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
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Preface to the Series

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

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~50 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

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

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

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

N. P. Samios, Director
March 2008

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.
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Fragmentation Functions from Belle
Ralf Seidl

Drell-Yan measurement with polarized proton beams
Yuji Goto

RHIC Data Analysis at CCJ
Yasushi Watanabe

Theory Presentations

QCD thermodynamics on the lattice
Peter Petreczky

The quark and gluon propagators at finite temperature
Masatoshi Hamada

Nucleon Structure on the Lattice
Shigemi Ohta

Study of eta' meson using domain-wall QCD
Taku Izubuchi

Improved Non-perturbative Renormalization
Yasumichi Aoki

Dynamical QCD+QED lattice simulations
Thomas Blum

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

Drell-Yan Lepton Pair Azimuthal Correlation: Lam-Tung Relation Revisited
Feng Yuan

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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)
Gyulassy, Miklos
Masaike, Akira
Milner, Richard
Mueller, Alfred
Ukawa, Akira

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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
Itaru Nakagawa
Measurement via W-Boson
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
Kieran Boyle
Asymmetry in Neutral Pion Production
11:30 The Double Longitudinal Spin Asymmetry in Unidentified
Dave Kawai
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 (Large Seminar Room)
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 (Large Seminar Room)
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

Tuesday, November 18, 2008

8:00 AM to 9:00 AM
SRC Executive Session (Room 2-160)
INTRODUCTORY TALKS (Large Seminar Room)
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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Scientific Review Committee for RIKEN BNL Research Center (RBRC-SRC)

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

Organization of RIKEN Nishina Center
(established on April 1 2006)
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."

[Diagram showing organizational structure]
RIKEN Review System and Schedule

RIKEN Advisory Council (RAC)
Report: April 22-25, 2009 (twice in 5 years)

Nishina Center Advisory Council (NCAC)
Report: January 15-17, 2009

RBRC-SRC
Review: Nov. 17-18, 2008

RRMF-AC
Review: Nov. 4-5, 2008

RBRC
RRMF
RIBF and other activities

Nishina Center Advisory Council
January 15-17, 2009

Name

Sydney Gales (Chair)
Shoji Nagamiya
Walter F. Henning
Robert Kiefl
Wit Busza
Andrew Taylor
Angela Bracco
Makoto Inoue
Alexey Korsheninnikov
Karlheinz Langanke
Hideyuki Sakai
WenQing Shen
Bradley Sherrill
Hiroshi Toki

Affiliation

GANIL
KEK, J-PARC Center
ANL (Chair NP-PAC)
University of British Columbia (Chair ML-PAC)
MIT (Chair RBRC-SRC)
ISIS, RAL (Chair RRMF-AC)
University of Milan
Kyoto University (Prof. Emeritus)
Kurchatov Institute
GSI
the University of Tokyo
SINAP, Chinese Academy of Science
NSCL, Michigan State University
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. Poulissou (TRIUMF)  
Y. Yano (RIKEN)  
A. Taylor (Chairperson, ISIS)  
E. Torikai (Yamanashi Univ.)  
J. Yamazato (KEK)
RIKEN Nishina Center (FY2008)

Budget
RIBF: 2,921M JY (including 1,149M JY for electricity)
RAL: 195M JY
BNL: 735M JY

Total: 3,851M JY
(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.
Schedule of RNC-AC, revision of the agreement with BNL, RAL

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<td>NCAC</td>
<td>Jan 15, 17</td>
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<tr>
<td>RAC</td>
<td>Apr 22, 24</td>
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Agreement Revision

- Valid for 5 years from Apr 30, 2007
- Extendable based on AC evaluation

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?
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.
About Dr. Yoshio Nishina

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)

Old Campus

2nd 50cm cyclotron
Magnet diameter 150cm
The first cyclotron in Japan

3rd cyclotron
Magnet diameter 65cm

The Japan first
Heavy Ion Accelerator
(1967 ~ 1990)

New Campus

4th 160cm cyclotron
Magnet diameter 210cm
RI Beam Factory
(newly operational in March 2007)

World's most intense exotic RI beam
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

On Nov. 7 2005 full excitation of sector magnets achieved. A 140-ton cold mass cooled down to 4.5 K for 3 weeks.
"Science": Dec. 2006

"Nature": Dec. 2006

Japan speeds up nuclear physics

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

- Discovery of Halo Nucleus
  - Discovery of high Tc Superconductivity
    - Nobel Prize
  - Halo Nucleus

- 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]. The paradigms of modern nuclear physics so that the former becomes the inevitable
REFERENCES


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?
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.
New cultivar created by ion beam irradiation

RIKEN-Battelle Collaboration Contract Oct. 30 2008
RBRC Scientific Review  
Committee Meeting

RBRC Overview

Nicholas P. Samios

Nov. 17, 2008

Brookhaven National Laboratory

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<th>RBRC</th>
<th>Major Physics Interests</th>
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<td>Spin Structure of the Proton</td>
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<td>High Energy Density Matter</td>
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<td>sQGP</td>
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<td>Color Glass Condensate</td>
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<td>Glasma</td>
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<td>Critical Point</td>
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<td>RHIC</td>
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<td>Lattice Gauge Calculations</td>
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<td>QCDOC (&gt;95% Efficiency)</td>
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</tbody>
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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$^{-1}$ ($\sim 10 \times$ Run 3)

Polarized pp 100 GeV $\times$ 100 GeV
20 pb$^{-1}$ ($\sim 3 \times$ Run 6)

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

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

$^{\nabla}$ 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
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 $250 \times 250$ GeV protons.

Anti-quark distributions

Achieved $\sim 50\%$ polarization
In Blue Ring

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

Collisions recorded in STAR Time Projection Chamber

Excellent Particle Identification

Analysis based on $\sim 3000$ good events collected at $\sim 0.7$ 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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
</table>

Test of Polarized Proton Acceleration to 250 GeV

45 % polarization on first acceleration to 250 GeV!

Loss at strong intrinsic resonance (136 GeV); correctable by adjusting betatron tunes.
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)

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Colliding Beam Species/Energy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>200 GeV p+p</td>
<td>~12 physics weeks to complete 200 GeV Au, measurements - could be swapped with 500 GeV Run 10 if &gt;6-month FY09 CR likely; STAR DAQ1000 fully operational</td>
</tr>
<tr>
<td>2010</td>
<td>500 GeV p+p</td>
<td>~5-6 physics weeks to commission collisions, work on polarization &amp; luminosity and obtain first W production signal to meet 2011 RIKEN milestone</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>9-10 physics weeks with PHENIX HBD, STAR DAQ1000 &amp; TOF permits low-mass dilepton response map and 1st Hi collision test of transverse stochastic cooling (one ring)</td>
</tr>
<tr>
<td>2011</td>
<td>Au+Au at assorted low E</td>
<td>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)</td>
</tr>
<tr>
<td></td>
<td>200 GeV U+U</td>
<td>1st U+U run with EBIS, to increase energy density coverage</td>
</tr>
<tr>
<td>2012</td>
<td>500 GeV p+p</td>
<td>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 AG measurements</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-H1 goal: heavy flavor, γ jet, quarkonium, multi-particle correlations</td>
</tr>
<tr>
<td>2013</td>
<td>500 GeV p+p</td>
<td>Reach ~300 pb^-1 to address 2013 DOE performance milestone on W production</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au or 2nd low-E scan</td>
<td>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</td>
</tr>
<tr>
<td>2014</td>
<td>200 GeV Au+Au or 2nd low-E scan</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>200 GeV p+p</td>
<td>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</td>
</tr>
</tbody>
</table>

RBRC Organization

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

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

Experimental Advisory Committee
A. Masahiko
K. Imai
Y. Makdisi

QCDQC Advisory Committee
M. Creutz (Chair)
R. Pisarski
S. Aoki
### Theory Fellows
- Aoki, S.
- Blum
- Fries
- Molner
- Tuchin

### Experimental Fellows
- Deshpande
- Kawai
- Okada

<table>
<thead>
<tr>
<th>Year</th>
<th>US Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>'07</td>
<td>Tsukuba</td>
</tr>
<tr>
<td>'08</td>
<td>U. of Conn.</td>
</tr>
<tr>
<td>'07</td>
<td>Texas A&amp;M</td>
</tr>
<tr>
<td>'08</td>
<td>Purdue U.</td>
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<tr>
<td>'07</td>
<td>U. of Iowa</td>
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<tr>
<td>'08</td>
<td>LBNL</td>
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<tr>
<td>'08</td>
<td>Arizona State</td>
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<td>'08</td>
<td>SUNY</td>
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<td>'08</td>
<td>CUNY</td>
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<td>BNL</td>
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<tr>
<td>'08</td>
<td>Penn State</td>
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<tr>
<td>'08</td>
<td>BNL/Columbia</td>
</tr>
<tr>
<td>'08</td>
<td>BNL</td>
</tr>
<tr>
<td>'08</td>
<td>BNL</td>
</tr>
</tbody>
</table>

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### Major Conference Participation

**Quark Matter 2008**

Jaipur, India, Feb. 4-10, 2008

Dominated by RHIC Physics

**Plenary**
- K. Fukushima
- T. Hatsuda
- L. Mc Lerran
- E. Shuryak
- R. Venugopalan

**Parallel**
- T. Hirano
- K. Itakura
- D. Kharzeev
- C. Marquet
- A. Mocsy
- D. Molnar
- Y. Nara
- P. Petreczky

**Panic 08**

Elat, Israel, Nov. 9-14, 2008

**Plenary**
- S. Aoki
- T. Hatsuda
- D. Kharzeev
- D. Son
- W. Vogelsang

**Parallel**
- A. Basilevsky
- A. Deshpande
- Y. Hidaka
- K. Imai
- 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 $\rightarrow$ 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.

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 $x \lesssim 10^{-2}$

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)
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

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
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

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!
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

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
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

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)
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

University Fellow
D. Kawai A. Deshpande K. Okada

Fellow
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)

Group Leader
Y. Akiba

Deputy GL
A. Deshpande

University Fellow
D. Kawai

Fellow
K. Okada
R. Seidl
S. Bathe

PostDoc
K. Boyle
M. Togawa

RBRC deputy director
RIKEN Chief Scientist
H. En'yo

RIKEN/RBRC @ BNL
Y. Goto
I. Nakagawa

• 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 leaders

Large role in PHENIX operations and data analysis
Local Polarimeter RICH
EMCal Muon arms
RICH-EMCAL trigger
Exp Group Activities

• Spin Physics: study of spin structure of proton
  RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX
  - $\Delta G$ measurement $A_{LL}$ of $\pi^0$, $\pi^\pm$, direct $\gamma$, charm, etc...
  - Spin of sea quark $W$ measurement at 500 GeV
  - Fragmentation Function at Belle $\rightarrow$ 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 $DG(x)$
  - $\pi^0 A_{LL}$ K. Boyle, Y. Fukao, A. Deshpande
  - $\pi^\pm A_{LL}$ D. Kavall, A. Dutta
  - Cluster (Jet) $A_{LL}$ K. Nakano, Y. Goto, YA
  - Direct $\gamma A_{LL}$ R. Bennett, K. Okada

• Transverse Spin
  - Forward $n A_N$ M. Togawa
  - Charm $A_N$ S. Dairaku, YA

• Fragmentation Function
  R. Seidl, K. Boyle
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.

Heavy Ion and p+p (unpolarized)

- Study of sQGP formed 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)
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

- ~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 postdocs 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
RBRC Overview
Heavy Ion and Upgrades

Y. Akiba

RBRC SRC review
2008/11/17

Exp Group Presentations

Y.A. "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 Triggar FEE Upgrades for Sea Quark Polarization Measurement via W-Boson"
Atsushi Takekani "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

- Spin Physics: study of spin structure of proton
  RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX
  - $\Delta G$ measurement $A_{LL}$ of $\pi^0$, $\pi^\pm$, direct $\gamma$, charm, etc...
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  - 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

- 4 (3) papers in review, including RUN8 $\Delta G$ paper
Recent PHENIX HI publications with RBRC/RIKEN contributions

- **J/ψ in Cu+Cu**
  - PRL101,122301
- **J/ψ in d+Au**
  - PRC77,024912
- **π⁰ R_A in Au+Au**
  - PRL accepted
  - arXiv:0801.4020

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

---

Hot results: low p_T direct photon

- 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 \( T \sim 220\text{MeV} \)
- Thermal photons from hydrodynamical models with \( T_{\text{ini}}=300 - 600\text{MeV} \) at \( \tau_0=0.6-0.15\text{fm/c} \)
  - are qualitative agreement with the data
PHENIX Upgrade (1) muTRIG

- $W \to \mu$ measurement 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 $4\pi$ 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/$\psi$ 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

Compton

—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.

\[(\text{signal}) = (\text{all photons}) - (\text{background photons})\]

\[(\text{isolated signal}) = (\text{all isolated photons}) - (\text{background isolated photons})\]

Cross section measurement

PHENIX Preliminary

\[\text{NLO pQCD} \quad \text{(by W. Vogelsang)} \]
CTEQ6M PDF
\[\mu = 1/2p_T, p_T, 2p_T\]

Run5pp
Consistent to
Run3 final
PRL98,012002(2007)

\[\text{p+p 200 GeV} \quad \text{Good agreement with pQCD}\]

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.

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

The isospin effect should appear at lower $p_T$. We are free from the experimental issues (cosmic ray event, $\pi^0$ photon merging.)

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 Sebastian Parmentier and Astrid Mermozi
The polarized PDF

Direct photon
It’s sensitive to the sign of $\Delta G$

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

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 π0/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.
Introduction

- 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
Hard Scattering Results in PHENIX

Most cited paper from RHIC
465 citations to date

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


EMCal Calibration Run-7

- 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

High $p_T \pi^0$ And Direct Photons Run7

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


High $p_T \pi^0$ . . . Outlook

- 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

The ATLAS Detector

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

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

Why Jets, $\gamma$-Jet?

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

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

$\sqrt{s_{NN}} = 200$ GeV

Jets in Heavy Ion Collisions

Challenge: background

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

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

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

\( \rightarrow E = 300 \) 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!


Jets at the LHC

Jet measurement in HI at LHC feasible, but still challenging

Key: beam fluctuations

jet cross section increases by orders of magnitude

soft background increases by \( \sim \) factor 2

Lateral Segmentation

Measurement of medium induced and fragmentation photons

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


Summary

- 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 $\gamma$-jet

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

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

$sqrt(s)=500$ GeV @ RHIC

Parity Violation Asymmetry
Clean flavor separation
w/o fragmentation uncertainty
Expected precision for $W \rightarrow \mu$ 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 acc. to smearing matrix in finer binning and unpolarized yields separately)

---

Current Muon System

- **Muon Tracking Chambers**
  - 3 stations of Cathode strip chambers
  - 3 gaps + 3 gaps + 2 gaps
  - Each gap has non-stereo-plane, stereo-plane, and anode plane

- **Muon Identifier**
  - 5 layers of larnocci tubes in x and y directions
  - 80 cm of steel plate absorber (total)
  - Provides trigger
Rejection Power: Approach

Inclusive $\mu$ Momentum Distribution

$P_T$-Trigger

Inclusive $\mu$ Production, 500 GeV/c

W

Trigger Does The Job

How New Trigger Works?

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

(I) RPC
(Resistive Plate Chambers)
NSF (Funded)

(II) MuTr FEE Upgrade
JSPS (Funded)

Combined Trigger Rejection ~12,000

RPC Collaboration

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K. Barish and R. Seto
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S. Hu, X. Li, F. Zhou and S. Zhou
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University of Colorado, Boulder

C.Y. Chi, W. Sippach and W. Zajc
Columbia University and Nevis Laboratory, New York

C. Butler, K. Dayana, X. He, C. Oakley and J. Ying
Georgia State University, Atlanta

J. Blackburn, M. Grosse Perdekamp, C. Lee, Y.-J. Kim, B. Meredith, T. Natori, N. Mucia,
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Y. Mao and R. Han
Peking University, Beijing, China

G. Bunce and R. Seidl
RIKEN BNL Research Center
General Ideas for using RPCs

Operation requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency &gt; 95%</td>
<td>RPCs have responses within ns</td>
</tr>
<tr>
<td>Time resolution ≤ 3 ns</td>
<td>Pseudo-radial readout</td>
</tr>
<tr>
<td>Average cluster size ≤ 2 strips</td>
<td>segmentation at different planes</td>
</tr>
<tr>
<td>Rate capability 0.5 kHz/cm²</td>
<td>around muon magnets</td>
</tr>
<tr>
<td>Number of streamers &lt; 10 %</td>
<td>Bakelite RPCs are relatively cheap, large plates available</td>
</tr>
<tr>
<td></td>
<td>Gaps still very thin</td>
</tr>
</tbody>
</table>

Use already established CMS Bakelite RPC technology and expertise

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
MuTrig-FEE Collaboration

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

1. Minimum deterioration to existing MuTR performance
2. High/reliable triggering efficiency

Bottom Line

To trigger
Logic

0.05Q

0.95Q

Existing FEE

Existing FEE

0.05Q

MuTr-AD Board

Parallel Output

Serial Output

with Optical Fiber

D/A Control

Power

Q

MuTr Chamber

ADC

12
Summary

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

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>MuTrig-FEE</td>
<td>Run09</td>
<td>Run10</td>
</tr>
<tr>
<td>RPC</td>
<td>Run10</td>
<td>Run11</td>
</tr>
</tbody>
</table>

Upgrade Projects are on schedule for comming exciting physics!
Backup Slides

However, not yet the end of story...
Backgrounds

1. Low PT $\pi, K$ Decay in Flight

2. Hi $P_T \pi, K$ punch through

Primary:
- Tracker Alignment
- Absorber
- EM Calorimeter
- Etc..

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)

$\Rightarrow$ Signal to background can be increased to 3/1
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 $\rightarrow$ 10cm $\rightarrow$ )
- Other backgrounds (small contributions):
  - Real high $P_T$ muons from hadron decays
  - Cosmic muons
  - Z-decays

Efficiencies using tight cuts as a function of $P_T$ and rapidity $\eta$

$W \rightarrow \mu$ 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
Absolute efficiencies 2d

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

Optimized cuts nearly 40% efficient everywhere
Raw RHICBOS
After efficiency and standard cuts. After smearing.
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)
  - CLAE, China
  - RPC module frame and readout strip plane (CLAE has access to CMS & one readout strip vendor)
  - 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
  - PHENIX, BNL, US
  - RPC group:
    - Installation (help from PHEXINX 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

FERMILAB test beam 2008

Proposal for a Silicon Vertex Tracker (VTX) for the PHENIX Experiment
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Brookhaven National Laboratory, Instrumentation Division, Upton, NY 11973-5000, USA
J.S. Haggerty, J.T. Mitchell, C.L. Woody
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As of May 2006 Proposal to DOE, 92 authors from 20 institutions

RIKEN VTX group as of 2008 Nov.

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Pixel Subsystem Manager: A. Taketani

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

Technician: J. Kanaya

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

KEK: M. Sekimoto

V.S. Pantuev, D. Walker
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B. Bassalleck, D.E. Fields, M. Malik
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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 $\gamma +$ jet final state.
- Flavor decomposition by using $W \rightarrow e$ 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
- $\gamma$ -Jet correlation

Overview of Silicon Vertex Tracker
- Fine granularity, low occupancy
  50$\mu$m x 450$\mu$m pixel sensor at inner 2 layers.
- Unique strip sensor
  80$\mu$m x 1000$\mu$m pixel pitch
- Large acceptance
  $|\eta|<1.2$, almost $2\pi$ in $\phi$ plane
- Self tracking capability
  2 pixel sensor layers ($r = 2.5, 5.0$ cm)
  2 strip sensor layers ($r = 10.0, 14.0$ cm)

VTX will be installed in 2010.
b/c flavor separation with VTX

Chi2 < 1.0
Collision Vertex

D^0 decay

Displaced vertex

\[ \tau (\mu m) \]

D, B
D^0 125
B^0 464

Primary event vertex

Distance to the Closest Approach [cm]
Au-Au central event

VTX will have DCA resolution \( \sim 50 \mu m \)
We can separate b->e and c->e component with VTX.
A DCA resolution (\( \sim 100 \mu m \)) is sufficient for b/c separation

Requirements for Vertex Tracker

**Physics side**

- High precision tracking for displaced vertex measurement.
  50\( \mu m \) displaced vertex resolution, \( \tau \sim 100 \mu m(D) , \sim 400 \mu m(B) \)
- Large coverage tracking capability with momentum resolution
  (\(|\eta|<1.2\), and full azimuthally with \( \sigma/P \sim 5\%P \))

**Environment side**

- High charged particle density ‘dN/d\( \eta \)’ \( \sim 700 @\eta=0 \)
- High Radiation Dose \( \sim 100K\text{Rad}@10\text{Years} \)
- High Luminosity \( 2*10^{32} \text{ cm}^{-2} \text{ s}^{-1}@PP \rightarrow \) High rate readout
- Low Material Budget \(<\) avoid multiple scattering and photon conversion for electron measurement by outer detectors.
**PIXEL (Sensor and Readout)**

**ANALOG**
- Input Pad
- Test
- Feedback Bias Circuit
- 3 bit Threshold Adjust

**DIGITAL**
- Synchronizer + Enable Logic
- Delay Unit
- Trigger Strobe
- Fast OR, Fast Mult

**Pixel size** \((\phi \times z)\) 50 \(\mu\)m x 425 \(\mu\)m

**Sensor Thickness** 200 \(\mu\)m

\(\Delta r_{\phi} = 1.28\text{cm}, \Delta z = 1.36\text{ cm} \) (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 > 4\(\mu\)sec depth
- Trigger capability > FAST OR logic for each crossing
- 4 event buffer after L1 trigger

---

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- Bump bonded
- Running 10MHz clock (RHIC 106nsec)
- Digital buffer for each channel > 4\(\mu\)sec depth
- Trigger capability > FAST OR logic for each crossing
- 4 event buffer after L1 trigger
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
Alignment and Assembly

- 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

Layer 1
Layer 2
Layer 3

Proton 120GeV@FERMILAB Test beam
Readout by PHENIX DAQ and confirmed functionality
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.

Backup
Bump bonding

Bump bond to silicon pixel sensor

Assembly with 10μm accuracy
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

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

pixel array: $80 \times 1000 \, \mu m^2$ pitch
Reading by p-side
5 $\mu m$ line, 3 $\mu m$ gap, 5 turns

- Pixel array: $80 \times 1000 \, \mu m^2$ pitch
  - so called “stripixel”
- Single sided (p-side), 2-dim. readout
  - Double metal structure
  - Charge sharing during x and u strip
- Detector size: $3.5 \times 6.2 \, cm^2 \times 625 mm$
  - 1536 channel / 1 sensor
Strip detector:
world’s first 2-dimensional readout from 1 side
pixel array: $80 \times 1000 \, \mu m^2$ pitch
Reading by p-side
5 $\mu m$ line, 3 $\mu m$ 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)

Clustered ADC for a (clustered ADC x=40) for HV 200 V

Beta-ray signal (after clustering)
S/N~10
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. \(2 \times 10^{10}\) ppp
    - Beam size: 5 ~ 30 mm

S/N ratio

Raw ADC distribution

Clustered ADC distribution

\[\sigma = 9.6\]

Channels “Stripixel” | Pedestal \(\sigma\) | MIP MPV | S/N
---|---|---|---
x | 9.6 | 98.6 | 10.3
u | 10.1 | 102.2 | 10.1

S/N ratio \(\sim 10\): consistent with the result of beta-ray

\(\Rightarrow\) Evaluation of the position resolution and detection efficiency with this S/N ration
Charge sharing in x and u for 0 Degree

Prototype (3 turns)  Current production (5 turns)

80 μm  80 μm
1 mm  1 mm

Diffused charge cloud

From KEK test (Old sensor setup : 3 turns)

Important parameter

\[ A_Q = \frac{Q_x - Q_u}{Q_x + Q_u} \]

Pitch width is not enough narrow for charge diffusion

Good charge sharing in x and u

Event display & Tracking

**preliminary**

Stripixel hit and fit for x

Tracking using 3 sensors
Residual distribution

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

\[ \text{Residual RMS in layer 2:} \]
- for channels x: 0.45 (RMS) x 80 \( \mu \)m (pixel size) = 36 \( \mu \)m
- for channels u: 0.50 (RMS) x 80 \( \mu \)m (pixel size) = 40 \( \mu \)m

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

Detection efficiency

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

\[ \text{Eff} = \frac{(\text{All count}) - (\text{Count in ADC} < 40)}{\text{All count}} \]

By tracking (x):

<table>
<thead>
<tr>
<th>Layer #</th>
<th>All count</th>
<th>Count in ADC &lt; 40</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1697</td>
<td>9</td>
<td>99.5 ± 0.2</td>
</tr>
</tbody>
</table>

By tracking (u):

<table>
<thead>
<tr>
<th>Layer #</th>
<th>All count</th>
<th>Count in ADC &lt; 40</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1559</td>
<td>18</td>
<td>98.9 ± 0.3</td>
</tr>
</tbody>
</table>

Results satisfy performance demand → Preparing for mass production.
Sequence of mass production (Plan)

- Silicon sensor QA (RBRC room)
- RBRC laboratory (physics building)
- 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.)

S. Bathe, K. Boyle, & SUNY group

For example, Leakage current vs. HV

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
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
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 $W^{\pm}$ 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

Max energy 100 GeV/c per beam
Future 250 GeV/c per beam
106 ns between bunch crossings

RHIC Polarized Collider

11/17/2008
Spin Physics with RHIC & RBRC
Polarization in AGS & RHIC

- Duel partial snakes largely eliminate luminosity dependence of beam polarization

### Polarized Collider Evolution

**Center of Mass: 200 GeV**

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

11/17/2008  Spin Physics with RHIC & RBRC  5

11/17/2008  Spin Physics with RHIC & RBRC  6
Beam polarimetry

- 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

- Beam & target are protons

Target polarization measured using
A Breit-Rabi polarimeter $\delta P < 2\%$
RHIC pC Polarimeter

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

\[
P_{\text{beam}} = - \frac{\varepsilon_N}{A_N^{pC}}
\]

\[
\varepsilon_N = \frac{N_L - N_R}{N_L + N_R}
\]

11/17/2008

pC Upgrade

Proposed pC polarimeters

- Detector Upgrade: Photo-Diodes instead of Si Strips
- Target Upgrade: Carbon nanotubes 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 $\Delta G$

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

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 $\Delta G$ (See Dave Kawai's talk)
- Direct photon, the golden channel for $\Delta G$
  - Luminosity starved process (See Kensuke Okada's talk)

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

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

11/17/2008 Spin Physics with RHIC & RBRC

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

11/17/2008 Spin Physics with RHIC & RBRC
PAC 2008 Run Plan (updated)

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Colliding Beam Species/Energy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>500 GeV p+p</td>
<td>-5-6 physics weeks to commission collisions, work on polarization &amp; luminosity and obtain first W production signal to meet 2011 RIKEN milestone</td>
</tr>
<tr>
<td>2010</td>
<td>200 GeV p+p</td>
<td>~12 physics weeks to complete 200 GeV A_{ll} measurements -STAR DAQ1000 fully operational</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>9-10 physics weeks with PHENIX HBD, STAR DAQ1000 &amp; TOF permits low-mass dilepton response map and 1st HI collision test of transverse stochastic cooling (one ring)</td>
</tr>
<tr>
<td>2011</td>
<td>Au+Au at assorted low E</td>
<td>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)</td>
</tr>
<tr>
<td></td>
<td>200 GeV U+U</td>
<td>1st U+U run with EBIS, to increase energy density coverage</td>
</tr>
<tr>
<td>2012</td>
<td>500 GeV p+p</td>
<td>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</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>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</td>
</tr>
<tr>
<td>2013</td>
<td>500 GeV p+p</td>
<td>Reach ~300 pb^-2 to address 2013 DOE performance milestone on W production</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au or 2nd low-E scan</td>
<td>To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX VTX and NCC and full STAR HFT</td>
</tr>
<tr>
<td>2014</td>
<td>200 GeV Au+Au or 2nd low-E scan</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>200 GeV p+p</td>
<td>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</td>
</tr>
</tbody>
</table>

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 showstoppers anticipated (details in Roser's talk)

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

11/17/2008 Spin Physics with RHIC & RBRC
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, Kawai, 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

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
Constraining $\Delta G$ by Measuring Double Helicity Asymmetry in Neutral Pion Production

Kieran Boyle
Review
November 17-18, 2008

Outline:
1. Physics introduction
2. Measurement of $\pi^0 A_{LL}$
3. Extracting $\Delta G$
4. $\Delta G$ Constraint
5. FF @ BELLE

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 ($\Delta G$) and Orbital Angular Momentum from quarks and gluons must give the rest

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

\[ \rightarrow A_{LL} \sim a_{gg} \Delta G^2 + b_{gq} \Delta G \Delta q + c_{qq} \Delta q^2 \]
\[ \Delta G \text{ from p+p: Measure } A_{LL} \]

\[ A_{LL} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}} = \sum_{a,b,c=q,q_g} \frac{\Delta f_a \otimes \Delta f_b \otimes \Delta \rho \otimes D_{\pi/c}}{f_a \otimes f_b \otimes \rho \otimes D_{\pi/c}} \]

- If \( \Delta f = \Delta q \), then we have this from \( p\)DIS
- So roughly, we have

\[ A_{LL} \approx a_{gg} \Delta g^2 + b_{gq} \Delta g \Delta q + c_{qq} \Delta q^2 \]

- The partonic fractions are \( p_T \), process, rapidity and \( \gamma\)'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 \( \Delta G \)

- 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 \( \sim 10\% \), and quite negligible at high \( p_T \) [PRD 76, 051106 (2007)].
Measuring $A_{LL}$

$$A_{LL} = \frac{1}{P_b P_y} \left( \frac{-R}{+R} \right)$$

- - = Opposite helicity
++ = Same helicity

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

Calculating $\pi^0 A_{LL}$

1. Calculate $A_{LL}(\pi^0 + BG)$ and $A_{LL}(BG)$ separately.
2. Get background ratio ($w_{BG}$) from fit of all data.
3. Subtract $A_{LL}(BG)$ from $A_{LL}(\pi^0 + BG)$:
   $$A_{LL}(\pi^0 + BG) = w_{\pi^0} \cdot A_{LL}(\pi^0) + w_{BG} \cdot A_{LL}(BG)$$

- $\pi^0$ and BG regions:
  - $\pm 25$ MeV around $\pi^0$ peak
  - BG region: two 50 MeV regions around peak

<table>
<thead>
<tr>
<th>$\pi^0 p_T$ (GeV/c)</th>
<th>BG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>18</td>
</tr>
<tr>
<td>4.4</td>
<td>8</td>
</tr>
<tr>
<td>10.0</td>
<td>6</td>
</tr>
</tbody>
</table>
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 $\Delta G$.

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

$A_{LL} \rightarrow \Delta G$

- Vary $\Delta G$ in GRSV fit, and then generate $A_{LL}$.
- Calculate $\chi^2$ for each expectation curve, and plot profile

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 $\Delta G$ 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

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

arXiv:0810.0694
Theoretical uncertainties

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 $\chi^2$ profile.
- At $\Delta x^2 = 9$ ($\sim 3\sigma$), we find consistent constraint:
  $-0.7 < \Delta G^{0.020.3} < 0.5$
- Our data are primarily sensitive to the size of $\Delta G^{0.020.3}$.

Theoretical Scale Uncertainty:

- $\pi^0$ cross section is described by NLO pQCD within sizable uncertainty in theoretical scale $\mu$.
- How does this affect $\Delta G$ constraint?
- Vary scale in $A_{LL}$ calc.
  - 0.1 uncertainty for positive constraint
  - Larger unc. for negative constraint

Kieran Boyle - RBRC Review - November 18, 2008

Fragmentation Functions @ BELLE

- Recall that the calculation of $\pi^0 A_{LL}$ requires the use of a fragmentation function (FF).
- Uncertainty on FF propagate to $\Delta G$. 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 $\pi^0$ (and $\eta$) FF.

HKNS results and uncertainties compared with other fits

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

Kieran Boyle - RBRC Review - November 18, 2008
Conclusions

- NLO pQCD is applicable at $\sqrt{s} = 200$ for $\pi^0$ production for $p_T > 2$ GeV, and can be used to extract $\Delta G$ from $A_{LL}$.
- PHENIX $\pi^0 A_{LL}$ measurement from Run5 and 6 offer a significant constraint on $\Delta G$, 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 $\Delta G$.
- We find for the Run5 and 6 results combined:
  \[ \Delta G_{\text{GRSV}}^{[0.02,0.3]} = 0.2 \pm 0.1(\text{stat}) \pm 0.1(\text{sys}) \]
  \[ +0.0\quad -0.4(\text{shape}) \pm 0.1(\text{scale}) \]
- 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 $\Delta g$ at slightly higher $x$
- Charged hadron $A_{LL}$ complementary to that of $A_{LL}^0$
  - Charged hadrons have different analyzing power for $\Delta g$
  - Comparison of $A_{LL}^0$ versus $A_{LL}^\pm$ may be sensitive to sign of $\Delta g$
  - Probing $\Delta g$ with different channels adds robustness to extraction of $\Delta g$
- 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 $\alpha \approx 87 \text{ mrad} / p_T [\text{GeV}/c]$
- Impose fiducial cuts, restrict to transverse momenta to $0.5 \text{ GeV}/c < p_T < 4.5 \text{ GeV}/c$
- 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 ($c_T \approx 1 - 10$ m) particles, estimated from tails in matching cut distributions
- Contribution from short-lived ($c_T << 1$ 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:

\[
A_{LL}^{Signal} = \frac{A_{LL}^{Signal+BG} - f \times A_{LL}^{BG}}{1 - f}
\]

Background Fractions

<table>
<thead>
<tr>
<th>( p_T ) (GeV/c)</th>
<th>( f(h^+) )</th>
<th>( f(h^-) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-1.0</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>1.0-2.0</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>3.0-4.5</td>
<td>0.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Cross-Checks for Systematic Effects

- Perform several tests for the presence of systematic errors in asymmetry determination
- Double spin asymmetries \( A_{LL}^{pp-h^+X} \) measured in each detector arm should be consistent
- Double spin asymmetries \( A_{LL}^{pp-h^-X} \) 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

<table>
<thead>
<tr>
<th>( p_T ) (GeV/c)</th>
<th>( \delta A_{LL}^{h^+} )</th>
<th>Shuffled Width ( h^+ )</th>
<th>( \delta A_{LL}^{h^-} )</th>
<th>Shuffled Width ( h^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-1.0</td>
<td>0.0020</td>
<td>0.0021</td>
<td>0.0022</td>
<td>0.0023</td>
</tr>
<tr>
<td>1.0-2.0</td>
<td>0.0041</td>
<td>0.0040</td>
<td>0.0047</td>
<td>0.0047</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>0.018</td>
<td>0.017</td>
<td>0.021</td>
<td>0.022</td>
</tr>
<tr>
<td>3.0-4.5</td>
<td>0.056</td>
<td>0.054</td>
<td>0.072</td>
<td>0.067</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$A_{LL}(h^+)$</th>
<th>$\delta A_{LL}(h^+)$</th>
<th>$A_{LL}(h^-)$</th>
<th>$\delta A_{LL}(h^-)$</th>
<th>$A_{LL}(h^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-1.0</td>
<td>0.0028</td>
<td>0.0021</td>
<td>-0.0036</td>
<td>0.0023</td>
<td></td>
</tr>
<tr>
<td>1.0-2.0</td>
<td>-0.0036</td>
<td>0.0042</td>
<td>-0.0086</td>
<td>0.0048</td>
<td></td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>0.0081</td>
<td>0.018</td>
<td>-0.011</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>3.0-4.5</td>
<td>-0.110</td>
<td>0.062</td>
<td>-0.072</td>
<td>0.082</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of Charged Hadron $A_{LL}$ with $A_{LL}^{\pi}$ results at $\sqrt{s} = 62.4$ GeV

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

Comparison of Charged Hadron and $\pi^0$ Asymmetries at $\sqrt{s}=62.4$ GeV

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 : $\frac{d^2 \sigma}{dp_T^2} = \frac{1}{\sqrt{s}} \frac{1}{\pi} G(x_T)$, 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 $x_T \rightarrow 1$
- 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 $\Delta g(x)$

![Graph showing comparison of positron charge asymmetries with GRSV model predictions.]

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 $\Delta g(x)$

![Graph showing comparison of negative charge asymmetries with GRSV model predictions.]

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 \( \Delta q(x) \)
- Difference of quarks with parallel and antiparallel polarization relative to longitudinally polarized proton (known from fixed target (SIDIS) experiments)

Transversity distribution function \( \delta q(x) \)
- Difference of quarks with parallel and antiparallel polarization relative to transversely polarized proton (first results from HERMES and COMPASS - with the help of Belle)
Motivation: Access to distribution functions (e.g., $\Delta q$, $\Delta g$) requires good knowledge of fragmentation functions (D,H,IFF).

\[
\frac{d\sigma}{dQ^2} = \int d\vec{t} \otimes \bar{\sigma} \otimes D^{(z)}
\]

- 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 $q \rightarrow$ hadron $h$

Fragmentation functions can be obtained in $e^+e^-$ annihilation

\[
z = \frac{2E_R}{\sqrt{s}} \quad \sqrt{s} = 10.52 \text{ GeV}
\]

- Process: $e^+ e^- \rightarrow hX$
- At leading order sum of unpolarized fragmentation functions from quark and anti-quark side

LO $F^4(z, s) = \frac{1}{\sum \epsilon_i \alpha_i} \sum \epsilon_i D_i(z)$

NLO $F^4(z, s) = \sum \frac{d\epsilon_i}{\epsilon_i} C_i(z; \epsilon_i \alpha_i) D_i(z)$

KBC review; Nov. 1999
R. Sallai: fragmentation function measurements in Belle
KEKB: Record Luminosities to study fragmentation functions

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

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

World fragmentation data and need for precise FFs

- Low $Q^2$ and high $z$ data not available
- Large uncertainty on gluon fragmentation
- Very important input for RHIC $Ag$ measurements

Status:
- Particle identification nearly finished
- Smearing understood
- Acceptance correction finished
Further unpolarized FF measurements

- Additional FF measurements planned:
  - \( \pi^0 \) (cross check with completely different systematics)
  - \( \eta \) (PHENIX \( A_{LL} \) measurement available, higher strange content??, STAR \( A_{NN} \))
  - Other decaying particles (\( K_S, f^0, \gamma \)??)
  - \( k_t \) dependent FFs

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

RHIC and SIDIS experiments measure:
- Transversity \( 6q(x) X \)
- Collins Fragmentation function \( H_1^c(x) \)
- Or Interference Fragmentation function (IFF)

2 Unknown Functions measured together

Transversity

Belle measures:
- Collins \( X \) Collins
- Or IFF \( X \) IFF

Universality understood
Evolution?
Collins effect in quark fragmentation: Left-Right asymmetry around spin axis

\[ k \quad : \quad \text{quark momentum} \]
\[ q\gamma \quad : \quad \text{quark spin} \]
\[ p_h \quad : \quad \text{hadron momentum} \]
\[ p_{h1} \quad : \quad \text{transverse hadron momentum} \]
\[ E_h = \frac{E_a}{E_q} \]
\[ = 2 \frac{E_h}{\sqrt{s}} : \text{relative hadron momentum} \]

**Collins Effect:**
Fragmentation with of a quark \( q \) with spin \( s_q \) into a spinless hadron \( h \) carries an azimuthal dependence:

\[ \alpha \left( \vec{k} \times \vec{p}_{h1} \right) \cdot \vec{s}_q \]
\[ \propto \sin \phi \]

Collins fragmentation in e⁺e⁻
Angles and Cross section \( \cos(\phi_1 + \phi_2) \) method

\[ z = \frac{2E_{h2}}{\sqrt{s}} , \quad \sqrt{s} = 10.52 \, \text{GeV} \]

2-hadron inclusive transverse momentum dependent cross section:

\[
\frac{d^3 \sigma(e⁺e⁻ \rightarrow h_1h_2X)}{d^3p_{h1}d^3p_{h2}} = 2B(\gamma) \cos(\phi_1 + \phi_2) \Pi_1^{(2)}(\phi_1) \Pi_2^{(3)}(\phi_2)
\]

\[ B(\gamma) = \gamma(1-\gamma) = \frac{1}{4} \frac{m^2}{s} \tan \theta \]

Net (anti-)alignment of transverse quark spins
Collins FF analysis: Effect is large

First direct measurement of the Collins effect:
Nonzero asymmetries
Long paper: Inclusion of Resonance data
29 → 547 pb⁻¹
10% asymmetry ~ 30% effect

Global transversity analysis

First global analysis 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 —

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet_1}(\pi^+\pi^-)_{jet_2}X$
- Similar to Collins analysis
- Directly applicable to semi-inclusive DIS and pp

- Early work by Collins, Heppelmann, Ladinsky [NPB 420, (1994)]
- Evolution by Ceccioipier et al. [PLB 650, (2007)]

Model predictions by:
- Stefani et al. [PRL 80, (1998)]
- Radici et al. [PRD 65, (2002)]

$$A \propto H_1^2(z_1, m_1)H_1^2(z_2, m_2)\cos(\phi_1 + \phi_2)$$

Expected sensitivities for 60 fb$^{-1}$

- $(\pi^+\pi^-) (\pi^+\pi^-)$ pairs as a function of the invariant mass $m_{\pi\pi,1} \times m_{\pi\pi,2}$
- Similar distributions to be shown as a function of $z_{\pi\pi,1} \times z_{\pi\pi,2}$
- Other hadron combinations ($\pi^0, K$)
- Global analysis possible as well: HERMES, COMPASS and PHENIX data already available, more to come
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 \( \rightarrow \) 547 fb\(^{-1}\)
• Significant, nonzero asymmetries \( \rightarrow \) 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 \( \Lambda \)-fragmentation function
  • A 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

\[\begin{align*}
\text{GPD's} & \quad H(x, k, \Delta) \quad \text{FT} \quad \Delta \quad \rightarrow \quad (1) \\
\text{Wigner function} & \quad W(x, k, \Delta) \\
\text{FT} \quad \Delta & \quad \rightarrow \quad \Delta = 0 \\
\text{GPD's} & \quad H(x, k, \Delta) \\
\text{TMD's} & \quad f(x, k) \quad \text{FT} \quad \rightarrow \quad q(x, k) \\
\end{align*}\]
**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**

- **Correlation** between nucleon transverse spin and parton transverse momentum ($k_T$)

$$ f_{1T}^+(u) > 0 \quad f_{1T}^-(d) < 0 $$

- **Transversity** correlation between nucleon transverse spin and parton transverse spin

$$ h_{1T}^+(u) > 0 \quad h_{1T}^-(d) < 0 $$

**Boer-Mulders function**

- Correlation between parton transverse spin and parton transverse momentum ($k_T$)

$$ h_{1T}^+(u) \text{ and } h_{1T}^-(d) \text{ expected to have the same sign...} $$
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 $\theta = 0.59$ ($\eta = 2.2$)
  - $\sim$ RHIC II luminosity
    - $10^{33}$ cm$^{-2}$sec$^{-1} \times 10^6$ sec = 1,000 pb$^{-1}$
  - $M_{\mu\mu} = 4.5 \sim 8$ GeV
  - Very simple PYTHIA simulation
    - Angle & $E_\mu$ (> 2 GeV) cut only
    - (no magnetic field, no detector acceptance)
**Drell-Yan at RHIC**

- Fixed-target (internal-target) experiment
  - $\sqrt{s} = 22$ GeV ($E_{lab} = 250$ GeV)
  - $\theta = 0.03$ to $\theta = 0.1$
  - $\sim 10$ times larger luminosity necessary
    - $10^{34}$ /cm$^2$/sec $\times 10^5$ sec $= 10,000$ pb$^{-1}$
  - $M_{\mu\mu} = 4.5 \sim 8$ GeV
- Very simple PYTHIA simulation
  - Angle $\& E_{\mu}$ ($> 2$ GeV) cut only
  - (no magnetic field, no detector acceptance)
    - more studies necessary for acceptance, dead time, etc. for realistic estimation

November 17, 2008

**Drell-Yan at RHIC**

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

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**Drell-Yan at RHIC**

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

- Internal target ($\sqrt{s} = 22$ GeV) with $L = 10,000$ pb$^{-1}$
  - 33,000 events in $M_{\mu\mu} = 4.5 \sim 8$ GeV
  - $x_1 = 0.25 \sim 0.4$

---

**Internal target experiment at RHIC**

- $10^{34}$ /cm$^2$/sec possible?
  - $2 \times 10^{11}$ /bunch $\times$ 10 MHz = $2 \times 10^{18}$ /sec
  - Storage cell $10^{14}$ /cm$^2$ thickness
  - $2 \times 10^{32}$ /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
    - $(2 \times 10^{11} \times 100) / (10^{7} /\text{mb/sec} \times 50 \text{ mb}) = 4 \times 10^{6}$ sec $\sim$ 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?)
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
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.

Growth of CCJ-HPSS data volume
Big pipe between BNL and RIKEN

Run5
Sustained > 5TB/day (peak > 200MB/s)

Run6

Run8

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).

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
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.
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 QDOC: 2.87Tflop
4 racks of RBRC QDOC: 3.28Tflop
NYBlue at BNL and LLNL
Lattice results on trace anomaly

\[ m_q = 0.1 m_s \to m_\pi \simeq 220 \text{ MeV} \quad m_\eta \cdot r_0 = 1.59 \]

\[ \frac{\Theta^{\mu\nu}(T)}{T^4} = \frac{\epsilon - 3p}{T^4} = \frac{1}{g^2} \{ (S_G)_0 - (S_G)_T \} - m_q \{ 2m_q (\bar{q}q)_0 - (\bar{q}q)_T \} + m_s (\bar{s}s)_0 - (\bar{s}s)_T \}

\[ R_\beta(\beta) = \frac{d\beta}{d\alpha}, \beta = 6/g^2 \]

\[ R_m = \frac{1}{m_q(\beta)} \frac{dm_q(\beta)}{d\beta} \]

\[ \frac{p(T)}{T^4} - \frac{p(T_0)}{T_0^4} = \int_{T_0}^T dt \frac{\Theta^{\mu\nu}(T')}{T'^5} \]

\[ s(T) = (\epsilon + p)/T \]

Pressure, energy density and speed of sound

Rapid rise in number of d.o.f at
\[ T = 180 - 200 \text{ MeV} \]

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

\[ L_{\text{ren}} = \exp(-F_Q(T)/T) \]

Renormalized chiral condensate

\[ \Delta_{s,t}(T) = \frac{\langle \bar{q}q \rangle_T - m_q \langle \bar{s}s \rangle_T}{\langle \bar{q}q \rangle_{T=0} - m_q \langle \bar{s}s \rangle_{T=0}} \]

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

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

\[ \chi_2^X = \frac{1}{VT^3}(N_X^2) \]

\[ \chi_2^X = \frac{1}{VT^3}((N_X^2) - 3(N_X^2)^2) \]

quarks are the carriers of conserved charges for \( T > T_c \)

\[ \chi_2^X \sim \frac{T-T_c}{T_c}^{2-n-\alpha} \]
Fluctuations of conserved charges

\[ \chi_{BQS}^{i,j,k} = \frac{\partial^i}{\partial \mu_B^i} \frac{\partial^j}{\partial \mu_Q^j} \frac{\partial^k}{\partial \mu_S^k} \frac{1}{V T^3} \ln Z(T,V), \quad \tilde{\mu}_X = \mu_X/T \]

\[ \chi_2^X = \frac{1}{V T^3} \langle N_X^4 \rangle - 3 \langle N_X^2 \rangle^2 \]

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

cutoff effects are under control

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

$W(r(x, y), z) \sim \exp(-\sigma_s(T) \cdot r \cdot z)$

$\sigma_s(T) \simeq \sigma(T = 0), \ T < T_c$

$T_0 T$

$\frac{T}{\sigma_s^{1/2}(T)}$

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

$c_M = 0.55(1)$

$g_3^2(T) = g^2(T)T(1 + g_{1f}(N_f, T)g^2(T) + ...)$

QCD thermodynamics with domain wall fermions

HotQCD Preliminary

$L_s = 96 \ p_{pb}$

$L_s = 32 \ p_{pb}$
• Calculations of thermodynamic quantities have been extended to lattices with temporal extent $N_t=8$. 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 $m_Q=0.05m_s$
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.

\[ T = 0 \quad \rightarrow \quad T_c \quad \rightarrow \quad T \]
- 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

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

when \( \vec{p} = 0 \)

\[ G(t) = G_4(t) \gamma_4 + G_s(t) \]

\[ Ns^3 \times N_t = 32^3 \times N_t \quad \# of \text{ conf.} = 40 \sim 50 \]

\[ \beta = 6.10 \]
\[ \kappa = 0.1346 \quad \text{Quark propagators include negative norm.} \]
\[ C_{SW} = 1.6787 \]
\[ a \sim 0.0882 [fm] \]
\[ G_4(t) = \frac{\cosh(m(t - \beta/2))}{\cosh(m(t + 1 - \beta/2))} \]

\[ \beta = 6.10 \]
\[ \kappa = 0.1346 \]
\[ C_{SW} = 1.6787 \]
\[ a \sim 0.0882[fm] \]
\[ N_s^3 \times N_t = 32^3 \times N_t \]
\[ N_t = 16, 14, 12, 10, 8, 6 \]
\[ \# \text{ of conf.} = 40 \sim 50 \]

**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 *1 [RBC and UKQCD Collaborations]

RBRC Scientific Review, November 17, 2008

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

• $24^3 \times 64 \times 16$ (2.7 fm across), $16^3 \times 32 \times 16$ (1.8 fm), ...
• Iwasaki gauge action, $\beta = 2.13$, and Domain-Wall Fermions (DWF) quarks, $M_S = 1.8$,
• $m_{\text{strange}} = 0.04$, $m_{\text{up-down}} = 0.03, 0.02, 0.01$ 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, $B_{K}^{\text{PEP}}(2\text{GeV}) = 0.524(10)(28)$,
• beginning to see SU(3) chiral perturbation failure, e.g. NLO corrections $\sim 0.5 \times \text{LO}$.

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

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Four isovector form factors parameterize neutron $\beta$ decay:

$$\langle p|V_{\mu}^{+}(x)|n\rangle = \bar{u}_{p} \left[ \gamma_{\mu} G_{V}(q^{2}) - q_{\mu} \sigma_{\lambda \mu} G_{T}(q^{2}) \right] u_{n} e^{i q \cdot x},$$

(1)

where $G_{V} = F_{1}$ and $G_{T} = F_{2}/2m_{N}$ in electromagnetic notations, and

$$\langle p|A_{\mu}^{+}(x)|n\rangle = \bar{u}_{p} \left[ \gamma_{\mu} \gamma_{5} G_{A}(q^{2}) + i q_{\mu} \gamma_{5} G_{T}(q^{2}) \right] u_{n} e^{i q \cdot x}.$$  

(2)

The vector and axial charges, $g_{V} = G_{V}(0)$, and the axial charge, $g_{A} = G_{A}(0)$, determines neutron life:

• $g_{V} = \cos \theta_{C}$,
• $g_{A} = 1.2695(20) \times g_{V}^{-1}$.

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 $\beta$ 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,
• $\pi NN$ coupling, $g_{\pi NN}$,
• pseudoscalar effective coupling, $g_{P}$, that enters the muon capture by nucleon, and so on.

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

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

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

\[
W^{[\mu\nu]}(x, Q^2) = i e^{\mu\nu\rho} \frac{g}{\nu} \left( S_n \left( g_1(x, Q^2) + g_2(x, Q^2) \right) - \frac{q \cdot S \cdot \nu}{\nu^2} g_2(x, Q^2) \right) ,
\]

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:

\[
2 \int_0^1 dx x^{n-1} F_1(x, Q^2) = \sum_{q=u,d} c_{1,n}^{(q)} \langle x^n \rangle_q(\mu) + O(1/Q^2) ,
\]

\[
2 \int_0^1 dx x^{n-2} F_2(x, Q^2) = \sum_{f=u,d} c_{2,n}^{(f)} \langle x^n \rangle_f(\mu) + O(1/Q^2) ,
\]

\[
2 \int_0^1 dx x^n g_1(x, Q^2) = \sum_{q=u,d} e_{1,n}^{(q)} \langle x^n \rangle_{\delta}(\mu) + O(1/Q^2) ,
\]

\[
2 \int_0^1 dx x^n g_2(x, Q^2) = \frac{1}{2} n + \frac{1}{2} \sum_{q=u,d} \left[ e_{2,n}^{(q)} d_{n}^{(q)}(\mu) - 2 e_{1,n}^{(q)} \langle x^n \rangle_{\delta}(\mu) \right] + O(1/Q^2) .
\]

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

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

We use the standard proton operator, \( B = \epsilon_{abc} (u^T_7 C_{\gamma_5} d_b) u_c \) 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

\[
C_{2pt}(t) = \sum_{\alpha,\beta} \left( \frac{1 + \gamma_5}{2} \right) \langle B_\beta(t_{\text{sink}}) \Bar{B}_\alpha(t_{\text{source}}) \rangle ,
\]

with \( t = t_{\text{sink}} - t_{\text{source}} \).

- Insert an appropriate observable operator \( O(\bar{q}, \tau) \) at time \( \tau, t_{\text{source}} \leq \tau \leq t_{\text{sink}} \), and possibly finite momentum transfer \( \bar{q} \), to obtain a form factor or structure function moment three-point function,

\[
C_{3pt}(t, \tau, \bar{q}) = \sum_{\alpha,\beta} \Gamma_{\alpha \beta} \langle B_\beta(t) O(\bar{q}, \tau) \Bar{B}_\alpha(t_{\text{source}}) \rangle ,
\]

with appropriate projection, \( \Gamma = \frac{1 + \gamma_5}{2} \), for the spin-uncpolarized, and \( \Gamma = \frac{1 + \gamma_5}{2} \gamma_5 \gamma_k, k \neq 4 \), 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. \( \langle O \rangle_{\text{bare}} = \frac{C_{3pt}(t, \tau)}{C_{2pt}(t)} \) 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 renormalization 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.

The RBC-UKQCD joint (2+1)-flavor dynamical DWF coarse ensembles\(^2\): 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, \(m_{\text{res}} = 0.003\).
- 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.

<table>
<thead>
<tr>
<th>(m_f a)</th>
<th># of config.'s meas. interval</th>
<th>(N_{\text{sources}})</th>
<th>(m_\pi ) (GeV)</th>
<th>(m_N ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>932</td>
<td>10</td>
<td>4</td>
<td>0.33</td>
</tr>
<tr>
<td>0.01</td>
<td>356</td>
<td>10</td>
<td>4</td>
<td>0.42</td>
</tr>
<tr>
<td>0.02</td>
<td>98</td>
<td>20</td>
<td>4</td>
<td>0.56</td>
</tr>
<tr>
<td>0.03</td>
<td>106</td>
<td>20</td>
<td>4</td>
<td>0.67</td>
</tr>
</tbody>
</table>

\(^2\)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, \(m_\pi\) 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.


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, $g_A$: 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 $m_L$ and they are monotonic: Scaling in $m_L$.
- Takeshi Yamazaki’s discovery. He also discovered this in 2-flavor dynamical Wilson.
- Was seen in quenched calculations, but as a much smaller effect.

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

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 C. Allton et al., [RBC+UKQCD], arXiv:0804.0473 [hep-lat].
Momentum dependence of vector current form factors are fit well by dipole form, \( \propto \left[ 1 + \frac{(r^2)}{12q^2} \right]^{-1} \), 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, \( G_P(q^2) \sim \frac{2F_\pi g_{\pi NN}}{q^2 + m_N^2} ; q^2 \sim -m_N^2 \), 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.

---

Moments of structure functions:

- The isovector tensor charge, $\langle 1 \rangle_{\Delta u-\Delta d}$, fully NPR ($Z = 0.789(3)$), can provide a prediction, $1.10(7)$, or $0.7$? We need to understand the finite-size correction and/or chiral extrapolation.

![Graph showing structure function moments vs. m^2[GeV^2]]

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


Conclusions: $(2+1)$-flavor, Iwasaki+DWF dynamical calculations with, $a^{-1} = 1.73(2)$ GeV, $(2.74(3)\text{fm})^3$ box, $m_{\text{phys}} = 0.00315(2)$, $m_{\text{strange}} = 0.04$, $m_u = 0.67, 0.56, 0.42$ 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, $g_A/g_T$. Demands 5-10 fm box.
- Yet $G_P$ yields $g_{\pi NN}$ and $g_P$ favorably comparing with experiments.
- Vector current is better-behaved: magnetic moment is good and radii call HBXPT 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 $\eta'$ 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 measurements
- Fitting procedures

Results

- Quenched approximation
- Dynamical quark 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

(quoted in PDG 2008)

- Meson include disconnected quark loops, $\eta'$

→ This talk
Strong $U(1)_A$ puzzle

- Pseudoscalar (PS) mesons are light as it would be NG-boson in quark (u,d,s) massless limit, where the spontaneous chiral symmetry breaking occurs: $SU(3)_V \times SU(3)_A \to SU(3)_V$
- But flavor singlet PS, $\eta'$, is special as $U(1)_A$ current is not conserved by quantum anomaly
  \[
  \partial_\mu \langle A^\mu_0(x) \rangle = 2m \langle P^0 \rangle + \frac{N_f}{16\pi^2} \langle F \bar{F}(x) \rangle
  \]
- DWF is chirally symmetric, has an integer definition of topological charge, thus an optimal lattice quark to study this puzzle.
- In $N_C \to \infty$, Witten-Veneziano formula:
  \[
  M_0^2 = m_{\eta'}^2 - m_{\pi}^2 = \frac{2N_f}{f_\pi} \frac{\langle Q_{\text{top}}^2 \rangle}{V}
  \]

Calculation details

- $N_F = 2$ 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.
- $\eta'$ has $\sim 15\%$ error
- $\pi^*$ and $f_{\pi^*}$
- Nonzero signal for $\omega$, 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 $r_0$)
- $\Lambda a = 1.87$ fm
- $m_{\text{res}} = 0.00137(4)$

<table>
<thead>
<tr>
<th>$m_f$</th>
<th>$M_{PS}/M_V$</th>
<th>Measured configs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.53(1)</td>
<td>940</td>
</tr>
<tr>
<td>0.03</td>
<td>0.60(1)</td>
<td>560</td>
</tr>
<tr>
<td>0.04</td>
<td>0.65(1)</td>
<td>470</td>
</tr>
</tbody>
</table>

New mesurements

- $Z_2$ random spacial-wall and space-time volume source.

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

which fullfills

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

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

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

- Lattice QCD
- Strong $U(1)_A$ puzzle
- Calculation details
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- New measurements
- Fitting procedures

Results

- Two (four) interpolation fields
  - $O_L = \bar{q}_L(x)\Gamma q_L(x)$: local interpolation fields
  - $O_S = \bar{q}_S(x)\Gamma q_S(x)$: smeared interpolation fields

- Standard fit
  \[
  \langle O_S(t)O_S^\dagger(0) \rangle = A_O \left[ e^{-m_{O}t} + m_{O}^{-1}(N_t-t) \right]
  \]

- Variational method
  \[
  X(t) = \begin{pmatrix}
  \langle O_L(t)O_L^\dagger(0) \rangle & \langle O_L(t)O_S^\dagger(0) \rangle \\
  \langle O_S(t)O_L^\dagger(0) \rangle & \langle O_S(t)O_S^\dagger(0) \rangle 
  \end{pmatrix}
  \]
  is diagonalized

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

  to get $\lambda_O(t, t_0) \rightarrow m^{-1}(t-t_0)$.
$\rho$ effective mass

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

$$LL > LS = SL > SS$$

holds.
\[ \pi^* \text{ quiz} \]

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

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

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

- 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

\[\langle 0 | A_\mu(x) | \pi^* (p) \rangle \propto p_4 = M_{\pi^*},\]

\[M_{\pi^*}^2 \propto 2 m_f\]

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

\[11 / 17\]

\[\pi^* \text{ quiz} \]

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

Results
- \( \rho \)
- \( \rho \) effective mass
- \( \pi^* \) quiz
- Answer of \( \pi^* \) quiz
- \( \pi^* \) results
- \( \eta' \) results
- \( \eta' \) results
- Summary

- Using,

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

- Using, \( \partial_4 \langle A_4(x) | \mathcal{O} \rangle = p_4 \langle A_4(x) | \mathcal{O} \rangle \), and

\[
\langle 0 | A_\mu(x) | \pi^* (p) \rangle \propto p_4 = M_{\pi^*},
\]

\[M_{\pi^*}^2 \propto 2 m_f\]

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\]

- Using, \( \partial_4 \langle A_4(x) | \mathcal{O} \rangle = p_4 \langle A_4(x) | \mathcal{O} \rangle \), and

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\langle 0 | A_\mu(x) | \pi^* (p) \rangle \propto p_4 = M_{\pi^*},
\]

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

\[11 / 17\]

Answer of \( \pi^* \) 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

\[M_{\pi^*}^2 \times f_{\pi^*} \propto 2 m_f\]

so if \( M_{\pi^*}^2 \neq 0 \),

\[f_{\pi^*} = C m_f\]

for small \( m_f \).

- The decay constant of \( \pi^* \) is zero at chiral limit, keeping \( \pi^* \) mass finite.
\( \pi^+ \) results

- Lattice QCD
- Strong \( U(1) \) puzzle
- Calculation details
- \( N_F = 2 \) ensemble
- New measurements
- Fitting procedures

Results
- \( \rho \)
- \( \rho \) effective mass
- \( \pi^+ \) quiz
- Answer of \( \pi^+ \) quiz
- \( \pi^+ \) results
- \( a_0, I = 1, J^{PC} = 0^{++} \)
- \( \eta' \)
- \( \eta' \) results
- Summary

\[ M_{\pi^+} a = 1.165(88), \]  
(5)

\[ M_{\pi^+} = 1.97(17) \text{GeV} \]  
(6)

(exp. \( \sim 1.3 \text{GeV} \))  
(7)

- variational methods with \( t_0 = 5 \)
- By a linear fit, \( m_f \rightarrow m_{ud} \)

\[ M_{\pi^-} a = 1.10(8) \text{GeV} \]  
(8)

\[ (\text{previously } m_{a_0} = 1.58(34) \text{GeV}) \]

- Most likely, 2nd excited states etc. are contaminated.
- Nevertheless we plot \( f_{\pi^+} \) at \( m_f = -m_{\text{res}} \).
- \( f_{\pi^-} \) is consistent with previous results.

a_0, I = 1, \( J^{PC} = 0^{++} \)

- Propagator is sensitive to the (partially) quenched pathologies.
- Most of the previous calculations obtained \( \sim 1.5 \) GeV with a few new calculation with \( \sim 1.0 \) 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:

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

\[ (\text{previously } m_{a_0} = 1.58(34) \text{GeV}) \]
$\eta'(x) = 1/\sqrt{N_f} \sum_f \bar{q}_f(x) \gamma_5 q_f(x)$ is consists of a connected quark loop, $C(t)$, and disconnected loops, $D(t)$:

\[
\langle \eta'(t) \eta'^\dagger(0) \rangle = C(t) - N_f D(t)
\]

\[
C(t) = \langle \text{Tr} [S_{t,0} \gamma_5 S_{t,0} \gamma_5] \rangle
\]

\[
D(t) = \langle \text{Tr} [S_{t,0} \gamma_5] \rangle \langle \text{Tr} [S_{t,0} \gamma_5] \rangle
\]  \hspace{1cm} (8) \hspace{1cm} (9) \hspace{1cm} (10)

\[
\frac{N_f D(t)}{C(t)} = 1 - B e^{-\Delta_{Mt}} \hspace{1cm} (12)
\]

\[
M_{\eta'}^2 = M_\pi^2 + M_0^2, \hspace{0.5cm} M_0^2 = \frac{2 N_f}{f_\pi^2} \chi, \hspace{0.5cm} \chi = \left( \frac{Q_{top}^2}{V} \right) \hspace{1cm} (13)
\]

**Results**

- $\rho$ effective mass
- $\pi^-$ results
- $\eta'$ results
- Summary

**Ratio plot**

\[
\frac{N_f D(t)}{C(t)} = 1 - B e^{-\Delta_{Mt}}
\]

- 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

- Lattice QCD
- Strong $f'(1)_A$ puzzle
- Calculation details
- $N_f = 2$ ensemble
- New measurements
- Fitting procedures

Results
- $\rho$
- $\eta'$ effective mass
- $\pi^*$ quiz
- Answer of $\pi^*$ quiz
- $\pi^*$ results
  - $a_{1+}, J^{PC} = 0^{++}$
- $\eta'$
- $\eta'$ results
- Summary

- $\rho \sim 10\%$ larger value at chiral limit
- $a_{10}$ lighter, $\sim 1$ GeV from 1.5 GeV.
- $\eta'$ has $\sim 15\%$ error
- $\pi^*$ and $f_{\pi^*}$
- Nonzero signal for $\omega$. 
Improved non-perturbative renormalization

Yasumichi Aoki

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

- $N_f=2+1$ results spread over ±20%
  - Hardly precise
  - Non-perturbative vs perturbative renormalization?
    - Staggered rooting problem?
- More precise results desired!
- Our result (RBC/UKQCD)
  \[
  m_s^{\text{MS}}(2\text{GeV}) = 107.3(4.4)_{\text{stat}}(4.9)_{\text{syst}}(9.7)_{\text{ren}} \text{MeV}.
  \]
- 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 $\Pi$ of bilinear operator $O = \bar{u}\Gamma d$
  \[
  \frac{Z_O}{Z_q} \frac{1}{12} \text{Tr}(\Pi_O P_O) = 1 \quad \text{at } p^2 = \mu^2, \ m \to 0
  \]

- matching to a continuum scheme (\(\overline{\text{MS}}\)) must be done at large momentum to reduce
  - truncation error of continuum perturbation theory
  - contamination of non-perturbative effect (NPE)
  \[\rightarrow\] 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 operator
  - $P$: 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, $1/p^2 \to 1/p^6$
  - 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:
    \[ \Lambda_A = \Lambda_Y? \Lambda_P = \Lambda_S? \]
  - Further detail on \( \Lambda \):
    \[ X \times ([\text{perturbative part}] + \frac{\Lambda_{QCD}^2}{p^2}, \frac{m_q\Lambda_{QCD}}{p^2} + \cdots) \]
    \[ + (pa)^2 + \cdots \]
    Hard to measure \hspace{1cm} \text{Easier}

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

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

- \( \Lambda_{A,P} \), \( \Lambda_{e} \) for exceptional or symmetric momenta
- \( \Lambda_{(e), (a)} \)
- \( p \) (except) \( m_q = 0.01 \)
- \( p \) (symm) \( m_q \leq 0.03 \)
- \( S \) (except) \( m_q = 0.01 \)
- \( S \) (symm) \( m_q = 0.02 \)

- Hard to measure \hspace{1cm} \text{Easier}

- \( S, P \) (chiral) symmetry
  - broken (MOM)
  - intact (sMOM)

- mass dependence
  - large (MOM) \( \rightarrow \) large sys. error
  - small (sMOM)
\[ s\text{MOM} \to \overline{\text{MS}} \quad \text{matching} \]

- sMOM \to \overline{\text{MS}} \quad \text{conversion factor}
  \[ C_m = 1 + \frac{\alpha_s}{4\pi} C_F c_m^{(1)} \quad c_m^{(1)} = \begin{cases} 0.484 - 0.172\xi & \text{(sMOM)} \\ 4 - \xi & \text{(MOM)} \end{cases} \]

- sMOM: smaller constant and gauge dependence

- size of 1-loop correction at \( \mu = 2 \text{ GeV} \) in Landau gauge
  \[
  \begin{cases}
  1.5\% \quad \text{(sMOM)} \\
  12.3\% \quad \text{(MOM, 1 loop)} \\
  6.2\% \quad \text{(MOM, 3 loop)}
  \end{cases}
  \]

- sMOM: very small already at 1 loop

---

error budget on \( Z_m \)

<table>
<thead>
<tr>
<th>MOM</th>
<th>sMOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>7% from ( m_s \neq 0 )</td>
<td>much smaller: few %</td>
</tr>
<tr>
<td>- NP contamination</td>
<td>1.5% already small at ( O(\alpha_s) )</td>
</tr>
<tr>
<td>6% from ( O(\alpha_s^3) )</td>
<td>a little smaller</td>
</tr>
<tr>
<td>3% statistical</td>
<td>- drastic improvement possible</td>
</tr>
<tr>
<td></td>
<td>→momentum source</td>
</tr>
<tr>
<td>9% in total</td>
<td>total: very small</td>
</tr>
</tbody>
</table>

- 9\% in total

- 7\% from \( m_s \neq 0 \)
sMOM $Z_m$

• 1 loop matching and 2 loop running makes flat $(pa)^2$ dep
• preliminary result, $(pa)^2 \rightarrow 0$ extrapolation not attempted
• consistent with $\text{MOM} \rightarrow \overline{\text{MS}}$ 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.
• sMOM $\rightarrow \overline{\text{MS}}$ 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
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!)

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.
Results from the valence quark sector

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

[Ran Zhou, Lattice 2008]

Results from the valence quark sector

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

[S. Chowdhury, Lattice 2008]
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 accommodated on QCDOC, NYBlue

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

Tomomi Ishikawa
(RIKEN BNL Research Center)
tomomi@quark.phy.bnl.gov

RBC/UKQCD Collaborations

RBRC Scientific Review Committee Meeting
November 17-18, 2008

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
    \[ \mathcal{M}_{B_q} = \langle \overline{B}_{q}^{0}|[\bar{b}\gamma_\mu P_L q][\bar{b}\gamma_\mu P_L q]|B_{q}^{0}\rangle = \frac{8}{3} m_{B_q} f_{B_q}^2 B_{B_q} \]
    \[ \Delta m_{B_q} = \text{(known factors)} \times |V_{tq}V_{tb}|^2 m_{B_q} f_{B_q}^2 B_{B_q} \]
B physics on the lattice

Difficulty of heavy-light system

- Basically, multi-scale problem
  - Light quark is too light.
    Large volume is needed.
    \[ L > 2 \text{ fm} \]
  - b-quark is too heavy.
    Small lattice spacing is needed.
    \[ a \ll (5 \text{ GeV})^{-1} = 0.04 \text{ fm} \]

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

Heavy Quark Effective Theory (HQET)

1/m_b expansion of QCD

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

- HQET: formal 1/m_b expansion of QCD
  \[ \bar{b} (\gamma_\mu D_\mu + m_b) b \rightarrow \mathcal{L}_{\text{stat}} + O(1/m_b), \]
  \[ \mathcal{L}_{\text{stat}} = \bar{b} (D_0 + \delta m) b \]
- Expansion is accurate for heavy quark mass \( m_b \gg \Lambda_{\text{QCD}} \)

Operator matching
- different renormalization \[ \rightarrow \] operator matching

\[ \begin{array}{ccc}
\text{continuum} & \leftrightarrow & \text{continuum} \\
\text{(full) QCD} & & \text{HQET} \\
\end{array} \]

\[ \begin{array}{ccc}
\text{lattice} & \leftrightarrow & \text{lattice} \\
\text{HQET} & & \text{HQET} \\
\end{array} \]

1-loop PT
[Eichten and Hill, 1990]

1-loop PT including O(a)
HQET on the lattice

Lattice discretization

\[ S_{\text{stat}} = \sum \bar{h}(\vec{x}, t) \left[ h(\vec{x}, t) - U_0^t(\vec{x}, t - 1) h(\vec{x}, t - 1) \right] \]

Gauge link smearing
- Static propagator is very noisy.

(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.

\[ A_\mu = \bar{h}\gamma_\mu\gamma_5 q, \quad A_0^{\text{cont}} = Z_A A_0^{\text{latt}} + O(a) \sim 10\% \]

\[ A_\mu = \bar{q}\gamma_\mu\gamma_5 q, \quad A_0^{\text{cont}} = Z_A A_0^{\text{latt}} + O(a^2) \sim 1\% \]

O(a) improvement of HQET operator

O(a) improvement

Introduction of O(a) counter terms

\[ A_0^{\text{cont}} = Z_A [A_0^{\text{latt}} + a \left( c_A \delta_0 A_0^{\text{latt}} + b_A m \bar{m} A_0^{\text{latt}} \right) + O(a^2) ] \]

Operator matching procedure
Effects of the O(a) improvement

- decay constants
  \( f_{B_d}, f_{B_s} : \downarrow 10\% \)

- bag parameters
  \( B_{B_d}, B_{B_s} : \uparrow 20\% \)

- matrix elements
  \( \mathcal{M}_{B_d}, \mathcal{M}_{B_s} : \text{small effect} \)

- SU(3) breaking ratio
  \[ \xi = \frac{f_{B_s}}{f_{B_d}} \sqrt{\frac{B_{B_s}}{B_{B_d}}} = \frac{m_{B_d}}{m_{B_s}} \sqrt{\frac{\mathcal{M}_{B_s}}{\mathcal{M}_{B_d}}} : \text{small effect} \]

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% \( \downarrow \).
  - Bag parameter \( B_B \) moves about 20% \( \uparrow \).
  - The effect for the matrix element \( \mathcal{M}_B \) and SU(3) breaking ratio \( \xi \) 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

- Heavy flavor SSA
  - 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

12/5/2008
Deep Inelastic Scattering probe partons in nucleon

Modern era: HERA

12/5/2008
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 26 May 1976)

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.

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)

\[
\frac{dN}{d\Omega} \propto 1 + \cos^2 \theta + \left( \frac{1}{3} - \frac{2}{3} \cos^2 \theta \right) A_0 \\
+ 2 \cos \theta \sin \theta \cos \phi A_1 + \frac{1}{3} \sin^2 \theta \cos 2\phi A_2 ,
\]

In the limit of \( Q^2 \to \) Infinity, Parton Model

\[
A_0 = Q^2 \langle (\vec{k}_1 - \vec{k}_2)^2 \rangle ,
\]

\[
A_1 = Q^2 |Q|^2 \langle (\vec{k}_1^2 - \vec{k}_2^2) \rangle ,
\]

\[
A_2 = 2Q^2 |Q|^2 \langle (\vec{k}_1^2 - \vec{k}_2^2)^2 \rangle - A_0 .
\]

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)

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

\[+ \gamma \sin \theta^* \cos 2\phi^* ,\]

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,

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

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

Pion induced experiments

E615, PRD39, 92

12/5/2008
**A_2** contribution from the Double initial state interaction

![Diagram](attachment:image.png)

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

- Total more than 200 diagrams

---

**Compare to the azimuthal symmetric one at small p_t**

\[
\frac{d\sigma}{dQ^2dydp_T} = \sigma_0 \frac{\alpha_s}{2\pi^2} C_F \frac{1}{Q^2} \int \frac{dx}{x} \sum_q \bar{c}_q \bar{q}(x) \left[ \frac{1 + \xi_1^2}{(1 - \xi_1)} - \delta(\xi_2 - 1) \right] + \frac{1 + \xi_2^2}{(1 - \xi_2)} \delta(\xi_1 - 1) + 2\delta(\xi_1 - 1) \delta(\xi_2 - 1) \ln \frac{Q^2}{Q^2_0} \]

\[
\sigma_0 = 4\pi \alpha_s^2 / 3N_C s Q^2
\]

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

---

12/5/2008
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

![Graph showing 2ν-(1−λ) vs. P_T (GeV/c)]
Neutrino astrophysics

Cecilia Lunardini
Arizona State University – Asst. prof.
RBRC - Fellow

After solar neutrinos: new challenges

- Understanding core collapse supernovae (SN) with $\nu$:
  - 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: $\nu$ from baryonic jets (Gamma Ray Bursts)
  - High energy $\nu$ from exotica (decay of heavy relics, ..)

- Ongoing tests of $\nu$ properties: using stars as $\nu$ factories
DUSEL: a multi-disciplinary facility

Proposed Timeline for Sanford Laboratory and DUSEL

<table>
<thead>
<tr>
<th>Sanford Laboratory at Homestake</th>
<th>Fiscal Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross Shaft Rehab and Pumping Column Commissioning</td>
<td>2007-2017</td>
</tr>
<tr>
<td>Yates Shaft Rehab</td>
<td></td>
</tr>
<tr>
<td>Gain safe access to 4850L for EEP construction start, and hold water level at 5000L</td>
<td></td>
</tr>
<tr>
<td>Install facility infrastructure for Davis Lab early experiments</td>
<td></td>
</tr>
<tr>
<td>Install and commission research instrumentation in Davis Lab</td>
<td></td>
</tr>
<tr>
<td>Early experiments in Davis Lab ready for operation</td>
<td></td>
</tr>
<tr>
<td>Continued rehabilitation and infrastructure upgrades for Sanford Lab</td>
<td></td>
</tr>
<tr>
<td>Transition from Sanford Lab to DUSEL Operations</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NSF Deep Underground Science and Engineering Laboratory at Homestake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake site selection announcement</td>
</tr>
<tr>
<td>DUSEL Preconstruction Planning and Development (R&amp;RA)</td>
</tr>
<tr>
<td>Preliminary Design Phase to develop Baseline Cost and Schedule</td>
</tr>
<tr>
<td>Preliminary Design Review and National Science Board Recommendation</td>
</tr>
<tr>
<td>Final Design Phase</td>
</tr>
<tr>
<td>Final Design Review and Authorization for Construction Start</td>
</tr>
<tr>
<td>DUSEL Facility - Proposed Construction and Commissioning (MREFC)</td>
</tr>
<tr>
<td>Proposed Construction Start</td>
</tr>
<tr>
<td>Near-Surface Campus Construction at 300L</td>
</tr>
<tr>
<td>300L Labs and Education and Outreach Facilities</td>
</tr>
<tr>
<td>Mid-Level Campus Construction at 4850 Level</td>
</tr>
<tr>
<td>4850L Common Facilities and Lab Module #1 (Excavation &amp; Lab Build-out)</td>
</tr>
<tr>
<td>4850L Lab Modules #2, #3 and #4</td>
</tr>
<tr>
<td>Deep-Level Campus Construction at 7400 Level</td>
</tr>
<tr>
<td>7400L Common Facilities and Lab Module #1 (Excavation &amp; Lab Build-out)</td>
</tr>
<tr>
<td>7400L Lab Modules #2 and #3</td>
</tr>
<tr>
<td>Surface Campus Construction</td>
</tr>
<tr>
<td>Phase 1 Offices and Laboratories</td>
</tr>
<tr>
<td>Phase 2 Offices and Laboratories</td>
</tr>
</tbody>
</table>
Scoping activities for DUSEL

- 2008 DUSEL meeting (April 2008, Lead, SD)
  - Water Cherenkov detector, 1 Mt
  - Liquid Argon detector, up to 100 kt


- DUSEL theory white paper from Ohio State U. meeting
  [http://www.ccapp.osu.edu/whitepaper.html](http://www.ccapp.osu.edu/whitepaper.html)
  - *Theorists support needed!*

Themes of my research

Physics that needs a new lab:
MeV – TeV $\nu$ from core collapse supernovae (SN)
The feeble signal of all SNe: diffuse flux

- Sum over the whole universe:
  \[ \sum \Phi^\star \]

- Background is the challenge!
  - Solar background removable

\[ \text{Number Flux} \ [\text{cm}^{-2} \ \text{s}^{-1} \ \text{MeV}^{-1}] \]

Neutrino Energy [MeV]


Status of theory: anti-\(\nu_e\) flux

- Differences due to different inputs/methods
**Experimental status (new!)**

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

<table>
<thead>
<tr>
<th>Species (experiment)</th>
<th>Previous best (cm(^{-2})s(^{-1}) 90%CL (\textit{direct limits only}))</th>
<th>New from SK (cm(^{-2})s(^{-1}) 90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-(\nu_e) (SK coll.)</td>
<td>1.2 ((E/\text{MeV}&gt;19.3))</td>
<td>1.4-2.0 ((E/\text{MeV}&gt;19.3))</td>
</tr>
<tr>
<td>(\nu_e) (SNO)</td>
<td>70, ((22.9&lt;E/\text{MeV}&lt;36.9))</td>
<td>42-54, ((22.9&lt;E/\text{MeV}&lt;36.9))</td>
</tr>
<tr>
<td>(\nu_\mu+\nu_\tau) (LSD)</td>
<td>(3 \times 10^7) ((E/\text{MeV}&gt;20))</td>
<td>((1.0-1.4) \times 10^3) ((E/\text{MeV}&gt;19.3))</td>
</tr>
<tr>
<td>Anti-(\nu_\mu) + anti-(\nu_\tau) (LSD)</td>
<td>(3.3 \times 10^7) ((E/\text{MeV}&gt;20))</td>
<td>((1.4-1.8) \times 10^3) ((E/\text{MeV}&gt;19.3))</td>
</tr>
</tbody>
</table>

**Including failed SNe: larger flux?**

C. L., Letter in preparation

- Contribution of BH-forming collapses
  - 10-20 % of the total, no explosion
  - \(\nu\) burst shorter and hotter: \(kE \sim 24\) MeV for anti-\(\nu_e\)

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

![Graph showing flux vs. E/MeV with NS, BH, and total contributions.](image-url)
Tomography of ONeMg SNe

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

- $^{97}\text{Tc}$ in Molybdenum rocks counts prehistoric $\nu_e$


$^{98}\text{Mo} + \nu_e \rightarrow ^{97}\text{Tc} + e^- + \nu$

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

- $^{97}\text{Tc}$ lifetime: $2.6 \times 10^6$ yrs: not primordial!
- Only $\nu_e$ SN data! Already available!

Modern version of the idea

- Include oscillations, *calculated cross sections*, known solar $\nu$ flux

R. Lazauskas, C.R., C. Volpe, to appear soon

<table>
<thead>
<tr>
<th>Tc97 atoms ($10^6$) in 10 kt rock</th>
<th>process</th>
<th>solar only</th>
<th>solar + supernova</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{98}\text{Mo} \rightarrow ^{97}\text{Tc}$</td>
<td>2.7</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>$^{97}\text{Mo} \rightarrow ^{97}\text{Tc}$</td>
<td>7.8</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>total ours</td>
<td>10.6</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>HJ, total</td>
<td>8.7</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>
High energy $\nu$ from deep jets in SN

• $\gamma$-Ray Bursts are from very few SNe with ultrarelativistic jets

• Slow ($\Gamma \sim$ few) jets could be very common in SNe $\rightarrow$ $\sim$ TeV flux of $\nu$ from SNe!

• Slow jet can be deep
  – $\nu$ oscillations
  – $\nu$ energy deposition (A. Loeb, C.L., in progress)
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: \( \bar{\ell} \ell \rightarrow H^0 \)
- Energy losses due to synchrotron radiation are suppressed by a factor of \( \left( \frac{m_e}{m_\mu} \right)^4 \approx 5 \times 10^{-10} \)
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)
  \[ D = \beta \gamma c t = \beta \gamma \times (660 \text{ m}) \]

Ionization Cooling

\((Dispersion, \ Li \ wedges, \ RF)\)

- Introduce x-E correlation (dispersion)
- All particles gain the same energy from RF acceleration
- Higher energy particles lose more energy as they pass through more absorber

Result:
- Reduced energy spread
- Unchanged mean energy
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)

Single-Cell Study Lattice

(Beam Direction)
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 \((x, P_x, \gamma, P_y)\) and longitudinal \((t, E)\) acceptances

![Closed orbit for \(P_{tot} = 164\ MeV/c\)](image-url)
Transverse Acceptance
x-P, Phase Space, R_{outer} = 120 mm

\[ P_{\text{tot}} = 164 \text{ MeV/c} \]

Transverse Stability: Look at Motion Around Closed Orbit

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

\[ \vec{u}(L) = \vec{f}(\vec{u}(0)) \]

\[ \vec{f}(0) = 0 \]

\[ \vec{u}(L) \approx M\vec{u}(0) \]

- Expand transfer function \( \vec{f}(\vec{u}) \) about the closed orbit to find transfer matrix \( M \)

- Examine eigenvalues: magnitude greater than one implies instability at that energy
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

Any Questions?
Probing Hot and Cold Nuclear Matter

Rainer Fries
Texas A&M University & RIKEN BNL

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)

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 \( \lambda \)

- 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 \( \pi \)
  - 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.

\[ \frac{dN}{dt} = \sum_{i} \lambda_i (p_i, T) N_i - \sum_{j} \lambda_j (p_j, T) M_j \]

- Here: reaction rates from elastic $2 \rightarrow 2$ collisions

\[
\begin{align*}
q + \bar{q} &\leftrightarrow g + g \\
q + g &\leftrightarrow g + q \\
g + Q &\leftrightarrow Q + g \\
g + g &\leftrightarrow Q + \bar{Q}
\end{align*}
\]

Quark / gluon conversions

- Photons and dileptons: inverse reaction negligible

- Heavy quarks production?

- Need to compare to $2 \rightarrow 3$ 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

\[
\begin{align*}
\text{jet} &\rightarrow \text{photon} \\
dN_{\text{me}} \rightarrow \frac{1}{\lambda} N_{\text{me}} \Rightarrow \frac{N_{\text{me} \rightarrow \text{photon}}}{\lambda}
\end{align*}
\]

\[ \text{Example: photons} \]
\[ \text{Need enough yield to outshine other sources of } N_{\text{me}}. \]

- Example 2: chemical equilibration of a rare probe particle

\[
\begin{align*}
\text{g} &\rightarrow s \\
g + s &\rightarrow s + g
\end{align*}
\]

\[ \text{Example: strangeness at RHIC} \]

\[ \text{Coupling of jets (not equilibrated) to the equilibrated medium should drive} \]

\[ \text{jets towards chemical equilibrium.} \]
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:

<table>
<thead>
<tr>
<th>Initial anisotropy</th>
<th>Final anisotropy</th>
<th>Elliptic flow $v_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>pressure gradient</td>
<td>collective flow</td>
</tr>
<tr>
<td>saturated hard probe</td>
<td>path length</td>
<td>quenching</td>
</tr>
<tr>
<td>rare hard $p_t$ probe</td>
<td>path length</td>
<td>additional production</td>
</tr>
</tbody>
</table>

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

Photons

- Conversion photons:
  - no clean experimental signal from single inclusive yields.
  - Conversion photons exhibit $v_2 < 0$
  - Another chance to catch them.
  - Other photon sources with vanishing or positive $v_2$ have to be added.

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

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

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.
Medium-induced energy loss at weak and strong coupling

Cyrille Marquet

Columbia University
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based on

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 $\hat{q} = 5 - 10$ GeV$^2$/fm
  however, for a weakly-coupled pQCD plasma we expect $\hat{q} \sim 1$ GeV$^2$/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

  $\psi \propto \frac{1}{k}$

  the energy of the gluon is denoted $\omega$
  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

  $P(m = 0) \sim \alpha_s \Lambda_c$  
  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 $t_c$
  average $p_T$ picked up in each scattering
  $p_T^2 \approx \mu^2 t_c \equiv \tilde{q} t_c$
  mean free path
  $\tilde{q} \equiv \mu^2 / \lambda \sim T^3$
  only property of the medium needed

- the saturation scale of the pQCD plasma
  only the fluctuations which pick up enough transverse momentum are freed $k_\perp < p_\perp$
  $p_T^2 = \tilde{q} \frac{\omega}{k_\perp^2} \Rightarrow k_\perp < (\tilde{q} \omega)^{1/4} \equiv Q_s$
  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
  $\omega = \gamma k_T = \gamma Q_s$ and $t_c = \gamma / Q_s$
  this allows to express $Q_s$ in terms of $T$ and E/M only
  $Q_s^2 = \sqrt{\tilde{q} \omega} \Rightarrow Q_s = (\tilde{q} \gamma)^{1/3} = T^{1/3}$ and $t_c = \gamma^{2/3} / T$
  and the heavy quark energy loss is
  $-\frac{dE}{dt} \approx \alpha_s N_c \frac{\gamma Q_s}{\gamma / Q_s} = \alpha_s N_c Q_s^2$

- 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 $Q_s^2 = \tilde{q} L$
  the radiated gluons which dominate the energy loss have
  $\omega = L k_\perp^2 = L Q_s^2$
Comparisons to RHIC data

- Armesto et al. (I)
- van Hees et al. (II)
- Moore & Teaney (III)

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 would 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 $\sim u$
  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 $v$: $x(t, u) = x_0 + vt + F(u)$
  $F(u) = \frac{1}{2u_h} \left[ \pi - \tan^{-1} \left( \frac{u}{u_h} \right) - \cot^{-1} \left( \frac{u}{u_h} \right) \right], \quad u_h = \pi T$
  corresponding rate of energy flow down the string:
  $-\frac{dE}{dt} = \frac{\sqrt{\pi} (\pi T)^2 v^2}{2\pi \sqrt{1 - v^2}}$
  [Herzog et al (2006)]
  [Gubser et al (2006)]
  [Liu et al (2006)]
  temperature $T = \text{temperature of the SYM plasma}$

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
<table>
<thead>
<tr>
<th>QCD at weak coupling</th>
<th>SYM at strong coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>heavy-quark energy loss</td>
<td>$-\frac{dE}{dt} \propto \alpha_s N_c Q_s^2$</td>
</tr>
<tr>
<td>coherence time $t_c$</td>
<td>$t_c = \gamma^{2/3}/T$</td>
</tr>
<tr>
<td>infinite matter or $t_c &lt; L$</td>
<td>$Q_s^2 = T^2 \gamma^{2/3}$</td>
</tr>
<tr>
<td>finite matter with $L &lt; t_c$</td>
<td>$Q_s^2 = \tilde{q} L$</td>
</tr>
</tbody>
</table>

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 $Q_s$

$$\frac{dE}{dt} \propto \left( \frac{\alpha_s N_c}{\sqrt{\lambda}} \right) Q_s^2 \quad \frac{dp_T^2}{dt} \propto \left( \frac{\alpha_s N_c}{\sqrt{\lambda}} \right) \frac{dQ_s^2}{dL}$$

• only the saturation scale differs between pQCD and SYM theories

$$Q_s^2 = T^2 (TL)^J \quad J = 1 \quad QCD \quad J = 2 \quad SYM$$

• the plasma length $L$ dependence is stronger in SYM compared to pQCD, for both the energy loss and $p_T$ broadening

• $Q_s$ 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 $\alpha_s N_c \frac{dQ_s^2}{dt}$

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

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

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

- 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

Denes Molnar
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

very opaque - large energy loss, even for heavy quarks

\[ R_{AA} = \frac{\text{measured yield}}{\text{expected yield for dilute system}} \]

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), ...

D. Molnar @ RBRC, Nov 17-18, 2008
Shear viscosity in QCD

Shear viscosity: \( T_{xy} = -\eta \frac{\partial v_x}{\partial y} \) acts to reduce velocity gradients

largely unknown at \( T \approx 200 - 400 \) 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):
\[
\eta/s \geq \frac{\hbar}{4\pi}
\]

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]

\[
T_{NS}^{\mu\nu} = T_{\text{ideal}}^{\mu\nu} + \eta (\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3} \Delta^{\mu\nu} \partial_\alpha u_\alpha) + \zeta \Delta^{\mu\nu} \partial_\alpha u_\alpha
\]

\[
N_{NS}^{\nu} = N_{\text{ideal}}^{\nu} + \kappa \left( \frac{n}{\varepsilon + p} \right)^2 \nabla^{\nu} \left( \frac{\mu}{T} \right)
\]

where \(\Delta^{\mu\nu} \equiv u^\mu u^\nu - g^{\mu\nu}\), \(\nabla^{\mu} = \Delta^{\mu\nu} \partial_\nu\) \([\partial_\mu \equiv u^\mu D + \nabla^\mu]\)

\(\eta, \zeta\) shear and bulk viscosities, \(\kappa\) heat conductivity

two problems:

correlation equations (e.g., heat flow) \(\rightarrow\) acausal Muller (76), Israel & Stewart (79) ...

instabilities Hiscock & Lindblom, PRD31, 725 (1985) ...

Causal dissipative hydro

Bulk pressure \(\Pi\), shear stress \(\pi^{\mu\nu}\), heat flow \(q^\mu\) are dynamical quantities

\[
T^{\mu\nu} \equiv T_{\text{ideal}}^{\mu\nu} + \pi^{\mu\nu} - \Pi \Delta^{\mu\nu}, \quad N^{\mu} \equiv N_{\text{ideal}}^{\mu} - \frac{n}{\varepsilon + p} q^\mu
\]

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 \((\tau_\Pi = \zeta \beta_0, \tau_q = \kappa_q T \beta_1, \tau_\pi = 2 \eta \beta_2)\)

Also follows from covariant transport - Grad's 14-moment approximation

\[
f(x, p) \approx [1 + \tilde{C}_\alpha p^\alpha + C_{\alpha\beta} p^\alpha p^\beta] f_{eq}(x, p)
\]
Complete set of Israel-Stewart equations of motion

\[ D\Pi = -\frac{1}{\tau\Pi} (\Pi + \zeta \nabla \mu u^\mu) \]
\[ -\frac{1}{2} \Pi \left( \nabla \mu u^\mu + D \ln \frac{\beta_0}{T} \right) \]
\[ + \frac{\alpha_0}{\beta_0} \partial_\mu q^\mu - \frac{\alpha_0'}{\beta_0} q^\mu D u_\mu \]

\[ Dq^\mu = -\frac{1}{\tau_q} \left[ q^\mu + \kappa_q \frac{T^2 n}{\varepsilon + p} \nabla \mu \left( \frac{\mu}{T} \right) \right] - u^\mu q_\nu D u^\nu \]
\[ -\frac{1}{2} q^\mu \left( \nabla _\lambda u ^\lambda + D \ln \frac{\beta_1}{T} \right) - \omega ^{\mu \lambda} q_\lambda \]
\[ -\frac{\alpha_0}{\beta_1} \nabla ^\mu \Pi + \frac{\alpha_1}{\beta_1} \left( \partial_\lambda \tau ^{\lambda \mu} + u^\mu \pi ^{\lambda \nu} \partial_\lambda u_\nu \right) + \frac{\alpha_0}{\beta_1} \Pi D u^\mu - \frac{\alpha_1}{\beta_1} \pi ^{\lambda \mu} D u_\lambda \]

\[ D\pi ^{\mu \nu} = -\frac{1}{\tau_\pi} \left( \pi ^{\mu \nu} - 2 \epsilon \nabla ^{(\mu) u ^{\nu)} \right) - \left( \pi ^{\lambda \mu} u ^{\nu} + \pi ^{\lambda \nu} u ^{\mu} \right) D u_\lambda \]
\[ -\frac{1}{2} \pi ^{\mu \nu} \left( \nabla _\lambda u ^\lambda + D \ln \frac{\beta_2}{T} \right) - 2 \pi ^{\langle \mu \nu \rangle} \pi ^{\langle \lambda \nu \rangle} \]
\[ -\frac{\alpha_1}{\beta_2} \nabla ^{(\mu) q ^{\nu)} + \frac{\alpha_1'}{\beta_2} q ^{(\mu) D u ^{\nu)} . \]

where \( A ^{(\mu \nu)} = \frac{1}{2} \Delta ^{\alpha \beta} \Delta ^{\nu \beta} (A _{\alpha \beta} + A _{\beta \alpha}) - \frac{1}{3} \Delta ^{\mu \nu} \Delta _{\alpha \beta} A ^{\alpha \beta} \quad \omega ^{\mu \nu} = \frac{1}{2} \Delta ^{\alpha \beta} \Delta ^{\nu \beta} (\partial_\beta u _\alpha - \partial_\alpha u _\beta) \)

Applicability of IS hydro

Israel-Stewart hydrodynamics comes from a quadratic truncation (Grad’s approach) that has no small control parameter.

⇒ 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 \( (\zeta = 0) \)

\[ \eta_s \approx \frac{4T}{5\sigma_{tr}}, \quad \tau_\pi \approx 1.2 \lambda_{tr} \equiv \frac{1.2}{n\sigma_{tr}} \quad \sigma_{tr} : \text{transport cross section} \]

Two scenarios: i) \( \sigma = \text{const} \) and ii) \( \eta/s \approx \text{const} \) (set via \( \sigma \propto \text{time}^{2/3} \)).

in both cases, longitudinally expanding system \( v_z = z/t \) (Bjorken flow)
**Pressure evolution for 0+1D longitudinal Bjorken expansion**

$P_{\text{ideal}} \propto \tau^{-4/3}$


$K_0 \equiv \tau_0 / \lambda_{tr,0}$ 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

$$K_0 \approx \frac{T_0 \tau_0}{5} \frac{s_0}{\eta s_0} \approx 12.8 \times \left( \frac{T_0}{1 \text{ GeV}} \right) \left( \frac{\tau_0}{1 \text{ fm}} \right) \left( \frac{1/(4\pi)}{\eta s_0/s_0} \right)$$

(4)

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

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

(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 $\sigma = \text{const} \sim 47\text{mb}$ (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: $\Pi = -\zeta \vec{v} \cdot \vec{v}$

largely unknown at $T \sim 200 - 400$ MeV relevant for RHIC

perturbatively tiny: $\zeta/s \sim 0.02\alpha_s^2$

on lattice: very preliminary

Arnold, Dogan, Moore, PRD74 ('06)

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

$$\frac{\Delta S_{\text{shear+bulk}}}{S_0} = \frac{S_f - S_0}{S_0} \lesssim 0.2 - 0.3$$

⇒ constrains initial shear and bulk stress, and initial time.

DM & Huovinen ('08): lattice EOS + Meyer's $\zeta/s$ (central points), $T_f = 180$ MeV

\[ \tau_0 = 0.6 \text{ fm} \]

\[ \tau_0 = 0.3 \text{ fm} \]

⇒ $\tau_0$ 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 $\eta/s \lesssim \text{few}/(4\pi)$
  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

\[ \partial_\mu T^{\mu\nu} = 0 \quad T^{ij} = p\delta^{ij} + \pi^{ij} \]

\[ \text{equilibrium correction} \]

- The “first order” stress tensor instantly assumes a definite form.

\[ \pi^{ij} = -\eta \left( \partial^i v^j + \partial^j v^i - \frac{2}{3} \delta^{ij} \partial \cdot v \right) \]

\[ O(\epsilon) = O(\epsilon) \]

- Can make “second order” models which relax to the correct form (Israel, Baier et al)

\[-\tau_R \partial_t \pi^{ij} + \text{other derivs} = \pi^{ij} + \eta \left( \partial^i v^j + \partial^j v^i - \frac{2}{3} \delta^{ij} \partial \cdot v \right) \]

\[ O(\epsilon^2) = O(\epsilon) + O(\epsilon) \]

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:

\[ T^{ij} \text{ is not asymptotic with } \sim \eta \left( \partial^i v^j + \partial^j v^i - \frac{2}{3} \delta^{ij} \partial \cdot v \right) \]

Freezeout is signaled by the equations.

3. Compute spectra:

\[ \text{Viscous corrections to the spectra grow with } p_T \]

\[ f_o \rightarrow f_o + \delta f \]

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
  \[ \frac{\eta}{e + p} \sim v_{\text{th}}^2 \tau_R \quad \quad p \sim e v_{\text{th}}^2 \]
- 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 $\eta/s$

Step 3: Viscous corrections to the distribution function $f_0 \to f_0 + \delta f$

- 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

\[ \delta f = F(|p|) p^i p^j \pi_{ij} \implies \delta f \propto f_0 p^i p^j \pi_{ij} \]

- Can fix the constant

\[ p \delta^{ij} + \pi^{ij} = \int \frac{d^3p}{(2\pi)^3} \frac{p^i p^j}{E_p} (f_0 + \delta f) \]

find

\[ \delta f = \frac{1}{2(e+p)T^2} f_0 p^i p^j \pi_{ij} \]
Viscous Hydro Results:

Not compared to data yet. $p/e = \frac{1}{3}$ massless bose gas. $\eta/s = \text{Const}$

Elliptic Flow as a function of viscosity and $p_T$, bottom line
$\eta/s = 0.2$ with $\delta f$ and without $\delta f$

$\eta/s = 0.05$ with $\delta f$ and without $\delta f$
$\eta/s = 0.2$ and gradients vs. $\pi^{ij}$

\[ \eta \langle \partial^i \nu^j \rangle = \eta \left( \partial^i u^j + \partial^j u^i - \frac{2}{3} \partial_i u^l \delta^{ij} \right) \]

Estimates the uncertainty

Compare to $\eta/s = 0.05$
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.
Quarkonia Transport in AdS/CFT:

- In AdS (colored) Heavy Quarks Experience a large drag:

$$\frac{dP}{dt} = -\frac{\pi}{2} \sqrt{\chi} T^2 P$$  \hspace{1cm} \text{(HKKKY; D.T., J. Casalderrey; S. Gubser)}

- How about colorless meson states?

$$\frac{dP}{dt} = 0 \text{ ???}$$  \hspace{1cm} \text{(Guijosa, Liu, Rajagopal, Wiedemann)}
Quarkonia in a Dipole Approximation

\[ \frac{1}{\pi T} \]

\[ \begin{array}{c}
\text{b} \\
\circ \\
\text{b}
\end{array} \]

\[ \mathbf{a}_o \]

\[ \frac{dP}{dt} = -\frac{T^2}{M} \times \frac{1}{\eta^2} \left( \frac{2\pi T}{M} \right)^6 \]

112.

Quarks: Where is the random motion in classical Gravity?

\[ \frac{dp}{dt} = -\eta_D p + \xi(t) \]

\begin{array}{c}
\text{Drag} \\
\text{Random Force}
\end{array} \]
Quantum Mechanics of the String in the Kruskal Plane

- The real time partition function of string for small fluctuations

\[ Z = \int \prod_{t_1} dX_1(t_1) \prod_{t_2} dX_2(t_2) \prod_{t,z} dx_1(t,z) dx_2(t,z) e^{iS_{NG}} \]

- The integrals over the internal coordinates can be done and yield

\[ Z = \int D X_1 D X_2 e^{i S_{\text{eff}}[X_1(X_1(t_1),X_2(t_2))]} \]

Result: Langevin with memory

- Find the average endpoint \( X_r = \left( X_1 + X_2 \right)/2 \) of the string obeys the expected Langevin equation

\[ M_0^0 \frac{d^2 X}{dt^2} + \int^t G_R(t - t')X(t') = \xi \]

- To quadratic order the retarded green function is

\[ G_R(\omega) = (\Delta M) \left( \omega^2 - i\omega \frac{\kappa}{2T} \right) \]

\[ \Delta M = \sqrt{\lambda T}/2 \quad \kappa = \sqrt{\pi T} \]

- Then find the following effective equation of motion

\[ M_{\text{kin}}(T) \frac{d^2 X}{dt^2} + \frac{\kappa}{2T} \frac{dX}{dt} = \xi \]

\[ M - \Delta M \]

\[ \text{drag} \]
Conclusions

- Quantum Mechanics of $AdS_5$ leads to thermal noise
  - Prototypical Example - Brownian Motion
- Other fields also fluctuate: the dilation $\phi$, the graviton $h^{\mu\nu}$, etc, fluctuate
  - Appealing gravity picture of meson diffusion

![Diagram](D7 Brane, Meson, Fluctuating graviton, Horizon)

- 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)

What is a semi-QGP?

Degrees of freedom
Mesons, baryons
Quarks, gluons

Order parameter = renormalized Polyakov Loop \( \ell = \frac{1}{N_c} \text{tr} P \exp \left( ig \int_0^{1/T} A_0 d\tau \right) \)

Global \( Z(N_c) \) symmetry
Broken at high \( T \)
Restored at low \( T \)

\( \langle \ell \rangle \) vs. \( T \)
Semi-QGP

Semi-QGP = partially deconfined QGP.

Degrees of freedom

"quarks", "gluons", "meson" and "baryon"

Heat bath \langle \text{tr} L_T \rangle \sim 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

\begin{itemize}
    \item Hadronic
    \item Semi-QGP
    \item Complete-QGP
\end{itemize}

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

\[ R(\ell) = \frac{\eta_{\text{semi-QGP}}}{\eta_{\text{complete-QGP}}} \]

Y.H., Pisarski ('08)

<table>
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<th>( N_f/N_c )</th>
<th>0</th>
<th>1/3</th>
<th>2/3</th>
<th>3/3</th>
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</thead>
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<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
</tr>
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</table>

Suppression! \( \sim \ell^2 \)

Large suppression \( \sim \ell^2 \)

Quark contribution dominates. \( q\bar{q} \) scattering

Why small viscosity?

Shear Viscosity: \( \eta \approx \frac{1}{3} n\bar{n}\lambda \)

Mean Momentum: \( \bar{p} \sim T \)

Complete QGP

Mean free path: \( \lambda^{-1} \sim n\sigma \)

\[ \eta \sim \frac{T}{\sigma} \quad \sigma \sim g^4/T^2 \]

Large cross section \( \rightarrow \) Small viscosity

Semi-QGP at small loop

Mean free path: \( \lambda^{-1} = \frac{\sum_{ab} n_a n_b \sigma_{ab}}{\sum_a n_a} \)

Color dependent

\[ \sum_a n_a \sim \ell^2 \]

\[ \sum_{ab} n_a n_b \sigma_{ab} \sim \ell^2 \sigma \]

\[ \eta \sim \frac{T}{\sigma} \ell^2 \]

Small viscosity!! at small \( \ell \)

even a small coupling
Viscosity/Entropy

\[ \eta \approx \frac{99.0 \times R(L)}{g^4(T) \ln(c/g(T))} \]

\[ g(T) : \text{one-loop running coupling} \]

\[ \frac{g^2(T_c)}{4\pi} \approx 0.3 \]

Lattice data from Cheng, et.al. PRD77, 014511(2008)

Large increase from \( T_c \) to 2 \( T_c \).
Clearly need results beyond leading log.

Summary

- Shear viscosity suppressed, near \( T_c \),
  \( \sim \ell^2 \). Quarks dominates.

- RHIC - probes semi-QGP? If so, not only \( \eta \),
  but \( R_A \), real photons, dileptons, also
  suppressed by powers of \( \ell \).

- LHC - into complete QGP?
  If so, LHC \( \neq \) 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

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

\[ \Phi^{(1)}(x_{01}; z_1) = \int_{z_0}^{z_1} \frac{dz_2}{z_2} \int \frac{d^2 x_{02}}{x_{02}^2} \frac{x_{01}^2}{x_{12}^2} \Phi^{(0)}(x_{01}; z_1). \]

- \begin{itemize}
  - Dipole in evolution
  - Gluon splitting
  - Gluonium with no gluons
\end{itemize}

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):

\[
d^2x_2 \left( \bar{Q}_{01} K_1(\bar{Q}_{01} x_{02}) \frac{\xi_2 \cdot x_{02}}{x_{02}} - \bar{Q}_{01} K_1(\bar{Q}_{01} x_{12}) \frac{\xi_2 \cdot x_{12}}{x_{12}} \right)^2
\]

with \( \bar{Q}_{01} = \frac{1}{x_{01} \sqrt{z}} \), \( z \) fraction of longitudinal momentum

Effects of the modified kernel

- Effective energy dependent cutoff (changing infrared cutoff) on the large dipole sizes

\[
x_{02}^{\text{max}} \sim \frac{x_{01}}{\sqrt{z_{\text{min}}}}
\]

- Suppressed diffusion in the impact parameter space: smaller cross sections.

\[
N(x_{01}, b_{01}) \sim \exp\left(-2 \frac{b_{01}}{x_{01} \sqrt{z}}\right)
\]

- 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.

\[ \Phi_{n+1}(r_1, \ldots, r_{n+1}) \propto \int \prod_{i=1}^{n} d^2r'_i K_{n+1}(\sqrt{Q^2 A(r_i, r'_i)}) \Phi_n(r'_1, \ldots, r'_n) \]

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
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.
Coherent and incoherent diffractive gluon production in pA collisions

Kirill Tuchin
(in collaboration with Y. Li)

Diffraction in particle physics

Pomerantchuk theorem: at $s \to \infty$ the amplitude is dominated by exchange of vacuum quantum numbers in t-channel.

$\Rightarrow$ Diffraction probes the high energy regime, i.e. low $x$ of QCD
**pp-scattering**

Scattering amplitude: $i\Gamma^{pp}(s, b)$

Optical theorem: $\sigma_{\text{tot}}^{pp} = 2 \int d^2 b \, \text{Re} \, \Gamma^{pp}(s, b)$

We can write: $\Gamma^{pp}(s, b) = 1 - e^{-ix^{pp}(s,b)}$

**pA-scattering**

Assume that all pN scatterings are independent:

$\chi^{pA}(s, B, \{b_a\}) = \sum_{a=1}^{A} \chi^{pN}_a(s, B - b_a)$

$\Gamma^{pA}(s, B, \{b_a\}) = 1 - \prod_{a=1}^{A} (1 - \Gamma^{pN}(s, B - b_a))$

$\sigma_{\text{tot}}^{pA} = 2 \int d^2 b \, \text{Re} \, \Gamma_{ii}^{pA}(s, b)$

where $\Gamma_{ij}^{pA}(s, B) = \langle A_i | \Gamma^{pA}(s, B, \{b_a\}) | A_j \rangle$
Neglecting motion of nucleons during the interaction:
\[
\Gamma_{ii}^{pA}(s, B) = \frac{1}{A} \prod_{a=1}^{A} d^2 b_a \rho T_A(b_a) \Gamma_{ii}^{pA}(s, B-b_a) \approx 1 - e^{-\int d^2 b_a \Gamma_{ii}^{pN}(s, b_a) \rho T_A(B-b_a)}
\]

Since \( R_p << R_A \):
\[
\Gamma_{ii}^{pA}(s, b) = 1 - e^{-\frac{1}{2} \sigma_{tot}^{pN} \rho T_A(b)}
\]

Coherent diffraction: \( A \) is intact
\[
\sigma_{CD}^{pA}(s) = \int d^2 b \left| \Gamma_{ii}^{pA}(s, b) \right|^2 = \int d^2 b \left( 1 - e^{-\frac{1}{2} \sigma_{tot}^{pN} \rho T_A(b)} \right)^2
\]

Incoherent diffraction: \( A \) dissociates into colorless debris
\[
\sigma_{ID}^{pA}(s) = \int d^2 B \sum_{i \neq j} \langle A_i | \Gamma_{ii}^{pA}(s, B, \{b_a\}) | A_j \rangle \langle A_j | \Gamma_{ij}^{pA}(s, B, \{b_a\}) | A_i \rangle
\]
\[
= \int d^2 B \sum_{i \neq j} \langle A_i | \Gamma_{ii}^{pA}(s, B, \{b_a\}) | A_j \rangle \langle A_j | \Gamma_{ij}^{pA}(s, B, \{b_a\}) | A_i \rangle - \int d^2 B \left| \langle A_i | \Gamma_{ii}^{pA}(s, B, \{b_a\}) | A_i \rangle \right|^2
\]
\[
= \int d^2 B \left[ \left| \langle A_i | \Gamma_{ii}^{pA}(s, B, \{b_a\}) | A_i \rangle \right|^2 - \left| \langle A_i | \Gamma_{ij}^{pA}(s, B, \{b_a\}) | A_i \rangle \right|^2 \right]
\]
\[
= \int d^2 b e^{-\sigma_{tot}^{pN} \rho T_A(b)} \left[ 1 - e^{-\sigma_{tot}^{pN} \rho T_A(b)} \right]
\]

**Diffraction in the dipole model**

Forward elastic dipole-nucleus scattering amplitude:
\[
N_A(r, b, Y) = \text{Re} \Gamma_{ii}^{q\bar{q}A}(s, b; r)
\]

Let \( x = \exp(-Y) \) if \( l_c = 1/(M_N x) \gg R_A \) \( \alpha_s A^{1/3} \sim 1 \), \( \alpha_s Y < 1 \)

\[
\sigma_{tot}^{q\bar{q}A}(s; r) = 2 \int d^2 b N_A(r, b, Y) = 2 \int d^2 b \left( 1 - e^{-\frac{1}{2} \sigma_{tot}^{q\bar{q}N}(s; r) \rho T_A(b)} \right)
\]

in the Born approximation:
\[
\sigma_{tot}^{q\bar{q}N}(s; r) = \frac{\alpha_s}{N_c} \pi r^2 x G(x, 1/r^2)
\]

Coherent diffraction:
\[
\sigma_{CD}^{q\bar{q}A}(s; r) = \int d^2 b \left| \Gamma_{ii}^{q\bar{q}A}(s, b; r) \right|^2 = \int d^2 b \left( 1 - e^{-\frac{1}{4} C_F \alpha_s^2 Q_{20}^2 r^2} \right)^2
\]

A.Mueller, 90
Diffractive gluon production

\[ \Gamma_{ii,\sigma}^{qgGA} = 1 - e^{-\frac{1}{8}(x - z_\sigma)^2 Q_{20}^2 - \frac{1}{8}(y - z_\sigma)^2 Q_{20}^2 - \frac{1}{8N_s}(x - y)^2 Q_{s0}^2} \]

Kopeliovich, Tarasov, Schafer, 99

Coherent diffraction

\[
\frac{d\sigma_{CD}(k, y)}{d^2k \, dy} = \frac{1}{(2\pi)^2} \int d^2b \, d^2z_1 \, d^2z_2 \, \Phi_{\perp}(x, y; z_1, z_2) \, e^{-ik \cdot (z_1 - z_2)}
\]

\[ \times \left( \Gamma_{ii}^{qgGA}(s, b; x, y, z_1) - \Gamma_{ii}^{qgA}(s, b; x, y) \right) \left( \Gamma_{ii}^{qgGA}(s, b; x, y, z_2) - \Gamma_{ii}^{qgA}(s, b; x, y) \right) \]

Kovner, Wiedeman 01, Kovchegov 01

Unlike the inclusive gluon production, the diffractive one vanishes when the onium size \( r = x - y \) larger than \( 1/Q_s \).

If \( \alpha_s Y \sim 1 \) the low \( x \) evolution effects must be taken into account:

\[ n(r, r', B - b, Y - y) \]

\[ N(r', b, y) \]

\[ N(r', b, y) \] satisfies the BK equation

\[
\frac{\partial N(x - y, b, y)}{\partial y} = \alpha_s N_s \frac{1}{2\pi^2} \int d^2z \frac{(x - y)^2}{(x - z)^2(y - z)^2} \left[ N(x - z, b, y) + N(y - z, b, y) - N(x - y, b, y) - N(x - z, b, y)N(y - z, b, y) \right]
\]

\[ n(r, r', B - b, Y - y) \] satisfies the BFKL equation (in accordance with the AGK cutting rules).
Incoherent diffraction

\[
\sum_{f \neq i} \langle A_i | \Gamma^{qgA}(s, B, \{b_a\}; x, y, z_1) | A_f \rangle^\dagger \langle A_f | \Gamma^{qgA}(s, B, \{b_a\}; x, y, z_2) | A_i \rangle
\]

\[
eq e^{-\frac{i}{2} \left[ \sigma_{qg}^{GN}(s; x, y, z_1) + \sigma_{qg}^{GN}(s; x, y, z_2) - \frac{1}{4\pi R_p^2} \sigma_{qg}^{GN}(s; x, y, z_1) \sigma_{qg}^{GN}(s; x, y, z_2) \right] \rho T_A(b)} \times \left\{ 1 - e^{-\frac{i}{2} \frac{1}{4\pi R_p^2} \sigma_{qg}^{GN}(s; x, y, z_1) \sigma_{qg}^{GN}(s; x, y, z_2) \rho T_A(b)} \right\}
\]

Since \(\alpha_s^2 A^{1/3} \sim 1\) \(\Rightarrow (\sigma_{qg}^{GN})^2 \rho T_A(b) \sim \alpha_s^2 A^{1/3} \sim \alpha_s^2\)

\(\Rightarrow\) we can expand

\[
\frac{d\sigma_{ID}(k, y)}{d^2k dy} = \frac{1}{(2\pi)^2} \frac{1}{8\pi R_p^2} \int d^2z_1 d^2z_2 \Phi^{qg}(x, y, z_1, z_2) e^{-ik(x_1 - x_2)} \rho T_A(b)
\]

\[
\times \left( \alpha_s^2 \sigma_{qg}^{GN}(s; x, y, z_1) e^{-\frac{i}{2} \sigma_{qg}^{GN}(s; x, y, z_1) \rho T_A(b)} - \sigma_{qg}^{GN}(s; x, y) e^{-\frac{i}{2} \sigma_{qg}^{GN}(s; x, y) \rho T_A(b)} \right)
\]

\[
\times \left( \alpha_s^2 \sigma_{qg}^{GN}(s; x, y, z_2) e^{-\frac{i}{2} \sigma_{qg}^{GN}(s; x, y, z_2) \rho T_A(b)} - \sigma_{qg}^{GN}(s; x, y) e^{-\frac{i}{2} \sigma_{qg}^{GN}(s; x, y) \rho T_A(b)} \right)
\]

**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).**
Experimental cuts will definitely enhance incoherent diffraction with respect to coherent one.

It's important to be able to experimentally distinguish ID and CD!

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.
**Gluon propagator and \( \bar{Q}Q \) potential in anisotropic pQCD**

Adrian Dumitru  
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Baruch College, CUNY

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

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Behavior of the potential in equilibrium at high T

\[ r_{\text{med}}(T) \approx 0.5 \text{ fm } (T_C/T) \]  
[Kaczmarek et al: PRD 70 (2004)]

\[ V_0 - \frac{\alpha'}{r} e^{-\mu r} + \frac{\sigma'}{\mu} (1 - e^{-\mu r}) \]

[Mocsy & Petreczky: PRD 77 (2008)]

\[ -\alpha + \sigma r \]

* Motivation II: expanding viscous plasma always (slightly) out of equilibrium

\[ f(p) = f_{iso}(\sqrt{p^2 + \xi p_z^2}) \]

anisotropy parameter

\[ p_T \]

\[ p_z \]

momentum distrib. \( f(p) \)

- Relation to viscosity: \[ \xi = 10 \frac{\eta}{T \tau} \frac{s}{s} \]  

- With \( \eta/s \sim 0.1, \tau T \sim 1-3 \), expect \( \xi \sim 1 \)
- **Lattice:**

\[
\langle \mathcal{O} \rangle = \int \mathcal{D}A \ e^{-S[A]} \ \mathcal{O}[A]
\]

average over isotropic gauge-field configurations (in momentum space)
⇒ non-equilibrium / viscosity effects are *not included*!

- need to rely on pQCD at short distance, models at large distance

---

- **Covariant-gauge gluon propagator in anisotrop. QGP**

1) HTL (retarded) self-energy

\[
\Pi^{\mu\nu} = g^2 \int \frac{d^3k}{(2\pi)^3} v^{\mu} \frac{\partial f(k)}{\partial k^\beta} \left( g^{\nu\beta} - \frac{v^\nu p^\beta}{p \cdot v + i\epsilon} \right)
\]

\[
(\Delta^{-1})^{\mu\nu}(p, \xi) = -p^2 g^{\mu\nu} + p^\mu p^\nu - \Pi^{\mu\nu}(p, \xi) - \frac{1}{\chi} p^\mu p^\nu
\]

invert: \((\Delta^{-1})^{\mu\sigma}\Delta_{\sigma}^{\ \ \nu} = g^{\mu\nu}\)

static limit:

\[
\Delta^{00}(\omega = 0, p) = \frac{p^2 + m_\alpha^2 + m_\gamma^2}{(p^2 + m_\alpha^2 + m_\gamma^2)(p^2 + m_\beta^2) - m_4^2}
\]
“Mass” scales:

\[
\begin{align*}
m_\alpha^2 &= -\frac{m_D^2}{2p_\perp^2 \sqrt{\xi}} \left( p_\perp^2 \arctan \sqrt{\xi} - \frac{p_\perp^2}{\sqrt{p^2 + \xi p_\perp^2}} \arctan \frac{\sqrt{\xi} p_\perp}{\sqrt{p^2 + \xi p_\perp^2}} \right) \\
m_\beta^2 &= m_D^2 \cdot \frac{(\sqrt{\xi} + (1 + \xi) \arctan \sqrt{\xi})(p^2 + \xi p_\perp^2) + \xi p_\perp \left( p_\perp \sqrt{\xi} + \frac{p_\perp^2(1+\xi)}{\sqrt{p^2 + \xi p_\perp^2}} \arctan \frac{\sqrt{\xi} p_\perp}{\sqrt{p^2 + \xi p_\perp^2}} \right)}{2\sqrt{\xi}(1 + \xi)(p^2 + \xi p_\perp^2)} \\
m_\gamma^2 &= -\frac{m_D^2}{2} \left( \frac{p^2}{\xi p_\perp^2 + p^2} - \frac{1 + 2\xi}{\sqrt{\xi}} \arctan \sqrt{\xi} + \frac{p_\perp p^2(2p^2 + 3\xi p_\perp^2)}{\sqrt{\xi}(\xi p_\perp^2 + p^2)^{3/2}} \arctan \frac{\sqrt{\xi} p_\perp}{\sqrt{p^2 + \xi p_\perp^2}} \right) \\
m_\delta^2 &= -\frac{\pi m_D^2 \xi p_\perp p_\perp |p|}{4(\xi p_\perp^2 + p^2)^{3/2}}.
\end{align*}
\]

Note:

for \( \xi = 0 \):

\[ m_\beta = m_D, \quad m_\alpha, \gamma, \delta = 0 \]

\[ \Rightarrow \Delta^{00}(\omega = 0, p) = \frac{1}{p^2 + m_D^2} \]

\[ \bullet \text{ 1-g exchange potential: F.T. of static propagator} \]

\[ V(r, \xi) = -g^2 C_F \int \frac{d^3 p}{(2\pi)^3} e^{ip \cdot r} \Delta^{00}(\omega = 0, p, \xi) \]

Limiting cases:

\[ \bullet \xi \to 0: \text{Debye-screened potential} \]

\[ V(r, \xi = 0) = V_{\text{iso}}(r) = -\frac{\alpha_s C_F}{r} e^{-r m_D} \]

\[ \bullet r \to 0: \text{Coulomb potential} \]

\[ V(r \to 0, \xi) = V_{\text{vac}}(r) = -\frac{\alpha_s C_F}{r} \]

(no string \( \sim \sigma r \) from perturbation theory)
• weak anisotropy $\xi \ll 1$: angular dependence of screening

$$V(r \parallel \hat{z}, \xi \ll 1) = V_{iso}(r) \left[ 1 + \xi \left( \frac{2 e^{\hat{r}} - 1}{\hat{r}^2} - \frac{2}{\hat{r}} - 1 - \frac{\hat{r}}{6} \right) \right]$$

$$= +0.27 \text{ for } \hat{r}=1$$

$$V(r \perp \hat{z}, \xi \ll 1) = V_{iso}(r) \left[ 1 + \xi \left( \frac{1 - e^{\hat{r}}}{\hat{r}^2} + \frac{1}{\hat{r}} + \frac{1}{2} + \frac{\hat{r}}{3} \right) \right]$$

$$= +0.12 \text{ for } \hat{r}=1$$

valid for $\hat{r} \equiv r m_D \lesssim 1$

• screening weaker for $r \parallel z$

• numerical results for arbitrary anisotropy $\xi$ and $r \parallel z$:

[Graphs showing $V(\hat{r})$ and $V(\hat{r}) / V_{iso}(\hat{r})$ for different values of $\xi$]

weakening of screening more pronounced at larger distance
• $r \parallel z$ versus $r \perp z$:

![Graph showing angular dependence](image)

- angular dependence stronger at larger distance
- as $r \to 0$, angular dependence disappears

**Discussion**

• anisotropy ($\xi > 0$) affects binding energy

ground state, $1 \gg \xi \gg m_D / (\alpha_s C_F m_Q)$:

$$\frac{\Delta E}{E_C} \approx \frac{4}{\alpha_s C_F} \frac{m_D}{m_Q} \left(-1 + \frac{\xi}{6} + \cdots\right)$$  

(upper universal, all states)

- temperature effect
- anisotropy / viscosity effect

• for larger states, shift of binding energy depends on angular momentum $\ell$! (not the same for $\eta_b$, $\Upsilon$, ...)
**Q free energy at \( \xi \neq 0 \) \((\to V_\infty/2)\)**

\[
L(x) = \mathcal{P} e^{ig \int d\tau A_0(x, \tau)}
\]

\[
\frac{1}{N} \langle \text{tr } L \rangle = e^{-F_Q/T} \sim 1 - F_Q/T
\]

\[
F_Q/T = 1 - \frac{1}{N} \langle \text{tr } L \rangle
\]

\[
\simeq -(ig)^2 \int d^3 x d\tau_1 d\tau_2 \frac{1}{N} \langle \text{tr } A_0(x, \tau_1) A_0(x, \tau_2) \rangle
\]

\[
= \frac{g^2 C_F}{T} \int \frac{d^3 k}{(2\pi)^3} \Delta_{00}(\omega = 0, k)
\]

\[
F_Q(\xi, T) = g^2 C_F \int \frac{d^3 k}{(2\pi)^3} \left[ \Delta_{00}(k) - \frac{1}{k^2} \right]
\]

\[
= -\alpha_s C_F m_D \left( 1 - \frac{1}{6} \xi + \frac{18 - \pi^2}{240} \xi^2 + \cdots \right)
\]

\~ \#T \Rightarrow \text{doesn't contribute to } V_\infty

---

**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 \((\to \text{width of quarkonium states})\)
  in an anisotropic plasma ?

Dynamical study of bare $\sigma$ pole with $1/N_c$ classifications

Toru Kojo (RIKEN BNL)
Daisuke Jido (YITP, Kyoto Univ.)

Introduction

The properties of exotica are fundamental issues in QCD.

\begin{align*}
\text{glueball} & \quad G G \\
\text{hadronic molecule} & \quad q q \, \bar{q} q \, \bar{q} q q q q \\
\text{multiquark} & \quad q q q q q
\end{align*}

$f_0 (1500) ? \quad \Lambda(1405) \text{ as KN molecule ?} \quad \Theta^+ (1540) ?$

Newly observed charmonia (X, Y, Z)

The $\sigma$ meson ($I=J=0$) is a candidate of these exotica:

\[ |\sigma \rangle \sim a |q \bar{q} \rangle + b |GG \rangle + c |\pi \pi \rangle + d |qqq\rangle + \ldots, \]

\[ (m + i \Gamma/2 \sim 500 + i 250 \text{ MeV}) \]

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

\[
|\sigma\rangle = a|\bar{q}q\rangle + b|GG\rangle + c|\pi\pi\rangle + d|qqqq\rangle + \ldots.
\]

- 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, \(\pi\pi\) scattering states.

---

**1/Nc classifications: 2q and 4q correlator**

- **2q correlator:**
  \[
  O(\text{Nc}) \quad \rightarrow \quad O(1)
  \]
  \(2q\)
  \(4q, \pi\pi\)
  \(GG\)

→ LO of 2q correlator is dominated by 2q state

- **4q correlator:**
  \[
  J_{MM}(x) = \sum_{F=1}^{3} (\bar{q}\tau_F \Gamma_M q)(\bar{q}\tau_F \Gamma_M q)
  \]
  (product of meson currents)

our interest

\[
O(\text{Nc}^2) \quad \rightarrow \quad O(\text{Nc}) \quad \rightarrow \quad O(1)
\]

**free MM, \pi\pi**
(2 closed color loops)

\[
4q, \text{2q, MM, } \pi\pi
\]

main contaminations
Isolation of resonance from $\pi\pi$ background

$4q$ current: $J_{MM}(x) = \sum_{F=1}^{3}(\bar{q}_F \Gamma_M q)(\bar{q}_F \Gamma_M q)$

- Overlap with $\pi\pi$ is determined from 3-point correlator:

  \[
  \begin{array}{c}
  \text{O(Nc)} \\
  \text{O(Nc)} \frac{1}{\sqrt{N_c}} \\
  \text{O(Nc)} \frac{1}{\sqrt{N_c}} \\
  \end{array}
  \quad \begin{array}{c}
  \text{O(1)} \\
  \text{O(1)} \frac{1}{\sqrt{N_c}} \\
  \text{O(1)} \frac{1}{\sqrt{N_c}} \\
  \end{array}
  \]

- \( \langle 0 | J_{MM} | \pi\pi \rangle \langle \pi\pi | J_{MM}^\dagger | 0 \rangle = O(1) \) (if \( M \neq \text{PS or A} \))

- Full \( \sigma \) spectrum \( \pi\pi \) (500)

QCD Sum Rules for reduced spectra

Borel transformed \((Q^2 \rightarrow M^2)\) dispersion relation

\[
\begin{align*}
\hat{L}_M \sum_n C_n(Q^2) \langle O_n \rangle & \iff \int ds \ e^{-\frac{s}{M^2}} \\
\text{OPE} & \text{ope}
\end{align*}
\]

taking the moments \( \rightarrow M(M^2, S_{th}), \lambda(M^2, S_{th}) \)

- \( S_{th} \) 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 \( N_c \), condensates can be factorized.
**Leading Nc results for 4q scalar mesons**

- We have also investigated other scalar correlators, and obtained consistent results.
- $4q$ is lighter than $2q$ by $200\sim 300$ MeV, irrespective of condensate values.

---

**Summary and Outlook**

- We proposed $1/N_c$ classifications for the study of exotica.
  - $1/N_c$ arguments are useful for the study of multiquark states.
  - $4q$ and meson molecule or scattering states can be studied separately.
- Dynamics of $\sigma$ meson are studied using the QCD sum rules.
  - In large $N_c$, 1-peak Ansatz for low energy part of spectrum & factorization of condensates are justified.
  - In $\sigma$ meson case, $4q$ component leads $200\sim 300$ MeV reduction of mass compared to $2q$ component.
  - $4q$ component has mass about $800\sim 900$ MeV, and does not solely explain the light mass ($500\text{MeV}$) of $\sigma$ meson.
    → importance of interplay with $\pi\pi$, $GG$, instanton effects, etc.
- It is interesting to apply $1/N_c$ to exotic charmonia (X,Y,Z) to clarify their properties, molecule-like or tetraquark-like structure.
Appendix. 1

Effective mass for $O(N_c)$ pure 2q correlators
(Without 2 meson intermediate states, instanton, and glueball.)

$2q\ (J^P = 1^-, S=1, L=0)$
Vector, $O(N_c)$ only

$2q\ (J^P = 0^+, S=1, L=1)$
Scalar, $O(N_c)$ only

Remark:
If we assume the $N_c$ scaling of condensates, the absence of the factorization violation leads the mass reduction when $N_c = 3 \rightarrow \infty$. 
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 \( \sim 12 \).

\[ \frac{1}{N_c} \text{ arguments resolve these problems} \]

- With appropriate currents \( \hat{J}_{MM}(x) \) (\( M = S, V, T \) meson)

\[
\begin{align*}
&\text{O}(N_c^2) & &2\pi & &E & \text{or} & \text{O}(N_c) & &2\pi & &E \\
&\frac{1}{2N_c^2} & &2\pi & &E & \text{or} & \text{O}(N_c) & &2\pi & &E \\
\end{align*}
\]

- Factorization for multi-quark, mixed condensates becomes exact!

\[
\langle 0 | (\bar{q}q)(\bar{Q}Q) | 0 \rangle = \text{O}(N_c) + \langle 0 | (\bar{q}q) | 0 \rangle \langle 0 | (\bar{Q}Q) | 0 \rangle + \sum_M \langle 0 | (\bar{q}q) | M \rangle \langle M | (\bar{Q}Q) | 0 \rangle \text{O}(N_c^{1/2})
\]

*Effective mass for \( O(N_c^2) + O(N_c) \) correlator*

( diagonal correlator: SS-SS, VV-VV case)

- \( N_c = \infty \) : only 2 meson scattering states
- \( N_c \to 3 \) : possible resonance + scattering states
  ( & violation of factorization approximation )

\[ \text{SS-SS, } O(N_c^2) + O(N_c), \text{ Eth } = 3.2 \text{ GeV} \quad \text{VV-VV, } O(N_c^2) + O(N_c), \text{ Eth } = 2.4 \text{ GeV} \]

![Graph showing effective mass vs. \( M^2 \)]

With \( N_c \to 3 \), typical effective mass shifts to low energy side. \( \rightarrow \) Resonance contribution?
Effective mass for $O(N_c)$ diagonal correlator

$O(N_c)$ part only $\rightarrow$ clean resonance spectra

without free scattering part

(Although diagonal correlators have the factorization violation of condensates)

**SS-SS, $O(N_c)$ only**

![Graph showing effective mass for SS-SS correlator with different energies and masses.]

**VV-VV, $O(N_c)$ only**

![Graph showing effective mass for VV-VV correlator with different energies and masses.]

Bare pole $\sim 800$ MeV  Bare pole $\sim 900$ MeV

Different correlators give qualitatively consistent results.

Effective mass for $O(N_c)$ off-diagonal correlator

Isolated pole & No factorization violation of condensates

**VV-SS mass**

![Graph showing effective mass for VV-SS correlator with different energies and masses.]

Bare pole $\sim 900$ MeV $< 2q$ mass $\sim 1.1$ GeV
Mass hierarchy: $\langle \bar{q} q \rangle$ & $\langle \bar{q} g_s \sigma G q \rangle$ dependence

$m_0^2 = \langle \bar{q} g_s \sigma G q \rangle / \langle \bar{q} q \rangle$

\[ m_R \ (I=J=0), \ m_0^2=0.7 \text{ GeV}^2 \]
\[ 0.8 \text{ GeV}^2 \]
\[ 0.9 \text{ GeV}^2 \]
\[ m_{2q} \ (I=J=0) \]

$\sim 150-200 \text{ MeV}$

$\sim 250-300 \text{ MeV}$

Bare mass relation: $\bar{m}_\rho < \bar{m}_{I=J=0} < \bar{m}_{I=J=0}$

Qualitative understanding

~ Crossing & annihilation diagrams

Here we consider $I=0$ & $I=2$ channel only.

Our $O(\text{Nc})$ OPE, main contribution comes from:

(with possible planar gluon lines inside quark loop)

Annihilation type

I=0 only
2q & 4q

Crossing type

I=0 & I=2
genuine 4q
Effective mass for crossing & annihilation diagrams

I = 0 only
annihilation, O(Nc) only

I = 0 & 2
crossing, O(Nc) only

SS-SS, $E_{th} = 1.15$ GeV
VV-VV, $E_{th} = 1.15$ GeV
VV-SS, $E_{th} = 1.20$ GeV
2q mass

SS-SS, $E_{th} = 1.3$ GeV
VV-VV, $E_{th} = 1.9$ GeV
VV-SS, $E_{th} = 1.9$ GeV
2q mass

Mass: $850 \sim 1000$ MeV
probably, no resonance

- Annihilation processes are mainly responsible to the existence of resonance below pure 2q state.
- No stability & consistency in Crossing processes
  $\rightarrow$ Absence of resonance in I = 2 channel at this order of Nc.

Appendix 2
Translation of QCD dynamics into hadronic ones
quark-gluon graph $\leftrightarrow$ hadron graph

$J = \bar{q} \Gamma q$

$O(N_c)$ meson $\rightarrow$ $\lambda_J$ $\rightarrow$ $O(N_c^{1/2})$

$g_{ijk} \rightarrow O(N_c^{-1/2})$

free scattering $\rightarrow$ scattering with interaction

$O(N_c^2) \gg O(N_c)$ $\rightarrow$ meson is free

decay intermediate state

$O(N_c) \gg O(N_c^0)$ $\rightarrow$ meson is stable

Products of meson operators:

$J_{MM}(x) = \sum_{F=1}^{3} (\bar{q} \tau_F \Gamma_{M} q) (\bar{q} \tau_F \Gamma_{M} q)$

$O(N_c^2)$

$O(N_c)$

$\hat{J}_{MM}(x)$

vanish when $M \neq \text{PS or A}$

$\Pi \Pi$ coupling starts from $O(1)$ (when $M \neq \text{PS or A}$)

$R \rightarrow \Pi \Pi$

$2M \rightarrow \Pi \Pi$

$\frac{1}{\sqrt{N_c}}$ $\Pi$
**Naive Nc scaling Ansatz for condensates**

GOR relation: \[ m^2 \pi f^2 = -2m_q \langle \bar{q}q \rangle \rightarrow \langle \bar{q}q \rangle = O(N_c) \]

Non-local quark condensate:
\[
\langle \bar{q}^a_i(0)q^b_j(x) \rangle = \delta^{ba} \delta_{ji} \times \left\{ \frac{1}{4N_c} \langle \bar{q}q \rangle + \frac{x^2}{2^6 N_c} \langle \bar{q}g_s \sigma Gq \rangle + \frac{\pi^2 x^4}{2^8 3} \times \frac{1}{N_c^2} \langle \bar{q}q \rangle \frac{\alpha_s}{\pi} G^2 + \ldots \right\}
\]

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:

\[ M^2 L_M \Pi^{(ope)} \approx \int_{0}^{s_{th}} ds \ e^{-\frac{s}{M^2}} \frac{1}{\pi} Im \Pi^{(phen)}(s) + \int_{s_{th}}^{\infty} ds \ e^{-\frac{s}{M^2}} \frac{1}{\pi} Im \Pi^{(ope)}(s) \]

- OPE bad
- OPE good

Borel window

- 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. $> 0.5$

\[ M_{\text{min}} < M < M_{\text{max}} \]
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
   \[ M_{\text{min}} < M < M_{\text{max}} \]

2. Plot the physical quantities as functions of \( M^2 \):
   averaged mass:
   \[ \bar{m}^2(M^2) = \frac{\int_{0}^{s_{\text{th}}} ds \ s e^{-\frac{s}{M^2}} \text{Im}\Pi(Q^2)}{\int_{0}^{s_{\text{th}}} ds \ e^{-\frac{s}{M^2}} \text{Im}\Pi(Q^2)} \]
   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)

---

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

RHIC – a High Luminosity (Polarized) Hadron Collider

Achieved peak luminosities (100 GeV, nucl.-pair):

<table>
<thead>
<tr>
<th>System</th>
<th>Luminosity (cm⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au–Au</td>
<td>120 x 10^{30}</td>
</tr>
<tr>
<td>p⁺⁻p⁺</td>
<td>35 x 10^{30}</td>
</tr>
</tbody>
</table>

Other large hadron colliders (scaled to 100 GeV):

<table>
<thead>
<tr>
<th>System</th>
<th>Luminosity (cm⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (p⁻pbar)</td>
<td>32 x 10^{30}</td>
</tr>
<tr>
<td>LHC (p⁻p, design)</td>
<td>140 x 10^{30}</td>
</tr>
</tbody>
</table>

Operated modes (beam energies):

- Au–Au: 4.6, 10, 32, 65, 100 GeV/n
- d–Au*: 100 GeV/n
- Cu–Cu: 11, 31, 100 GeV/n
- p⁺⁻p⁺: 11, 31, 100 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)
Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.
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

Before instability

After instability with ~ 10 ms growth rate

RHIC Luminosity Limit – Intra-Beam Scattering (IBS)

First successes in addressing IBS:
- Longitudinal stochastic cooling
- Stronger focusing lattice that suppresses 30% of transverse IBS → 20% smaller transverse emittance after 5 hours.

Intensities

Luminosities

- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

BROOKHAVEN NATIONAL LABORATORY
RHIC – First Polarized Hadron Collider

Without Siberian snakes: $v_{sp} = \gamma = 1.79 \text{ E}/\text{m} \rightarrow \sim 1000$ depolarizing resonances
With Siberian snakes (local $180^\circ$ spin rotators): $v_{sp} = \frac{1}{2} \rightarrow$ no first order resonances
Two partial Siberian snakes ($11^\circ$ and $27^\circ$ spin rotators) in AGS

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 $360^\circ$ twist

Courtesy of A. Luccio
Luminosity and Polarization Lifetimes in RHIC at 100 GeV

- Start of acceleration ramp
- Start of collisions
- Collimation complete

60 % polarization

Test of Polarized Proton Acceleration to 250 GeV

- Injection
- 250 GeV

45 % polarization on first acceleration to 250 GeV!

Loss at strong intrinsic resonance (136 GeV); correctable by adjusting betatron tunes.
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

[Image of graph showing current of bunches with 2, 3, or 4 collisions]

Tests of $\sqrt{s} = 9$ GeV Au-Au operation in RHIC

- 2007 data
- 2008 data: 56 bunches, STAR collisions
- Working points: blue (0.105, 0.110), yellow (0.114, 0.103)
- 2.75 hours
- 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

[T. Satogata, RHIC Retreat 2008]
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)
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: \(40 \times 10^{26} \text{ cm}^{-2} \text{s}^{-1}\); 500 GeV p-p: \(2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\)]
  - 0.5 m $\beta^*$ 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: \(6 - 12 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\)]
  - 0.3 m $\beta^*$ for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for beam-beam compensation (R&D underway)
  - Allows for higher intensity or lower emittance (× 2-4)
- eRHIC: high luminosity (\(\geq 1 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\)) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>Achieved</th>
<th>Luminosity upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV/nucleon</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>No of bunches</td>
<td>...</td>
<td>103</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>(10^9)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ave. delivered luminosity**</td>
<td>(10^{26} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>12</td>
<td>40*</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>100</td>
<td>100 (250)</td>
</tr>
<tr>
<td>No of bunches</td>
<td>...</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>(10^{11})</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Ave. delivered luminosity**</td>
<td>(10^{30} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>23</td>
<td>80 (200)</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

* 5 × ‘enhanced’ luminosity and 20 × design luminosity
** without vertex cuts
Spin Plan Projections

---|---|---|---|---|---|---|---|---|---|---
No. of bunches | 111 | 111 | 111 | 111 | 111 | 111 | 111 | 111 | 111 | 111
Peak current | 5x10^10 | 1.4 | 1.5 | 1.5 | 1.6 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0
Luminosity | mA | 187 | 205 | 250 | 264 | 280 | 280 | 280 | 280 | 280
J | T | 1.0 | 1.0 | 0.8 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6
Beam-beam parameter | Ip | 5x10^-9 | 5.6 | 4.9 | 4.1 | 5.6 | 7.5 | 7.5 | 7.5 | 7.5
Peak luminosity (GeV) | T | 26 | 35 | 40 | 46 | 50 | 50 | 50 | 50 | 50
Avg. peak luminosity | % | 74 | 61 | 80 | 80 | 80 | 80 | 80 | 80 | 80
Avg. store luminosity (GeV) | (T/mm)^-1 | 25 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40
Time at store | % | 46 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60
Max. luminosity (GeV) | T | 6.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5
Min. luminosity (GeV) | T | 40 | 19 | 13 | 15 | 18 | 20 | 20 | 20 | 20
Max. luminosity/n (500 GeV) | T | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50
Min. luminosity/n (500 GeV) | T | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50
Ach. polarization | % | 65 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55
RHIC ring polarization, mm | % | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50

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

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
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 \(\times\) 10\(^{11}\) charges/bunch with \(\varepsilon_{N,\text{rms}} = 1-2 \mu\text{m}\))
- Achieved 1.7 \(\times\) 10\(^{9}\) Au\(^{33+}\) in 20 \(\mu\text{s}\) pulse with 8 A electron beam (60% neutralization)
- Construction of EBIS, RFQ and IH Linac complete by 2010

EBIS Pre-injector Layout

<table>
<thead>
<tr>
<th>Ion</th>
<th>He - U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q/m</td>
<td>(\geq 1/6)</td>
</tr>
<tr>
<td>Current</td>
<td>(&gt; 1.5) emA (for 1 turn inj)</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>10 (\mu\text{s})</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Time to switch species</td>
<td>1 second</td>
</tr>
</tbody>
</table>
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

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
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 (~1/2 normal injection energy)

Successful operation of longitudinal stochastic cooling

Future runs/upgrade plans:

- Luminosity upgrade to $40 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ through high energy beam cooling
- High luminosity 250 x 250 GeV polarized proton run at $2 \times 10^{32}$ 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
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

- 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

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 \( v_{sp} = 0.5 \), only partial spin flip
- Two AC dipoles with vertical spin precession in between creates rotating drive field
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: $f_\pi$ 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: $\epsilon'/\epsilon$

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
  * 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:
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 $m_\pi = 540$ 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 $\psi_L$ and $\psi_R$ leaving small residual $\chi_{SB}$

• Lattice theory has chiral symmetry like continuum theory
  * $m_{\text{quark}} = m_{\text{input}} + m_{\text{res}}\{1 + O[(a\Lambda_{QCD})^2]\}$
  * Operator mixing: like continuum with small corrections ($m_{\text{res}}^2$)
  * 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

Neutral-Kaon Mixing from (2 + 1)-Flavor Domain-Wall QCD


(RBC and UKQCD Collaborations)


Nonperturbative renormalization of quark bilinear operators and $B_K$ using domain wall fermions


(RBC and UKQCD Collaborations)

3. hep-lat/0804.0473, accepted by PRD: quark masses and decay constants

BNL-HEP-06/5, 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

### Summary of Calculations

<table>
<thead>
<tr>
<th></th>
<th>$1/a = 1.73(3)$ GeV</th>
<th>$1/a = 2.42(4)$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\pi$ (dyn. mass)</td>
<td>331, 419, 558, 672 MeV</td>
<td>310, 365, 420 MeV</td>
</tr>
<tr>
<td>$m_{\bar{s}s}$</td>
<td>743 MeV</td>
<td>780 MeV</td>
</tr>
<tr>
<td>lightest valence $m_\pi$</td>
<td>240 MeV</td>
<td>235 MeV</td>
</tr>
<tr>
<td>Volume</td>
<td>$(2.74 \text{ fm})^3$</td>
<td>$(2.60 \text{ fm})^3$</td>
</tr>
<tr>
<td>$m_{\text{res}}$ (unrenorm.)</td>
<td>5.4 MeV</td>
<td>1.6 MeV</td>
</tr>
<tr>
<td>Ensemble length</td>
<td>5000 MD units</td>
<td>~6000 MD units</td>
</tr>
<tr>
<td>Computer time</td>
<td>~ 2.0 Tflop-ys QCDOC</td>
<td>2.9 TFlops-ys QCDOC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(over 1.8 calendar yrs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~5 TFlops-ys BG/P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(over 0.7 calendar yrs)</td>
</tr>
</tbody>
</table>

#### DWF Production time history

$32^3 \times 64 \times 16, m_s = 0.03$

- $m_l = 0.004$ QCDOC(DOE)
- $m_l = 0.004$ BG/P (2K,4K)
- $m_l = 0.004$ QCDOC(UKQCD)
- $m_l = 0.006$ QCDOC 4K (UKQCD)
- $m_l = 0.006$ ANL BG/P
- $m_l = 0.008$ ANL BG/P 2K
- $48^3 \times 64 \times 16, m_l = 0.002$ ANL BG/P (4,8K)

Chulwoo Jung
Partially Quenched Chiral Perturbation Theory

- Let masses in propagators differ from masses in determinants
- Expansion in powers of
  \[ \frac{m^2_{PS}}{(4\pi f)^2} \quad \frac{p^2}{(4\pi f)^2} \]

- SU(2) ChPT: \( m_1 \) is light and only pion masses enter in logs
- SU(3) ChPT: \( m_1 \) and \( m_s \) are considered light, and both enter logs
- Example (Sharpe and Shoresh, 2000) with six free parameters

\[
m_P^2 = \chi_V \left\{ 1 + \frac{48}{f^2} (2L_0 - L_4)\chi + \frac{16}{f^2} (2L_5 - L_5)\chi \right\} \\
\chi_V \log \chi_V - \frac{(\chi_V - \chi_l)(\chi_V - \chi_s)}{(\chi_V - \chi_l)^2} \chi_V \log \chi_V \\
+ \frac{\chi_V - \chi_l)(\chi_V - \chi_s)}{\chi_V - \chi_l} (1 + \log \chi_V) + \frac{(\chi_s - \chi_l)(\chi_s - \chi_s)}{(\chi_V - \chi_s)^2} \chi_s \log \chi_s \right\} \\
\chi_l = 2B_0(m_1 + m_{\text{res}})
\]

SU(2) Chiral Perturbation Theory, \( 1/a = 1.73 \) GeV

\[
m_\pi = 331 \text{ MeV ensemble}
\]

\[
m_\pi = 419 \text{ MeV ensemble}
\]
SU(2) ChPT for Kaons

- Light quark logarithms needed to extrapolate to physical $m_u$, $m_d$
- Only needs $m_\pi/m_K$ 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

\[
e = \hat{B}_K \Im \lambda_i \frac{G_F^2 f_K^2 m_K M_K^2}{12\sqrt{2}\pi^2 \Delta M_K} \{\Re \lambda_c \{\eta_1 S_0(x_e) - \eta_3 S_0(x_c, x_t)\} - \Re \lambda_t \eta_2 S_0(x_t)\} \exp(i\pi/4)
\]

\[
\langle \bar{K}^0 | Q^{(\Delta S=2)}(\mu) | K^0 \rangle \equiv \frac{8}{3} B_K(\mu) f_K^2 m_K^2
\]
\( \varepsilon \) and the Unitarity Triangle

- Summer 2007 plot uses \( B_K = 0.75 \pm 0.17 \) to plot band
- \( B_K \) from lattice not used in fit

\[
\begin{array}{c}
\end{array}
\]

CKMfitter Group (J. Charles et al.),

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.

\[(\bar{s}d)^{\text{lat}}_{V-A} (\bar{s}d)^{\text{lat}}_{V-A} = Z_1 (\mu a) (\bar{s}d)_{V-A} (\bar{s}d)_{V-A} + Z_2 (\mu a) (\bar{s}d)_{V+A} (\bar{s}d)_{V+A} + Z_3 (\mu a) (\bar{s}d)_{P-S} (\bar{s}d)_{P-S} + Z_4 (\mu a) (\bar{s}d)_{P+S} (\bar{s}d)_{P+S} + Z_5 (\mu a) (\bar{s}d)_T (\bar{s}d)_T\]

- Mixings are $O(m^2_{\text{res}})$ 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.

\[
\begin{align*}
Z_{B_K}^{\text{RI}}(2\text{GeV}) & = 0.910(5)_{\text{stat}}(13)_{\text{syst}} \\
Z_{B_K}^{\text{MS}}(2\text{GeV}) & = 0.928(5)_{\text{stat}}(23)_{\text{syst}}
\end{align*}
\]

Physical results using SU(2) ChPT

\[
\begin{align*}
f & = 114.8(4.1)_{\text{stat}}(8.1)_{\text{syst}} \text{MeV}, \\
B_{\text{MS}}(2\text{GeV}) & = 2.52(0.11)_{\text{stat}}(0.23)_{\text{ren}}(0.12)_{\text{syst}} \text{GeV}, \\
\Sigma_{\text{MS}}(2\text{GeV}) & = \left(255(8)_{\text{stat}}(9)_{\text{ren}}(13)_{\text{syst}} \text{MeV}\right)^3, \\
\bar{t}_3 & = 3.13(0.33)_{\text{stat}}(0.24)_{\text{syst}}, \\
\bar{t}_4 & = 4.43(0.14)_{\text{stat}}(0.77)_{\text{syst}}, \\
A_3 & = 666(110)_{\text{stat}}(80)_{\text{syst}} \text{MeV}, \\
A_4 & = 1,274(92)_{\text{stat}}(490)_{\text{syst}} \text{MeV}, \\
m_{ud}^{\text{MS}}(2\text{GeV}) & = 3.72(0.16)_{\text{stat}}(0.33)_{\text{ren}}(0.18)_{\text{syst}} \text{MeV}, \\
m_{u}^{\text{MS}}(2\text{GeV}) & = 107.3(4.4)_{\text{stat}}(9.7)_{\text{ren}}(4.9)_{\text{syst}} \text{MeV}, \\
m_{d}^{\text{MS}}(2\text{GeV}) & = 1:28.8(0.4)_{\text{stat}}(1.6)_{\text{syst}}, \\
m_{ud} : m_s & = 1:28.8(0.4)_{\text{stat}}(1.6)_{\text{syst}}, \\
f_{\pi} & = 124.1(3.6)_{\text{stat}}(6.9)_{\text{syst}} \text{MeV}, \\
f_{K} & = 149.6(3.6)_{\text{stat}}(6.3)_{\text{syst}} \text{MeV}, \\
f_{K} / f_{\pi} & = 1.205(0.018)_{\text{stat}}(0.062)_{\text{syst}}, \\
B_{K}^{\text{MS}}(2\text{GeV}) & = 0.524(0.010)_{\text{stat}}(0.013)_{\text{ren}}(0.025)_{\text{syst}}.
\end{align*}
\]
Other Lattice Results for $B_K$

- Laurent Lellouch reviewed kaon physics and ChPT at Lattice 2008
- Summary of $B_K$ given by Lellouch

<table>
<thead>
<tr>
<th>ref.</th>
<th>$N_f$</th>
<th>action</th>
<th>$a$ [fm]</th>
<th>$L_{M}$</th>
<th>$M_r$ [MeV]</th>
<th>$\hat{B}_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLQCD '08 (Hashimoto)</td>
<td>2</td>
<td>Overlap</td>
<td>0.12</td>
<td>2.7</td>
<td>$\geq 290$</td>
<td>0.734(5)(50)</td>
</tr>
<tr>
<td>ETM '08 (Vladikas)</td>
<td>2</td>
<td>OS/tmQCD</td>
<td>0.07,0.09</td>
<td>3.1</td>
<td>$\geq 300$</td>
<td>0.785(10)(16)</td>
</tr>
<tr>
<td>HPQCD/UKQCD '06</td>
<td>2+1</td>
<td>$K_S^{\text{HYP}}_{\text{MELC}}$</td>
<td>0.125</td>
<td>4.5</td>
<td>$\geq 360$</td>
<td>0.85(2)(18)</td>
</tr>
<tr>
<td>RBC/UKQCD '07-08 (Scholtz)</td>
<td>2+1</td>
<td>DWF</td>
<td>0.11</td>
<td>4.6</td>
<td>$\geq 330$</td>
<td>0.717(14)(39)</td>
</tr>
<tr>
<td>Bae et al '08 (Lee)</td>
<td>2+1</td>
<td>$K_S^{\text{HYP}}_{\text{MELC}}$</td>
<td>$\geq 0.06$</td>
<td>4</td>
<td>$\geq 240$</td>
<td>$\Delta B_K \rightarrow 3%$</td>
</tr>
</tbody>
</table>

SU(3) ChPT for $m_{PS} < 420$ MeV

![Graphs showing SU(3) ChPT for $m_{PS} < 420$ MeV](image)
Summary of SU(3) ChPT Fits

- Fit functions agree 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

<table>
<thead>
<tr>
<th></th>
<th>$L_4^{(3)}$</th>
<th>$L_5^{(3)}$</th>
<th>$L_6^{(3)}$</th>
<th>$L_8^{(3)}$</th>
<th>$(2L_8^{(3)} - L_5^{(3)})$</th>
<th>$(2L_6^{(3)} - L_4^{(3)})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>this work$^a$</td>
<td>1.4(0.8)(-)</td>
<td>8.7(1.0)(-)</td>
<td>0.7(0.6)(-)</td>
<td>5.6(0.4)(-)</td>
<td>2.4(0.4)(-)</td>
<td>0.0(0.4)(-)</td>
</tr>
<tr>
<td>Bijnens, NLO</td>
<td>≡ 0</td>
<td>14.6</td>
<td>≡ 0</td>
<td>10.0</td>
<td>5.4</td>
<td>≡ 0</td>
</tr>
<tr>
<td>Bijnens, NNLO</td>
<td>≡ 0</td>
<td>9.7(1.1)</td>
<td>≡ 0</td>
<td>6.0(1.8)</td>
<td>2.3$^b$</td>
<td>≡ 0</td>
</tr>
<tr>
<td>MILC, 2007</td>
<td>1.3(3.0)(±3.0)</td>
<td>13.9(2.0)(±2.0)</td>
<td>2.4(2.0)(±2.0)</td>
<td>7.8(1.0)(1.0)</td>
<td>2.6(1.0)(1.0)</td>
<td>3.4(1.0)(±2.0)</td>
</tr>
</tbody>
</table>

$f_{PS}$ comparison SU(2) and SU(3) ChPT

---

304
SU(2) ChPT fits to new $1/a = 2.42$ GeV data

**PRELIMINARY**

<table>
<thead>
<tr>
<th>$m_T$ (MeV)</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>272</td>
</tr>
<tr>
<td>365</td>
<td>312</td>
</tr>
<tr>
<td>420</td>
<td>226</td>
</tr>
</tbody>
</table>

- 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

![Graph showing $B_K$ from $1/a = 2.42$ GeV data]

$B_K$ with $m_T = 0.03$ and fit $m_x \leq 0.008$
CP Violation in the Kaon System

Two amplitudes determine \( \epsilon \) and \( \epsilon' \)
\[
\frac{\eta_{+-}}{A(K^0 \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon' \quad \frac{\eta_{00}}{A(K^0 \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon'
\]

Measurements of 2 real numbers needed:
\[
|\epsilon| \quad |\eta_{00}/\eta_{+-}|^2 \approx 1 - 6 \Re(\epsilon'/\epsilon) \approx 1 - 6 \epsilon'/\epsilon
\]

Defining \( A(K^0 \rightarrow \pi\pi(I)) = A_I e^{i\delta_I} \) gives
\[
\epsilon' = \frac{i \epsilon e^{i(\delta_2 - \delta_0)}}{\sqrt{2}} \left( \frac{\Re A_2}{\Re A_0} - \frac{\Im A_0}{\Re A_0} \right)
\]
and the \( \Delta I = 1/2 \) rule
\[
\omega = \frac{\Re A_0}{\Re A_2} \sim 22
\]

\[
K \rightarrow \pi\pi \text{ in 3-flavor Effective Theory}
\]

- Hamiltonian for 3-flavor effective theory: only 7 of 10 operators independent

\[
\mathcal{H}(\Delta S = 1) = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[ z_i(\mu) + \tau y_i(\mu) \right] Q_i \right\}
\]

- \( K \rightarrow \pi\pi \) from lattice calculations and LO chiral perturbation theory.

<table>
<thead>
<tr>
<th>Irrep</th>
<th>Isospin</th>
<th>( K^+ \rightarrow \pi^+ )</th>
<th>( K^0 \rightarrow \pi^+\pi^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(27,1)</td>
<td>1/2, 3/2</td>
<td>(-\frac{4m_M^2}{f^2}\alpha^{(27,1)})</td>
<td>(-\frac{4i}{f^3}m^2_{K^0}\alpha^{(27,1)})</td>
</tr>
<tr>
<td>(8,8)</td>
<td>1/2, 3/2</td>
<td>(-\frac{12}{f^2}\alpha^{(8,8)})</td>
<td>(-\frac{12i}{f^3}\alpha^{(8,8)})</td>
</tr>
<tr>
<td>(8,1)</td>
<td>1/2</td>
<td>(\frac{4m_M^2}{f^2}(\alpha_1^{(8,1)} - \alpha_2^{(8,1)}))</td>
<td>(\frac{4i}{f^3}m^2_{K^0}\alpha_1^{(8,1)})</td>
</tr>
</tbody>
</table>

- (8,1) coefficient \( \alpha_2^{(8,1)} \) is power divergent, \( \mathcal{O}(1/a^2) \). Determine from \( K \rightarrow |0\rangle \)
LO and NLO contributions to SU(3) fits

![Graph illustrating LO and NLO contributions to SU(3) fits.]

Fit another ratio

![Graph illustrating fit to another ratio.]

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LO and NLO contributions to second fit

\[ \langle \pi^+ | O^{(2)}(K^0\bar{K}^0)| K^+ \rangle / \langle m_K \rangle \]

\[ m_s + m_{\text{res}} \]

\[ m_t = 0.005 \]

\[ m_s = 0.005 \]

leading order

log

analytical

\[ \epsilon^* / \epsilon \] from 2+1 flavor DWF QCD

- 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 $m_\pi$
- Extrapolation to continuum limit forthcoming
- Current $B_K$ result has 5% total error. Lattice error may soon (no longer?) be smaller than other errors in $\varepsilon$
- $\varepsilon'/\varepsilon$ 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 $p \sim 2$ GeV
  - Discrete lattice breaks chiral symmetry
  - Uncertain systematic errors.
RBRC lattice program

• 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 $\varepsilon'/\varepsilon$
  – Landmark calculation
  – Result, $\varepsilon'/\varepsilon = -4.0(2.3) \times 10^{-4}$, far from experiment: $17.2(1.8) \times 10^{-4}$
  – 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 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)

• $B_K^{\overline{MS}} = 0.524 (0.010)_{\text{stat}} (0.013)_{\text{ren}} (0.025)_{\text{syst}}$
• $f_K/f_\pi = 1.205 (0.018)_{\text{stat}} (0.062)_{\text{syst}}$
• $(m_u+m_d)/2 = 3.72 (0.16)_{\text{stat}} (0.33)_{\text{ren}} (0.18)_{\text{syst}}$ MeV
• $m_s = 107.3 (4.4)_{\text{stat}} (9.7)_{\text{ren}} (4.9)_{\text{syst}}$ MeV
• $Kl3: f_\pi(0) = 0.9644 (33)_{\text{stat}} (37)_{\text{syst}}$
• 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 $K \to \pi\pi$, $\Delta I = 1/2$ rule and $\epsilon'/\epsilon$
  - 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
  - $\epsilon'/\epsilon = 7.6 (68)_{\text{stat}}(256)_{\text{syst}} 10^{-4}$
  - Must calculate $K \to \pi\pi$ directly

Next Opportunities
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
  - $\eta'$ mass
  - Nucleon decay
  - $g_4$
  - 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:
    - $K \rightarrow \pi \pi$, $\Delta I = \frac{1}{2}$ rule and $\varepsilon'/\varepsilon$
    - Nucleons in large volumes

RBRC Review - Nov. 18, 2008 (12)
Next Opportunities : 2-5 years

- Light quark limit, $m_\pi \sim 135$ MeV requires:
  - $1/a \sim 1.7 - 2.5$ GeV
  - $L = 5 - 6$ fm
  - $64^3 \times 128$ 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 $2^6 = 64$ performance increase.
  - $75x$ QCDQC upgrade

QCDCQ Project
(QCD with Chiral Quarks)
QCDOC

- 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

QCDOC

- Target:
  - 300 Tflops sustained
  - 16 TByte memory
  - $5M cost
  - If approved, construction starts in Fall 2009

- 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

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 \( \Delta I = \frac{1}{2} \) rule and \( c' \) 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, \( T \leq T_c \)
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 → ππ)
  - 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 (polarized)
- d+Au
- Cu+Cu
- Au+Au

Energy:
- $s_{NN}^{1/2}=200$ GeV
- Also @ 130 GeV
  - 62 GeV
  - 56 GeV
  - 22 GeV (10 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 \( \pi^0 A_{LL} \) in RUN5+RUN6 have a strong constraint on \( \Delta G(x) \)
  - Data: Ldt\( \sim 10/\)pb or P4L\( \sim 1/\)pb
  - Large gluon polarization at \( x\sim 0.1 \) 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/\( \text{pb} @ 60-65\%) \) will give stronger upper limit (red) on positive \( \Delta G \) or reveal a small non-zero value of \( \Delta G \)

---

Rare probe data from RHIC/PHENIX

- **High pT suppression**
- **J/\( \psi \) suppression**
- **Heavy Quark energy loss and flow**
- **Low pT direct photon**
- **Low mass lepton pair enhancement**

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.
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
\( \mu \text{Trig} \)

---

RHIC and PHENIX Upgrades

<table>
<thead>
<tr>
<th>Current MOU</th>
<th>RHIC</th>
<th>PHENIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFY07-11</td>
<td>RUN9 stoch. cooling 1</td>
<td>( \mu \text{TrFee} ) (part)</td>
</tr>
<tr>
<td></td>
<td>RUN10 stoch. cooling 2</td>
<td>( \mu \text{TrFee} ) (full)</td>
</tr>
<tr>
<td></td>
<td>RUN11 EBIS (U+U)</td>
<td>VTX</td>
</tr>
<tr>
<td></td>
<td>RUN12 56 MHz RF</td>
<td>VTX</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Next MOU</th>
<th>RUN13 (Forward Cal?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFY12-18</td>
<td></td>
</tr>
</tbody>
</table>

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  
1000/pb @ 500 GeV  
P4L=75/pb  
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.  
mu Trig and VTX are crucial for many of these measurements
Physics by muTRIG upgrade: 
Δq-Δq̅ at RHIC via W production

\[ A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \]

Expected precision for \( A_L \) of \( W \rightarrow \mu \)

- Realistic simulation using RESBOS
- Black points: 300/pb (before luminosity upgrades)
- Open points: 1300/pb (with RHIC luminosity upgrades)
**Direct photon $A_{LL}$**

**Present status**

- Run 5: $2.5 \text{pb}^{-1}$, $p=47\% \rightarrow P^4L=0.12 \text{pb}^{-1}$
- Run 6: $7 \text{pb}^{-1}$, $p=57\% \rightarrow P^4L=0.74 \text{pb}^{-1}$

With Lumi upgrade:

- $300 \text{pb}^{-1}$, $P=70\% \rightarrow P^4L=72 \text{pb}^{-1} \rightarrow 10$ times smaller stat. error than RUN6
- $<1\%$ statistical error

Significant constraint on $\Delta G$ via clean channel.

---

**Drell Yan $A_N$**

- Large single spin asymmetry in Drell Yan is expected Sivers effect
- DY yield for $300/\text{pb @} 200 \text{ GeV}$ in PHENIX muon arm is more than $10000 \rightarrow$ stat error of $O(1\%)$ can be achieved
- Effect is larger for high $x$. Lower energy run ($\sim 100 \text{ GeV}$) is useful to access higher $x$. 
Expected $R_{AA}(b \rightarrow e)$ and $R_{AA}(c \rightarrow e)$ with VTX

- Strong suppression of single electrons from heavy flavor decay is one of the most surprising results in RUN4
- The present measurement is mixture of $b \rightarrow e$ and $c \rightarrow e$
- VTX can separately measure RAA of $b \rightarrow e$ and $c \rightarrow e$
- Additional factor of 10 improvement with RHIC luminosity upgrade.

Expected $v_2(b \rightarrow e)$ and $v_2(c \rightarrow e)$ with VTX

- $v_2$ of single electron is measured by PHENIX in RUN4
- The measured $v_2$ is mixture of $b \rightarrow e$ and $c \rightarrow e$
- With VTX, we can change the mixture of $b$ and $c$
- With VTX, we can separate $b \rightarrow e$ and $c \rightarrow e$ component
- Additional factor of >10 improvement in RHIC-2
High Statistics $J/\psi$ Measurements in A+A

- With RHIC luminosity upgrades, RAA of $J/\psi$ is extended to ~10 GeV/c
- $V_2$ of $J/\psi$ --- crucial test for $J/\psi$ 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
  - $v_2$
  - Source size
- RHIC luminosity behaves $E_{beam}^2$ or $E_{beam}^3$ ($E<10\text{GeV}$). High Luminosity and long running time is needed for E scan at low E
Energy scan: Onset of light quark opacity

- 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)

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Colliding Beam</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>500 GeV p+p</td>
<td>~5-6 physics weeks to commission collisions, work on polarization &amp; luminosity and obtain first W production signal to meet RIKEN milestone</td>
</tr>
<tr>
<td>2010</td>
<td>200 GeV p+p</td>
<td>~12 physics weeks to complete 200 GeV Au+Au measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009. STAR DAQ1000 fully operational</td>
</tr>
<tr>
<td></td>
<td>Au+Au</td>
<td>9-10 physics weeks with PHENIX HBBD. STAR DAQ1000 &amp; TOF permits low-mass dilepton response map and 1st collision test of transverse stochastic cooling (installed in one ring)</td>
</tr>
<tr>
<td>2011</td>
<td>U+U</td>
<td>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)</td>
</tr>
<tr>
<td>2012</td>
<td>500 GeV p+p</td>
<td>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 J@ measurements</td>
</tr>
<tr>
<td></td>
<td>Au+Au</td>
<td>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</td>
</tr>
<tr>
<td>2013</td>
<td>500 GeV p+p</td>
<td>Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production and sea antiquark polarizations</td>
</tr>
<tr>
<td></td>
<td>Au+Au or 2nd low-E scan</td>
<td>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 VTX and NCC and full STAR HFT</td>
</tr>
<tr>
<td>2014</td>
<td>200 GeV Au+Au or 2nd low-E scan</td>
<td>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</td>
</tr>
<tr>
<td></td>
<td>Au+Au</td>
<td>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</td>
</tr>
</tbody>
</table>

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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 $W \rightarrow \mu$ 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 $J/\psi$, 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

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

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?
Measurements of the Glue at HERA

Scaling violations of $F_2(x,Q^2)$
Linear DGLAP equations

Gluons: not well understood!

Nonlinear effects: Saturation!
High gluon densities most easily accessed in nuclei
BK/JIMWLK propose:
Characteristic scale $Q_s(x,A)$
Color glass condensate!
e-A data at low x, also at low $Q^2$
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.

\( \Rightarrow \) non-linear QCD regime reached at significantly lower energy in e+A than in e+p

\[
\begin{align*}
\frac{s_{HERA}}{s_{EIC}} & \approx (330 \text{ GeV})^2 \\
\frac{s_{EIC}}{s_{HERA}} & \approx \frac{1}{27} \\
\end{align*}
\]

Instead of extending \( x, Q \) reach we increase \( Q_s \)

\( Q^2 \sim sx \): EIC factor behind (10+100 GeV)

\[
\begin{align*}
Q_s^2(HERA) &= Q_s^2(EIC) - Q_0^2 x_{HERA}^{-1/3} = c Q_0^2 A^{1/3} x_{EIC}^{-1/3} \\
x_{EIC} &= x_{HERA} \cdot c^3 A \\
c^3 A &= 0.5^3 \cdot 197 \approx 25
\end{align*}
\]

11/18/2008

---

eA physics drives e-beam energy!

<table>
<thead>
<tr>
<th>EIC Beam Energy (GeV)</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>low-x reach compared to HERA (e+p equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2+100</td>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>10+100</td>
<td>63</td>
<td>18</td>
</tr>
<tr>
<td>20+100</td>
<td>89</td>
<td>36</td>
</tr>
<tr>
<td>20+130</td>
<td>102</td>
<td>50</td>
</tr>
<tr>
<td>30+130</td>
<td>125</td>
<td>71</td>
</tr>
</tbody>
</table>

- 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

11/18/2008
Recent: $\Delta G(x) @ Q^2 = 10 \text{ GeV}^2$

- Global analysis: DIS, SIDIS, RHIC-Spin
- Uncertainty on $\Delta G$ large at low $x$

Status: Nucleon Spin puzzle

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

- DIS fixed target Experiments
  - $\sim 0.23 \pm 0.03$
- DIS & RHIC Spin
  - Transverse Spin
  - GPDs, TMDs
- RHIC Spin Dis experiments
  - $\sim 0.0 \pm 0.0$ (unknown)
  - $0.02 < x < 0.3$

11/18/2008
Fundamental Questions in QCD

- 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

Electron Ion Collider

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

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:
  - $X = 10^{-2} \rightarrow 0.7$ ($Q^2 > 1$ GeV$^2$)
  - $Q^2 = 0 \rightarrow 10^3$ GeV$^2$
- Polarization of $e_p$ and light ion beams at least ~70% or better
- Heavy ions of ALL species
- Machine Luminosities envisioned
  - $L(ep) \sim 10^{31-34}$ cm$^{-2}$ sec$^{-1}$
- Integrated Luminosity goal:
  - 50 $fb^{-1}$ in 10 years
  - possible with $10^{33}$ cm$^{-2}$ sec$^{-1}$

11/18/2008

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 $L \sim 10^{33-34}$ cm$^{-2}$ sec$^{-1}$

A staged approach with significantly reduced initial cost possible

11/18/2008
Staged EIC=eRHIC@BNL

~2.8 GeV presently seems possible. What would it take to increase the e-beam energy to 4 GeV?

11/18/2008
EIC @ Jefferson Laboratory:
Electron Light Ion Collider (ELIC)

Most ambitious: $L_{\text{max}} \sim \text{few } 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$

Scientific Frontiers of eRHIC/EIC

- 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 $\rightarrow$ Generalized Parton Distributions
  - Precision measurements of QCD and of EW parameters in SM

- Un-polarized Nucleon Structure
  - Understanding confinement with low $x$/low$Q^2$ 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 $e$-$p/e$-$A$
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:
  - $Q^2 > 0.7 \text{ (GeV}^2\text{)}$
  - $Q^2 = 0 \rightarrow 10^3 \text{ GeV}^2$
- Polarization of e,p and light ion beams
  at least ~ 70% or better
  - Heavy ions of ALL species
- Machine Luminosities envisioned
  - $L(ep) \sim \text{few } 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$

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
    - $g_1, \Delta G$, 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
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

8 meters (for scale)

TOF
Offset IP
PbWO₄
ECAL

HCAL
Tracking
RICH
Solenoid

11/18/2008

World Data on $F_2^p$

HERA $F_2$

Region of existing $g_1^p$ data

An makes it possible!
DVCS/Vector Meson Production: Access to Quark & gluon GPDs (OAM?)

- Hard Exclusive DIS process
- $\gamma$ (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!

$$\int x d^3 x [H(x, t, \xi) + E(x, t, \xi)] = 2J_{\text{quark}} = \Sigma + 2L_q$$

Experimental effort just beginning...To fully explore this physics beam Charge asymmetries need to be measured... => Luminosity Hungry Measurement

Parity Violation Studies
(studied ELIC 150 x 7 GeV, D-e scattering)

Measurement of Weinberg angle at a different scale

Due to finite $Y$

$$\frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W} \bigg|_{Y = 0.46} \approx \frac{1}{2} \left( \frac{\delta A_d}{A_d} \right)$$

$A_d \approx 2.9 \times 10^{-4}$

Assumed $10^{35}$ /cm$^2$/s, 10 weeks & 100% machine and detector efficiency
Sub 0.5% polarimetry
Preliminary e-A simulations

Simulations to demonstrate the quality of EIC measurements

Assume:
L = 3.8 \times 10^{33} \text{ cm}^2 \text{ s}^{-1} (100x \text{ Hera})
T = 10 \text{ weeks}
duty cycle: 50%
L \sim 1/A (approx)

F_L = \alpha_x G(x, Q^2) \text{ requires vs scan, } Q^2/\chi = y

Plots above:
\int L dt = (10 + 100) \text{ GeV}
\int L dt = (10 + 50) \text{ GeV}
\int L dt = (5 + 50) \text{ GeV}
statistical error only

Outlook: Experiments & Lattice QCD

Outlook
- Dramatic increase in computer resources for Lattice QCD
- Teraflops \rightarrow Petaflops \rightarrow Exaflops
- Innovation in algorithms
- Chiral fermions down to physical pion mass
- Disconnected diagrams
- Calculate proton and neutron separately; not just difference
- Strongness 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 \Delta G

11/18/2008
"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."


---

**EIC Working Group Structures**

**Steering Committee**
- Abhay Deshpande, Stony Brook (Co-Chair/Contact person)
- Rolf Ent, JLab
- Charles Hyde, ODUJUBP, France
- Peter Jacobs, LBL
- Richard Milner, MIT (Co-Chair/Contact person)
- Thomas Ulrich, BNL
- Raju Venugopalan, BNL
- Antje Bruehl, Jlab
- Werner Vogelsang, BNL

**Working Groups and Convenors**
- **ep Physics**
  - Antje Bruehl, JLAB
  - Ernst Sichtermann, LBL
  - Werner Vogelsang, BNL
  - Christian Weiss, JLAB
- **eA Physics**
  - Vadim Guzey, JLAB
  - Dave Morrison, BNL
  - Thomas Ulrich, BNL
  - Raju Venugopalan, BNL
- **Detector**
  - Elke Aschenauer, JLAB
  - Edward Kinney, Colorado
  - Remo Surrow, MIT
- **Electron Beam Polarimetry**
  - Wolfgang Lorenzon, Michigan

**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)
- Xianglei Ji (U. Maryland)
- Robin Klimper (U. Hamburg)
- Alfred Michler (Columbia)
- Katsuhiro Oide (KEK)
- Naohito Saito (KEK)
- Uli Wienands (SLAC)

First meeting Spring-09

Next Meeting December 11-13, 2008
at Lawrence Berkeley Laboratory
- Details on EIC webpage:
  - http://web.mit.edu/eicc
Other e-N colliders...

- (MANUEL @ FAIR) --> Very preliminary

MAinz concept for NUcleon ELepton ion collider @ GSI/Fair (D. von Harrach)
- Parameters: CM between COMPASS and HERMES; s=100 and 200 GeV$^2$; Luminosity $\sim 10^{33}$ 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 $\sim$80% for both beams be achieved?
Other e-N colliders...

- 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

Conclusions & Summary

- 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
A Short View of RHIC's Long-Term Future

Steve Vigdor
RBRC Review Meeting
Nov. 18, 2008

A Long Term (Evolving) Strategic View for RHIC

Legend:
- R&D
- Construction
- Multiple small projects
CD0: DOE Critical Decision, mission need

RHIC, RHIC-II, LHC-HI and EIC science share a common theme...
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.
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 $l/L \, dt$ within $|z| < 20 \text{ cm}$, vs. no cooling

- 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.

Calculation by M. Blaskiewicz.
**RHIC Spin Luminosity and Polarization Goals**

Planned luminosity improvements:
- reduce $\beta^*$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>Achieved</th>
<th>Luminosity upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>p(^\uparrow)-p(^\uparrow) operation</td>
<td></td>
<td>(2006/08)</td>
<td>(~ 2012)</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>100</td>
<td>100 (250)</td>
</tr>
<tr>
<td>No of bunches</td>
<td>...</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^{11}$</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Ave. delivered lum.**</td>
<td>$10^{30}$ cm(^{-2})s(^{-1})</td>
<td>23</td>
<td>80 (200)</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

**without vertex cuts**

---

**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; $\gamma$ - 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).
### 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)

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Colliding Beam Species/Energy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>500 GeV p+p</td>
<td>Assuming ~April 1 start, about 5-6 physics weeks to commission collisions, work on polarization &amp; luminosity and obtain first W production signal to meet RIKEN milestone</td>
</tr>
<tr>
<td>2010</td>
<td>200 GeV p+p</td>
<td>~12 physics weeks to complete 200 GeV A_u measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009; STAR DAQ1000 fully operational</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>9-10 physics weeks with PHENIX HBD, STAR DAQ1000 &amp; TOF permits low-mass dilepton response map and 1^st^ collision test of transverse stochastic cooling (one ring)</td>
</tr>
<tr>
<td>2011</td>
<td>Au+Au at assorted low E</td>
<td>1^st^ energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals are recorded; commission PHENIX VTX (at least prototype)</td>
</tr>
<tr>
<td></td>
<td>200 GeV U+U</td>
<td>1^st^ U+U run with EBIS, to increase energy density coverage</td>
</tr>
<tr>
<td>2012</td>
<td>500 GeV p+p</td>
<td>1^st^ 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 A^&amp;^G measurements</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au</td>
<td>Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-H goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations</td>
</tr>
<tr>
<td>2013</td>
<td>500 GeV p+p</td>
<td>Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production</td>
</tr>
<tr>
<td></td>
<td>200 GeV Au+Au or 2^nd^ low-E scan</td>
<td>To be determined from 1^st^ low-E scan and 1^st^ upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT</td>
</tr>
<tr>
<td>2014</td>
<td>200 GeV Au+Au or 2^nd^ low-E scan</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>200 GeV p+p</td>
<td>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</td>
</tr>
</tbody>
</table>

### Run Plan, Detector & Luminosity Upgrades Address All New RHIC-Related Performance Milestones

<table>
<thead>
<tr>
<th>Year</th>
<th>#</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>HP8</td>
<td>Measure flavor-identified quark contributions to the spin of the quark via the longitudinal-spin asymmetry of W production.</td>
</tr>
<tr>
<td>2013</td>
<td>HP12 (update of HP1)</td>
<td>Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if quarks have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.</td>
</tr>
<tr>
<td>2015</td>
<td>HP13 (new)</td>
<td>Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering.</td>
</tr>
<tr>
<td>2014</td>
<td>DM9 (new)</td>
<td>Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.</td>
</tr>
<tr>
<td>2014</td>
<td>DM10 (new)</td>
<td>Measure jet and photon production and their correlations in A=200 iron+iron collisions at energies from medium RHIC energies to the highest achievable energies at LHC.</td>
</tr>
<tr>
<td>2015</td>
<td>DM11 (new)</td>
<td>Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at sNN = 200 GeV to search for evidence of a critical point in the QCD matter phase diagram.</td>
</tr>
<tr>
<td>2016</td>
<td>DM12 (new)</td>
<td>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.</td>
</tr>
<tr>
<td>2018</td>
<td>DM13 (new)</td>
<td>Measure real and virtual thermal photon production in p+p, d+Au and Au+Au collisions at energies up to sNN = 200 GeV.</td>
</tr>
</tbody>
</table>

N.B. Some will be missed if budgets do not permit 2 species/year runs in FY10-14

Brookhaven Science Associates

Brookhaven National Laboratory

351
Where Do Heavy-Ion Collisions at LHC Fit In?

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.

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).
Act 3

Long-Term (>2020) Future of RHIC Physics: EIC → eRHIC

Add ERL injector with polarized e⁻ source to enable e⁺p,³He 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 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⁻²s⁻¹ e⁺p
**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?

---

**Polarized $\vec{e} + \vec{N}$ at EIC**

- Polarized DIS, $\gamma$-gluon fusion to determine gluon polarization down to $x \sim$ few $\times 10^{-4}$
- Bjorken sum rule test to $\leq 2\%$ precision
- SIDIS for low-$x$ sea-quark polarization and transverse spin studies

More luminosity-hungry:

- Polarized DVCS, exclusive reactions + LQCD $\Rightarrow$ GPD's $\Rightarrow$ map low-$x$ transverse position-dep. PDF's; $J_q$ from Ji sum rule
- 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.
Further Development of Luminosity Improvements: Coherent Electron Cooling

**Hadrons**

**Electrons**

**Modulator**: hadron beam structure introduces density modulation in e-beam

**Wiggler**: FEL amplification \(\times 10^{2-3}\) 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**

19.6 m

**Kicker** 3 m **Wiggler 7m** 4 m **Modulator**

Uses 20 MeV R&D ERL already under development at BNL

CeC of high-energy hadron beams: high-gain FEL based on high-brightness ERL (V. Litvinenko & Y. Derbenev) ⇒ 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\textsuperscript{-} beam interacting with proton beam can compensate head-on beam-beam tune spread (\times 2 luminosity?)
- Single and multi-particle simulation underway
- Possible implementation in RHIC by 2014

Intermediate-Term Possibilities: 1\textsuperscript{st} (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 e\textsuperscript{-} on 100 GeV/N heavy ions and 250 GeV p\textsuperscript{+}
- First look at saturation surface for nuclei in e+A DIS, confirmation of nuclear “oomph” factor; e+A diffraction tests of high gluon occupancy
- e+p program emphasizing transverse-spin SIDIS over broad Q\textsuperscript{2}-range \Rightarrow TMD evolution; detection of boosted target fragments to probe spin-dependent correlations, intrinsic heavy flavor in nucleon; extend 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)

<table>
<thead>
<tr>
<th></th>
<th>not cooled</th>
<th>pre-cooled</th>
<th>high energy cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>e</td>
<td>p</td>
</tr>
<tr>
<td>Energy, GeV</td>
<td></td>
<td>250</td>
<td>2</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>111</td>
<td></td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity, $10^{11}$</td>
<td>2.0</td>
<td>0.31</td>
<td>2.0</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>32</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>Normalized emittance, 1e-6 m, 95% for p / rms for e</td>
<td>15</td>
<td>37</td>
<td>6</td>
</tr>
<tr>
<td>rms emittance, nm</td>
<td>9.4</td>
<td>9.4</td>
<td>3.8</td>
</tr>
<tr>
<td>$\beta^*$, cm</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>rms bunch length, cm</td>
<td>40</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>beam-beam for p / disruption for e</td>
<td>1.5e-3</td>
<td>12</td>
<td>3.8e-3</td>
</tr>
<tr>
<td>Peak Luminosity, 1e32, cm$^{-2}$sr$^{-1}$s$^{-1}$</td>
<td>0.93</td>
<td>2.3</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Also a test-bed for high-energy coherent e-cooling to prepare for full EIC.

---

### Novel Storage Ring EDM Exp’ts @ AGS?

**EDM storage ring**

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 $\theta_{QCD}$ vs. SUSY (latter strongly enhanced in $d$).

See Y. Semertzidis talk, 10/07/08.
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.
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 Japanese 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;  
• RHIC Physics Fellow/Assistant Professor—RBRC/U. of Connecticut, Storrs, January 1, 2004 - present.

Award and Honors:  
DOE-GANN Fellowship: August 1990 - May 1993;  

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

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  
*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:**  
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.


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.

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)
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.


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**: Uzegorod (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.

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
RIKEN Spin Program Research Associate, April 1, 2001 – present

Awards and Honors: Fellowship: Japan Society for the Promotion of Science, 1995-1997

Feng Yuan  
Birthplace: Huangmei, China  
DOB: March 10, 1972

Ph.D.  
2000, Peking University, P.R. China

Experience:  
Postdoctoral Research Associate, U. of Heidelberg, Germany, September 2000 to February 2002; Postdoctoral Research Associate, U. of Maryland, College Park, March 2002 to August 2004;
Research Associate, RIKEN BNL Research Center, Theory Group, September 1, 2004 – present.

Publication Reference List RBRC Experimental Group, 1995-2008


50) Measurements of the electron-helicity dependent cross-sections of deeply virtual compton scattering with CEBAF at 12-GeV. Julie Roche et al. JLAB-PR12-06-114, Sep 2006. 43pp. e-Print: nucl-ex/0609015


64) Polarized proton collisions at RHIC. M. Bai et al. with G. Bunce. PAC-2005-MOPA007, May 2005. 3pp. Prepared for Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005. Published in Knoxville 2005, Particle Accelerator Conference 600


90) S. S. Adler et al. [PHENIX Collaboration], "Measurement of identified pi0 and inclusive photon v(2) and implication to the direct photon production in s(NN)**(1/2) = 200-GeV Au + Au collisions," arXiv:nucl-ex/0508019.

92) S. S. Adler et al. [PHENIX Collaboration], "Modifications to di-jet hadron pair correlations in Au + Au collisions at s(NN)**(1/2) = 200-GeV." arXiv:nucl-ex/0507004.


124) K. Abe et al. "STUDY OF $B^- \rightarrow D^{*0} \pi^-$ ($D^{*0} \rightarrow D^* (\pi^-) \pi$) DECAYS." Belle Collaboration (K. Abe et al.) Submitted to Phys. Rev. D, hep-ex/0307021 (2004).

125) K. Abe et al. "COMMENT ON $E+\pi$- ANNIHILATION INTO $J / \psi$ J / $\psi$." Belle Collaboration (K. Abe et al.), hep-ex/0306015.


139) G. Bunce [PHENIX Collaboration], "A first measurement of the helicity asymmetries for polarized proton collisions at $s^{(1/2)} = 200$-GeV," Prepared for Lake Louise Winter Institute 2004 on Fundamental Interactions (LL WI 2004), Lake Louise, Alberta, Canada, 15-21 Feb 2004


154) R. Alford et al., "Field Measurements in the AGS Warm Snake," EPAC-2004-WEPLT114 Presented at the 9th European Particle Accelerator Conference (EPAC 2004), Lucerne, Switzerland, 5-9 Jul 2004


170) F. Bauer [PHENIX Collaboration], "Longitudinal double spin asymmetries in neutral pion production at PHENIX," Prepared for 12th International Workshop on Deep Inelastic Scattering (DIS 2004), Strbske Pleso, Slovakia, 14-18 Apr 2004


172) G. Bunce, "Vernon Hughes - To Learn Fundamental Things 1921-2003," Prepared for 10th International Workshop on High-Energy Spin Physics (SPIN 03), Dubna, Russia, 16-20 Sep 2003

173) A. Bravar et al., "Overview of Polarimetry at RHIC and Elastic pC to pC Scattering at Very Low Momentum Transfer," Prepared for 10th International Workshop on High-Energy Spin Physics (SPIN 03), Dubna, Russia, 16-20 Sep 2003

174) G. Bunce, "The RHIC Spin Program," Prepared for 10th International Workshop on High-Energy Spin Physics (SPIN 03), Dubna, Russia, 16-20 Sep 2003

175) O. Jinnouchi et al., "Results of RHIC pC CNI Polarimeter Run-03," Prepared for 10th International Workshop on High-Energy Spin Physics (SPIN 03), Dubna, Russia, 16-20 Sep 2003


190) A. Drees et al. [PHENIX Collaboration], "Heavy ion collisions at collider energies: Insights from PHENIX," Pramana 60, 639 (2003).


243) H. Enyo, "RHIC spin project: Opening a new era of hadron physics," Prepared for 4th Italy - Japan Symposium on Heavy Ion Physics, Tokyo, Japan, 26-29 Sep 2001


259) N. Saito [the Asymmetry Analysis Collaboration], "Polarized parton distribution functions in the nucleon," RIKEN-AF-NP-359


261) C. Allgower et al., "Measurement of single-spin asymmetries of pi+, pi-, and protons inclusively produced on a carbon target with a 21.6-GeV/c incident polarized proton beam," IFVE-99-14


268) N. Saito, "Physics at RHIC," Prepared for 13th Topical Conference on Hadron Collider Physics, Mumbai, India, 14-20 Jan 1999


270) N. Saito, "RHIC wo mochiita ko-energy spin butsuri," RIKEN-AF-NP-283


277) N. Saito, "Spin physics at RHIC," RIKEN-AF-NP-251 Circum-Pan-Pacific Workshop on High Energy Spin Physics'96 Kobe University, Japan 2-4 Oct 1996


281) N. Saito, "Spin physics with PHENIX detector system at RHIC," Prepared for Riken Symposium on Spin Structure of the Nucleon, Wako, Japan, 18-19 Dec 1995


18. A. Dumitru, D. H. Rischke, "Collective Dynamics in Highly


48. J. T. Lenaghan and D. Rischke, "The O(N) Model at Finite Temperature: Renormalization of the Gap Equations in Hartree and


147. Tom Blum, Shigemi Ohta, Shoichi Sasaki, "Domain Wall Fermion Calculation of Nucleon g_A/g_\nu," [ hep-lat/0011011], Proceedings of the


172. Jürgen Schaffner-Bielich, "Strange Dibaryons in Neutron Stars and in Heavy-Ion Collisions," [nucl-th/0011078], Invited talk at HYP2000:


230. Shoichi Sasaki, Tom Blum, Shigemi Ohta, and Kostas Orginos, "Nucleon Axial Charge From Quenched Lattice QCD With Domain Wall Fermions And Improved Gauge Action," [hep-lat/0110053],


246. Se-yong Kim, Shigemi Ohta, "Zero Temperature Phase Structure of Multiflavor QCD," [hep-lat/0111040], Presented at 19th International Symposium on Lattice Field Theory (LATTICE 2001), Berlin, Germany,


298. Steffen A. Bass, Berndt Muller, Dinesh K. Srivastava, "Semihard Scattering of Partons at SPS and RHIC: A Study in Contrast,"


316. S. Jeon, J. Jalilian-Marian, I. Sarcevic, "Prompt Photon and Inclusive $\pi^0$ Production at RHIC and LHC," [nucl-th/0211084], Talk given at 16th International Conference on Ultrarelativistic Nucleus-Nucleus


332. Stefan Kretzer, "Fragmentation Functions and Implications for Spin Physics," Proceedings of the Conference on the Intersections of Particle


370. Steffen A. Bass, Berndt Muller, Dinesh K. Srivastava, “Transverse Momentum Distribution of Net Baryon Number at RHIC,”


392. Tetsufumi Hirano and Yasushi Nara, "Energy Loss of Partons Traversing a QGP Fluid," [nucl-th/0211096], 16th International


444. P. Petreczky, “QCD Thermodynamics on Lattice,”


490. Norikazu Yamada, Sinya Aoki, and Yoshinobu Kuramashi, “One-loop Determination of Mass Dependent O(a) Improvement Coefficients for the Heavy-light Vector and Axial-vector Currents with Relativistic


[BNL Fiscal Year: October 1, 2005 to September 30, 2006]


582. Feng Yuan, "Single Spin Asymmetry and Quark Orbital Motion in Nucleon," PANIC 05, Particles and Nuclei International Conference, October


[Begin: BNL FY: October 1, 2006 to September 30, 2007]


623. Taku Izubuchi and Oleg Lochtik, "Perturbative Renormalization for Static and Domain-wall Bilinears and Four-Fermion Operators with Improved Gauge Actions,"


Wall QCD on a (2 fm)$^3$ Lattice: Light Meson Spectroscopy with $L_s = 16$" [hep-lat/0701013], Physical Review D (submitted).


649. Boyle, Peter, Ohta, Shigemi, “Localisation and Chiral Symmetry in 2+1 Flavour Domain Wall QCD,”


Begin: BNL FY: October 1, 2007 to September 30, 2008


691. Feng Yuan, "Parton Distributions and Spin -Orbital Correlations" Workshop at JLab, Exclusive Reactions at high Momentum Transfer. To be publ. in World Scientific.


698. Yoshimasu Hidaka “Model study of the sign problem in a mean-field approximation” The XXV International Symposium on Lattice Field Theory, Regensburg, Germany, July 30-August 4, 2007; Proceedings of Science.


701. Rainer J. Fries (Texas A&M, RIKEN BNL), Simon Turbide, Charles Gale (McGill U.) Dinesh K. Srivastava (VECC Kolkata) “Photons and


703. Kirill Tuchin, Frithjof Karsch, Dmitri Kharzeev “Universal properties of bulk viscosity near the QCD phase transition” (submitted).


709. Agnes Mocsy, E. S. Fraga (Instituto de Fisica, Brazil) “Connecting an Effective Model of Confinement and Chiral Symmetry to lattice QCD” Brazilian Journal of Physics, Vol. 37, no. 1B, March, 2007.


719. Taku Izubuchi (Kanazawa U., Japan and RIKEN “Eta' meson from two flavor dynamical domain wall fermions”


721. Yukio Nemoto, Masakiyo Kitazawa, Tomoi Koide, Teiji Kunihiro "Fermionic Collective modes in QGP near critical temperatures" Yukawa International Seminar 2006, Yukawa Institute for Theoretical Physics, Kyoto


728. Yasumichio Aoki, P. Boyle, P. Cooney, L. Del Debbio. R. Kenway, R. Tweedie "Proton decay from 2+1 flavor domain wall QCD"

729. Y. Li and K. Tuchin "Gluon multiplicity in coherent diffraction of
onium on a heavy nucleus", to be submitted to Phys. Rev. D


731. Y. Li and K. Tuchin "Spectrum of diffractively produced gluons in onium-nucleus collisions", to be submitted to Nuclear Physics A.


733. Blum, Thomas; Doi, Takumi; Hayakawa, Masashi; Izubuchi, Taku; Yamada, Norkazu “Determination of light quark masses form the electromagnetic splitting of pseudoscalar meson masses computed with two flavors of domain wall fermions” submitted to Physical Review D 76 11 114508.

734. Hadaka, Yoshimasa, Kitazawa, Masakiyo “Spectrum of soft mode with thermal mass of quarks above critical temperature” submitted to International Journal of Modern Physics e-Nuclear Physics, 16 7/8 2394 2399.


737. Hidaka, Yoshimasa; McLerran, Larry; Pisarski, Robert “Baryons and the phase diagram for a large number of colors and flavors”

738. C. Lunardini, “Upper limits on the diffuse supernova neutrino flux from the SuperKamiokande data".
739. Y. Ki, K. Tuchin "Spectrum of diffractively produced gluons in onium-nucleus collisions", to be submitted to Nuclear Physics A.
740. Yang Li and Kirill Tuchin, "Probing the low-x structure of nuclear matter with the diffractive hadron production in pA collisions".
742. Takeshi Yamazaki "On-shell $\Delta I = 3/2$ kaon weak matrix elements with non-zero total momentum".
745. W. Liu and R. J. Fries "Elliptic Flow of Rare High-Momentum Probes in Nuclear Collisions"
746. R. J. Fries, B. Muller and A. Schafer "Decoherence and Entropy Production in Relativistic Nuclear Collisions"
749. H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan "Pretzelosity distribution function and the single spin
\[ A_{H} \sin(\frac{3φ}{1-T}) \] asymmetry "submitted to Phys. Rev. D
750. F. Yuan, Jina Zhou "Single Spin Asymmetries in Heavy Quark and Antiquark Productions", Phys. Lett. B.
752. D. Kharzeev, E. Levin, M Nardi and K. Tuchin "J/Psi production in heavy-ion collisions and gluon saturation"
753. Mocsy, Agnes "Melting Sequence of Quarkonia", Proc. 24\textsuperscript{th} Winter Workshop on Nuclear Dynamics.

754. Mocsy, Agnes; Petreczky, Peter "Quarkonium Melting Above Deconfinement" submitted to IOP Publishing for peer review, 14 July 2008.

755. Kirill Tuchin, D. Kharzeev, E. Levin and M. Nardi
"Gluon saturation effects in JPs\i production in heavy ion collisions."

756. Shigemi Ohta and Takeshi Yamazaki [RBC and UKQCD Collaborations] "Nucleon structure with dynamical (2+1)-flavor domain-wall fermions lattice QCD".

757. K. Tuchin, D. Kharzeev and E. Levin "Broken scale invariance, massless dilaton and confinement in QCD".

\textbf{Begin: BNL FY: October 1, 2008 to September 30, 2009}

758. PACS-CS collaboration N. Ukita et. al. "SU(2) and SU(3) chiral perturbation theory analyses on meson and baryon masses in 2+1 flavor lattice QCD"

759. PACS-CS collaboration D. Kadoh et. al. "2+1 flavor lattice QCD simulation with O(a)-improved Wilson quarks"

760. PACS-CS collaboration Y. Namekawa et. al. "Charm quark system in 2+1 flavor lattice QCD using the PACS-CS configurations"

761. H. Fujii, K. Fukushima, Y. Hidaka "Initial energy and gluon distribution form the Glalsma in the heavy-ion collisions"

762. Shigemi Ohta et al. "Nucleon from factors with (2+1)-flavor dynamical domain-wall fermions"
Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

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