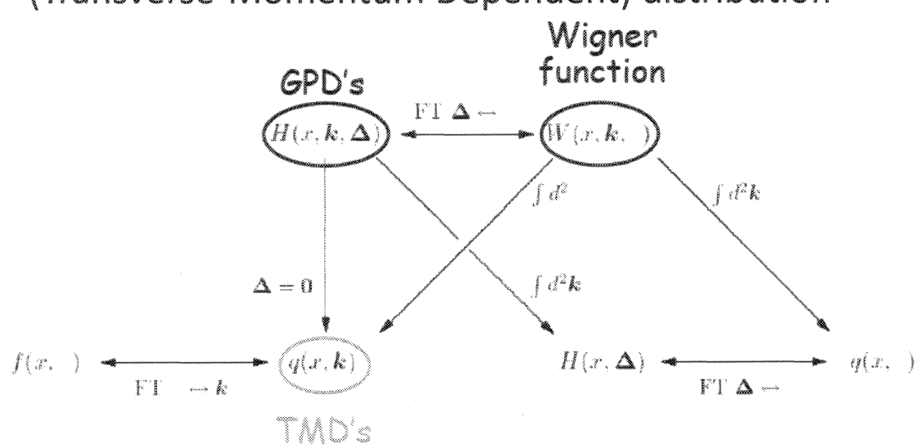
RBRC-SRC-Review

November 17, 2008

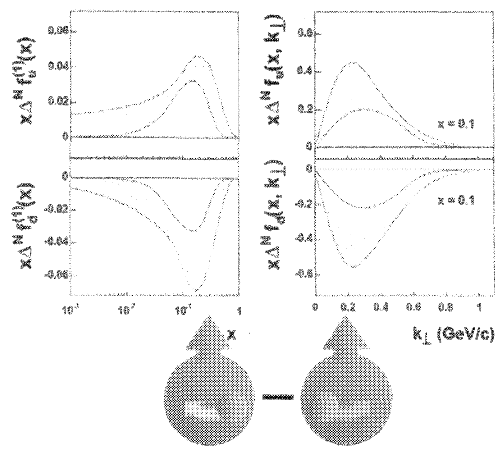
Yuji Goto (RIKEN/RBRC)

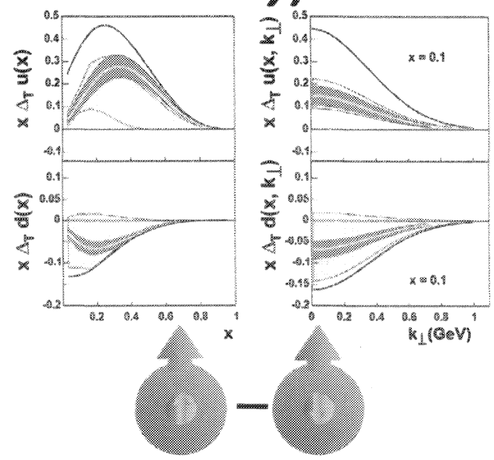
Physics motivation

- Spin structure of the nucleon
  - From collinear structure to multi-dimensional structure
    - Orbital angular momentum
    - Shape of the nucleon
    - With transverse-spin asymmetry measurements
  - GPD (Generalized Parton Distribution) and TMD (Transverse-Momentum Dependent) distribution



TMD functions (and transversity)



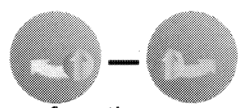


Sivers function:
correlation between nucleon transverse spin and parton transverse momentum (k_T)

$f_{1T}^{\perp}(u) > 0 \;\; f_{1T}^{\perp}(d) < 0$ or opposite sign...

Transversity:
correlation between nucleon transverse spin and parton transverse spin

$h_1(u) > 0 \;\; h_1(d) < 0$

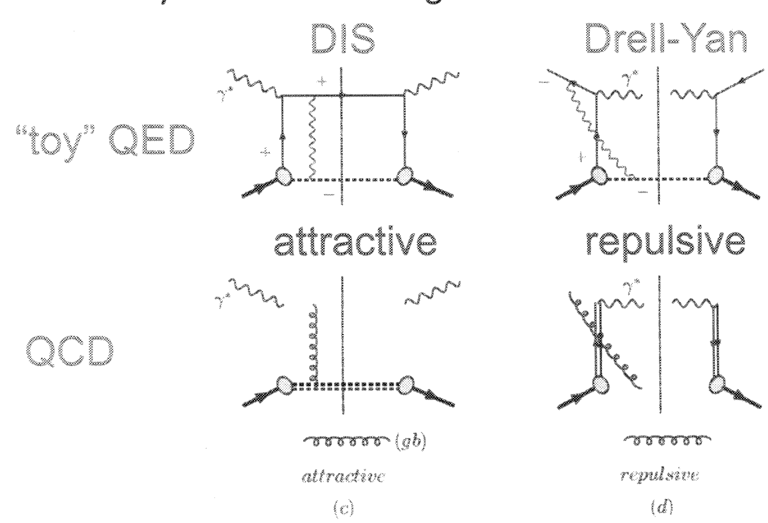


Boer-Mulders function:
correlation between parton transverse spin and parton transverse momentum (k_T)

$h_1^{\perp}(u)$ and $h_1^{\perp}(d)$ expected to have the same sign...

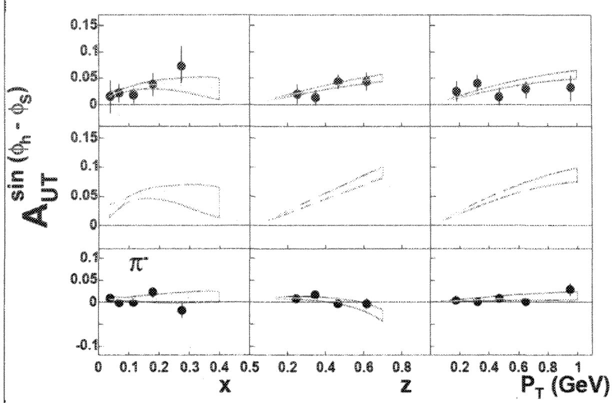
Sivers function measurement

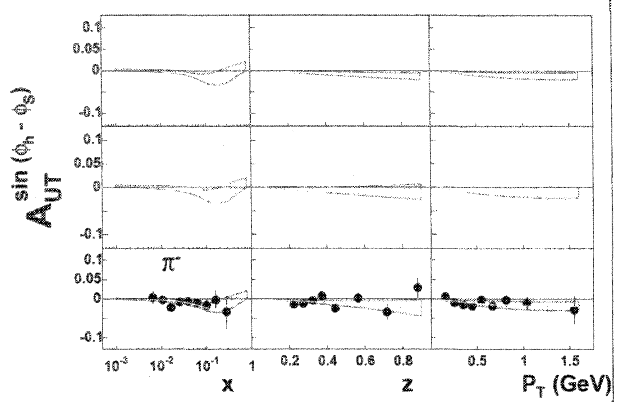
- Sign of Sivers function determined by single transverse-spin (SSA) measurement of DIS and Drell-Yan processes
  - Should be opposite each other
    - Initial-state interaction or final-state interaction with remnant partons
  - Test of TMD factorization
  - Explanation by Werner and Feng...



Sivers function measurement

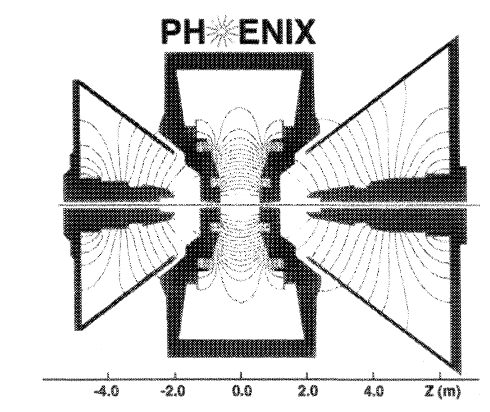
- < 1% level multi-points measurements have already been done for SSA of DIS process
- comparable level measurement needs to be done for SSA of Drell-Yan process for comparison



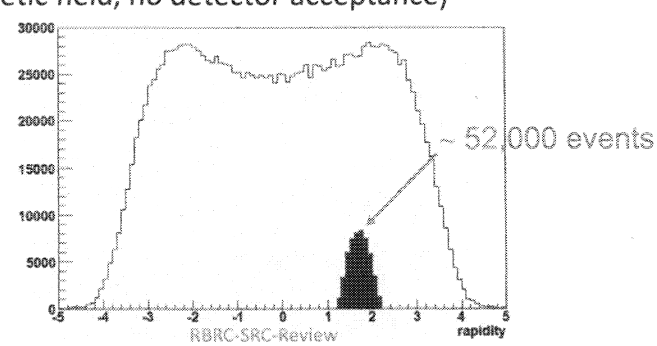


Drell-Yan at RHIC

- Collider experiment
  - $\sqrt{s}$ = 500 GeV
  - PHENIX muon arm
    - $\theta = 0.22$ ($\eta = 1.2$) to $\theta = 0.59$ ($\eta = 2.2$)
  - ~ RHIC II luminosity
    - 10^{33} /cm^2/sec × 10^6 sec = 1,000 pb^{-1}
  - $M_{\mu\mu}$ = 4.5 ~ 8 GeV
  - Very simple PYTHIA simulation
    - Angle & E_μ (> 2 GeV) cut only
    - (no magnetic field, no detector acceptance)

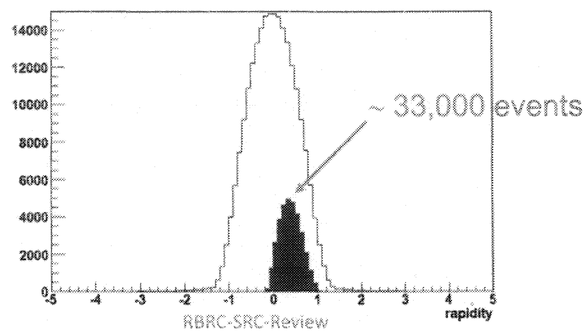


Magnetic field lines for the two Central Magnet coils in combined (++) mode



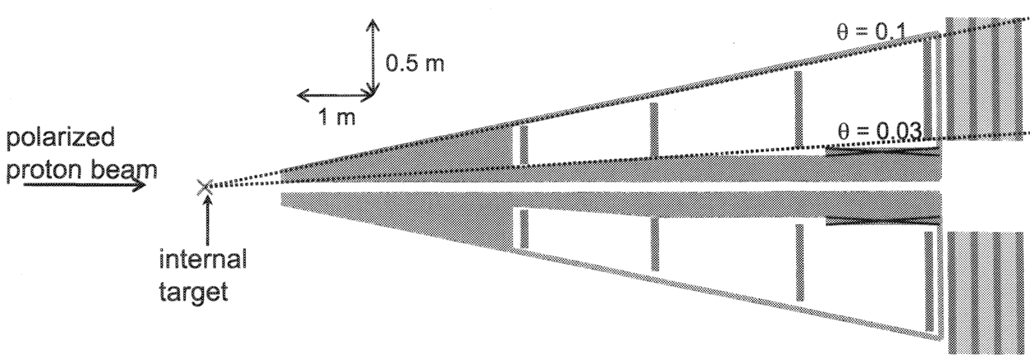
Drell-Yan at RHIC

- Fixed-target (internal-target) experiment
  - $\sqrt{s}$ = 22 GeV (E_{lab} = 250 GeV)
  - θ = 0.03 to θ = 0.1
  - ~ 10 times larger luminosity necessary
    - 10^{34} /cm^2/sec × 10^6 sec = 10,000 pb^{-1}
  - $M_{\mu\mu}$ = 4.5 ~ 8 GeV
  - Very simple PYTHIA simulation
    - Angle & E_μ (> 2 GeV) cut only
    - (no magnetic field, no detector acceptance)
      - more studies necessary for acceptance, dead time, etc. for realistic estimation



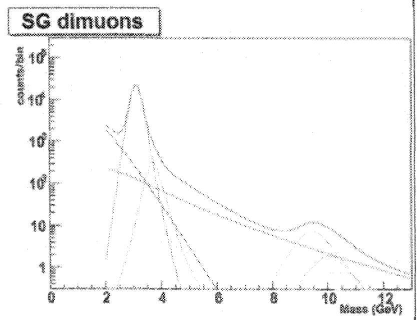
Drell-Yan at RHIC

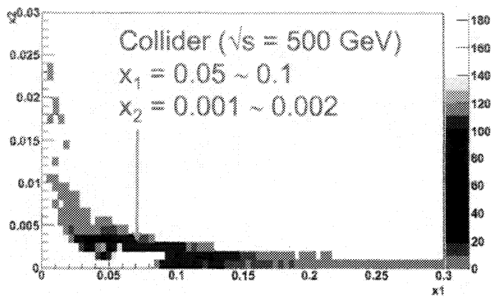
- Internal-target experiment
  - Detector idea
  - Similar to PHENIX muon arm...

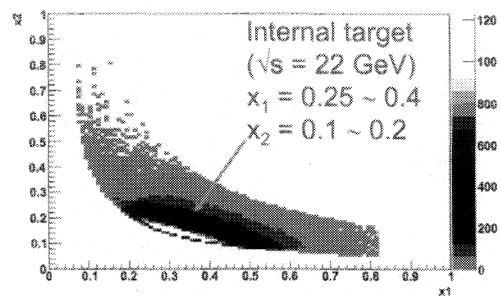


Drell-Yan at RHIC

- Collider ($\sqrt{s}$ = 500 GeV) with L = 1,000 pb^{-1}
  - 52,000 events in $M_{\mu\mu}$ = 4.5 ~ 8 GeV
  - Large background from b-quark
    - $M_{\mu\mu}$ > 6 GeV cut more appropriate
  - x_1 = 0.05 ~ 0.1
- Internal target ($\sqrt{s}$ = 22 GeV) with L = 10,000 pb^{-1}
  - 33,000 events in $M_{\mu\mu}$ = 4.5 ~ 8 GeV
  - x_1 = 0.25 ~ 0.4







Internal target experiment at RHIC

- 10^{34} /cm^2/sec possible ?
  - 2×10^{11} /bunch × 10 MHz = 2×10^{18} /sec
  - Storage cell 10^{14} /cm^2 thickness
  - 2×10^{32} /cm^2/sec possible
  - 50-times larger luminosity necessary
- Thicker target ?
  - Pellet target 10^{15} – 10^{16} /cm^2 thickness
  - Solid target 10^{16} – 10^{18} /cm^2 thickness
- Limitations
  - Beam lifetime
    - For simultaneous operation with collider experiments
    - ($2\times10^{11}\times100$) / (10^7 /mb/sec×50 mb) = 4×10^6 sec ~ 11 hours
      - Realistically may be < 1 hour lifetime
      - Unacceptable for collider experiments

Internal target experiment at RHIC

- Larger number of beams in one bunch?
  - And 3-times more number of bunches (35 nsec interval)?
    - Injection kicker and electron cloud issues...
  - Coherent electron cooling?
  - Bunch merging at RHIC?
    - Larger beam emittance and depolarization?
- Radiation issue
  - Hopefully solvable by shielding...

Conclusion

- Importance of multi-dimensional understanding of nucleon spin structure
  - For orbital angular momentum and shape of the nucleon
  - With transverse-spin asymmetry measurements of Drell-Yan process
    - Sivers function by SSA measurement
    - (transversity and Boer-Mulders function)
- Internal-target experiment at RHIC may be another option
  - In addition to collider experiments
  - Though there seem to be many issues
- Sure to be an interesting option to be studied more
  - (Not only for Drell-Yan)
  - (Not only for spin? Heavy-ion exp, too?)

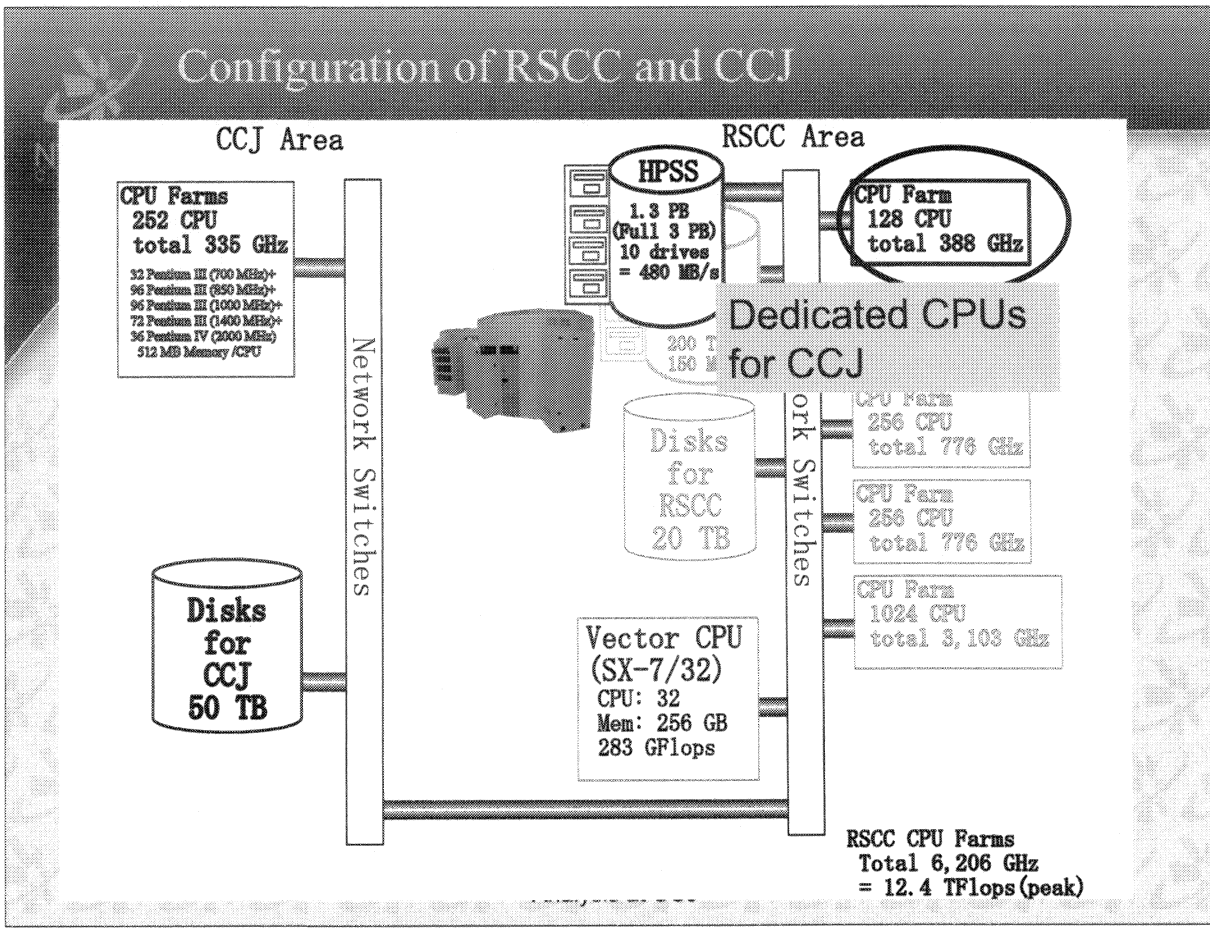
RHIC Data Analysis at CCJ

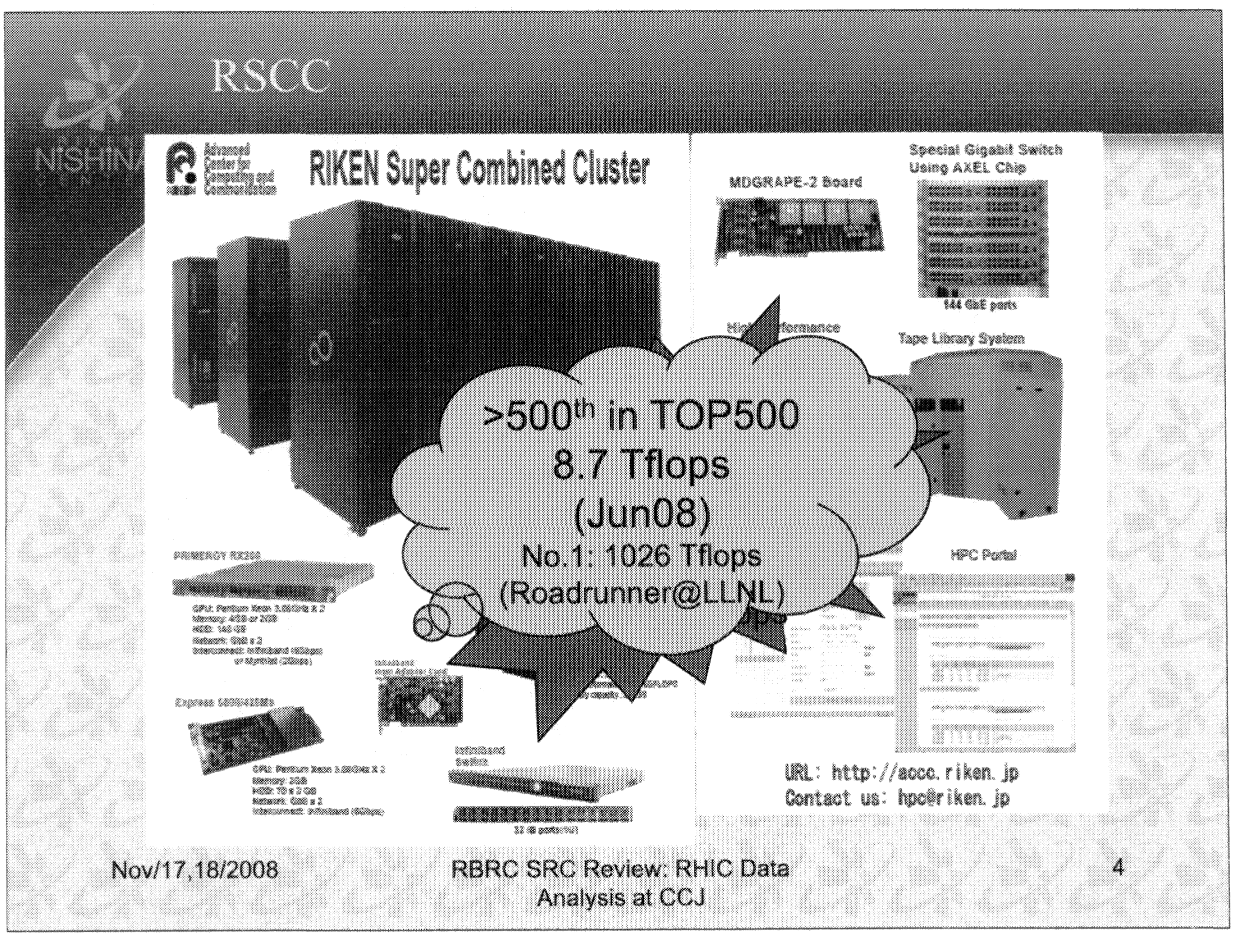
Yasushi Watanabe
RIKEN/RBRC

RIKEN CCJ : Overview

- Scope
  - Center for analysis of RHIC Spin Physics
  - Principal remote site of computing for PHENIX data reconstruction: All pp run was done at CCJ
  - Regional Asia computing center
- Infrastructure
  - CPU: 128 CPU at RSCC (3 GHz Xeon)
    - » RSCC: Super computer for Riken in general

    ~100 CPU at CCJ (1.4 & 2 GHz Pentium)
  - Disk Storage : ~100 TB
  - Tape Storage: ~1.5 PB


Configuration of RSCC and CCJ
CCJ Area
RSCC Area
CPU Farms
252 CPU
total 335 GHz
32 Pentium III (700 MHz)+
96 Pentium III (850 MHz)+
96 Pentium III (1000 MHz)+
72 Pentium III (1400 MHz)+
36 Pentium IV (2000 MHz)
512 MB Memory /CPU
Network Switches
Disks for CCJ 50 TB
HPSS
1.3 PB
(Full 3 PB)
10 drives
= 480 MB/s
CPU Farm
128 CPU
total 388 GHz
Dedicated CPUs for CCJ
Disks for RSCC 20 TB
CPU Farm
256 CPU
total 776 GHz
CPU Farm
256 CPU
total 776 GHz
CPU Farm
1024 CPU
total 3,103 GHz
Vector CPU
(SX-7/32)
CPU: 32
Mem: 256 GB
283 GFlops
RSCC CPU Farms
Total 6,206 GHz
= 12.4 TFlops(peak)


RSCC
RIKEN Super Combined Cluster
MDGRAPE-2 Board
Special Gigabit Switch
Using AXEL Chip
144 GbE ports
Tape Library System
HPC Portal
>500th in TOP500
8.7 Tflops
(Jun08)
No.1: 1026 Tflops
(Roadrunner@LLNL)
URL: http://accc.riken.jp
Contact us: hpc@riken.jp
Nov/17,18/2008
RBRC SRC Review: RHIC Data Analysis at CCJ
4

What was done on CCJ since 2000

- 18 official projects
  - Simulation, DST production (mainly for pp run) and related works
- 75 research plans
  - Simulation, filtering, trigger study, and detailed analysis…each individual has own analysis project
    - They are not only for pp run but also for heavy ion runs.

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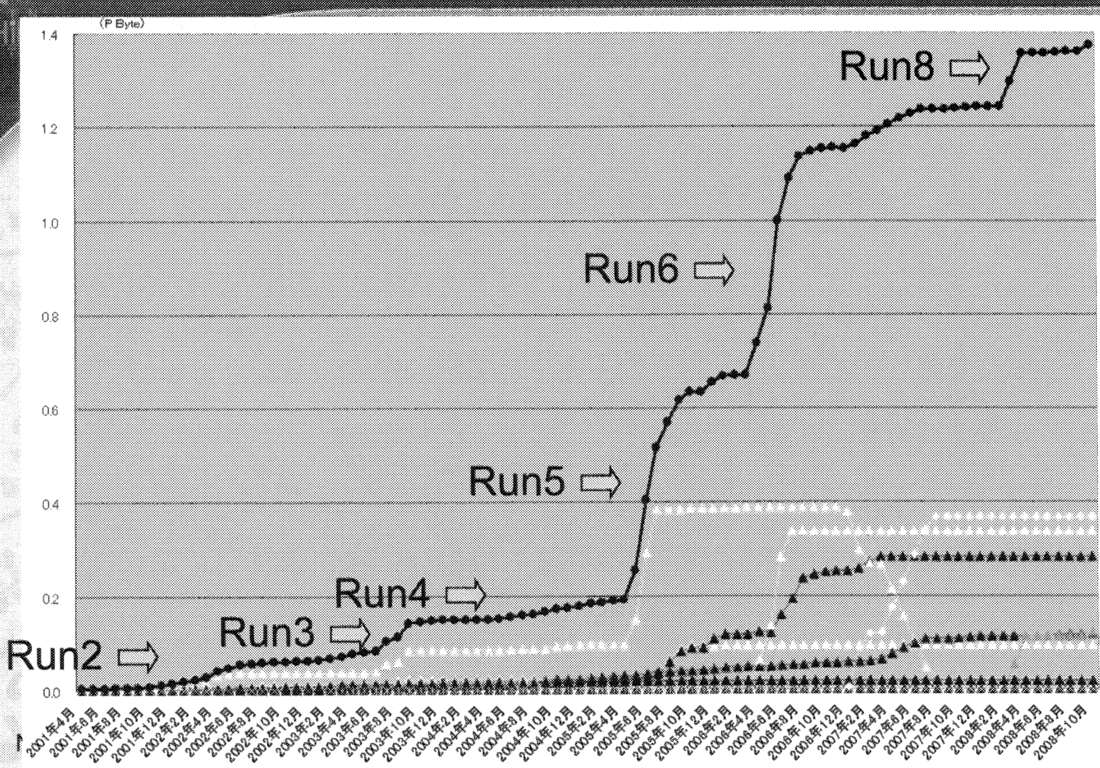
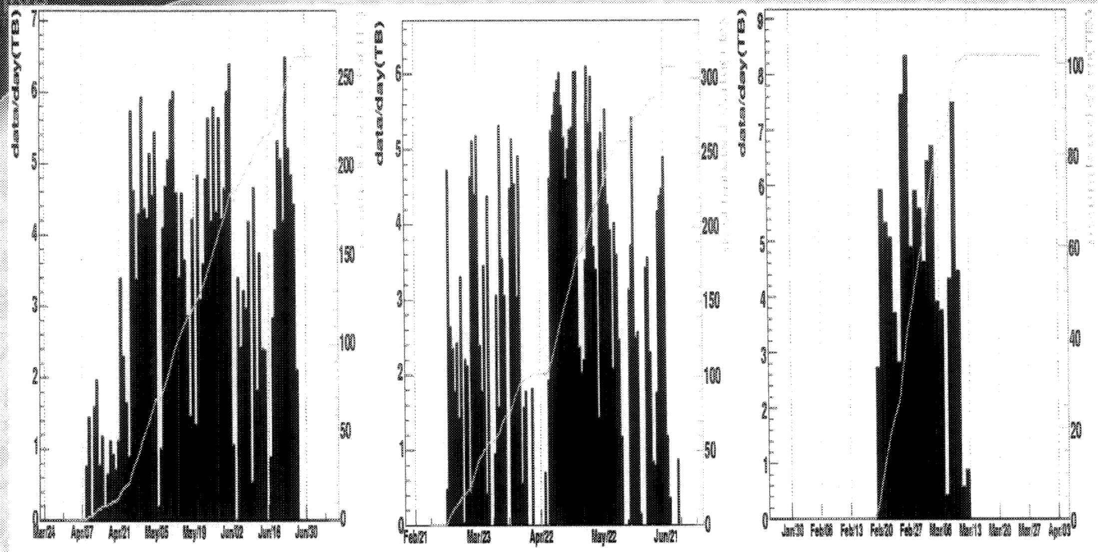
Growth of CCJ-HPSS data volume



Analysis at CCJ

Big pipe between BNL and RIKEN



Run5 Run6 Run8

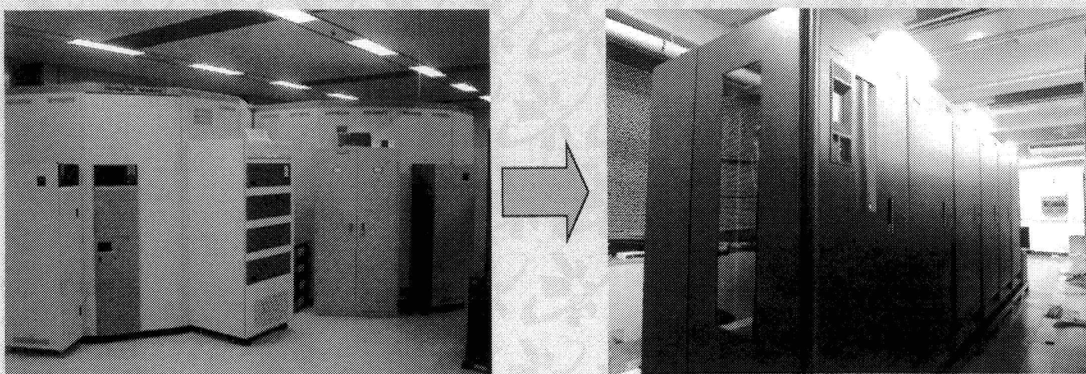
Sustained > 5TB/day (peak > 200MB/s)

Next RSCC will be launched in Aug/2009

- CPU: 96 Tflops (vs. 12 Tflops now)
  - x86-64(Intel Core i7, quad cores/CPU) x 2048
- Disk: 500 TBytes (vs. 20 TBytes now)
- Tape: 4 PBytes (=5,000 cartridges)
  - CCJ: 2.4 PBytes will be assigned
  - 12 LTO4 drives
  - More 5,000 empty cartridge slots
- Internal network: InfiniBand 2 GB/s

Replacement has been started already

- 1.4 PB data must be transferred to new tapes before the retirement (July/2009).



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CCJ original small cluster

- Scope: Dedicated for data intensive jobs
  - Filtering , sorting…
  - 2U chassis/node x 18 nodes
    - Quad core CPU x 2 => 8 cores/node
    - 1 TB SATA disk x 8 => 8 TB/node
      - Each core has a disk
    - Fastest way to feed data to cores.
- Total: 144 cores and 144 TB
  - Big enough capacity relative to nDST data size (<100 TB)
- Coming soon… March/2009

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Summary

- CCJ is continuously working well as a regional computing center for PHENIX for many years
- The big network pipe between BNL and RIKEN makes real time data transfer possible.
    - Production at remote site (CCJ) is realized
    - Redundant data store is against disaster
- Next RSCC (launched at Aug/2009) and a small cluster are good presents for CCJ.

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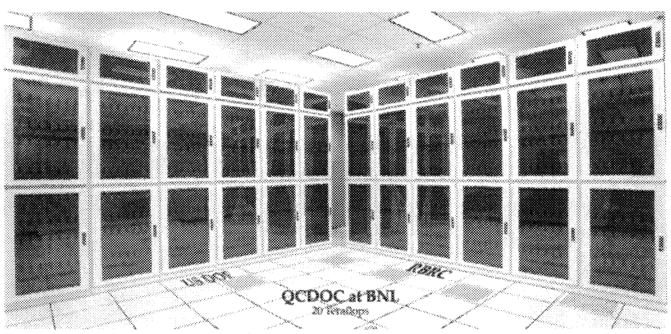
QCD Thermodynamics on the Lattice

Péter Petreczky (RIKEN-BNL and Physics, BNL)

RBC-Bielefeld collaboration :
S. Ejiri, F. Karsch, C. Jung, C. Miao, P. Petreczky (BNL), N. Christ, R. Mawhiney (Columbia)
O. Kaczmarek, E. Laermann, S. Mukherjee C. Schmidt (Bielefeld),
Cheng (LLNL), W. Soeldner (GSI)
Former members : Datta, van der Heide, Huebner, Liddle, Petrov, Pica, Umeda

- Extending the EoS and Tc calculations to Nt=8 tother with hotQCD collaboration
- Study of fluctuations of conserved charges on Nt=4 and 6 lattices
- Study of spatial correlation functions at high temperature
- Charm contribution to QCD thermodynamics
- QCD thermodynamics with domain wall fermions

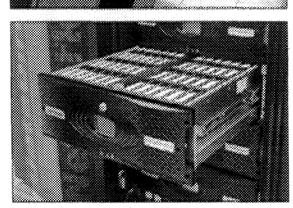
Computational resources



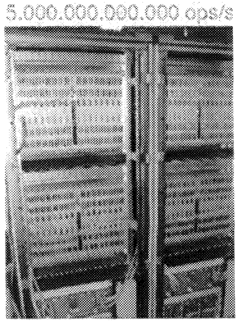
3.5 racks of RBRC QCDOC: 2.87Tflop

4 racks of RBRC QCDOC: 3.28Tflop

NYBlue at BNL and LLNL



BI – apeNEXT
5.000.000.000.000 ops/s



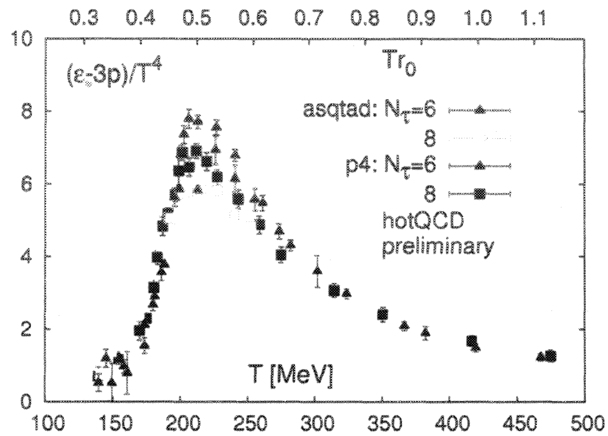
Lattice results on trace anomaly

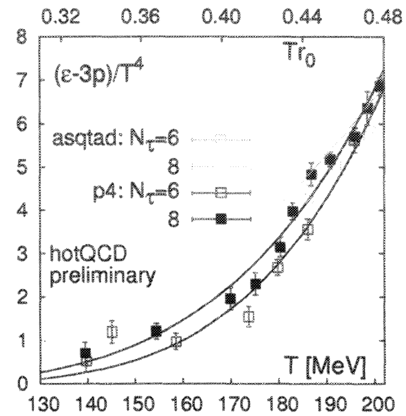
$m_q = 0.1 m_s \leftrightarrow m_\pi \simeq 220\text{MeV} \quad m_\eta \cdot r_0 = 1.59$

$$\frac{\Theta^{\mu\mu}(T)}{T^4} = \frac{\epsilon - 3p}{T^4} = \{\langle S_G\rangle_0 - \langle S_G\rangle_T\} - \{2m_q(\langle\bar{q}q\rangle_0 - \langle\bar{q}q\rangle) + m_s(\langle\bar{s}s\rangle_0 - \langle\bar{s}s\rangle_T)\}$$

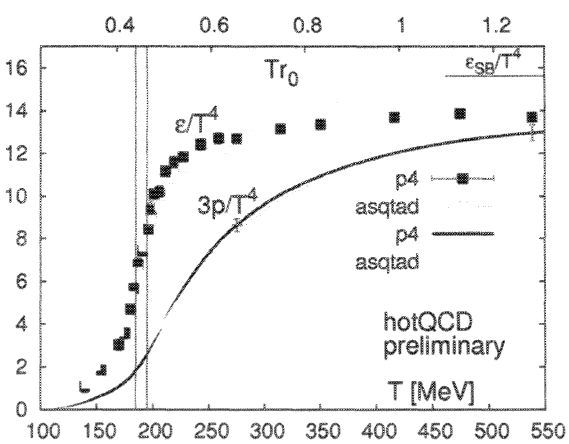
$$R_\beta(\beta) = -\frac{d\beta}{da},\ \beta = 6/g^2 \qquad \frac{p(T)}{T^4} - \frac{p(T_0)}{T_0^4} = \int_{T_0}^{T} dT' \frac{\Theta^{\mu\mu}(T')}{T'^5}$$

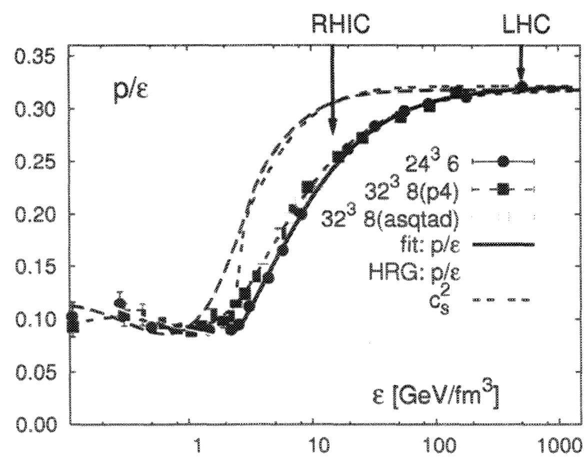
$$R_m = \frac{1}{m_q(\beta)} \frac{dm_q(\beta)}{d\beta} \qquad s(T) = (\epsilon + p)/T$$





Pressure, energy density and speed of sound





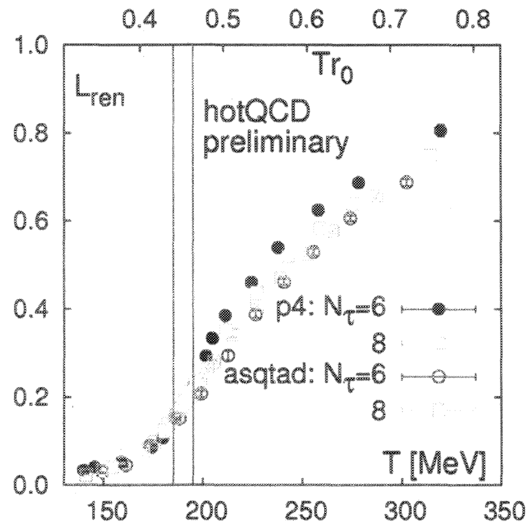
rapid rise in number of d.o.f at *T=180-200* MeV

10-15% deviation from the ideal gas limit

lattice discretization errors are small

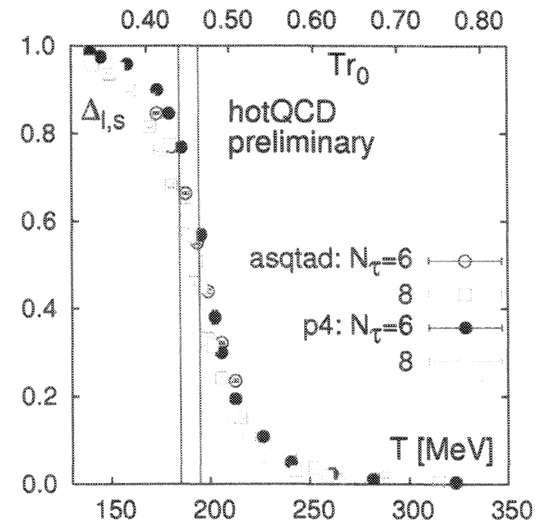
The softest point corresponds to $\epsilon \simeq 1\text{GeV/fm}^3$

Deconfinement and chiral transition



Polyakov loop

$L_{ren} = \exp(-F_Q(T)/T)$



Renormalized chiral condensate

$$\Delta_{s,l}(T) = \frac{\langle \bar{q}q\rangle_T - \frac{m_q}{m_s}\langle \bar{s}s\rangle_T}{\langle \bar{q}q\rangle_{T=0} - \frac{m_q}{m_s}\langle \bar{s}s\rangle_{T=0}}$$

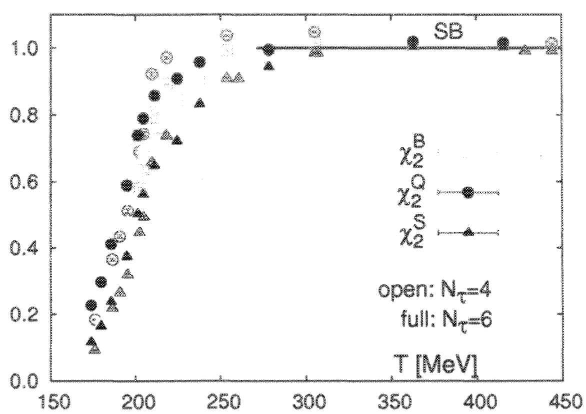
rise in the entropy and energy density happens in the same temperature interval where the rapid change of the chiral condensate and Polyakov loop takes place

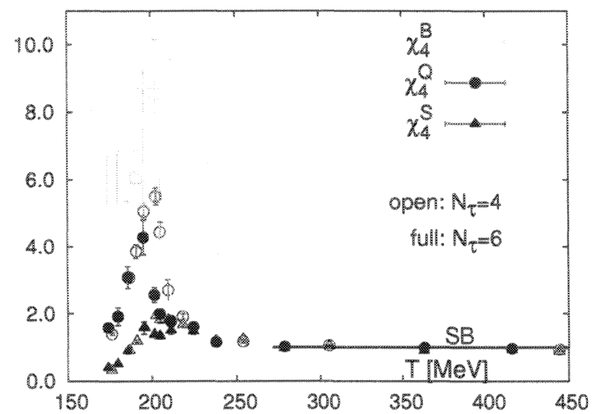
Fluctuations of conserved charges

$$\chi^{BQS}_{i,j,k} = \frac{\partial^i}{\partial \hat{\mu}^i_B}\frac{\partial^j}{\partial \hat{\mu}^j_Q}\frac{\partial^k}{\partial \hat{\mu}^k_S}\frac{1}{VT^3}\ln Z(T,V),\ \hat{\mu}_X = \mu_X/T$$

$$\chi^X_2 = \frac{1}{VT^3}\langle N^2_X\rangle$$

$$\chi^X_2 = \frac{1}{VT^3}(\langle N^4_X\rangle - 3\langle N^2_X\rangle^2)$$





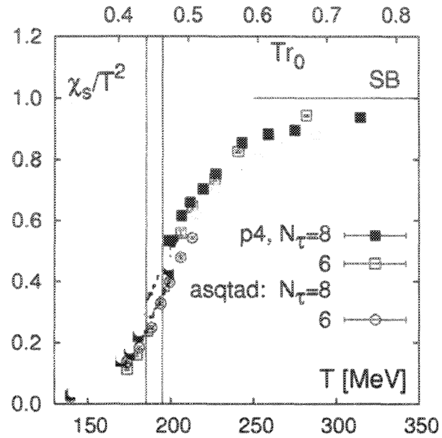
quarks are the carriers of conserved charges for

$$\chi^X_{2n} \sim \left|\frac{T-T_c}{T_c}\right|^{2-n-\alpha}$$

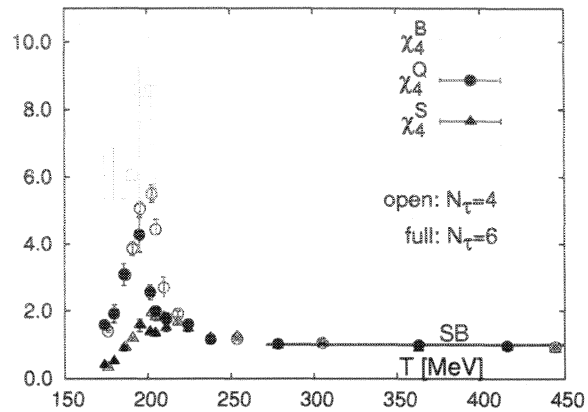
Fluctuations of conserved charges

$$\chi_{i,j,k}^{BQS} = \frac{\partial^i}{\partial \hat{\mu}_B^i} \frac{\partial^j}{\partial \hat{\mu}_Q^j} \frac{\partial^k}{\partial \hat{\mu}_S^k} \frac{1}{VT^3} \ln Z(T,V), \; \hat{\mu}_X = \mu_X / T$$

$$\chi_2^X = \frac{1}{VT^3} \langle N_X^2 \rangle$$



$$\chi_2^X = \frac{1}{VT^3} (\langle N_X^4 \rangle - 3 \langle N_X^2 \rangle^2)$$

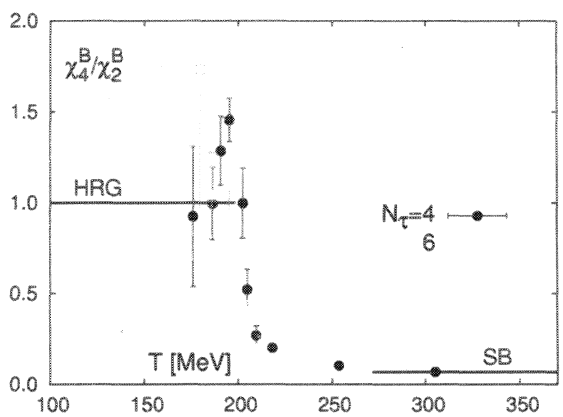


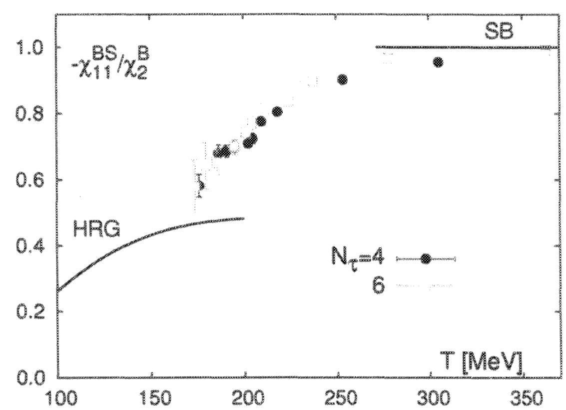
cutoff effects are under control

$$\chi_{2n}^X \sim \left| \frac{T - T_c}{T_c} \right|^{2-n-\alpha}$$

Fluctuations in the hadron resonance gas model

Hadron resonance gas (HRG) can be used for reference for low temperature thermodynamics in the same way as the ideal quark gluon gas as a reference for the thermodynamics at high T.

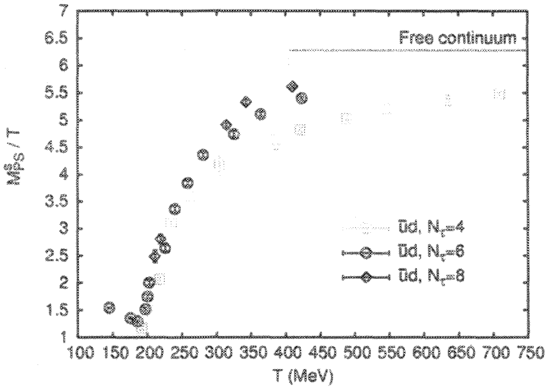


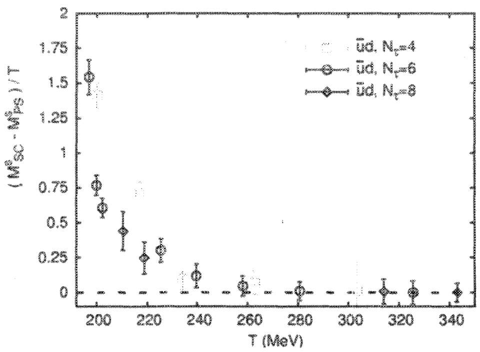


Ratio of different susceptibilities are less sensitive to the details of the hadron spectrum and therefore better suitable for comparison to lattice data.

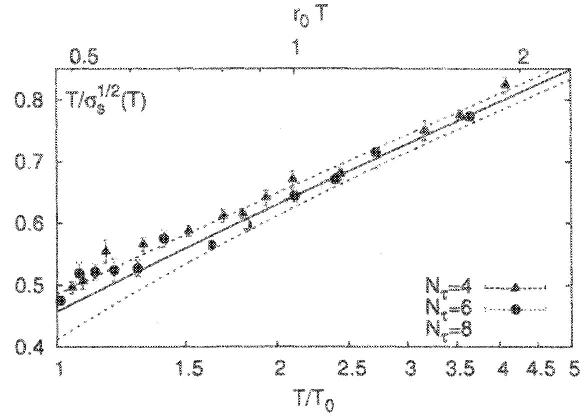
Spatial correlators at T>0

Meson screening masses





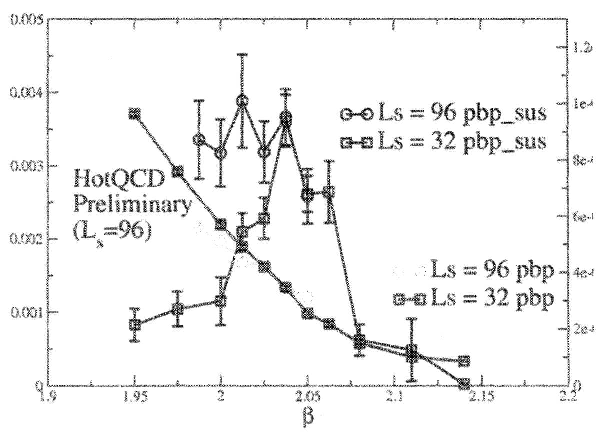
$$W(r(x,y),z) \sim \exp(-\sigma_s(T)\cdot r \cdot z)$$
$$\sigma_s(T) \simeq \sigma(T=0),\ T < T_c$$

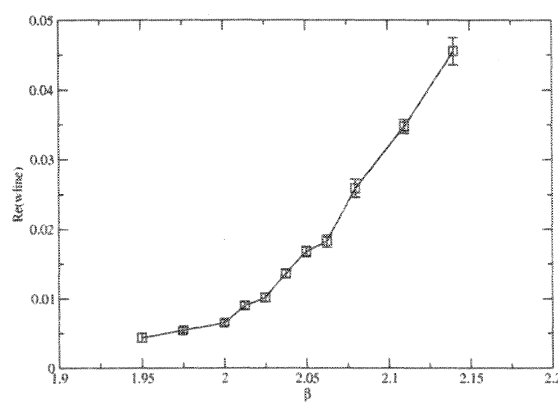


$$\sigma_s = c_M \cdot g_3^4(T)$$

$c_M = 0.55(1)$
$g_3^2(T) = g^2(T)T(1 + c_1(N_f,T)g^2(T) + \ldots)$

QCD thermodynamics with domain wall fermions





Summary

• Calculations of thermodynamic quantities have been extended to lattices with temporal extent Nt=8. Comparison with previous results as well as with asqtad action shows no significant cutoff effects

• Study of fluctuations shows that quantum numbers are carried by weakly interacting quarks for T > 250 MeV

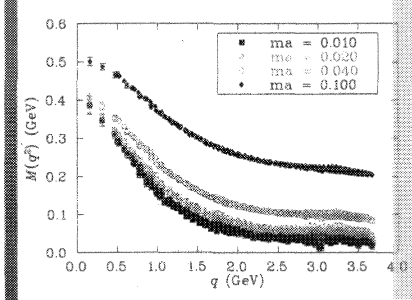
• At high temperatures non-perturbative effects are due to soft chromomagnetic fields

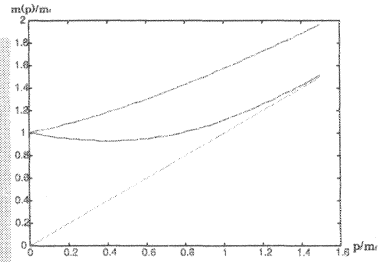
• Calculations being extended to smaller ("physical") quark mass mq=0.05ms

The Quark and Gluon Propagators at finite temperature

Masatoshi Hamada

Mass function
(Lattice QCD, Bowman, et al.)
Ultraviolet : bare quark mass
Infrared : chiral condensate





High temperature limit
(Hard thermal loop)
Quasi-particle
Plasmino

Karsch & Kitazawa
2-pole fitting work well
in Landau gauge.

$T = 0$ $\longrightarrow$ T_c $\longrightarrow$ T

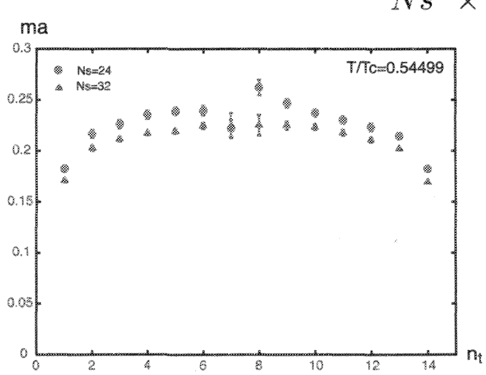
- **Quark propagators in the confinement and the deconfinement phases**
- **Quenched SU(3) lattice QCD simulations**
- **Wilson gauge and clover (O(a) improved) fermion actions**
- **Landau gauge fixing**

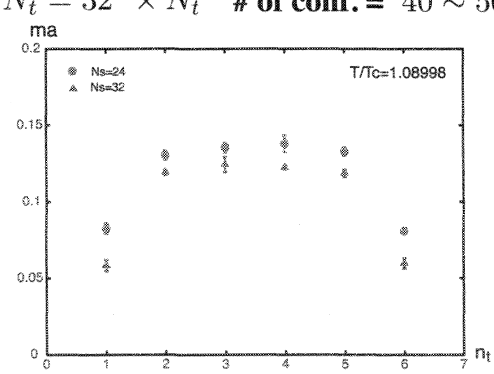
$$G(x_4 - y_4) = \langle \psi(x_4)\bar{\psi}(y_4)\rangle = \sum_{\vec{x},\vec{y}} \langle W^{-1}(x, y; U)\rangle$$

when $\vec{p} = 0$

$$G(t) = G_4(t)\gamma_4 + G_s(t)$$

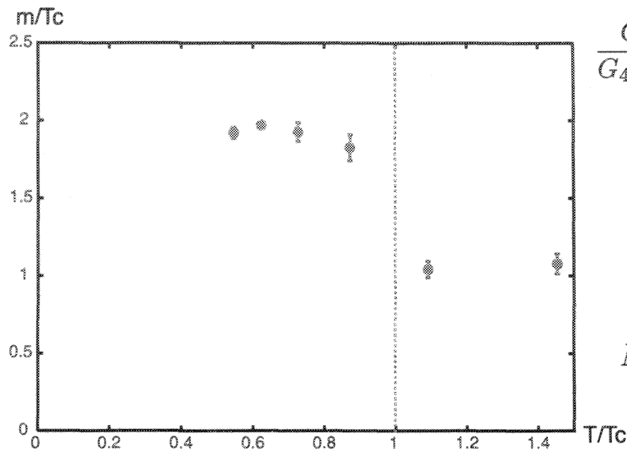
$Ns^3 \times N_t = 32^3 \times N_t$ **# of conf. =** $40 \sim 50$





$$\beta = 6.10$$
$$\kappa = 0.1346$$
$$C_{SW} = 1.6787$$
$$a \sim 0.0882[fm]$$

Quark propagators include negative norm.



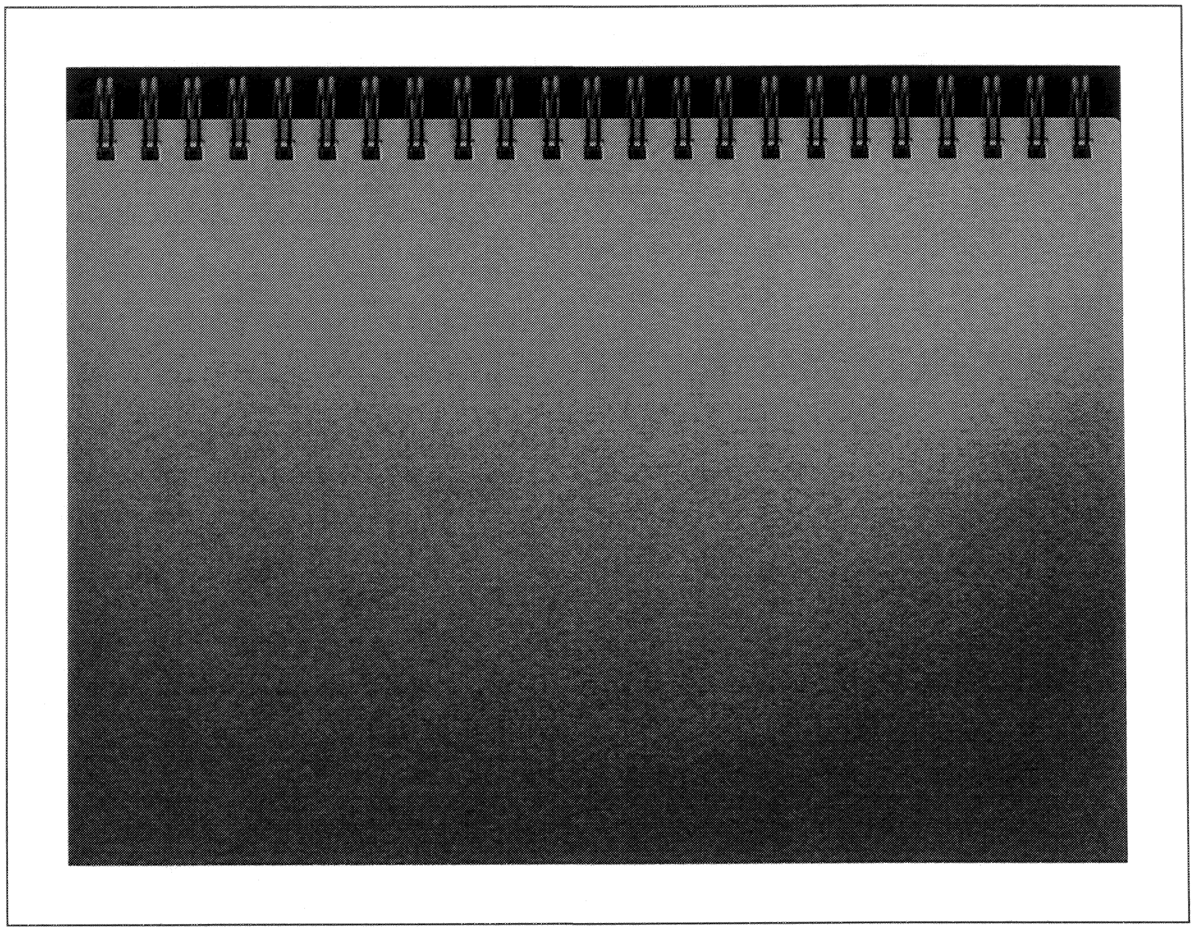
$$\frac{G_4(t)}{G_4(t+1)} = \frac{\cosh(m(t-\beta/2))}{\cosh(m(t+1-\beta/2))}$$

$$\beta = 6.10$$
$$\kappa = 0.1346$$
$$C_{SW} = 1.6787$$
$$a \sim 0.0882[fm]$$
$$Ns^3 \times N_t = 32^3 \times N_t$$
$$N_t = 16, 14, 12, 10, 8, 6$$

# of conf. = $40 \sim 50$

Summary & Future

- The quark mass in the confinement phase is twice one in the deconfinement phase.
- Quark propagators in the confinement phase include a negative norm.
- It needs to check gauge dependence and to calculate full QCD.
- Gluon propagators at finite temperature.



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

Shigemi Ohta *†‡ [RBC and UKQCD Collaborations]

RBRC Scientific Review, November 17, 2008

RBC and UKQCD collaborations jointly produced (2+1)-flavor dynamical DWF ensembles:

- $24^3 \times 64 \times 16$ (2.7fm across), $16^3 \times 32 \times 16$ (1.8 fm), ...
- Iwasaki gauge action, $\beta = 2.13$, and Domain-Wall Fermions (DWF) quarks, $M_5 = 1.8$,
- $m_{\rm strange}a = 0.04$, $m_{\rm up-down}a = 0.03$, 0.02, 0.01 and 0.005, with $a^{-1} \sim 1.7$ GeV.

Best ever hadron structure calculations: flavor and chiral symmetries and lattice volume.

- Very accurate determination of kaon bag parameter, $B_K^{\overline{\rm MS}}(2{\rm GeV}) = 0.524(10)(28)$,
- beginning to see SU(3) chiral perturbation failure, e.g. NLO corrections $\sim 0.5\times$LO.

Here we report some low moments of isovector nucleon structure functions calculated by Takeshi Yamazaki, Huey-Wen Lin, Shoichi Sasaki, Tom Blum, James Zanotti, Robert Tweedie, ... and are now nearly final.

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Four isovector form factors parameterize neutron β decay:

$$\langle p|V_\mu^+(x)|n\rangle = \bar{u}_p \left[\gamma_\mu G_V(q^2) - q_\lambda \sigma_{\lambda\mu} G_T(q^2)\right] u_n e^{iq\cdot x}, \quad (1)$$

where $G_V = F_1$ and $G_T = \dfrac{F_2}{2m_N}$ in electromagnetic notations, and

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

The vector and axial charges, $g_V = G_V(0)$, and the axial charge, $g_A = G_A(0)$, determines neutron life:

- $g_V = \cos\theta_C$,
- $g_A = 1.2695(29) \times g_V$ [1].

It is an interesting and important challenge for numerical lattice QCD to reproduce this value.

Nucleon form factor experiments of course are not limited to neutron β decays:

- Vast data of lepton elastic scattering exist at wide range of momentum transfer values.
- We can extract mean-squared radii, of the respective form factors,
- anomalous magnetic moment,
- πNN coupling, $g_{\pi NN}$,
- pseudoscalar effective coupling, g_P, that enters the muon capture by nucleon,

and so on.

[1] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33**, 1 (2006).

The structure functions are measured in deep inelastic scattering of leptons off nucleon: $\sigma \propto l^{\mu\nu} W_{\mu\nu}$.

Since the leptonic tensor, $l_{\mu\nu}$, is known, we can extract the hadronic tensor:

$$W^{\{\mu\nu\}}(x, Q^2) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_1(x, Q^2) + \left(P^\mu - \frac{\nu}{q^2} q^\mu\right)\left(P^\nu - \frac{\nu}{q^2} q^\nu\right) \frac{F_2(x, Q^2)}{\nu}, \tag{3}$$

$$W^{[\mu\nu]}(x, Q^2) = i\epsilon^{\mu\nu\rho\sigma} q_\rho \left(\frac{S_\sigma}{\nu}(g_1(x, Q^2) + g_2(x, Q^2)) - \frac{q \cdot S P_\sigma}{\nu^2} g_2(x, Q^2)\right), \tag{4}$$

with kinematic variables defined as $\nu = q \cdot P$, $S^2 = -M^2$, and $x = Q^2/2\nu$, and $Q^2 = |q^2|$.

Their moments are described in terms of Wilson's operator product expansion:

$$\begin{aligned}
2\int_0^1 dx\, x^{n-1} F_1(x, Q^2) &= \sum_{q=u,d} c_{1,n}^{(q)} \langle x^n \rangle_q(\mu) + O(1/Q^2), \\
\int_0^1 dx\, x^{n-2} F_2(x, Q^2) &= \sum_{f=u,d} c_{2,n}^{(q)} \langle x^n \rangle_q(\mu) + O(1/Q^2), \\
2\int_0^1 dx\, x^n g_1(x, Q^2) &= \sum_{q=u,d} e_{1,n}^{(q)} \langle x^n \rangle_{\Delta q}(\mu) + O(1/Q^2), \\
2\int_0^1 dx\, x^n g_2(x, Q^2) &= \frac{1}{2}\frac{n}{n+1} \sum_{q=u,d} \left[e_{2,n}^q\, d_n^q(\mu) - 2e_{1,n}^q \langle x^n \rangle_{\Delta q}(\mu)\right] + O(1/Q^2).
\end{aligned} \tag{5}$$

$\langle x^n \rangle_q(\mu)$, $\langle x^n \rangle_{\Delta q}(\mu)$ and $d_n^q(\mu)$ are calculable on the lattice as forward matrix elements of certain local operators.

In addition, the tensor charge, $\langle 1 \rangle_{\delta q}(\mu)$, is beginning to be reported by experiments.

We use the standard proton operator, $B = \epsilon_{abc}(u_a^T C \gamma_5 d_b) u_c$ to create and annihilate proton states.

- Gaussian-smeared with radius of 7, to optimize overlap with the ground state at finite momenta.
- Project the positive-parity ground state, so our two-point proton function takes the form

$$C_{\rm 2pt}(t) = \sum_{\alpha,\beta} \left(\frac{1+\gamma_t}{2}\right)_{\alpha\beta} \langle B_\beta(t_{\rm sink}) \overline{B}_\alpha(t_{\rm source})\rangle, \tag{6}$$

  with $t = t_{\rm sink} - t_{\rm source}$.
- Insert an appropriate observable operator $O(\vec{q}, \tau)$ at time τ, $t_{\rm source} \le \tau \le t_{\rm sink}$, and possibly finite momentum transfer $\vec{q}$, to obtain a form factor or structure function moment three-point function,

$$C_{\rm 3pt}^{\Gamma,O}(t, \tau.\vec{q}) = \sum_{\alpha,\beta} \Gamma_{\alpha\beta} \langle B_\beta(t_{\rm sink}) O(\vec{q}, t) \overline{B}_\alpha(t_{\rm source})\rangle, \tag{7}$$

  with appropriate projection, $\Gamma = \frac{1+\gamma_t}{2}$, for the spin-unpolarized, and $\Gamma = \frac{1+\gamma_t}{2} i\gamma_5\gamma_k, k \neq 4$, for the polarized.
- Ratios of these two- and three-point functions give plateaux for $0 < \tau < t$ that give the bare lattice matrix elements of desired observables: e.g. $\langle O \rangle^{\rm bare} = \frac{C_{\rm 3pt}^{\Gamma,O}(t,\tau)}{C_{\rm 2pt}(t)}$ at $q^2 = 0$. At finite q^2 we need to take care of extra kinematics.
- Renormalize the structure function moments by Rome-Southampton RI-MOM non-perturbative renomalization prescription[2]

The good continuum-like flavor and chiral symmetries of domain-wall fermions are very useful here in eliminating unwanted lattice-artifact mixings that are present in many other fermion schemes.

[2]C. Dawson *et al.*, Nucl. Phys. B **514**, 313 (1998) [arXiv:hep-lat/9707009].

The RBC-UKQCD joint (2+1)-flavor dynamical DWF coarse ensembles[3]: generated with

- Iwasaki action at the coupling $\beta = 2.13$, corresponding to the lattice cut off of about $a^{-1} = 1.73(3)$ GeV.
- Two lattice volumes, $16^3 \times 32$ and $24^3 \times 64$, corresponding to linear spatial extent of about 1.8 and 2.7 fm.
- The dynamical strange and up and down quarks are described by DWF actions with the fifth-dimensional mass of $M_5 = 1.8$.
- The strange mass is set at 0.04 in lattice unit and turns out to be about twelve percent heavier than physical including the additive correction of the residual mass, $m_{\rm res} = 0.003$.
- The degenerate up and down mass is varied at 0.03, 0.02, 0.01 and 0.005, corresponding to pion mass of about 0.67, 0.56, 0.42 and 0.33 GeV and nucleon mass are about 1.55, 1.39, 1.22 and 1.15 GeV.

$m_f a$	# of config.'s	meas. interval	$N_{\rm sources}$	m_π (GeV)	m_N (GeV)
0.005	932	10	4	0.33	1.15
0.01	356	10	4	0.42	1.22
0.02	98	20	4	0.56	1.39
0.03	106	20	4	0.67	1.55

[3] C. Allton *et al.*, [RBC+UKQCD], arXiv:0804.0473 [hep-lat].

Two important sources of systematic error:

- finite spatial size of the lattice, and
- excited states contamination.

Finite size: chiral-perturbation-inspired analysis meson observables suggests

- a dimensionless product, $m_\pi L$,

of the calculated pion mass, m_π and lattice linear spatial extent, L, should be set greater than 4

- to drive the finite-volume correction below one percent.

The available lattice calculations seem to support this.

While our present parameters satisfy this condition, it should be emphasized that this criterion is

- not known sufficient for baryon observables.

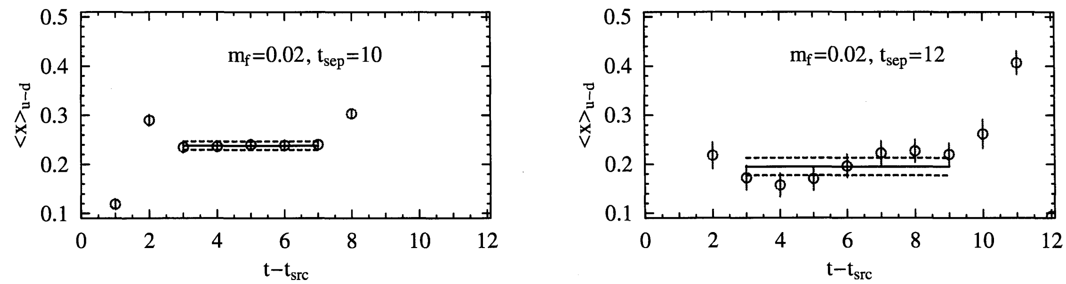
It is important to check this through the present calculations, and it is indeed an important purpose.

Excited-state contamination: adjust the time separation, t, between the source and sink

- so the resultant nucleon observables are free of contamination from excited states.

The separation has to be made longer as we set the quark masses lighter.

Our previous study with two dynamical flavors of DWF quarks[4] helps with a similar cutoff $\sim$ 1.7 GeV.



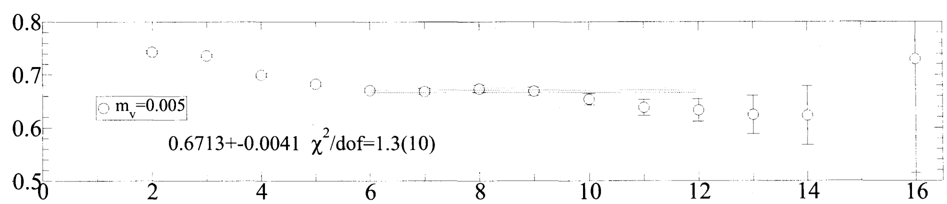
Clear systematic difference is seen between the shorter time separation of 10, or about 1.16 fm, and longer 12, or 1.39 fm: the former averages about 0.24 while the latter about 0.20:

- 1.2 fm separation is too short for nucleon with 0.5 GeV pion.

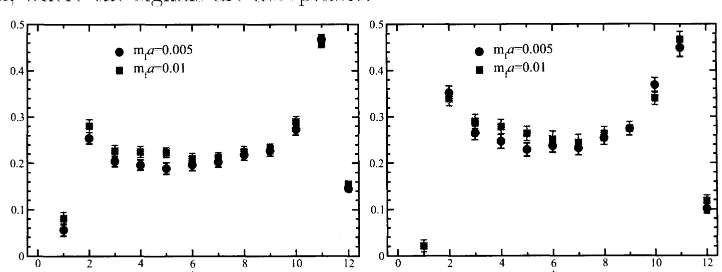
Present work with lighter, $\sim$0.3 GeV, pion, needs longer separation.

[4]H. W. Lin, T. Blum, S. Ohta, S. Sasaki and T. Yamazaki, [RBC], arXiv:0802.0863 [hep-lat].

We need a longer than 1.2 fm separation in this work, at least. However, the nucleon signal does not allow longer than 1.4 fm.

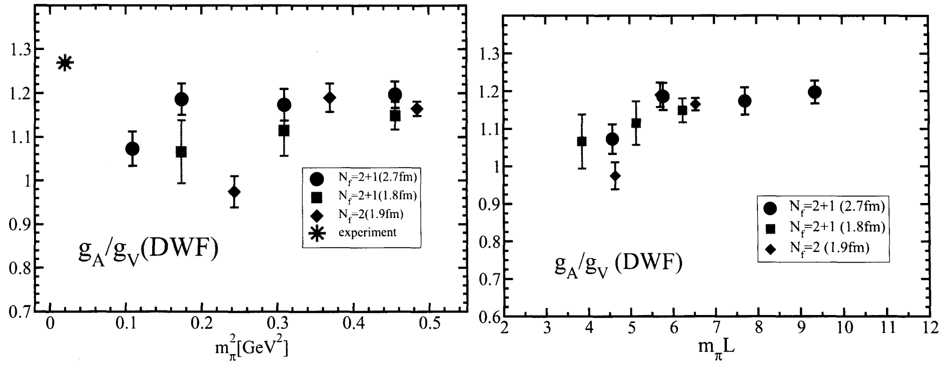


We settle with 1.4 fm, where the signals are acceptable.



To confirm this choice is sufficiently long to eliminate the excited-state contamination, we need to collect more statistics at a longer source-sink separation.

Axial charge[5], g_A: actually a renormalized ratio g_A/g_V,



With heavy up/down, they are all in proximity of the experiment, and do not depend on the up/down mass.

- However at lighter mass they deviate away from the experiment, depending on the volume.

Size effect? Indeed! Replot in $m_\pi L$ and they are monotonic: Scaling in $m_\pi L$.

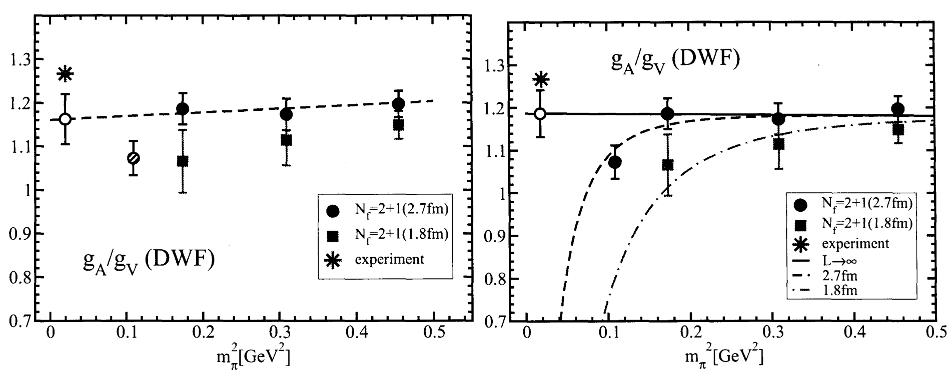
- Takeshi Yamazaki's discovery. He also discovered this in 2-flavor dynamical Wilson.
- Was seen in quenched calculations[6], but as a much smaller effect.

3 fm box no longer makes sense for nucleon structure studies: need larger box, 5-7 fm.

[5]T. Yamazaki *et al.* [RBC+UKQCD], Phys. Rev. Lett. **100**, 171602 (2008) [arXiv:0801.4016 [hep-lat]].

[6]S. Sasaki, K. Orginos, S. Ohta and T. Blum [RBCK], Phys. Rev. D **68**, 054509 (2003) [arXiv:hep-lat/0306007]; see also S. Sasaki and T. Yamazaki, Phys. Rev. D **78**, 014510 (2008) [arXiv:0709.3150 [hep-lat]].

Extrapolation to physical pion mass still possible: $1.20(6)_{\text{stat.}}(4)_{\text{syst.}}$.



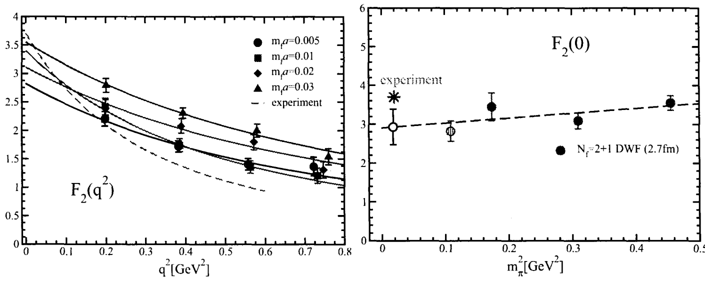
Vector charge: conserved, and so no excited-state contamination.

- Very accurately calculated: $Z_V = Z_A = 1/g_V = 1/1.3918(19) = 0.7185(10)$,

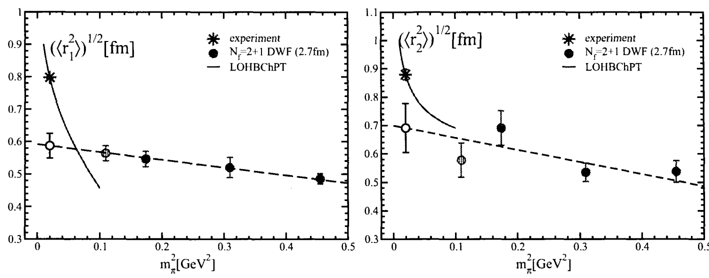
agrees very well with meson-sector estimate of $Z_A = 0.7161(1)$[7].

[7]C. Allton *et al.*, [RBC+UKQCD], arXiv:0804.0473 [hep-lat].

Momentum dependence of vector current form factors are fit well by dipole form, $\propto \left[1+\frac{\langle r^2\rangle}{12}q^2\right]^{-1}$, yielding anomalous magnetic moment,

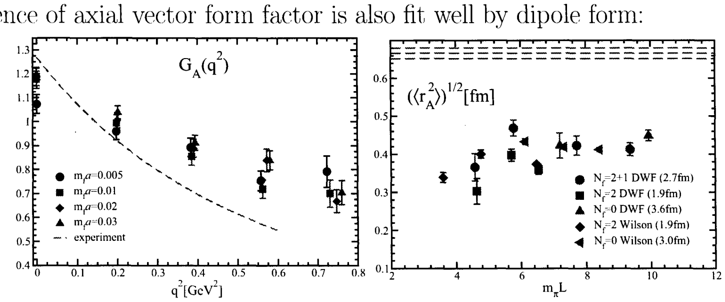


and Dirac and Pauli mean-squared radii.

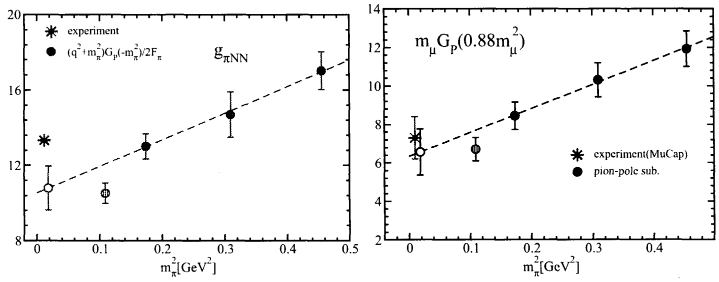


The former calls heavy-baryon chiral perturbation into question.

Momentum dependence of axial vector form factor is also fit well by dipole form:

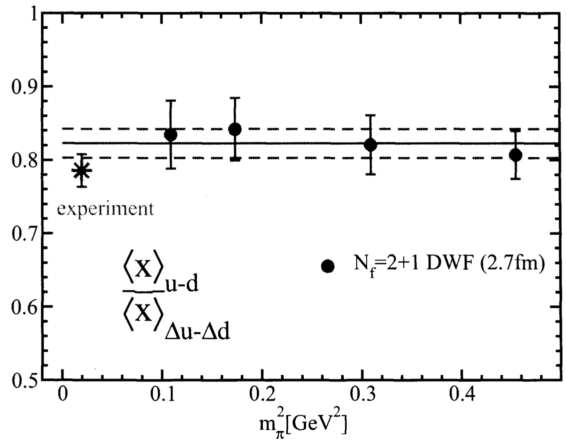


From the induced pseudoscalar form factor, $G_P(q^2)$, we extract pion-nucleon coupling, $g_{\pi NN}$, from the residue at the pion pole, $G_P(q^2) \sim \frac{2F_\pi g_{\pi NN}}{q^2+m_\pi^2}$, $q^2 \sim -m_\pi^2$,



and the effective coupling, $g_P = m_\mu G_P(q^2 = 0.88m_\mu^2)$, for muon capture. Both compare favorably with experiments, albeit the finite-size effect at the lightest mass.

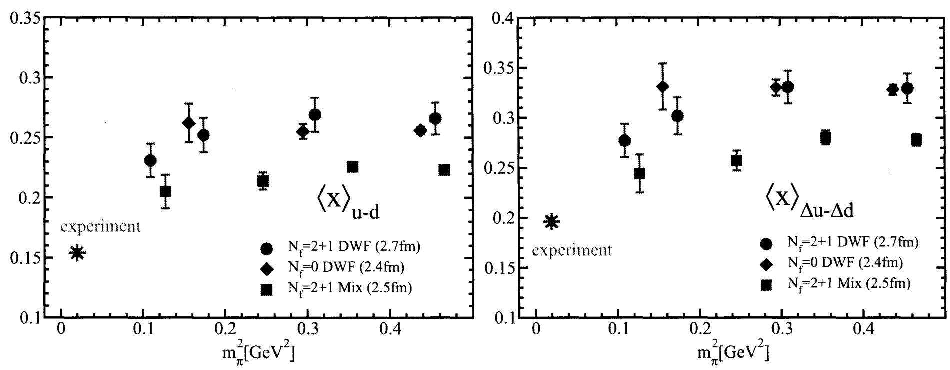
Moments of structure functions: the lattice ratio, $\langle x \rangle_{u-d}/\langle x \rangle_{\Delta u - \Delta d}$, of the isovector quark momentum fraction to the helicity fraction, is naturally renormalized on the lattice, much like the form factor ratio, g_A/g_V,



- It does not show any discernible dependence on the up/down quark mass, and
- in excellent agreement with the experiment.
- In contrast to g_A/g_V, however, this quantity does not deviate away from the experiment.

This suggests the moments of inelastic structure functions such as the momentum fraction, $\langle x \rangle_{u-d}$, and helicity fraction, $\langle x \rangle_{\Delta u - \Delta d}$, may not suffer so severely from the finite-size effect that plagues elastic form factor calculations. To clarify this, we are performing follow up calculations at the smaller volume of 1.8 fm.

Moments of structure functions: absolute values, $\langle x \rangle_{u-d}$, and $\langle x \rangle_{\Delta u - \Delta d}$, fully non-perturbatively renormalized ($Z = 1.15(4)$ and $1.15(3)$).



Both trend down toward the experiment at the lightest up/down mass:

- May well be real physics, as lighter quarks share its momentum more with other degrees of freedom.

To test this, we are conducting follow-up calculations on the smaller, 1.8 fm, volume.

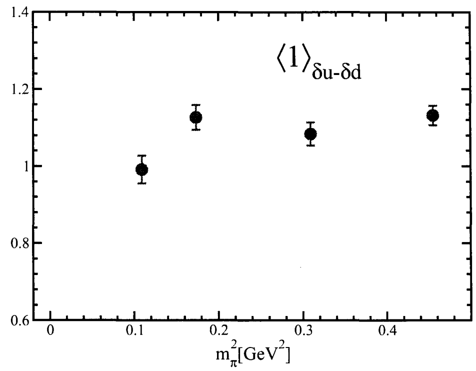
LHPC/MILC non-unitary mixed-action calculations[8] are significantly lower, by about 20 %, than ours. Likely caused by their use of

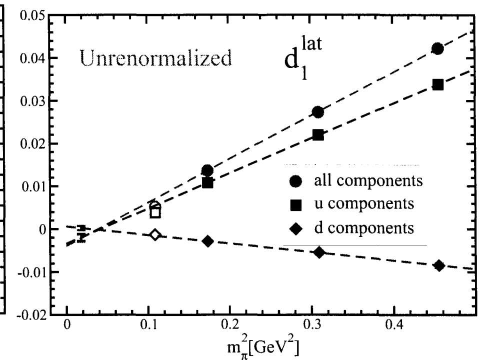
- only perturbative renormalization or the significantly shorter source/sink separation in time, or both.

[8]Ph. Hagler *et al.* [LHPC], Phys. Rev. D **77**, 094502 (2008) [arXiv:0705.4295 [hep-lat]].

Moments of structure functions:

- The isovector tensor charge, $\langle 1 \rangle_{\delta u - \delta d}$, fully NPR ($Z = 0.783(3)$), can provide a prediction, 1.10(7), or 0.7? We need to understand the finite-size correction and/or chiral extrapolation.





- Twist-3 d_1, though not renormalized yet, seems to support the Wandzura-Wilczek relation[9].

[9] S. Wandzura and F. Wilczek, Phys. Lett. B **72**, 195 (1977).

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

Large finite-size effect seen in axial-current form factors: major obstacle that demands larger volume:

- Most clearly seen in a naturally renormalized quantity, g_A/g_V. Demands 5-10 fm box.
- Yet G_P yeilds $g_{\pi NN}$ and g_P favorably comparing with experiments.
- Vector current is better-behaved: magnetic moment is good and radii call HBχPT into question.

In contrast, a similarly naturally renormalized ratio, $\langle x \rangle_{u-d}/\langle x \rangle_{\Delta u - \Delta d}$, does not suffer such a finite-size effect.

- It is consistent with experiment, and does not show any discernible quark-mass dependence.

In absolute values,

- Lightest points show an encouraging trend toward experiments in both momentum and helicity fractions.
  - Light quark or finite volume? Plan to check the smaller 1.8-fm box.
  - But they are different from corresponding LHPC/MILC results. NPR? Unitarity? Source/sink?
- Structure function renormalizations are now complete: typically 15-20 % effect.

Need better understanding of finite-size effects and chiral behaviors:

- Exploring auxiliary determinant calculations, with $(\sim 5\text{fm})^3$ volume and $\sim$200-MeV pion.

Study of η' meson using domain-wall QCD

Taku Izubuchi

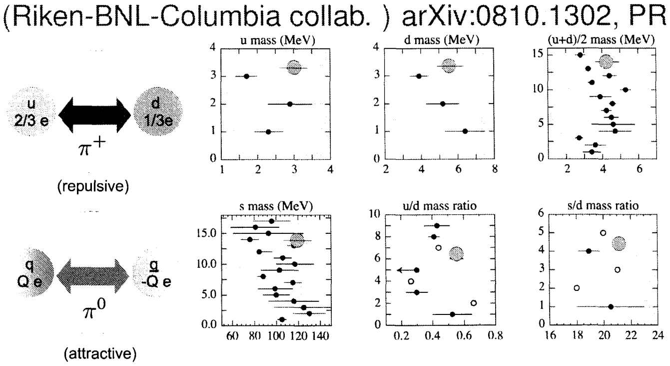
November 13, 2008

Lattice QCD

- Lattice QCD
- Strong $U(1)_A$ puzzle
- Calculation details
- $N_F = 2$ ensemble
- New mesurements
- Fitting procedures

Results

- Quenched approximation
- Dynamical quak effects ($N_F = 2, 2 + 1$)
- Isospin breaking from quark masses $m_u \neq m_d$.
  R. Zhou, T. Blum, T. Doi, M. Hayakawa, TI, N. Yamada
  (Riken-BNL-Columbia collab.) arXiv:0810.1302, PRD76:114508.



  (quoted in PDG 2008)
- Messon include disconnected quark loops, η'
  $\longrightarrow$ This talk

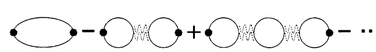
Strong $U(1)_A$ puzzle

- psuedoscalar (PS) mesons are light as it would be NG-boson in quark (u,d,s) massless limit, where the spontaneous chiral symmetry breaking occurs: $SU(3)_V \times SU(3)_A \rightarrow SU(3)_V$
- But flavor singlet PS, η', is special as $U(1)_A$ current is not conserved by quantum anomaly

$$\partial_\mu \langle A^0_\mu(x) \rangle = 2m\langle P^0 \rangle + \frac{N_f}{16\pi^2}\langle F\tilde{F}(x)\rangle$$

- DWF is chirally symmetric, has an integer definition of topolgical charge , thus an optimal lattice quark to study this puzzle.
- In $N_C \rightarrow \infty$, Witten-Veneziano formula:

$$M_0^2 = m_{\eta'}^2 - m_\pi^2 = \frac{2N_f}{f_\pi}\frac{\langle Q_{top}^2\rangle}{V}$$



Calculation details

- Lattice QCD
- Strong $U(1)_A$ puzzle
- Calculation details
- $N_F = 2$ ensemble
- New mesurements
- Fitting procedures

Results

- $N_F = 2$ dynamical DWQCD vacuume
  - Gaussian smearing (Wupertal smear)
  - Using the 2x2 correlators {unsmear, smear}-{unsmear, smear}
  - Positive definite correlators
  - Excited states
  - More frequent measurements in trajectories
- $\rho \sim$ 10% larger value at chiral limit
- a_0 lighter, $\sim$ 1 GeV from 1.5 GeV.
- η' has $\sim$ 15 % error
- π^* and f_{π^*}
- Nonzero signal for ω, the singlet vector meson.

- $N_F = 2 + 1$ calculations will be very interesting.

$N_F = 2$ ensemble

- $\beta = 0.80$ DBW2
- a^{-1} = 1.688(21) GeV (from r_0)
- La = 1.87 fm
- m_{res} = 0.00137(4)

m_f	M_{PS}/M_V	mesured configs
0.02	0.53(1)	940
0.03	0.60(1)	560
0.04	0.65(1)	470

New mesurements

- Z_2 randome spacial-wall and space-time volume source.

$$\xi^{(n)}(x) = \frac{1}{\sqrt{2}}[\xi_1^{(n)} + i\xi_2^{(n)}(x)], \quad \xi_1, \xi_2 = \pm 1 \tag{1}$$

which fullfills

$$\frac{1}{N_{\text{noise}}} \sum_{n=1}^{N_{\text{noise}}} \xi^{(n)}(x)\xi^{(n)}(x) = 0, \quad \frac{1}{N_{\text{noise}}} \sum_{n=1}^{N_{\text{noise}}} \xi^{(n)}(x)\xi^{(n)\dagger}(x) = \delta_{x,y} \tag{2}$$

- Gauge convariant smearing for both of quarks (Gaussian-shape smearing, Wuppertal) also to source and sink:

$$q_L(x) \to q_S(x) = \sum_y \left[\left\{ 1 + \frac{\omega^2}{4N} \sum_{i=1}^{3} (\nabla_i + \nabla_i^\dagger) \right\}^N \right]_{x,y} q_L(y)$$

Fitting procedures

- Two (four) intepolation fields
  - $O_L = \overline{q_L}(x)\Gamma q_L(x)$: local intepolation fields
  - $O_S = \overline{q_S}(x)\Gamma q_S(x)$: smared intepolation fields
- Standard fit

$$\langle O_S(t) O_S^\dagger(0)\rangle = A_O \left[e^{-m_O t} + m^{-m_O(N_t - t)} \right]$$

- Variational method

$$X(t) = \begin{pmatrix} \langle O_L(t) O_L^\dagger(0)\rangle & \langle O_L(t) O_S^\dagger(0)\rangle \\ \langle O_S(t) O_L^\dagger(0)\rangle & \langle O_S(t) O_S^\dagger(0)\rangle \end{pmatrix} \quad (3)$$

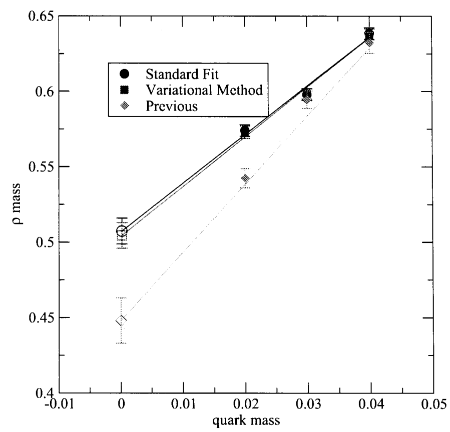
is dianoalized

$$X^{-1/2}(t_0) X(t) X^{-1/2}(t_0) \to \begin{pmatrix} \lambda_O(t,t_0) & \\ & \lambda_O^*(t,t_0) \end{pmatrix}$$

to get $\lambda_O^{(*)}(t,t_0) \to m^{-m_{O^{(*)}}(t-t_0)}$.

Results

ρ

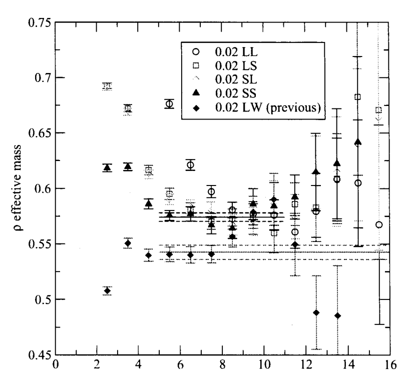


- $m_f = 0.02$ point get 5 % larger
- , which makes the chiral limit 10 % larger
- Both the standard fit and variational gives consistent results.
- From $M_\rho = 770$ MeV at (previously estimated) ud mass point,

$$a_{m_\rho}^{-1} = 1.526(26)GeV \quad (4)$$

$$r_0 = 0.5530(93)fm,$$

ρ effective mass



- Prevdue measuremnt using point-wall (LW) might have excited state contamination with negative coefficient.
- Excited state contamination in smeared-smeared should only increase mass, effective mass is ought to come down from above.
- This was also pointed out in $N_F = 2 + 1$ case.
- This discrepancy is visible only for m_f =0.02 point, previous results are consistent with the new one on other masses.
- Within statistical error, inequalities,

$$\text{LL} > \text{LS} = \text{SL} > \text{SS}$$

holds.

π^* quiz

- Axial Ward-Takahashi identity (in spacial momentum zero sector)

$$\partial_4 \langle A_4(x) \mathcal{O} \rangle = 2m_f \langle J_5(x) \mathcal{O} \rangle$$

$$\partial_4 \langle 0|A_4(x)|\pi^* \rangle e^{-p_4 t} \langle \pi^* | \mathcal{O} | 0 \rangle = 2m_f \langle J_5(x) \mathcal{O} \rangle$$

- Chose $\mathcal{O}$ such that

$$\langle 0|\mathcal{O}|\pi\rangle = 0, \quad \langle 0|\mathcal{O}|\pi^*\rangle \neq 0,$$

- Using, $\partial_4 \langle A_4(x)\mathcal{O}\rangle = p_4 \langle A_4(x)\mathcal{O}\rangle$, and $\langle 0|A_\mu(x)|\pi^*(p)\rangle \propto p_4 = M_{\pi^*}$,

$$M^2_{\pi^*} \propto 2m_f$$

- RHS is zero for $m_f \to 0$, but π^* is not NG bosons, should be massive in the chiral limit. What's wrong ?

Answer of π^* quiz

- $\langle 0|A_\mu(x)|\pi^*(p)\rangle \propto p_4 = M_{\pi^*}$, is true, but writing propotinality coefficient explicitly,

$$\langle 0|A_\mu(x)|\pi^*(p)\rangle = p_4 f_{\pi^*}$$

- the PCAC relation becomes

$$M^2_{\pi^*} \times f_{\pi^*} \propto 2m_f$$

so if $M^2_{\pi^*} \neq 0$,

$$f_{\pi^*} = C m_f$$

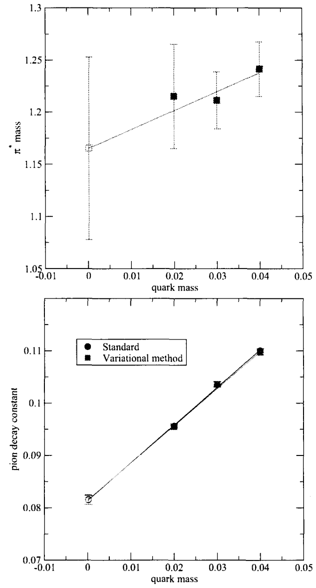
for small m_f.

- The decay constant of π^* is zero at chiral limit, keeping π^* mass finite.

π^* results

- Lattice QCD
- Strong $U(1)_A$ puzzle
- Calculation details
- $N_F = 2$ ensemble
- New mesurements
- Fitting procedures

Results
- ρ
- ρ effective mass
- π^* quiz
- Answer of π^* quiz
- π^* results
- $a_0, I = 1, J^{PC} = 0^{++}$
- η'
- η' results
- Summary



- variational methods with $t_0 = 5$
- By a linear fit, $m_f \to m_{ud}$

$$M_{\pi^*} a = 1.165(88), \quad (5)$$

$$M_{\pi^*} = 1.97(17)\text{GeV} \quad (6)$$

(exp. ~ 1.3GeV) (7)

- Most likely, 2nd excited states etc. are contaminated.
- Nevertheless we plot f_{π^*} at $m_f = -m_{res}$.
- f_π is consistent with previous results.

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$a_0, I = 1, J^{PC} = 0^{++}$

- Lattice QCD
- Strong $U(1)_A$ puzzle
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Results
- ρ
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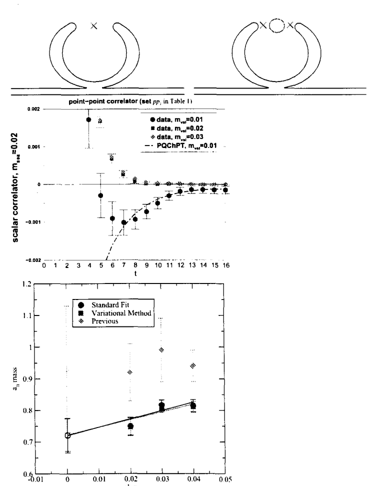
- $a_0, I = 1, J^{PC} = 0^{++}$
- η'
- η' results
- Summary

- Propagator is sensitive to the (partially) quenched pathologies.
- Most of the previous calculations obtained ~ 1.5 GeV with a few new calculation with ~ 1.0 GeV.
- There are interesting interpretations for $a_0(980), a_0(1450)$: molecule, hybrid, ..
- After the smearing and accumulate the data our new result is:



$$m_{a_0} = 1.10(8)\text{GeV}$$

(previously $m_{a_0} = 1.58(34)$GeV)

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η'

- Lattice QCD
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- New mesurements
- Fitting procedures

Results
- ρ
- ρ effective mass
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- Answer of π^* quiz
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- $a_0, I = 1, J^{PC} = 0^{++}$
- η'
- η' results
- Summary

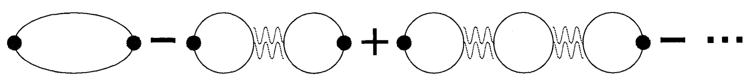
- $\eta'(x) = 1/\sqrt{N_f}\sum_f \bar{q}_f(x)\gamma_5 q_f(x)$ is consists of a connected quark loop, C(t), and disconnected loops, D(t):

$$\langle \eta'(t)\eta'^\dagger(0)\rangle = C(t) - N_f D(t) \tag{8}$$

$$C(t) = \langle \mathrm{Tr}\,[S_{t,0}\gamma_5 S_{0,t}\gamma_5]\rangle, \tag{9}$$

$$D(t) = \langle \mathrm{Tr}\,[S_{t,0}\gamma_5]\rangle\langle \mathrm{Tr}\,[S_{0,t}\gamma_5]\rangle, \tag{10}$$

(11)



-

$$\frac{N_f D(t)}{C(t)} = 1 - Be^{-\Delta M t} \tag{12}$$

$$M_{\eta'}^2 = M_\pi^2 + M_0^2, \quad M_0^2 = \frac{2N_f}{f_\pi^2}\chi, \quad \chi = \langle \frac{Q_{top}^2}{V}\rangle \tag{13}$$

η' results

- Lattice QCD
- Strong $U(1)_A$ puzzle
- Calculation details
- $N_F = 2$ ensemble
- New mesurements
- Fitting procedures

Results
- ρ
- ρ effective mass
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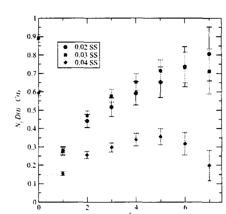
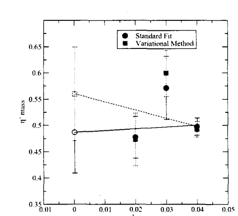




- Ratio plot

$$\frac{N_f D(t)}{C(t)} = 1 - Be^{-\Delta M t}$$

- statistic error is 15% for upto 500 hundred configuration with smearing technics.
-

$$M_{\eta'} = 813(126)\text{MeV}$$

$$M_\omega = 785(193)\text{MeV}$$

Summary

- $\rho \sim$ 10% larger value at chiral limit
- a_0 lighter, $\sim$ 1 GeV from 1.5 GeV.
- 'η' has $\sim$ 15 % error
- π^* and f_{π^*}
- Nonzero signal for ω.

Improved non-perturbative renormalization

Yasumichi Aoki Research Center

Scientific Review Committee Meeting

11/17/08

This talk is based on the works:

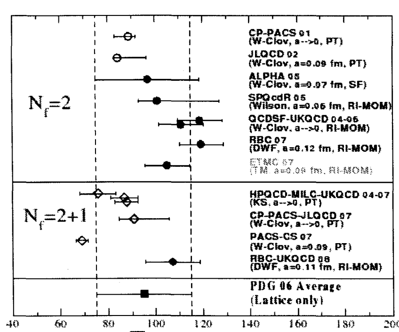
- Physical results from 2+1 flavor domain wall QCD and SU(2) chiral perturbation theory [to appear in PRD]
  - RBC and UKQCD collaborations
  - bare quark mass estimate
- Non-perturbative renormalization of quark bilinear operators and B_K using domain wall fermions [PRD 78 (08) 054510]
  - RBC and UKQCD collaborations
  - idea of non-exceptional momenta for improvement
- Quark bilinear operators renormalized in MOM-scheme for the symmetric subtraction point [in preparation]
  - C. Sturm, Y. Aoki, N. H. Christ, T. Izubuchi, and A. Soni
  - construction of a non-exceptional RI-MOM scheme for mass renormalization and 1 loop matching
- Ongoing numerical work on non-perturbative renormalization

2+1 flavor DWF simulation

- Precise determination from first principles within reach:
  - QCD parameter, basic weak matrix elements
- Light quark masses m_u, m_d, m_s
  - Fundamental parameter
  - Comparison with other fermions (Wilson, staggered)
- Precision test of the standard model
  - B_K, $K \to \pi\pi$
- These parameter needs renormalization

Strange quark mass

K. Jansen, Lattice 2008



Stat. error only for PACS-CS

- N_f=2+1 results spread over ±20%
  - Hardly precise
  - Non-perturbative vs perturbative renormalization ?
  - Staggered rooting problem ?
- More precise results desired !
- Our result (RBC/UKQCD)

$$m_s^{\overline{\mathrm{MS}}}(2\mathrm{GeV}) = 107.3(4.4)_{\mathrm{stat}}(4.9)_{\mathrm{syst}}(9.7)\mathrm{ren}\mathrm{MeV}.$$

- improvement of renormalization needed

RI/MOM scheme

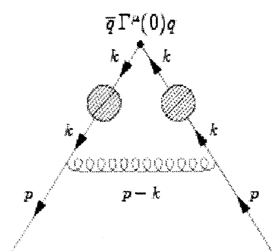
- impose renormalization condition on the vertex functions with off-shell quark states with momentum *p* at mass less limit: [Martinelli et al NPB445(95)81].
- renormalization condition on the vertex function Π of bilinear operator $O = \overline{u}\Gamma d$

$$\frac{Z_O}{Z_q}\frac{1}{12}\mathrm{Tr}(\Pi_O P_O) = 1 \qquad \text{at } p^2 = \mu^2,\ m \to 0$$

- matching to a continuum scheme ($\overline{\mathrm{MS}}$) must be done at large momentum to reduce
  - truncation error of continuum perturbation theory
  - contamination of non-perturbative effect (NPE)

  $\longrightarrow$ These indeed are the main sources of the systematic error of Z_m
- Window: $\Lambda_{QCD} \ll p \ll a^{-1}$

Typical NPE contamination in MOM scheme



- $1/p^2$ through Weinberg's theorem for the exceptional momenta used in the conventional MOM:
  - one gluon exchange: $1/p^2$
  - upper part affected by different NP depending on the opeator
  - P: with pion pole: $1/m_f$
  - S: double pole (quench) from topological near zero mode
  - A-V: $1/p^2$
- Suppressed if $p_1 \neq p_2$ non-exceptional momenta
  - p cannot reroute through 1 gluon exchange
  - No pion, pole, double pole, $1/p^2 \longrightarrow 1/p^6$
  - sMOM scheme: all 3 momenta scale as |p| : constructed

Systematic error of MOM scheme

- How to evaluate unwanted non-perturbative contamination:
  - Spontaneous chiral symmetry breaking:

$$\Lambda_A = \Lambda_V? \; \Lambda_P = \Lambda_S?$$

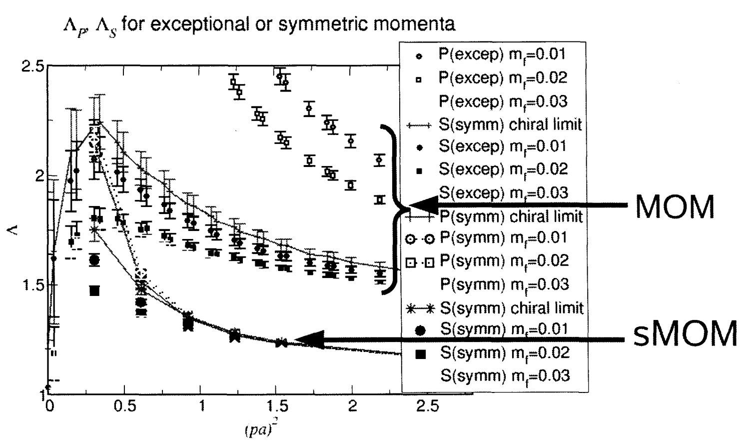
  - Further detail on Λ:

$$X \times \left([\text{perturbative part}] + \overbrace{\frac{\Lambda_{QCD}^2}{p^2}, \; \frac{m_q \Lambda_{QCD}}{p^2}}^{} + \cdots\right)$$
$$+(pa)^2 + \cdots$$

Hard to measure   Easier

- m_q depending part @ $m_q \approx \Lambda_{QCD}$ represents the error

MOM and sMOM $\Lambda_{S,P} = Z_q Z_m$



- S, P (chiral) symmetry
  - broken (MOM)
  - intact (sMOM)
- mass dependence
  - large (MOM)→large sys. error
  - small (sMOM)

sMOM → $\overline{\text{MS}}$ matching

- sMOM → $\overline{\text{MS}}$ conversion factor

$$C_m = 1 + \frac{\alpha_s}{4\pi} C_F c_m^{(1)} \qquad c_m^{(1)} = \begin{cases} 0.484 - 0.172\xi & \text{(sMOM)} \\ 4 - \xi & \text{(MOM)} \end{cases}$$

  - sMOM: smaller constant and gauge dependence

- size of 1-loop correction at $\mu = 2$ GeV in Landau gauge

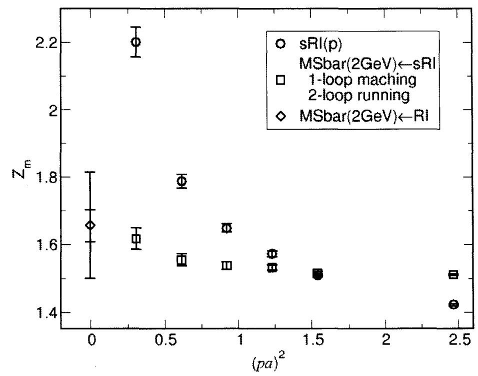
$$\begin{cases} 1.5\% & \text{(sMOM)} \\ 12.3\% & \text{(MOM, 1 loop)} \\ 6.2\% & \text{(MOM, 3 loop)} \end{cases}$$

  - sMOM: very small already at 1 loop

error budget on Z_m

MOM	sMOM
• 7% from $m_s \neq 0$	• much smaller: few %
– NP contamination	
• 6% from $O(\alpha_s^3)$	• 1.5% already small at $O(\alpha_s)$
• 3% statistical	• a little smaller
	– drastic improvement possible →momentum source
• 9% in total	• total: very small

sMOM Z_m



- 1 loop matching and 2 loop running makes flat $(pa)^2$ dep
- preliminary result, $(pa)^2 \to 0$ extrapolation not attempted
- consistent with $\mathrm{MOM} \to \overline{\mathrm{MS}}$ which has large systematic error

Summary

- Improvement of the renormalization helps precise determination of QCD and Standard Model parameters
- conventional MOM scheme uses exceptional momenta, thus has sizable, unwanted non-perturbative contamination. Non-exceptional momenta should be used to reduce it.
- sMOM scheme using non-exceptional momenta constructed for bilinear operators and quark mass.
- $\mathrm{sMOM} \to \overline{\mathrm{MS}}$ matching calculated in 1 loop. The correction appeared to be very small.
- Using NPR data with 2+1 f DWF, sMOM scheme NPR were studied. Large reduction of the systematic error has been observed.
- Systematic error on Z_m reduced very much. Promising!
- Similar technique could be useful for other operators: B_K etc.

Dynamical QED+QCD Lattice Simulations

Tom Blum
(University of Connecticut, RIKEN BNL Research Center)

RBRC Scientific Review, BNL, November 17, 2008

Outline

- Motivation
- Results from the valence sector
- Proposal for dynamical simulations

1

Motivation

- Previous work is incomplete
  - photons not coupled to sea quarks
  - Hadron mass splittings
  - Low energy constants at NLO unknown
  - (g-2 OK, working at fixed order in QED PT)
- Chiral Magnetic Effect [Kharzeev, *et al.*]
- First calculation of this kind (hard to see all possibilities? And pitfalls!)

2

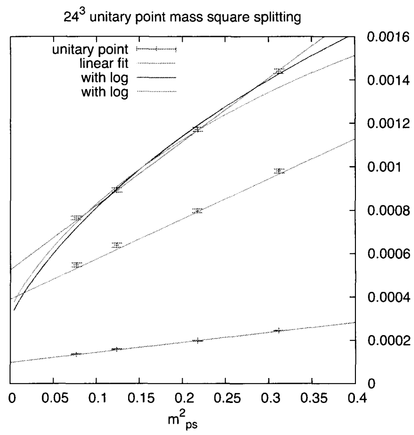
Motivation: Chiral Magnetic Effect

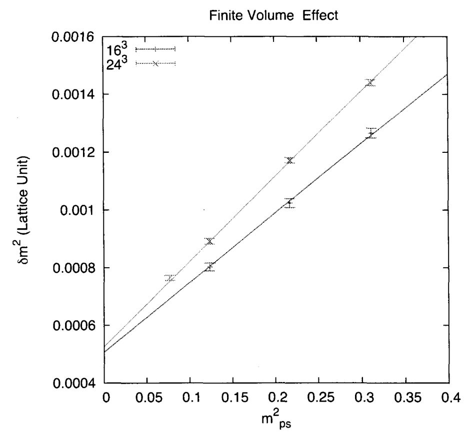
- Investigate CP violation above T_c (QCD) [Kharzeev, Pisarski, and Tytgat; Kharzeev(2006); Fukushima, Kharzeev, and Warringa (2008); Kharzeev, McLerran, and Warringa (2008); and many others]
- Directly observe effects due to **instantons** in RHIC experiments (event-by-event basis)
- Need (model independent) lattice demonstration of effect. Later, provide help with phenomenology
- Physics is well suited to lattice, especially with emerging "technologies" (RHMC, Auxiliary Determinant, ...)
- Domain Wall Fermion (DWF) thermodynamics coming of age.

3

Results from the valence quark sector

Pion mass splitting (squared) due to QED (2+1 flavors, DWF)

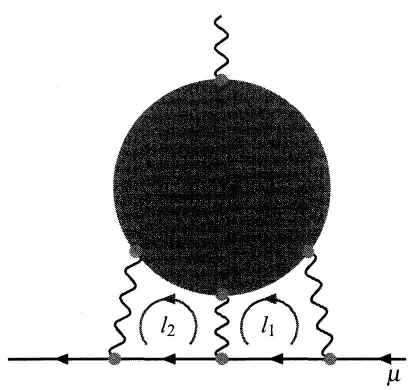


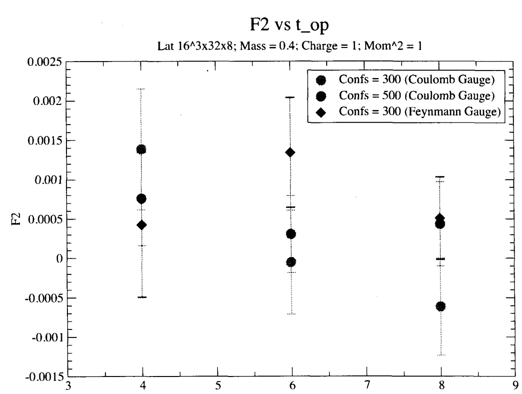


[Ran Zhou, Lattice 2008]

4

Results from the valence quark sector





[S. Chowdhury, Lattice 2008]

Light-by-light scattering in pure QED (warm up: g-2 hadronic contribution). No signal yet.

5

Proposal for dynamical simulations

- Extend current Columbia Physics System (CPS) code
- $2+1$ flavors $\rightarrow 1+1+1$ ($Q = 2/3, -1/3, -1/3$) (m_u, m_d, m_s).
- Straightforward use of existing Rational Hybrid Monte Carlo code with modified QCD force term to include photons, added QED force terms
- For Chiral Magnetic Effect, need external magnetic field, chiral chemical potential (if topology not fixed)
- Start above T_c, follow new RBC DWF simulations using Auxiliary Determinant. But also simulate in *fixed* topological charge sector (JLQCD)
- small pilot study easily accomodated on QCDOC, NYBlue

6

Summary and Outlook

- Current valence QED+QCD calculations productive
  - Hardon mass splittings, NLO QED LEC's
  - g-2 difficult, on-going
- Chiral magnetic effect, very interesting QCD physics!
  - take advantage of existing RBC/UKQCD infrastructure
  - Aim for first results next spring

7

Perturbative O(a) matching in static heavy and domain-wall light quark system

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RBC/UKQCD Collaborations

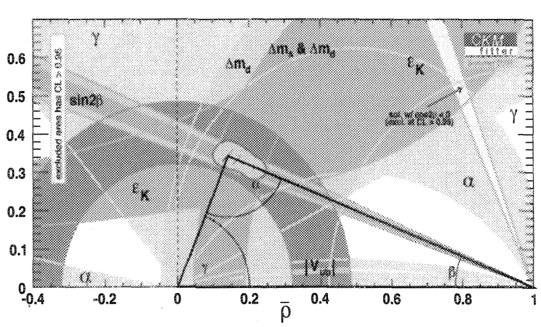
RBRC Scientific Review Committee Meeting
November 17-18, 2008

1

B physics on the lattice

- Lattice QCD with b-quarks
  - Valuably contribute to CKM-physics
  - Provide an approach to determine parameters which is experimentally difficult to obtain:
    - b-quark mass m_b
    - B meson decay constant

$$\langle B_q(p)|A_\mu|0\rangle = ip_\mu f_{B_q}$$
$$A_\mu = \bar{b}\gamma_\mu\gamma_5 q$$
$$q = \{d, s\}$$



    - Hadronic matrix element

$$\mathcal{M}_{B_q} = \langle \overline{B}^0_q|[\bar{b}\gamma_\mu P_L q][\bar{b}\gamma_\mu P_L q]|B^0_q\rangle = \frac{8}{3}m^2_{B_q} f^2_{B_q} B_{B_q}$$
$$\Delta m_{B_q} = (\text{known factors}) \times \left|V^*_{tq}V_{tb}\right|^2 m_{B_q} f^2_{B_q} B_{B_q}$$

2

B physics on the lattice

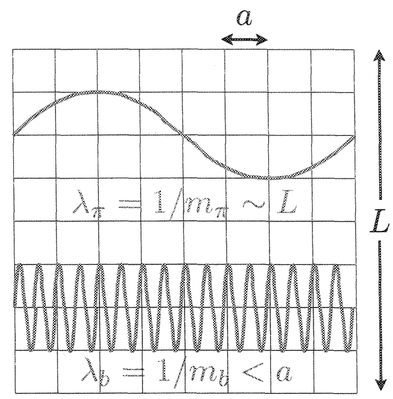
- Difficulty of heavy-light system
  - Basically, multi-scale problem
    - Light quark is too light.

      Large volume is needed.

      $L > 2\ \mathrm{fm}$
    - b-quark is too heavy.

      Small lattice spacing is needed.

      $a \ll (5\ \mathrm{GeV})^{-1} = 0.04\ \mathrm{fm}$



  - Various framework to avoid the problem
    - Heavy Quark Effective Theory (HQET)
    - Non-relativistic QCD (NRQCD)
    - Relativistic Heavy Quark Formalism

3

Heavy Quark Effective Theory (HQET)

- $1/m_b$ expansion of QCD

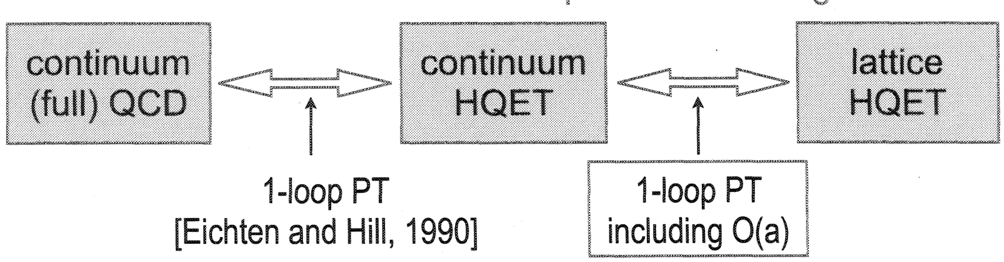
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{2g_0^2}\mathrm{Tr}F_{\mu\nu}F_{\mu\nu} + \sum_f \bar{\Psi}_f\left(\gamma_\mu D_\mu + m_f\right)\Psi_f$$

- HQET: formal $1/m_b$ expansion of QCD

$$\bar{b}\left(\gamma_\mu D_\mu + m_b\right)b \quad \longrightarrow \quad \mathcal{L}_{\mathrm{stat}} + O(1/m_b),$$
$$\mathcal{L}_{\mathrm{stat}} = \bar{h}\left(D_0 + \delta m\right)h$$

- Expansion is accurate for heavy quark mass $m_h \gg \Lambda_{\mathrm{QCD}}$

- Operator matching
  - different renormalization $\longrightarrow$ operator matching



4

HQET on the lattice

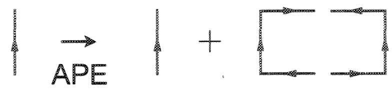
- Lattice discretization [Eichten and Hill, 1990]

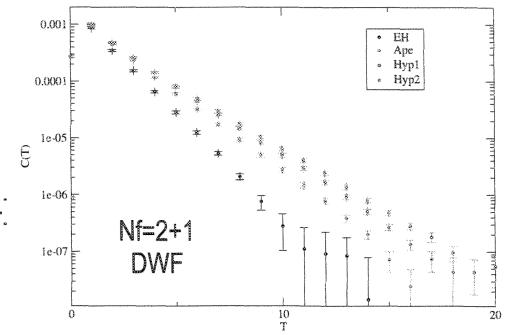
$$S_{\rm stat} = \sum_{\vec{x},t} \bar{h}(\vec{x},t)\left[h(\vec{x},t) - U_0^\dagger(\vec{x},t-1)h(\vec{x},t-1)\right]$$

- Gauge link smearing
  - Static propagator is very noisy.

  ⟶ link smearing (APE, HYP1, HYP2)

  [Della Morte et al.(ALPHA), 2004]





[J. Wennekers(RBC/UKQCD), Lattice 2007]

- O(a) in the HQET operator
  - HQET operators have O(a) error. $A_\mu = \bar{h}\gamma_\mu\gamma_5 q, \quad A_0^{\rm cont} = Z_A A_0^{\rm latt} + O(a)$ ~10%

  ⟺ light-light (DWF) case: $A_\mu = \bar{q}\gamma_\mu\gamma_5 q, \quad A_0^{\rm cont} = Z_A A_0^{\rm latt} + O(a^2)$ ~1%

5

$O(a)$ improvement of HQET operator

- O(a) improvement

  Introduction of O(a) counter terms

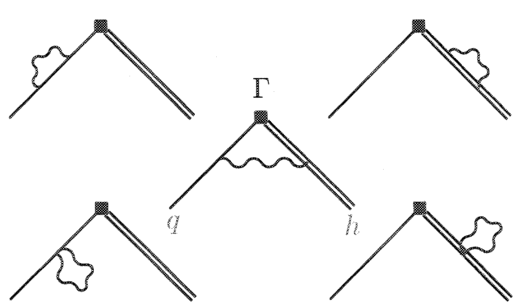
$$A_0^{\rm cont} = Z_A[A_0^{\rm latt} + a\underbrace{(\overset{O(pa)}{c_A\partial_0 A_0^{\rm latt}} + \overset{O(m_q a)}{b_A m_l A_0^{\rm latt}})}_{\rm counter\ terms}] + O(a^2)$$

- Operator matching procedure

scattering amplitude $\langle h|A_0|q\rangle^{\rm cont}$

⇕ **matching** $\longrightarrow Z_A,\ c_A,\ b_A$

scattering amplitude $\langle h|A_0|q\rangle^{\rm latt}$



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Effects of the O(a) improvement

- decay constants

  $f_{B_d},\ f_{B_s}$: ↓ 10%

- bag parameters

  $B_{B_d},\ B_{B_s}$: ↑ 20%

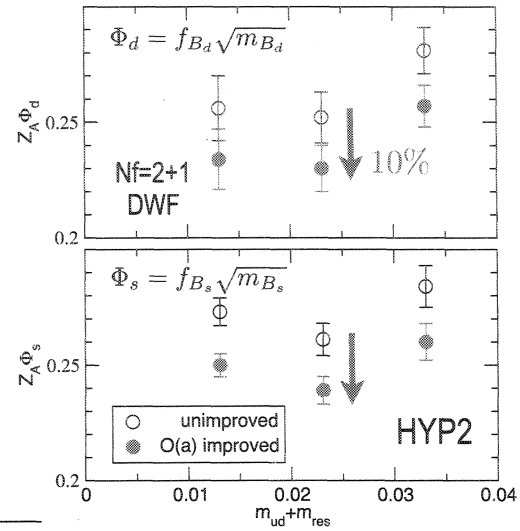
- matrix elements

  $\mathcal{M}_{B_d},\ \mathcal{M}_{B_s}$: small effect

- SU(3) breaking ratio

$$\xi = \frac{f_{B_s}}{f_{B_d}}\sqrt{\frac{B_{B_s}}{B_{B_d}}} = \frac{m_{B_d}}{m_{B_s}}\sqrt{\frac{\mathcal{M}_{B_s}}{\mathcal{M}_{B_d}}}$$: small effect

$(\beta = 2.13,\ a \sim 0.12\ \text{fm},\ V = 16^3 \times 32 \times 16)$



Summary and future plans

- O(a) improvement of HQET operators
  - O(a) error exists even for static heavy - domain-wall light.
  - 1-loop perturbative calculation including the gauge link smearing
- Effects of the O(a) improvement
  - Decay constant f_B moves about 10% ↓.
  - Bag parameter B_B moves about 20% ↑.
  - The effect for the matrix element $\mathcal{M}_B$ and SU(3) breaking ratio ξ is small.
- Future plans
  - Precise analysis using the $O(a)$ improvement
  - Non-perturbative determination of the matching factor and the $O(a)$ improvement coefficient
  - $O(1/m_b)$ correction

Drell-Yan Lepton Pair Azimuthal Asymmetry:

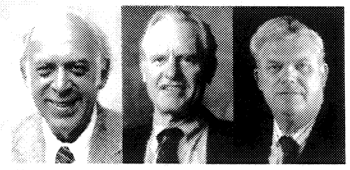
--- Lam-Tung Relation Revisited

Feng Yuan
Lawrence Berkeley National Laboratory
RBRC, Brookhaven National Laboratory

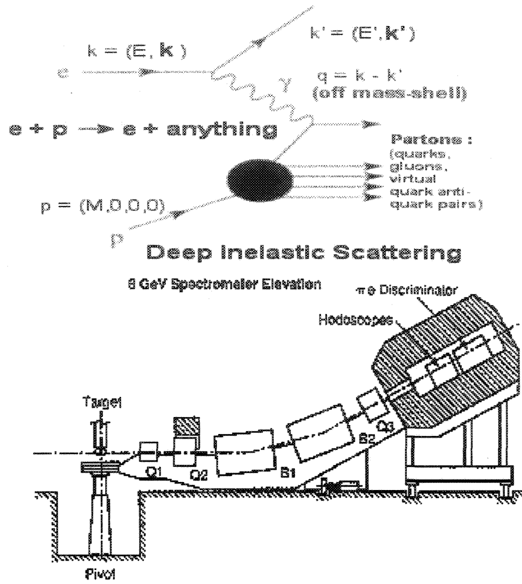
Summary of 2008

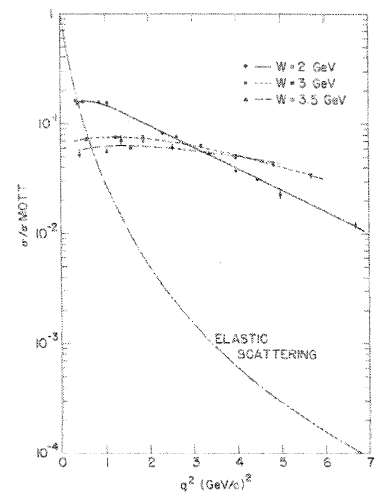
- **Collins contribution to SSA**
  - Azimuthal asymmetric distribution of hadrons inside a jet at hadron collider, F.Yuan, **Phys.Rev.Lett.100:032003,2008**
  - Collins Asymmetry at Hadron Colliders, F.Yuan, **Phys.Rev.D77:074019,2008**
  - Single Spin Asymmetry in Inclusive Hadron Production in pp Scattering from Collins Mechanism, F.Yuan, **Phys.Lett.B666:44-47,2008**
- **Heavy flavor SSA**
  - Heavy Quarkonium Production in Single Transverse Polarized High Energy Scattering, F.Yuan, **Phys.Rev.D78:014024,2008**
  - Single Spin Asymmetries in Heavy Quark and Antiquark Productions, F. Yuan, J. Zhou, **Phys.Lett.B668:216-220,2008**
  - Accessing tri-gluon correlations in the nucleon via the single spin asymmetry in open charm production, Z. Kang, J.Qiu, W.Vogelsang, F. Yuan, **arXiv:0810.3333**
- On the Relation Between Mechanisms for Single-Transverse-Spin Asymmetries, Y. Koike, W.Vogelsang, F. Yuan, **Phys.Lett.B659:878-884,2008**
- Hyperon Polarization in Unpolarized Scattering Processes, J. Zhou, F. Yuan, Z. Liang, **arXiv:0808.3629**
- Pretzelosity distribution function h**perp(1T) and the single spin asymmetry A**sin(3phi-phi(s))(UT), H.Avakian, A. Efremov,P. Schweitzer, F. Yuan, **arXiv:0805.3355**
- Plus several conference proceedings, and **some preprints**

Deep Inelastic Scattering probe partons in nucleon

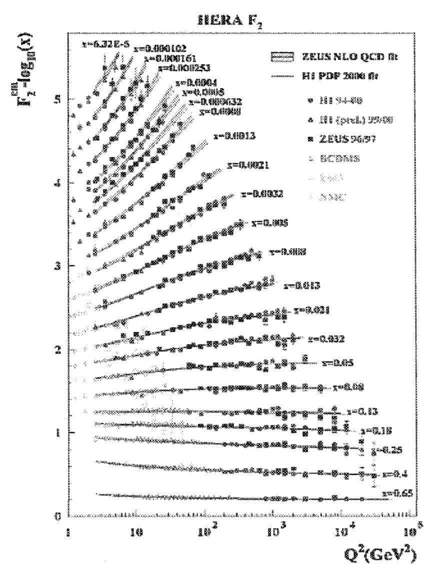


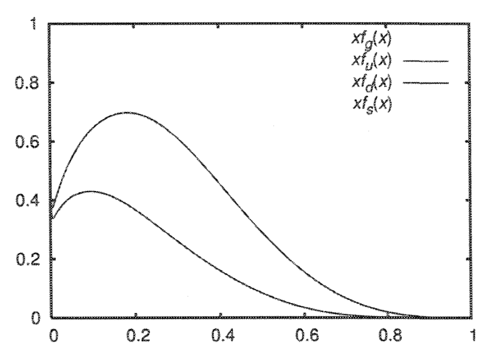
Friedman Kendall Taylor





Modern era: HERA





CTEQ6

Reverse the DIS: Drell-Yan

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

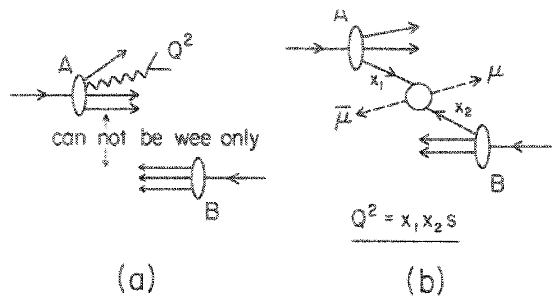
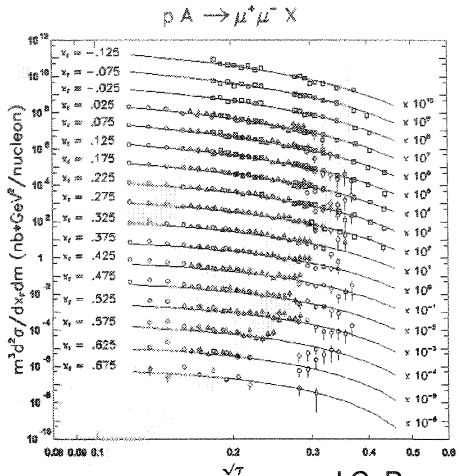


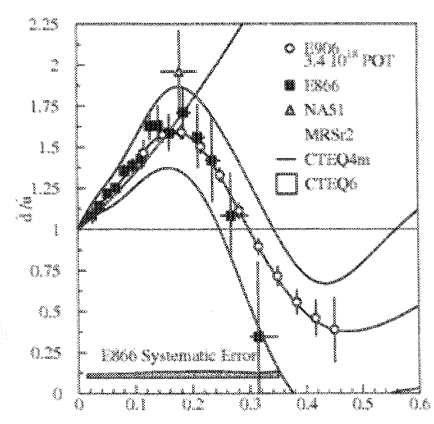
FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.



J.C. Peng

Importance of Drell-Yan Measurement

- Input for the global fit of the parton distributions
- Especially for sea quarks



More over: angular distribution in Drell-Yan

Angular distribution of dileptons in high-energy hadron collisions*

John C. Collins and Davison E. Soper
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 28 February 1977)

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta + (\tfrac{1}{2} - \tfrac{3}{2}\cos^2\theta)A_0$$

$$+ 2\cos\theta\sin\theta\cos\phi\, A_1 + \tfrac{1}{2}\sin^2\theta\cos 2\phi\, A_2 ,$$

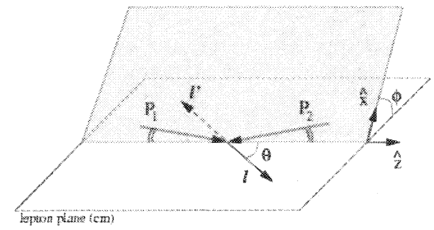


FIG. 1: The Collins-Soper frame. Boer-Vogelsang

In the limit of Q^2→Infinity, Parton Model

$$A_0 \approx Q^{-2}\langle(\vec{k}_{aT} - \vec{k}_{bT})^2\rangle ,$$

$$A_1 \approx Q^{-1}|\vec{Q}_T|^{-1}\langle\vec{k}_{aT}{}^2 - \vec{k}_{bT}{}^2\rangle ,$$

$$A_2 \approx 2Q^{-2}|\vec{Q}_T|^{-2}\langle[\vec{k}_{aT}{}^2 - \vec{k}_{bT}{}^2]^2\rangle - A_0 .$$

<<1

Burst of ideas to study QCD dynamics in Drell-Yan process

Systematic approach to inclusive lepton pair production in hadronic collisions

C. S. Lam and Wu-Ki Tung*
Department of Physics, McGill University, Montreal, P.Q., H3A 2T8, Canada
(Received 2 May 1978)

Lam-Tung Relation ⇨

$$\frac{d\sigma}{d^4q\, d\Omega^*} \propto 1 + \alpha\cos^2\theta^* + \beta\sin 2\theta\cos\phi^*$$

$$+ \gamma\sin^2\theta^*\cos 2\phi^* ,$$

Eq. (7) implies

$$1 - \alpha = 4\gamma$$

Parton model prediction, but insensitive to QCD Corrections.

For example:

Simple Prediction of Quantum Chromodynamics for Angular Distribution of Dileptons in Hadron Collisions

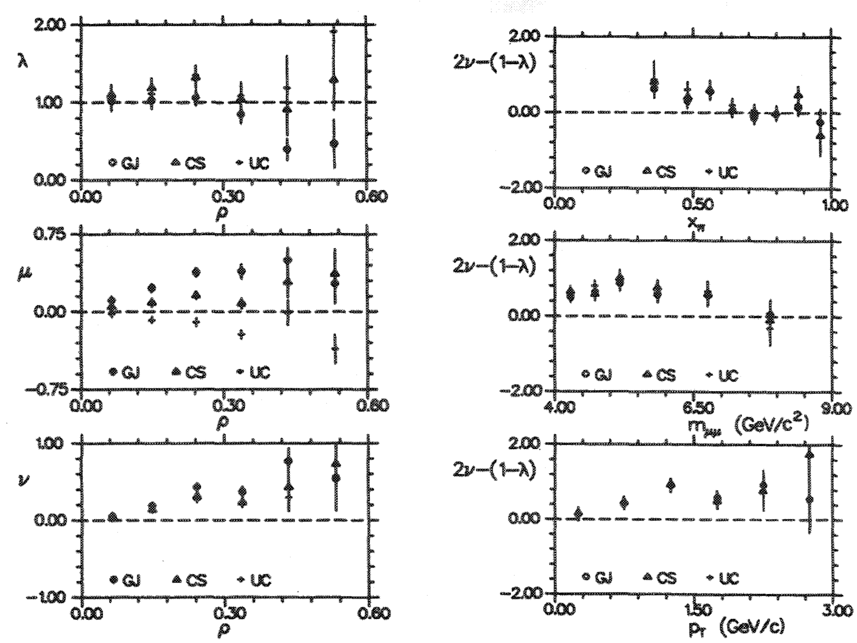
John C. Collins
Princeton University, Princeton, New Jersey 08540
(Received 27 September 1978)

- Gluon radiation contribution, 

$$\frac{dN}{d\Omega}=\frac{3}{16\pi}\left[\frac{q^2+\frac{3}{2}q_\perp^{\,2}}{q^2+q_\perp^{\,2}}+\frac{q^2-\frac{1}{2}q_\perp^{\,2}}{q^2+q_\perp^{\,2}}\cos^2\theta+\frac{2W_\Delta}{2W_T+W_L}\sin 2\theta\cos\varphi+\frac{\frac{1}{2}q_\perp^{\,2}}{q^2+q_\perp^{\,2}}\sin^2\theta\cos 2\varphi\right],$$

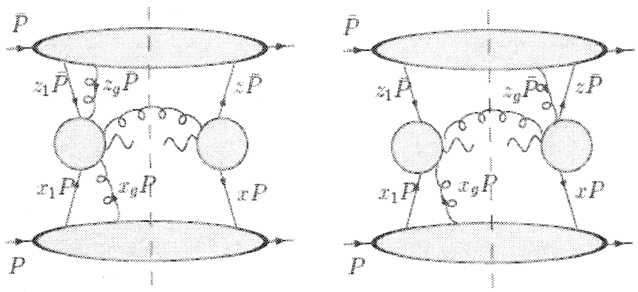
  - Lam-Tung relation is still valid
    - Boer-Vogelsang, 2006
    - Berger-Qiu, 2007

Pion induced experiments



E615, PRD39, 92

A_2 contribution from the Double initial state interaction



Brodsky, et al., 2002
Qiu-Sterman, 91,98

- Total more than 200 diagrams

Compare to the azimuthal symmetric one at small p_t

$$\frac{d\sigma}{d\Omega dx_B dz_B d^2Q_\perp} = \frac{\alpha_{em}^2}{3Q^2}\cos(2\phi)y(1-y)\frac{2}{Q_\perp^4}\frac{\alpha_s}{2\pi^2}\sum_\alpha e_\alpha^2$$

A_2

$$\int\frac{dx}{x}\frac{dz}{z}\left\{A\bar{T}_{F,\bar{\alpha}}^{(\sigma)}(z,z)\delta(\hat{\xi}-1)+\bar{A}T_{F,\alpha}^{(\sigma)}(x,x)\delta(\xi-1)\right.$$
$$\left.+2C_F\delta(\xi-1)\delta(\hat{\xi}-1)T_{F,\alpha}^{(\sigma)}(x,x)\bar{T}_{F,\bar{\alpha}}^{(\sigma)}(z,z)\ln\frac{Q^2}{Q_\perp^2}\right\}$$

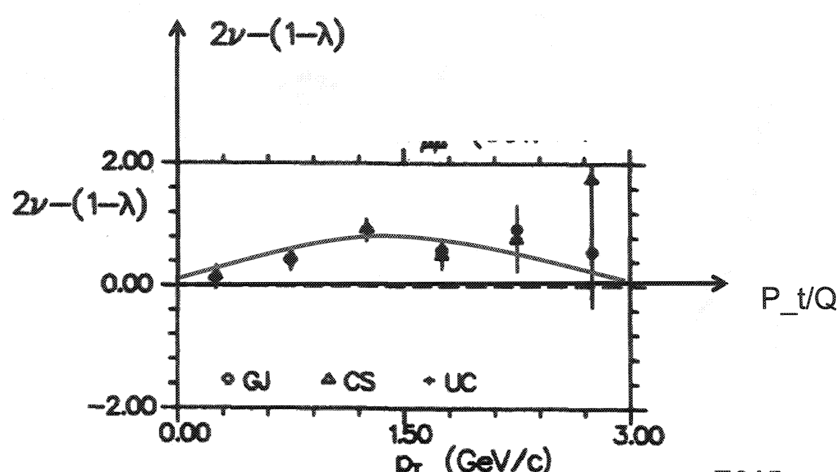
$$\frac{d^4\sigma^{q\bar{q}\to\gamma^* g}}{dQ^2dyd^2q_\perp} = \sigma_0\frac{\alpha_s}{2\pi^2}C_F\frac{1}{q_\perp^2}\int\frac{dx}{x}\frac{dx'}{x'}\sum_q e_q^2 q(x)\bar{q}(x')\left[\frac{1+\xi_1^2}{(1-\xi_1)_+}\delta(\xi_2-1)\right.$$
$$\left.+\frac{1+\xi_2^2}{(1-\xi_2)_+}\delta(\xi_1-1)+2\delta(\xi_1-1)\delta(\xi_2-1)\ln\frac{Q^2}{q_\perp^2}\right]. \quad \sigma_0 = 4\pi\alpha_{\rm em}^2/3N_C sQ^2$$

- It is not suppressed by 1/Q^2 as predicted before

Transverse momentum spectrum

- At small transverse momentum
  - A_2 is in order of 1
  - Lam-Tung relation is violated
  - Resummation does not change the power counting for A_2
- At large transverse momentum
  - A_0, A_2 in order of 1
  - Lam-Tung relation survive

Lam-Tung relation: Revisited



E615

Neutrino astrophysics

Cecilia Lunardini

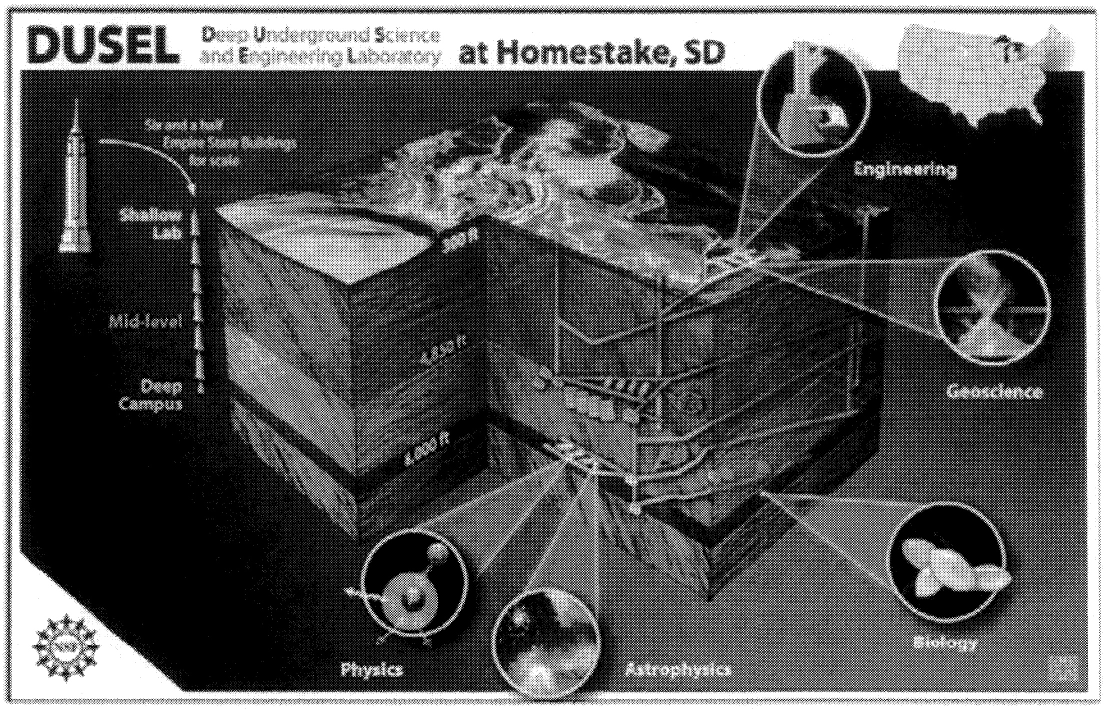
Arizona State University – Asst. prof.

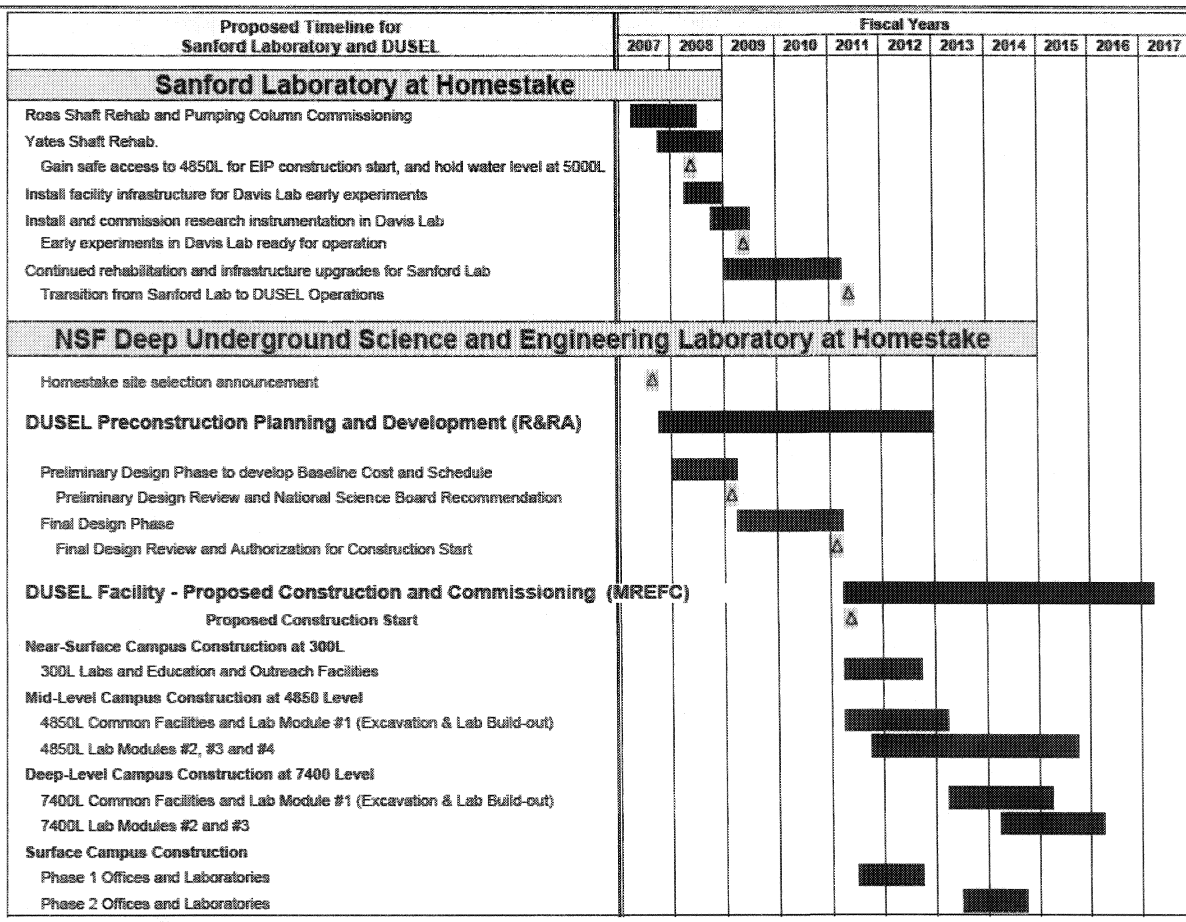
RBRC - Fellow

After solar neutrinos: new challenges

- Understanding core collapse supernovae (SN) with ν:
  - Dominate the energetics
  - Participate in the synthesis of heavy elements
  - Contribute to powering the explosion
- Exploring and understanding the sky at high energy (>TeV)
  - Origin of cosmic rays: ν from baryonic jets (Gamma Ray Bursts)
  - High energy ν from exotica (decay of heavy relics, ..)
- Ongoing tests of ν properties: using stars as ν factories

DUSEL: a multi-disciplinary facility





Scoping activities for DUSEL

- 2008 DUSEL meeting (april 2008, Lead, SD)
  - Water Cherenkov detector, 1 Mt
  - Liquid Argon detector, up to 100 kt
- *Underground Detectors Investigating GrandUnification* (UDiG, October 2008, BNL) http://www.bnl.gov/udig/
- DUSEL theory white paper from Ohio State U. meeting http://www.ccapp.osu.edu/whitepaper.html
  - *Theorists support needed!*

Themes of my research

Physics that needs a new lab:

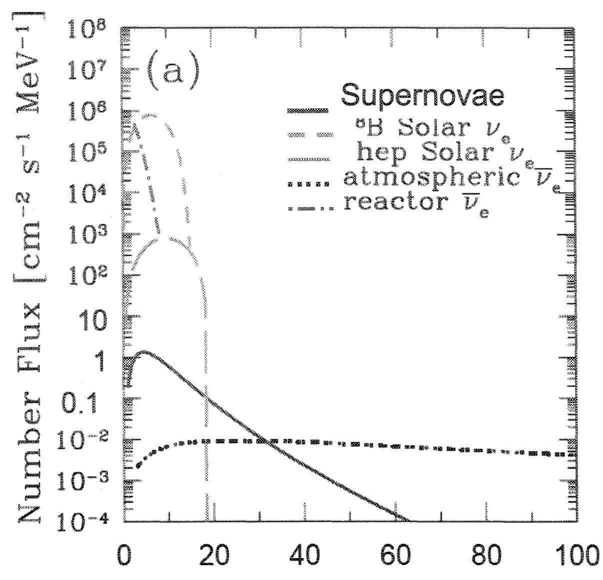
MeV – TeV ν from core collapse supernovae (SN)

The feeble signal of all Sne: diffuse flux

- Sum over the whole universe:

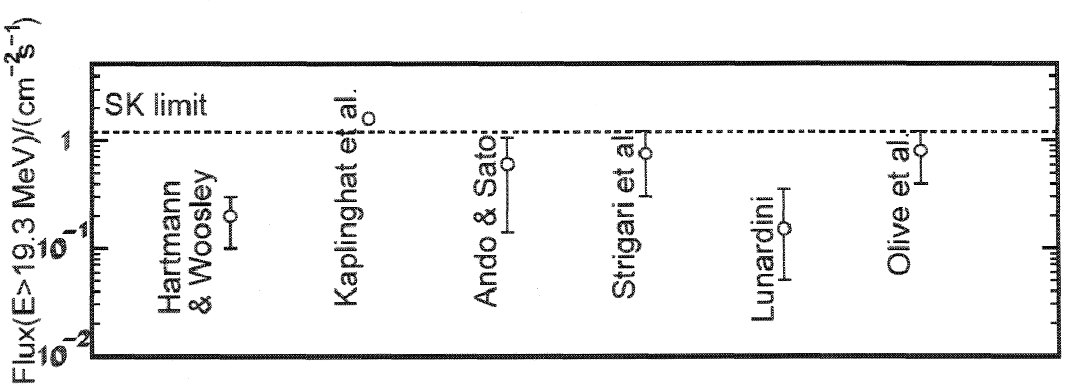
$$\sum_{\star} \Phi_{\nu}^{\star}$$

- Background is the challenge!
  - Solar background removable



S. Ando and K. Sato, New J.Phys.6:170,2004.

Status of theory: anti-ν_e flux



- Differences due to different inputs/methods

Experimental status (new!)

C. L. and O.L.G. Peres, JCAP08(2008)033

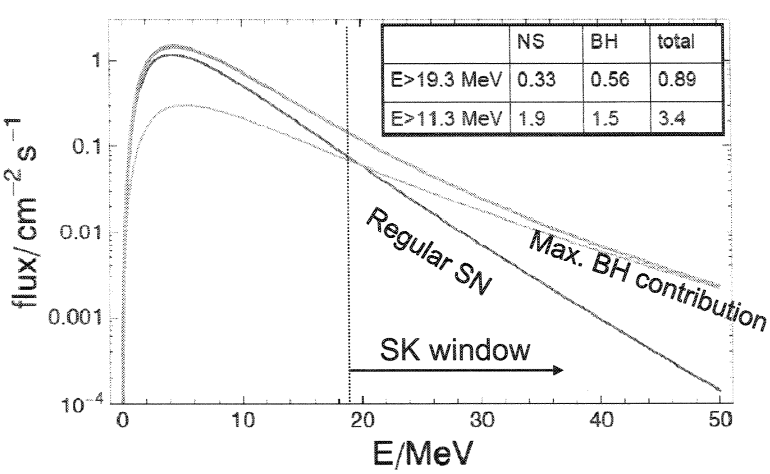
Species (experiment)	Previous best ($cm^{-2}s^{-1}$) 90%CL *(direct limits only)*	New from SK ($cm^{-2}s^{-1}$) 90% CL
Anti-ν_e (SK coll.)	1.2 (E/MeV>19.3)	1.4-2.0 (E/MeV>19.3)
ν_e (SNO)	70, (22.9<E/MeV<36.9)	42-54, (22.9<E/MeV<36.9)
$\nu_\mu+\nu_\tau$ (LSD)	3 10^7 (E/MeV>20)	(1.0-1.4) 10^3 (E/MeV>19.3)
Anti-ν_μ + anti-ν_τ (LSD)	3.3 10^7 (E/MeV>20)	(1.4-1.8) 10^3 (E/MeV>19.3)

Including failed SNe: larger flux?

C. L., Letter in preparation

- Contribution of BH-forming collapses
  - 10-20 % of the total, no explosion
  - ν burst shorter and hotter: kE 1~ 24 MeV for anti-ν_e

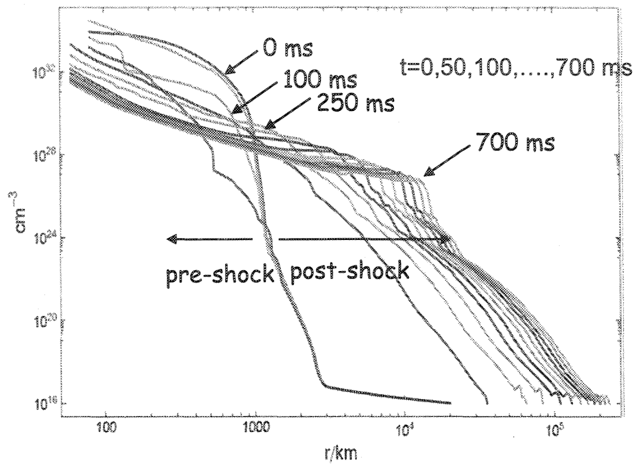
Sumiyoshi et al., arXiv:0706.3762 , Fischer et al., arXiv:0809.5129

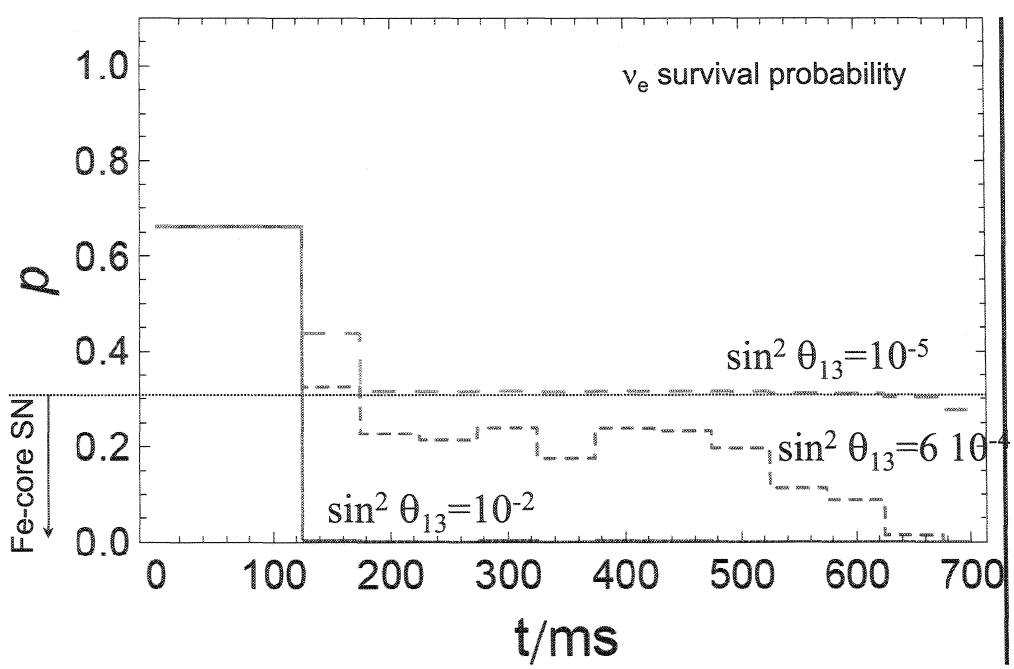


Tomography of ONeMg SNe

C.L., B. Mueller and H.T. Janka, Phys.Rev.D78:023016,2008

- Small progenitor: 8-10 M_{sun}
- Up to 20% of all SNe!
  - Next galactic SN?
- ***Sharp density step*** at base of He shell
  - Destroyed by shockwave





Geochemical signatures of SN

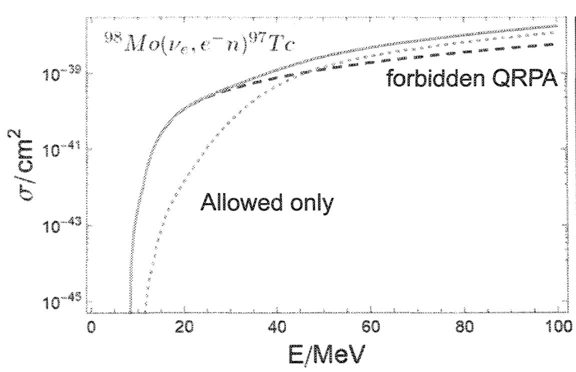
- ^{97}Tc in Molybdenum rocks counts prehistoric ν_e Haxton & Johnson, Nature 333 (1988) 325–329.

$$^{98}\mathrm{Mo} + \nu_e \rightarrow {}^{97}\mathrm{Tc} + e^- + n$$

$$^{97}\mathrm{Mo} + \nu_e \rightarrow {}^{97}\mathrm{Tc} + e^-$$

  - ^{97}Tc lifetime: 2.6 10^6 yrs: not primordial!
  - Only ν_e SN data! Already available!

- Modern version of the idea
  - Include oscillations, *calculated cross sections,* known solar ν flux R. Lazauskas, C.L., C. Volpe, to appear soon



Tc97 atoms (10^6) in 10 kt rock

process	solar only	solar + supernova
$^{98}Mo \rightarrow {}^{97}Tc$	2.7	3.5
$^{97}Mo \rightarrow {}^{97}Tc$	7.8	7.9
total ours	10.6	11.4
HJ, total	8.7	11.9

High energy ν from deep jets in SN

- γ-Ray Bursts are from *very few* SNe with ultrarelativistic jets
- *Slow* (Γ ~ few) jets could be very common in SNe → ~ *TeV flux of ν from SNe!*

P. Meszaros and E. Waxman, Phys. Rev.Lett. 87 (2001) 171102

- Slow jet can be deep
  - ν *oscillations*
  - ν *energy deposition (A. Loeb, C.L., in progress)*

A Beam Cooling Scheme for a Muon Collider

RBRC Scientific Review Committee Meeting

Adam C. Lichtl
RIKEN-BNL Research Center
in conjunction with the
BNL Advanced Accelerator Group

November 17, 2008

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Muon Colliders:

The Next Generation of Accelerators

- Precision physics from s-channel processes using a leptonic probe
- Factor of $\left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$ enhancement of the Higgs production cross-section: $l\bar{l} \to H^0$
- Energy losses due to synchrotron radiation are suppressed by a factor of $\left(\frac{m_e}{m_\mu}\right)^4 \approx 5 \times 10^{-10}$

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Muon Beam Cooling

- Muons are produced by in-flight decays of a pion beam, resulting in a large initial phase space distribution: $(\Delta x, \Delta P_x, \Delta y, \Delta P_y, \Delta t, \Delta E)$
- To be suitable for a collider, the muon beam must be 'cooled' longitudinally and transversely
- Due to the 2.2 us muon lifetime, avoid multi-turn cooling schemes requiring long distances (e.g. stochastic cooling, electron cooling)

$$D = \beta\gamma c\tau = \beta\gamma \times (660\ \mathrm{m})$$

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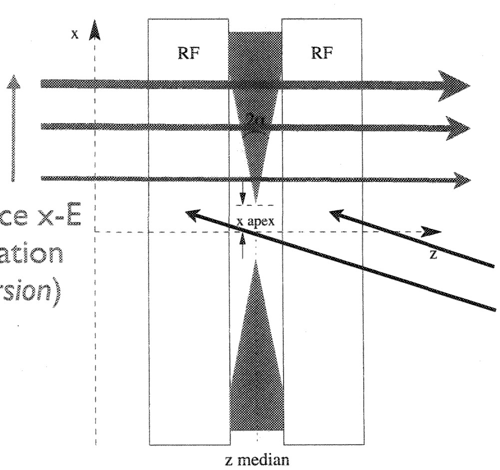
Ionization Cooling (*Dispersion*, Li wedges, RF)

Introduce x-E correlation (*dispersion*)



Higher energy particles lose more energy as they pass through more absorber

All particles gain the same energy from RF acceleration

Result:
* Reduced energy spread
* Unchanged mean energy

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Dispersion Creation via a Solenoid Lattice

- Periodic lattice of alternating solenoid magnets with tilts and offsets to produce dispersion (design from Yuri Alexahin at FNAL)
- Motion through tilted/offset solenoids creates transverse-transverse and transverse-longitudinal phase space coupling (6D cooling)
- Expect non-linear behavior for large beam envelopes
- Analyze using beam tracking code (Geant4, G4beamline, custom analysis programs)

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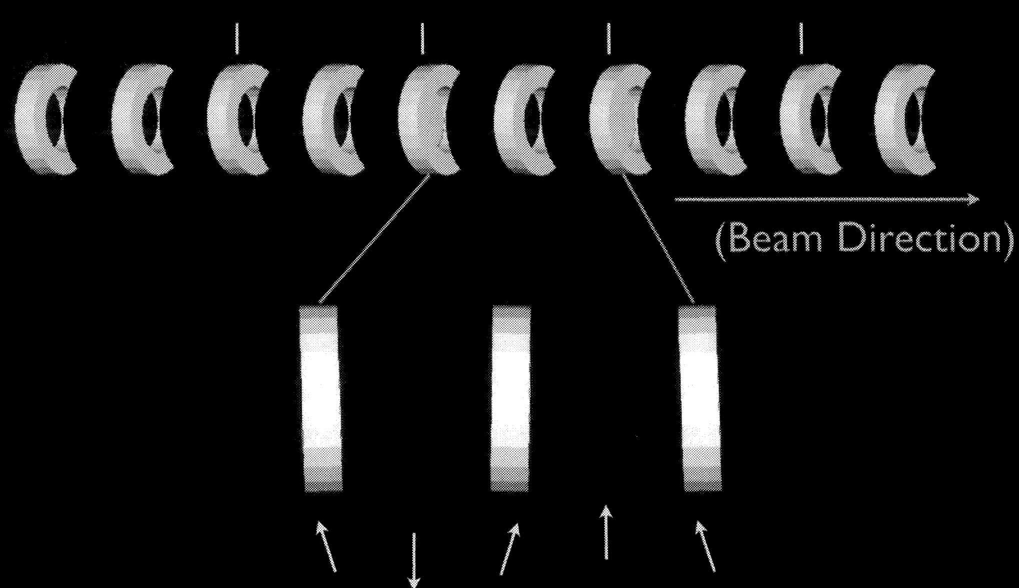
Single-Cell Study Lattice



Research Activities

- Find closed orbits through the periodic structure as a function of energy
- Examine betatron and synchrotron oscillations of particles near each closed orbit
- Identify resonances and map out stable and unstable regions in beam energy
  - A cooling channel must have large transverse (x, P_x, y, P_y) and longitudinal (t, E) acceptances

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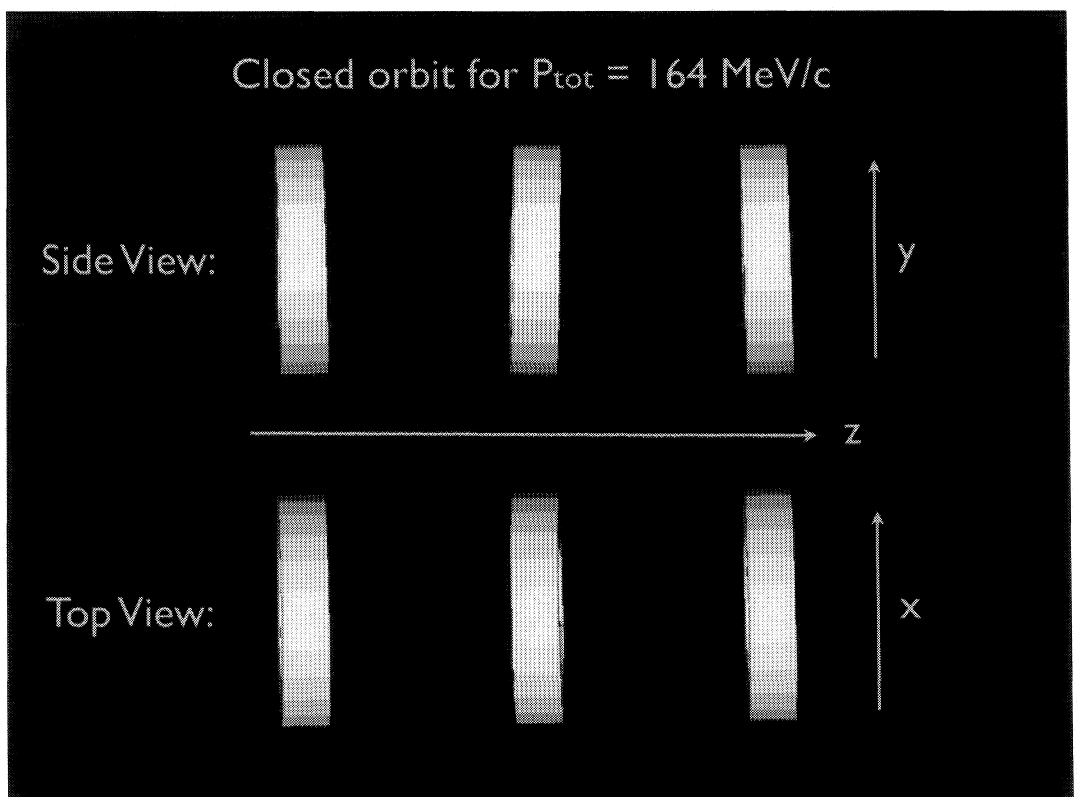
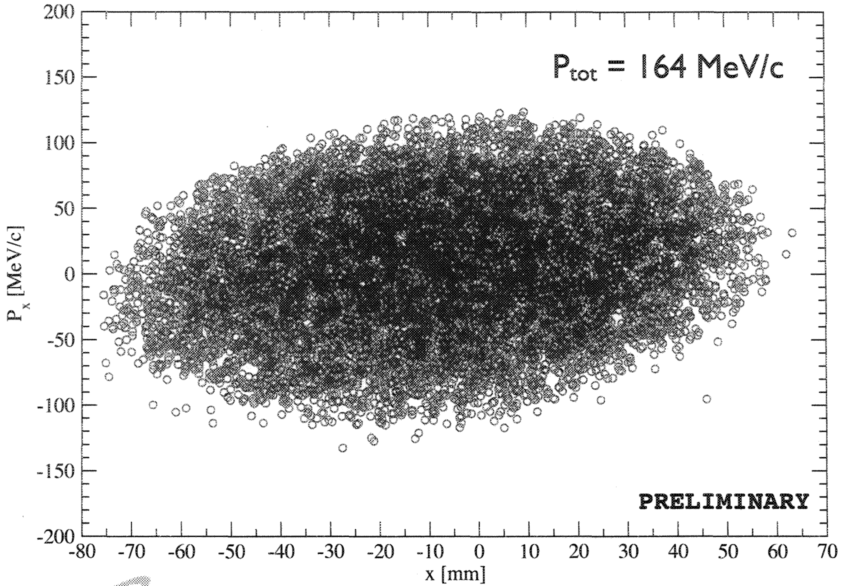


Transverse Acceptance

x-P_x Phase Space, R_{inner} = 120 mm



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Transverse Stability: Look at Motion Around Closed Orbit

$$\vec{u}(z) = \begin{bmatrix} x(z) - x^{(c)}(z) \\ P_x(z) - P_x^{(c)}(z) \\ y(z) - y^{(c)}(z) \\ P_y(z) - P_y^{(c)}(z) \end{bmatrix}$$

$$\vec{u}(L) = \vec{f}(\vec{u}(0))$$

$$\vec{f}(\vec{0}) = \vec{0}$$

$$\vec{u}(L) \approx \mathbf{M}\vec{u}(0)$$

- Expand transfer function $\vec{f}(\vec{u})$ about the closed orbit to find transfer matrix $\mathbf{M}$
- Examine eigenvalues: magnitude greater than one implies instability at that energy

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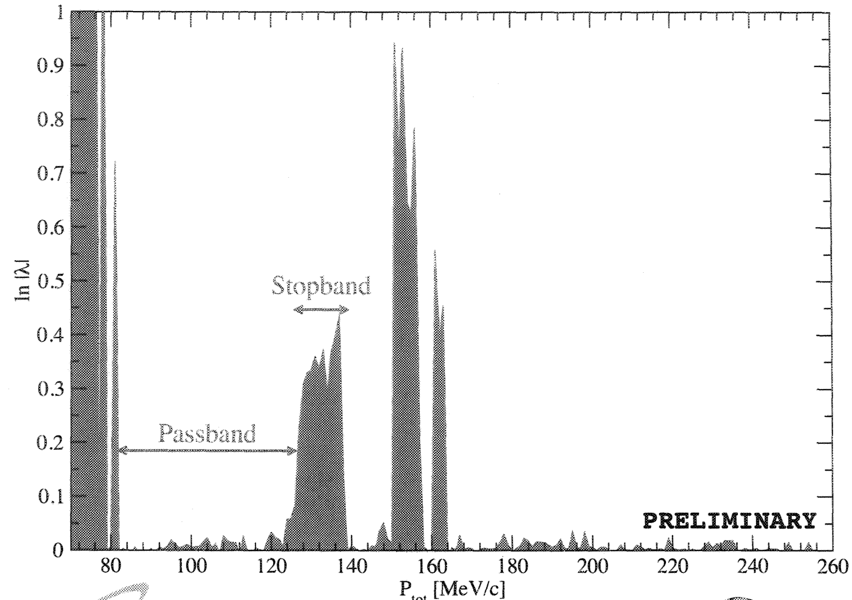
Transverse Beam Stability Regions

(Passbands and Stopbands)



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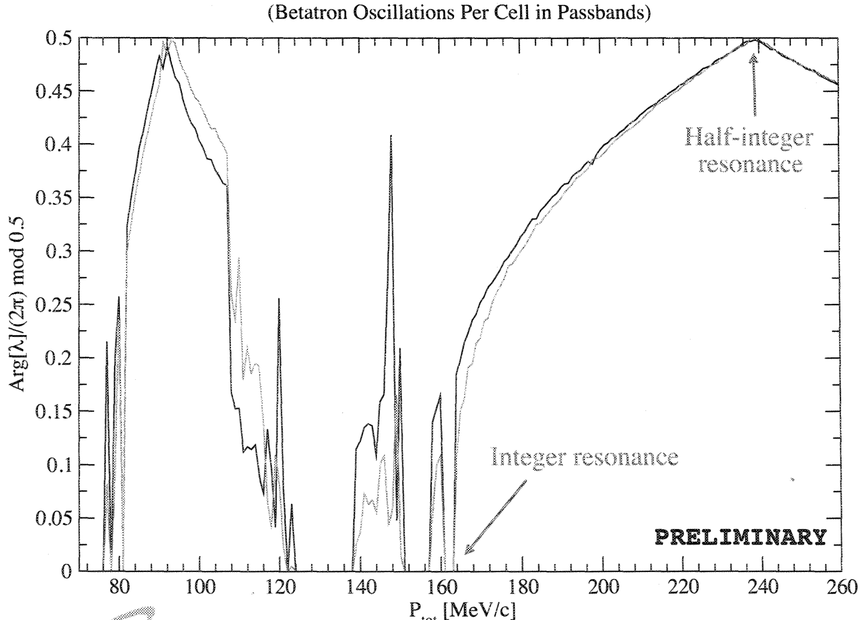
Betatron Tune I and II

(Betatron Oscillations Per Cell in Passbands)



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Current Work and Outlook

- High-precision transverse study (improve closed-orbit search, reduce noise)
- Examine perturbative deformation from a straight solenoid lattice (parameterize solenoid tilts and offsets)
- Longitudinal behavior characterization
- Choose a stable region for operation, and tune lattice parameters to optimize dispersion-acceptance trade-off

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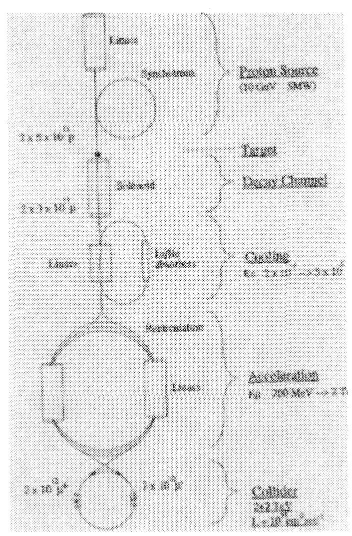
Any Questions?



BROOKHAVEN NATIONAL LABORATORY

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RIKEN BNL Research Center

Probing Hot and Cold Nuclear Matter

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Texas A&M University & RIKEN BNL

RIKEN BNL Research Center

RIKEN Review, Brookhaven National Lab
November 17, 2008

Chemistry with Hard Probes

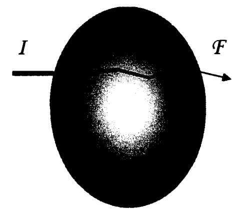
- Flavor conversions
- Photons and strangeness
- Elliptic flow

with:
W. Liu (Texas A&M)

Phys. Rev. C 77, 054902 (2008)
Phys. Rev. C 78, 037902 (2008)
arXiv:0805.3721

Hard Probes

- Simplest measurement for medium probes: opacity
  - Jet quenching and broadening
  - Related to transport coefficient $\hat{q} = \frac{\mu^2}{\lambda}$



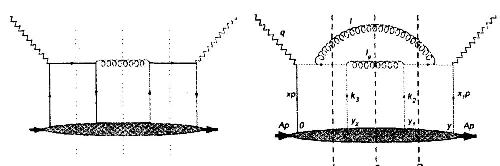
- How else can we use hard probes?
  - **Measure changes in chemistry of the probe!**
  - Complementary information: access to mean free path λ.
- Here: trace flavor changes of the leading jet parton coupling to the medium *(gluons; light, strange and heavy quarks; photons)*
  - Hadronization: parton chemistry $\rightarrow$ hadron chemistry
  - Caveat: hadronization itself might also be changed, not accounted for here.

[see e.g. Sapeta and Wiedemann, EPJ C55 (2008)]

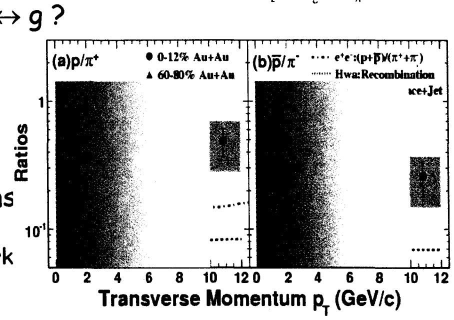
Leading Jet Partons

- Flavor of a jet is NOT a conserved quantity in a medium.
  - Only well-defined locally!

Example for $q \rightarrow g$
(HT formalism in SIDIS on nucleus)
[Schäfer, Wang, Zhang]



- Motivation: do we already see $q \leftrightarrow g$?
  - Relative quenching factor 9/4 not observed in data: STAR *p* vs π
  - Caveat: strong dependence on fragmentation functions.



- Could be explained by conversions
  - Model with (large) elastic cross sections gives 30% depletion of quark jets. [Ko, Liu, Zhang]

Conversion Rates

- Coupled rate equations for numbers of jet particles (flavors a, b, c, ...) in a fireball simulation.

$$\frac{dN^a}{dt} = -\sum_b \Gamma^{a\to b}(p_T,T)N^a + \sum_c \Gamma^{c\to a}(p_T,T)N^c$$

- Here: reaction rates from elastic 2 → 2 collisions

Quark / gluon conversions	Photons and dileptons; inverse reaction negligible	Heavy quarks production?
$q+\bar{q} \leftrightarrow g+g$ $q+g \leftrightarrow g+q$	$q+\bar{q} \to \gamma+g$ $q+g \to \gamma+q$	$g+Q \leftrightarrow Q+g$ $g+g \leftrightarrow Q+\bar{Q}$

- Need to compare to 2 → 3 processes.
- Non-perturbative mechanisms?

Two Examples for Rare Probes

- Example 1: excess production of particles which are rare in the medium and rare in the probe sample

$$\frac{dN^{rare}}{dt} = \frac{1}{\lambda}N^{jet} \Rightarrow \frac{N^{rare,\,excess}}{N^{jet}} = \frac{L}{\lambda}$$

  - Example: photons
  - Need enough yield to outshine other sources of N^{rare}.

- Example 2: chemical equilibration of a rare probe particle

e.g. $g+s \to s+g$

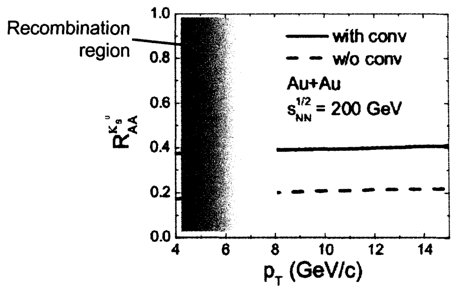
$$w_{jet} = \left(\frac{s}{u+d}\right)_{jet} \approx 5\% \quad @\,10\text{ GeV for RHIC}$$

$$w_{ce} = \left(\frac{s}{u+d}\right)_{medium} \approx 50\%$$

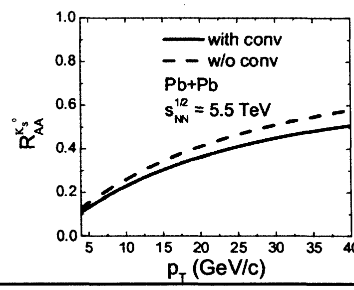
  - Example: strangeness at RHIC
  - Coupling of jets (not equilibrated) to the equilibrated medium should drive jets towards chemical equilibrium.

Numerical Results: Strangeness

- Kaons: see expected enhancement at RHIC
  - Measure above the recombination region!

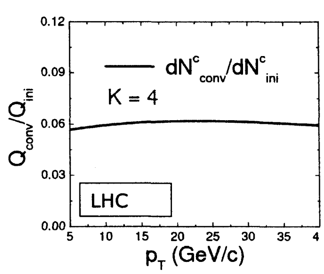


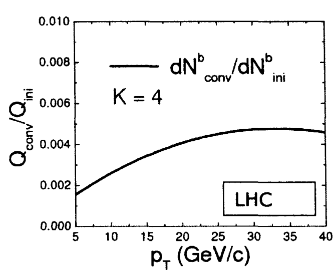
- No enhancement at LHC
  - Too much initial strangeness!
  - Maybe it works with charm at LHC?



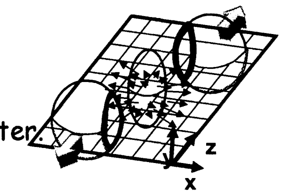
Numerical Results: Heavy Quarks

- Have to take into account threshold effect
- At RHIC: additional heavy quark production marginal
- LHC: not at all like strangeness at RHIC; additional yield small
  - Reason: charm not chemically equilibrated at LHC
  - Results in small chemical gradient between jet and medium charm
  - Also: threshold effect



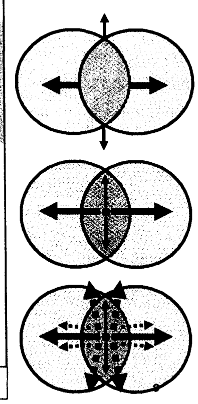


Elliptic Flow v_2



- Azimuthal anisotropy for finite impact parameter
- Three different mechanisms:

	Initial anisotropy	Final anisotropy	Elliptic flow v_2
Bulk	pressure gradient	collective flow	$v_2 > 0$
saturated hard probe	path length	quenching	$v_2 > 0$
rare hard P_T probe	path length	additional production	$v_2 < 0$



[Turbide, Gale & RJF, PRL 96 (2006)]

Photons

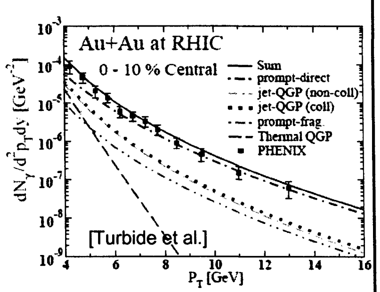
- Conversion photons:
  - no clean experimental signal from single inclusive yields.

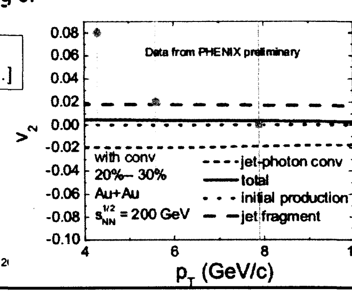
[RJF, Müller, Srivastava, Srivastava, Gale, RJF; Zakharov;.....; Zhang, Vitev]

- Conversion photons exhibit $v_2 < 0$
  - Another chance to catch them.
  - Other photon sources with vanishing or positive v_2 have to be added.

[Turbide, Gale, RJF; Chatterjee, Frodermann, Heinz, Srivastava; ...]

- First direct photon v2 results
  - Still inconclusive.
  - Large negative v_2 excluded.

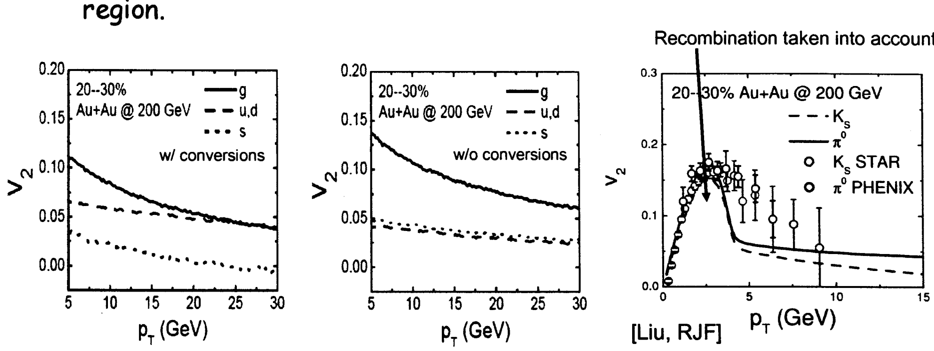




[Liu, RJF]

Strangeness Elliptic Flow

- Strangeness as non-equilibrated probe at RHIC: additional strange quarks have negative v_2.
- Expect suppression of kaon v_2 outside of the recombination region.



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Summary

- Jet chemistry can reveal complementary information about the mean free path of hard probes in a nuclear medium.
- Interesting rare probes at RHIC: excess of photons, dileptons, strangeness
- No heavy quark excess even at LHC
- Negative elliptic flow v_2 from conversion processes: photons, kaons.
- Next: more realistic calculations; 2-particle correlations.

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Medium-induced energy loss at weak and strong coupling

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Columbia University

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based on

F. Dominguez, C. Marquet, A. Mueller, B. Wu and B.-W. Xiao, *Nucl. Phys.* **A811** (2008) 197

Motivations

- it is unclear if the perturbative QCD approach can describe the suppression of high-p_T particles in Au+Au collisions at RHIC:

  in the case of light quarks, comparisons between models and data indicate the need for a large jet quenching parameter $\hat{q} = 5 - 10\ \text{GeV}^2/\text{fm}$

  however, for a weakly-coupled pQCD plasma we expect $\hat{q} \simeq 1\ \text{GeV}^2/\text{fm}$

  in the case of heavy quarks, high-p_T electrons from c and b decays indicate a similar suppression than for light quarks

  the dead-cone effect in pQCD implies a weaker suppression for heavier quarks

  $\Rightarrow$ this motivates to think about a strongly-coupled plasma

- for the *N*=4 SYM theory, the AdS/CFT correspondence allows to investigate the strong coupling regime

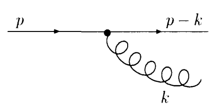
  the tools to address the QCD dynamics at strong coupling are limited, but the results for the SYM theory may provide insight on strongly-coupled gauge theories in general, some aspects may be universal

Heavy quark energy loss in a weakly-coupled QCD plasma

The heavy quark wave function

- consider a heavy quark of mass *M* and energy *E*

the heavy quark wave function at lowest order



the energy of the gluon is denoted ω

its transverse momentum is denoted $k_\perp$

the virtuality of the fluctuations is measured by their lifetime or coherence time

$t_c = \omega / k_\perp^2$ short-lived fluctuations are highly virtual

the probability of this fluctuation is $P = \sum_{\substack{color\\spin}} |\psi|^2 = P(m=0)\left(1 + \frac{\omega^2}{\gamma^2 k_\perp^2}\right)^{-2}$

$P(m=0) \sim \alpha_s N_c$

Lorentz factor of the heavy quark $\gamma = E/M$

- the dead cone effect

compared to massless quarks, the fluctuation with $\omega > \gamma\ k_\perp$ are suppressed

$\Rightarrow$ absence of radiation in a forward cone

Medium induced gluon radiation

- multiple scattering of the radiated gluon

this is how the virtual gluon in the heavy quark wave function is put on shell
it becomes emitted radiation if it picks up enough transverse momentum

the accumulated transverse momentum picked up by a gluon of coherence time t_c

$$p_T^2 = \mu^2 \, \frac{t_c}{\lambda} \equiv \hat{q} \, t_c$$

average p_T picked up in each scattering

mean free path

$\hat{q} \equiv \mu^2/\lambda \sim T^3$

only property of the medium needed

- the saturation scale of the pQCD plasma

only the fluctuations which pick up enough transverse momentum are freed $k_\perp < p_\perp$

$$p_\perp^2 = \hat{q} \, \frac{\omega}{k_\perp^2} \quad \Rightarrow \quad k_\perp < (\hat{q}\omega)^{1/4} \equiv Q_s$$

this discussion is also valid for light quarks

Heavy quark energy loss

- the case of infinite extend matter

for heavy quarks, the radiated gluons which dominate the energy loss have

$$\omega = \gamma \; k_T = \gamma \; Q_s \quad \text{and} \quad t_c = \gamma/Q_s$$

this allows to express Qs in terms of *T* and E/M only

$$Q_s^2 = \sqrt{\hat{q}\;\omega} \quad \Rightarrow \quad Q_s = (\hat{q}\gamma)^{1/3} = T\;\gamma^{1/3} \quad \text{and} \quad t_c = \gamma^{2/3}/T$$

and the heavy quark energy loss is $-\dfrac{dE}{dt} \simeq \alpha_s N_c \; \dfrac{\gamma Q_s}{\gamma/Q_s} = \alpha_s N_c \; Q_s^2$

- the case of finite extend matter of length $L < \gamma^{2/3}/T$

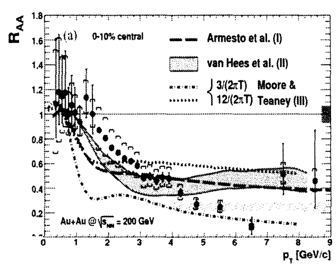
the relevant fluctuations in the wave function have a smaller energy $\omega < L \; k_T^2$

the maximum transverse momentum that gluons can pick-up is $Q_s^2 = \hat{q} \; L$

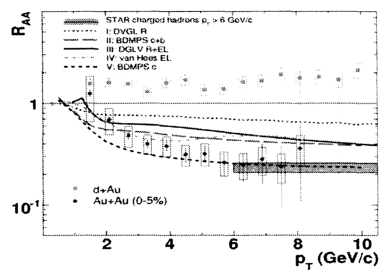
the radiated gluons which dominate the energy loss have $\omega = L \; k_\perp^2 = L \; Q_s^2$

Comparisons to RHIC data

PHENIX, PRL 172301 (2007)



STAR, PRL 192301 (2007)



trend: models underestimate the suppression

the theory curves are obtained after taking into account the plasma geometry and expansion

the measurements do not distinguish the charm and bottom quark contributions

in the future, separating the contributions from charm and bottom quarks woud be helpful

Heavy quark energy loss in a strongly-coupled SYM plasma

The trailing string picture

- the AdS/CFT calculation

the quantum dynamics of the SYM theory is mapped into classical dynamics in a fifth dimension u

the heavy quark is propagating on the boundary with a string attached to it, hanging down in the fifth dimension, points on the string can be identified to quantum fluctuations in the quark wave function with virtuality ~ u

the string dynamics is given by the Nambu-Goto action

- the string shape and energy flow

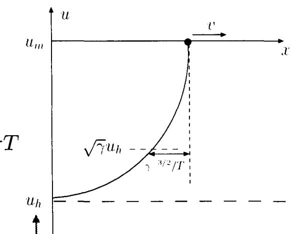
the string shape when the quark is being pulled at a constant velocity v: $x(t,u) = x_0 + vt + F(u)$

$$F(u) = \frac{1}{2u_h}\left[\frac{\pi}{2} - tan^{-1}\left(\frac{u}{u_h}\right) - cot^{-1}\left(\frac{u}{u_h}\right)\right] \quad u_h = \pi T$$

corresponding rate of energy flow down the string:

$$-\frac{dE}{dt} = \frac{\sqrt{\lambda}}{2\pi}(\pi T)^2 \frac{v^2}{\sqrt{1-v^2}}$$

Herzog et al (2006)
Gubser et al (2006)
Liu et al (2006)



black-hole horizon with Hawking temperature T = temperature of the SYM plasma

The saturation scale

- key observation

the part of string above $u = \sqrt{\gamma}\ u_h$ is genuinely part of heavy quark
the part of string below $\sqrt{\gamma}\ u_h$ is emitted radiation
by analogy with the weak coupling case, we call $Q_s = \sqrt{\gamma}\ u_h$ the saturation scale

- results for energy loss

	QCD at weak coupling	SYM at strong coupling
heavy-quark energy loss	$-\frac{dE}{dt} \propto \alpha_s N_c\ Q_s^2$	$-\frac{dE}{dt} \propto \sqrt{\lambda}\ Q_s^2$
coherence time t_c	$t_c = \gamma^{2/3}/T$	$t_c = \gamma^{1/2}/T$
infinite matter or $t_c < L$	$Q_s^2 = T^2\gamma^{2/3}$	$Q_s^2 = T^2\gamma$
finite matter with $L < t_c$	$Q_s^2 = \hat{q}\ L$	$Q_s^2 = T^4\ L^2$

first estimate of the plasma length dependence of heavy quark energy loss

Conclusions

- same parametric form for the heavy quark energy loss and p_T broadening when written in terms of the saturation scale Qs

$$-\frac{dE}{dt} \propto \left(\frac{\alpha_s N_c}{\sqrt{\lambda}}\right) Q_s^2 \quad \frac{dp_\perp^2}{dt} \propto \left(\frac{\alpha_s N_c}{\sqrt{\lambda}}\right) \frac{dQ_s^2}{dL} \quad \begin{matrix} QCD \\ SYM \end{matrix}$$

- only the saturation scale differs between pQCD and SYM theories

$$Q_s^2 = T^2 (TL)^J \quad \begin{matrix} J=1 & QCD \\ J=2 & SYM \end{matrix}$$

- the plasma length *L* dependence is stronger in SYM compared to pQCD, for both the energy loss and p_T broadening
- Qs appears in other calculations, deep inelastic scattering and quarkonium dissociation

About p_T broadening

results for p_T broadening

- $\frac{dp_T^2}{dt} \propto \sqrt{\lambda}\frac{dQ_s^2}{dt}$ again, similar to radiative p_T broadening in pQCD $\alpha_s N_c \; dQ_s^2/dt$

  $t = t_c, \;\; L$ for infinite or finite length plasma

- one easily gets the infinite matter result $dp_T^2/dt \propto \sqrt{\lambda\gamma}\; T^3$ which is non trivial to get with a direct calculation Gubser (2007), Solana and Teaney (2007)

- in the finite matter case, $\langle p_T^2 \rangle \propto T^4 L^2$ (at weak-coupling: $\langle p_T^2 \rangle \propto T^3 L$)

- same parametric form for the p_T broadening in pQCD and SYM at strong coupling !

- at strong coupling: no multiple scattering with local transfer of momentum
  $\Rightarrow$ no equivalent of $\hat{q}$

Viscous hydrodynamics and RHIC

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RIKEN/BNL Research Center & Purdue University

for RBRC Annual Review

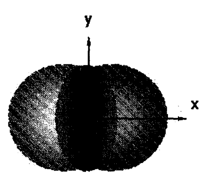
Nov 17-18, 2008, RIKEN BNL Research Center, Upton, NY

- Viscosity, causal viscous hydrodynamics (Israel-Stewart)
- Region of validity for viscous hydrodynamics, shear viscosity at RHIC
- Implications of bulk viscosity

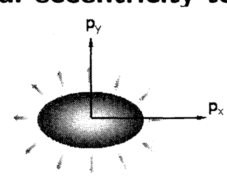
in collaboration with Pasi Huovinen

Thermalization at RHIC 

efficient conversion of spatial eccentricity to momentum anisotropy



$\longrightarrow$

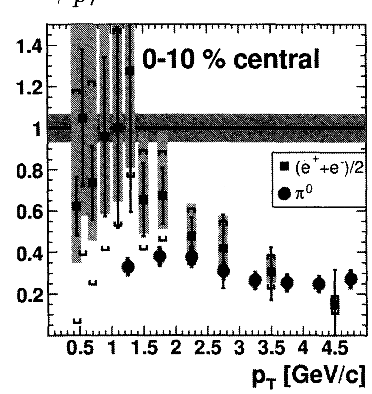


"elliptic flow"

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

very opaque - large energy loss, even for heavy quarks

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



Ideal (nondissipative) hydrodynamics describes particle spectra and elliptic flow surprisingly well Kolb & Heinz, QGP Vol. 3 [nucl-th/0305084], Kolb, Heinz, Huovinen et al ('01), ...

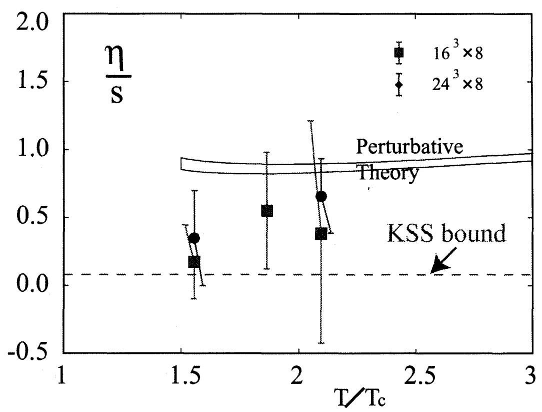
Shear viscosity in QCD

shear viscosity: $T_{xy} = -\eta \frac{\partial v_x}{\partial y}$ **acts to reduce velocity gradients**

largely unknown at $T \sim 200 - 400$ **MeV relevant for RHIC**

perturbatively: $\eta/s \sim 1$**,** **lattice QCD: very preliminary**

Nakamura & Sakai, NPA774, 775 ('06):



Meyer, PRD76, 101701 ('07)

upper bounds:

$\eta/s(T{=}1.65T_c) < 0.96$

$\eta/s(T{=}1.24T_c) < 1.08$

- **no quarks (gluons only)**
- **crude lattices**

$\mathcal{N} = 4$ **super Yang-Mills (**$\neq$ **QCD):** $\eta/s \geq \hbar/4\pi$

Policastro, Son, Starinets, PRL87 ('02)
Kovtun, Son, Starinets, PRL94 ('05)

In heavy-ion collision, gradients are large and therefore viscosity should matter. We could constrain it from RHIC data using:

- **causal dissipative hydrodynamics**

  Israel, Stewart; ... Muronga, Rischke; Teaney et al; Romatschke et al; Heinz et al, DM & Huovinen

- **covariant transport (see last year's review)**

  Israel, de Groot,... Zhang, Gyulassy, DM, Pratt, Xu, Greiner...

Dissipative hydrodynamics

relativistic Navier-Stokes hydro: small corrections linear in gradients [Landau]

$$T^{\mu\nu}_{NS} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha$$
$$N^\nu_{NS} = N^\nu_{ideal} + \kappa\left(\frac{n}{\varepsilon + p}\right)^2 \nabla^\nu\left(\frac{\mu}{T}\right)$$

where $\Delta^{\mu\nu} \equiv u^\mu u^\nu - g^{\mu\nu}$, $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$ $[\partial^\mu \equiv u^\mu D + \nabla^\mu]$

η, ζ **shear and bulk viscosities,** κ **heat conductivity**

two problems:

parabolic equations (e.g., heat flow) $\longrightarrow$ **acausal** Müller ('76), Israel & Stewart ('79) ...

instabilities Hiscock & Lindblom, PRD31, 725 (1985) ...

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Causal dissipative hydro

Bulk pressure Π**, shear stress** $\pi^{\mu\nu}$**, heat flow** q^μ **are dynamical quantities**

$$T^{\mu\nu} \equiv T^{\mu\nu}_{ideal} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu}, \qquad N^\mu \equiv N^\mu_{ideal} - \frac{n}{e+p}q^\mu$$

Israel-Stewart theory [Ann.Phys 100 & 118]**: relaxation equations**

$$\dot{X} = -\frac{1}{\tau_X}(X - X_{NS}) + X\,Y_X + Z_X$$

$\Rightarrow$ **alleviates the causality problem** ($\tau_\Pi = \zeta\beta_0$, $\tau_q = \kappa_q T\beta_1$, $\tau_\pi = 2\eta_s\beta_2$)

Also follows from covariant transport - Grad's 14-moment approximation

$$f(x,p) \approx [1 + \tilde{C}_\alpha p^\alpha + C_{\alpha\beta}p^\alpha p^\beta] f_{eq}(x,p)$$

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Complete set of Israel-Stewart equations of motion

$$
\begin{aligned}
D\Pi &= -\frac{1}{\tau_\Pi}\left(\Pi + \zeta\nabla_\mu u^\mu\right) \qquad (1)\\
&\quad -\frac{1}{2}\Pi\left(\nabla_\mu u^\mu + D\ln\frac{\beta_0}{T}\right)\\
&\quad +\frac{\alpha_0}{\beta_0}\partial_\mu q^\mu - \frac{a_0'}{\beta_0}q^\mu D u_\mu\\
Dq^\mu &= -\frac{1}{\tau_q}\left[q^\mu + \kappa_q\frac{T^2 n}{\varepsilon+p}\nabla^\mu\left(\frac{\mu}{T}\right)\right] - u^\mu q_\nu D u^\nu \qquad (2)\\
&\quad -\frac{1}{2}q^\mu\left(\nabla_\lambda u^\lambda + D\ln\frac{\beta_1}{T}\right) - \omega^{\mu\lambda}q_\lambda\\
&\quad -\frac{\alpha_0}{\beta_1}\nabla^\mu\Pi + \frac{\alpha_1}{\beta_1}(\partial_\lambda\pi^{\lambda\mu} + u^\mu\pi^{\lambda\nu}\partial_\lambda u_\nu) + \frac{a_0}{\beta_1}\Pi D u^\mu - \frac{a_1}{\beta_1}\pi^{\lambda\mu}D u_\lambda\\
D\pi^{\mu\nu} &= -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - (\pi^{\lambda\mu}u^\nu + \pi^{\lambda\nu}u^\mu)D u_\lambda \qquad (3)\\
&\quad -\frac{1}{2}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda + D\ln\frac{\beta_2}{T}\right) - 2\pi_\lambda{}^{\langle\mu}\omega^{\nu\rangle\lambda}\\
&\quad -\frac{\alpha_1}{\beta_2}\nabla^{\langle\mu}q^{\nu\rangle} + \frac{a_1'}{\beta_2}q^{\langle\mu}D u^{\nu\rangle}\ .
\end{aligned}
$$

where $A^{\langle\mu\nu\rangle} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(A_{\alpha\beta}+A_{\beta\alpha}) - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta}A^{\alpha\beta}$, $\qquad \omega^{\mu\nu} \equiv \frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta}(\partial_\beta u_\alpha - \partial_\alpha u_\beta)$

Applicability of IS hydro

Israel-Stewart hydrodynamics comes from a quadratic truncation (Grad's approach) that has no small control parameter.

$\Rightarrow$ **crucial to test its validity against a nonequilibrium theory**

HERE: test IS hydro against $2 \to 2$ covariant transport

massless $e = 3p$ equation of state ($\zeta = 0$)

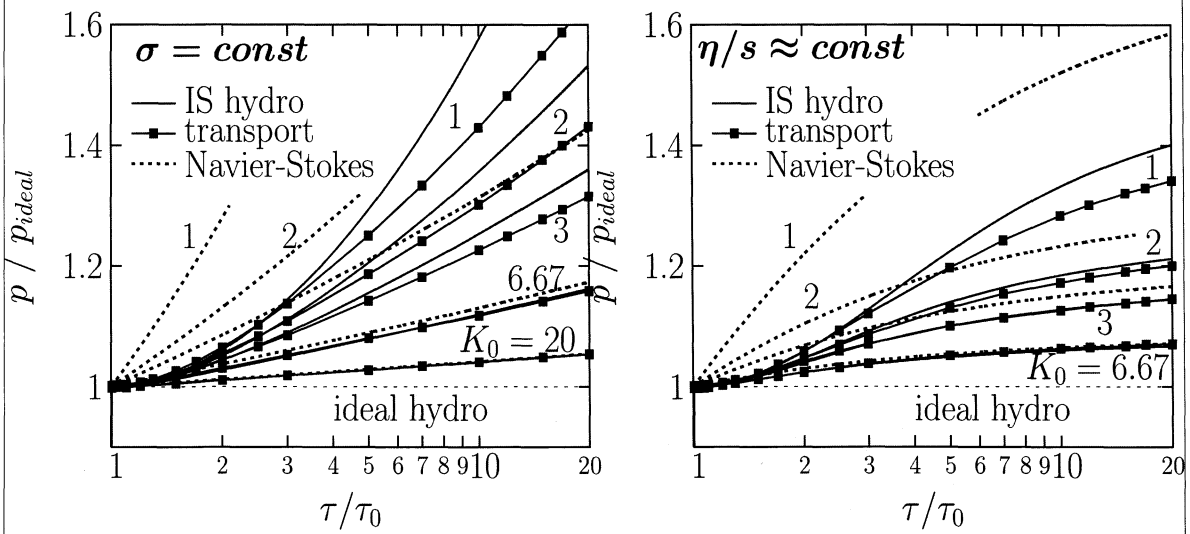
$$\eta_s \approx \frac{4T}{5\sigma_{tr}}\ , \quad \tau_\pi \approx 1.2\lambda_{tr} \equiv \frac{1.2}{n\sigma_{tr}} \qquad \sigma_{tr}:\ \text{transport cross section}$$

Two scenarios: i) $\sigma = const$ **and ii)** $\eta/s \approx const$ **(set via** $\sigma \propto time^{2/3}$**).**

in both cases, longitudinally expanding system $v_z = z/t$ **(Bjorken flow)**

Pressure evolution for 0+1D longitudinal Bjorken expansion - $p_{ideal} \propto \tau^{-4/3}$

Huovinen & DM, arXiv:0808.0953 $K_0 \equiv \tau_0/\lambda_{tr,0}$ **inverse Knudsen number**



IS hydro applicable when $K_0 \gtrsim 2-3$**, i.e.,** $\lambda_{tr} \lesssim 0.3 - 0.5\ \tau_0$

while Navier-Stokes needs $K_0 \gtrsim 6$

Connection to viscosity Huovinen & DM, arXiv:0808.0953

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

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

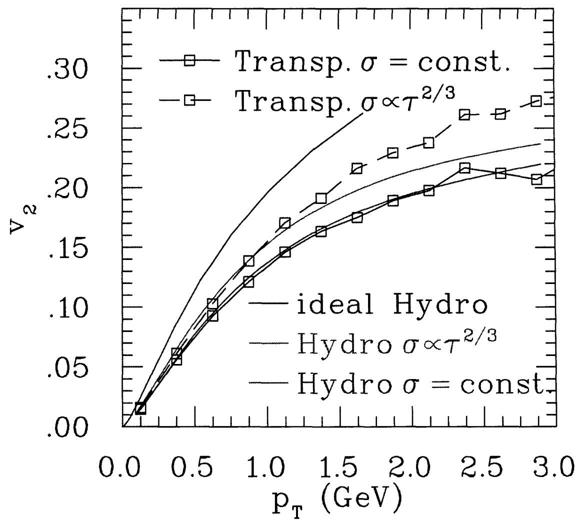
$$K_0 \gtrsim 2-3 \qquad \Rightarrow \qquad \frac{\eta}{s} \lesssim \frac{1-2}{4\pi} \qquad (5)$$

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

When IS hydro is accurate, dissipative corrections to pressure and entropy do not exceed 20% significantly.

IS hydro vs transport in 2+1D

Huovinen & DM, JPG35 ('08):



- **excellent agreement when σ = const $\sim 47mb$ (also reproduces RHIC data)**
- **good agreement for $\eta/s \approx 1/(4\pi)$, i.e., $\sigma \propto \tau^{2/3}$**

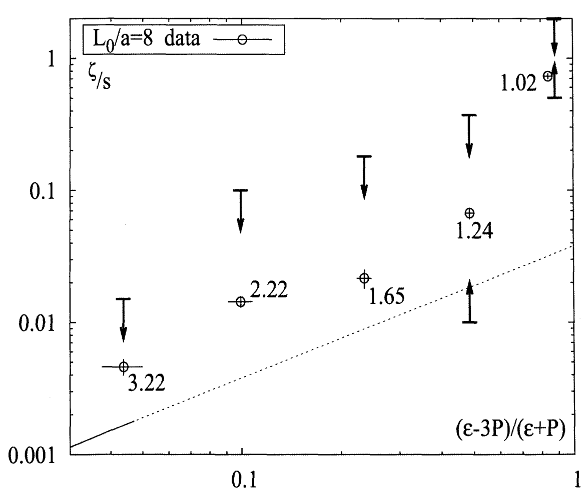
Bulk viscosity

acts against compression/dilution: $\Pi = -\zeta\vec{\nabla}\vec{v}$

largely unknown at $T \sim 200 - 400$ **MeV relevant for RHIC**

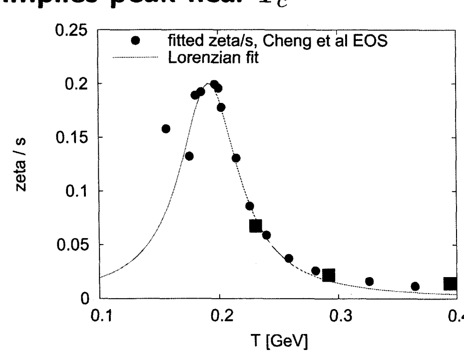
perturbatively tiny: $\zeta/s \sim 0.02\alpha_s^2$,
Arnold, Dogan, Moore, PRD74 ('06)

on lattice: very preliminary
Meyer, arXiv:0710.3717



- **no quarks (gluons only)**
- **crude lattices**

implies peak near T_c

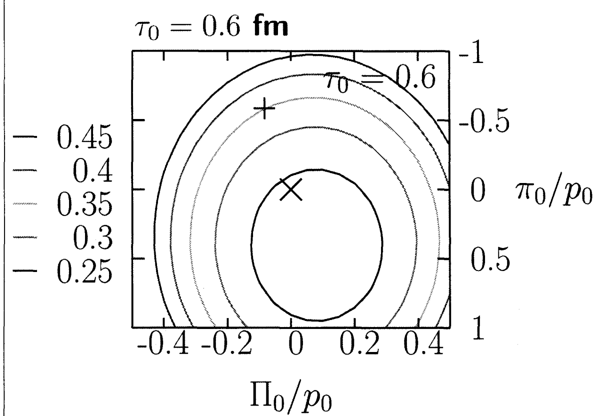


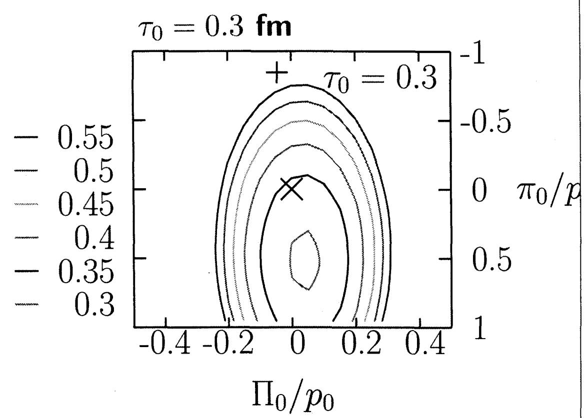
Bulk viscosity generates extra entropy. Hydro only applies if that is modest

$$\frac{\Delta S^{shear+bulk}}{S_0} = \frac{S_f - S_0}{S_0} \lesssim 0.2 - 0.3$$

$\Rightarrow$ **constrains initial shear and bulk stress, and initial time.**

DM & Huovinen ('08): **lattice EOS + Meyer's ζ/s (central points),** $T_f = 180$ MeV





$\Rightarrow \tau_0$ **cannot be much smaller than** 0.6 **fm to avoid too much entropy increase**

Summary

Progress so far:

- **we can solve causal viscous hydro in 2+1D**
- **IS hydro is a good approximation, if shear viscosity is not too large** $\eta/s \lesssim few/(4\pi)$

  must use complete set of Israel-Stewart equations
- $\eta/s \sim \mathcal{O}(1)/(4\pi)$ **is compatible with RHIC** $v_2(p_T)$ **data (charged hadrons)**
- **if bulk viscosity is significant (Meyer's central values), viscous hydro is applicable only for more limited initial conditions. E.g., need** $\tau_0 \gtrsim 0.5$ **fm.**

Missing ingredients:

- **establish IS hydro region of validity for realistic equation of state**
- **include bulk viscosity in 2+1D (in progress)**
- **couple hydro to hadron transport (proper freezeout)**

Progress in Hydrodynamics and AdS/CFT

Derek Teaney
SUNY Stonybrook and RBRC Fellow

STONY BROOK
STATE UNIVERSITY OF NEW YORK

Hydrodynamics at RHIC

Solving Navier Stokes

- The Navier Stokes equations

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{ij} = \underbrace{p\delta^{ij}}_{\text{equilibrium}} + \underbrace{\pi^{ij}}_{\text{correction}}$$

- The "first order" stress tensor instantly assumes a definite form.

$$\begin{aligned} \pi^{ij} &= -\eta\left(\partial^i v^j + \partial^j v^i - \frac{2}{3}\delta^{ij}\partial\cdot v\right) \\ O(\epsilon) &= O(\epsilon) \end{aligned}$$

- Can make "second order" models which relax to the correct form (Israel, Baier *et al*)

$$\begin{aligned} -\tau_R\,\partial_t\pi^{ij} + \text{other derivs} &= \pi^{ij} + \eta\left(\partial^i v^j + \partial^j v^i - \frac{2}{3}\delta^{ij}\partial\cdot v\right) \\ O(\epsilon^2) &= O(\epsilon) + O(\epsilon) \end{aligned}$$

Can solve these models

Running Viscous Hydro in Three Steps

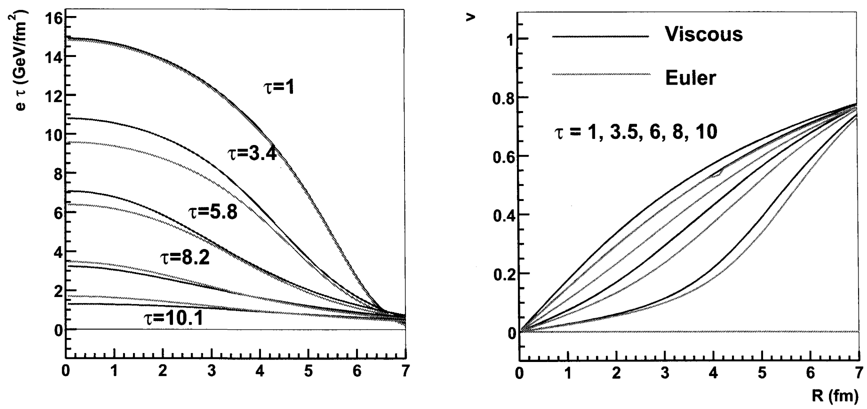
1. Run the evolution and monitor the viscous terms
2. When the viscous term is about half of the pressure:
   - T^{ij} is not asymptotic with $\sim \eta(\partial^i v^j + \partial^j v^i - \frac{2}{3}\delta^{ij}\partial_l v^l)$

   Freezeout is signaled by the equations.
3. Compute spectra:
   - Viscous corrections to the spectra grow with p_T

   $$f_o \rightarrow f_o + \delta f$$

   Maximum p_T is also signaled by the equations.

Bjorken Solution with transverse expansion: Step 1 ($\eta/s = 0.2$)



Viscous corrections do NOT integrate to give an O(1) change to the flow.

Freezeout

- Freezeout when the expansion rate is too fast

$$\tau_R \partial_\mu u^\mu \sim 1$$

- The viscosity is related to the relaxation time

$$\frac{\eta}{e+p} \sim v_{\rm th}^2 \tau_R \qquad\qquad p \sim e\, v_{\rm th}^2$$

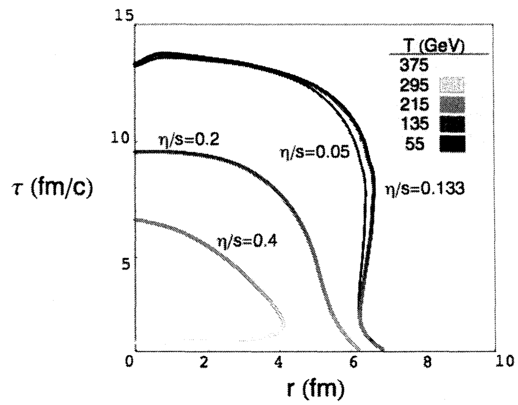
- So the freezeout criterion is

$$\frac{\eta}{p}\, \partial_\mu u^\mu \sim 1$$

Monitor the viscous terms and compute freezeout: Step 2

- Contours where viscous terms become O(1)

$$\frac{\eta}{p}\partial_\mu u^\mu = \frac{1}{2}$$



The space-time volume where hydro applies depends strongly on η/s

Step 3: Viscous corrections to the distribution function $f_o \to f_o + \delta f$

- Corrections to thermal distribution function $f_0 \to f_0 + \delta f$
  - Must be proportional to strains
  - Must be a scalar
  - General form in rest frame and ansatz

$$\delta f = F(|\mathbf{p}|)p^i p^j \pi_{ij} \Longrightarrow \delta f \propto f_0\, p^i p^j \pi_{ij}$$

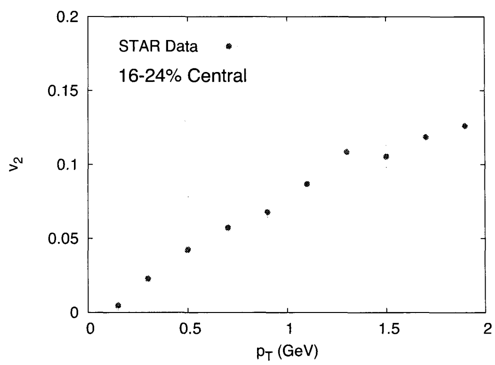
  - Can fix the constant

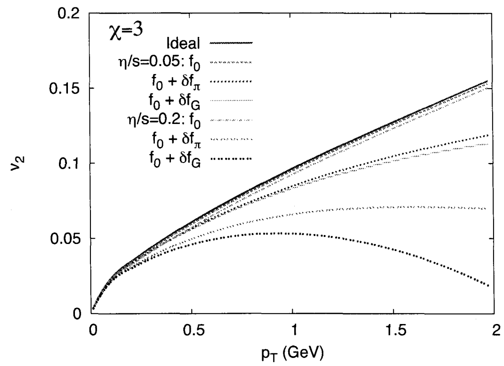
$$p\delta^{ij} + \pi^{ij} = \int \frac{d^3p}{(2\pi)^3}\,\frac{p^i p^j}{E_{\mathbf{p}}}\,(f_0 + \delta f)$$

find

$$\delta f = \frac{1}{2(e+p)T^2}\, f_o\, p^i p^j \pi_{ij}$$

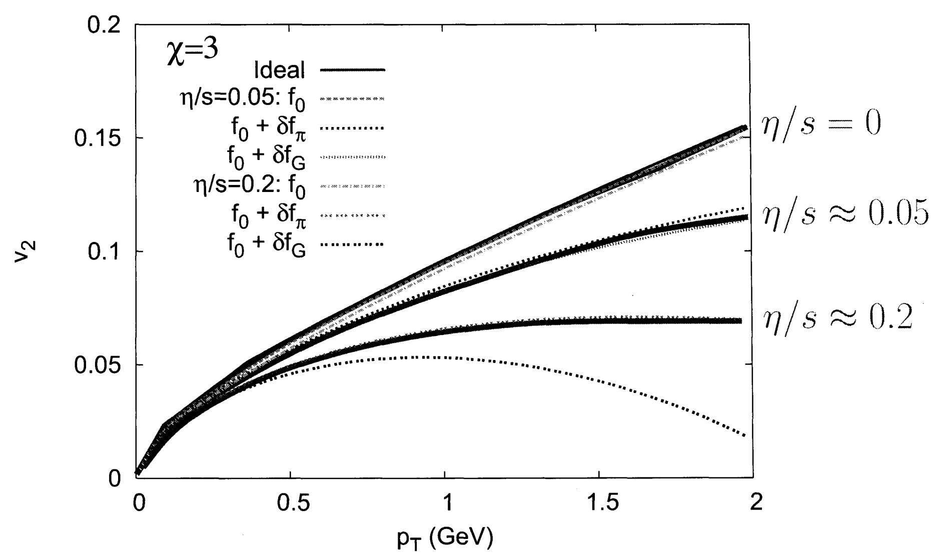
Viscous Hydro Results:



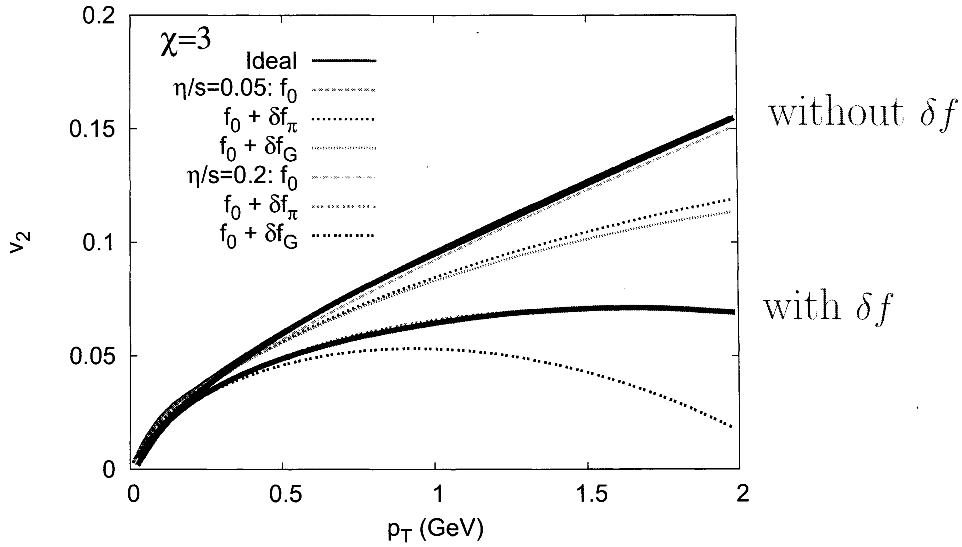


Not compared to data yet. $p/e = \frac{1}{3}$ massless bose gas. $\eta/s = $ Const

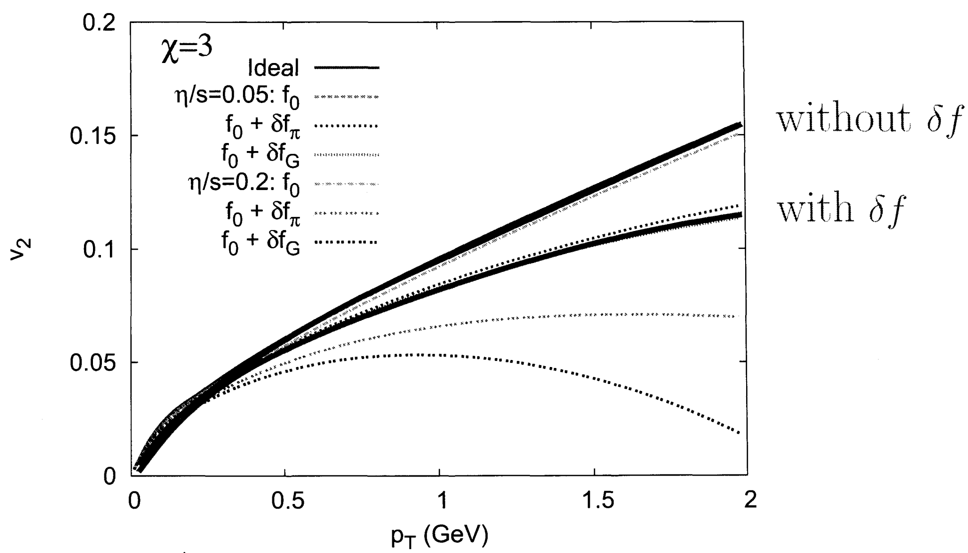
Elliptic Flow as a function of viscosity and p_T, bottom line



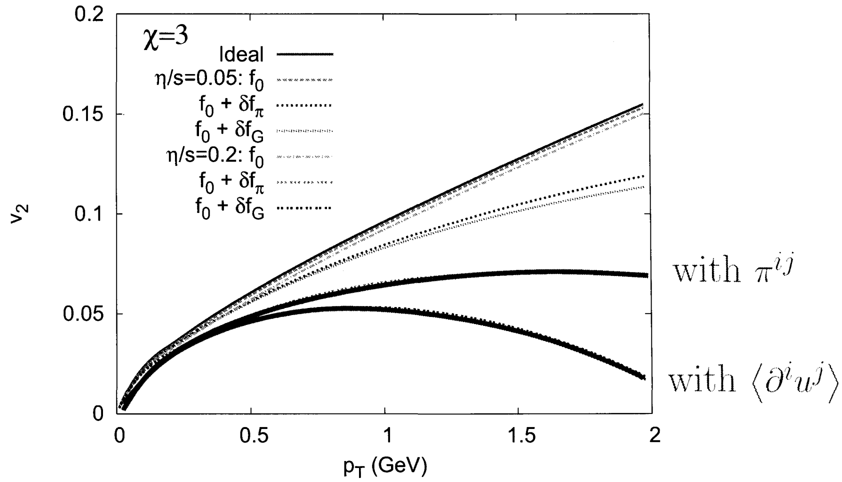
$\eta/s = 0.2$ with δf and without δf



$\eta/s = 0.05$ with δf and without δf



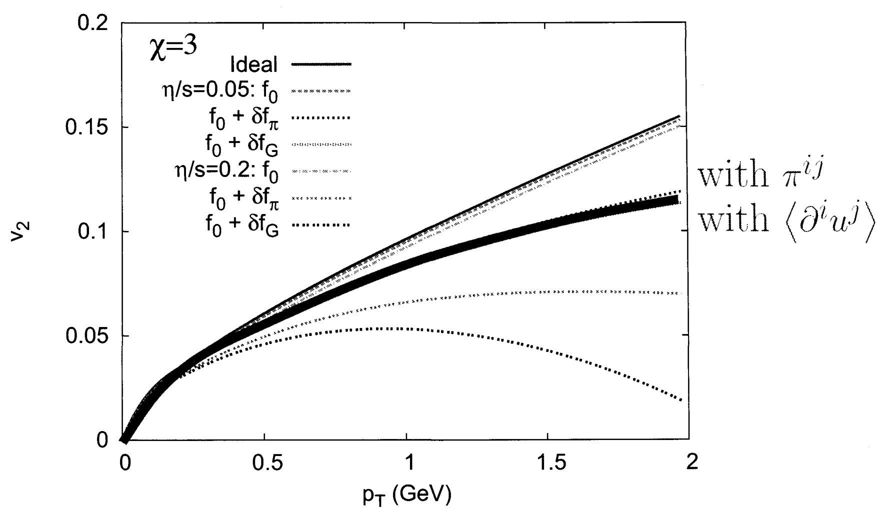
$\eta/s = 0.2$ and gradients vs. π^{ij}



$$\eta \left\langle \partial^i v^j \right\rangle = \eta \left(\partial^i u^j + \partial^j u^i - \frac{2}{3} \partial_l u^l \delta^{ij} \right)$$

Estimates the uncertainty

Compare to $\eta/s = 0.05$

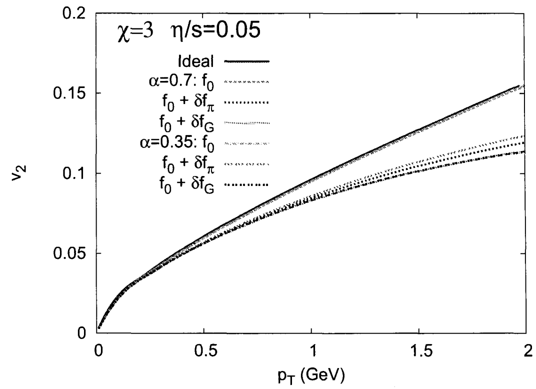


$\eta \left\langle \partial^i v^j \right\rangle$ and π^{ij}

Independent of second derivative terms (K. Dusling, DT)

$$-\tau_R\, \partial_t \pi^{ij} + \text{other derivs} = \pi^{ij} + \eta\left(\partial^i v^j + \partial^j v^i - \frac{2}{3}\delta^{ij}\partial\cdot v\right)$$

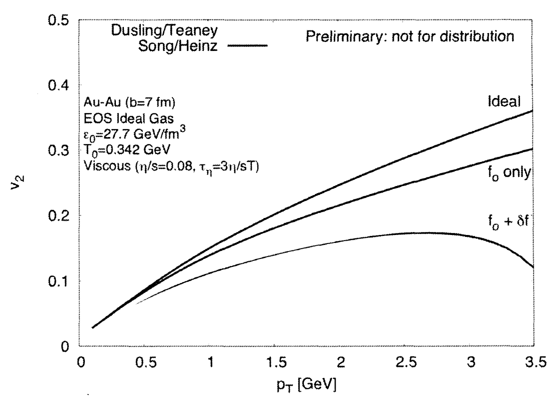
$$O(\epsilon^2) = O(\epsilon) + O(\epsilon)$$



Gradient expansion is working. Temperature is a good concept.

Worse at larger viscosities and larger p_T

Comparison with Huichao Son and U. Heinz



Codes agree. Differ in how second order terms are implemented

Noise and Transpot of Quarkonia in AdS/CFT

Quarkonia Transport in AdS/CFT:

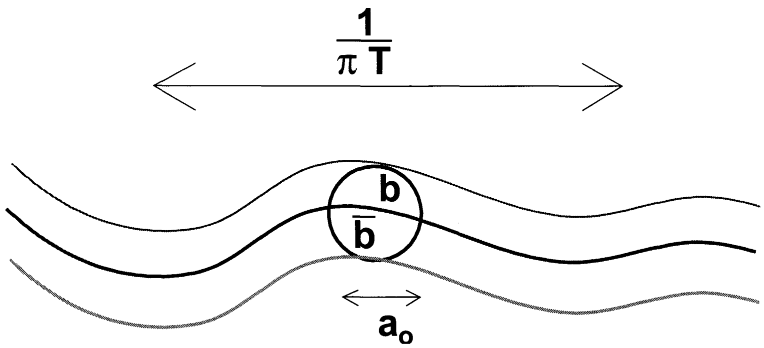
- In AdS (colored) Heavy Quarks Experience a large drag:

$$\frac{dP}{dt} = -\underbrace{\frac{\pi}{2}\sqrt{\lambda}T^2}\ P \qquad \text{(HKKKY; D.T., J. Casalderrey ; S. Gubser)}$$

- How about colorless meson states?

$$\frac{dP}{dt} = 0\ ???? \qquad \text{(Guijosa, Liu, Rajagopal, Wiedemann)}$$

Quarkonia in a Dipole Approximation



$$\frac{dP}{dt} = -\frac{T^2}{M} \times \frac{1}{N^2} \left(\frac{2\pi T}{M_J}\right)^6 112.$$

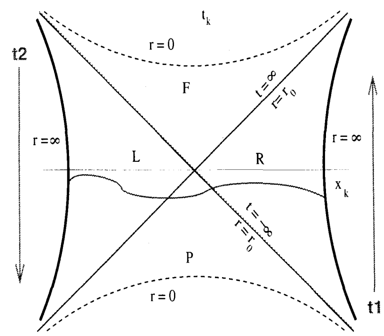
Quarks: Where is the random motion in classical Gravity?

$$\frac{dp}{dt} = -\underbrace{\eta_D p}_{\text{Drag}} + \underbrace{\xi(t)}_{\text{Random Force}}$$

Quantum Mechanics of the String in the Kruskal Plane

- The real time partition function of string for small fluctuations

$$Z = \int \prod_{t_1} dX_1(t_1) \prod dX_2(t_2) \prod_{t,z} d\mathbf{x}_1(t,z) d\mathbf{x}_2(t,z) e^{iS_{NG}}$$



- The integrals over the internal coordinates can be done and yield

$$Z = \int DX_1 DX_2 \, e^{iS_{\rm eff}[X_{\rm cl}(X_1(t_1), X_2(t_2))]}$$

Result: Langevin with memory

- Find the average endpoint $X_r = (X_1 + X_2)/2$ of the string obeys the expected Langevin equation

$$M_Q^0 \frac{d^2 X}{dt^2} + \int^t G_R(t-t') X(t') = \xi$$

- To quadratic order the retarded green function is

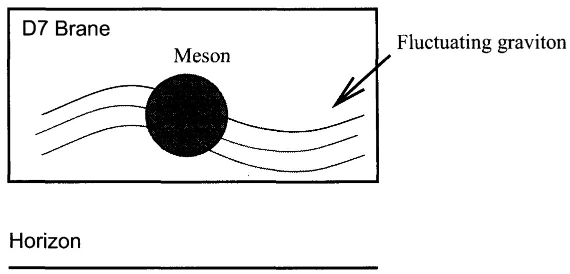
$$G_R(\omega) = \underbrace{(\Delta M)}_{\Delta M = \sqrt{\lambda} T/2} \quad \omega^2 - i\omega \underbrace{\frac{\kappa}{2T}}_{\kappa = \sqrt{\lambda}\pi T^3}$$

- Then find the following effective equation of motion

$$\underbrace{M_{\rm kin}(T)}_{M - \Delta M} \frac{d^2 X}{dt^2} + \underbrace{\frac{\kappa}{2T} \frac{dX}{dt}}_{\rm drag} = \xi$$

Conclusions

- Quantum Mechanics of AdS_5 leads to thermal noise
  - Prototypical Example - Brownian Motion
- Other fields also fluctuate: the dilation ϕ, the graviton $h^{\mu\nu}$, etc, fluctuate
  - Appealing gravity picture of meson diffusion



  - These fluctuating background fields jostle the meson giving diffusion

Suppression of the Shear Viscosity in a "semi" Quark Gluon Plasma

RBRC Scientific Review Committee Meeting

Yoshimasa Hidaka (RBRC)

Collaboration with R. D. Pisarski (BNL)

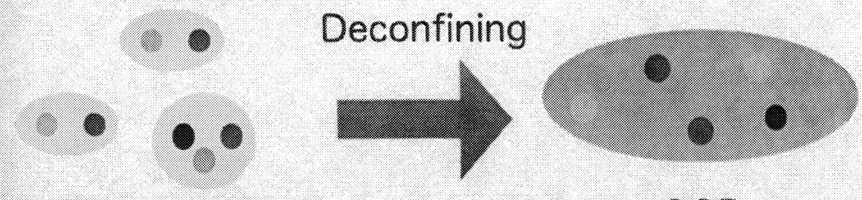
Based on Phys. Rev. D78:071501(2008)

What is a semi-QGP?

Degrees of freedom

Mesons, baryons — Quarks, gluons

Deconfining



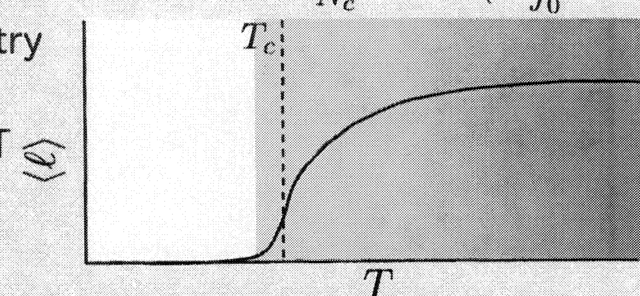
Hadron phase — QGP

Order parameter =renormalized Polyakov Loop $\ell = \frac{1}{N_c}\mathrm{tr}P\exp\left(ig\int_0^{1/T} A_0 d\tau\right)$

Global Z(N_c) symmetry

Broken at high T

Restored at low T

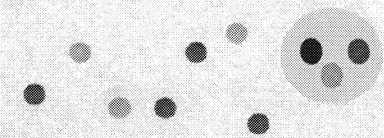


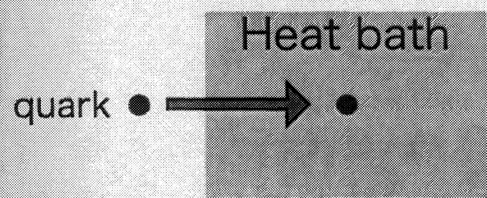
Semi-QGP

Semi-QGP = partially deconfined QGP.

Degrees of freedom

"quarks", "gluons", "meson" and "baryon"



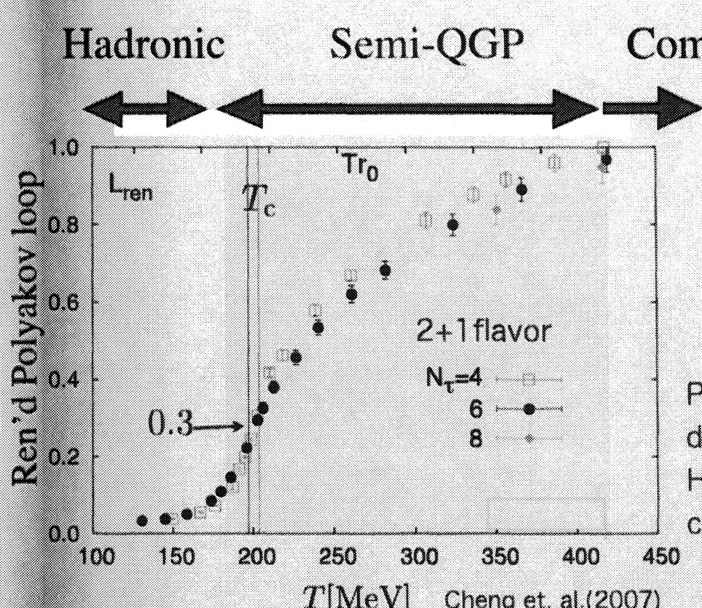


$\langle \mathrm{tr} L_r \rangle \sim \mathrm{e}^{-f_r/T}$

Probability of colored particle is suppressed by Polyakov loop.

Semi-QGP is qualitatively different from the complete QGP.

Semi-QGP Window



Cheng et. al.(2007)

Semi-QGP Window
$0.8T_c - 2 \sim 3T_c$

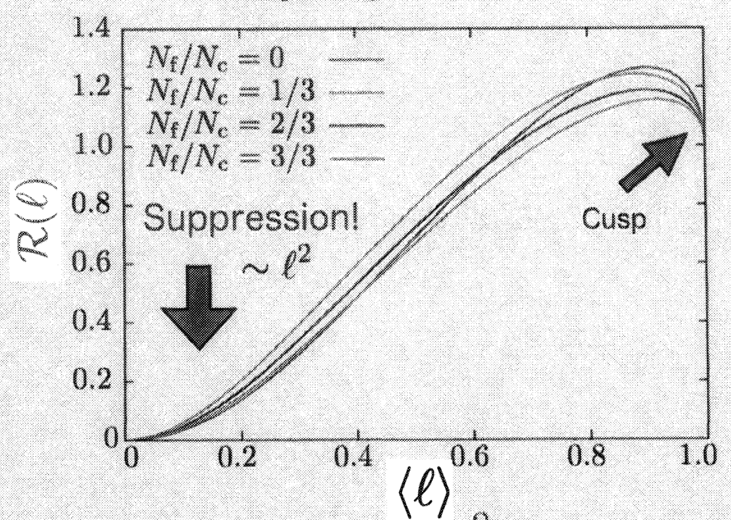
Maybe RHIC probes the semi-QGP!!

Pressure, susceptibilities change dramatically in the semi-QGP. How about transport coefficients?

Viscosity in semi-QGP

Y.H., Pisarski('08)

Ratio: $\mathcal{R}(\ell) = \dfrac{\eta_{\text{semi-QGP}}}{\eta_{\text{complete-QGP}}}$



Large suppression $\sim \ell^2$

Quark contribution dominates. $q\bar{q}$ scattering

Why small viscosity?

Shear Viscosity: $\eta \approx \frac{1}{3} n \bar{p} \lambda$ Mean Momentum: $\bar{p} \sim T$

Complete QGP

Mean free path: $\lambda^{-1} \sim n\sigma$ ➡ $\eta \sim \dfrac{T}{\sigma}$ $\sigma \sim g^4/T^2$

Large cross section
➡ Small viscosity

Semi-QGP at small loop

Mean free path: $\lambda^{-1} = \dfrac{\sum_{ab} n_a n_b \sigma_{ab}}{\sum_a n_a}$ Color dependent

$$\sum_a n_a \sim \ell^2$$

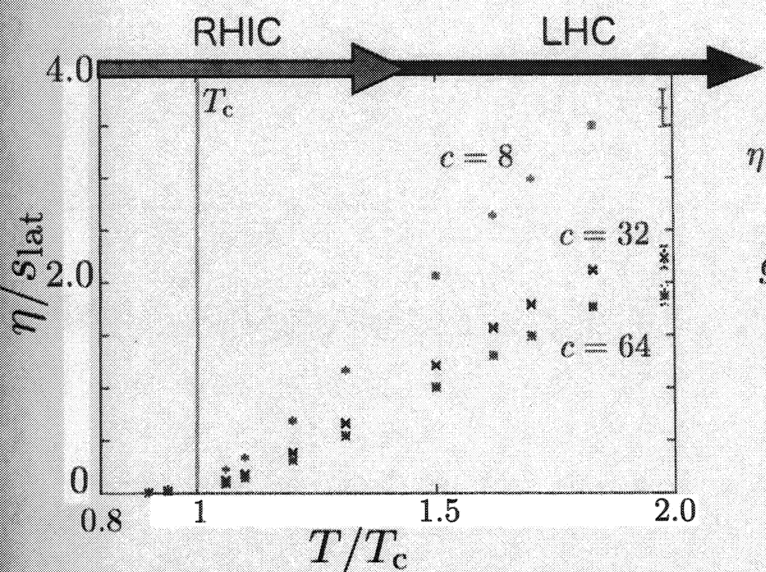
$$\sum_{ab} n_a n_b \sigma_{ab} \sim \ell^2 \sigma$$

➡ $\eta \sim \dfrac{T}{\sigma} \ell^2$ Small viscosity!!

at small ℓ

even a small coupling

Viscosity/Entropy



$$\eta \approx \frac{99.0 \times R(L)}{g^4(T)\ln(c/g(T))}$$

$g(T)$:one-loop running coupling

$$\frac{g^2(T_c)}{4\pi} \simeq 0.3$$

Lattice data from Cheng, et.al. PRD77, 014511(2008)

Large increase from *Tc* to 2 *Tc*.

Clearly need results beyond leading log.

Summary

- Shear viscosity suppressed, near Tc, $\sim \ell^2$. Quarks dominates.

- RHIC - probes semi-QGP? If so, not only η, but R_{AA}, real photons, dileptons, also suppressed by powers of ℓ .

- LHC - into complete QGP?
  If so, LHC ≠ RHIC, a BIG shear viscosity at LHC at short times, and a large multiplicity, unlike strong QGP.

Resummation in the high energy limit

Subtitle: *the exact kinematics in the small x dipole evolution*

Anna Stasto

Outline

- Dipole evolution at high energy
- Modified kernel for the dipole splitting
- Exact kinematics and the multigluon amplitudes

in collaboration with L. Motyka

High energy hadron wave function

Wave function point of view: increasing energy, leads to increasing number of gluons in the wave function

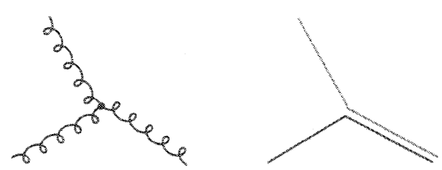
Onium: quark-antiquark pair

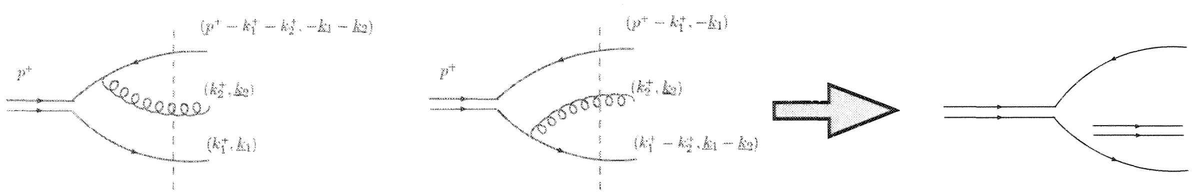
Small energy | Large energy

Scattering amplitudes: evolved hadron wave function scatters on a target.

Multicolor limit and dipoles

Treat number of colors N_c as a large parameter. In first approximation keep leading terms in N_c

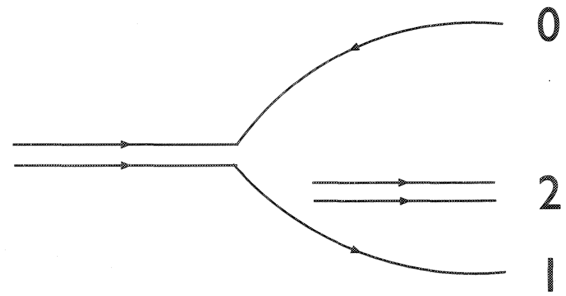




Color dipoles: degrees of freedom at high energy and large N_c limit

Dipole evolution

A.Mueller



$$\Phi^{(1)}(\underline{x}_{01}; z_1) = \int_{z_0}^{z_1} \frac{dz_2}{z_2} \int \frac{d^2\underline{x}_{02}\, x_{01}^2}{x_{02}^2\, x_{12}^2} \Phi^{(0)}(\underline{x}_{01}; z_1) \, .$$

onium with one gluon — splitting — onium with no gluons

Factorization of soft gluons

Dipoles in the high energy limit

- Evolution equation for the dipole splitting with the energy
- Fast growth of the dipole density with increasing energy
- Fast diffusion in impact parameter space
- Large cross sections

Exact kinematics

- Need to include more exact kinematics
- Part of the large higher order corrections
- Cross sections more reliable phenomenologically

Result: kernel rapidity dependent, memory term in the evolution. The new dipole emissions depend on the history of the cascade.

Corrected dipole splitting kernel (with modified Bessel functions):

$$d^2\underline{x}_2 \left(\overline{Q}_{01} K_1(\overline{Q}_{01} x_{02}) \frac{\epsilon_2 \cdot \underline{x}_{02}}{x_{02}} - \overline{Q}_{01} K_1(\overline{Q}_{01} x_{12}) \frac{\epsilon_2 \cdot \underline{x}_{12}}{x_{12}} \right)^2$$

with $\overline{Q}_{01} = \frac{1}{x_{01}} \sqrt{z}\,,$ $\quad z$ fraction of longitudinal momentum

Effects of the modified kernel

$$d^2\underline{x}_2 \left(\overline{Q}_{01} K_1(\overline{Q}_{01} x_{02}) \frac{\epsilon_2 \cdot \underline{x}_{02}}{x_{02}} - \overline{Q}_{01} K_1(\overline{Q}_{01} x_{12}) \frac{\epsilon_2 \cdot \underline{x}_{12}}{x_{12}} \right)^2 \qquad \overline{Q}_{01} = \frac{1}{x_{01}} \sqrt{z}\,,$$

- Effective energy dependent cutoff (changing infrared cutoff) on the large dipole sizes

$$x_{02}^{\max} \simeq \frac{x_{01}}{\sqrt{z_{\min}}}\,.$$

- Suppressed diffusion in the impact parameter space: smaller cross sections.

$$N(x_{01}, b_{01}) \sim \exp(-2 \frac{b_{01}}{x_{01}} \sqrt{z})\,.$$

- Consistent with the part of the next-to-leading corrections

- Violation of the 2-dim conformal symmetry. Longitudinal and transverse components coupled.

Multigluon wave functions

- Modified kernel: still derived by making some approximations (ex. eikonal vertices).
- Evaluate the multigluon wave functions in the light cone perturbation theory exactly.

$$\Phi_{n+1}(r_1,\ldots,r_{n+1}) \propto \int \prod_{i=1}^{n} d^2r_i'\, K_{n+1}(\sqrt{Q^2 A(r_i,r_i')})\, \Phi_n(r_1',\ldots,r_n')$$

wave function with n+1 gluons — wave function with n gluons

Recursion relations between wave functions with n and n+1 gluons.

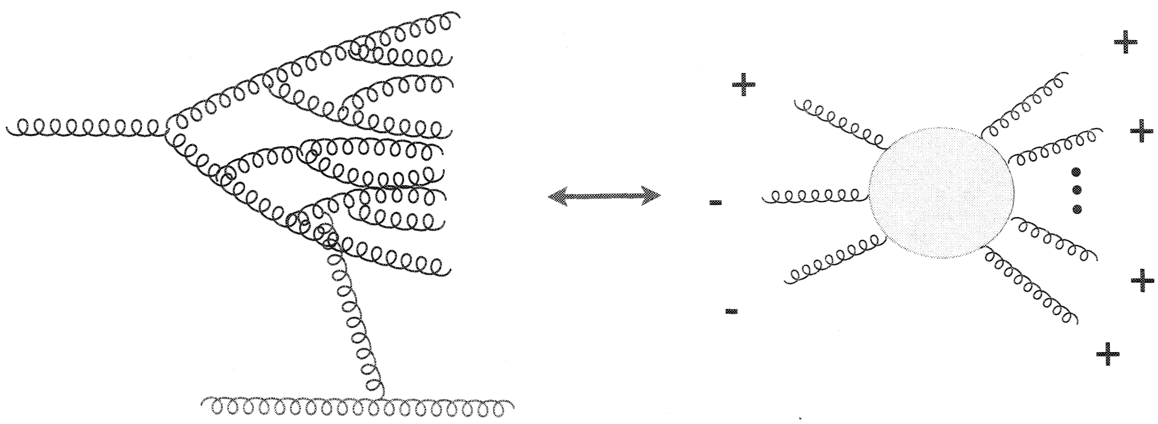
Unlike the previous case, the splitting depends on the number of gluons and the positions of all dipoles (gluons).

Multigluon wave functions and amplitudes

- Multigluon wave functions in light cone perturbation theory
- Recursion relations: off-shell and on-shell initial momenta
- Scattering amplitudes (on-shell)
- Consistency check with the maximally helicity violating amplitudes

Light cone amplitude: scattering of the light cone wave function

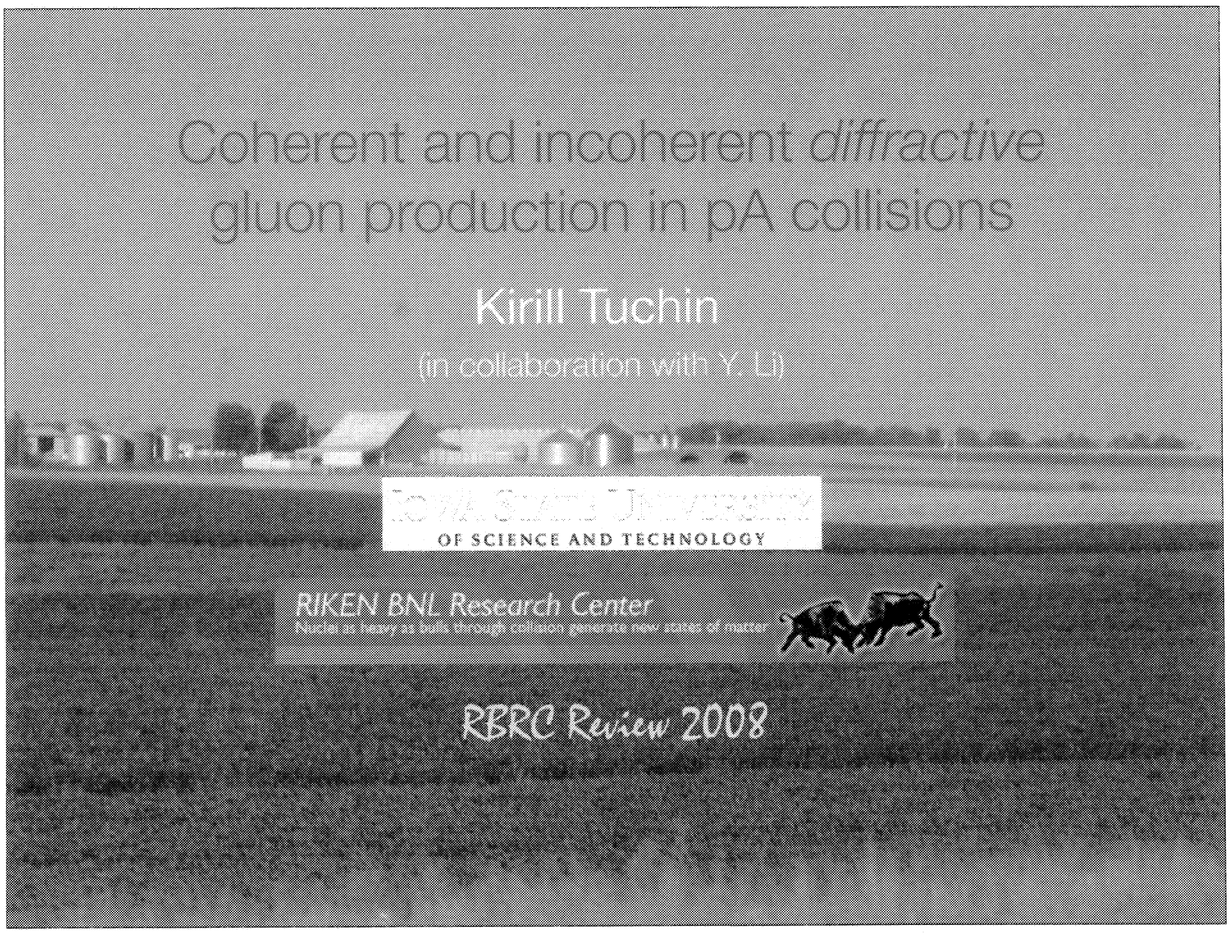
Maximally helicity violating amplitude



So far checked only in the limit of large rapidity difference between the hadron and the target .

Summary

- Dipole evolution modified to include effects from more exact kinematics.
- Qualitative and quantitative change of the evolution: sliding cutoff (with energy), suppressed diffusion, coupling of longitudinal and transverse components ,no 2-dim conformal invariance.
- Resummation of the multi-gluon amplitudes in the light cone perturbation theory.
- Recursion relations for the off-shell and on-shell amplitudes.
- Consistency check with the maximally helicity violating amplitudes.



Diffraction in particle physics

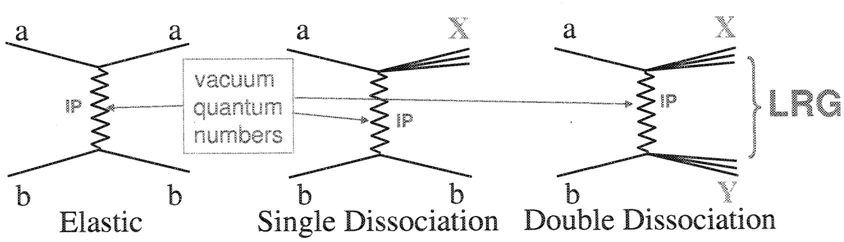


fig. courtesy by
Arneodo and Diehl

Pomerantchuk theorem: at s→∞ the amplitude is dominated by exchange of vacuum quantum numbers in t-channel.

⇒ Diffraction probes the high energy regime, i.e. low x of QCD

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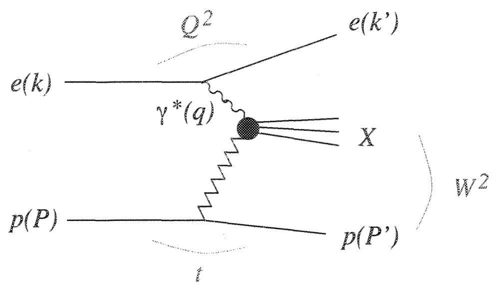
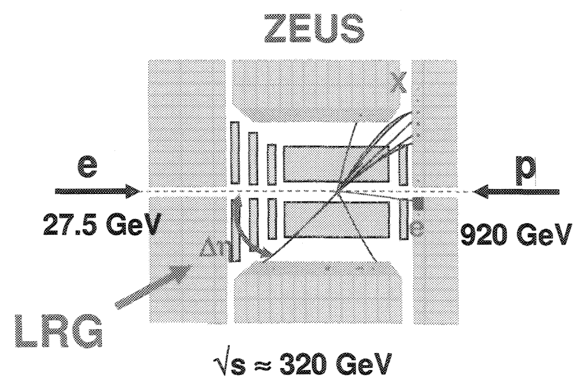
Diffraction at HERA





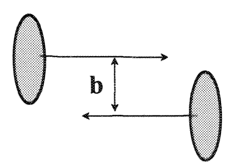
3

pp-scattering

Scattering amplitude: $i\Gamma^{pp}(s, \mathbf{b})$

Optical theorem: $\sigma_{\text{tot}}^{pp} = 2 \int d^2b \, \text{Re} \, \Gamma^{pp}(s, \mathbf{b})$

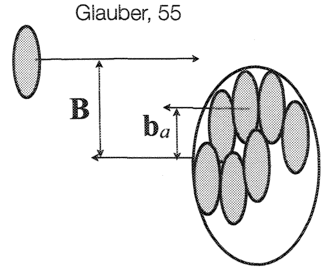
We can write: $\Gamma^{pp}(s, \mathbf{b}) = 1 - e^{-i\chi^{pp}(s,\mathbf{b})}$



pA-scattering

Assume that all pN scatterings are independent:

Glauber, 55



$$\chi^{pA}(s, \mathbf{B}, \{\mathbf{b}_a\}) = \sum_{a=1}^{A} \chi_a^{pN}(s, \mathbf{B} - \mathbf{b}_a)$$

$$\Gamma^{pA}(s, \mathbf{B}, \{\mathbf{b}_a\}) = 1 - \prod_{a=1}^{A} \left(1 - \Gamma^{pN}(s, \mathbf{B} - \mathbf{b}_a)\right)$$

$\sigma_{\text{tot}}^{pA} = 2 \int d^2b \, \text{Re} \, \Gamma_{ii}^{pA}(s, \mathbf{b})$ where $\Gamma_{if}^{pA}(s, \mathbf{B}) = \langle A_i | \Gamma^{pA}(s, \mathbf{B}, \{\mathbf{b}_a\}) | A_f \rangle$

4

Neglecting motion of nucleons during the interaction:

$$\Gamma_{ii}^{pA}(s,\mathbf{B}) = \frac{1}{A}\int\prod_{a=1}^{A} d^2b_a\,\rho T_A(\mathbf{b}_a)\,\Gamma^{pA}(s,\mathbf{B}-\mathbf{b}_a) \;\approx 1 - e^{-\int d^2b_a\,\Gamma^{pN}(s,\mathbf{b}_a)\,\rho T_A(\mathbf{B}-\mathbf{b}_a)}$$

Since $R_p << R_A$: $\Gamma_{ii}^{pA}(s,\mathbf{b}) = 1 - e^{-\frac{1}{2}\sigma_{\rm tot}^{pN}\,\rho T_A(\mathbf{b})}$

Coherent diffraction: A is intact

$$\sigma_{\rm CD}^{pA}(s) = \int d^2b\,\left|\Gamma_{ii}^{pA}(s,\mathbf{b})\right|^2 = \int d^2b\left(1 - e^{-\frac{1}{2}\sigma_{\rm tot}^{pN}\,\rho T_A(\mathbf{b})}\right)^2$$

Incoherent diffraction: A dissociates into colorless debris

$$\sigma_{\rm ID}^{pA}(s) = \int d^2B\sum_{i\neq f}\langle A_i|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_f\rangle^\dagger\langle A_f|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_i\rangle$$

$$= \int d^2B\sum_{f}\langle A_i|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_f\rangle^\dagger\langle A_f|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_i\rangle - \int d^2B\,\left|\langle A_i|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_i\rangle\right|^2$$

$$= \int d^2B\left[\langle A_i|\,\left|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})\right|^2|A_i\rangle - \left|\langle A_i|\Gamma^{pA}(s,\mathbf{B},\{\mathbf{b}_a\})|A_i\rangle\right|^2\right]$$

$$= \int d^2b\,e^{-\sigma_{\rm in}^{pN}\,\rho T_A(\mathbf{b})}\left[1 - e^{-\sigma_{\rm el}^{pN}\,\rho T_A(\mathbf{b})}\right]$$

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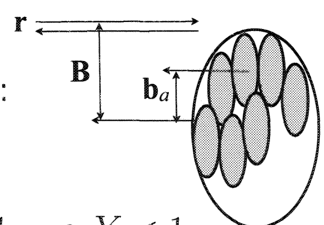
Diffraction in the dipole model



Forward elastic dipole-nucleus scattering amplitude:

$$N_A(\mathbf{r},\mathbf{b},Y) = {\rm Re}\,\Gamma_{ii}^{q\bar{q}A}(s,\mathbf{b};\mathbf{r})$$

Let x=exp$(-Y)$ If $l_c = 1/(M_N\,x) \gg R_A$ $\alpha_s^2 A^{1/3}\sim 1,$ $\alpha_s Y < 1$

$$\sigma_{\rm tot}^{q\bar{q}A}(s;\mathbf{r}) = 2\int d^2b\,N_A(\mathbf{r},\mathbf{b},Y) = 2\int d^2b\,\left(1 - e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{r})\,\rho T_A(\mathbf{b})}\right)$$ A.Mueller, 90

in the Born approximation: $\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{r}) = \frac{\alpha_s}{N_c}\pi^2\mathbf{r}^2\,xG(x,1/\mathbf{r}^2)$

Coherent diffraction:

$$\sigma_{\rm CD}^{q\bar{q}A}(s;\mathbf{r}) = \int d^2b\,\left|\Gamma_{ii}^{q\bar{q}A}(s,\mathbf{b};\mathbf{r})\right|^2 = \int d^2b\left(1 - e^{-\frac{1}{4}\frac{C_F}{N_c}Q_{s0}^2\,\mathbf{r}^2}\right)^2$$

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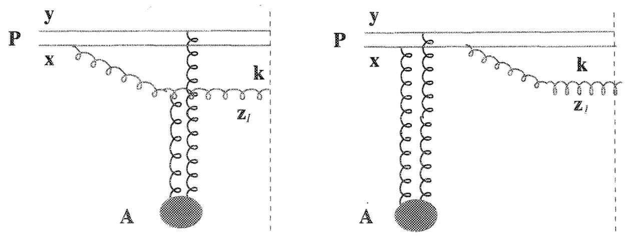
Diffractive gluon production



$$\Gamma^{q\bar{q}GA}_{ii,\sigma} = 1 - e^{-\frac{1}{8}(\mathbf{x}-\mathbf{z}_\sigma)^2 Q_{s0}^2 - \frac{1}{8}(\mathbf{y}-\mathbf{z}_\sigma)^2 Q_{s0}^2 - \frac{1}{8N_c^2}(\mathbf{x}-\mathbf{y})^2 Q_{s0}^2}$$

Kopeliovich, Tarasov, Schafer,99

Coherent diffraction

$$\frac{d\sigma_{\rm CD}(k,y)}{d^2k\,dy} = \frac{1}{(2\pi)^2}\int d^2b\, d^2z_1\, d^2z_2\, \Phi^{q\bar{q}}(\mathbf{x},\mathbf{y},\mathbf{z}_1,\mathbf{z}_2)\, e^{-i\mathbf{k}\cdot(\mathbf{z}_1-\mathbf{z}_2)}$$
$$\times \left(\Gamma_{ii}^{q\bar{q}GA}(s,\mathbf{b};\mathbf{x},\mathbf{y},\mathbf{z}_1) - \Gamma_{ii}^{q\bar{q}A}(s,\mathbf{b};\mathbf{x},\mathbf{y})\right)\left(\Gamma_{ii}^{q\bar{q}GA}(s,\mathbf{b};\mathbf{x},\mathbf{y},\mathbf{z}_2) - \Gamma_{ii}^{q\bar{q}A}(s,\mathbf{b};\mathbf{x},\mathbf{y})\right)$$

Kovner, Wiedeman 01, Kovchegov 01

Unlike the inclusive gluon production, the diffractive one vanishes when the onium size **r=x-y** larger than 1/Qs.

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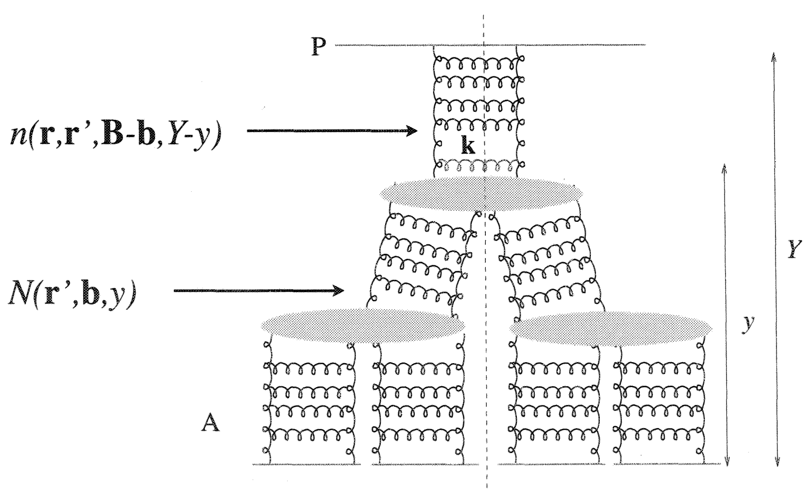
If $\alpha_s Y \sim 1$ the low x evolution effects must be taken into account:



N(**r**',**b**,*y*) satisfies the BK equation

$$\frac{\partial N(\mathbf{x}-\mathbf{y},\mathbf{b},y)}{\partial y} = \frac{\alpha_s N_c}{2\pi^2}\int d^2z\,\frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{y}-\mathbf{z})^2}\big[N(\mathbf{x}-\mathbf{z},\mathbf{b},y)$$
$$+N(\mathbf{y}-\mathbf{z},\mathbf{b},y) - N(\mathbf{x}-\mathbf{y},\mathbf{b},y) - N(\mathbf{x}-\mathbf{z},\mathbf{b},y)N(\mathbf{y}-\mathbf{z},\mathbf{b},y)\big]$$

n(**r**,**r**',**B**-**b**,*Y*-*y*) satisfies the BFKL equation (in accordance with the AGK cutting rules).

8

Incoherent diffraction

$$\sum_{f\neq i}\langle A_i|\Gamma^{q\bar{q}GA}(s,\mathbf{B},\{\mathbf{b}_a\};\mathbf{x},\mathbf{y},\mathbf{z}_1)|A_f\rangle^{\dagger}\langle A_f|\Gamma_2^{q\bar{q}GA}(s,\mathbf{B},\{\mathbf{b}_a\};\mathbf{x},\mathbf{y},\mathbf{z}_2)|A_i\rangle$$

$$= e^{-\frac{1}{2}\left[\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_1)+\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_2)-\frac{1}{4\pi R_p^2}\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_1)\,\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_2)\right]\rho T_A(\mathbf{b})}$$

$$\times\left\{1-e^{-\frac{1}{2}\frac{1}{4\pi R_p^2}\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_1)\,\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_2)\,\rho T_A(\mathbf{b})}\right\}$$

Since $\alpha_s^2 A^{1/3}\sim 1 \;\Rightarrow\; \left(\sigma_{\rm tot}^{q\bar{q}GN}\right)^2\rho T_A(\mathbf{b})\sim\alpha_s^4 A^{1/3}\sim\alpha_s^2$

$\Rightarrow$ we can expand

$$\frac{d\sigma_{\rm ID}(k,y)}{d^2k\,dy}=\frac{1}{(2\pi)^2}\frac{1}{8\pi R_p^2}\int d^2b\,d^2z_1\,d^2z_2\,\Phi^{q\bar{q}}(\mathbf{x},\mathbf{y},\mathbf{z}_1,\mathbf{z}_2)\,e^{-i\mathbf{k}\cdot(\mathbf{z}_1-\mathbf{z}_2)}\,\rho T_A(\mathbf{b})$$

$$\times\left(\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_1)\,e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_1)\,\rho T_A(\mathbf{b})}-\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{x},\mathbf{y})\,e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{x},\mathbf{y})\,\rho T_A(\mathbf{b})}\right)$$

$$\times\left(\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_2)\,e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}GN}(s;\mathbf{x},\mathbf{y},\mathbf{z}_2)\,\rho T_A(\mathbf{b})}-\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{x},\mathbf{y})\,e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{x},\mathbf{y})\,\rho T_A(\mathbf{b})}\right)$$

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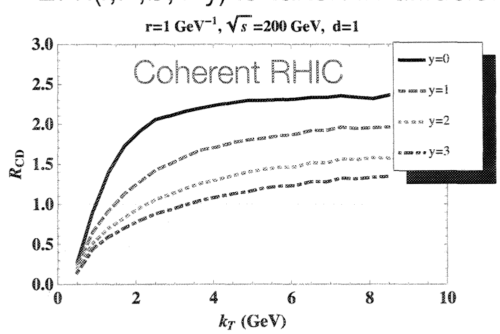
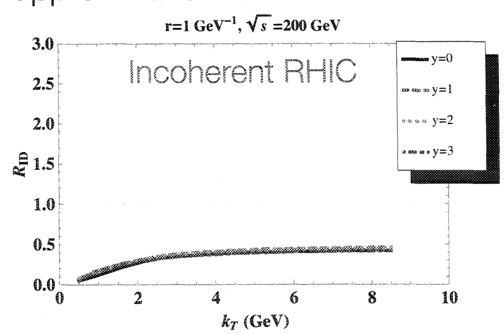
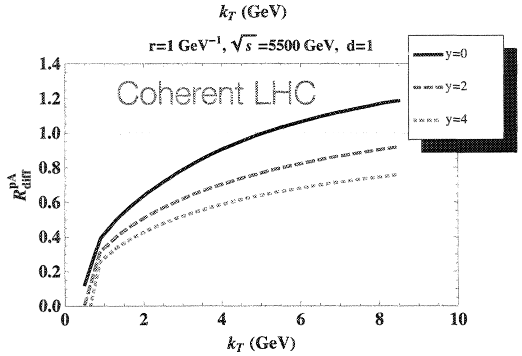
Numerical analysis

1. As a model for $N_A(r,b,Y)$ we use the KKT model.
2. n(r,r',b,Y-y) is taken in diffusion approximation to BFKL.







Strong dependence of the coherent diffraction on y continues also at LHC (unlike inclusive hadron production).

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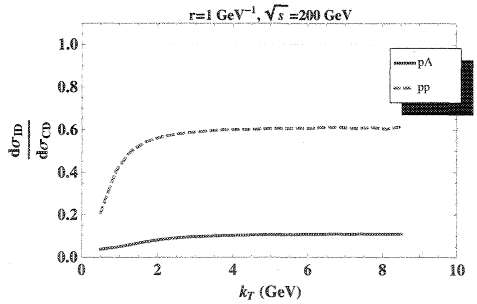
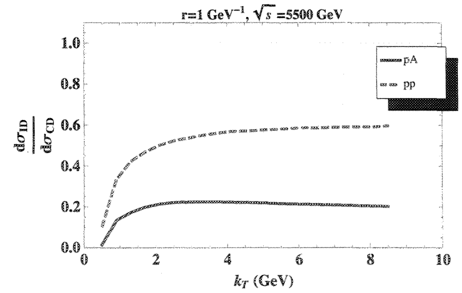
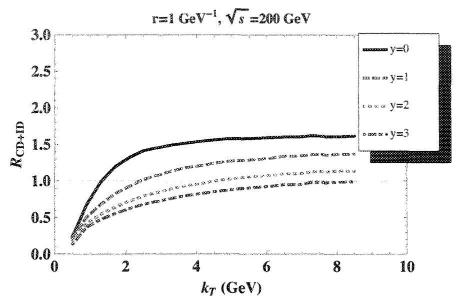
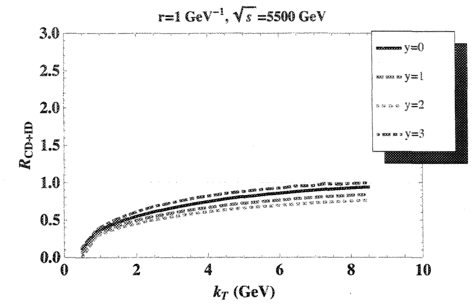




Experimental cuts will definitely enhance incoherent diffraction with respect to coherent one.





It's important to be able to experimentally distinguish ID and CD!

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Conclusions

1. Coherent diffractive hadron production is more sensitive to the low x structure functions than inclusive hadron production.

2. It can serve as an efficient tool for studying the gluon saturation at EIC, RHICII and LHC.

3. Need to resolve coherent and incoherent components.

12

Gluon propagator and $\bar{Q}Q$ potential in anisotropic pQCD

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Collaborators: Yun Guo, Mike Strickland (PLB 2008)

- Motivation
- Covariant-gauge gluon propagator in aniso. QGP
- Static limit: heavy-quark potential
- Results and discussion

- Motivation:

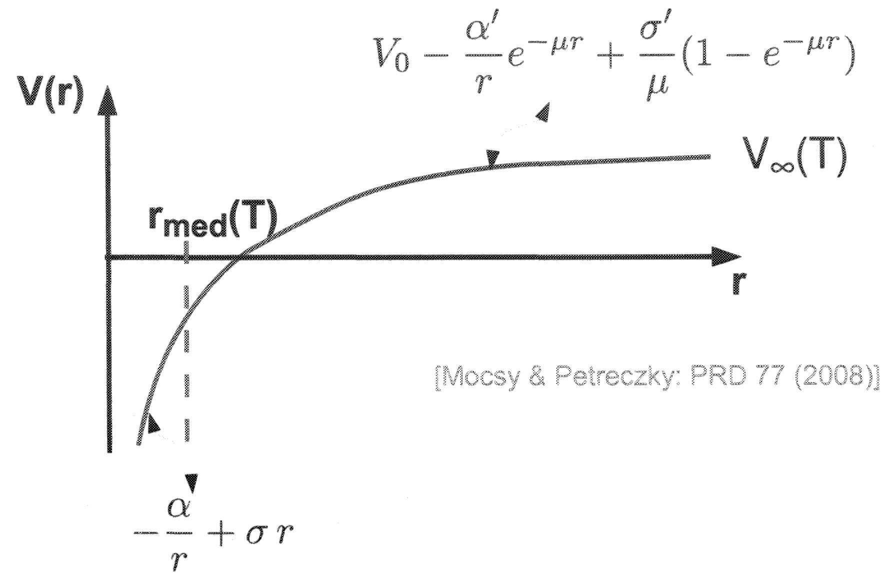
  ✗ $Q\bar{Q}$ bound states may survive above T_C
  (Jakovac et al, PRD 07; Aarts et al, PRD 07)

  ✗ test potential models at T>0
  (Karsch, Mehr, Satz, ZPC 88;
  Petreczky and Mocsy, 2005-2008)

  ✗ here:
  $Q\bar{Q}$ potential away from perfect equilibrium:
  dependence on viscosity and expansion rate

Behavior of the potential in equilibrium at high T

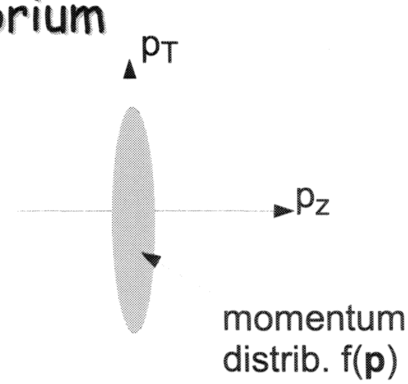
$$r_{\rm med}(T) \approx 0.5 \text{ fm } (T_C/T)$$ [Kaczmarek et al: PRD 70 (2004)]



Motivation II: expanding viscous plasma always (slightly) out of equilibrium

$$f(\mathbf{p}) = f_{iso}(\sqrt{\mathbf{p}^2 + \xi p_z^2})$$

anisotropy parameter



- Relation to viscosity: $\xi = \frac{10}{T\tau}\frac{\eta}{s}$

[e.g. Asakawa, Bass, Müller: Prog. Theor. Phys. 116 (2007) p. 725]

- With η/s~0.1, τT~1-3, expect ξ~1

Lattice:

$$\langle \mathcal{O} \rangle = \int \mathcal{D}A \; e^{-S[A]} \; \mathcal{O}[A]$$

average over isotropic gauge-field configurations (in momentum space)
$\Rightarrow$ non-equilibrium / viscosity effects are *not included* !

- need to rely on pQCD at short distance, models at large distance

Covariant-gauge gluon propagator in anisotr. QGP

1) HTL (retarded) self-energy

$$\Pi^{\mu\nu} = g^2 \int \frac{d^3k}{(2\pi)^3} \, v^\mu \frac{\partial f(\mathbf{k})}{\partial k^\beta} \left(g^{\nu\beta} - \frac{v^\nu p^\beta}{p \cdot v + i\epsilon} \right)$$

$$\left(\Delta^{-1}\right)^{\mu\nu}(p,\xi) = -p^2 g^{\mu\nu} + p^\mu p^\nu - \Pi^{\mu\nu}(p,\xi) - \frac{1}{\lambda} p^\mu p^\nu$$

invert: $\quad (\Delta^{-1})^{\mu\sigma} \Delta_\sigma{}^{\nu} = g^{\mu\nu}$

static limit:

$$\Delta^{00}(\omega = 0, \mathbf{p}) = \frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

"Mass" scales:

$$
\begin{aligned}
m_\alpha^2 &= -\frac{m_D^2}{2p_\perp^2\sqrt{\xi}}\left(p_z^2 \arctan\sqrt{\xi} - \frac{p_z \mathsf{p}^2}{\sqrt{\mathsf{p}^2+\xi p_\perp^2}}\arctan\frac{\sqrt{\xi}p_z}{\sqrt{\mathsf{p}^2+\xi p_\perp^2}}\right) \\
m_\beta^2 &= m_D^2 \frac{(\sqrt{\xi}+(1+\xi)\arctan\sqrt{\xi})(\mathsf{p}^2+\xi p_\perp^2)+\xi p_z\left(p_z\sqrt{\xi}+\frac{\mathsf{p}^2(1+\xi)}{\sqrt{\mathsf{p}^2+\xi p_\perp^2}}\arctan\frac{\sqrt{\xi}p_z}{\sqrt{\mathsf{p}^2+\xi p_\perp^2}}\right)}{2\sqrt{\xi}(1+\xi)(\mathsf{p}^2+\xi p_\perp^2)} \\
m_\gamma^2 &= -\frac{m_D^2}{2}\left(\frac{\mathsf{p}^2}{\xi p_\perp^2+\mathsf{p}^2} - \frac{1+\frac{2p_z^2}{p_\perp^2}}{\sqrt{\xi}}\arctan\sqrt{\xi} + \frac{p_z\mathsf{p}^2(2\mathsf{p}^2+3\xi p_\perp^2)}{\sqrt{\xi}(\xi p_\perp^2+\mathsf{p}^2)^{\frac{3}{2}}p_\perp^2}\arctan\frac{\sqrt{\xi}p_z}{\sqrt{\mathsf{p}^2+\xi p_\perp^2}}\right) \\
m_\delta^2 &= -\frac{\pi m_D^2 \xi p_z p_\perp |\mathsf{p}|}{4(\xi p_\perp^2+\mathsf{p}^2)^{\frac{3}{2}}}.
\end{aligned}
$$

Note:

$$
\text{for } \xi = 0: \quad m_\beta = m_D \quad , \quad m_{\alpha,\gamma,\delta} = 0
$$

$$
\rightarrow \Delta^{00}(\omega = 0, \mathsf{p}) = \frac{1}{\mathsf{p}^2 + m_D^2}
$$

1-g exchange potential: F.T. of static propagator

$$
V(\mathsf{r},\xi) = -g^2 C_F \int \frac{d^3\mathsf{p}}{(2\pi)^3}\, e^{i\mathsf{p}\cdot\mathsf{r}} \Delta^{00}(\omega=0,\mathsf{p},\xi)
$$

Limiting cases:

- $\xi \to 0$: Debye-screened potential

$$
V(\mathsf{r},\xi=0) \;=\; V_{\rm iso}(r) \;=\; -\,\frac{\alpha_s C_F}{r}\,e^{-r m_D}
$$

- $r \to 0$: Coulomb potential

$$
V(\mathsf{r}\to 0,\xi) \;=\; V_{\rm vac}(r) \;=\; -\,\frac{\alpha_s C_F}{r}
$$

(no string ~σr from perturbation theory)

• weak anisotropy ξ«1: angular dependence of screening

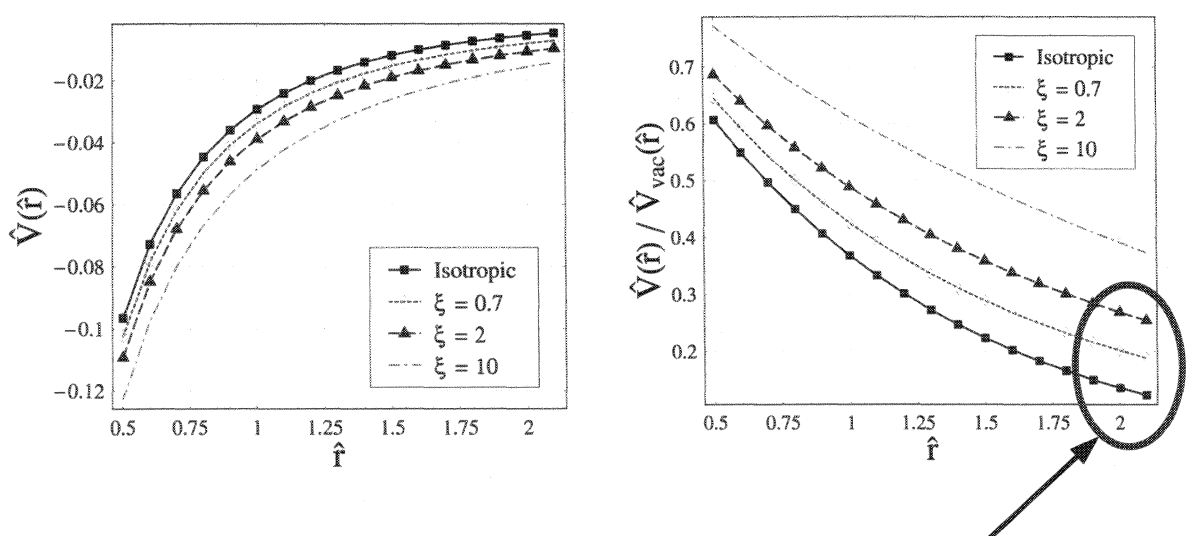
$$V(\mathbf{r} \parallel \hat{z}, \xi \ll 1) = V_{iso}(r)\left[1 + \xi \underbrace{\left(2\frac{e^{\hat{r}}-1}{\hat{r}^2} - \frac{2}{\hat{r}} - 1 - \frac{\hat{r}}{6}\right)}_{=+0.27 \text{ for } \hat{r}=1}\right]$$

$$V(\mathbf{r} \perp \hat{z}, \xi \ll 1) = V_{iso}(r)\left[1 + \xi \underbrace{\left(\frac{1-e^{\hat{r}}}{\hat{r}^2} + \frac{1}{\hat{r}} + \frac{1}{2} + \frac{\hat{r}}{3}\right)}_{=+0.12 \text{ for } \hat{r}=1}\right]$$

valid for $\hat{r} \equiv r\, m_D \lesssim 1$

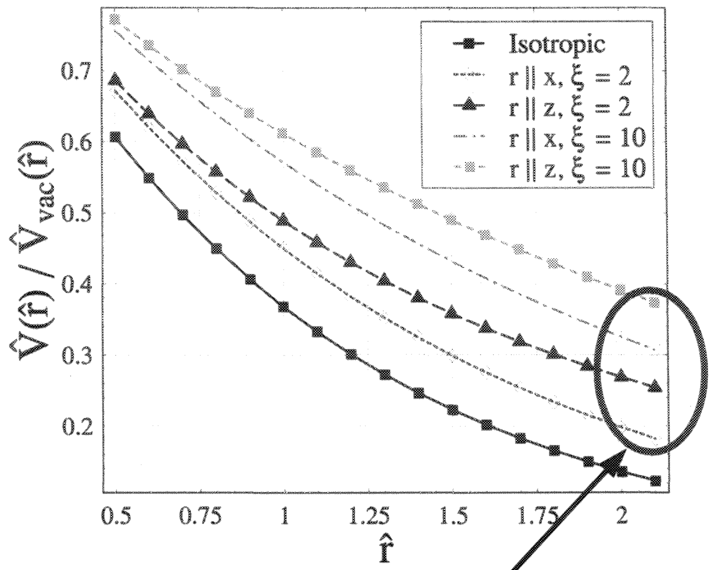
◆ screening weaker for r ∥ z

• numerical results for arbitrary anisotropy ξ and r ∥ z:



weakening of screening more pronounced at larger distance

• r ∥ z versus r ⊥ z:



- angular dependence stronger at larger distance
- as r→0, angular dependence disappears

Discussion

• anisotropy (ξ>0) affects binding energy

ground state, 1 » ξ » m_D / (α_s C_F m_Q) :

$$\frac{\Delta E}{E_C} \approx \frac{4}{\alpha_s C_F}\frac{m_D}{m_Q}\left(-1+\frac{\xi}{6}+\cdots\right)$$ (universal, all states)

temperature effect

anisotropy / viscosity effect

• for larger states, shift of binding energy depends on angular momentum ℓ ! (not the same for η_b, Υ, ...)

Q free energy at ξ≠0 (—> $V_\infty/2$)

$$
\begin{aligned}
L(x) &= \mathcal{P}e^{ig\int d\tau A_0(x,\tau)} \\
\frac{1}{N}\langle \mathrm{tr}\, L\rangle &= e^{-F_Q/T} \sim 1 - F_Q/T \\
F_Q/T &= 1 - \frac{1}{N}\langle \mathrm{tr}\, L\rangle \\
&\simeq -(ig)^2 \int d^3x d\tau_1 d\tau_2 \, \frac{1}{N}\langle \mathrm{tr}\, A_0(x,\tau_1)A_0(x,\tau_2)\rangle \\
&= \frac{g^2 C_F}{T} \int \frac{d^3k}{(2\pi)^3} \, \Delta_{00}(\omega=0,\mathsf{k}) \\
F_Q(\xi,T) &= g^2\, C_F \int \frac{d^3k}{(2\pi)^3} \left[\Delta_{00}(\mathsf{k}) - \frac{1}{\mathsf{k}^2}\right] \\
&= -\alpha_s C_F m_D \left(1 - \frac{1}{6}\xi + \frac{18-\pi^2}{240}\xi^2 + \cdots\right)
\end{aligned}
$$

~ #T ⇒ doesn't contribute to V_∞

Outlook:

- determine wave functions, binding energies etc in anisotropic plasma from potential model (model long-distance part, solve 3d Schrödinger eq.)
  work in progress, hopefully some results soon
- imaginary part of potential (→ width of quarkonium states) in an anisotropic plasma ?
  [Laine et al: JHEP (2007); Mocsy, Petreczky: PRL 99 (2007)]

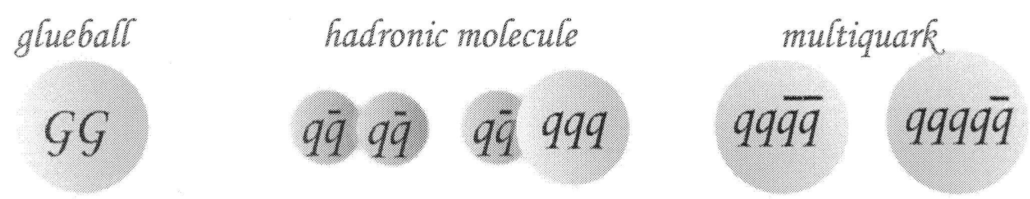
Dynamical study of bare σ pole with 1/Nc classifications

Toru Kojo (RIKEN BNL)

Daisuke Jido (YITP, Kyoto Univ.)

Introduction

The properties of exotica are fundamental issues in QCD.



f0 (1500) ?

Λ(1405) as KN molecule ?

Θ+ (1540) ?

Newly observed charmonia (X, Y, Z)

The σ meson (I=J=0) is a candidate of these exotica:

$$|\sigma\rangle \sim \; a\,|q\bar{q}\rangle + b\,|GG\rangle + c\,|\pi\pi\rangle + d\,|qq\bar{q}\bar{q}\rangle + \ldots\ldots ,$$

$$(m + i\,\Gamma/2 \; \sim 500 + i\,250 \;\; MeV)$$

thus is good laboratory to study the properties of exotic components & their interplay.

Strategy to study the exotic components

Our study of the exotic components is based on:

- the study of correlators made of quark–gluon fields
  → quantitative results without bias
- the classification of quark–gluon graphs based on 1/Nc
  → relation between quark–gluon dynamics and hadronic states

$$|\sigma\rangle \sim \underbrace{a\,|q\bar{q}\rangle + b\,|GG\rangle + c\,|\pi\pi\rangle + d\,|qq\bar{q}\bar{q}\rangle}_{} + \ldots..$$

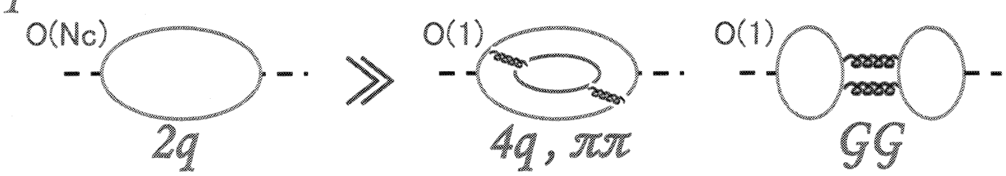
mixing is mediated by higher order of O(1/Nc)

→ separate investigation of each exotic state is possible.

In this work, we focus on the *4q* component, separating *GG*, and, in particular, *ππ* scattering states.

1/Nc classifications: 2q and 4q correlator

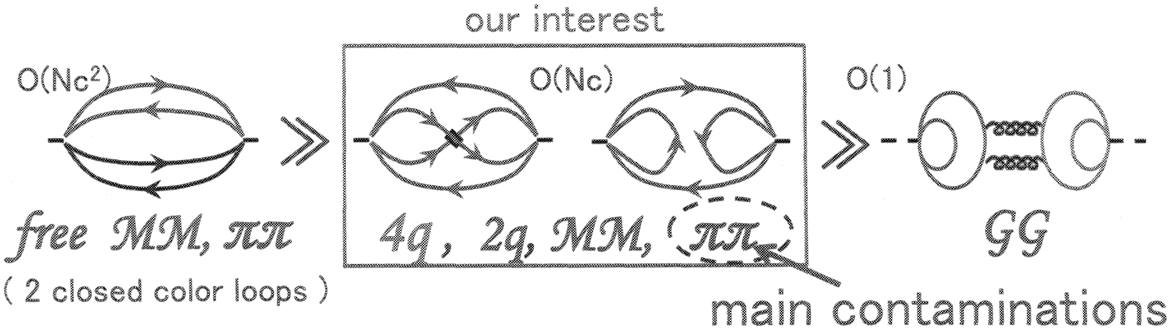
- $2q$ correlator:



→ LO of $2q$ correlator is dominated by $2q$ state

- $4q$ correlator: $J_{\underline{M}\,\underline{M}}(x)=\sum_{F=1}^{3}(\bar{q}\tau_F\Gamma_{\underline{M}}q)(\bar{q}\tau_F\Gamma_{\underline{M}}q)$

(product of meson currents)



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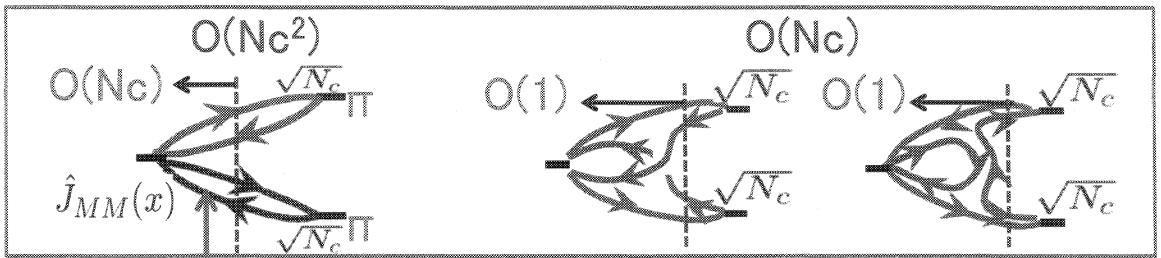
Isolation of resonance from $\pi\pi$ background

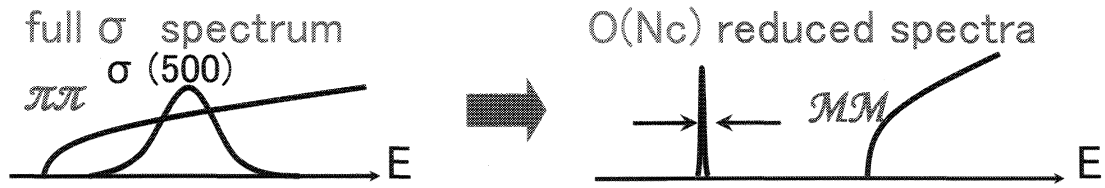
4q current: $J_{MM}(x) = \sum_{F=1}^{3} (\bar{q}\tau_F \Gamma_M q)(\bar{q}\tau_F \Gamma_M q)$

- Overlap with $\pi\pi$ is determined from 3-point correlator:



vanish when M ≠PS or A

⟹ $\langle 0|J_{MM}|\pi\pi\rangle\langle\pi\pi|J^{\dagger}_{MM}|0\rangle = O(1)$! (if M ≠PS or A)



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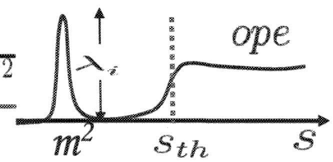
QCD Sum Rules for reduced spectra

Borel transformed ($Q^2 \rightarrow M^2$) dispersion relation

$$\hat{L}_M \sum_n C_n(Q^2)\langle O_n\rangle \Longleftrightarrow \int ds\, e^{-\frac{s}{M^2}}$$

OPE: $C_n(Q^2)$ hard, $\langle O_n\rangle$ soft



taking the moments ⟹ $m(M^2, S_{th})$, $\lambda(M^2, S_{th})$

- Sth will be fixed to achieve the least sensitivity of physical parameters against artificial expansion parameter M.
- We evaluate physical parameters taking small M (i.e., large 1/M) to suppress the high energy part in the spectral sum rules.

- We calculate the OPE up to dim.12 to include low E contributions.
- In large Nc, condensates can be factorized.

Leading Nc results for 4q scalar mesons

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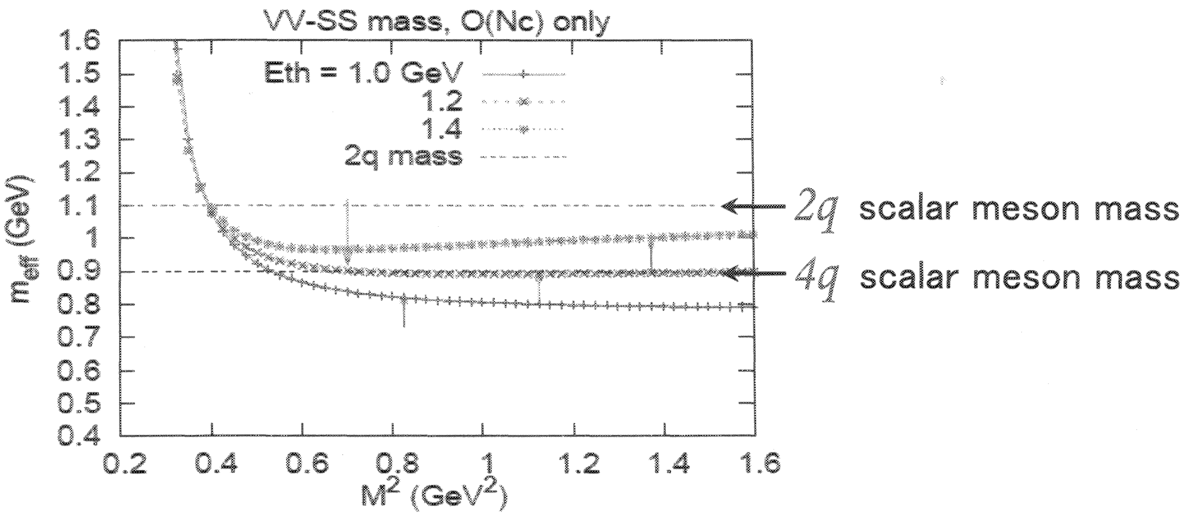

- We have also investigated other scalar correlators, and obtained consistent results.
- *4q* is lighter than *2q* by 200〜300 MeV, irrespective of condensate values.

Summary and Outlook

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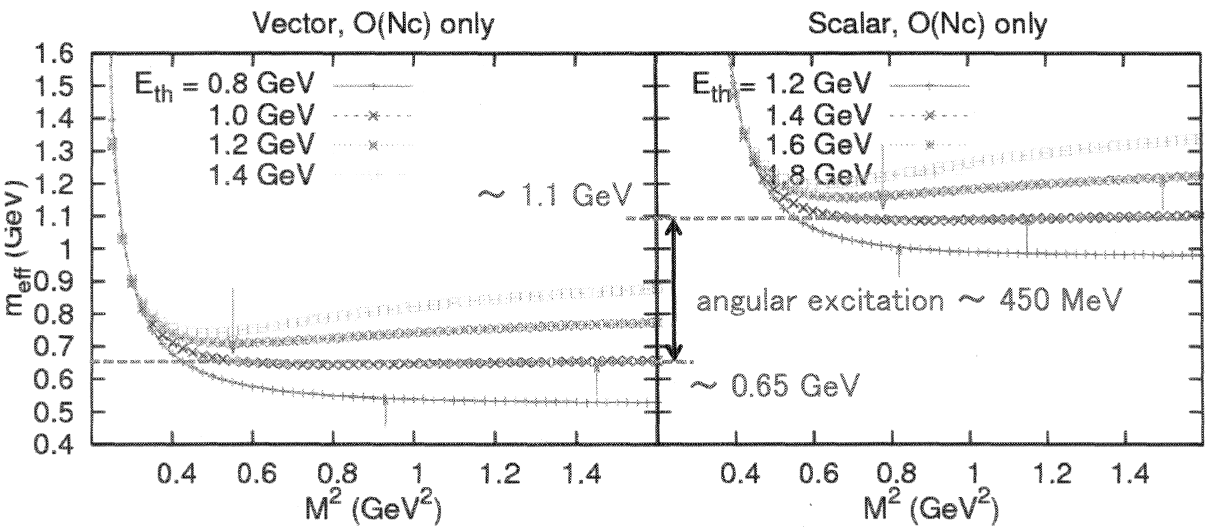
- **We proposed 1/Nc classifications for the study of exotica.**
  - 1/Nc arguments are useful for the study of multiquark states.
  - *4q* and meson molecule or scattering states can be studied separately.
- **Dynamics of σ meson are studied using the QCD sum rules.**
  - In large Nc, 1−peak Ansatz for low energy part of spectrum & factorization of condensates are justified.
  - In σ meson case, *4q* component leads 200〜300 MeV reduction of mass compared to *2q*. component.
  - *4q*. component has mass about 800〜900 MeV, and does not solely explain the light mass (500MeV) of σ meson.
    → importance of interplay with $\pi\pi$, GG, instanton effects, etc..
- **It is interesting to apply 1/Nc to exotic charmonia (X,Y,Z) to clarify their properties, molecule−like or tetraquark−like structure.**

Appendix. 1

Effective mass for O(Nc) pure 2q correlators

(Without 2 meson intermediate states, instanton, and glueball.)

2q ($J^P = 1^-$, S=1, L=0) 2q ($J^P = 0^+$, S=1, L=1)



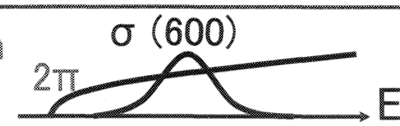
Remark:

If we assume the Nc scaling of condensates, the absence of the factorization violation leads the mass reduction when Nc = 3 → ∞.

Problems to analyze the tetraquark correlators

Complicated form of spectral function

$\pi\pi$ scattering states & large width

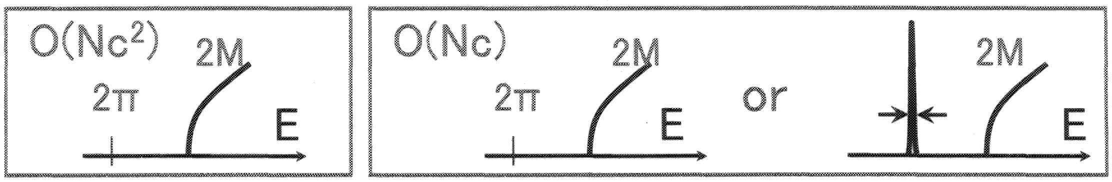


Ambiguities in the value of higher dimension condensates

Tetraquark correlators must be expanded up to dimension ~ 12.

⬇ 1/Nc arguments resolve these problems

- With appropriate currents $\hat{J}_{MM}(x)$ (M = S, V, T meson)



- Factorization for multi-quark, mixed condensates becomes exact!

$$\langle 0|(\bar{q}q)(\bar{Q}Q)|0\rangle = \boxed{\langle 0|\bar{q}q|0\rangle\langle 0|\bar{Q}Q|0\rangle} + \sum_M \langle 0|\bar{q}q|M\rangle\langle M|\bar{Q}Q|0\rangle$$

$O(N_c)$ $\qquad$ $O(N_c^{1/2})$

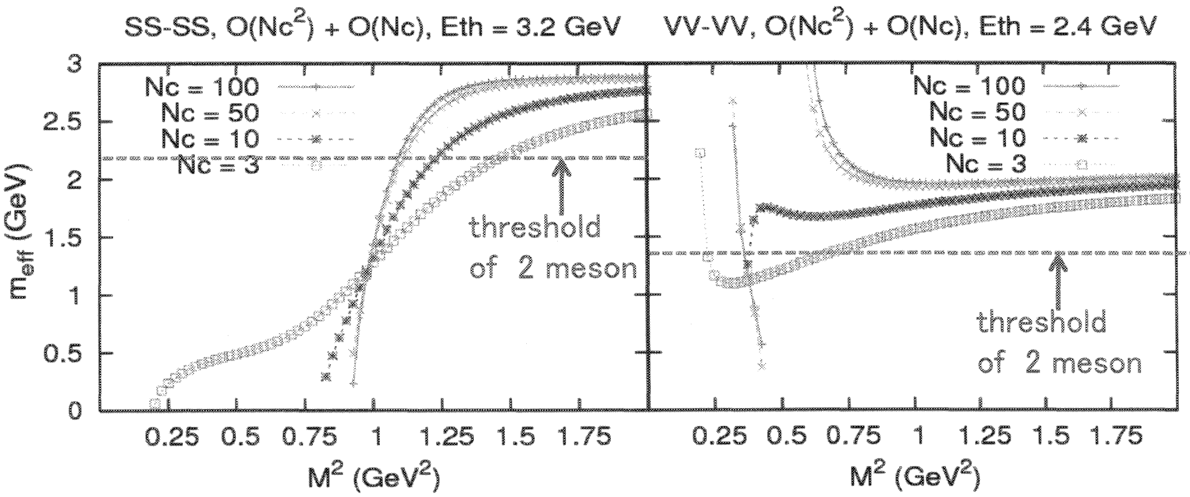
Effective mass for O(Nc²) + O(Nc) correlator

(diagonal correlator: SS–SS, VV–VV case)

Nc = ∞ : only 2 meson scattering states

Nc → 3 : possible resonance + scattering states

(& violation of factorization approximation)

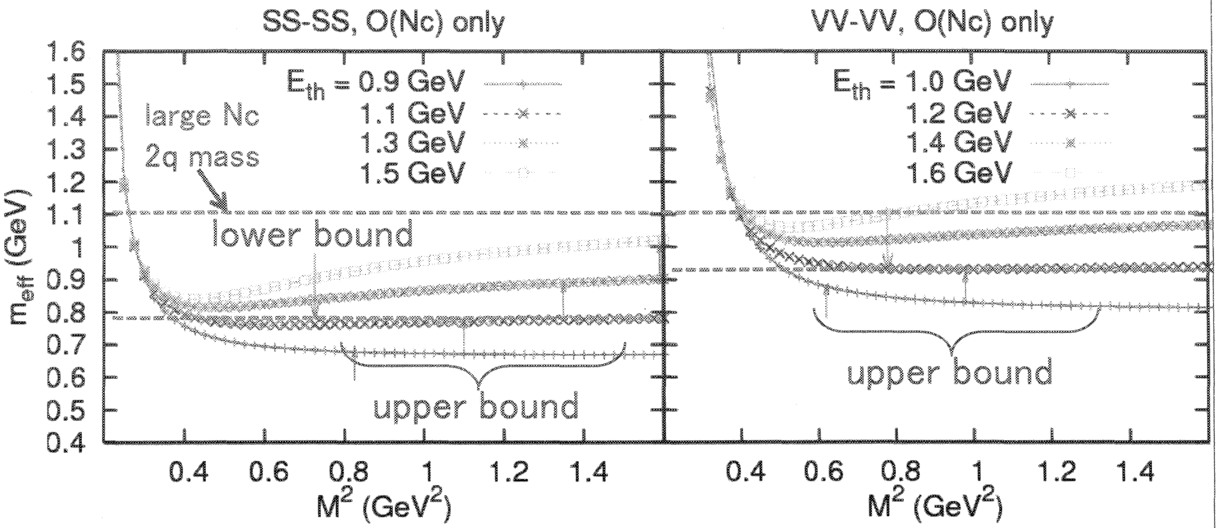


With Nc → 3, typical effective mass shifts to low energy side. → Resonance contribution ?

Effective mass for O(Nc) diagonal correlator

O(Nc) part only → clean resonance spectra
without free scattering part

(Although diagonal correlators have the factorization violation of condensates)

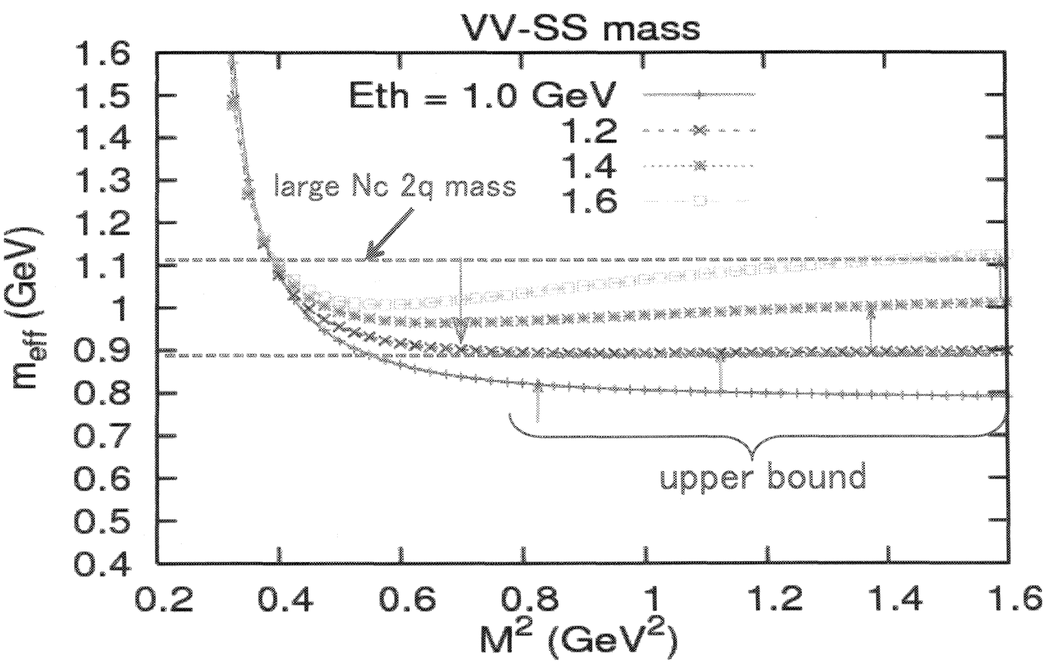


Bare pole ~ 800 MeV   Bare pole ~ 900 MeV

Different correlators give qualitatively consistent results.

Effective mass for O(Nc) off-diagonal correlator

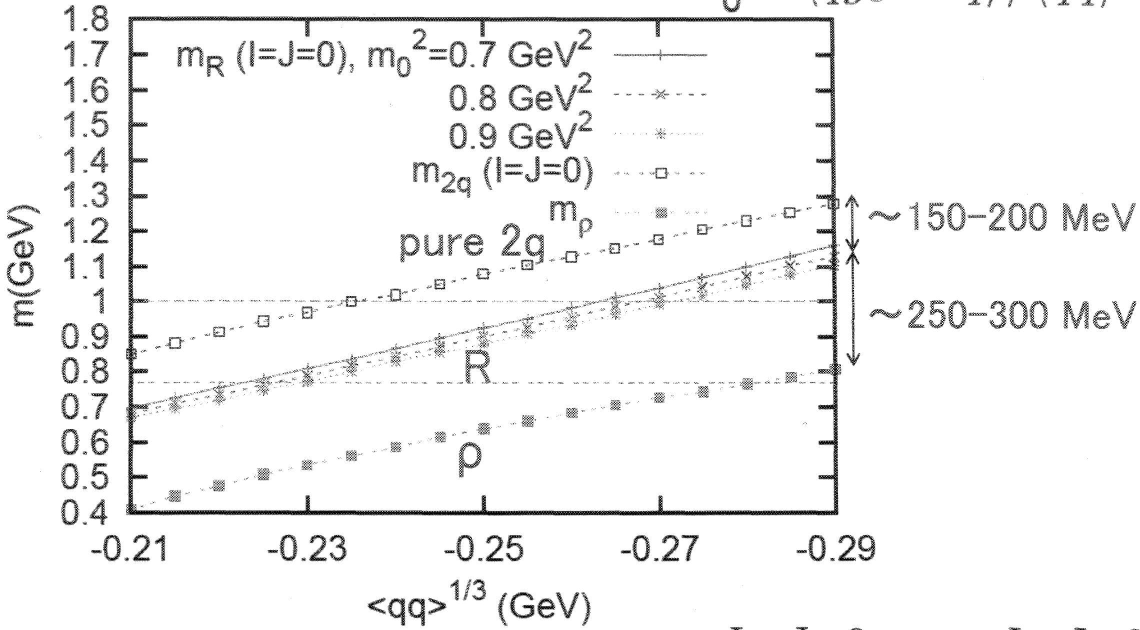
Isolated pole & No factorization violation of condensates



Bare pole ~ 900 MeV < 2q mass ~ 1.1 GeV

Mass hierarchy: $\langle\bar{q}q\rangle$ & $\langle\bar{q}g_s\sigma Gq\rangle$ *dependence*

$m_0^2 = \langle\bar{q}g_s\sigma Gq\rangle / \langle\bar{q}q\rangle$



Bare mass relation: $\bar{m}_\rho < \bar{m}_R^{I=J=0} < \bar{m}_{2q}^{I=J=0}$

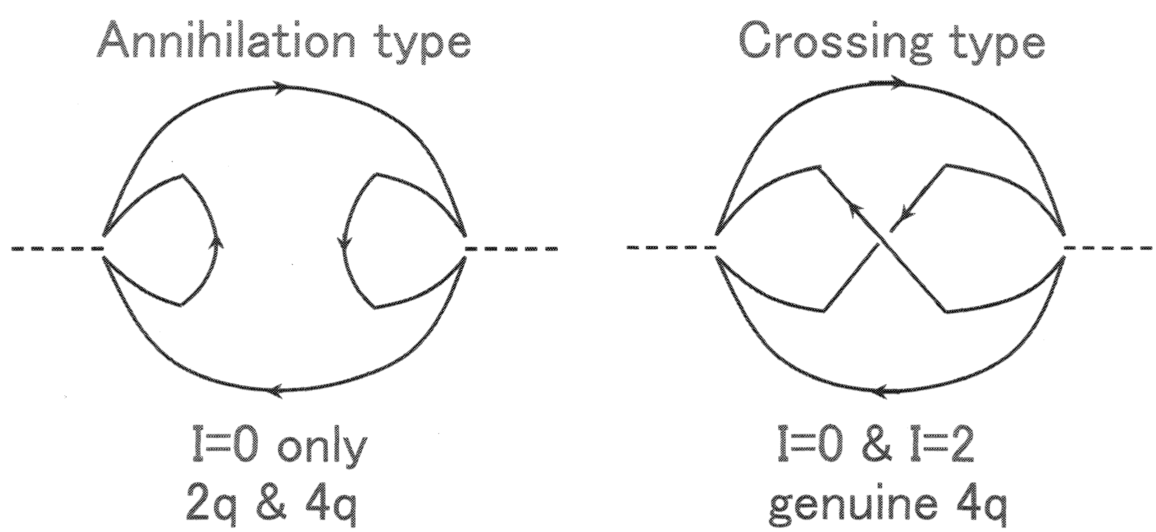
Qualitative understanding

~ Crossing & annihilation diagrams

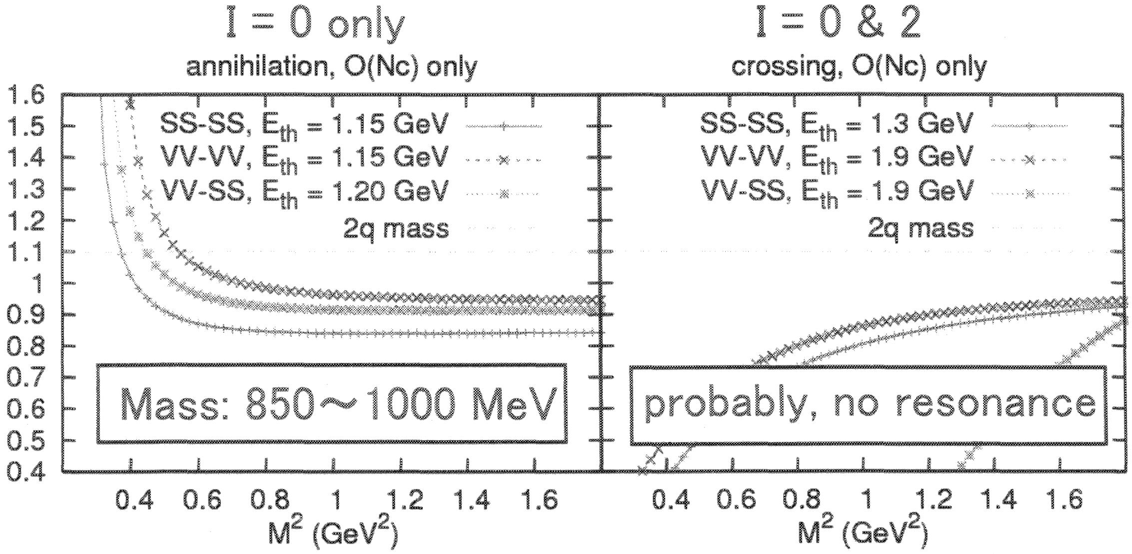
Here we consider I=0 & I=2 channel only.

Our O (Nc) OPE, main contribution comes from:

(with possible planar gluon lines inside quark loop)



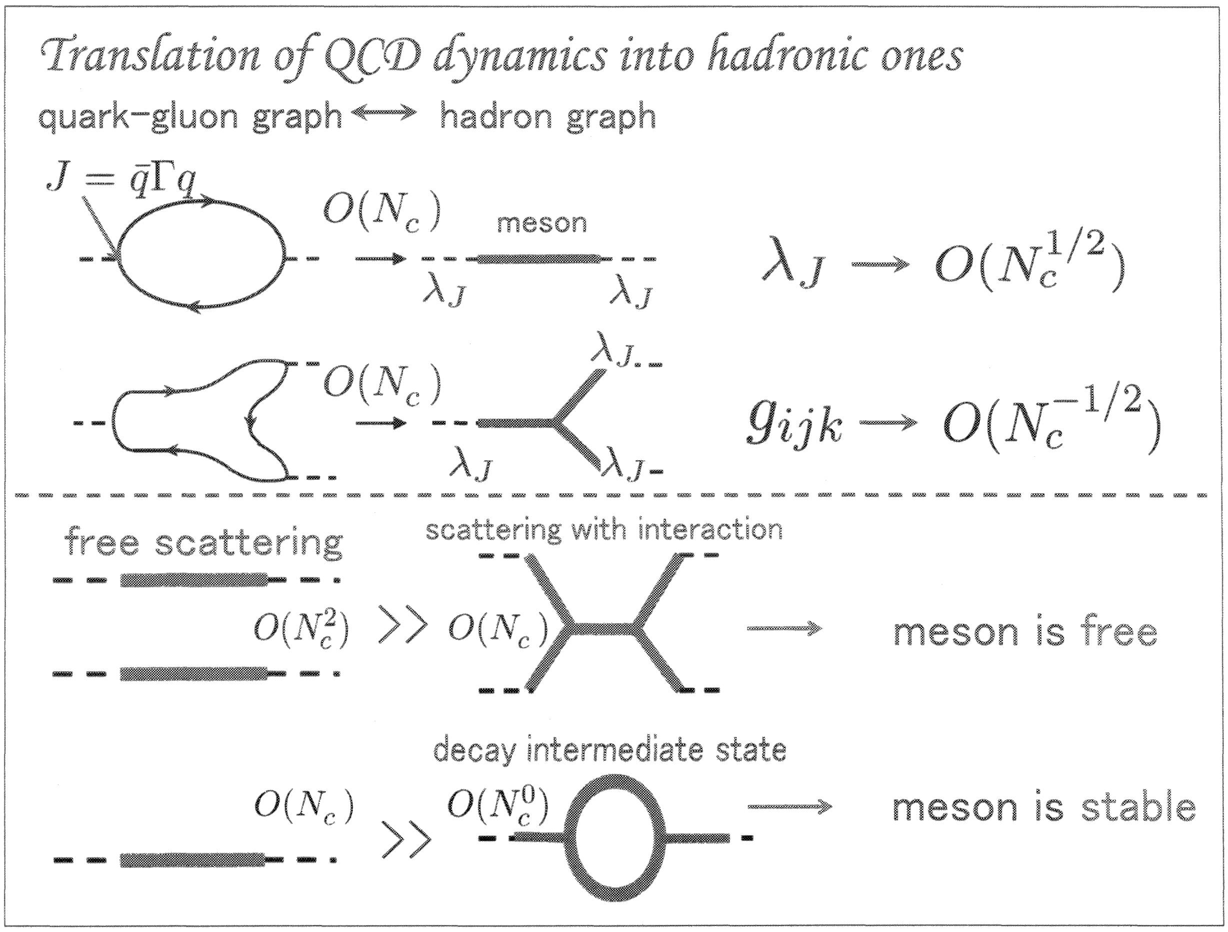
Effective mass for crossing & annihilation diagrams

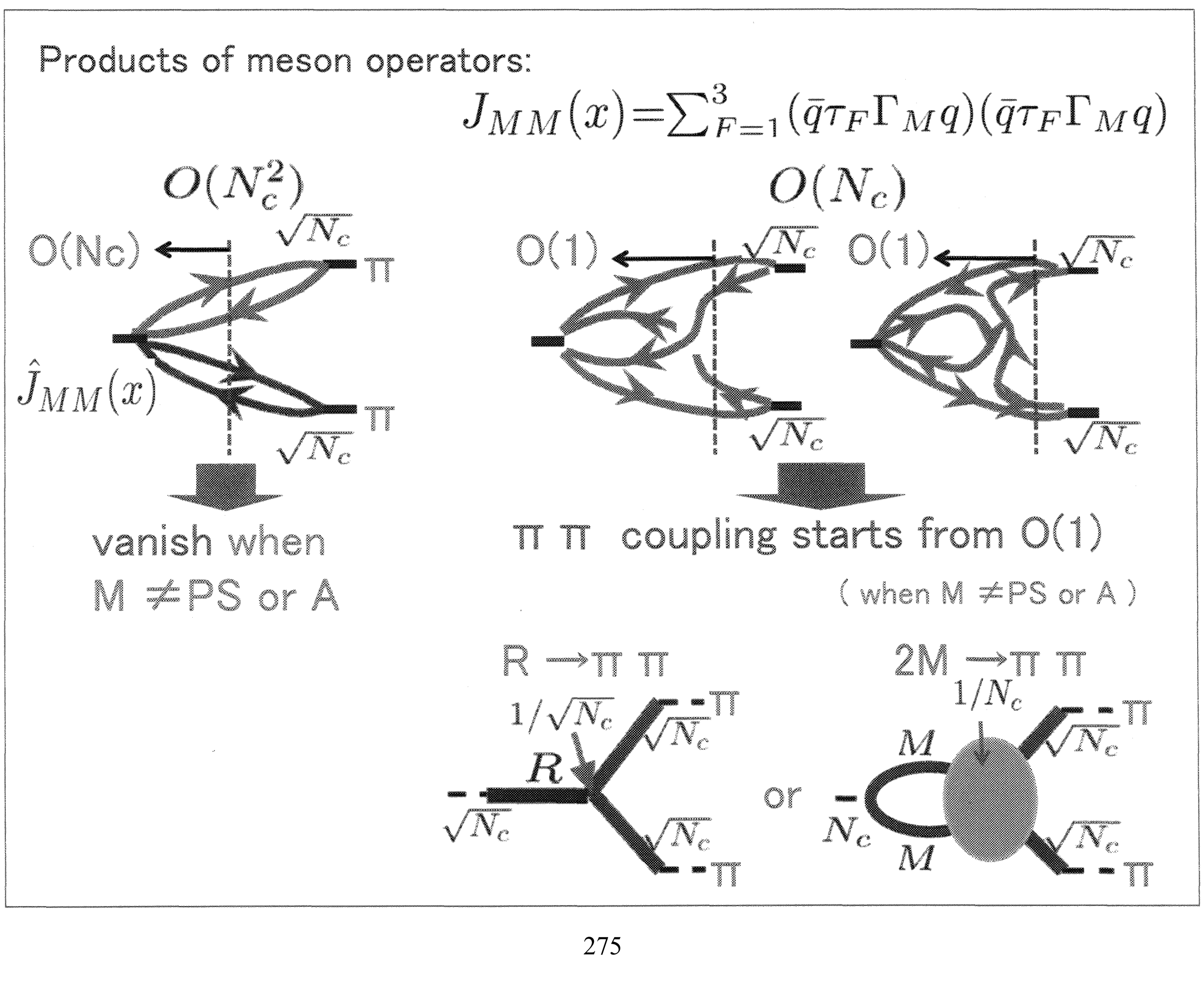


- Annihilation processes are mainly responsible to the existence of resonance below pure 2q state.
- No stability & consistency in Crossing processes

⟶ Absence of resonance in I = 2 channel at this order of Nc.

Appendix. 2


Translation of QCD dynamics into hadronic ones
quark–gluon graph ⟷ hadron graph
$J=\bar{q}\Gamma q$
$O(N_c)$
meson
λ_J
λ_J
$\lambda_J \to O(N_c^{1/2})$
$O(N_c)$
λ_J
λ_J
λ_J
$g_{ijk} \to O(N_c^{-1/2})$
free scattering
scattering with interaction
$O(N_c^2)$ >> $O(N_c)$
meson is free
decay intermediate state
$O(N_c)$ >> $O(N_c^0)$
meson is stable


Products of meson operators:
$J_{MM}(x)=\sum_{F=1}^{3}(\bar{q}\tau_F\Gamma_M q)(\bar{q}\tau_F\Gamma_M q)$
$O(N_c^2)$
O(Nc)
$\sqrt{N_c}$
π
$\hat{J}_{MM}(x)$
π
$\sqrt{N_c}$
vanish when
M ≠PS or A
$O(N_c)$
O(1)
$\sqrt{N_c}$
O(1)
$\sqrt{N_c}$
$\sqrt{N_c}$
$\sqrt{N_c}$
π π coupling starts from O(1)
(when M ≠PS or A)
R →π π
$1/\sqrt{N_c}$
R
π
$\sqrt{N_c}$
$\sqrt{N_c}$
$\sqrt{N_c}$
π
or
2M →π π
$1/N_c$
M
π
$\sqrt{N_c}$
N_c
M
$\sqrt{N_c}$
π

Naive Nc scaling Ansatz for condensates

GOR relation: $m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle \longrightarrow \langle\bar{q}q\rangle = O(N_c)$ (with $f_\pi^2 \sim O(N_c)$)

Non-local quark condensate:

$$\langle\bar{q}_i^a(0)q_j^b(x)\rangle = \delta^{ba}\delta_{ji}\times\left\{\frac{1}{4N_c}\langle\bar{q}q\rangle + \frac{x^2}{2^6N_c}\langle\bar{q}g_s\sigma Gq\rangle + \frac{\pi^2x^4}{2^83}\times\frac{1}{N_c^2}\langle\bar{q}q\rangle\langle\frac{\alpha_s}{\pi}G^2\rangle + ...\right\}$$

We impose:

Naive Nc scaling Ansatz:

$$\langle\bar{q}q\rangle|_{N_c} = \frac{N_c}{3}\langle\bar{q}q\rangle|_{N_c=3}$$

$$\langle\bar{q}g_s\sigma Gq\rangle|_{N_c} = \frac{N_c}{3}\langle\bar{q}g_s\sigma Gq\rangle|_{N_c=3}$$

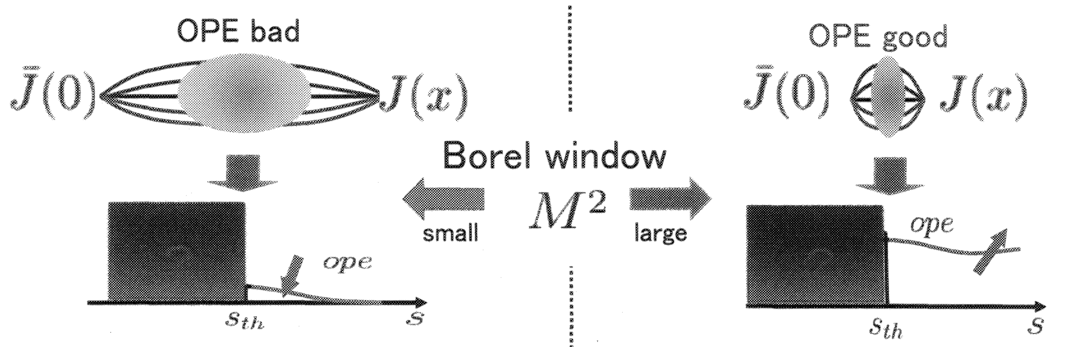
$$\langle\frac{\alpha_s}{\pi}G^2\rangle|_{N_c} = \frac{N_c}{3}\langle\frac{\alpha_s}{\pi}G^2\rangle|_{N_c=3}$$

These scaling are necessary to retain meson SR at large Nc not too far from those in Nc=3 theory.

■ *Constraint on M*

Information of low energy

■ $$M^2 L_M\Pi^{(ope)} \simeq \int_0^{s_{th}} ds\, e^{-\frac{s}{M^2}}\frac{1}{\pi}Im\Pi^{(phen)}(s) + \int_{s_{th}}^{\infty} ds\, e^{-\frac{s}{M^2}}\frac{1}{\pi}Im\Pi^{(ope)}(s)$$



■ Setting up of Borel window is the most important procedure:

constraint for OPE convergence: highest dim. / whole OPE < 0.1

constraint for ground state saturation: pole / whole spectral func. > 0.5

M$_{min}$ < M < M$_{max}$

■ *Procedures for estimating the physical quantities*

- 1, Set the Borel window for each Sth :

constraint for OPE convergence — highest dim. / whole OPE < 0.1

constraint for continuum suppression — pole / whole spectral func. > 0.5

$$M_{min} < M < M_{max}$$

- 2, Plot the physical quantities as functions of M^2 :

averaged mass: $$\bar{m}^2(M^2) = \frac{\int_0^{s_{th}} ds\ s\ e^{-\frac{s}{M^2}} \mathrm{Im}\Pi(Q^2)}{\int_0^{s_{th}} ds\ e^{-\frac{s}{M^2}} \mathrm{Im}\Pi(Q^2)}$$

If peak-like exists, averaged mass is stable against M variation.

- 3, Change Sth :

(Criteria to fix Sth depends on the situation (next slide) , but typically Sth is fixed around the second resonance)

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1/Nc classification of hadronic states

~ Tetraquark core in the sigma meson

Toru Kojo (RIKEN BNL)

Daisuke Jido (YITP, Kyoto Univ.)

RHIC Upgrades

Luminosity and polarization evolution

Plans for luminosity upgrades

Low energy RHIC running (Critical point energy scan)

EBIS project status

eRHIC

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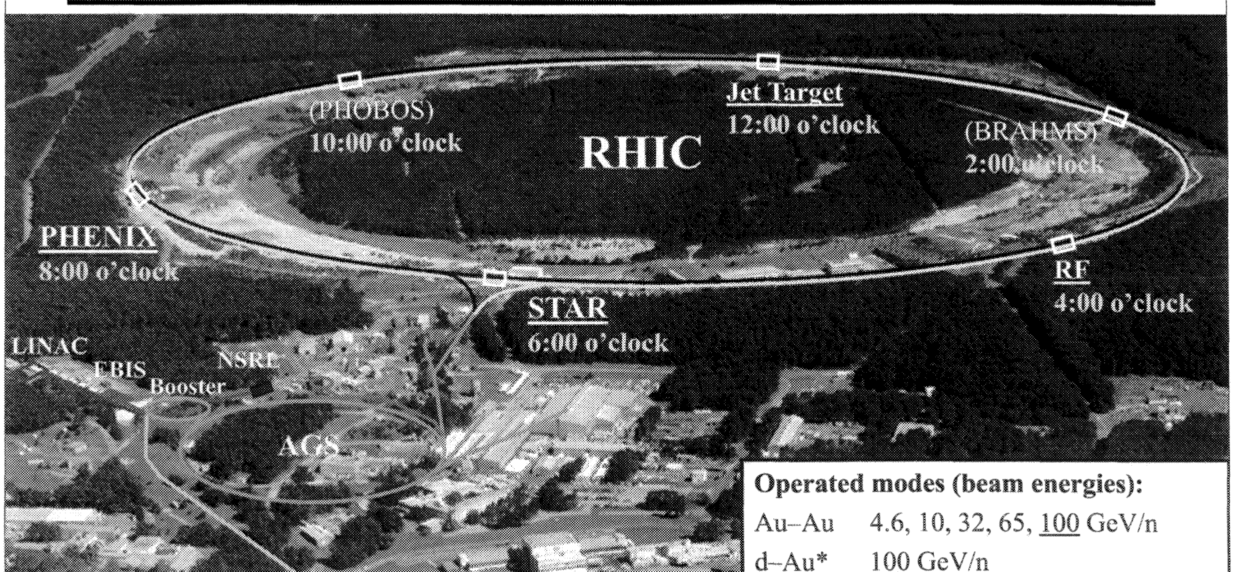
Thomas Roser
RBRC SRC Review
November 18, 2008

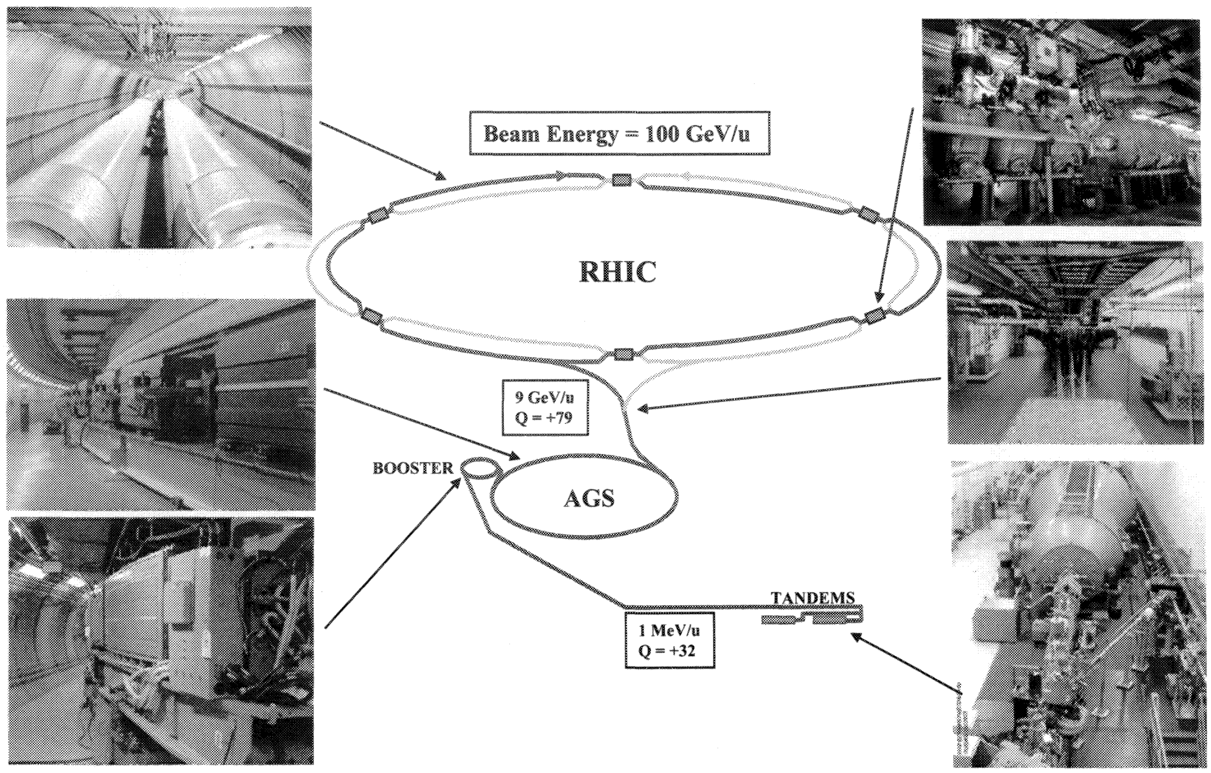
RHIC – a High Luminosity (Polarized) Hadron Collider



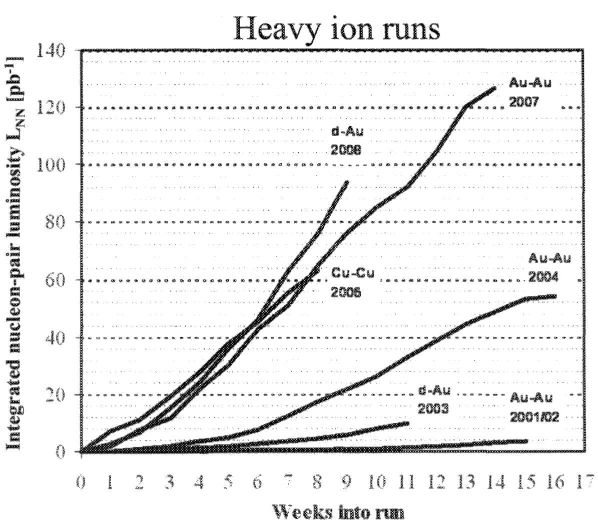
Achieved peak luminosities (100 GeV, nucl.-pair):	
Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}
Other large hadron colliders (scaled to 100 GeV):	
Tevatron (p – pbar)	32×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

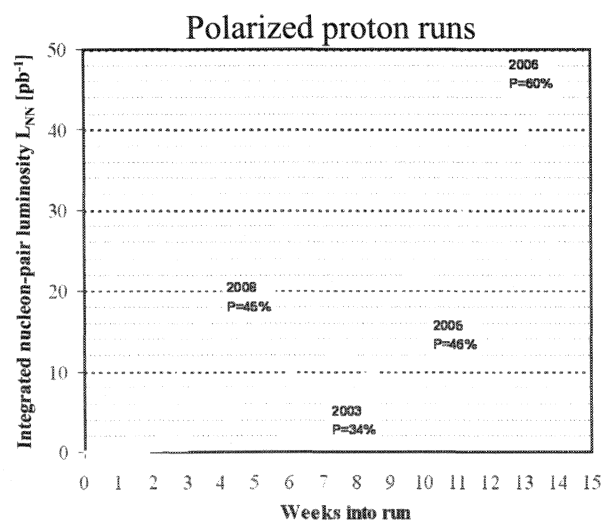
Operated modes (beam energies):	
Au–Au	4.6, 10, 32, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u> GeV
Planned or possible future modes:	
p↑–p↑	250 GeV
Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

Gold Ion Collisions at RHIC



Delivered Integrated Luminosity and Polarization





Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

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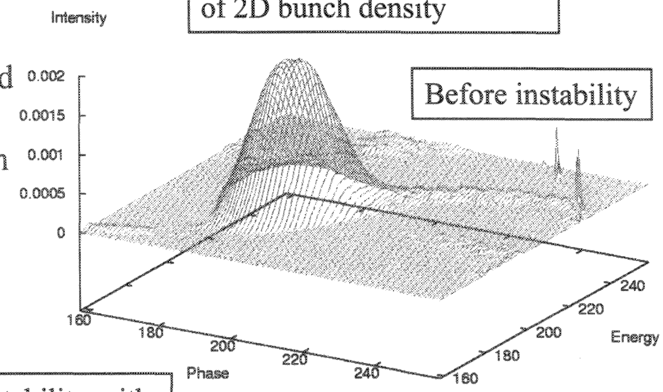
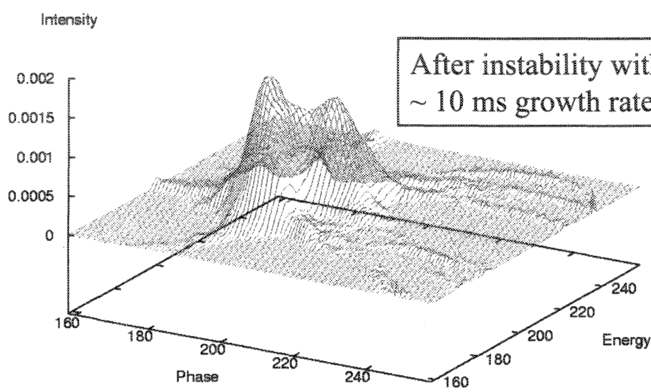
Luminosity Limit – Fast Instability Near Transition

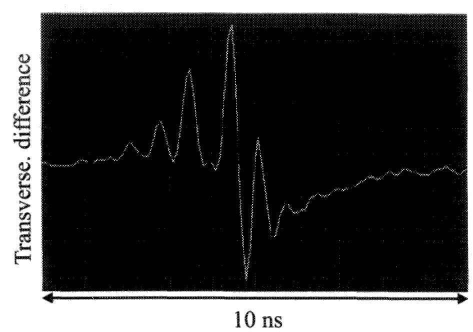
- Fast transverse instability (~ GHz)
- High sensitivity around transition (high peak current, zero chromaticity)
- Effect of broadband impedance and electron clouds
- Cures: octupoles, suppress electron clouds, chromaticity jump, active damper (?)

Tomographic reconstruction of 2D bunch density

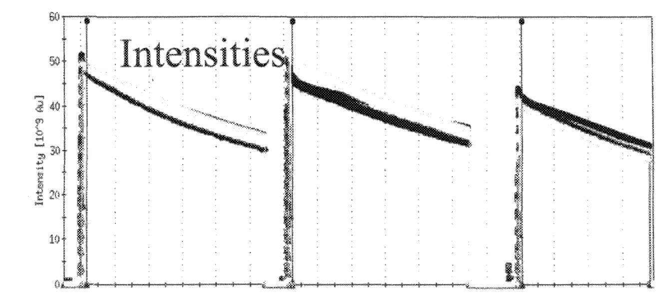


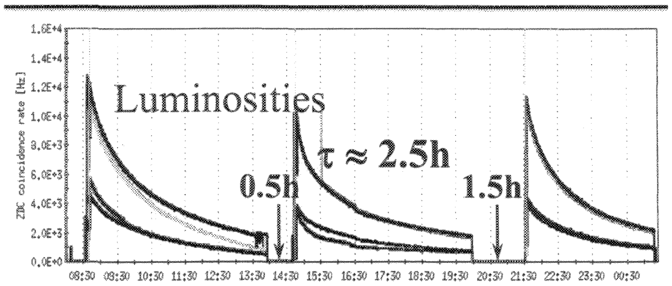


After instability with ~ 10 ms growth rate



RHIC Luminosity Limit – Intra-Beam Scattering (IBS)

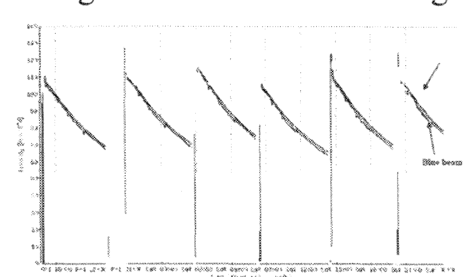




- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

<u>First successes in addressing IBS:</u>

- Longitudinal stochastic cooling



- Stronger focusing lattice that suppresses 30% of transverse IBS → 20% smaller transverse emittance after 5 hours.

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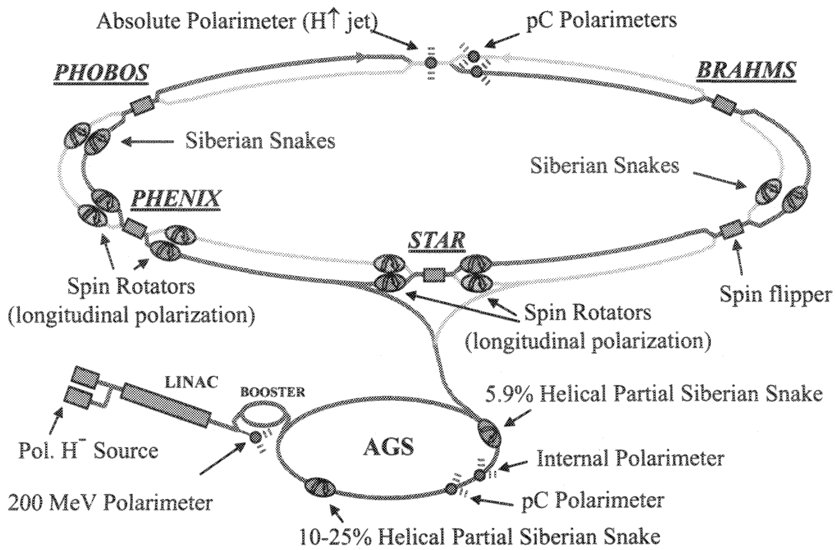
RHIC – First Polarized Hadron Collider



Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

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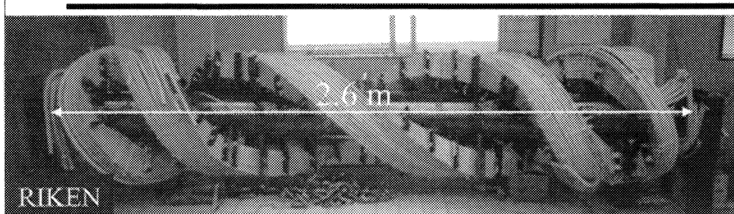
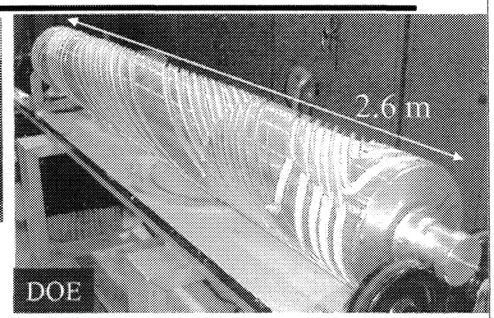
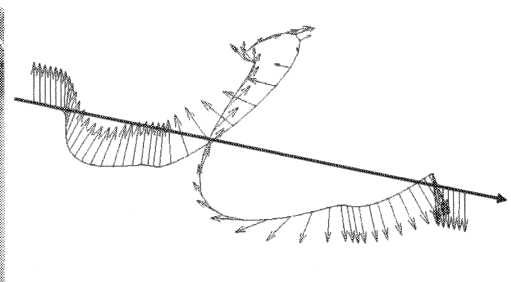
Siberian Snakes

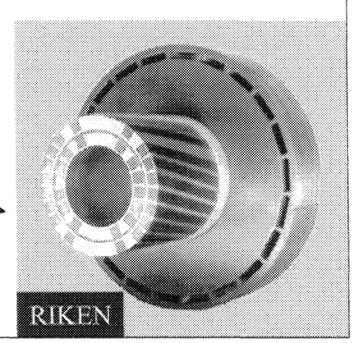




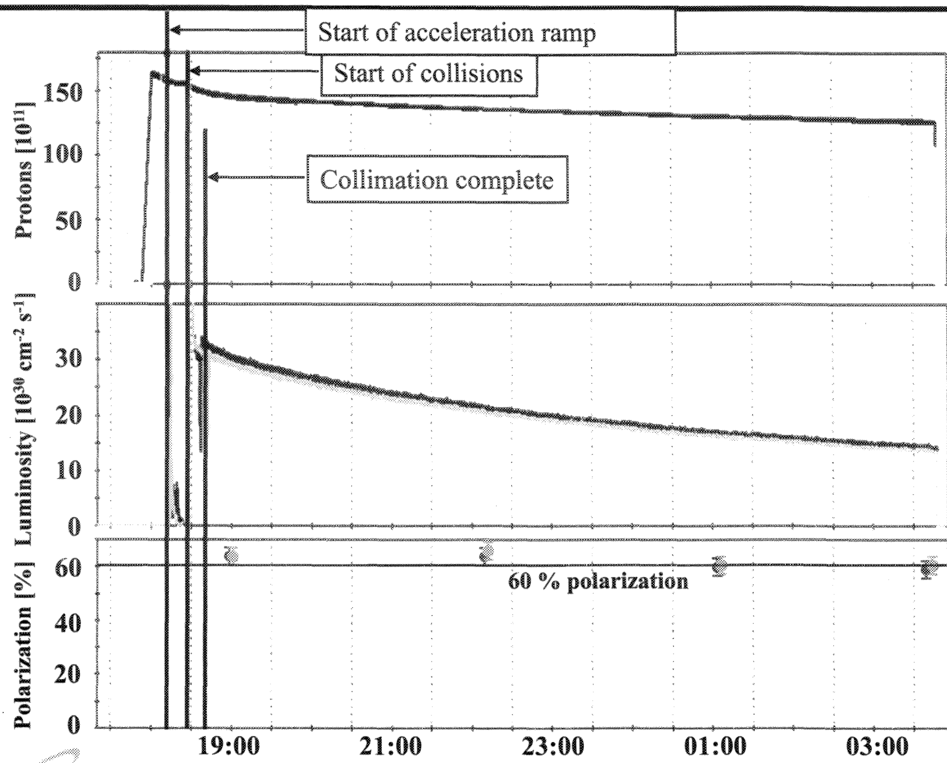
- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist



Courtesy of A. Luccio



Luminosity and Polarization Lifetimes in RHIC at 100 GeV



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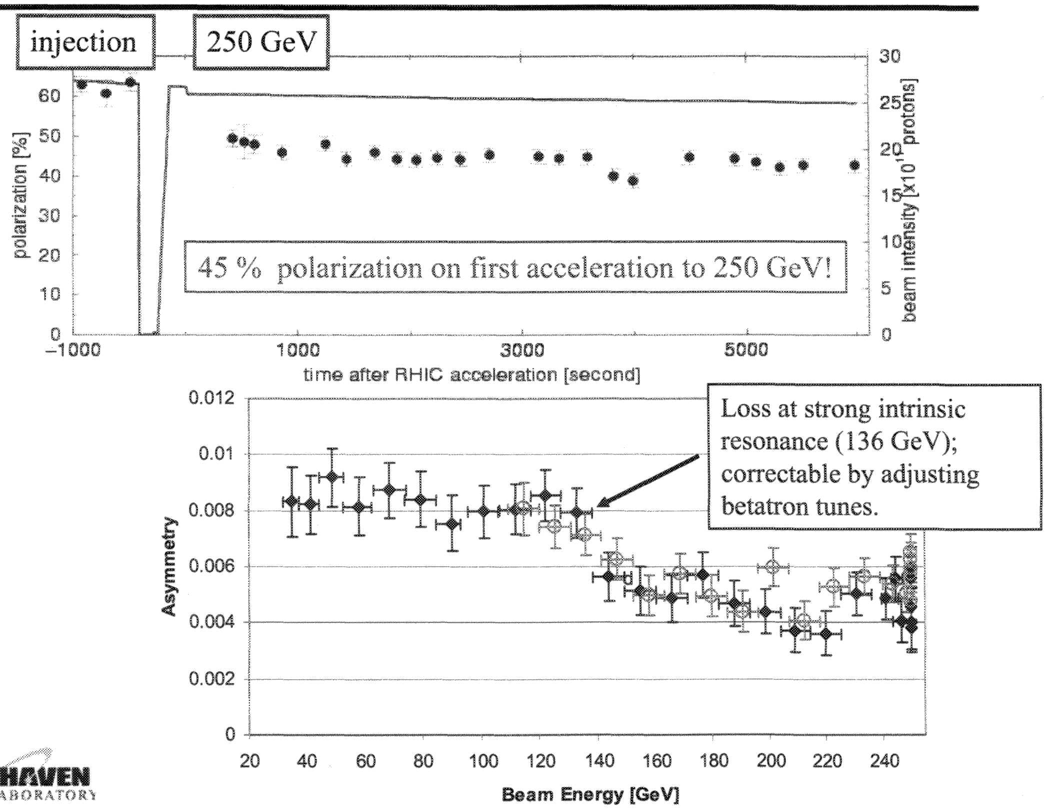
Test of Polarized Proton Acceleration to 250 GeV



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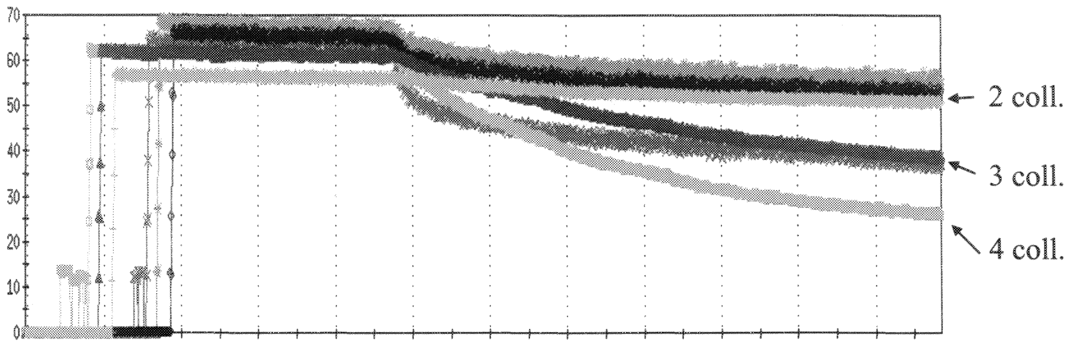
Luminosity Limit – Head-on Beam-Beam Interaction

- First strong-strong hadron collider (after ISR)
- Limits high luminosity pp operation (beam-beam tune spread ~ 0.01)
- Cures: Non-linear (chromaticity) corrections, better working point, electron lens



Current of bunches with 2, 3, or 4 collisions

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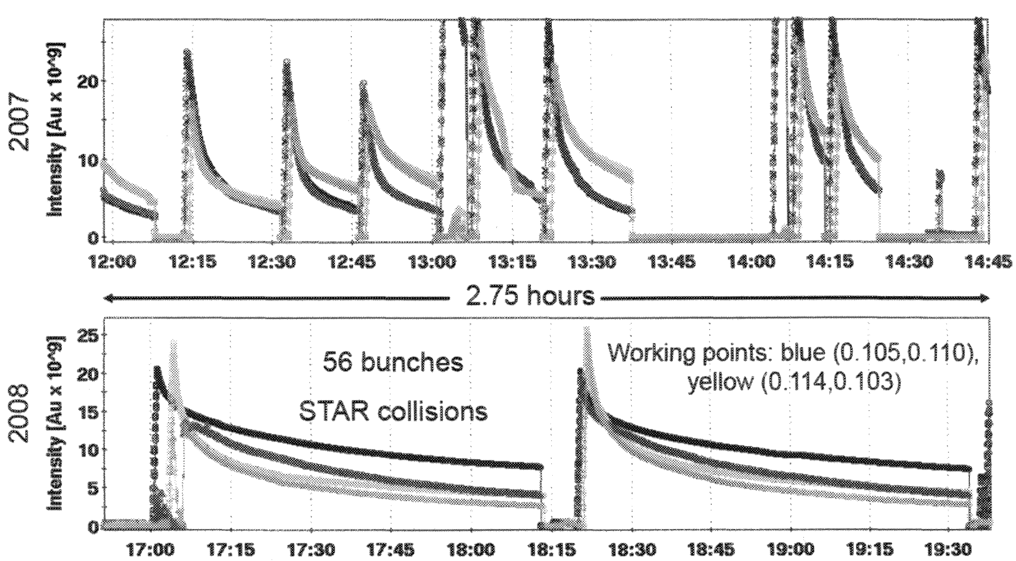
Tests of $\sqrt{s}$ = 9 GeV Au - Au operation in RHIC



- 2008 blue beam lifetime: 3.5 minutes (fast), 50 minutes (slow)
- Sextupole reversal and elimination of octupoles clearly helped beam lifetime
- Injection efficiency and yellow beam lifetime can clearly benefit from further tuning

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[T. Satogata, RHIC Retreat 2008]

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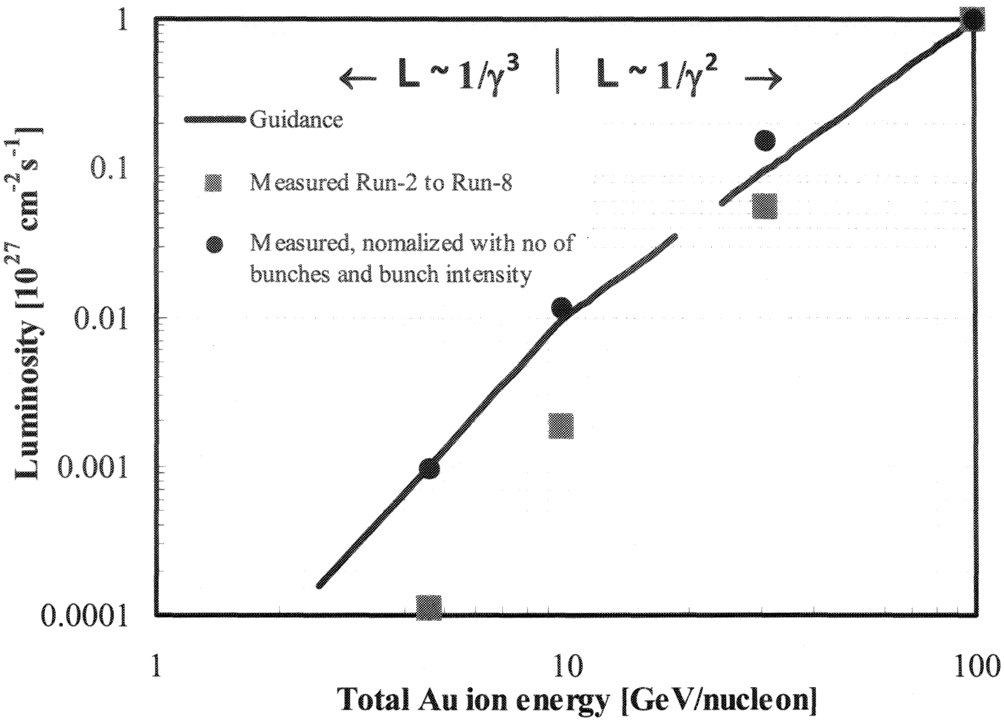
Luminosity scaling with energy



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Low energy Au-Au operation – Luminosity upgrade options

E-cooling in RHIC

- Luminosity limited by space charge (space charge limit $\Delta Q_{sc} = 0.05$)
- Expect 3-6 times more luminosity when operating at space charge limit
- Electron cooling either with dc beam (Fermilab Pelletron) or with rf beam (56 MHz SRF gun, 703 SRF gun – under construction)

Top-off mode

- Replace 1 - 4 RHIC bunches every AGS cycle, beam stays in RHIC only 3 - 7 min; ~ 2 - 3 more luminosity
- Needs modification of RHIC injection and extraction kickers and experiments need to stay on during continuous refill (likely ok, test desirable)

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RHIC Facility Upgrade Plans

- EBIS (~ 2011) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)
- RHIC luminosity upgrade (~ 2012):
  [Au-Au: 40×10^{26} cm^{-2} s^{-1}; 500 GeV p-p: 2×10^{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: 6 - 12×10^{32} cm^{-2} s^{-1}]
  - 0.3 m β^* for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for beam-beam compensation (R&D underway)
  - Allows for higher bunch intensity or lower emittance (× 2-4)
- eRHIC: high luminosity ($\geq 1 \times 10^{33}$ cm^{-2} s^{-1}) eA and pol. ep collider using 10 - 20 GeV electron driver, based on Energy Recovering Linac (ERL), and strong cooling of hadron beams (~ 2020)
  Exploring gluons at extreme density!

RHIC Luminosity and Polarization Goals

Parameter	unit	Achieved	Luminosity upgrade
Au-Au operation		**(2007)**	**(~ 2011)**
Energy	**GeV/nucleon**	**100**	**100**
No of bunches	**...**	**103**	**111**
Bunch intensity	**10^9**	**1**	**1**
Ave. delivered luminosity**	**10^{26} cm^{-2}s^{-1}**	**12**	**40***
p↑- p↑ operation		**(2006/08)**	**(~ 2012)**
Energy	**GeV**	**100**	**100 (250)**
No of bunches	**...**	**111**	**111**
Bunch intensity	**10^{11}**	**1.5**	**2.0**
Ave. delivered luminosity**	**10^{30} cm^{-2}s^{-1}**	**23**	**80 (200)**
Polarization	**%**	**60**	**70**

* 5 × 'enhanced' luminosity and 20 × design luminosity
** without vertex cuts

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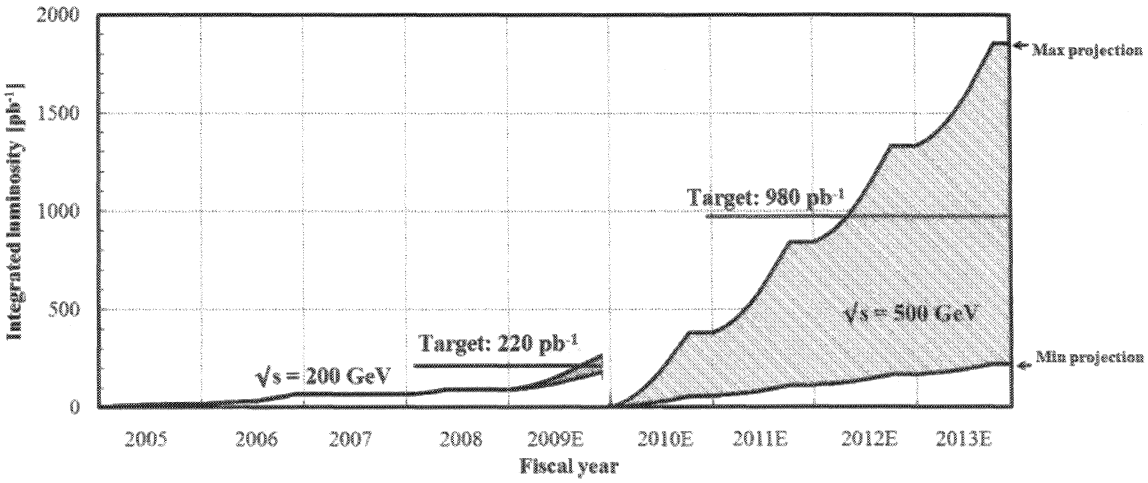
Spin Plan Projections



Fiscal year		2006	2008	2009E	2010E	2011E	2012E	2013E
No of bunches	...	111	111	111	111	111	111	111
Protons/bunch, initial	10^{11}	1.4	1.5	1.8	1.9	2.0	2.0	2.0
Avg. beam current/ring	mA	187	205	250	264	280	280	280
β^*	m	1.0	1.0	0.8	0.7	0.6	0.6	0.5
Beam-beam parameter/IP	10^{-3}	5.6	4.9	6.1	7.4	7.5	7.5	7.5
Peak luminosity (200 GeV)	$10^{30}cm^{-2}s^{-1}$	28	35	63	96	121	129	137
Avg./peak luminosity	%	64	65	63	62	60	60	60
Avg. store luminosity (200 GeV)	$10^{30}cm^{-2}s^{-1}$	18	23	40	60	73	77	82
Time in store	%	46	60	60	60	60	60	60
Max luminosity/week (200 GeV)	pb^{-1}	6.5	7.5	14.5	21.6	26.4	28.0	29.8
Min luminosity/week (200 GeV)	pb^{-1}			7.5	7.5	7.5	7.5	7.5
Max luminosity/run (200 GeV)	pb^{-1}	46	19	130	150	180	200	210
Min luminosity/run (200 GeV)	pb^{-1}			70	50	50	50	50
Max luminosity/run (500 GeV)	pb^{-1}				375	450	500	525
Min luminosity/run (500 GeV)	pb^{-1}				125	125	125	125
AGS polarization, extraction, min/max	%	65[1]	55[1]	55/65	55/70	55/70	55/75	55/75
RHIC avg. store polarization, min/max	%	58	45	50/60	50/65	50/70	50/70	50/70

[1] The AGS polarization may be restated in the future after the used analyzing power is calibrated in RHIC at injection in a polarization measurement with the polarized hydrogen jet.

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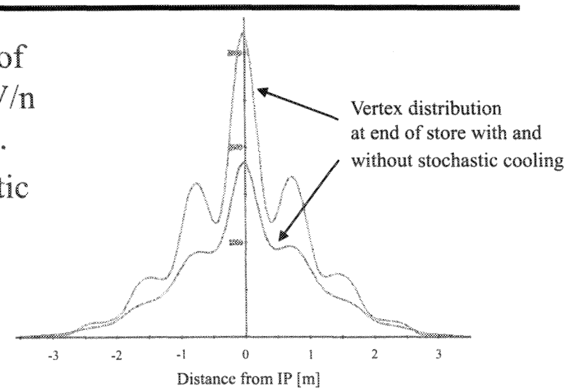
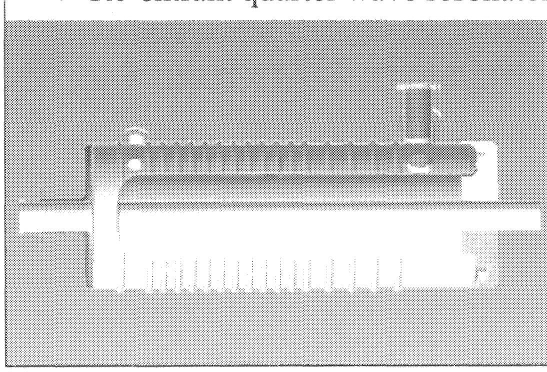
Stochastic Cooling and 56 MHz SRF cavity

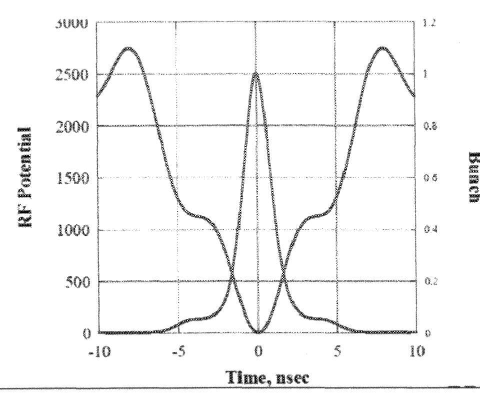
- Longitudinal stochastic cooling of core of bunched beam demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Full longitudinal and transverse stochastic cooling under construction

56 MHz SRF storage cavity:

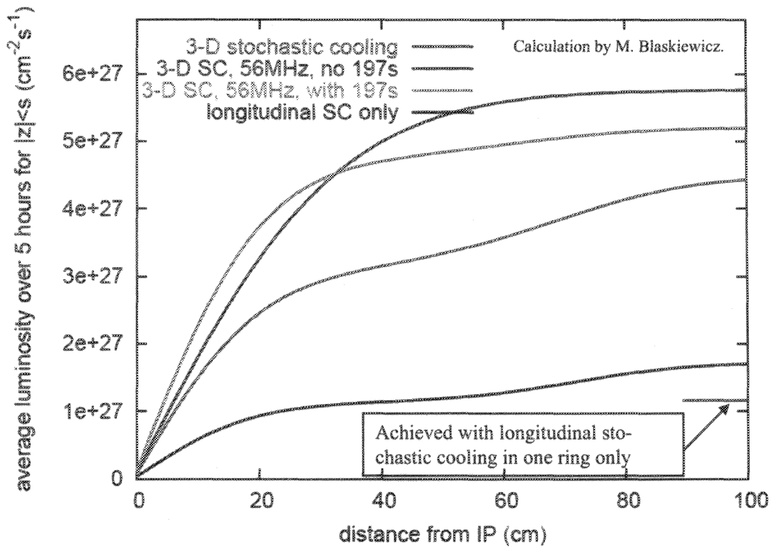
- Avoid rebucketing operation.
- Greatly reduces satellite bunches
- Re-entrant quarter wave resonator



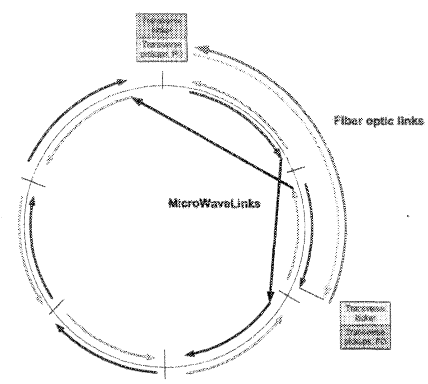


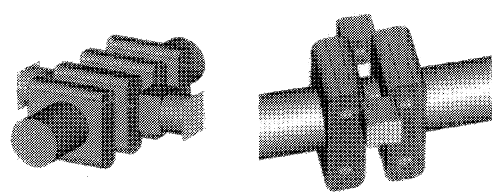


Luminosity Increase with Full Stochastic Cooling



- Transverse stochastic cooling in one plane only
- Second plane cooled through x-y coupling
- 5 – 8 GHz bandwidth split up into 16 frequency bands
- Each frequency has its own cavity kicker





Longitudinal kickers Transverse kickers

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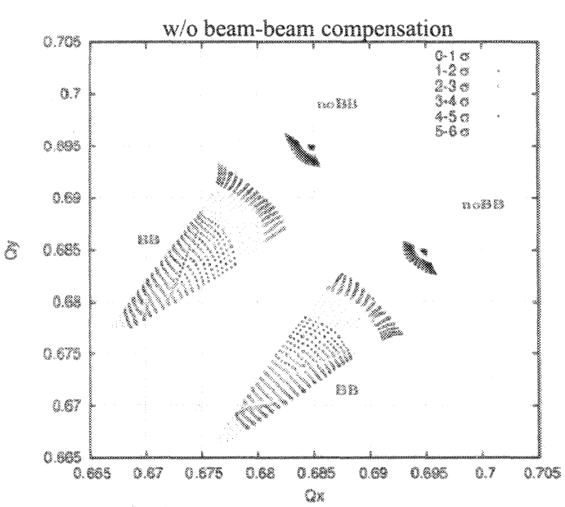
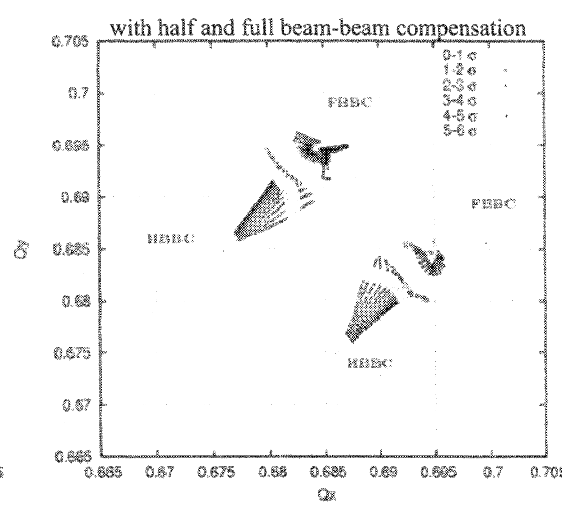
Electron Lenses for pp Operation

- Polarized proton luminosity is limited by head-on beam-beam tune spread
- Low energy electron beam (similar to EBIS) interacting with proton beam can compensate head-on beam-beam tune spread (× 2 - 4 luminosity?)
- Single and multi particle simulation underway





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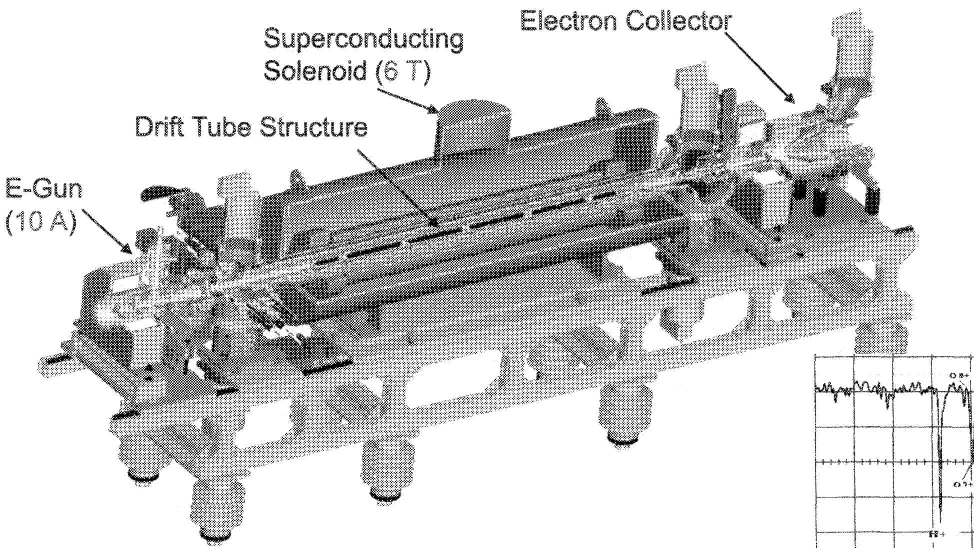
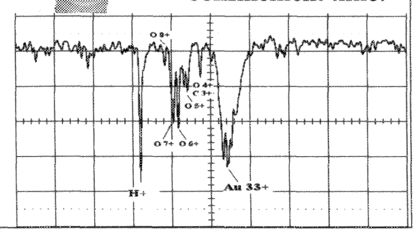
Electron Beam Ion Source (EBIS)

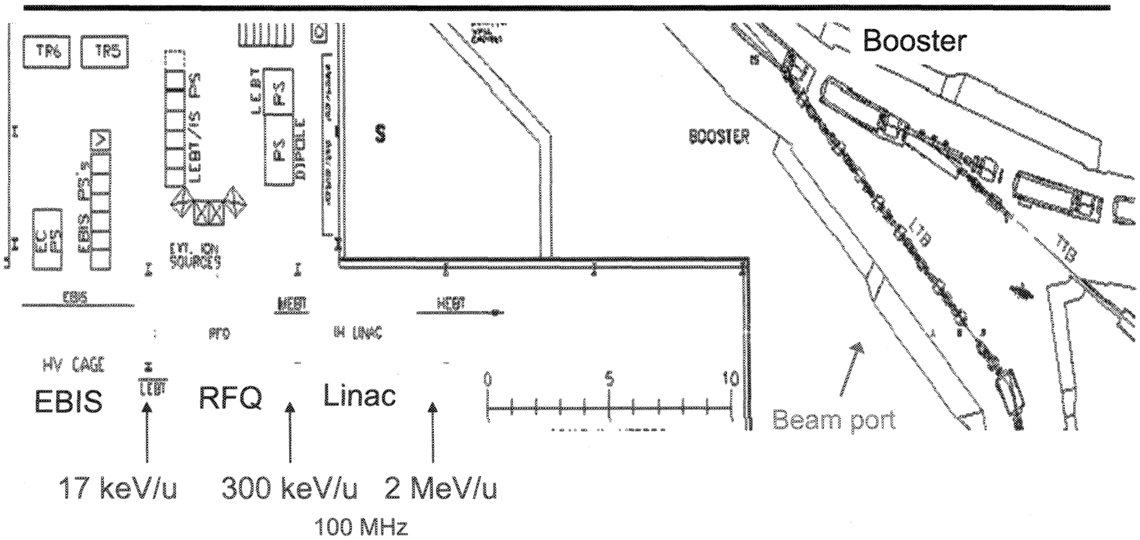
- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He^3 (eRHIC) (~ 1-2 × 10^{11} charges/bunch with $\varepsilon_{N,rms}$ = 1-2 μm)
- Achieved 1.7 × 10^9 Au^{33+} in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction of EBIS, RFQ and IH Linac complete by 2010



Gold charge state with only 40 ms confinement time.



EBIS Pre-injector Layout



Funding profile:

	FY2005	FY2006	FY2007	FY2008	FY2009	Total
DOE NP	0.7	2.1	5.1	4.2	2.7	14.8
NASA	0.5	3.0	1.0			4.5
Total	1.2	5.1	6.1	4.2	2.7	19.3

Ion	He - U
Q/m	≥1/6
Current	> 1.5 emA (for 1 turn inj)
Pulse Length	10 μs
Rep. Rate	5 Hz
Time to switch species	1 second

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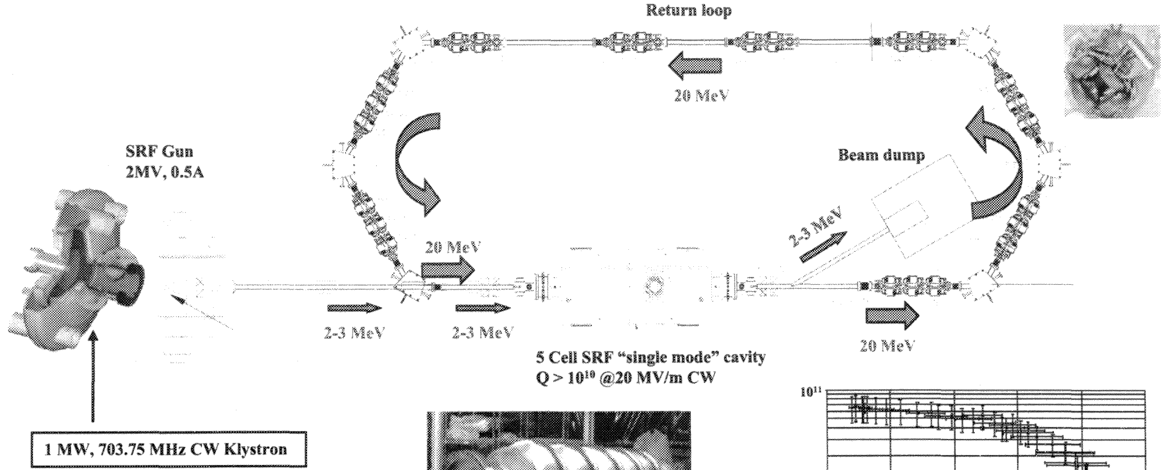
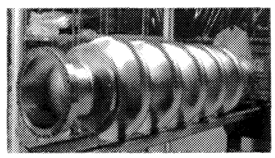
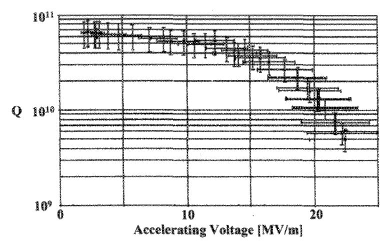
Energy Recovery Linac (ERL) Test Facility

- 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
- Start of commissioning: 2009 - 2010.







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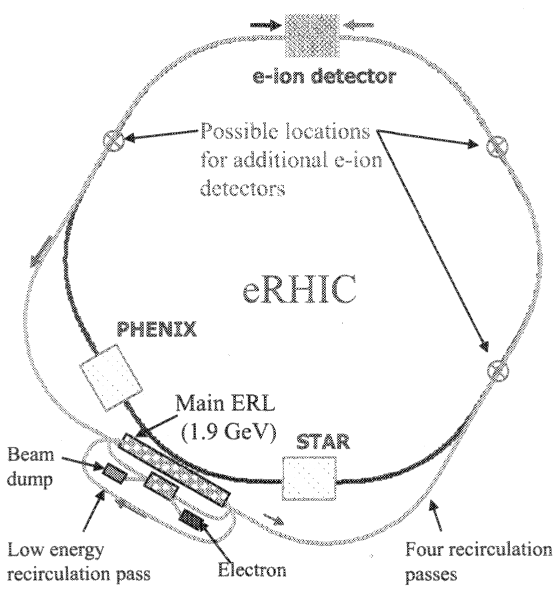
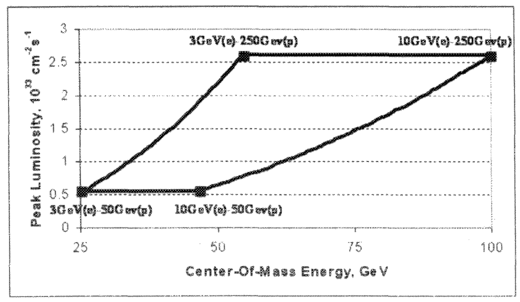
ERL – Based Electron-Ion Collider (eRHIC)





- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- 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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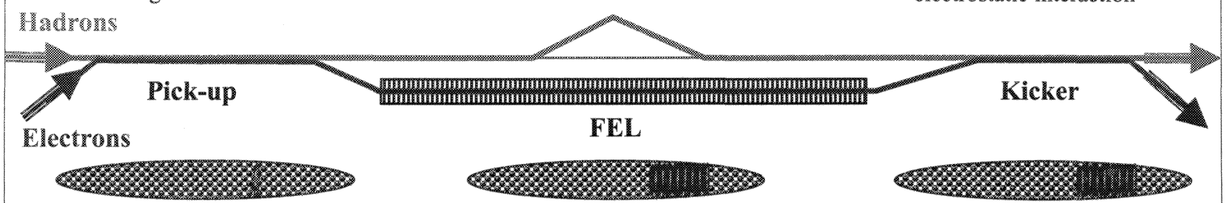
Coherent Electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration in RHIC 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

Since 2000 RHIC has collided, at many different collision energies,

- Gold on gold with luminosity exceeding design luminosity by factor of six
- Asymmetric ions at high luminosity
- Polarized protons with 60 % average beam polarization

Successful test of Au collisions at very low energy (~ ½ normal injection energy)

Successful operation of longitudinal stochastic cooling

Future runs / upgrade plans:

- Luminosity upgrade to 40×10^{26} cm^{-2} s^{-1} through high energy beam cooling
- High luminosity 250 x 250 GeV polarized proton run at 2×10^{32} cm^{-2} s^{-1} and later at $6 - 12 \times 10^{32}$ cm^{-2} s^{-1}
- Uranium beams from EBIS
- High luminosity polarized electron ion collider - eRHIC

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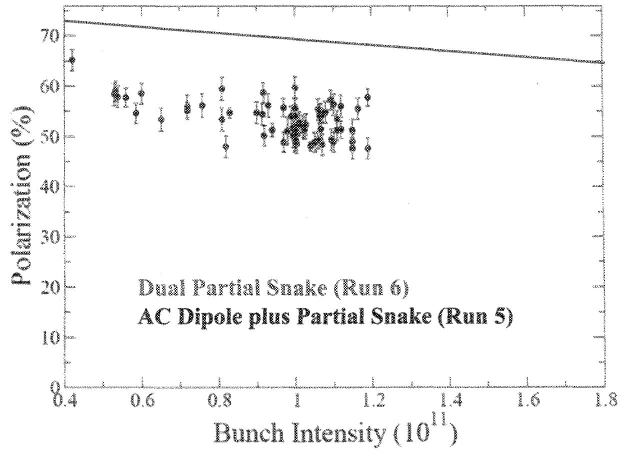
Back-up Slides

Run-7 and Run-8 p↑-p↑ operation – polarization

- Source
  - P = 80 - 82% in Run-8 after 85 - 89% in Run-7
  - Aim for P = 85% in Run-9
- AGS
  - Tested stronger snake and near integer horizontal tune in Run-7
  - Tested injection on the fly (no flat bottom) in Run-8
  - In both cases significant intensity dependent polarization
  - Returned to Run-6 setup with P = 55% at extraction vs. P = 65% in Run-6
    (half of the loss due to source, other half due to only 10 days of tuning)
  - For Run-9 use Run-6 set-up with tune jump for horizontal resonances
- RHIC
  - About 10% (absolute) lower P than in Run-6, more problems in Yellow
  - Learned that horizontal orbit angle through snakes needs better control
  - Need RHIC pC CNI polarimeter upgrade for better reliability

AGS Polarization



$\varepsilon_{N,rms} \sim 2\ \mu m$

- Dual Partial Snake in AGS avoided depolarization from all vertical depolarizing resonances. Strong partial snakes also drive weak horizontal depolarizing resonances. (~ 5-10% polarization loss)
- Plan to use tune jump for weak horizontal resonances

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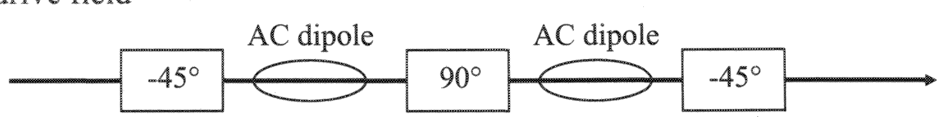
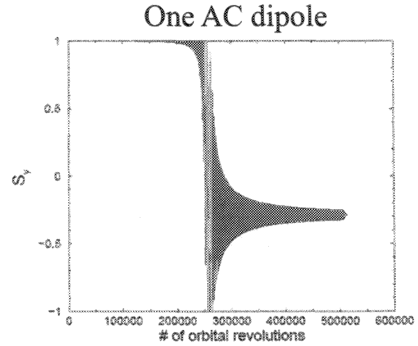
Spin Flipper (plan)

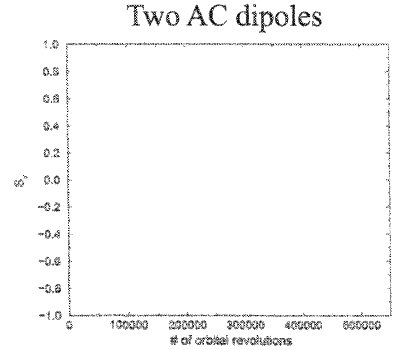
- Use spin resonance driven by AC dipole(s) to induce spin flip
- Single AC dipole (oscillation) drives two resonances that interfere at $\nu_{sp} = 0.5$, only partial spin flip
- Two AC dipoles with vertical spin precession in between creates rotating drive field



One AC dipole



Two AC dipoles



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RBC Collaboration Research Highlights

Robert Mawhinney
RBRC Review
November 17-18, 2008

1. Focus on main T=0 projects involving majority of collaborators
2. Describe recent RBC/UKQCD calculations using domain wall fermions
   a. Light pseudoscalar decay constants: f_π and f_K
   b. Light quark masses: $m_u = m_d$ and m_s
   c. Kaon bag parameter for indirect CP violation: B_K
3. Discuss SU(2) and SU(3) chiral perturbation theory fits to lattice data
4. Using SU(3) ChPT for $\Delta S = 1$ weak matrix elements: ε'/ε

Collaboration Members

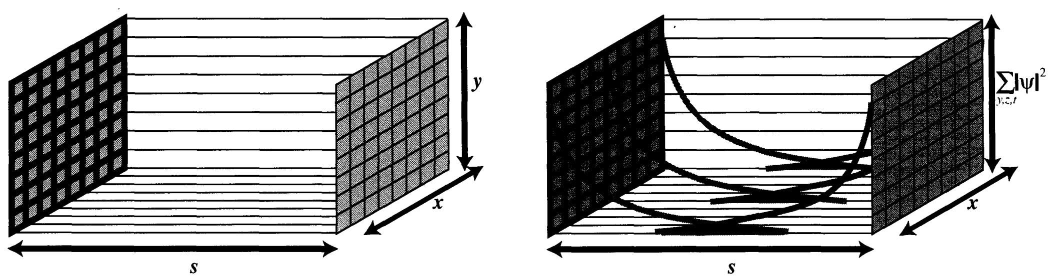
- RBC members:
  - RBRC: Y. Aoki, T. Blum (UConn), T. Ishikawa, T. Izubuchi, S. Ohta
  - BNL: C. Jung, A. Soni, R. Van de Water, O. Witzel
  - BNL thermo: S. Ejiri, P. Hegde, F. Karsch, C. Miao, P. Petreczky
  - Columbia: N. Christ, M. Endres, C. Kim, X. Jin, M. Li, Q. Liu, M. Lightman, R. Mawhinney, H. Peng, S. Takeda
  - University of Connecticut: T. Blum, C. Saumitra, R. Zhou
  - University of Virginia: C. Dawson
  - Other members: M. Cheng, K. Huebner, M. Lin, C. Schmidt, E. Scholz, W. Soeldner, P. Vranas, T. Yamazaki
- UKQCD members:
  - C. Allton, D. Antonio, K. Bowler, P. Boyle, D. Brommel, M. Clark, M. Donnellan, J. Flynn, A. Hart, A. Juettner, C. Kelly, A. Kennedy, R. Kenway, C. Maynard, B. Pendleton, C. Sachrajda, R. Tweedie, J. Wennekers, J. Zanotti

Primary Activities of RBC Collaboration

- Essentially all work done with 2+1 flavor QCD
  - * Domain wall fermions (DWF) at T = 0 ← This talk
  - * P4 staggered fermions and DWF at finite temperature
- Rational Hybrid Monte Carlo (Clark and Kennedy)
  - * Speed up of DWF lattice generation by 5.4× with m_π = 540 MeV
  - * Allowed simulations with lighter pions than previously achievable
  - * Exact algorithm
  - * Used for both DWF and P4 simulations, via CPS software suite
  - * See good sampling of topology in ensembles
- T = 0 DWF simulations done in collaboration with UKQCD
- Large volumes of data being produced - many people involved in production, analysis, and renormalization of results.

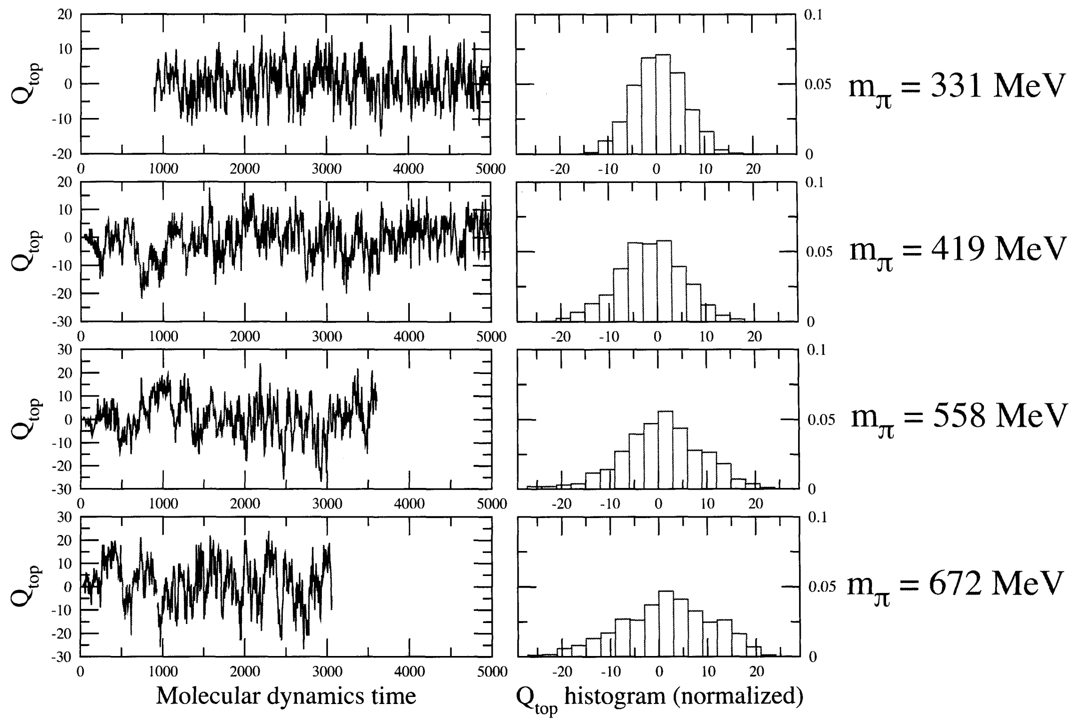
Why Domain Wall Fermions?

- Adding 5th dimension separates ψ_L and ψ_R leaving small residual χSB



- Lattice theory has chiral symmetry like continuum theory
  - * $m_{quark} = m_{input} + m_{res}\{1 + O[(a\Lambda_{QCD})^2]\}$
  - * Operator mixing: like continuum with small corrections (m^2_{res})
  - * Non-perturbative renormalization works well
- 5th dimension L_s = 16 means ~10× harder computationally
- RBC Collaboration has played pioneering role in numerical DWF QCD
- Large volume (~3 fm) 2+1 flavor ensembles using DWF available now

Topological Charge Evolution



1. Physical Review Letters, 100:032001, 2008: B_K

PRL **100,** 032001 (2008) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2008

Neutral-Kaon Mixing from (2 + 1)-Flavor Domain-Wall QCD

D. J. Antonio,[1] P. A. Boyle,[1] T. Blum,[8,2] N. H. Christ,[3] S. D. Cohen,[3] C. Dawson,[2] T. Izubuchi,[2,6] R. D. Kenway,[1] C. Jung,[4] S. Li,[3] M. F. Lin,[3] R. D. Mawhinney,[3] J. Noaki,[7,9] S. Ohta,[9,2,10] B. J. Pendleton,[1] E. E. Scholz,[4] A. Soni,[4] R. J. Tweedie,[1] and A. Yamaguchi[5]

(RBC and UKQCD Collaborations)

2. Physics Review D 78, 054510 (2008): Non-perturbative renormalization

PHYSICAL REVIEW D **78,** 054510 (2008)

Nonperturbative renormalization of quark bilinear operators and B_K using domain wall fermions

Y. Aoki,[1] P. A. Boyle,[2] N. H. Christ,[3] C. Dawson,[1,*] M. A. Donnellan,[4] T. Izubuchi,[1,5] A. Jüttner,[4] S. Li,[3] R. D. Mawhinney,[3] J. Noaki,[6] C. T. Sachrajda,[4] A. Soni,[7] R. J. Tweedie,[2] and A. Yamaguchi[8]

(RBC and UKQCD Collaborations)

3. hep-lat/0804.0473, accepted by PRD: quark masses and decay constants

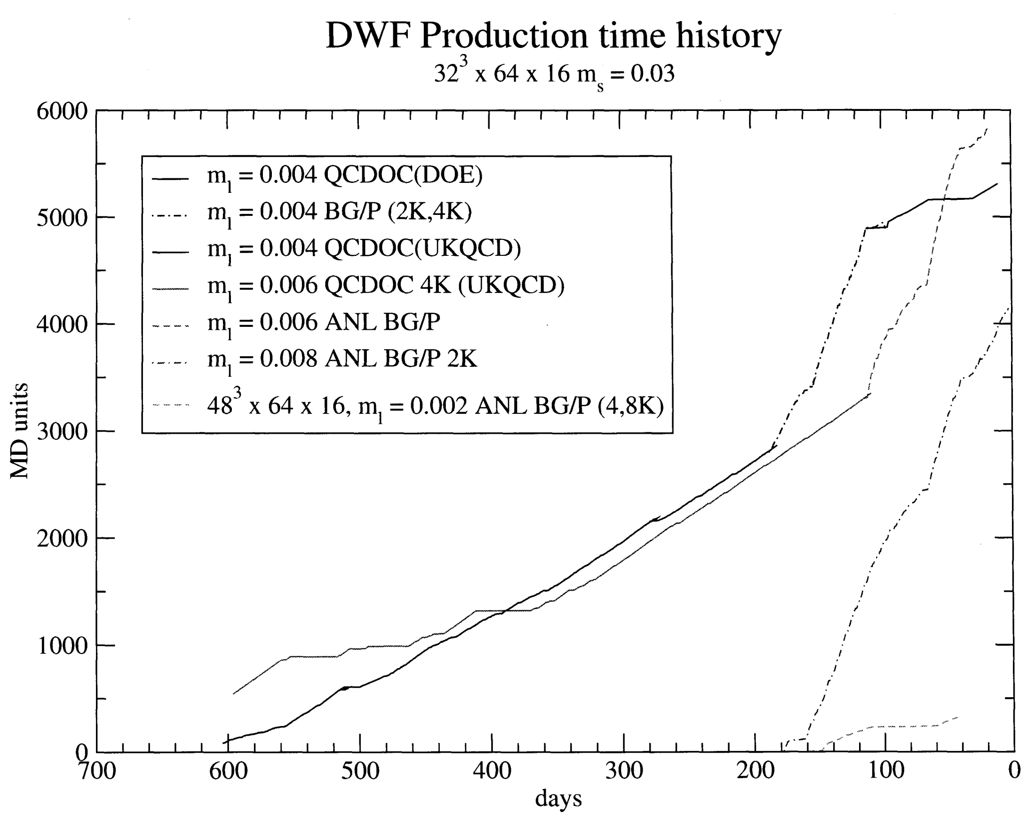
BNL-HET-08/5, CU-TP-1182, Edinburgh 2008/06, KEK-TH-1232, RBRC-730, SHEP-0812

Physical Results from 2+1 Flavor Domain Wall QCD and SU(2) Chiral Perturbation Theory

C. Allton,[1] D.J. Antonio,[2] Y. Aoki,[3] T. Blum,[3,4] P.A. Boyle,[2] N.H. Christ,[5] S.D. Cohen*,[5] M.A. Clark,[6] C. Dawson†,[3] M.A. Donnellan,[7] J.M. Flynn,[7] A. Hart,[2] T. Izubuchi,[3,8] A. Jüttner‡,[7] C. Jung,[9] A.D. Kennedy,[2] R.D. Kenway,[2] M. Li,[5] S. Li,[5] M.F. Lin§,[5] R.D. Mawhinney,[5] C.M. Maynard,[10] S. Ohta,[11,12,3] B.J. Pendleton,[2] C.T. Sachrajda,[7] S. Sasaki,[3,13] E.E. Scholz,[9] A. Soni,[9] R.J. Tweedie,[2] J. Wennekers,[2] T. Yamazaki,[4] and J.M. Zanotti[2]

Summary of Calculations

	1/a = 1.73(3) GeV	1/a = 2.42(4) GeV
m_π (dyn. mass)	331, 419, 558, 672 MeV	310, 365, 420 MeV
$m_{\bar{s}s}$	743 MeV	780 MeV
lightest valence m_π	240 MeV	235 MeV
Volume	$(2.74\ \text{fm})^3$	$(2.60\ \text{fm})^3$
m_{res} (unrenorm.)	5.4 MeV	1.6 MeV
Ensemble length	5000 MD units (lightest 2 π's)	~6000 MD units
Computer time	~ 2.0 Tflop-yrs QCDOC	2.9 TFlops-yrs QCDOC (over 1.8 calendar yrs) ~5 TFlops-yrs BG/P (over 0.7 calendar yrs)



Chulwoo Jung

Partially Quenched Chiral Perturbation Theory

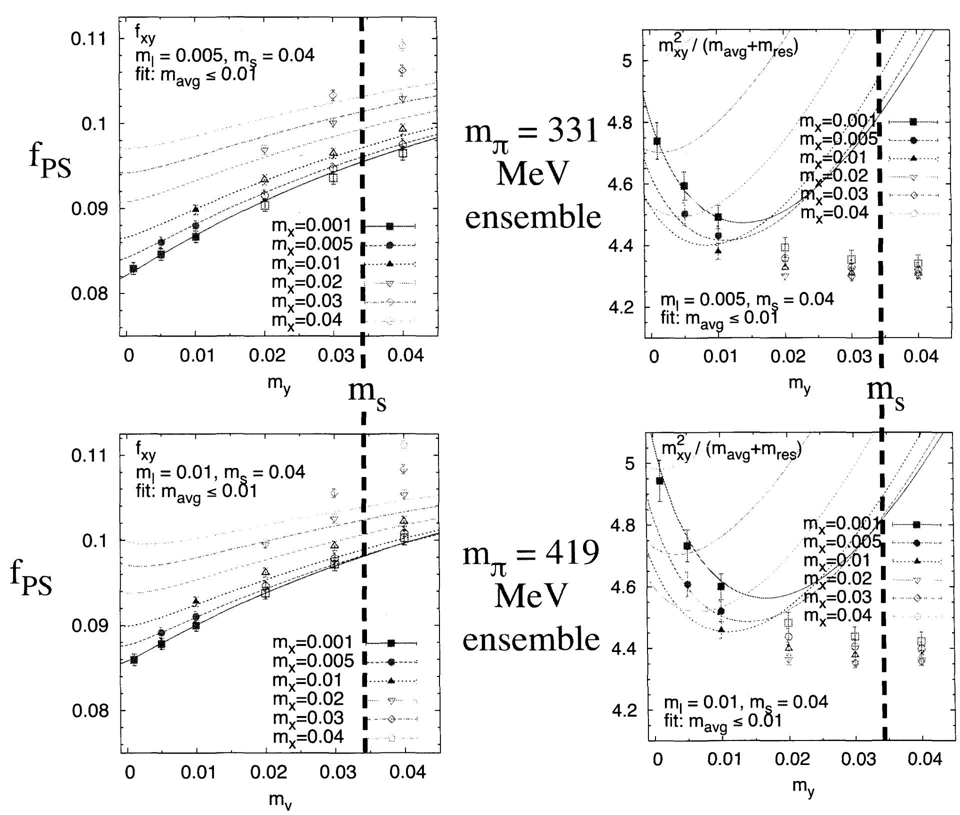
- Let masses in propagators differ from masses in determinanats
- Expansion in powers of

$$\frac{m_{PS}^2}{(4\pi f)^2} \qquad \frac{p^2}{(4\pi f)^2}$$

- SU(2) ChPT: m_l is light and only pion masses enter in logs
- SU(3) ChPT: m_l and m_s are considered light, and both enter logs
- Example (Sharpe and Shoresh, 2000) with six free parameters

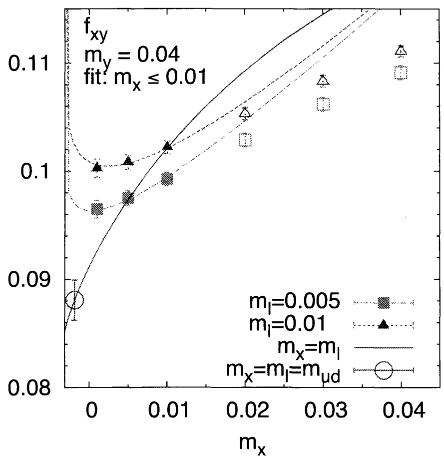
$$\begin{aligned}
m_P^2 &= \chi_V \left\{ 1 + \frac{48}{f^2}(2L_6 - L_4)\bar{\chi} + \frac{16}{f^2}(2L_8 - L_5)\chi_V \right. \\
&\quad + \frac{1}{24 f^2 \pi^2}\left[\frac{2\chi_V - \chi_l - \chi_s}{\chi_V - \chi_\eta}\chi_V \log\chi_V - \frac{(\chi_V - \chi_l)(\chi_V - \chi_s)}{(\chi_V - \chi_\eta)^2}\chi_V \log\chi_V \right. \\
&\quad \left.\left. + \frac{(\chi_V - \chi_l)(\chi_V - \chi_s)}{\chi_V - \chi_\eta}(1 + \log\chi_V) + \frac{(\chi_\eta - \chi_l)(\chi_\eta - \chi_s)}{(\chi_V - \chi_\eta)^2}\chi_\eta \log\chi_\eta \right] \right\} \\
f_P &= f\left\{ 1 + \frac{8}{f^2}(3L_4\bar{\chi} + L_5\chi_V) \right. \\
&\quad \left. - \frac{1}{16\pi^2 f^2}\left[(\chi_V + \chi_l)\log\frac{\chi_V + \chi_l}{2} + \frac{\chi_V + \chi_s}{2}\log\frac{\chi_V + \chi_s}{2} \right] \right\} \\
\chi_i &= 2B_0(m_i + m_{\rm res})
\end{aligned}$$

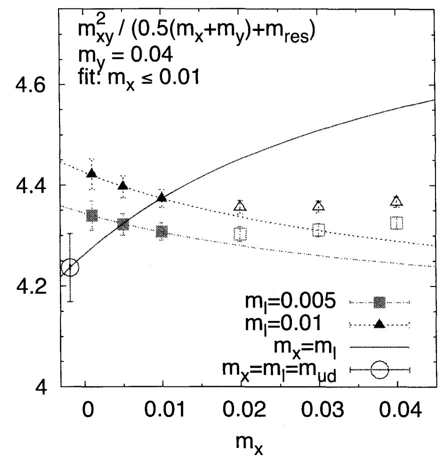
SU(2) Chiral Perturbation Theory, 1/a = 1.73 GeV



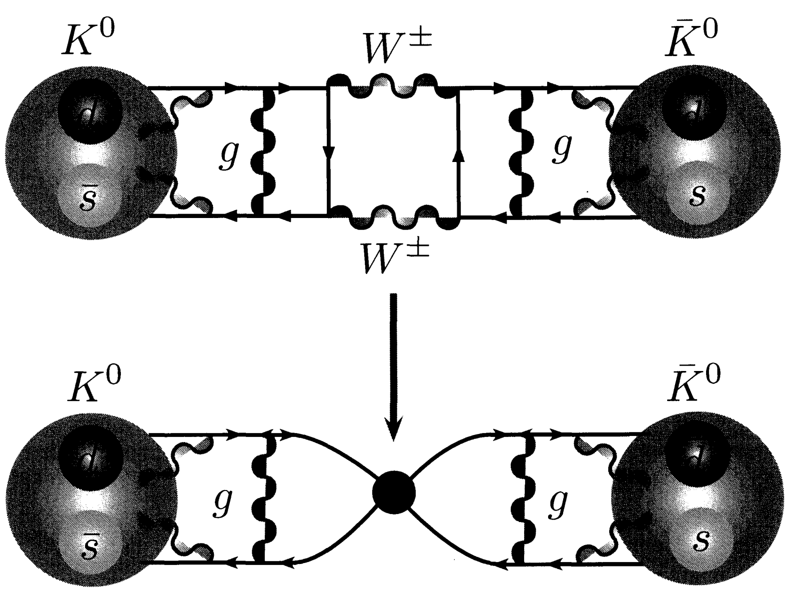
SU(2) ChPT for Kaons

- Light quark logarithms needed to extrapolate to phyiscal m_u, m_d
- Only needs m_π/m_K small, not m_K / $4\pi f$ small
- Correct for m_s = 1.15 times physical value with valence results.
- Partially quenched logs curve in opposite direction to unitary logs





Low Energy Standard Model Diagrams for B_K



Electroweak process at high energy scales reduce to a single 4-fermion operator at low energies

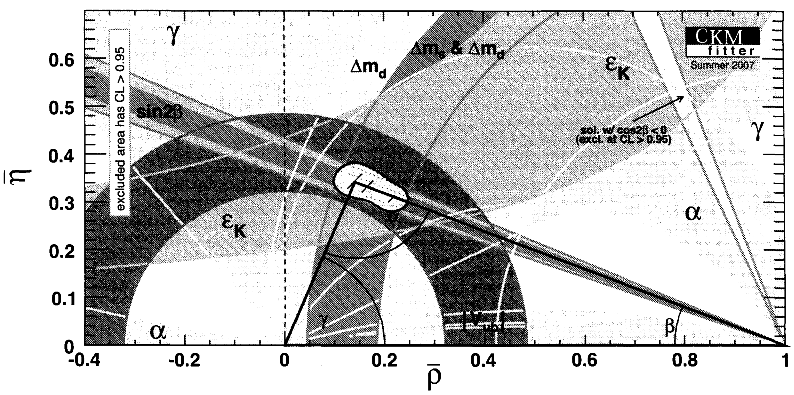
Need correctly normalized value of the $Q^{\Delta S=2}$ operator in kaon states.

$$\epsilon = \hat{B}_K \, \mathrm{Im}\lambda_t \frac{G_F^2 f_K^2 m_K M_W^2}{12\sqrt{2}\pi^2 \Delta M_K} \{\mathrm{Re}\lambda_c [\eta_1 S_0(x_c) - \eta_3 S_0(x_c, x_t)] - \mathrm{Re}\lambda_t \, \eta_2 S_0(x_t)\} \exp(i\pi/4)$$

$$\langle \overline{K}^0 | Q^{(\Delta S=2)}(\mu) | K^0 | \rangle \equiv \frac{8}{3} B_K(\mu) f_K^2 m_K^2$$

ε and the Unitarity Triangle

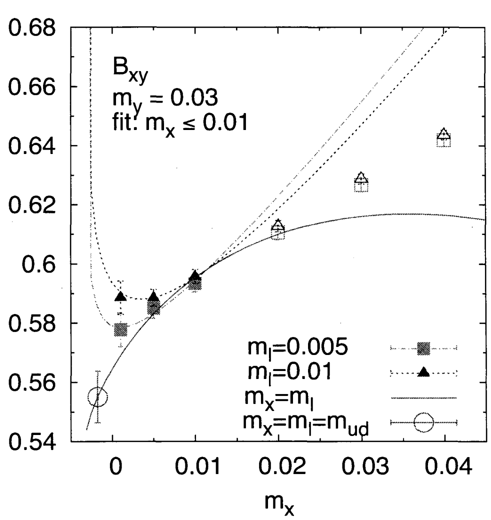
- Summer 2007 plot uses B_K = 0.75 [+0.17 -0.15] to plot band
- B_K from lattice not used in fit

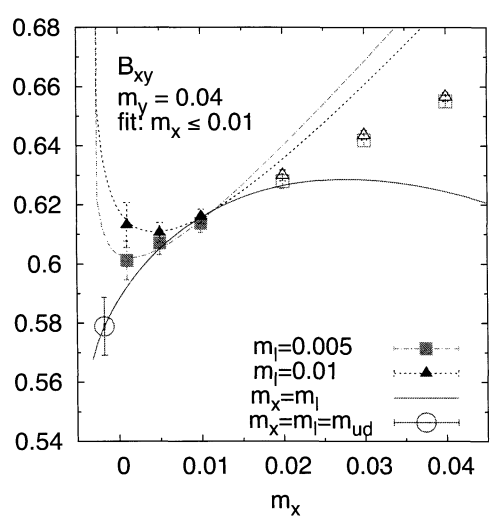


CKMfitter Group (J. Charles et al.),
Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],
updated results and plots available at: http://ckmfitter.in2p3.fr

SU(2) ChPT for B_K

- Extrapolate to light quark limit including pion chiral logs
- Logs give 10% difference between measured values and physical point
- Have two different valence strange quark masses to interpolate to physical value





Operator Renormalization and Mixing

- For DWF, lattice B_K can be renormalized non-perturbatively
- Chiral symmetry vital to control mixing with other operators

$$\begin{aligned}(\bar{s}d)^{\mathrm{lat}}_{V-A}\,(\bar{s}d)^{\mathrm{lat}}_{V-A} = {} & Z_1(\mu a)\,(\bar{s}d)_{V-A}\,(\bar{s}d)_{V-A}\\ & + Z_2(\mu a)\,(\bar{s}d)_{V+A}\,(\bar{s}d)_{V+A}\\ & + Z_3(\mu a)\,(\bar{s}d)_{P-S}\,(\bar{s}d)_{P-S}\\ & + Z_4(\mu a)\,(\bar{s}d)_{P+S}\,(\bar{s}d)_{P+S}\\ & + Z_5(\mu a)\,(\bar{s}d)_{T}\,(\bar{s}d)_{T}\end{aligned}$$

- Mixings are $O(m^2_{res})$ and make contributions from other operators, which are non-zero in chiral limit, negligible.
- Current NPR work done at exceptional momentum point, which yields larger errors. Non-exceptional momentum investigations underway

$$\begin{aligned}Z^{\mathrm{RI}}_{B_K}(2\mathrm{GeV}) &= 0.910(05)_{\mathrm{stat}}(13)_{\mathrm{syst}}\\ Z^{\overline{\mathrm{MS}}}_{B_K}(2\mathrm{GeV}) &= 0.928(05)_{\mathrm{stat}}(23)_{\mathrm{syst}}\end{aligned}$$

Physical results using SU(2) ChPT

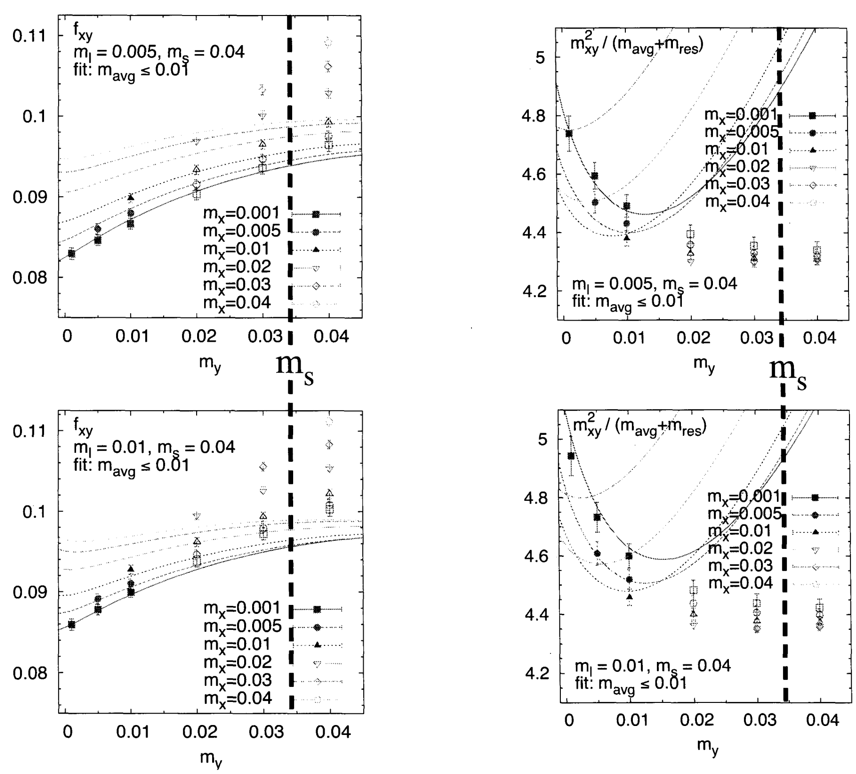
$$\begin{aligned}
f &= 114.8(4.1)_{\mathrm{stat}}(8.1)_{\mathrm{syst}}\,\mathrm{MeV},\\
B^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) &= 2.52(0.11)_{\mathrm{stat}}(0.23)_{\mathrm{ren}}(0.12)_{\mathrm{syst}}\,\mathrm{GeV},\\
\Sigma^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) &= \left(255(8)_{\mathrm{stat}}(8)_{\mathrm{ren}}(13)_{\mathrm{syst}}\,\mathrm{MeV}\right)^3,\\
\bar{l}_3 &= 3.13(0.33)_{\mathrm{stat}}(0.24)_{\mathrm{syst}},\\
\bar{l}_4 &= 4.43(0.14)_{\mathrm{stat}}(0.77)_{\mathrm{syst}},\\
\Lambda_3 &= 666(110)_{\mathrm{stat}}(80)_{\mathrm{syst}}\,\mathrm{MeV},\\
\Lambda_4 &= 1{,}274(92)_{\mathrm{stat}}(490)_{\mathrm{syst}}\,\mathrm{MeV},\\
m_{ud}^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) &= 3.72(0.16)_{\mathrm{stat}}(0.33)_{\mathrm{ren}}(0.18)_{\mathrm{syst}}\,\mathrm{MeV},\\
m_{s}^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) &= 107.3(4.4)_{\mathrm{stat}}(9.7)_{\mathrm{ren}}(4.9)_{\mathrm{syst}}\,\mathrm{MeV},\\
\widetilde{m}_{ud} : \widetilde{m}_s &= 1 : 28.8(0.4)_{\mathrm{stat}}(1.6)_{\mathrm{syst}},\\
f_\pi &= 124.1(3.6)_{\mathrm{stat}}(6.9)_{\mathrm{syst}}\,\mathrm{MeV},\\
f_K &= 149.6(3.6)_{\mathrm{stat}}(6.3)_{\mathrm{syst}}\,\mathrm{MeV},\\
f_K/f_\pi &= 1.205(0.018)_{\mathrm{stat}}(0.062)_{\mathrm{syst}},\\
B_K^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) &= 0.524(0.010)_{\mathrm{stat}}(0.013)_{\mathrm{ren}}(0.025)_{\mathrm{syst}}.
\end{aligned}$$

Other Lattice Results for B_K

- Laurent Lellouch reviewed kaon physics and ChPT at Lattice 2008
- Summary of B_K given by Lellouch

ref.	N_f	action	a[fm]	LM_π	M_π[MeV]	$\hat{B}_K$
JLQCD '08 (Hashimoto)	2	Overlap	0.12	2.7	$\gtrsim$ 290	0.734(5)(50)
ETM '08 (Vladikas)	2	OS/tmQCD	0.07,0.09	3.1	$\gtrsim$ 300	0.785(10)(16)
HPQCD/ UKQCD '06	2+1	KS^{HYP}_{MILC}	0.125	4.5	$\gtrsim$ 360	0.85(2)(18)
RBC/ UKQCD '07-08 (Scholz)	2+1	DWF	0.11	4.6	$\gtrsim$ 330	0.717(14)(39)
Bae et al '08 (Lee)	2+1	KS^{HYP}_{MILC}	$\gtrsim$ 0.06	4	$\gtrsim$ 240	$\delta B_K \to 3\%$

SU(3) ChPT for m_{PS} < 420 MeV

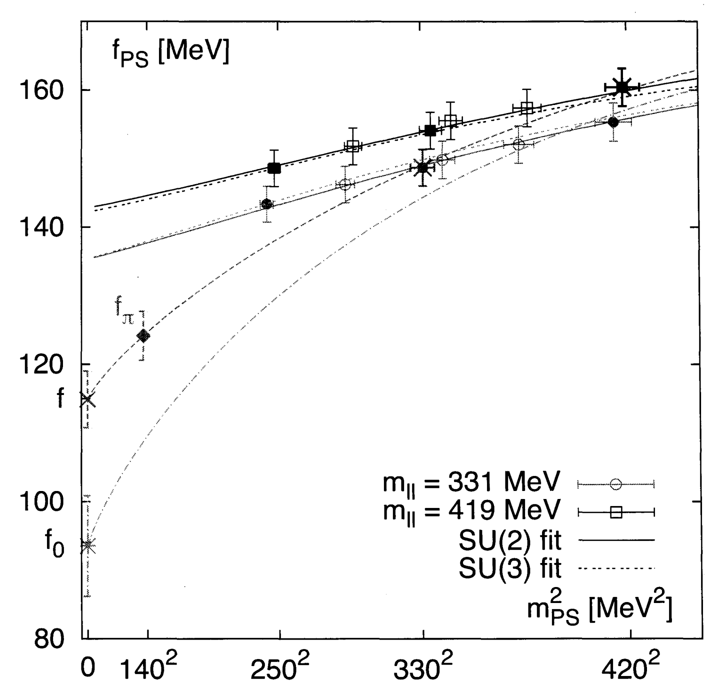


Summary of SU(3) ChPT Fits

- Fit functions agreee with data for m_{PS} < 420 MeV
- For quark masses near m_s fits differ from data by up to 10%
- NLO corrections are up to 50-70% of leading order term
- Such large NLO corrections indicate poor convergence
- Caveat: we only have data for a single dynamical strange quark mass, which may be outside of range where NLO SU(3) ChPT is reliable.
- Naively quote results for LECs from our fits
- Generally in good agreement with others

	$L_4^{(3)}$	$L_5^{(3)}$	$L_6^{(3)}$	$L_8^{(3)}$	$(2L_8^{(3)} - L_5^{(3)})$	$(2L_6^{(3)} - L_4^{(3)})$
this work[a]	1.4(0.8)(–)	8.7(1.0)(–)	0.7(0.6)(–)	5.6(0.4)(–)	2.4(0.4)(–)	0.0(0.4)(–)
Bijnens, NLO	$\equiv 0$	14.6	$\equiv 0$	10.0	5.4	$\equiv 0$
Bijnens, NNLO	$\equiv 0$	9.7(1.1)	$\equiv 0$	6.0(1.8)	2.3[b]	$\equiv 0$
MILC, 2007	$1.3(3.0)(^{+3.0}_{-1.0})$	$13.9(2.0)(^{+2.0}_{-1.0})$	$2.4(2.0)(^{+2.0}_{-1.0})$	7.8(1.0)(1.0)	2.6(1.0)(1.0)	$3.4(1.0)(^{+2.0}_{-3.0})$

f_{PS} comparison SU(2) and SU(3) ChPT

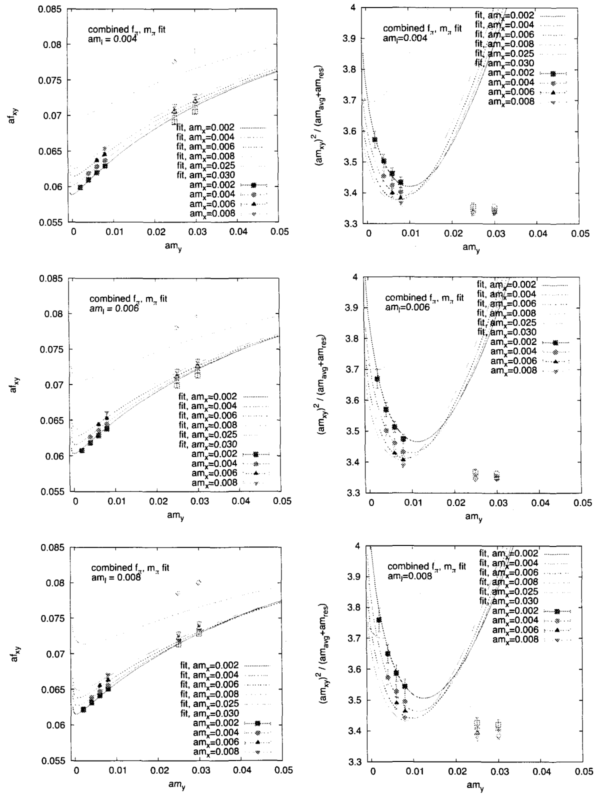


SU(2) ChPT fits to new 1/a = 2.42 GeV data

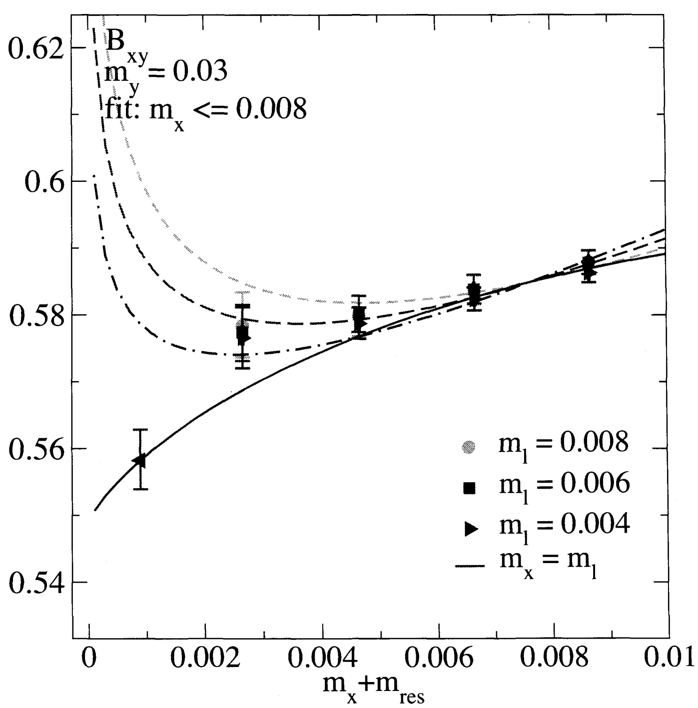
PRELIMINARY

m_π (MeV)	Measurements
310	272
365	312
420	226

- SU(2) ChPT fits our data well
- LEC's quite close to values from 1/a = 1.73 GeV
- Will provide further information about SU(3) ChPT



PRELIMINARY B_K from 1/a = 2.42 GeV data



CP Violation in the Kaon System

Two amplitudes determine ϵ and ϵ'

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \qquad \eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

Measurements of 2 real numbers needed:

$$|\epsilon| \qquad |\eta_{00}/\eta_{+-}|^2 \approx 1 - 6\,\mathrm{Re}\,(\epsilon'/\epsilon) \approx 1 - 6\,\epsilon'/\epsilon$$

Defining $A(K^0 \to \pi\pi(I)) = A_I e^{(i\delta_I)}$ gives

$$\epsilon' = \frac{i e^{i(\delta_2-\delta_0)}}{\sqrt{2}} \left(\frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0}\right) \left(\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right)$$

and the $\Delta I = 1/2$ rule

$$\omega \equiv \frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} \simeq 22$$

$K \to \pi\pi$ in 3-flavor Effective Theory

- Hamiltonian for 3-flavor effective theory: only 7 of 10 operators independent

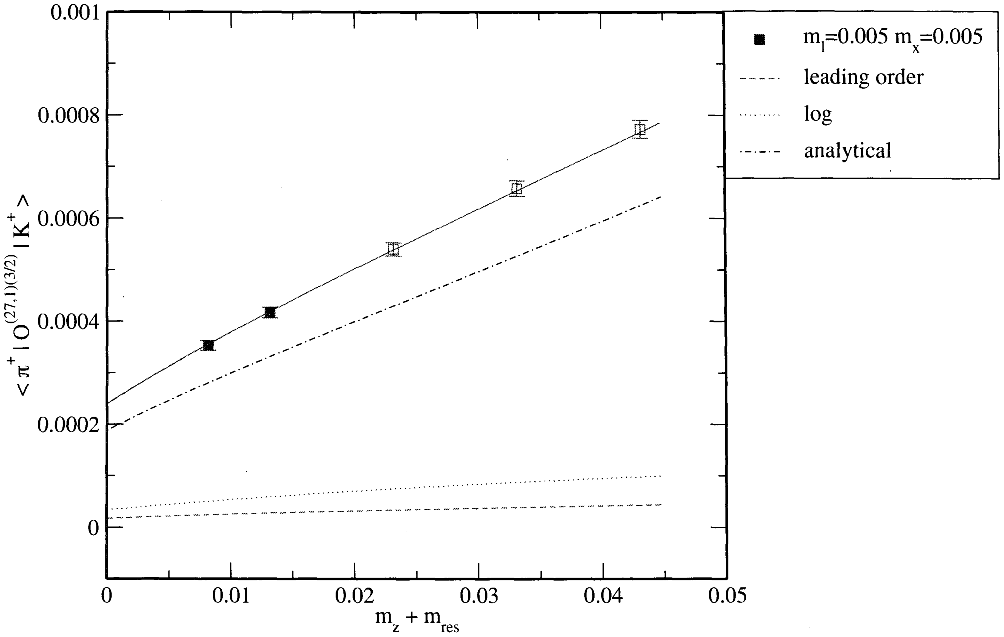
$$\mathcal{H}^{(\Delta S=1)} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[z_i(\mu) + \tau y_i(\mu)\right] Q_i \right\}$$

- $K \to \pi\pi$ from lattice calculations and LO chiral perturbation theory.

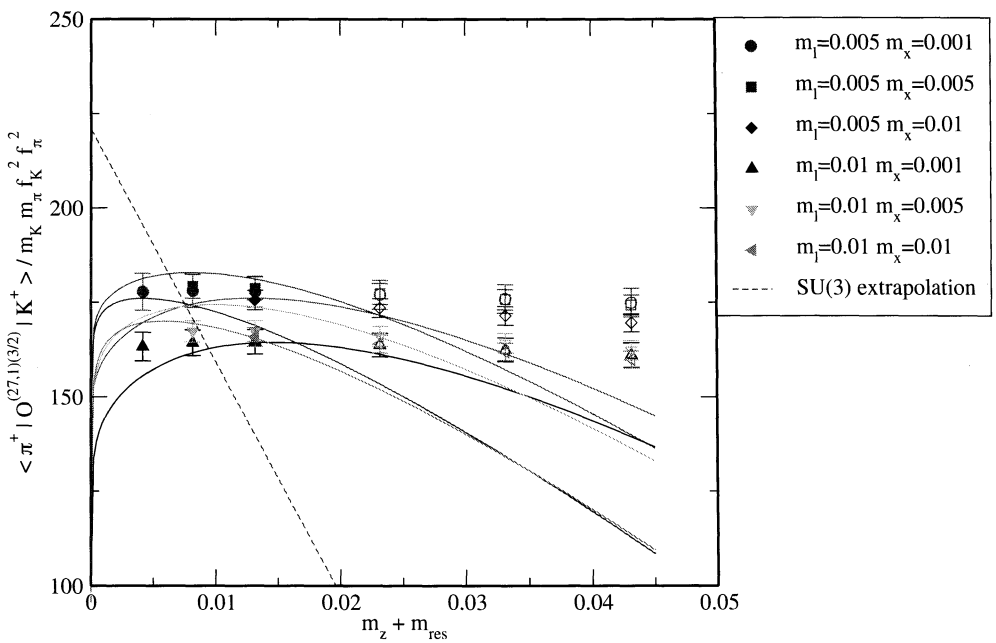
Irrep	Isospin	$K^+ \to \pi^+$	$K^0 \to \pi^+\pi^-$
(27,1)	1/2, 3/2	$-\frac{4m_M^2}{f^2}\alpha^{(27,1)}$	$-\frac{4i}{f^3} m_{K^0}^2 \alpha^{(27,1)}$
(8,8)	1/2, 3/2	$-\frac{12}{f^2}\alpha^{(8,8)}$	$-\frac{12i}{f^3}\alpha^{(8,8)}$
(8,1)	1/2	$\frac{4m_M^2}{f^2}(\alpha_1^{(8,1)} - \alpha_2^{(8,1)})$	$\frac{4i}{f^3} m_{K^0}^2 \alpha_1^{(8,1)}$

- (8,1) coefficient $\alpha_2^{(8,1)}$ is power divergent, $\mathcal{O}(1/a^2)$. Determine from $K \to |0\rangle$

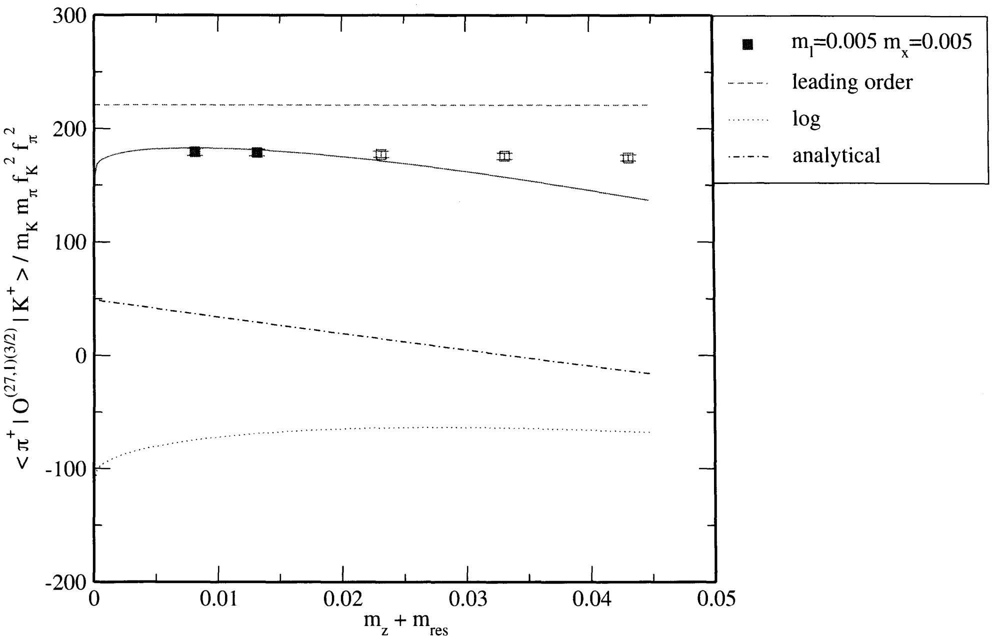
LO and NLO contributions to SU(3) fits



Fit another ratio

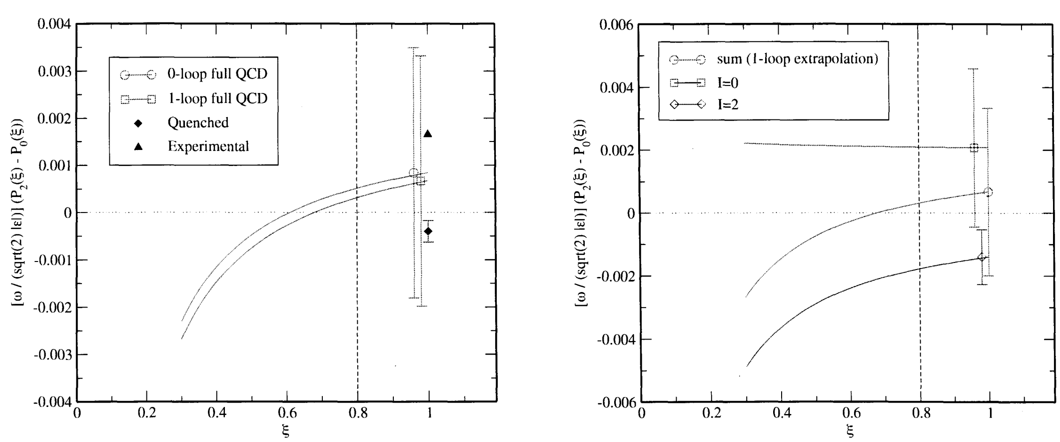


LO and NLO contributions to second fit



ε′/ε from 2+1 flavor DWF QCD

- Columbia PhD Thesis, Sam Li, June 2008, paper in preparation
- Full QCD - remove quenching errors from earlier calculations.
- Non-perturbative subtraction of mixing with lower dimensional operators controlled, as is mixing between 10 relevant operators
- SU(3) ChPT convergence very poor - estimate 100% errors on individual matrix elements



Summary

- RBC/UKQCD have large ensembles for 2+1 flavor DWF QCD
- Physics analysis complete from 1/a = 1.73 GeV ensemble
- Final analysis underway for 1/a = 2.42 GeV ensemble
- SU(2) ChPT used for extrapolation to physical m_π
- Extrapolation to continuum limit forthcoming
- Curent B_K result has 5% total error. Lattice error may soon (no longer?) be smaller than other errors in ε
- ε'/ε needs direct approach, not relying on SU(3) ChPT.
- These ensembles used for many other measurements

Lattice QCD: Future Strategy and the QCDCQ Project

November 18, 2008

Norman H. Christ

Outline

- Lattice QCD past and present
- Next opportunities
- QCDCQ project

Past and Present

Past

- Lattice methods easily reveal non-perturbative properties of QCD:
  - Confinement
  - Vacuum chiral symmetry breaking
  - QCD phase transition
- Limited phenomenological importance:
  - Quenched approximation.
  - Light quarks too massive: $m_\pi \geq 500$ MeV
  - Reliance on perturbation theory at p ~ 2 GeV
  - Discrete lattice breaks chiral symmetry
  - Uncertain systematic errors.

RBRC lattice program
(1998-2005 – QCDSP)

- Develop domain wall fermion method:
  - Dramatically reduced lattice chiral symmetry breaking – understood how it works.
  - Study Dirac spectrum, verify Banks-Casher.
  - Optimize gauge action (DBW2).
- Develop non-perturbative renormalization

RBRC lattice program
(1998-2005)

- Tackle $K \rightarrow \pi\,\pi : \Delta I = \frac{1}{2}$ rule and ε'/ε
  - Landmark calculation
  - Result, ε'/ε = - 4.0(2.3) 10^{-4}, far from experiment: 17.2(1.8) 10^{-4}
  - Serious quenching errors
- Explore 2-flavor, full-QCD DWF simulations (no quenching)
- So far mostly computation/theoretical physics – limited relevance to experiment.

RBRC lattice program
(2005 - present)

- Now joint RBC/UKQCD project
- Generate large 2+1 flavor ensemble:
  - 1/a = 1.73 and 2.42 GeV,
  - $(2.7\ \text{fm})^3$ box
  - $m_\pi \geq 320$ MeV
- All errors (nearly) under control
- Highly relevant for phenomenology
- New finite temperature studies
  - Staggered (p4) quarks
  - Direct importance to RHIC program.

RBRC lattice program: Results
(1/*a*=1.73 GeV)

- $B_K^{\overline{MS}} = 0.524\ (0.010)_{stat}(0.013)_{ren}(0.025)_{syst}$
- $f_K/f_\pi = 1.205\ (0.018)_{stat}(0.062)_{syst}$
- $(m_u+m_d)/2 = 3.72\ (0.16)_{stat}(0.33)_{ren}(0.18)_{syst}$MeV
- $m_s = 107.3\ (4.4)_{stat}(9.7)_{ren}(4.9)_{syst}$MeV
- $Kl3$: $f_+(0) = 0.9644\ (33)_{stat}(37)_{syst}$
- Many other interesting results!

RBRC lattice program: Results
($1/a$=1.73 GeV)

- These results used SU(2) x SU(2) ChPT
- SU(3) x SU(3) ChPT fails for physical m_K
- Again examine $K \rightarrow \pi\pi$, $\Delta I = ½$ rule and ε'/ε
  - Requires SU(3) x SU(3) ChPT
  - $\Delta I = 3/2$ SU(3) x SU(3) ChPT fails
  - $\Delta I = 1/2$ too many LECs for our data
  - $\varepsilon'/\varepsilon = 7.6\,(68)_{stat}(256)_{syst}\,10^{-4}$
  - Must calculate $K \rightarrow \pi\pi$ directly

RBRC Review - Nov. 18, 2008 (9)

Next Opportunities

RBRC Review - Nov. 18, 2008 (10)

Next Opportunities: 1-2 years

- Complete $1/a = 1.73 - 2.43$ GeV comparison
- Calculate a variety of important quantities:
  - Charm and bottom physics
  - NEDM
  - g-2
  - E&M-splittings
  - η' mass
  - Nucleon decay
  - g_A
  - Nucleon structure
  - New ideas!

RBRC Review - Nov. 18, 2008 (11)

Next Opportunities : 1-2 years

- Begin a new direction: explore chiral limit
  - Decreasing quark mass requires:
    - Increasing volume, $m_\pi L \sim 4$.
    - Decreasing residual mass.
    - Requires a new action.
  - First large-scale simulation ready to start:
    - $1/a$=1.4 GeV
    - $(4.5\text{ fm})^3$ volume
    - $m_\pi \geq 180$ MeV
- New quantities become accessible:
  - $K \rightarrow \pi\pi$, $\Delta I = ½$ rule and ε'/ε
  - Nucleons in large volumes

RBRC Review - Nov. 18, 2008 (12)

Next Opportunities : 2-5 years

- Light quark limit, m_π~135 MeV requires:
  - $1/a \sim 1.7 - 2.5$ GeV
  - L = 5 – 6 fm
  - 64^3 x 128 lattice volumes
  - New $1/a$=1.4 GeV study is important 1st exploration!
- Substantial boost in computer power required:
  - $32^3 \rightarrow 64^3$ requires $\sim 2^6 = 64$ performance increase.
  - 75x QCDOC upgrade

QCDCQ Project
(QCD with Chiral Quarks)

QCDCQ

- Goal
  - QCDOC design begun in 1999: now 9-year old technology.
  - Important opportunities:
    - 180 → 45 nm feature size
    - Enables multiple cores/chip and FPUs/core.
  - 100x boost in cost performance: $1/Mflops → $0.01/Mflops
- Strategy
  - Joint RBRC/Columbia/Edinburgh/IBM project.
  - Follow-on to QCDOC – BlueGene projects.
  - Joint research project builds two 300 Tflops prototype computers:
    - RBRC
    - Edinburgh

QCDCQ

- Target:
  - 300 Tflops sustained
  - 16 TByte memory
  - $5M cost
  - If approved, construction starts in Fall 2009
  - Machine available in Summer 2010.
- Columbia/Edinburgh/RBRC design team responsible for processor-memory interface
  - P. Boyle/Edinburgh
  - N. Christ, R. Mawhinney/Columbia
  - C. Kim/RBRC
- Optimize design for high QCD efficiency.

QCDCQ
Project status

- Feb 2007: Design work begun.
- Aug 2007: IBM design review passed.
- Nov 2007:
  - CU/Edinburgh/IBM collaboration agreement signed.
  - Full access to design tools and data.
- Nov 2008: VHDL design complete

RBRC Review - Nov. 18, 2008 (17)

Physics Opportunities

- Controlling the chiral limit – most important challenge for lattice QCD
  - Pions and kaons with physical masses.
  - Nucleon structure at large volume, nearly physical masses.
- Study of $\pi\,\pi$ states will be possible:
  - Decades old problems of $\Delta I = ½$ rule and ε'/ε are likely soluble.
  - First preparatory studies now underway on QCDOC, NYBlue and Argonne BG/P machines.
- Finite temperature studies will reach a new level of accuracy:
  - Go from $N_T = 8$, 10 and 12 (staggered), 5% EOS
  - Use chiral, DWF fermions, $N_T = 8$ & 10, $T \lesssim T_c$

RBRC Review - Nov. 18, 2008 (18)

Preparation Essential

- Present 2+1 flavor, QCDOC ensembles required earlier large-scale 2 flavor QCDSP experiments:

  QCDSP (300 Gflops) → QCDOC (4 Tflops)

- Working QCDOC code and well understood physics goals were required to exploit Argonne BG/P:

  QCDOC (4 Tflops) → BG/P-ANL (20 Tflops)

- Large-scale QCDOC+BG/P chiral experiments have now begun:

  BG/P-ANL (20 Tflops) → QCDCQ (300 Tflops)

- Strong physics program on QCDCQ will be needed to quickly exploit the next machines:
  - RIKEN 10 Pflops Kobe computer
  - ANL/LLNL DOE 10 Pflops leadership class machines

Conclusion

- Exciting physics program --- important physics problems are being solved.
- Large and varied group of physicists --- many opportunities to learn.
- Next computer project offers a new level of research potential.
  - Accurate 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 chiral fermions and at 50% smaller lattice spacings

Physics with RHIC/PHENIX upgrades

Y. Akiba

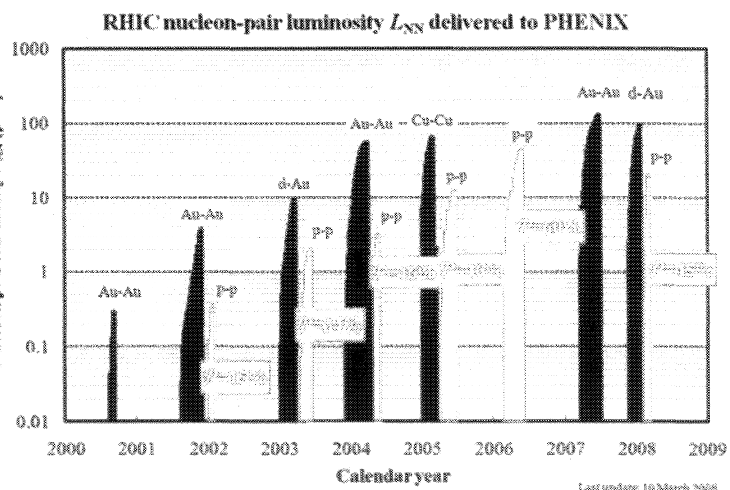
RBRC SRC review
2008/11/18

RHIC runs (2001-2008)

Beam species:
- p+p (polaized)
- d+Au
- Cu+Cu
- Au+Au

Energy:
$s_{NN}^{1/2}$=200 GeV

Also @ 130 GeV
62 GeV
56 GeV
22 GeV
(10 GeV)

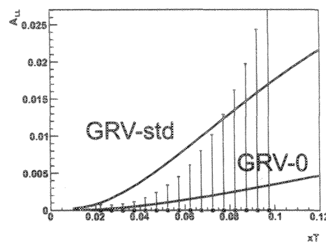


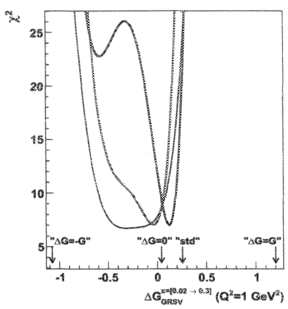
130 GeV ←——— 200 GeV ———→

Rapid increase in the Luminosity and polarization have been driving the rich physics output of RHIC in both of p+p and heavy ion

$\Delta G(x)$ now and near future

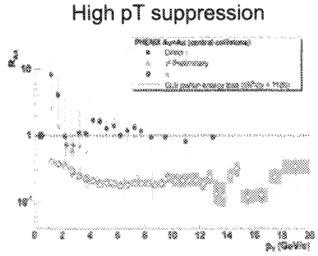
- Measurement of π^0 A_{LL} in RUN5+RUn6 have a strong constraint on $\Delta G(x)$
  - Data: Ldt~10/pb or P4L~1/pb
  - Large gluon polarization at x~0.1 is now ruled out.
  - The gluon polarization appeared to be smaller than "GRV std" model.
- Next 200 GeV run will be the last one for $\Delta G(x)$ program in the present PHENIX configuration. Additional data from the next run (~25/pb @60-65%) will give stronger upper limit (red) on positive ΔG or reveal a small non-zero value of ΔG



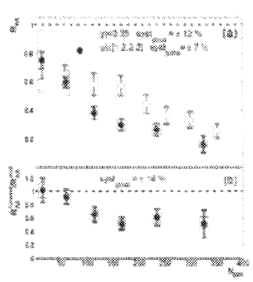


Rare probe data from RHIC/PHENIX

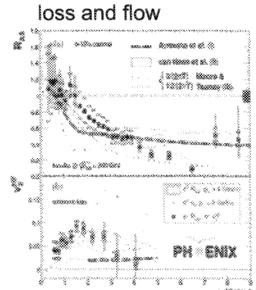
High pT suppression



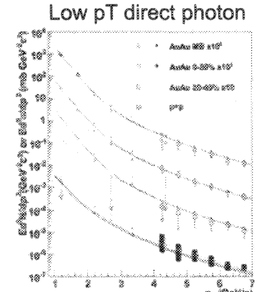
J/Ψ suppression



Heavy Quark energy loss and flow



Low pT direct photon

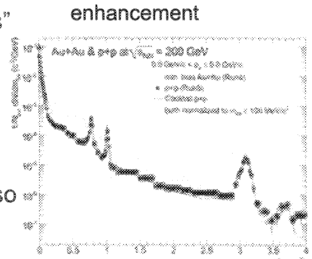


First round results of "rare probes" are obtained in RUN4 Au+Au.

Most measurements are still limited by the statistics

Detector upgrade (e.g VTX) is also required for improving the measurements

Low mass lepton pair enhancement



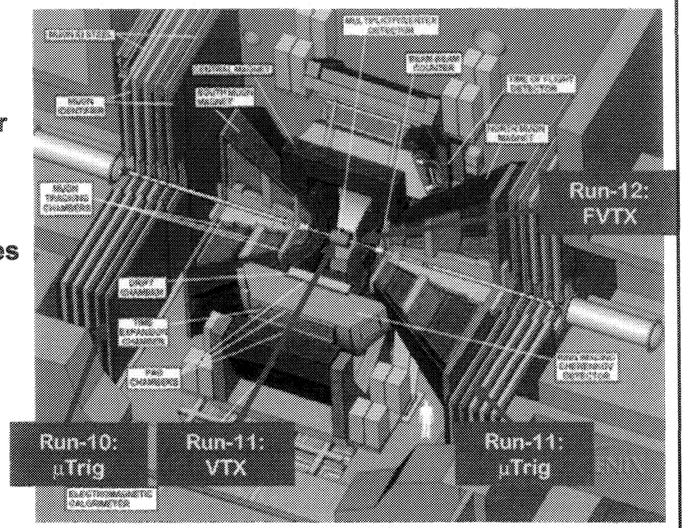
PHENIX detector upgrades

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



RHIC and PHENIX Upgrades

Current MOU
JFY07-11

	RHIC	PHENIX
RUN9	stoch. cooling 1 9 MHz RF	μTrFEE (part)
RUN10	stoch. cooling 2	μTrFEE(full) RPC_S
RUN11	EBIS (U+U)	VTX RPCN
RUN12	56 MHz RF	FVTX
RUN13		(Forward Cal?)

Next MOU
JFY12-18

Current MOU ends in the middle of RUN12
All RHIC Luminosity Upgrades and PHENIX Upgrades become ready at the beginning of Next RIKEN MOU

Expected luminosity after upgrades

- p+p 30/pb/week delivered @ 200 GeV
  75/pb/week delivered @ 500 GeV
  polarization ~70%

  Total: 300/pb @ 200 GeV P4L=75/pb
  1000/pb @500 GeV P4L=250/pb

  Ldt~10/pb (P4L~1/pb) so far recorded at PHENIX
- Au+Au (U+U)
  ~1.4 /nb/week delivered
  → 0.7 /nb/week by PHENIX

  total ~10/nb

  0.24/nb recorded in RUN4

  0.7/nb recorded in RUN7

Physics with luminosity and PHENIX upgrades

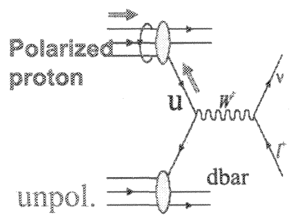
- Spin Physics
  sea q polarization
  - W A_L

  ΔG
  - π^0 A_{LL}
  - direct g A_{LL}
  - γ+jet A_{LL}
  - heavy quark A_{LL}

  Transversity
  - Drell Yan A_N
  - Heavy quark A_N
- Heavy Ion Physics
  - High pT R_{AA}
  - Jet correlation
  - gamma+jet
  - J/ψ R_{AA}
  - J/ψ v_2
  - Upsilon
  - Heavy quark R_{AA}
  - heavy quark v_2
  - Thermal photon
  - Thermal dilepton

These are only partial list.
μTrig and VTX are crucial for many of these measurements

Physics by muTRIG upgrade:
Δq-$\Delta\bar{q}$ at RHIC via W production



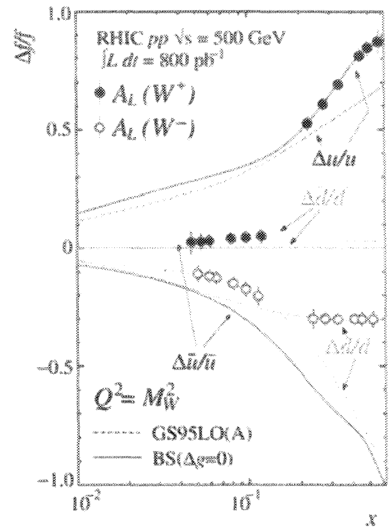
$\Delta d + \bar{u} \rightarrow W^-$

$\Delta \bar{u} + d \rightarrow W^-$

$\Delta \bar{d} + u \rightarrow W^+$

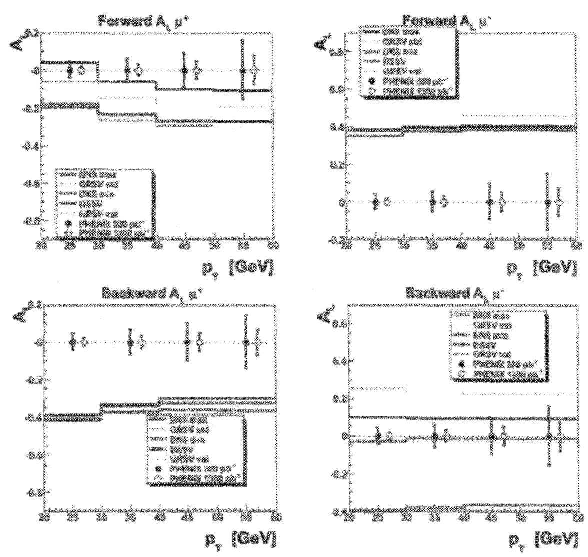
$\Delta u + \bar{d} \rightarrow W^+$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



Expected precision for A_L of W→μ

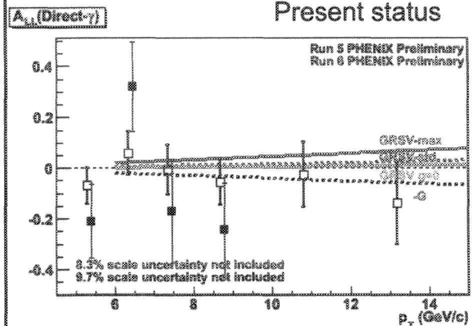
- Realistic simulation using RESBOS
- Black points: 300/pb (before luminosity upgrades)
- Open points: 1300/pb (with RHIC luminosity upgrades)



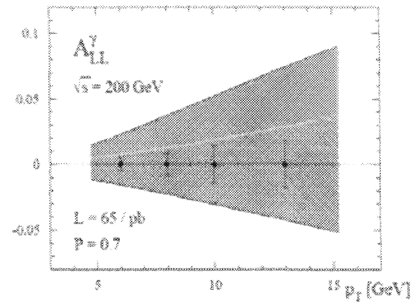
R.Seidl: RPC design

Direct photon A_{LL}

Present status



Near Future

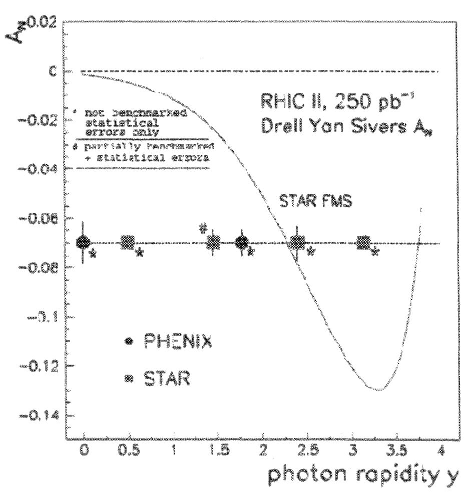


Run5: 2.5pb^{-1}, p=47% → P^4L=0.12pb^{-1}
Run6: 7pb^{-1}, p=57% → P^4L=0.74pb^{-1}

With Lumi upgrade:
300pb^{-1}, P=70% → P^4L=72pb^{-1} → 10 times smaller stat. error than RUN6
→ <1% statistical error
Significant constraint on ΔG via clean channel.

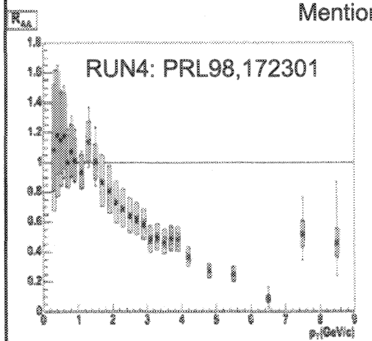
Drell Yan A_N

- Large single spin asymmetry in Drell Yan is expected Sivers effect
- DY yield for 300/pb @ 200 GeV in PHENIX muon arm is more than 10000 → stat error of O(1%) can be achieved
- Effect is larger for high x. Lower energy run (~100 GeV) is useful to access higher x.

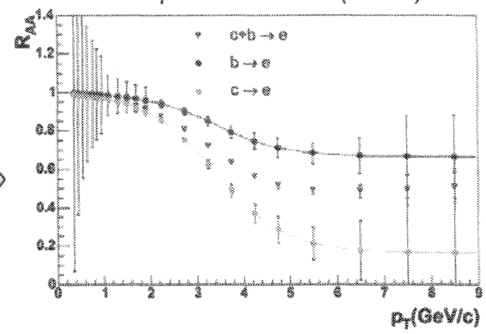


Expected R_{AA}(b→e) and R_{AA}(c→e) with VTX

Mention RHIC-2



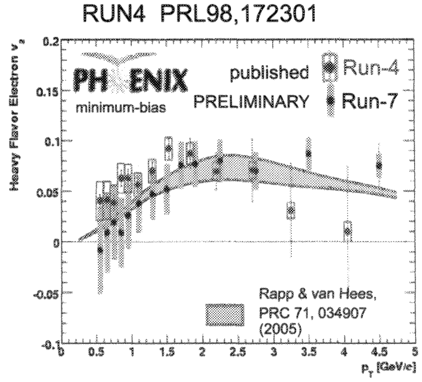
Expected with VTX (0.4/nb)



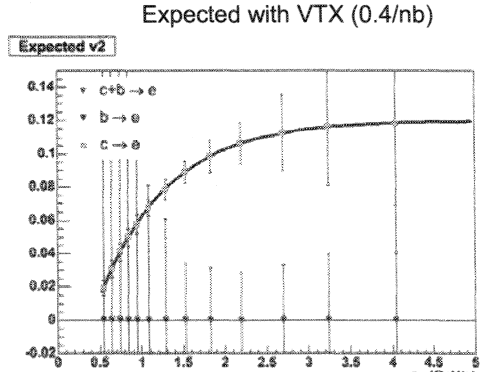
- Strong suppression of single electrons from heavy flavor decay is one of the most surprising results in RUN4
- The present measurement is mixture of b→e and c→e
- VTX can separately measure RAA of b→e and c→e
- Additional factor of 10 improvement with RHIC luminoisty upgrade.

Expected v_2(b→e) and v_2(c→e) with VTX

RUN4 PRL98,172301

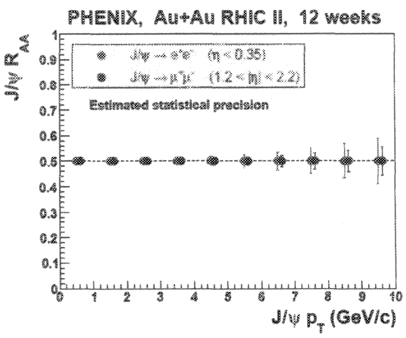


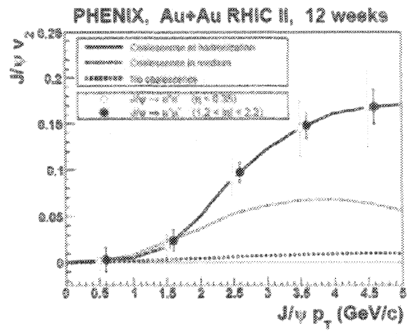
Expected with VTX (0.4/nb)



- V_2 of single electron is measured by PHENIX in RUN4
- The measured v_2 is mixture of b→e and c→e
- With VTX, we can change the mixture of b and c
- With VTX, we can separate b→e and c→e component
- Additional factor of >10 improvement in RHIC-2

High Statistics J/ψ Measurements in A+A

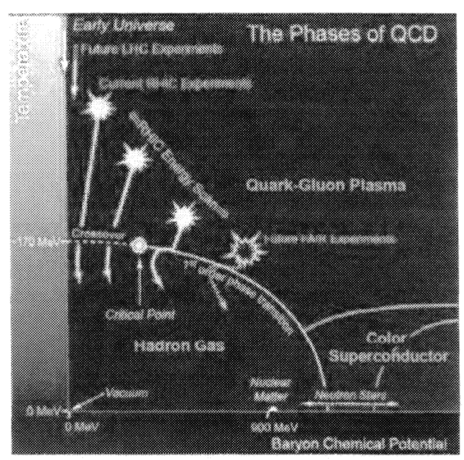




- With RHIC luminostiy upgrades, RAA of J/y is extended to ~10 GeV/c
- V_2 of J/ψ --- crucial test for J/ψ regeneration by c+cbar recombination

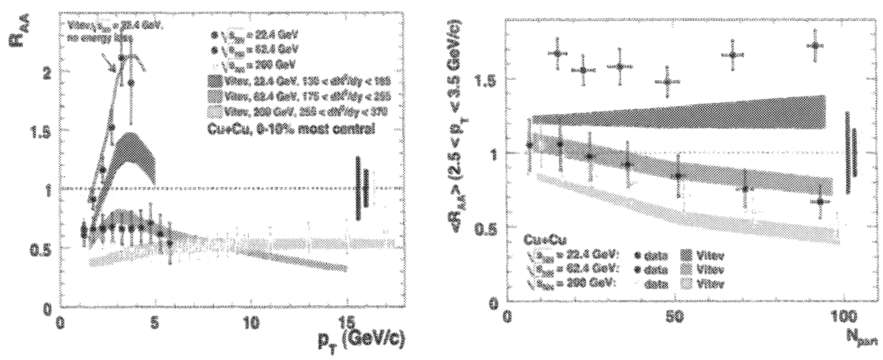
HI Energy Scan: Search for CEP

- Theory suggests that there is critical end point (CEP) in QCD phase diagram
- Location of the
- Energy scan at RHIC can discover the CEP
- The signals and the search strategy is now being discussed
  Singular behavior in
  - Fluctuation
  - v2
  - Source size
- RHIC luminosity behaves E_{beam}^2 or E_{beam}^3 (E<10GeV). High Luminosity and long running time is needed for E scan at low E



Energy scan: Onset of light quark opacity

PRL101,162301



- RAA < 1 for 62 GeV and 200 GeV
- RAA > 1 for 22.4 GeV

Where is the onset of the light quark opacity?

Same question for heavy quark

Tentative 5 year plan (by S. Vigdor)

Fiscal Year	Colliding Beam Species/Energy	Comments
2009	500 GeV p+p	~5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet RIKEN milestone
2010	200 GeV p+p	~12 physics weeks to complete 200 GeV A_{LL} measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009; STAR DAQ1000 fully operational
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st collision test of transverse stochastic cooling (installed in one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long production run with full stochastic cooling upgrade implemented, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II science goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production and sea antiquark polarizations
	200 GeV Au+Au or 2nd low-E scan	To be determined by results from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E electron cooling, and on installation/commissioning of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling
	200 GeV p+p	Address 2015 DOE performance milestone on transverse SSA for γ-jet; reference data for HI runs with new detector subsystems; test electron lenses for p+p beam-beam tune spread reduction

Summary

- RHIC upgrades
  - 4 times of Luminosity of RUN8 p+p
  - 4 times of Luminosity of RUN7 Au+Au
- Detector upgrade projects are on going to expand physics capabilities of PHENIX
  - VTX Heavy flavor tagging, large solid angle
  - muTRIG Essential for W→μ measurement at 500 GeV
- Both of the luminosity upgrades and PHENIX upgrades will be completed at the beginning of next MOU (2012)
- With the luminosity upgrade and PHENIX upgrades
  - W measurement
  - Heavy flavor measurement
  - High statistics measurement of J/ψ, direct photon, Drell Yan, etc
  - Energy scan to search for onset of QGP formation and the critical end point (CEP)

The study of fundamental structure of matter

Physics & status of
The Electron Ion Collider (EIC) or eRHIC at BNL

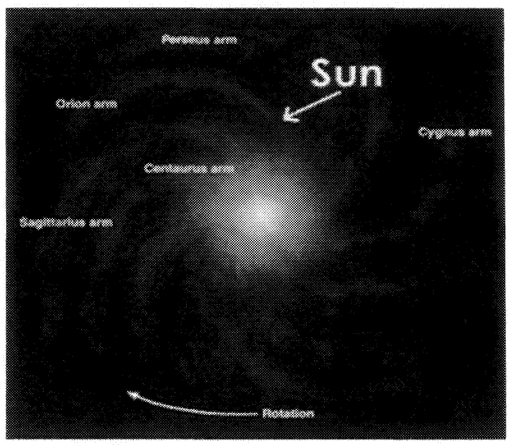
Abhay Deshpande
Stony Brook University
RIKEN BNL Research Center

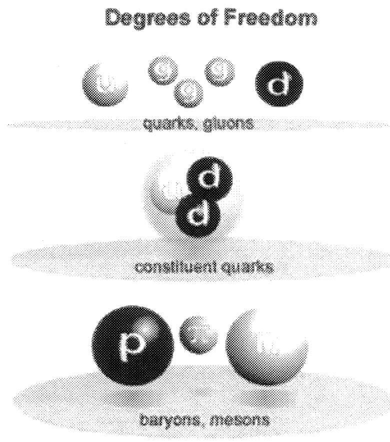
Deshpande A., et al, Annual Revies of Nuclear & Particle Science, 2005, 55:165-228
NSAC Long Range Plan 2007, arXiv:0809.3137

Outline

- Broad physics motivation
  - Understanding the fundamental structure of matter;
  - The role played by the "gluons" within nuclei and polarized protons
- Electron Ion Collider (EIC)
  - The collider options, layouts & staged realization
  - Possible measurements: some simulations studies
- Status of the EIC in the US
- Other e-N collider proposals being considered around the world
- Summary & Concluding remarks…

Building blocks of the observable universe





- Visible universe is made of protons and neutrons
- QCD tries to describe these fundamental building blocks of matter in terms of quarks and **their interactions, through gluons**

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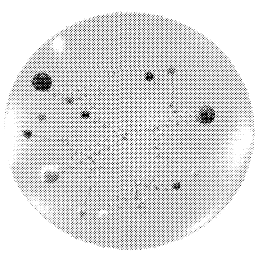
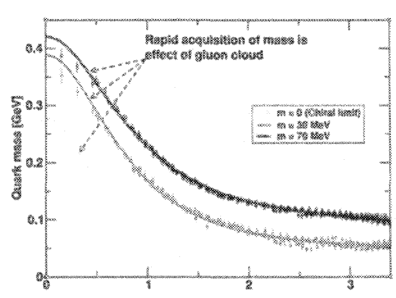
QCD and the Origin of Mass





- 99% of the proton's mass/energy is due to the self-generating gluon field
  - Higgs mechanism has no role
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.
- **How well do we know the gluon's role in the structure of the nucleon?**

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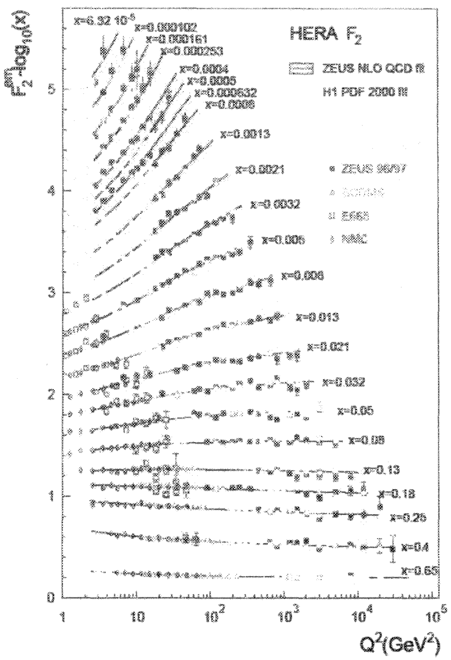
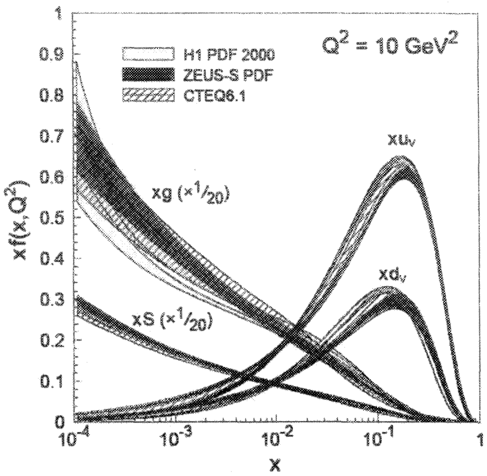
Measurements of the Glue at HERA

STONY BROOK
STATE UNIVERSITY OF NEW YORK



Scaling violations of $F_2(x,Q^2)$
Linear DGLAP equations



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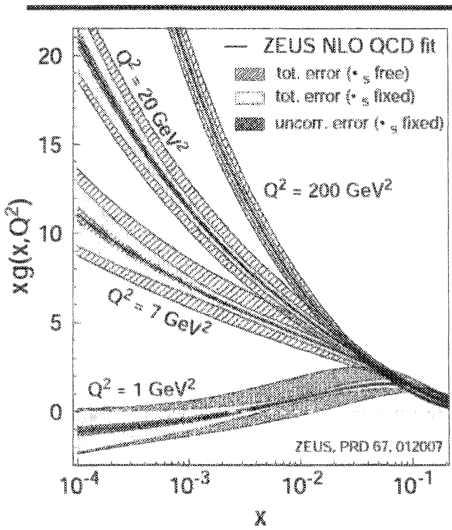
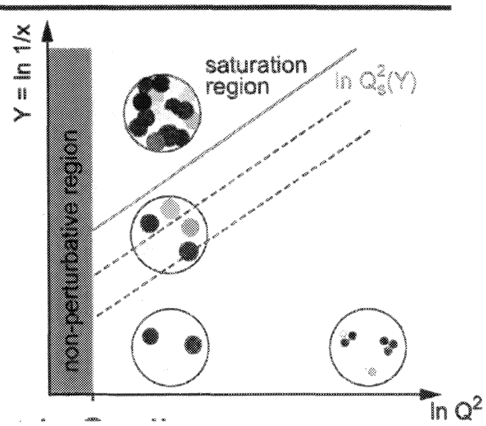
5

Gluons: not well understood!

STONY BROOK
STATE UNIVERSITY OF NEW YORK





Linear DGLAP @ low x:
Rises with Q^2? Cross sections?
Small, even negative at low Q^2

Nonlinear effects: Saturation!
High gluon densities most easily accessed in nuclei
BK/JIMWLK propose:
Characteristic scale $Q_s(x,A)$
Color glass condensate!

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e-A data at low x, also at low Q^2 6

How does e-A really help?

Nuclear Oomph Factor: $(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$

Teaney et al.

⇒ non-linear QCD regime reached at significantly lower energy in e+A than in e+p

$$s_{Hera} \approx (330 \text{ GeV})^2$$
$$s_{EIC} \approx (63 \text{ GeV})^2$$
$$\frac{s_{EIC}}{s_{Hera}} \approx \frac{1}{27}$$

Instead of extending *x*, *Q* reach we increase Q_s
$Q^2 \sim sx$: EIC factor behind (10+100 GeV)

$$Q_s^2(Hera) = Q_s^2(EIC) \to Q_0^2\, x_{Hera}^{-1/3} = c\, Q_0^2\, A^{1/3}\, x_{EIC}^{-1/3}$$
$$x_{EIC} = x_{Hera} \cdot c^3 A$$
$$c^3 A = 0.5^3 \cdot 197 \approx 25$$

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eA physics drives e-beam energy!

EIC Beam Energy (GeV)	√s (GeV)	low-x reach compared to HERA (e+p equivalent)
2+100	28	4
10+100	63	18
20+100	89	36
20+130	102	50
30+130	125	71

- We do not know for sure where saturation will be seen
- What is a safe margin over HERA?
  - A 50-100 times improvement may be desired

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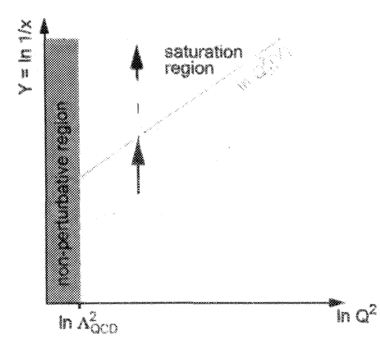
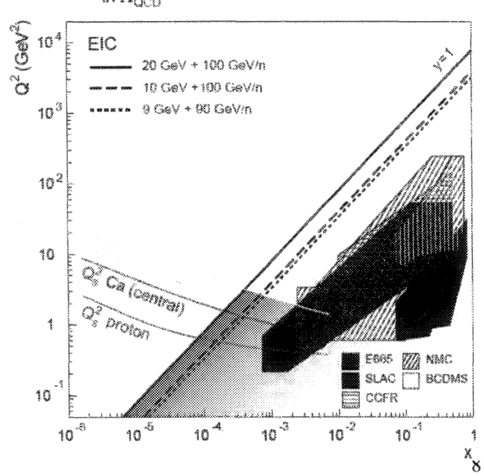
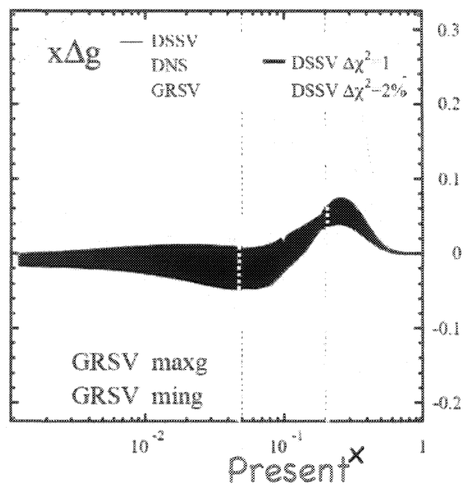




De Florian, Sassot, Stratmann & Vogelsang

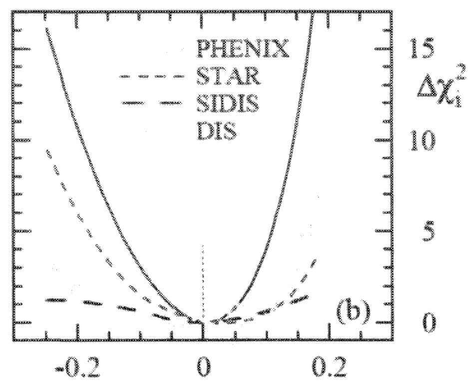
Recent: $\Delta G(x)$ @ Q^2=10 GeV^2



small-x
$0.001 \leq x \leq 0.05$

large-x
$x \geq 0.2$

- Global analysis: DIS, SIDIS, RHIC-Spin
- Uncertainly on ΔG large at low x



$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\ \mathrm{GeV}^2)dx$$

9

Status: Nucleon Spin puzzle

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

??

DIS fixed target Experiments
~0.23+/-0.03

DIS & RHIC Spin
Transverse Spin
GPDs, TMDs
~??
Not 0?

RHIC Spin
DIS experiments
~0.0 +/- (unknown)
0.02<x<0.3

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Fundamental Questions in QCD

STONY BROOK
STATE UNIVERSITY OF NEW YORK

- How do gluons contribute to the structure of the nucleon?
- What role do the gluons play in determining the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do the gluons contribute to the structure of the nuclei?
- What are the properties of *high density* gluon matter?
- How do fast quarks and gluons interact when they traverse through nuclear matter?

How do we get to the answers?

Precise imaging of the sea-quarks and gluons in the nucleon

Need to explore a new QCD frontier: of strong color fields in nuclei

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Electron Ion Collider

STONY BROOK
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A high energy, high luminosity polarized electron-proton and electron-ion collider will enable us to explore some of the most fundamental and universal aspects of QCD

Deshpande A., et al. Ann. Rev. of Nucl. Part. Sci. 2005, 55:165-228
NSAC Long Range Plan 2007, arXiv:0809.3137

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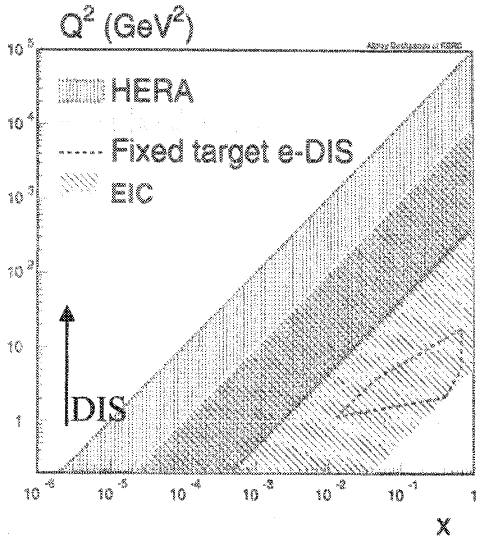
eRHIC: EIC@BNL



- **New kinematic region**
- E_e = 10 GeV (~5-20 GeV variable)
- E_p = 250 GeV (~50-250 GeV)
- E_A= 100 GeV
- Sqrt[S_{ep}] = 30-100 GeV
- Kinematic reach of EIC:
  - X = 10^{-4} --> 0.7 (Q^2 > 1 GeV^2)
  - Q^2 = 0 --> 10^4 GeV^2
- Polarization of e,p and light ion beams at least ~ 70% or better
- Heavy ions of ALL species
- Machine Luminosities envisioned
  - L(ep) ~10^{33-34} cm^{-2} sec^{-1}
- **Integrated Luminosity goal:**
  - **50 fb^{-1} in 10 years**
  - **possible with 10^{33} cm^{-2} sec^{-1}**

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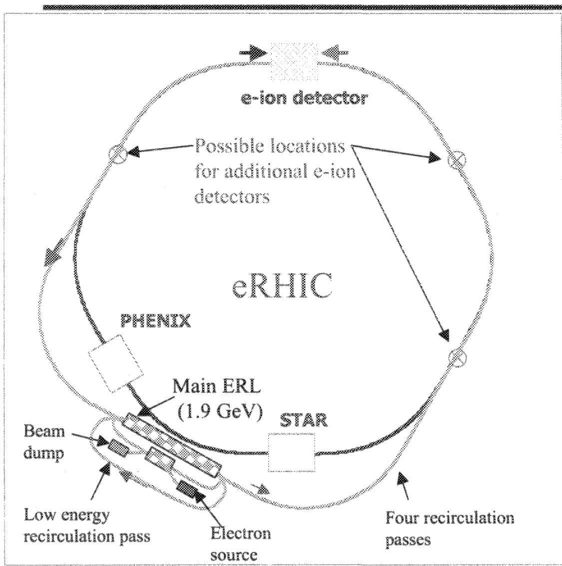
ERL-based eRHIC Design (Circa 2008)



- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- 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: compact storage ring

Can reach L ~ 10^{33-34} cm^{-2} sec^{-1}

A staged approach with significantly reduced initial cost possible

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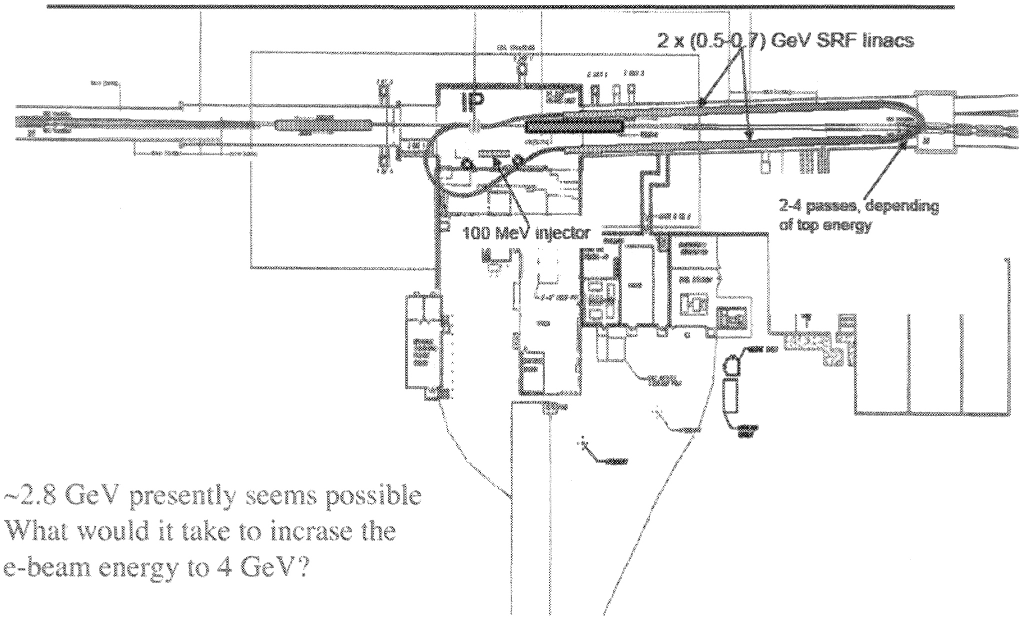
Staged EIC=eRHIC@BNL



~2.8 GeV presently seems possible
What would it take to incrase the
e-beam energy to 4 GeV?

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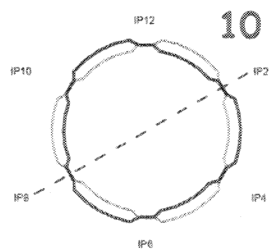
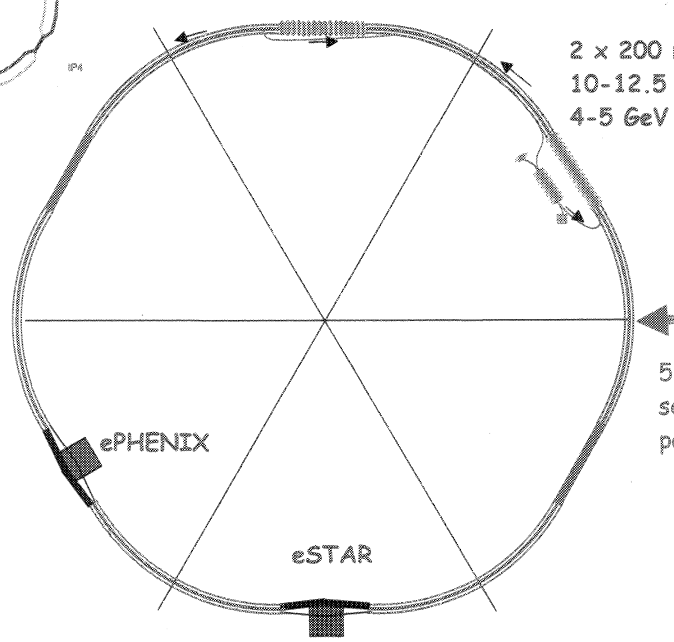
10 (20) GeV e x 250 (325) GeV p eRHIC
with ERL inside RHIC tunnel





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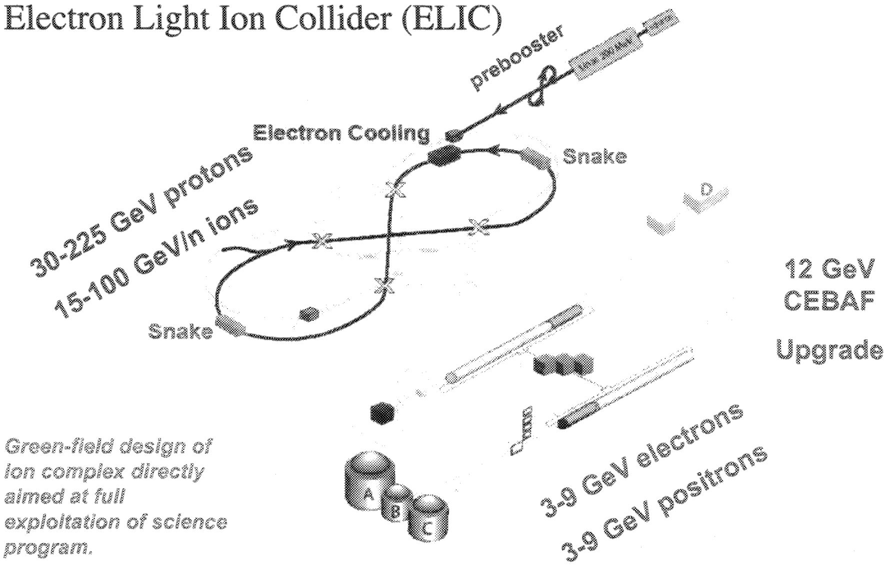
EIC @ Jefferson Laboratory:

Electron Light Ion Collider (ELIC)



Green-field design of ion complex directly aimed at full exploitation of science program.

Most ambitious: L_{max} ~ few x 10^{34} cm^{-2} sec^{-1}

Scientific Frontiers of eRHIC/EIC

Polarized Beams

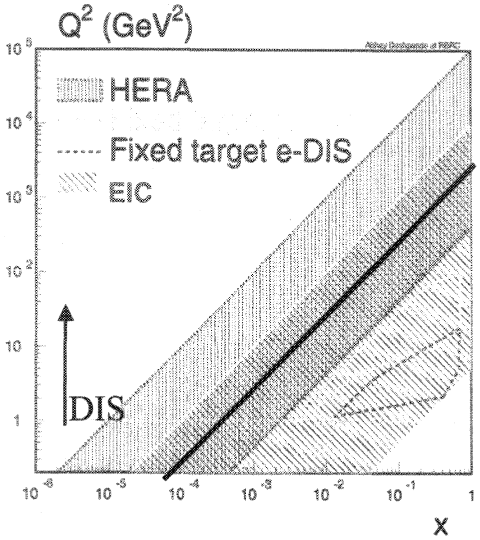
low Lumi high

- Nucleon Spin structure
  - Polarized quark and gluon distributions
    - Longitudinal spin structure (Low x critical)
    - Transverse spin structure (wide Q^2 arm critical)
  - Correlations between partons
    - Exclusive processes --> Generalized Parton Distributions
  - Precision measurements of QCD and of EW parameters in SM

- Un-polarized Nucleon Structure
  - Understanding confinement with low x/lowQ^2 measurements
  - Un-polarized quark and gluon distributions
- Nuclear Structure, role of partons in nuclei
  - Confinement in nuclei through comparison e-p/e-A scattering
- Hadronization in nucleons and nuclei & effect of nuclear media
  - How do knocked off partons evolve in to colorless hadrons
- Partonic matter under extreme conditions
  - For various A, compare e-p/e-A

Proton & Nuclear Beams

Stage 1 eRHIC: EIC@BNL



- **New kinematic region**
- E_e = 3 GeV
- E_p = 250 GeV (~50-250 GeV)
- E_A= 100 GeV
- Sqrt[S_{ep}] = 30-50 GeV
- Kinematic reach of EIC:
  - X = 10^{-3} --> 0.7 (Q^2 > 1 GeV^2)
  - Q^2 = 0 --> 10^3 GeV^2
- Polarization of e,p and light ion beams at least ~ 70% or better
- Heavy ions of ALL species
- Machine Luminosities envisioned
  - L(ep) ~few x 10^{32} cm^{-2} sec^{-1}

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Physics of Stage 1 eRHIC/EIC

- Polarized/un-polarized Proton/He3 beams
  - Transverse spin effects in a broad Q^2 range: disentangle the various transverse spin phenomena being discovered
  - First detailed study of the Q^2 evolution of TMDs
  - Systematic study of target fragmentation including "intrinsic charm/heavy flavors" in protons
  - Extension of inclusive and semi-inclusive longitudinal e-N scattering beyond the present experimental reach
    - g1, ΔG, high-x, aspects of twist-2 physics for spin SFs
- Un-polarized nuclear beams
  - Intrinsic heavy flavor quarks in nuclei
  - First ever study of e-A diffractive physics
  - Detailed study of EMC effect in pQCD region; its connection to jet suppression seen in HI collisions
  - Detailed study of physics of low A nuclei

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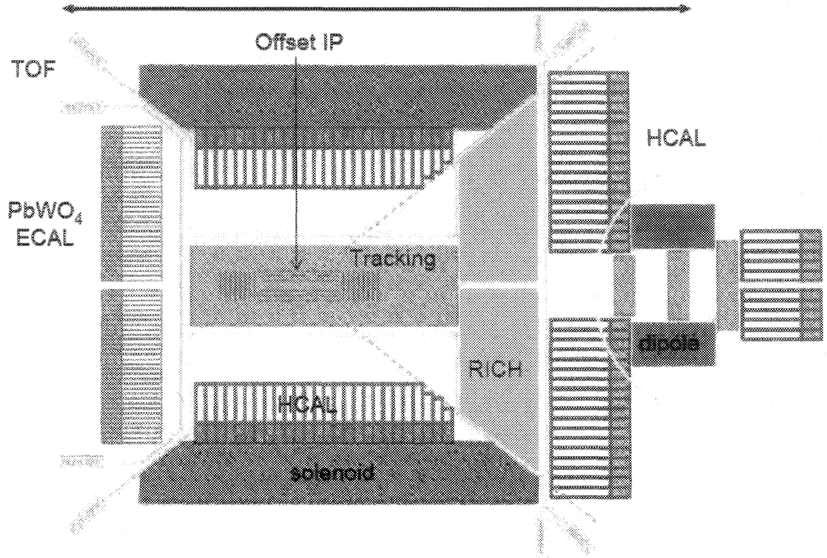
Based on experience and lessons learnt from HERA:

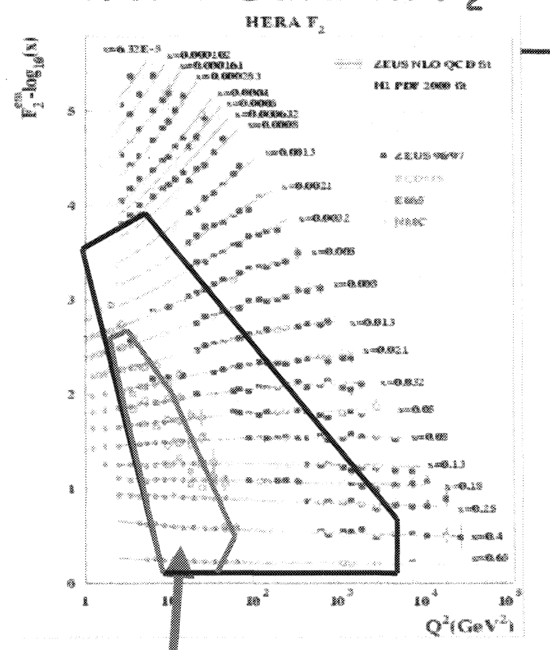
(Conventional HERA like detector by B. Surrow & a forward detector concept by A. Caldwell)

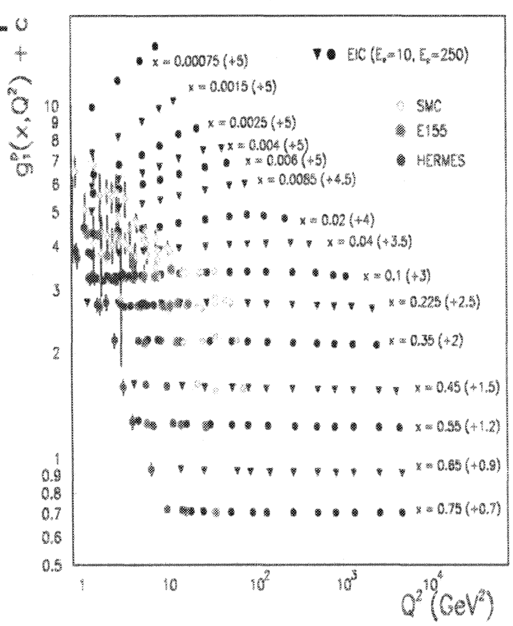
Emerging detector concept

T. Horn, R. Ent



World Data on F_2^p World Data on g_1^p

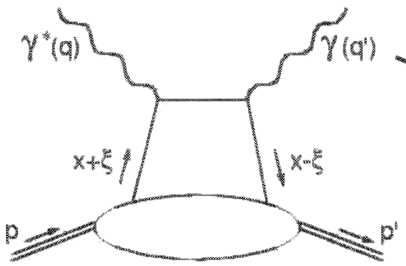




Region of existing g_1^p data

An [EIC logo] makes it possible!

DVCS/Vector Meson Production: Access to Quark & gluon GPDs (OAM?)



- Hard Exclusive DIS process
- γ (default) but also **vector mesons** possible
- Remove a parton & put another back in!

• Claim: possible access to --> Generalized parton distributions with theoretically clean connections to partonic orbital angular momentum!

$$\int x dx [H(x,t,\xi) + E(x,t,\xi)] = 2J_{quark} = \Sigma + 2L_q$$

$t \downarrow 0$ $t \downarrow 0 \dashrightarrow -Q^2$

Experimental effort just beginning…To fully explore this physics beam Charge asymmetries need to be measured… => Luminosity Hungry Measurement

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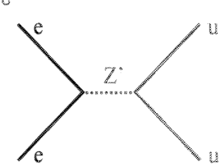
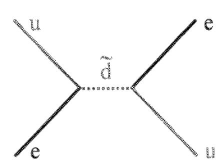
Parity Violation Studies (studied ELIC 150 x 7 GeV, D-e scattering)

Measurement of Weinberg angle at a different scale

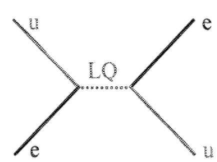
E_6 Z' Based Extensions



RPV SUSY Extensions



Leptoquarks

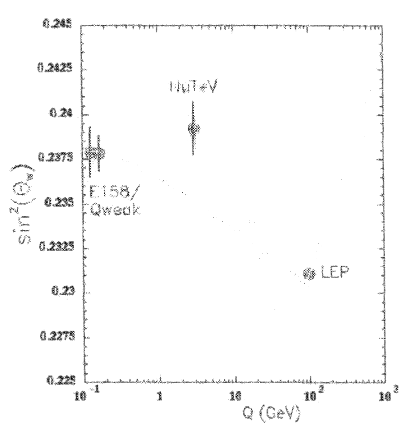


Due to finite Y

$$\left.\frac{\delta \sin^2\theta_W}{\sin^2\theta_W}\right|_{Y=0.46} \approx \frac{1}{2}\left(\frac{\delta A_d}{A_d}\right)$$

$$A_d \approx 2.9 \times 10^{-4}$$

Assumed 10^{35} /cm²/s, 10 weeks &
100% machine and detector efficiency
Sub 0.5% polarimetry



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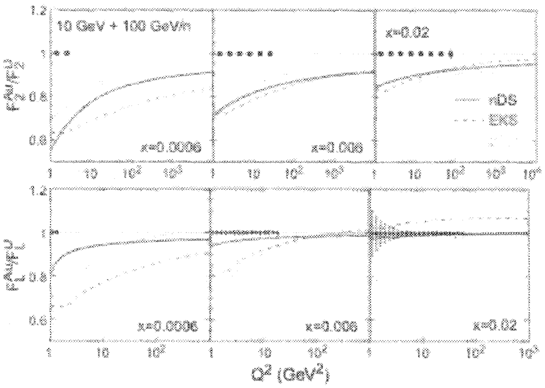
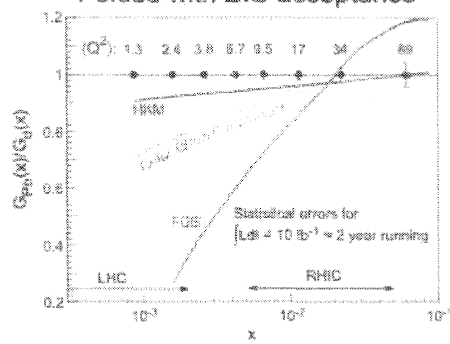
Preliminary e-A simulations

Simulations to demonstrate the quality of EIC measurements



Folded with EIC acceptance



$F_L \sim \alpha_s\, G(x,Q^2)$ requires $\sqrt{s}$ scan, $Q^2/xs = y$

Assume:

L = $3.8\ 10^{33}$ cm^{-2} s^{-1} (100x Hera)
T = 10 weeks
duty cycle: 50%
L ~ 1/A (approx)

Plots above:
$\int Ldt$ = (10+100) GeV
= (10+50) GeV
= (5+50) GeV
statistical error only

Outlook: Experiments & Lattice QCD

Outlook

- Dramatic increase in computer resources for Lattice QCD
  - Teraflops → Petaflops → Exaflops
- Innovation in algorithms
- Chiral fermions down to physical pion mass
- Disconnected diagrams
  - Calculate proton and neutron separately, not just difference
  - Strangeness content of nucleon
- Gluon observables
  - Contribution to mass, momentum, spin

Synergy between Lattice and Experiment

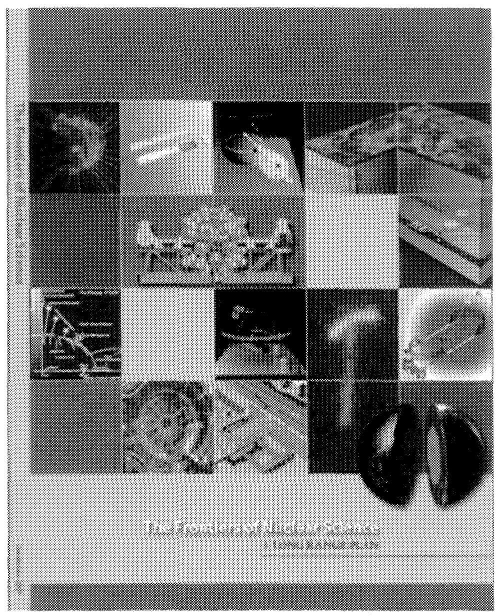
- Use solution of QCD as a quantitative tool in concert with experiment
- Example: GPD's
  - Experiment: Integrals over GPD's
  - Lattice: Moments of GPD's
  - Together, obtain much stronger constraints on GPD's than from either alone

J. Negele @ UIUC/RBRC WS on ΔG

NSAC 2007 Long Range Plan

"*An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:*

***We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely* image the gluons in the proton.**"



NSAC Long Range Plan 2007, arXiv:0809.3137

EIC Working Group Structures

Steering Committee
- Abhay Deshpande, Stony Brook (Co-Chair/Contact person)
- Rolf Ent, Jlab
- Charles Hyde, ODU/UBP, France
- Peter Jacobs, LBL
- Richard Milner, MIT (Co-Chair/Contact person)
- Thomas Ulrich, BNL
- Raju Venugopalan, BNL
- Antje Bruell, Jlab
- Werner Vogelsang, BNL

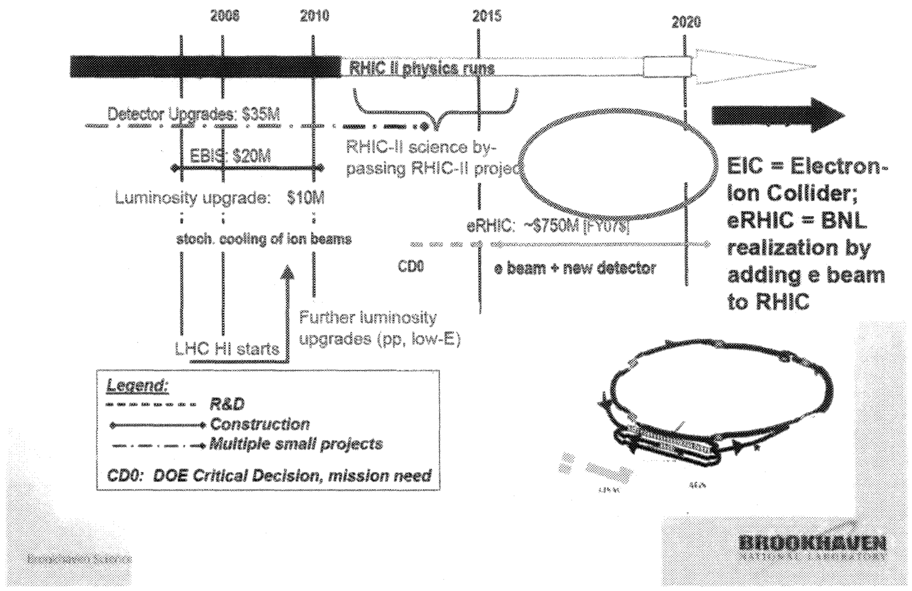
International Advisory Committee (appointed by BNL +Jlab Directors)
- Jochen Bartels (DESY)
- Allen Caldwell (MPI, Munich)
- Albert De Roeck (CERN)
- Walter Henning (ANL)
- Dave Hertzog (UIUC)
- Xiangdong Ji (U. Maryland)
- Robert Klanner (U. Hamburg)
- Alfred Mueller (Columbia)
- Katsunobu Oide (KEK)
- Naohito Saito (KEK)
- Uli Wienands (SLAC)

First meeting Spring-09

Working Groups and Convenors
- **ep Physics**
  - Antje Bruell, JLAB
  - Ernst Sichtermann, LBL
  - Werner Vogelsang, BNL
  - Christian Weiss, JLAB
- **eA Physics**
  - Vadim Guzey, JLAB
  - Dave Morrison, BNL
  - Thomas Ullrich, BNL
  - Raju Venugopalan, BNL
- **Detector**
  - Elke Aschenauer, JLAB
  - Edward Kinney, Colorado
  - Bernd Surrow, MIT
- **Electron Beam Polarimetry**
  - Wolfgang Lorenzon, Michigan

Next Meeting December 11-13, 2008 at Lawrence Berkeley Laboratory -Details on EIC webpage:
- http://web.mit.edu/eicc

S. Vigdor, BNL Associate Laboratory Director, NP/HE
RHIC-AGS User's Meeting June, 2008



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Other e-N colliders…

- (MANUEL @ FAIR) --> Very preliminary

  MAinz concept for NUcleon ELectron ion collider @ GSI/Fair (D. von Harrach)

  - Parameters: CM between COMPASS and HERMES; s=100 and 200 GeV^2; Luminosity ~ 10^{33} cm^{-2} sec^{-1}
  - Physics: dedicated study of hadronic structure & strong interactions
  - Realization: add polarized e injector to PAX using COSY as an e-storage ring at 3 GeV/c & fill HESR with polarized protons at 15 GeV
- Open questions: can lumi be reached? Can polarization of ~80% for both beams be achieved?

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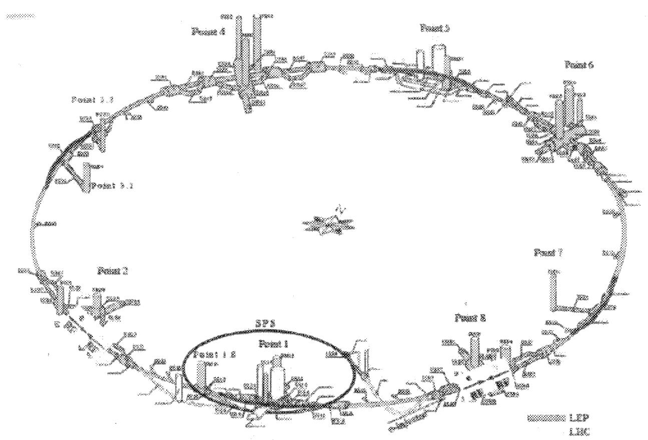
Other e-N colliders…

STONY BROOK



- LHeC: electron beam complex to collide with LHC
- 70 GeV e x 7 TeV p
- Physics motivation: mostly Beyond-SM but also extremely low x physics may be possible
  - No polarization of protons
- Conceptual Design Report requested by the CERN council by 2010

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Conclusions & Summary

STONY BROOK

- QCD physics case for a future e-N collider is strong and continues to be refined: Of broad interest is a study of gluons in nuclei and precision study of polarized nucleons
  - **With appropriate modifications of the collider parameters, a new paradigm of physics: precision tests of SM may be possible.**
- Many international and national laboratories & communities interested:
  - **BNL, Jlab, CERN and FAIR + their users**
- US milestone in future: 2012 Long range planning process for the Nuclear Physics community
- Staged realization of the project is under active consideration for the eRHIC: in fact, (some think) **the only way to realize this project**
- **RBRC is ideally poised to take on a new challenge:**
  - **Intellectual connection, location, timing and the present member's and leadership's involvement in both are ideally suited to make a decisive impact on the eRHIC project and hence on the world QCD frontier**
  - **Many in the Nuclear Physics community expect RBRC to be one of those who will lead the way**

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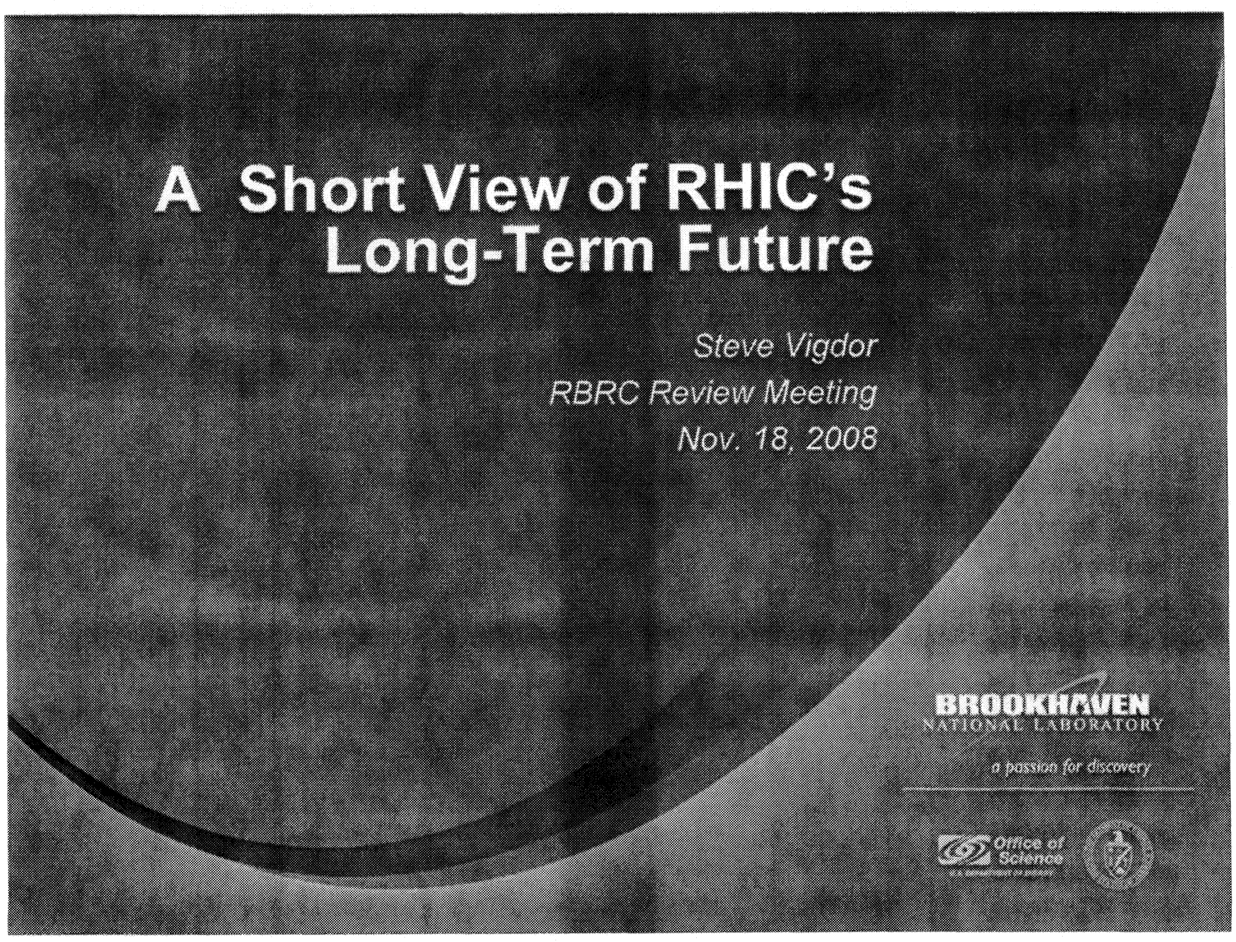
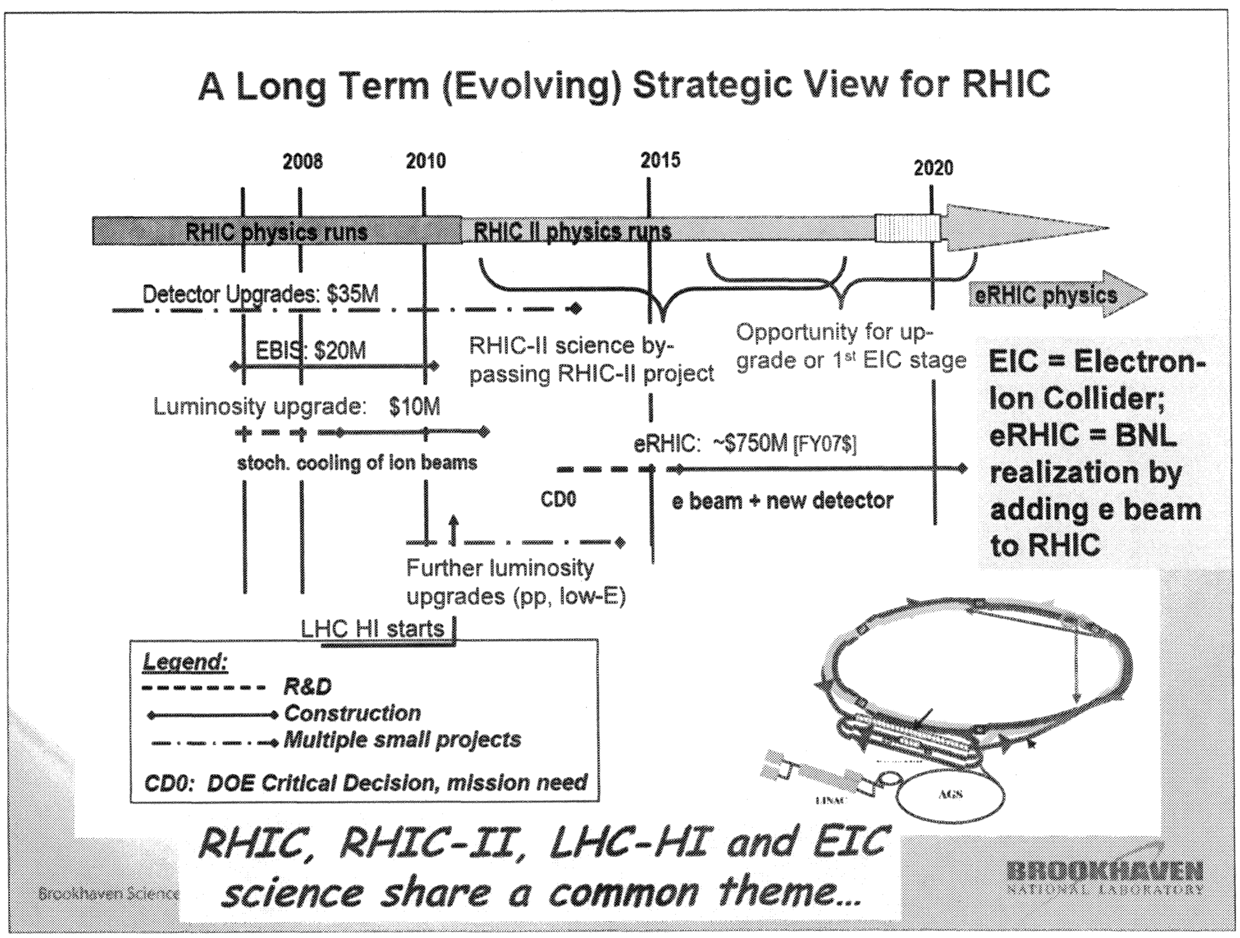

A Short View of RHIC's Long-Term Future
Steve Vigdor
RBRC Review Meeting
Nov. 18, 2008
BROOKHAVEN
NATIONAL LABORATORY
a passion for discovery
Office of Science


A Long Term (Evolving) Strategic View for RHIC
2008
2010
2015
2020
RHIC physics runs
RHIC II physics runs
eRHIC physics
Detector Upgrades: $35M
EBIS: $20M
RHIC-II science by-passing RHIC-II project
Opportunity for up-grade or 1st EIC stage
Luminosity upgrade: $10M
stoch. cooling of ion beams
eRHIC: ~$750M [FY07$]
CD0
e beam + new detector
Further luminosity upgrades (pp, low-E)
LHC HI starts
Legend:
R&D
Construction
Multiple small projects
CD0: DOE Critical Decision, mission need
EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC
LINAC
AGS
RHIC, RHIC-II, LHC-HI and EIC science share a common theme...
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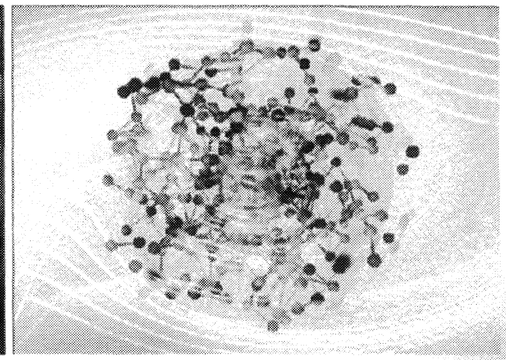
RHIC Science: Condensed Matter Physics with a Force of a Different Color



What are the unique quantum many-body manifestations of a *non-Abelian* gauge theory and self-interacting force carriers? Are there lessons for other fundamental theories, that are more difficult to subject to laboratory investigation? How do we pump/probe fleeting partonic matter in 10^{-23} s?

Apply to
new matter: *quantify properties of "near-perfect liquid" seen @ RHIC*
old matter: *determine partonic decomposition of p spin @ RHIC & eRHIC*
hot matter: *search for critical point in QCD phase diagram in RHIC E-scan*
cold matter: *expose & map intense force field (Color Glass Condensate) at heart of all ordinary matter, using eRHIC*

Making It All Happen, in 3 Acts...

I. Push time scale for RHIC-II science program earlier than Long Range Plan (~2017 start)

-- with stochastic cooling, luminosity upgrade by 2012; detector upgrades ongoing, all completed by ~2014

II. Formulate upgrade plan for ~2016-2021 period

-- possibilities on following slides: 1st stage EIC; AGS precision experiments

III. Make EIC science case and technical feasibility more compelling by next LRP (~2012-13?), for implementation in early 2020's

-- deepen (more transformational, less incremental) and broaden (add electroweak symmetry tests) science case; grow e-A experimental community; continue aggressive R&D program; consider staging strategies; work with JLab to move toward optimized design.

Act 1

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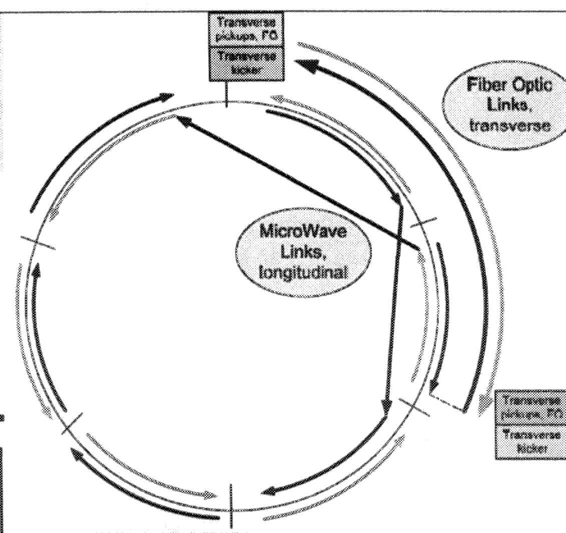
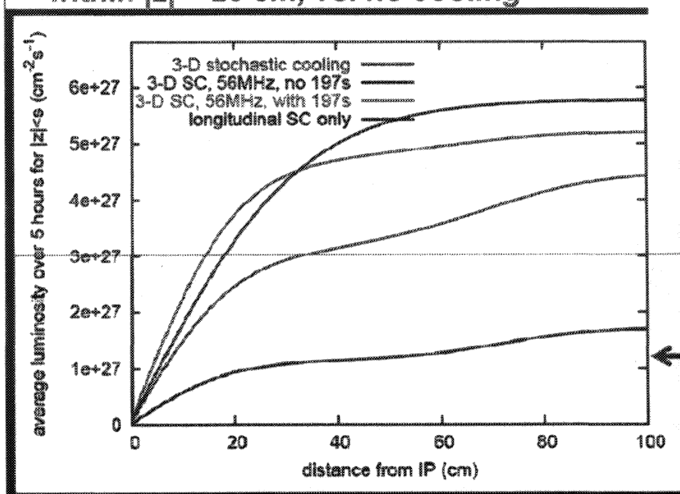
Stochastic Cooling Facilitates RHIC-II Science Without RHIC-II Project

- By 2012: 1 transverse cooling system per ring ⇒ rely on coupling between radial and vertical betatron tunes to transfer cooling to 2nd transverse plane
- Anticipate gain factor ~ 6-8 in ∫L dt within |z| < 20 cm, vs. no cooling





Achieved in Run-7

Yellow longitudinal stochastic cooling only.

Calculation by M. Blaskiewicz.

- 56 MHz SRF reduces leakage to neighboring rf beam buckets
- Combine 56 with present 197 MHz RF ⇒ tighten vertex distrib'n, as needed with short micro-vertex upgrades.

RHIC Spin Luminosity and Polarization Goals

Planned luminosity improvements:

- *reduce β^* from 1.0 to 0.5 m*
- *non-linear chromaticity correction*
- *mitigate 10 Hz quad triplet vibration*
- *transfer line and booster mods.*
- *near-integer working point*
- *9 MHz and 56 MHz RF upgrades*

Planned polarization improvements:

- *horizontal tune jumps in AGS*
- *improved orbit control in RHIC snakes*

Parameter	unit	Achieved	Luminosity upgrade
p↑- p↑ operation		(2006/08)	(~ 2012)
Energy	GeV	100	100 (250)
No of bunches	...	111	111
Bunch intensity	10^{11}	1.5	2.0
Ave. delivered lum.**	10^{30} cm^{-2}s^{-1}	23	80 (200)
Polarization	%	60	70

** without vertex cuts

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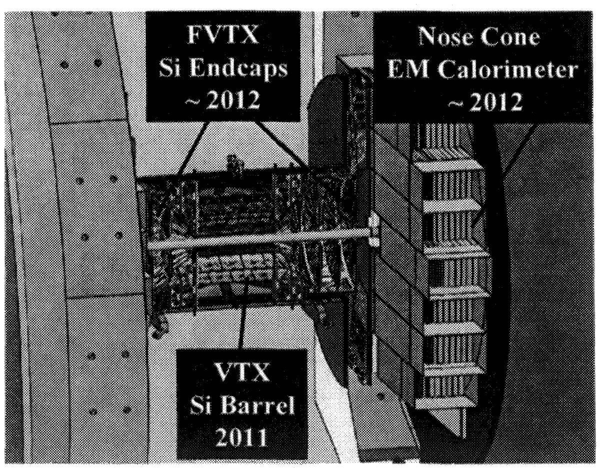
Ongoing Detector Upgrades are Critical to RHIC and RHIC-II Science Program

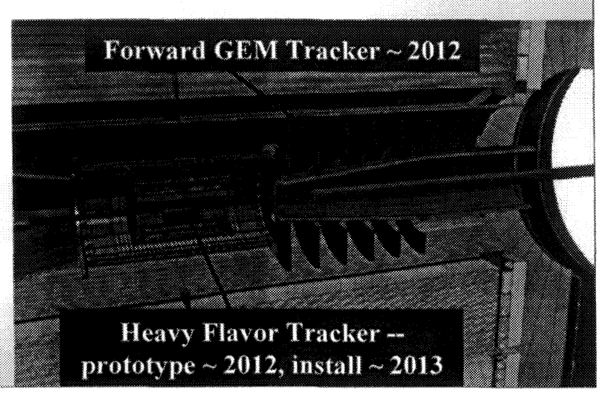


~1-2 new subsystems/year in PHENIX & STAR have immediate physics payoff: e.g., low-mass dileptons; CGC tests; W production triggering and cleanliness; heavy flavor physics; γ - jet acceptance ...

See Jacak, Xu, Ludlam and O'Brien talks for details.

Ongoing suite of upgrades should be completed ~2013-14.

Closer BNL supervision & consulting on project management issues needed to smooth recent glitches (see O'Brien).



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Tentative RHIC Run Plan Following 2008 PAC Recommendations
(assumes 6-month FY09 CR, 2-species runs in FY10-14 & best info on detector upgrade schedules)

Fiscal Year	Colliding Beam Species/Energy	Comments
2009	500 GeV p+p	Assuming ~April 1 start, about 5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet RIKEN milestone
2010	200 GeV p+p	~12 physics weeks to complete 200 GeV A_{LL} measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009; STAR DAQ1000 fully operational
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st collision test of transverse stochastic cooling (one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production
	200 GeV Au+Au or 2nd low-E scan	To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling.
	200 GeV p+p	Address 2015 DOE performance milestone on transverse SSA for γ-jet; reference data with new detector subsystems; test e-lenses for p+p beam-beam tune spread reduction

Run Plan, Detector & Luminosity Upgrades Address All New RHIC-Related Performance Milestones

Year	#	Milestone
2013	HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12 (update of HP1)	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
2014	DM9 (new)	Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.
2014	DM10 (new)	Measure jet and photon production and their correlations in A≈200 ion+ion collisions at energies from medium RHIC energies to the highest achievable energies at LHC.
2015	DM11 (new)	Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at √sNN between 5 and 60 GeV to search for evidence of a critical point in the QCD matter phase diagram.
2016	DM12 (new)	Measure production rates, high pT spectra, and correlations in heavy-ion collisions at √sNN = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.
2018	DM13 (new)	Measure real and virtual thermal photon production in p + p, d + Au and Au + Au collisions at energies up to √sNN = 200 GeV.

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N.B. Some will be missed if budgets do not permit 2 species/year runs in FY10-14

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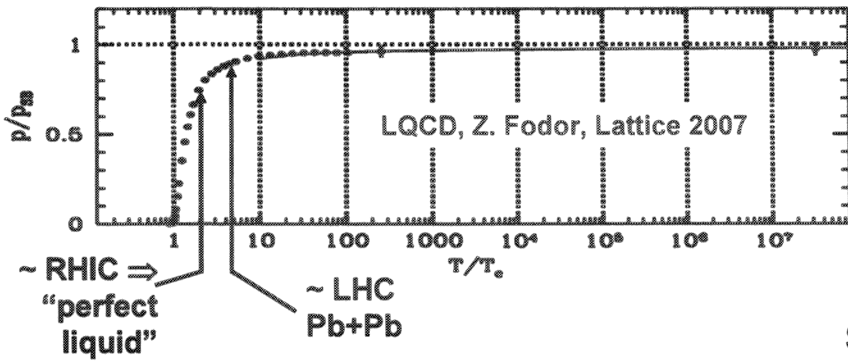
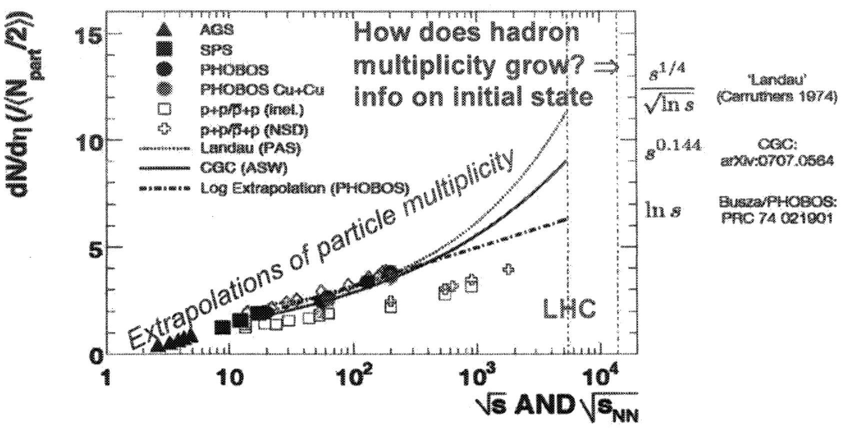
Where Do Heavy-Ion Collisions at LHC Fit In?



← Ideal gas

Does matter still behave as an ideal liquid, or does shear viscosity grow from RHIC?



Some pump/probe tools get sharper at LHC -- *e.g., full jet reconstruction/ resolution* -- but effects of interest *(parton E loss)* may be small or vanishing perturbations: *LHC is exploratory.*

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Take-Away Message #1

- We are developing detailed strategic planning to optimize the impact of RHIC results during period when LHC HI starts. RHIC's versatility, creative accelerator physicists, aggressive detector upgrade plans are critical to the success of this plan, as are budgets sufficient to run two beam species per year.
- RHIC will focus on systematic measurements to enhance understanding and discovery potential: quantifying properties of perfect liquid; searching for manifestations of QCD vacuum transformation; searching for QCD critical point; improving constraints on polarization of gluons and sea antiquarks in a polarized proton.
- The plan accommodates a 6-month CR in FY09, but would be impacted by a much longer CR.
- RHIC-II science continues well beyond 6-year run plan shown, fueled by further possible luminosity improvements from stochastic cooling upgrades (HI) and electron lenses (pp).

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Act 3

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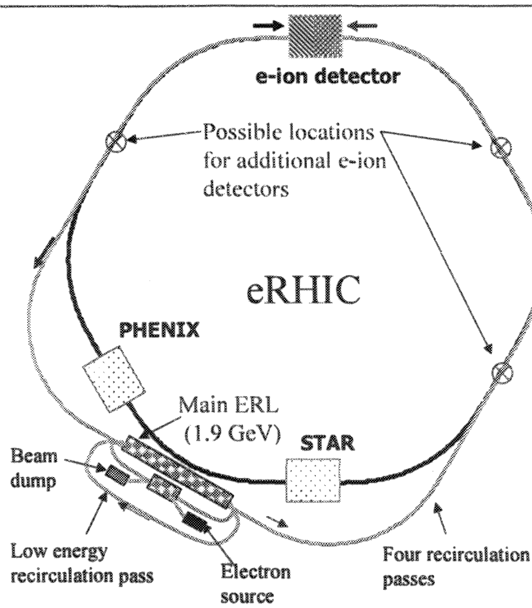

Long-Term (>2020) Future of RHIC Physics: EIC → eRHIC

Add ERL injector with polarized e^- source to enable $\vec{e}+\vec{p}$, $^3\vec{He}$ and e+A (up to Uranium) to study matter in gluon-dominated regime

- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 in RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) permit multiple detectors;
- 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 $\vec{e}^+$ source
- R&D already under way on various accelerator issues; more to come.

- ***Subsequent stages/ alternative layouts could increase e-beam & ion-beam energies and L from nominal 10 × 250 GeV, ~3 × 10^{33} $cm^{-2}s^{-1}$ $\vec{e}+\vec{p}$***

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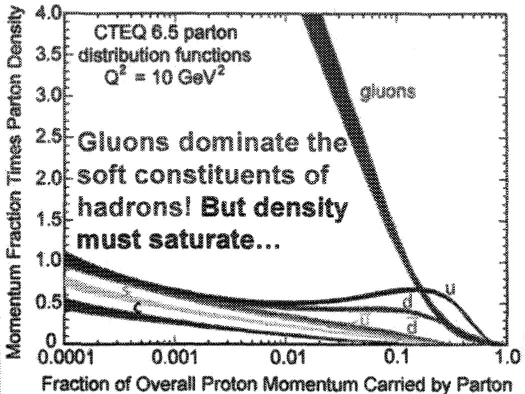
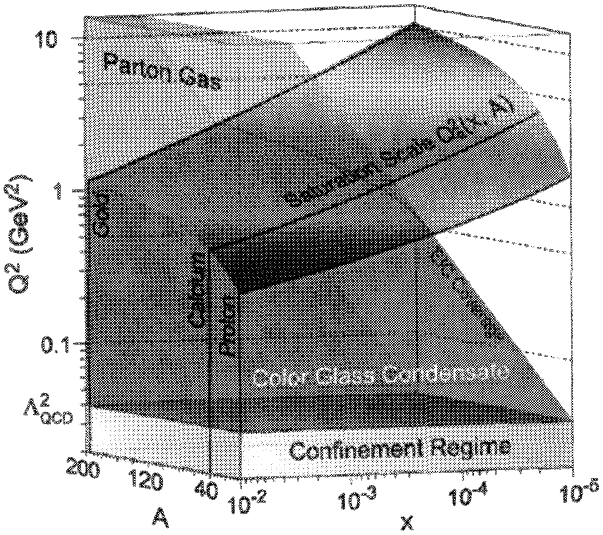
EIC Science: Study of Force (Gluon)-Dominated Matter

Search for supersymmetry @ LHC, ILC (?): ***seeking to unify matter and forces***

Electron-Ion Collider: ***reveal that Nature blurs the distinction***

Deep inelastic scattering @ HERA ⇒





EIC probes *weak* coupling regime of very high gluon density, where gauge boson occupancy >> 1. *All ordinary matter has at its heart an intense, semi-classical force field* -- can we demonstrate its universal behavior?

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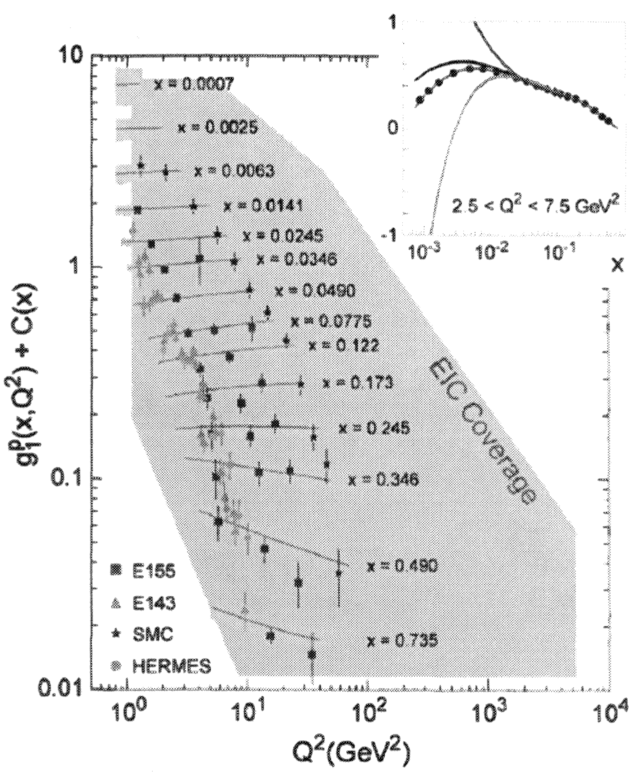
Polarized $\vec{e} + \vec{N}$ at EIC



- ***Polarized DIS, γ-gluon fusion to determine gluon polarization down to x ~ few × 10^{-4}***
- ***Bjorken sum rule test to ≲ 2% precision***
- ***SIDIS for low-x sea-quark polarization and transverse spin studies***

More luminosity-hungry:

- ***Polarized DVCS, exclusive reactions + LQCD ⇒ GPD's ⇒ map low-x transverse position-dep. PDF's; J_q from Ji sum rule***
- ***Parity violation in $\vec{e}$+p,d at high Q^2 to study running of weak coupling below Z-pole***

Note INT workshops on EIC science, Fall '09 and '10.

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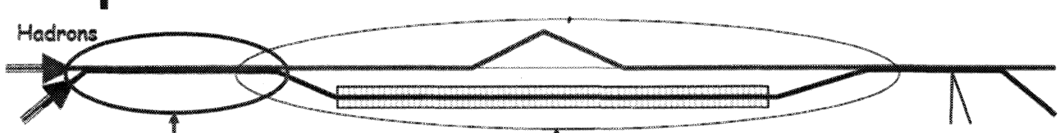
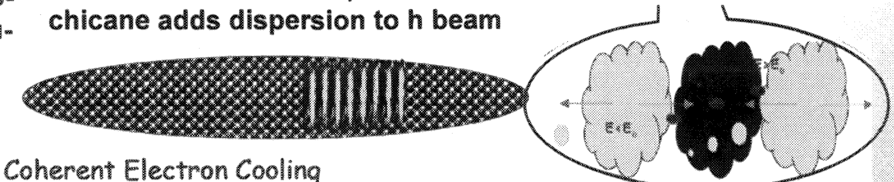
Further Development of Luminosity Improvements: Coherent Electron Cooling



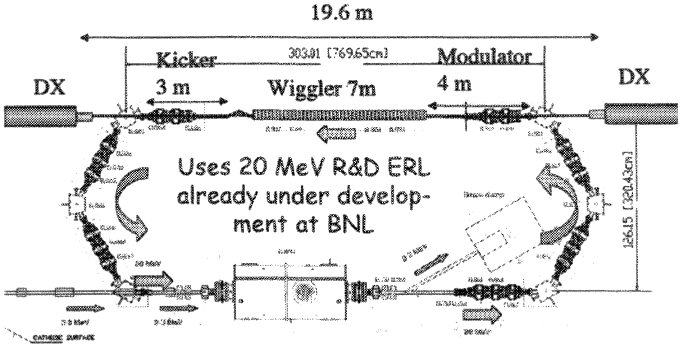
Modulator: hadron beam structure introduces density modulation in e-beam

Wiggler: FEL amplification (x $10^{2\text{-}3}$) of e-beam modulations, while chicane adds dispersion to h beam

Kicker: attraction to e-beam density peak reduces ion-beam E spread.



IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



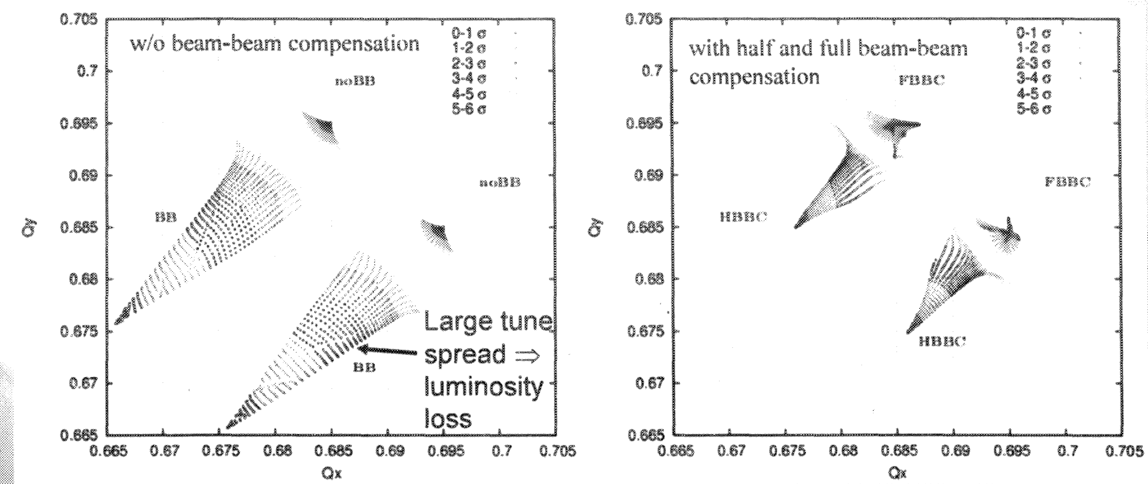
CeC of high-energy hadron beams: high-gain FEL based on high-brightness ERL (V. Litvinenko & Y. Derbenev) $\Rightarrow$ boost LHC and EIC luminosities?

Plan proof-of-principle test @ RHIC by 2014 with Au beam.

Does not address beam-beam limit on RHIC p+p luminosity.

Further p Beam Improvements Under Development: Electron Lenses

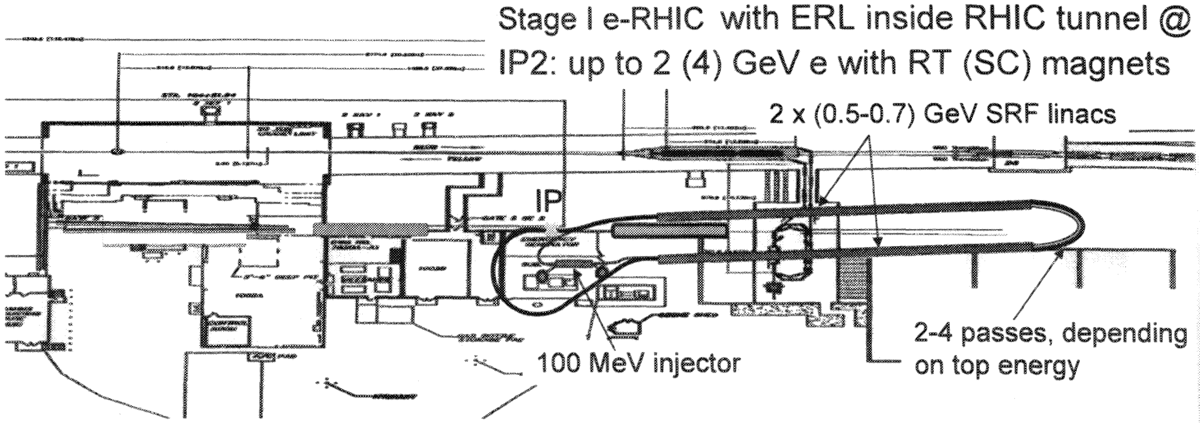
- p-p luminosity limited by head-on beam-beam tune spread
- Low energy (~5 keV) e^- beam interacting with proton beam can compensate head-on beam-beam tune spread (× 2 luminosity?)
- Single and multi-particle simulation underway
- Possible implementation in RHIC by 2014



See T. Roser talk, 10/11/08.

Intermediate-Term Possibilities: 1st (Medium Energy) Stage of EIC?

Stage I e-RHIC with ERL inside RHIC tunnel @ IP2: up to 2 (4) GeV e with RT (SC) magnets



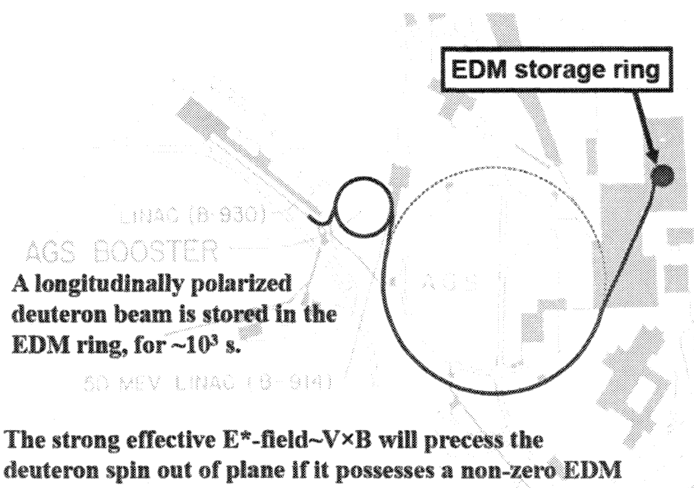
- ***Would enable few GeV $\vec{e}^-$ on 100 GeV/N heavy ions and 250 GeV $\vec{p}$***
- ***First look at saturation surface for nuclei in e+A DIS, confirmation of nuclear "oomph" factor; e+A diffraction tests of high gluon occupancy***
- ***$\vec{e}$-$\vec{p}$ program emphasizing transverse-spin SIDIS over broad Q^2-range ⇒ TMD evolution; detection of boosted target fragments to probe spin-dependent correlations, intrinsic heavy flavor in nucleon; extend $\overrightarrow{DIS}$.***
- ***Need to develop science case, detector design, cost estimate.***
- ***Most equipment would be reused later in full EIC***

ME-EIC parameters for e-p collisions (2 GeV option, 50 mA polarized e source, maintaining pp, pA, AA collisions at RHIC detectors)

	not cooled		pre-cooled		high energy cooling	
	p	e	p	e	p	e
Energy, GeV	**250**	**2**	**250**	**2**	**250**	**2**
Number of bunches	**111**		**111**		**111**	
Bunch intensity, 10^{11}	**2.0**	**0.31**	**2.0**	**0.31**	**2.0**	**0.31**
Bunch charge, nC	**32**	**5**	**32**	**5**	**32**	**5**
Normalized emittance, 1e-6 m, 95% for p / rms for e	**15**	**37**	**6**	**14.7**	**1.5**	**3.7**
rms emittance, nm	**9.4**	**9.4**	**3.8**	**3.8**	**0.94**	**0.94**
beta*, cm	**50**	**50**	**50**	**50**	**50**	**50**
rms bunch length, cm	**40**	**1**	**40**	**1**	**40**	**1**
beam-beam for p /disruption for e	**1.5e-3**	**12**	**3.8e-3**	**31**	**0.015**	**120**
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	0.93		2.3		9.3	

Also a test-bed for high-energy coherent e-cooling to prepare for full EIC.

Novel Storage Ring EDM Exp'ts @ AGS ?



- ***Inject longitudinally pol'd $\vec{p}$ or $\vec{d}$ beam, via AGS, into dedicated storage ring***
- ***Choose magic momentum + static $\vec{E}$, $\vec{B}$ combination (B=0 for protons) to ~cancel (g-2) horizontal spin precession***
- ***Search for EDM signature of vertical polarization build-up due to precession in strong $\vec{E}$-field (static for p, $\vec{v} \times \vec{B}$ for d)***
- ***Cancel many systematic errors by measuring for counter-rotating (vertically separated) beams simultaneously.***
- ***Sensitivity goal ~ few $\times 10^{-29}$ e·cm for p, ~ 10^{-29} e·cm for d***
- ***If EDM $\neq 0$ observed for n, p and/or d, the combination powerfully constrains the source. E.g., the three systems have quite different sensitivities to θ_{QCD} vs. SUSY (latter strongly enhanced in d).***

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See Y. Semertzidis talk, 10/07/08.

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Summary

1) There is a detailed, coherent plan for RHIC operations & science through ~2015, but it needs more stable budgets to achieve. This will keep RHIC at forefront during LHC HI launch.

2) Accelerator planning for intermediate- and long-term future options is proceeding rapidly, aided by creative ideas about hadron beam cooling that can be tested at RHIC.

3) The science case and user community for eRHIC and for a possible first medium-energy stage of eRHIC need further development by the time of the next LRP in 2012-13.

4) There are many options for continued mutually beneficial collaboration between RIKEN and BNL in planning and carrying out the long-term science program and in interpreting the results.

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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.

Rainer Fries: **Birthplace**: Regensburg, Germany **DOB**: Aug.10, 1971
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

Yoshinori Fukao **Birthplace**: Aichi, Japan **DOB**: April 5, 1978

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.

Yuji Goto **Birthplace**: Shizuoka, Japan **DOB**: November 25, 1965

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.

Masatoshi, Hamada **Birthplace**: Kiryu, Japan **DOB:** July 09, 1982

Ph.D. Now Student, Kyushu Univ., Fukuoka, Japan
Undergraduate: 31/March/2005, Kyushu Univ., Fukuoka, Japan
Master: 31/March/2007, Kyushu Univ., Fukuoka, Japan

Award and Honors:

None

Tomomi Ishikawa **Birthplace**: Tottori, Japan **DOB**: December 25, 1971

Ph.D. 2002, Hiroshima University, Japan

Experience: Researcher, Hiroshima University, April 2002 to March 2003;
Institute Researcher, University of Tsukuba, Center for Computational Sciences,
April 2003 - September 2006;
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.

Cecilia Lunardini **Birthplace**: Piacenza, Italy **DOB**: March 27, 1974
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: January 2003: Prize "Giorgio Gamberini" issued by Scuola Normale in Pisa (Italy) for a PhD thesis in Theoretical Physics.
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.

Cyrille Marquet **Birthplace**: Boulogne-Billancourt, France **DOB**: September 23, 1980
Ph.D. 2006, University of Paris VI, France
Experience: Research Associate, RIKEN BNL Research Center (Theory)

October 2, 2006 - present

Dénes Molnár **Birthplace**: Debrecen, Hungary **DOB**: June 24, 1974
Ph.D. 2002, Columbia University, New York
Experience: Postdoctoral Fellow, Nuclear Theory Group, The Ohio State University, Columbus, 2002-2003;
Postdoctoral Researcher, Nuclear Theory Group, The Ohio State University, 2003-2005;
•RHIC Physics Fellow, RBRC Theory Group/Assistant Professor, Purdue University, West Lafayette, IN, September 2005 to present
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;
RIKEN SPIN Program Researcher, RBRC Experimental Group, December 2004 - present.
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.

Kensuke Okada **Birthplace**: Japan **DOB**: November 20, 1970
Ph.D. 2001, Nagoya University
Experience: Contract Researcher at RIKEN, Wako, Japan, June 2001-March 31, 2002
Research Associate, RIKEN BNL Research Center (Experiment),
April 1, 2003 – March 31, 2006;
RIKEN Fellow, RIKEN BNL Research Center (Experiment),
April 1, 2006 - present.

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:

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
Senior Research Scientist, RIKEN, 1999- present
RIKEN Spin Program Researcher, April 1, 2001 – present.

Derek Teaney **Birthplace**: New York, NY **DOB**: Sept. 26, 1972
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;
•RHIC Physics Fellow, RBRC Theory Group/Assistant Professor, Iowa State University, Ames

Awards and Honors: Prize for research achievements from the School of Physics and Astronomy, Tel Aviv University, 2000.

Yasushi Watanabe **Birthplace**: Tokyo, Japan **DOB**: February 12, 1961
Ph.D. 1993, University of Tokyo, Japan
Experience: Scientific Researcher, RIKEN, 1991
Research Collaborator, PHENIX/RBRC
Scientific Researcher, RIKEN, RBRC, 1998-2001
RIKEN Spin Program Researcher, April 1, 2001 – present

Satoshi Yokkaichi **Birthplace**: Iwamizawa, Hokkaido, Japan **DOB**: Dec. 10, 1966
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
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