Proceedings of RIKEN BNL Research Center Workshop Volume 77

RBRC Scientific Review Committee Meeting

October 10-12, 2005

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 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 currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen 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 ~40 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. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-six 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. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
October 2005

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

Preface to the Series ................................................................. i

Introduction
  N. P. Samios ........................................................................... 1

Meeting Agenda ...................................................................... 3

RBRC Scientific Review Committee Membership ......................... 7

RBRC ADMINISTRATION PRESENTATIONS

RIKEN BNL Research Center (RBRC) Overview
  N. P. Samios ........................................................................... 11

RBRC Experimental Group Overview
  Hideto En'yo ......................................................................... 29

Theoretical Physics at RBRC Strong Interactions and QCD
  Larry McLerran .................................................................... 51

THEORY PRESENTATIONS

Calculations of Cross Sections and Spin Asymmetries in
Hadronic Scattering
  Werner Vogelsang ............................................................... 65

Global Analysis: Update of Fragmentation Functions
  Stefan Kretzer ..................................................................... 77

Single Transverse Spin Physics: From DIS to Hadronic Collisions
  Feng Yuan ........................................................................... 89

Thermalization in the Color Glass Condensate
  Kirill Tuchin ....................................................................... 101

Quarkonia Correlators Above Deconfinement
  Ágnes Mócsy ...................................................................... 117

Properties of the Plasma Created at RHIC
  Denes Molnar ...................................................................... 127

Charge Transfer Fluctuations as a QGP Signal
  Sangyong Jeon .................................................................... 145

Effective Action for High Energy QCD with the Pomeron Loop
  Yoshitaka Hatta ................................................................. 157
THEORY PRESENTATIONS (Continued)

Feedback Effects on the Pairing Interaction in Color Superconductors  
Kei Iida ................................................................. 169

Phase Structure and Instability in Dense Quark Matter  
Kenji Fukushima ..................................................... 177

Charm Mesons with DWF Quarks on a Quenched 3 GeV Lattice  
Shigemi Ohta .......................................................... 193

Electromagnetic Properties of Hadrons with Two Flavor Dynamical Domain Wall Fermions  
Thomas Blum .......................................................... 211

Quarkonia Correlators and Special Functions at T>0  
Peter Petreczky ....................................................... 229

Spin 3/2 Pentaquark from Lattice QCD  
Isospin Breaking of Baryon Masses from Lattice QCD  
Takumi Doi ............................................................. 235

ΔI= 3/2 Kaon Weak Matrix Elements with Non-zero Total Momentum  
Takeshi Yamazaki .................................................... 255

Neutron Electric Dipole Moment from Lattice QCD Calculations  
Sinya Aoki ............................................................... 263

RESEARCH SUMMARY - THEORY  
Taku Izubuchi .......................................................... 275

Steffen A. Bass ........................................................ 287

Takanori Sugihara .................................................... 297

QCDSP/QCDOC: PHYSICS RESULTS AND PROSPECTS/PROJECT STATUS  
Overview  
N. P. Samios .......................................................... 303

RBRC Lattice QCD - An Overview  
Norman H. Christ ................................................... 309

Meson Spectrum and Kaon Physics  
Christopher Dawson ............................................... 335
QCDSP/QCDOC: PHYSICS RESULTS AND PROSPECTS/PROJECT STATUS (Cont'd.)

Thermodynamics of Strongly Interacting Matter
First Results from QCDOC
    Frithjof Karsch ................................................................. 347

Beta Decay on the Lattice
    Shoichi Sasaki ................................................................. 369

EXPERIMENTAL PRESENTATIONS

RHIC Heavy Ion Physics
    Yasuyuki Akiba ................................................................. 391

RHIC Polarimetry
    Itaru Nakagawa ................................................................. 401

The Pursuit of Polarized Gluon Distribution in the Nucleon with PHENIX
    Abhay Deshpande ............................................................... 419

Spin Fest--2005 Data Analysis
    Yuji Goto ........................................................................ 435

Relative Luminosity Measurement at PHENIX
    David Kawall ................................................................. 451

Measurement of Direct Photons in $|s|=200$ GeV p+p Collisions
    Kensuke Okada ................................................................. 463

Spin Dependent Fragmentation Function Results from Belle
    Matthias Grosse Perdekamp .............................................. 479

Toward Measuring the Internal Spin-dependent Transverse
Momentum of Quarks and Gluons in the Proton at RHIC
    Douglas Fields ................................................................. 503

CCJ-Status and Progress
    Yasusi Watanabe ................................................................. 517

A Silicon Vertex Tracker for PHENIX
    Atsushi Taketani ................................................................. 533

PHENIX Muon Trigger Upgrade
    Wei Xie ........................................................................ 553
CURRICULA VITAE – SUMMARY .......................................................... 569

RBRC PUBLICATIONS

Experimental Group Publications .................................................. 585
Theory Group Publications ......................................................... 603

Additional RIKEN BNL Research Center Proceedings Volumes .......... 671

Contact Information
The eighth evaluation of the RIKEN BNL Research Center (RBRC) took place on October 10-12, 2005, at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC) were Dr. Jean-Paul Blaizot, Professor Makoto Kobayashi, Dr. Akira Masaieke, Professor Charles Young Prescott (Chair), Professor Stephen Sharpe (absent), and Professor Jack Sandweiss. We are grateful to Professor Akira Ukawa who was appointed to the SRC to cover Professor Sharpe's area of expertise. In addition to reviewing this year's program, the committee, augmented by Professor Kozi Nakai, evaluated the RBRC proposal for a five-year extension of the RIKEN BNL Collaboration MOU beyond 2007. Dr. Koji Kaya, Director of the Discovery Research Institute, RIKEN, Japan, presided over the session on the extension proposal. 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. In addition, a special session was held in connection with the RBRC QCDSP and QCDOC supercomputers. Professor Norman H. Christ, a collaborator from Columbia University, gave a presentation on the progress and status of the project, and Professor Frithjof Karsch of BNL presented the first physics results from QCDOC. 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
## Agenda

### Monday, October 10, 2005

<table>
<thead>
<tr>
<th>Time</th>
<th>Presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 AM to 9:00 AM</td>
<td>Open Executive Session &amp; Working Breakfast (Room 2-160) (Presentations by RIKEN/RBRC Administration)</td>
</tr>
<tr>
<td>9:00 AM to 10:30 AM</td>
<td><strong>THEORY GROUP PRESENTATIONS—LARRY MCLERRAN, CHAIR</strong></td>
</tr>
<tr>
<td>9:00</td>
<td>Calculations of Cross Sections and Spin Asymmetries in Hadronic Scattering                      Werner Vogelsang</td>
</tr>
<tr>
<td>9:10</td>
<td>Global Analysis: Update of Fragmentation Functions                                               Stefan Kretzer</td>
</tr>
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<td>9:20</td>
<td>Single Transverse Spin Physics: From DIS to Hadronic Collisions                                  Feng Yuan</td>
</tr>
<tr>
<td>9:30</td>
<td>Thermalization in the Color Glass Condensate                                                      Kirill Tuchin</td>
</tr>
<tr>
<td>9:40</td>
<td>Quarkonia Correlators Above Deconfinement                                                         Ágnes Mócsy</td>
</tr>
<tr>
<td>9:50</td>
<td>Properties of the Plasma Created at RHIC                                                          Denes Molnar</td>
</tr>
<tr>
<td>10:00</td>
<td>Charge Transfer Fluctuations as a QGP Signal                                                       Sangyong Jeon</td>
</tr>
<tr>
<td>10:10</td>
<td>Effective Action for High Energy QCD with the Pomeron Loop                                        Yoshitaka Hatta</td>
</tr>
<tr>
<td>10:20 AM</td>
<td>Break</td>
</tr>
<tr>
<td>11:00 AM to 12:30 PM</td>
<td><strong>THEORY GROUP PRESENTATIONS—ANTHONY BALTZ, CHAIR</strong></td>
</tr>
<tr>
<td>11:00</td>
<td>Feedback Effects on the Pairing Interaction in Color Superconductors                               Kei Iida (Presented by Kenji Fukushima) Kenji Fukushima</td>
</tr>
<tr>
<td>11:15</td>
<td>Charm Mesons with DWF Quarks on a Quenched 3 GeV Lattice                                         Shigemi Ohta</td>
</tr>
<tr>
<td>11:25</td>
<td>Electromagnetic Properties of Hadrons with Two Flavor Dynamical Domain Wall Fermions             Thomas Blum</td>
</tr>
<tr>
<td>11:35</td>
<td>Quarkonia Correlators and Special Functions at T&gt;0                                                Peter Petreczky</td>
</tr>
<tr>
<td>11:45</td>
<td>Spin 3/2 Pentaquark from Lattice QCD Isospin Breaking of Baryon Masses from Lattice QCD           Takumi Doi</td>
</tr>
</tbody>
</table>
Monday, October 10, 2005 (Continued)

Large Seminar Room

11:55 $\Delta I = 3/2$ Kaon Weak Matrix Elements with Non-zero Total Momentum Takeshi Yamazaki

12:05 Neutron Electric Dipole Moment from Lattice QCD Calculations Sinya Aoki

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

1:30 PM to 3:00 PM EXPERIMENTAL GROUP PRESENTATIONS --HIDETO EN'YO, CHAIR

1:30 RHIC Heavy Ion Physics Yasuyuki Akiba
1:45 RHIC Polarimetry Itaru Nakagawa
2:00 The Pursuit of Polarized Gluon Distribution in the Nucleon with PHENIX Abhay Deshpande
2:15 Spin Fest--2005 Data Analysis Yuji Goto
2:30 Relative Luminosity Measurement at PHENIX David Kawall
2:45 Measurement of Direct Photons in $|s| = 200$ GeV $p+p$ Collisions Kensuke Okada

3:00 Break

3:30 PM to 4:45 PM EXPERIMENTAL GROUP PRESENTATIONS--GERRY BUNCE, CHAIR

3:30 Spin Dependent Fragmentation Function Results From Belle Matthias Grosse Perdekamp
3:45 Toward Measuring the Internal Spin-dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC Douglas Fields
4:00 CCJ- Status and Progress Yasushi Watanabe
4:15 A Silicon Vertex Tracker for PHENIX Atsushi Taketani
4:30 PHENIX Muon Trigger Upgrade Wei Xie

~5:00 PM SRC Executive Session (Room 2-160)
**Tuesday, October 11, 2005**

8:00 AM to 8:30 AM  
*SRC Executive Session and Continental Breakfast (Room 2-160)*

Large Seminar Room

8:30 AM to 10:00 AM  
**QCDSP/QCDOC: Physics Results and Prospects/Project Status**  
8:30  
Overview  
Nicholas P. Samios

8:35  
RBRC Lattice QCD - An Overview  
Norman H. Christ

8:55  
Meson Spectrum and Kaon Physics  
Christopher Dawson

9:15  
Thermodynamics of Strongly Interacting Matter--First Results from QCDOC  
Frithjof Karsch

9:35  
Beta Decay on the Lattice  
Shoichi Sasaki

10:00 AM to 12:30 PM Meetings with Individual RBRC Staff  
(Possible Tours)

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:30 PM to 1:30 PM</td>
<td><em>SRC Executive Session and Working Lunch (Room 2-160)</em></td>
</tr>
<tr>
<td>1:30 PM to 3:30 PM</td>
<td>Meetings with Individual RBRC Staff (Continued)</td>
</tr>
<tr>
<td>3:30 PM to 4:00 PM</td>
<td><em>SRC Executive Session (Room 2-160)</em></td>
</tr>
<tr>
<td>4:00 PM to 5:00 PM</td>
<td>Meeting with RBRC Administration (Room 2-160)</td>
</tr>
</tbody>
</table>

**Wednesday, October 12, 2005**

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

9:00 AM to 11:00 AM  
RBRC Proposal for a 5-year Extension of the RIKEN BNL Collaboration MOU Beyond 2007

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
</table>
| 9:00 AM | Overview  
Nicholas P. Samios |
| 9:20 | Spin  
Hideto En'yo |
| 9:40 | Theory  
Larry McLerran |
| 10:00 | Break |
| 10:20 | Computing  
Norman Christ |
| 10:40 | RHIC Operations  
Thomas Roser |
| 11:00 AM to 3:30 PM | *SRC Executive Sessions and Working Lunch (Room 2-160)* |
| 3:30 PM to 4:00 PM | Closeout/Adjourn (Room 2-160) |
RBRC Scientific Review Committee Membership 2005

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

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E-mail: kaya@riken.jp
RBRC ADMINISTRATION
PRESENTATIONS
RBRC Overview

Nicholas P. Samios
One of the major discoveries emerging from RHIC is the creation of a form of hot dense (10 to 30 times denser than a nucleon) matter whose properties are consistent with those of a strongly coupled plasma of subatomic quarks and gluons – the so-called quark-gluon plasma that existed a few microseconds after the birth of the universe.
<table>
<thead>
<tr>
<th>Run</th>
<th>FY</th>
<th>Collision Type</th>
<th>Energy (GeV)</th>
<th>Luminosity (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>FY 00</td>
<td>Au x Au</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Run 2</td>
<td>FY 01-02</td>
<td>Au x Au</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>Run 3</td>
<td>FY 03</td>
<td>d x Au</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Run 4</td>
<td>FY 04</td>
<td>Au x Au</td>
<td>200</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b x b(30% pol)</td>
<td>3</td>
</tr>
<tr>
<td>Run 5</td>
<td>FY 05</td>
<td>Cu x Cu</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62</td>
<td>0.5</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>b b (50% pol)</td>
<td>12</td>
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<tr>
<td>Run 6</td>
<td>FY 06</td>
<td>b b (70% pol)</td>
<td>200</td>
<td>20-100</td>
</tr>
</tbody>
</table>
The Relativistic Heavy Ion Collider Run-5
Copper-Copper Operation 2004/05

Run-5 preparation:
- Retreat
- Summary
- Projections
- Injector parameters
- Run-5 parameters
- Injectors
- List
- Organization

Total delivered luminosities:
(from January 11, 2005)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>100GeV/u</th>
<th>31.2GeV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenix</td>
<td>15.16</td>
<td>520</td>
</tr>
<tr>
<td>Star</td>
<td>14.99</td>
<td>470</td>
</tr>
<tr>
<td>Brahms</td>
<td>6.15</td>
<td>300</td>
</tr>
<tr>
<td>Phobos</td>
<td>5.67</td>
<td>250</td>
</tr>
</tbody>
</table>

Run Coordinator: Fulvia Pilat pilat@bnl.gov 7273 (BNL beeper) 631-576-5475 (cell) 631-344-3134 (office)
Deputy: Mei Bai mbai@bnl.gov xxxx (BNL beeper) 631-721-6948 (cell) 631-344-3397 (office) 631-696-1266 (home)

Last modified: Wed Mar 23 010:30 EDT 2005
Put the results together

The matter is dense

We look forward to working with the theory community to extract the properties of the matter

The matter modifies jets

The matter may melt but regenerate J/ψ's

The matter is strongly coupled

The matter is hot
Analyzed Runs 1, 2, 3, 4, 5

<table>
<thead>
<tr>
<th>Run</th>
<th>Collider</th>
<th>Energy 1</th>
<th>Cross Section 1</th>
<th>Energy 2</th>
<th>Cross Section 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Au x Au</td>
<td>200 GeV/A</td>
<td>1300 µb⁻¹</td>
<td>62 GeV/A</td>
<td>20 µb⁻¹</td>
</tr>
<tr>
<td>5</td>
<td>Cu x Cu</td>
<td>200 GeV/A</td>
<td>15 nb⁻¹</td>
<td>62 GeV/A</td>
<td>0.5 nb⁻¹</td>
</tr>
</tbody>
</table>

Investigate properties of hot dense matter.

Color Glass Condensate

New Probes: \( J/\psi \)

- Direct photons
- Open Charm
The Relativistic Heavy Ion Collider Run-5
Polarized Proton Operation

[Star] [Phenix] [Phobos] [Brahms] [RHICSpin]

RHIC AGS Machine Status [Scheduling Physics] [Beam Experiments]

C-AD Broadcast [Ring Temperatures] [Retreat 2005]

[Loop] [OC Log] [Configuration Control]

RHIC PP Log [RHIC Shift Leaders Schedule] [RHIC Run Plan] [RHIC 205GeV Development Plan]

[AGS PP Log] [AGS Shift Leaders Schedule] [AGS Run Schedule] [AGS Recipe]

RHIC Parameters:

<table>
<thead>
<tr>
<th>energy (Gigamers)</th>
<th>working point (Qx,Qy) for the ramp</th>
<th>lattice (IP 6 8 10 12 2 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>injection</td>
<td>46.5</td>
<td>B:28.73,29.72, Y:28.72,29.73</td>
</tr>
<tr>
<td>ramp</td>
<td>46.5 -- 191.5</td>
<td>B:28.73,29.72, Y:28.72,29.73</td>
</tr>
<tr>
<td>store</td>
<td>191.5</td>
<td>B:28.69, 29.68, Y:28.68,29.69</td>
</tr>
</tbody>
</table>

RHIC Timeline

- AGS pp Setup: March 3 --
- RHIC pp setup: March 24 0800 -- March 30 0800
- Access: March 30 0800 -- April 1 0800
  - Jet installation
  - CNI installation
  - AGS cold snake installation
- Ramp development: April 1 0000 -- April 17 0000
- Physics Run:
  - Start: April 17 0000. RHIC fill: 06905
  - End: June 25 1000. RHIC fill: 07327

RHIC performance:

- Luminosity performance:
  - A total of 12.6pb-1 with longitudinal polarization
  - A total of 160nb-1 with vertical polarization was recorded by experiments
- Polarization performance:
  - Average (Blue/Yellow): 49.5/44.5
  - Maximum (Blue/Yellow): 61.9/58.4
  - 205 GeV development
- Beam was accelerated to 205GeV. A polarization of 30% was measured in both rings at 205GeV
- Started to provide collisions of 56 bunches at 205 GeV for Physics around midnight of June 3

Run5 RHIC p*p* Delivered Integrated Luminosity

Avg. Lumi | Polarization | Fig. of Merit
----------|-------------|----------------
6e30      | B: 49.5, Y: 534.5nb-1
          | 44.5        |
Avg Weekly Luminosity Total Luminosity

1.34pb-1 12.6pb-1

Spin Program

All components in place
Polarimeters
Gas jet polarized target
Warm helical snake (RIKEN)
Cold helical snake
Spin rotators and Siberian snakes

Run 4  p x p  200 GeV/C  3 pb\(^{-1}\)
Run 5  200 GeV/c  12 pb\(^{-1}\)

Polarization – blue & yellow 45-50%
with cold snake 70% expected

Run 6  200 GeV/c  \sim 50 pb\(^{-1}\) FY'06

RBRC - Time to exploit the investment in spin program
RHIC pp accelerator complex

Absolute Polarimeter (H jet) → RHIC pC Polarimeters

Siberian Snakes

Spin Rotators

Partial Siberian Snake → Spin Rotators

Strong AGS Snake

Pol. H Source → LINAC

200 MeV Polarimeter

RF Dipole

AGS

Helical Partial Siberian Snake → AGS Internal Polarimeter

AGS pC Polarimeters
QCDSP/QCDOC

QCDSP  Operations (0.6 teraflops)
       Efficiency > 99%

QCDOC  Operational 10 teraflops
       Dedicated May 26, 2005
       90% Lattice QCD
       10% other

UK QCDOC  10 teraflops
          Assembled, tested, shipped
          and operational

DOE QCDOC  10 teraflops
           Assembled, tested and operational
RBRC

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: H. En’yo
Deputy Group Leader: G. Bunce

Theory Advisory Committee:
T. D. Lee
L. McLerran, Chair
A. Baltz
M. Creutz
F. Karsch
M. Gyulassy
R. Pisarski

Experimental Advisory Committee:
A. Masaike
J. Sandweiss
N. Saito

Workshops/Meetings: 10
Publications: 95 Theory/~60 Experiment
Seminars: 5/week
Other Articles: 1/11
Outstanding Junior Investigator (OJI) Awards

RBRC: Six Awards

Stephanov, M. (2001)
von Kolck, U. (2001)
Blum, T. (2005)
Plenary Speakers at International Lattice Gauge Conference
Dublin 2005

Chris Dawson
Taku Izubuchi
Tom Blum
Tilo Wettig  (Graduate)

***

Plenary Speakers at QM 2005, Budapest

Dénes Molnár
Kazunori Itakura (Graduate)
Dima Kharzeev  (Graduate)
Yasuyuki Akiba
## Weekly Seminars

<table>
<thead>
<tr>
<th>Subject</th>
<th>Day(s)</th>
<th>Time</th>
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<tr>
<td>Spin Physics <em>(Theory &amp; Exp)</em></td>
<td>Tuesdays</td>
<td>10:00 a.m.</td>
<td>Y. Goto, W. Vogelsang, A. Deshpande</td>
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<td>Tuesdays</td>
<td>11:00 a.m.</td>
<td>W. Vogelsang with BNL Staff</td>
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<tr>
<td>Nuclear Physics</td>
<td>Tuesdays</td>
<td>11:00 a.m.</td>
<td>S. Ohta with BNL Theorists</td>
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<td>High Energy-RIKEN Theory</td>
<td>Wednesdays</td>
<td>1:30 p.m.</td>
<td>P. Petreczky, K. Iida</td>
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<td>QCD and RHIC Physics <em>(Theory &amp; Exp)</em></td>
<td>Thursdays</td>
<td>12:30 p.m.</td>
<td>P. Petreczky with BNL Staff</td>
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<td>Nuclear Physics-RIKEN Theory</td>
<td>Fridays</td>
<td>2:00 p.m.</td>
<td>P. Petreczky, K. Iida</td>
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Future Workshops: RBRC/BNL

Odderon Searches at RHIC
Organizers: Wlodek Guryn, Yuri Kovchegov, Larry Trueman and Werner Vogelsang
Dates: September 13-15, 2005

Heavy Flavor Production and Hot/Dense Quark Matter
Organizers: Yasuyuki Akiba, H.Huang, R. Rapp, Kirill Tuchin, and Wei Xie
Dates: December 12-14, 2005

RHIC Collisions at Low Energies
Organizer: T. Ludlam, et al.
Dates: February 2006

RHIC Physics and the Standard Model: A Workshop and Symposium
Organizers: A. Deshpande, D. Kharzeev, R. Venugopalan and Werner Vogelsang
Dates: June 25-30, 2006
New Universities:

Theory

Iowa State University: Kirill Tuchin
Purdue University: Denes Molnar
SUNY, Stony Brook: Urs Wiedemann

Prospective

UCLA
Texas A&M
Penn State

Experiment

U. of Massachusetts, Amherst: David Kawall

New Hires:

Theory: Post Doc: Ágnes Mócsy
Experiment: Fellow: Kensuke Okada
Post Doc: Patricia Liebing
RBRC Experimental Group Overview

Hideto En'yo
RBRC Experimental Group
Overview

RBRC Scientific Review Committee
10-12 October 2005

Hideto En’yo
PHENIX Experiment
15 Nations, 60 Institutes
500 Physicists
# History

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Polarized Proton in RHIC
The first spin collider

KEK OPPPS, Tuned for RHIC at TRIUMPH

Booster: No Spin Resonance

AGS New SNAKE made in RIKEN

AGS cold snake

Snakes and Spin Rotators in the Tunnel
RIKEN construction

Proton and its spin motion in Snake

Snake Magnet/Spin Rotator
Data transfer between RIKEN and BNL
Network: ~60MB/sec
Sending by air: ~20MB/sec (≈200GB×60 tapes/week)
using media tape (1 tape=200GB, 1 case=60 tapes)
Data transfer challenge over the Pacific with network

CCJ archived run5pp data amount(Thu May 19 09:58:50 JST 2005)
Personnel

Status and recent movements

• RIKEN+RBRC is the second biggest PHENIX participating institute next to BNL.
• Yasuyuki Akiba and Matthias Perdecamp are appointed as deputy spokes persons of PHENIX collaboration (two out of two),
• Yasuyuki Akiba is responsible for the construction of the vertex detector upgrade in PHENIX.
• Since Akiba started, RBRC is expanding QGP physics activity

- M. Kaneta moved to Tohoku University (tenure)
- O. Jinnouchi moved to University of Tokyo (tenure)
- J. Heuser to GSI and A. Kiyomichi to JAERI (tenure equiv.)
- Dave Kawall (Fellow, starts June 04)
- New RIKEN tenure I. Nakagawa joined 1st of Dec.04
- J. Asai joined 1st of April04, (Kiso Tokken)
- N. Kamihara joined 1st of April05, (Kiso Tokken from JRA)
- S. Kametani and Y. Onuki joined 1st of April05 for Upgrade work at Wako
- Kensuke Okada will be a new fellow
- Patricia Liebing will join in January as New Research Associate
Member of RBRC Experiment 2004/5

- Students
  - 15 Students, 8 Spin, 3 HI, 4 Upgrade

- Important Visitors

- Fellows/Postdocs

- Tenure

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- Tenure Breakdown:
  - JFY2001: 8
  - JFY2002: 10
  - JFY2003: 12

- Total Students: 10, 12, 15, 19

- Total Visitors: 5, 7, 9, 14
# Student Status (RBRC&Wako)

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<td>F. Kajihara</td>
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<td>D. Gabbart</td>
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<td>R. Seidl</td>
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<td>PT</td>
</tr>
</tbody>
</table>

This physics program attracts young people. They graduate, and new ones join.
Experiment G. Organization

**RBRC**
- Hideto Enyo
- Gerry Bunce
- Matthias Grosse Perdekamp
- Abhay L Deshpande
- Douglas E. Field
- David Kawall
- Xie Wei
- Kensuke Okada
  (Osamu Jin-nouchi)
  (Masashi Kaneta)
- Naohito Saito (Visitor)

**RIKEN/Wako**
- Masahiro Okamura
- Kiyoshi Tanida
- Atsushi Taketani
- Rykov Vladimir
- Junji. Tojo
- Hisa Torii
- Yoshiyuki Onuki
- Hiroyuki Kano
- Nobuyuki Kamihara
- Kohei Fujiwara
- Yasuyoshi Inoue
- Hiroki Kanoh
- Takuma Horaguchi

**WAKO/CCJ**
- Takashi Ichihara
- Yasushi Watanabe
- Satoshi Yokkaichi
- Soichiro Kametani

**BELLE**
- R. Seidl (RBRC Visitor)
- A. Ogawa (RBRC Visitor)
What is the fly wheel in the proton

Proton Spin

$J = \frac{1}{2}$

Proton Spin Crisis
2005
First long longitudinal-spin polarized-proton run
Figure of merit (LP4) more than 40 times larger than that of previous runs

Spin Fest : Y. Goto
CCJ: Y. Watanabe
Toward Gluon Polarization

- A. Deshpande (π, Jets)
- K. Okada (Direct photon)

\[ \pi^0 A_L \text{ from pp at } \sqrt{s} = 200 \text{ GeV} \]
- Run 4
- Combined

Scaling error of \( \sim 65\% \) is not included.

\[ p_T \text{ (GeV/c)} \]

\[ \text{Ed}^2 / dp_T^2 \text{ (pb GeV}^2 c^2) \]

- NLO pQCD
- CTEQ6M PDF

\[ \mu = 1/2p_T, p_T, 2p_T \]

- Theory without correction
- Blue/green line, PYTHIA default/LO
- Solid/dashed, with/without trigger bias
- Shade, maximum scale uncertainty of pT cone

\[ \text{Asymmetry} \]

\[ A g = g \text{ input} \]

\[ 0.25 \text{ pb}^{-1}, 26\% \text{ pol.} \]

pT cone (GeV/c)
Transversity (or Orbital motion)

We discovered huge forward neutron asymmetry

We discovered that Jet fragment remembers spin
Beam Polarization and Relative Luminosity

I. Nakagwa, D.Kawall

Relative Pol
Absolute Pol.

Relative Lumi.

rotator off

rotator on

Spin Direction at Collision
Detector Upgrade in PHENIX

Pixel barrels
(50 μm x 425 μm)
Strip barrels
(80 μm x 3 cm)
(50 μm x 2 mm)

1 - 2% $X_0$ per layer
barrel resolution < 50 μm
endcap resolution < 150 μm

A. Taketani
Muon-trigger upgrade

- Requirement towards the $\sqrt{s} = 500$ GeV run
- Resistive Plate Chamber technology chosen by PHENIX
  - cheap – wide coverage possible
  - can leverage existing RPC R&D from CMS
  - timing information
  - 3-dim space point for enhanced pattern recognition
- Two small prototypes successfully tested in 2005 run
  - Approved NSF-MRI -- 1st Arm in 2008, 2nd Arm in 2009
The world first Polarized Collider is now producing Exciting Physics Results

We are in full swing and will continue to be
Theoretical Physics at RIKEN BNL Research Center
Strong Interactions and QCD

Larry McLerran
Theoretical Physics at RIKEN-BNL Center
Strong Interactions and QCD

How are strongly interacting particles made from fundamental constituents?

How do fundamental interactions of QCD produce mass and confinement?

What is the behavior of strongly interacting matter in bulk?
Nuclear Matter → Quark Gluon Plasma

What is the physics beyond the standard model?
Tests of CKM matrix.

All issues intertwined!
Require understanding and computation.
Current Interests in RIKEN-BNL Center

Lattice Gauge Theory

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

Structure of Hadrons

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

Color Glass Condensate and Quark Gluon Plasma

RHIC Phenomenology

Everything for

\[ x \leq 10^{-2} \]
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)

Will here preliminary results from QCDOC on

The weak interactions in strongly interacting particles

CP violation in kaon decays

Spectra of exotic hadronic states, such as pentaquark

Low energy matrix elements

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

Goals:

Turn study of high energy density matter into a precise science

Understand from first principles in QCD, the high energy limit
Why is BNL 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
Relations

QCD and Lattice Gauge Theory

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

Spin and pQCD

Vogelsang is tenured
Kretzer a joint PD with NT
Larry Trueman in HEP

RHIC Physics

Strong collaboration with NT group
RIKEN-BNL Theoretical Physics Fellows

Graduates

D. Bodeker, Tenured C4, Bielefeld
D. Kharzeev, Tenured BNL
D. Rishke, Tenured C-4 Frankfurt
D. Son, Tenured U of Washington
R. Venugopalan, Tenured BNL
T. Wettig, Tenured C-3 Regensburg
M. Stephanov, Tenured U of Ill, Chicago
U. Van Kolck, Tenured U of Arizona
T. Schaefer, Tenured U of N. Carolina
A. Kusenko, Tenured UCLA
W. Vogelsang, Tenured at BNL

New Fellows:

D. Molnar: Purdue
K. Tuchin: Iowa State
U. Weidemann Stony Brook

Current Fellows

S. Bass, Duke
T. Izubuchi, Kanazawa
S. Jeon, McGill
T. Blum, U of Connecticut
P. Petreczky, BNL (NT)
S. Sasaki, Tokyo (NT)
S. Aoki, Tsukuba
K. Iida (NT)

Next Year:

Texas A&M
Penn State U.
Minnesota?
UCLA?......
RBRC Postdoctoral Fellows:

Spin:  
S. Kretzer  
F. Yuan  
H. Yokoya  

High Density Matter-Phenomenology  
Y. Hatta  
T. Doi  
K. Fukushima  
K. Iida  
T. Sugihara  
A. Mocsy  

Lattice:  
S. Ohta  
Y. Nemoto, J. Noaki, N. Yamada, T. Yamazaki  
K. Hashimoto
THEORY PRESENTATIONS
Calculations of Cross Sections and Spin Asymmetries in Hadronic Scattering

Werner Vogelsang
Calculations of cross sections and spin asymmetries in hadronic scattering

Werner Vogelsang
RBRC & BNL Nuclear Theory

RBRC Scientific Review, 10/10/2005

Exciting program with polarized protons underway at RHIC:

What carries the proton spin?

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

- RHIC addresses the proton spin structure in new ways
- RBRC helps in major way to carry theory effort
collaboration with BNL Nuclear Theory, High Energy Theory
• QCD spin physics theory in RBRC:
  Feng Yuan, Stefan Kretzer, Hiroshi Yokoya (PhD 03/05), WV

• some examples from past year:
  * single-transverse spin asymmetries in DIS and $p^{\uparrow}p$
    Yuan, WV (to appear in PRD), Kouvaris, Qiu, Yuan, WV
  $\rightarrow$ * QCD soft-gluon resummations
    Shimizu, Sterman, Yokoya, WV PRD 71 (2005) 114007
  * analysis of fragmentation fcts. in $e^+e^-$ and $pp \rightarrow \pi^0X$
    Kretzer, Yokoya (in preparation)
  * NLO QCD corrections to $p^{\uparrow}p^{\uparrow} \rightarrow \pi X$
    Mukherjee, Stratmann, WV PRD 72 (2005) 034011
  * NLO QCD corrections to $\gamma p \rightarrow \pi X$

• “Spin plan” for DOE (02/05)
  * reviews all plans & prospects
    (will show some examples)
  * major participation of RBRC members, theory & exp.


• Review article “Study of the fundamental structure of matter with an electron-ion collider”
  A. Deshpande, R. Milner, R. Venugopalan, WV
The calculation is the theorist’s main task! needs: precision → higher orders in QCD perturbation th.

**RHIC offers good possibilities to probe Δg:**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow π + X$ [61, 62]</td>
<td>$g\bar{g} \rightarrow gg$</td>
<td>$Δg$</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow jet(1) + X$ [71, 72]</td>
<td>$g\bar{g} \rightarrow gg$</td>
<td>$Δg$ (as above)</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow γ + X$</td>
<td>$g\bar{g} \rightarrow γγ$</td>
<td>$Δg$</td>
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<tr>
<td>$p\bar{p} \rightarrow γ + jet + X$</td>
<td>$g\bar{g} \rightarrow γγ$</td>
<td>$Δg$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow γγ + X$ [67, 73, 74, 75, 76]</td>
<td>$g\bar{g} \rightarrow γγ$</td>
<td>$Δg, Δg$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow DX, DX$ [77]</td>
<td>$g\bar{g} \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$Δg$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow μ^+μ^- X$ (Drell-Yan) [78, 79, 80]</td>
<td>$q\bar{q} \rightarrow γ^* \rightarrow μ^+μ^-$</td>
<td>$Δg, Δg$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow (Z^0, W^+) X$</td>
<td>$q\bar{q} \rightarrow Z^0, q\bar{q} \rightarrow W^+$</td>
<td>$Δg, Δg$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow (Z^0, W^+) X$ [78]</td>
<td>$q\bar{q} \rightarrow W^+, q\bar{q} \rightarrow W^+$</td>
<td>$Δg, Δg$</td>
<td></td>
</tr>
</tbody>
</table>

NLO corrections known in all cases.

69
• Calculations are already successful in unpolarized pp at RHIC:

\[ pp \rightarrow \pi^0 X \]

Contributions by subprocesses
\[ pp \rightarrow \gamma X \]

**PHENIX Preliminary (Subtraction)**

**PHENIX Preliminary (Isolation)**

Shaded box represents systematic errors

- NLO pQCD (by Wilkens)
- CTEQ6M PDF
- \( \mu = 1/2 p_T, p_T, 2p_T \)

\[ E \sigma d^3p^3 \text{(pbGe}\text{V}^2) \]

\[ p_T \text{(GeV/c)} \]

\[ x, Q^2 = 5 \text{ GeV}^2 \]

**gluon polarization**

\[ \Delta g(x) = \frac{\text{jet}}{\text{pion}} \]

Weak constraint from DIS scaling violations

Probed by \( \bar{p}p \) collisions at RHIC!
Due to current "uncertainty" of gluon polarization

Expected RHIC stat. uncertainties

Now efforts underway for "global analysis"
(Deshpande, Stratmann, Kretzer, WV, ... + CTEQ)

• A long-standing problem: \( pp \to \pi^0 X \)

...well described by NLO at RHIC

...but data much higher than NLO at fixed-target energies!

• Detailed understanding of this issue is also important for spin physics at RHIC
Resummation of important higher-order corrections beyond NLO

de Florian, WV

PRD 71 (2005) 114004

\[ \frac{d^3\sigma_{ab}}{dp_T} = \frac{d^3\sigma_{ab}^{\text{Born}}}{dp_T} \left[ 1 + A_1 \alpha_s \ln^2 \left( 1 - \frac{2}{k_T^2} \right) + B_1 \alpha_s \ln \left( 1 - \frac{2}{k_T^2} \right) \right] \]

\[ + \ldots + A_k \alpha_s^k \ln^2 \left( 1 - \frac{2}{k_T^2} \right) + \ldots \]

\[ \hat{x}_T \equiv \frac{2p_T}{\sqrt{s}} \]

"threshold" logarithms

new terms lead to strong enhancement & improvement of theory vs. data

Application to prompt photons: \( pp \to \gamma X \)

"direct" contributions:

relatively small resum. effects

(Catani et al.; Sterman, WV;
Kidonakis, Owens)

"fragmentation" contributions:

d e Florian, WV

PRD 72 (2005) 014014

a bit like \( \pi^0 \) production, but less gg \( \to \) gg because \( D_{g\gamma} \) is smaller
de Florian, WV

\[ \frac{E \cdot d^3\sigma}{d^3p} (\text{pb/GeV}^2) \]
\[ \sqrt{S} = 24.3 \text{ GeV} \quad -0.2 \leq \eta \leq 1 \]

CTEQ6

\[ \frac{E \cdot d^3\sigma}{d^3p} (\mu b/\text{GeV}^2) \]
\[ \sqrt{S} = 31.5 \text{ GeV} \quad |\eta| \leq 0.75 \]

CTEQ6
• tremendous success of NLO at collider energies

• allows detailed understanding of spin asymmetries at RHIC

• at lower energies: resummation crucial helps to achieve quantitative understanding of pion and photon spectra
Global Analysis: Update of Fragmentation Functions

Stefan Kretzer
Global Analysis:
Update of Fragmentation Functions

Stefan Kretzer
Brookhaven National Laboratory &
RIKEN-BNL

RBRC Scientific Review Committee Meeting
October 10, 2005
Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model – the Factorization Theorem

\[ F_A^\lambda(x, \frac{m}{Q}, \frac{M}{Q}) = \sum_a F_a(x, \frac{Q}{\mu}, \frac{M}{Q}) + \mathcal{O}(\frac{\Lambda^2}{Q}) \]

Experimental Input

Parton Dist. Fn. Non-Perturbative Parametrization at \( Q_0 \)

Hard Cross-section perturbative calculable

DGLAP Evolution to \( Q \)
Semi-Inclusive Reactions

\[ + \mathcal{O} \left( \frac{\lambda}{p_T} \right)^n \]
Hadroproduction: $pp_\pi X$ at 200 GeV cms

Fractional contributions from initial/final state partons

Central Rapidity

<table>
<thead>
<tr>
<th>$P_\pi$ [GeV]</th>
<th>gg</th>
<th>qg+qq</th>
<th>qq</th>
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<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0.4</td>
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<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>0.1</td>
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<tr>
<td>12</td>
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</table>

Forward Rapidity

<table>
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<th>$E_\pi$ [GeV]</th>
<th>gg</th>
<th>qg</th>
<th>gg</th>
</tr>
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<tbody>
<tr>
<td>30</td>
<td>0.5</td>
<td>0</td>
<td>0.4</td>
</tr>
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<td>0.2</td>
</tr>
<tr>
<td>60</td>
<td>0.2</td>
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</table>

Initial

Final
Average Scaling Variables

- Symmetric / asymmetric kinematics for central / forward rapidity
- Large z fragmentation is probed.
- PDFs are well known in the relevant x range
Gluon Fragmentation in $b\bar{b}g$ 3-jet topologies

Experimental Fragmentation Function

$$D_g^h(x_E, \mu^2) \equiv \frac{1}{N_{tot}} \frac{\Delta N_g^h}{\Delta x_E}; \quad x_E \equiv \frac{E_h}{E_g^{jet}}$$

LO QCD scaling violations

$$\int_{\mu^2}^{(p_{max}^\perp)^2} \frac{dp_\perp^2}{p_\perp^2} \left[ P_{ji}^{(0)}(z) \right]_{p_\perp=0} = P_{ji}^{(0)}(z) \ln \left( \frac{p_{max}^\perp}{\mu} \right)^2$$

$$\frac{dD_g^h(x_E, \mu^2)}{d \ln \mu^2} \bigg|_{\mu=E_g^{jet} \sin(\theta/2)}$$

LO - DGLAP
Summary

Old:

Update:

(Data-Theory) / Theory
The parton model limit does not exist for fragmentation functions:

Hadron mass effects and delicately entwined.

dynamical higher twists are
Qualitative (dual) features:

- Heavier (light) hadrons come with a harder FF. (The low scale evolution is cut-off.)

- Heavier hadrons are suppressed. (The virtual parton has to survive a multiple of its perturbative lifetime)

- Factorization will set in at larger $p_T$ for massive particles: $p_T \gg M^2 / z$!
Quantitative (order of magnitude) estimate:

\[ p_{\perp}^{2\pi} \approx 3 \text{ GeV} \]

\[ x_1 \approx x_2 \approx 0.1 \]

\[ z \approx 0.5 \]

And slowly approaching \( M_\rho \) with increasing \( p_{\perp}^{2\pi} \).
Single Transverse Spin Physics--From DIS to Hadronic Collisions

Feng Yuan
(Single) Transverse Spin Physics
-- from DIS to hadronic collisions

Feng Yuan
RBRC, Brookhaven National Laboratory


Oct. 10, 2005
RBRC Scientific Review
What is Single Spin Asymmetry?

- Consider scattering of a transversely-polarized spin-1/2 hadron \((S, p)\) with another hadron, observing a particle of momentum \(k\).

The cross section can have a term depending on the azimuthal angle of \(k\):

\[
\frac{d\sigma}{d\Omega} \sim S \cdot (p \times k)
\]

which produce an asymmetry \(A_N\) when \(S\) flips: SSA.
SSA at RHIC


Oct. 10, 2005

RBRC Scientific Review
Naïve Parton Model Fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA:

  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass.
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to

- Two ways to generate sizable SSA
  - Transverse momentum dependent (TMD) parton distributions
  - Twist-three mechanism (Qiu-Sterman)
TMD Distribution: the definition

\[ Q(x, k_\perp, \mu, x_\zeta) = \frac{1}{2} \int \frac{d\xi^-}{2\pi} e^{-ix_\zeta - P^+} \int \frac{d^2b_\perp}{(2\pi)^2} e^{ib_\perp \cdot \vec{k}_\perp} \times \langle P | \bar{\psi}'_q(\xi^-, 0, \vec{b}_\perp) L_v^\dagger(\infty; \xi^-, 0, \vec{b}_\perp) \gamma^+ L_v(\infty; 0) \psi'_q(0) | P \rangle \]

Gauge Invariance requires the Gauge Link

Oct. 10, 2005

RBRC Scientific Review

Brodsky,Hwang, Schmidt 02'
Collins 02'
Belitsky,Ji,Yuan 02'
QCD Factorization

\[ F(x_B, z_h, P_{h\perp}, Q^2) = \sum_{q=u,d,s,...} e_q^2 \int d^2 \vec{k}_\perp d^2 \vec{p}_\perp d^2 \vec{\ell}_\perp \]
\[ \times q (x_B, k_\perp, \mu^2, x_B \xi, \rho) \tilde{q}_h (z_h, p_\perp, \mu^2, \xi/z_h, \rho) S(\vec{\ell}_\perp, \mu^2, \rho) \]
\[ \times H (Q^2, \mu^2, \rho) \delta^2(z_h \vec{k}_\perp + \vec{p}_\perp + \vec{\ell}_\perp - \vec{P}_{h\perp}) \]
TMDs at RHIC

- Drell-Yan
  SSA for Drell-Yan: Sivers function has opposite sign, $q_T^{DY} = -q_T^{DIS}$, because of the gauge link changing direction.

- Di-Jet Correlation
  There is no factorization proof yet. It is likely factorizable in terms of TMDs. However, the universality of Sivers function for this case is not clear yet. We assume they are the same as DY.
SSA for Drell-Yan

Drell-Yan $A_N$ at RHIC

$5 < M_{\mu^+\mu^-} < 10$ GeV

Oct. 10, 2005
RBRC Scientific Review
Di-jet Correlation

Jet2: $P_{2\perp}$

Jet1: $P_{1\perp}$

\[ \vec{S}_\perp \times \vec{q}_\perp \approx |S_\perp| \left( \text{Sgn}(\pi - \theta) \cos \phi_1 + \sin \phi_1 \frac{|q_\perp|}{2|P_\perp|} \right) \]

\[
\begin{align*}
    d\sigma & \propto d\sigma_{UU} + \vec{S}_\perp \times \vec{q}_\perp d\sigma_{TU} \\
    & = d\sigma_{UU} + \cos \phi_1 d\sigma_{TU}^{(1)} + \sin \phi_1 d\sigma_{TU}^{(2)}
\end{align*}
\]
$\cos \phi$ Asymmetry

Di-jet $A_N$ at RHIC

$0 < y_2 < 1$

$-2 < y_2 < 3$

$0 < y_{1,2} < 1$

$0 < y_1 < 1$ & $2 < y_2 < 3$

$2 < y_{1,2} < 3$

$6 < P_T < 10 \text{GeV}$
Thermalization in the Color Glass Condensates

Kirill Tuchin
Thermalization in the Color Glass Condensate

Kirill Tuchin

Iowa State University and RBRC

In collaboration with D. Kharzeev and E. Levin
Modern picture of AA collisions

• Initial state: the Color Glass Condensate
  – Particle spectra, multiplicities …

• Final state: the Quark Gluon Plasma
  – Elliptic flow, jet quenching …

What is the mechanism which evolves CGC into QGP?
Hydrodynamic models are successful if thermalization time $\sim t \approx 0.5$ fm.

Naively: $\sim t \sim 1/(\hbar) \sim 1$ fm/$\sim s \gg 1$ fm

Why thermalization is so fast??

"Bottom-up thermalization":

$$\alpha t = 1/\alpha_s^{13/5} Q_s$$

Baier, Mueller, Schiff, Son, 01
Possible solutions?

- Plasma instabilities may speed up the thermalization process
  
  Mrowczynski, 88; 
  Arnold, Lenaghan, Moore, 03

 ✓ However, ~t is still very close to "bottom-up" estimate.

- Early isotropization may help explain $v_2$.
  
  Arnold, Lenaghan, Moore, Yaffe, 04; 
  Rebhan, Romatschke, Strickland, 04

- No thermalization from Feynman diagrams.
  
  Kovchegov, 05
1. Parton lifetime is $\Delta = k_i^+ / k_i^{\Delta^2} \gg \Delta_{i+1} \gg \Delta t$ (Parton model)

2. Fast partons are sources of the classical field.
   (McLerran, Venugopalan)
Properties of dense partonic system

1. 2D density \( Q_s^2 \sim xG(x,Q_s)/\lambda R_A^2 \sim 1/x^\lambda \)
is a hard scale increasing with rapidity \( y = \ln(1/x) \)

- Typical transverse size of a parton \( x_\perp \sim 1/Q_s \)
decreases down the partonic ladder.
- The potential \( A_+(x_\perp \sim x_i, x_\perp \approx x_i) \approx A_+(x_i, R_\perp) \)
- Therefore, \( |E_\perp| = |H_\perp| \ll E_z \)
- Even at small \( x_\perp \) longitudinal electric field dominates the Lagrangian.
Early and later times

2. Since evolution of fast partons is frozen in time, the color field $E_z$ of faster partons is constant at $t=0$.

3. At later times the lightcone potential of the pointlike charge is $A_+ \sim 1/x_-$.

- We calculate particle production in an external time-dependent background field.
- This calculation makes it possible to include nonperturbative effects.

- Model potential: $A_+(x_-) = -E_0 \frac{x_-}{x_-^2 \omega^2 + 1}$
Our formalism

- Inclusive gluon production cross section is

\[
\varepsilon \frac{d\sigma}{d^3p} = \frac{4\pi N_c}{N_c^2 - 1} \frac{1}{p_\perp^2} \int dk_\perp^2 \alpha_s \varphi_P(Y - y, k_\perp^2) \varphi_T(y, (p - k)_\perp^2)
\]

- Unintegrated gluon distribution is related to the imaginary part of the gluon propagator:

\[
\varphi_P(Y - y, p_\perp) = \int d^2 k_\perp \Gamma^2(G \to 2G) \text{Im}D(Y - y, \vec{p}_\perp - \vec{k}_\perp) \text{Im}D(Y - y, \vec{p}_\perp)
\]
Solution

Equation of motion of the quantum field $W_{\mu}$

$$\left(-\left(\partial_{\lambda} - igA_{\lambda}\right)^2 \delta_{\mu\nu} + 2i g F_{\mu\nu}[A]\right) W_{\mu} = 0$$

Can be solved in the WKB approximation for the function $S = i \ln W$

Known solutions:
- exact in Minkowski spacetime in constant field: Sauter (1931), Weisskopf (1936), Schwinger (1951);
- WKB in Minkowski spacetime in any field: Popov (1972);
FIG. 3: Motion of a particle in the light-cone coordinates. We used \( \text{eq1} \) and \( \text{eq2} \) to derive parametric equation \( x_+ x_- = p^2 t^2 \) (assuming \( x_0^+ = x_0^- = 0 \)). At \( x_+ < 0 \) the particle moves freely along the light cone \( x_- = 0 \) until the point \( x_- = x_+ = 0 \) at which it tunnels along the line \( x_- = x_+ \) (Euclidean path, shown by dashed line) to a real trajectory at \( x_+ > 0 \). At this point particles move along \( x_+ > x_- \) branch of the parabola, while antiparticles along the \( x_+ < x_- \) branch.

---
Adiabaticity parameter

\[ \omega = \frac{k_\omega \omega}{gE_0} \]

- Early times: \( \approx \frac{k_+}{k_{i+}} \ll 1 \)

\[ -p(p_-) \sim S_p e^{-p_-^2/Q_s^2} \]

This is MV model!

- Later times: due to interactions between the gluons the frequency \( \sim k_- \) increases from 0 to \( Q_s \) \( \gamma \sim 1 \)

\[ \epsilon_p(p_\epsilon) \sim S_p e^{\epsilon\epsilon/T} \]

Where \( T=0.17 \ Q_s \). Equillibration time follows from equation of motion: \( \sim 1/Q_s \)
Summary

• We develop an approach to the particle production at high energy which incorporates the main idea of the CGC as well as the non-perturbative Schwinger-type mechanism.

• Within this approach we
  – reproduce the McLerran-Venugopalan result at early times of the collision, when the fields are static;
  – show that the particle spectrum is thermal at later times, when the fields rapidly oscillate;
  – argue that the transition time between the two regimes is short.

• Our approach is applicable also to DIS.
Quarkonia Correlators Above Deconfinement

Ágnes Mócsy
Quarkonia Correlators Above Deconfinement

Áanes Mócsy

RIKEN BNL
Research Center

RBRC Scientific Review Committee Meeting, BNL October 10, 2005

* Why interested in quarkonia correlators
* How to calculate correlators
* Phenomenology versus lattice
* Open questions

based on A.M., P. Petreczky: hep-ph/0411262
hep-ph/05
Why interested in quarkonia correlators?
Tell about the modification of quarkonia properties in a hot medium.

Efforts to identify deconfinement - experiments SPS-CERN, RHIC-BNL...
- theory, phenomenology
- lattice QCD

* Screening prevents $J/\psi$ binding above $T_c$ Matsui, Satz '86
  color screening length < size of resonance

* Sequential dissolution - higher excitations melt earlier Digal, Petreczky, Satz '01

**Potential Model** $J/\psi$ disappears at $1.1T_c$

$T = 0$ — Cornell potential

$T \neq 0$ We don't know. e.g. screened Cornell potential

Ágnes Mócsy
**Lattice QCD**

* $J/\psi$ melts abruptly at $1.6T_c < T < 1.9T_c$  
  Umeda: Asakawa, Hatsuda '04

* $J/\psi$, $\eta_c$ survive $\sim 1.5T_c$ & gradually melt by $\sim 3T_c$  
  $+\,$ masses don't change

  $\chi_c^0, \chi_c^1$ dissolve $\sim 1.1T_c$  
  Datta, Karsch, Petreczky, Wetzorke '04

* $\eta_b$ unchanged $\sim 2T_c$ & $\chi_b$ at $\sim 1.15 \, T_c$  
  Petrov, Petreczky 'QM05

Euclidean current correlator measured

\[
\langle \bar{q} q \rangle \langle \bar{b} b \rangle
\]

Spectral function - w/ MEM

Can quarkonia exist as resonances above deconfinement?

Ágnes Mócsy
How to calculate correlators

* Model spectral function: bound states + continuum

\[ \text{Mass } M_i, \text{ amplitude } F_i, \text{ radius } R_i \text{ from Schrodinger equation w/} \]

\[ \text{screened Cornell potential} \]

\[ \text{OR} \]

\[ \text{potential fitted to lattice internal energy} \]

* Threshold \( s_0(T) = 2 m_q(T) = 2m + V_1(T) \)

* Correlator ratio:
  deviation from 1 suggests medium effects

\[ \frac{W(r,T)}{\sigma^2} \]

asymptotic value \( V_1(T) \)

Ágnes Mócsy
Quarkonia properties

Masses

\[ \frac{M(T)}{M(T=0)} \]

- don't change substantially, except the \( \chi_c \)

Radii

\[ \langle r^2 \rangle^{1/2} \text{[fm]} \]

- \( \chi_c \) melts early
- \( bb^- \) survive to higher \( T \) than \( cc \)
- \( \chi_b \) approximately same size as \( \eta_c \)

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Phenomenology vs. Lattice: 1P Scalar

\[ \chi_{c0} \text{ modified at } \sim 1.1T_c \]

\[ \chi_{b0} \text{ modified at } \sim 1.13T_c \]

Qualitative agreement w/ lattice.

Correlator enhanced, even though \[ \chi_{c0} \text{ state becomes negligible} \] Qualitatively \~ behavior, even though \[ \chi_b \text{ survives until much higher } T \text{ than } \chi_c \]

Enhancement due to thermal shift of the continuum threshold - dominates

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Phenomenology vs. Lattice: $1S$ Pseudoscalar

Increase in correlators

No agreement w/ lattice.

Contribution from continuum due to threshold reduction

Drop at large $\tau$ in $\eta_b$ due to amplitude reduction

Ágnes Mócsy
Conclusions & Open Questions

Quarkonia melting at $T_c$ - proposed sign for deconfinement challenged by lattice data - some quarkonia survives well above $T_c$

First analysis of quarkonia correlators in potential model

$T$-dependence of the correlators not in agreement with the lattice

Increase in correlators - due to threshold decrease -- lattice doesn't see

Tested w/ different potentials -
no qualitative changes in the $T$-dependence of the correlators

* Can medium effects on heavy quark boundstates be described by potential models?

* Do we miss some physics on the lattice?
  Info about continuum hidden in the lattice artifacts?

Ágnes Mócsy
Properties of the Plasma Created at RHIC

Denes Molnar
Properties of the plasma created at RHIC

Denes Molnar

Aug 15, 2005 - RIKEN/BNL Research Center & Purdue University
previously - Ohio State University

prepared for RBRC Review

Oct 10-12, 2005, RIKEN/BNL, Upton, NY

RHIC "Little Bang"

\[ \text{Au} \quad \rightarrow \quad \star \quad \leftarrow \quad \text{Au} \]

quark-gluon plasma?
Dynamical frameworks

parton cascade

Covariant Transport
- Boltzmann 1<->2, 2->2
- Inelastic 3<->2
- Correlations

Transp + Phase trans.

color Boltzmann-Vlasov

"color glass"

Classical Field Theory
- 2+1D Yang-Mills
- 3+1D Yang-Mills
- Walecka?

"Holy Grail"

Nonequilibrium QFT
- 1+1D $\phi^4$
- extend to 2+1D, 3+1D
- gauge theories

hydro

Hydrodynamics
- Euler (ideal) hydro 3+1D
- Viscous hydro 2+1D, 3+1D

Lattice QCD
- Equation of State
- Screening
- Transport coefficients
- Quasi-particles
- Finite baryon density

lattice
Quark-gluon kinetic theory

Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...  

Incoherent, particle limit of underlying quantum theory (QCD). Nonequilibrium approach.

**Boltzmann transport eqn:**  
\[ f_i(\vec{x}, \vec{p}, t) \] - quark/gluon phase space distributions  

\[
p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = S_i(\vec{x}, \vec{p}, t) + C_{i,\text{el.}}^i[f](\vec{x}, \vec{p}, t) + C_{i,\text{inel.}}^i[f](\vec{x}, \vec{p}, t) + ... \]

- on-shell dynamics \((p^2 = m^2 \geq 0)\)

other variants: e.g., VNI(b), off-shell partons Kinder-Geiger, Shrivastava, Mueller, Bass, ...

* OSCAR code repository @ http://nt3.phys.columbia.edu/OSCAR *
Relevant parameters

**mean free path**: characterizes local conditions

\[ \lambda(x) \equiv \frac{1}{\text{cross section} \times \text{density}(x)} \]

\(\lambda = 0 \quad \text{- ideal hydrodynamics} \)

\(\lambda = \infty \quad \text{- free streaming} \)

**transport opacity**: time-integrated, spatially averaged  

[DM & Gyulassy NPA 697 ('02)]

\[ \chi \equiv \langle n_{\text{colli}} \rangle \langle \sin^2 \theta_{CM} \rangle \quad \sim \# \text{ of collisions per parton} \times \text{momentum transfer efficiency} \]
Elliptic flow ($v_2$)

one of the most important observables

spatial anisotropy $\rightarrow$ final azimuthal momentum anisotropy

$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

- measures strength of interactions
- self-quenching, develops at early times
Strong interactions at RHIC

DM & Gyulassy, NPA 697 ('02): \( v_2(p_T, opacity) \)

\[ \begin{align*}
\sigma_{el} &\approx 45 \text{ mb} \\
\sigma_{el} &\approx 20 \text{ mb} \\
\sigma_{el} &\approx 8 \text{ mb} \\
\sigma_{el} &\approx 0.6 \text{ mb}
\end{align*} \]

\( dN_g/d\eta_{cent} = 1000 \)

\( \text{MPC Au+Au @ 130A GeV duality} \)

\( p_{T\perp} \text{ [GeV]} \)

**need 15x perturbative opacities** - \( \sigma_{el} \times dN_g/d\eta \approx 45 \text{ mb} \times 1000 \)

(saturated gluon \( \frac{dN_{cent}}{d\eta} = 1000 \), \( T_{eff} \approx 0.7 \text{ GeV} \), \( \tau_0 = 0.1 \text{ fm} \), 1 parton \( \rightarrow \) 1 \( \pi \) hadronization)

\( \Rightarrow \text{strongly-interacting quark-gluon plasma (sQGP)} \)
Still not ideal fluid(!)

Even $\sigma_{gg\rightarrow gg} \sim 50$ mb is insufficient for ideal hydro (perturbative QGP: $\sim 3$ mb)

DM & Huovinen, PRL94 ('05):

- dissipation reduces $v_2$ by 30 – 50%
- in addition, it slows cooling

was already seen in 1+1D transport
Gyulassy, Pang & Zhang ('97)
also there in 1+1D viscous hydro
Danielewicz & Gyulassy ('85)

$$\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = \frac{(\zeta + \frac{4}{3}\eta)}{\tau^2}$$

viscosity very small - but gradients very large
Heavy quark equilibration

~ "Brownian motion" in plasma

\[ m_g, m_u, m_d, m_s \sim T \]

\[ m_c \sim 1.2 \text{ GeV} \gg T \]

\[ v \sim \sqrt{T/m} \]

\[ p \sim \sqrt{m \cdot T} \]

\[ N_{\text{coll}} \sim p/\Delta q \sim \sqrt{m/T} \]

heavy quarks very heavy \( \Rightarrow \) need more collisions to randomize

more quantitative indicator: viscosity grows with mass

**classical kinetic theory:** \[ \eta \approx 0.553 \sqrt{mT/\sigma_{el}} \]

**O(N) model:** Aarts & Martinez ('04) \( \rightarrow \)

RBRC Review, Oct 10-12, 2005
Expect charm elliptic flow

DM, JPS 31 ('04): parton $v_2(p_T)$

Laue [STAR] '04: decay electron $D \rightarrow K^(*) e \nu$ data

significant charm equilibration in opaque plasma,
charm $v_2$ reaches light parton $v_2$ above $p_T > 2 - 3$ GeV

similar results from parton cascade ZPC Zhang et al '05, Fokker-Planck approach Teaney et al '05

RBRC Review, Oct 10-12, 2005
Charm suppression at high-pT

\[ R_{AA} \equiv \frac{\text{yield in } A + A \text{ collision}}{\text{yield for independent } N + N \text{ scatterings}} \]

DM '04: pion \( R_{AA} \)

- \( b = 8 \text{fm}, 3 \text{mb} \)
- \( b = 8 \text{fm}, 10 \text{mb} \)

charm \( R_{AA} \) (10 mb)

\[ \text{canonical explanation: suppression is due to energy loss} \]

expect weaker suppression for charm than for light hadrons at high pT

current excitement/puzzle: data suggest similar suppression for light and charm(?!)

RBRC Review, Oct 10-12, 2005

Denes Molnar
Plasma “push”  DM ’05

in opaque plasma, initially soft partons can get accelerated to surprisingly high $p_T$ in multiple collisions

⇒ three components:

- energy loss → partons that lose energy via interactions
- corona → partons that escape without interactions
- “push” → partons that interact and gain energy
  (“remnant” of hydrodynamic behavior)
**corona, quench, push fractions vs pT**

DM, nucl-th/0503051: \( \sim 6 \times \) pQCD opacities

- + corona
- quench \( p_{T,i} > p_{T,f} \)
- push \( p_{T,i} < p_{T,f} \)

**elliptic flow contributions vs pT**

- + corona
- \( \bowtie \) quench \( p_{T,i} > p_{T,f} \)
- \( \blacksquare \) push \( p_{T,i} < p_{T,f} \)
- \( \triangledown \) total

significant \( \sim 20\% \) "push" component even at \( p_T \sim 8 \) GeV

\( v_2 \) is higher and decreases slower at high \( p_T \) relative to pure energy loss case
distribution of initial momenta for fixed final momentum bins, $|y_{fin}| < 1$

(only quench + "push" plotted, normalized)

DM, nucl-th/0503051: $\sim 6 \times$ pQCD opacities

"lucky" $p_{T,i} \sim 1$ GeV soft partons can end up at $p_T \sim 7 - 8$ GeV
Conclusions

- **What we learned:**
  - large elliptic flow observed at RHIC indicates a very opaque parton system
  - but even 45 mb elastic parton-parton cross sections are insufficient to reach the ideal hydrodynamic limit $\Rightarrow$ not ideal fluid
  - at such extreme opacities significant charm quark elliptic flow is expected at moderately high $p_T > 2 - 3$ GeV
  - also, initially soft partons can get accelerated to surprisingly high $p_T$ in multiple collisions $\Rightarrow$ energy loss is not the only mechanism that plays a role

- **Open issues/Next steps:**
  - map out parameter space - centrality, A, collision energy (LHC), bottom, ...
  - improve parton cascade - inelastic channels, coherence effects
  - compare to simpler limits - viscous hydrodynamics (Navier-Stokes), Fokker-Planck
  - combine with classical fields - QCD analog of plasma physics
Need to build bridges

parton cascade

Covariant Transport
Boltzmann 1<->2, 2->2
Inelastic 3<->2
Correlations

Transp + Phase trans.

color Boltzm.~Vlasov

“color glass”

Classical Field Theory
2+1D Yang–Mills
3+1D Yang–Mills
Walecka?

Nonequilibrium QFT
I+1D $\phi^4$
extend to 2+1D, 3+1D
gauge theories

“Holy Grail”

establish an international collaboration for QCD transport theory
Charge Transfer Fluctuations as a QSP Signal

Sangyong Jeon
Charge Transfer Fluctuations as a QGP signal

Sangyong Jeon
with Lijun Shi & Marcus Bleicher

Physics, McGill

RBRC
Charge Transfer Fluctuations

(Thomas, Quigg, Chao (1973), Shi, Jeon, hep-ph/0503085, To appera in PRC)

- Charge Transfer:

\[ u(y) = \frac{[Q_F(y) - Q_B(y)]}{2} \]

where

\[ \begin{cases} 
Q_F(y) = \text{Net charge in the forward region of } y \\
Q_B(y) = \text{Net charge in the backward region of } y 
\end{cases} \]

Observable:

\[ \kappa(y) \equiv \frac{\langle \Delta u(y)^2 \rangle}{dN_{ch}/dy} \]
Suppose a neutral cluster $R$ decays near $y$.

- $R \rightarrow h^+ + h^-$ with a typical $\Delta y = \lambda$

- For each $R$ decay, $u(y)$ changes by $\pm 1 \implies$ Random walk

- $D_u(y) = \langle (\Delta u(y))^2 \rangle = N_{\text{steps}}(y) \approx \lambda \frac{dN_{\text{cluster}}}{dy}$

- Since $dN_{\text{cluster}}/dy \propto dN_{\text{ch}}/dy$,

\[
\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)
\]

Measures the local charge correlation length.
The difference:

Hadron Gas only

\[ \lambda_{HG} \]

Hadron Gas + QGP

\[ p \lambda_{QGP} + q \lambda_{HG} < \lambda_{HG} \]
Hadronic models $\Longrightarrow$ constant $\kappa$

![Graphs showing data for different models and percentage ranges.](image)

- UrQMD, Central 6%
- HIJING 0-5%
- HIJING 20-30%
- HIJING 40-50%
- $0.63dN_{ch}/d\eta$
- $0.64dN_{ch}/d\eta$
- $0.68dN_{ch}/d\eta$
- $D_u(\eta)$, 0-5%
- $D_u(\eta)$, 20-30%
- $D_u(\eta)$, 40-50%

RQMD, Cent., Semi-Peri.
\[ \kappa(\eta) = \frac{\gamma_{\text{HG}}}{2} - \frac{\gamma_{\text{QGP}}}{2} \left( \frac{\gamma_{\text{HG}}}{\gamma_{\text{QGP}}} - 1 \right) \frac{dN_{\text{QGP}}/d\eta}{dN_{\text{ch}}/d\eta} \]
HG – STAR acceptance

Hadronic models with the single component results

\[ \gamma = 1.75 \]

HIJING all centrality
UrQMD central

\[ \gamma = 1.75 \]

RQMD all centrality
HG + QGP - STAR acceptance

End point fixed by \( \langle \Delta Q^2 \rangle / N_{\text{ch}} \)
Conclusions

- Charge transfer: \( u(y) = (Q_F(y) - Q_B(y))/2 \)

- \( \kappa(y) \equiv \langle \Delta u(y)^2 \rangle / dN_{ch}/dy \): A measure of local charge correlation length \( \implies \) Captures inhomogeneity

- QGP may be created in a small region around midrapidity. As collisions become more central
  - Large acceptance: \( \kappa(y) \) develops a dip in the middle
  - Small acceptance: \( \kappa(0) \) becomes smaller faster than \( \kappa(y_0) \) \( \implies \) Flattening

- Net baryon transfer fluctuation. Net strange transfer fluctuation

- \( \langle \Delta N_{ch}^F(y) \Delta N_{ch}^B(y) \rangle \)
Effective Action for High Energy QCD with the Pomeron Loop

Yoshitaka Hatta
Effective action for high energy QCD with the Pomeron loop

Yoshitaka Hatta (RBRC)

In collaboration with E. Iancu, L. McLerran, A. Stasto, D. Triantafyllopoulos
hep-ph/0504182, 0505235 (NPA, in press)
QCD evolution equations at small-$x$

BFKL, BKP

\[ S^{4\alpha_s \ln 2} \]

Free propagator

rapidity ordering
Balitsky-Kovchegov-JIMWLK equation

\[ gA^+ \sim 1 \]

Dressed propagator

Intended for dense-dilute scatterings. Saturation at fixed impact parameter. Total cross section still violates the Froissart bound.
Beyond the B-JIMWLK^{2} equation

An evolution equation with all possible reggeon number changing vertices describes both the gluon recombination and the gluon multiplication, namely, Pomeron loops.
Effective action approach

Lipatov, Verlinde bros, Balitsky...

Effective action

\[ S_{\text{JIMWLK}} = A^- \eta[V, V^+] A^- \]

\[ V^+ = \text{P} \exp(ig \int dx^- A^+) \]

Kernel of the evolution equation

\[ K_{\text{JIMWLK}} = \frac{\delta}{\delta A^+} \eta[V, V^+] \frac{\delta}{\delta A^+} \]

The complete kernel which contains Pomeron loops must be self-dual, i.e., invariant under \( A^+ \leftrightarrow \frac{\delta}{\delta A^+} \).

(Kovner&Lublinsky,05)
Construction of the effective action

The total gauge field \( A^+ + a^\mu + \delta A^- \)

classical semi-hard soft

\[
\exp(iS_{\text{eff}}[A, \delta A]) = \int_{0A^+} \! Da \exp(iS_{\text{YM}} - iJ^\mu A_\mu + iS_{\text{WZ}})
\]

\[
S_{\text{eff}} = -\frac{1}{2} \int_{xy} (D_v F^{vi})^a_x G_{ab}^{ij} (x, y)(D_\lambda F^{\lambda j})^b_y
\]
Background field propagator in the light cone gauge

\[ iG(x, y; \delta A^-) \propto \ln \frac{1}{b} \delta(x_T - y_T) \left[ \theta(x^+ - y^+) W_{x^+,y^+}(x_T) + \theta(y^+ - x^+) W_{y^+,x^+}(x_T) \right] \]

\[ W = T \exp(-\int dx^+ \frac{\delta}{\delta A^+}) \]

\[ S_{\text{eff}} = -\frac{1}{2} \int_{xy} (2D_+ F^{+i})^a_x G^{ij}_{ab}(x, y; A^i, A^-)(2D_+ F^{+j})^b_y \]

All order in \( \frac{\delta}{\delta A^+} \)\hspace{1cm} All order in \( A^+ \)

Integration over \( x^\pm \) leads to a 2D nonlinear sigma model.
Two-dimensional effective theory of Wilson lines

\[ S_{\text{eff}} = \frac{i}{2\pi g^2 N_c} \ln \frac{1}{b} \int_\mathbb{R} \text{Tr} \left[ V_{\infty}^\dagger (\partial^i W_{-\infty})(\partial^i V_{-\infty}) W_{\infty}^\dagger + V_{\infty}^\dagger W_{-\infty} (\partial^i V_{-\infty})(\partial^i W_{\infty}^\dagger) 
\right. \\
\left. + (\partial^i W_{\infty}^\dagger)(\partial^i V_{\infty}) W_{-\infty} V_{-\infty} + W_{\infty}^\dagger (\partial^i V_{\infty})(\partial^i W_{-\infty}) V_{-\infty} \right] \]

\[ V_{\infty}^\dagger W_{-\infty} V_{-\infty} W_{\infty}^\dagger = 1 \]

zero curvature

\[ S_{\text{eff}} \text{ is invariant under } V^+ \leftrightarrow W, \text{ i.e., } S_{\text{eff}} \text{ is self-dual.} \]
Summary

- B-JIMWLK^2 equation misses Pomeron loops. Necessity to construct a self-dual kernel.
- We constructed an important contribution to the complete kernel by combining the CGC and the effective action approaches.
- There are other diagrams still to be calculated to obtain the complete kernel.
Feedback Effects on the Pairing Interaction in Color Superconductors

Kei Iida
(Presented by Kenji Fukushima)
Feedback effects on the pairing interaction in color superconductors

Kei Iida (RIKEN BNL Research Center)
presented by Kenji Fukushima

Contents
1. Introduction
2. Gap equation in weak coupling
3. Gap equation with feedback effects
4. Ginzburg-Landau theory: strong coupling corrections
5. Conclusion

Reference

Introduction

QCD phase diagram

Crucial features of color superconductors

Superfluidity
— presence of a condensate of quark Cooper pairs and superfluid baryon density ($n_s$)

Color Meissner effects
— transverse color fields screened in a spatial scale of order the London penetration depth $\sim (\mu / g^2 n_s)^{1/2}$
What happens if quark matter occurs in compact stars

Possible color superconductivity — strong coupling regime

How is the feedback correction to the weak coupling pairing gap?

Study of this correction is limited to the case of zero temperature [order-of-magnitude estimates by Rischke, PRD 64 (2001) 094003].

Focus of this work

Feedback corrections near the transition temperature
— dominated by the color Meissner screening of the long-range magnetic force
— altering the gap magnitude in a different way among different phases

System

massless quarks of uds flavors and RGB colors
Fermi momenta common to all colors and flavors

Cooper pairing between quarks

\[ \Delta \]

On-shell gap at relative pair momentum \(|k|=k_F\)

\[ \left( \Phi^+ \right)_{abj} = \varepsilon_{abc} \varepsilon_{ijl} (d_e)_l \]

Two optimal states

1. Color-flavor locked (CFL) state

\[ d_R^* \cdot d_G = d_G^* \cdot d_B = d_B^* \cdot d_R = 0, \quad |d_R| = |d_G| = |d_B| \]

("isotropic")

2. Flavor color superconducting (2SC) state

\[ d_R \parallel d_G \parallel d_B \]

("anisotropic")

172
Gap equation in weak coupling

\[ D_{\mu\nu}(p) = \frac{\delta_{\alpha\beta} P^T}{|p|^2 + \frac{1}{4}\frac{m_D^2 g^2}{|p|}} - \frac{\delta_{\alpha\beta} P^L}{|p|^2 + \left(m_D^2 + \frac{3m_M^2 h(p)}{4}ight)} \]

\[ m_D^2 \approx \frac{N_f g^2 \mu^2}{18\pi^2} \]

Gluon propagator (in Landau gauge)

For \(|p_0| \ll |p| \ll \mu\) (forward scattering),

\[ D_{\mu\nu}^\alpha(p) \approx \frac{\delta_{\alpha\beta} P^T}{|p|^2 + \frac{1}{4}\frac{m_D^2 g^2}{|p|}} - \frac{\delta_{\alpha\beta} P^L}{|p|^2 + \left(m_D^2 + \frac{3m_M^2 h(p)}{4}\right)} \]

Gap equation for 2SC near \(T_c\)

\[ d_F = \left(1 - \frac{7}{12} \frac{T - T_c}{T_c} \right) d_F - \frac{7\zeta(3) g}{16\pi T_c^3} d_F + O(d_F^3), \quad g = \frac{g}{3\sqrt{2}\pi} \]

\(\Delta^\text{Landau damping (no static screening)} \quad \Delta^\text{Debye screening}\)

\(\text{Cf.}\) The CFL state is more favorable than the 2SC state in weak coupling.

Gap equation with feedback corrections

\[ D_{\mu\nu}^\alpha(p) \approx \frac{\delta_{\alpha\beta} P^T}{|p|^2 - i\pi m_D g^2 / 4|p| + \left(m_M^2 + f(p)\right)} - \frac{\delta_{\alpha\beta} P^L}{|p|^2 - \left(m_D^2 + \frac{3m_M^2 h(p)}{4}\right)} \]

\[ m_D^2 \approx \frac{N_f g^2 \mu^2}{18\pi^2} \]

Gluon propagator near \(T_c\) (in Landau gauge)

For \(|p_0| \ll |p| \ll \mu\) (forward scattering),

\[ D_{\mu\nu}^\alpha(p) \approx \frac{\delta_{\alpha\beta} P^T}{|p|^2 - i\pi m_D g^2 / 4|p| + \left(m_M^2 + f(p)\right)} - \frac{\delta_{\alpha\beta} P^L}{|p|^2 + \left(m_D^2 + \frac{3m_M^2 h(p)}{4}\right)} \]

\[ m_D^2 \approx \frac{N_f g^2 \mu^2}{18\pi^2} \]

Meissner screening

with BCS kernel \(f(p) = \frac{6}{7\zeta(3)} \sum_{s=0}^{\infty} \frac{\int_0^\infty dx}{(s+1/2)^2 + (\sqrt{2}\pi \chi/2\pi T_c)^2} \)

\[ \rightarrow \begin{cases} 1, & |p| \ll T_c \text{ (London limit)} \\ 3\pi^4 T_c / 14\zeta(3) |p|, & |p| \gg T_c \text{ (Pippard limit)} \end{cases} \]

\(\text{Cf.}\) The gluon momenta \(p\) of order \(T_c\) are most important for the feedback effects.

173
Gap equation with feedback corrections (contd.)

\[ \Delta = \alpha \Delta \]

\[ \Delta \]

Meissner screening

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>2SC</th>
<th>CFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0</td>
<td>attractive</td>
</tr>
<tr>
<td>4-7</td>
<td>+</td>
<td>none</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>repulsive</td>
</tr>
</tbody>
</table>

Feedback effects near \( T_c \)

to leading order in \( g \), the 2SC gap increases by a factor of \( (1 - Cg/2)^{1/2} \), \( C = 0.409 \ldots \)
the CFL gap decreases by a factor of \( (1 + 3Cg)^{1/2} \)

Ginzburg-Landau theory


Ginzburg-Landau free energy

\[ \Delta \Omega = \Omega_s - \Omega_n = \alpha \sum_a |d_a|^2 + \beta_1 \left( \sum_a |d_a|^2 \right)^2 + \beta_2 \sum_{ab} |d_a^* \cdot d_b|^2 \]

Phase diagram near \( T_c \)

Strong coupling corrections

\[ \beta_1 = \frac{7 \zeta(3)}{8(\pi T_c)^2} \left( 1 + \frac{3}{2} \frac{Cg}{2} \right) N \left( \frac{\mu}{3} \right) \]

\[ \beta_2 = \frac{7 \zeta(3)}{8(\pi T_c)^2} \left( 1 - \frac{15}{2} Cg \right) N \left( \frac{\mu}{3} \right) \]

\[ \alpha = 4 N \left( \frac{\mu}{3} \right) \frac{T - T_c}{T_c} \]

Corrections are of order \( \log^1 (\mu / T) \) rather than \( T_c / \mu \) as encountered in \(^3\)He.
Conclusion

The feedback role that the gap dependence of the pairing interaction plays in the gap equation for color superconductors near $T_c$

- dominated by the color Meissner screening of the long-range transverse force

- increasing the 2SC gap, while decreasing the CFL gap
  - complicated color dependence of the Meissner-screened pairing force

- leading to strong coupling corrections to the parameters characterizing the fourth order terms in the Ginzburg-Landau free energy
  - of order $g^{-1}(\mu / T_c)$ due to the long-range nature of the pairing force
Phase Structure and Instability in Dense Quark Matter

Kenji Fukushima
Phase Structure and Instability in Dense Quark Matter

Kenji Fukushima
(RIKEN BNL Research Center)


October 2005
Simple Questions

- What happens eventually when matter is heated and heated?
  - Quark-Gluon Plasma in Relativistic Heavy-Ion Collisions

- What happens eventually when matter is squeezed and squeezed?
  - Color Superconductor in the cores of compact stellar objects

October 2005
Conjectured QCD Phase Diagram

- (s)QGP
- ~170 MeV
- Chiral Critical End-Point
- 2SC uSC dSC
- Color Superconductors
- Hadron
- Gapless CFL
- Crystalline CSC

No Experiment
No Lattice
Many Phases...

October 2005
Phase Diagram at High Density

Really Stable? Instability??
Cooper Pairing Pattern

Diquark Condensate

\[ \Delta_{\alpha i} \propto \epsilon_{\alpha \beta \gamma} \epsilon_{ijk} \left\langle \overline{\psi}_{\beta j} i\gamma_5 C \overline{\psi}_{\gamma k} \right\rangle \]

Anti-symmetric in Color (attractive in OGE)
Anti-symmetric in Flavor, Positive Parity (energetically)
Anti-symmetric in Spin

Color-Flavor Locking

\[ \Delta_{\alpha i} = \delta_{\alpha i} \Delta_i \quad \text{analogous to the } ^3\text{He B phase} \]

\[ \Delta_s \to \Delta_{ud} \ (\text{or } \Delta_3) \]
\[ \Delta_{ds} \ (\text{or } \Delta_1) \]
\[ \Delta_{su} \ (\text{or } \Delta_2) \]

\[ \begin{align*}
ru - gd & \quad \text{gu - rd} \\
go - rd & \quad \text{gd - bs} \\
bd - gs & \quad \text{bs - ru} \\
r - bs & \quad \text{rs - bu}
\end{align*} \]

October 2005
Family of Color Superconductors

\[ \Delta_{ud}, \Delta_{ds}, \Delta_{su} \neq 0 \]  Color - Flavor Locked (CFL) Phase

\[ \Delta_{ds} = 0, \ \Delta_{su}, \Delta_{ud} \neq 0 \]  uSC

\[ \Delta_{su} = 0, \ \Delta_{ds}, \Delta_{ud} \neq 0 \]  dSC

\[ \Delta_{ds} = \Delta_{su} = 0, \ \Delta_{ud} \neq 0 \]  2SC

\[ \Delta_{ud} = \Delta_{ds} = \Delta_{su} = 0 \]  UQM
Effect of Non-Zero $M_s$

$M_s \neq 0$

$$\sqrt{p^2 + M_s^2} - \mu \approx p - \left( \mu - \frac{M_s^2}{2\mu} \right)$$

Fermi Surface Mismatch

October 2005
Gapless Superconductor

Gapless dispersion appears when \( \delta \mu > 2\Delta \)

\[ \text{CFL} \]
\[ \downarrow \]
\[ \text{gapless CFL (gCFL)} \]

This happens for \( \Delta_{ds} \) pairing, which makes \( \Delta_{ds} \) disfavored. \( \Delta_{ds} \) vanishes first \( \Rightarrow \) uSC

Unstable???
Phase Structure

High Density

October 2005

Fukushima-Kouvaris-Rajagopal ('04)

Low Density
Unstable Regions

\[ \text{Temperature [MeV]} \]

\[ M_s^2/\mu \text{ [MeV]} \]

Fukushima ('05)

October 2005
**Chromomagnetic Instability**

**Meissner Screening Mass**

In CFL (global) color symmetry is all broken ➔ All gluons are massive.

Meissner mass is imaginary in the gCFL phase, especially at low temperatures.

**Gapless Quarks**

October 2005
Unstable Regions

Instability for $A_1$ and $A_2$

Instability for $A_3$ and $A_8$ and $A_\gamma$

Instability for $A_4$ and $A_5$ (solid)

Instability for $A_6$ and $A_7$ (dashed)

October 2005

Fukushima ('05)
Summary

Chromomagnetic instability in three-flavor quark matter has been analyzed.
Meissner screening mass for respective gluons has been calculated.
gCFL is not stable at all!
uSC and 2SC have unstable regions.
Unstable regions are mapped onto the phase diagram including (g)CFL, uSC, (g)2SC.
Phase boundaries toward the LOFF states.

October 2005
Charm Mesons with DWF Quarks on a Quenched 3 GeV Lattice

Shigemi Ohta
Preliminary report on RBC spectroscopy calculations on a DBW2 quenched gauge ensemble,

- at lattice cutoff $a^{-1}$ of about 3 GeV,
- all the quarks represented by domain-wall fermions (DWF),
- $D$ and $D_s$ mesons with $J^P = 0^-, 1^-, 0^+$ and $1^+$:
  - masses well reproduced to within a few %,
  - splittings $\Delta J$ between parity partners over estimated by 10-20 %,
  - only 60-65 % of hyperfine splittings reproduced,
  - $0^-$ decay constant $f_D$ within experimental error and $f_{D_s}$ encouraging.
- charmonia analyses exist as well, with $J^P = 0^-, 1^-, 0^+$ and $1^+$ (but not today.)
Charm as DWF: originally investigated for kaon matrix elements with “charm-in” using DWF.

- Nori pushed it further for test of various heavy quark schemes, and $D$ and $D_s$ meson spectroscopy.
- HueyWen is pushing a relativistic scheme under supervision by Norman Christ.

Here we use a combination of DWF quark and DBW2 gluon actions:

- DWF (domain wall fermions) preserves almost exact chiral symmetry, and
- DBW2 ("doubly blocked Wilson 2") action improves approach to the continuum.

The combination allows us to have

- good chiral behavior, *i.e.* close enough to the continuum, and
- sufficiently large volume.
Recent discoveries of $D$ and $D_s$ meson excited states provide an interesting target for DWF charm.

Mass:

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>mass (MeV)</th>
<th>charm-nonstrange</th>
<th>mass (MeV)</th>
<th>charm-strange</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^±(0^-)$</td>
<td>1869.4(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D^{*±}(1^-)$</td>
<td>2010.0(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_0^*(0^±?)$</td>
<td>230817(15)(28)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D'_1(1^+)$</td>
<td>242726(20)(15)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_0^*(1^-)$</td>
<td>23174(9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_0^*(0^+)$</td>
<td>24593(1.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Splittings:

<table>
<thead>
<tr>
<th>light quark</th>
<th>$0^+ - 0^-$ (MeV)</th>
<th>$1^+ - 1^-$ (MeV)</th>
<th>between parities $\Delta_{qJ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>349.1</td>
<td>347.2</td>
<td></td>
</tr>
<tr>
<td>$ud$</td>
<td>439</td>
<td>417</td>
<td></td>
</tr>
</tbody>
</table>

- insensitive to $J$, $\Delta_{q0} \sim \Delta_{q1}$,
- $m_l$ dependent, $\Delta_{ud} > \Delta_s$.

"hyperfine" $\Delta_{hf}$

<table>
<thead>
<tr>
<th>light quark</th>
<th>$1^- - 0^-$ (MeV)</th>
<th>$1^+ - 0^+$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>143.8</td>
<td>141.9</td>
</tr>
<tr>
<td>$ud$</td>
<td>140.6</td>
<td>119</td>
</tr>
</tbody>
</table>

- independent of $m_l$ or parity.
Model studies:

- Before the discoveries, Bardeen, Eichten and Hill\textsuperscript{1} predicted this
  - based on their $SU(3)_L \times SU(3)_R$ symmetry for heavy-light systems.
  - $\Delta J \sim 350\text{MeV}$ is weakly dependent on the heavy quark mass: $\Delta J = \Delta J(m_{\text{heavy}})$.
  - A Goldberger-Treiman like relation in the pion emission from the positive-parity states, $g_\pi = \Delta J / f_\pi$.
- Afterwards, Nowak, Rho and Zahed\textsuperscript{2} made similar prediction from a different view point.
- Becirevic, Fajfer and Prelovsek\textsuperscript{3} discussed $\Delta J$ dependence on the light quark mass,
  - found $\Delta_{ud,J} > \Delta_{s,J}$ is difficult to understand.

Earlier lattice works:

- Peter Boyle (UKQCD)$^4$ was the first to study these and other related states on the lattice.
  - Wilson gauge action at $\beta = 6.0$ and tadpole improved clover.
  - Hyperfine splittings scale well, lying significantly below their experimental values.
  - Overestimates $\Delta_J$?

- NRQCD (J. Hein et al.)$^5$:
  - $\sim 2$ fm boxes at $\beta = 5.7$ and 6.2.
  - Overestimates $\Delta_J$.

- Gunnar Bali$^6$:
  - confirms earlier overestimates of $\Delta_J$: $(450-500)\pm 50$ MeV?

- MILC (M. di Pierro et al.)$^7$: Fermilab heavy quark and MILC sea,
  - similar over estimation of $\Delta_J$ seen.

- UKQCD (A.M. Green et al)$^8$: static heavy quark
  - Quenched and two-flavor dynamical configurations.
  - Weak dependence on light-quark mass?

---


Earlier lattice works (continued):

- UKQCD (A. Dougall, R.D. Kenway, C.M. Maynard, C. McNeile):\(^9\)
  - Quenched Wilson gauge at $\beta = 5.93, 6.0, 6.2$; two-flavor clover at $\beta = 5.2$ and $\kappa_{\text{sea}} = 0.135$.
  - $\Delta$ for spin 0 and 1 are degenerate.

Earlier lattice works on decay constants:

- ALPHA (A. Juttner and J. Rolf):\(^10\), improved Wilson: $f_{D_s} = 252(9)$ MeV.
- FNAL/MILC/HPQCD\(^11\): $f_D = 201(3)(17)$ MeV and $f_{D_s} = 249(3)(16)$ MeV with MILC 2+1 lattices.

\(^11\)C. Aubin et al., arXiv:hep-lat/0506030.
Advantages of domain-wall fermions (DWF):

- Describes light-quark chiral symmetry well: $O(a)$ error exponentially suppressed.
- Describes charm propagation on the lattice: $m_{\text{heavy}} a \sim 0.4 - 0.5$ still pegged.
- Present calculation:
  - quenched DBW2,
  - $\beta = 1.22$, $a^{-1} \sim 3$GeV,
  - $L_s = 10$, $M_5 = 1.65$,
  - $24^3 \times 48 \times 10$ ($\sim (1.6\text{fm})^3$) volume,
  - $m_{\text{light}} a = 0.08, 0.016, 0.024, 0.032$, and 0.040,
  - $m_{\text{heavy}} a = 0.1, 0.2, 0.3, 0.4$ and 0.5,
  - 103 configurations.

Allow explore both quark-mass dependences and $\Delta s_0-\Delta s_1$ degeneracy.
Effective mass: e.g. $m_{\text{heavy}} a = 0.3$ and $m_{\text{light}} a = 0.040$,

reasonable plateaux allow meson mass extraction for all of $0^\pm$ and $1^\pm$. 
Scales:

- known from previous RBC works\textsuperscript{12} are,
  - lattice cutoff: $a^{-1} = 2.914(54)$ GeV set by $m_\rho$,
  - strange mass: $m_s a \sim 0.030$ set by $m_K$.
- charm mass: using the above and one of the following known meson mass,
  - $D_s(0^-)$: results in $m_c a = 0.35965$ we use this in the following,
  - $\eta_c$: 0.35595,
  - $J/\psi$: 0.37048.

Quenched systematics are of course expected.

\textsuperscript{12}Y. Aoki et al., arXiv:hep-lat/0508011.
$D_s$ meson mass: preliminary results are

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>experiment (MeV)</th>
<th>this calculation (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s^{\pm}(0^-)$</td>
<td>1968.3(5)</td>
<td>1968.3 (input)</td>
</tr>
<tr>
<td>$D_s^{*\pm}(1^-)$</td>
<td>2112.1(7)</td>
<td>2055(6) (2.7% under)</td>
</tr>
<tr>
<td>$D_s^{*0}(0^+)$</td>
<td>2317.4(9)</td>
<td>2380(30) (2.5% over)</td>
</tr>
<tr>
<td>$D_s^{*1}(1^+)$</td>
<td>2459.3(1.3)</td>
<td>2460(40) (0.03% over)</td>
</tr>
</tbody>
</table>

in reasonable agreement with the experiments.

Parity splittings:

- $\Delta_{s,0} = 410(30)$ MeV, 18% over estimate compared with 349 MeV experiment,
- $\Delta_{s,1} = 380(20)$ MeV, 10% over estimate compared with 347 MeV experiment,

statistically degenerate and seem better than earlier lattice calculations.

Hyperfine splitting: about 87(6) MeV, reproduces about 60% of the 144 MeV experiment.
To summarize quark masss dependences of parity splittings:

For dependence on $m_{\text{heavy}}$:
- seem statistically degenerate for $m_{\text{heavy}}a = 0.4$ and 0.3, but
- but $\Delta J=0 > \Delta J=1$ for lighter $m_{\text{heavy}}$.
And on $m_{\text{light}}$: both increases toward lighter $m_{\text{light}}$. 
$D$ meson mass: extrapolate from $m_{\text{light}}a = 0.040, 0.032, \text{and} 0.024, \text{and} 0.016 \text{and} 0.008$ if possible. Preliminary results are

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>experiment (MeV)</th>
<th>this calculation (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\pm(0^-)$</td>
<td>1869.4(5)</td>
<td>1876.7(1.2) (0.4% over)</td>
</tr>
<tr>
<td>$D^{*\pm}(1^-)$</td>
<td>2010.0(5)</td>
<td>1968(2) (2% under)</td>
</tr>
<tr>
<td>$D_0^*(0^{+?})$</td>
<td>2308(17)(15)(28)</td>
<td>2362(20) (2.5% over)</td>
</tr>
<tr>
<td>$D_1^*(1^+)$</td>
<td>2427(26)(20)(15)</td>
<td>2455(17) (1.2% over)</td>
</tr>
</tbody>
</table>

again in reasonable agreement with the experiments.

Parity splittings:

- $\Delta_{s,0} = 487(20)$ MeV, 11\% over estimate compared with 439 MeV experiment,
- $\Delta_{s,1} = 490(17)$ MeV, 18\% over estimate compared with 417 MeV experiment, statistically degenerate.

Hyperfine splitting: about 91(2) MeV, reproduces about 65\% of the 141 MeV experiment.
Pseudoscalar meson decay constant: \( f_P = \frac{\langle \text{vac}|A_t|P \rangle}{m_P} \).

We use a ratio \( \frac{A_{\text{point-wall}}^{A_t P}}{\sqrt{\frac{m_P}{2} V A_{\text{wall-wall}}^{PP}}} \).

We obtain bare values of

- \( f_{D_s} \) of 0.0742(21) or 216(6) MeV by interpolation to \( m_{\text{strange}}a = 0.030 \) and \( m_{\text{charm}}a = 0.360 \)
- \( f_D \) of 0.0696(7) or 203(2) MeV by linear extrapolation, or
- \( f_D \) of 0.0717(7) or 209(2) MeV by quadratic extrapolation.
We can use heavy-light current renormalization by Aoki, Kuramashi and Yamada:

\[ Z_A^{HL} = Z_A^{LL,NP} \times \sqrt{Z_{dw}(am_{\text{charm}})/Z_{dw}(0)}, \]

where the tree-level domain-wall fermion wave function renormalization is given by

\[ Z_{dw}(am_f, \omega) = \frac{am_f[1 + (am_f)^2] \cosh(m_p) - 2(am_f)^2 \omega \sinh(am_p)}{[1 - (am_f)^2] \sinh(am_p)}, \]

and

\[ Z_{dw}(0) = \frac{1}{\omega(2 - \omega)}, \]

with \( \omega = 2 - M_5 \) and

\[ am_p = \ln \left| \frac{-(am_f)^2 + \sqrt{[1 + (am_f)^2]^2 + (am_f)^2 \omega^2 (\omega^2 - 4)}}{1 + (am_f)^2 - 2\omega(am_f)} \right|. \]

With \( am_{\text{charm}} = 0.36 \), we obtain \( \sqrt{Z_{dw}(am_{\text{charm}})/Z_{dw}(0)} = 1.1834 \), and accordingly

\[ Z_A^{HL} = 1.0509 \]

with \( Z_A^{LL,NP} = 0.888. \)

Preliminary renormalized values are: \( f_{D_s} = 226(6) \) MeV and \( f_D = 212(2) \) (lin.) or 219(2) MeV (quad.). Experimentally, \( f_D = 230(42)(10) \) MeV and \( f_{D_s} = 266(32) \) MeV.
Summary: we are studying charm-light systems with DWF and $a^{-1} \sim 2.914(54)$ GeV gauge ensemble.

- DWF seems able to describe charm on quenched DBW2 ensemble at this cutoff,
- With $m_{\text{strange}} = 0.030$ and $m_{\text{charm}} = 0.36$,
  - $J^P = 0^\pm$ and $1^\pm D$ and $D_s$ meson masses are well reproduced to within a few $\%$,
  - parity splitting, $\Delta J$, are better reproduced than previous works, with only 10-20 $\%$ over estimations,
  - experimental observation of $\Delta_{ud} > \Delta_s$ is reproduced,
  - hyperfine splittings are only 60-65 $\%$ reproduced,
  - decay constant calculation on going, $f_D$ within experimental error and $f_{D_s}$ encouraging.
- $\Delta J=0$ and $\Delta J=1$ are degenerate for $m_{\text{heavy}} > 0.2-0.3$,
- $\Delta J=0$ increases as $m_{\text{heavy}}$ decreases further, while
- $\Delta J=1$ seems not to increase so much (supported by $K_1(1270) - K^*(892)$),

Future:

- finalize the analyses (all the numbers above are yet preliminary),
- would be interesting to check the Goldberger-Treiman relation, $g_\pi = \Delta / f_\pi$.
  - perhaps requires a better, relativistic scheme than this brute-force approach.
Electromagnetic Properties of Hadrons with Two Flavor Dynamical Domain Wall Fermions

Thomas Blum
Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions

T. Blum (RBRC and Univ. of Connecticut),

in collaboration with

Norikazu Yamada (KEK) M. Hayakawa (RIKEN),
T. Izubuchi (Kanazawa, RBRC),

for RBC Collaboration
**Introduction**

EM properties of hadrons offer rich source of interesting/important phenomena.

- **Mass splitting:** $\pi^+ - \pi^0 \sim +5$ MeV, $K^+ - K^0 \sim -4$ MeV, $\rho^+ - \rho^0 \sim 0$ MeV, $p - n \sim -1$ MeV, \ldots
- $\Gamma_{\rho^+} - \Gamma_{\rho^0} : \Gamma(\tau \rightarrow \text{hadrons}) \rightarrow \sigma(e^+e^- \rightarrow \text{hadrons})$ in $g - 2$
- light by light in $g - 2$

**EM splittings**

\[
\begin{align*}
EM \text{ splittings} &= (m_d - m_u) + \text{QED} \\
\text{Introducing } \text{QED} \text{ to Lattice} &\Rightarrow (m_d - m_u)
\end{align*}
\]

**Previous work:** A. Duncan, E. Eichten, H. Thacker, PRL76(1996)3894 in quenched approximation

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions – p.3
# QCD Configurations

RBC, hep-lat/0411006

**Use Two-flavor Dynamical Domain Wall QCD by RBC**

<table>
<thead>
<tr>
<th>$\beta_{\text{QCD}}$, Gauge Action</th>
<th>0.8, DBW2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/\alpha$</td>
<td>1.691(53) GeV from $m_\rho=770$ MeV</td>
</tr>
<tr>
<td>Lattice size</td>
<td>1.688(21)(^{+69}_{-04}) GeV from $r_0=0.5$ fm</td>
</tr>
<tr>
<td>Domain-wall height</td>
<td>$V = 16^3 \times 32$, $L_s=12 \Leftrightarrow V \sim (2$ fm$)^3$</td>
</tr>
<tr>
<td>Sea Quark Masses</td>
<td>$M_5=1.8.$</td>
</tr>
<tr>
<td># of Trajectories</td>
<td>0.02, 0.03, 0.04 $\Leftrightarrow \frac{1}{2}m_s, \frac{3}{4}m_s, m_s$</td>
</tr>
<tr>
<td></td>
<td>5,000+ for each sea quark</td>
</tr>
<tr>
<td></td>
<td>(Measurement every 20–30 trajectories)</td>
</tr>
</tbody>
</table>

$U_{\text{QCD}n,\mu}$

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions – $\mu$. 

Quenched non-compact QED

\[ S_{em} = \sum_n \frac{1}{4e^2} (\partial_\mu A_{em,n,\nu} - \partial_\nu A_{em,n,\mu})^2, \]
\[ (\partial_\mu f_n = f_{n+\mu} - f_n) \]
Invariant under \( A_{em,n,\mu} \rightarrow A_{em,n,\mu} + \partial_\mu \Lambda_n. \)

Advantages:

- No auto-correlation even for arbitrarily small coupling
- No photon self-coupling \( \rightarrow \) free theory: the coupling does not run.

Generation of quenched QED:

i. Generate \( \tilde{A}_{em,p,\mu} \) in mom. space

   with a constraint of Coulomb gauge: \( \sum_{j=1}^{3} \partial_j^* A_{em,n,j} = 0 \)

ii. Fourier transformation to obtain \( A_{em,n,\mu} \) in coordinate space

\[ U_{em,n,\mu} = e^{ie A_{em,n,\mu}} \]

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions - p.4
Combining QED to QCD

QCD → QCD+QED theory,

in continuum, \[ \mathcal{D} = \mathcal{D} + ig A_{\text{qcd}} + i Q_q e A_{\text{em}} \]

on the lattice, \[ U_{\text{qcd}\times\text{em}} = U_{\text{qcd}} \times (U_{\text{em}})^{Q_q} \]

Use \( U_{\text{qcd}\times\text{em}} \) to solve valence quark propagators

- \( U_{\text{qcd}\times\text{em}} \) depends on \( Q_q \), e.g. \( Q_u = 2/3 \), \( Q_d = -1/3 \).
  - up and down quark propagators are treated separately.
- \( e \) dependence can be searched by changing \( Q_q \).
  - \( e = \sqrt{4\pi/137} \), \( 1.0 \) are examined.
- one QED configuration per a QCD configuration
Comments on $\pi^0$

QED breaks Isospin symmetry.

- $\pi^0$-singlet mixing:
The effects start from $O(\alpha_{em}^2)$. → ignored

- Disconnected diagram:
  $\langle P^3(t) P^3(0) \rangle$ and $\langle A_4^3(t) A_4^3(0) \rangle$ receive a contribution from

  \[
  \langle 0 \mid \tau^3 \star \tau^3 \mid 0 \rangle
  \]

  How large does this contribute to $m_{\pi^0}$? $O(\alpha_{em})$ or $O(\alpha_{em}^2)$?

  While we can estimate the disconnected diagram explicitly, we are ignoring it at the present.
Effective mass plots

\[ e = \sqrt{\frac{4\pi}{137}} \sim 0.3 \]
Effective mass plots

\[ e = 1.0 \]

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions – p.i
Symmetry

In pure QCD, $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \rightarrow 3$ NG bosons $\rightarrow \pi^\pm$.

In continuum (QCD + QED) case,
\[
\partial_\mu A_\mu^a(x) = 2mP^a(x) + i \bar{q}(x) \left[ \frac{\tau^a}{2}, Q \right] eA_{em}(x) \gamma_5 q(x),
\]
where $A_\mu^a(x)$: axial-vector current, $Q = \frac{1}{3} \begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix} = \frac{1}{6}1_2 + \frac{1}{2}\tau^3$.

When $m = 0$, only $A_\mu^3$ conserves.

- $U(1)_{3,L} \times U(1)_{3,R} \rightarrow U(1)_{3,V} \rightarrow 1$ NG boson $\rightarrow \pi^0$
- Others are massive even in $m = 0$ (e.g. $m_{\pi^\pm}^2 \sim \alpha_{em}m_\rho^2$).
Chiral extrapolation

ChPT ⇒ functional form in chiral extrapolation
We have data only at three dynamical points \( (m_{\text{valence}} = m_{\text{sea}}) \).

We fit data to linear functions of quark mass,

\[
\text{Charged: } \quad m_{\pi^+}^2 = \alpha_{\text{em}} \Delta_+^{(0)} + 2 \left( B_0 + \alpha_{\text{em}} \Delta_+^{(m)} \right) (m_f + m_{\text{res}})
\]

\[
\text{Neutral (NG boson): } \quad m_{\pi^0}^2 = 2 \left( B_0 + \alpha_{\text{em}} \Delta_0^{(m)} \right) (m_f + m_{\text{res}})
\]

Determine \( B_0, \Delta_+^{(0)}, \Delta_+^{(m)}, \Delta_0^{(m)} \) and \( m_{\text{res}} \).

First \( m_{\text{res}} \) from \( m_{\pi^0}^2 \) is shown.
Use $\pi^Q$ (pion in pure QCD), $m_{\pi^Q}^2 = 2 B_0 (m_f + m_{\text{res}}^{\text{QCD}})$.
\[ \Delta_+^{(m)} + \Delta_0^{(m)} \text{ and } \Delta_+^{(0)} \]

\[ m^2_{\pi^+} - m^2_{\pi^0} = \alpha_{\text{em}} \left( \Delta_+^{(0)} + 2(\Delta_+^{(m)} + \Delta_0^{(m)}) (m_f + m_{\text{res}}) \right) \]

\[ e = \sqrt{4\pi/137} \]

\[
\begin{array}{c}
\text{Slope } \Rightarrow \Delta_+^{(m)} + \Delta_0^{(m)}, \text{ Intersection } \Rightarrow \Delta_+^{(0)}
\end{array}
\]
\[ m_{\pi^0}^2 - m_{\pi^0 Q}^2 = 2 \alpha_{\text{em}} \Delta_0^{(m)} (m_f + m_{\text{res}}) \]

\[ e = \sqrt{4\pi/137}, \text{ and } 1.0 \]

Slope \[ \rightarrow \Delta_0^{(m)} \]

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions – p.1
Summary of bare low energy constants

We obtain

\[ <AA>: B_0 = 2.09(4), \quad \Delta^{(0)}_+ = 0.0429(71), \quad \Delta^{(m)}_+ = 2.28(31), \quad \Delta^{(m)}_{\pi^0} = 1.60(28), \]
\[ <PP>: B_0 = 2.06(4), \quad \Delta^{(0)}_+ = 0.0466(51), \quad \Delta^{(m)}_+ = 2.56(29), \quad \Delta^{(m)}_{\pi^0} = 1.94(27) \]

in lattice unit.

With above results, quark masses determination are examined. Since we are unable to pursue non-degenerate effects, we simply assume the same LEC for Kaons:

\[
m_{K^+}^2 = \alpha_{em} \Delta_+^{(0)} + (B_0 + \alpha_{em} \Delta_+^{(m)})(m_{f,1} + m_{res,1} + m_{f,2} + m_{res,2}) \\
m_{K^0}^2 = \quad (B_0 + \alpha_{em} \Delta_0^{(m)})(m_{f,1} + m_{res,1} + m_{f,2} + m_{res,2})
\]
Systematic errors

- Absence of disconnected diagrams
- Finite volume effects
  Model estimates suggest about 10% increase for $\Delta^{(0)}$. How about others?
- Scaling violation
- Quenched QED and dynamical strange quark
**Summary**

**Conclusion:**
- Determinations of quark masses by EM splitting are examined in dynamical DW QCD+QED.

**Future:**
- Mesons consisting of non-degenerate quarks → more realistic determination
- Study of systematic errors
- Vector mesons and baryons (Doi's Talk) in progress.
Quarkonia Correlators and Spectral Functions at $T>0$

Peter Petreczky
Quarkonia correlators and spectral functions at $T>0$

Péter Petreczky

RBRC and Physics Department

QGP formation $\rightarrow$ dissolution of different quarkonium states

Matsui and Satz '86

$\langle r^2 \rangle^{1/2}$ fm $\begin{array}{cccc}
    c\bar{c} & \psi'(2S) & \chi_c(1P) & J/\psi(1S) \\
    b\bar{b} & \Upsilon''(3S), \chi_b(2P) & \chi_b(1P) & \Upsilon(1S)
\end{array}$

Temperature

e.g. $\gamma^*$, dilepton rate

Lattice correlator $\rightarrow$ G($\tau, T$) $= \int_0^\infty d\omega \sigma(\omega, T) \frac{\cosh(\omega(\tau - 1/(2T)))}{\sinh(\omega/(2T))}$

spectral functions: coupling of the medium with external probe

Charmonia and bottomonia spectral functions from lattice,
A. Jakovác, P.P., K. Petrov, A. Velytsky, hep-lat/0509138, work in progress

Transport of heavy quarks in QGP, P.P. and D. Teaney, hep-ph/0507318
Charmonia correlators and spectral functions

no change in $\sigma(\omega, T)$

$G(\tau, T)/G(\tau, T = 0) = 1$

in agreement with Datta, Karsch, P.P., Wetzorke, PRD 69 (04) 094507
Bottomonia correlators and spectral functions

\[ \xi = \frac{a_s}{a_t} = 4, \ a_t^{-1} = 10.9 \ \text{GeV}, \ N_t = 16 - 36 \]

1S states are dissolved only at \( T > 3T_c \)

1P states are dissolved at \( T \sim 1.15T_c \)

expected \( \chi_b \) survive till \( \sim 1.5T_c \)

A. Jakovác, P.P., K. Petrov, A. Velytsky, hep-lat/0509138
Vector correlator and heavy quark diffusion

Pseudo-scalar ($\eta_c$)

1S charmonium states survive

Vector ($J/\psi$)

Vector current is conserved $\rightarrow$ fluctuations of charm number

$$\sigma_V(\omega) = F_{J/\psi}(T)\delta(\omega^2 - m_{J/\psi}^2(T)) + \frac{1}{4\pi^2}\omega^2 \sqrt{1 - \frac{4m_D^2(T)}{\omega^2}} + \chi_s(T) \left( \frac{T}{M} \right) \omega \delta(\omega)$$

$$\frac{1}{3} \chi_s(T) \frac{T}{M} \omega \frac{1}{\pi} \frac{\eta}{\omega^2 + \eta^2}$$

Effective Langevin theory

$$\eta = \frac{T}{MD} \partial_t N_c + D\nabla^2 N_c = 0$$

Interactions $\leftrightarrow$ Free streaming: Collision less

Botzmann equation

RHIC: large transport of heavy quarks should be seen in the lattice correlator

P.P. and D. Teaney, hep-ph/0507318
Spin 3/2 Pentaquark from Lattice QCD
Isospin Breaking of Baryon Masses from Lattice QCD

Takumi Doi
Spin $3/2$ pentaquark from lattice QCD

Isospin breaking of baryon masses from lattice QCD

Takumi Doi (RBRC)

(1) In collaboration with
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(2) In collaboration with
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$^1$(Univ. of Connecticut) $^2$(RBRC) $^3$(RIKEN) $^4$(Kanazawa U.) $^5$(KEK)

10/10/2005 talk@RBRC Review Committee
Introduction(pentaquark study)

- The "discovery" of $\Theta^+ (1540)$ baryon by LEPS(2003) heralds a new era of exotics in QCD.
  - $B = +1, S = +1 \rightarrow$ manifestly exotic (uudds)
  - Other exotics? (Tetra, Nona ...)
- The controversial status for $\Theta^+$
  - 10 positive results vs. many null results (high-energy, CLAS)
- Lattice QCD is another powerful "experiment".
  - Confirm/exclude the existence of $\Theta^+$
  - What is the possible spin/parity?

10/10/2005

talk@RBRC Review Committee
Possibility of higher spin state

- $J^P=1/2^-$ (NK s-wave) vs. $1/2^+$ (NK p-wave)
- Lattice, Sum rule
- If $J^P=3/2^-$
  - Decay to NK is suppressed by D-wave
    c.f. $N+K^*=1.83\text{GeV}$, $K+\Delta=1.73\text{GeV}$ ($I\neq 0$)
    - Large centrifugal barrier $\rightarrow$ narrow width
- If $J^P=3/2^+$
  - LS-partner of JW model
  - Decay to NK is p-wave

Y.Kanada-En'yo et al. hep-ph/0404144
R.L.Jaffe et al. hep-ph/0408046
T.Shinozaki et al. hep-ph/0409103

10/10/2005

Talk@RBRC Review Committee
The difficulty in Lattice QCD

Difficult to separate $\Theta^+$ from two particle scattering state

It is difficult to extract excited state signal besides ground state signal

$$\Pi(t) = \sum x \langle \eta(x)\eta(0) \rangle = \sum \lambda_i^2 \exp(-E_i t)$$

$$\lim_{t \to \infty} \lambda_g^2 \exp(-E_g t)$$

$\Rightarrow$ NK state will dominate

$\Theta^+ (\text{exp})$: 1540MeV
N+K: 1440MeV
N+K*: 1800MeV
Volume dependence and Hybrid Boundary Condition (HBC)

- Momenta are discretized!
  - Periodic BC (PBC) \( \rightarrow p_i = 2n_i \pi / L \)
  - Anti-periodic BC (APBC) \( \rightarrow p_i = (2n_i + 1) \pi / L \)

<table>
<thead>
<tr>
<th></th>
<th>PBC</th>
<th>HBC</th>
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<tbody>
<tr>
<td>u-quark</td>
<td>PBC</td>
<td>APBC</td>
</tr>
<tr>
<td>d-quark</td>
<td>PBC</td>
<td>APBC</td>
</tr>
<tr>
<td>s-quark</td>
<td>PBC</td>
<td>PBC</td>
</tr>
<tr>
<td>N (uud, udd)</td>
<td>PBC ( \rightarrow \vec{p}_{min} = \vec{0} )</td>
<td>APBC ( \rightarrow \vec{p}_{min} = \pi \vec{n} / L )</td>
</tr>
<tr>
<td>K, K* (u\bar{s}, d\bar{s})</td>
<td>PBC ( \rightarrow \vec{p}_{min} = \vec{0} )</td>
<td>APBC ( \rightarrow \vec{p}_{min} = \pi \vec{n} / L )</td>
</tr>
<tr>
<td>( \Theta^+ ) (uudd\bar{s})</td>
<td>PBC ( \rightarrow \vec{p}_{min} = \vec{0} )</td>
<td>PBC ( \rightarrow \vec{p}_{min} = \vec{0} )</td>
</tr>
</tbody>
</table>

\[ E_{min}(NK) \simeq \sqrt{m_N^2 + p_{min}^2} + \sqrt{m_K^2 + p_{min}^2} \]

10/10/2005
1/2(+) $J^P = 1/2(+)$

$1/2(-) J^P = 1/2(-)$

3/2(+) $J^P = 3/2(+)$

3/2(-) $J^P = 3/2(-)$

$|\vec{p}_{\text{min}}| = 2\pi/L \ (\text{PBC})$

$\rightarrow \sqrt{3}\pi/L \ (\text{HBC})$ (P/D-wave)

$|\vec{p}_{\text{min}}| = 0 \ (\text{PBC})$

$\rightarrow \sqrt{3}\pi/L \ (\text{HBC})$ (S-wave)
Effective mass for $J^P=3/2(-)$

**NK*-type**

No light 5Q

**t=**2a

**diquark-type**

Too noisy

**twisted- NK*-type**

$\eta_\mu = \epsilon^{abc} \{ u^T d C \gamma_5 d_b \} u_c \cdot (\bar{s}_d \gamma_\mu d_d) + (u \leftrightarrow d)$

$\tilde{\eta}_\mu = \epsilon^{abc} \{ u^T d C \gamma_5 d_b \} u_d \cdot (\bar{s}_d \gamma_\mu d_c) + (u \leftrightarrow d)$

$\eta_\mu = \epsilon^{abc} \epsilon^{def} \epsilon e_{fg} \{ u^T d C \gamma_5 d_b \} \{ u^T d C \gamma_5 \gamma_\mu d_c \} C \bar{s}_g$
HBC analysis for $J^P=3/2(-)$
(NK*-type op.)

Standard (Periodic) BC

Hybrid BC (HBC)

Considering the energy shift of PBC $\rightarrow$ HBC, the plateau is NK*(s-wave) scatt. state.

talk@RBRC Review Committee
Chiral extrapolation ($J^P=3/2(-/+/+)$)

**3/2(-)**

NK (d-wave)

NK* (s-wave)

**3/2(+)**

NK (p-wave)

NK* (p-wave)

**NK* type:**

$M(5Q)=2.17(4)$GeV

$M(5Q)=2.64(7)$GeV

**twisted NK* type:**

$M(5Q)=2.11(4)$GeV

$M(5Q)=2.48(10)$GeV

**diquark type:**

-----

$M(5Q)=2.42(6)$GeV

$M(5Q)=2.48(10)$GeV

We find no light low-lying 5Q state for both of $J^P=3/2(-/+/+)$

10/10/2005

talk@RBRC Review Committee
Isospin breaking of baryon masses from lattice QCD

Takumi Doi (RBRC)

(2) In collaboration with
T.Blum\textsuperscript{1,2}, M.Hayakawa\textsuperscript{3}, T.Izubuchi\textsuperscript{2,4}, N.Yamada\textsuperscript{5}
\textsuperscript{1}(Univ. of Connecticut) \textsuperscript{2}(RBRC) \textsuperscript{3}(RIKEN) \textsuperscript{4}(Kanazawa U.) \textsuperscript{5}(KEK)

10/10/2005 talk@RBRC Review Committee
Motivation

- Isospin breaking of hadrons is related to important physics in QCD/QED.

- Mass splitting:
  - $\pi^+ - \pi^- = +4.59 \text{ MeV}$
  - $K^+ - K^0 = -4.00 \text{ MeV}$
  - $p - n = -1.29 \text{ MeV}$

  [Origin]: QED + $(m_u - m_d)$

  ➔ quark mass ➔ strong CP problem?

- Vacuum polarization contribution in muon g-2

One of the longstanding problem

QED: $p > n$
QCD: $p < n$
Gasser-Leutwyler(82)
Framework

- **Quenched QED + unquenched QCD**

  **QED configs:**
  \[ S_{em} = \frac{1}{4}e^2 \sum (\partial_{\mu}A_{\nu}^{em} - \partial_{\nu}A_{\mu}^{em})^2 \]
  - quenched non-compact QED
    - Free theory, no run in coupling, no autocorrelation

  **QCD configs:**
  - Nf=2 dynamical domain-wall QCD
    - good chiral symmetry (RBC, hep-lat/0411006)
    - DBW2 gauge action, beta=0.8
    - \( a^{-1}=1.7 \text{GeV}, V=16^3 \times 32 \times 12, m_u, m_d = 1/2 m_s - m_s \)

10/10/2005  talk@RBRC Review Committee
Baryon correlation function

- Two point correlation function \( \sum_{\vec{x}} \langle J_p(x) \bar{J}_p(0) \rangle \)
  with QCD+QED propagator

\[
\bar{q}(x) [ U_{\mu}^{QCD}(x) \times (U_{\mu}^{QED})^Q ] q(x + \mu)
\]

- Note: in order to obtain the first order isospin breaking to the mass, it is not necessary to include the isospin breaking in the wave function.

- Charge dependence is analyzed with

\[
e = 0, \sqrt{4\pi}/137(=0.3), (0.6), 1.0
\]

where \( Q_u = +2/3e, Q_d = -1/3e \)

10/10/2005
talk@RBRC Review Committee
We focus on the mass difference directly.

- \( \Pi(\text{proton}) = A_p \exp(-m_p t) \)
- \( \Pi(\text{neutron}) = A_n \exp(-m_n t) \)

- \( R = \frac{\Pi(\text{proton})}{\Pi(\text{neutron})} \)
  - \( R \approx (1 + \delta A) + (m_n - m_p) t , \quad (\delta A = (A_p - A_n)/A_n) \)

- The slope of \( t \) is directly related to the proton-neutron mass difference

- Statistical fluctuation is expected to be canceled in the ratio, which improves S/N
The negative slope corresponds to \( m(\text{proton}) > m(\text{neutron}) \) from the QED effect \((m_u=m_d)\). The results from different \( Q \) agree with each other (relative error is smaller for large \( Q \)).
The lattice result indicates proton > neutron (QED)  
c.f. Cottingham formula:  
\[ M(p)-M(n)(QED)= 0.76 \text{MeV} \]  
Quark mass difference is expected to flip the inequality proton < neutron

\[ M(p)-M(n) \approx 0.5-1.5 \text{MeV} \]  
(very preliminary)

Finite volume artifact could be large

10/10/2005
Summary

Pentaquark study
- We have studied $\Theta^+$ in $J^P=3/2(+/\sim)$ channels as well as $J^P=1/2(+/\sim)$ with clover fermion on anisotropic lattice using NK*-type, twisted NK*-type, diquark-type currents.
- Only massive states have been found:
  - $J^P=3/2(-)$: $m=2.1-2.2\text{GeV}$
  - $J^P=3/2(+)$: $m=2.4-2.6\text{GeV}$
- HBC method has found no compact 5Q resonance.
- Future: Multiquark state physics, Other exotics

Isospin breaking study
- We have studied the QED effect on baryon masses from quenched QED + Nf=2 dynamical domain wall QCD.
  - Focusing the isospin breaking is important to improve S/N
  - $M(\text{proton})-M(\text{neutron})=0.5-1.5\text{MeV} (\text{QED})$
    - Tendency is consistent with model calc.
- $M(\text{proton})<M(\text{neutron})$ from quark mass is next step
- Future: Finite volume artifact, Other octet/decuplet, etc.

10/10/2005 talk@RBRC Review Committee
DI = 3/2 Kaon Weak Matrix Elements with Non-zero Total Momentum

Takeshi Yamazaki
$\Delta I = 3/2$ kaon weak matrix elements with non-zero total momentum

Takeshi YAMAZAKI
for the RBC Collaboration

RIKEN BNL Research Center

the annual RBRC Scientific Review Committee Meeting
October 10 - 12 2005
Introduction

Motivation:
Understand strong interaction effect in weak decay process

$K \rightarrow \pi\pi$ weak decay process has unsolved puzzle

$\Delta I = 1/2$ selection rule

$$\frac{\text{Re}A(K^0 \rightarrow (\pi\pi)_0)}{\text{Re}A(K^0 \rightarrow (\pi\pi)_2)} = \frac{\text{Re}A_0}{\text{Re}A_2} \approx 22$$

CP violation parameter $\varepsilon'/\varepsilon$.

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} 
(20.7 \pm 2.8) \times 10^{-4} & \text{(KTeV)} \\
(15.3 \pm 2.6) \times 10^{-4} & \text{(NA48)}
\end{cases}$$

Recently new method for calculation of weak matrix elements is proposed by two groups.

'05 Kim, Sachrajda and Sharpe, and Christ, Kim and Yamazaki

Purpose
To attempt generalized formula to

$\Delta I = 3/2 \ K \rightarrow \pi\pi$ decay and obtain $\text{Re}A_2$
Generalized formula ($\tilde{P} = (0, 0, 2\pi/L)$)

'05 Kim, Sachrajda and Sharpe, and Christ, Kim and Yamazaki

Relation of on-shell decay amplitude in infinite volume $|A|$(CM) and in finite volume $|M|$(Lab, $\tilde{P} \neq 0$)

$$|A|^2 = 8\pi\gamma^2 \left(\frac{E_{\pi\pi}}{p}\right)^3 \left\{ p' \frac{\partial \delta}{\partial p'} + p' \frac{\partial \phi_{\tilde{P}}}{\partial p'} \right\}_{p' = p} |M|^2$$

where

$$E_{\pi\pi}^2 = (E_{\pi\pi}^{\text{Lab}})^2 - \tilde{P}^2 = 4(m_{\pi}^2 + p^2) = m_K^2, \quad \gamma = E_{\pi\pi}^{\text{Lab}} / E_{\pi\pi}$$

$\delta$ : scattering phase shift

$$\tan \phi_{\tilde{P}}(q) = -\frac{\gamma q \pi^{3/2}}{Z_{00}(1; q^2; \gamma)},$$

$$Z_{00}(1; q^2; \gamma) = \frac{1}{\sqrt{4\pi}} \sum_{n \in \mathbb{Z}^3} \frac{1}{n_1^2 + n_2^2 + \gamma^{-2}(n_3 + 1/2)^2 - q^2}$$

$\delta(p)$ is obtained by $\delta(p) = n\pi - \phi_{\tilde{P}}(q), \quad q = Lp/2\pi$.

'95 Rummukainen and Gottlieb

$\delta_l (l > 0)$ is neglected.
$I = 2$ Scattering phase shift

To obtain $\frac{\partial \delta}{\partial p}$, we carry out global fitting of $T(m^2_{\pi}, p^2)$ for $m^2_{\pi}$ and $p^2$

$$T(m^2_{\pi}, p^2) = \frac{\tan \delta(p) E_{\pi\pi}}{p} = \frac{2}{2} = A_{10}m^2_{\pi} + A_{20}m^4_{\pi} + A_{01}p^2$$

$\partial \delta / \partial p$ is extracted from fit result. (Solid lines in right figures)
Preliminary result of Re$A_2[\text{GeV}]$ ($\mu = 1.44[\text{GeV}]$)

Dashed lines are results of global fittings.

Result at physical point,

$m_\pi = 0.140[\text{GeV}]$

$m_K = 0.498[\text{GeV}]$

$p = 0.206[\text{GeV}]$, is presented by red square symbol.

Fitting function

$\text{Re}A_2 = C_{00} + C_{10}m_\pi^2 + C_{01}p^2 + C_{11}m_\pi^2 p^2$

| fitting result | $2.54(43) \times 10^{-8}$ |
| experiment     | $1.50 \times 10^{-8}$ |
Neutron Electric Dipole Moment from Lattice QCD Calculations

Sinya Aoki
Neutron Electric Dipole Moment from Lattice QCD Calculations

Sinya Aoki (RBRC/University of Tsukuba) for CP-PACS collaboration

The annual RBRC Scientific Review Committee Meeting at BNL
October 10, 2005
Introduction

$\theta$ term in QCD

$$i\theta \frac{1}{32\pi^2} \int d^4 x \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu}(x) F_{\alpha\beta}(x) \equiv i\theta Q$$

CP odd, topological

Neutron Electric Dipole Moment (NEDM)

Experimental bound

$$|\vec{d}_n\theta| \leq 6.3 \times 10^{-26} e \cdot cm$$

Model estimates

$$|\vec{d}_n| \approx 10^{-15} \sim 10^{-17} e \cdot cm$$

$$\theta = \theta_{QCD} + \theta_{EW} \leq O(10^{-8})$$

Strong CP problem!

However a sign of NEDM disagrees among various models!

The first principle calculation of NEDM is desired.
This is a challenge of lattice QCD!

My Talk:
Feasibility study for lattice QCD Calculations of NEDM by two different methods.
NEDM from electromagnetic form factors

\[
\langle N(p, s) | J_{\mu}^{EM} | N(p', s') \rangle = \bar{u}(p, s) \left[ \frac{F_3(q^2)}{2m_N} q_\nu \sigma_{\mu\nu} \gamma_5 + \cdots \right] u(p', s')
\]

\[
q^2 \rightarrow 0 \quad \text{CP-odd part} \quad q = p - p'
\]

NEDM

\[
|\vec{d}_n| = \lim_{q^2 \rightarrow 0} \frac{F_3(q^2)}{2m_N} = \frac{F_3(0)}{2m_N}
\]

Lattice simulations

3-pt function

\[
G_{\theta}^{\mu N}(q, t, \tau) = \langle \theta | N(\vec{p}, t) J_{\mu}^{EM}(\vec{q}, \tau) \bar{N}(\vec{p}', 0) | \theta \rangle
\]

Quenched QCD with RG action

domain-wall quarks (chiral symmetry)

\[
16^3 \times 32 \times 16, \quad \beta = 2.6 (a \simeq 0.1 \text{fm})
\]

\[
m_f a = 0.03, \quad m_\pi/m_\rho \simeq 0.62
\]
$F_3(q^2)$ from two extractions (A, B)

Preliminary $q^2 \simeq 0.58 \text{GeV}^2$

\[
\frac{1}{2m_N} F_3^n(q^2) = -2.4(4) \times 10^{-15} \text{e} \cdot \text{cm} \quad \frac{1}{2m_N} F_3^p(q^2) = 2.2(6) \times 10^{-15} \text{e} \cdot \text{cm}
\]

\[q^2 \rightarrow 0 \quad ?\]

cf. Crewther-DiVicchia-Veneziano-Witten: $|d_n| = +3.6 \times 10^{-16} \text{e} \cdot \text{cm}$
NEDM from Energy Shift

- spin-dependent energy shift in the presence of the constant electric fields
  \[ m^\uparrow_{N\theta} (\vec{E}) - m^\downarrow_{N\theta} (\vec{E}) = 2d_n(\theta) \cdot \vec{E} = 20d_n \cdot \vec{E} + O(\theta^2) \]

- real electric field in link variables
  \[ U_k(x) \to e^{qE_k t} U_k(x), \quad k = 1, 2, 3 \]

  Periodicity in time is broken \[ \to |E| \ll 1 \quad (\alpha^2 E = 0.004) \]

- no disconnected loops, no \( q^2 \to 0 \) extrapolation

Simulation parameters are same except \( m_f a = 0.12, m_\pi / m_\rho \approx 0.62 \)

\[ R(E_z, \theta; t) = \frac{G_{NN}^\theta (t, E_z)_{11}}{G_{NN}^\theta (t, E_z)_{22}} = Z \exp[-d_n(\theta) E_z t] + \cdots \]

\[ d_n(\theta) = d_n^\theta \vec{\sigma} \]

\[ G_{NN}^\theta (t, E_z) = \sum_Q \langle 0| N(t) \vec{N}(0)|0\rangle (E_z) e^{i\theta Q} \]

Reweighting in Q
Preliminary results

\[
\begin{align*}
\{ \quad d_n &= -1.6(6) \times 10^{-15} e \cdot cm \\
\{ \quad d_p &= 1.6(8) \times 10^{-15} e \cdot cm
\end{align*}
\]

cf. Crewther-DiVicchia-Veneziano-Witten: \(|d_n| = 3.6 \times 10^{-16} e \cdot cm\)
Our full QCD configurations are generated by Clover quarks. Does this method work for Clover quarks?

The method works also for Clover fermion!

Conclusions

- The 1st method (EDM form factor) works with quenched DWF.
- The 2nd method (Energy shift) also works.
  - quenched DWF
  - quenched Clover fermion
- Future works by the 2nd method
  - lighter quark mass in quenched Clover Fermion
- NEDM by Clover fermion on 2 and 2+1 flavor dynamical configurations of CP-PACS/JLQCD
RESEARCH SUMMARY

THEORY
Activity Report in the Year 2005

Taku Izubuchi
Taku Izubuchi’s activity report in the year of 2005

- Finalizing the project of two flavour, $N_F = 2$, dynamical domain wall fermion (DWF) [4].

- Flavor singlet meson $\eta'$ spectrum on $N_F = 2$ DWF configuration [7].

- Analysis of effective theory (chiral perturbation theory) in the case of mixed action, in which two different discretization are used for sea quark and valence quark[3][5].

- Quark mass determination for $N_F = 2$ DWF configuration[8] (summarized in this proceedings).

- QED effects, especially for mass splitting, between charged and neutral particles in pseudo scalar meson and nucleon[1][9].

- Hadronic contribution in muon anomalous magnetic moment, especially for light-by-light contribution[2][9].

- Review talk and its proceedings for lattice QCD Hadron spectrum at Lattice 2005 conference (Dublin) [8].

- $N_F = 2 + 1$ dynamical DWF project, especially for analysis of static quark potential and meson spectrum[7].
Light quark masses

Quark mass is a fundamental parameter of the standard model Lagrangian, which is not directly accessible from experiments due to confinement.

- Lattice QCD: map between hadronic observables (hadron mass, decay constant) and quark mass,
  \[ M_{\text{had}}(m_q) = M_{\text{had}}^{(\text{exp})} \]

- fix lattice scale, \( a^{-1} \) (Sommer scale \( r_0, m_\rho, f_\pi \))
- Extrapolate to chiral regime (\( m_{u,d} \sim \mathcal{O}(1) \) MeV).
- mass renormalization, \( Z \) factors, for non-lattice community.
- Extrapolate to continuum (\( a \to 0 \)).
map between hadronic mass and quark mass on lattice

- Set lattice scale, \( a^{-1} \), from \( m_\rho \), \( r_0 \), or \( f_\pi \).

- Quark mass at physical Kaon mass (horizontal line)

- By using non-degenerate ChPT formula (red dots), \( a m_{\text{strange}} = 0.0446(29) \) is extracted.

- If one uses dynamical, \( m_{\text{sea}} = m_{\text{val}} \), points instead of \( N_F = 2 \) sea quarks, one finds \( a m_{\text{strange}} = 0.04177(64) \), 7\% smaller than partially quenched analysis.
NPR(RI-MOM) on dynamical lattice

- measure quark propagator $S_F(q)$, on Landau gauge fixed gauge configuration.

- calculate amputated green function of bilinear operators, $\Gamma = 1, \gamma_5, \gamma_5\gamma_\mu, \ldots$

\[
\Pi_\Gamma = \langle u(-p)[\bar{u}\Gamma d]\bar{d}(q) \rangle_{AMP}
\]

\[
\Lambda_\Gamma = \left. \frac{\text{Tr}(\Gamma \Pi_\Gamma)}{\text{Tr}(\Gamma \Gamma)} \right|_{p^2, q^2 = \mu^2}
\]

on lattice ensemble.

- Subtract mass pole to avoid non-perturbative effects ($\langle \bar{q}q \rangle$) by fitting

\[
\Lambda_{\gamma_5} = \frac{c_1}{m_q} + \frac{Z_q}{Z_P} + c_3m_q + \cdots
\]

at $\Lambda_{QCD} \ll |p| \ll a^{-1}$ on each sea quark ensemble.

($Z_q$ quark field normalization, $Z_{P,S,A}$ pseudoscalar, scalar, axial current)
NPR(RI-MOM) on dynamical lattice...

- $\Lambda_P \approx \Lambda_S \approx \partial S^{-1}/\partial m \rightarrow \frac{Z_q}{Z_P}$
- convert from RI to $\overline{MS}$ with $c(pa)^2$ subtraction.
- constant fit all $m_{sea}$ (mild dependency).
- $Z_P = 0.62(5)$
  ($250 \text{ MeV} \leq \Lambda_{QCD} \leq 300 \text{ MeV}$)
- preliminary results from $N_F = 2$ DWF:
  
  $m_s = 126(9) \left( \begin{array}{c} +10 \\ -3 \end{array} \right) \text{ MeV}$

  $\overline{m} = 4.21(33) \left( \begin{array}{c} +23 \\ -10 \end{array} \right) \text{ MeV}$

- The second errors are due to difference between $Z_P$ and $Z_S$, also $\Lambda_{QCD}$ dependence.
recent dynamical strange quark masses

Preliminary

\[ m_s (\text{MS } \mu=2\text{GeV}) \ [\text{MeV}] \]

\[ (a/r_0)^2 \]

Legend:
- \(\bullet\) ALPHA \(N_f=2\) NPR
- \(\square\) ALPHA \(N_f=2\) NPR
- \(\triangle\) CP-PACS \(N_f=2\) pert
- \(\diamond\) CP-PACS/JLQCD, \(N_f=3\), pert.
- \(\Delta\) JLQCD \(N_f=2\) pert
- \(\triangleleft\) HPQCD, MILC, UKQCD \(N_f=3\), pert
- \(\triangleright\) QCDSF UKQCD, \(N_f=2\), VWI, NPR
- \(\triangleleft\) QCDSF UKQCD, \(N_f=2\), AWI, NPR
- \(\blacksquare\) RBC \(N_f=2\) NPR
- \(\blacksquare\) SPQcDR \(N_f=2\) NPR
status of quark mass determination

- $N_F = 2, 3$ (difference is small in CP-PACS/JLQCD)
- scale is $r_0 = 0.5$ fm. (MILC corresponds to $r_0 = 0.467$ fm, not corrected)
- uncertainties from chiral extrapolation?
- operator renormalization from perturbative calculation tends to give smaller $Z_m$?

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<td>$Z_{V,A}$</td>
<td>0.7574(1)</td>
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<td>$Z_{S,P}$</td>
<td>0.62(5)</td>
<td>0.847</td>
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References


2004/2005 Progress Report

Steffen A. Bass
In the following, I briefly outline the main research projects I have been involved in since the last RIKEN-BNL Research Center Review in November of 2004:

I. THE PARTON RECOMBINATION MODEL

Recent data from the Relativistic Heavy Ion Collider (RHIC) have shown a strong nuclear suppression of the pion yield at transverse momenta larger than 2 GeV/c in central Au + Au collisions, compared to p + p interactions [1]. This is widely seen as the experimental confirmation of jet quenching, the phenomenon that high energy partons lose energy when they travel through the hot medium created in a heavy ion collision [2-4], entailing a suppression of intermediate and high $P_T$ hadrons.

However, the experiments at RHIC have provided new puzzles. The amount of suppression seems to depend on the hadron species. In fact, in the production of protons and antiprotons between 2 and 4 GeV/c the suppression seems to be completely absent. Generally, pions and kaons appear to suffer from a strong energy loss while baryons and antibaryons do not. Two stunning experimental facts exemplify this [5-8]. First, the ratio of protons over positively charged pions is equal or above one for $P_T > 1.5$ GeV/c and is approximately constant up to 4 GeV/c. Second, the nuclear suppression factor $R_{AA}$ below 4 GeV/c is close to one for protons and lambdas, while it is about 0.3 for pions.

There have been recent attempts to describe the different behavior of baryons and mesons through the existence of gluon junctions [9] or alternatively through recombination as the dominant mechanism of hadronization [10-12]. The recombination picture has attracted additional attention due to the observation that the elliptic flow pattern of different hadron species can be explained by a simple recombination mechanism [13-15]. The anisotropies $v_2$ for the different hadrons are compatible with a universal value of $v_2$ in the parton phase, related to the hadronic flow by factors of two and three depending on the number of valence
quarks [16].

The competition between recombination and fragmentation delays the onset of the perturbative/fragmentation regime to relatively high transverse momentum of 4–6 GeV/c, depending on the hadron species, providing a natural explanation for the aforementioned phenomena. To this date, parton recombination has developed into the most successful model for describing hadron production at RHIC in the intermediate transverse momentum domain.

A. Two-Particle Correlations

One of the biggest challenges for the recombination models to date has been the measurement of dynamic two-particle correlations. The picture of quarks recombining from a collectively flowing, deconfined thermal quark plasma appears to be at odds with the observation of "jet-like" correlations of hadrons observed in the same transverse momentum range of 2 to 5 GeV/c [17, 18]. The experiments at RHIC measure the associated particle yield per trigger hadron $A$. After subtracting the uncorrelated background and using the notation $\Delta \phi = |\phi_A - \phi_B|$, the relevant observable is defined as

$$Y_{AB}(\Delta \phi) = N_A^{-1} \left( \frac{dN_{AB}}{d(\Delta \phi)} - \frac{d(N_A N_B)}{d(\Delta \phi)} \right).$$

(1)

Triggering on a hadron, e.g., with transverse momentum $2.5 \text{ GeV/c} < p_T < 4 \text{ GeV/c}$, the data shows an enhancement of hadron emission in a narrow angular cone around the direction of the trigger hadron in a momentum window below 2.5 GeV/c. Can such correlations be reconciled with the claim that hadrons in this momentum range are mostly created by recombination of quarks?

Obviously, the existence of such correlations is incompatible with any model assuming that no correlations exist among the quarks before recombination, since such correlations require deviations from a global thermal equilibrium in the quark phase. However, it can be shown that correlations among partons in a quark-gluon plasma naturally translate into correlations between hadrons formed by recombination of quarks [19]. Correlations are even enhanced by an amplification factor $Q = n_A n_B$ similar to the scaling of elliptic flow. The interaction of hard partons with the medium has been discussed as one plausible mechanism for the existence of such parton correlations, even though other scenarios for the creation
of parton-parton correlations in the deconfined phase are possible. A numerical example displayed in figure 1 shows that two-parton correlations of order $\approx 10\%$ will be sufficient to explain hadron correlations as measured by the PHENIX collaboration. One may conclude that the existence of localized angular correlations among hadrons are not in contradiction with the recombination scenario but rather indicative for the existence of correlations among quarks prior to hadronization.

![FIG. 1: $Y_{AA}^{cone}$ which is $Y_{AB}$ integrated over $0 \leq \Delta \phi \leq 0.94$, for meson (left panel) and baryon triggers (right panel) as a function of centrality. The inset shows the associated yield as a function of $\Delta \phi$ at an impact parameter $b = 8$ fm.](image)

![FIG. 2: Relative difference $(\tilde{v}_{2}^{(B)} - \tilde{v}_{2}^{(M)})/(\tilde{v}_{2}^{(B)} + \tilde{v}_{2}^{(M)})$ between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component.](image)

B. Beyond the Valence Quark Approximation

Recombination models usually are based on the concept of constituent quark recombination, which assumes that the probability for the emission of a hadron from a deconfined medium is proportional to the probability for finding the valence quarks of the hadron in the density matrix describing the source. The baryon enhancement, as well as the different momentum dependence of meson and baryon anisotropies, rely essentially on the different number of valence quarks in mesons (two) and baryons (three). The simplicity of this concept has been criticized, because it does not do justice to the complexity of the internal structure of hadrons in quantum chromodynamics (QCD). The question is how a more realistic treatment of the internal structure of hadrons in QCD affects these observables.
In the light-cone frame, where formally the hadron momentum $P \to \infty$ and the momentum fractions of the partons are the only dynamic degrees of freedom, a meson $M$ with valence quarks $q_\alpha$ and $\bar{q}_\beta$ can then be written as an expansion in terms of increasingly complex Fock states:

$$|M\rangle = \int_0^1 dx_a dx_b \delta(x_a + x_b - 1) c_1(x_a, x_b) |q_\alpha(x_a)\bar{q}_\beta(x_b)\rangle$$

$$+ \int_0^1 dx_a dx_b dx_c \delta(x_a + x_b + x_c - 1) c_2(x_a, x_b, x_c) |q_\alpha(x_a)\bar{q}_\beta(x_b)\bar{q}_\gamma(x_c)\rangle$$

$$+ \int_0^1 dx_a dx_b dx_c dx_d \delta(x_a + x_b + x_c + x_d - 1) c_3(x_a, x_b, x_c, x_d) |q_\alpha(x_a)\bar{q}_\beta(x_b)\bar{q}_\gamma(x_c)\bar{q}_\delta(x_d)\rangle + \ldots$$

(2)

It has been shown [20] that the yield of relativistic parton clusters is independent of the number of partons in the cluster. Therefore, hadron spectra remain unaffected by the inclusion of a higher Fock state with an additional gluon. One important implication is that gluon degrees of freedom could be accommodated during hadronization. They simply become part of the quark-gluon wave functions of the produced hadrons, but remain hidden constituents because the commonly produced hadrons do not contain valence gluons.

However, higher Fock states introduce deviations from the scaling law for elliptic flow. Using a narrow wave function limit, one can easily generalize the well-known valence quark scaling law to higher Fock states:

$$v_2^{(H)}(P) \approx \sum_\nu |c_\nu|^2 n_\nu v_2(P/n_\nu)$$

(3)

Figure 2 shows the relative difference $(\tilde{v}_2^{(B)} - \tilde{v}_2^{(M)})/(\tilde{v}_2^{(B)} + \tilde{v}_2^{(M)})$ between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component (0%, 30%, 50%). In all cases, baryons have a slightly larger scaled $\tilde{v}_2$ than mesons at small momenta. This effect is likely to be overwhelmed by the influence of mass differences, which have been neglected in the sudden recombination model. At larger momenta, the scaled meson $\tilde{v}_2$ is slightly larger. In principle, these violations on the order of $\sim 10\%$ should be visible in a scaling analysis and first observations along these lines have been reported at this meeting [21].

It should be emphasized that the interpretation of elliptic flow data from RHIC proving the existence of quark degrees of freedom in the bulk matter is still valid. However, the connection of the measured elliptic flow to the quark elliptic flow might be less straightforward than anticipated.
II. A NOVEL HYDRO+MICRO TRANSPORT APPROACH

Hybrid macroscopical/microscopical transport models, employing hydrodynamics for the early dense reaction phase and microscopic non-equilibrium dynamics for the later, dilute reaction stages are particularly well suited for the investigation of the QGP equation of state as well as hadronic final state interactions in the SPS, RHIC and LHC energy domains. Together with a collaborator I have been at the forefront of the development of this novel class of transport models [22], and research along this very promising approach has been rapidly expanding [23–26].

The applicability of our original hybrid micro/macro model [22] used for previous studies is hampered by the hydrodynamic component only utilizing a boost-invariant 1+1 dimensional calculation, which does not allow for calculations of elliptic flow or quantities away from mid-rapidity. Therefore we are currently undertaking the extension of the hydrodynamical component of our model to a fully three dimensional hydrodynamics code [27]. Progress in the development of a full 3D hydrodynamical model has been slower than originally anticipated, in particular concerning the development of the interface between the hydrodynamical model and the microscopic transport in the hadronic phase. However, significant progress has been made over the past 2-3 months: we now have both, a fully working 3D hydrodynamical model and an interface to UrQMD and are currently in the process of determining the initial conditions necessary for addressing the RHIC data. Note that two different sets of initial conditions will need to be found – one for the application of the purely hydrodynamic approach and one for the combined macro+micro approach. It is our goal to find a set of initial conditions for both approaches (stand-alone hydrodynamics as well as the hybrid hydro+UrQMD approach) which will allow us to consistently describe all aspects of the low to intermediate transverse momentum physics data at RHIC – most importantly identified hadron spectra, elliptic flow, (pseudo-)rapidity distributions as well as two particle correlations. It should be noted that the much celebrated current success of hydrodynamics at RHIC has come at the expense of using different initial conditions for the description of spectra and elliptic flow – it is our intention to significantly improve upon this unsatisfactory situation.

Once we have demonstrated the functionality of our model in addressing the current RHIC data, we intend to follow our proposed project by investigating
• the sensitivity of hadronic observables (e.g. $v_2$, $m_T$-spectra and particle-yields) on the QGP equation of state and the critical temperature $T_C$.

• radial flow expansion parameters and $v_2$ coefficients of multi-strange baryons for different initial conditions: since multi-strange baryons are thought to decouple early from the hadronic evolution of the system (due to their small hadronic cross sections), they are expected to yield a direct probe of the collective expansion of the system at the hadronization hypersurface. Collision rates and freeze-out time distributions of multi-strange baryons will be calculated to verify/falsify the conjecture of early decoupling at the phase-boundary.

• HBT interferometry: all current hydrodynamic calculations have failed to reasonably describe the measured RHIC HBT data, giving rise to the so-called HBT puzzle at RHIC. Utilizing a 3D-hydro without any assumptions on boost-invariance for the calculation of the correlation functions will allow us to determine whether the previous failure of hydrodynamics in the HBT sector is due to simplifying assumptions such as boost-invariance or due to more general features of the hydrodynamic evolution (such as an overestimation of the lifetime of the system).


Research Summary

Takanori Sugihara
Matrix product representation of gauge invariant states in a $Z_2$ lattice gauge theory

Takanori Sugihara
RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

The importance of the first-principle study in quantum chromodynamics is increasing largely because RHIC experiment has started and LHC is also coming. For precise description of high-energy heavy ion collisions, gauge theory needs to be studied at finite temperature and density in a systematic way. Lattice gauge theory is the most useful method for studying the quark-gluon systems at zero and finite temperature. However, Monte Carlo integration does not work for lattice gauge theory with large chemical potential because of the severe sign problem. It would be worthwhile to pursue a systematic variational approach to gauge theory. In this work, we propose an efficient variational method for $Z_2$ lattice gauge theory based on the matrix product ansatz. The method is applied to ladder and square lattices. The Gauss law needs to be imposed on quantum states to guarantee gauge invariance when one studies gauge theory in hamiltonian formalism. On the ladder lattice, we identify gauge invariant low-lying states by evaluating expectation values of the Gauss law operator after numerical diagonalization of the gauge hamiltonian. On the square lattice, the second order phase transition is well reproduced. The obtained value of the critical coupling is $\lambda \sim 3.12$, which is close to the past numerical results. However, our lattice size $L = 12$ is still small. Further refinement will be given elsewhere.

References


QCDSP/QCDOC
PHYSICS RESULTS AND
PROSPECTS/PROJECT STATUS
QCDOC Overview

Nicholas P. Samios
Computing at RBRC

QCDSP
Funded by RIKEN
0.6 teraflops
Operational 1998 -
Efficiency >99%

QCDOC
Funded by RIKEN
10 teraflops
Dedicated May 2005
Operational 2005 -

Other
DOE QCDOC 10 teraflops Operational
UK QCDOC 10 teraflops Operational
Utilized by RBRC Physicists
Administration of RBRC QCDOC

Responsible Individual: RBRC Director

QCDOC Collaboration

RBRC, Columbia University, BNL and U.K.

Regular Meetings

Physics, Schedules, Etc/

Director's Committee:

N.P. Samios, L. McLerran, N. Christ,

R. Mawhinney

Six-Week Intervals

Physics, schedules, allotment of resources

Oversight Committee:

S. Aoki, M. Creutz, R. Pisarski

Reports to Director on QCDOC Operations
<table>
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<td>Rack 8</td>
<td>N_f=2+1 DWF (MF. Lin)</td>
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<td>Rack 9</td>
<td>m_l/ms=0.02/0.04, 640 trajectories</td>
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<td>Rack 10</td>
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<td>Rack 12</td>
<td>QCD thermo, N_f=6 scale setting, ( \beta = 2.744 ), N_f=3, m=0.02 (Jung)</td>
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<td>Rack 13</td>
<td>QCD thermo, 32^3x6, m=0.01 ( \beta = 2.67 ) (Jung)</td>
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<td>Rack 14</td>
<td>QCD thermo, 32^3x6, m=0.01 ( \beta = 2.66 ) (Jung)</td>
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<td>Rack 15</td>
<td>QCD thermo, 16^3x6, old p4 (Schmidt) short jobs/code debugging (general)</td>
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<td>DOE usage</td>
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<td>Rack 17</td>
<td>QCD thermo, N_f=6 old p4 (Schmidt)</td>
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<td>Rack 18</td>
<td>QCD thermo, ( \beta = 2.917 ), m=0.05 scale setting (Jung) eta' mass (Izubuchi/Hashimoto),</td>
<td></td>
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</tr>
</tbody>
</table>
RBRC Lattice QCD - An Overview

Norman H. Christ
RBRC Lattice QCD --- an Overview

RBRC Review

October 11, 2005

Norman H. Christ
Outline

- QCDOC status
- Lattice configurations
- Physics topics
- 2- and 3-flavor simulations
- $K \rightarrow \pi + \pi$
- Heavy quarks
- Outlook
QCDOC Collaboration

- Columbia (DOE)
  - Norman Christ
  - Saul Cohen
  - Calin Cristian
  - Zhihua Dong
  - Changhoan Kim
  - Ludmila Levkova
  - Xiaodong Liao
  - Meifeng Lin
  - Guofeng Liu
  - Robert Mawhinney
  - Shu Li
  - Azusa Yamaguchi

- BNL (SciDAC)
  - Chulwoo Jung
  - Konstantin Petrov
  - Stratos Efstathiadis

- UKQCD (PPARC)
  - Peter Boyle
  - Mike Clark
  - Balint Joo

- RBRC (RIKEN)
  - Shigemi Ohta
  - Tilo Wettig

- IBM
  - Dong Chen
  - Alan Gara
  - Design groups:
    - Yorktown Heights, NY
    - Rochester, MN
    - Raleigh, NC

RBRC Review - Oct. 11, 2005
QCDQC Architecture

- IBM-fabricated, single-chip node.
  (50 million transistors, 5 Watt, 1.3cm x 1.3cm)
- Processor:
  - PowerPC 32-bit RISC.
  - 64-bit, 1 Gflops floating point unit.
- Memory/node: 4 Mbyte (on-chip) & 128 Mbyte DIMM.
- 6-dim communications network.
- Ethernet connection to each node.
- ~7-8 Watt/node, 15 in³ per node.
**QCDQC construction**

QCDQC ASIC (1 node) 🔄

← Daughter board (2 nodes)

Mother board (64 nodes) 🔄

← Rack (1024 nodes)
Brookhaven Installation

RBRC (right) and DOE (left) 12K-node QCDOC machines
QCDOC now in full production

- QCDOC dedicated May 2005
- First QCDOC results presented at Lattice 2005 in Dublin.
- Thanks for successful installation to BNL scientists and technical staff:
  
  Ed Mcfadden
  Eric Blum
  Ed Brosnan
  Christopher
  Channing
  Andrew Como
  Joe Depace
  
  Efstratios Efstathiadis
  Don Gates
  Chulwoo Jung
  Kostya Petrov
  Paul Poleski
  
  Led by Bob Mawhinney

RBRC Review - Oct. 11, 2005
## Current QCDQC Usage

*(September 13, 2005)*

<table>
<thead>
<tr>
<th>Rack</th>
<th>Usage Details</th>
</tr>
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<tbody>
<tr>
<td>ACC0</td>
<td>½ rack-CU NPR, heavy quark action (HW. Lin)</td>
</tr>
<tr>
<td>Rack 2</td>
<td>CU K→pi+pi, quenched, DWF, (Yamazaki)</td>
</tr>
<tr>
<td>Rack 3</td>
<td>CU N_f=2+1, B_K (Cohen) / eigenvalue tuning (MF Lin)</td>
</tr>
<tr>
<td>Racks 4-7</td>
<td>RBRC N_f=2+1, DWF (Mawhinney) ml/ms=0.03/0.04</td>
</tr>
<tr>
<td>Racks 8-11</td>
<td>RBRC N_f=2+1 DWF (MF. Lin) ml/ms=0.02/0.04</td>
</tr>
<tr>
<td>Rack 12</td>
<td>RBRC QCD thermo, 16^3x32, p4fat7 scale setting (Jung)</td>
</tr>
<tr>
<td>Rack 13</td>
<td>RBRC QCD thermo, 32^3x6, p4fat7, m=0.01 (Jung)</td>
</tr>
<tr>
<td>Rack 14</td>
<td>RBRC QCD thermo, 32^3x6, p4fat7, m=0.01 (Jung)</td>
</tr>
<tr>
<td>Rack 15</td>
<td>RBRC QCD thermo, 16^3x6, p4fat3 (Schmidt)/general use</td>
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<tr>
<td>Rack 17</td>
<td>DOE QCD thermo, N_t=6, p4fat3 (Schmidt)</td>
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<tr>
<td>Rack 18</td>
<td>DOE QCD thermo, 16^3x32, p4fat7 scale setting (Jung)</td>
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<td>Rack 19</td>
<td>DOE Kl3 decay (Sasaki)</td>
</tr>
<tr>
<td>Rack 20-21</td>
<td>DOE η' mass (Izubuchi/Hashimoto),</td>
</tr>
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</table>
RBC Collaboration

RBRC
Tom Blum (U. Conn.)
Chris Dawson
Takumi Doi
Koichi Hashimoto
Taku Izubuchi (Kanazawa)
Shigemi Ohta (KEK)
Shoichi Sasaki
Takeshi Yamazaki

BNL
Michael Creutz
Saumen Datta
Chulwoo Jung
Frithjof Karsch
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Konstantin Petrov
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Amajit Soni
Takashi Umeda

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K.C. Bowler
P.A. Boyle
M.A. Clark
B. Joo

A.D. Kennedy
R.D. Kenway
C.M. Maynard
R.J. Tweedie
A. Yamaguchi

RBRC Review - Oct. 11, 2005 (9)
## Lattice Configurations

<table>
<thead>
<tr>
<th>Action</th>
<th>Quark Flavors</th>
<th>Lattice spacing (1/a)</th>
<th>Volume</th>
<th>Parameters</th>
<th># confs. / trajs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBW2</td>
<td>0</td>
<td>1.3 GeV</td>
<td>$16^3 \times 32$</td>
<td>$\beta = 0.87$</td>
<td>129</td>
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<td>Wilson</td>
<td>0</td>
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<td>$16^3 \times 32$</td>
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<td>Wilson</td>
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<td>2.0 GeV</td>
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<td>DBW2</td>
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<td>2.0 GeV</td>
<td>$16^3 \times 32$</td>
<td>$\beta = 1.04$</td>
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<tr>
<td>DBW2</td>
<td>0</td>
<td>3.0 GeV</td>
<td>$24^3 \times 48$</td>
<td>$\beta = 1.22$</td>
<td>106</td>
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<tr>
<td>DBW2</td>
<td>2</td>
<td>1.7 GeV</td>
<td>$16^3 \times 32$</td>
<td>$\beta = 0.8$</td>
<td>5000</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$m_{sea} = 0.02/0.03/0.04$</td>
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<tr>
<td>DBW2</td>
<td>2+1</td>
<td>1.6 GeV</td>
<td>$16^3 \times 32$</td>
<td>$\beta = 0.72$</td>
<td>6000</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>$m_{ud}/m_s = (0.01, 0.02, 0.03)/0.04$</td>
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<tr>
<td>Iwasaki</td>
<td>2+1</td>
<td>1.8 GeV</td>
<td>$24^3 \times 64$</td>
<td>$\beta = 2.13$</td>
<td>underway</td>
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<td></td>
<td>$m_{ud}/m_s = (0.01, 0.02, 0.03)/0.04$</td>
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</tbody>
</table>
Physics Topics

- Hadron spectrum.
- K meson decays
  - $\Delta = \frac{1}{2}$ rule
  - $\varepsilon'/\varepsilon$
  - $K^0 - \bar{K}^0$ mixing ($B_K$)
  - $Kl3$ decay
- Static quark potential
- Muon g-2
- Electromagnetic splittings
- $\eta'$ mass
- $\pi + \pi$ phase shifts
- Nucleon structure
  - $g_a$
  - Structure functions
  - Excited states
- Heavy quarks
  - Charm spectrum
  - $B - \bar{B}$ mixing
- QCD at finite temperature
  - Properties of transition
  - Equation of state
  - Heavy quark systems
  - $\mu \neq 0$

RBRC Review - Oct. 11, 2005 (11)
Two-flavor DWF simulations

- $16^3 \times 32$, $L_s=12$, $1/a=1.7$ GeV
- Provide gauge configurations used in many calculation
- hep-lat/0411006

<table>
<thead>
<tr>
<th>$m_{ud}/m_s$</th>
<th>Trajectories</th>
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<tr>
<td>0.5</td>
<td>5361</td>
</tr>
<tr>
<td>0.75</td>
<td>6195</td>
</tr>
<tr>
<td>1.0</td>
<td>5605</td>
</tr>
</tbody>
</table>

(Relied on improved algorithms of Dawson and Izubuchi)
2+1 Flavor Simulations
(MF Lin, S. Cohen, R. Mawhinney and UKQCD)

- More quark flavors $\rightarrow$ rougher gauge fields and larger $m_{res}$.
- Explore a series of quark masses, lattice spacings and action variants to minimize this effect. ($16^3 \times 32, L_s = 8$)

### 2+1 flavors, RHMC

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$c_1$</th>
<th>$m_t$</th>
<th>$m_h$</th>
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<tbody>
<tr>
<td>0.72</td>
<td>-1.4069</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>0.72</td>
<td>-1.4069</td>
<td>0.02</td>
<td>0.04</td>
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<tr>
<td>0.72</td>
<td>-1.4069</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>0.764</td>
<td>-1.4069</td>
<td>0.02</td>
<td>0.04</td>
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<td>0.764</td>
<td>-1.4069</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>0.78</td>
<td>-1.4069</td>
<td>0.02</td>
<td>0.04</td>
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<tr>
<td>0.78</td>
<td>-1.4069</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>2.13</td>
<td>-0.331</td>
<td>0.02</td>
<td>0.04</td>
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<tr>
<td>2.13</td>
<td>-0.331</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>2.2</td>
<td>-0.331</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>2.2</td>
<td>-0.331</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>2.3</td>
<td>-0.331</td>
<td>0.04</td>
<td>0.04</td>
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</table>

### 3 flavors, "R" algorithm

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$c_1$</th>
<th>$m_t$</th>
<th>$m_h$</th>
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<td>0.80</td>
<td>-1.4069</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.72</td>
<td>-1.4069</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>0.72</td>
<td>-1.4069</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.48</td>
<td>-2.3</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.32</td>
<td>-3.57</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.16</td>
<td>-7.47</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.53</td>
<td>-2.3</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.36</td>
<td>-3.57</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.33</td>
<td>-3.57</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

RBRC Review - Oct. 11, 2005
Results of Experiments

- Some improvement for large rectangle coefficient:

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{c}_1 & \beta & m_{\text{res}} & m_\rho a & \alpha^{-1}(\text{GeV}) \\
\hline
-1.4069 & 0.72 & 1.182(7)e-02 & 0.530(9) & 1.45(2) \\
-2.3 & 0.48 & 8.04(6)e-03 & 0.534(8) & 1.44(2) \\
-3.57 & 0.32 & 7.77(5)e-03 & 0.518(8) & 1.49(2) \\
-7.47 & 0.16 & 6.70(10)e-03 & 0.542(7) & 1.42(2) \\
\hline
\end{array}
\]

- Topological charge evolves very slowly for DBW2 action:

(A. Yamaguchi)

Decide on Iwasaki action, \( \beta = 2.13 \)
\( \Rightarrow 1/a \geq 1.8 \text{ GeV}, m_{\text{strange}} = 0.04 \) and \( L_s = 16 \)
Generating $N_f=2+1$ Configurations

- $24^3 \times 64$ volume
- $m_{\text{strange}} \equiv 0.04$
- $L_s = 16$
- $m_{\text{res}} \equiv 0.002$
- $1/a \equiv 1.8$ GeV
- 2.7 Fermi box
- Exact RHMC method (UKQCD)
- 4x RHMC speedup being implemented.
$K \rightarrow \pi + \pi$ (Changhoan Kim)

- Avoid the Miani-Testa theorem by imposing “anti-periodic” boundary conditions and using Lellouch-Luscher.
- Quenched, $1/\alpha=1.3$ GeV, $16^3 \times 32$, DWF, $L_s=12$, 129 configurations.

<table>
<thead>
<tr>
<th>In units of MeV</th>
<th>$m_K$</th>
<th>$m_\pi$</th>
<th>$p_\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>910</td>
<td>352</td>
<td>290</td>
</tr>
<tr>
<td>Nature</td>
<td>496</td>
<td>138</td>
<td>206</td>
</tr>
</tbody>
</table>

RBRC Review - Oct. 11, 2005 (16)
$K \rightarrow \pi + \pi$ (Changhoan Kim)

- Lattices doubled and data taken from both sides.
- Final pions projected onto non-zero momentum.
- Average over three choices for the anti-periodic direction.

<table>
<thead>
<tr>
<th>$2\pi n/16$</th>
<th>$O_{27} \times 100$</th>
<th>$O_{88} \times 100$</th>
<th>$O_{88m} \times 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1.230(24)</td>
<td>-8.22(17)</td>
<td>-2.989(59)</td>
</tr>
<tr>
<td>$\pi/16$</td>
<td>-2.114(60)</td>
<td>-6.88(23)</td>
<td>-2.815(85)</td>
</tr>
<tr>
<td>$2\pi n/16$</td>
<td>-2.16(12)</td>
<td>-3.89(40)</td>
<td>-1.82(13)</td>
</tr>
<tr>
<td>$3\pi n/16$</td>
<td>-2.30(35)</td>
<td>-1.8(10)</td>
<td>-1.40(32)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Our result</th>
<th>Comparison</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{27}$</td>
<td>$7.30(28) \times 10^{-8}$</td>
<td>$1.497 \times 10^{-8}$</td>
<td>Expt.</td>
</tr>
<tr>
<td>$O_{88} + O_{88m}$</td>
<td>$6.65(70) \times 10^{-12}$</td>
<td>$1.20(22) \times 10^{-11}$</td>
<td>$\chi$PT</td>
</tr>
</tbody>
</table>

RBRC Review - Oct. 11, 2005 (17)
$|A|^2 = \frac{m_\pi^2}{4\pi} \frac{\delta}{k_\pi} \left[ \frac{\delta}{k_\pi} + \frac{\phi}{\partial k} \right] M^2$

- Extend Luscher/Leinweber-Luscher to state.
- Must be dynamical to split $\eta + \eta$.
- Suppress unwanted $\pi^- + \pi^-$ states.
- $(\bar{u}d\bar{d})$ tricks don't work.
- Use G-parity boundary conditions.

$\Delta I = 1/2$?

$K \to \pi^+ + \pi^-$ (Takeshi Yamazaki)
Heavy quarks

- Charm physics using domain wall fermions. \((HW \text{ Lin, Ohta, Yamada})\)
- \(B \bar{B}\) mixing using domain wall light quarks and "static" heavy quarks. \((Gadiyak, Loktik hep-lat/0509075)\)
- Relativistic heavy quark action determined non-perturbatively. \((HW \text{ Lin, Christ})\)

\[ B \bar{B} \text{ mixing} \]

Static approx, \(N_f = 2\):
- \(f_s/f_d = 1.29(4)(6)\)
- \(B_s/B_d = 1.06(6)(4)\)
- \(\xi = 1.33(8)(8)\)
Non-perturbative calculation of RHQ action

(\textit{HW Lin})

- Start with 7 parameters (\((ma)\)\(^n\) errors removed):

\[
S = \sum_x \overline{\psi}(x)[m_0 + \gamma_0 D_0 + \zeta \gamma \cdot \bar{D} - r_t D_0^2 - r_s \sum_i D_i^2 \\
- \sum_i \frac{i}{2} \sigma_{0i} F_{0i} + \sum_{i,j} \frac{i}{2} c_B \sigma_{ij} F_{ij} + \xi \{D_0, D_i\} \sigma_{0i}] \psi(x)
\]

- Use EOM to set \(r_t = 1\) and \(\xi = 0\). (Aoki, et al.)
- Use field transformation to set \(r_s = \zeta\). (Fermilab)
- Use step-scaling to connect small \(1/a=5.4\) GeV lattice (\(m_{\text{charm}} \ll 1/a\)) with \(1/a=2.4\) GeV lattice.
- Match hh and hl spectrum as well as fix \(m_1/m_2 = 1\).
Step-scaling strategy

\[ V=24^3 \times 48 \quad V=16^3 \times 32 \]

- **DWF**
  - \( m_a = 0.2 \)
  - \( a^{-1} = 5.4 \text{ GeV} \)

- **RHQ**
  - \( m_a = 0.3 \)
  - \( a^{-1} = 3.6 \text{ GeV} \)

- **RHQ**
  - \( m_a = 0.3 \)
  - \( a^{-1} = 3.6 \text{ GeV} \)

- **RHQ**
  - \( m_a = 0.45 \)
  - \( a^{-1} = 2.4 \text{ GeV} \)

- **RHQ**
  - \( m_a = 0.45 \)
  - \( a^{-1} = 2.4 \text{ GeV} \)

- **RHQ**
  - \( m_a = 0.65 \)
  - \( a^{-1} = 1.6 \text{ GeV} \)

RBRC Review - Oct. 11, 2005 (21)
Check lattice scales

- Comparison of static quark potential between $1/a = 3.6$ ($\beta=6.351$, circles) and $5.4$ ($\beta=6.638$, squares) lattices:

- Result: $a_1/a_2 = 1.51(2)$
First results

- Trial RHQ parameters for $1/a=3.6$ GeV lattice

<table>
<thead>
<tr>
<th>Label</th>
<th>$m_0$</th>
<th>$c_B$</th>
<th>$c_E$</th>
<th>$\zeta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>1.552</td>
<td>1.458</td>
<td>1.013</td>
</tr>
<tr>
<td>2</td>
<td>0.07</td>
<td>1.547</td>
<td>1.424</td>
<td>1.001</td>
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<tr>
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<td>1.580</td>
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- RHQ parameters for $1/a = 3.6 \text{GeV}$ matching $1/a = 5.4 \text{DWF}$

<table>
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RBRC Review - Oct. 11, 2005 (23)
Outlook

- QCDQC and the $24^3 \times 64$, 3-flavor lattices will permit substantial physics achievements over the next 3-4 years.
  - K meson decays
    - $\Delta = \frac{1}{2}$ rule
    - CP violation: $\epsilon'/\epsilon$ and $K^0 - \bar{K}^0$ mixing ($B_K$)
  - Nucleon properties
    - Charges and form factors
    - Structure functions
  - Bottom and charm physics
  - Quark matter under extreme conditions.

- We are beginning to plan the next computer:
  Perhaps 64 nodes on a chip and a petaflops scale RBRC machine by 2009?
Meson Spectrum and Kaon Physics

Chris Dawson
Meson Spectrum and Kaon Physics

Chris Dawson
RIKEN-BNL Research Center

[RBC Collaboration]
$B_K$ and the CKM

Recall:

$$|\epsilon_K| = C_\epsilon A^2 \lambda^6 \bar{\eta} \left[ -\eta_1 S(x_c) + \eta_2 S(x_t)(A^2 \lambda^4 (1 - \bar{\rho}) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

▷ This is the CKMfitter group's plot from EPS 2005.

▷ PDG : $\hat{B}_K = 0.68 - 1.06$

▷ For both these results, the value quoted is the result of lattice calculations; the main error is from the use of the quenched approximation.
$N_f = 2$ Dynamical Domain Wall Fermions

Vital to move beyond the quenched approximation. A (bad) estimate of the size of these effects is the dominant error.

The RBC undertook a two year project using the QCDSP supercomputer to perform the first large-scale calculations using two dynamical flavours of domain wall quarks.

- three different masses: 0.02, 0.03 and 0.04 ($m_s/2 \rightarrow m_s$).
- $a^{-1} \sim 1.7$GeV
- on lattices of size $16^3 \times 32$ ($\sim (2\text{fm})^3 \times 4\text{fm}$)
- Non-degenerate d and s quark masses.

Drawbacks:

- the "less quenched" approximation
- single lattice spacing.
- small(-ish) volume.
- relatively heavy dynamical masses.
\( N_f = 2 \) Dynamical Domain Wall Fermions: \( B_K \)

Our dynamical result is only 3\% lower than the quenched results closest in lattice spacing.

▷ need:
  ▷ two lattice spacings
  ▷ larger volumes
  ▷ smaller masses
  ▷ correct number of quarks

In many ways this calculation was a "warm up".
\( N_f = 2 \) Dynamical Domain Wall Fermions: \( \eta' \)

> Extraction still very noisy; need larger statistics on the QCDQC.
Dynamical DWF on the QCDOC

Previous results: QCDSP supercomputers based at the RBRC and Columbia.

- $\sim 1$ TFlops (peak)

The QCDOC computers: RBRC (BNL), UKQCD (Edinburgh), US Machine (BNL).

- each $\sim 10$ TFlops (peak).

Joint project UKQCD, RBC using (parts of) all three machines: 2+1 flavour Dynamical DWF

- larger lattice sizes ($24^3 \times 64$)
- lighter dynamical masses ($\rightarrow m_s/4$)
- (at least) two lattice spacings...

One of the first physics targets is $B_K$
This shows

\[
\frac{m_{PS}}{m_1 + m_2}
\]

compared to the predictions of chiral perturbation theory.
Preliminary Results: Decay Constants

![Graph showing decay constant vs. NLO chiral perturbation theory]

- The pseudo-scalar decay constant, again fitted versus NLO chiral perturbation theory.
Preliminary Results: $B_K$

Bare $B_K$; $m_{\text{dyn},a}=0.01$

Bare $B_K$

Bare numbers broadly consistent with $N_f = 2$ case:

$\triangleright$ trend down with dynamical mass (not significant alone).
$\triangleright$ little effect seen from non-degenerate masses.
Thermodynamics of Strongly Interacting Matter
First Results from QCDOC

Frithjof Karsch
Thermodynamics of strongly interacting matter
– first results from QCDOC –

- RHIC heavy ion program and LGT calculations
- The new LGT thermodynamics group at BNL
- Towards a calculation of the QCD EoS with a physical quark mass spectrum
- Conclusions
LGT group focusing on QCD thermodynamics aims at understanding the properties of elementary particle matter under extreme conditions and thus will provide theoretical support to the experimental heavy ion program at BNL.
state-of-the-art EoS (LGT)

- $T_c = (173 \pm 8 \pm \text{sys}) \text{ MeV}$
- $\epsilon_c = (0.3 - 1.3) \text{GeV/fm}^3$
- $\epsilon/T^4$ for $m_\pi \simeq 700 \text{ MeV}$; quark masses still too large

hydrodynamics, elliptic flow

- RHIC observes large $v_2$; hydrodynamic description is sensitive to the QCD EoS
- steep EoS $\Rightarrow$ small velocity of sound $\Rightarrow$ less elliptic flow

bound states or quasi-particles? – sQCD or HTL resummation?
small quark masses require huge computational effort $\Rightarrow$ QCDOC
Deconfinement and Quarkonium suppression

in-medium spectral functions

- T-dependence of spectral functions reflects dissolution of heavy quark bound states
- Lattice and MEM systematics limit current predictive power

charmonium yield (RHIC)

- SPS and RHIC: quarkonium yield is suppressed at high energy density
- Conversion of absorption length or $N_{col}$ into a temperature requires knowledge of the EoS

Does the charmonium suppression at SPS turn into charmonium enhancement at RHIC? Does it show up in the bottomonium spectrum?
Chiral symmetry and thermal dileptons

broadening of spectral functions
- pion and rho disappear as "narrow" resonances in the QGP;
- low energy part of vector spectral functions seems to be cut off

enhancement of low mass dileptons
- low mass dileptons cannot be explained by ordinary hadronic cocktail;
- broadening of the rho-resonance can explain the enhancement

LGT and HTL-resummed calculations disagree on low energy spectrum; sQCD interprets "bump" as evidence for quasi-particle bound states

low-ω region infrared sensitive ⇒ huge computational effort ⇒ QCDOC
The (thermal) lattice group at BNL

Frithjof Karsch, group leader (since 02/05)

Saumen Datta, Assistant Scientist (since 07/05)

Christian Schmidt, Res. Associate (since 04/05)

Peter Petreczky, Assistant Scientist (since 10/02)

Takashi Umeda, Res. Associate (since 06/05)

N.N., Res. Associate (FY 2006)
The QCD-thermodynamics lattice collaboration-network

BNL/RIKEN
Tom Blum
Saumen Datta
Chris Dawson
Chulwoo Jung
Frithjof Karsch
Peter Petreczky
Kostya Petrov (⇒ NBI)
Christian Schmidt
Takashi Umeda
Felix Zantow
Tokyo
Shinji Ejiri

Columbia
Michael Cheng
Norman Christ
Robert Mawhinney

Bielefeld
Matthias Döring
Olaf Kaczmarek
Edwin Laermann
Chuan Miao
Stanislav Shchereedin
Jan van der Heide
Sönke Wissel
Current major research topics of the LGT thermodynamics group

- \( T_c, \) EoS (\( \mu = 0 \) and \( \mu > 0 \)) with light dynamical quarks: 
  (2+1)-flavor QCD, close to physical \( m_\pi / m_K \) ratio; 
  exploring the continuum limit: \( \alpha \simeq (0.1 - 0.2) \) fm 
  analyzing the thermodynamic limit: \( V \simeq 500 \text{ fm}^3 \)

  \[ \Rightarrow \text{lattice sizes up to: } 32^3 \times 8; \quad \text{CPU-time: } \sim 2.5 \text{ TFlops-years (sust.)} \]

- In-medium hadron properties, charmonium, dilepton/photon rates: 
  quenched QCD on fine lattices (\( \alpha \simeq 0.02 \) fm); 
  analyzing light quark mesons with improved fermion formulations; 
  exploring infra-red sensitivity of dilepton rates; 
  analyzing charmonium and bottomonium spectra; colored bound state?

  \[ \Rightarrow \text{lattice sizes up to: } 128^3 \times 32; \quad \text{CPU-time: } \sim (2-3) \text{ TFlops-years (sust.)} \]
Status reports on the current research program

Lattice 2005, July 25-30, Dublin

- Chulwoo Jung, Thermodynamics using p4-improved staggered fermion action on QCDOC, hep-lat/0510xxx
- Michael Cheng, Scaling test of the p4-improved staggered fermion action, hep-lat/0509099
- K. Petrov, A. Jakovac, P. Petreczky and A. Velytsky, Bottomonia correlators and spectral functions at zero and finite temperature, hep-lat/0509138

PANIC 2005, October 24-28, Santa Fe

- Saumen Datta, Lattice results on behaviour of quarkonia in a gluonic plasma
- Christian Schmidt, QCD thermodynamics with an almost realistic quark mass spectrum
- Frithjof Karsch (plenary), Lattice QCD at high temperature and the QGP
Critical behavior in hot and dense matter:

**QCD phase diagram**

- **Continuous/rapid (crossover) transition**
- **Quark-gluon plasma**
  - Deconfined, $\chi$-symmetric
- **Chiral critical point**
- **Color superconductor**

Continuous transition for small chemical potential and small quark masses at

$$T_c \approx 170 \text{ MeV}$$

$$\epsilon_c \approx 0.7 \text{ GeV/fm}^3$$

2nd order phase transition;

Ising universality class

$$T_c(\mu)$$ under investigation

Recent doubts on order of transition

A. Di Giacomo et al., hep-lat/0603030

Location of CCP uncertain;

Volume dependence (Fodor/Katz)

Improving accuracy on $T_c$ is mandatory to make contact to HIC phenomenology.
Thermodynamics of (2+1)-flavor QCD

The current research project on QCD/DOC:

- determination of $T_c$: $N_\tau = 4, 6, 8, N_\sigma = 8, 16, 32$
- explore $T = 0$ scales ($r_0, \sqrt{\sigma}, m_\rho$) on $16^3 \times 32$ lattices
- calculation of the EoS: $N_\tau = 4, 6$
- analyze volume dependence in the vicinity of $T_c$
- non-zero quark chemical potentials (Taylor expansion)
- exploration of the phase diagram; CCP; density fluctuations
- analysis of various gluonic and hadronic screening lengths
The p4 action...

We use the $1 \times 2$ Symanzik improved gauge action

$$S_G = \beta \sum_{x, \nu > \mu} \frac{5}{3} \left(1 - \frac{1}{3} \text{Re} \text{Tr} \begin{array}{c} \mu \nu \\ (x) \end{array} \right) - \frac{1}{6} \left(1 - \frac{1}{6} \text{Re} \text{Tr} \begin{array}{c} \mu \nu \\ (x) \end{array} \right) + \begin{array}{c} \mu \nu \\ (x) \end{array}$$

and the p4-action fermion action $m_f \delta_{i,j} + M[U]_{ij}$ with

$$M[U]_{ij} = \eta_i \left\{ \frac{3}{8} A[U]_{ij} + \frac{1}{48} B[U]_{ij} \right\}$$

$$A[U]_{ij} = \quad \begin{array}{c} i \to j \\ - \quad j \to i \end{array}$$

$$B[U]_{ij} = \quad \begin{array}{c} i \downarrow j \\ + \quad i \downarrow j \end{array}$$
...combined with fat3/fat7 links

the 1-link term gets modified

\[ M[U]_{ij} = \frac{1}{2} \eta_i \left\{ FAT[U]_{ij} - \frac{1}{4} A[U]_{ij} + \frac{1}{24} B[U]_{ij} \right\} \]

with \( FAT \) denoting MILC-FAT7

\[ FAT[U]_{ij} = \quad i \rightarrow j \quad - \quad j \leftarrow i \]

\[ i \rightarrow j = \quad c_1 \quad + c_3 \quad + c_5 \quad + c_7 \]

\[ c_1 = 1/8 \quad , \quad c_3 = 1/16 \quad , \quad c_5 = 1/64 \quad , \quad c_7 = 1/384 \]
p4fat: improved rotational and flavor symmetry

improved rotational symmetry:

better short distance properties of heavy quark potential;

reduced cut-off dependence of bulk thermodynamics

improved flavor symmetry:

reduced mass of non-Goldstone pions
Performance of the p4fat7 program

- Performance of p4fat7 codes on QCDOC, 420Mhz, 1024 nodes, MFlops/node; optimization of parallel transport and matrix inversion
- Most runs use $4^4$ or $4^3 \times 6$: they reach about 30% efficiency; $2^4$ or $2^3 \times 4$ run with about 60% of that speed

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<td>$4^3 \times 6$</td>
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<td>317</td>
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<tr>
<td>$4^2 \times 6^2$</td>
<td>576</td>
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<td>264</td>
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</table>

- p4fat7: real time performance
- $16^3 \times 32$, $m_P S / m_V \approx 0.4$: 1024 node rack: $\sim 680$ traj./day
Determination of $T_c$ (I)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

1$^{st}$ step: 3-flavor QCD, calculation of critical couplings for several quark masses and lattice sizes ($N_\tau = 4, 6, N_\sigma = 8, 16, 32$)

- reached small quark masses $m_{PS}/m_V < 0.4$
- achieved high statistics up to 7000 traj. per $\beta$-value
- small $\beta$ separations allow Ferrenberg-Swendsen analysis also for $N_\tau = 6$

critical couplings (p4fat3 and p4fat7) from maxima of susceptibilities
Determination of $T_c$ (II)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

$\beta$nd step: determining the scale at $\beta_c$, e.g. $m_V a(\beta_c(N_\tau))$ and

$$1/T_c = N_\tau a(\beta_c(N_\tau)) \Rightarrow T_c/m_V = 1/(m_V a N_\tau)$$

- scale determined on $16^3 \times 32$ lattices
- will check consistency of different actions
- aim at consistent picture from different scales

![Graph showing critical temperature from vector meson mass vs. $(m_{PS}/m_V)^2$ with data points and error bars for different actions and volumes.](image)
Determination of $T_c$ (III)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

next steps:

a) improve scale calculations: heavy quark potential
b) switch to (2+1)-flavor QCD
c) start calculation of equation of state
d) ....

...to guide your thoughts:

$T_c r_0 \simeq 2T_c \ [GeV]$
Conclusions

- The new LGT group at BNL had a perfect start:
  It is fully integrated in the RBRC/BNL environment

- The computing resources at RBRC (QCDOC) and the well
  established international collaborations of the group allow to
  perform research on QCD thermodynamics at the forefront of
  the field

- First results on QCD thermodynamics are encouraging and will
  contribute to a strengthening of the theoretical background for
  the experimental HI-program at RHIC
Beta Decay on the Lattice

Shoichi Sasaki
Beta decay on the lattice

Shoichi Sasaki (RBRC/Tokyo U.)
Semi-leptonic decays

Kaon beta decay ($K_{l3}$ decay):

$$K^+ \rightarrow \pi^0 + l^+ + \nu_l \quad K^0 \rightarrow \pi^- + l^+ + \nu_l$$

Hyperon beta decay:

$$B' \rightarrow B + l^\pm + \nu_l (\bar{\nu}_l)$$
$K_{13}$ decays (1)

The 2nd simplest weak decay of Kaon

- **leptonic decay**
  \[ K^+ \rightarrow \mu^+ + \nu_\mu \quad F_K \]  Kaon decay constant

- **semi-leptonic decay**
  \[ K^+ \rightarrow \pi^0 + l^+ + \nu_l \]

$\Delta S = 1$ decay ($s \rightarrow u$)

the best determination of the weak mixing element $V_{us}$

![Diagram showing the decay $K \rightarrow V_{us} \pi$]
**K_{l3} decays (2)**

*K_{l3} decay is described by 2 form factors*

\[
\langle \pi(p) | \bar{s} \gamma_\mu u | K(k) \rangle = f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu
\]

**SU(3) limit:**

\[
f_+(0) = -1, \quad f_-(0) = 0
\]

\[
\Gamma_{\text{exp.}} \propto |f_+(0)|^2 |V_{us}|^2
\]

\[
|V_{us}| = 0.2200(26) \text{ (PDG, 2004)}
\]

**Precise evaluation of the SU(3) breaking effect on**

\[f_+(0)\] \text{ is required for determining } |V_{us}|
Simulations

- 2 flavors DWF + DBW2 gauge action
- Lattice cutoff: $1/a \sim 1.7$ GeV ($\beta = 0.80$, $c_1 = -1.4069$)
- Small residual quark mass: a few MeV ($L_5 = 12$, $M_5 = 1.8$)
- Lattice size: $V = 16^3 \times 32$, $L_a \sim 1.9$ fm
- sea quark mass: $m_{\text{light}} = 0.02$ (QCDSP) 0.03, 0.04 (QCDOC)
- valence quark mass: $3 \times m_{\text{strange}} \in [0.02, 0.03, 0.04, 0.05]$
- # of statistics: each 94 measurements
$K_{\ell 3}$ decays (3)

Lattice calculation (double ratio method)

$$C_{\mu}^{K\pi}(t, t') = \sum_{x, x'} \langle O_\pi(x, t)V_\mu(x', t')O_K^\dagger(0, 0) \rangle$$

$$R(t, t') = \frac{C_4^{K\pi}(t, t')C_4^{\pi K}(t, t')}{C_4^{KK}(t, t')C_4^{\pi\pi}(t, t')} \quad \Rightarrow \quad \frac{(M_K + M_\pi)^2}{4M_KM_\pi} |f_0(q_{\text{max}}^2)|^2$$

$$f_0(q^2) \equiv f_+(q^2) + \frac{q^2}{M_K^2 - M_\pi^2} f_-(q^2) \quad q_{\text{max}} = M_K - M_\pi$$

In this ratio, various uncertainties, such as the statistical fluctuation, are canceled at least partially.
Preliminary results

Presented by T. Kaneko at Lattice 2005

<table>
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<tr>
<th>$m_{\text{light}}$</th>
<th>$m_{\text{strange}}$</th>
<th>$f_+(0)$ [method1]</th>
<th>$f_+(0)$ [method2]</th>
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<td>0.02</td>
<td>0.03</td>
<td>0.9984(9)</td>
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<tr>
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<td>0.9944(29)</td>
<td>0.9951(14)</td>
</tr>
<tr>
<td>0.02</td>
<td>0.05</td>
<td>0.9887(56)</td>
<td>0.9893(27)</td>
</tr>
</tbody>
</table>

$f_+(0)$ at simulated quark mass can be determined with both systematic and statistical accuracies of $< 1\%$.

Analysis of data at $m_{\text{light}} = 0.03, 0.04$ is underway.
Hyperon Beta Decay

✓ the baryonic-version of semileptonic decay

- Alternative way to determine $|V_{us}|$ other than $K_{l3}$ decays

✓ the SU(3)-extension of neutron beta decay

- Axial vector form factor as well as Vector form factor (V-A int.)

- the SU(3) breaking effect: analysis of quark spin fractions

$$\Delta \Sigma (= \Delta u + \Delta d + \Delta s)_{\text{Exp.}} = 0.31 \pm 0.04$$
the octet baryons \((p, n, \Lambda^0, \Sigma^{\pm, 0}, \Xi^{0, -})\) admit various \(\beta\)-type decays

\[
B' \rightarrow B + l^\pm + \nu_l(v_l)
\]

Decays (V-A) are described in terms of 6 form factors

\[
\langle B|V_\alpha - A_\alpha|B'\rangle = \bar{u}_B(p) \left[ f_1(q^2)\gamma_\alpha + f_2(q^2)q_\beta\sigma_\beta\gamma_\alpha + f_3(q^2)q_\alpha \right.
\]

\[
+ g_1(q^2)\gamma_\alpha\gamma_5 + g_2(q^2)q_\beta\sigma_\beta\gamma_5 + g_3(q^2)q_\alpha\gamma_5 \left. \right] \ u_{B'}(p')
\]
Quark spin fraction $\Delta \Sigma$

Assumption: SU(3) symmetry

\[
\left(\frac{g_A}{g_V}\right)_{np} = F + D = \Delta u - \Delta d \\
\left(\frac{g_A}{g_V}\right)_{\Delta p} = F + \frac{1}{3}D = (2\Delta u - \Delta d - \Delta s)/3 \\
\left(\frac{g_A}{g_V}\right)_{\Xi \Sigma} = F - \frac{1}{3}D = (\Delta u + \Delta d - 2\Delta s)/3 \\
\left(\frac{g_A}{g_V}\right)_{\Sigma n} = F - D = \Delta d - \Delta s
\]

\[
\Delta \Sigma (= \Delta u + \Delta d + \Delta s)_{\text{Expt.}} = 0.31 \pm 0.04
\]

which may have hidden systematic error stemming from unknown SU(3) breaking effects on hyperon decay.
Hyperon decays on the lattice

- Preliminary results of vector form factor $f_1$
  \[ \Sigma^- \rightarrow n e \bar{\nu}_e \]
  
  - D. Becirevic et al., hep-lat/0411016
  - D. Guadagnoli et al., hep-lat/0409048

- Quenched clover, $\beta=6.2$, $24^3 \times 56$ (120 configs.)

- No results for axial form factors $g_1$ or $g_1 / f_1$

  - A long standing puzzle in the axial-vector coupling $g_A = g_1(0)$ in lattice QCD
Long-standing puzzle

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

One of the simplest nucleon matrix elements:

- lowest moment
- zero momentum transfer
- no disconnected contribution

\[ g_A (\text{exp.}) = 1.267 (3) \]

\[ \langle p | (V_\mu^1 + iV_\mu^2) - (A_\mu^1 + iA_\mu^2) | n \rangle = \langle p | V_\mu^3 - A_\mu^3 | p \rangle \]

- Lattice results always fail to reproduce experimental value about 20% discrepancy

V=16^3 x 32, \beta=6.0 (quenched), \beta=5.6 (full)
LHPC-SESAM collaboration, Phys. Rev. D66 (02) 034506
Quench DWF calculation of $g_A$

- Domain wall fermions
  - excellent chiral properties
  - the lightest pion mass, $M_\pi \sim 0.39$ GeV
  - especially the relation $Z_V = Z_A$
  - $(g_A/g_V)^{\text{latt}}$ directly yields the renormalized value of $g_A$

✓ Clear finite volume dependence
  - a 20% increase from 1.2 fm to 2.4 fm
  - Linear extrapolation yields $g_A = 1.212 (27)$
Hyperon Beta Decay ($\Xi^0 \rightarrow \Sigma^+$)

<table>
<thead>
<tr>
<th>$B' \rightarrow Bl\nu$</th>
<th>$f_1^{SU(3)}$</th>
<th>$g_1/f_1$ (Exp.)</th>
<th>$(g_1/f_1)^{SU(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \rightarrow p$</td>
<td>1</td>
<td>1.2670± 0.0030</td>
<td>$F + D$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow p$</td>
<td>$-\frac{\sqrt{6}}{2}$</td>
<td>0.718± 0.015</td>
<td>$F + \frac{1}{3}D$</td>
</tr>
<tr>
<td>$\Sigma^- \rightarrow n$</td>
<td>-1</td>
<td>-0.340± 0.017</td>
<td>$F - D$</td>
</tr>
<tr>
<td>$\Xi^- \rightarrow \Lambda$</td>
<td>$\frac{\sqrt{6}}{2}$</td>
<td>0.25± 0.05</td>
<td>$F - \frac{1}{3}D$</td>
</tr>
<tr>
<td>$\Xi^- \rightarrow \Sigma^0$</td>
<td>$\frac{\sqrt{2}}{2}$</td>
<td>N/A</td>
<td>$F + D$</td>
</tr>
</tbody>
</table>

$\Xi^0 \rightarrow \Sigma^+$ is the direct analogue of $n \rightarrow p$ under $d \leftrightarrow s$
Hyperon Decay Project
on QCDOC

TEST Run on a rack of QCDOC (1024 nodes machine)

- $N_f=0$, DBW2, $16^3 \times 32 \times 16$, $\beta=0.87$ ($a^{-1} \sim 1.3\text{GeV}$),
- $m_l = 0.04$, $m_s = 0.08$
- # of statistics: 29

- 3 decays: $n \rightarrow p$, $\Sigma \rightarrow n$, $\Xi \rightarrow \Sigma$
$m_t=0.04$, $m_s=0.08$

- $\Xi \rightarrow \Sigma$ (exp. $+1.30 \pm 0.21$)
- $n \rightarrow p$ (exp. $+1.2670 \pm 0.003$)
- $\Sigma \rightarrow n$ (exp. $-0.340 \pm 0.017$)

very preliminary
2 + 1 flavor DWF QCD on QCDOC

- DWF + Iwasaki gauge action
- Lattice cutoff: 1/a $\sim$ 1.8 GeV ($\beta = 2.13$, $c_1 = -0.331$)
- Lattice size: $V = 24^3 \times 64 \times 16$ 
  $L_a \sim 2.6$ fm
- $m_{light} = 3/4, 1/2, 1/4$ of $m_{strange}$ 
  $M_{\pi} \sim 250, 500, 750$ MeV

RIKEN BNL Research Center Dedicates 
New Supercomputer (QCDOC) for Physics Research 
in collaboration with Columbia, UKQCD
Summary / Outlook

* RBRC lattice QCD collaboration pursues theoretical research on the SU(3) breaking effect through a first principles calculation.

* The computation of weak matrix elements in lattice QCD is now progressing with steadily increasing accuracy by utilizing domain wall fermions (DWF).

* All physics program will run on QCDOC to achieve high precision calculations using 2+1 flavors of dynamical DWF quarks.
EXPERIMENTAL PRESENTATIONS
RHIC Heavy Ion Physics

Yasuyuki Akiba
RHIC Heavy Ion Physics

Y. Akiba

Presentation
RBRC Scientific Review Committee
October 12, 2005

RHIC and RHIC: Unique QCD laboratory

RHIC: Accelerator dedicated for study of QCD (strong nuclear force)
RBRC theory: Center of QCD theory from Lattice to pQCD to Heavy Ion
RBRC and RIKEN plays leading role in both of the spin and heavy ion physics
Heavy Ion Physics at RHIC

- Create very high temperature and dense matter
  - As existed a few μ sec after the BIG BANG
  - Collide heavy nuclei to achieve maximum volume
  - 5 Runs since the start of RHIC in year 2000
    - Au+Au (Run1,2,4) d+Au (Run3) Cu+Cu (Run5)
- RHIC has produced high density partonic matter
  - The four experiments of RHIC concluded in their white papers that RHIC Au+Au collisions produced very high density matter
  - The matter is strongly interacting, and it behaves like an ideal fluid (perfect liquid) – unexpected discovery.
- Next step: Detailed study of the newly discovered matter
  - How hot and dense is the medium?
  - Is thermal equilibrium achieved?
  - Is the matter de-confined?
  - What is the equation of state?

Major achievements since last SRC (Nov 2004)

The last 1 year is very productive for RHIC/PHENIX and RIKEN/RBRC group of PHENIX

- Publications
  - A large contribution from RIKEN/RBRC to PHENIX publications
- PHENIX White Paper publication
  - Summary of the first 3 years of RHIC/PHENIX operation
  - Concluded that "a new form of partonic matter is formed at RHIC"
- RUN5 Cu+Cu and p+p
  - Most successful RUN of RHIC/PHENIX
    - Very high statistics Cu+Cu data
    - Very high statistics polarized proton run → First ΔG(x) measurement
- RUN4/RUN5 data analysis and QM05 conference
  - New results from PHENIX dominated the conference
    - 3 plenary talks, 20 parallel talks and >60 posters
  - A big step forward to determine the properties of the partonic matter created at RHIC
RIKEN/RBRC in PHENIX

RIKEN/RBRC personnel have important roles and positions in PHENIX, one of the two major experiments at RHIC.

Deputy Spokesperson (2 out of 2)
- Y. Akiba (RIKEN)
- M. G-Perdekamp (U. Illinois/RBRC)

Executive Council Members (4 out of 13)
- Y. Akiba (RIKEN)
- M. G-Perdekamp (U. Illinois/RBRC)
- A. Deshpande (StonyBrook/RBRC)
- N. Saito (Kyoto/RIKEN)

Physics Working Group Conveners (3 out of 14)
- (M. Kanel) (RBRC → Tohoku) (until June 2005)
- X. Wei (RBRC)
- A. Deshpande (StonyBrook/RBRC)
- K. Tanida (RIKEN) (from June 2005)

PHENIX VTX Upgrade Project
- Y. Akiba (RIKEN) project manager
- H. Ohnishi (RIKEN) pixel subsystem manager
- A. Deshpande (StonyBrook/RBRC) strip subsystem manager

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

PHENIX publications

23 PRL, 9 PRC, 1 PRD, 1 PLB and 1 NPA papers published since start of RHIC.
Total citations ~2200 and growing.

12 papers published since the last SRC meeting (Nov 2004)
6 papers have RIKEN/RBRC person(s) as member(s)(*) of the paper writing committee
3 papers have RIKEN/RBRC person as the chairperson(**) of the committee

<table>
<thead>
<tr>
<th>Paper Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRL93,202002</td>
<td>Run3 p+p $A_L$ (The first Spin Physics paper) (*)</td>
</tr>
<tr>
<td>PRL94,062001</td>
<td>Run2 Au+Au charm (**)</td>
</tr>
<tr>
<td>PRL94,062002</td>
<td>Run3 d+Au forward hadron</td>
</tr>
<tr>
<td>PRL94,062003</td>
<td>Run2 pp direct photon (*)</td>
</tr>
<tr>
<td>PRL93,034008</td>
<td>NotVEE (*)</td>
</tr>
<tr>
<td>PRL94,122002</td>
<td>Run2 Au+Au d+Au</td>
</tr>
<tr>
<td>PRL94,062002</td>
<td>Run2 pp direct photon (*)</td>
</tr>
<tr>
<td>PRC71,051902</td>
<td>Run2 Au+Au baryon jet corr</td>
</tr>
<tr>
<td>PRC71,051902</td>
<td>Run2 Au+Au d+Au</td>
</tr>
<tr>
<td>PRC71,051902</td>
<td>Run2 pp direct photon (*)</td>
</tr>
<tr>
<td>PRC71,051903</td>
<td>Run2 Au+Au baryon jet corr</td>
</tr>
<tr>
<td>PRC72,024001</td>
<td>Run2 Au+Au charm v2 (*)</td>
</tr>
<tr>
<td>nucl-ex10507004</td>
<td>RUN2 Charged particle jet correlation</td>
</tr>
<tr>
<td>nucl-ex10507073</td>
<td>Run2 $A_B$ for p+p and charged hadrons (The 2nd Spin Physics result) (*)</td>
</tr>
<tr>
<td>nucl-ex105070132</td>
<td>Run3 J/ψ production in p+p and d+Au (*)</td>
</tr>
<tr>
<td>nucl-ex10508034</td>
<td>Run2 Open charm production in p+p via single electron (*)</td>
</tr>
<tr>
<td>nucl-ex10508019</td>
<td>Run2 Elliptic flow of $n$ and photon (*)</td>
</tr>
</tbody>
</table>
PHENIX “White Paper”

- Summary of PHENIX results from RHIC Runs 1-3
  - 126 pages
  - 56 figures
  - 267 references
- Part of “First Three Years of Experiments at RHIC” special volume in Nuclear Physics A (August 8, 2005). The white papers of all 4 RHIC experiments are in the volume
- Concluded that a new state of dense matter formed
- PHENIX paper has already received 64 citations

Next Step: New results from RUN4/RUN5

- Conclusion of the PHENIX White Paper
  In conclusion, there is compelling experimental evidence that heavy ion collisions at RHIC produce a state of matter characterized by very high energy densities,...
  ...additional incisive experimental measurements combined with continued refinement of the theoretical description is needed to achieve a complete understanding of the state of matter created at RHIC.

- PHENIX analyzed the high statistics (>10^6 events) data of RUN4/RUN5 to probe the properties of the dense matter formed at RHIC. The preliminary results from the analysis were presented in Quark Matter 2005 conference, the most important conference in the field in this summer.

- Some of the highlights are presented in the following slides
The matter is so opaque that even a 20 GeV $\pi^0$ is stopped.

- Suppression is very strong ($R_{AA}=0.21$) and flat up to 20 GeV/c
- Common suppression for $\pi^0$ and $\eta$; it is at partonic level
- $\epsilon > 15$ GeV/fm$^2$: $dN/dy > 1100$

The matter is so dense that even heavy quarks are stopped

- Even heavy quark (charm) suffers substantial energy loss in the matter
- The data provide a strong constraint on the energy loss models.
- The data suggest large c-quark-medium cross section: evidence for strongly coupled QGP?
The matter is so strongly coupled that even heavy quarks flow

- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high $p_T$.
- Is this due to $b$-quark contribution?
- The data favors the model that charm quark itself flows at low $p_T$.
- Charm flow supports high parton density and strong coupling in the matter. It is not a weakly coupled gas.

The matter is so hot that it emits (thermal?) photon copiously

- The first promising result of direct photon measurement at low $p_T$ from low-mass electron pair analysis.
- Are these thermal photons? The rate is above pQCD calculation. The method can be used in $p+p$ collisions.
- If it is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter.
- $T_{\gamma}^{\text{min}} \sim 500-600$ MeV !?
  $T_{\gamma}^{\text{max}} \sim 300-400$ MeV !?
The matter is so dense that it melts(?) $J/\psi$ (and regenerates it?)

- $J/\psi$'s are clearly suppressed beyond the cold nuclear matter effect.
- The preliminary data are consistent with the predicted suppression + re-generation at the energy density of RHIC collisions.
- Can be tested by $v_2(J/\psi)$?

---

The matter is so dense that it modifies the shape of jets

- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Dielectric constant
- Di-jet tomography is a powerful tool to probe the matter

---

![Graph showing $J/\psi$ nuclear modification factor $R_{AA}$](image1)

![Graph showing jet shapes](image2)
Summary

- A new form of dense matter is created in heavy ion collision at RHIC
  - Suppression of high pT particles due to matter effect
  - Large elliptic flow -- the matter behaves like a perfect liquid
- The next step of heavy ion physics at RHIC is to determine the property of the newly discovered matter
  - Importance of penetrating probes such as direct photon, heavy quarks and J/ψ
  - Upgrade of the detector for better measurement of the matter properties and to explore the full physics opportunity
- RIKEN and RBRC plays very important role in this rapidly evolving field of physics
RHIC Polarimetry

Itaru Nakagawa
RHIC Polarimetry

RIKEN / RBRC

I. Nakagawa
Polarimetry: Impact on RHIC-SPIN

Single Spin Asymmetries

Physics Asymmetries

\[ A_N = \frac{1}{P_B} \left( \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \right) \]

Double Spin Asymmetries

\[ A_{LL} = \frac{1}{P_B^2} \left( \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} \right) \Rightarrow \Delta G \]

Polarization measurement by Elastic pp/pA

(polarized) proton beam

\[ P_B = \frac{1}{A_N} \cdot \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}} \]

polarized proton target or Carbon target

recoil proton or Carbon

\[ t = (p_{\text{out}} - p_{\text{in}})^2 < 0 \]
$A_N$ at Coulomb Nuclear Interference (CNI) Region

\[ A_N \approx C_1 \frac{\sigma_{\text{had}}}{s} + C_2 \frac{\sigma_{\text{non-had}}}{t} \]

Regge poles
Pomeron exchange

$A_N$ is a sensitive probe of hadronic spin flip

$pp$ Analyzing Power
E704@FNAL
$p = 200$ GeV/c
PRD48(93)3026

$pc$ Analyzing Power
zero hadronic spin-flip
With hadronic spin-flip (E950)

RHIC Polarimetry

PHOBOS

absolute pH polarimeter

RHIC

PHENIX

Spin Rotators

Inside the RHIC tunnel at IP 12 area

Siberian Snakes

STAR

5% Snake

AGS quasi-elastic polarimeter

Pol. Proton Source

200 MeV polarimeter

20% Snake

Rf Dipoles

AGS pC "CNI" polarimeter
pC Detector Setup

- Ultra thin Carbon ribbon Target (3.5μg/cm²)
- Thin dead layer for low energy carbon spectroscopy
- 2mm pitch 12 strips
- 10mm p⁺ implants (~150 nm depth)
- 72 strips in total

Wave Form Digitizer (WFD)

- 420 Msamples/sec
- Pulse Height
- Bunch ID
- TOF
- Integral (Q)
- TMAX
- revolution #

Select carbons at on-board LUT
- Scaler data
- Asymmetry calculation
- Online results (to experiments)

offline
Event by event data
- Stored in on-board memory
- Used for offline detailed study
Event Selection

\[ \text{tof} = \sqrt{\frac{M_C}{2T_{\text{kin}}}} L \]

Run 5

\[ M_C \sim 11.17 \text{ GeV} \]
\[ \sigma_M \sim 1.5 \text{ GeV} \]
Run05 Online Results

Run5 yellow Online Polarization (Physics Runs)

Number of Runs = 523

Run5 blue Online Polarization (Physics Runs)

Number of Runs = 642

Polarization Profile for Yellow: 7133

Polarization Profile for blue: 7151

Count Rate [Hz]

DA/0 Rate [Hz]

Target Position (counts)
pC extended t-range $A_N$

From Run4

- $\chi^2 / \text{ndf} = 55.32 / 12$
- $p_0 = 0.05056 \pm 0.00162$
- $p_1 = -0.01268 \pm 0.009278$

No Hadronic Spin flip

Best Fit with Hadronic Spin-flip

hep-ph/0305085
pp elastic (Jet Target)
Run05 Setup

Left-right pairs

Si detectors (8cm * 5cm)*3*2sides

1ch width = 4mm (400strips)

Strip runs vertical with beam
Recoil Si Spectrometer

6 Si detectors covering the blue beam $\Rightarrow$

MEASURE
- energy (res. $< 50$ keV)
- time of flight (res. $< 2$ ns)
- scattering angle (res. $\sim 5$ mrad)

of recoil protons from $pp \rightarrow pp$ elastic scattering

$A_N^{beam}(t) = - A_N^{target}(t)$ for elastic scattering only!

$P_{beam} = - P_{target} \cdot \epsilon_N^{beam} / \epsilon_N^{target}$

HAVE "design"
- azimuthal coverage
- one Si layer only
  $\Rightarrow$ smaller energy range
  $\Rightarrow$ reduced bkg rejection power

72 x 64 mm$^2$
What's New Run05

Sequential / Simultaneous measurement of blue & yellow

• Statistical Advantage

• RUN5 Background > 2×Run4 Background
Online Asymmetry

\[ \chi^2 / \text{ndf} \quad 5.53 / 9 \]
\[ \text{Prob} \quad 0.7955 \]
\[ p_0 \quad 0.4981 \pm 0.02067 \]

\[ \chi^2 / \text{ndf} \quad 10.57 / 9 \]
\[ \text{Prob} \quad 0.3112 \]
\[ p_0 \quad 0.4982 \pm 0.01871 \]
Spin-Flip Amplitude in pp-A$_N$A$_{NN}$

No need of Hadronic Spin-flip $\Rightarrow$ Contradictory to pC!
Summary

- pC
  - Improved ground
  - Explored \(-t>0.05\text{GeV}\)
  - Beam profile measurements
- pp
  - Sequential/Simultaneous measurements
  - Blue/yellow statistics \(\times 2\) Run4
- Hadronc Spin flip in \(A_N\) and \(A_{NN}\)
  - Crucial role in pC
  - Very small in pp
The Pursuit of Polarized Gluon Distribution in the Nucleon with PHENIX

Abhay Deshpande
The pursuit of polarized gluon distribution in the nucleon with PHENIX

Abhay Deshpande
State University of New York at Stony Brook
Riken BNL Research Center

October 11, 2005
Overview

- Relevance of polarized gluon distribution in nucleon spin puzzle

- PHENIX Spin measurements towards understanding the spin puzzle
  - $A_{LL}(X^0)$ from Run-3 & Run-4 : a quick reminder
  - **RHIC Run-5 and expectation from PHENIX**
    - Run-6 and beyond

- Putting all data in perspective: a new initiative on combining world’s spin data
Gluon Contribution to Nucleon Spin is Unknown

- SMC, PRD58, 112002 (1998)
- Analysis of world's all available data (SMC, SLAC, HERMES…)
- Quark contribution to nucleon spin well constrained but **gluon contribution has huge uncertainties**

\[ \Delta \Sigma = \int_0^1 \Delta \Sigma(x, Q^2 = 1\text{GeV}^2) dx = 0.23 \pm 0.05 \]

\[ \Delta G = \int_0^1 \Delta G(x, Q^2 = 1\text{GeV}^2) dx = 1.0^{+1.4}_{-0.5} \]

- Since then many other analyses have been published with qualitatively identical results (E143 Collaboration, AAC Collaboration, E. Leader et al.)
- **New techniques to get to gluon spin necessary:** RHIC Spin ideal

Gluon Spin Investigations: A. Deshpande (SBU/RBRC)
Polarized Gluon Measurements with PHENIX

- Many channels involving polarized gluons in the initial state of scattering:
  - Allow independent constraints on the measurement
  - Have different experimental systematic uncertainties

- Measurements with PHENIX detector
  - Inclusive neutral and charged pion production
    - 2003-2005/6
  - Inclusive prompt photon production (details in K. Okada's talk)
    - 2005-2008/9

- Future upgrade (Si VTX TRK: A. Taketani) will allow additional measurements of gluon distribution using Xjet production, heavy quark production .... etc.
  - Beyond 2009 mostly in the 500 GeV CM program
  - Extend the kinematic range to lower x
X(pp→X⁰ X): Corner stone of RHIC measurements

- A well understood process: cross sections calculable in NLO pQCD in mid & high rapidity
**X^0** production and partonic contributions

- Fractional contribution of partonic scattering to total neutral pion production
- Gluon interactions dominate the low pT region
- In the every low pT (< 3 GeV) gg process dominates.
  - Asymmetry insensitive to the sign of gluon distribution
  - Needs measurement at high pT (5-10 GeV) where qg process important &
  - Measurements of charged pions (see later)

\[ f_{\pi^0} = \frac{\sigma_{xx \to \pi^0 X}}{\sigma_{pp \to \pi^0 X}} \]

Gluon Spin Investigations: A. Deshpande (SBU/RBRC)
PHENIX Run 3+4 vs. Gluon Parameterizations

<table>
<thead>
<tr>
<th>Year</th>
<th>L pb(^{-1})</th>
<th>P (%)</th>
<th>Fig. Of Merit: P(^{1/4})L (nb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.35</td>
<td>27</td>
<td>1.5</td>
</tr>
<tr>
<td>2004</td>
<td>0.12</td>
<td>38</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Data seem to prefer low value of XG?
X\(^2\) probability 24% for GRSV-std and 3% for GRSV-max

GRSV-std corresponds to XG = 0.5 at Q\(^2\) = 1 GeV\(^2\) while GRSV-max corresponds to about 1.8 at the same scale.

Need to improve this measurement ASAP!

Run-5 pp: March 05 - May 05

- CAD hardware upgrades: Cold Siberian Snake in AGS commissioning, significantly increased NEG coated beam pipes.
- Highlights of RHIC accelerator performance:
  - Average ~47-50% beam polarization (routinely available)
  - Number of bunches in each ring 56 (beginning) --> 110 (towards the end)
  - **Delivered** luminosity 12.8 pb$^{-1}$ in ~11 weeks of operation
  - Acceleration of polarized protons to 205 GeV/c, success demonstrated by (transverse orientation at experiments only)
    - Measured asymmetry by RHIC CNI polarimeters
    - PHENIX confirmed observation of forward neutron asymmetry
- PHENIX took its largest single sample of polarized pp data
  - 260 TB data, with various trigger setups
  - ~3.8 pb$^{-1}$ of longitudinal double spin collisions, 0.16 pb$^{-1}$ of transverse spin collisions.
  - All data transferred to CCJ almost in real time for preparing and starting the production quickly

3.8 pb$^{-1}$ at 48% polarization corresponds to 205 nb$^{-1}$ in Figure of Merit
~40 times better than 2003+2004!
Run-5 Neutral Pion Asymmetry Analysis
status and prospects

- Relative luminosity studies [K. Boyle(SBU)]: Interesting new effects observed:
  - First tests/trials with increased number of bunches in fills by CAD, studied
    and mostly understood
  - Expect no major show stoppers, relative luminosity uncertainty presently
    estimated to be the same as in the previous years

- Detector (EMCal, TOF) efficiency studies [Y. Fukao (Kyoto/RIKEN), K. Nakano
  (Tokyo/RIKNE)] -- DONE

- Beam polarization in Run-5 using online values
  - Preliminary values expected (soon)

- $A_{LL}(X^0)$ Run-5 Result expected to be released at PANIC'05
  - Kieran Boyle and Yoshi Fukao to present the results in a parallel session
Run-5 Neutral Pion Asymmetry

- GRSV std corresponds to a very small polarized gluon integral
  - $X_G \sim 0.5$ at $Q^2=1$ GeV$^2$
- While Run 3+4 seem only to rule out GRSV-max parameterization, Run 5 data will allow us to get the first definitive estimate for the magnitude of the polarized gluon distribution’s first moment

Gluon Spin Investigations: A. Deshpande (SBU/RBRC)
Charged pion asymmetries: Sign of XG?

- Run-5 neutral pion asymmetry estimates & charged pion asymmetries will resolve the sign of the XG as well!

$$\pi^- \quad \pi^0 \quad \pi^+$$

**idea:** $qg$ starts to dominate for $p_T \gtrsim 5$ GeV and $D_{UU}^{\pi^-} > D_{UU}^{\pi^0} > D_{UU}^{\pi^+}$, $D_{gq}^{\pi^+} = D_{gq}^{\pi^-}$

**expect:** sensitivity to sign of $\Delta g$, e.g., positive $\Delta g$: $A_{UU}^{\pi^+} > A_{UU}^{\pi^0} > A_{UU}^{\pi^-}$

M. Stratmann et al.

Gluon Spin Investigations: A. Deshpande (SBU/RBRC)
Plans for Run-6 & Beyond

- Many other efforts underway for XG measurements in the near future:
  - Neutral pions result consolidation + charged pion asymmetries
  - Direct photon (see K. Okada's talk)
  - $A_{LL}$ of Jet-like cluster: Jet surrogates in PHENIX! (K. Nakano, APS/DNP)

- By 2009 we expect ~90 pb$^{-1}$ luminosity in PHENIX at 200 GeV CM accumulated in 35 weeks of pp running
  - Completion of 200 GeV CM program

- Si VTX TRK will be available at this time and **500 GeV** program begins
  - XG with g-jet co-incidence
  - XG with heavy quark production

*stigations: A. Deshpande (SBU/RBRC)
Global Analysis of Polarized Scattering Data: A new initiative

- We must extract maximum information out of the existing and anticipated data (including the polarized DIS and RHIC pp)
  - **Require:** “A Global Analysis” of all available data using the state-of-the-art theoretical formulism and tools
  - **Emphasis:** Careful evaluation of experimental and theoretical uncertainties
  - General method clear & obvious, details of including pp at NLO complicated, but W. Vogelsang et al have developed early ideas

- A new initiative is being considered with RHIC experimentalists, theorists & members of CTEQ collaboration:
  - CTEQ willing to provide the tools for such an analysis
  - BNL/Stony Brook theory & other CTEQ colleagues are willing to help!

- A group of us will start this shortly across collaborations with an aim to develop this as the 200 GeV RHIC Spin program ramps up

Gluon Spin Investigations: A. Deshpande (SBU/RBRC)
Concluding Thoughts

• These are exciting times for RHIC Spin!

• First conclusive results on XG from RHIC may be just around the corner
  – Neutral pion production has paved the way and charged pion & direct photon analyses will follow
  – Intermediate term outlook is exciting due to the anticipation of a huge amount of RHIC polarized pp data

• Utilizing these data in the most comprehensive way to extract maximum knowledge is essential & will require the a CTEQ/MRST like effort. This needs to start now.
Spin Fest - 2005 Data Analysis

Yuji Goto
Spin Fest – 2005 Data Analysis

RBRC Review
October 10, 2005
Yuji Goto
PHENIX Spin Fest

- July 11th – September 2nd
  - just after 2005 polarized-proton run ended on June 25th …
  - Pacific-spin 05 symposium in Tokyo: July 5-8

- at radiation laboratory, RIKEN Wako institute
  - two meetings every week connecting to BNL etc. by telephone
    - regular Spin PWG meeting (every Thursday morning: 9am-11am)
    - extra Spin Fest meeting (every Tuesday morning: 9am-11am)
  - theory lecture course: July 25-29
  - seminars by participants and guests every week
    - every Monday afternoon: 2pm-
    - coordinator: Kiyoshi Tanida
  - workshop at Nikko: August 17-19
Goals

- Fast-track analysis of central-arm data in 2005 polarized-proton run
  - physics goals: $\pi^0 A_{LL}$, direct-photon cross section, ...
  - monitoring of quality of data as it is being produced, alerting the group to possible hardware software problems and if there are any serious real physics problems ...
  - on BNL side, supporting this effort from a distance when needed: input from detector groups and specialists, ...
  - physics analysis of transverse physics data will start immediately ...

- Preparation of full production of central-arm & muon-arm data
  - to start in or after the spin fest ...

- Formation of a strong spin analysis group
  - develop specializations, know each other's qualities, and learn to work as a cohesive group, ...

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Analysis plans

Run5pp beam time

Apr, May, Jun → Jul, Aug, Sep

Spin fest

run4pp production

data transfer

spin nDST production / CDEV filtering

relative luminosity

fast-track analysis

multiple-collision analysis

local polarimeter

longitudinal-run analysis

vernier-scan analysis

EMCal calibration

fast-track production

QA of fast-track production

$\pi^0 A_{LL}$ fast-track analysis

DC/PC/etc. calibration

run5pp full production

QA of full production

as of May 18 ...

October 10, 2005

Yuji Goto
# Participants

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<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Arrival</th>
<th>Departure</th>
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<tr>
<td>Kenichi Nakano</td>
<td>TITech</td>
<td>6/28</td>
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<td>Ming Liu</td>
<td>LANL</td>
<td>6/29</td>
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<td>Hiro Hieijsm</td>
<td>UIUC</td>
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<td>Ralf Seidl</td>
<td>UIUC</td>
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<td>Oleg Eyser</td>
<td>UCR</td>
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<td>Mickey Chiu</td>
<td>UIUC</td>
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<td>Manabu Togawa</td>
<td>Kyoto</td>
<td>7/7</td>
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<td>Matthias Perdekamp</td>
<td>UIUC/RBRC</td>
<td>7/8</td>
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<td>Doug Fields</td>
<td>UNM/RBRC</td>
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<td>Edward R. Kinney</td>
<td>Colorado</td>
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<td>Frank Ellinghaus</td>
<td>Colorado</td>
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<td>Kenneth N. Barish</td>
<td>UCR</td>
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<td>Ran Han</td>
<td>Peking</td>
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<td>Joseph Seele</td>
<td>Colorado</td>
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<td>Petr Mikes</td>
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<td>Kensuke Okada</td>
<td>RBRC</td>
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<td>Dave Kawall</td>
<td>UMass/RBRC</td>
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<td>Gerry Bunce</td>
<td>BNL/RBRC</td>
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<td>Abhay Deshpande</td>
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<td>Kazuya Aoki</td>
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<td>Sasha Bazilovsky</td>
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<td>Astrid Morreale</td>
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<td>Tomas Liska</td>
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<tr>
<td>Naohito Sato</td>
<td>Kyoto/RBRC</td>
<td>8/22</td>
<td>9/2</td>
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- from US, Czech, China, and Japan
  - 11 staff members
  - 7 postdocs
  - 12 students

- and many people who stay at BNL, RIKEN Wako, etc.

October 10, 2005

Yuji Goto
Coordinators and supporting staffs

- Overall coordinators of the analysis
  - Yuji Goto, Kiyoshi Tanida (at RIKEN), and Abhay Deshpande (at BNL)

- Period coordinators
  
<table>
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<tr>
<th>Period</th>
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<td>June 28</td>
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<td>July 11</td>
<td>Ken Barish (UCR)</td>
<td>Wei Xie (RBRC)</td>
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<td>Abhay Deshpande (SBU/RBRC)</td>
<td>Imran Younus (UNM)</td>
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<td>August 8</td>
<td>Yuji Goto (RIKEN)</td>
<td>Dave Kawall (UMass/RBRC)</td>
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<tr>
<td>August 22</td>
<td>Naohito Saito (Kyoto)</td>
<td>Mickey Chiu (UIUC)</td>
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- Supporting staffs
  - Yasushi Watanabe (computer and network in general)
  - Takashi Ichihara, Satoshi Yokkaichi and Souichiro Kametani (CCJ)
  - Hisa Torii (CCJ production)
  - Ms. Kiyama (many many supports in general) !!!
Technical tasks

- data transfer
- relative luminosity
  - fast track analysis
  - multiple-collision analysis
- local polarimeter
  - rotator commissioning done!
  - longitudinal-run analysis
- normalization
  - vernier-scan analysis
- fast-track production
  - EMCal calibration/QA
  - PC/DC calibration/QA
  - ERT analysis
  - $\pi^0 A_{LL}$ analysis
- full production
  - calibration/QA
- simulation (if necessary ...)
  - Fast MC
  - full PISA production

Mickey, Satoshi, Yasushi, ...
Dave, Yoshi, Kieran, Robert, Imran, Sasha, Oleg, ...
Manabu, Kieran, Joe, ...
Dave, Robert, Sasha, Oleg, Joe, ...
Hisa and production team ...
Kenichi, Yoshi, Takuma, ...
Kazuya, Manabu, ...
Kensuke, ...
Sasha, Kieran, Yoshi, ...
Hisa and production team ...
Imran, ...

October 10, 2005

Yuji Goto
Physics analysis

- $\pi^0$
  - Sasha, Kieran, Yoshi, Dave, Imran, ...
- direct photon
  - Kensuke, Robert, Kenichi, Sasha, Takuma, Dave, ...
- $\eta$
  - Frank, Joe, Hiro, ...
- $h^{\pm}/\pi^{\pm}$
  - Kieran, Waled, ...
- jet
  - Kenichi, ...
- $e^{\pm}$
  - Manabu, ...
- $\Lambda$
  - Ran, Kazuya, ...
- 200 GeV transverse-polarization data
  - Mickey, Oleg, Christine, Hiro, ...
- 410 GeV transverse-polarization data
  - Manabu, ...

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CCJ production

- Production team
  - Hisa Torii (RIKEN), Oleg Eyser (UCR), Joe Seele (Colorado), Ran Han (Peking), Antonin Kral, Petr Mikes and Tomas Liska (Prague)

- Production contributors and monitoring shifters
  - Mickey Chiu (UIUC, analysis coordinator), Frank Ellinghaus (Colorado, data transfer), Imran Younus (UNM, shift in US), Mikhail Stepanov (NMSU, shift in US), Astrid Morreale (UCR, shift in Japan), Christina Hagemann (UNM, shift in US) and Kazuya Aoki (Kyoto, shift in Japan)

run5pp Production Status

Fast-track production of 260 TB data (!) finished on September 6!!

October 10, 2005
Yuji Goto
**Weekly seminars**

- **July 11:**
  - 14:00 Sivers measurement using back to back di-hadrons by Mickey Chiu (UIUC)

- **July 20: (Wednesday)**
  - 14:00 Testing fundamental symmetries with molecules by Dave Kawall (UMass/RBRC)
  - 15:30 High pT measurements in PHENIX by Ken Barish (UCR)

- **July 25:**
  - 14:00 Silicon detector development and radiation hardness for nuclear and high energy physics experiments at BNL and around the world by Zheng Li (BNL Instrumentation)
  - 15:30 High statistics search for Theta(+) in gamma+d -> K(+) K(-) p reaction by Tsutomu Mibe (Ohio)

- **August 1:**
  - 14:00 Absolute polarimetry in RHIC -- How to measure the beam polarization? What is the principle? by Hiromi Okada (Kyoto)
  - 15:30 Silicon-Tungsten Calorimeter for the Forward Direction in the PHENIX Experiment at RHIC by Keiji Nakamura (RIKEN)
Theory lectures

- July 25th (Mon) – 29th (Fri)

Outline of the lectures

Lecture 1: basic ideas; exploring the QCD final state
Lecture 2: origin of singularities; infrared safety
Lecture 3: QCD initial-state; factorization; renormalization
Lecture 4: more on factorization & renormalization; pdfs
Lecture 5: applications in hadron-hadron collisions; pdfs

Lectures on Perturbative QCD or from basic principles to current applications by Marco Stratmann (Regensburg Univ.)

Contents

Parton Distribution Functions (PDFs)
1. Unpolarized PDFs
2. Polarized PDFs: General Analysis Method
3. Polarized PDFs: Recent Progress
4. RHIC-Spin and Other Topics
5. K. Sudoh, Hadron Productions and Polarized PDFs

and after-lecture discussions ...

October 10, 2005

Yuji Goto
Workshop at Nikko

- Joint workshop of PHENIX spin fest and RIKEN radiation laboratory
  - more than 20 participants
  - at Kinugawa Onsen Hotel
- August 17 (Wed):
  - 9:00 RIKEN Wako → bus→ 12:00 Nikko
  - 12:00-17:00 lunch and excursion around Nikko Toshogu shrine
  - 17:00 to Kinugawa Onsen Hotel and dinner
  - 19:00-21:00 *** session 1 ***
- August 18 (Thu)
  - 9:00-12:00 *** session 2 ***
  - 12:00-15:00 lunch and official excursion to Ryuoh-Kyo
  - 15:00-18:00 *** session 3 ***
  - 18:00 banquet
- August 19 (Fri)
  - 10:00 hotel → bus→ deep Nikko: excursion at Kegon fall, Chuzenji lake, etc.
  - 16:00 Nikko → bus→ 19:00 RIKEN Wako

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Yuji Goto
Workshop at Nikko

Session 1 – chair: Yasushi Watanabe (RIKEN)
- Kazutaka Sudoh (KEK)
- Sergei Kondrashev (ITEP) Laser Ion Source of Highly Charged Ions for Synchrotrons
- Takeshi Kanesue (Kyushu U.) ion production with laser
- Megumi Naruki (RIKEN) In-medium modification of rho/omega mesons
- Ryotaro Muto (RIKEN) In-medium modification of phi meson
- Maki Kurosawa (SUT)

Session 2 – chair: Hideto Enyo (RIKEN)
- Sasha Bazilevsky (BNL) Pi0 cross section and A_LL in pp Run5: status and expected sensitivities
- Kieran Boyle (SBU) Relative Luminosity un Run5
- Robert Bennett (SBU) Vernier Scans in Run5
- Vladimir Rykov (RIKEN) Status report on the analysis of spin transfer to anti-Lambda-hyperon from longitudinally polarized protons
- Ran Han (Peking) Spin flavor structure of Nucleon via W Production
- Yuji Goto (RIKEN) Transverse back to back Di-Hadron Jets
- Yasushi Watanabe (RIKEN) CCJ - past, present, and future
- Tomas Liska (Prague) Massive Data Production on Distributed Computational Environment

Session 3 – chair: Koji Nakai (SUT)
- Oleg Eyser (UCR) Transverse single spin asymmetries in charged hadrons
- Waled Emam (UCR) A First Look at the Charged Pion
- Kiyoshi Tanida (RIKEN) Single spin asymmetry in very forward particles in polarized p-p collision
- Atsushi Taketani (RIKEN) PHENIX VTX Upgrade
- Junkichi Asai (RIKEN)
- Yoshiyuki Onuki (RIKEN) PHENIX/Pixel detector assembly

October 10, 2005

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Achievements and future outlook

- Fast-track production of central-arm data in 2005 polarized-proton run DONE
- Detector calibration, QA, analysis of the relative luminosity, local polarimeter, normalization, etc. ONGOING
- Preliminary $\pi^0 A_{LL}$ data of 2005 polarized-proton run will be shown at PANIC05 conference (Santa Fe, October 24-)
- Full production of central-arm & muon-arm data will start SOON
- Many new longitudinal & transverse spin results of variety of physics channels will be obtained:
  - direct photon, $\eta$, $\pi^\pm$, jet, $e^\pm$, $\mu^\pm$, $J/\psi$, $\Lambda$, 200 GeV & 410 GeV transverse-polarization data, …
- Spin analysis group is formed stronger involving many US/European/Asian institutions
- It is worthwhile to plan the similar activity for future runs !!!

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Yuji Goto
Relative Luminosity Measurement at PHENIX

David Kawall
Relative Luminosity Measurement at PHENIX

D. Kawall, RBRC

\[
A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{\langle P_b P_y \rangle} \frac{N_{++} - R \cdot N_{+-}}{N_{++} + R \cdot N_{+-}}; \quad R = \frac{L_{++}}{L_{+-}}
\]

\[
\frac{\partial A_{LL}}{\partial R} \delta R \approx \frac{1}{2\langle P_b P_y \rangle} \delta R
\]

- To measure 1% asymmetry with \( P_{beam} \approx 50% \), need \( \delta R < 10^{-3} \)
- Higher polarization reduces sensitivity to uncertainty in \( R \)
- Order of magnitude requirement: \( \delta R \leq \text{few} \times 10^{-4} \)

- How do measure relative luminosity?
- What difficulties do we expect?
- What should we do? (Work in progress)
Relative Luminosity Measurement at PHENIX

- Collisions defined by coincidence of signals in Beam-Beam Counters (BBCs)
- Located at $\pm 1.44$ m from interaction point, cover $\Delta \phi = 2\pi$, $3.0 \leq |\eta| \leq 3.9$
- Average hit time is formed from PMTs in north and south BBC arms separately
- From difference of north and south BBC hit times can reconstruct $z$ of vertex
- Central arm acceptance requires event vertex $|z| < 30$ cm, muon arms less restrictive
- Have separate scalers for each bunch pair to measure collision rate for different helicity combinations
- Measure $R$ with scalers attached to this minimum-bias trigger, $R = \frac{BBC_{++} + BBC_{--}}{BBC_{+-} + BBC_{-+}}$
PHENIX Interaction Region

- Same pairs of bunches always collide
- Since bunches are accelerated individually, luminosity of each bunch pair is different
Complications in Extracting $R$ as Luminosity Increases

- At design luminosity, we expect $\approx 1$ $pp$ collision/crossing
- 70 percent of all crossings may contain 2 or more $pp$ collisions
- At least two complications will result:

1. BBC scaler counting minimum-bias triggers only counts 0 or 1 $pp$ interactions/crossing
   - $\mu =$ average number of $pp$ interactions/crossing passing vertex cut,
   - $\epsilon =$ probability that one arm of BBC detects the collision,

\[
\frac{\text{Number of BBC Triggers}}{\text{Number of Crossings}} = 1 - e^{-\mu\epsilon} \left[ 2 - e^{-\mu\epsilon(1-\epsilon)} \right]
\]

- Minimum-bias trigger rate not simple function of luminosity
- Would do better by measuring something linear in $pp$ interactions/crossing
- Accuracy in extracting $R = \mu_{++}/\mu_{+-}$ depends on knowledge of $\epsilon = \epsilon(z)$
- Even if we know $\epsilon(z) \Rightarrow$ still need to know true vertex distribution
Partial Solution to Determining Relative Luminosity

- In Run 5 we recorded BBC phototube multiplicity/crossing in PHENIX scalers
  - Linear in luminosity to much higher $pp$ rates than BBC trigger rate

- Clear evidence in Run 5 of multiple collisions/crossing
- Multiplicity determined with high precision for each crossing in each run
- But - collisions outside of PHENIX vertex acceptance also contribute to multiplicity
- To extract luminosity requires knowledge of the vertex distribution and $\epsilon(z)$
Second Complication: Determining the Z Vertex with the BBC

(2) We need to measure luminosity delivered inside PHENIX vertex cuts (± 30 cm)
- With multiple \( pp \) interactions/crossing, will count events outside of PHENIX acceptance

- Collisions at A & B outside PHENIX vertex
- Can be interpreted as collisions at C and D
- Vertex reconstructed by BBC is distorted
- Measurement of luminosity inside vertex limits distorted
Possible Solution: Determine Vertex Distribution with Wall Current Monitor

- Image charges induced in beam pipe by bunched protons are shunted through resistors and resulting voltage sampled at 4 GHz
- Provides longitudinal profile of each blue and yellow bunch
- Can attempt to predict vertex distribution
Predicted Vertex Distribution using Wall Current Monitor

- Construct vertex from WCM data, account for $\beta^* = 1$ m, smear with ZDC resolution
- Fit 50 crossings, $\chi^2/N \approx 1.13$ for $N \approx 250$, vertex RMS predicted to 2 mm
- Predicts "true" vertex in absence of effects of multiple collisions/crossing
- (ZDCLL1 trigger selects $|z| < 150$ cm)
Possible Approach to Determining Relative Luminosity

- ZDC vertex predicted from wall current monitor is reasonable
- Comparing vertex predicted with WCM to observed BBC vertex yields $\varepsilon(z)/\varepsilon(0)$
- For each crossing, knowledge of WCM profiles, $\varepsilon(z)$, and BBC multiplicity may allow us to extract relative luminosity in high rate environment
- All assumptions can be cross-checked with observed vertex distribution and trigger rate
- Cross-talk in WCM needs to be reduced
- Should get spin flipper commissioned:
  - Allows us to flip polarization of all bunches in a beam
  - Then individual bunch pairs can have $\int L_{++} dt \approx \int L_{+-} dt \approx \int L_{--} dt \approx \int L_{-+} dt$
- Dramatically reduced uncertainties in $R$ from vertex shape and multiple collisions/crossing
- Relative luminosity $R \approx 1$ by construction
- Other approaches still being considered
Measurement of Direct Photons in $|s| = 200$ GeV $p+p$ Collisions

Kensuke Okada
Measurement of Direct Photons in $\sqrt{s}=200\text{GeV}$ p+p collisions

K. Okada

RBRC review

October, 2005
Motivations

- Test of our theoretical understanding based on QCD
- Direct information on gluon distribution in the proton
  With polarized beam at RHIC, it is a probe for gluon polarization
- Reference for A+A collisions

\[
\begin{align*}
\text{Compton} & \quad \gamma \\
\text{Annihilation} & \quad \bar{q} \\
\end{align*}
\]

80~90% Dominant

20~10%

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Data

RHIC run3 p+p

2003 April-May
\(\sqrt{s}=200\text{GeV}\) Proton-proton collisions
Luminosity= 240nb\(^{-1}\)

RHIC-PHENIX detector

**Central Arm** (West)
(Rapidity \(|y|<0.35\))
- Electromagnetic Calorimeter (EMCal)
  - Photon detection
  - High granularity (~10*10mrad\(^2\))
- Drift chamber (DC)
  - Charged hadron veto

**Beam forward / backward**
(Rapidity 3.1<\(|y|<3.9\))
- Beam-beam counter (BBC)
  - Triggering and vertex determination
  - Luminosity measurement

BBC and EMCal Trigger for the data taking

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Analysis Strategy

Photon cluster selection
- Photon shape cut (important to remove merged $\pi^0$ clusters)
- Charged veto with DC track
- Timing cut

$\pi^0$ photon tag
- Count photons with $\pi^0$ partner
- Estimate $\pi^0$ photons without partner
  (it is only kinematics and geometrical issue)

Other hadron to photon estimation ($\eta, \omega$, etc.)
- Scale $\pi^0$ photon contribution by their production and branching ratio

The rest is our direct photon signal !! (Subtraction method)
Subtraction method

Preliminary Subtraction

Systematic error sources

- Luminosity
- Energy scale
- Non photon BG
- Pi0 tag
- Missing $\pi^0$
- Non $\pi^0$ photon

pT region
- Low
- Mid
- High

West arm only

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Subtraction method

NLO pQCD calculation explains the data well.

At low p_T, the data show an excess.
— with large systematic error
— but may be soft physics contributions as well

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K. Okada
Isolation cut method: 2 goals

1. Check if our direct photon signal is isolated.
   (with LO view, they are isolated)

- A confirmation is done by applying the same isolation cut
  on photons from $\pi^0$
Isolation cut method: 2 goals

Can we extract contribution of direct production?

NLO pQCD calculation by W. Vogelsang (p+p at $\sqrt{s}=200$ GeV)
Isolation cut with PHENIX

- Starting from isolated photons
  \[ 0.1 E_\gamma > E_{\text{cone}} (R=0.5\text{rad}) \]

- \( E_{\text{cone}} \): photon energy
  + charged particle momentum

- For the estimation of hadron contribution,
  "Isolated \( \pi^0 \) photon" is introduced
  They have \( \pi^0 \) partner.
  They pass the isolation cut when the partner energy is excluded.
Isolation cut method

Isolation cut

\[ 0.1E_{\gamma} > E_{\text{cone}}(R=0.5\text{rad}) \]

No correction for isolation cut efficiency was applied.
Ratios

1. Direct photon : isolation / subtraction
   Photon from $\pi^0$ : isolated photon / all

PHENIX Preliminary

Isolation cut
$0.1 E_\gamma > E_{\text{cone}}(R=0.5\text{rad})$

Photons from $\pi^0$ is reduced by the isolation cut.
Direct photons are clearly isolated at high pT region.

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K. Okada
Iso/sub ratio with a theory calculation

At high \( p_T \), theory predictions are consistent with the data.

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K. Okada
Prospects for $\Delta g$ measurement

For the asymmetry measurements, the purity is important.

$$dA_{LL,\text{signal}} = D \times dA_{LL, \text{all photon}}$$

$1/D$: purity (=signal/all)

With the isolation cut, the purity is about 80% for $p_T > 10 \text{GeV/c}$. And most direct photons remains.

In Run5, we took $\sim 3.5 \text{pb}^{-1}$ with 50% pol. (The figure of merit ($P^4L$) = 0.22 pb$^{-1}$)

We need a little more luminosity and polarization for photon $A_{LL}$.
Summary

We are preparing for publication.
Spin Dependent Fragmentation Function Results from Belle

Matthias Grosse Perdekamp
The Collins Fragmentation Function

Why is it interesting to measure the Collins FF?

The Belle Experiment

Collins Asymmetries: First Results

Outlook
Collins Effect in Quark Fragmentation

J.C. Collins, Nucl. Phys. B396, 161(1993) and

**Collins Effect:**
Fragmentation of a transversely polarized quark \( q \) into spin-less hadron \( h \) carries an azimuthal dependence:

\[
\propto \left( \vec{k} \times \vec{p}_{h\perp} \right) \cdot \vec{s}_q
\]

\[
\propto \sin \phi
\]

\( k \): quark momentum

\( s_q \): quark spin

\( p_h \): hadron momentum

\( p_{h\perp} \): transverse hadron momentum

\[ z_h = \frac{E_h}{E_q} \]

\[ = 2 \frac{E_h}{\sqrt{s}} : \text{relative hadron momentum} \]
Example: Left–Right Asymmetry in Pion Rates

Collins Effect

\[ A_T = \frac{N_L - N_R}{N_L + N_R} \neq 0! \]

\( N_L \): pions to the left

\( N_R \): pions to the right
Number density for finding a spin-less hadron $h$ from a transversely polarized quark, $q$:

$$D_{q}^{h}(z, P_{h\perp}) = D_{1}^{q,h}(z) + H_{1}^{\perp q,h}(z, P_{h\perp}^{2}) \frac{(\hat{k} \times \vec{\omega}) \cdot \vec{\omega}}{zM_{h}}$$

unpolarized FF  Collins FF
Important test case for QCD
Interesting symmetry properties
Tests of universality and factorization between $e^+e^-$, DIS and $p-p$ collisions
Connection between microscopic and macroscopic observables:

Probe/analyzer for transverse quark spin
Critical input for transverse proton spin program
at DESY, CERN, JLab and RHIC
Event Structure in $e^+e^-$ at Belle

Near-side Hemisphere:
$h_i, i=1,N_h$ with $z_i$

Far-side:
$h_j, j=1,N_f$ with $z_j$

Spin averaged Inclusive Cross Section:

$$
\frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1)\overline{D_1}(z_2)
$$

$$
A(y) = \left(\frac{1}{2} - y + y^2\right)_{(cm)} = \frac{1}{4} \left(1 + \cos^2 \Theta\right)
$$

$z = \frac{2E_h}{\sqrt{s}}, \sqrt{s} = 10.52$ GeV

$<N_{h+-}> = 6.4$
Collins FF in $e^+e^-$:
Correlation between Hemispheres!

- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible. $sin \varphi$ modulation will average out!

- Correlation between two hemispheres with $sin \varphi_i$ Collins single spin asymmetries results in $cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

- Fraction of sample with anti-parallel quark- and anti-quark spin direction $\sim sin^2\theta$ (assuming negligible beam polarization)
Collins FF: Angles and Cross Section for the \( \cos(\phi_1 + \phi_2) \) Method

2-hadron inclusive transverse momentum dependent Cross Section:

\[
\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2q_T} = \Lambda B(y) \cos(\phi_1 + \phi_2) H_1^1(z_1) \overline{H}_1^1(z_2)
\]

\[
B(y) = y(1-y) = \frac{1}{4} \sin^2 \Theta
\]

Net anti-alignment of Transverse quark spins

October 10th Spin Dependent Fragmentation Function Results from Belle
KEKB: \( L > 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)

- KEKB
  - Asymmetric collider
  - 8GeV \( e^- + 3.5\text{GeV } e^+ \)
  - \( \sqrt{s} = 10.58\text{GeV } (Y(4S)) \)
    \( e^+e^- \rightarrow Y(4S) \rightarrow B \bar{B} \)
  - Off-resonance: 10.52 GeV
    \( e^+e^- \rightarrow q \bar{q} \) (u,d,s,c)
  - Integrated Luminosity: >400 fb\(^{-1} \)
    \( >30\text{fb}^{-1} \Rightarrow \text{off-resonance} \)

**October 10th**  Spin Dependent Fragmentation Function Results from Belle
October 10th  Spin Dependent Fragmentation Function Results from Belle
Belle Detector

Aerogel Cherenkov cnt. 
n=1.015~1.030

3.5GeV e^+

TOF counter

8GeV e^-

SC solenoid

1.5T

Csl(Tl) 16X_0

Tracking + dE/dx

small cell + He/C_2H_5

Si vtx. det.

3 lyr. DSSD

μ / K detection

14/15 lyr. RPC + Fe

Good tracking and particle identification!
Typical hadronic events at Belle

\[ \text{thrust} = \frac{\sum p_i \cdot n}{\sum |p_i|} \]

\( \sim 1 \quad \sim 0.5 \)
**Applied cuts, binning**

- **Off-resonance data**
  (in the future also resonance)
- **Track selection:**
  - $p_T > 0.1 \text{GeV}$
  - vertex cut:
    - $dr < 2 \text{cm}$, $|dz| < 4 \text{cm}$
- **Acceptance cut**
  - $-0.6 < \cos \theta_i < 0.9$
- **Event selection:**
  - $N\text{track} \geq 3$
  - Thrust $> 0.8$
  - $Z_1, Z_2 > 0.2$

- **Light quark selection**
- **Hemisphere cut**
  \[
  (P_{h_2} \cdot \hat{n}) \hat{n} \cdot (P_{h_1} \cdot \hat{n}) \hat{n} < 0
  \]
- **Opening angle cuts:**
  - $\cos(2\phi_0)$ method: $\psi > 120^\circ$
  - $\cos(\phi_1+\phi_2)$
    method: $\psi_1 < 60^\circ, \psi_2 > 120^\circ$

\[\begin{array}{cccc}
1 & 4 & 5 & 6 \\
2 & 5 & 7 & 8 \\
3 & 6 & 8 & 9 \\
\end{array}\]

$z$-binning: 0.2 0.3 0.5 0.7 1.0
Examples of fitting the azimuthal asymmetries

- Cosine modulations clearly visible
- No change in cosine moments when including higher harmonics (even though double ratios will contain them)

\[
\frac{N(\phi)}{N_0} = \frac{aD_1 \bar{D}_1 + \cos(2\phi) (bH_1 \bar{H}_1 + cD_1 \bar{D}_1)}{aD_1 \bar{D}_1} = P2 + P1 \cos(2\phi)
\]

- \(D_1\): spin averaged fragmentation function,
- \(H_1\): Collins fragmentation function
Results for $\pi$-pairs for 30fb$^{-1}$

- Significant non-zero asymmetries
- Rising behaviour vs. $z$
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function

hep-ex/0507063
Systematic errors

Other errors: smearing, pid, charm content

- MC double ratio
- Charge sign ratio
- Higher moments
- Double ratio method
An experimentalist's interpretation: fitting parameterizations of the Collins function(s)

- Take unpolarized parameterizations (Kretzer at $Q^2=2.5\text{GeV}^2$)

- Assume

$$H_{1,fav}^\perp = a z^b (1 - z)^c$$

(PDF-like behaviour)

- Assume

$$H_{1,unfav}^\perp / H_{1,fav}^\perp = -0.1$$

- Sensitivity studies in progress
Summary:

- Observation of large azimuthal asymmetries in light quark fragmentation
  - first measurement of the Collins effect!

- Fundamental interesting + urgently awaited input for the transverse spin physics programs at RHIC but also DESY, CERN and JLab

Outlook:

- (Much) more spin dependent FFs:
  - interference fragmentation
  - Collins FF for VMs
  - Lambdas

- Precision measurement of spin averaged fragmentation functions as input to RHIC program to extract the gluon polarization through $A_{LL}$ measurements in inclusive hadron production

(see appended slides)
Global Picture: Test Transverse Spin Sum Rule and Fundamental Tensor Charge

Transversity $\times$ Collins
Transversity $\times$ IFF
HERMES, COMPASS
JLAB, $e^{-}$ RHIC $e^{-}$ LHC

$e^+e^- \rightarrow$ Collins FF
Interference FF

PP
A$_8$ for inclusive hadrons, A$_{1+}$ in Jets
A$_{1+}$ in Jets: transversity $\times$ Collins
transversity $\times$ IFF
A$_{1+}$ Drell-Yan
transversity $\times$ transversity

BRAHMS, PHENIX, STAR, GSI

Theory

RBRC
Belle Fragmentation Functions as Input for: \( \Delta G \) from QCD Analysis of \( A_{LL} \) (incl. hadrons)

PHENIX \( \pi^0 \) cross section at \( |\eta| < 0.35 \)


**DIS**

- \( q(x, Q^2) \)
- \( \Delta q(x, Q^2) \)
- \( G(x, Q^2) \)

**e^+e^-**

- \( D^\pi_q(z, Q^2) \)
- \( D^\pi_g(z, Q^2) \)

**pQCD**

- \( \sigma^{p_s p_s}_{p_1 p_2} \)

**Deviation connected to uncertainties in FFs \( \rightarrow \) gluon FF!**

\[ A_{LL} \equiv \frac{d \Delta \sigma}{d \sigma} = \frac{d \sigma^{++} - d \sigma^{--}}{d \sigma^{++} + d \sigma^{--}} \]
Compelation of data available for the charged hadron FF

\[ z = \frac{E^h}{\sqrt{s}/2} \]

Belle: Charged h\(^{+/-}\), pions, kaons, protons

1% of data sample → work in progress

Precision at high z!
Toward Measuring the Internal Spin-Dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC

Douglas E. Fields
Toward Measuring the Internal Spin-Dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC

D.E. Fields

University of New Mexico/RBRC
• Measuring transverse momentum of jets
• Looking for a correlation of this measurement with spin direction
• Initial measurements in Run03
• Status of Run05
• Summary
Jet Transverse Momentum, $k_T$

- Back-to-back nature of jets is broken by initial state transverse momentum $k_T$

- Additionally, if one doesn't measure the jet, but rather the jet fragments (say, the leading particle and correlated particles), the back-to-back nature of these fragments is also broken by the jet fragmentation transverse momentum $j_T$
Sources of $k_T$

Intrinsic $k_T \approx 200$ MeV/c

(b) $< k_T >_{h-q} \neq 0$

Breaks collinear factorization

Soft QCD radiation.

An example - $J/\psi$ production.

$h_A$

$g$

$J/\psi$

$h_E$

Extra gluon kick

$\langle p_T \rangle_{J/\psi} = 1.8 \pm 0.23 \pm 0.16$ GeV/c

One can consider the possibility that spin-correlated transverse momentum (orbital angular momentum) may contribute to jet $k_T$.

**k\textsubscript{T} Measurement in PHENIX**

\[ C_{ij}(\Delta \phi) = \text{norm} \cdot \frac{dN_{\text{real},ij}}{d\Delta \phi_{ij}} / \frac{dN_{\text{mixed},ij}}{d\Delta \phi_{ij}} \]

Intra-jet pairs angular width: \( \sigma_N \rightarrow \langle j_T \rangle \)
Inter-jet pairs angular width: \( \sigma_F \rightarrow \langle j_T \rangle \oplus \langle k_T \rangle \)

\[ p+p \sqrt{s} = 200 \text{ GeV} \quad 1.5<p_T<2.0 \]

Fit = const + Gauss(0) + Gauss(\pm\pi)
Spin Sorted Analysis

- Do exactly the same analysis sorted on same and opposite helicity bunch crossings, extract $\langle z_{k+} \rangle_{RMS}$ and look at the difference.

Oct. 10, 2005

D.E. Fields - UNM/RBRC
Run03 data is binned into two bins in trigger particle ($\pi^0$) $p_T$:
- $1\text{ GeV/c}^2 < p_T < 3\text{ GeV/c}^2$
- $3\text{ GeV/c}^2 < p_T < 5\text{ GeV/c}^2$

\[ \sqrt{\left\langle j_T^2 \right\rangle} = \left\langle p_{\text{assoc}} \right\rangle \sin \sigma_N \]

\[ \sqrt{\left\langle z^2 \right\rangle \left\langle k_T^2 \right\rangle} \propto \frac{1}{x_h} \sqrt{\left\langle p_{\text{out}}^2 \right\rangle - \left\langle j_T^2 \right\rangle (1 + x_h^2)} \]

\[ p_{\text{out}} \propto p_{\text{assoc}} \sin \sigma_A \]

\[ x_h = \frac{p_{\text{assoc}}}{p_{\text{trigg}}} \]

Oct. 10, 2005

D.E. Fields - UNM/RBRC
We must check the uncertainties to make sure there are no systematic errors.
- Bunch shuffling
Helicity assignments are randomized, and then the $k_T$ difference calculated for each randomized set.

The width of the distribution for all the randomized sets should be the same as our statistical errors on the previous plot.
Run05 has $\sim x10$ statistics, so that the uncertainty goes from $\pm 75\text{MeV}$ to $\pm 24\text{MeV}$ in the $3.0 < p_{T\uparrow} < 5.0\text{Gev/c}$ bin.

- It has $\sim x2$ in polarization, so the effect grows by $\sim x4$.

- NanoDSTs are produced, analysis should be done in $\sim 2$ months.
We have an analysis tool that allows us to measure initial state average transverse momentum of jets.

We are studying this effect in longitudinal spin-sorted collisions to see if there is a spin-dependent coherent transverse momentum.

Is there a connection to parton OAM? Theoretical guidance needed!

Run05 is under analysis.
CCJ - Status and Progress

Yasushi Watanabe
CCJ - status and progress -

Y. Watanabe
RIKEN/RBRC

Presented on October 10 2005 at RBRC review
RIKEN CCJ : Overview

♦ Scope
  - Center for the analysis of RHIC Spin Physics
  - Principal remote site of computing for PHENIX reconstruction
  - Regional Asia computing center

♦ Size
  - CPU performance : 508 Pentium III/4 CPU (Total: 1,111 GHz)
  - Disk Storage : 50 TB
  - Tape Storage: ~800 TB ( = 4,000 tapes, expandable to 1.1 PB)
    - Maximum transfer rate: 240 MB/s (30 MB/s/drive x 8 tape drives)
CCJ growing history

CPU power reached to ζ times

- CCJÅ252 CPU & RSCC pc2c 256 CPU
The RSCC

RIKEN Super Combined Cluster

29th in TOP500
8.7 Tflops
(Jun05)
No.1: 137 Tflops

CPU: Pentium Xeon 3.06GHz X 2
Memory: 4GB or 2GB
HDD: 148 GB
Network: Gigabit Ethernet
Interconnect: Infiniband (8GBps) or Myrinet (20GBps)
Express 8Gbps/420Mps

CPU: Pentium Xeon 3.06GHz X 2
Memory: 2GB
HDD: 75 GB x 2
Network: Gigabit Ethernet
Interconnect: Infiniband (8GBps)

MDGRAPE-2 Board
Special Gigabit Switch Using AXEL Chip
144 GbE ports
High Performance Storage System
Tape Library System
HPC Portal

URL: http://accs.riken.jp
Contact us: hpc@riken.jp
Current configuration of CCJ

CCJ Area

- CPU Farms: 252 CPUs, total 335 GHz
  - 22: Process III (760 MHz)
  - 26: Process III (952 MHz)
  - 46: Process III (650 MHz)
  - 22: Process III (470 MHz)
  - 36: Process IV (650 MHz)

- Network Switches

- Disks for CCJ: 50 TB

- Vector CPU (SX-7/32)
  - CPU: 32
  - Mem: 256 GB
  - 283 GFlops

RSOC Area

- CPU Farm: 256 CPUs, total 776 GHz
- 800 TB
- Full 1.2 PB
- 240 MB/s

- Network Switches

- RSCC CPU Farms
  - Total 6,206 GHz
  - = 12.4 TFlops (peak)
A slide shown in last year

- Going to decide with PHENIX to produce official DST of Run5 pp data at CCJ
  - Because shortage of CPU power at RCF/PHENIX

- Data transfer challenge
  - Estimated pp data volume of Run5: 300~500 TB
    - 60~100 MB/s needs to be sustained for 8 weeks
  - Network transfer: primary option
    - Going to develop
  - Tape transfer: secondary option
    - Already confirmed method
Data transfer challenge
Growth of data stored in the CCJ-HPSS
PHENIX experiment uses Grid to transfer 270 TB of data to Japan

- This seems to be the first time that a data transfer of such magnitude was sustained over many weeks in actual production

http://www.cerncourier.com/main/article/45/7/15
Members of data transfer

- PHENIX
  - M. Chiu, H. Hiejima, M. Purschke, D. Morrison, Shift Crews

- RCF
  - T. Throwe, R. Popescu, S. Misawa, J. Riordan, Y. Dantong

- CCJ
  - T. Ichihara, S. Yokkaichi, A. Kiyomichi, S. Kametani, Y. Watanabe

- ...many advisers
Raw data transfer of Run6?

- How much it is?
  - Run5pp ~260 TB: Run6 > 500 TB (= 2,500 tapes)
    - The CCJ-HPSS (silo) will overflow...
  - Three options
    - Introduce newly developed drives (500 GB / cartridge?)
      - Present drive: 200 GB / cartridge
    - Borrow (or invade into) another silo (still empty)
    - Take out cartridges of past run's.

- Network bottleneck
  - 1 Gbps (U. Tokyo – RIKEN) needs to be upgraded
    - Requesting
Analysis for the PHENIX experiment with CCJ in the year

- **Official productions and simulations**
  - Run5 pp data transfer and production at CCJ

- **Major analysis projects**
  - Run2-pp vernier scan analysis - Y. Goto
  - Transferring full set of run3 nanoDST to CCJ - M. Kaneta
  - Simulation of Photonic Electron in the PHENIX Run3 d+Au Experiment - F. Kajihara
  - Transfer of nanoDST's from 2nd production for 62.4GeV Au+Au - M. Kaneta
  - PYTHIA-PISA with run3 environment - K. Okada
  - run3 200 GeV d+Au nanoDST's copy from RCF to CCJ - M. Kaneta
  - pi0 Simulation of Photonic Electron in the PHENIX Run4 Au+Au Experiment - F. Kajihara
  - Run4 200GeV Au+Au Stripe-2 CNT and PWG nanoDST's copy from RCF to CCJ - T. Isobe
  - Run4 200GeV Au+Au compact EWG nanoDST's copy from RCF to CCJ - F. Kajihara
  - Study of hadron production at RHIC-PHENIX run4/5 - M. Oka
  - Estimate blocking effect of single electron by materials using PISA for run3pp - M. Togawa
  - Generate run5 pDST for analyzing local pol data - M. Togawa
  - Analysis of Jet Production A_LL - K. Nakano
A Silicon Vertex Tracker for PHENIX

Atsushi Taketani
A Silicon Vertex Tracker for PHENIX

Atsushi Taketani

1. Physics goal
2. Structure of detector
3. Status and plan
4. Expected performance
5. Summary
PHENIX Vertex Group (86 Participants from 15 institutions)

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Z. Li
Brookhaven National Laboratory, Instrumentation Division
Brookhaven National Laboratory, Physics Department
A.D. Frawley
Florida State University
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S. Skulnik, G. Sleege, G. Tuttle
Iowa State University, Ames,
M. Tanaka
KEK

RIKEN/RBRC
+ supported people

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Los Alamos National Laboratory
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Niigata University
T.C. Awes, M. Bobrek, C.L. Britton, W.L. Bryan, K.N. Castleberry, V. Cianciolo, Y.V. Efremenko,
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O. Drapier, F. Fleuret, M. Gonin, R. G. de Cassagnac, A. Romana E. Tujuba
Eole Polytechnique
K. Kruita, Y. Inoue
Rikkyo University
Physics Goals

Open up new horizon!

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

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.
Physics Goal

Heavy Ion Program

Spin Program

- Charm and bottom identification by displaced vertex
- Jet identification with larger acceptance
Within a constant level of effort budget, the Subcommittee recommends that certain essential investments be made. These include:

- Construction of the PHENIX Silicon Vertex Tracker and the STAR Time-of-Flight Barrel;
- Participation in the LHC Heavy-Ion program;
- Investment in RHIC accelerator and detector R&D;
- Construction of the EBIS;
- Support at the present level for university and national laboratory research;
- Provision for RHIC running time sufficient to preserve the integrity of the Heavy-Ion and Spin Physics programs.
Current PHENIX
Pioneering High Energy Nuclear Interaction Experiment

PHENIX Detector
1. Central Arm
   - Charged Hadrons detection
     \[ |h| < 0.35, \text{Df} = p \]

2. Muon Arm
   - Muon detection
     \[ 1.2 < |h| < 2.4, 2p \text{ in } f \]

3. Forward detectors
   - Luminosity Monitoring
   - Centrality
   - Local polarimetry

- Good particle identification (But no direct b/c identification)
- High Rate and High Detector granularity.
- Limited geometrical coverage (Not \(2\pi \) in central region)
Requirements for Vertex Tracker

**Physics side**

- High precision tracking for displaced vertex measurement. 40μm displaced vertex resolution, ct ~ 100μm(D), ~400μm(B)
- Large coverage tracking capability with momentum resolution (|η|<1.2, and full azimuthally with σ/P ~ 5%P)
- High charged particle density ‘dN/dη’ ~ 700 @η=0
- High Radiation Dose ~100KRad@10Years
- High Luminosity $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ @PP -> High rate readout
- Low Material Budget <- avoid multiple scattering and photon conversion for electron measurement by outer detectors.
Structure

- Barrel region
  - $|\eta| < 1.2$, almost $2\pi$ in $\phi$
  - Pixel sensor at inner 2 layers
  - Strip sensors at outer 2 layers

- Forward region
  - $1.2 < |\eta| < 2.7$, 2p in $\phi$
  - 4 layers of mini strip
    - (50 x 2000 to 11000 $\mu$m)
  - Trigger capable

R = 10 and 14

R = 2.5 and 5cm
PIXEL (Sensor and Readout)

Pixel size ($\phi \times z$)  50 $\mu$m x 425 $\mu$m  
Sensor Thickness  200um  
$\Delta r\phi = 1.36$cm, $\Delta z = 1.28$ cm  
256 x 32 = 8192 channel / sensor  
4 sensor / chip  
4 chip / ladder.

Readout by ALICE_LHCB1 chip

- Amp + Discriminator / channel
- Bump bonded( 2 dim. Soldering) to each pixel
- Running 10MHz clock ( RHIC 106nsec )
- Digital buffer for each channel > 4usec depth
- Trigger capability > FAST OR logic for each crossing

Used at NA60 (Rad hard)
PIXEL readout

Al-Kapton Bus readout to minimize material (120micron pitch)

Ground

Silicon Pixel Sensor

Read out chip

Bump bonding

200um

400um
PIXEL readout

4x parallel readout

LICE chip is 32bit input/40MHz x 16bit output

Ver.1 is running.

Ver.2 will come in Summer

PHENIX Digital Pilot
Sensor elements:

Two strip-pixel arrays on a single-sided wafer of 500 µm thickness, with 384 + 384 channels on 3 x 3 cm² area.

Position resolution is 25µm by test beam

Developed at BNL Instrumentation Gr.

✓ Single sided
✓ 1+1 dimensional readout (X and U direction)
✓ 3cm x 3cm sensor ξ2 / chip
✓ 768 X strip and 768 U strips/chip
Strip Readout

SVX4 Readout chip

- Developed by FNAL for TEVATRON RUN2b (Rad hard)
- 8 bit ADC for each channel
- 128 channel per chip

Readout Test board (Testing now)

- 3 SVX Chip
- Packing factor is same
- Control by onboard FPGA
Schedule and status

- Pixel Readout test End of 2005
- Strip Readout test Fall of 2005
- Structure design study Start now
- Prototype ladder Early 2006
- Production (Japan) Start in 2005
- Production (US) 2007
- Installation complete 2009
  (Possible early partial implementation)

- Total cost ~8M US$ (Japan, US, France)
# Expected Performance

Expected occupancy at Au-Au 200GeV most central event

<table>
<thead>
<tr>
<th>Layer</th>
<th>radius</th>
<th>Sensor</th>
<th>Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>2.5 cm</td>
<td>Pixel</td>
<td>0.53%</td>
</tr>
<tr>
<td>Layer 2</td>
<td>5.0 cm</td>
<td>Pixel</td>
<td>0.16%</td>
</tr>
<tr>
<td>Layer 3</td>
<td>10.0 cm</td>
<td>Strip</td>
<td>4.5% (x-strip)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.7% (u-strip)</td>
</tr>
<tr>
<td>Layer 4</td>
<td>14.0 cm</td>
<td>Strip</td>
<td>2.5% (x-strip)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.7% (u-strip)</td>
</tr>
</tbody>
</table>

Chi2 < 1.0

Collision Vertex

Distance to the Closest Approach [cm]
Spin performance
parton X reconstruction by $\gamma + \text{Jet}$

Using only Photon information

Photon + 2$\pi$ VTX tracker

Great improvement with VTX
Summary

- PHENIX Silicon Vertex Tracker will open new physics horizon for both Heavy Ion and Spin program of RHIC.
- There are two of inner pixel layers, two of outer strip layers and forward mini-strips
- Hardware R&D work is on going.
- Plans underway for early partial implementation.
PHENIX Muon Trigger Upgrade

Wie Xie
PHENIX Muon Trigger Upgrade

W. Xie (RBRC)
**PHYSICS Motivation:** Spin Dependent Quark and Anti-Quark Distributions

\[ u(x) \approx \bar{d}(x) \]

Drell-Yan Process:

\[
\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right]
\]

Oct. 2005

RBRC Scientific Program Review 2
**PHYSICS Motivation:** Spin Dependent Quark and Anti-Quark Distributions

**Question:** \[ \Delta \bar{u}(x_1) = \Delta \bar{d}(x_2) \ ?? \]

![Diagram](image)

\[ A_L(W^+) = \frac{\Delta \bar{u}(x_a)}{u(x_a)} , \quad x_a >> x_b \]

\[ A_L(W^+) = -\frac{\Delta \bar{d}(x_b)}{\bar{d}(x_b)} , \quad x_b >> x_a \]

**Direct measurement of quark/antiquark spin:**

\[ A_L^W = \frac{1}{p} \times \frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)d(x_2) + \bar{d}(x_1)u(x_2)} \]

Oct. 2005

RBRC Scientific Program Review
PHYSICS Motivation: Spin Dependent Quark and Anti-Quark Distributions

Inclusive $\mu$ Production, 500 GeV/c

Accurate Measurement of Quark/Antiquark spin

Oct. 2005

RBRC Scientific Program Review
Major Problem to be Solved first: Muon Trigger Upgrade

- Collision rates in 500GeV run: ~12MHz.

- PHENIX DAQ bandwidth: 5KHz (can go up to 12kHz)

- Bandwidth assignment for muon trigger: 1kHz.

- Need trigger rejection factor = \( \frac{\text{Collision Rate}}{\text{Trigger Rate}} = \frac{12 \text{MHz}}{1 \text{kHz}} \approx 10^4 \)

- Current muon level-1 trigger rate: ~30kHz.

- Need additional rejection of 30
PHENIX Muon Arms

Muon Tracker Chamber
Station#1, station#2, station#3

Nosecone+Central Magnet

MuID Road:
MuID LL1 Trigger.
Rate: ~30kHz

P>2.5GeV

Gap#1, Gap#2, Gap#3, Gap#4, Gap#5

Muon Identifier Chambers (MuID)

Oct. 2005
RBRC Scientific Program Review
Muon Trigger Upgrade Plan

Muon Tracker Chamber
Station#1, station#2, station#3

RPC 2
Steel
RPC 3

P>2.5GeV

MuID Road:
MuID LL1 Trigger
Rate: ~30kHz

Gap#1, Gap#2, Gap#3, Gap#4, Gap#5

Muon Identifier Chambers (MuID)

Oct. 2005
RBRC Scientific Program Review
Muon Trigger Upgrade Plan

MuID Road match RPC hits X momentum cut from RPC = Trigger Upgrade

(Look up Table)

\[ \delta(\phi) = \text{angle I} - \text{angle II}: \text{momentum cut} \]

<table>
<thead>
<tr>
<th>( \delta(\phi) ) deg</th>
<th>&lt;0.7</th>
<th>&lt;1.0</th>
<th>&lt;2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt (GeV)</td>
<td>10.0</td>
<td>7.0</td>
<td>3.5</td>
</tr>
<tr>
<td>rejection</td>
<td>36000</td>
<td>19980</td>
<td>10090</td>
</tr>
</tbody>
</table>

Oct. 2005

RBRC Scientific Program Review
Muon Trigger Upgrade Plan

\[
\text{efficiency} = \frac{\text{accepted signal}}{\text{total input signal}}
\]

Very Efficient for High pT Muons
Trigger Chamber Technology: Resistive Plate Chamber

The chamber structure:
- **Gap:** 2 mm
- **HV electrodes:** 100 μm graphite
- **Gas pressure:** ~ 1 Atm
- **Gas mixture:** ~ 95% F134a, ~ 4.5% Iso-Butane, 0.5% SF6
- **Bakelite resistivity:** $10^{10} - 10^{12} \ \Omega \text{cm}$

$\Rightarrow$ 2–3 kHz/cm² in avalanche mode!

Oct. 2005

RBRC Scientific Program Review
R&D effort: RPC test during RUN5

Y. Mao et al., PKU university

Oct. 2005
RPCs

avalanche mode signal

streamer mode signal
NSF Proposal Has been Approved!

University of Colorado
Frank Ellinghaus, Ed Kinney, Jamie Nagle, Joseph Seele, Matt Wysocki

University of California at Riverside
Ken Barish, Stefan Bathe, Tim Hester, Xinhua Li, Astrid Morreale, Richard Seto, Alexander Solin

University of Illinois at Urbana Champaign

Iowa State University
John Lajoie, John Hill, Gary Sleege

Kyoto University
Kazuya Aoki, Ken-ichi Imai, Naohito Saito, Kohei Shoji

Columbia University
Cheng Yi Chi, William Zajc

RBRC
Gerry Bunce, Wei Xie

Abilene Christian University
Rusty Towell, Larry Isenhower

Peking University
Yajun Mao, Ran Han, Hongxue Ye, Hongtao Liu

Oct. 2005

RBRC Scientific Program Review
Project Schedule

• R&D from 2005-2007

• build RPC for half of the south muon spectrometer by September 2007, install for the run in winter 2007 and 2008.

• build remaining modules for both spectrometers by September 2008

• complete mechanical integration of RPCs into PHENIX by January 2009.
Parallel Project: Muon Tracker Trigger

<table>
<thead>
<tr>
<th>Sagitta&lt;= 1 strip</th>
<th>Sagitta&lt;= 2 strips</th>
<th>Sagitta&lt;= 3 strips</th>
</tr>
</thead>
<tbody>
<tr>
<td>23700</td>
<td>10900</td>
<td>7180</td>
</tr>
</tbody>
</table>

Enough rejection power with good efficiency for high pT muons

Oct. 2005

RBRC Scientific Program Review
CURRICULA VITAE

SUMMARY
CURRICULA VITAE - SUMMARY
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.

Junkichi Asai
Birthplace: Kyoto, Japan       DOB: January 8, 1976
Doctor of Sciences: 2004, University of Tokyo, Japan

Steffen A. Bass
Birthplace: Frankfurt, Germany       DOB: May 17, 1968
Ph.D. 1997, J. W. Goethe Universitat Frankfurt, Germany
Experience: Feodor Lynen Fellow and Research Associate, Duke University, 1998-99
Visiting Assistant Professor, Michigan State University, 1999
*RHIC Physics Fellow/Assistant Professor--RBRC/Duke, September 1, 2000 – August 31, 2005.
BNL/RBRC Research Collaborator, September 2000 – present.

Awards and Honors: W. E. -Heraeus-Award, W.E.-Heraeus Foundation, Germany, 1993
Feodor-Lynen Fellow, A. v. Humboldt Foundation, Germany, 1997
U.S. Department of Energy Division of Nuclear Physics Outstanding Junior Investigator Award, 2003.
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.  
**Awards and Honors:**  
DOE-GANN Fellowship: August 1990 - May 1993;  
Year 2005 Department of Energy Outstanding Junior Investigator Award,  
High Energy Physics.

Christopher Dawson  
**Birthplace:** Preston, Lancashire, UK  
**DOB:** July 6, 1973  
**Ph.D.**  
1998, University of Southampton, UK  
**Experience:**  
Research Associate, High Energy Theory Group, BNL  
RIKEN BNL Fellow, October 1, 2001 – present  

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.

Takumi Doi  
**Birthplace:** Hiroshima, Japan  
**DOB:** November 16, 1976  
**Ph.D.**  
2004, Tokyo Institute of Technology, Japan  
**Experience:**  
Fellowships: The Japan Scholarship Foundation, Department of Physics, Tokyo  
Institute of Technology, 1999-2001, JSPS Research Fellowships for Young  
Scientists, Department of Physics, Tokyo Institute of Technology, 2001-2004;  
RIKEN Spin Program Research Associate, RBRC, April 1, 2004 – present.  
**Awards and Honors:**  
Fellowships: JSPS Fellowship, The Iwakuni Foundation for Scholarship,  
Tokyo University, 1995-1999; Awards: The Tejima Memorial Research Award for  
Ph.D. Thesis.

Douglas Fields  
**Birthplace:** U.S.A.  
**DOB:** July 2, 1963  
**Ph.D.**  
1991, Indiana University, Bloomington  
**Experience:**  
Postdoctoral Research Associate, Los Alamos National Laboratory, 1992-1995  
Research Associate Professor, University of New Mexico, 1995-2001  
Member of the PHENIX Collaboration, BNL, 1995-present  
•RHIC Physics Fellow/Assistant Professor—RBRC-E, University of New Mexico,  
September 1, 2001 – present.
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.

---

Kenji Fukushima  
**Birthplace:** Tokyo, Japan  
**DOB:** January 29, 1975

**Ph.D.**  
2002, University of Tokyo, Komaba  

**Experience:**  
Research Fellow of the Japan Society for the Promotion of Science (JSPS),  
University of Tokyo, Japan, April 1999 to August 2003; Visiting Scientist,  
Massachusetts Institute of Technology, Department of Physics, September 2003 -  
March 2005; RSP Research Associate, RBRC Theory Group, April 2005 - present.

**Awards and Honors:** JSPS Fellowship

---

Dominik Gabbert  
**Birthplace:** Krefeld, Germany  
**DOB:** June 26, 1979

**Vordiplom**  
2001, Student at Technical University, Munich, Germany for Master Thesis;  
Visiting Scholar at U. of Illinois, Urbana-Champaign.

**Experience:**  
RBRC Young Researcher, RBRC Experimental Group, January 2004 – 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.

---

Matthias Grosse-Perdekamp  
**Birthplace:** Schwenningen, Germany  
**DOB:** December 1, 1963

**Ph.D.**  
1995, University of California at Los Angeles  

**Experience:**  
Associate Research Scientist, Yale University 1995-1998  
Research Scientist, Mainz University, 1998-1999  
RIKEN BNL Fellow, January 1999 – August 31, 2002.  
Member of the PHENIX and BELLE Collaborations;  
• RHIC Physics Fellow/Assistant Professor—RBRC-E; University of Illinois,  
Urbana Champaign, September 1, 2002 – present.  
Deputy Spokesperson for PHENIX, 2004 – present.  

**Awards and Honors:** Foreign Scholar Award, UCLA, 1990; Gustav Mie Preis, Freiburg  
University, 1991.

---

Koichi Hashimoto  
**Birthplace:** Fukui, Japan  
**DOB:** December 20, 1979

**M.Sci.**  
2003, Kanazawa University  

**Experience:**  
Visiting Student, RBRC, September-October 2003.  
RIKEN Spin Program Young Researcher, RBRC Theory Group,  
Yoshitaka Hatta
Birthplace: Kyoto, Japan
DOB: August 5, 1976
Ph.D. 2004, Kyoto University, Department of Physics
RIKEN Junior Research Associate (Theory), 2002 - 2004.
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2004 – present.

Tetsufumi Hirano
Birthplace: Kanagawa, Japan
DOB: September 17, 1972
Ph.D. 2001, Waseda University, Japan
Experience: Research Associate, Waseda University, Japan, April 1999 to March 2001
Postdoctoral Fellow at University of Tokyo, Japan, April 2001 to March 2003.
RIKEN Spin Program Research Associate, RBRC Theory Group,
Visiting Scientist RBRC/Columbia University, September 1, 2004 – present.
Awards and Honors: JPS Theory Award for Distinguished Young Researchers in Nuclear Physics (2002).

Takuma Horaguchi
Birthplace: Iwate, Japan
DOB: September 29, 1977
Graduate School: Tokyo University of Science, Japan
RIKEN Junior Research Associate (Experiment), April 1, 2003 – present.

Takashi Ichihara
Birthplace: Japan
DOB: February 22, 1958
Ph.D. 1987, Kyoto University, Japan
Experience: Research Scientist, RIKEN, Japan, 1987-1995
Senior Research Scientist, RIKEN, Japan, 1995-1998
Assistant Chief Scientist, RIKEN, Japan, 1998
Researcher, RBRC Experimental Group, 1998
RIKEN Spin Program Researcher, November 1999- present

Kei Iida
Birthplace: Aomori, Japan
DOB: July 28, 1970
Ph.D. 1998, University of Tokyo
Experience: Postdoctoral Research Fellow, JSPS, U. of Tokyo, April 1998– March 2001;
Visiting Postdoctoral Research Associate, U. of Illinois at Urbana-Champaign, September 1999-March 2001.
RIKEN Fellow, RBRC Theory Group, April 2004-present.
RIKEN Special Postdoctoral Grant, April 2001-2004.

Takashi Ikeda
Birthplace: Saitama, Japan
DOB: December 2, 1973
Ph.D. 2002, University of Tokyo, Japan
Experience: Special Postdoctoral Researcher, RIKEN;

574
Taku Izubuchi  
**Birthplace:** Tokyo, Japan  
**DOB:** February 15, 1970  
**Ph.D.**  
University of Tokyo  
**Experience:**  
Postdoc, Tsukuba University, April 1997-November 1999.  
Research Associate (with tenure), Department of Physics, Kanazawa University, December 1999 – February 2001  
Brookhaven National Laboratory, High Energy Theory Group, March 2001 – February 2003  
Research Associate (with tenure), Department of Physics, Kanazawa University, March 2003 – present.  
*RBRC Visiting Fellow with Kanazawa University, April 1, 2003 – present.  
**Awards and Honors:**  

Sangyong Jeon  
**Birthplace:** Pusan, Korea  
**DOB:** March 7, 1964  
**Ph.D.**  
University of Washington, Seattle  
**Experience:**  
Postdoctoral Research, University of Washington, Particle Theory Group, February 1995 to June 1995  
Postdoctoral Research, University of Minnesota, Nuclear Theory Group, August 1995 to September 1998  
Postdoctoral Research, Lawrence Berkeley National Laboratory, Nuclear Science Division, October 1998-December 31, 2000  
*RHIC Physics Fellow/Assistant Professor--RBRC/McGill, January 2001 - present  
**Awards and Honors:** Tuition Scholarship, Seoul National University, 1983-1984  
Baumgartner Fellowship, University of Washington, 1987-1989  
Weis Prize, University of Washington, 1990; Polish Ministry of National Education Award for Outstanding Team Research, 2003.

Osamu Jinnouchi  
**Birthplace:** Saga, Japan  
**DOB:** June 13, 1972  
**Ph.D.**  
University of Tokyo  
**Experience:**  
Research Fellow of the Japan Society for the Promotion of Science, January 1999 to March 2001  
Research Associate, RBRC Experimental Group, April 1, 2003 – Feb. 28, 2005.

Nobuyuki Kamihara  
**Birthplace:** Yokohama, Japan  
**DOB:** June 29, 1974  
**M.Sc.**  
2002, Master Course of Fundamental Physics, Tokyo Institute of Technology  
**Experience:**  
Graduate student at Tokyo Institute of Technology/Student Trainee at RIKEN, 2002 - present  
RIKEN Spin Program Research Associate, RBRC-Experiment, effective September 2005.
Masashi Kaneta  
**Birthplace:** Hiroshima, Japan  
**DOB:** November 5, 1971

**Ph.D.**  
1999, Hiroshima University, Japan

**Experience:**  
Member of NA44 Experiment at CERN, 1994-present  
Member of Beam-Beam Counter (BBC) Group for PHENIX Experiment, 1994-1999; Member of TOF Detector Group in PHENIX Experiment at RHIC, 1999; Member of STAR Experiment at RHIC, 1999-present;  
Postdoctoral Fellow at KEK, 1999; Postdoctoral Fellow Physicist at  
Member of STAR Experiment at RHIC, 1999-2003;  

---

David M. Kawall  
**Birthplace:** Glasgow, UK  
**DOB:** April 13, 1965

**Ph.D.**  
1996, Stanford University

**Experience:**  
Associate Research Scientist, Yale University, Physics Department, 1995-2004.  
RIKEN BNL Fellow, RBRC Experimental Group, June 1, 2004 – January 2005.  
•RHIC Physics Fellow, RBRC Experimental Group/Assistant Professor,  
University of Massachusetts, Amherst, January 2005 - present

**Awards and Honors:**  
G. David Scott Scholarship in Physics, Trinity College Scholarship, Faculty Scholar, Varsity Fund National Admission Scholarship, William R. Hossack Memorial Scholarship in Mathematics and Physics

---

Stefan A. Kretzer  
**Birthplace:** Dortmund, Germany  
**DOB:** November 26, 1968

**Ph.D.**  
1999, University of Dortmund

**Experience:**  
Visiting Research Associate at Michigan State University, 2000-2002  
Research Associate, Brookhaven National Laboratory, October 2002 – present;  
Research Associate, Joint RBRC/Nuclear Theory Group, BNL, April 2003 present.

**Awards and Honors:**  

---

Kazuyoshi Kurita  
**Birthplace:** Tokyo, Japan  
**DOB:** August 11, 1963

**Ph.D.**  
1992, Columbia University, New York

**Experience:**  
June, 1991 Research Associate, Univ. of Tsukuba  
April 1994 Assistant Prof., Univ. of Tsukuba  
April 1997 Postdoctoral Researcher, RIKEN  
Oct. 1997 Special Postdoctoral Researcher, RIKEN  
RIKEN BNL Fellow, April 2000 – March 31, 2002;  

**Awards and Honors:**  
Educational Research Award, Tsukuba Gakuto Foundation, July 1992

---

576
Alexander Kusenko  
**Birthplace:** Simferopol, Ukraine  
**DOB:** March 17, 1966

**Ph.D.:** 1994, State University of New York, Stony Brook

**Experience:** Postdoctoral Researcher, University of Pennsylvania; CERN Fellow, Theory Division, CERN, Switzerland; Postdoctoral Researcher, UCLA  
- RHIC Physics Fellow/Assistant Professor (2003 Promoted to Associate Professor with tenure)—RBRC/UCLA, October 1999 – September 2004.  
- BNL/RBRC Research Collaborator, October 1999 – present.

**Awards and Honors:** Peter Kahn Fellowship, Sigma Xi Award for Excellence in Research, Sigma Xi Society Award, President's Award to a Distinguished Doctoral Candidate

Zheng Li  
**Birthplace:** China

**Ph.D.:** 1986, Pennsylvania State University, University Park

**Experience:** Physicist, Brookhaven National Laboratory, Instrumentation Division, November 1986 - present.  
- RIKEN Spin Program Visiting Scientist, Experimental Group, May 2003 to present

**Awards and Honors:** Davey Fellowship, 1981, The Pennsylvania State University; Award for Excellent Academic Performance, 1977-1981, Peking University; Visiting Professor, Beijing Institute of Semiconductors, 1998-present; Dual Professor, Xiangtan University, China, 1999-present; Science and Technology Award, Brookhaven National Laboratory, 2005.

Ágnes Mócsy  
**Birthplace:** Romania  
**DOB:** September 10, 1971

**Ph.D.:** 2001, University of Minnesota, Minneapolis

**Experience:** Adjunct/Post Doc, The Niels Bohr Institute, Copenhagen, Denmark, October 2001 to September 2003; Post Doc/Humboldt Research Fellow, Theoretical Physics Institute and Frankfurt Institute for Advanced Studies J. W. Goethe University, Frankfurt, Germany, October 2003 to September 2005; Research Associate, RBRC Theory Group, October 1, 2005 - present.

**Awards and Honors:** Merit Scholarship, Babes-Bolyai University, Cluj-Napoca, Romania, 1990-1994; Study Scholarship, Eötvös University, Budapest, Hungary, 1993; NORDPLUS Award Scholarship, The Niels Bohr Institute, Copenhagen, Denmark, 1995-1996; Louise T. Dosdall Fellowship, University of Minnesota, Minneapolis, 2000-2001; Alexander von Humboldt Research Fellowship, J. W. Goethe University, Frankfurt, Germany 2004-2005.

Dénès 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.  

Ken'ichi Nakano  
**Birthplace:** Hiroshima, Japan  
**DOB:** May 24, 1980  
**B.S.:** 2003, Tokyo Institute of Technology  
**Experience:** Master Course Student, Tokyo Institute of Technology  
- RIKEN Jr. Research Associate, April 1, 2005 - 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 - present.

Peter Petreczky  
**Birthplace:** Uzsgorod (Ungvar), Ukraine  
**DOB:** February 17, 1973  
**Ph.D.:** 1999, Eötvös University, Budapest, Hungary  
**Experience:**
- Research Fellow, Bielefeld University, Germany, 1999-2002  
- Goldhaber Fellow, Brookhaven National Laboratory, October 2002 - Sept. 2005;  
- RIKEN BNL Fellow, RBRC Theory Group joint with Nuclear Theory October 1, 2003 - September 30, 2005;  
- RIKEN BNL Fellow/Assistant Physicist joint with Lattice Gauge Group, October 1, 2005 to present.  
**Awards and Honors:** Goldhaber Fellowship, 2002.
Naohito Saito  
**Birthplace:** Aomori, Japan  
**DOB:** November 28, 1964  
**Ph.D.:** 1995, Kyoto University, Japan  
**Experience:**  
1993 July, Research Fellow, Kyoto University, Japan  
1995 April, RIKEN Special Post Doctoral Fellow  
RIKEN/RBRC Researcher, 1996 April to March 2001  
RIKEN Spin Program Researcher, April 1, 2001 – March 31, 2002;  
Visiting Scientist, Experimental Group, RBRC, with Kyoto University, Japan,  
Spring 2002 – present.  
**Awards and Honors:** Fellowship: Japan Society for the Promotion of Science, 1993-1995

Shoichi Sasaki  
**Birthplace:** Tokyo, Japan  
**DOB:** May 31, 1968  
**Ph.D.:** 1997, Osaka University, Japan  
**Experience:**  
Research Fellow of JSPS, Yukawa Inst. Theor. Physics, Kyoto U., Japan, April 1997 to August 31, 1998;  
RIKEN BNL Research Associate, September 1998 to September 30, 2000;  
Assistant Professor, University of Tokyo, October 2000 – present.  
**Awards and Honors:** Fellowship: Japan Society for the Promotion of Science, 1997-1998;  
JPS Best Paper Award from Japan Physical Society, 1999.  

Thomas M. Schaefer  
**Birthplace:** Hanau, Germany  
**DOB:** May 18, 1965  
**Ph.D.:** 1992, University of Regensburg  
**Experience:**  
Postdoctoral Research Associate, State University of New York at Stony Brook  
Postdoctoral Research Associate Institute for Nuclear Theory, University of Washington; Member Institute for Advanced Study, Princeton;  
• RHIC Physics Fellow/Assistant Professor--RBRC/ SUNY, Stony Brook, January 2000 – December 31, 2002.  
• RHIC Physics Fellow/Associate Professor (with Tenure)—RBRC/North Carolina State University January 1, 2003 – December 31, 2004;  
BNL/RBRC Research Collaborator, January 2002 - present  
**Awards and Honors:** Member, Studienstiftung des deutschen Volkes;  
Fellowship, German Academic Exchange Service  
Feodor Lynen Fellowship, Alexander v. Humboldt Foundation  
U.S. Department of Energy Division of Nuclear Physics Outstanding Junior Investigator Award, 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
Mikhail Stephanov  
**Birthplace:** Moscow, Russia  
**DOB:** April 19, 1966  
**Ph.D.** 1994, Oxford University, U.K.  
**Experience:**  
Postdoctoral Research Associate, U. of Illinois at Urbana-Champaign  
Postdoctoral Research Associate, ITP, SUNY at Stony Brook  
*RHIC Physics Fellow/Assistant Professor (2003 Promoted to Associate Professor with tenure). --RBRC/ University of Illinois at Chicago, October 1, 1999 to September 2004; BNL/RBRC Research Collaborator, October 1999 to present.  
**Awards and Honors:** Soros Scholarship, Overseas Graduate Scholarship from Jesus College, Oxford; U.S. Department of Energy Division of Nuclear Physics Outstanding Junior Investigator Award, 2001; Alfred P. Sloan Fellowship, 2002.

Takanori Sugihara  
**Birthplace:** Japan  
**DOB:** April 29, 1969  
**Ph.D.** 1997, Kyushu University  
**Experience:**  
Research Associate, RCNP, Osaka University, May 1997 – March 1999;  
JSPS Postdoctoral Fellow, Nagoya University, April 1999-March 2002  
Research Student, Nagoya University, April 2002 - September 2002;  
RIKEN Spin Program (RSP) Research Associate, RIKEN BNL Research Center (Theory Group), October 2002 – September 30, 2005.

Tsuguchika Tabaru  
**Birthplace:** Ehime, Japan  
**DOB:** July 31, 1971  
**Ph.D.** 2001, Kyoto University  
**Experience:**  
Research Fellow of the Japan Society for the Promotion of Science, April 1996 – March 1999;  
Contract Researcher of RIKEN, April 2001 – March 2002  
RIKEN Special Postdoctoral Researcher, RIKEN Spin Program (RSP) Research Associate, RIKEN BNL Research Center, Experimental Group, April 2003 – present.

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.

Kiyoshi Tanida  
**Birthplace:** Japan  
**DOB:** February 8, 1974  
**Ph.D.** 2000, University of Tokyo  
**Experience:**  
JSPS Special Research Fellow, University of Tokyo, January 2000 – March 2000;  
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Post-doctoral Researcher at the Institute for Theoretical Physics at State University of New York, Stony Brook, January 1999 to March 2000  
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671
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672
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