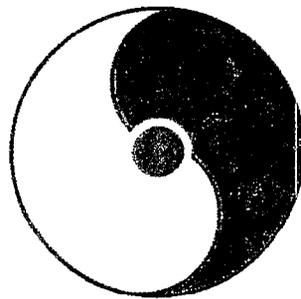


RBRC Scientific Review Committee Meeting

November 29-30, 2001



Organizers

T. D. Lee and 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.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are eight Fellows and seven Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program has increased to include ten theorists and one experimentalist in the current academic year, 2001-2002. Beginning this year there is a new RIKEN Spin Program at RBRC with four Researchers and three Research Associates.

In addition, the Center 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 thirty-eight proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998.

T. D. Lee
November 30, 2001

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

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Photographer: Hiro Horie

Graphic Design: Theresa A. Esposito, Information Services Division

Additional RIKEN BNL Research Center Proceedings Volumes

Contact Information

RBRC Scientific Review Committee Meeting

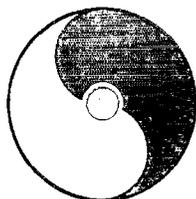
November 29-30, 2001

Brookhaven National Laboratory, Upton, NY 11973

The fourth evaluation of the RIKEN BNL Research Center (RBRC) took place on November 29-30, 2001, at Brookhaven National Laboratory. The members of the Scientific Review Committee were Dr. Jean-Paul Blaizot, Dr. Akira Masaike, Professor Tetsuo Matsui, Professor Claudio Rebbi, and Professor Jack Sandweiss, Committee Chair. In order to illustrate the breadth and scope of the program, each member of the Center made a presentation on his research efforts. In addition, a special presentation was given jointly by our collaborators, Professors Norman Christ and Robert Mawhinney of Columbia University, on the progress and status of the RBRC Supercomputer program. Although the main purpose of this review is a report to RIKEN Management (Dr. S. Kobayashi) 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. As such we have made this compilation and present it to the community for its information and enlightenment.

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

T. D. Lee & N. P. Samios



RIKEN BNL Research Center

Bldg. 510, Brookhaven National Laboratory, Upton, NY 11973, USA

**RBRC Scientific Review Committee Meeting
Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510, Open Sessions -- Large Seminar Room
November 29-30, 2001
Agenda**

Committee Members: Jean-Paul Blaizot, Akira Masaike, Tetsuo Matsui, Claudio Rebbi,
Jack Sandweiss, Chair

Thursday, November 29, 2001

8:00 AM to 9:00 AM *Review Committee Executive Session & Working Breakfast
(Summary Presentations by T.D. Lee and N.P. Samios) Room 2-160*

Large Seminar Room

9:00 AM to 11:00 AM EXPERIMENTAL PRESENTATIONS – GERRY BUNCE, CHAIR

- | | | |
|-------|---|---------------------------|
| 09:00 | Introduction of Experimental Group and Discussion | Hideto En'yo |
| 09:15 | Physics of RHIC Spin, RIKEN, and RBRC | Naohito Saito |
| 09:30 | PHENIX Triggers for Spin; New Belle Collaboration to Study Spin Dependent Fragmentation Functions | Matthias Grosse Perdekamp |
| 09:45 | Asymmetry Measurement of Charged Hadrons - First Look at the Gluon Polarization in 2001 | Yuji Goto |
| 10:00 | Electromagnetic Calorimeter: From Heavy Ion to Spin Physics | Alexander Bazilevsky |
| 10:15 | Hunting for Physics Beyond the Standard Model at RHIC with Parity Violation | Jiro Murata |
| 10:30 | Polarimetry for RHIC | Kazu Kurita |
| 10:45 | A New Local Polarimeter for RHIC and EIC | Abhay Deshpande |
| 11:00 | Break | |

11:15 AM to 12:30 PM EXPERIMENTAL PRESENTATIONS – HIDE TO EN'YO, CHAIR

- | | | |
|---------------------|--|---------------------|
| 11:15 | Normalization Trigger Counters for PHENIX | Brendan Fox |
| 11:30 | Muon Identifiers for PHENIX-Status | Atsushi Taketani |
| 11:45 | Muons at PHENIX; Measurement of the Hadronic Spin-Flip Amplitude in Proton-Carbon Elastic Scattering | Douglas Fields |
| 12:00 | Alignment Calibration of the South Muon Tracker in PHENIX | Hideyuki Kobayashi |
| 12:15 | The CC-J Computer Facility at RIKEN | Takashi Ichihara |
| 12:30 PM to 1:30 PM | <i>Executive Session - Working Lunch</i> | <i>(Room 2-160)</i> |

Thursday, November 29, 2001 (Continued)

Large Seminar Room

1:30 PM to 3:30 PM THEORY PRESENTATIONS – ANTHONY BALTZ, CHAIR

- | | | |
|------|---|------------------|
| 1:30 | Classical Computation of Gluons in Heavy Ion Collisions | Yasushi Nara |
| 1:45 | The Flow of Colored Glass in Heavy Ion Collisions | Raju Venugopalan |
| 2:00 | Partons and QCD in High-Energy Hadronic Collisions | Werner Vogelsang |
| 2:15 | Hadronic Probes of Quark Gluon Plasma | Sangyong Jeon |
| 2:30 | Dense and Baryon Rich QCD | Misha Stephanov |
| 2:45 | Gluons Out of Equilibrium | Dietrich Bödeker |
| 3:00 | Gluon Saturation from Small-x Evolution Equation | Kazunori Itakura |
| 3:15 | Renormalization Group Improvement of the Time Dependent
Ginzburg-Landau Equation at Finite Temperature | Yukio Nemoto |
| 3:30 | Break | |

4:00 PM to 5:30 PM THEORY PRESENTATIONS – SHIGEMI OHTA, CHAIR

- | | | |
|------|---|----------------|
| 4:00 | Domain Walls in High-Density QCD and in Atomic Bose-Einstein
Condensates | Dam Thanh Son |
| 4:15 | Chiral Properties of Domain Wall Fermions with Improved Gauge
Actions | Kostas Orginos |
| 4:30 | Hadron Spectrum for Quenched Domain-Wall Fermions
With an Improved Gauge Action | Yasumichi Aoki |
| 4:45 | Localization of Chirality for Domain Wall Fermion Eigenvectors | Chris Dawson |
| 5:00 | CP Violation in K Decay from Lattice QCD | Thomas Blum |
| 5:15 | Calculation of Non-Leptonic Kaon Decay Amplitudes from $K \rightarrow \pi$
Matrix Elements in Quenched Domain-Wall QCD | Junichi Noaki |

5:30 PM *Executive Session - (Room 2-160)*

7:00 PM Reception and Dinner (See Invitation)

Friday, November 30, 2001

8:00 AM to 8:30 AM

Executive Session and Continental Breakfast (Room 2-160)

Large Seminar Room

8:30 AM to 9:30 AM

QCDSB/QCDOC: Physics Results and Prospects/Project Status
Norman H. Christ and Robert Mawhinney

9:30 AM to 1:00 PM

Meetings with Individual RBRC Staff

Theorists (Room 2-160)

Host Liaison: Anthony Baltz

Experimentalists (Room 2-78)

Host Liaisons: Hideto En'yo and G. Bunce

1:00 PM to 2:00 PM

Executive Session and Lunch --(Room 2-160)

2:00 PM to 3:30 PM

Meetings with Individual RBRC Staff (Continued)
(Possible Tours)

3:30 PM to 5:00 PM

Executive Session -- (Room 2-160)

5:00 PM to 6:00 PM

Meeting with T. D. Lee and N. P. Samios --(Room 2-160)

6:00 PM

Adjourn

RBRC Scientific Review Committee Membership 2001

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RBRC Theory Group

T. D. Lee

T. D. Lee, RBRC Director
N. P. Samios, RBRC Deputy Director
Hideto En'yo, RBRC Associate Director

* * * *

RBRC Research Scientists (2000 – 2001)

Theory Group

T.D. Lee, Group Leader

Anthony Baltz, Deputy Group Leader

Research Associates

(Post Docs)

Aoki, Y.
Itakura, K.
Nara, Y.
Nemoto, Y.
Noaki, J.
Orginos, K.
Schaffner-Bielich, J.

Advisory Committee

Baltz, A.
Creutz, M.
Gyulassy, M.
McLerran, L.
Pisarski, R.

Fellows

Blum, T.
Dawson, C.
Vogelsang, W.

Consultants/

Visiting Scientists

Gyulassy, M.
Jaffe, R.
Shuryak, E.

Tenure Track/RHIC Fellows

Bass, S. (Duke)
Bödeker, D. (BNL)
Kusenko, A. (UCLA)
Jeon, S. (McGill)
Schaefer, T. (SUNY, SB)
Son, D. T. (Columbia)
Stephanov, M. (U. of IL, Chicago)
van Kolck, U. (Arizona)
Venugopalan, R. (BNL)
Wettig, T. (Yale)

Collaborators/

Associates

Mawhinney, R.
Ohta, S.

Computer Scientist

Dong, Z.

Boer, D. (Post Doc--left 6/27/01)

Rischke, D. (RHIC Fellow—left 1/31/01)

For '02 , RBRC Theory Group

Special post-doctoral fellow . (RIKEN)

(recommended and funded by RIKEN,
& approved by RBRC Theory Adv. Committee)

Takashi Ikeda

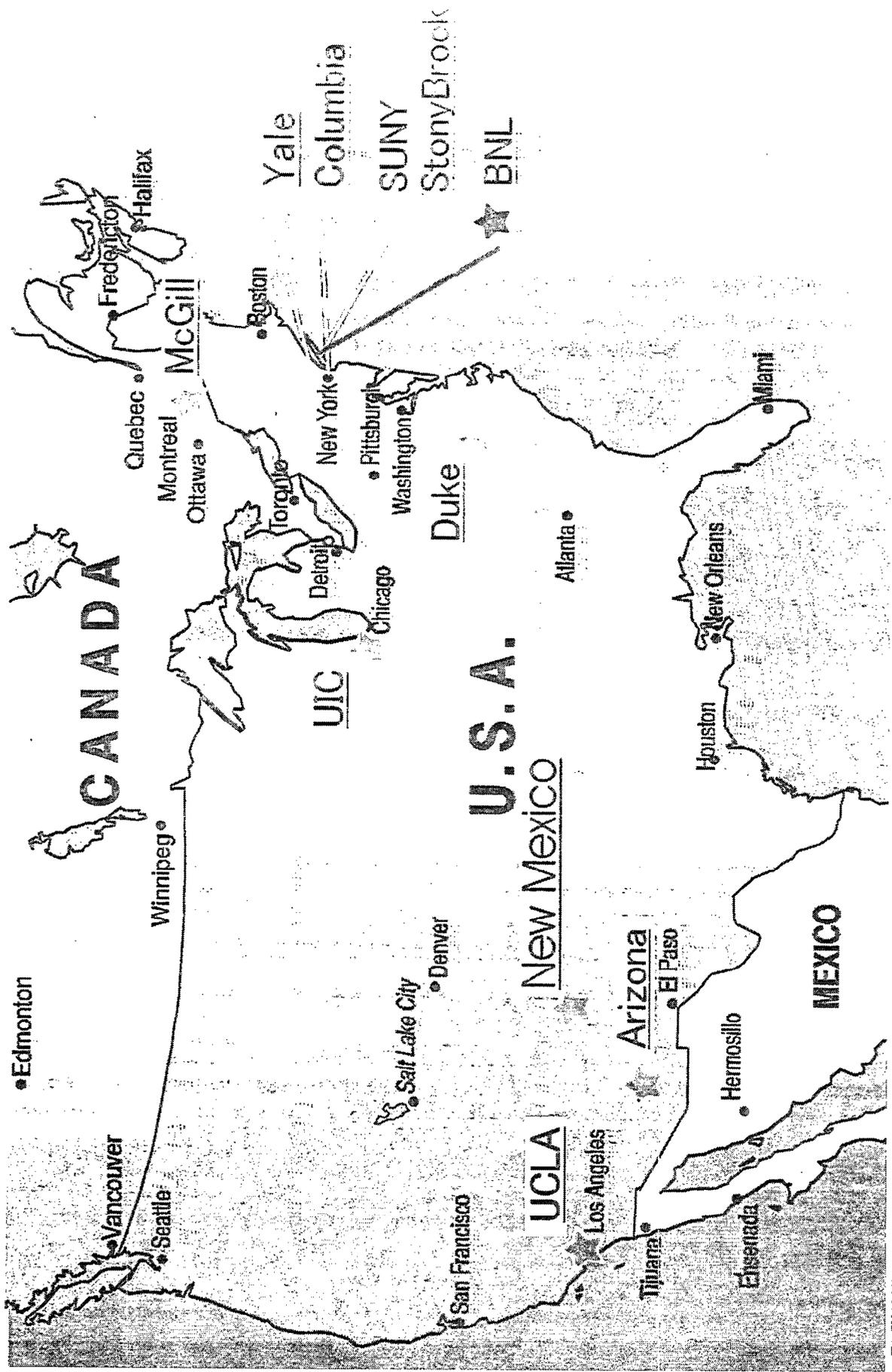
Univ. of Tokyo , March '02

new RBRC Research Associates

(ad. sent to Physics Today

& CERN Courier)

RHIC Physics Fellow (established in '99)



Tenned Graduates : D. Kharzeev ('00) , D. H. Rischke ('01)
D. Böderer ('01) . (In '02, D.T. Son & A. Koenko are expected)

Weekly Seminars

Spin Physics	Tuesdays (10:00 a.m.)	Organized by Y. Goto and W. Vogelsang
Nuclear Physics	Tuesdays (11:00 a.m.)	Organized jointly with BNL Staff
High Energy-RIKEN Theory	Wednesdays (1:30 p.m.)	Organized jointly with BNL Theorists
QCD and RHIC Physics	Thursdays (12:30 p.m.)	Organized by D. Bödeker
High Energy Theory Lunch Talks	Fridays (12:00 Noon)	Organized by S. Dawson
Nuclear Physics-RIKEN Theory	Fridays (2:00 p.m.)	Organized jointly with BNL Staff

PUBLICATION LIST

RBRC-1 H. Fujii and H. Shin, "Dilepton Production in Meson Condensed Matter," Prog. Theor. Physics 98, 1139 (1997).

.....

RBRC-31 D. Kharzeev, R. D. Pisarski, and M. Tytgat, Possibility of Spontaneous Parity Violation in Hot QCD, Phys. Rev. Lett. 81, No. 3, 512-515 (1998).

Presented at the First Anniversary Celebration, October 16, 1998.

PUBLICATION LIST (Cont'd)

RBRC-60 Daniël Boer, "Intrinsic Transverse Momentum and Transverse Spin Asymmetries," [hep-ph/9905336] *Proceedings of the 7th International Workshop on "Deep Inelastic Scattering and QCD," (DIS99) DESY-Zeuthen, April 19-23, 1999. Nuclear Physics B (Proc. Suppl.)* 79, 638 (1999).

Presented at the RBRC Scientific Review Committee Meeting, May 27-28, 1999

.....

RBRC-139. A. Ali Khan, S. Aoki, Y. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, T. Izubuchi, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. I. Nagai, J. Noaki, M. Okawa, H. P. Shanahan, Y. Taniguchi, A. Ukawa, and T. Yoshie (CP-PACS Collaboration), "Chiral Properties of Domain-wall Quarks in Quenched QCD," [hep-lat/0007014], *Phys. Rev. D* 63, 114504-1-19 (2001).

Presented at the RBRC Scientific Review Committee Meeting, September 28-29, 2000

PUBLICATION LIST (Cont'd)

.....

- RBRC-231. K. Orginos [RBC Collaboration] "Chiral Properties of Domain Wall Fermions With Improved Gauge Actions," [hep-lat 0110074], to appear in the *Proceedings of the XIX International Symposium on Lattice Field Theory "LATTICE 2001,"* Berlin, Germany, August 19-24, 2001; Nucl. Phys. B. (Proc. Suppl.)

Presented at RBRC Scientific Review Committee Meeting, November 29-30, 2001

Proceedings of RBRC Workshops

Volume 28 Equilibrium & Non-Equilibrium Aspects of Hot, Dense (BNL-52613)
QCD, July 17-30, 2000; RBRC and BNL Nuclear Theory Workshop
Organizers: D. Boyanovsky, H. J. de Vega, L. McLerran,
R. D. Pisarski

Volume 29 Future Transversity Measurements, (BNL-52612)
September 18-20, 2000
Organizers: Daniël Boer and Matthias Grosse Perdekamp
Scientific Advisory Committee:
Robert L. Jaffe, Piet Mulders, Wolf-Dieter Nowak



Volume 30 RBRC Scientific Review Committee Meeting (BNL-52603)
September 28-29, 2000
Organizers: T. D. Lee and N. P. Samios

Volume 31 RHIC Spin Physics II & IV Polarized Partons at High
 Q^2 Region (BNL-52617)
August 3, 2000 at BNL; October 14, 2000 at Kyoto Univ.
Organizing Committee: 8/3--Gerry Bunce and Steve Vigdor;
10/14--K. Imai, H. En'yo, N. Saito, T. Kunihiro, T. Uematsu,
S. Kumano, Y. Koike, M. Okamura;
Scientific Advisory Committee: T. Roser, D. Underwood,
X. Ji, J. Soffer, L. C. Bland, K. Yazaki, A. Masaike

- Volume 32 RHIC Spin Physics V (BNL 52628)
February 21, 2001
Organizing Committee: Gerry Bunce, Naohito Saito, Steve Vigdor, Thomas Roser,
Hal Spinka, Hideto En'yo, Leslie C. Bland, Wlodek Guryn
- Volume 33 Spin Physics At RHIC in Year-1 and Beyond (BNL-52635)
May 14-18, 2001
Organizing Committee: Leslie Bland, Daniël Boer, Naohito Saito,
Werner Vogelsang
- Volume 34 High Energy QCD: Beyond the Pomeron (BNL-52641)
May 21-25, 2001
Organizing Committee: John Dainton, Wlodek Guryn, Dmitri Kharzeev, and
Yuri Kovchegov
- Volume 35 RIKEN Winter School, Quarks, Hadrons and Nuclei-QCD Hard Processes and the
Nucleon Spin (BNL 52643)
December 1-5, 2000, RIKEN, Japan
Organizers: N. Saito, T.-A. Shibata, and K. Yazaki
- Volume 36 RHIC Spin Collaboration Meeting VI (BNL-52642)
October 1, 2001
Organizers: Les Bland and Naohito Saito

Future RBRC Workshops

Date: March 11-15, 2002
Title: RBRC Workshop on Hadron Structure from
Lattice QCD
Organizers: Thomas Blum, Daniël Boer, Michael Creutz,
Shigemi Ohta, Kostas Orginos

Date: Spring 2002
Title: RBRC Workshop on Theory Studies
for RHIC-Spin
Organizers: Werner Vogelsang

Other RBRC Scientific Articles Proceedings Volumes:

Volume 1 Prospects for Spin Physics at RHIC

**Gerry Bunce, Naohito Saito, Jacques Soffer, Werner Vogelsang
July 2000**

Volume 2 Status Report on the Calculation of ϵ'/ϵ

**RBRC-Brookhaven-Columbia Collaboration
November 2000**

Volume 3 Scientific Presentations: 7th Meeting of the Management

**Steering Committee of the RIKEN BNL Collaboration, RIKEN,
Wako, Japan, February 13-14, 2001.**

Volume 4-CP Violation in K Decay From Lattice QCD

**Thomas Blum and Robert Mawhinney
RBRC-Brookhaven-Columbia QCDSF Collaboration
July 26, 2001**

Outstanding Junior Investigator Award

In Nuclear Theory this year, the two

OJI selected by DOE are both

RBRC members:

M. Stephanov

U. van Kolck

In the Quark Matter 2001 International
Conference, 5 Plenary Session invited
talks were given by RBRC Scientists

Dirk Rischke, critical review on the
extraction of freezeout parameters

Steffen Bass, collision dynamics and
cascades

Raju Venugopalan, small x -physics

Dam Son, energy loss and parton
thermalization

Nao hito Saito, RHIC Spin Program

+ several Parallel Session presentations

Institute for Nuclear Theory, U. of Wash.
Lattice QCD and Hadron Phenomenology
9/24 - 12/7 / 2001

RBRC invitees: Y. Aoki, C. Dawson,
K. Itakura, J. Noaki + K. Orginos

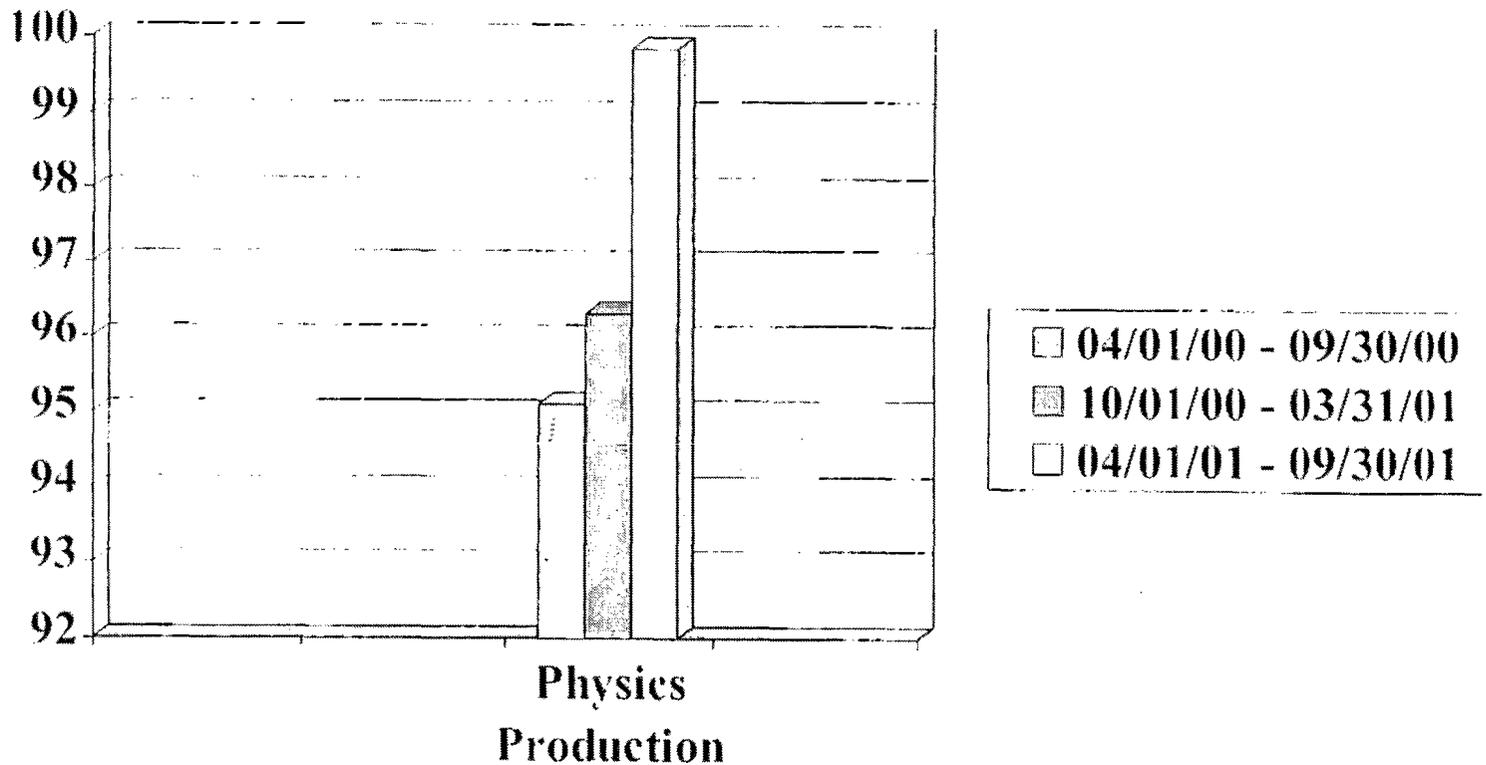
Institute for Theoretical Physics, Santa Barbara
QCD and Gauge Theory Dynamics in the
RHIC Era

4/1/02 - 6/28/02

RBRC invitees: S. Bass, T. Blum,
T. Schafer, D. Son, M. Stephanov,
R. Venugopalan

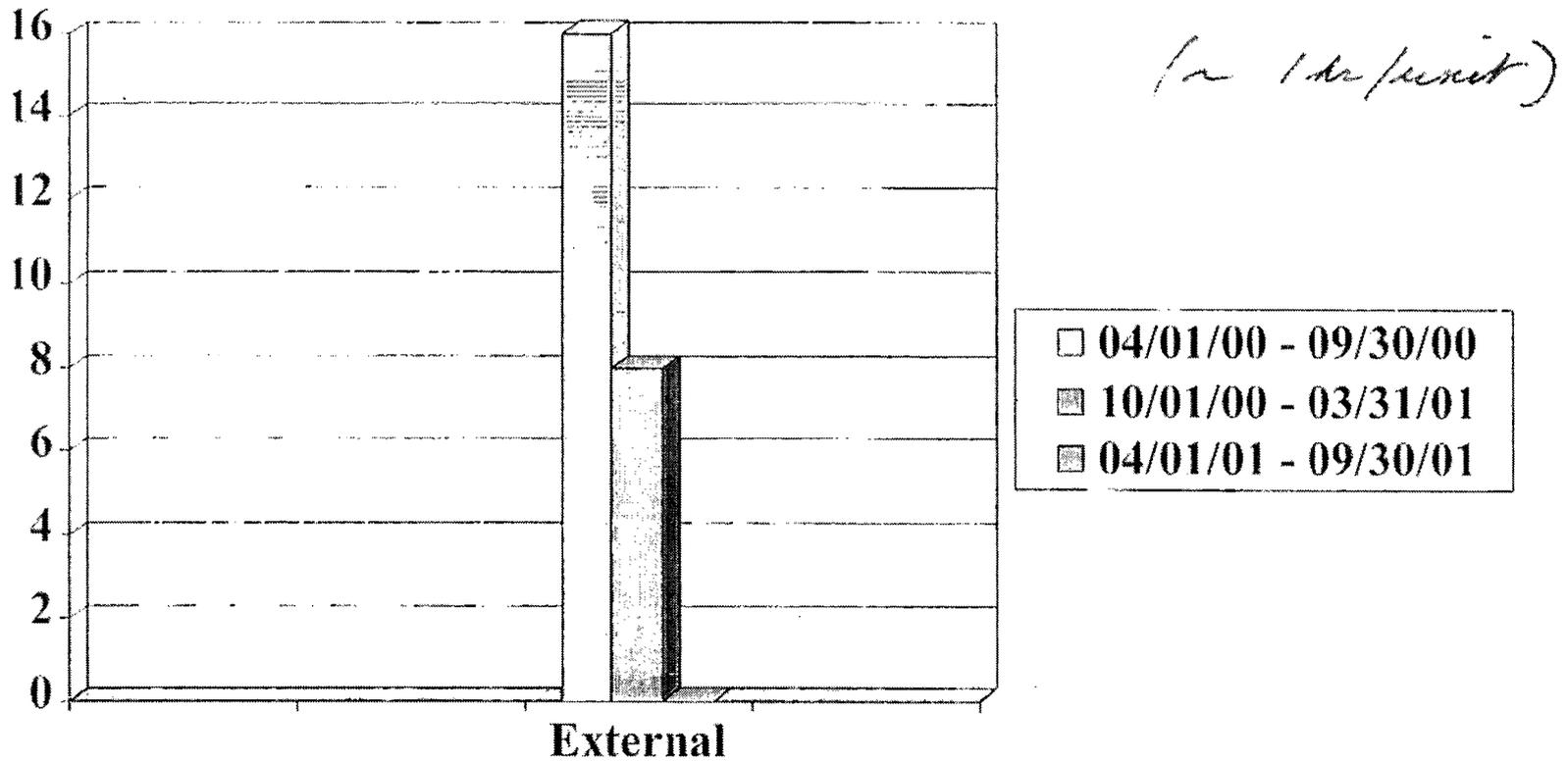
D. Khazeev, formerly a RBRC Fellow
is one of the organizers

RBRC – QCDSP Percent of Uptime



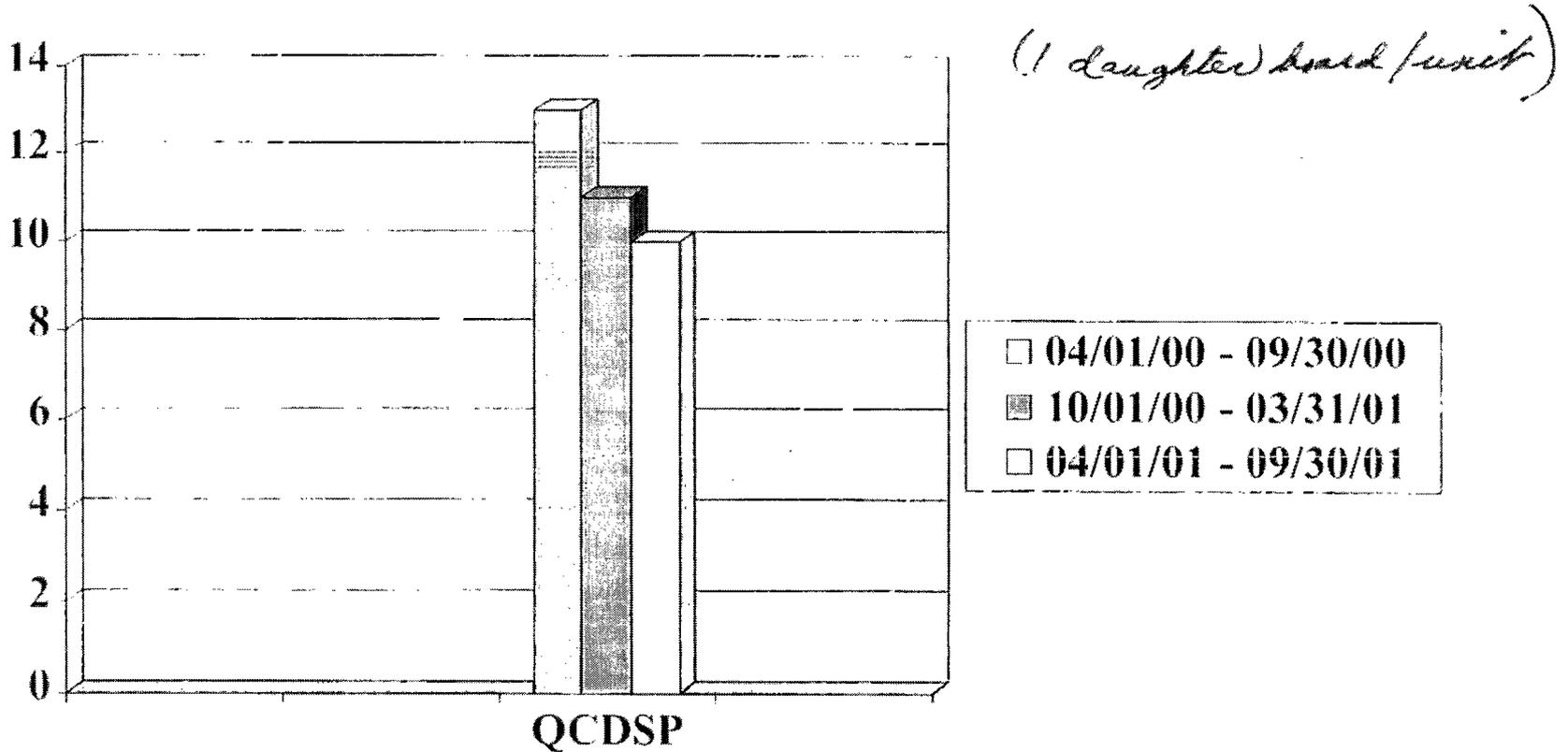
RBRC – QCDSP

Number of External Failures



RBRC – QCDSP

Number of Hardware Failures



Status

10 Teraflops QCDQC

R + D

(RBRC-component
completed)

Construction Proposal

(approved by RIKEN)

Funding Profile

(to be finalized)



RIKEN BNL Research Center

CP VIOLATION IN K DECAY FROM LATTICE QCD

**Thomas Blum and Robert Mawhinney
RBRC-Brookhaven-Columbia QCDSP Collaboration**

July 26, 2001

RBRC Scientific Articles

Volume 4

Building 510A, Brookhaven National Laboratory, Upton, N.Y 11973-5000, USA

Comparison with Experimental Results

Quantity	Experiment	This calculation
Re A_0 (GeV)	3.33×10^{-7}	$3.26(19) \times 10^{-7}$
Re A_2 (GeV)	1.50×10^{-8}	$1.279(57) \times 10^{-8}$
$\frac{Amp(K \rightarrow 2\pi)_{I=0}}{\omega} \equiv \omega$	22.2	25.5(57)
" (") $I=2$ Re (ϵ'/ϵ)	$15.3(26) \times 10^{-4}$ (NA48)	$-4.4(24) \times 10^{-4}$
	$20.7(28) \times 10^{-4}$ (KTev)	

$$\frac{\frac{Rate(K_L^0 \rightarrow \pi^+\pi^-)}{Rate(K_S^0 \rightarrow \pi^+\pi^-)}}{\frac{Rate(K_L^0 \rightarrow \pi^0\pi^0)}{Rate(K_S^0 \rightarrow \pi^0\pi^0)}} = \left| \frac{\epsilon + \epsilon'}{\epsilon - 2\epsilon'} \right|^2 \approx 1 + 6 Re(\epsilon'/\epsilon)$$

A New Method to Solve the N-dim Schrödinger Eqn (N arbitrary)

TDL, R. Friedberg & W. Q. Zhao

(2nd order)

- Reduction of an N-dim. Schrödinger

Eq to a series of 1-dim

(1st order)

linear eqs.

RPRC # 68

Ann. of Phys. 288 (2001)

- Convergence of the Series

Expansion in terms of

RPRC # 176

Ann. of Phys. (in press)

the Sturm-Liouville Green's fn

(instead of the coupling), with

Explicit Expressions for the

double-well potential

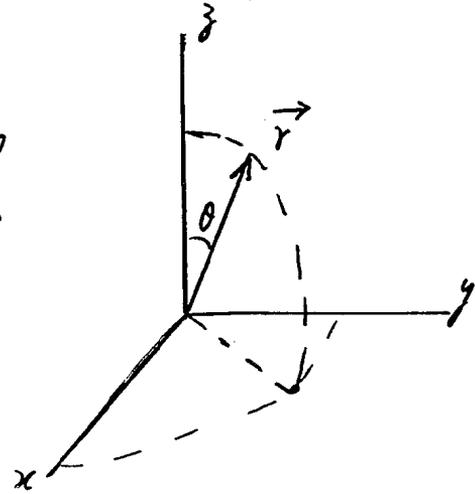
Stark Effect

$$H = -\frac{1}{2} \nabla^2 - \frac{ze^2}{r} + \epsilon r \cos \theta$$

Studied by Bohr (1915)

Schrodinger (1926)

...



In 1954, Foley et al found

$$E = -\frac{1}{2} z^2 e^4 - \frac{9}{4} \frac{\epsilon^2}{z^4 e^8} + O(\epsilon^4)$$

The new method gives exact result in closed form to any order in ϵ^2

$$H\psi = E\psi, \quad \psi = e^{-S}$$

$$S = ze^2 r + \frac{\epsilon r}{z^2 e^4} \cos \theta \cdot \left(1 + \frac{1}{2} ze^2 r \right) - \frac{\epsilon^2 r^2}{z^4 e^8} \left\{ \frac{7}{16} (1 + \cos^2 \theta) + \frac{1}{24} ze^2 r (1 + 3 \cos^2 \theta) \right\} + \frac{\epsilon^3 r}{z^8 e^{16}} \cos \theta \left\{ \frac{53}{8} \left(1 + \frac{1}{2} ze^2 r \right) + \frac{13}{48} (ze^2 r)^2 (3 + \cos^2 \theta) + \frac{1}{16} (ze^2 r)^3 (1 + \cos^2 \theta) \right\} + \dots$$

$$E = -\frac{1}{2} z^2 e^4 - \frac{9}{4} \frac{\epsilon^2}{z^4 e^8} - \frac{3555}{64} \frac{\epsilon^4}{z^{10} e^{20}} + \dots$$

RBRC Experimental Group

N. P. Samios

T. D. Lee, RBRC Director
N. P. Samios, RBRC Deputy Director
Hideto En'yo, RBRC Associate Director

* * * *

RBRC Research Scientists (2000 – 2001)
Experimental Group
Hideto En'yo, Group Leader
Gerry Bunce, Deputy Group Leader

Research Associates
(Post Docs)

Bazilevsky, A.

Fellows

Deshpande, A.

Fox, B.

Goto, Y.

Grosse-Perdekamp, M.

Kurita, K.

Tenure Track/RHIC Fellow
Fields, D. (UNM)

RIKEN Spin Program
(RSP) Researchers

Ichihara, T.

Saito, N.

Taketani, A.

Watanabe, Y.

RIKEN Spin Program
(RSP) Research Associates

Kobayashi, H.

Murata, J. (RIKEN)

Yokkaichi, S.

RIKEN Spin Program Visiting Scientist
Lange, J. S.

Advisory Committee

Masaïke, A.

Nagamiya, S.

Sandweiss, J.

Consultants

Jaffe, R.

Roser, T.

Makdisi, Y.

Tannenbaum, M.

Visiting Scientists

Imai, K.

Okamura, M.

Shibata, T.-A.

Visiting Res. Assoc.

Jinnouchi, O.

Okada, K.

Visiting Jr. Res. Assoc.

Kamihara, N.

Sato, H.

Tojo, J.

Torii, H.

Experimental Group Activities

Belle Collaboration

Spin Fragmentation Structure Function

Preparation for Spin Run

Nov. 8 -- 2 weeks AGS machine ready for Spin
Nov. 26-- 3 weeks RHIC machine preparation for Spin
Dec. 21 5 weeks polarized proton running

Beam-beam Counters

Measure total cross section

Polarimeter in yellow ring

(A polarimeter already in the blue ring)

Measure polarization

Electronics

Dead time reduction at high rates
More Efficient running

Meetings

Tuesday 10:00 a.m. Spin Discussion
Tuesday 2:00 p.m. Round Table Discussion

RHIC Accelerator

Energy: 100 GeV/A x 100 GeV/A
Gold on Gold

Luminosity: $2 \times 10^{26}/\text{cm}^2/\text{sec}$ Gold on Gold

} Achieved

For Polarized Proton

Expect:

Energy: 100 GeV x 100 GeV
Ultimate
250 GeV x 250 GeV

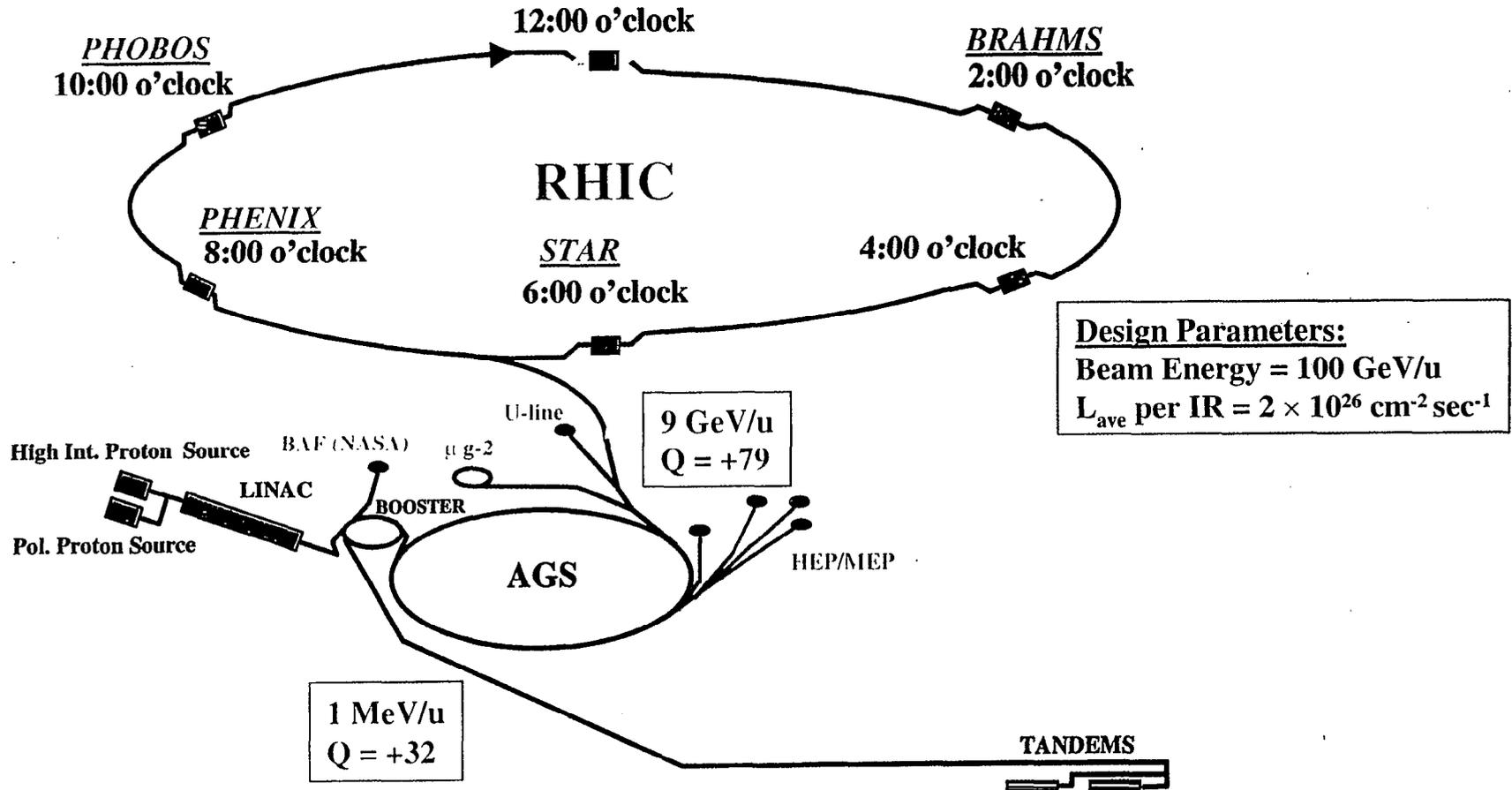
Luminosity: (1-5) $10^{30}/\text{cm}^2/\text{sec}$

Polarization: 50% Ultimate 70%

2001 – 2002 Run All 4 snakes – Transverse Spin
100 GeV x 100 GeV – Longitudinal Spin

2002 – 2003 Run All rotators – Longitudinal Spin
250 GeV x 250 GeV

Gold Ion Collisions in RHIC

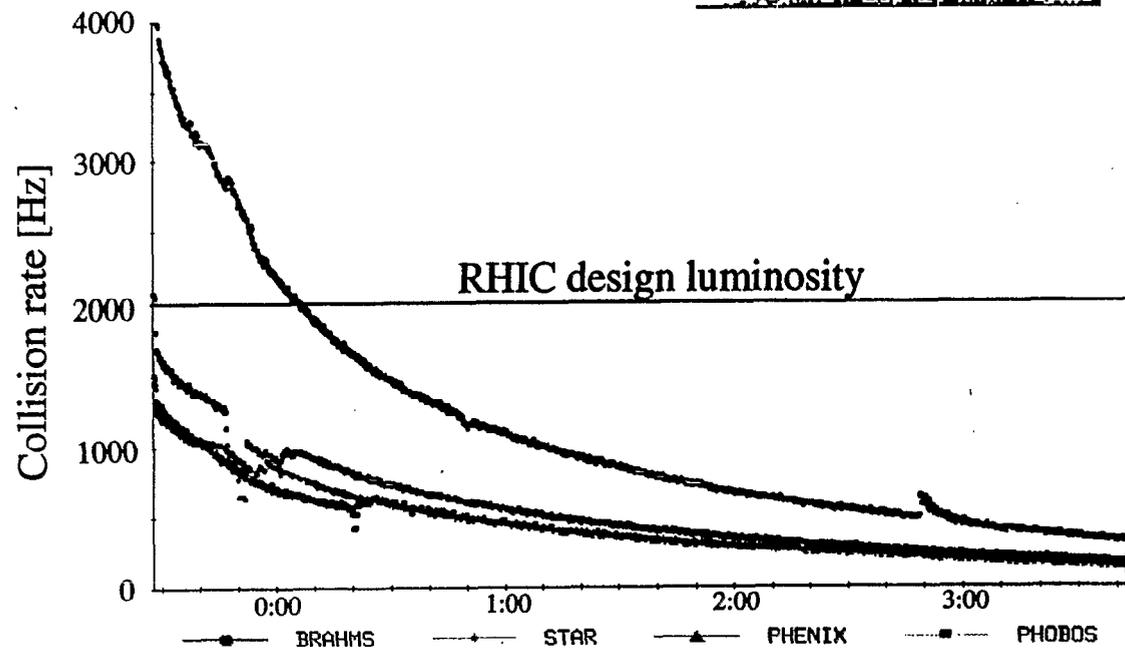
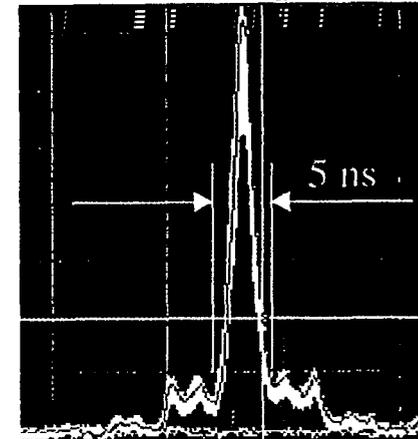


38

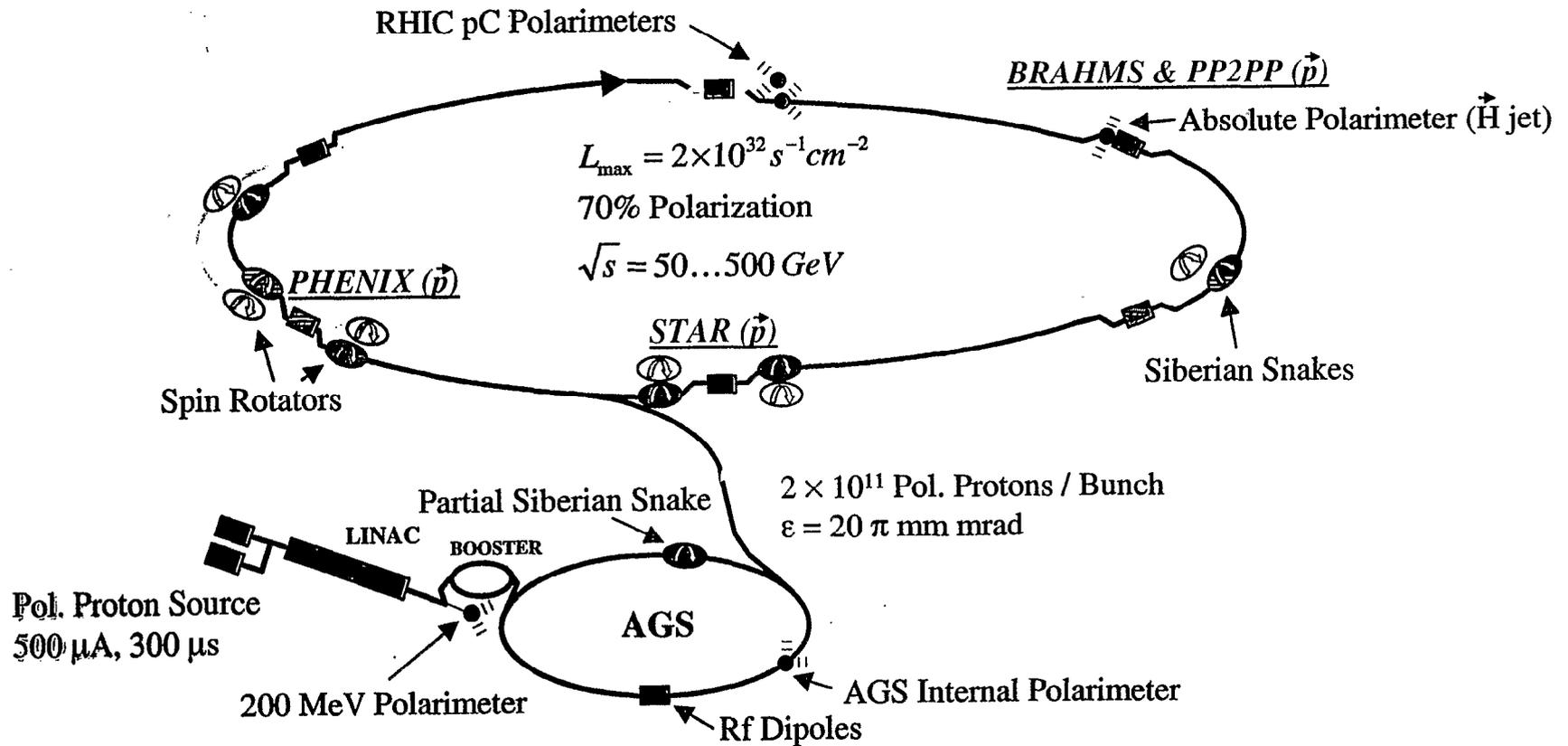
RHIC performance

- Collisions at RHIC design beam energy (100 GeV/nucl)
- 200 MHz rf system operational
 - 5 ns bunch length and an interaction region with $\sigma \sim 25$ cm
- Luminosity exceeding RHIC design luminosity of $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
- 40% availability is limiting total integrated luminosity

RHIC bunch profile



Polarized Proton Collisions in RHIC



40

EXPERIMENTAL PRESENTATIONS

Introduction of Experimental Group and Discussion

Hideto En'yo

RBRC Review '2001

Introduction to the RBRC Experimental Group

Hideto En'yo

Members of RBRC experiment

- Group Leaders:
 - Hideto Enyo (Wako)
 - Gerry Bunce(deputy)
- Fellows/Postdoc
 - Matthias Grosse Perdekamp
 - Abhay L. Deshpande
 - Brendan Fox
 - Yuji Goto
 - Kazuyoshi Kurita
 - Douglas E. Field (New Mexico)
 - Alexander Bazilevsky

- RIKEN Spin Program
 - Naohito Saito
 - Atsushi Taketani
 - Takashi Ichihara (WakoCCJ)
 - Yasushi Watanabe(WakoCCJ)
 - Satoshi Yokkaichi(WakoCCJ)
 - Hideyuki Kobayashi
 - Jiro Murata (Wako)

- Hisa Torii
- Junji Tojo
- Hiroki Sato
- Nobuyuki Kamihara

- Kensuke Okada (June)
- Osamu Jinnouchi (April)

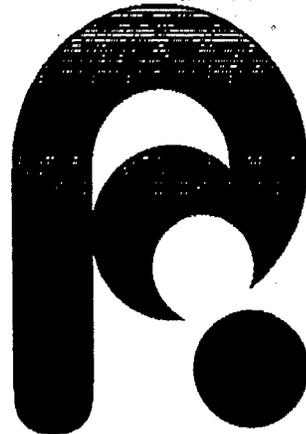
New members

- New Researcher in Radiation Lab
 - Kiyoshi Tanida (U-Tokyo JSPS) 1st October will join the Si-tracker development ?
- Silicon Strip/Pixel detector for PHENIX Upgrade based on Radiation Laboratory, to deal with CERN-NA60 and CERN-ALICE to start with
 - Hiroaki Ohnishi (BNL) 1st Jan.
 - Johann Hauser (SUNY) 1st April
 - Rykov Vladimir (Wayn State U) 1st Mar ?
- New Researcher in Radiation Lab
 - Application closes on 26th December 1st April CERN courier ad.

TENURE TRACK RESEARCHER POSITION FOR RHIC SPIN PROGRAM

RIKEN (The Institute of Physical and Chemical Research) invites applications for a tenure track researcher position with our RHIC spin program.

The successful applicant is supposed to be resident at Brookhaven National Laboratory and play a leading role to carry out our experimental activities using polarized proton collisions at RHIC.



RIKEN

In this program we are involved in the PHENIX experiment, and other activities related to the polarized proton acceleration.

Interested candidates should send a vitae (photo attached), list of publication, copies of the important publications (less than 5), two letters of recommendation, abstract of the research history and description of research interest to:

**Dr. H. En'yo, Radiation Laboratory,
RIKEN, Hirosawa 2-1, Wako, Saitama
351-0198 Japan, before 26th December 2001.**

For further information contact:

Hideto En'yo: Fax: +81-48-462-4641,

E-mail: enyo@riken.go.jp, or refer to

<http://www.riken.go.jp/> and

<http://www.rarf.riken.go.jp/lab/radiation/>.

Major events

- RBRC Visiting Researcher (unpaid) is established
 - Analysis Proposal to Belle in KEK (Spin in Fragmentation)
 - M.G. Perdekamp (RBRC, Contact person for BELLE)
 - Soeren Lange (Frankfurt, STAR)
 - Akio Ogawa (Penn State U, STAR)
 - New postdoc for Belle (seeking)
 - CERN pixel development (will soon be established in RBRC)
 - This is also a contract of RIKEN (trip etc. can be supported)
 - RBRC Theory will also use this framework
- 4 Kyoto Students (NEW) joined SLAC test
 - Muto, Sakuma, Togawa, Fukao
 - Did we impress them well?

Major event

- Special Doctoral Fellow Ship of RIKEN (For Japanese only) is open through RBRC exp and Radiation Lab in Wako. Next year applicant call will also made for RBRC theory.)
 - From April 1st. T. Kawabata (Kyoto-U) and J.Tojo (Kyoto-U , currently RBRC student) will start with RBRC experimental group. Takashi Ikeda (U-Tokyo) will start with RBRC theory group.
- Junior Research Associate of RIKEN is called through RBRC exp+theory and Radiation Lab. (For Japanese only)
 - Got 2 applicants in RBRC exp, and 1 applicant in RBRC theory.
- JRA for non-Japanese is under development. Will be available next year.

Conclusion

UPGRADE

Kiyoshi Tanida
Hiroaki Ohnishi
Johann Hauser
Rykov Vladimir

BELLE

Soeren Lange (VISITOR)
Akio Ogawa (VISITOR)
New postdoc

RBRC

Hideto Enyo
Gerry Bunce
Matthias Grosse Perdekamp
Abhay L. Deshpande
Brendan Fox
Yuji Goto
Kazuyoshi Kurita
Douglas E. Field
Alexander Bazilevsky
T. Kawabata
J. Tojo

RIKEN/RBRC

Naohito Saito
Atsushi Taketani
Hideyuki Kobayashi
Kensuke Okada
Osamu Jinnouchi

RBRC STUDENT

Hisa Torii
Hiroki Sato
Nobuyuki Kamihara
JRA?
JRA2?

WAKO/CCJ

Takashi Ichihara
Yasushi Watanabe
Satoshi Yokkaichi

Physics of RHIC Spin, RIKEN, and RBRC

Naohito Saito



PHYSICS of RHIC SPIN

– RIKEN and RBRC Activities–

RBRC Scientific Review
November 29-30, 2001

Naohito Saito

RIKEN / RIKEN BNL Research Center



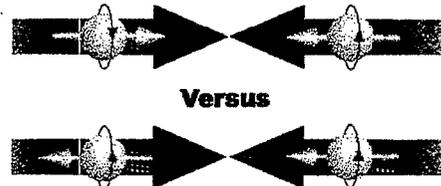
Spin Physics at RHIC



Measure Spin Asymmetries in *pp* collision to pin down

Spin Structure of the Nucleon

- Proton Spin Sum Rule
- Transversity Distributions



Spin Dependence of Fundamental Interactions

- Parity Violating Interaction
- CP Violation in Quark Sector and Higgs Sector

Spin Dependence of Fragmentation

- E.g. Lambda fragmentation function

Spin Dependence in *pp* elastic scattering

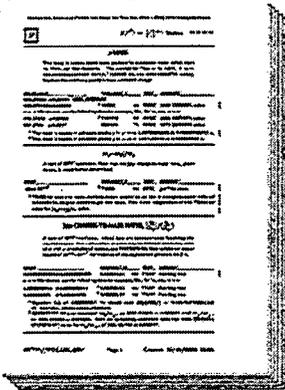




Why Spin Physics?



“Spin” is a fundamental observable.



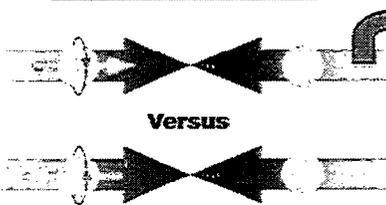
$$\Delta\Sigma = 0.1 \sim 0.2$$

Total fraction of the proton spin carried by the quark spin; Scheme dependent.

Proton Spin



Axial vector nature is useful in symmetry tests



Parity
Time
Reversal

	P	T
position	x	$-x$
momentum	p	$-p$
spin	σ	$-\sigma$



Naohito Saito (RIKEN/RBRC)



RHIC Spin Structure Studies at a Glance



Δg measurements

process	measure	PHENIX	STAR
$A_{LL}(pp \rightarrow \gamma(jet)X)$	$\Delta g \times A_1^p$	yes	yes
$A_{LL}(pp \rightarrow \pi X)$	$\Delta g \times (\Delta g + \Delta\Sigma)$	yes	yes
$A_{LL}(pp \rightarrow jet X)$	$\Delta g \times (\Delta g + \Delta\Sigma)$	no	yes
$A_{LL}(pp \rightarrow QQbar X)$	$\Delta g \times \Delta g$	yes	no
$A_{LL}(pp \rightarrow J/\psi X)$	$\Delta g \times \Delta g$	yes	no
$A_{LL}(pp \rightarrow \chi_2 X)$	$\Delta g \times \Delta g$	yes?	no

L/E Upgrade desirable

Δq measurements

process	measure	PHENIX	STAR
$A_L(pp \rightarrow W^+ X)$	$\Delta u, \Delta dbar$	yes	yes
$A_L(pp \rightarrow W^- X)$	$\Delta d, \Delta ubar$	yes	yes
$A_{LL}(pp \rightarrow l^+ l^- X)$	$\Delta q \times \Delta qbar$	yes	yes?
$A_L(pp \rightarrow WcX)$	$\Delta s, \Delta sbar$	yes	yes

δq measurements

process	measure	PHENIX	STAR
$A_T(pp \rightarrow (\pi^+ \pi^-) X)$	$\delta q \times D$	yes	yes
$A_{\pi}(pp \rightarrow l^+ l^- X)$	$\delta q \times \delta qbar$	yes	yes?
$A_T(pp \rightarrow \gamma(\pi^+ \pi^-) X)$	$\delta q \times D$	yes	yes



Naohito Saito (RIKEN/RBRC)



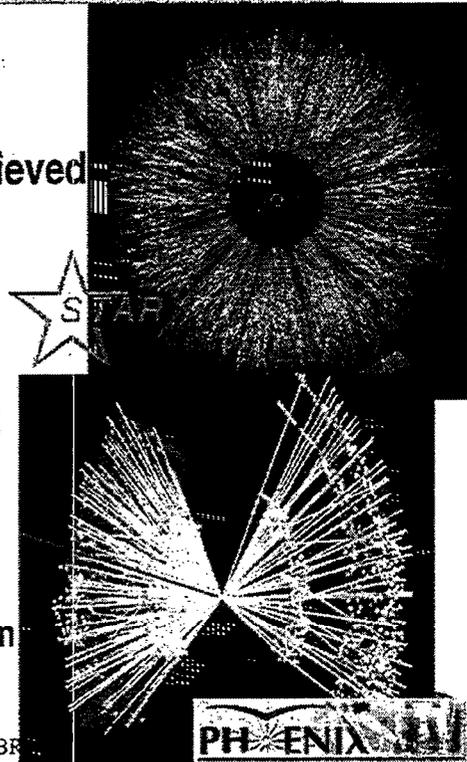


RHIC Year-1 and ... now Year-2



- First Collision of Gold beams at 56 and 130 GeV/A last year
- 10% of Designed Luminosity achieved
- Successful Physics Run
 - All Four Experiments Commissioned
 - Several papers are produced:
- Successful Spin Commissioning!

- First Collision of Gold beams at 200 GeV/A !!!
 - Currently running with Au+Au Beam
 - First Muon Data from PHENIX



Naohito Saito (RIKEN/RBRC)



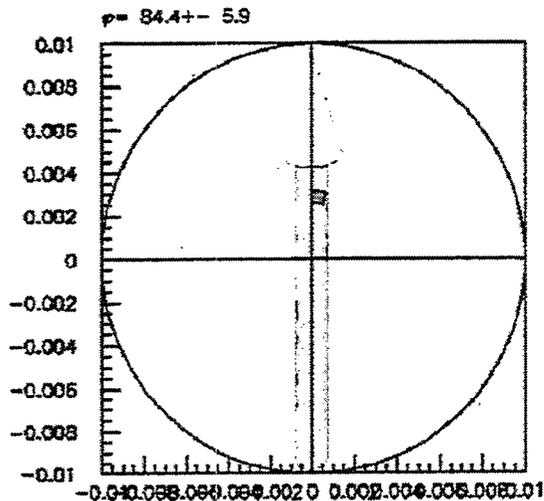
Successful Spin Commissioning



September 13, 2000 : The Exciting Day

- The First Polarized Proton Beam Stored at RHIC
 - $G\gamma=46.5$ (24.3 GeV/c)
- Then Accelerated up to ~30GeV/c with Snake on
 - Spin Orientation Rotated as Expected

Participating Groups:
 BNL
 RIKEN, Japan
 RBRC
 ANL
 Indiana
 Kyoto
 ITEP Moscow



Naohito Saito (RIKEN/RBRC)





Goals of the 1st Spin Physics Run

RIKEN

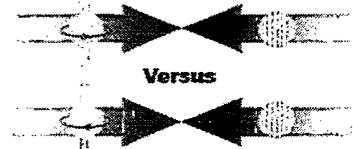
Establish Stable Asymmetry Measurements

- Beam Polarization > 50%
- Luminosity $\sim 5E30\text{cm}^{-2}\text{s}^{-1}$

1 week of transverse polarization

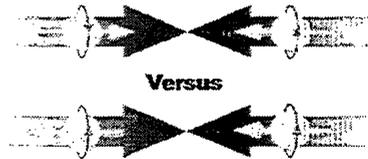
($\sim 0.75\text{pb}^{-1}$)

- $A_N \sim$ Higher Twist Effects



4 weeks of longitudinal polarization ($\sim 3\text{pb}^{-1}$)

- A_{LL} for pion $\sim \Delta g$ Measurements
- A_{LL} for J/ψ in muon Arm

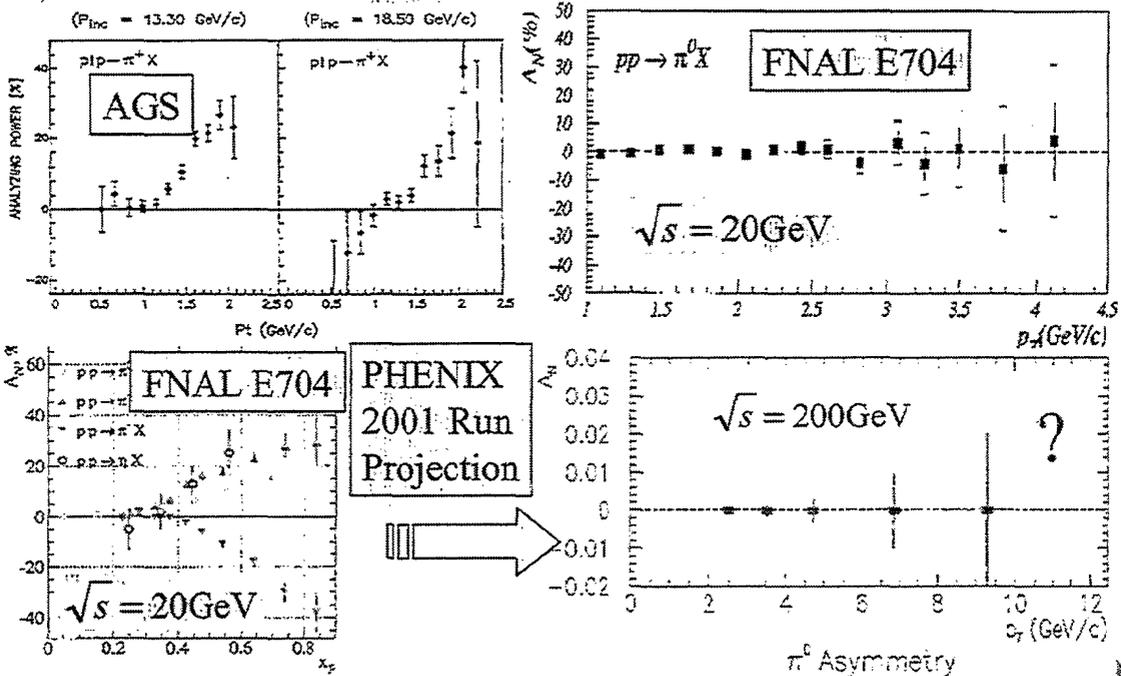


Naohito Saito (RIKEN/RBRC)



Single Transverse Spin Asymmetry

RIKEN

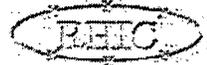


Naohito Saito (RIKEN/RBRC)

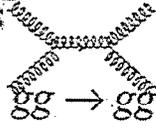




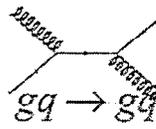
Double Longitudinal Spin Asym



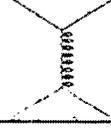
Hi Statistics Pion Data! Sensitive to $\Delta g(x)$!



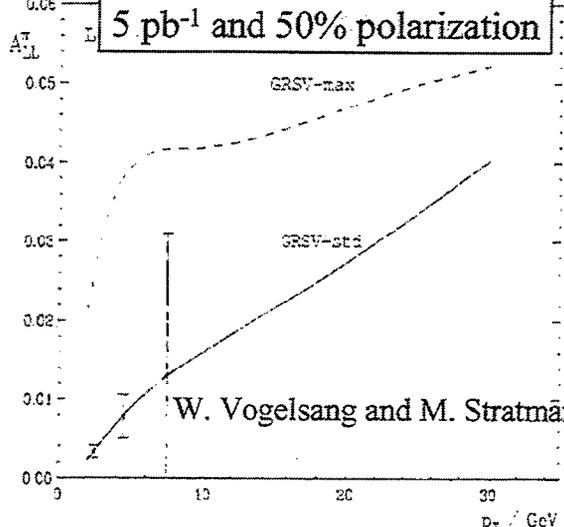
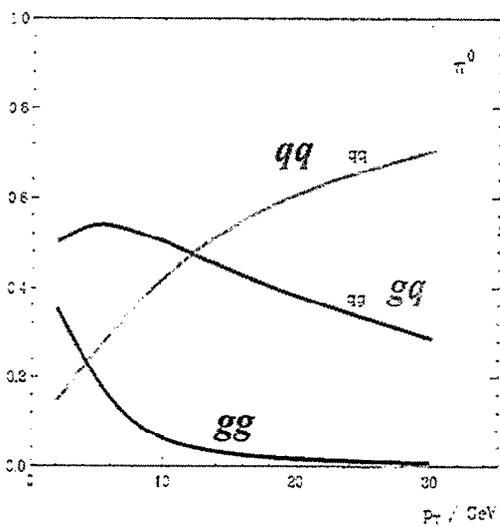
$$\propto \frac{\Delta G \Delta G}{G G}$$



$$\propto \frac{\Delta q \Delta G}{q G}$$



$$\propto \frac{\Delta q \Delta q}{q q}$$



5 pb⁻¹ and 50% polarization

W. Vogelsang and M. Stratmann



Naohito Saito (RIKEN/RBRC)



RHIC Spin Plan (PHENIX and STAR)



Year	CM Energy	Weeks	Int. Lum.	Remarks
FY2001	200 GeV	5	7 pb ⁻¹	Gluon pol. with pions
FY2002	200 GeV	8	160 pb ⁻¹	Gluon pol. with direct γ , jets
	500 GeV	2	90 pb ⁻¹	PV W production, u-quark pol.
FY2003	200 GeV	8	160 pb ⁻¹	Gluon pol. with γ +jet
	500 GeV	2	120 pb ⁻¹	First ubar, dbar pol. meas.
FY2004	500 GeV	8	480 pb ⁻¹	Gluon pol. with γ +jet, γ jet+jet, heavy flavor, ubar, dbar pol.
	200 GeV	2	48 pb ⁻¹	Gluon pol. with γ , γ +jet, heavy flavor
FY2005	500 GeV	5	300 pb ⁻¹	More statistics
	200 GeV	5	120 pb ⁻¹	
FY2006	200 GeV	10	210 pb ⁻¹	Transversity measurements

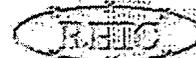


Naohito Saito (RIKEN/RBRC)





RIKEN and RBRC Activities



- Outline of our activities to achieve the goals of this year and near future will be described.
 - PHENIX Detector Subsystem Involvement
 - RHIC Polarimetry
 - Physics Analysis



Naohito Saito (RIKEN/ RBRC)



**PHENIX Triggers for Spin; New Belle Collaboration to
Study Spin Dependent Fragmentation Functions**

Matthias Grosse Perdekamp

The PHENIX EMC-RICH Trigger

Matthias Grosse Perdekamp, RBRC

Trigger layout and organization

Physics and trigger channels for the 2001 proton run

Hardware status and schedule

CAMAC based local level 1 for 2001 proton run

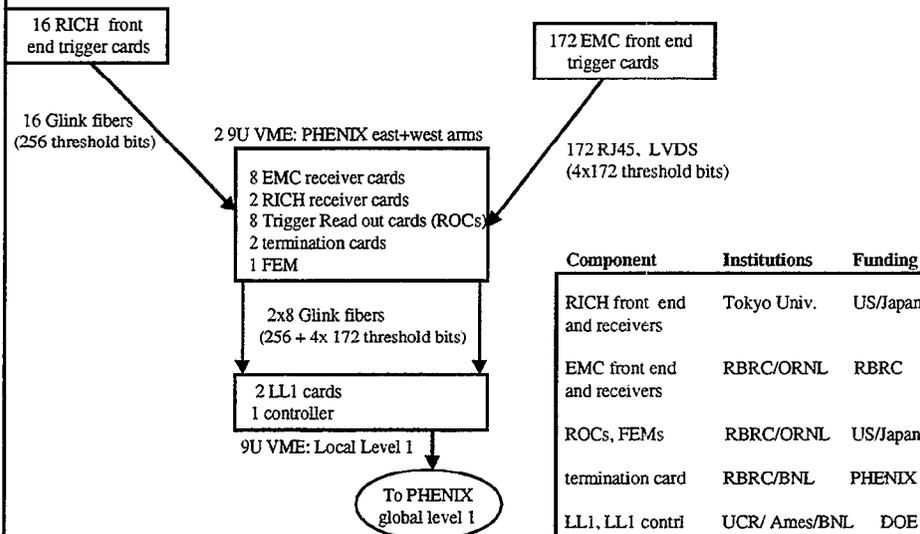
Expected Rejections



November 29, 2001

PHENIX EMC-RICH Trigger

EMC-RICH Trigger: Layout and Organization



November 29, 2001

PHENIX EMC-RICH Trigger

Physics/trigger channels for 2001 proton run

	Spin	HI - comparison	trigger	rate
Central arm EMC-RICH	$A_{\mu}^{\pi^0}$	$\pi^0 - p_t$ - spectrum	EMC 4x4 tiles > 2 and 3 GeV	0.2kHz
	$A_{\mu}^{h^{+-}}$	$h^{+-} - p_t$ - spectrum	EMC 2x2 tiles > 0.9 GeV	1.4kHz
	$A_{\mu}^{e^{+-}}, A_{\mu}^{\pi^{+-}}$	single $e^{+-}, J/\psi$	EMC 2x2 tiles > 0.9 GeV \otimes RICH	0.1kHz
	NA	ϕ	2xRICH \rightarrow 30	0.1kHz
Muon arm	$A_{\mu}^{J/\psi}$	J/ψ	1 deep muon (last mult gap)	0.2kHz
	Clock	min bias		0.5kHz
	NTC BBC	min bias		0.5kHz

3.0kHz

Rates based on $L = 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$



Level 2 needs to reduce this to archiving rate of about 800Hz

November 29, 2001

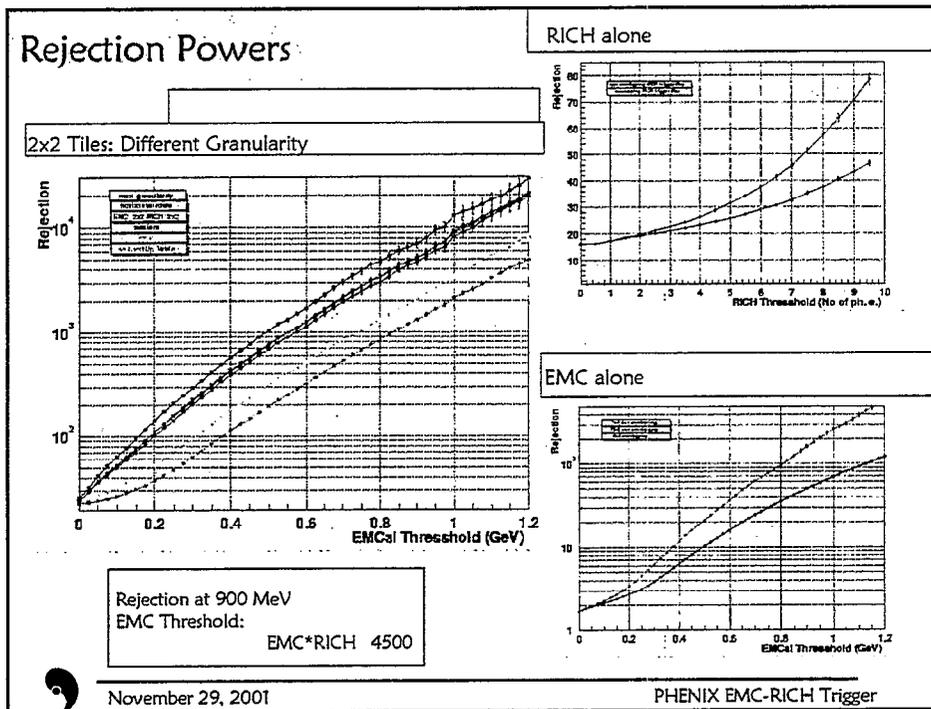
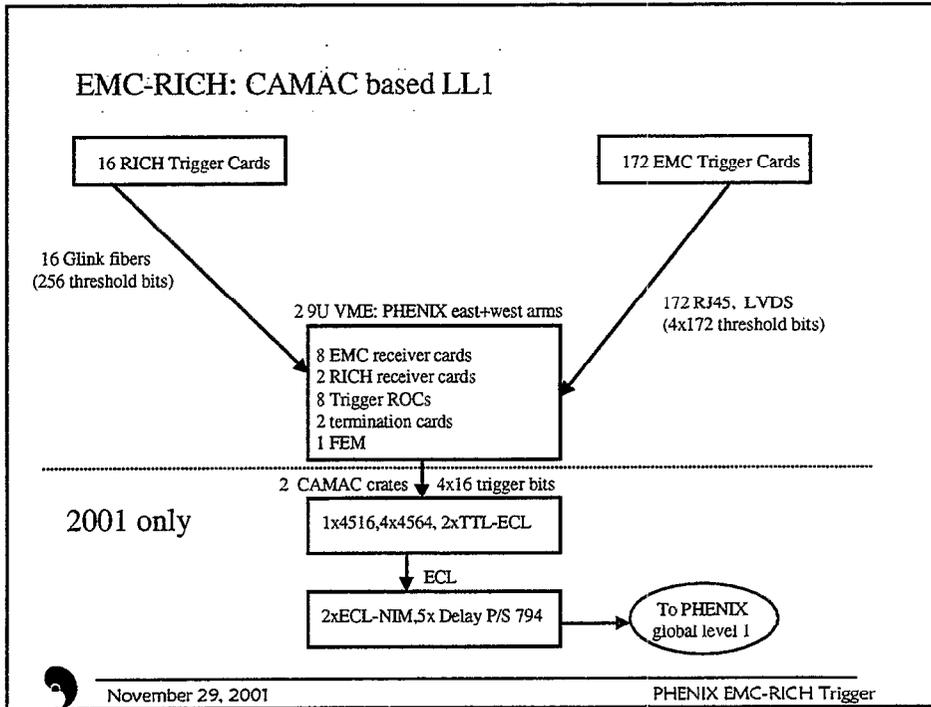
PHENIX EMC-RICH Trigger

EMC-RICH Status and Schedule

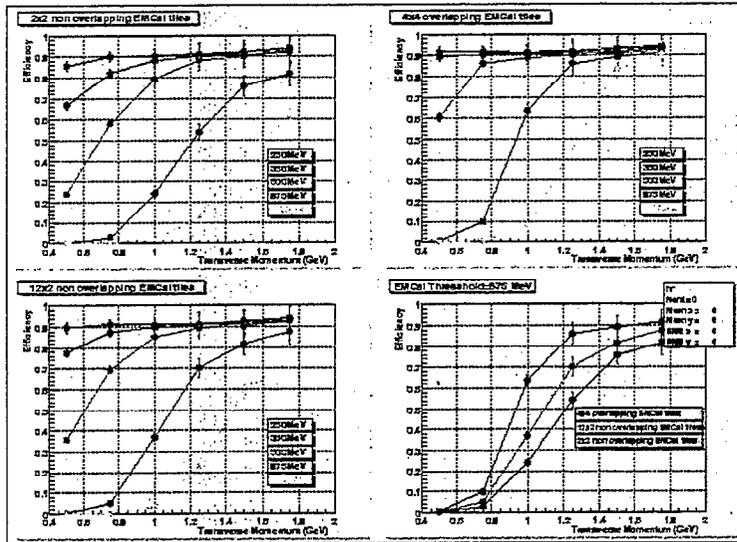
Cards	Ordered (spares)	Received	Tests	Installation
EMC FE-Trigger Card	200(28)	198	ORNL/BNL: 198(150)	122: Bal Nov 26
RICH FE-Trigger Card	20(4)	4	ongoing (Tokyo)	4: Bal Nov 26
EMC Receiver	20(16)	20	ongoing (BNL)	2: Bal Nov 26
EMC Termination Board	4(1)	2	ongoing(BNL)	1: Bal. Nov 26
RICH Receiver	6(4)	4	ongoing (Tokyo)	2: Bal. Nov 26
Trigger ROCs (muId)	16(18)	18	18 (BNL)	3: Bal. Nov 26
Trigger FEMs (muId)	2(2)	2	done (Vince)	1: Bal. Nov 26
LL1 (muId)	2(1)	0	Schedule for the board is not	finalized.

November 29, 2001

PHENIX EMC-RICH Trigger



Efficiencies for Electrons from Open Charm



November 29, 2001

PHENIX EMC-RICH Trigger

Fragmentation Function Measurements at Belle

Matthias Grosse Perdekamp, RBRC

Motivation: Avenues to Transversity

The Belle Experiment

How to Access Collins and Interference Fragmentation

Rates

November 29, 2001

PHENIX EMC-RICH Trigger

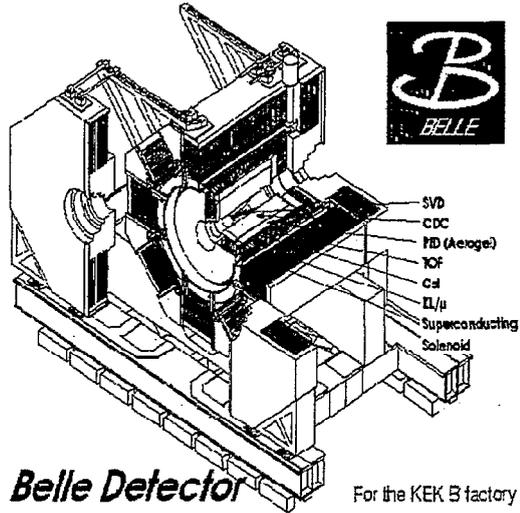
B factories : Belle, Babar, Cleo...

Belle
8GeV+3.5GeV
1.3/fb/week

Babar
9GeV+3.1GeV
~1/fb/week

Cleo
4.7GeV+5.6GeV
~0.35/fb/week

All have almost hermetic
collider detector with
good PID



Belle Detector

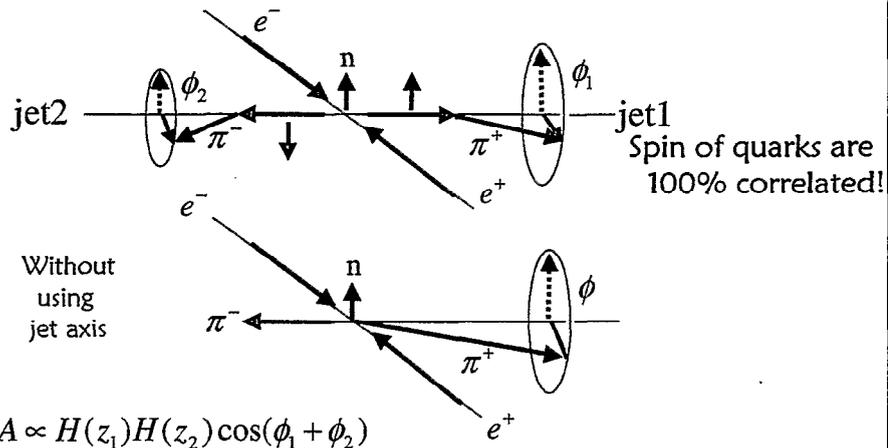
For the KEK B factory



November 29, 2001

PHENIX EMC-RICH Trigger

$$e^+e^- \rightarrow (\pi^+)_{jet1} (\pi^-)_{jet2} X$$



$$A \propto H(z_1)H(z_2) \cos(\phi_1 + \phi_2)$$

$$= H(z_1)H(z_2) \cos(2\phi)$$

Extracting the Collins Function



November 29, 2001

PHENIX EMC-RICH Trigger

FF measurements at b-factories

Experimental Requirements e^+e^-	Belle
Jet production from light quarks	Off resonance data
Energy at which pQCD is applicable	$s \sim 100 \text{ GeV}^2$
Moderate energy for analyzing power FF decreases as energy increases	$s(\text{Belle}) \ll s(\text{LEP})$ Q^2 evolution is interesting
Avoid extra complication from Z pole	" $s(\text{Belle}) < M_Z$
Requires good detector: Wide acceptance Momentum/mass resolution PID capability	Belle!

H*H and F*F can be measured (time frame: + 2years)



November 29, 2001

PHENIX EMC-RICH Trigger

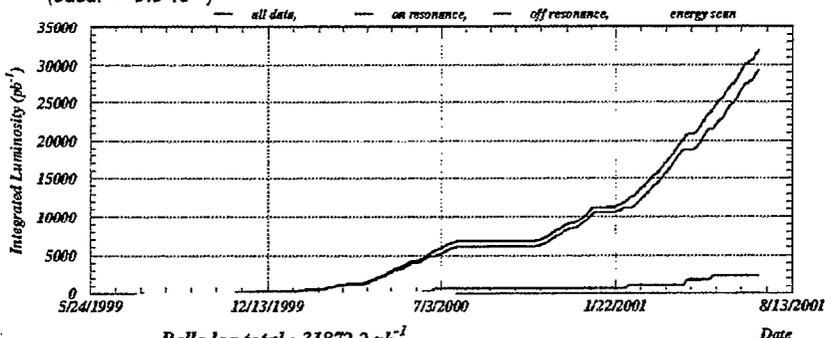
Belle Luminosity Information

On-Resonance

10.58 GeV
 bb cross section = 1.19 nb
 ~32/fb on tape
 ~240/pb/day
 peak L = $4.44 \cdot 10^{33} \text{ cm/cm/s}$
 World Record!
 design L = $10.0 \cdot 10^{33} \text{ cm/cm/s}$
 (Babar = $3.3 \cdot 10^{33}$)

Off-Resonance

10.52 GeV
 cross section = 3.08 nb
 Motivation : Background study
 2.3/fb = $6.4 \cdot 10^6$ Events on tape
 DST processing speed ~850/pb/day
 Analysis ~50 events/sec on i686 450MHz



November 29, 2001

PHENIX EMC-RICH Trigger

Rate estimates

CC	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0 (z1)
0-0.2	0.00031	0.00068	0.0014	0.0032	0.0072
0.2-0.4	0.00068	0.0015	0.0031	0.0070	0.016
0.4-0.6	0.0014	0.0030	0.0063	0.014	0.032
0.6-0.8	0.0032	0.0070	0.014	0.033	0.073
0.8-1.0	0.0072	0.016	0.032	0.073	0.16

Cq	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
0-0.2	0.0014	0.00063	0.0012	0.0027	0.0060
0.2-0.4	0.0029	0.0014	0.0027	0.0058	0.013
0.4-0.6	0.0061	0.0028	0.0055	0.012	0.027
0.6-0.8	0.014	0.0064	0.013	0.027	0.062
0.8-1.0	0.030	0.014	0.028	0.061	0.14

qq	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
0-0.2	0.0058	0.0027	0.0053	0.012	0.026
0.2-0.4	0.0027	0.0013	0.0025	0.0053	0.012
0.4-0.6	0.0053	0.0025	0.0048	0.010	0.024
0.6-0.8	0.012	0.0053	0.010	0.023	0.051
0.8-1.0	0.026	0.012	0.024	0.051	0.12

(Z2)

Estimate of
 $\delta(F^*F) = \delta A / \cos(\phi + \phi)$
 For $\sim 2.3/\text{fb} \sim 6\text{M Events}$

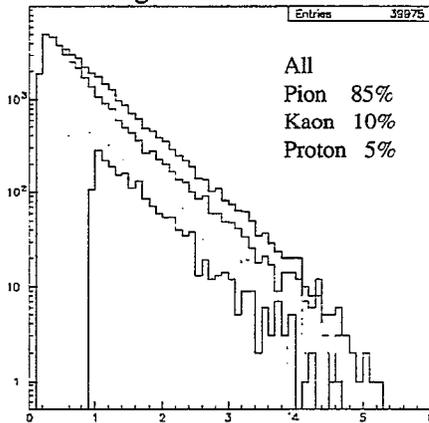
corresponding to ~ 2
 weeks of off resonance
 data taking on tape.

November 29, 2001

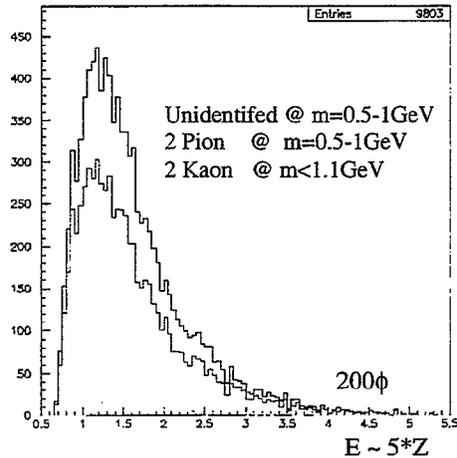
PHENIX EMC-RICH Trigger

z distributions

Charged Hadrons for Collins



Pairs for \tilde{q}_1



10K total / 5K hadronic Event \sim Belle has 1500 times more data



November 29, 2001

PHENIX EMC-RICH Trigger

Current Activities

Belle A small group of RHIC experimenters has joined Belle
Matthias G. Perdekamp (RBRC)
Ogawa Akio (Penn State Univ)
Soeren Lange (University of Frankfurt)

Belle collaborators:
Soeren Lange
Bruce Yabsley (KEK)

Theoretical aspects:
Daniel Boer (RBRC / Free University)
Robert Jaffe (MIT)

Delphi	Oliver Passon (Wuppertal Univ) Klaus Hamacher (Wuppertal Univ)
Opal	Albert de Roeck (CERN)
Babar	?
Cleo	??



November 29, 2001

PHENIX EMC-RICH Trigger

Conclusions

- $\delta q(x)$ remain as the last unmeasured leading twist distribution functions and have attracted strong theoretical interest. Experimental methods are at hand to access transversity distributions.
- HERMES and Belle will provide first reliable information on the size of the analyzing powers in the near future.
- RHIC's transversity program comprises several channels to access transversity. A rigorous program can be carried out with existing detectors and 10 weeks of beam time but require knowledge of certain fragmentation functions: Belle



November 29, 2001

PHENIX EMC-RICH Trigger

**Asymmetry Measurement of Charged Hadrons -
First Look at the Gluon Polarization in 2001**

Yuji Goto

***Asymmetry Measurement
of Charged Hadrons
– first look at the gluon polarization in 2001***

RBRC Review 2001

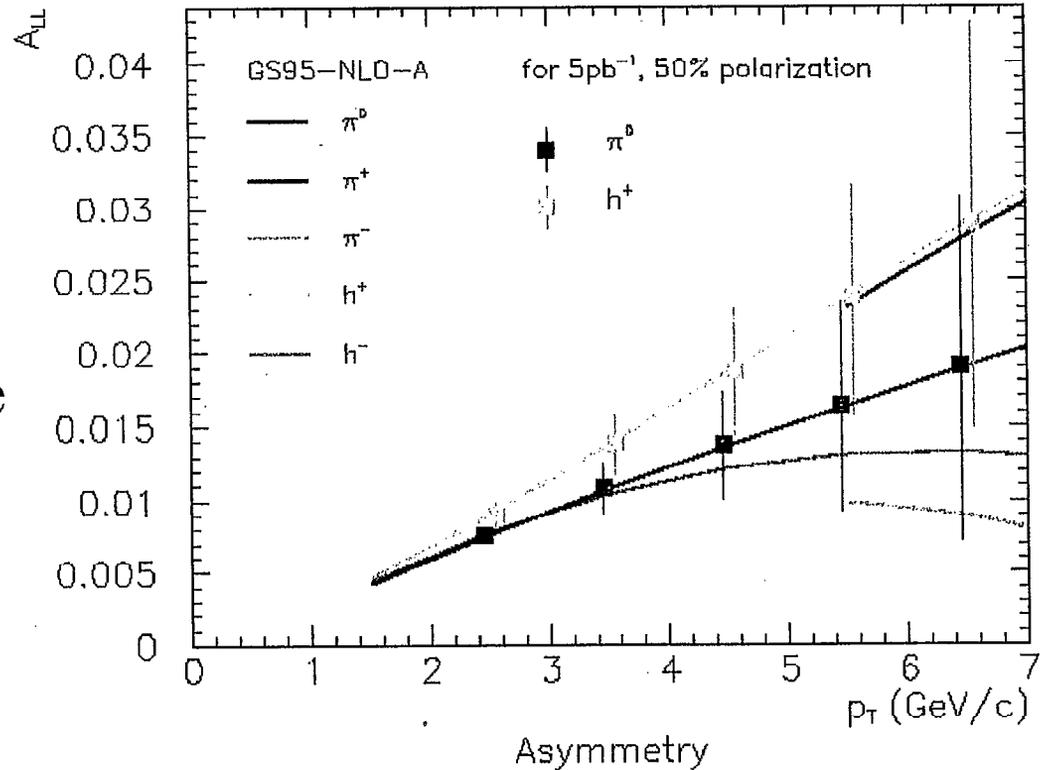
November 29, 2001

Yuji Goto

Spin physics with pions/hadrons

- π^0/π^\pm /charged-hadrons
 - gluon polarization information in 1st year of polarized proton collisions
 - different asymmetry for neutral/charged pions/hadrons by quark-flavor decomposition
- π^\pm /charged-hadrons in the PHENIX central arms
 - $2\text{GeV}/c < p_T < 5\text{GeV}/c$: no PID
 - $p_T > 5\text{GeV}/c$: π -ID by EMCAL/RICH

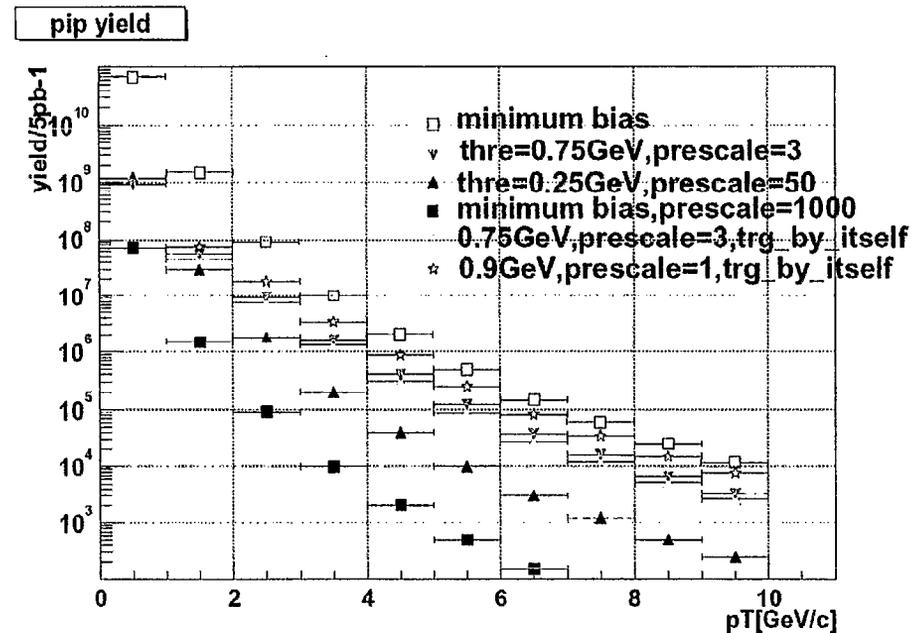
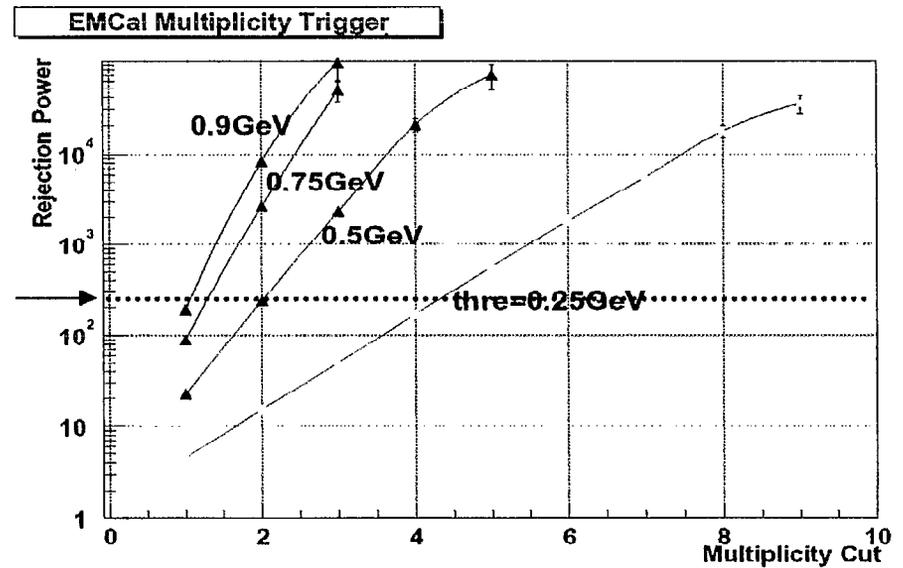
76



Charged hadron trigger

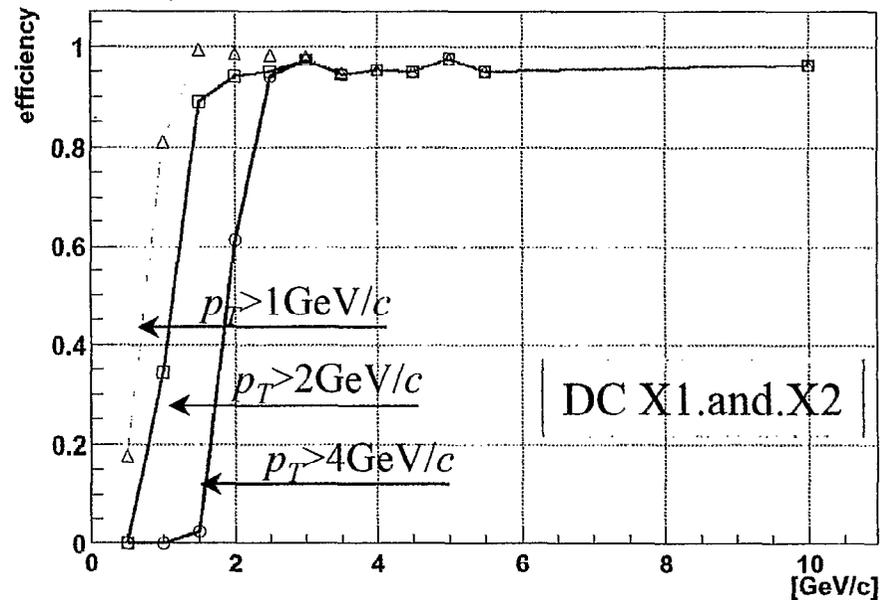
- requirements
 - yield \rightarrow efficiency
 - $\delta A_{LL} < 0.5\%$ in each bin required
 - 2×10^5 entries in each bin necessary for 50% polarization
 - trigger rate \rightarrow rejection factor
 - min.bias 250kHz at maximum
 - down to 2-3kHz by 1st-level trigger
 - down to 800Hz by 2nd-level trigger
- 1st-level trigger
 - EMCal multiplicity trigger for $p_T > 2\text{GeV}/c$
 - large trigger bias
 - \rightarrow inclusive trigger (multiplicity=1)

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Charged hadron trigger

- 2nd-level trigger
 - drift chamber (DC) trigger on the event builder
- proposal
 - 1st-level trigger
 - inclusive trigger
 - 0.9GeV threshold
 - rejection factor ~ 190
 - trigger rate $\sim 1.3\text{kHz}$
 - 2nd-level trigger
 - $p_T > 2\text{GeV}/c$
 - rejection factor ~ 6
 - trigger rate ~ 220



Electromagnetic Calorimeter: From Heavy Ion to Spin Physics

Alexander Bazilevsky



PHENIX

PHENIX EMCal: from Heavy Ion to Spin Physics

Alexander Bazilevsky

RBRC Scientific Review Committee Meeting
November 29-30, 2001

- ✓ Major results from Au-Au Run-2000
- ✓ Towards polarized-*pp* Run-2001

Run-2000 “EMCal” results

Au-Au at $\sqrt{s_{NN}}=130$ GeV

- Energy Density
 $dE_t/d\eta$
- Transverse energy scaling
 $dE_t/d\eta$ and $\langle E_t \rangle / \langle N_{ch} \rangle$ vs $N_{\text{participant}}$
- Jet Quenching?
Suppression of π^0 at large p_t

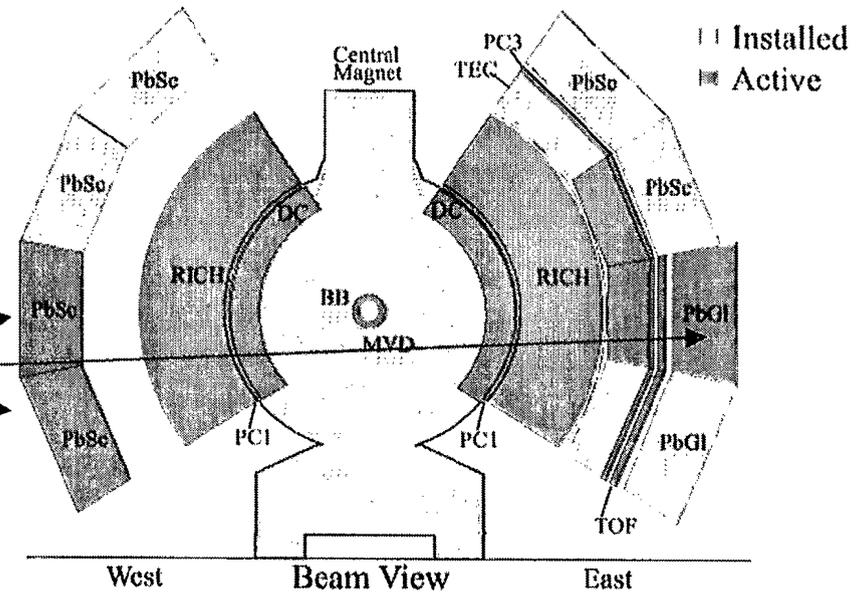
Run-2000 configuration

- **Two central arms**

- Mechanically ~complete
- Roughly half of aperture instrumented
- 3 EMCal sectors of 8 (2 PbSc + 1PbGl)

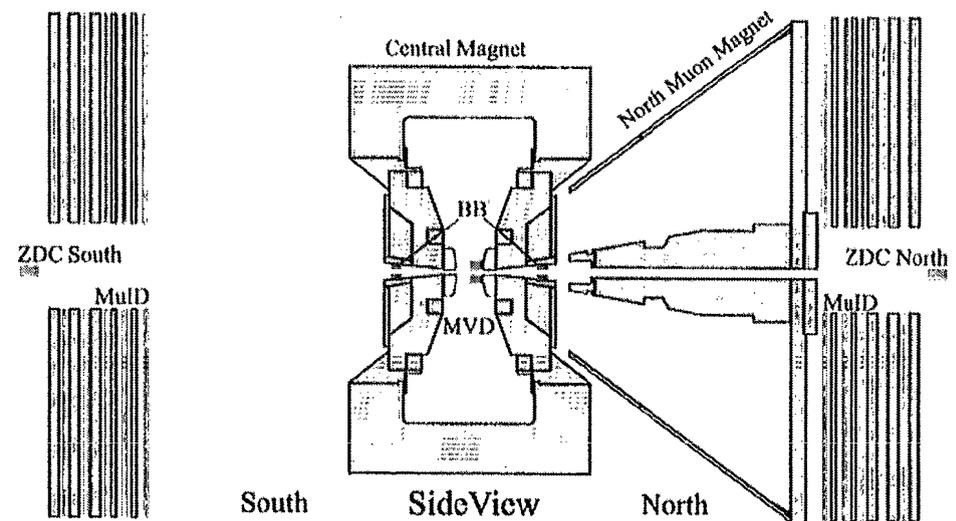
83

PHENIX Detector - First Year Physics Run



- **Global detectors**

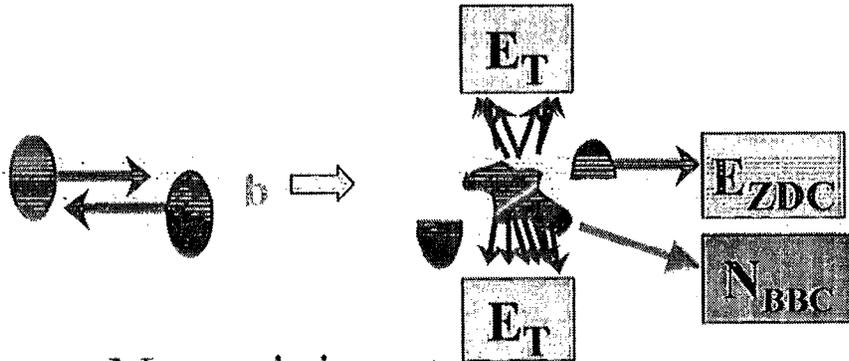
- Zero-degree Calorimeters (ZDCs)
- Beam-Beam Counters (BBCs)
- Multiplicity and Vertex Detector (MVD, engineering run)



Centrality Selection

Define centrality classes

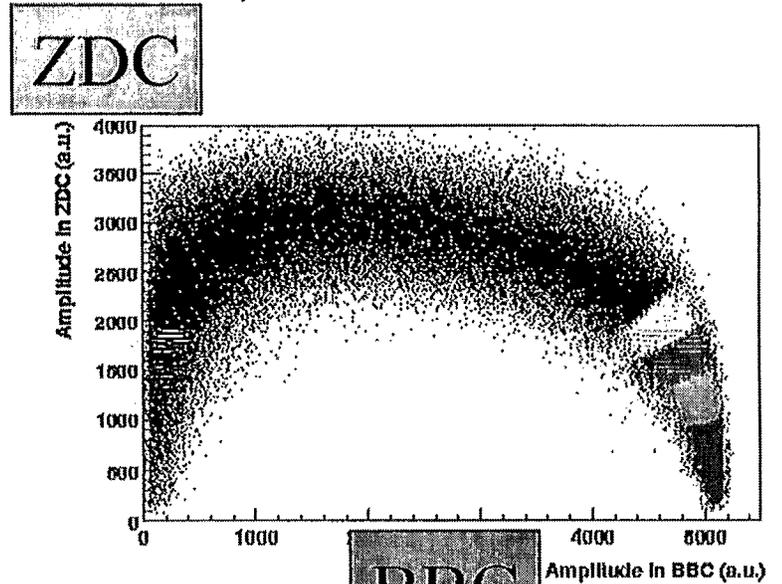
ZeroDegreeCalor vs BeamBeamCounter



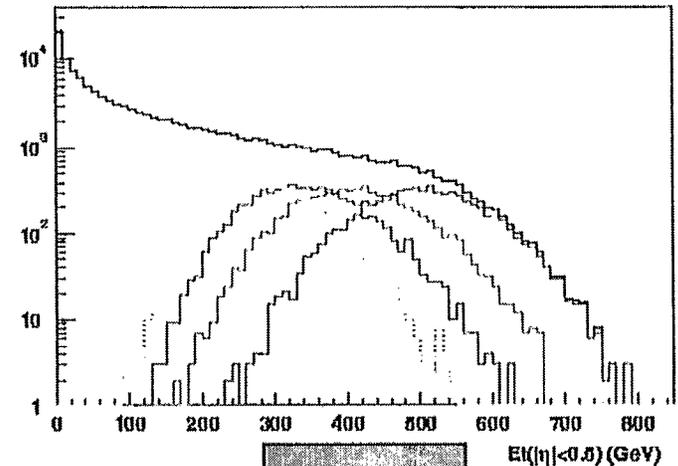
Extract N participants
Glauber model

Normalized to $\sigma=7.2$ b

0%-5%	$\langle E_T \rangle = 503$ GeV
5%-10%	$\langle E_T \rangle = 409$ GeV
10%-15%	$\langle E_T \rangle = 340$ GeV



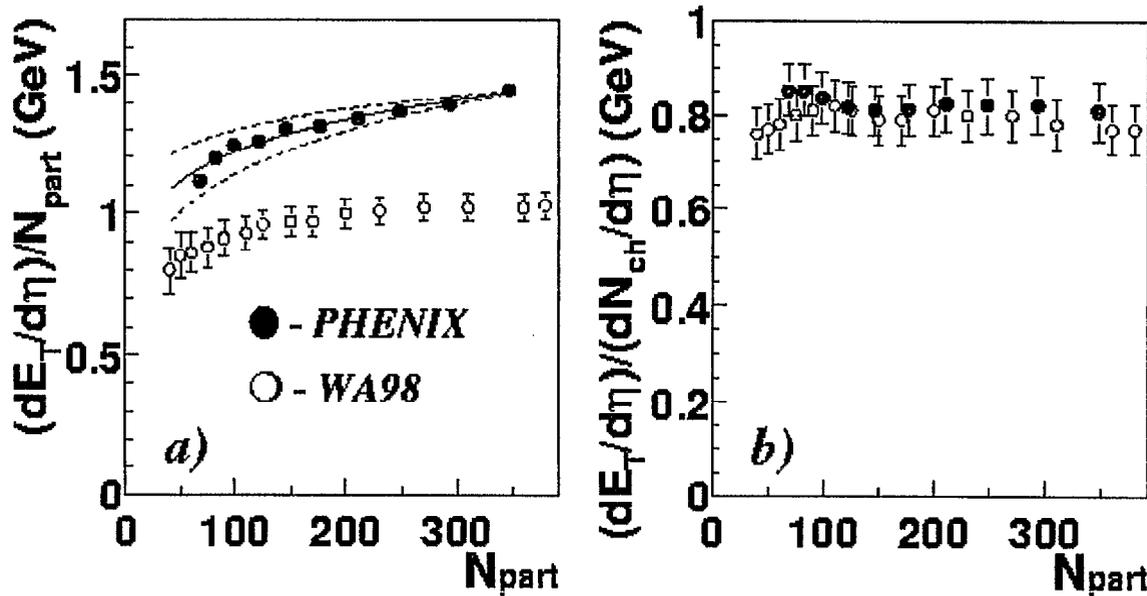
$dN/d\eta$



EMC

Et vs N of participants

PRL 87 (2001) 052301



✓ Fit: $dE_t/d\eta \propto N_{part}^\alpha$:
 PHENIX: $\alpha=1.13\pm0.05$
 WA98: $\alpha=1.08\pm0.06$

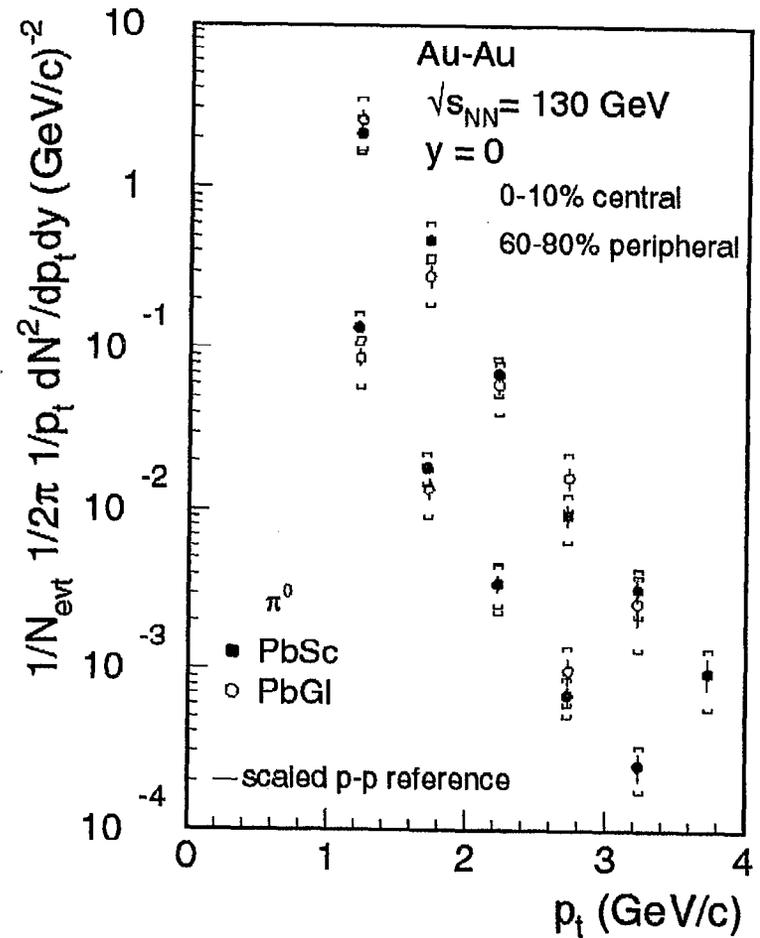
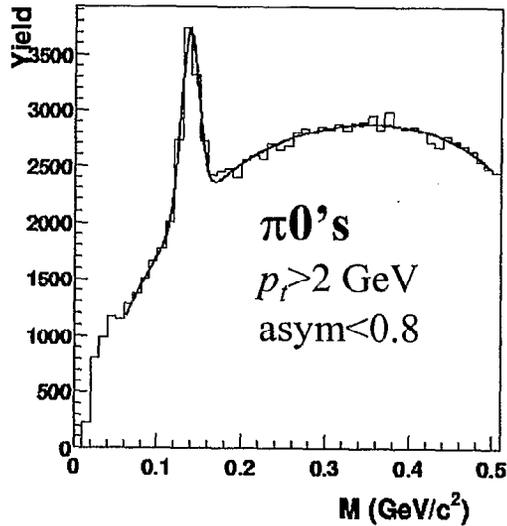
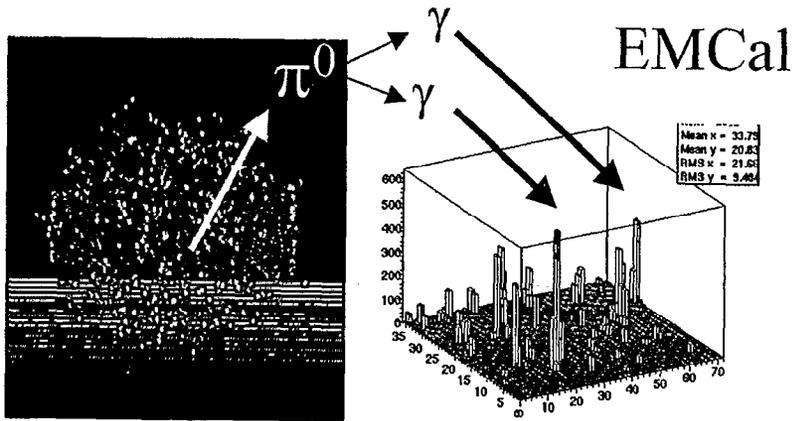
✓ $\langle E_t \rangle / \langle N_{ch} \rangle$ remains constant with N_{part}
 Additional energy density achieved by increase in particle production

Energy density (Bjorken)

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy}$$

$$\varepsilon \sim 4.6 \text{ GeV/fm}^3 \sim 1.6 \times \text{CERN}$$

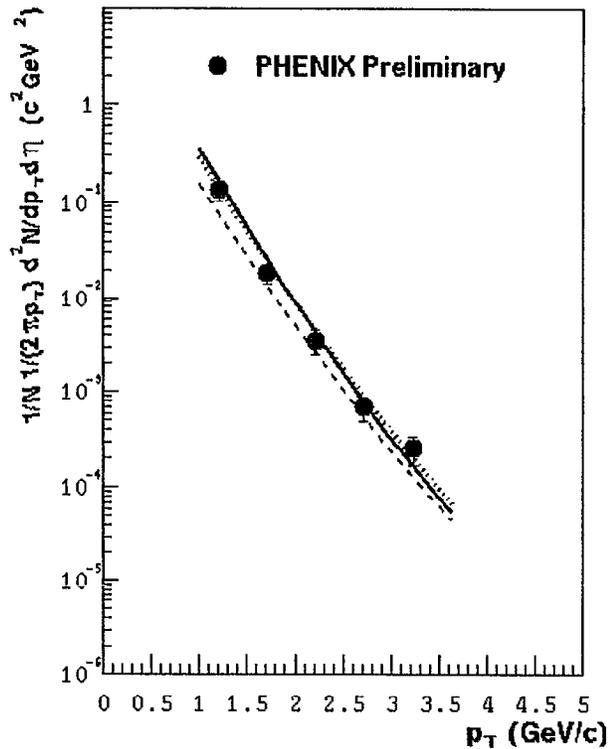
π^0 reconstruction



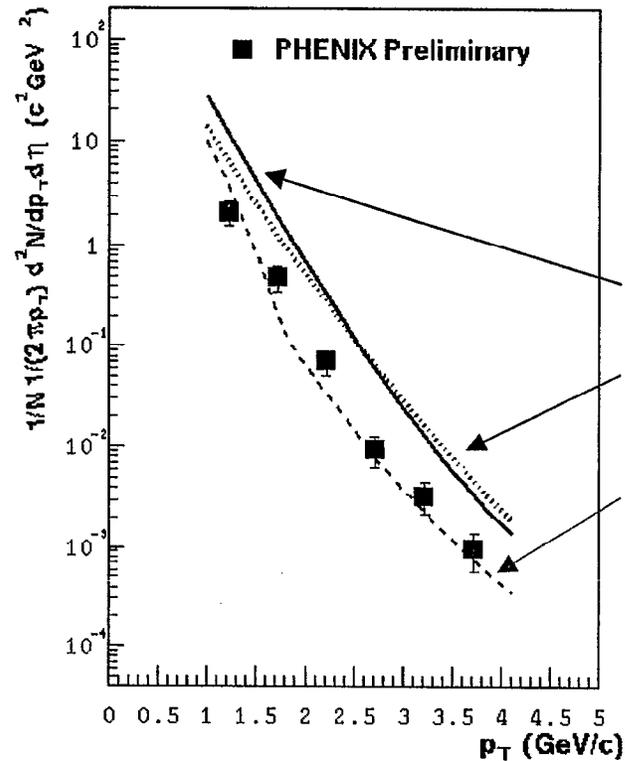
Results from PbSc and PbGl
are consistent

π^0 p_t distribution

Peripheral



10% central



X.N. Wang, Phys. Rev. C61, 064910 (2000).

no nuclear effects
 pt-broadening +
 Shadowing
 $dE/dx = 0.25$ GeV/fm

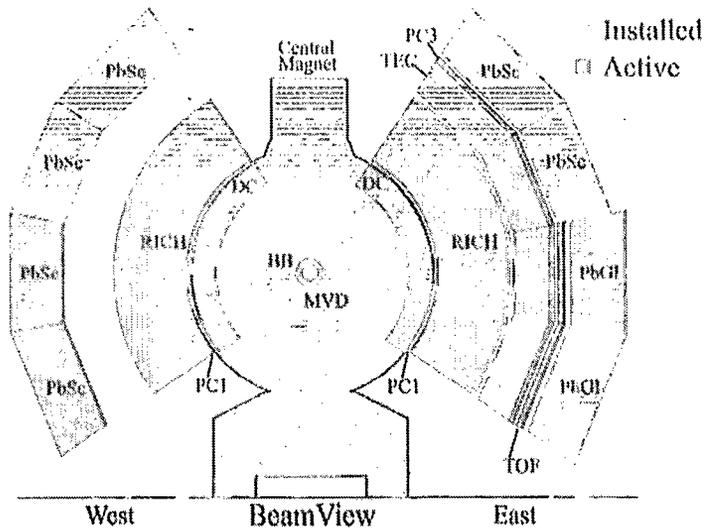
☐ Good agreement with pQCD calculations

☐ pQCD overestimates the cross section \Rightarrow Jet Quenching ?

From Run-2000 to Run-2001

Run-2000

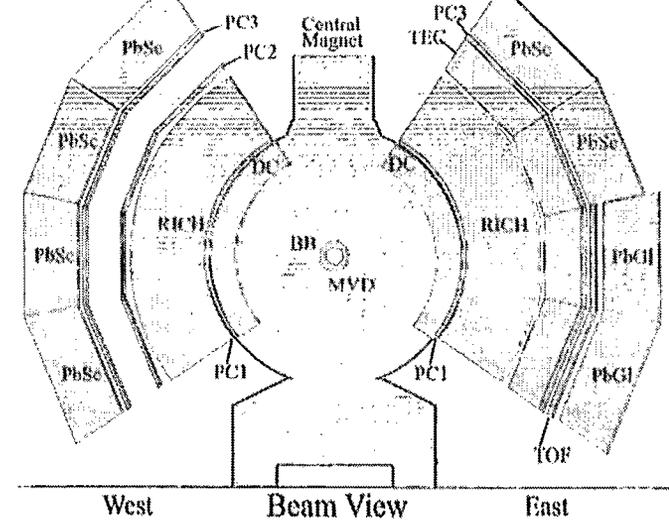
PHENIX Detector - First Year Physics Run



3 EMCAL sectors
(2 PbSc + 1 PbGl)

Run-2001

PHENIX Detector



8 EMCAL sectors
(6 PbSc + 2 PbGl)

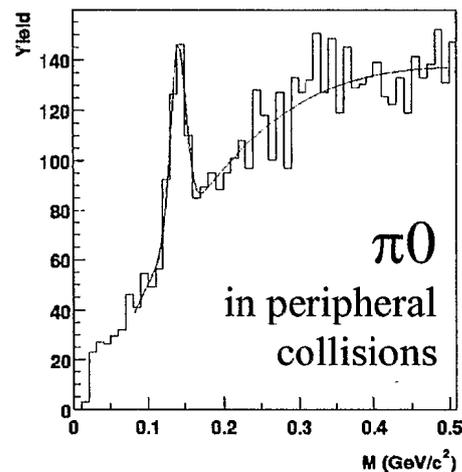
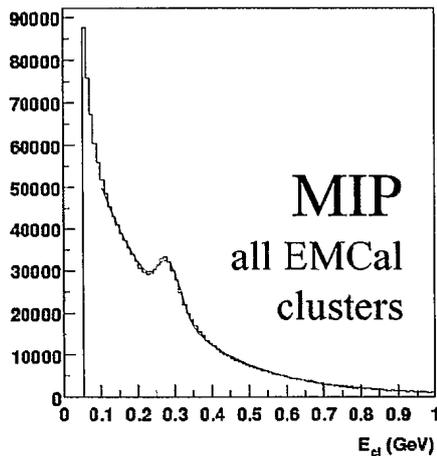
Run-2001 Au-Au data

EMCal calibration

- ✓ Set with MIP peak position on the SuperModule level (12x12 towers)
 - Residual tower by tower variation is $\sim 5\%$
 - Global calibration accuracy is within 1.5%
- ✓ Checked with π^0 mass peak
 - accuracy about 2% - limited statistics

PHENIX preliminary results

Will be ready by
the time of presentation



EMCal in pol-*pp* run-2001

EMCal main goal in coming pol-*pp* run:

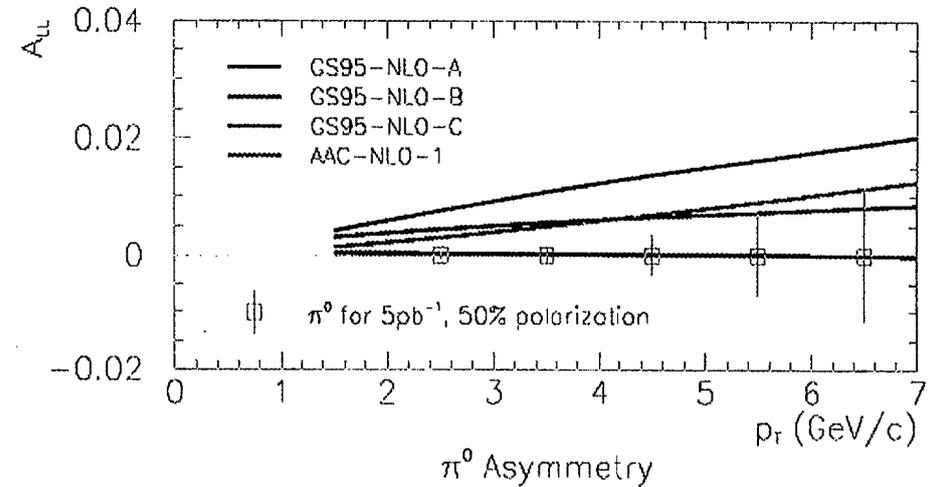
First measurements of Δg through π^0 production asymmetry in longitudinally polarized proton collisions

$$A_{LL}^{EXP} = \frac{1}{P_{B1} P_{B2}} \cdot \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

P – Beam polarization

N – Number of events

L – Luminosity

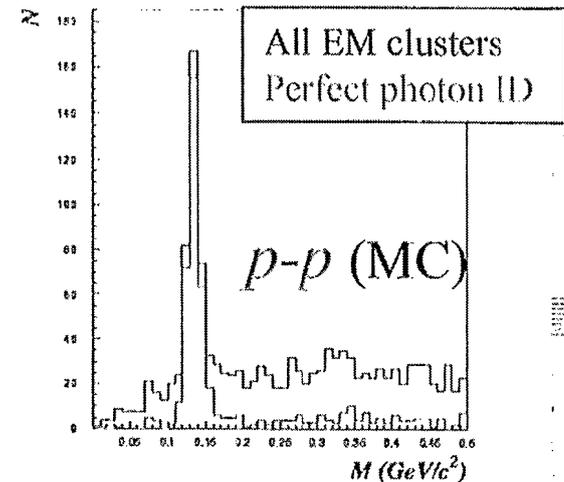
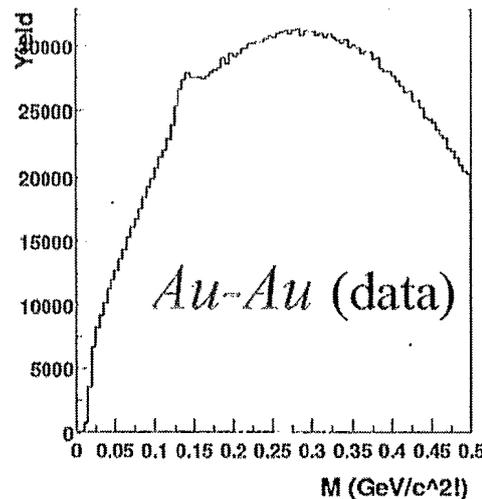


π^0 reconstruction: from *Au-Au* to *p-p*

$\sim 1M$ “minibias” events

$P_T(\gamma\gamma) > 2 \text{ GeV}/c$

p-p “life” is much easier than *Au-Au*

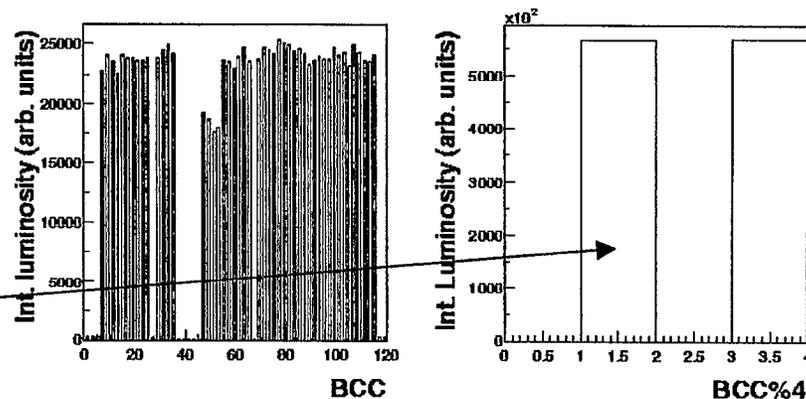


Asymmetry measurements

55 bunches (of 120) filled (only odd numbers)

Asymmetry measurement
exercise done in Au-Au data

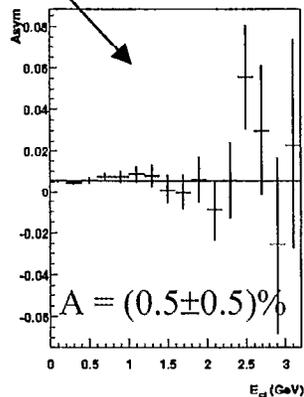
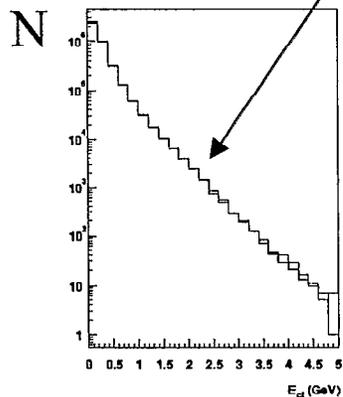
$$A_{LL} = \frac{N_{black}/L_{black} - N_{red}/L_{red}}{N_{black}/L_{black} + N_{red}/L_{red}}$$



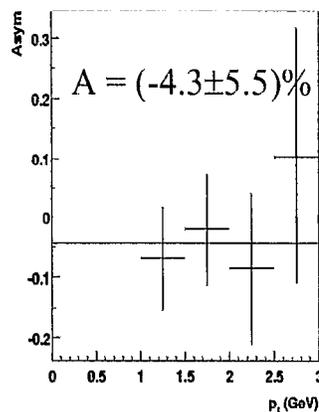
Assuming bunches # 1,5,9 ...
with parallel polarization
Assuming bunches # 3,7,11 ...
with anti-parallel polarization

T6

Photon-like clusters in EMCal



π^0 's



So far so good:
no (false) asymmetries
in Au-Au data

Summary

- ❑ First interesting (and intriguing !) results obtained in Au-Au collisions at $\sqrt{s_{NN}}=130$ GeV
- ❑ New data collected in Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV; first results already coming
- ❑ First data from polarized proton collisions coming soon; EMCal ready for first data analysis

Hunting for Physics Beyond the Standard Model at RHIC with Parity Violation

Jiro Murata

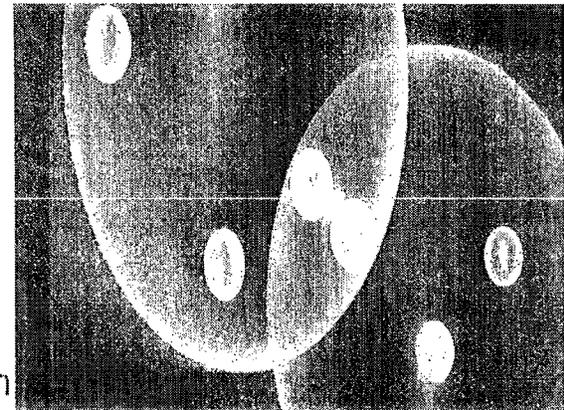


Simulation Study for Hunting Contact Interaction at RHIC

Jiro Murata

Contents

- Overview of BYSM at RHIC
- Event generator for BYSM physics
- Contact Interaction
- Simulation Formalism
- Interference Correction
- Results on Drell-Yan
- Results on Jet Production
- Fine Structure of Jacobean Peak
- Comparison with Other Theoretical Calculation
- PV in pion production
- Strategy to the GOAL





Overview of BYSM in RHIC

RHIC-Spin

RHIC: polarized proton-proton collider at $\sqrt{s} = 200, 500, (650) \text{ GeV}$

Provide Various Symmetry Test in Hadronic Reaction

➡ BYSM Asymmetries ?

Beam Energy isn't too low ???

RHIC 0.5 TeV (850pb⁻¹)

TEVATRON 2 TeV (30fb⁻¹) by 2006

LHC 14 TeV (100fb⁻¹)

Systematic Error can be significantly suppressed by measuring spin asymmetries

Beam polarization makes RHIC competitive to TEVATRON Run IIb!

Next generation lepton colliders also needs beam polarization to compete with hadron colliders.

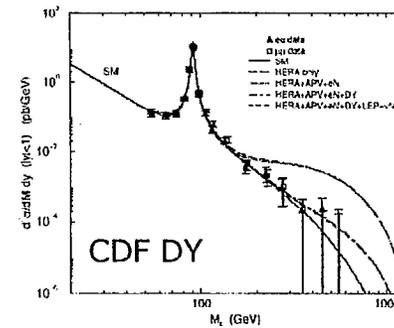
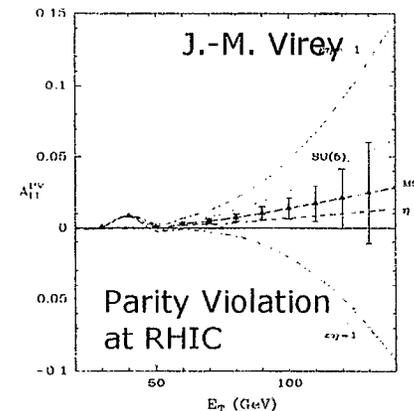


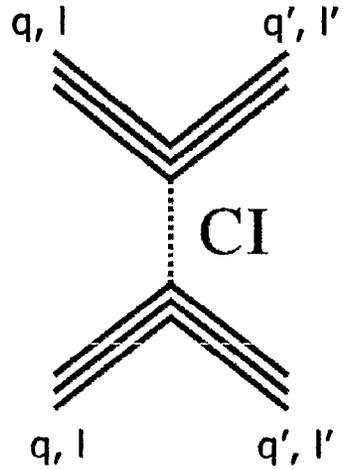
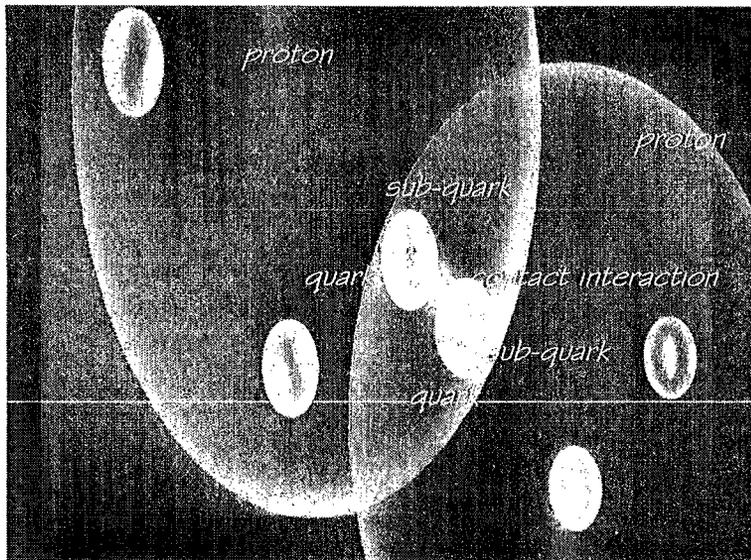
FIG. 2. The differential cross-section $d^2\sigma/dM_T dy$ (pb/GeV) as a function of M_T (GeV) for the SM (solid line) and the four different contact interactions (dashed, dotted, dash-dotted, and long-dashed lines) for the HERA data (open circles) and the HERA/APV/e⁺e⁻ data (open squares) (see Table III). The cross-section is averaged over $y = \pm 1/3$ and $\sqrt{s} = 200$ GeV.





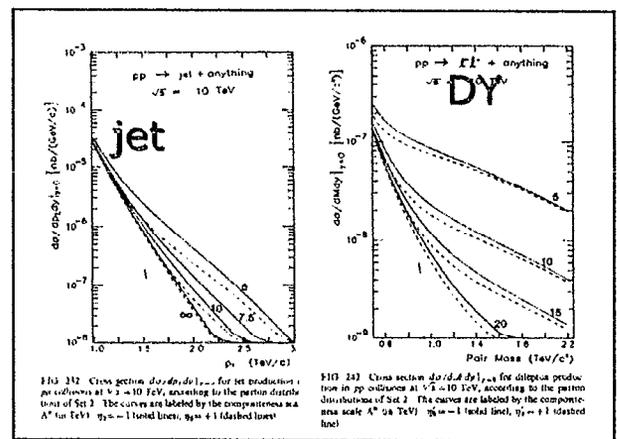
Contact Interaction, (quark/lepton) Compositeness

Model Independent Scale Parameter Λ



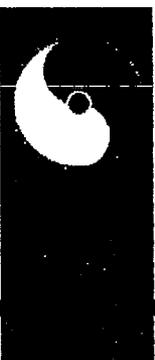
quark (lepton)
Form Factor

$$F(Q^2) = \frac{1}{1+Q^2/\Lambda^2}$$



E. Eichten et al;
Rev.Mod.Phys.v56,n4 (84) 579

**Interference bet. SM & CI : Positive or Negative
Coupling Chirality: Left-handed - Right-handed**
Contact Interaction can be Parity Violating Interaction



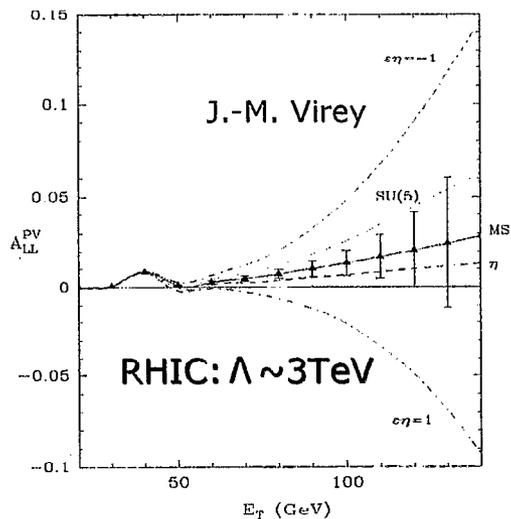
Motivation for the Simulation Study

Symmetry Test @ RHIC



Physics Beyond Standard Model !?
NEED Simulation as SM Reference

Parity Violation on Jet Production



un-polarized

- New Physics in PYTHIA
- 4th generation fermions
- New gauge boson
- Leptoquarks
- Compositeness
- Excited fermions
- Technicolor

polarized

Pol-PDF
Matrix Elements



Asymmetry Weight

1. *Cross Check of Theoretical Calculation using same Matrix Elements and pol-PDF (SM+CI)*
2. *Full Detector Simulation using Event Generator for Direct Comparison (SM)*

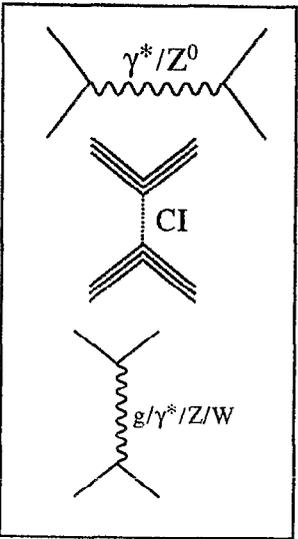
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Interference Effect and New Interaction in PYTHIA

DY: $\gamma + Z + \gamma\text{-}Z$
 $+ CI + \gamma\text{-}CI + Z\text{-}CI$
 ISUB 165 (Single Sub-Process)

Jet: $g + \gamma + Z + W$
 $+ g\text{-}\gamma + g\text{-}Z + g\text{-}W + \gamma\text{-}Z + \gamma\text{-}W + Z\text{-}W$
 $+ CI + g\text{-}CI + \gamma\text{-}CI + Z\text{-}CI + W\text{-}CI$
 QCD: ISUB 11,12 = $g + CI + g\text{-}CI$
 EW: ISUB 165, 166 = $\gamma + Z + W + \gamma\text{-}Z + \gamma\text{-}W + Z\text{-}W$
 $+ CI + \gamma\text{-}CI + Z\text{-}CI + W\text{-}CI$



Separating sub-process: QCD + EW = No Interference !
 No Way to include QCD-EW Interference: $g\text{-}\gamma + g\text{-}Z + g\text{-}W$

Event Generation -> QCD process only
 Event by Event Weight for Asymmetry Weight:

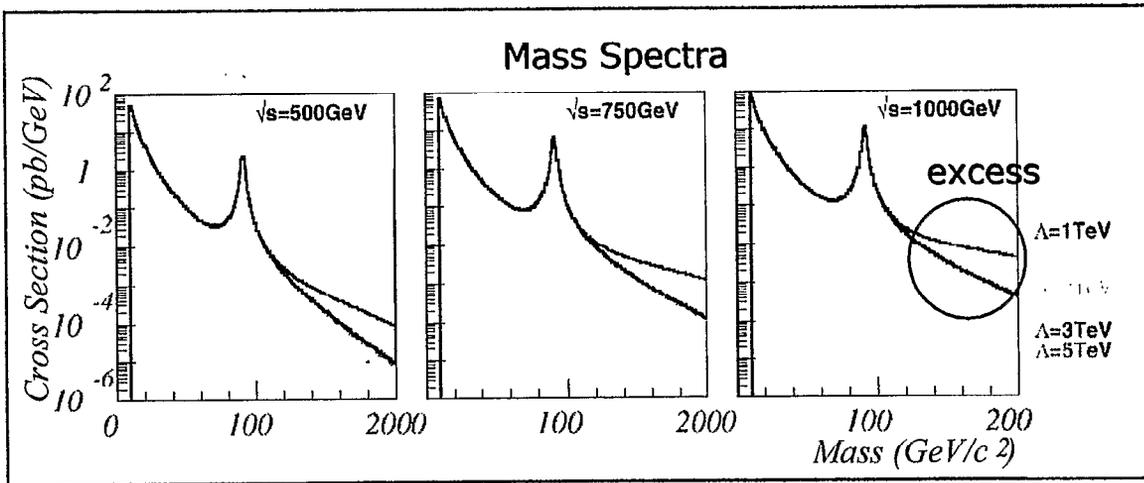
$$Weight \rightarrow Weight \times \frac{\sum_{process} \sigma_{process}}{\sigma_{process=|QCD|^2}}$$

96



Event Generation Results on Drell-Yan Process

100



PYTHIA ONLY
 Constructive Interference ($\epsilon = 1$)
 MSTP(5)=4 all quarks are composite
 KFPR(165)=13 CI goes muon channel
 Pure Left-handed (Small Effect)

Dominant Term $\propto \frac{1}{\Lambda^2}$

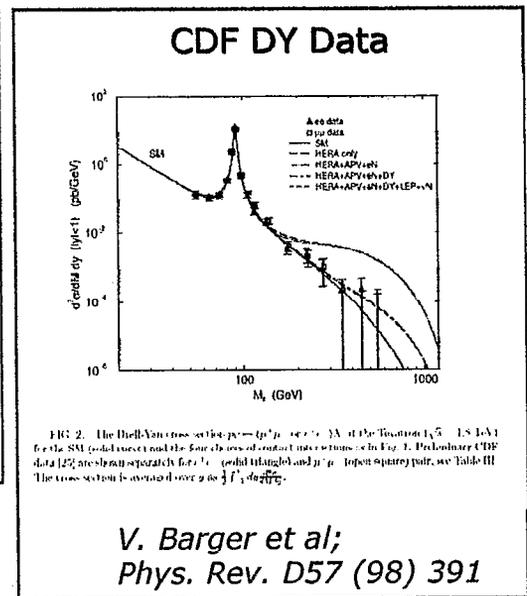


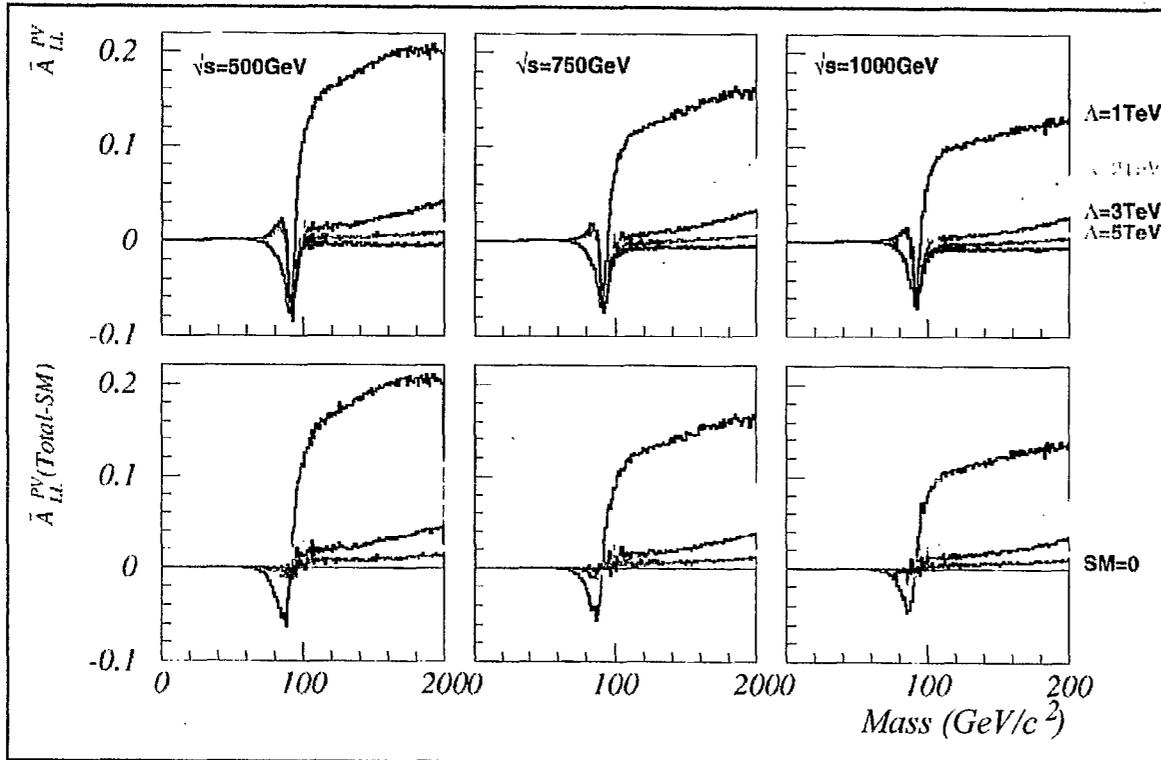
FIG. 2. The Drell-Yan cross section $\sigma_{DY}(p^+p^- \rightarrow \mu^+\mu^-)$ at the location $\sqrt{s} = 1.8$ TeV for the SM (solid lines) and the four cases of contact interactions (see Fig. 1). Preliminary CDF data [22] are shown separately for e^+e^- (open triangles) and $\mu^+\mu^-$ (open squares) pairs, see Table III. The cross section is averaged over 2π in ϕ , $d\sigma/dy$.

V. Barger et al;
 Phys. Rev. D57 (98) 391



Expected Parity Violation for Drell-Yan

101



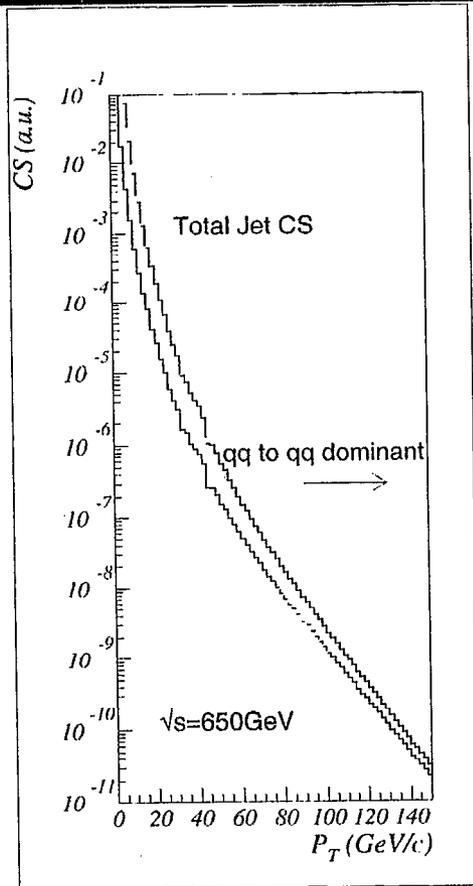
Constructive Interference
Pure Left-handed
PDF: GS95NLO-A
pp->dimuon

Sensitive Region
1. $\sim 80\text{GeV} < \text{Mass} < Z$
2. $\text{Mass} > Z$



Simulate quark-quark Contact Interaction

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$gg \rightarrow gg$
 $gg \rightarrow q\bar{q}$
 $q\bar{q} \rightarrow gg$
 $qg \rightarrow qg$

g

82 Terms [DY:6 Terms]

$qq \rightarrow qq$
 $\bar{q}\bar{q} \rightarrow \bar{q}\bar{q}$
 $q\bar{q} \rightarrow q\bar{q}$

g, γ , Z, g- γ , g-Z, γ -Z
CI, g-CI, γ -CI, Z-CI

$qq' \rightarrow qq'$
 $\bar{q}\bar{q}' \rightarrow \bar{q}\bar{q}'$
 $q\bar{q}' \rightarrow q\bar{q}'$
 $q\bar{q} \rightarrow q'\bar{q}'$

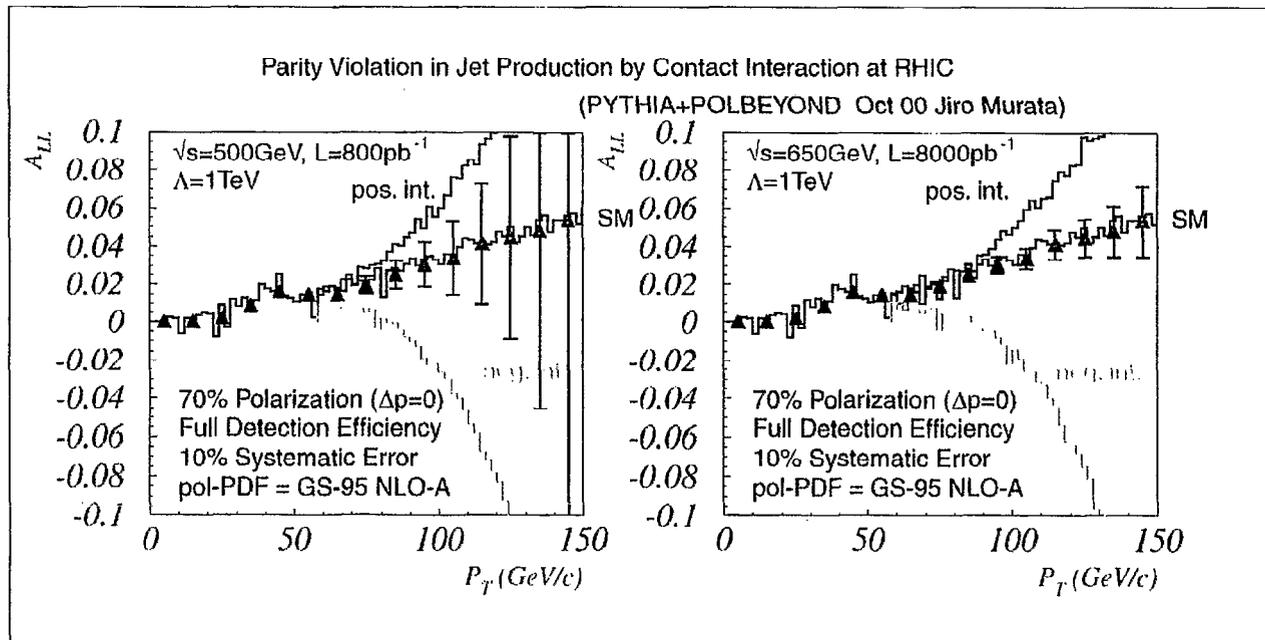
g, γ , Z, W, γ -Z, g-W, γ -W, Z-W
CI, γ -CI, Z-CI, W-CI

Should Have C.I. Sensitivity on high Pt !



Sensitivity of the Contact Interaction in Jet Asymmetry

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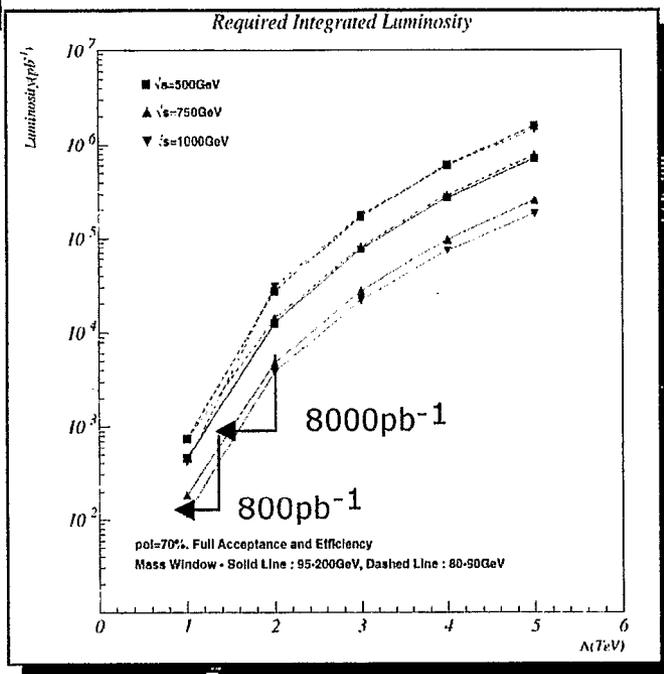


Event Generation = QCD + EW (Separated Sub-Processes)
-> Interference bet. QCD & EW was not correctly treated
Without Interference Correction



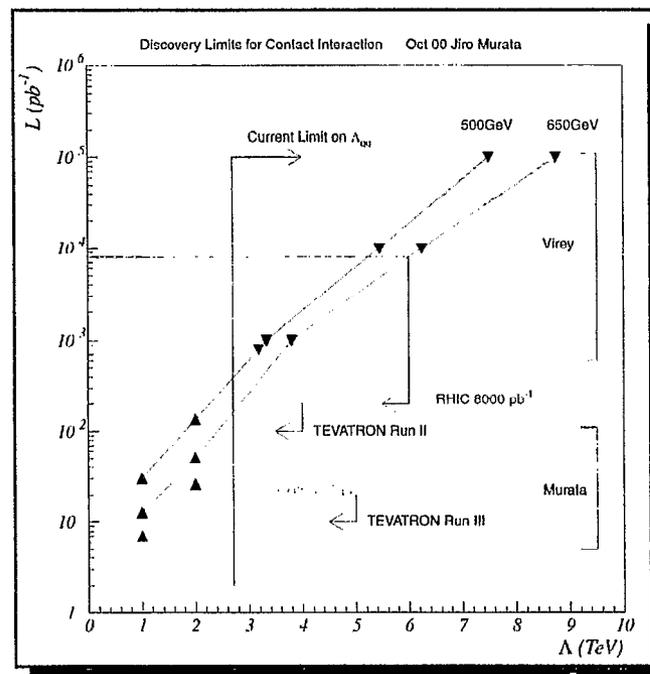
Discovery Limit on Drell-Yan and Jet Production Processes

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Λ limit < 1.2 TeV @ 800 pb

Clean, but small statics ...



If chirality -> Full Parity Violation

Λ limit ~ 3.2 TeV @ 800 pb⁻¹

Now we see that we can have sensitivity !

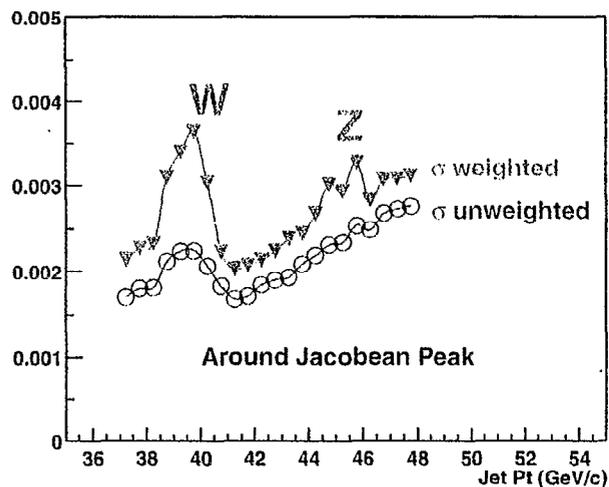
What we must do is a precise SM calculation as reference



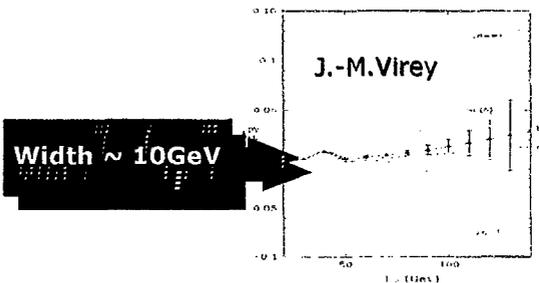
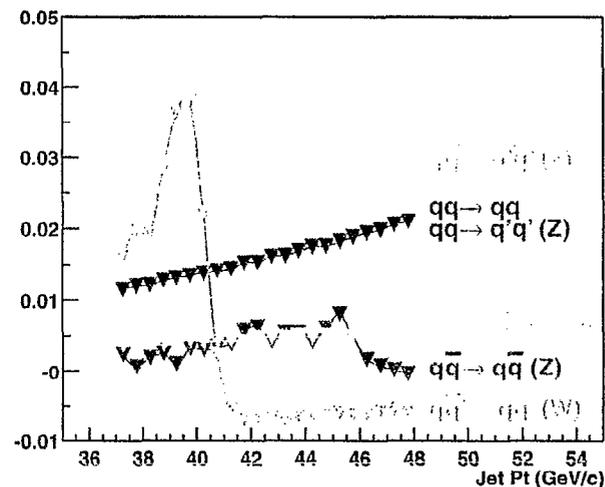
After Interference Correction; Fine Structure of the Jacobean Peak

105

Total PV Asymmetry



Process Separated PV Asymmetry

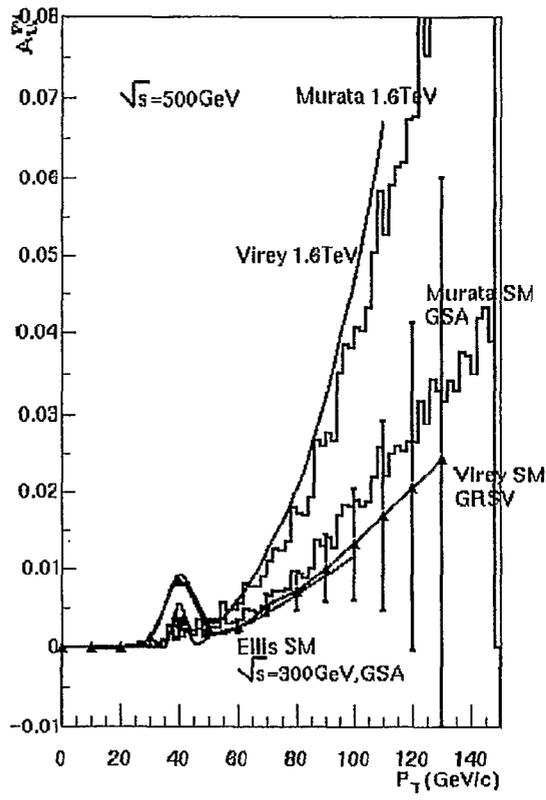


Jacobian Peak Width \sim W Width
Major Process : $q \bar{q}' \rightarrow q \bar{q}'$
(Dominant: QCD-W, QCD-Z Int.)
A little Z Contribution



Comparison with Other Theoretical Calculations

PV Asymmetry A_{LL}^{PV} for Inclusive Jet



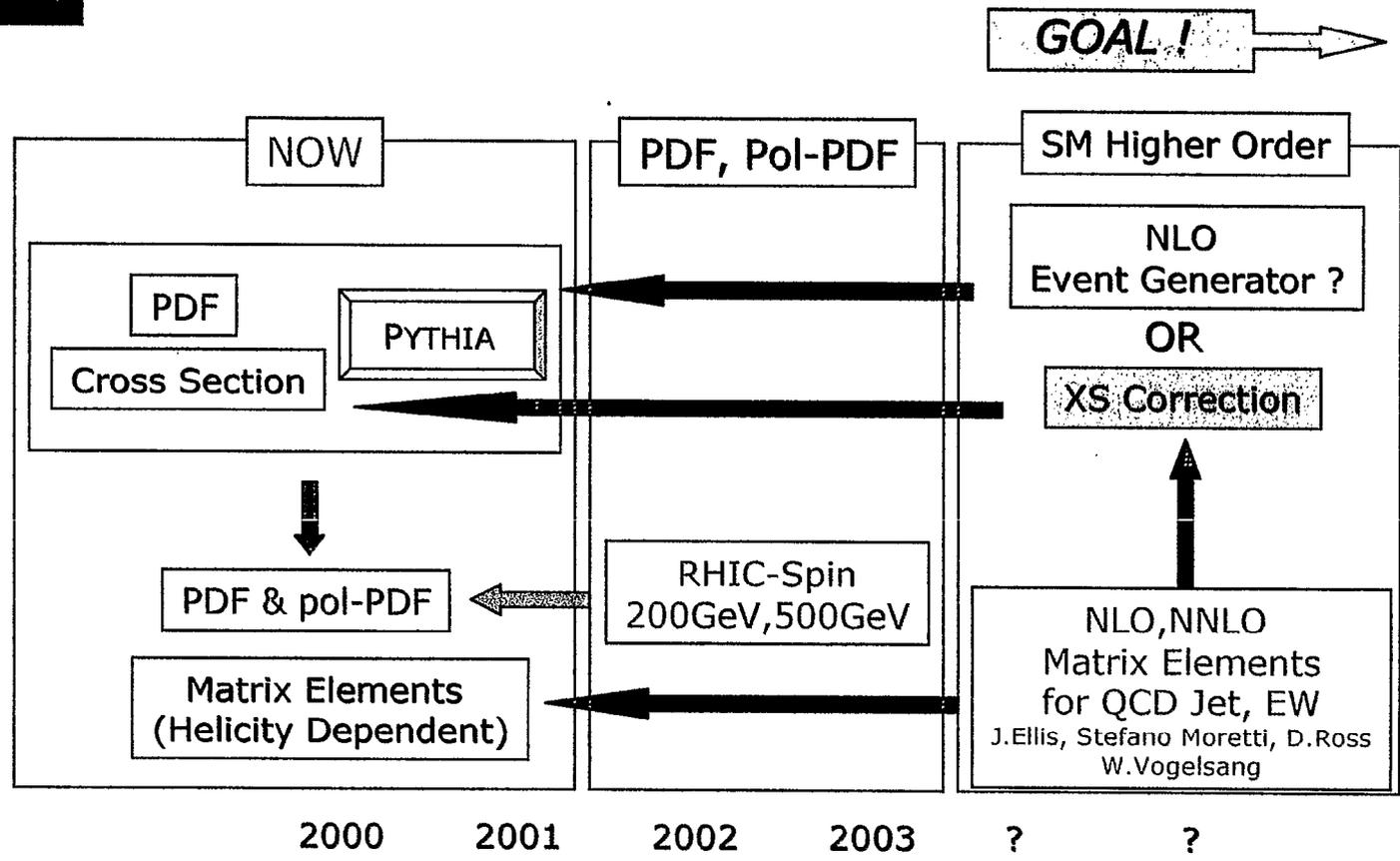
- Present Study 500GeV, GSA, $\gamma \sim 0$, LO
SM & Lambda=1.6TeV
 - J. -M. Virey 500GeV, GRSV, $\gamma=0$, LO
SM & Lambda=1.6TeV
 - J. Ellis et al. 300GeV & 600GeV, GSA, $\gamma=0$, NLO
SM
- NLO Dependence is $\sim 1\%$
 PDF Dependence should be studied
 Jacobean Peak is sensitive to interference treatment

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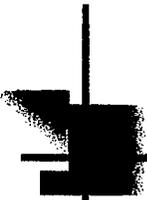
Strategy

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Polarimetry for RHIC

Kazu Kurita



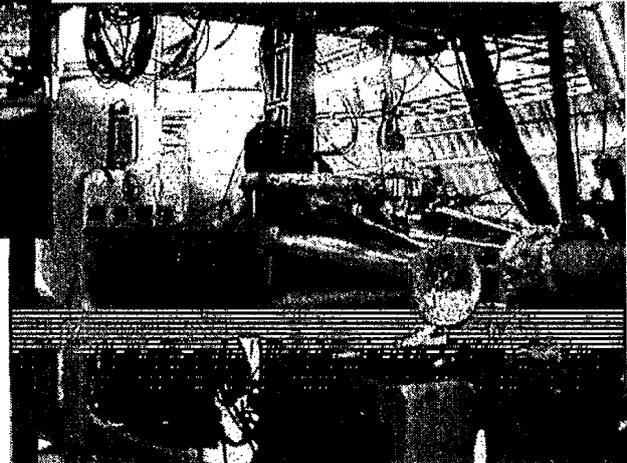
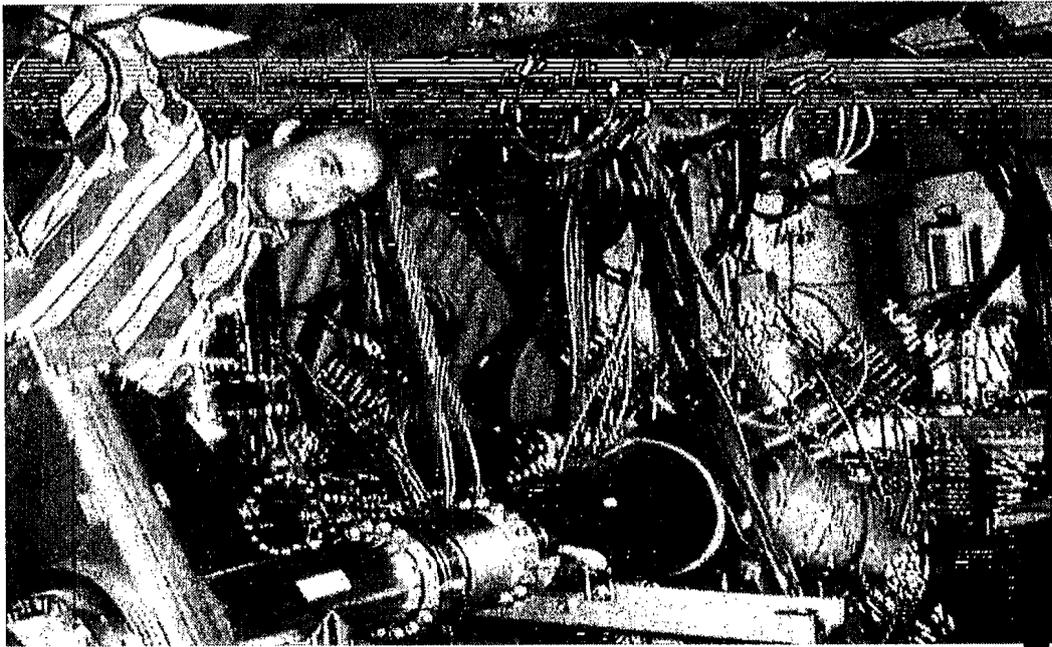
RHIC Polarimeter

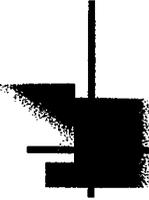
RBRC Review
Nov. 29, 2001
Kazu Kurita (RBRC)

Outline

- RHIC Polarimeter
 - 1, run2001 configuration
 - 2, WFD readout
 - 3, RHIC control and the format
- 200MeV Polarimeter Calibration

Two Polarimeters in RHIC





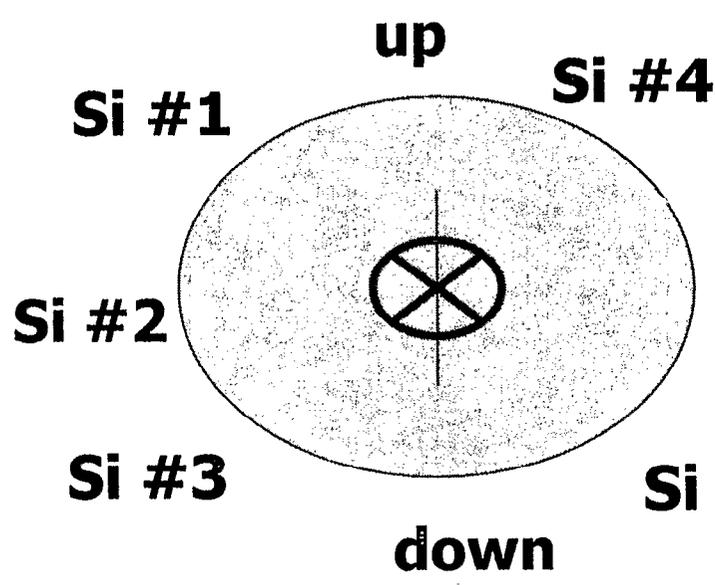
Run2001 Configuration

- Blue and Yellow polarimeters
- Six Si detectors in each rings
- 12x6 strips * 2 rings = 144 strips
- WFD 4 ch x 12 modules = 48
- Two snakes in each rings

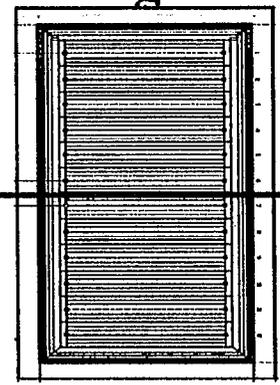


Si Detector Orientation

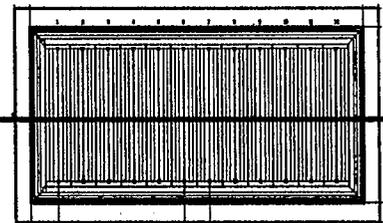
2001 configuration



45 degree Si

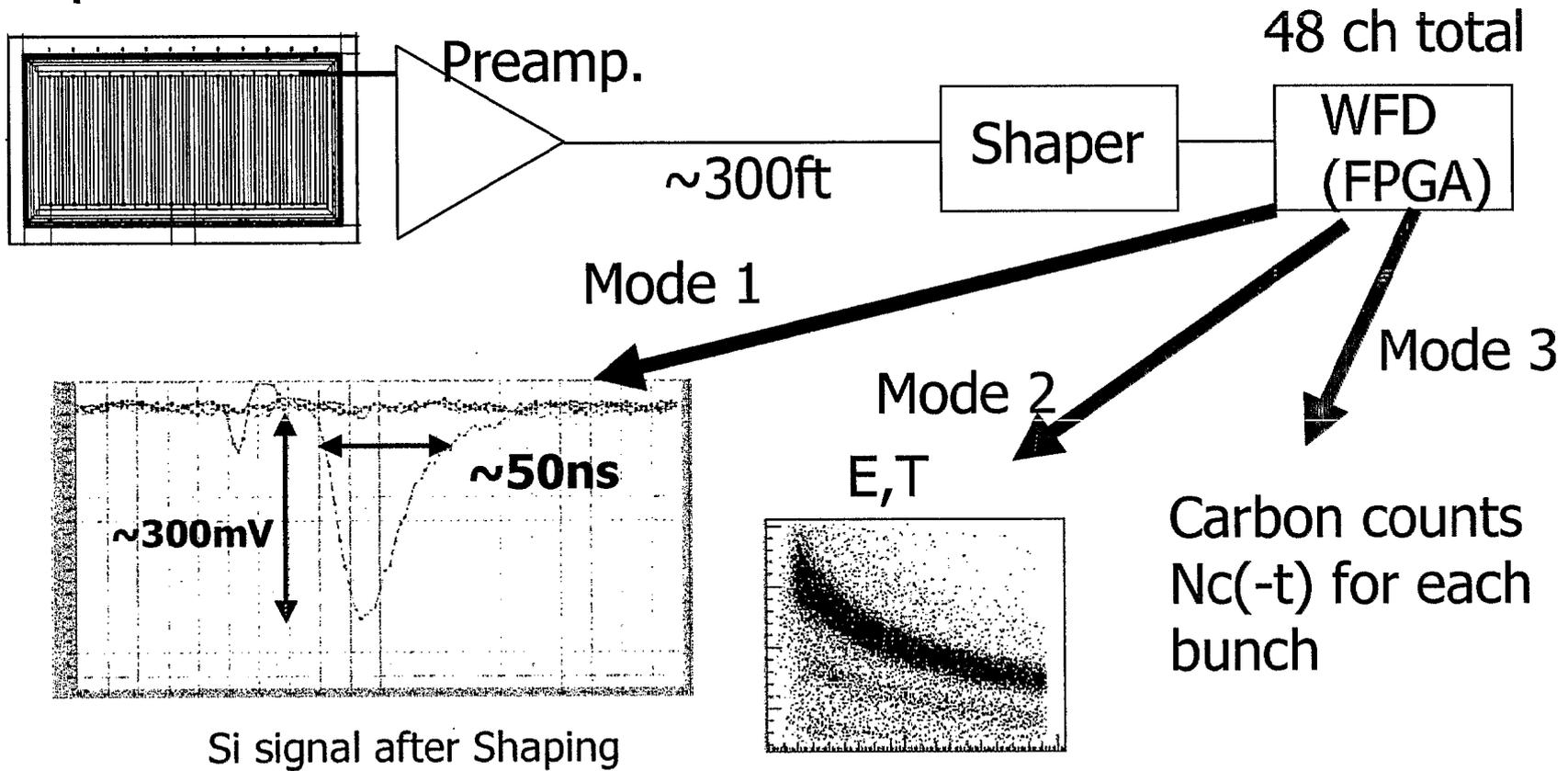


Si #5



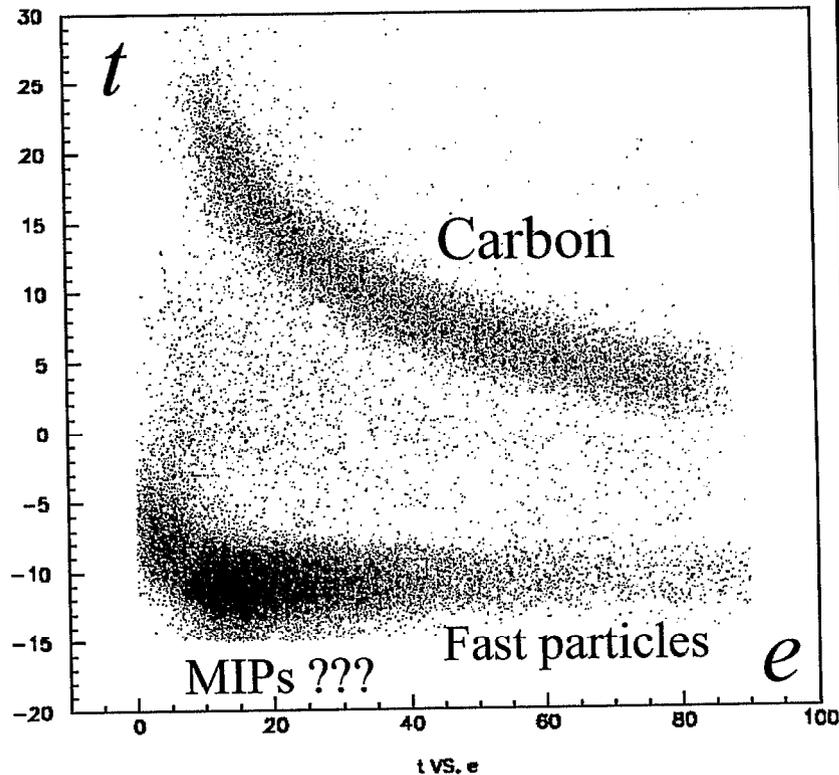
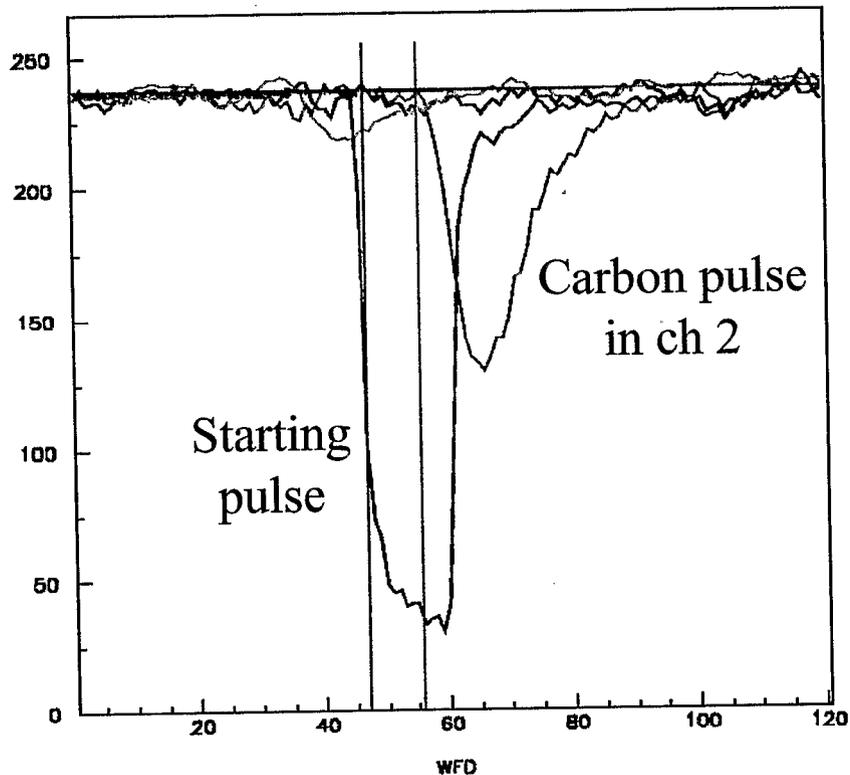
90 degree Si

Si Detector Read Out



WFD commissioning last year

RSC Meeting

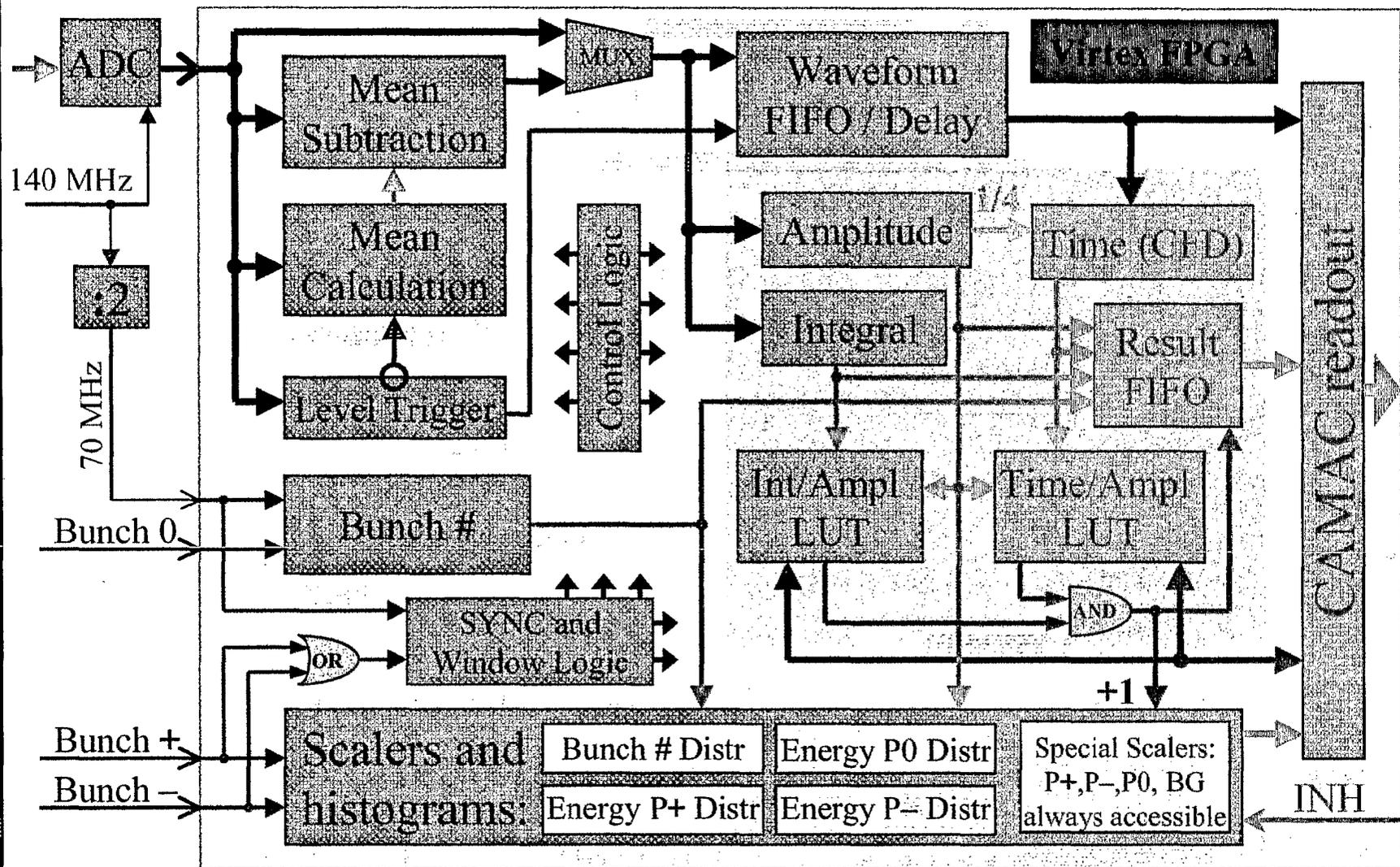


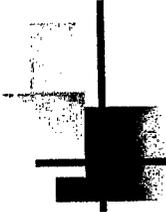
- 1 WFD module V1, 4 channels
- Common external trigger, 3 chans relative to reference pulse on ch. 4
- Waveforms are read to PC

- Off-line event reconstruction

FPGA Block Diagram

RSC Meeting

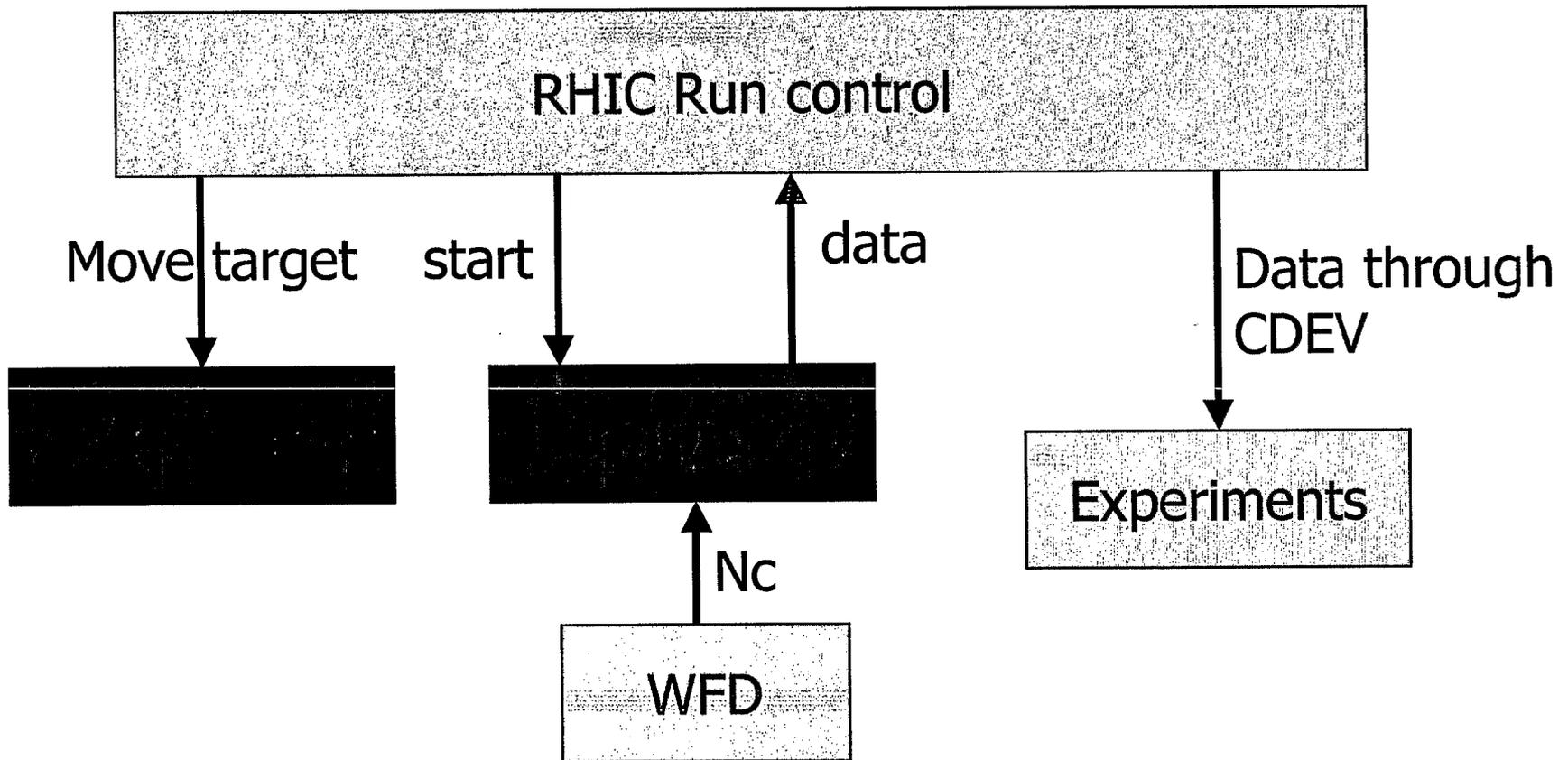




Histograms Archived at 1012

- Bunch by bunch Carbon counts within defined energy range
- Energy dependent Carbon counts for +,-,0 beam bunches
- 32 T x 16(8) E banana plot (New)

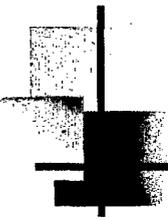
RHIC Run Control





Data format

```
typedef struct {
  double runIdS; // FILL.XXX --- where XXX is the run number
  long startTimeS; // Unix time
  long stopTimeS; // Unix time
  char daqVersionS[80];
  char cutIdS[80];
  char targetIdS[80]; // "Horz.tagret3" or "Vert.target6" etc.
  long encoderPositionS[2];
  long statusS; // bit pattern if <0 data is not usable
  char statusStringS[80];
  long totalCountsS;
  long upCountsS;
  long downCountsS;
  long unpolCountsS;
  long countsUpLeftS[360];
  long countsLeftS[360];
  long countsDownLeftS[360];
  long countsDownRightS[360];
  long countsRightS[360];
  long countsUpRightS[360];
  float avgAsymXS;
  float avgAsymX45S;
  float avgAsymX90S;
  float avgAsymYS;
  float avgAsymErrorXS;
  float avgAsymErrorX45S;
  float avgAsymErrorX90S;
  float avgAsymErrorYS;
  float bunchAsymXS[360];
  float bunchAsymYS[360];
  float bunchAsymErrorXS[360];
  float bunchAsymErrorYS[360];
  float beamEnergyS; // the same as ringSpec.color:beamEnergyM just for reference
  float analyzingPowerS;
  float analyzingPowerErrorS;
  long numberEventsS; // provided by MCR before measurement
  long maxTimeS; // provided by MCR before measurement, triggers measurement
} polDataStruct;
```



RHIC Polarimeter Summary

- Successful WFD readout last year
- Commission of the second Polarimeter is to be done
- Online Carbon count processing is planned.
- History plots on the WEB to show the stability of the measurements

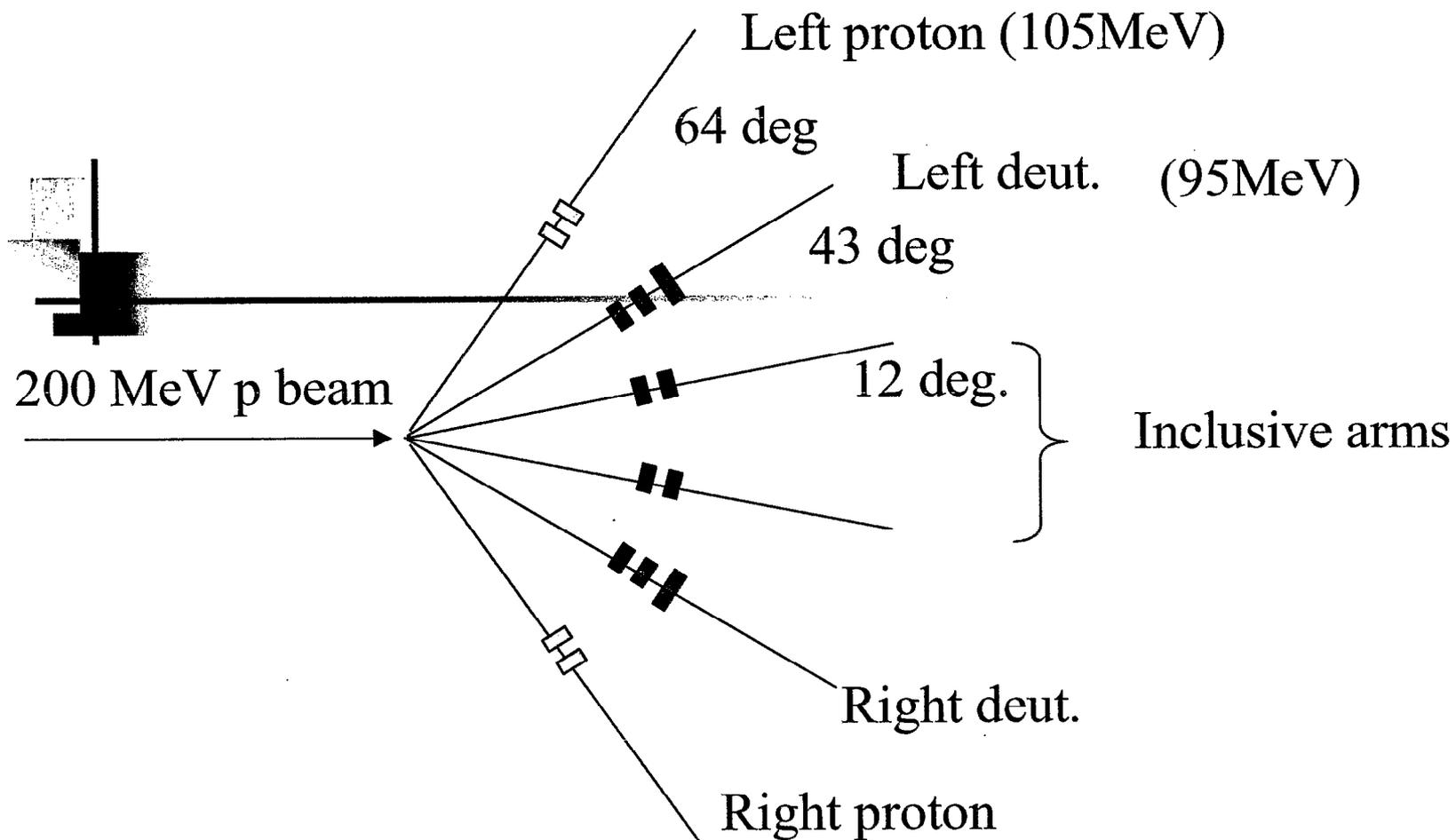
200MeV Polarimeter Issues

- 1, Question on the absolute polarization
- 2, Stability of the polarimeter (rate dep. etc..)

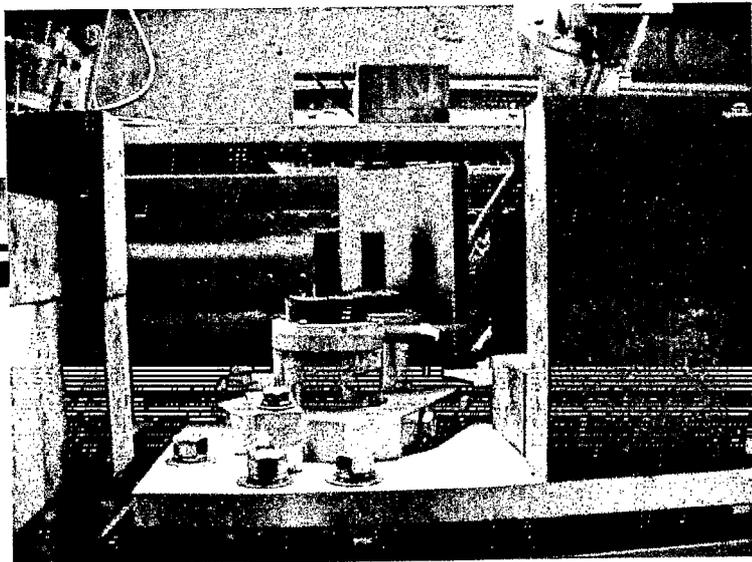


P+d polarimeter calibrated at IUCF to 1% level

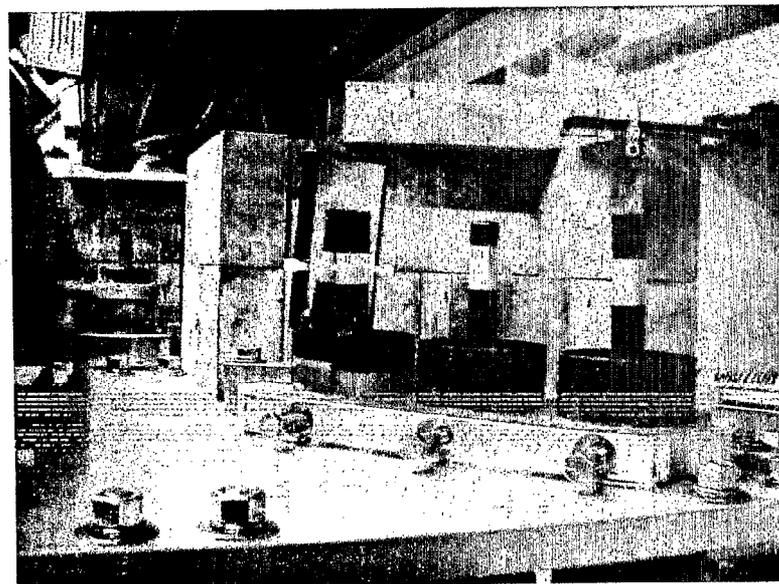
Ed Stephenson
Anatoli
Haixin
Dima, Igor, Kazu



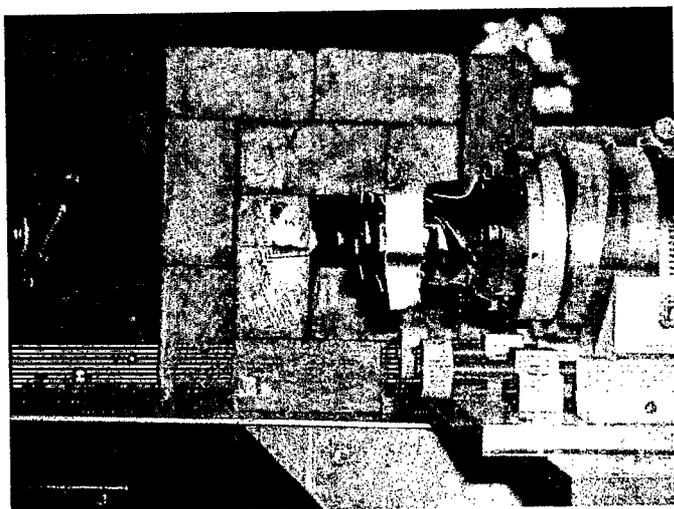
- Inclusive counter $dE_1 * dE_2$
 - Deuteron arm $dE * E * \text{veto}$
 - Proton arm $dE_1 * dE_2$
- } LD*RP or RD*LP



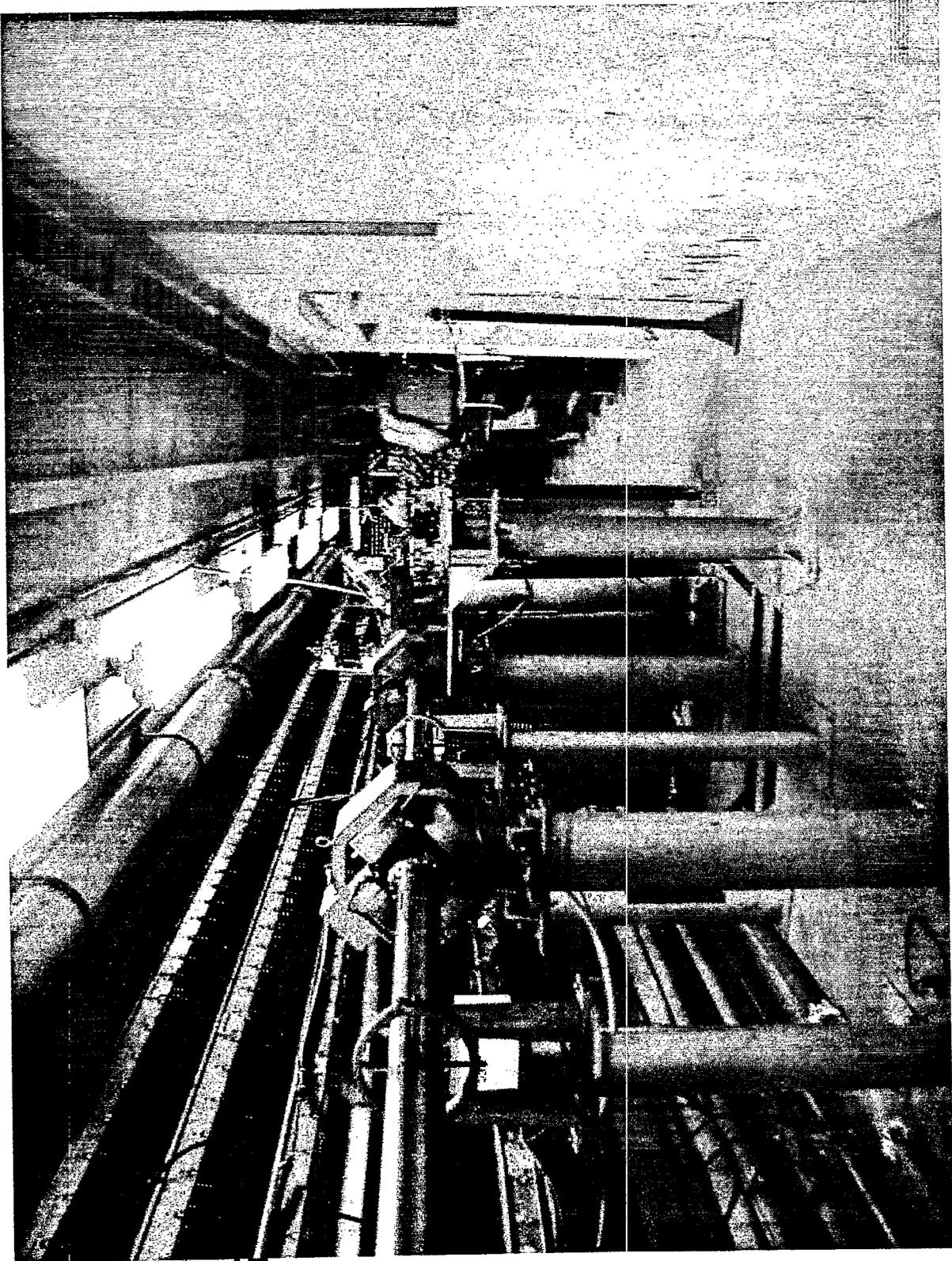
Proton Arm



Deuteron Arm



12 degree counters





pD Polarimeter Summary

- Careful p+d asymmetry analysis was done and compared to pC polarimeter with 1-2% statistical error
- To study the rate dependence of the pC polarimeter, smaller scintillators and faster DAQ are going to be installed.

A New Local Polarimeter for RHIC and EIC

Abhay Deshpande

Phenix Local Polarimeter

Abhay Deshpande

Work Done With

B. Fox, A. Basilevsky, Y. Goto, N. Saito, G. Bunce, Y. Makdisi

Lots of “visiting” help from

Y. Fukao, K. Imai, R. Muto, M. Togawa, F. Sakuma,

Y. Watanabe

Local Special Help from

L. Bland

Why another polarimeter?

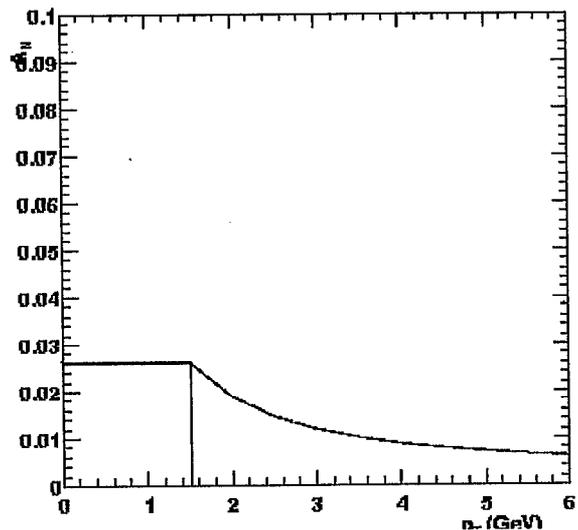
- It is expected that eventually (when high energy polarized proton beams for experiments become a “routine”) one would measure beam polarization in a storage ring only at one place!
- Until then, we should be skeptical!
 - we are about to have the first polarized proton collider: one should have as many cross checks as possible of all “beliefs” we may have about the polarization of the protons
- PHENIX & STAR will have spin rotators which will turn the transverse spin orientation of the protons to longitudinal and back between the two spin rotators
- How longitudinal would the proton spin be between the two spin rotators in the experimental areas?
- Need for direct measurement of longitudinal orientation of spins between the two rotators.

The idea behind the π^0 polarimeter

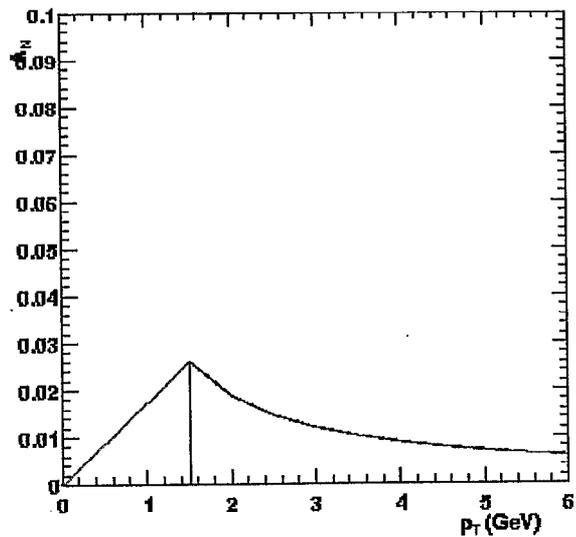
- Robust analyzing power in forward π^0 production in inclusive forward transverse pp scattering has been observed at low \sqrt{s} (~20 GeV)
- At these energies soft QCD effects are dominant and there have been attempts of model building for these.
- If the analyzing power persists at RHIC energies, it could be used as a polarimeter:
 - ➔ Rotators OFF: Perform measurement with transverse polarized protons and measure asymmetry... calibrate and use as polarimeter
 - ➔ Rotators ON: If protons are absolutely longitudinal in PHENIX & STAR, there should be no asymmetry seen what so ever.... A way to check if the spin rotator magnets are working properly.

Theory & Expectation

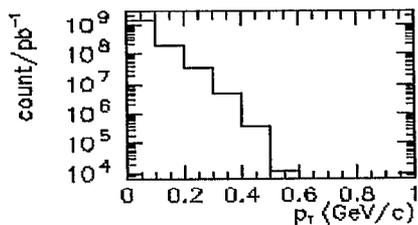
$\sqrt{s}=200\text{GeV}$ $x_F=0.4$ $\lambda=80\text{MeV}$



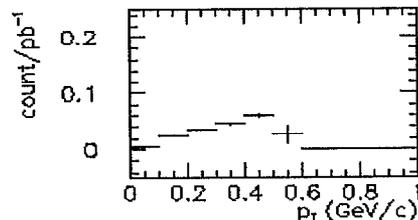
$\sqrt{s}=200\text{GeV}$ $x_F=0.4$ $\lambda=80\text{MeV}$



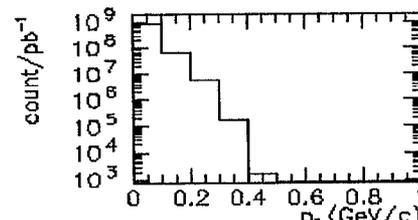
A. Deshpan



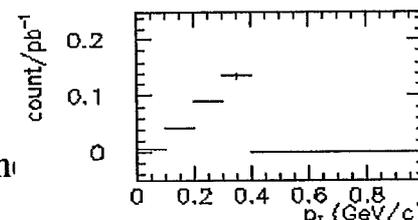
5x12



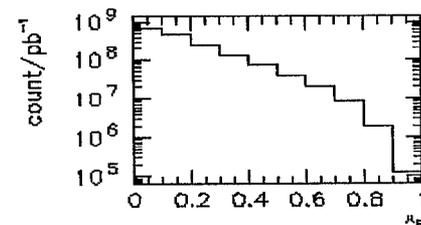
5x12



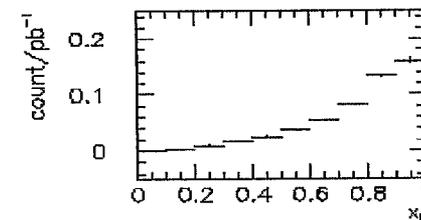
5x5



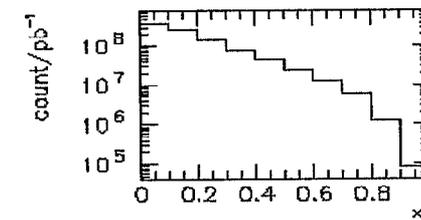
5x5



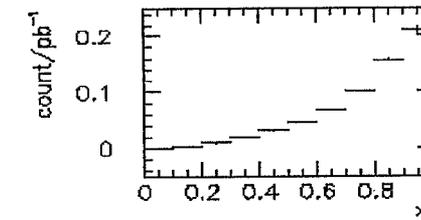
5x12



5x12

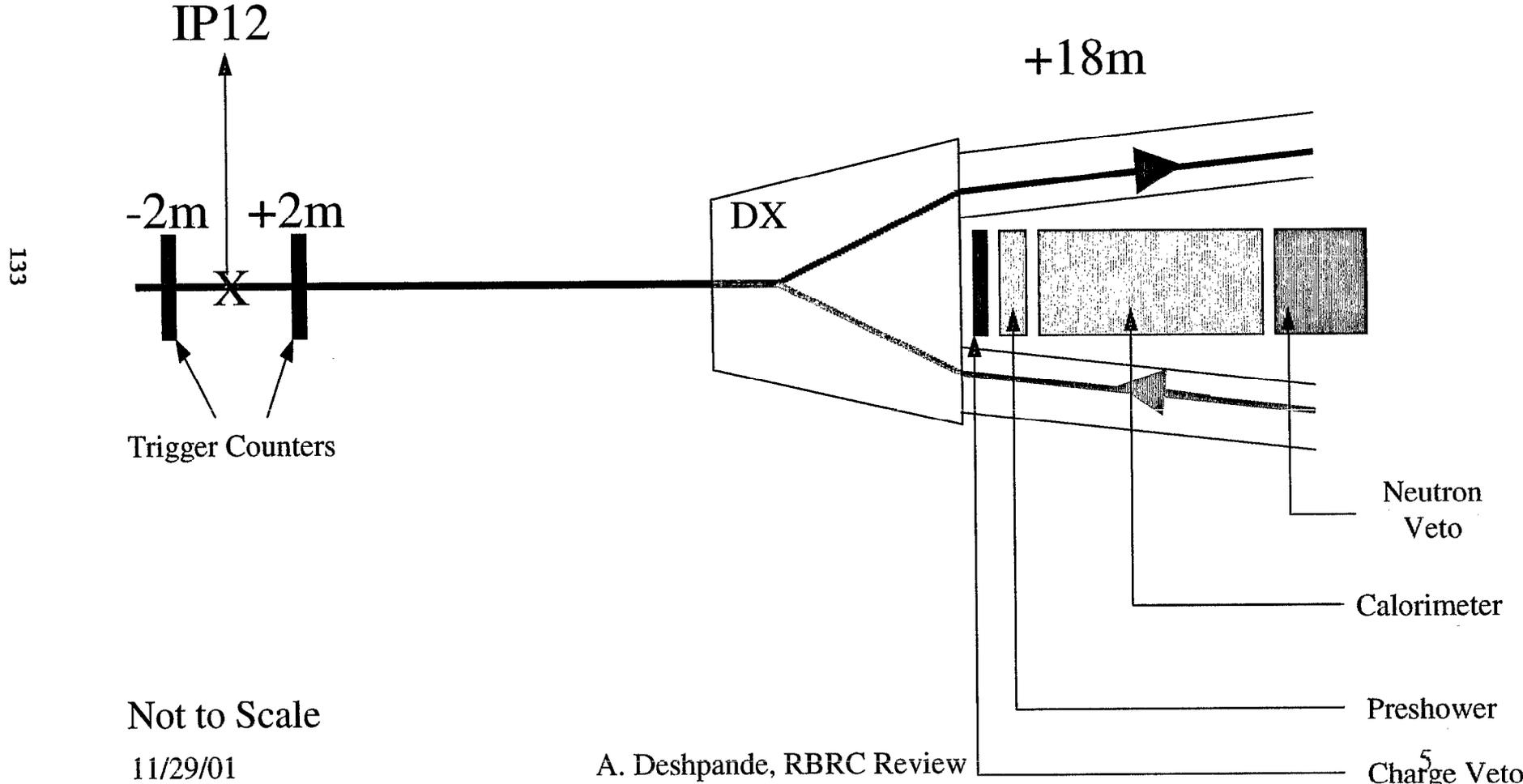


5x5



5x5

Schematic of the Experiment



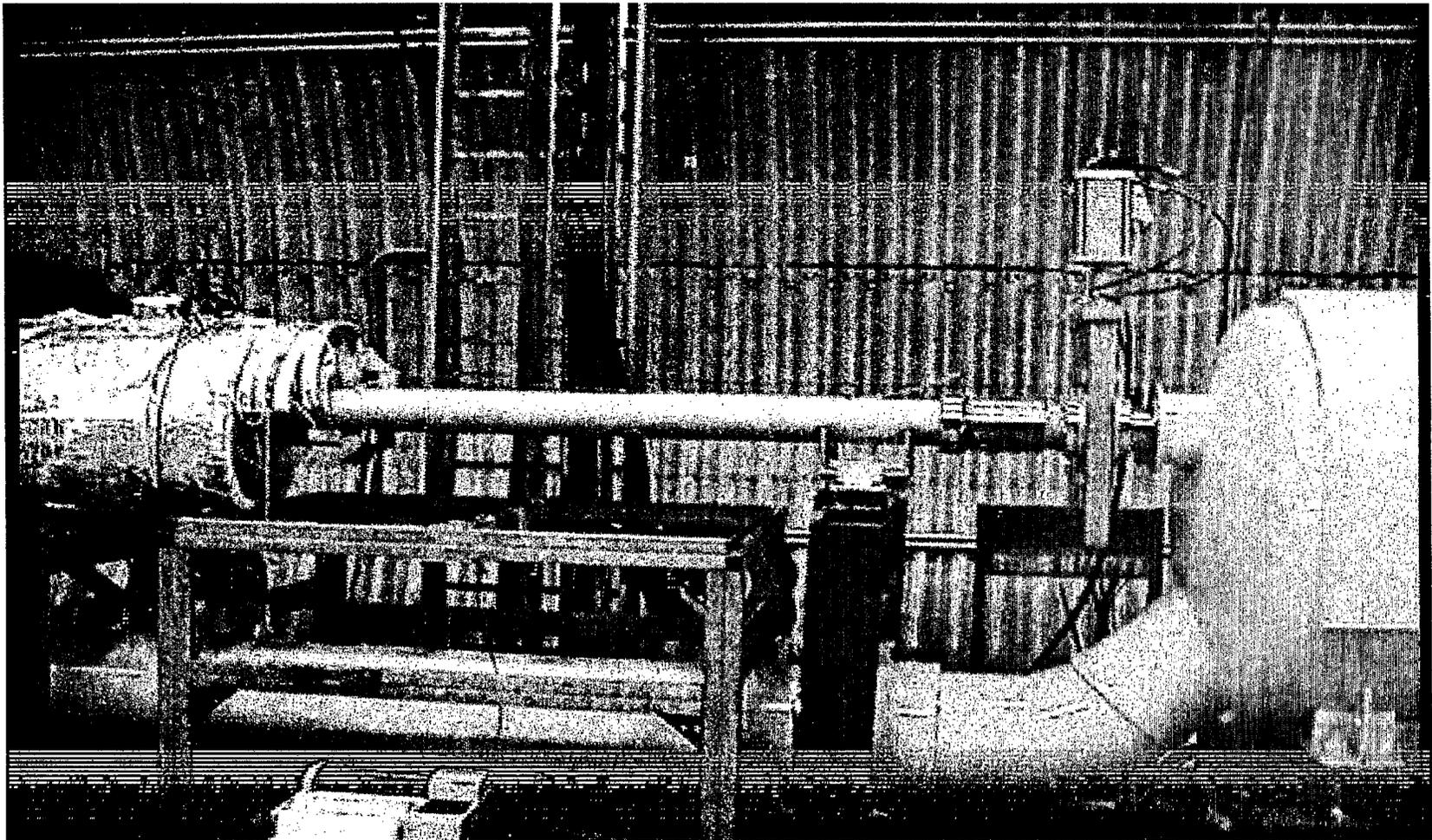
Not to Scale

11/29/01

A. Deshpande, RBRC Review

Charge Veto

Polarimeter Location: 12 O'clock West

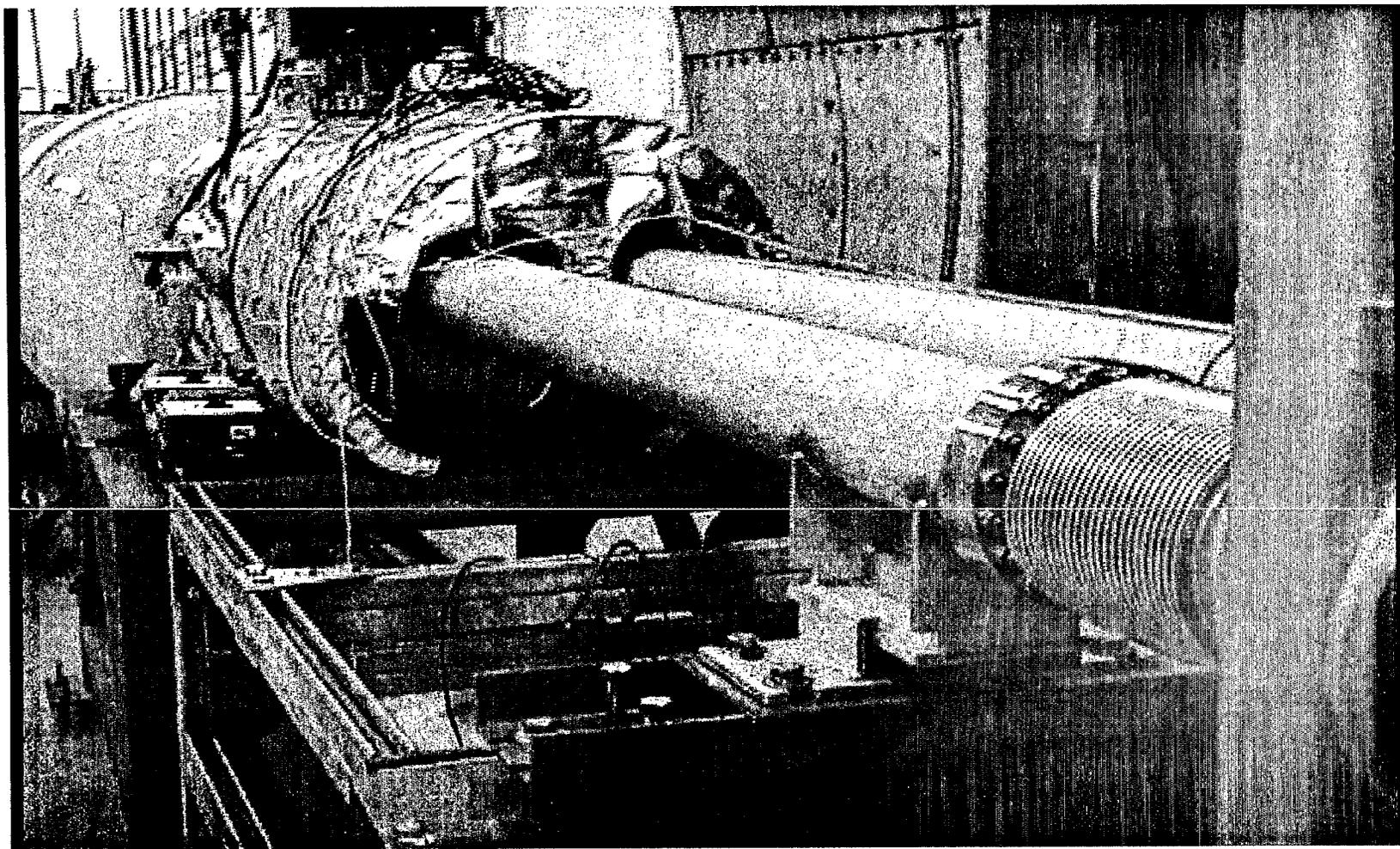


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11/29/01

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Polarimeter Location: 12 O'clock West

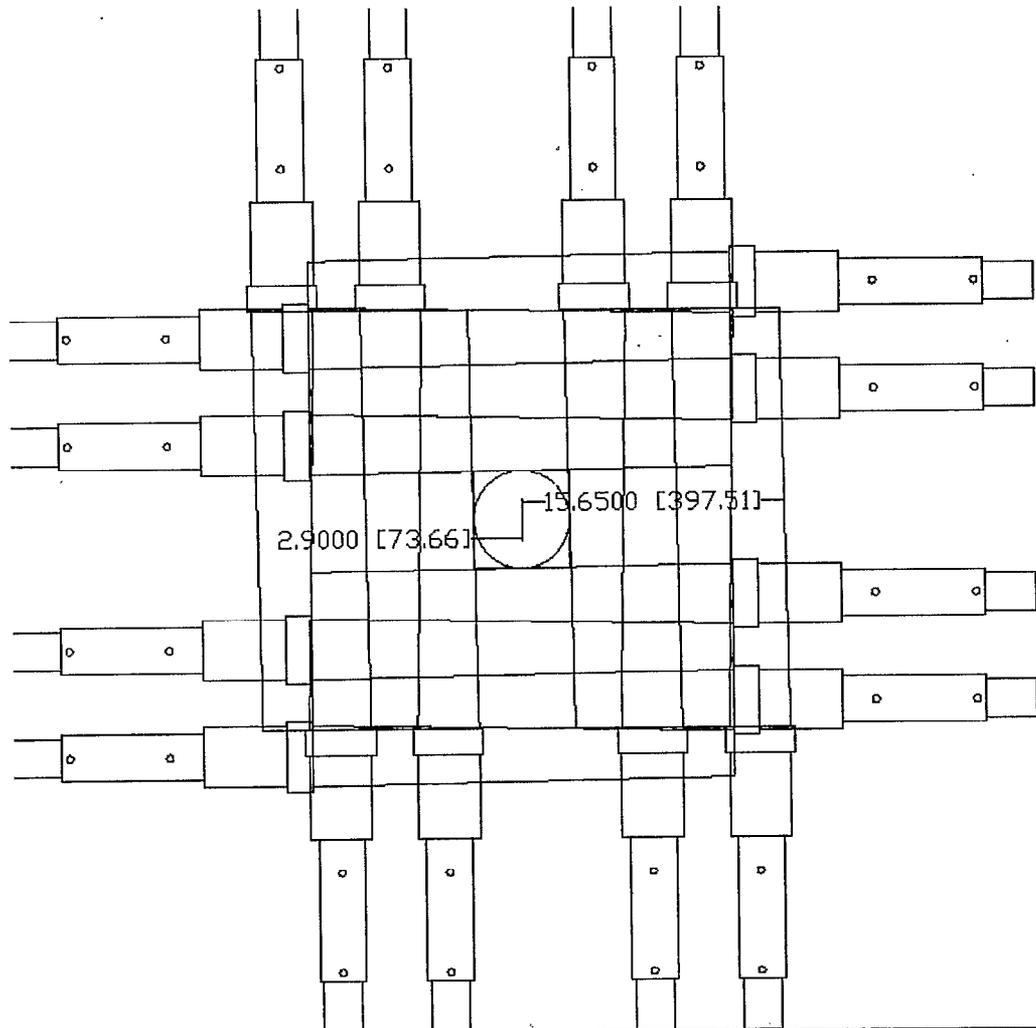


135

11/29/01

A. Deshpande, RBRC Review

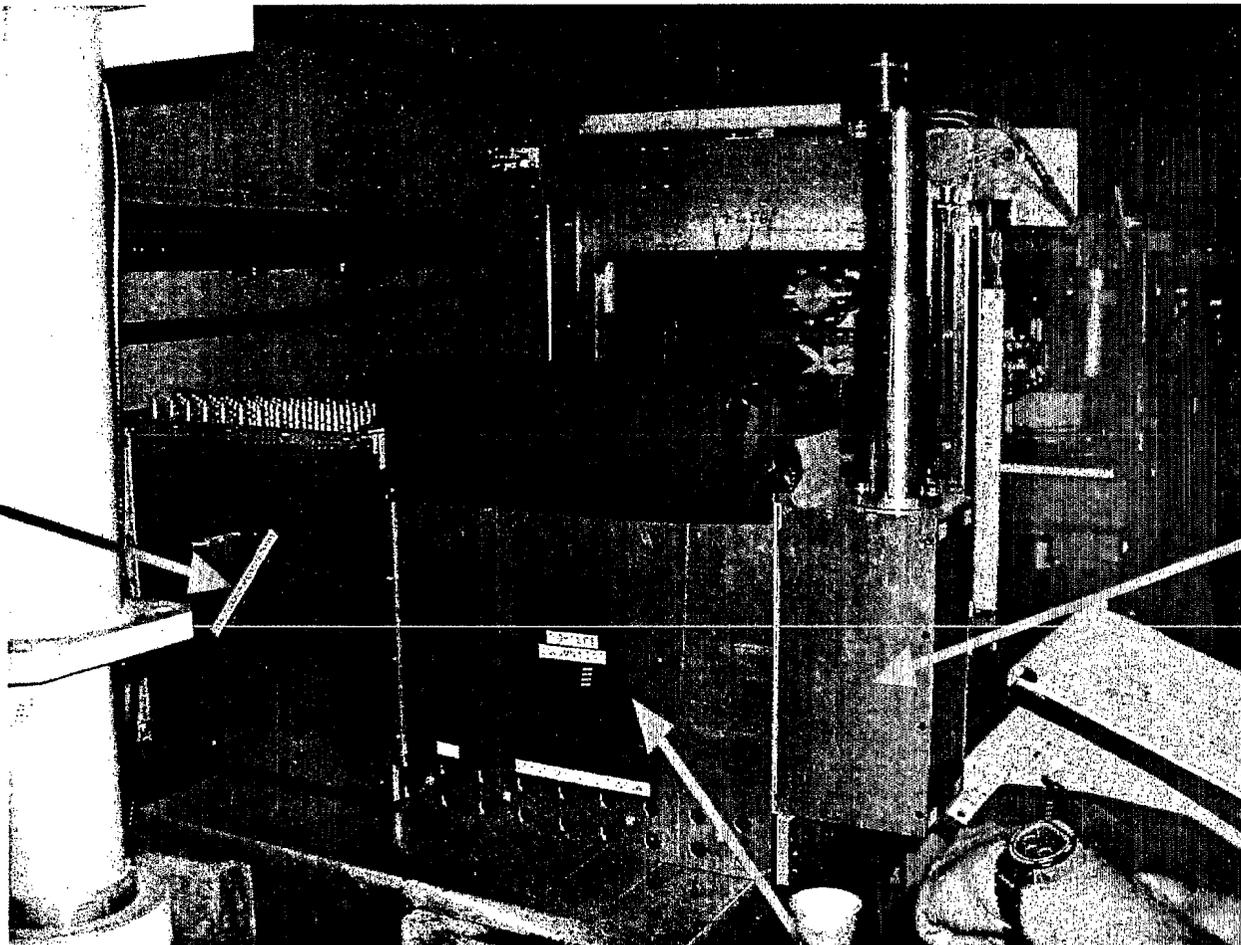
Layout of Scintillator Paddles



- Trigger Counters separated by +/-2m from IP12
- Each : 16 plastic scintillators (AGS-E850: EVA)
- Operating Voltage:
 - -2000V @ ~2mA (SHV RG-59 cables) (LRS 1440 supply)
 - -300V @ ~1mA (booster) (BNC RG-58 cables) (Bertan supply modified for 500 V max)

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The Calorimeter



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Signal
box

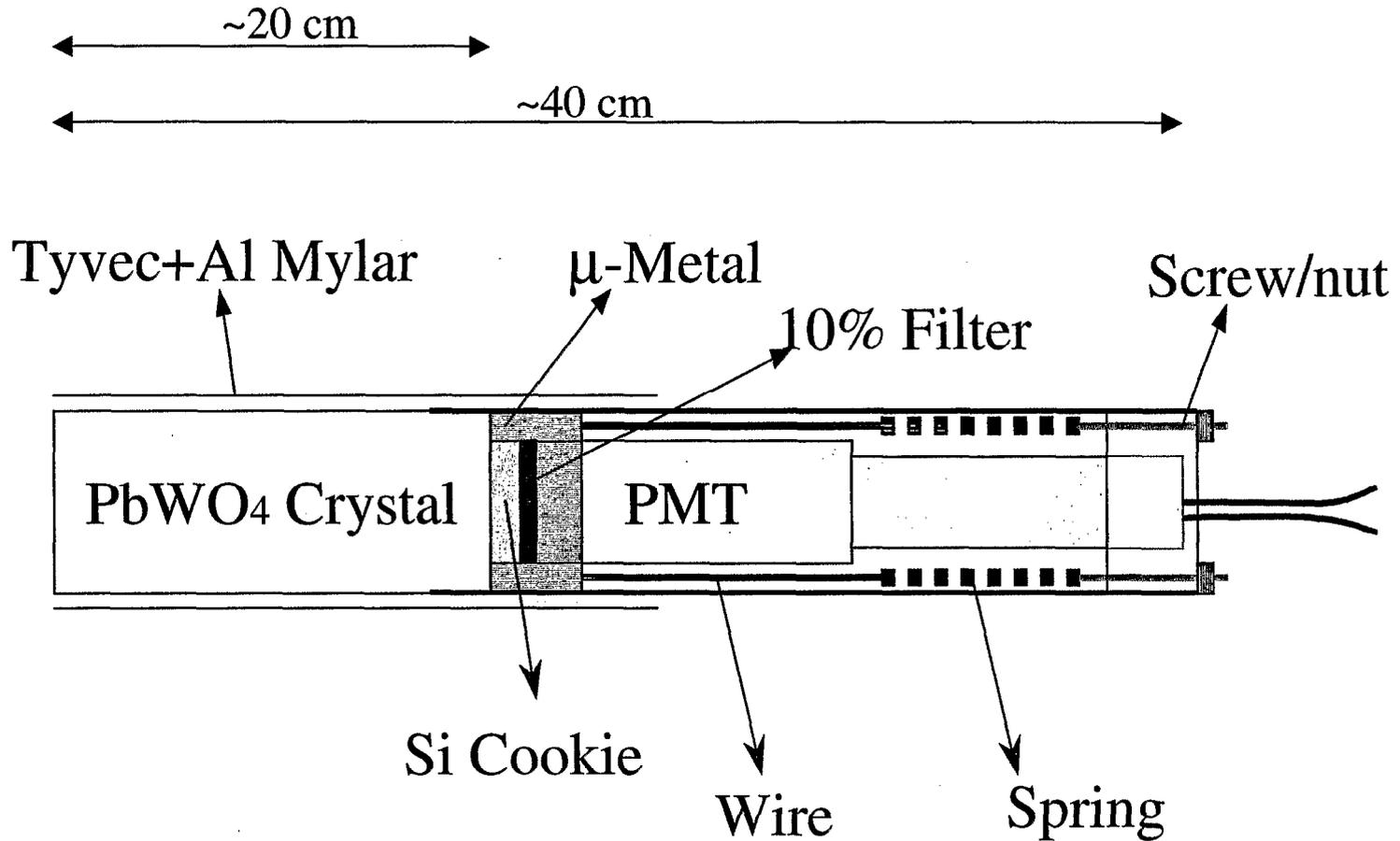
GMS

Calorimeter

11/29/01

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Single Tower Schematic



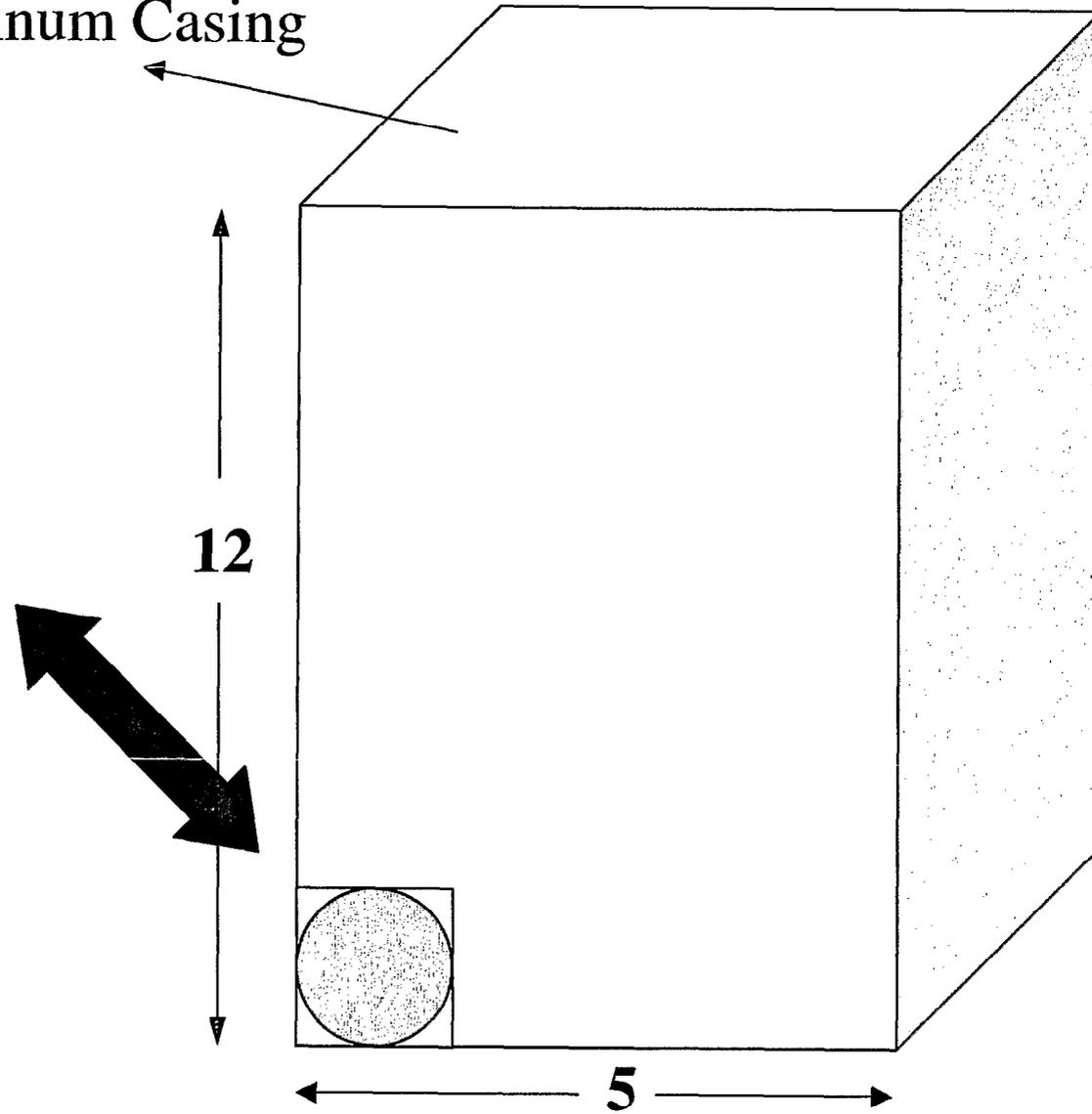
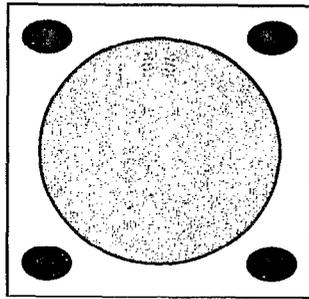
138

PbWO_4 Crystal: 2cm x 2cm x 20cm
11/29/01
PMT: Hamamatsu $\frac{3}{4}$ inch R4125 with manufacturer fabricated base

A. Deshpande, RBRC Review

Not to scale

Aluminum Casing

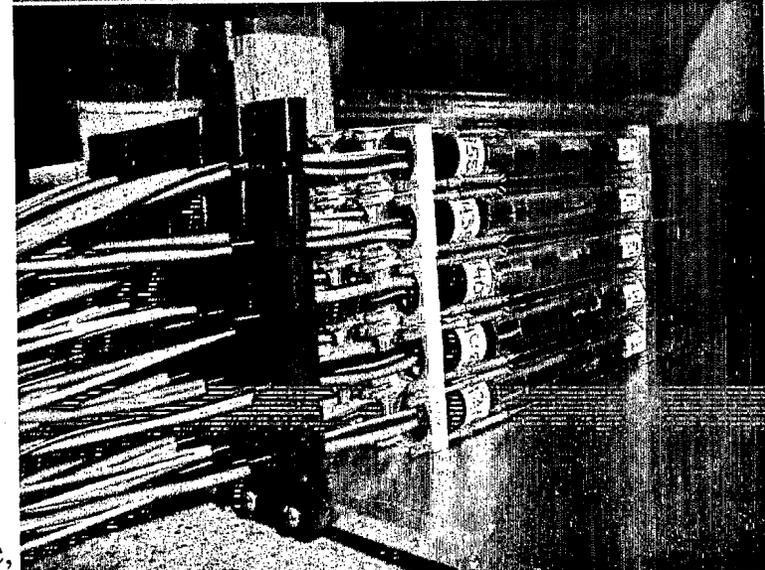
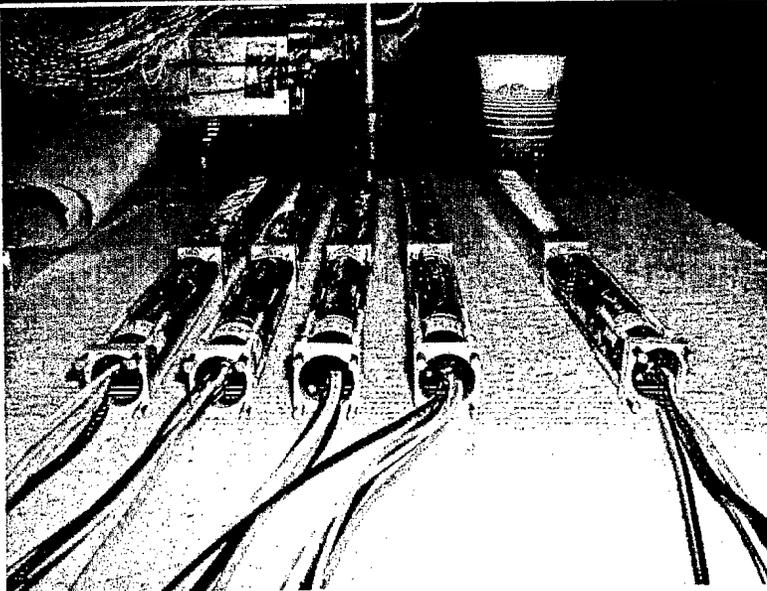
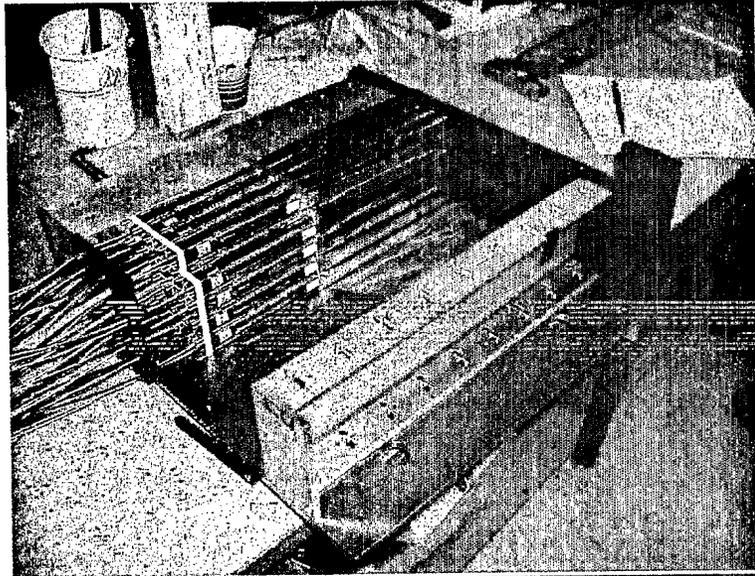


**Schematic
Not to scale**

The Towers & The Calorimeter

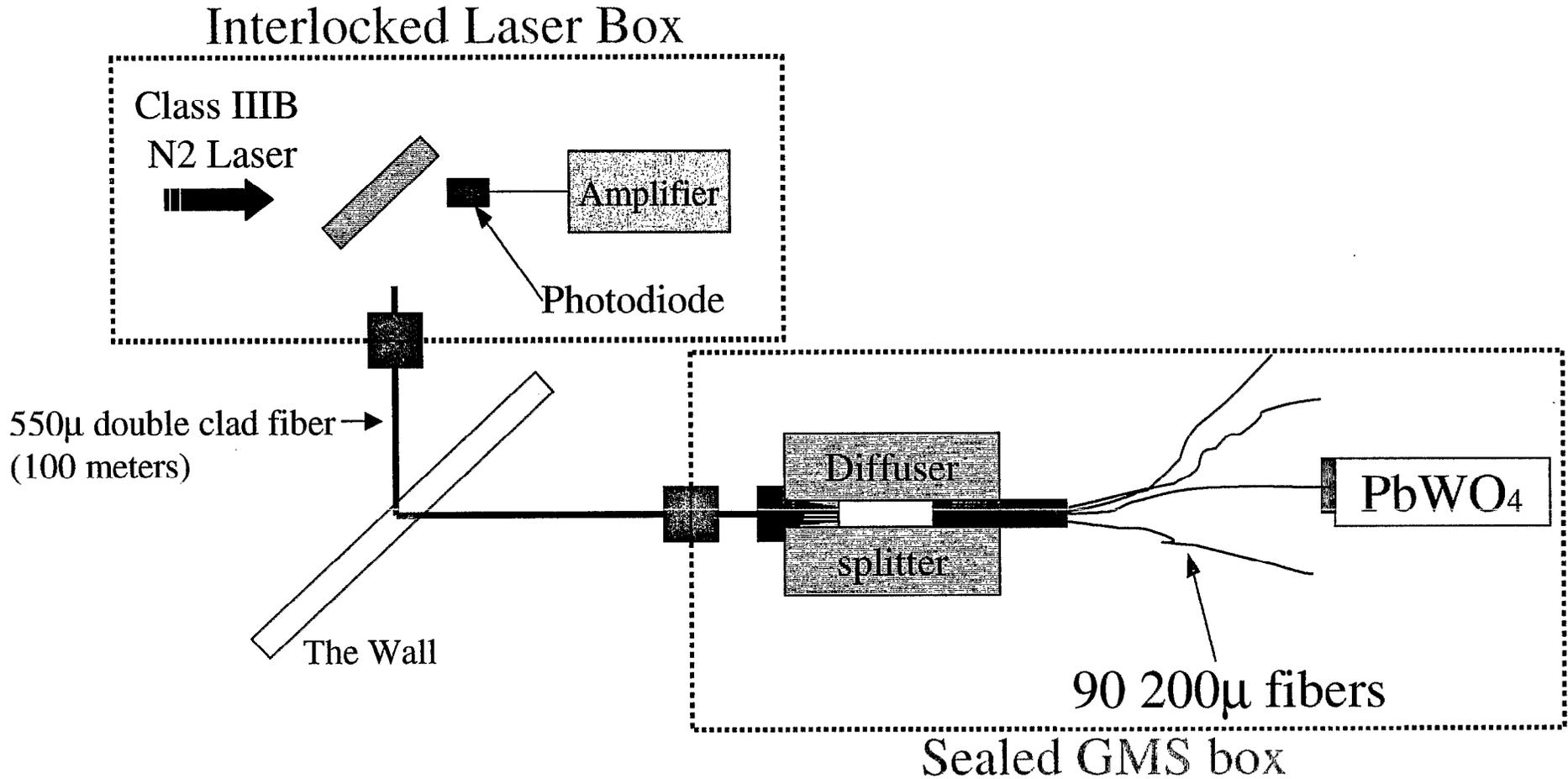
Don V. L.
Bill D., Bill L.
Rudy A., Aron K.

140



bande,

Schematic of the Local Polarimeter GMS

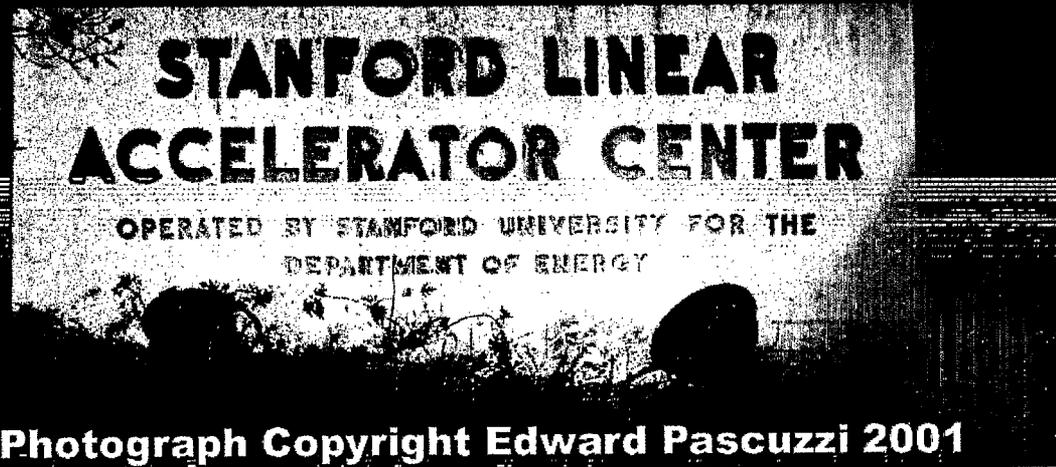


Not to scale

11/29/01

A. Deshpande, RBRC Review

Test Beam At



Photograph Copyright Edward Pascuzzi 2001

Brookhaven National Laboratory

L. Bland

RIKEN-BNL Research Center

G. Bunce, A. Deshpande, Y. Goto, B. Fox, E. Pascuzzi*

Kyoto University

Y. Fukao, K. Imai, R. Muto, M. Togawa, F. Sakuma

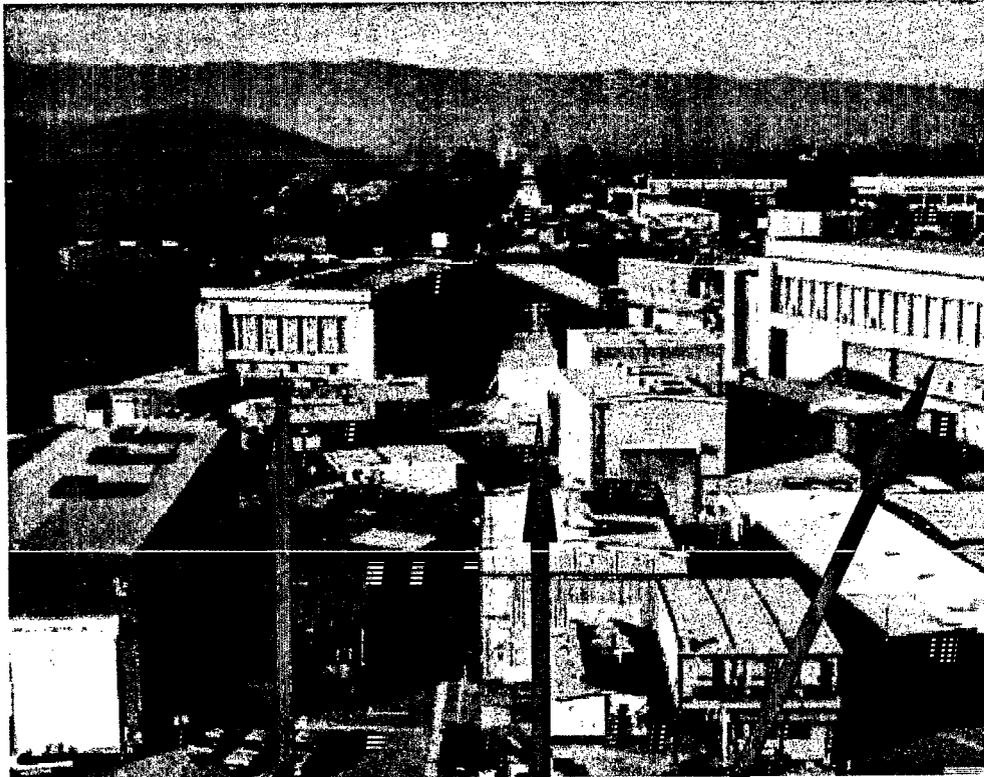
Does not include names of people who worked very hard at BNL....

11/29/01

A. Deshpande, RBRC Review

* Visitor, North Shore High School, Long Island

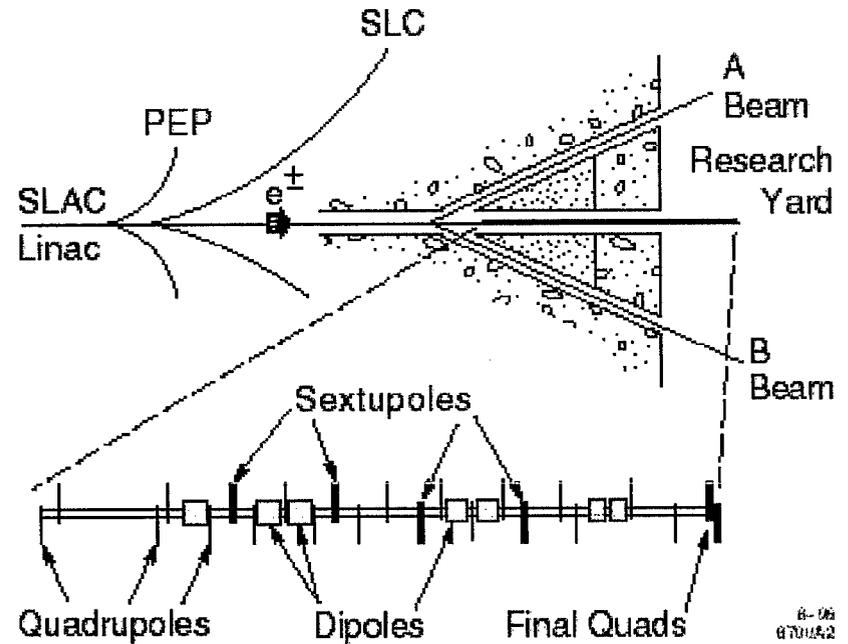
Final Focus Test Beam



End Station B

End Station A

FFTB



Built by an international collaboration to work on achieving minute beam spots

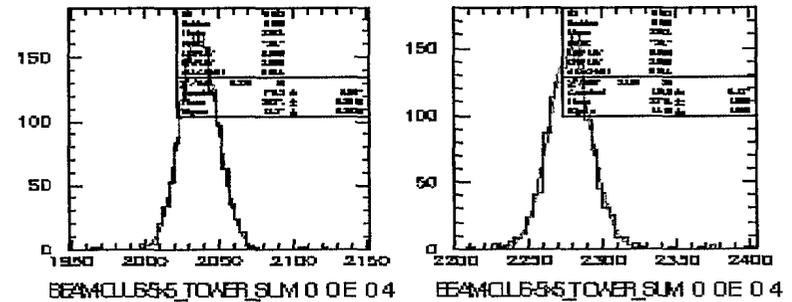
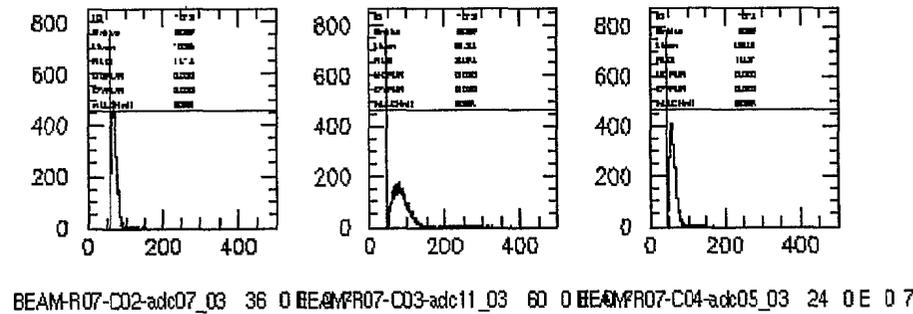
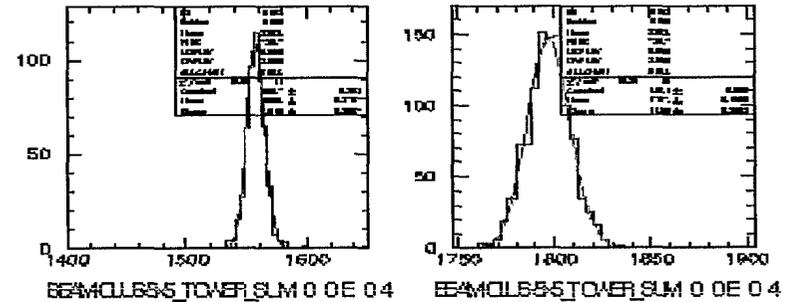
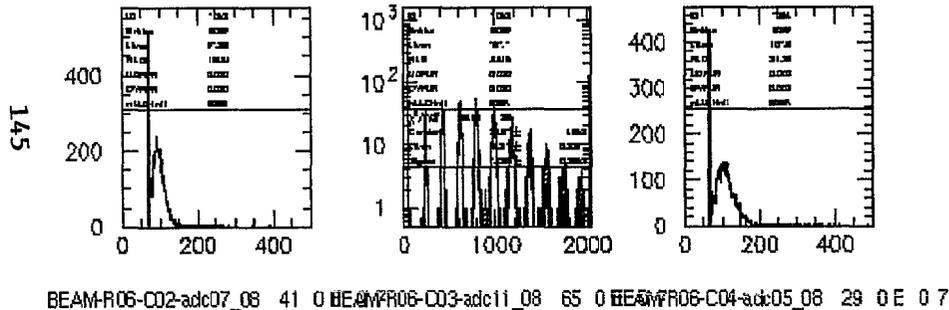
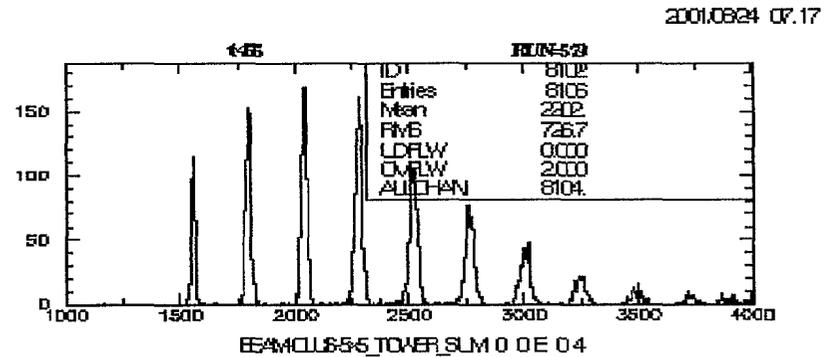
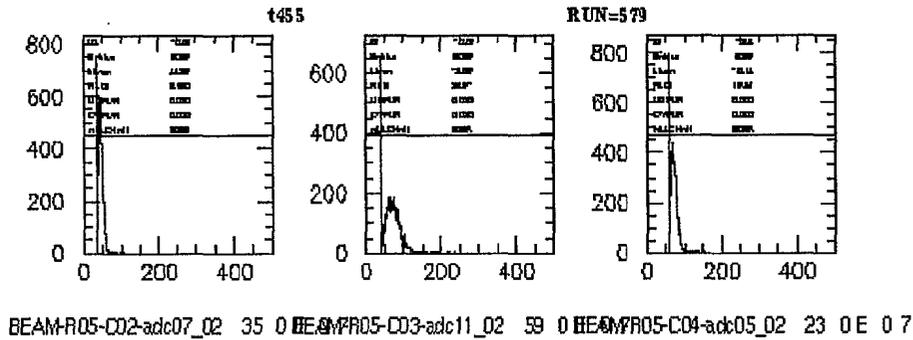
For work on NLC:

1998: 1 micron(wide) by 0.06 micron(height)

Test Beam at SLAC!

- Electron beam 10 Hz
- Dial beam energy : 1,5,10,15,20 GeV
- Dial number of electron per pulse: 1,2,3,4,5...
- Beam spot at our IP controllable at ~mm level
- Setup 1 hr, any changes from there on ~5 minutes

1st Look at what we had...



Center block: Column 3, Row 6 and its

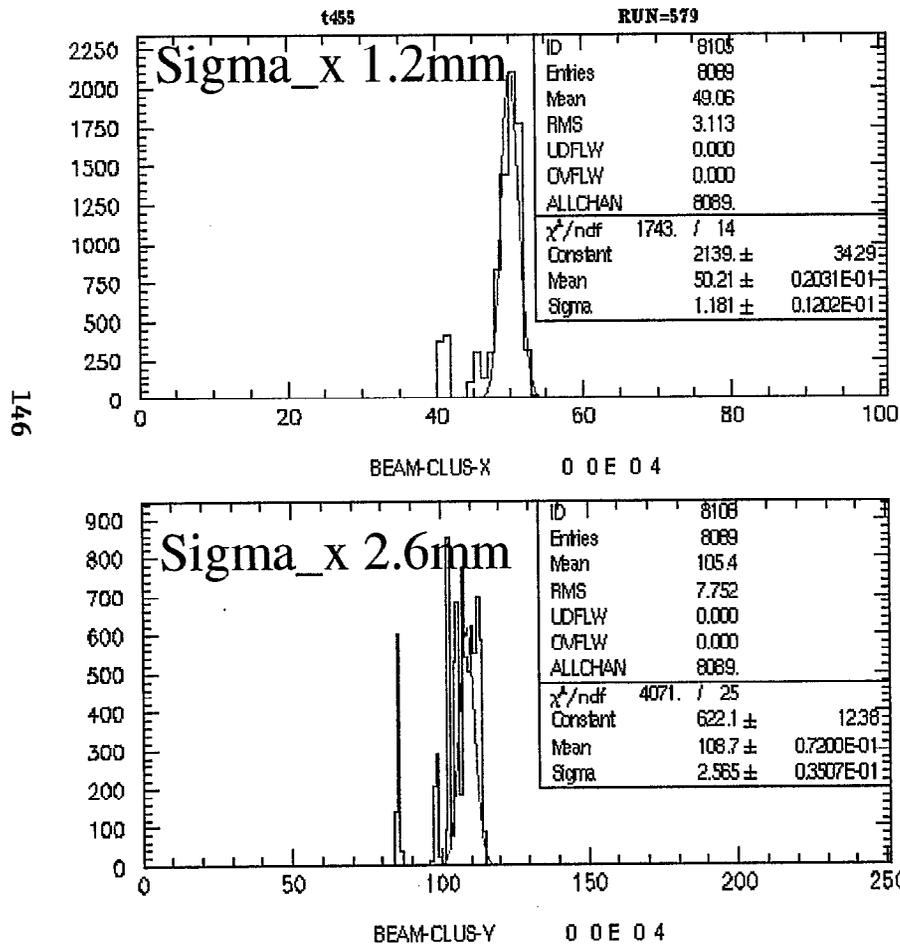
1,2,3,4... electron peaks

11/29/01

neighborhood

A. Deshpande, RBRC Review

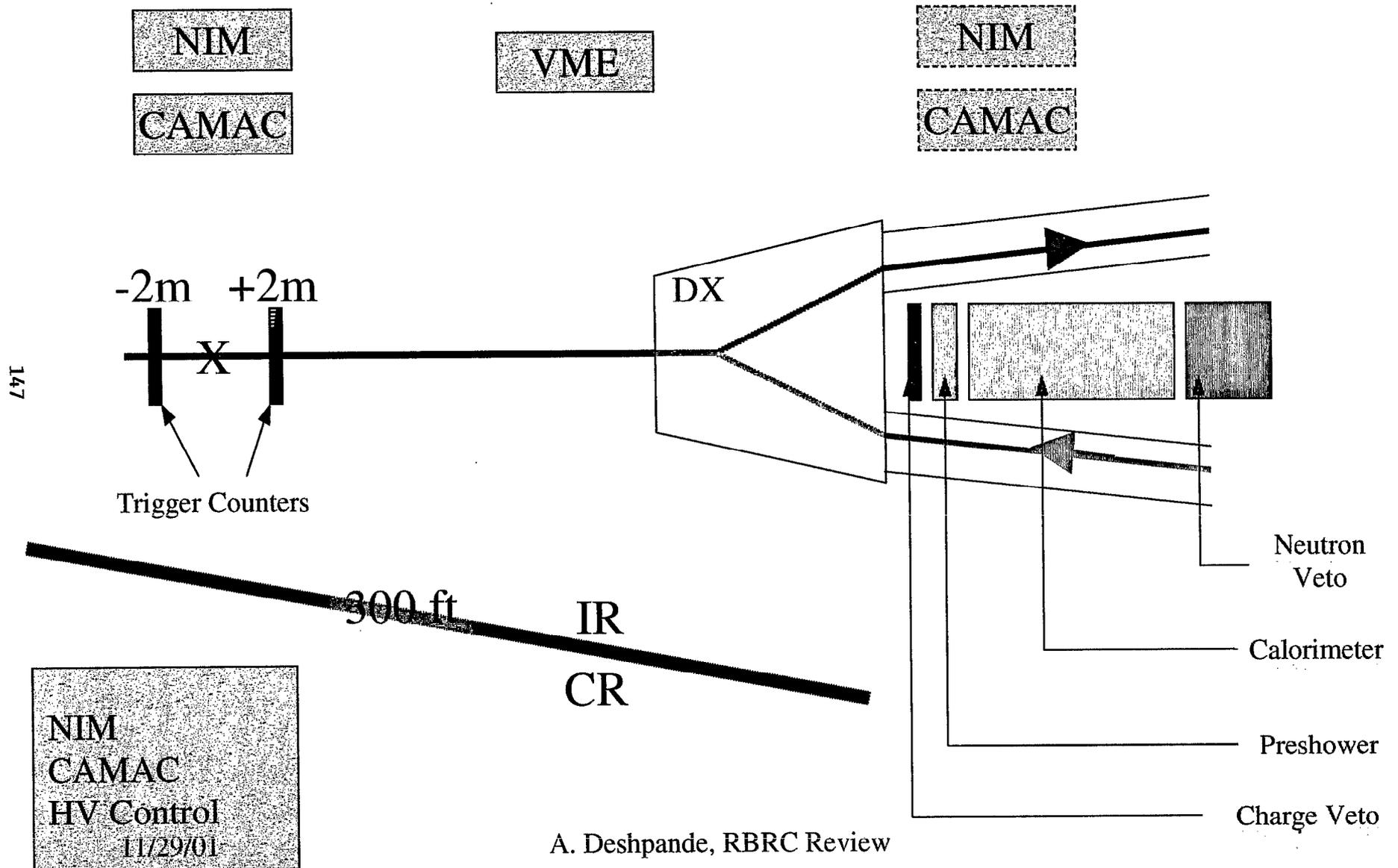
1st look at what we had....



- Pedestal setup
- GMS setup: Laser, filters, optical fiber(s), spectralon diffuser
- HV voltage setup for gain matching/calibration for each tower
- Start scanning for energy sharing between neighboring blocks
- Position resolution critical for our purpose:
 - a) Max Energy → Central Block
 - b) Energy shared with surrounding block → gives the position resolution...
- ➔ Energy deposition in central as well as corner and edge blocks crucial
- ➔ Detail study of shower profile

11/29/01 Eventually settled on 1 X 1 mm and 2 X 2 mm beams

Readout Electronics & DAQ Layout & Status



Status

- Trigger counters in and connected, powered and tested
- Calorimeter in, connected, powered and preliminary GMS tests performed
- Preshower counter ready to be installed
- Charge veto counter and neutron veto counters to be installed soon

- GMS system tests performed at BNL seem to differ from the results from SLAC
- Reason not known yet, will have to be investigated in place
- Cosmic calibration of the preshower counter seems to be fine
- May have to rely on this
- Always a possibility to re-calibrate in a known energy beam... tagged photon beam at NSLS/LEGs experiment at BNL

The Electron Ion Collider (EIC)

- EIC: New name of the eRHIC
- EIC = eRHIC + EPIC
- At BNL one only needs an electron beam facility to collide with the already existing polarized proton and heavy ion beams
- Possibility of LINAC & RING being discussed amongst accelerator groups here at BNL and outside: 6-10 GeV polarized electron beam
- Would allow polarized ep as well as eA physics at one place & if designed appropriately, would allow the heavy ion RHIC program and the polarized proton programs to continue..... Choose a new IP where nothing exists: IP12

The Whitepaper submitted to NSAC was received well.

Desire among significant number of physicists to form a collaboration.

A Meeting towards that and focus groups on interaction point development & detector development organized at BNL in February/March 2002

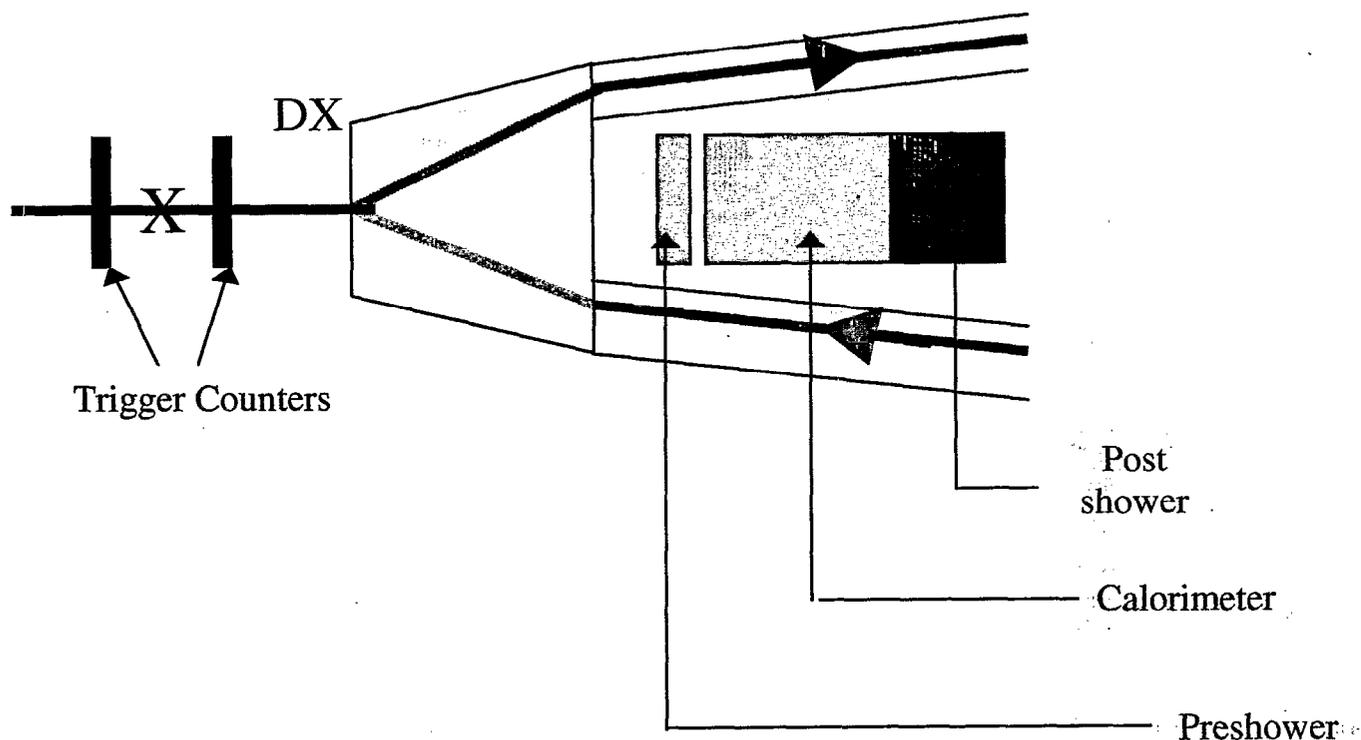
Phenix Local Polarimeter

G. Bunce, A. Deshpande, B. Fox, Y. Goto, K. Imai, Y. Makdisi, N. Saito

Introduction:

The Phenix Local Polarimeter (PLP) is an exploratory effort aiming to see if the transverse proton beam polarization using the analyzing power in the inclusive forward Pi^0 production in polarized p-p scattering. Such an asymmetry has been observed in the past but at lower \sqrt{s} (~ 20 GeV) where soft QCD processes are dominant. Whether this effect persists at the high energies RHIC remains to be seen. If it does exist, the apparatus (the Polarimeter) will be integrated into the Phenix Detector for the future spin running at Phenix. In Phenix it can be used in two ways. First, when the spin rotators are switched off, this apparatus should be able to measure the asymmetry and hence measure the polarization. Second, when the spin rotators are on, i.e. the protons in the Phenix interaction region are "supposed to be" longitudinal no asymmetry should be observed. This is, in a way is a cross check, that the spin rotators are functioning properly.

Apparatus: Schematic diagram (not to scale is shown below)



The apparatus consists of two sets of 16 hodoscopes (trigger counters) which are located about ± 2 m from the 12 o'clock interaction point (IP). About 18m on the east of the IP behind the DX magnet we plan to setup a pre-shower detector, a calorimeter and a post-

shower detector. The calorimeter will detect the left/right asymmetry in Pi^0 production through the decay of Pi^0 s into photons. The pre-shower detector and the post shower detectors are used to establish the existence of photons over the low and high energy neutron backgrounds that might exist in the RHIC collision environment.

Status:

The trigger hodoscopes were installed in to the RHIC ring on November 8th, 2001. The Calorimeter is built and was tested in a high energy electron beam at SLAC in August 2001. It is back at BNL, and will be installed in RHIC on November 26th 2001 and will be used during the polarized proton run. The data collected at SLAC are being analyzed by two students at Kyoto University which should give us an absolute calibration for the calibration. At the moment we have a preliminary result which we will use in the beginning of the run. The pre-shower detector is in place, while the post shower detector and the DAQ is being assembled at the moment.

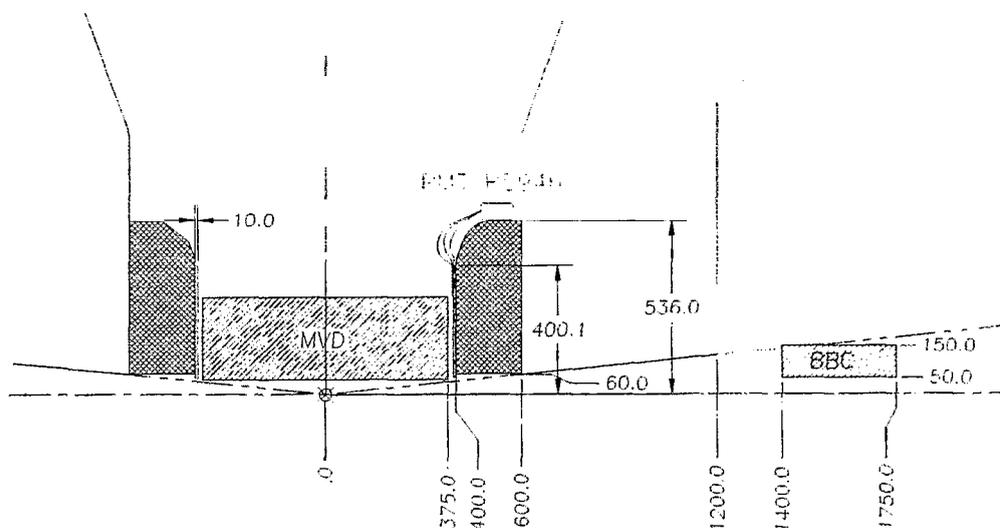
Normalization Trigger Counters for PHENIX

Brendan Fox

Phenix Normalization Trigger Counters (NTCs)

A. Denisov, A. Deshpande, B. Fox, E. O'Brien, N. Saito, S. White

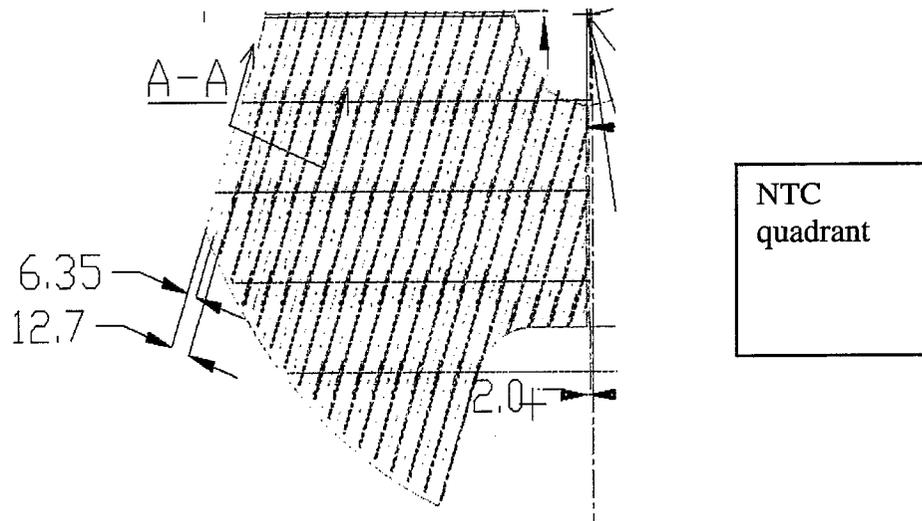
We intend to install normalization trigger counters (NTCs) in the PHENIX IR for the proton-proton running period in 2001. This detector system consists of two, identical, fiber-readout scintillator counters. Each of these counters will be situated between the endplates of the MVD and the brass nosecone in the vertex region of the PHENIX detector -- one will be on the north side; the other will be on the south side of the PHENIX detector. The schematic diagram of the position of NTCs in Phenix is shown below.



These detectors will provide:

- a normalization device with a greater coverage of the cross section than the existing BBCs. The latter sees about 70% of the cross section. With the NTCs, the figure is in the upper 80s. As a result of this increased coverage, the error in the total pp-cross section will be reduced significantly, thereby improving the ability to use the pp data to compared with the HI running. In addition, the knowledge of the relative luminosity of different bunches is critical for the spin program. This detector aids this effort by providing another measurement to compare with the ZDCs and BBCs coincidence rate and thereby assure that this critical quantity is measured correctly.
- a means for separating beam gas from beam-beam events by forming a coincidence between the counters on each end of the PHENIX detector,

- an efficient and clean trigger with a different bias than the other "standard" PHENIX triggers, thereby aiding with understanding the bias of the events collected during pp-running.
- a possible backup trigger for the muon arm. In the unlikely event that the muonID trigger board is not working at the time of the pp-running, the backup blue logic trigger for the muon arm needs to have some road width device to reject the unacceptable rate of cosmic ray events. Quadrants of the NTC counters would provide the needed coincidence.



Muon Identifiers for PHENIX-Status

Atsushi Taketani

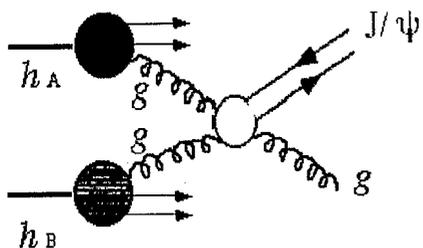
Muon identifiers for PHENIX

Status

1. Introduction of MuId
2. Hardware (Gas, HV)
3. Software (Reconstruction, Online)
4. Operation (Trigger)
5. Summary

Physics Goal of Muon Arm for Spin Physics

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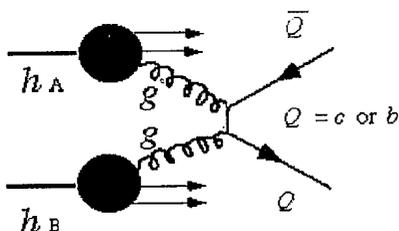
J/ψ



Production Mechanism

- ✓ Total cross section
- ✓ Polarization

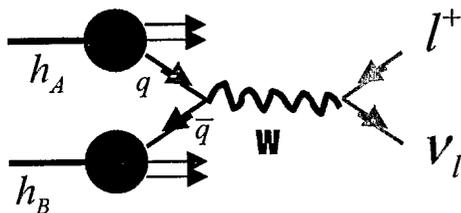
Gluon Polarization



Open Heavy Flavor



Gluon Polarization



W/Z, Drell-Yan

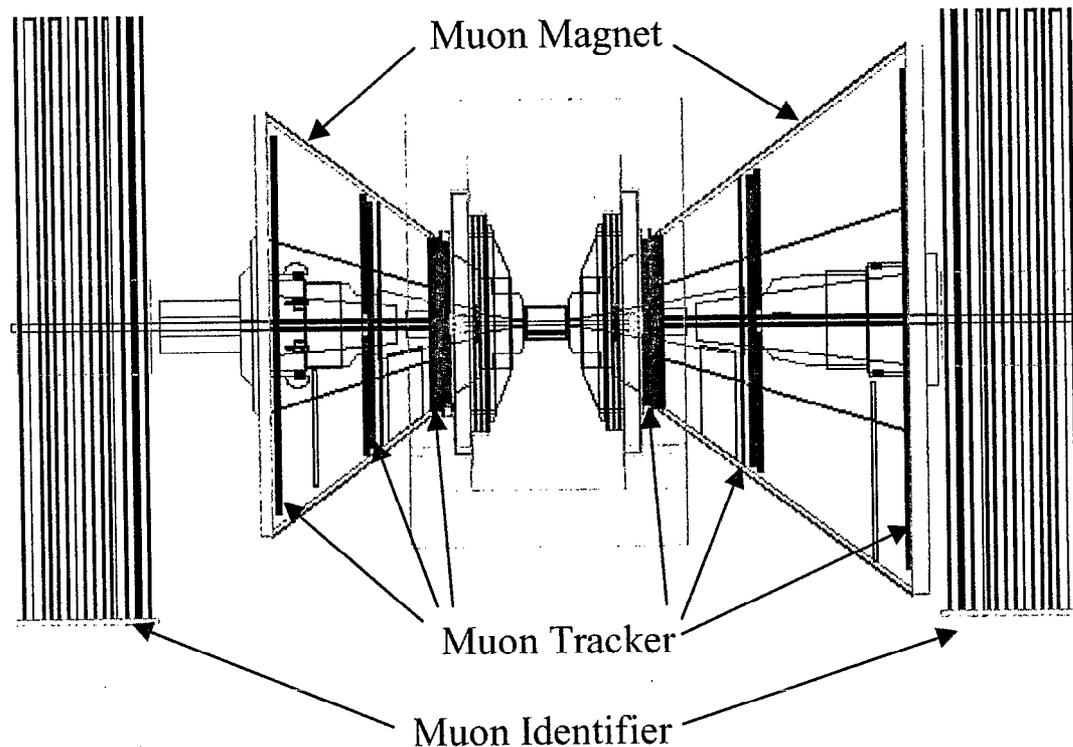


Quark Polarization

The PHENIX Muon Arms

South Muon Arm

North Muon Arm



Acceptance: $1.2 < |\eta| < 2.4$

Total absorber $\sim 10 \lambda_{int}$

Minimum Momentum $\sim 2\text{GeV}/c$

2001 South Muon Arm
operation started

2002~ Both Arms operation

MuID

South Arm : ready for physics

North Arm : detector has been installed. Need integration.

Muon Identifier (MuID)

- 5 layers of chambers (Iarocci tubes) sandwiched in steel
- π misidentification probability $\sim 3 \times 10^{-4}$
- used as a trigger counter

Muon Tracker (MuTr)

- Cathode-readout strip chambers at three stations
- $\sigma_x \sim 100\mu\text{m} \rightarrow \Delta p/p \sim 3\% @ 3 \sim 10\text{GeV}/c$

Construction history

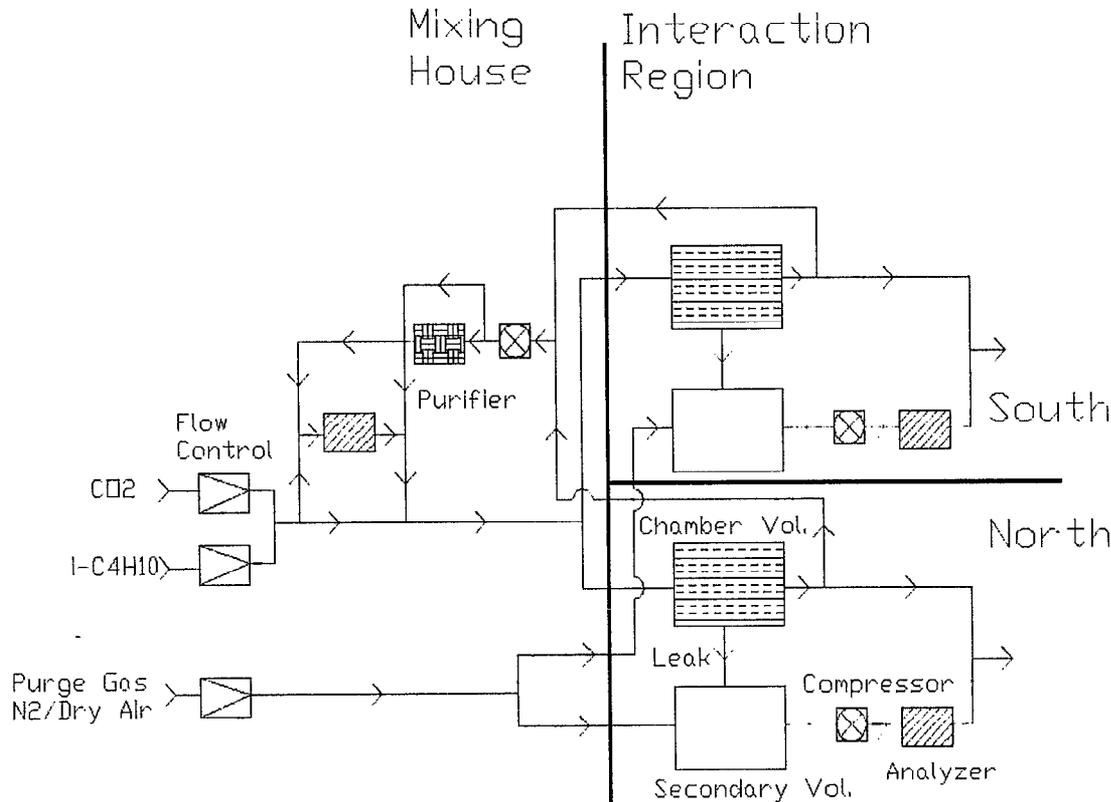
- 97-98 Construction Detector
- 99 Flood recovery, design infrastructure(Gas, HV)
- 00 Integration started
First commissioning with Au-Au collision
- 01 Completed South
Taking data now.

Reconstruction program development has been simultaneously going.

Total 4 Fellows, 3 Postdocs, 6 Students has been working.

RIKEN, RBRC, Kyoto, CIAE, and TiTech

Gas System



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- **CO₂+iC₄H₁₀ (upto 9.3%)**

flammable gas component

- **Big volume**

600 chains

50m³ volume

Distributed in large space

- **Recirculation up to 50% of flow**
- **Operated since May**

South : chamber operation gas

North : N₂ to maintain chamber health

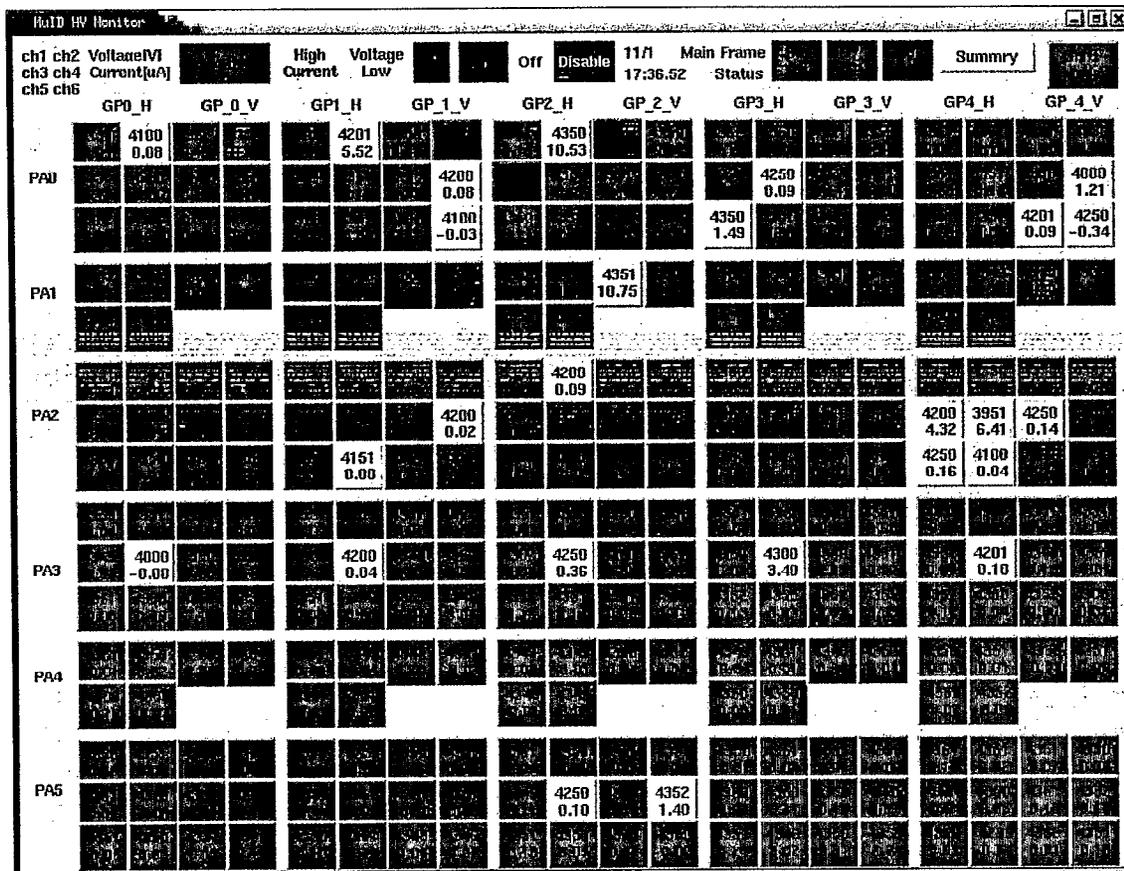
- **No Major problem**

A compressor fail -> replaced

Low pressure for C₄H₁₀ supply

-> try to fix as of Nov 10

High Voltage



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-  Operational
-  Low voltage
-  Dead
-  High current

Atsushi Taketani, RBRC Review

● Total 300 Chain

South Arm only

● Simple operation

Automatic trip/crash recovery

GUI operation

● Trip/Spark protection

● Log HV history

Efficiency for analysis

● Stable operation

Since July.

~90% chains are operational

More than 95% coverage.

Online Monitoring

MuID Summary: Run 32120

Total Events Examined: 1012

Events Examined for Cable Graphs: 1012

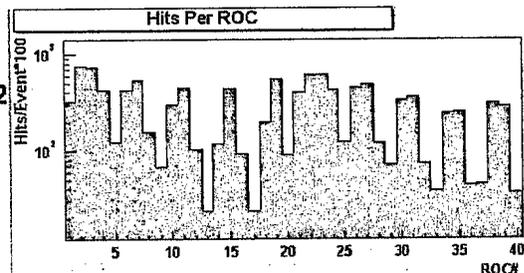
Hit Rate: 112.61

ROC OK Errors: 0

Beam OK Errors: 0

No Packet Errors: 0

Instructions: Look for dead gaps.



● Monitor Detector Status

HV chain

Electronics

Data acquisition

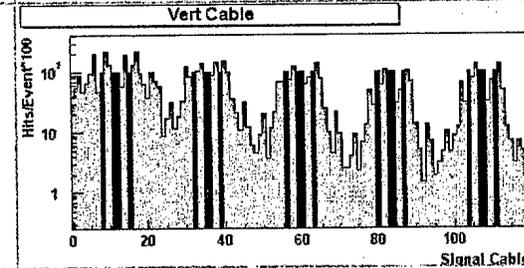
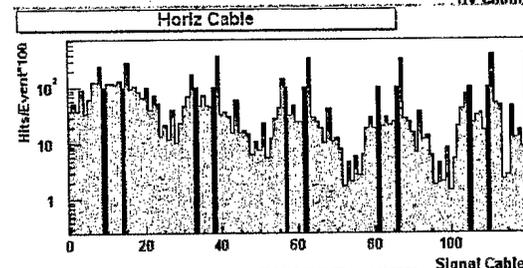
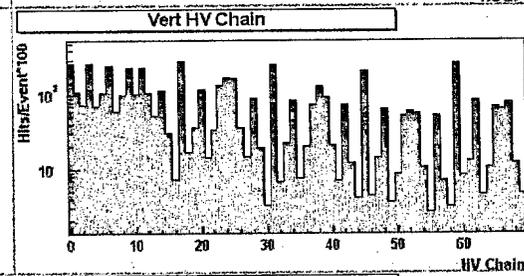
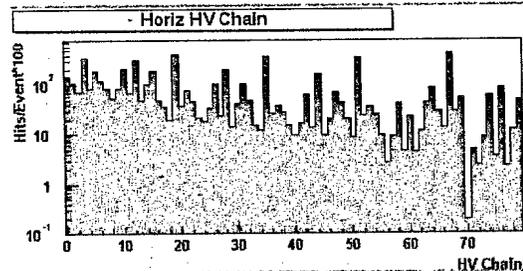
● Real time Monitoring

● Useful for Diagnostics

Timing scan

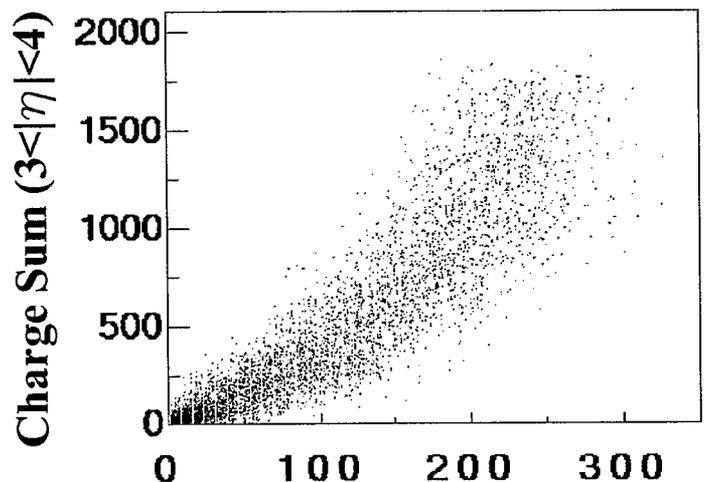
Threshold scan

HV scan

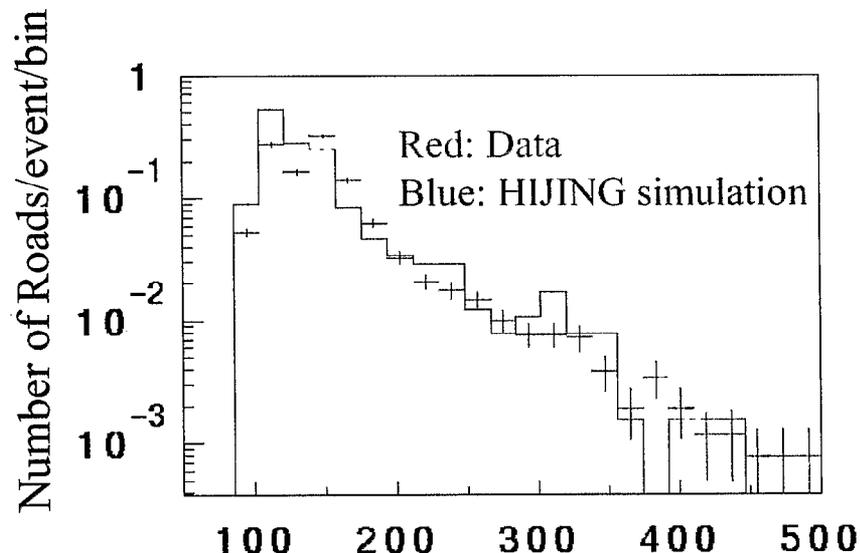


Reconstruction and data

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Total number of hits in MuID



Distance from Beam pipe(cm)

MuID is seeing beam collision

Data seems similar to MC.

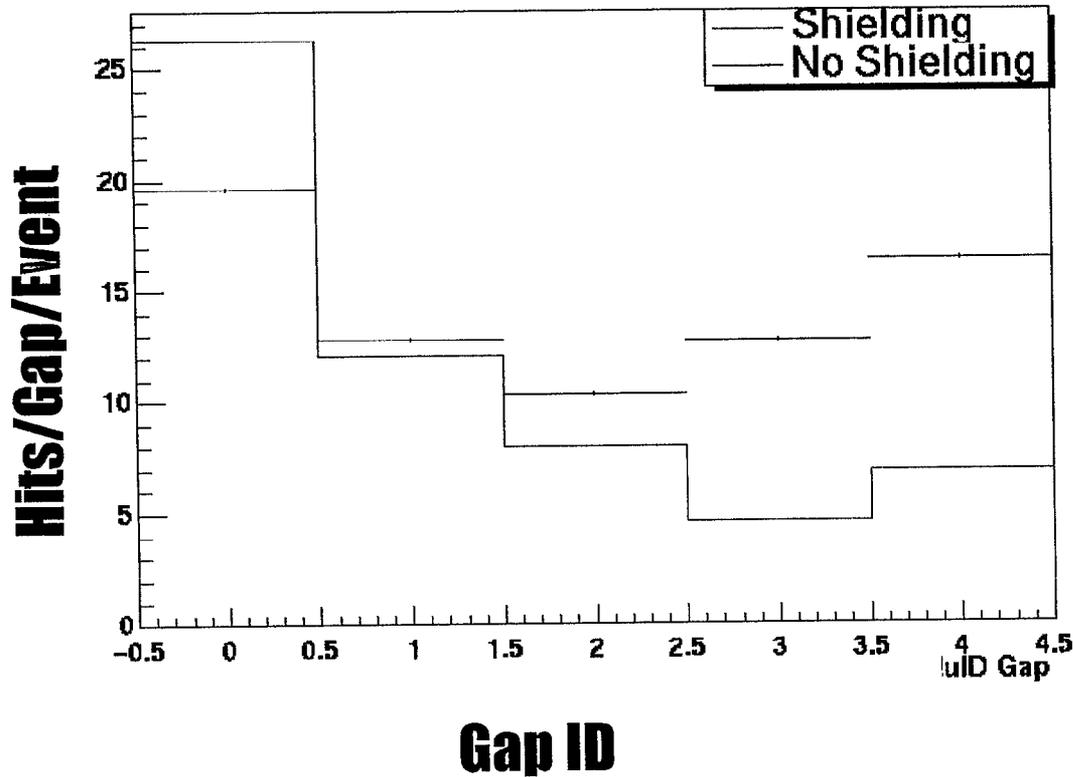
Efficiency degrades 20% at central Au-Au collision by MC.

Reconstruction program is working.

Atsushi Taketani, RBRC Review

Trigger

Hit rate



Observed higher hit rate

Low energy charged hadrons is dominant background source by MC study.

Stacking shield

6 inches width steel between beam pipe and MuID panels

Reduce hit rate

Up to 5times

Trigger Rejection factor

5->44, fit to bandwidth.

Spin run will be OK.

Simplified Level 1 trigger

Full Level 2 trigger

Summary

- South MuId is working.
- Ready for Polarized Proton run.
- North MuId will be ready for Y2002 run.

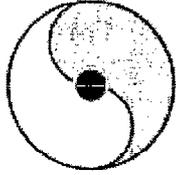
Shield implementation

LV1 trigger for higher luminosity.

Muons at PHENIX; Measurement of the Hadronic Spin-Flip Amplitude in Proton-Carbon Elastic Scattering

Douglas Fields

1) Muons at Phenix.



2) Measurement of the hadronic spin-flip amplitude in proton-carbon elastic scattering.

- *Muons in PHENIX:*

- *Motivation.*

- *Muon Spectrometers.*

- *Muon Tracking.*

- *Triggering and Physics Integration.*

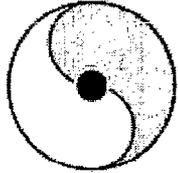
- *E950:*

- *As a test for the RHIC polarimeters.*

- *Measurement of the hadronic spin-flip amplitude.*

- *As a calibration for RHIC polarimeters.*



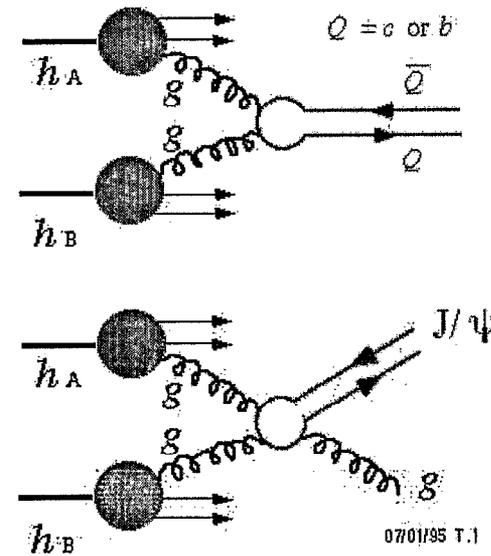


RHIC Physics

- *Quark-Gluon Plasma detected via suppression of J/Ψ .*

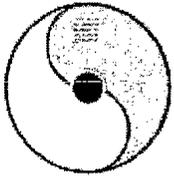
- *Gluon polarization via heavy quark production.*

Gluon Fusion



07/01/95 T.1

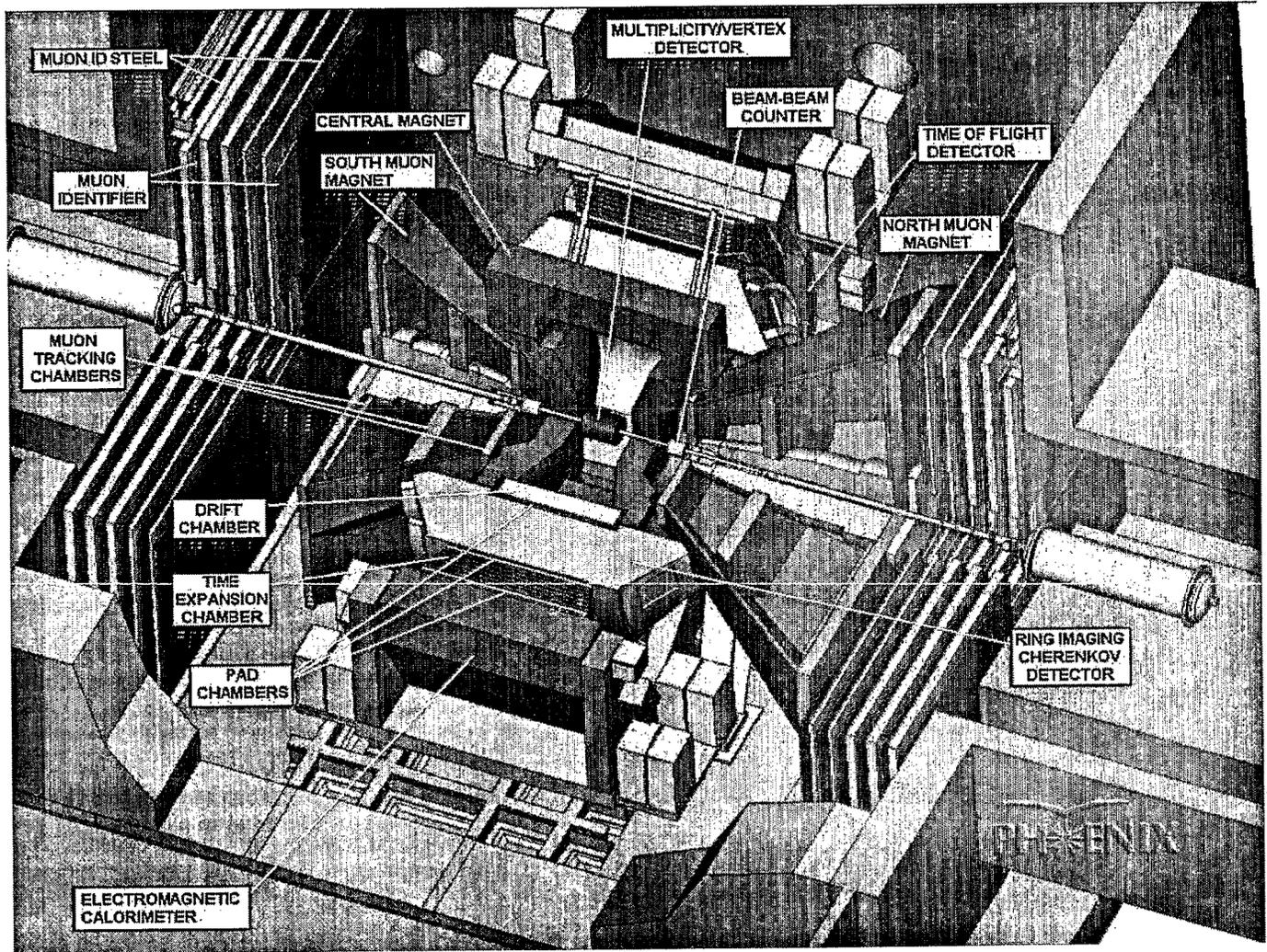




PHENIX

Experiment

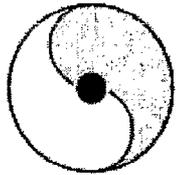
- *Hadrons*
- *Leptons*
- *Photons*



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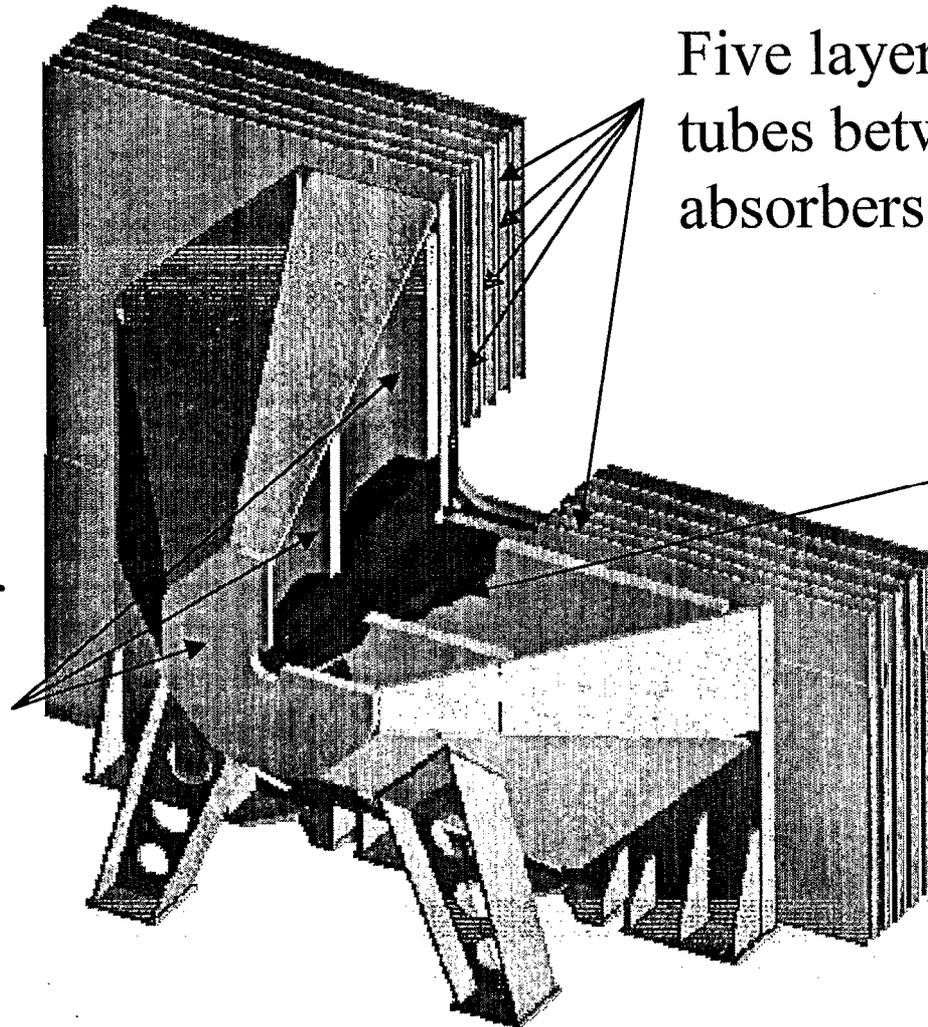
Douglas E. Fields – UNM/RBRC



PHENIX

Experiment

Integrated spectrometer to measure a wide range of muon energies

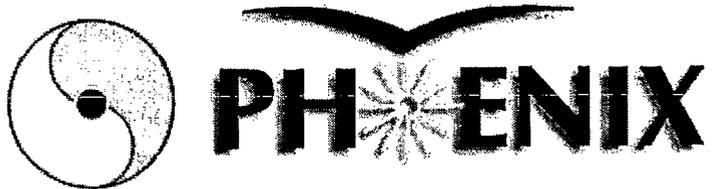


Five layers of Iarocci tubes between steel absorbers

Radial field magnet

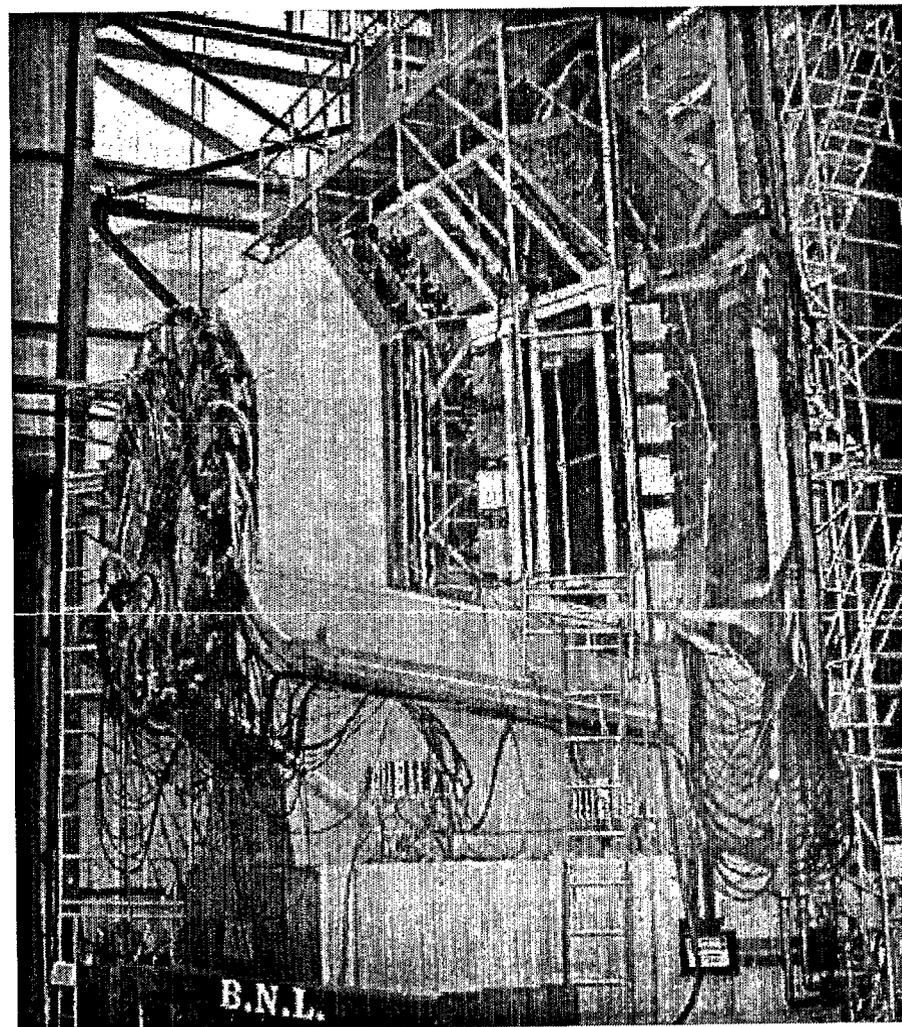
Three layers of Cathode Strip Chambers for stations 1 & 2, two layers for station 3.

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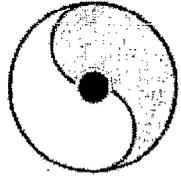


South Muon Arm

- *3 tracking stations*
 - *Cathode strip R/O*
 - *100 μ m res./plane*
 - *60 μ m res./station*
- *Forward coverage*
 - *1.2 < $|y|$ < 2.3*
 - *$-\pi < \phi < \pi$*
- *Mass resolution*
 - *$\Delta M(J/\psi) = 105 \text{ MeV}$*
 - *$\Delta M(Y) = 180 \text{ MeV}$*



Douglas E. Fields – UNM/RBRC



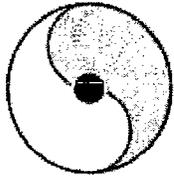
South Station One Muon Tracker



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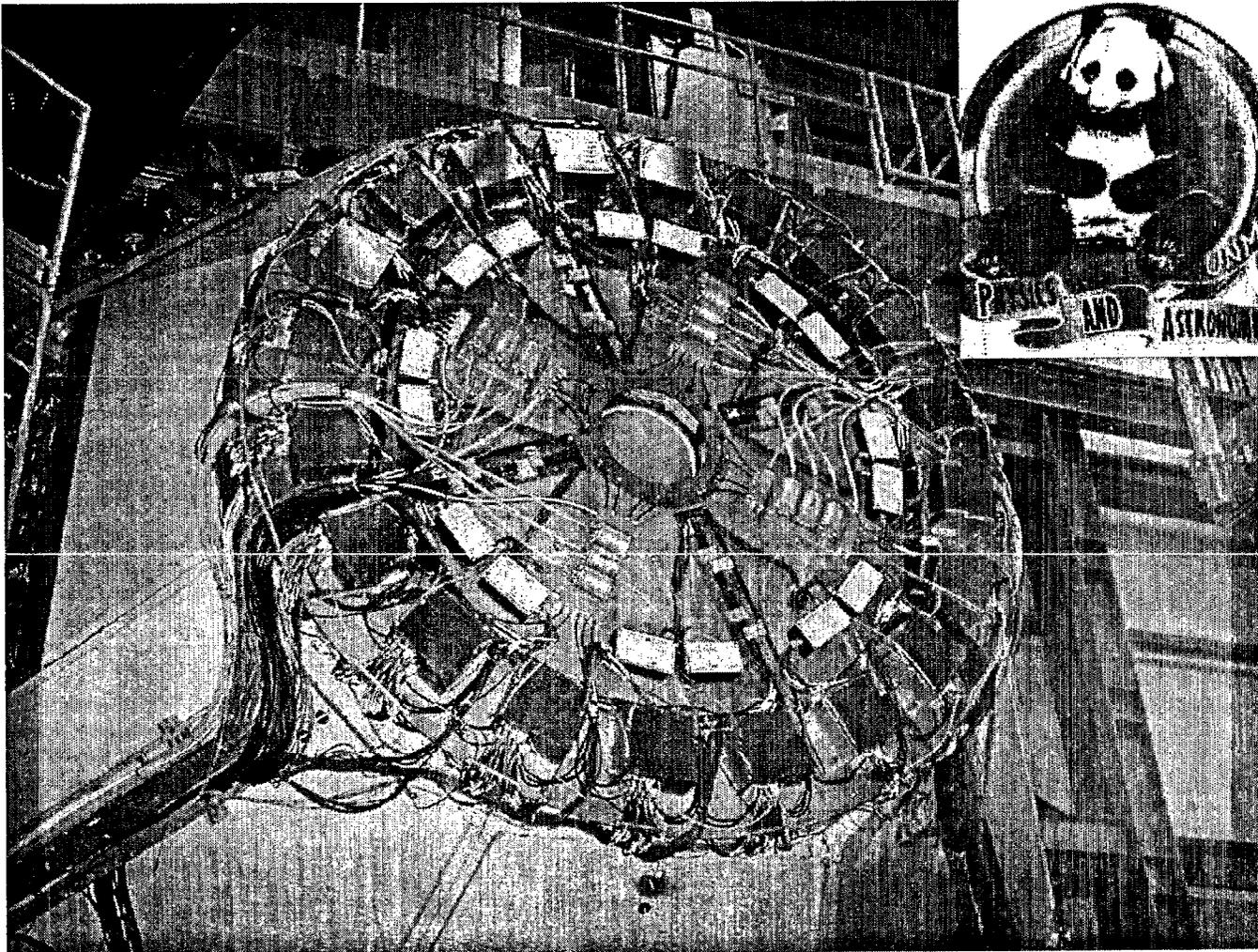
11/8/01

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PHENIX

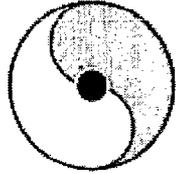
Experiment



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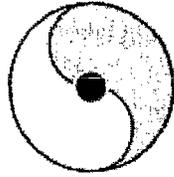
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Triggering and Physics Integration

- *Muon Identifier provides Level-1 trigger for Muon Arms.*
- *Muon Tracking can be used in Level-2 trigger to help suppress ghost hits in identifier and also trigger on Mass.*
- *South Muon Arm is integrated into the DAQ system and is within the data bandwidth requirements for HI running, but may need further trigger for high energy $p+p$ running.*
- *Chamber resolution has been checked for real data and data analysis is ongoing.*



Measurement of the hadronic spin-flip amplitude in proton-carbon elastic scattering.

- ***p+C Coulomb-nuclear interference***

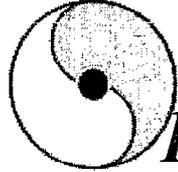
Pros

- ✓ *Inexpensive setup*
- ✓ *Solid target*
- ✓ *High figure of merit*
- ✓ *Little energy dependence*
- ✓ *Polarization profile*

Cons

- X *Difficult Carbon recoil detection*
- X *Not absolute*

- ***IUCF test of silicon detectors CE75***
- ***AGS Prototype experiment E950***

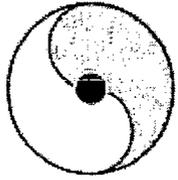


Theory

p+C Coulomb Nuclear Interference (CNI) *(also p+p CNI)*

**CNI is an interference effect between the purely
Coulombic spin-flip term and the hadronic non spin-
flip term in the scattering potential.**

**For the interference term to be important, the scattering
must take place “outside of the nucleus ($r \gg R$), but well
within the screening radius of the atomic electrons
($r \ll a_0$)”.**

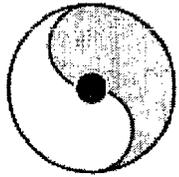


Theory

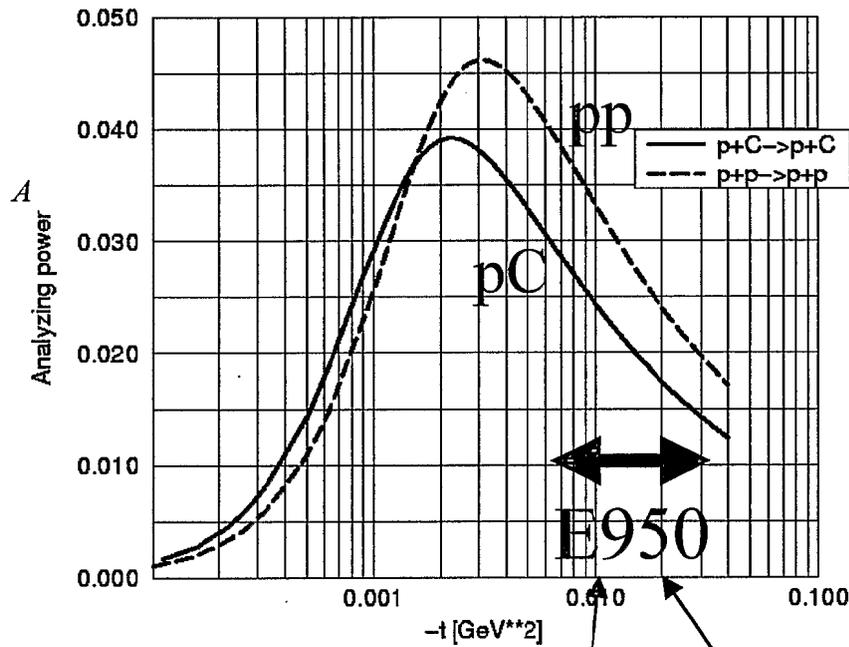
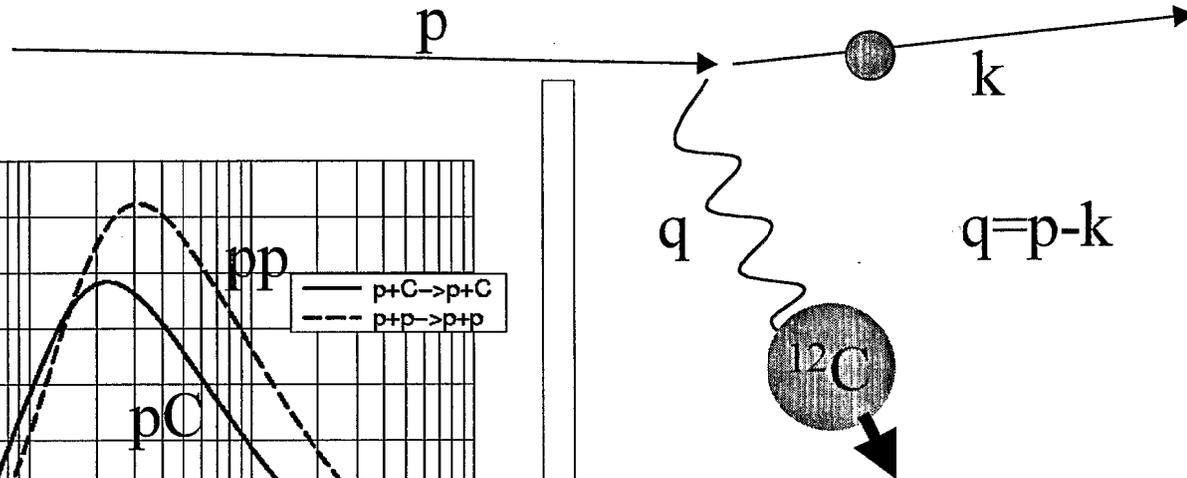
∴ CNI analyzing power is given by:

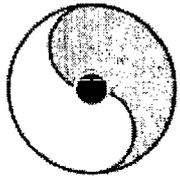
$$A_N = \frac{\sqrt{-t} F_A^h(t) \left\{ F_A^{em}(t) \frac{t_c}{t} [\kappa(1 - \delta\rho) - 2(\text{Im} r_5 - \delta \text{Re} r_5)] - 2F_A^h(t)(\text{Re} r_5 - \rho \text{Im} r_5) \right\}}{m_p \left(\frac{t_c}{t} \right)^2 [F_A^{em}(t)] - 2(\rho + \delta) \frac{t_c}{t} F_A^h(t) F_A^{em}(t) + \left(1 + \rho^2 - \frac{1}{m_p^2} |r_5|^2 \right) [F_A^h(t)]}$$

- ∴ so no direct energy dependence. But, the hadronic spin-flip
- ∴ term is unknown, so assuming IT has no energy dependence,
- ∴ this method is only good for a relative polarimeter (compare
- ∴ polarizations at injection and after acceleration). However,
- ∴ at 25 - 250 GeV, Hadronic A_N is thought to be <10% of the
- ∴ CNI A_N .

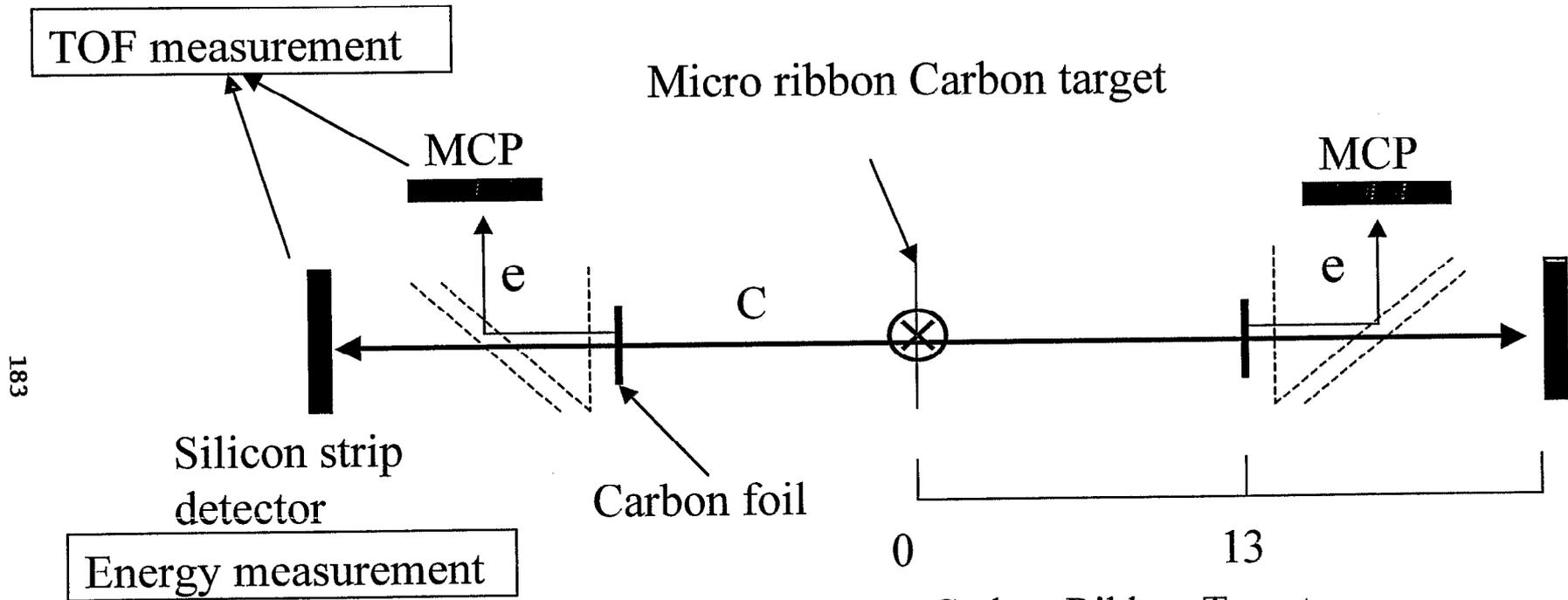


Theory





AGS E950 Experimental Setup

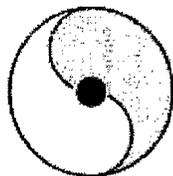


•Carbon Ribbon Targets

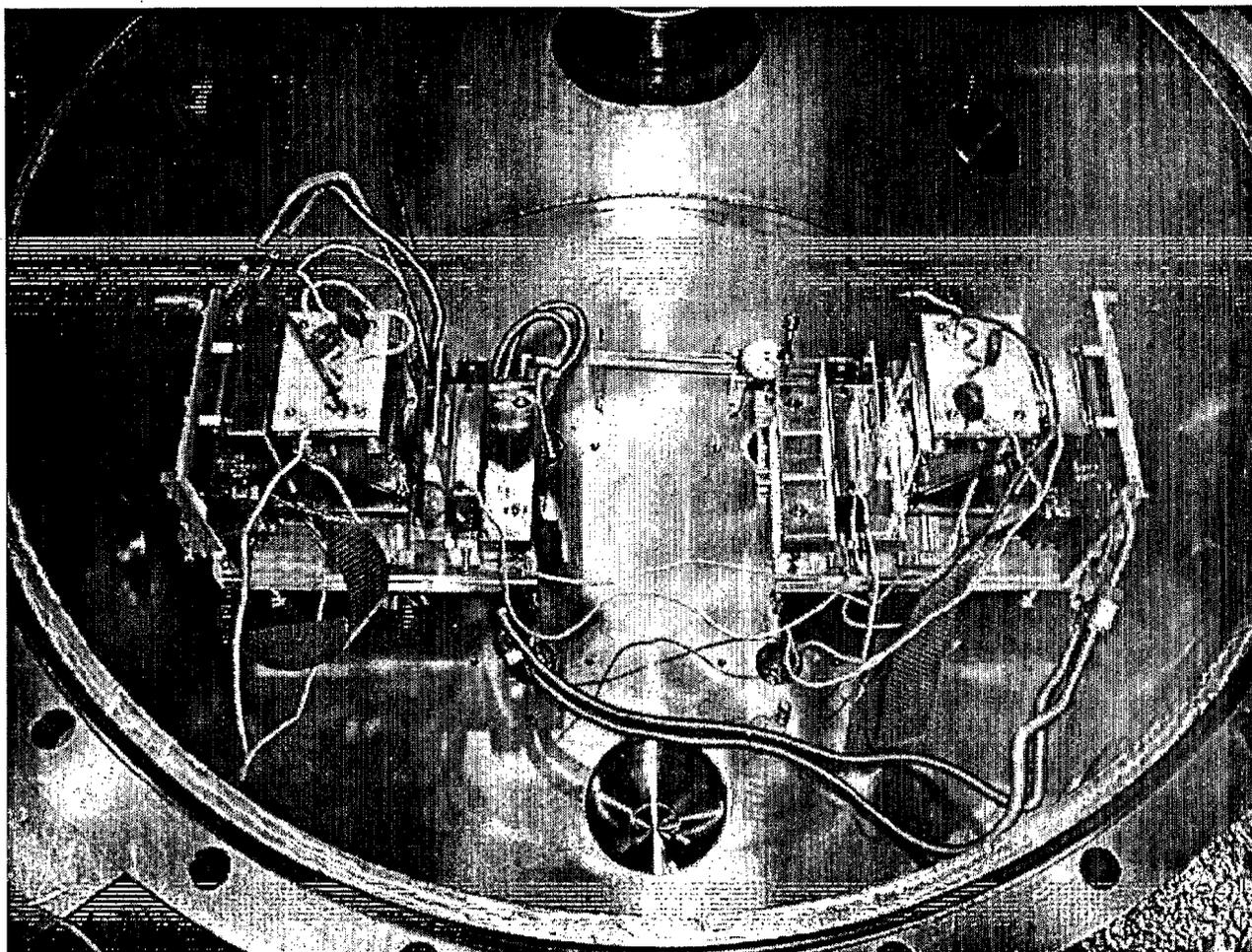
•6 μm wide

•3.7 $\mu\text{g}/\text{cm}^2$ thick

•3cm long



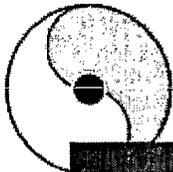
AGS E950 Experimental Setup



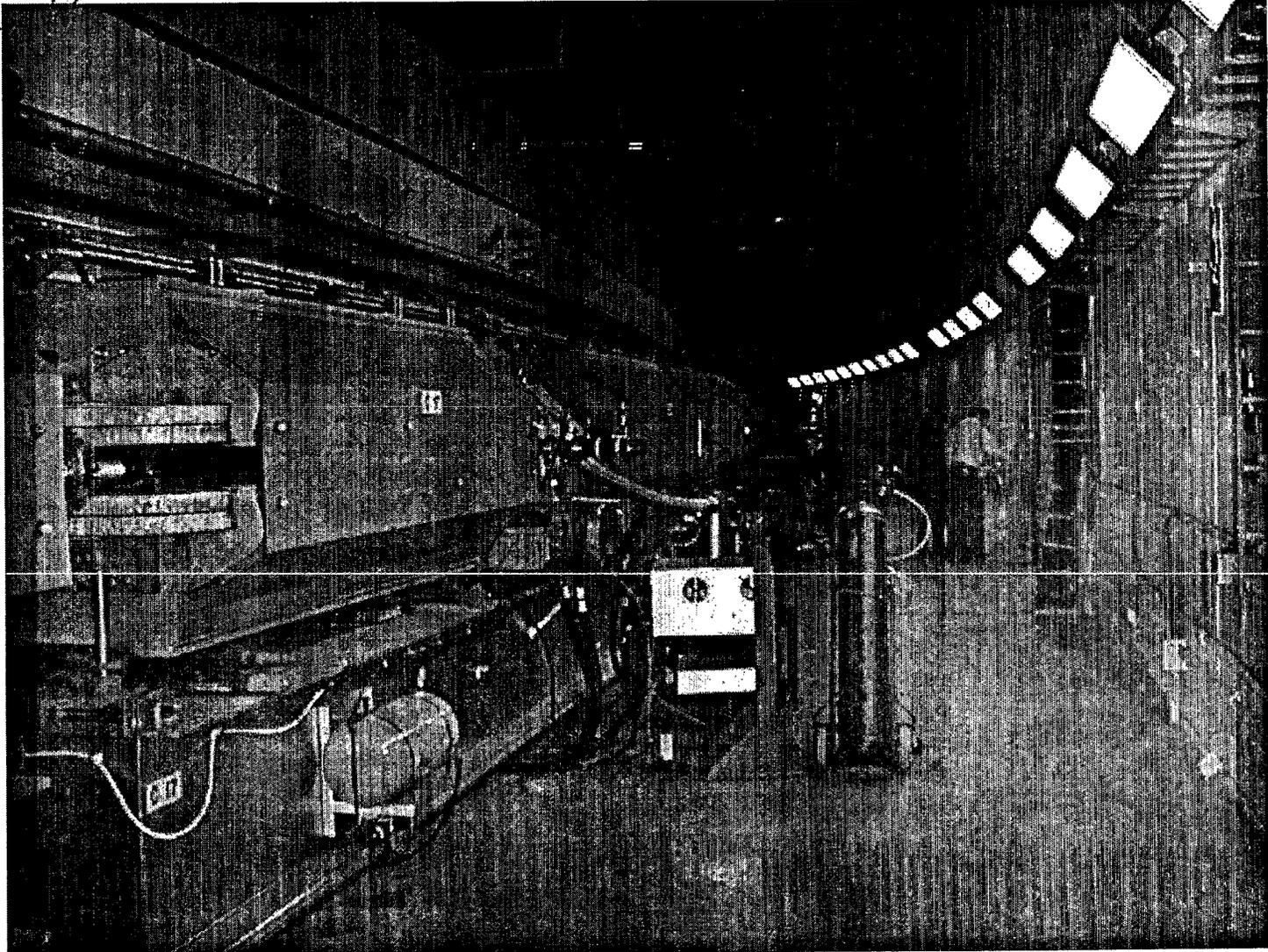
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11/8/01

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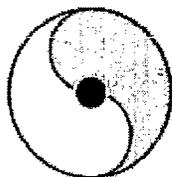
AGS E950 Experimental Setup



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11/8/01

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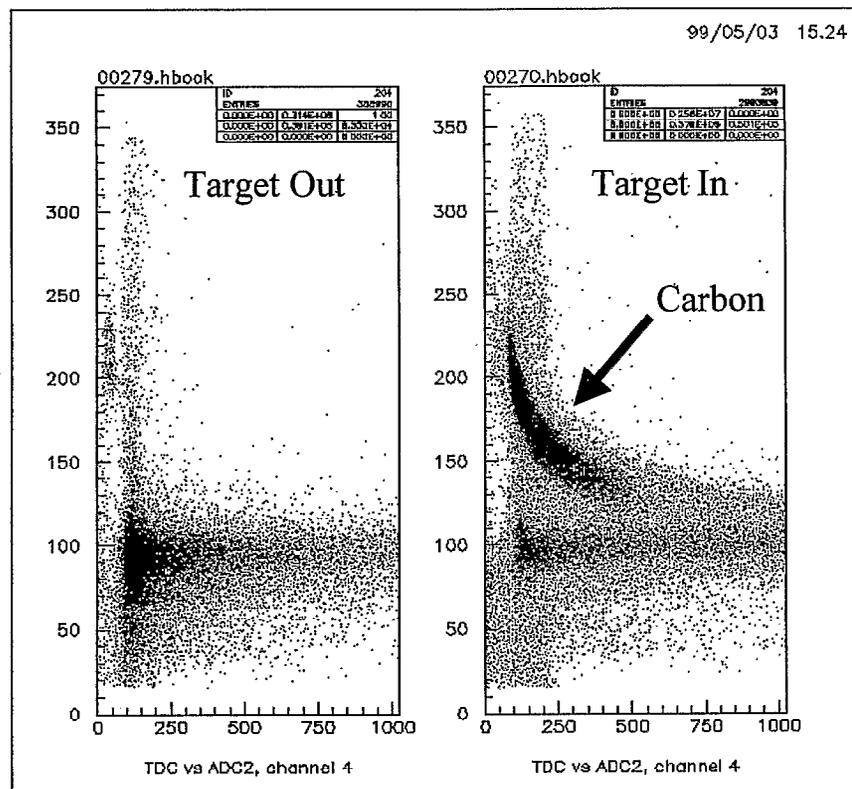


E950 On-line Analysis

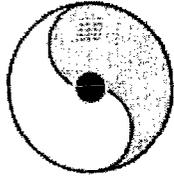
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- Target out configuration still had frame.
- Got sufficiently good t and E resolution to identify Carbons
- Detected Carbons down to 250keV

TDC distribution

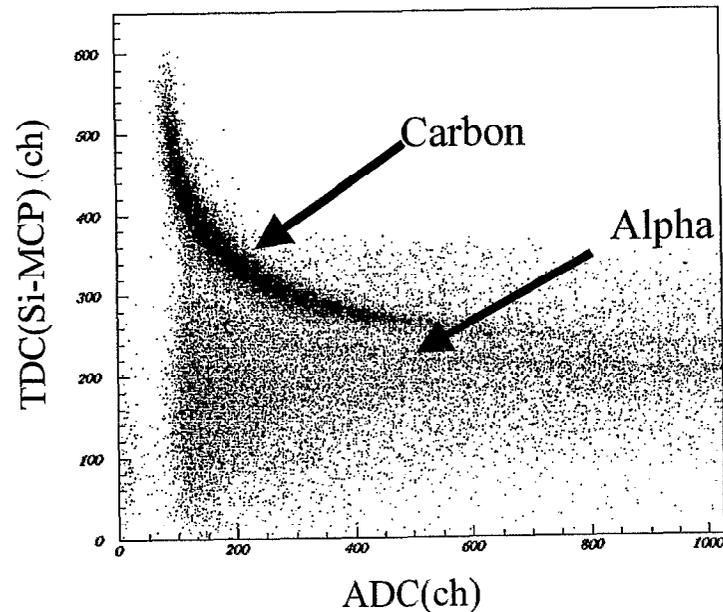


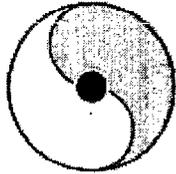
ADC distribution



E950 On-line Analysis

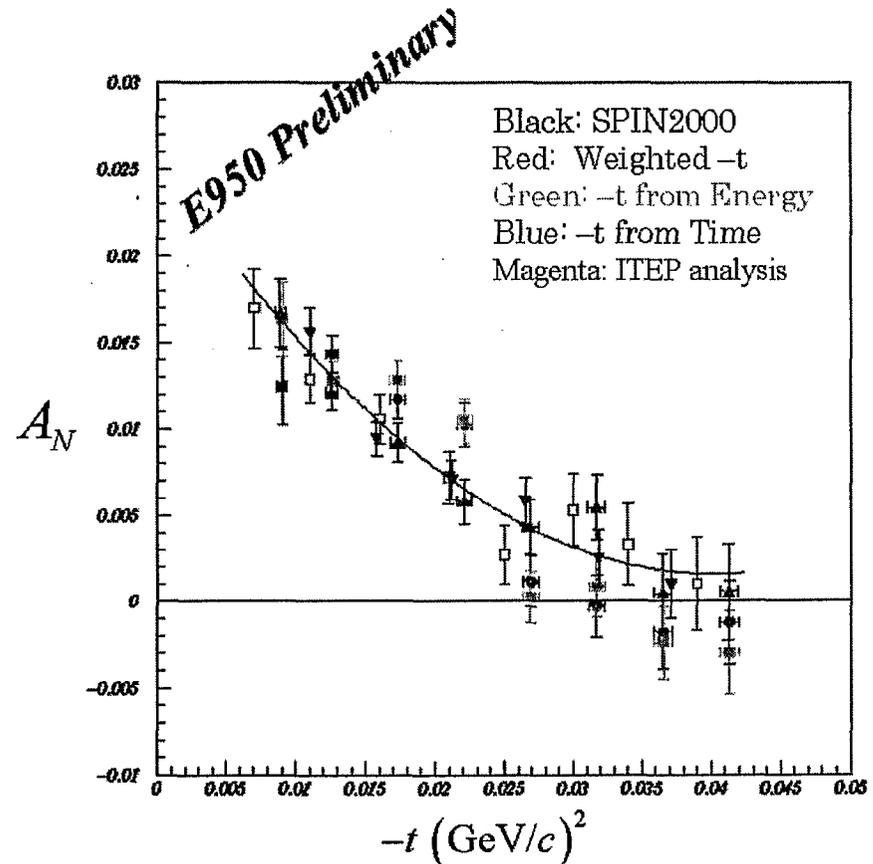
- Bunch width was ~ 25 ns.
- TDC start was beam RF.
- Inherent 7.2ns width from beam bunches.
- Using Si - MCP gives inherent Si time resolution of 2.5ns .

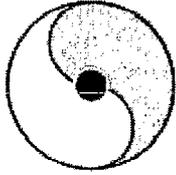




E950 Results

- Fits very well to theoretical curve with small contribution from hadron spin-flip.
- Nice physics measurement of VERY small asymmetry.
- Proof of principle for RHIC polarimeter.





Summary

- *South Muon Arm is operational and taking data this year.*
- *North Muon Arm is being completed and will be ready for installation in the upcoming RHIC shutdown.*
- *E950 was a successful test for the RHIC polarimeters and a paper is forthcoming.*

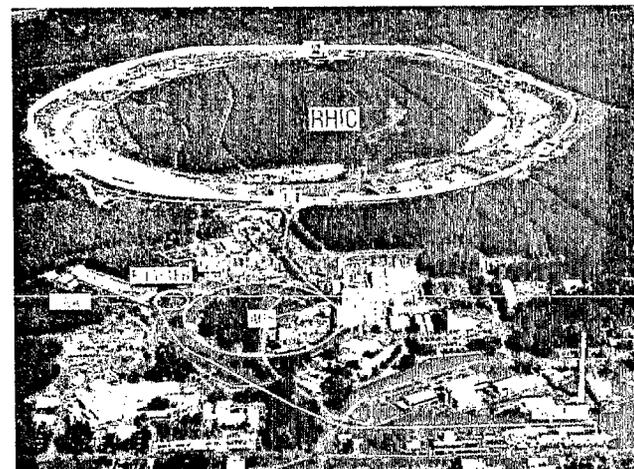
Alignment Calibration of the South Muon Tracker in PHENIX

Hideyuki Kobayashi

Alignment and Calibration of the PHENIX Muon Tracker

RIKEN BNL Research Center
Hideyuki Kobayashi

RHIC at BNL



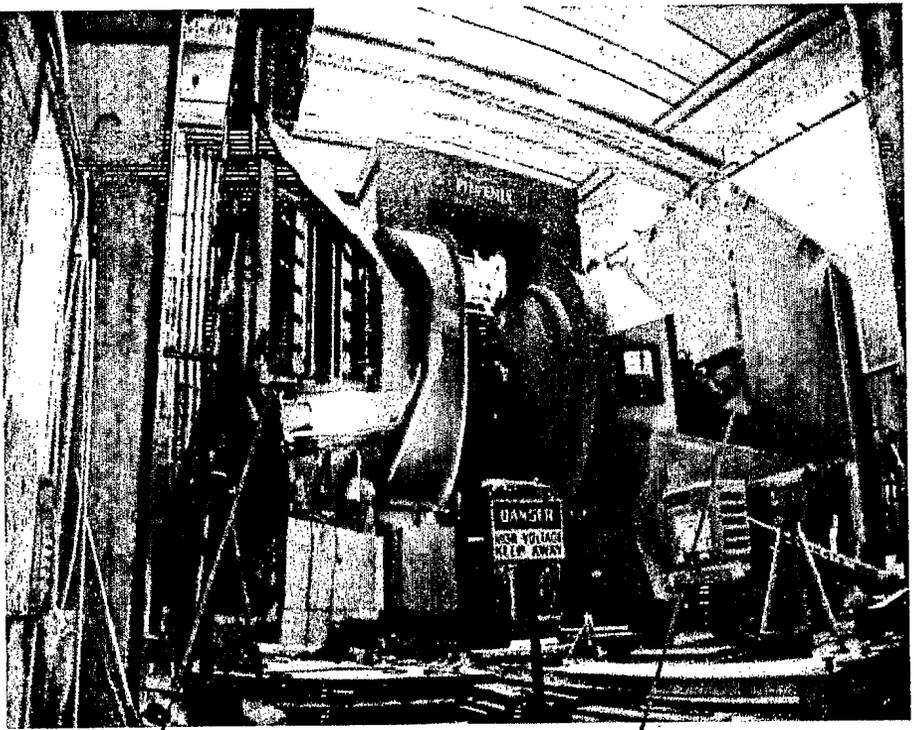
Contents

1. PHENIX Muon Tracker
2. Resolution Requirement
3. Structure of the Muon Tracker
4. Geometry Alignment
5. Optical Alignment System
6. Summary

$$\begin{array}{l} \text{Au+Au} \quad \sqrt{s_{NN}} = 200 \text{ GeV} \\ \text{polarized p+p} \quad \sqrt{s} = 200, 500 \text{ GeV} \end{array}$$

PHENIX Muon Tracker

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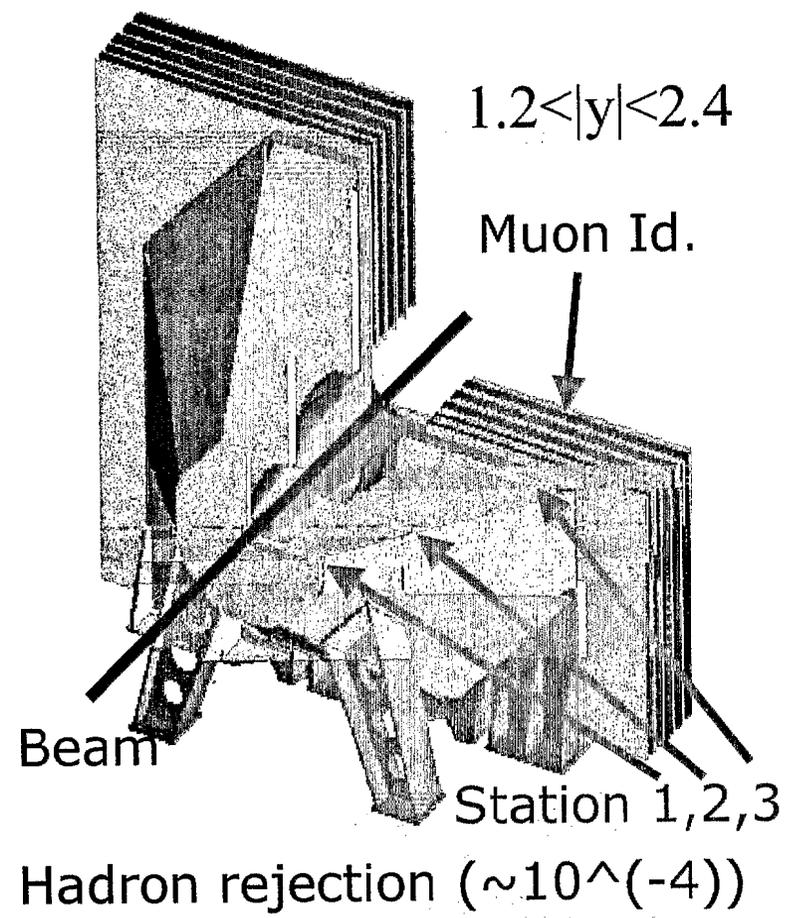
South Muon Arm
Up and running

North Muon Arm
Year 2002~

11/29-30/2001

Hideyuki Kobayashi

Radial Field Magnet



Physics with Muon Arms

■ Physics Processes for QGP search and Spin Physics

- Vector meson production (J/ψ , Y , ϕ , ...)
- Drell-Yan process (muon pairs)
- Open heavy flavor from gluon collision (muon tag)
- W production (single high-Pt muons)

Resolution Requirement

Deflection at Station 2 $d=1$ cm (~ 0.5 Tm) Muon $p=10$ GeV/c

Distinguish Vector Meson Productions

- $\Upsilon(1S)(9.46\text{GeV})$ from $\Upsilon(2S+3S)(10.02, 10.36\text{GeV})$

Chamber resolution dominates.

Resolution at Υ mass $\sigma(M_{\Upsilon}) = 200$ MeV

Requirement: 100 micron per cathode.

- $J/\Psi(3.097\text{GeV})$ from $\Psi'(3.686\text{GeV})$

Multiple scattering and chamber resolution.

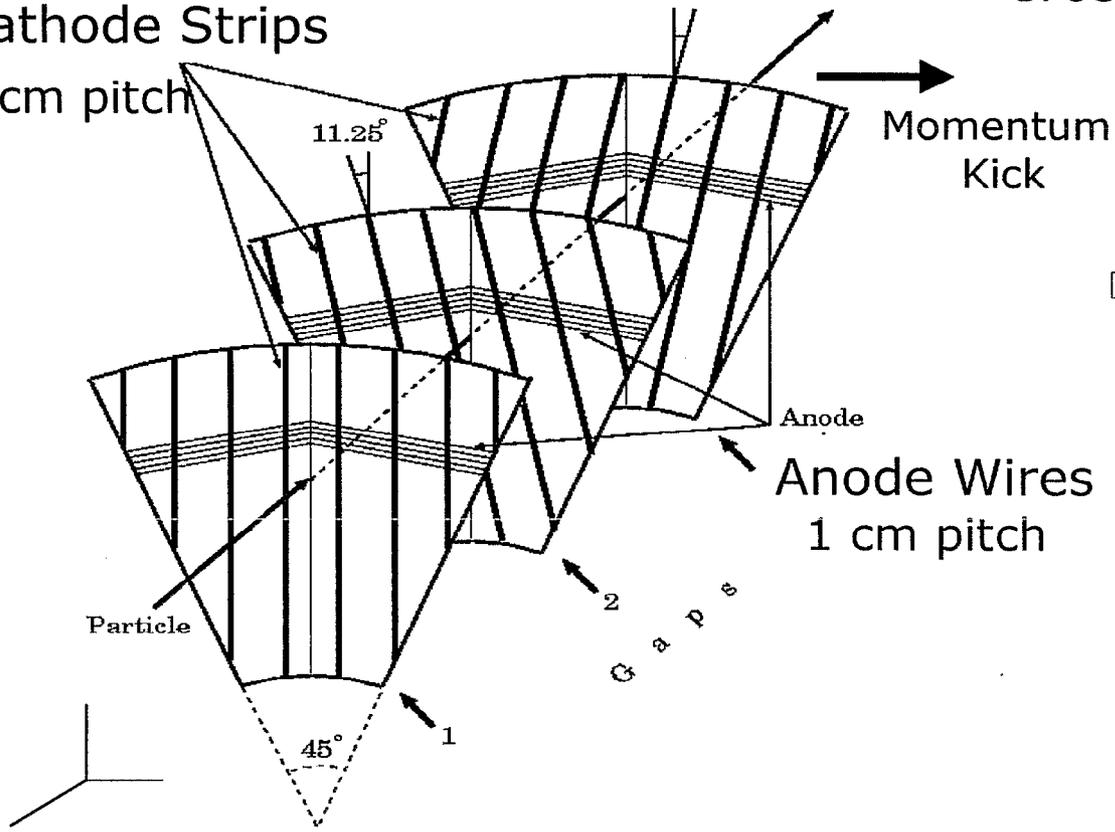
Resolution at J/Ψ mass $\sigma(M_{J/\Psi}) = 108$ MeV

Requirement: 300 micron per cathode.

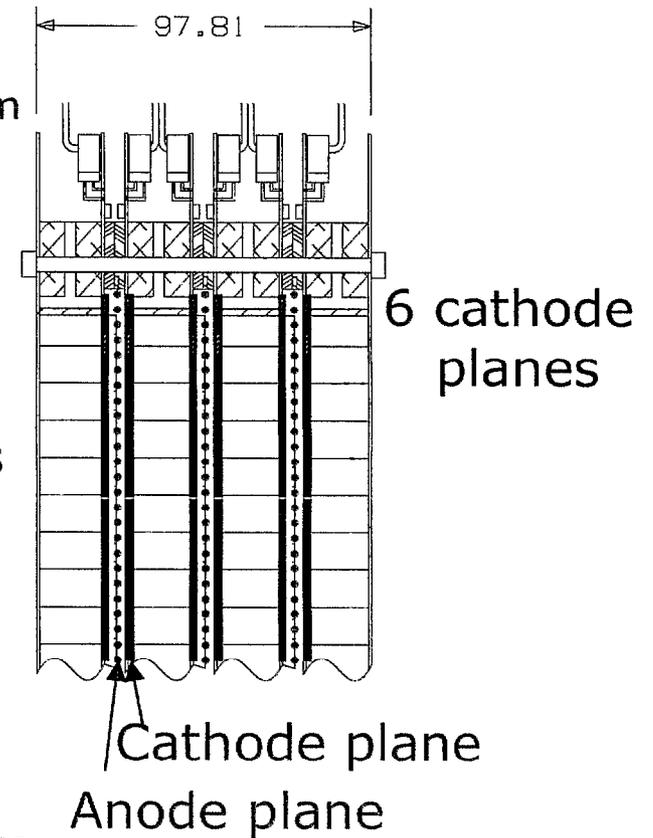
Structure of a Station

Cathode Strips
1 cm pitch

197



Cross Section of Station 1



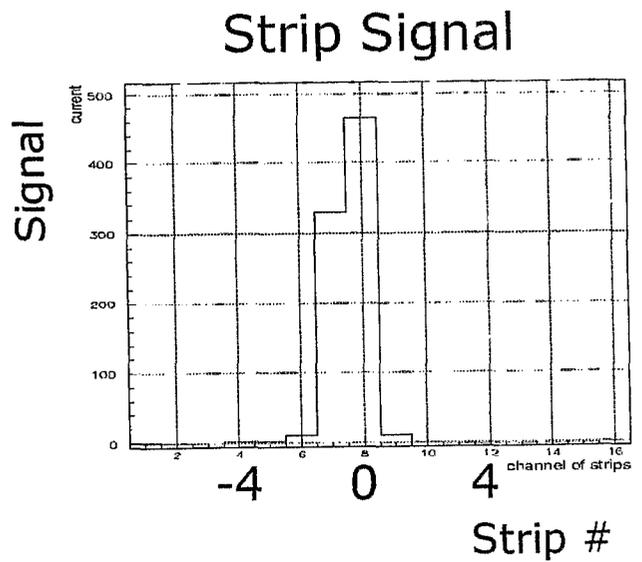
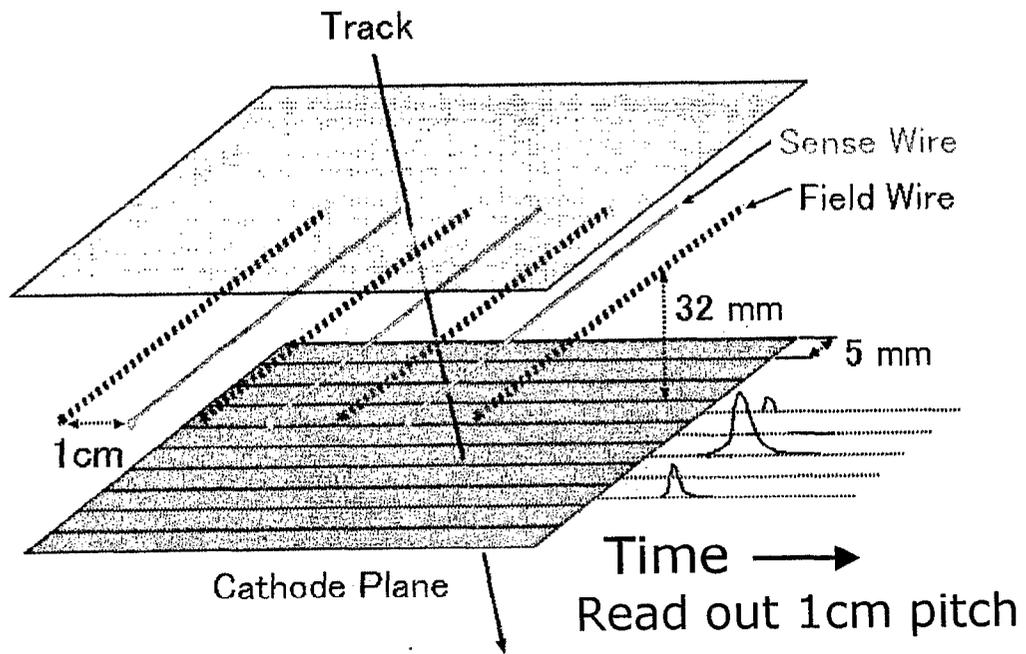
Internal alignment <25 mm

Cathode Strip Chamber

Cathode read out

Requirement
Noise/Signal < 1%

198



Ar:CO₂:CF₄ = 50:30:20

Average # of strips/track ~ 2.4

Inter Station Alignment

Relative station alignment requirement $< 25 \text{ um}$

✦ Initial alignment

- Au-Au collision field OFF straight tracks.
- Cosmic ray field OFF straight tracks.

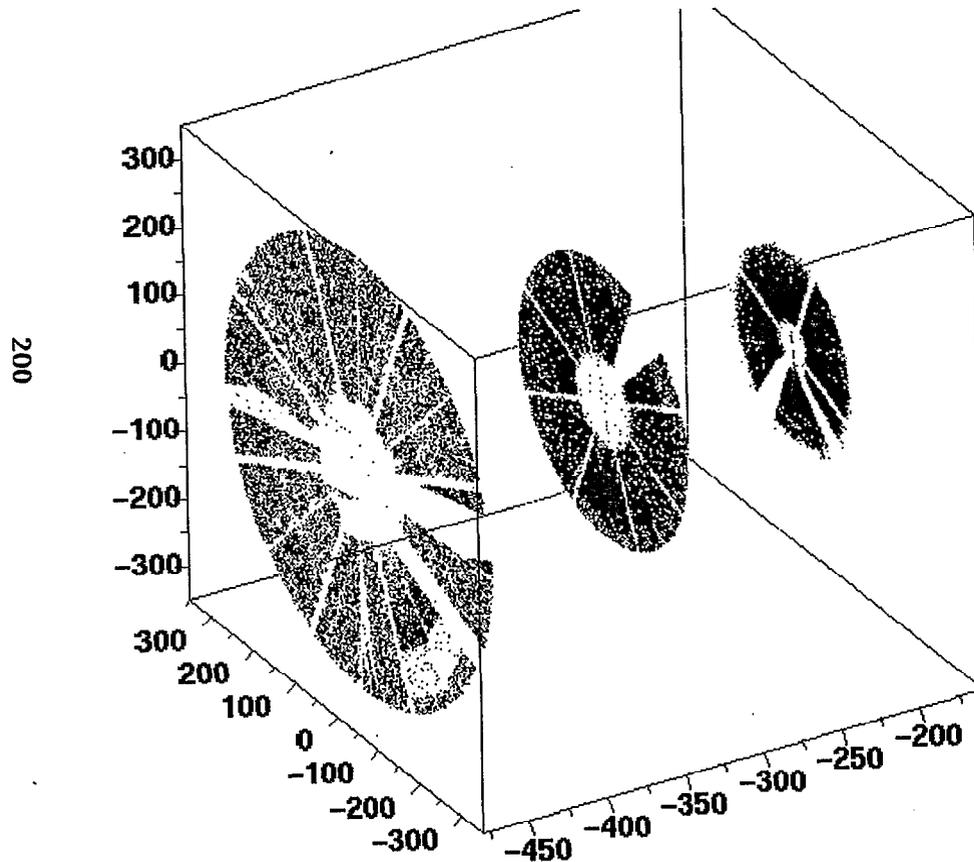
Analysis is underway.

✦ Real time alignment

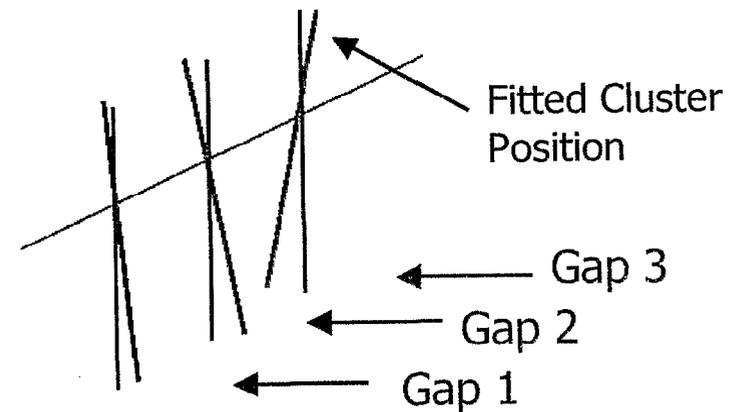
- Optical alignment system

Initial Alignment Determination (Field OFF Straight Track Analysis)

XY Intersection of Fitted Clusters



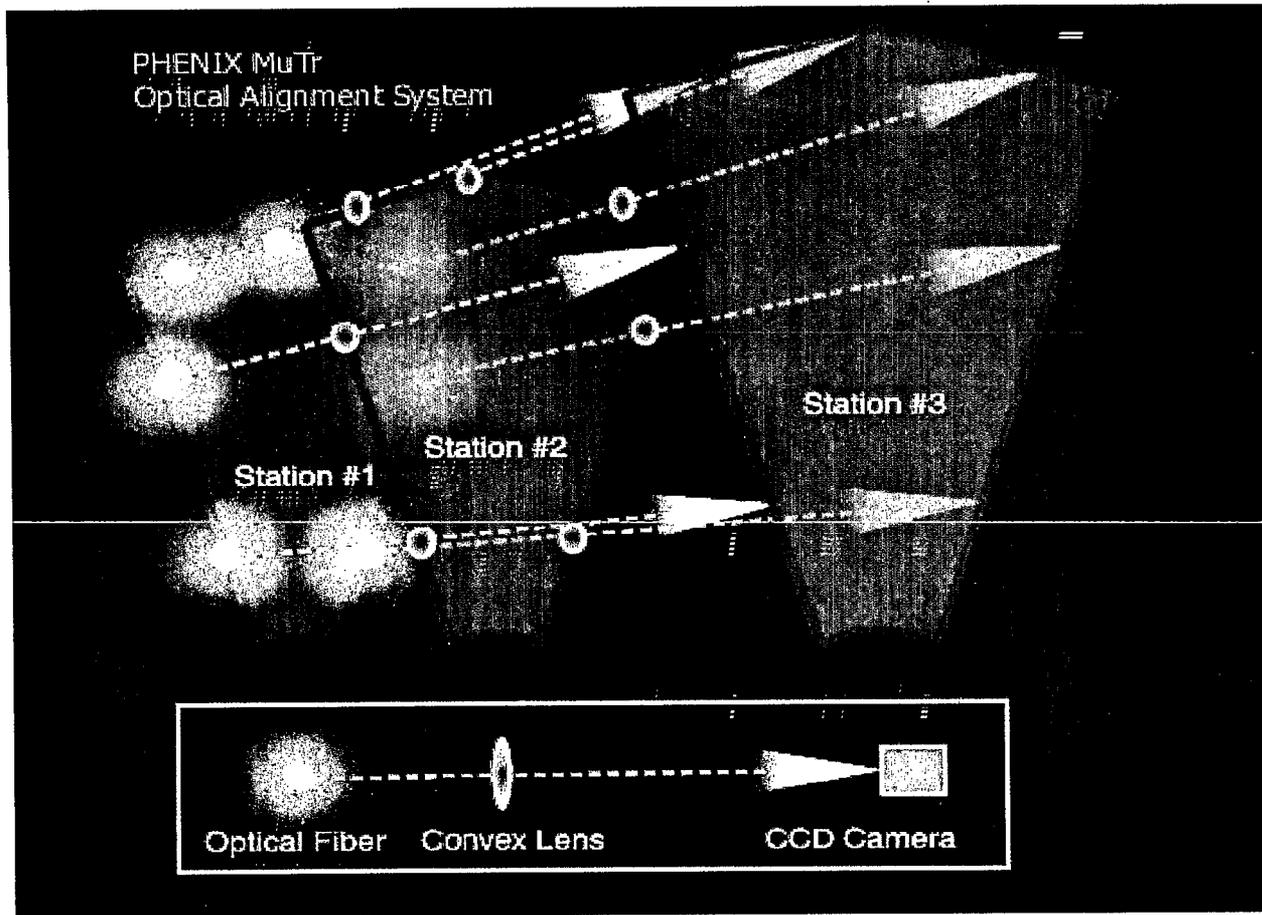
Straight Track in a Station



- Intra station tracks are used to find inter station tracks.
- Inter station alignment calibration using Field OFF data is underway.

Optical Alignment System

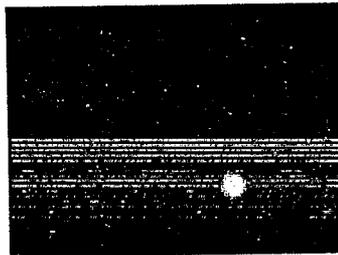
7 set of straightness Monitor in One Octant



Correct

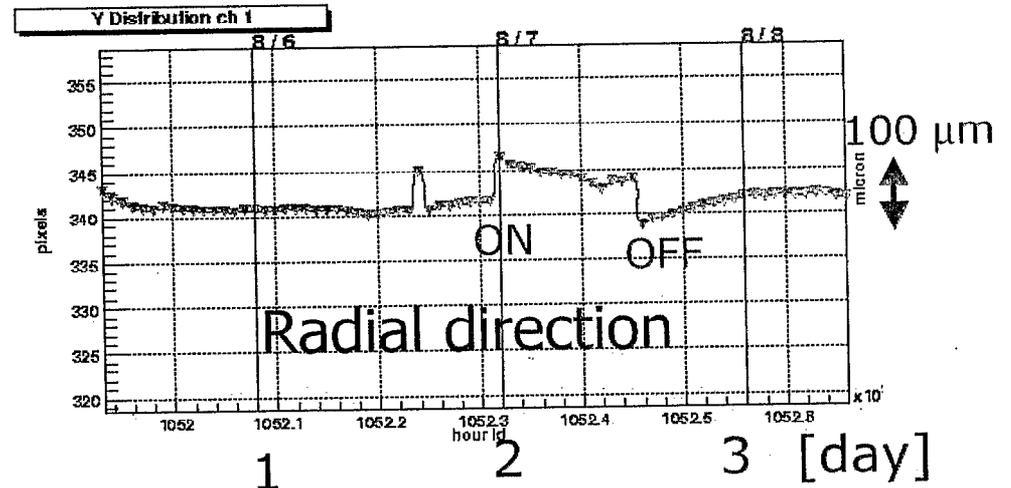
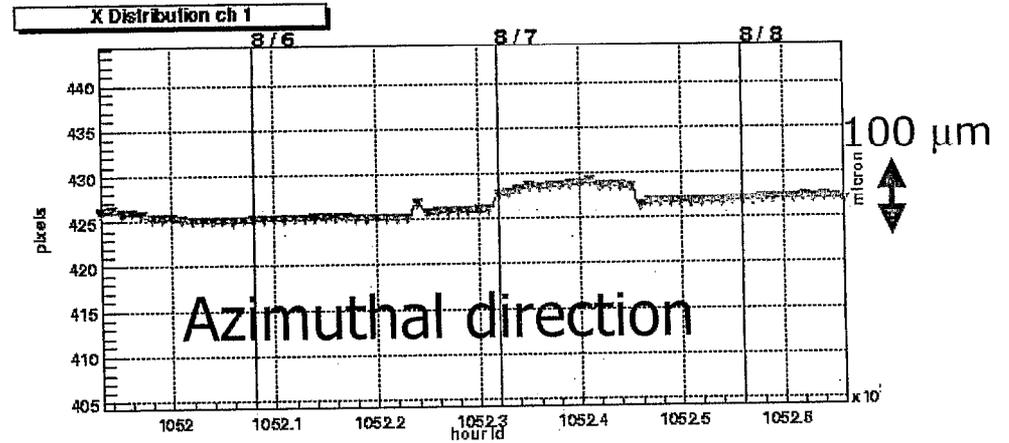
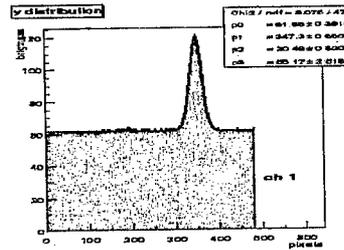
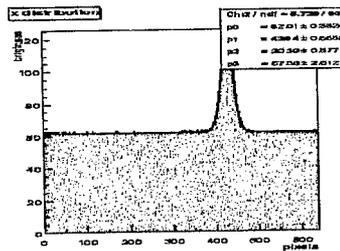
- ✘ Thermal expansion or contraction.
- ✘ Any alignment change by magnetic field, temperature etc.

Alignment Monitoring



10 um
Pixel CCD

Spot size
 $d=400\mu\text{m}$



- ✦ 2~10 um accuracy
- ✦ 60 um Position change by field magnet ON/OFF detected.

Summary

- # The PHENIX South Muon Tracker up and running.
- # Resolution in a station ($\sim 300 \mu\text{m}$) measured, which is good enough for J/Ψ detection for this year.
- # Alignment requirement between stations ($< 25 \mu\text{m}$)
 - Initial alignment = Field off straight track analysis.
 - Real time alignment = Optical Alignment System.
- # Alignment change ($\sim 60 \mu\text{m}$) due to magnetic field ON/OFF observed.

The CC-J Computer Facility at RIKEN

Takashi Ichihara

CCJ status

Computing Center in Japan for spin physics at RHIC

T. Ichihara, Y. Watanabe, S. Yokkaichi, O. Jinnouchi, N. Saito,
H. En'yo, M. Ishihara, Y.Goto⁽¹⁾, S. Sawada⁽²⁾, H. Hamagaki⁽³⁾
RIKEN, RBRC⁽¹⁾, KEK⁽²⁾, CNS⁽³⁾

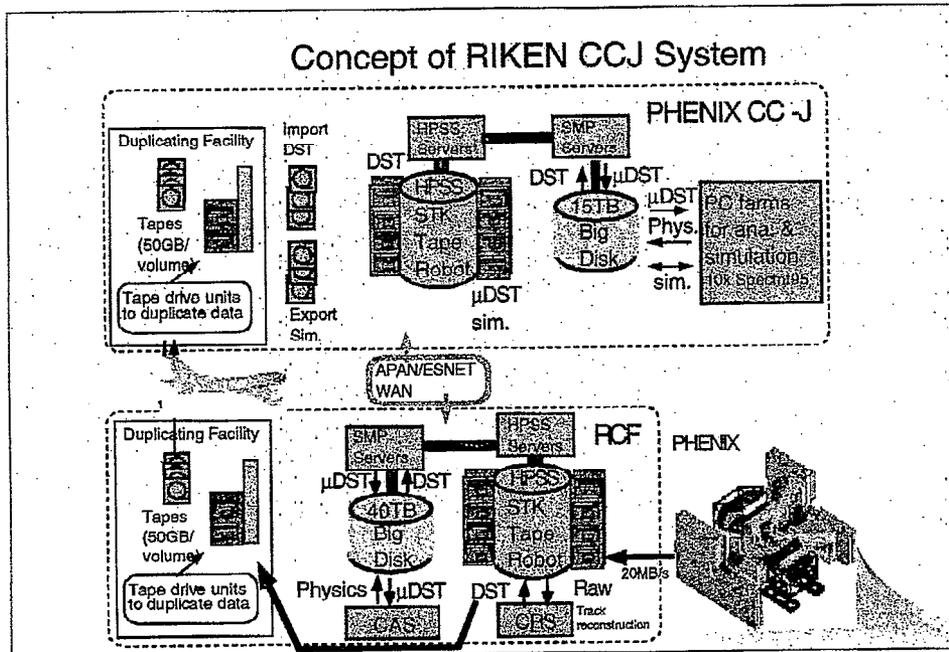
Presented on 29th November 2001 at RBRC Review at BNL



RIKEN CCJ : Overview

- ◆ Scope
 - Center for the analysis of RHIC Spin Physics
 - **Principal site of computing for PHENIX simulation**
 - PHENIX CC-J is aiming at covering most of the simulation tasks of the whole PHENIX experiments
 - **Regional Asia** computing center
- ◆ Size
 - Data amount: handing 225 TB /year
 - Disk Storage : ~ 20 TB, Tape Library: ~500 TB
 - CPU performance : 13 k SPECint95 (~300 Pentium 3/4 CPU)
- ◆ Schedule
 - R&D for the CC-J started in April '98 at RBRC in BNL
 - Construction began in April '99 over a three years period
 - CCJ started operation in June 2000
 - CCJ will reach full scale in 2002





System Requirement for CCJ

- ◆ **Annual Data amount**

• DST	150 TB
• micro-DST	45 TB
• Simulated Data	30 TB
• Total	225 TB
- ◆ **Hierarchical Storage System**
 - Handle data amount of 225 TB/year
 - Total I/O bandwidth: 112 MB/s
 - HPSS system
- ◆ **Disk storage system**
 - 20 TB capacity
 - All RAID system
 - I/O bandwidth: 520 MB/s
- ◆ **CPU (SPECint95)**

Simulation	8200
Sim. Reconst	1300
Sim. ana.	170
Theor. Mode	800
Data Analysis	2000
Total	12470 SPECint95
	(= 120K SPECint2000)
- ◆ **Data Accessibility (exchange 225 TB/year)**
 - ◆ Data Duplication Facility (tape cartridge)
 - ◆ Wide Area Network (IMnet/APAN/ESnet)
- ◆ **Software Environment**
 - ◆ AFS, Objectivity/DB, Batch Queuing System

Requirements as a Regional Computing Center

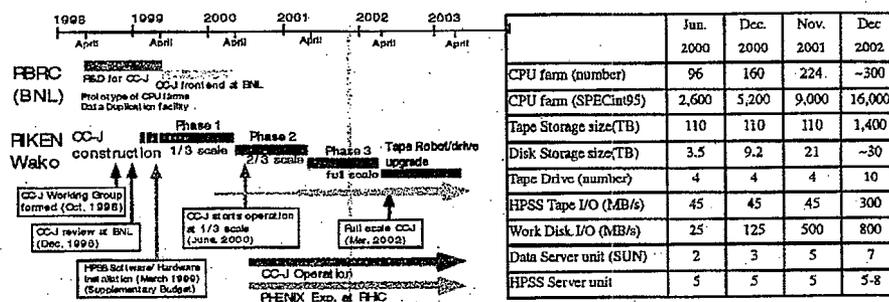
▲ Software Environment

- Software environment of the CCJ needed be **compatible** to the PHENIX software environment at the RHIC Computing Facility (RCF) at BNL
 - AFS (/afs/rhic)
 - Remote access over the network is very slow and unstable (AFS sever : BNL)
 - daily mirroring at CCJ and accessed via NFS from Linux farms
 - Objectivity/DB
 - Remote access over the network is very slow and unstable (AMS server: BNL)
 - Local AMS server at CCJ (daily update DB)
 - Batch Queuing System: **Load Sharing Facility (LSF 4.1)**
 - RedHat Linux 6.1 (Kernel 2.2.19 with nfsv3 enabled), gcc-2.95.3 etc.
 - Veritas File System (Journaling file system on Solaris): free from fsck for ~TB disk

▲ Data Accessibility

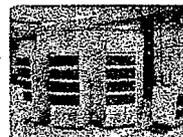
- Need to exchange data of **225 TB/year** to BNL RCF
 - Most part of the data exchange is carried out with **SD3 tape cartridges**
 - Data duplicating Facility at both (10 MB/s performance by airborne)
 - Some part of the data exchange is carried out over the **Wide Area Network (WAN)**
 - CC-J will use Asia-Pacific Advanced Network (**APAN**) for US-Japan connection
 - <http://www.apan.net/>
 - APAN has currently ~100 Mbps bandwidth for Japan-US(STAR TAP) connection
 - 3 MB/s transfer performance was obtained using bfttp protocol.

Plan and current status of RIKEN CCJ



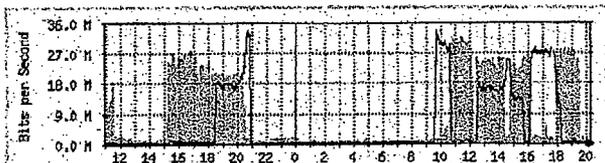
Upgrade plan in the next year (2002)

- ▲ CPU farms (224 CPU -> ~300 CPU)
- ▲ **Tape Library system**
 - Current capacity **110 TB** (Experimental data : **250 TB/year**)
 - Add new tape Library (STK silo, storing 5000 tapes)
 - Upgrade plan : tape drive
 - Current : redwood 11.2 MB/s 50 GB/volume
 - 2002Q2: 9940B 30 MB/s 200 GB/volume
 - 250 TB/silo (redwood) -> **1000 TB/silo** (9940B)
 - Total tape capacity (110 TB -> 1400 TB[1.4 PB])
- ▲ LAN backbone (1 Gbps -> 4-8 Gbps)
- ▲ etc.



File Transfer over WAN

- **RIKEN** - (Imnet) - **APAN** (~100 Mbps) -startap- ESnet - **BNL**
 - Round Trip Time(RTT) for **RIKEN-BNL** :170 ms
 - RFC1323 (TCP Extensions for high performance, May 1992) describes the method of using large TCP window-size (> 64 KB)
 - **FTP performance** : 290 KB/s (64 KB window size), 640 KB/s(512KB window)
 - Large TCP-window size is necessary to obtain high-transfer rate
- **BBFTP** (<http://doc.in2p3.fr/bbftp/>)
 - Software designed to quickly transfer files across a wide area network.
 - It has been written for the **babar** experiment in order to transfer big files
 - transferring data through **several parallel tcp streams**
 - **RIKEN-BNL bbftp Performance** (10 tcp streams for each session)
 - 1.5 MB/s (1-session) 3 MB/s (3-sessions)
- **APAN US-Japan link upgraded ! (120 Mbps to 1.2 Gbps Oct. 2002)**



MRTG graph during bbftp transfer between RIEKN and BNL

Analysis for the first PHENIX experiment with CCJ

- ▲ Quark Matter 2001 conference (Jan 2001)
 - 21 papers using CCJ / total 33 PHENIX papers
- ▲ Simulation
 - 100k event simulation/reconst. (Hayashi)
 - DC Simulation (Jane)
 - Muon Moc Data Challenge (MDC) (Satohiro) 100k Au+Au (June 2001)
- ▲ DST Production
 - 1 TB of Raw Data (Year-1) was transferred via WAN from BNL to RIKEN
 - PHENIX official DST (v03) production (Sawada) (Dec. 2000)
 - about 40% of DSTs produced at CCJ and transferred to BNL RCF
- ▲ Detector calibration/simulation
 - TOF - (Kiyomochi, Chujo, Suzuki)
 - EMCal - (Torii, Oyama, Matsumoto)
 - RICH - (Akiba, Shigaki, Sakaguchi)
- ▲ Physics/simulation
 - Single electron spectrum - (Akiba, Hachiya)
 - Hadron particle ratio/spectrum (Ohnishi, Chujo)
 - Photon [π^0] spectrum (Oyama, Sakaguchi)

QM2001 papers using CCJ

21 papers using CCJ / total 33 PHENIX papers

▲ Plenary Session -	
• Bil Zekic	Results from PHENIX
• N. Sato	RHIC Spin Program
• Alexander Milov	Et and N(paired) at RHIC
• Gabor David	Neutral Pion Distributions at RHIC
• Yasuyuki Akiba	Electron Measurements at RHIC
• Axel Drees	RHIC Reportur IV - Hard Scattering
▲ Parallel Session -	
• Hirosaki Hamagaki	Particle Identification capability of the PHENIX experiment
• Sebastian White	Calorimetry and Global Event Characterization in PHENIX
• Julia Velkovska	Pt spectra of identified hadrons measured with the PHENIX experiment at RHIC
• Federica Messer	Spectra and angular correlation of high momentum charged particles in PHENIX
• Alexei Denicov	Common Event Characterization in the RHIC Experiments
• Roy Lacey	Elliptic Flow Measurements with the PHENIX Detector System
• Stephen Johnson	First Results on Two-Particle Correlations Determined by the PHENIX Experiment at RHIC
• Hiroaki Ohsishi	Particle ratios in PHENIX at RHIC
▲ Poster Session -	
• Indrani Ojha	Comparison of event generator predictions for the charged particle
• Alexander Bazilevsky	Transverse energy measurements with the PHENIX detector at RHIC
• Yajun Mao	The PHENIX Muon Identifier Subsystem
• Yasuo Maekawa	Performance of the Time-of-Flight Counter in PHENIX
• Takao Sakaguchi	Performance of the PHENIX Ring Imaging Cherenkov Detector
• Toru Sugitate	Performance of the Beam-Beam Counter in PHENIX
• Hisayuki Torii	Performance of the PHENIX EM Calorimeter in PHENIX

CCJ Operation

- ▲ Operation, maintenance and development of CC-J are carried out under the charge of the CCJ Planning and Coordinate Office (PCO).

CCJ Director (Chief Scientist of the Radiation Lab.)

H. En'yo

Planning and Coordination Office

manager	T. Ichihara	(RIKEN and RBRC)
technical manager	Y. Watanabe	(RIKEN and RBRC)
scientific programming coordinator	H. En'yo	(RIKEN and RBRC, PHENIX-EC)
	H. Hamagaki	(CNS-U-Tokyo, PHENIX-EC)
PHENIX Liaison	N. Saito	(RIKEN and RBRC)
computer scientists	S. Yokkaichi	(RIKEN)
	O. Jimmouchi	(RIKEN)
	Y. Goto	(RBRC)
	S. Sawada	(KEK)

Technical Management Office

Manager, Data duplication	Y. Watanabe	(RIKEN and RBRC)
System engineer	N. Ohaki (IBM Japan)	
Tape duplication operator	(TBD)	

Summary

- ▲ Construction of the CCJ started in 1999.
 - The CCJ operation started in June 2000 at 1/3 scale.
 - 43 user's account created.
- ▲ Recent Hardware/upgrade and software improvement :
 - 224 Linux CPU(90k Specint2000), 21 TB disk, 100TB HPSS Tape library.
 - Data Duplicating Facility at BNL RCF started operation in Dec 2000.
- ▲ Upgrade plan in the next year
 - Tape robot(new silo), tape drive, LAN, CPU farms, WAN transfer
- ▲ PHENIX Year -1 experiment : summer in 2000
 - Analysis of the PHENIX first experiment with CCJ
 - Official DST (v03) Production
 - Simulations, Detector calibration
 - Physics analysis/simulation
 - Quark Matter 2001 conference (Jan 2001)
 - 21 papers using CCJ / total 33 PHENIX paper
- ▲ PHENIX Year 2 (2001) Run started in August 2001
 - DST production for year-2 run is now under preparation at BNL
- ▲ Spin experiments at RHIC will start in December 2001.
 - planning to transfer all the spin-exp. data to CCJ

THEORY PRESENTATIONS

Classical Computation of Gluons in Heavy Ion Collisions

Yasushi Nara

Classical computation of gluons in heavy ion collisions

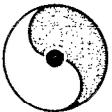
Yasushi Nara with
Alex Krasnitz^a, Raju Venugopalan^{b,c}

a UCEH, Universidade do Algarve,

b RIKEN-BNL Research Center,

c Physics Department, Brookhaven National Laboratory

- classical SU(3) Yang-Mills solution: A. Krasnitz, Y. Nara and R. Venugopalan, hep-ph/0108092. Phys. Rev. Lett. **87** 192302 (2001).
- Time evolutions of anisotropy and elliptic flow from CGC



RTTC collaboration

- S. Cheng, S. Pratt, P. Csizmadia, Y. Nara, D. Molnar, M. Gyulassy, S. E. Vance, and B. Zhang, "The effect of finite-range interactions in classical transport theory," nucl-th/0107001. submitted.
- Y. Nara, S. E. Vance and P. Csizmadia, "A Study of Parton Energy Loss in Au+Au Collisions at RHIC using Transport Theory," nucl-th/0109018. submitted to Phys. Lett. B.

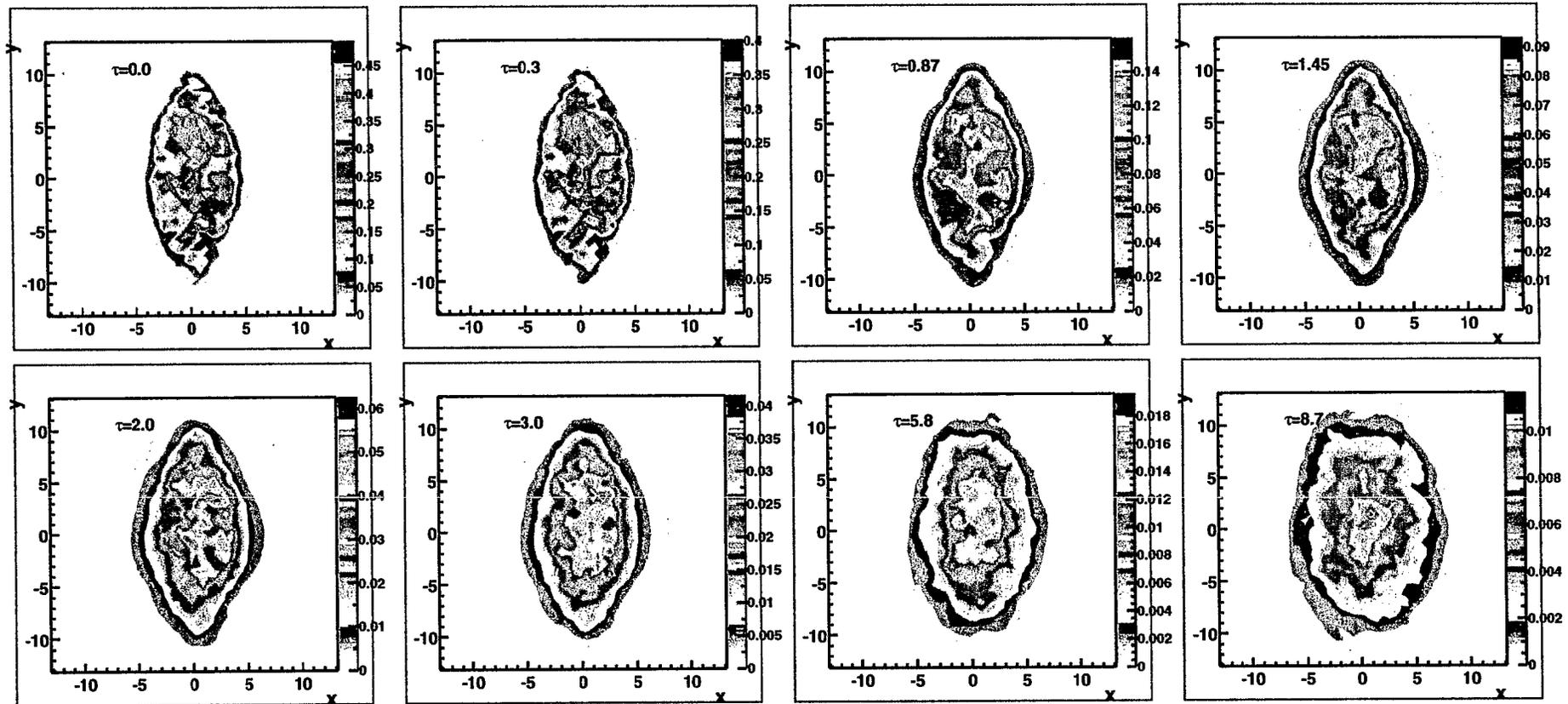
220

JAM collaboration

- N. Otuka, P. K. Sahu, M. Isse, Y. Nara and A. Ohnishi, "Re-hardening of hadron transverse mass spectra in relativistic heavy-ion collisions," nucl-th/0102051. submitted to Phys. Rev. Lett.
- Y. Hirata, A. Ohnishi, Y. Nara, T. Kido, T. Maruyama, N. Otuka, K. Niita, H. Takada, S. Chiba "Sideward Peak of Intermediate Mass Fragments in High Energy Proton Induced Reactions" nucl-th/0111019 submitted to Nucl. Phys. A.



Time evolution of energy density (10 events average)



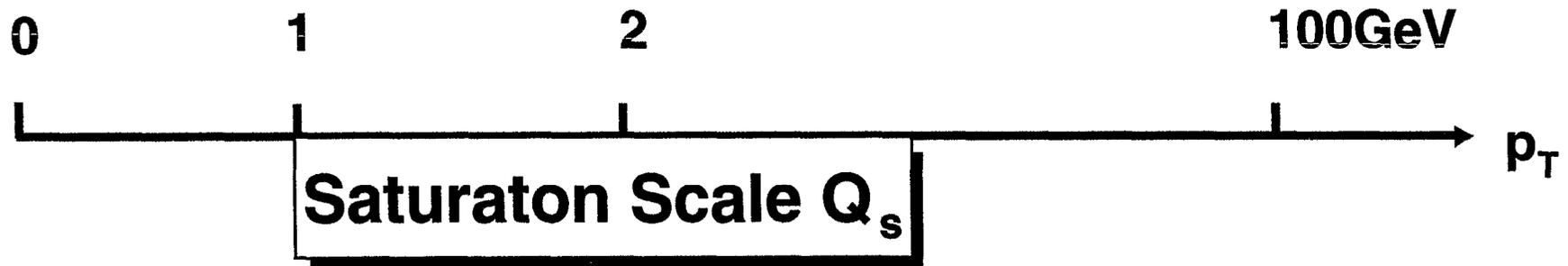
Nucleus-Nucleus Collisions at collider energies

1. before collisions \rightarrow color glass condensate
2. production of soft gluons and mini-jet gluons \rightarrow classical Yang-Mills and pQCD
3. toward the thermalization \rightarrow time evolution by Boltzmann equation
4. thermalized parton matter? \rightarrow hydro
5. hadronization
6. expanding hadron gas \rightarrow hadronic transport (RQMD,UrQMD,JAM...)
7. freeze out

Purpose: compute coherent gluon production from CGC



small x gluons from McLerran-Venugopalan Model



Classical Yang-Mills field Perturbation theory (mini-jets)

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- at small x ($x \equiv P_p/P_h$) rapid growth of partons by branching $g \rightarrow g + g$. But at some point, branchings stop, because of absorption $g + g \rightarrow g$. Parton density should be saturate at some point.
- What is the saturation scale Λ_s ? $\Lambda_s^2 \sim \alpha_s x G(x, Q_s^2) T_A(b)$.
 - RHIC: $\Lambda_s \cong 2 \sim 1$ GeV
 - LHC: $\Lambda_s \cong 4 \sim 2$ GeV



Classical Effective field theory approach

- Sources of soft gluons are valence quarks and hard gluons.

$$P([\rho]) = \exp\left(-\frac{1}{2\Lambda_s^2} \int d^2x_\perp \rho^2(x_\perp)\right)$$

with $\Lambda_s \equiv g^2 \mu$, μ^2 : the average squared color charge per unit area

- The scale Λ_s and the size of the nucleus R are the only physically relevant dimensional parameters
- real time lattice simulation of classical Yang-Mills eq.
- the Kogut-Susskind Hamiltonian in 2+1 dimensions coupled to an adjoint scalar field.
- Initial color charge is sampled in the almond shape (open boundary condition).

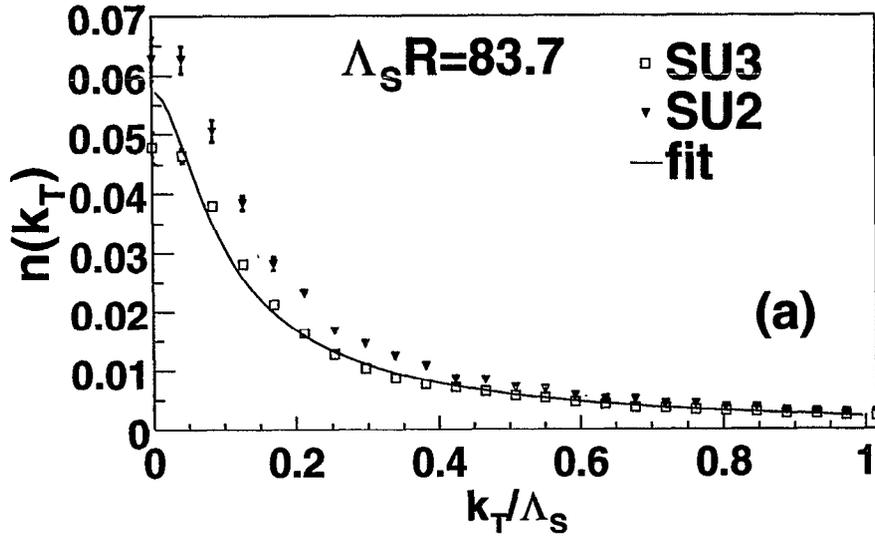
$$\mu_\pm^2(\mathbf{s}) = \mu_0^2 T_A(\mathbf{s} \pm \mathbf{b}/2),$$

where $T_A(\mathbf{s}) = \int_{-\infty}^{\infty} dz \rho(\mathbf{r})$ is a thickness function.

- Assume sphere nuclei with surface.



Transverse momentum distribution of gluons



$$n(k_T) = \tilde{f}_n / (N_c^2 - 1)$$

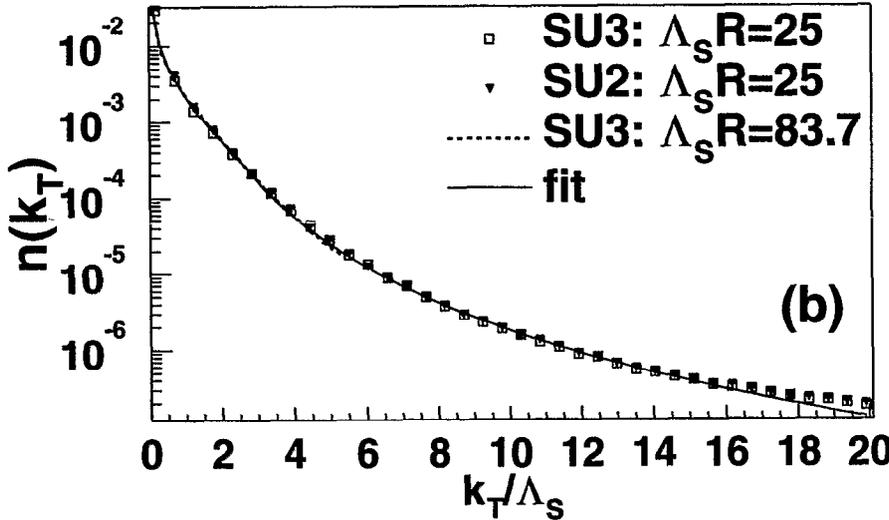
The SU(3) gluon momentum distribution can be fitted by the following function,

$$\frac{1}{\pi R^2} \frac{dN}{d\eta d^2 k_T} = \frac{1}{g^2} \tilde{f}_n(k_T/\Lambda_s), \quad (1)$$

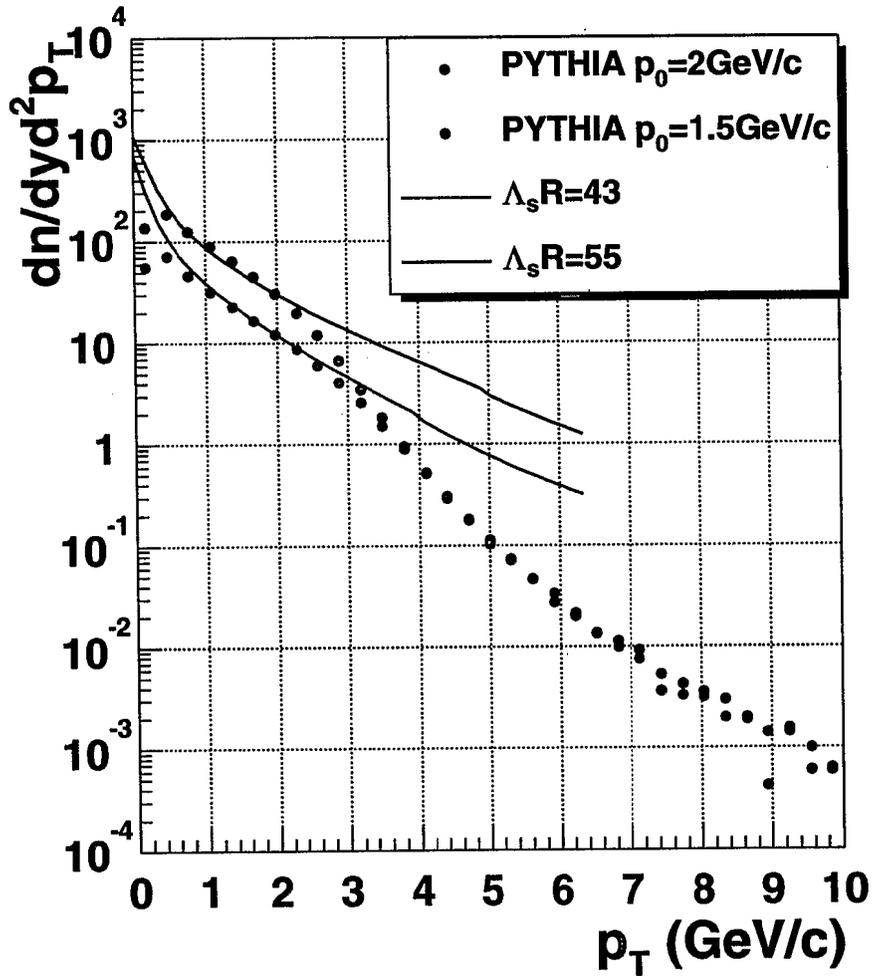
where $\tilde{f}_n(k_T/\Lambda_s)$ is

$$\tilde{f}_n = \begin{cases} a_1 \left[\exp\left(\sqrt{k_T^2 + m^2}/T_{\text{eff}}\right) - 1 \right]^{-1} & (k_T/\Lambda_s \leq 3) \\ a_2 \Lambda_s^4 \log(4\pi k_T/\Lambda_s) k_T^{-4} & (k_T/\Lambda_s > 3) \end{cases} \quad (2)$$

with $a_1 = 0.0295$, $m = 0.067\Lambda_s$, $T_{\text{eff}} = 0.93\Lambda_s$, and $a_2 = 0.0343$.



classical + pQCD initial conditions



PYTHIA:
leading order pQCD scattering
initial, final state radiation
Primordial k_T



Elliptic flow in the early stage of the collisions?

Elliptic flow parameter v_2 is defined by the second Fourier coefficient:

$$\begin{aligned} v_2 &= \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \\ &= \frac{\int_{-\pi}^{\pi} d\phi \cos(2\phi) \int p_T dp_T \frac{d^3 N}{dy p_T dp_T d\phi}}{\int_{-\pi}^{\pi} d\phi \int p_T dp_T \frac{d^3 N}{dy p_T dp_T d\phi}}. \end{aligned}$$

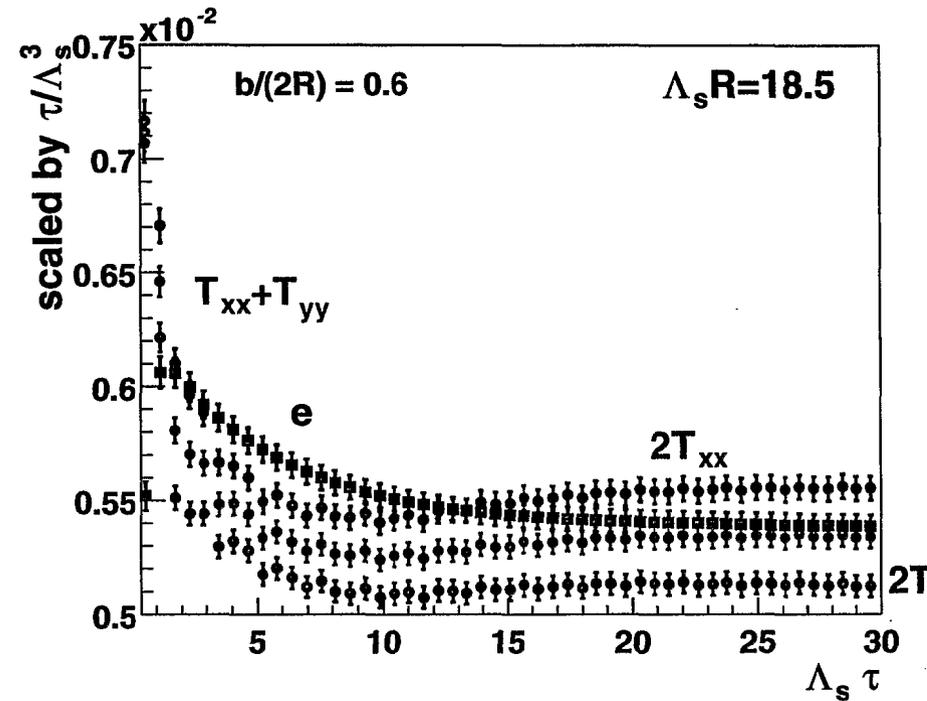
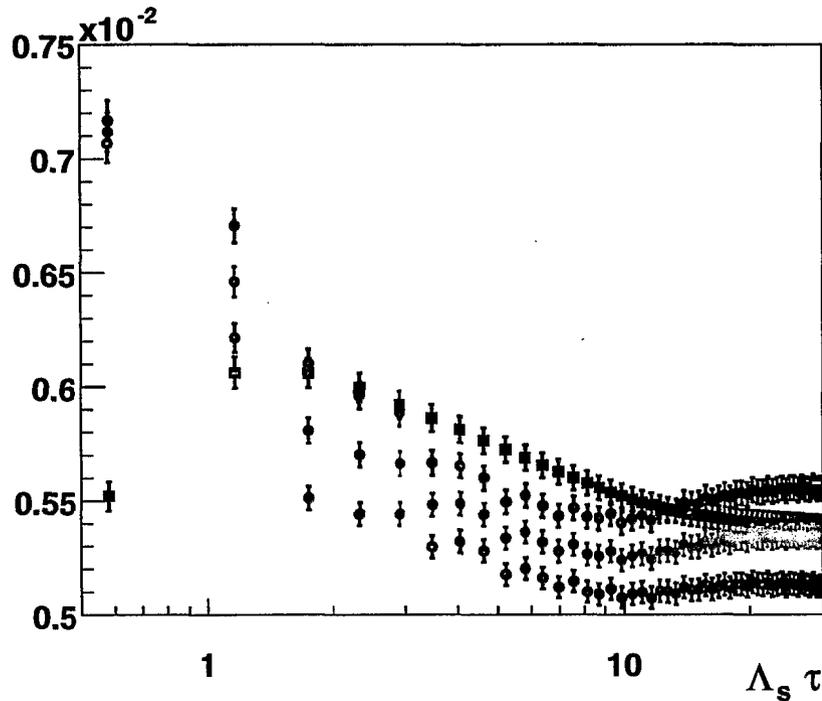
1. Hydrodynamics works well at RHIC.
2. Elliptic flow is expected to be generated at early times in heavy ion collisions. (It reflects spatial anisotropy to momentum anisotropy due to interaction)
3. How much elliptic flow is produced before thermalization?
4. classical Yang-Mills field theory is proposed to describe early stage of nucleus-nucleus collisions. (talks by L. McLerran, K. Itakura, R. Venugopalan)

Purpose: compute elliptic flow of gluons from the CGC



Time evolution of energy momentum tensor

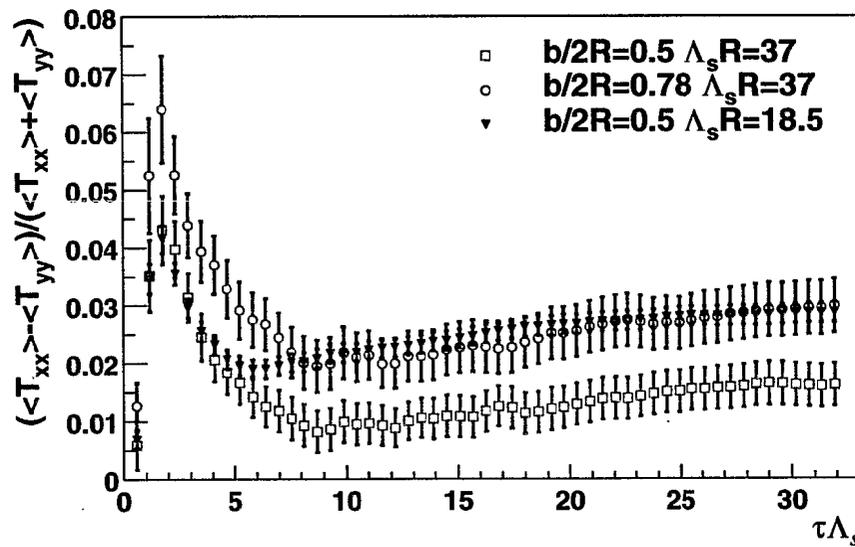
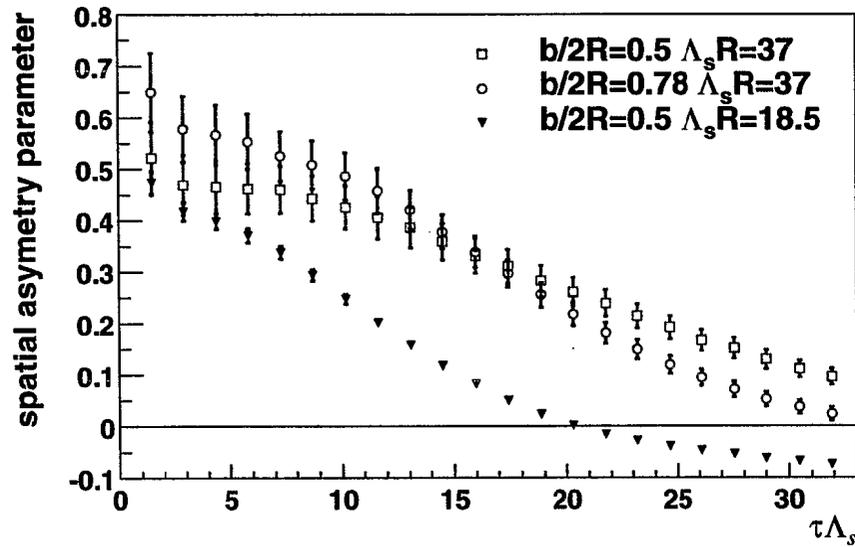
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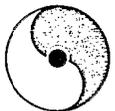
- Strongly interacting system at early times
- Free streaming in the transverse plain at later times $e = T_{xx} + T_{yy}$.



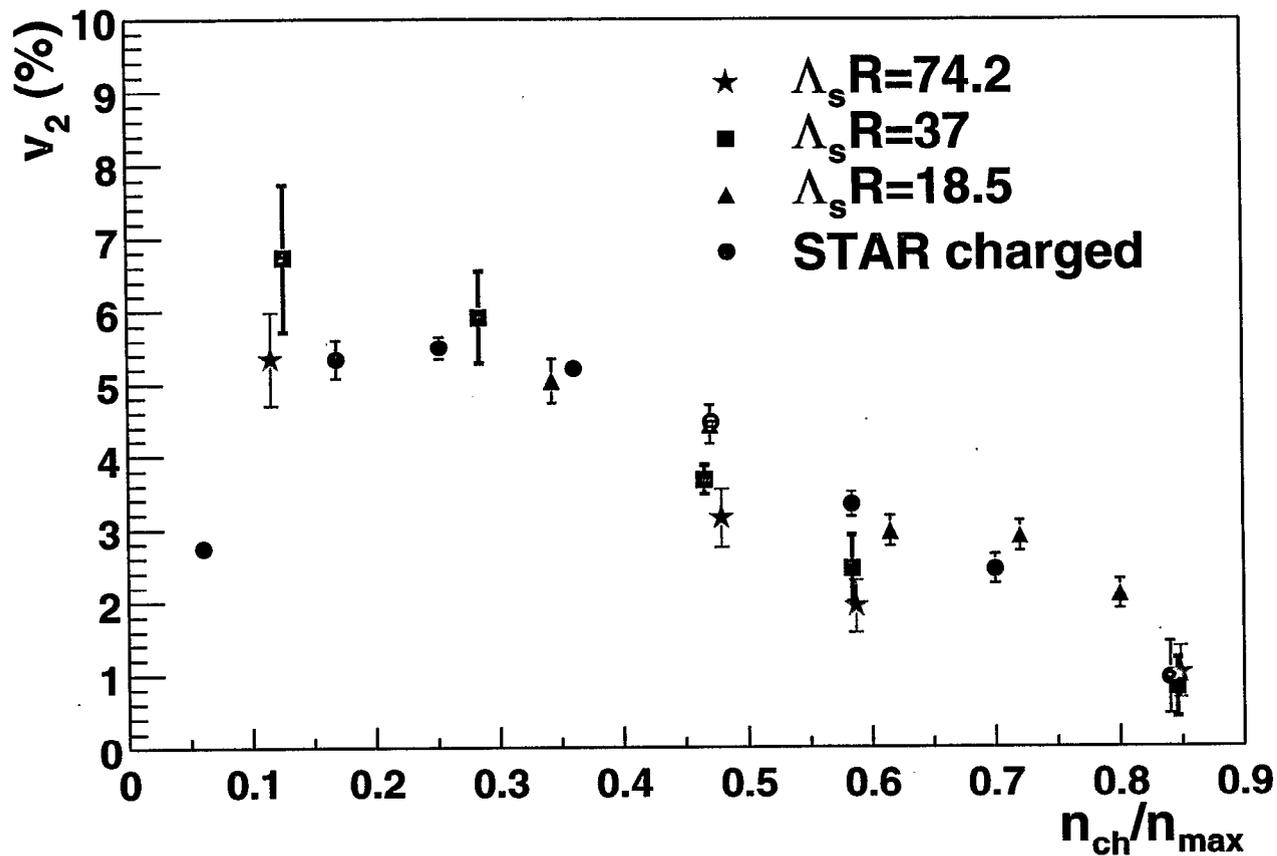
Time evolution of anisotropy parameters



- $\tau\Lambda_s < 2$: rapid production
- $2 < \tau\Lambda_s < 10$: relaxation, spatial asymmetry almost constant
- $10 < \tau\Lambda_s < 20$: gradual increase spatial asymmetry decrease
- $\tau\Lambda_s > 20$: free streaming in the transverse



Centrality dependence of v_2



- $\Lambda_s R$ smaller $\rightarrow v_2$ larger, saturate at large $\Lambda_s R$?
- $v_2(\text{RHIC}) \geq v_2(\text{LHC})$, $v_2(\text{small system}) \geq v_2(\text{large system})$



Summary and Outlook

- Nonperturbative gluon production from classical SU(3) Yang-Mills equation by using real time lattice simulation.
- There is a overlapping region between classical calculation and pQCD (PYTHIA). Smooth transition from soft gluon to minijet?
- The elliptic flow parameters from the CGC by 2-D real time lattice simulation.
- Large amount of v_2 is generated from classical field. i.e. well before thermalization of gluons.

Outlook

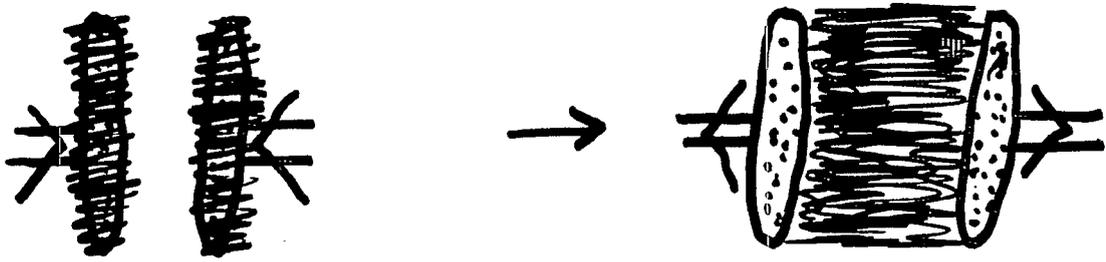
Systematic study and extensions:

- Rapidity and centrality dependence of particle multiplicities.
- p_T dependence of v_2 and transverse collective flow from CGC.
- 3-D simulation.
- Subsequent time evolution of gluons using Boltzmann theory.



The Flow of Colored Glass in Heavy Ion Collisions

Raju Venugopalan



- AT HIGH ENERGIES, PARTON DISTRIBUTIONS SATURATE WITH $F_{UV}^2 \propto 1/\alpha_s(\Lambda_s)$

SEMI-HARD SCALE $\gg \Lambda_{QCD}$

- USE CLASSICAL METHODS TO COMPUTE INITIAL CONDITIONS FOR HEAVY ION COLLISION

- COMPUTE:

- * a) INITIAL NUMBER AND ENERGY DISTRIBUTIONS
- * b) CHERN SIMONS #
- c) ELLIPTIC & RADIAL FLOW (SEE Y. NARA'S TALK)
- d) 2 PARTICLE CORRELATIONS (?)

Scaling relations

Initial momentum distribution of produced gluons (Color Glass Condensate):

$$\frac{1}{\sigma} \frac{dN_g}{d\eta d^2p_t} = \frac{1}{\alpha_s(Q_s^2)} f_g \left(\frac{p_t^2}{Q_s^2} \right)$$

f_g : universal, dimensionless function for produced gluons

σ : transverse area of the two colliding nuclei

Q_s^2 : saturation scale for gluons,
depends on energy, centrality, and
atomic number

[Krasnitz and Venugopalan, PRL 86 (2001) 1717]

Assumed dynamical picture:

- Initial gluon distribution characterized by saturated gluons
- free streaming evolution producing additional partons
- freeze-out to hadrons

scaling properties of initial state are preserved:

universal function $f_g \rightarrow f$ (hadrons)

saturation momentum $Q_s \rightarrow p_s$ (hadrons)

Note: $Q_s \neq p_s$ but p_s has same energy, centrality dependence as Q_s

Picture works for multiplicity and η distributions at RHIC

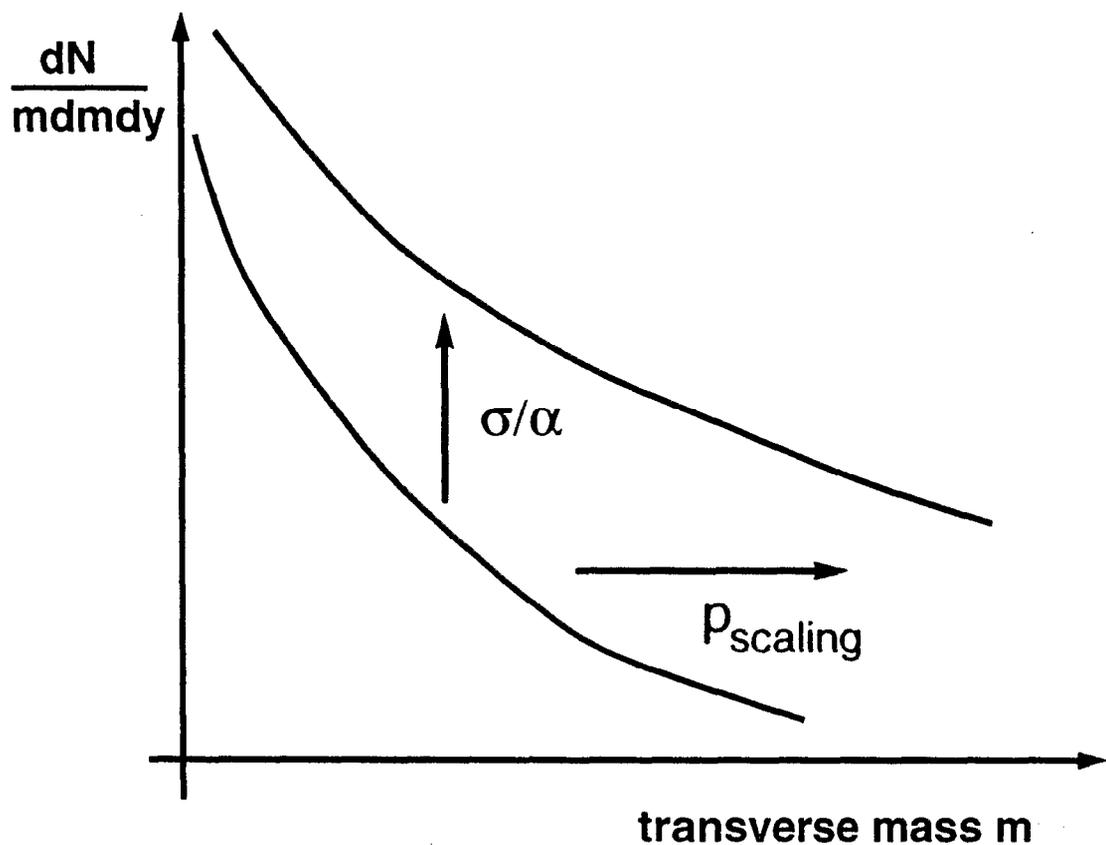
[Kharzeev, Nardi, PLB507, 121 (2001); Kharzeev, Levin, nucl-th/0108006]

Question: can we describe the p_t spectra (without hydrodynamical flow) in that picture?

Particle spectra at RHIC

check universality of scaling function f by rescaling of $dN/dy dp_t^2$ and m_t , so that data of different centralities are on top of each other:

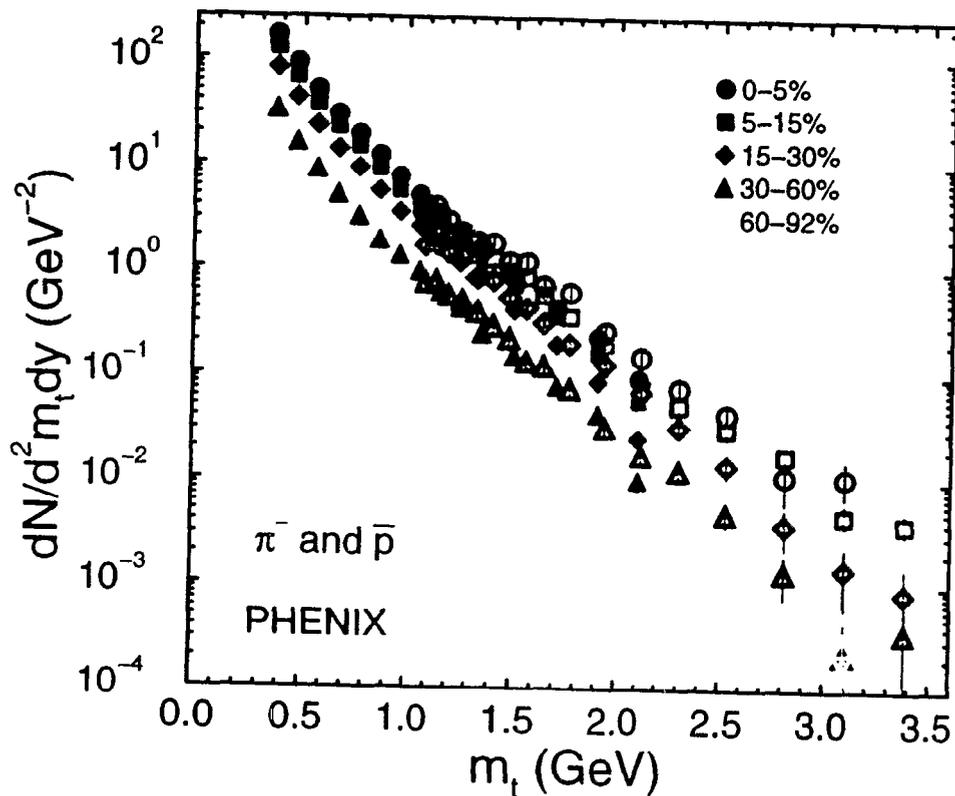
$$\frac{dN_h}{dy d^2m_t} = \frac{\sigma}{\alpha_s(p_s)^{k_h}} \cdot f\left(\frac{m_t}{p_s}\right)$$



Scaling with centrality

generalized m_t scaling for all centralities?

check for π^- and \bar{p} :

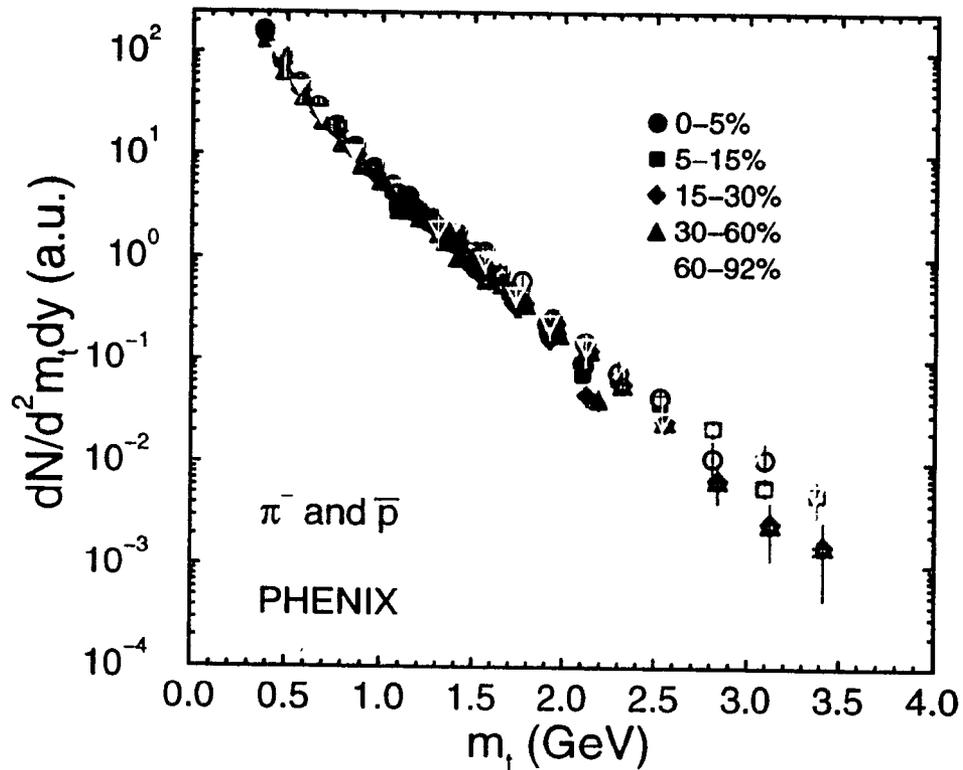


$\implies \pi^-$ and \bar{p} data form a continuous curve for each centrality bin

Rescaled m_t distributions

rescale different centrality bins as

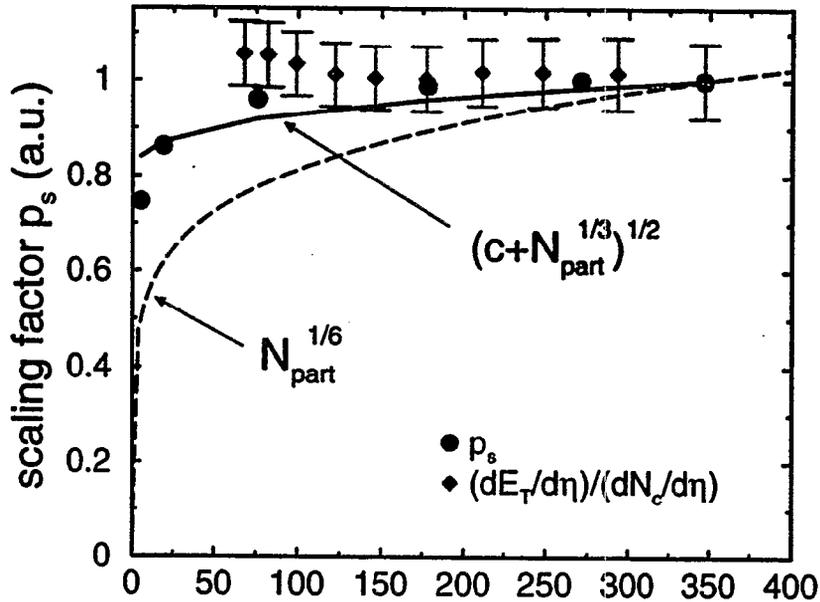
$$\frac{1}{\sigma} \frac{dN_h}{dy d^2m_t} \rightarrow \frac{1}{\lambda} \frac{1}{\sigma} \frac{dN_h}{dy d^2m_t} \quad \text{and} \quad m_t \rightarrow \frac{m_t}{\lambda'}$$



\Rightarrow one universal function f describing all centrality bins!

Scaling of the transverse momentum

parameters p_s normalized to most central bin:



expect to scale like $Q_s \sim N_{\text{part}}^{1/6}$ but

$$p_s^2/p_{s,c}^2 = c + c' \cdot N_{\text{part}}^{1/3} = 0.61 + 0.39(N_{\text{part}}/347)^{1/3}$$

compatible with transverse energy per charged particle

(PHENIX coll., PRL 87, 0523201 (2001))

constant c stands for the finite transverse momenta for pp collisions ($\langle p_t \rangle \sim p_s$),

compatible with $\langle p_t \rangle$ reported by UAM and STAR

• CHERN-SIMONS # FLUCTUATIONS IN
HI-COLLISIONS

• FOR $\lambda \rightarrow \infty$, YANG-MILLS EQNS. ARE
BOOST INVARIANT; HI-DYNAMICS IS
IN 2+1-DIMENSIONS.

• NO-GO THM. FORBIDS SPHALERON
TRANSITIONS.

• NON-ZERO C-S # GENERATED BY
FLUCTUATIONS: $\langle \chi^2 \rangle \neq 0$
|||
 $(\int d^4x \vec{E} \cdot \vec{B})^2$

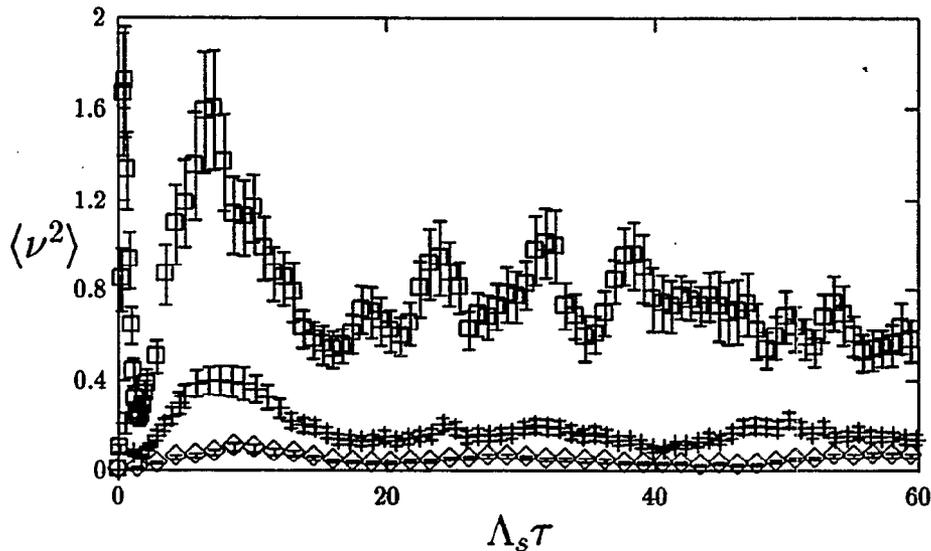


Figure 1: Average squared topological charge vs the proper time (in units of Λ_s^{-1}) for $\Lambda_s L = 74.2$ (diamonds), 148.4 (pluses), and 297 (squares). The latter two values of $\Lambda_s L$ correspond to the RHIC ($\Lambda_s = 2$ GeV) and LHC ($\Lambda_s = 4$ GeV) regimes respectively.

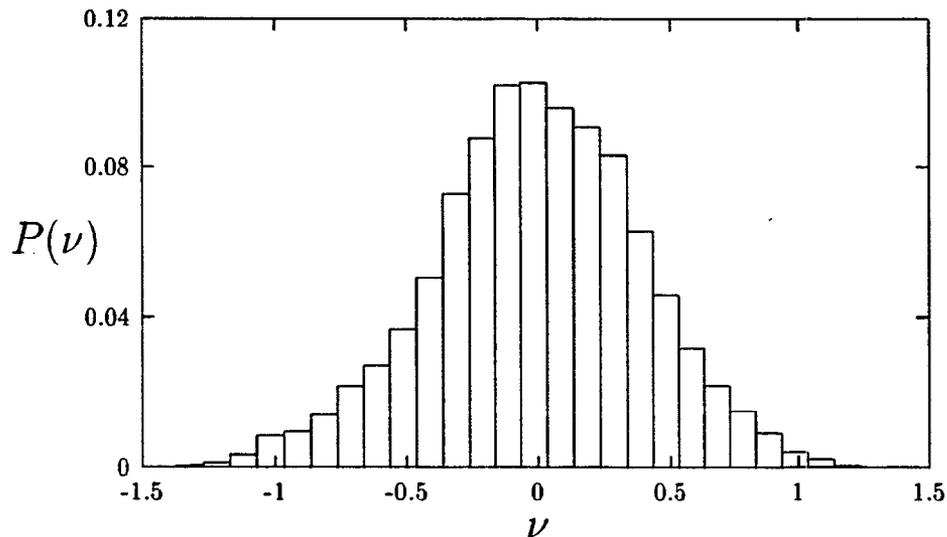


Figure 2: Probability distribution of ν in the proper time interval $30 \leq \Lambda_s \tau \leq 65$ for $\Lambda_s L = 148.4$. These corresponds to $3 \text{ fm} \leq \tau \leq 6 \text{ fm}$ for an estimated value $\Lambda_s = 2$ GeV for RHIC energies.

- $\langle v \rangle_{\text{RMS}}$ FROM FLUCTUATIONS IS SMALL
 - 1 UNIT PER TWO UNITS OF RAPIDITY AT RHIC
 - 1 UNIT PER UNIT OF RAPIDITY AT LHC.

- $\langle v \rangle_{\text{RMS}}$ FROM SPHALERON TRANSITIONS IN A HOT QGP IS MUCH LARGER
 - 20 UNITS PER UNIT OF RAPIDITY

- SMALL VALUE OF $\langle v \rangle_{\text{RMS}}$ MAY PROVIDE FAVORABLE CONDITIONS FOR CREATION OF P-ODD BUBBLES A LA KHARBEEV PISARSKI

Partons and QCD in High-Energy Hadronic Collisions

Werner Vogelsang

Two topics :

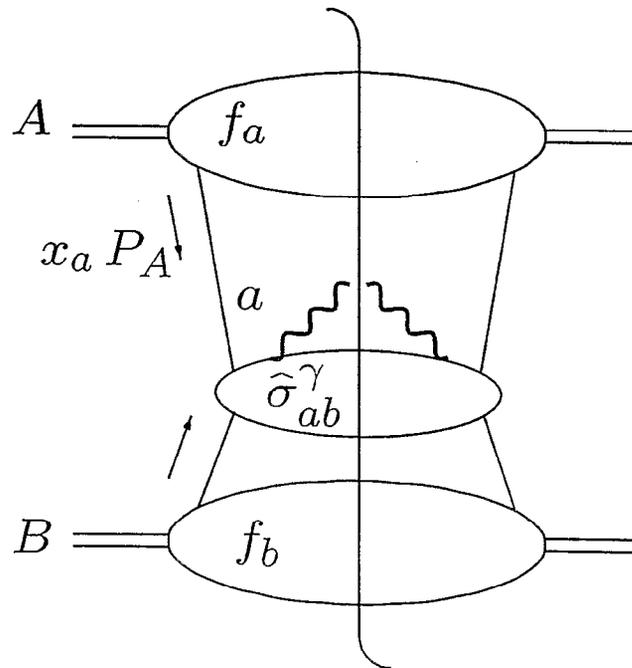
- Toward “global analyses” of polarized parton distribution functions
work in collab. with M. Stratmann
- Soft-gluon resummation for electroweak boson production
work in collab. with A. Kotzev and G. Sterman

I. "Global analysis"

Polarized $\vec{p}\vec{p}$ collisions at RHIC :
much new information on nucleon spin structure

QCD factorization theorem :
Reactions characterized by a hard scale
(Q, p_T, m_{HQ}, \dots) can be described as

$$d\sigma = \sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}_{ab}$$



- partonic cross sections $\hat{\sigma}_{ab}$ are perturbative, and predicted by QCD
- pdfs are *universal* : the same in all reactions
 - notion of "nucleon structure"
 - allows tests of QCD
 - enables us to look for "new things"

To learn from data need to efficiently evaluate

$$d\sigma = \sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}_{ab}$$

- a lesson from unpolarized case
- need “global analysis”
 - input pdfs at scale μ_0 in terms of ansatz with free parameters
 - evolve to scale μ relevant to a data point
 - compare to data and assign χ^2 value
 - vary parameters and minimize χ^2
- requires typically 1000’s of evaluations of the cross section
- want $\hat{\sigma}_{ab}$ at next-to-leading order
 - theoretical uncertainties decrease
 - numerically involved and time-consuming
- *very* hard to reconcile
- need fast and practical way of using higher-order cross sections in global fits of parton distribution functions

“Mellin technique”

Moments of a function $f(x)$:

$$f^n \equiv \int_0^1 dx x^{n-1} f(x)$$

General cross section for producing final state H with observed variable O

$$\begin{aligned} \frac{d\sigma^H}{dO} &= \sum_{a,b,c} \int_{\text{exp-bin}} dT \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \int_{z_c^{\min}}^1 dz_c \\ &\times f_a(x_a, \mu_F) f_b(x_b, \mu_F) D_c^H(z_c, \mu'_F) \\ &\times \frac{d\hat{\sigma}_{ab}^c}{dO dT}(x_a P_A, x_b P_B, P_H/z_c, T, \mu_R, \mu_F, \mu'_F), \end{aligned}$$

Express pdfs by their Mellin inverses :

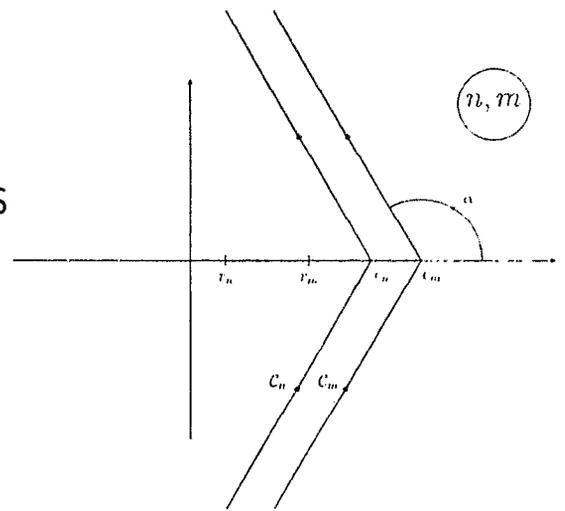
$$f_a(x_a, \mu_F) = \frac{1}{2\pi i} \int_{\mathcal{C}_n} dn x_a^{-n} f_a^n(\mu_F)$$

$$f_b(x_b, \mu_F) = \frac{1}{2\pi i} \int_{\mathcal{C}_m} dm x_b^{-m} f_b^m(\mu_F)$$

Find :

$$\begin{aligned}
 \frac{d\sigma^H}{dO} &= \frac{1}{(2\pi i)^2} \sum_{a,b,c} \int_{C_n} dn \int_{C_m} dm f_a^n(\mu_F) f_b^m(\mu_F) \\
 &\times \int_{\text{exp-bin}} dT \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \int_{z_c^{\min}}^1 dz_c x_a^{-n} x_b^{-m} D_c^H(z_c, \mu'_F) \\
 &\times \frac{d\hat{\sigma}_{ab}^c}{dO dT}(x_a P_A, x_b P_B, P_H/z_c, T, \mu_R, \mu_F, \mu'_F) \\
 &\equiv \sum_{a,b} \int_{C_n} dn \int_{C_m} dm f_a^n(\mu_F) f_b^m(\mu_F) \tilde{\sigma}_{ab}^H(n, m, O, \mu_R, \mu_F)
 \end{aligned}$$

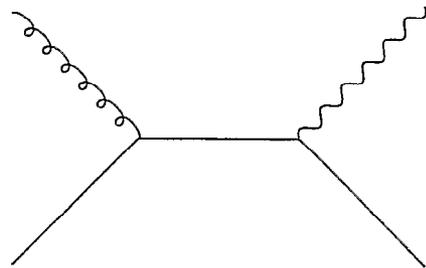
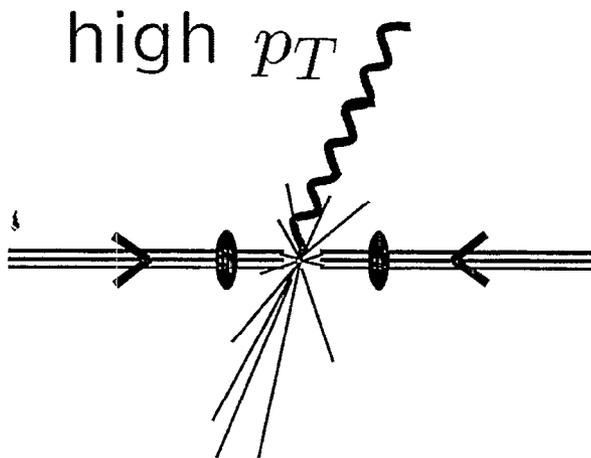
- $\tilde{\sigma}_{ab}^H(n, m, O, \mu_R, \mu_F)$ is cross section for “dummy” pdfs $x_a^{-n} \times x_b^{-m}$
- contains all tedious integrations
- can be pre-calculated on a suitable grid in n, m
- for optimal contours, *exponential decrease* of x_a^{-n}, x_b^{-m} along contours
- pdfs fall off at least as fast as $1/|n|^4, 1/|m|^4$



Finally, n, m integrations are all that's left !

Example : Prompt γ at RHIC

$$\frac{d\Delta\sigma^\gamma}{dp_T} = \sum_{a,b} \int_{\eta\text{-bin}} d\eta \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \Delta f_a(x_a, \mu_F) \Delta f_b(x_b, \mu_F) \\ \times \frac{d\Delta\hat{\sigma}_{ab}^\gamma}{dp_T d\eta}(x_a P_A, x_b P_B, p_T, \eta, \mu_R, \mu_F)$$



Toy analysis :

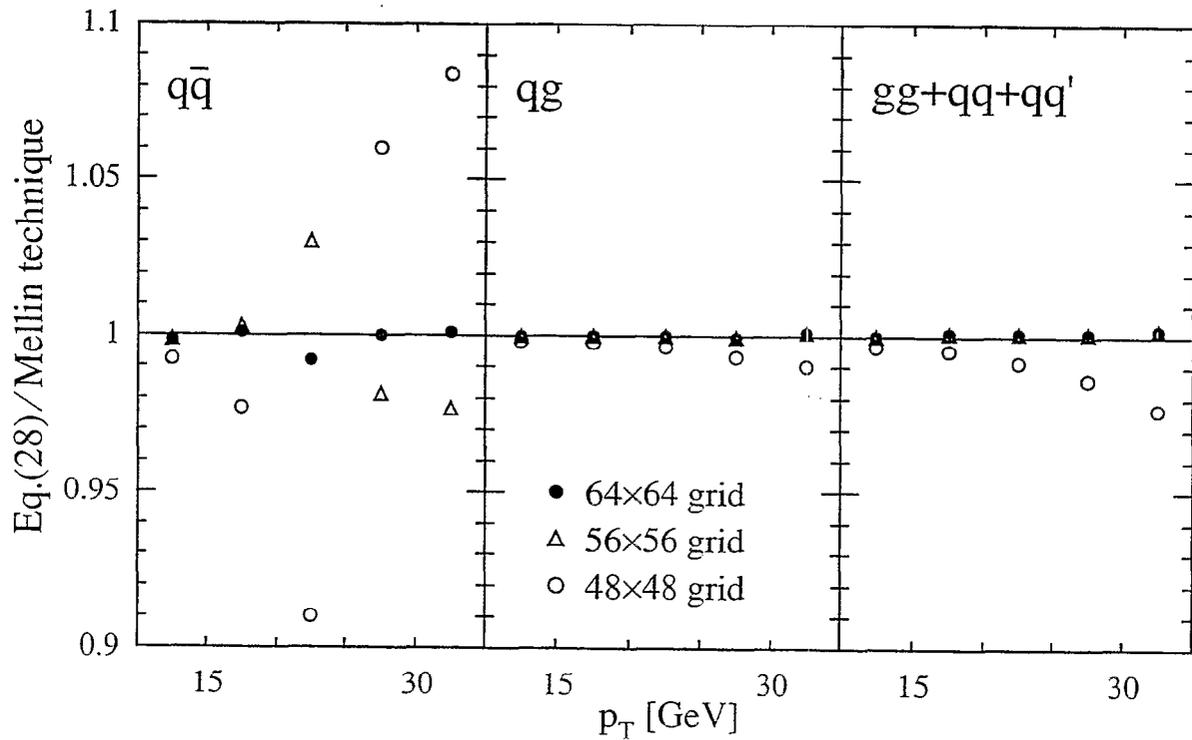
- NLO, scales $\mu_F = \mu_R = p_T$
- “fictitious” RHIC data points at $p_T = 12.5, 17.5, 22.5, 27.5, 32.5$ GeV
calc. with $\text{PHOS} \oplus$ random Gaussian 1σ shift
- fit to DIS *and* prompt photon “data”
ansatz for gluon density :

$$\Delta g(x, \mu_0) = N x^\alpha (1-x)^\beta (1+\gamma x) g(x, \mu_0)$$

- large number of fits to obtain “error band”

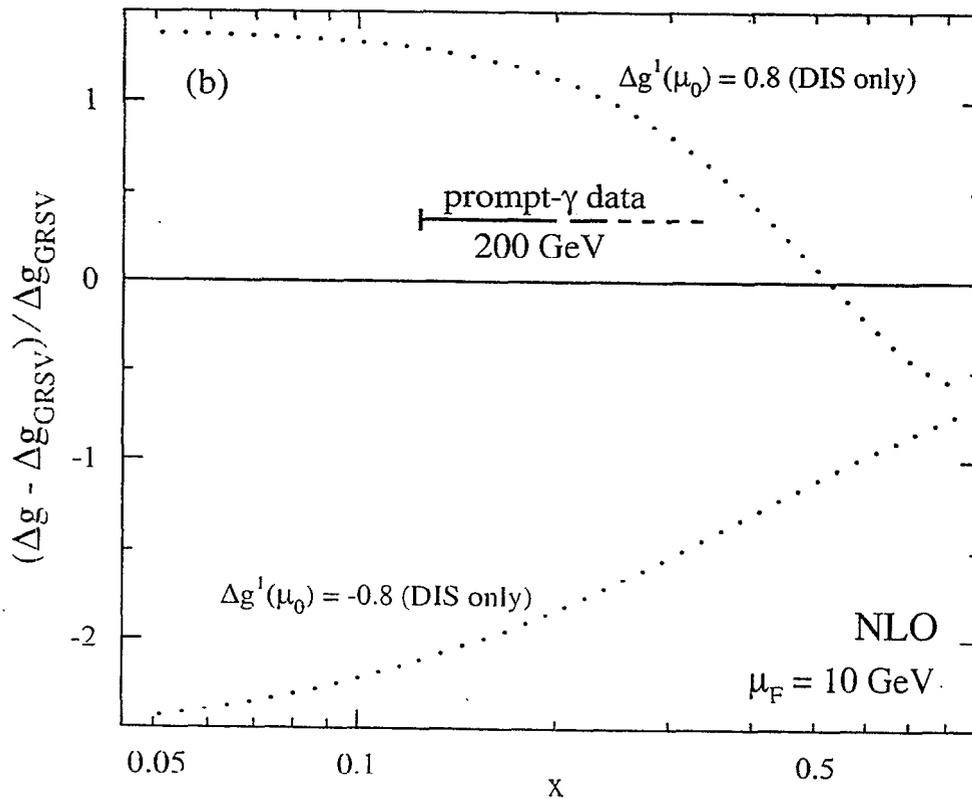
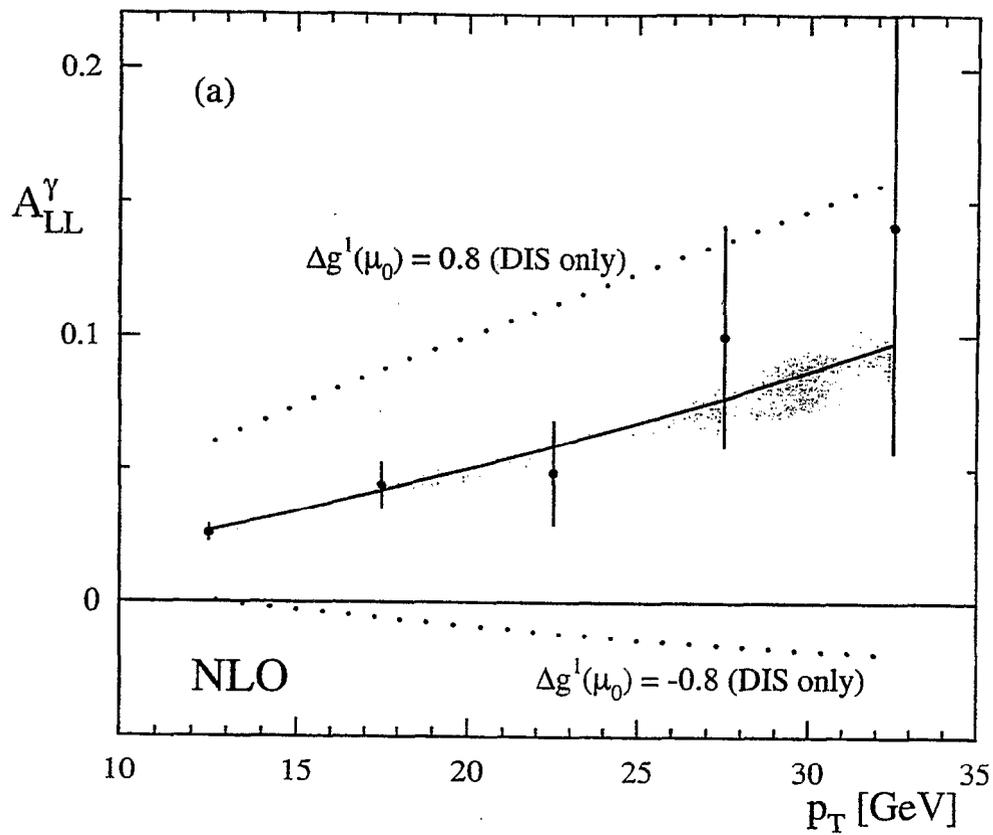
Accuracy of method :

(Stratmann, WV)



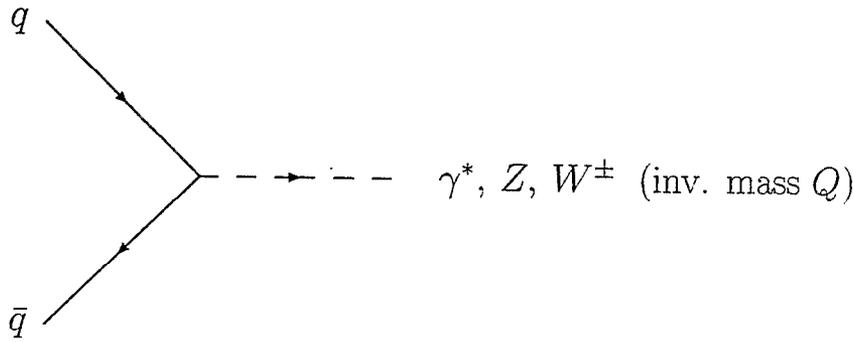
Evaluation of cross section extremely fast :

- generation of grids in n, m takes ~ 5 hrs.
- after that :
1000 evaluations of cr. sec. in ~ 10 sec.



(further constraints by data at $\sqrt{S} = 500$ GeV)

II. Soft-gluon resummation for electroweak boson production



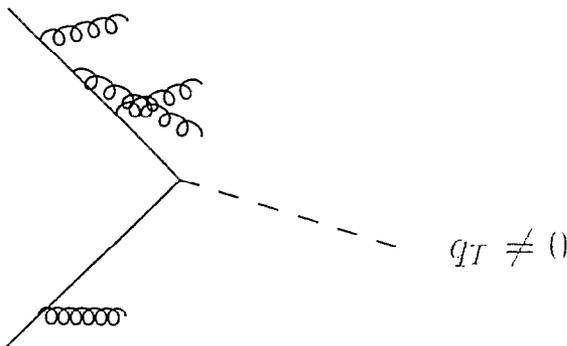
large QCD corrections if

- $z = Q^2/\hat{s} \sim 1$: all gluon radiation soft

$$\mathcal{O}(\alpha_s^k) \text{ in PT : } \frac{d\hat{\sigma}^{(k)}}{dQ^2} \sim \alpha_s^k \left[\frac{\ln^{2k-1}(1-z)}{(1-z)} \right]_+ + \dots$$

can be resummed to all orders : Sleight, Catani, De Ruijter, Vogt

- q_T of boson measured, and $q_T^2 \ll Q^2$



$$\mathcal{O}(\alpha_s^k) \text{ in PT : } \frac{d\hat{\sigma}^{(k)}}{dQ^2 dq_T^2} \sim \alpha_s^k \left[\frac{\ln^{2k-1}(Q^2/q_T^2)}{q_T^2} \right]_+ + \dots$$

resummation :

Laenen, Sterman, WV :

logarithms at threshold and at $q_T = 0$ can be resummed *simultaneously*

- exponentiate in transform space
- “jointly” resummed partonic cross section :

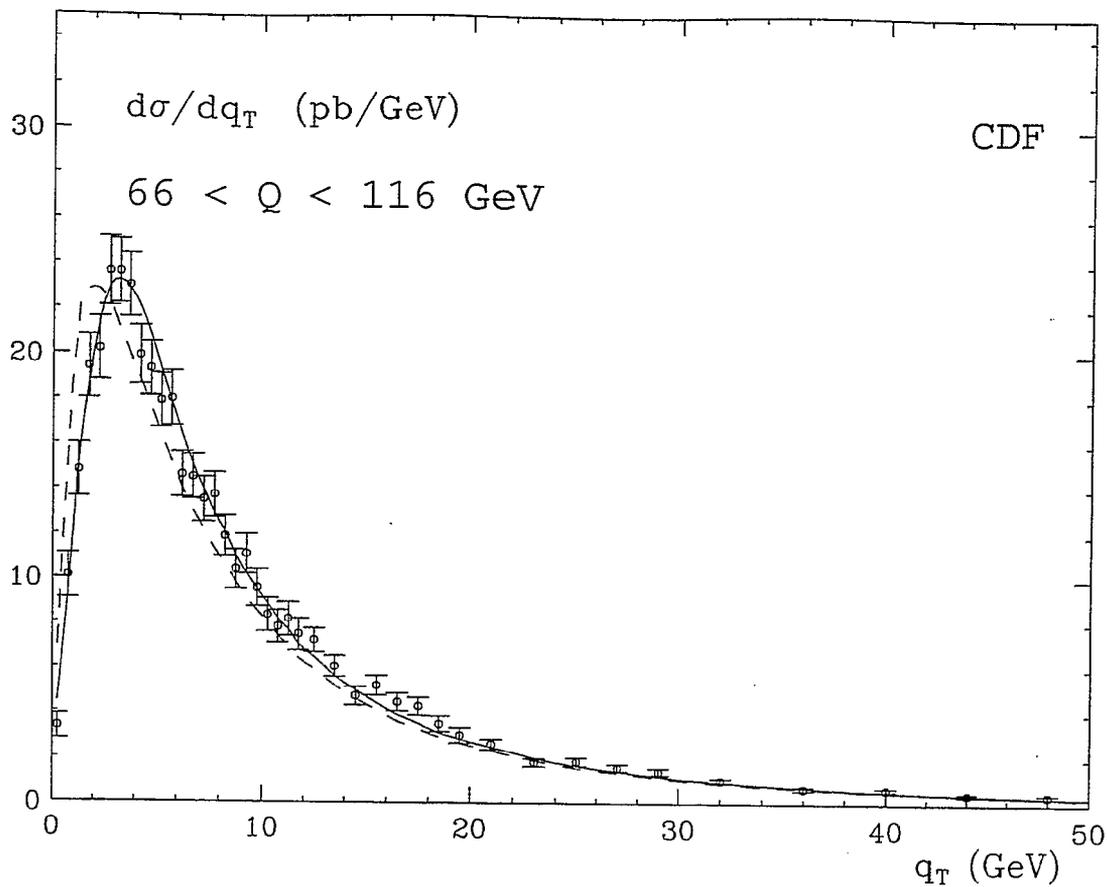
$$\frac{d\hat{\sigma}^{\text{res}}}{dQ^2 dq_T^2} \propto \exp \left\{ 2 C_F \int_0^Q \frac{dk_T}{k_T} \alpha_s(k_T) \left[J_0(bk_T) K_0\left(\frac{2Nk_T}{Q}\right) + \ln\left(\frac{\bar{N}k_T}{Q}\right) \right] \right\}$$

- \longrightarrow threshold resummation for $N \gg bQ$
- \longrightarrow q_T resummation for $bQ \gg N$
- integration over running coupling :

guide to form of non-perturbative corrections

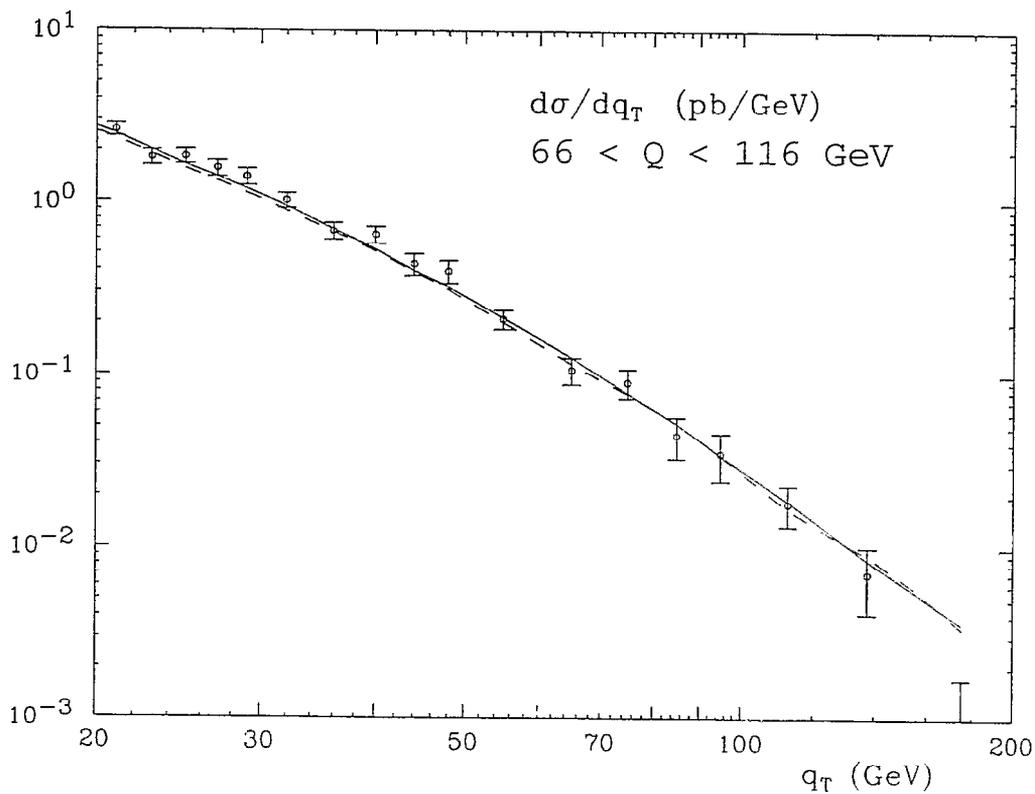
exponent at low- k_T :

$$\sim \left(\frac{b^2}{4} - \frac{N^2}{Q^2} \right) \int_0^\lambda dk_T k_T \alpha_s(k_T) \ln \left(\frac{\bar{N}k_T}{Q} \right)$$



dashed : "purely perturbative"

solid : Gaussian smearing $-gb^2$ with $g = 1.3$ GeV²



Hadronic Probes of Quark Gluon Plasma

Sangyong Jeon

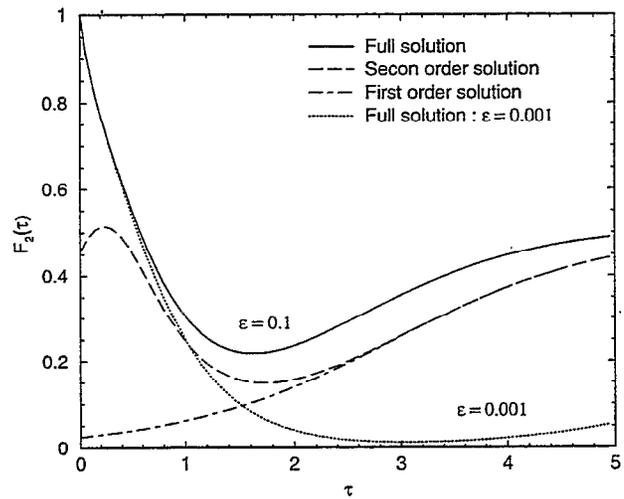
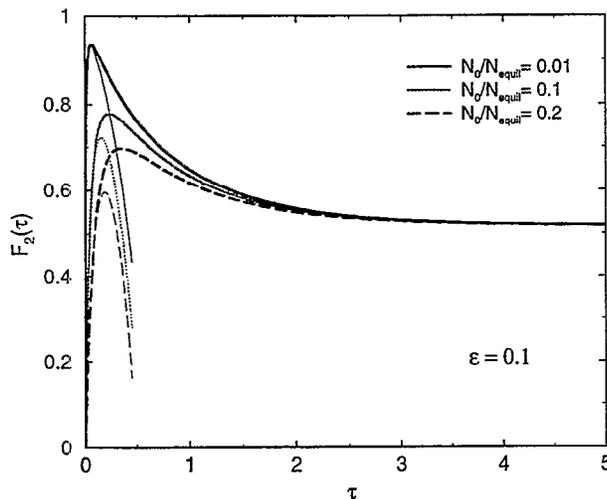
Hadronic Signals of QGP

- Signals from fluctuations
 - * High-energy and/or big system study
 - * Low-energy and/or small system study
- Pseudo-scalar and tensor channel study of initial state and the in-plasma gluons.

Fluctuations In Small Systems

- Small systems: Micro-Canonical instead of Grand-Canonical
- Master Equation:

$$\frac{dP_n}{d\tau} = \epsilon [P_{n-1} - P_n] - [n^2 P_n - (n+1)^2 P_{n+1}]$$



- Information on initial population
- Possible information about the freeze-out time

Balance Function and Fluctuations

S. Jeon, Scott Pratt (Michigan State U):

hep-ph/0110043

- Charge Fluctuation per final state charged degree of freedom

$$D/4 = \frac{\langle \Delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle}$$

Small if QGP forms: Fractional charges and gluon entropy

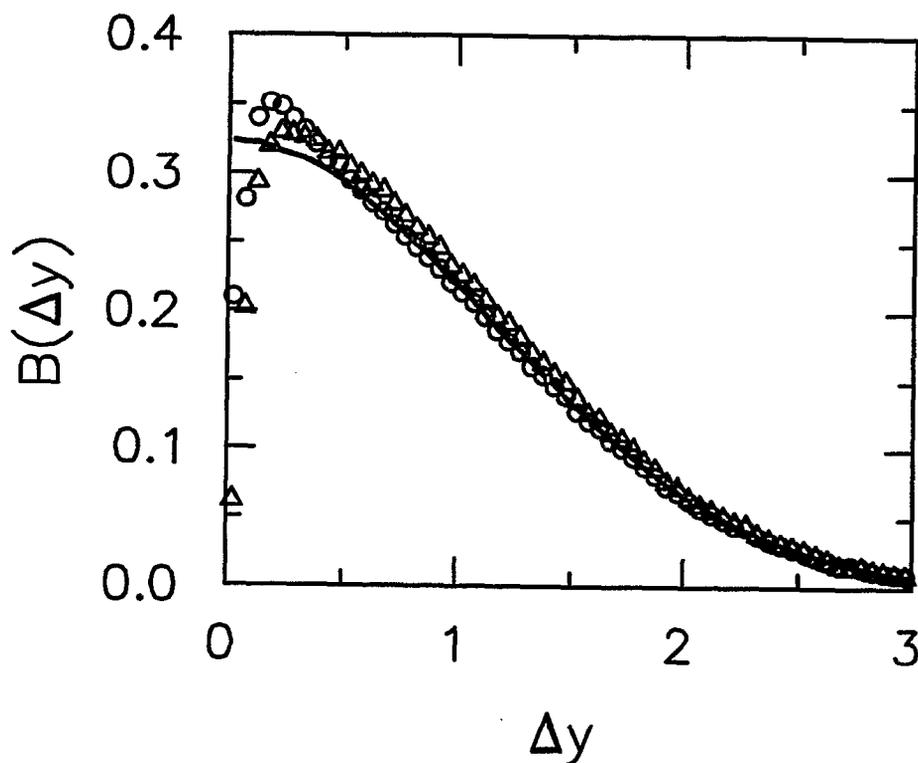
- Balance Function:
 - * Roughly: Conditional probability to find a charge-conjugate partner
 - * Measures correlation between charge conjugate states
 - * Correlation length is small if QGP forms
- Relation between the two?

* Precise definition:

$$B_{+-}(\Delta|Y) = \frac{1}{2} \left(\frac{D_{++}(\Delta|Y)}{\langle N_+ \rangle} - \frac{D_{-+}(\Delta|Y)}{\langle N_+ \rangle} + \frac{D_{--}(\Delta|Y)}{\langle N_- \rangle} - \frac{D_{+-}(\Delta|Y)}{\langle N_- \rangle} \right)$$

* Relation:

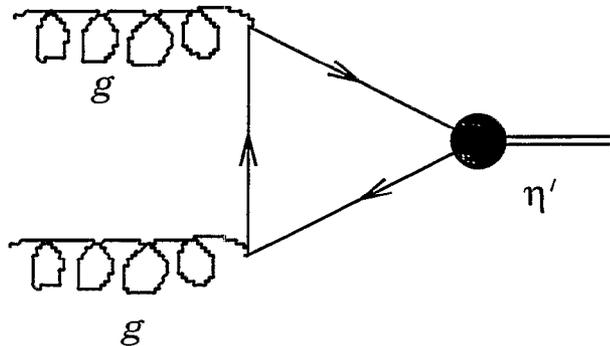
$$\frac{\Delta Q^2}{\langle N_{\text{ch}} \rangle} = 1 - \int_0^Y d\Delta B_{+-}(\Delta|Y)$$



A model Calculation of the Balance Function

η' as a Probe of Gluonic Structures

- Motivation:



- Atwood and Soni's $gg\eta'$ coupling vertex [PLB 405, 150, '97]

$$M_{\lambda\gamma}\delta^{ab} = H(p^2, q^2, P^2) \delta^{ab} \epsilon_{\mu\nu\alpha\beta} p^\mu q^\nu (\epsilon_p^\alpha)_\lambda (\epsilon_q^\beta)_\gamma$$

with $H_0 = H(0, 0, M_{\eta'}^2) \approx 1.8 \text{ GeV}^{-1}$

- Hadronization Matrix Element:

$$|T_{gg \rightarrow \eta'}|^2 = \frac{1}{64} H_0^2 M_{\eta'}^4$$

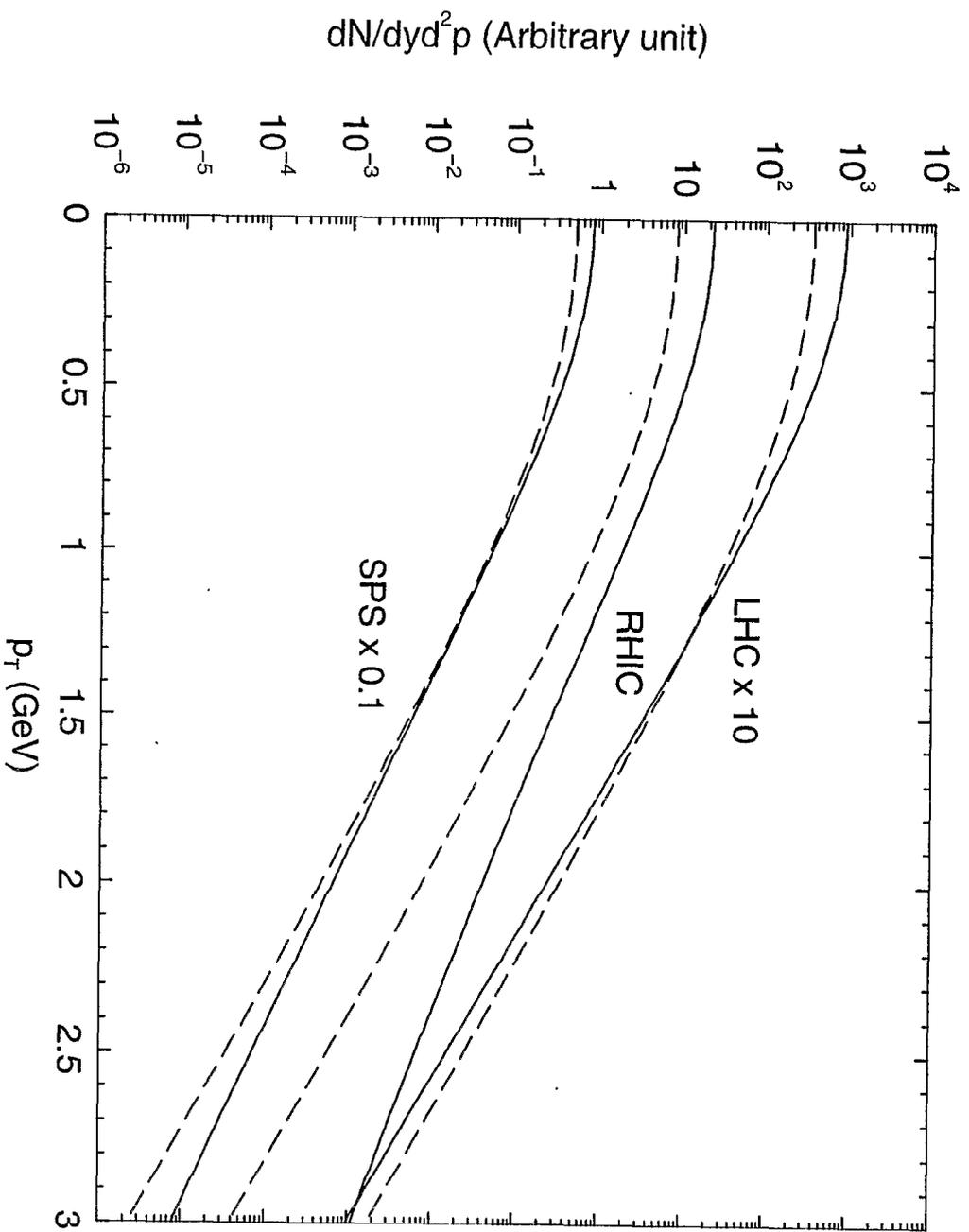
- Use this to probe Gluon properties of QGP and heavy nuclei

η' in Nucleus-Nucleus Collision

- Motivation: Gluon dominated relativistic heavy ion collision
- Tool: Boltzmann equation

$$\frac{df_{\eta'}}{dt} = \frac{1}{\tau_{\text{rel}}\gamma_P} (f_{\text{eq}} - f_{\eta'})$$

- Time evolution of $f_{\eta'}$ from $\tau_{\text{had}} - \tau_{\text{rel}}$ to τ_{had} (τ_{rel} : the mean-free-time of η' inside hot gluons)
- 2 – 3 times more η' at RHIC and LHC due to the hot initial temperature
- Initial condition dependence of p_T spectrum:



η' in proton-Nucleus Collisions

- Motivation: Can access very small x at moderate Q_f
- Tool: Factorized Cross-section formula

$$\frac{d\sigma^{pA \rightarrow \eta' X}}{d^2P_t dx_L} = \frac{\pi H_0^2}{64 x_E} x_1 G^p(x_1, Q_f^2) x_2 G^A(x_2, Q_f^2, P_t)$$

$$x_1 \approx M_{\eta'}^2 / s x_2 \quad \text{and} \quad x_2 \approx M_T e^{-y} / \sqrt{s}$$

- Direct measurement of $xG^A(x, Q^2, P_t)$ as long as x_L is within the known region.
 $Q^2 \approx 1 \text{ GeV}^2 \approx M_{\eta'}^2$

- Orders of magnitude smaller x than previously probed at this Q (Fermilab $x \sim 10^{-3}$)

$$2.2 \times 10^{-5} < x_- < 0.005 \quad (\text{RHIC})$$

$$3.2 \times 10^{-8} < x_- < 1.7 \times 10^{-4} \quad (\text{LHC})$$

Outlook

- Fluctuation study on-going — Data soon available
- η' in-medium properties
- Other hadronic probe of gluonic system
 - * Glueballs
 - * Tensor Mesons
 - * Chemical properties of hadronic system coming out of gluon dominated system

Dense and Baryon Rich QCD

Misha Stephanov

Hot and Dense QCD:
*Pion Propagation Near Chiral Phase
Transition*

M.A. Stephanov
(collaboration with D.T. Son)

- Soft pion dispersion relation can be determined from *static* quantities only (\Rightarrow can be measured on Euclidean lattice):

(analogy: spin waves in antiferromagnets)

$$\omega^2 = u^2(\mathbf{p}^2 + m^2) - \text{dispersion relation } (|\mathbf{p}| \ll m_\sigma).$$

u – “velocity” of pions; m – screening mass.

m – from static (zero-frequency) correlator of $\pi^a \equiv i\bar{\psi}\gamma^5\tau^a\psi$:

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \frac{\langle \pi^a(x)\pi^b(0) \rangle}{\langle \bar{\psi}\psi \rangle^2} = \frac{1}{f^2} \frac{\delta^{ab}}{\mathbf{q}^2 + m^2},$$

f – T -dependent static pion “decay constant”.

u – from the ratio of 2 static quantities:

$$\boxed{u^2 = \frac{f^2}{\chi_{I5}},} \quad \text{where}$$

$$\int d\tau dV \langle A_0^a(x)A_0^b(0) \rangle = \delta^{ab}\chi_{I5}, \quad A_0^a \equiv \bar{\psi}\gamma^0\gamma^5\frac{\tau^a}{2}\psi.$$

χ_{I5} – axial isospin susceptibility.

valid for “all” $T < T_c$, (at $T = 0$: $f^2 = \chi_{I5} = f_\pi^2$).

- Derivation using effective Lagrangian method

Microscopic (QCD) Lagrangian:

$$\mathcal{L}_{\text{quark}} = i\bar{\psi}\gamma^\mu D_\mu\psi - (\bar{\psi}_L M \psi_R + \text{h.c.}) + \mu_{I5} A_0^3,$$

$M = \text{diag}(m_u, m_d)$ is the quark mass matrix; μ_{I5} is chem. potential of the axial isospin charge A_0^3 .

Eff. (pion) Lagrangian, the most general allowed by symmetries, to lowest order in momenta:

$$\mathcal{L}_{\text{eff}} = \frac{f_t^2}{4} \text{Tr} \nabla_0 \Sigma \nabla_0 \Sigma^\dagger - \frac{f_s^2}{4} \text{Tr} \partial_i \Sigma \partial_i \Sigma^\dagger + \frac{f_m^2}{2} \text{Re Tr} M \Sigma,$$

from which we derive $\omega^2 = u^2(\mathbf{p}^2 + m^2)$ with

$$u^2 = \frac{f_s^2}{f_t^2} \quad \text{and} \quad m^2 = \frac{m_q f_m^2}{f_s^2}.$$

The (T -dependent) coefficients f_t , f_s and f_m , can be found in terms of microscopic correlators by matching derivatives w.r.t. M and μ_{I5} .

$\mu_{I5} \equiv$ time component of a vector potential for axial isospin \rightarrow local $SU(2)_A$ symmetry \rightarrow

$$\nabla_0 \Sigma \equiv \partial_0 \Sigma - \frac{i}{2} \mu_{I5} (\tau_3 \Sigma + \Sigma \tau_3).$$

Thus, matching 2nd derivative:

$$\chi_{I5} = \frac{\partial^2 \mathcal{P}}{\partial \mu_{I5}^2} = f_t^2.$$

Derivatives w.r.t. M give: $f_m^2 = -\langle \bar{\psi} \psi \rangle$ and $f_s = f$.

Thus: $\boxed{u^2 = f^2 / \chi_{I5}}$ and $f^2 m^2 = -m_q \langle \bar{\psi} \psi \rangle$ (GOR).

- Critical behavior

What happens with u and m when $T \rightarrow T_c$?

Theory of *static* critical phenomena can be used.

Near T_c , but not too close to T_c : $m \ll m_\sigma \ll T$.

In the range of momenta $m \ll |\mathbf{q}| \ll m_\sigma$ we have

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \langle \pi^a(x) \pi^b(0) \rangle = \delta^{ab} \frac{\langle \bar{\psi}\psi \rangle^2}{f^2} \frac{1}{\mathbf{q}^2}.$$

For momenta such that $m_\sigma \ll |\mathbf{q}| \ll T$:

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \langle \bar{\psi}\psi(x) \bar{\psi}\psi(0) \rangle \sim \frac{1}{|\mathbf{q}|^{2-\eta}}.$$

In this regime correlators of $\sigma = \bar{\psi}\psi$ and $\pi^a = i\bar{\psi}\gamma^5\tau^a\psi$ are degenerate, since they are related by the $SU(2)_A$ symmetry, which is restored at T_c . Matching at the scale $|\mathbf{q}| \sim m_\sigma$:

$$f^2 = A m_\sigma^{-\eta} \langle \bar{\psi}\psi \rangle^2.$$

$\eta \approx 0.03$ – $O(4)$ universality class in $d = 3$.

Using $m_\sigma \sim t^\nu$ and $\langle \bar{\psi}\psi \rangle \sim t^\beta$, where $t = (T_c - T)/T_c$:

$$f^2 \sim t^{2\beta-\nu\eta} = t^{(d-2)\nu} = t^\nu,$$

$\nu \approx 0.73$ and $\beta \approx 0.38$, $d = 3$.

χ_{I5} is *finite* at $T = T_c$. Thus,

$$u^2 = \frac{f^2}{\chi_{I5}} \sim f^2 \sim t^\nu \rightarrow 0 \text{ at } T_c$$

○ Critical behavior (contd.)

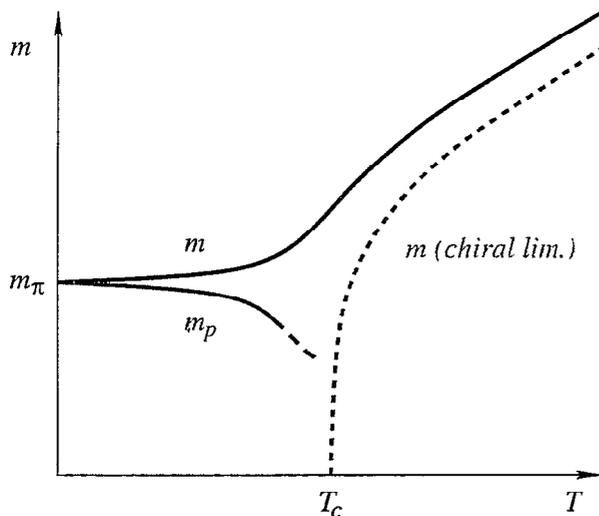
$$m^2 = -\frac{m_q \langle \bar{\psi} \psi \rangle}{f^2} \sim m_q t^{\beta-\nu}.$$

since $\beta < \nu$ — the static screening pion mass *grows* (at fixed $m_q \neq 0$) as $T \rightarrow T_c$.

The *pole* mass of the pion, m_p , scales differently:

$$m_p^2 \equiv u^2 m^2 = -\frac{m_q \langle \bar{\psi} \psi \rangle}{\chi_{I5}} \sim m_q t^\beta.$$

\Rightarrow the pole mass of the pion *drops* as $T \rightarrow T_c$.



● Potentially observable consequences

◇ In statistical models

$\Delta m_p \equiv m_p - m_\pi \approx m_\pi ((m_q/\Lambda_{\text{QCD}})^{1/2\delta} - 1) \approx -0.3 m_\pi$
 translates into $\exp(-\Delta m_p/T_{\text{ch}}) \approx 1.3$ enhancement of pion abundance.

◇ $u < 1 \Rightarrow$ Cherenkov radiation of pions by a hard probe.

Gluons Out of Equilibrium

Dietrich Bödeker

Strongly coupled gluons out of equilibrium

Dietrich Bödeker, RBRC and BNL

Small coupling, $g \ll 1$ and large fields,

$$A_\mu \sim \frac{1}{g} \partial_\mu$$

→ non-linearities in Yang-Mills equations become essential, strong coupling

examples:

- magnetic scale gluons ($k \sim g^2 T$) close to thermal equilibrium
- small- x gluons “colored glass condensate”

Non-perturbative calculations for many body systems out of equilibrium, that is, in real time?

quantum field theory: no

classical field theory: yes

classical field theory applies when occupation numbers of (bosonic) fields are large
strongly coupled gluons have occupation number

$$n(k) \sim \frac{1}{g^2} \gg 1$$

typically quantum modes (modes with small occupation number) can not be neglected

idea: try to find effective classical theory by integrating out quantum degrees of freedom

general problem: classical thermal field theory has UV divergences,
non-local for real time

Dynamics of magnetic scale gluons

unequal time correlation functions

$$\mathcal{C}(t) = \langle O(t)O(0) \rangle$$

determined by Langevin equation

$$\frac{3}{m_D^2} (c_1 + \mathbf{v} \cdot \mathbf{D}) \mathbf{v} \cdot \mathbf{D} \times \mathbf{B} + (C + v \cdot D) \widetilde{W} = \mathbf{v} \cdot \mathbf{E} + \xi,$$

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$\widetilde{W}(x, \mathbf{v})$ adjoint rep phase space density matrix of plasma particles, C linear collision operator, ξ Gaussian white noise

- no propagating gauge field waves \rightarrow solves problem of non-local UV divergences
- generalizes the leading log effective theory

$$\mathbf{D} \times \mathbf{B} = \sigma \mathbf{E} + \zeta$$

to leading order in g and all orders in $[\log(1/g)]^{-1}$

leading log equation

- for gluon fields only
- UV finite
- single length scale $R \sim (g^2 T)^{-1}$
- single time scale $\tau \sim [g^4 \log(1/g) T]^{-1}$

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leading order equation

- for gluon fields and particle phase space density
- UV divergences
- one length scale $R \sim (g^2 T)^{-1}$ (two if one counts logs)
- two time scales $\tau \sim (g^4 T)^{-1}$, $\tau \sim (g^2 T)^{-1}$

issues to be addressed for leading order equation

- relation to thermodynamics of soft gluons
- expansion in $[\log(1/g)]^{-1}$
- role of “fast” modes with $\tau \sim (g^2 T)^{-1}$
- renormalization

Relation to thermodynamics

Langevin equations generate probability distribution for field configurations $P(\phi, t)$

leading log Langevin equation:

$$P(\mathbf{A}, t) \rightarrow \exp \left[-\frac{H}{T} \right], \quad H = \frac{1}{2} \int d^3x \mathbf{B}^2$$

for $t \rightarrow \infty \Leftrightarrow$ 3-dimensional chromodynamics, obtained through dimensional reduction and by integrating out A_0

Fokker-Planck equation for $P(\mathbf{A}, \widetilde{W}, t) \Rightarrow$

$$P(\mathbf{A}, \widetilde{W}, t) \rightarrow \exp \left[-\frac{H}{T} \right], \quad H = \frac{1}{2} \int d^3x \left\{ \mathbf{B}^2 + m_D^2 \int_{\mathbf{v}} \widetilde{W}^2 \right\}$$

\widetilde{W} Gaussian free field for thermodynamics \Rightarrow same gauge field thermodynamics as from eq. (3)

\widetilde{W} has non-trivial effect on dynamics

Perturbation theory

- UV behavior: renormalizability, continuum limit?

expansion in $[\log(1/g)]^{-1}$: systematic improvement of leading log Langevin equation

classical field theory can be written as path integral

→ “quantum field theory”, Feynman rules (not Lorentz invariant)

$$\langle O[A, \widetilde{W}] \rangle_{\text{noise}} = \int [dA][d\widetilde{W}][d\lambda] e^{-S} O[A, \widetilde{W}]$$

$$S = \int_{x, \mathbf{v}} \left\{ \frac{T}{m_D^2} \lambda C \lambda - i\lambda \left[\frac{3}{m_D^2} (c_1 + \mathbf{v} \cdot \mathbf{D}) \mathbf{v} \cdot \mathbf{D} \times \mathbf{B} + (C + v \cdot D) \widetilde{W} - \mathbf{v} \cdot \mathbf{E} \right] \right\}$$

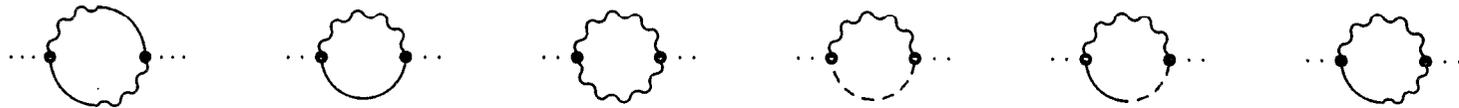
gauge fixing: flow gauge

$$\kappa A_0 = \nabla \cdot \mathbf{A}$$

One loop self-energies

high frequency ($\omega \sim g^2 T$) modes do not decouple

$\lambda\lambda$:



288 λA_0 :



determine color conductivity at next to leading order in $[\log(1/g)]^{-1}$

result is gauge fixing independent and agrees with Arnold, Yaffe

Renormalizability

large momentum behavior of propagators

$$\langle \mathbf{A}_{\text{tr}} \mathbf{A}_{\text{tr}} \rangle \sim \frac{1}{k^5}$$

but

$$\langle \widetilde{W} \widetilde{W} \rangle \sim \langle \widetilde{W} A_0 \rangle \sim \langle A_0 A_0 \rangle \sim \frac{1}{k}$$

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n -point functions for λ have bad UV behavior

$$\sim \int d^4k \frac{1}{k^2}$$

$$\sim \int d^4k \frac{1}{k^3}$$

however, contribution to gauge field dynamics suppressed by powers of g
non-physical, higher loops will contribute at the same order

Gluon Saturation from Small- x Evolution Equation

Kazunori Itakura

Gluon Saturation from

Small- x Evolution Equation

Kazu Itakura (RERC)

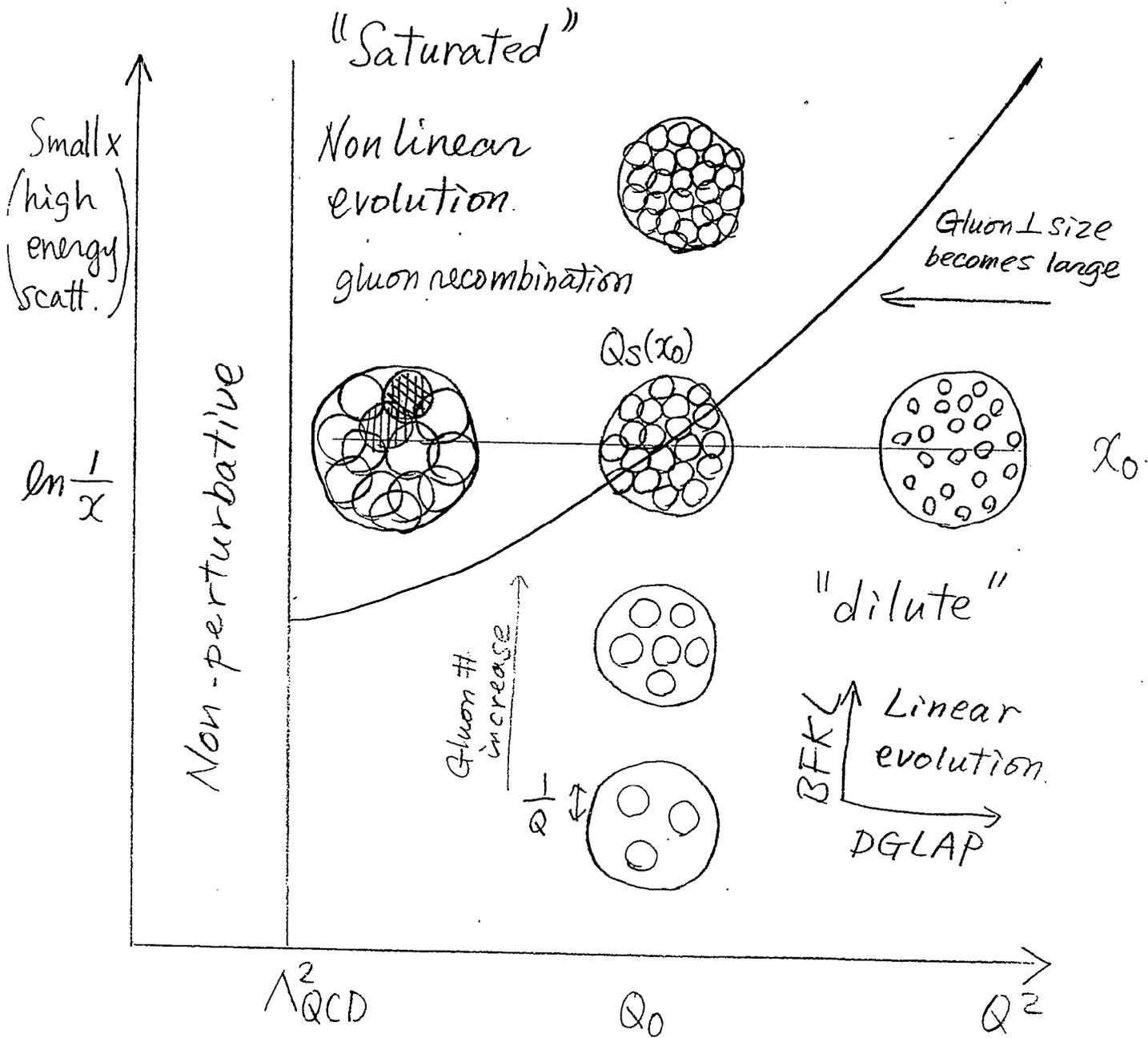
Edmond Iancu (Saclay)

Larry McLerran (BNL)

- Gluon Saturation
- Color Glass Condensate
- Evolution Equation
- Approximate Solutions (MFA, RPA)
- Summary

Gluon Saturation

L2



Saturated gluon with { high field strength
coherent gluon field

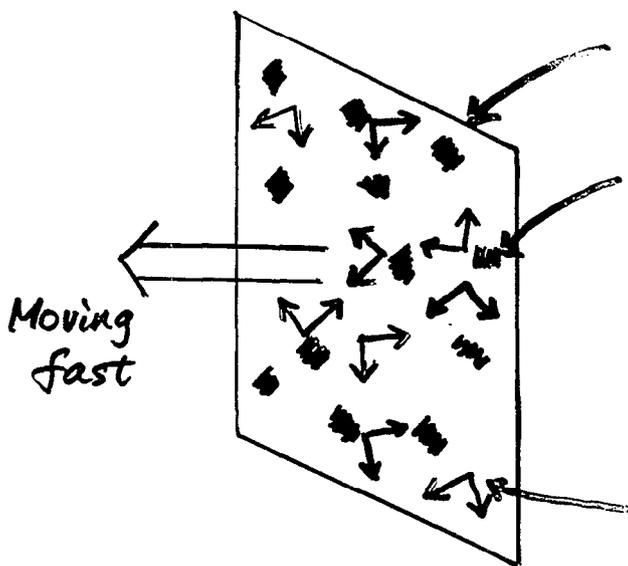
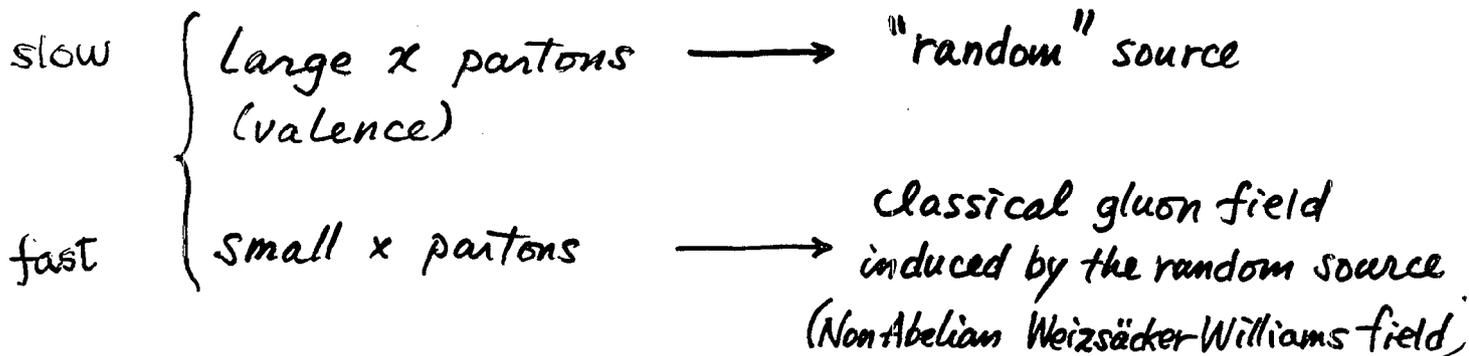
\Rightarrow "Color Glass Condensate"

Color Glass Condensate

McLerran-Venugopalan
 Jalilian-Marian, Leonidov
 Kovner, Weigert, ...

Effective theory of saturated gluons

Separation of degrees of freedom



Very thin sheet

valence partons $P_a(x_\perp)$

weight function

$$W[P] = \exp \left\{ -\frac{1}{2} \int d^2x_\perp \frac{P^2(x_\perp)}{\mu^2} \right\}$$

Gaussian

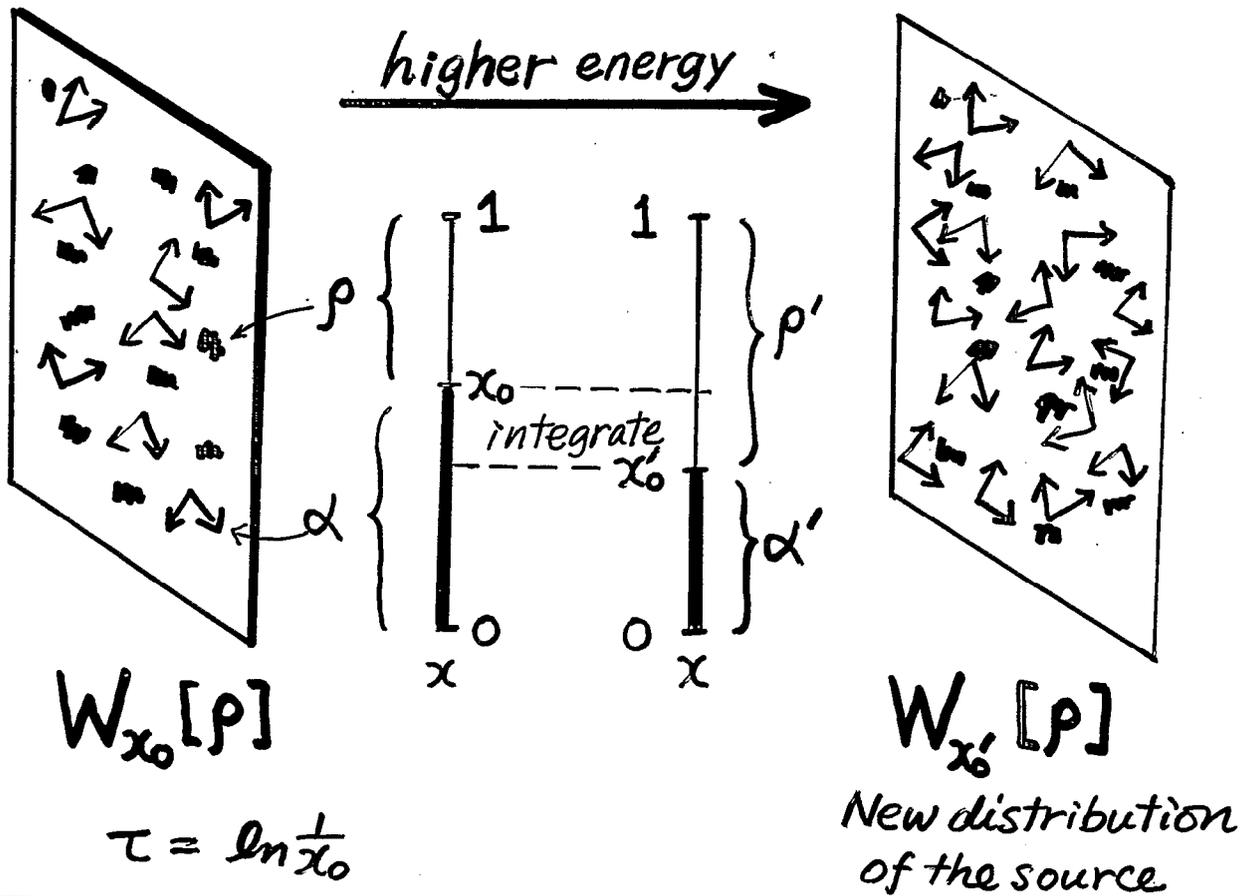
Classical gluon field $A^i(x_\perp)$

$$A^i(x_\perp) = \frac{i}{g} U \partial^i U^\dagger$$

$$U^\dagger(x_\perp) = P \exp \left\{ i g \int^{x^-} dz^- N(z^-, x_\perp) \right\}$$

Evolution Equation

Jalilian-Monari, Leonidou-Koumaki, Weigert, Iancu, McLerran, Ferreira



$$\frac{\partial}{\partial \tau} W_\tau[\alpha] = \frac{1}{2} \frac{\delta}{\delta \alpha_\tau^a(x_\perp)} \left[\chi_{x_\perp y_\perp}^{ab} \frac{\delta}{\delta \alpha_\tau^b(y_\perp)} W_\tau[\alpha] \right]$$

$$\chi_{x_\perp y_\perp}^{ab} = \alpha_s \int \frac{d^2 z_\perp}{(2\pi)^2} \frac{z_\perp^i - x_\perp^i}{(z_\perp - x_\perp)^2} \frac{z_\perp^i - y_\perp^i}{(z_\perp - y_\perp)^2} \left(1 + V_x^+ V_y - V_x^+ V_z - V_z^+ V_y \right)$$

$$V_x^+ = U^+(x^- = e^T \cdot x_\perp)$$

$$\alpha_\tau(x_\perp) = \alpha(x^- = e^T \cdot x_\perp)$$

α is a function of p $W[p] \rightarrow W[\alpha]$

Solving the Evolution Equation

- functional differential equation
- highly non-linear due to $\chi[\alpha]$

$$\frac{\partial W_\tau[\alpha]}{\partial \tau} = \frac{1}{2} \frac{\delta}{\delta \alpha} \left(\chi[\alpha] \frac{\delta}{\delta \alpha} W_\tau[\alpha] \right)$$

“Mean Field Approximation”

“Random Phase Approximation”

Replace $\chi[\alpha]$ by $\langle \chi[\alpha] \rangle_\tau$

Ignore α dependence of $\chi[\alpha]$

Both lead to

$$\frac{\partial W_\tau[\alpha]}{\partial \tau} = \frac{1}{2} \chi_\tau \frac{\delta^2}{\delta \alpha^2} W_\tau[\alpha]$$

Solution is Gaussian

$$W_\tau[\alpha] \sim e^{-\frac{1}{2} \int \alpha \frac{1}{\chi} \alpha} \sim e^{-\int \frac{p^2}{\mu^2}}$$

Mean Field Approximation

Self consistency condition

$$\langle \chi[\alpha] \rangle_\tau \equiv \chi_\tau(x_L - y_L) = \int \mathcal{D}\alpha \underbrace{e^{-\frac{1}{2}\alpha \frac{1}{8}\alpha}}_{\text{MFA } W_\tau[\alpha]} \chi[\alpha]$$

$$S_\tau(x_L - y_L) \equiv \langle \text{tr}(V_x^\dagger V_y) \rangle_\tau \quad \text{dipole scattering amplitude}$$

$$\frac{\partial}{\partial \tau} S_\tau(x - y) = \bar{\alpha}_s \int \frac{d^2 z_L}{(2\pi)} \frac{z^i - x^i}{(z_L - x_L)^2} \frac{z^i - y^i}{(z_L - y_L)^2}$$

$$\times \left(1 + S_\tau(x - y) - S_\tau(x - z) - S_\tau(z - y) \right) S_\tau(x - y)$$

Short distance $|x_L - y_L| \ll 1/\bar{\alpha}_s$

$$S_\tau(x_L - y_L) \simeq 1 - (x_L - y_L)^2 \# \alpha G(x, 1/(x - y)^2)$$

- Leading log \rightarrow DLA equation
- First nonlinear \rightarrow Mueller-Qiu equation correction
- Saturation scale Q_s

$$Q_s^2(\tau) \propto \alpha G(x, Q_s^2(\tau)) \quad Q_s^2(\tau) \sim e^{4\bar{\alpha}_s \tau} \text{DLA}$$

- Gluon number density per unit trans. area.

$$N_\tau(k_L) = \frac{1}{\pi R^2} \frac{d(\alpha G)}{d^2 k_L} \propto \frac{1}{k_L^2}$$

Random Phase Approximation

At long distance $|x_1 - y_1| \gg 1/Q_s$

$$\langle V_x^+ V_y \rangle \approx 0$$

We can ignore all the Wilson lines in χ .

$$\chi = \int d^2z_1 K_{xyz} \left(1 + \cancel{V_x^+ V_y} - \cancel{V_x^+ V_z} - \cancel{V_z^+ V_y} \right)$$

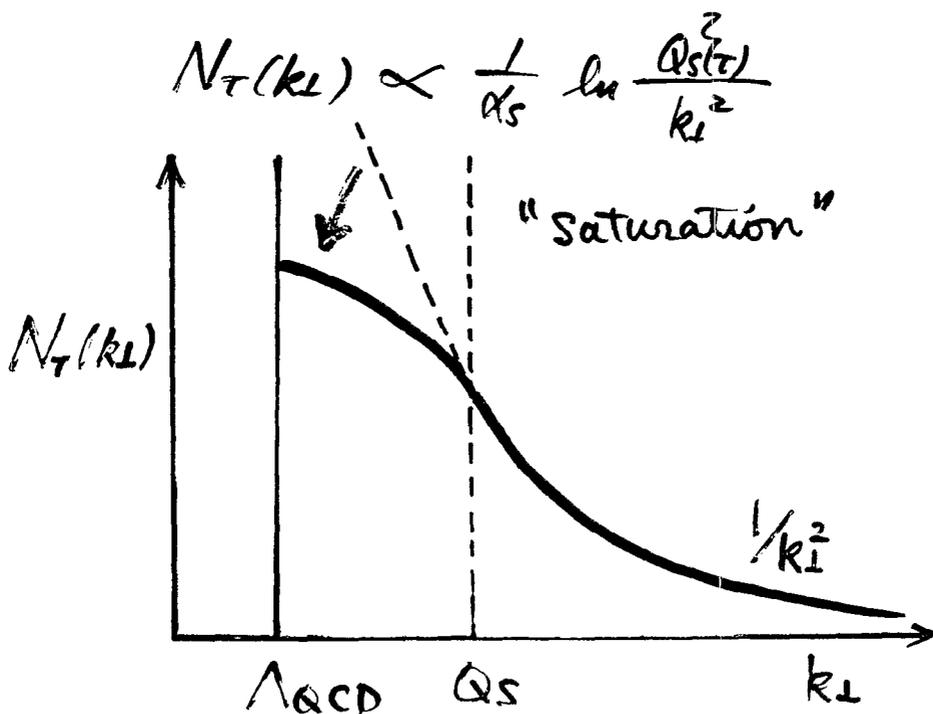
RPA

- Two point function gives a consistent result.

$$\langle V_x^+ V_y \rangle \approx \exp \left\{ -\frac{1}{8} \left[2n(Q_s^2(\tau)(x_1 - y_1)^2) \right]^2 \right\}$$

rapidly decreasing func.

- Gluon # density



Summary

- Color Glass Condensate is the effective theory of saturated gluons at small x .
- Small- x evolution equation for the weight function $W_\tau[\rho]$ is solved by MFA and RPA.
- MFA works well at high momentum region and reproduces DLA and MQ equations.
- RPA works well at low momentum region and leads to gluon saturation.

Renormalization Group Improvement of the Time Dependent Ginzburg-Landau Equation at Finite Temperature

Yukio Nemoto

**Renormalization Group
Improvement
of the Time Dependent
Ginzburg-Landau Equation
at Finite Temperature**

Yukio Nemoto(RBRC)

Teiji Kunihiro (YITP,Kyoto)

Time-Dependent Ginzburg-Landau (TDGL) eq.

Spatial variation of an order parameter of phase transition.

⇒ GL equation

$$-\frac{1}{2m}(\nabla^2 - 2ieA)\Delta + \alpha\Delta + \beta\Delta^3 = 0 \quad (1)$$

An extension to the description of space-time development

⇒ TDGL equation.

$$\gamma_1 \frac{d\Delta}{dt} + \gamma_2 \frac{d^2\Delta}{dt^2} = -\frac{1}{2m}\nabla^2\Delta + \alpha\Delta + \beta\Delta^3 \quad (2)$$

**Various application of the TDGL eq.
Dynamical critical phenomena**

e.g., (for the chiral phase transition)

- Disoriented Chiral Condensate**
- Relativistic Heavy-Ion Collision**
- Color Superconductivity**

Microscopic derivation of the TDGL eq.

BCS \Rightarrow GL eq.

Gor'kov 1959

BCS \Rightarrow TDGL eq.

Abrahams, Tsuneto 1966

two limited cases ($T = 0, T \approx T_C$)

(Otherwise Landau damping terms diverge.)

Chiral effective theory (NJL model) has the same problem.

NJL \Rightarrow TDGL

Eguchi, Sugawara 1974 (for $T = 0$)

Our purpose

We employ the RG equation to the Landau damping which causes divergence. \Rightarrow coarse graining of time scale.

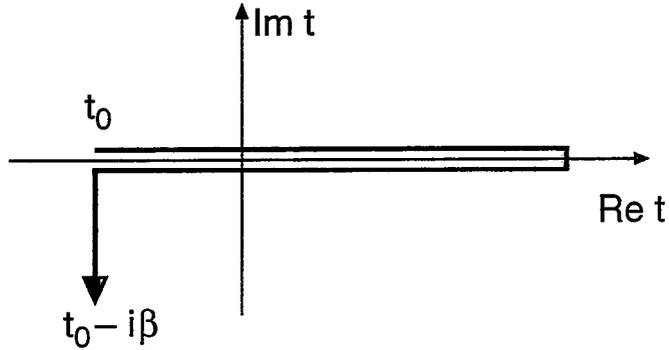
We use the 2-flavor NJL model.

2-flavor NJL model

$$\mathcal{L} = \bar{q}i\not{\partial}q + g[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2] \quad (3)$$

The Green function satisfies the equation

$$(i\not{\partial}_x - M(t_x; t_0))S(x, x') = \delta_c^4(x - x') \quad (4)$$



(closed time path)

Self-consistency condition

$$M(t; t_0) = 2gi\text{Tr}[S(x, x^+)] \quad (5)$$

We neglect the fluctuation of pions, for simplicity.

t_0 : initial time (assumes local equilibrium)

In relative and center-of-mass coordinates,

$$S(t = t_x - t_y, T = (t_x + t_y)/2)$$

t : microscopic variable,

T : macroscopic variable

The lowest order solution (=Hartree)

$$S(t, t^+) = S_0(t, t^+), \quad M(t; t_0) = M(T) \quad (6)$$

The next order

$$\begin{aligned} S(t, t^+) &= S_0(t, t^+) \\ &+ \int_c dt' \int d^3y S_0(t, t') (M(t') - M(T)) \\ &\quad \times S_0(t', t^+) \end{aligned} \quad (7)$$

$M(t')$ is expanded around $t(=T)$

$$M(t') = M(t) + (t' - t) \frac{dM}{dt} + \frac{1}{2} (t' - t)^2 \frac{d^2M}{dt^2} + \dots \quad (8)$$

Each derivative-term is not periodic in the imaginary time direction. (T.S.Evans 1998)

\Rightarrow One cannot perform the naive Fourier transformation.

\Rightarrow We compute the time-integral directly.

At the order $O\left(\frac{dM}{dt}\right)$

$$\begin{aligned}
 M(t; t_0) = & 8gN_c \int \frac{d^3k}{(2\pi)^3} \left[\frac{M(T)}{E} (1 - 2f(E)) \right. \\
 & - i \frac{1}{E^2} \frac{E^2 - M(T)^2}{E} \left\{ -e^{2i(t-t_0)E} f(E)^2 \right. \\
 & + e^{-2i(t-t_0)E} (1 - f(E))^2 \\
 & \left. \left. + M(T)^2 \beta (\beta - 2i(t - t_0)) f(E)(1 - f(E)) \right\} \right. \\
 & \left. \times \frac{dM(t)}{dt} \right], \quad E = \sqrt{k^2 + M(T)^2} \quad (9)
 \end{aligned}$$

Note 1: We neglect the variation of the temperature.

Note 2: The Landau damping term is divergent if one performs F.T. in time. This means $t_0 \rightarrow -\infty$.

Note 3: The Landau damping term is finite, but appears as a secular term in our case.

This is similar to the situation of kinetic equations. (Boyanovsky et.al.)

Note 4: The second-derivative term has the same structure.

The initial time t_0 is important!

Treatments of the secular terms

⇒ Renormalization group approach

t_0 is considered as the macroscopic variable, $t_0 \sim T$.

$$\boxed{\left. \frac{dM(t;t_0)}{dt_0} \right|_{t_0=T}}$$

This means that we extract the slow (macroscopic) motion. Note $\frac{d}{dt} \neq \frac{d}{dT}$.

The result is

$$\frac{dM}{dT} = -2gN_c \int \frac{d^3k}{(2\pi)^3} M(T)^2 \beta^2 f(E)(1-f(E)) \frac{dM}{dt} \quad (10)$$

The t -derivative is written as

$$\frac{dM}{dt} = \left[1 - 8N_c \int \frac{d^3k}{(2\pi)^3} \frac{1}{E} \left\{ \frac{E^2 - M(t)^2}{E^2} (1 - 2f(E)) + M(t)\beta f(E)(1 - f(E)) \right\} \right]^{-1} \quad (11)$$

and finally replaces $t \rightarrow T$.

Comments

- It is straightforward to extend this result to systems at finite density.
- At $T \approx T_c$, the TDGL eq. is diffusion-like in superconductor, while it is wave-like in the NJL model.

Summary

We have derived the TDGL eq. from the NJL model at finite temperature. The important is to set up the (finite) initial time t_0 . The Landau damping terms are then divergence-less and appear as the secular terms. The secular terms are removed by extracting the slow motion of time, whose idea is based on the renormalization group method. (e.g., Ei, Fujii and Kunihiro(2000))

Future works

- Generalization (pion, vector, axialvector fields)
- Derivation: $\text{BCS} \implies \text{TDGL}$ eq.
- Applications to various phenomena (DCC etc.)

Domain Walls in High-Density QCD and in Atomic Bose-Einstein Condensates

Dam Thanh Son

CONFINEMENT AND DOMAIN WALLS IN HIGH DENSITY QUARK MATTER

D. T. Son

D. Rischke, DTS, M. Stephanov PRL 87 (2001) 062001
DTS, M. Stephanov, A. Zhitnitsky PRL 86 (2001) 3955

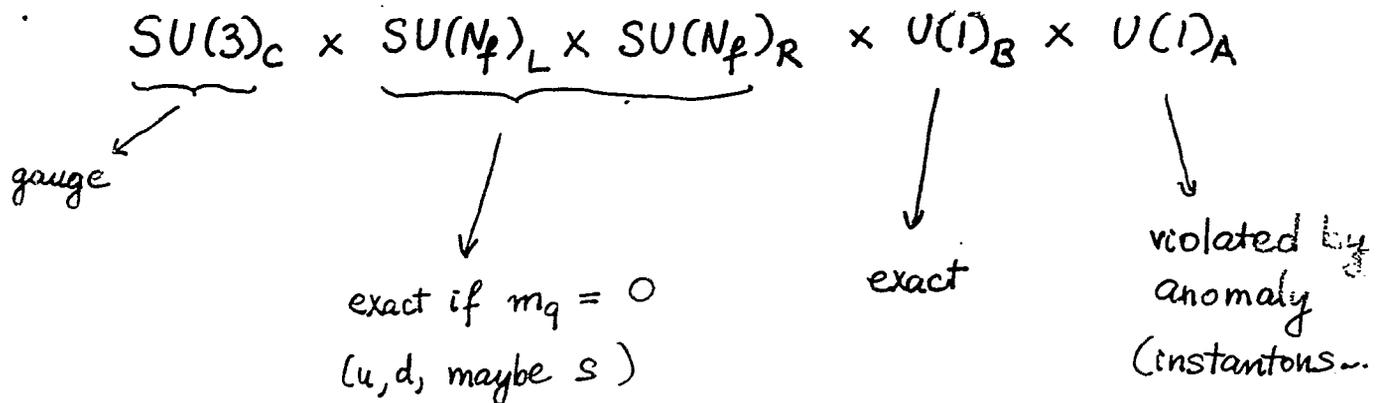
QCD Lagrangian and symmetries

$$L = \bar{q} (i\not{D} - m) q - \frac{1}{4} F_{\mu\nu}^2$$

$$q = \begin{pmatrix} q_L \\ q_R \end{pmatrix}_{ai}$$

$$a = 1, 2, 3$$

$$i = u, d, s, \dots$$



$$SU(3)_C : q^a \rightarrow \Lambda^{ab}(x) q^b$$

$$A_\mu \rightarrow \Lambda A_\mu \Lambda^{-1} + \Lambda \partial_\mu \Lambda^{-1}$$

$$SU(3)_L : q_L^i \rightarrow U^{ij} q_L^j$$

$$SU(3)_R : q_R^i \rightarrow U^{ij} q_R^j$$

$$U(1)_B : q_L \rightarrow e^{i\alpha} q_L \quad q_R \rightarrow e^{i\alpha} q_R$$

$$U(1)_A : q_L \rightarrow e^{i\alpha} q_L \quad q_R \rightarrow e^{-i\alpha} q_R$$

$$\text{In vacuum : } SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V$$

$$\langle \bar{q}_L q_R \rangle \neq 0$$

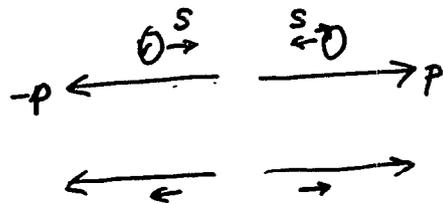
Symmetries at high densities: depends on N_f

• $N_f = 2$ (u, d)

quark pairing

$$\langle q_L q_L \rangle \neq 0$$

$$\langle q_R q_R \rangle \neq 0$$



More precisely:

$$X^a = \epsilon^{abc} \epsilon^{ij} \epsilon^{\alpha\beta} \langle q_{L\alpha}^{bi} q_{L\beta}^{cj} \rangle^*$$

$$Y^a = \epsilon^{abc} \epsilon^{ij} \epsilon^{\alpha\beta} \langle q_{R\alpha}^{bi} q_{R\beta}^{cj} \rangle^*$$

If $X^a \parallel Y^a$: $SU(3)_c \rightarrow SU(2)_c$

Chiral $SU(2)_L \times SU(2)_R$ unbroken ϵ_{ij}

X^a and Y^a are not gauge invariant

but $\Sigma = X^{a*} Y^a$ is gauge invariant

breaks $U(1)_A$ symmetry

$$q_L \rightarrow e^{i\alpha} q_L$$

$$q_R \rightarrow e^{-i\alpha} q_R$$

$$X \rightarrow e^{-2i\alpha} X$$

$$Y \rightarrow e^{2i\alpha} Y$$

$$\Sigma \rightarrow e^{4i\alpha} \Sigma$$

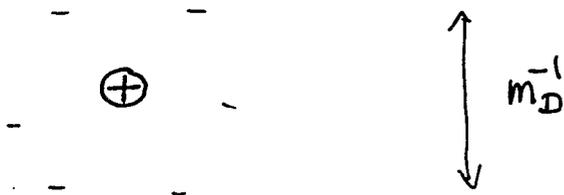
DECONFINEMENT ?

Naively: distance between quarks $\sim \mu^{-1} \ll \Lambda_{\text{QCD}}^{-1}$
quarks become free at high densities

BUT: unbroken $SU(2)_c$ must be confining.
How?

Look at a test charge in plasma

Normal plasma:

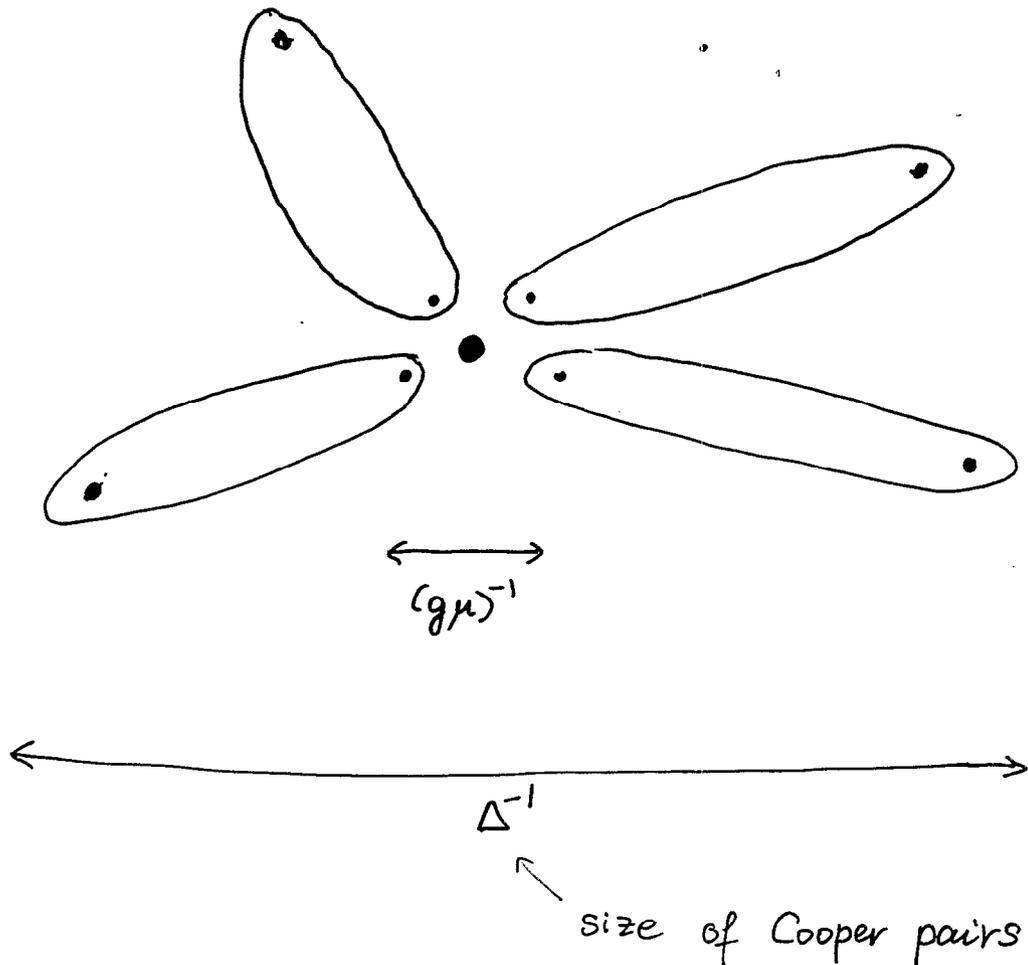


test charge attracts oppositely charged particles
in plasma

\Rightarrow Debye screening

$$m_D \sim g\mu$$

Test $SU(2)_c$ charge in color superconductor



Test charge cannot be completely screened at distances larger Δ^{-1} : Cooper pairs are $SU(2)_c$ neutral

But: medium is polarizable

\Rightarrow \uparrow dielectric constant $\epsilon \neq 1$
color

like water

Confinement:

Effective Lagrangian for gluons (energies below Δ)

$$L = \frac{\epsilon}{2} \vec{E}^a \cdot \vec{E}^a - \frac{1}{2} \vec{B}^a \cdot \vec{B}^a \quad \epsilon = \frac{g^2 \mu^2}{18\pi^2 \Delta^2}$$

2 effects:

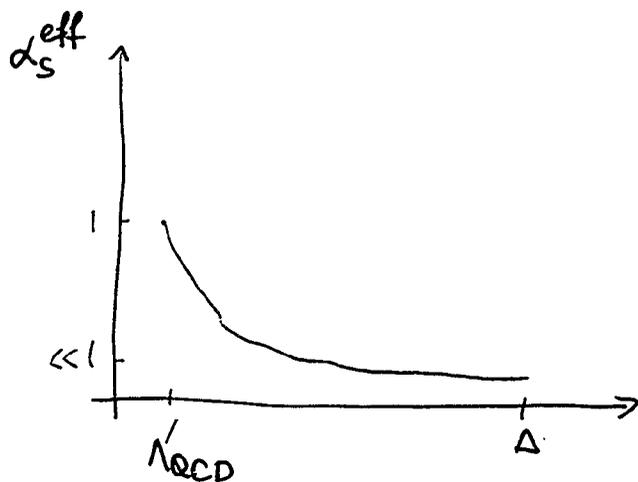
- Coulomb's law $\frac{g^2}{r} \rightarrow \frac{g^2}{\epsilon r}$

$$g_{\text{eff}}^2 = \frac{g^2}{\epsilon}$$

- Gluon velocity $v = \frac{1}{\sqrt{\epsilon}} \ll 1$

$$\alpha_s = \frac{g^2}{4\pi \hbar c} \rightarrow \alpha_s^{\text{eff}} = \frac{g_{\text{eff}}^2}{4\pi \hbar c} = \frac{g^2}{4\pi} \cdot \frac{1}{\sqrt{\epsilon}}$$

\Rightarrow effective strong coupling is very small at scale Δ



$$\Lambda_{\text{QCD}}' \sim \Delta \exp\left(-\frac{2\pi}{\beta_0 \alpha_s^{\text{eff}}}\right)$$

$$\sim \Delta \exp\left(-\frac{2\sqrt{2}\pi}{11} \frac{\mu}{g\Delta}\right)$$

depending on Δ
can be from $O(1 \text{ keV})$

to $O(10 \text{ MeV})$

DOMAIN WALLS

Recall: ~~color~~ color superconductivity breaks $U(1)_A$
Spontaneously

Let ϕ be the $U(1)_A$ phase of the condensate

$$\Sigma = |\Sigma| e^{i\phi}$$

then if $U(1)_A$ was an exact symmetry

$$L_{\text{eff}} = f^2 [(\partial_0 \phi)^2 - u^2 (\partial_i \phi)^2]$$

$$= \frac{\mu^2}{8\pi^2}$$

$U(1)_A$ susceptibility

$$= \frac{1}{3}$$

BUT: $U(1)_A$ is explicitly violated by:

- quark masses
- anomaly, instantons

Explicit violation of $U(1)_A$ becomes weaker at
higher density

(instantons become more dilute)

$$L = f^2 [(\partial_0 \varphi)^2 - u^2 (\partial_i \varphi)^2] - V(\varphi)$$

↑ from instantons, quark masses
periodic

$$V(\varphi) = -a \mu^2 \Delta^2 \cos \varphi$$

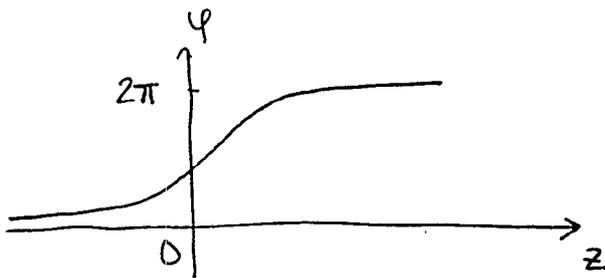
$$a \rightarrow 0$$

$$\mu \rightarrow \infty$$

$$a \sim \underbrace{O\left(\left(\frac{\Lambda_{\text{QCD}}}{\mu}\right)^{29/3}\right)}_{\text{instantons}} + \underbrace{O\left(\frac{m_u m_d}{\mu^2}\right)}_{\text{quark masses}}$$

This is Sine-Gordon theory

which possesses domain wall solution



$$\varphi(z) = 4 \arctan e^{mz/u}$$

$$m = 2\pi \sqrt{a} \Delta$$

mass of pseudoscalar
singlet

Notes: 1) Needs $m \lesssim 2\Delta$

for effective theory to be effective

2) Ground states on 2 sides of domain wall
are identical

⇒ non-topological domain wall

(similar to $N=1$ axion domain walls)

Chiral Properties of Domain Wall Fermions with Improved Gauge Actions

Kostas Orginos

Chiral properties of Domain Wall Fermions with Improved Gauge actions



K. Orginos

RBC group

- Introduction and Motivation.
 - Chiral properties of DWF.
 - Gauge Actions.
 - Tests and Comparisons.
 - Conclusions.
-

Introduction - Motivation

Domain Wall Fermion Chiral Ward Identity:

[Furman & Shamir Nucl.Phys. B439 (1995)]

$$\begin{aligned}\Delta_\mu \langle \mathcal{A}_\mu^a(x) O(y) \rangle &= 2m_f \langle J_5^a(x) O(y) \rangle \\ &+ 2 \langle J_{5q}^a(x) O(y) \rangle + i \langle \delta^a O(y) \rangle.\end{aligned}$$

$\mathcal{A}_\mu^a(x)$: Axial Current

$J_5^a(x)$: Pseudo-scalar density

$J_{5q}^a(x)$: Anomalous Pseudo-scalar density

$$\lim_{L_s \rightarrow \infty} \langle J_{5q}^a(x) O(y) \rangle = 0$$

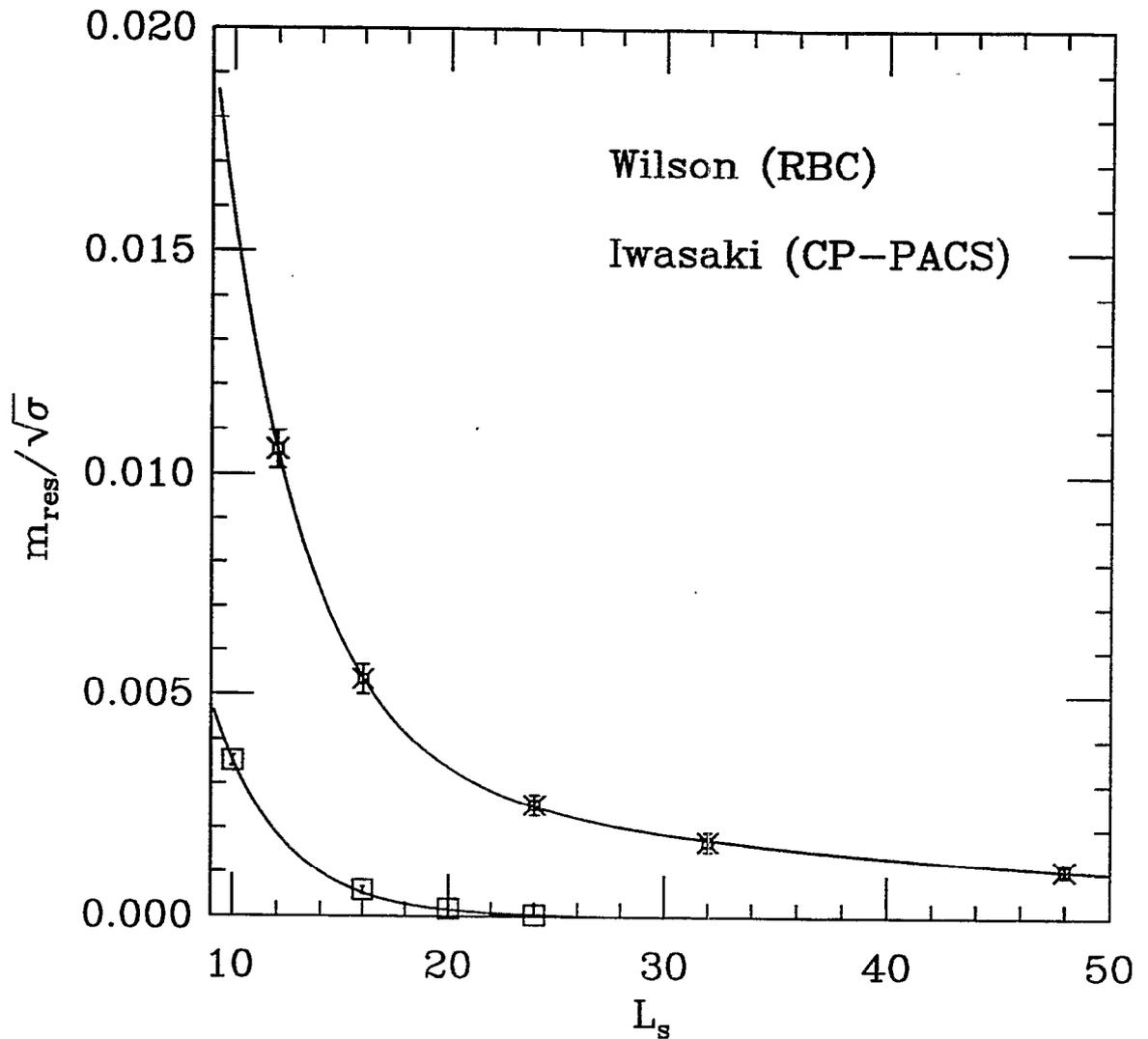
- $L_s \rightarrow \infty$: Exact chiral symmetry
- Finite L_s : Exponentially suppressed breaking

Measure of Chiral Symmetry Breaking:

$$m_{\text{res}} = \frac{\langle J_{5q}^a(0) J_5^a(t) \rangle}{\langle J_5^a(0) J_5^a(t) \rangle} \Big|_{t \gg t_{\text{min}}}$$

Assume at low energy $J_{5q}^a \sim m_{\text{res}} J_5^a$

Data



- Exponential suppression is small.
at $a^{-1} = 2\text{GeV}$ $m_{\text{res}} \sim q^{L_s}$
Wilson gauge $q \sim .97$
Iwasaki gauge $q \sim .74$
- m_{res} varies with the Gauge Action.

Objective

Minimize Chiral Symmetry breaking in the space of Gauge Actions.

Actions Tested:

- Wilson: $S_g = \frac{\beta}{3} \text{Re Tr} \langle 1 - \square \rangle$

- One loop Symanzik:

$$S_g = \frac{\beta}{3} \text{Re Tr} \left[c_0 \langle 1 - \square \rangle + 2c_1 \langle 1 - \text{rectangle} \rangle + \frac{4}{3} c_2 \langle 1 - \text{pentagon} \rangle \right]$$

c_i computed by 1-loop tadpole improved perturbation theory.

[Lüscher & Weisz Phys.Lett. B158 (1985)]

[Alford *et.al.* Phys.Lett. B361 (1995)]

- Iwasaki:

$$S_g = \frac{\beta}{3} \text{Re Tr} \left[(1 - 8c_1) \langle 1 - \square \rangle + 2c_1 \langle 1 - \text{rectangle} \rangle \right]$$

With $c_1 = -0.331$ computed by perturbative RG blocking.

[Iwasaki (1983)]

- DBW2: Same as Iwasaki but $c_1 = -1.4067$ computed non-perturbatively by RG blocking.

[Takaishi Phys.Rev. D54 (1996)]

The DBW2 action

Doubly Blocked Wilson 2 [Takaishi Phys.Rev. D54 (1996)]

- Start from Wilson $\beta = 6.3$ on a $32^3 \times 64$ lattice
- Doubly Block by a factor 2 (Swendsen's Blocking)
- Solve the Schwinger-Dyson equations to find the effective action.
- Truncate to the two coupling space:

$$S_g = \beta_{11} \frac{1}{3} \text{ReTr} \langle 1 - \text{loop} \rangle + \beta_{12} \frac{1}{3} \text{ReTr} \langle 1 - \text{rectangle} \rangle$$

DBW2 definition:

$$\frac{\beta_{12}}{\beta_{11}} = -0.1148$$

QCD-TARO [Nucl.Phys. B577 (2000)] studied the RG flow on the 2D plane of couplings and showed that DBW2 is approximately RG invariant.

The transfer matrix

Chiral Symmetry breaking is controlled by the nearly unit eigenvalues of the Transfer Matrix \mathcal{T} in the 5th dimension.

[Boriçi hep-lat/9912040]

$$\mathcal{T}^{-1} = \frac{1 + \mathcal{H}_t}{1 - \mathcal{H}_t}$$

with

$$\mathcal{H}_t = \frac{1}{2 + \mathcal{D}_w^\dagger(-M_5)} \gamma_5 \mathcal{D}_w(-M_5)$$

- $\mathcal{H}_t |n\rangle = 0 \Rightarrow \gamma_5 \mathcal{D}_w(-M_5) |n\rangle = 0 \Rightarrow \mathcal{T} |n\rangle = 1$
- $\gamma_5 \mathcal{D}_w(-M_5)$ has a lot of nearly zero eigenvalues.
[Neuberger, Narayanan] [Edwards, Heller, Narayanan]
[Hernandez *et.al.* Nucl.Phys. B552 (1999) ; hep-lat/0007015]
- Their frequency decreases rapidly as the continuum limit is approached.
- Proposals of improvement: “*Just remove them*”

[See above citations]

Improved Chirality \iff Suppressed \mathcal{H}_t Zero modes

We would like to:

- See the signal of \mathcal{H}_t Zero modes
- Chirality Breaking per configuration:

$$R(t) = \frac{J_{5q}^a(0)J_5^a(t)}{J_5^a(0)J_5^a(t)}$$

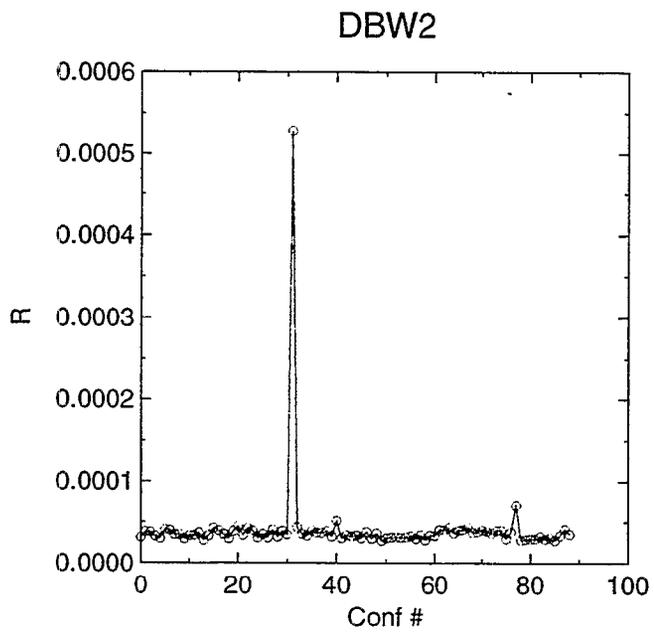
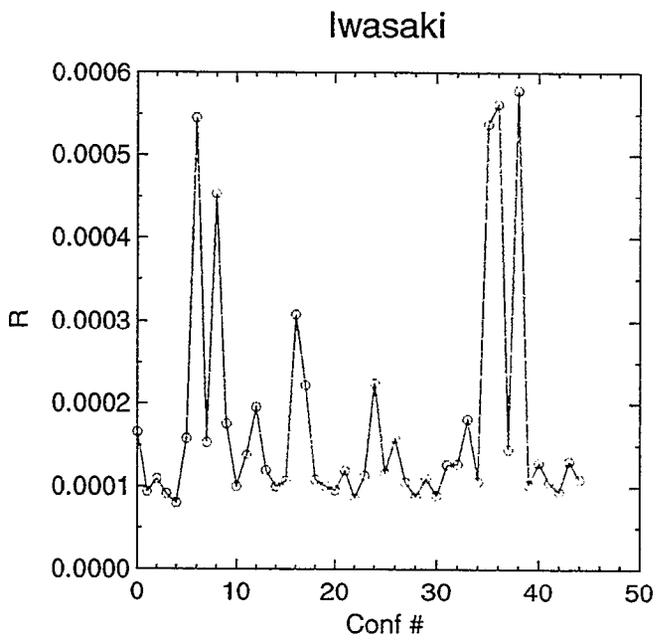
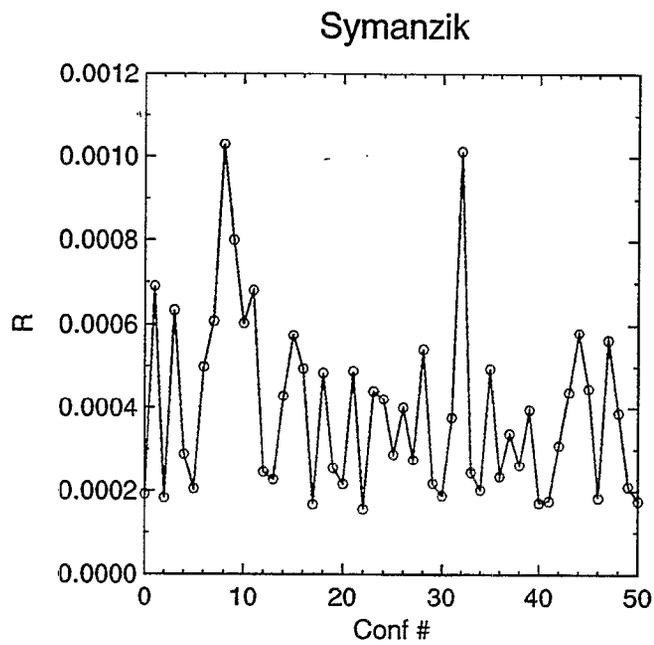
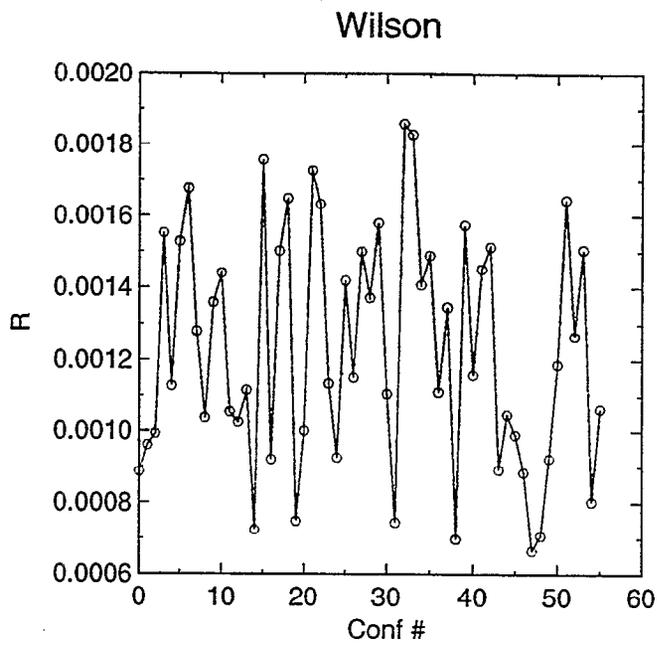
- See how much we can change the number of Zero modes by changing the gauge action, and hence improve Chiral Symmetry

Simulations

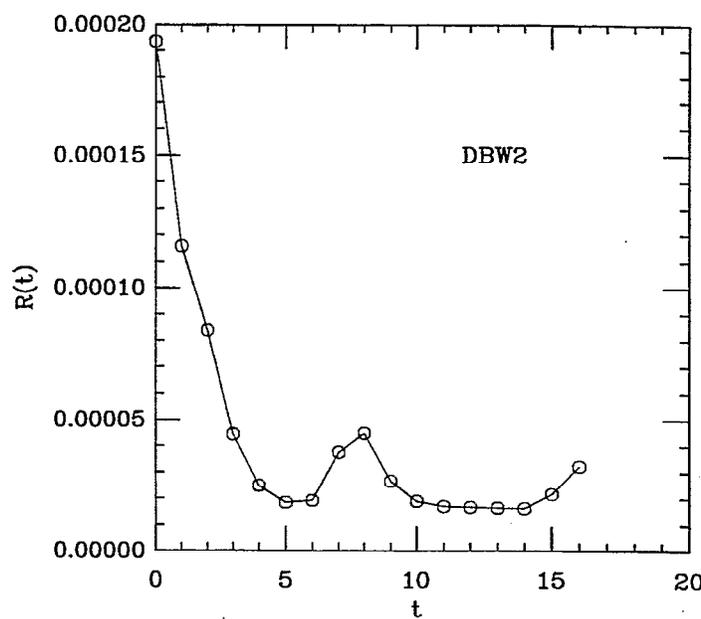
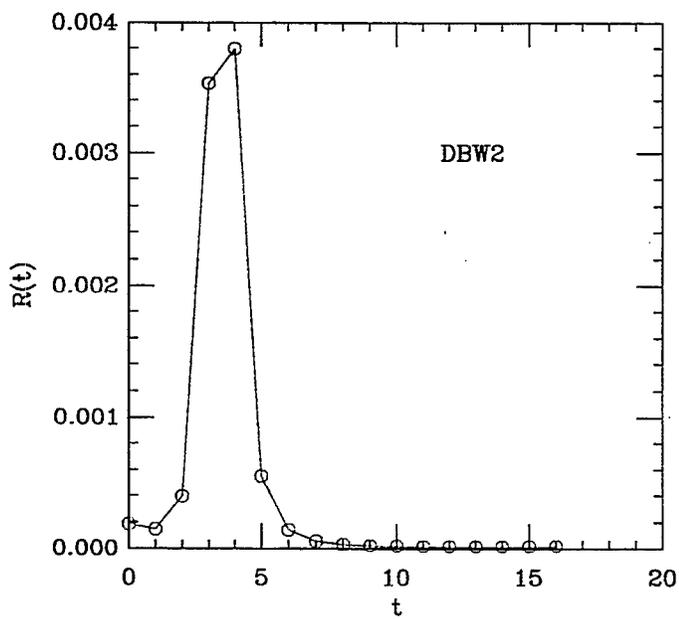
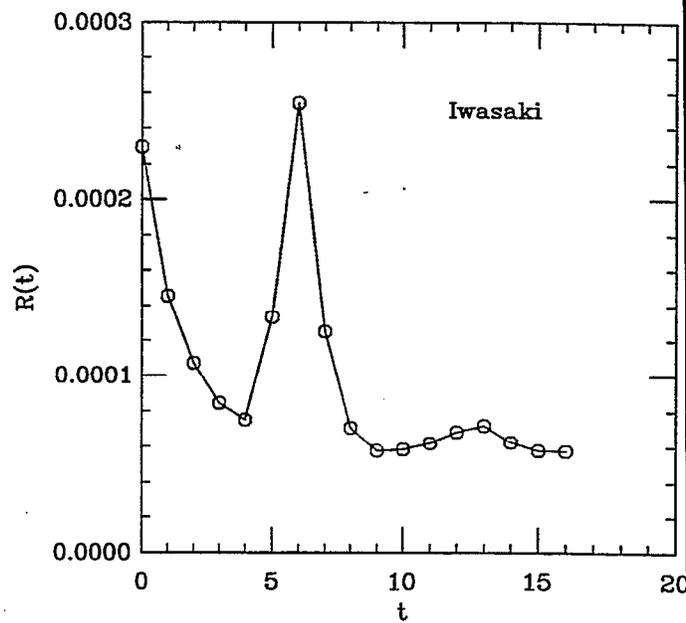
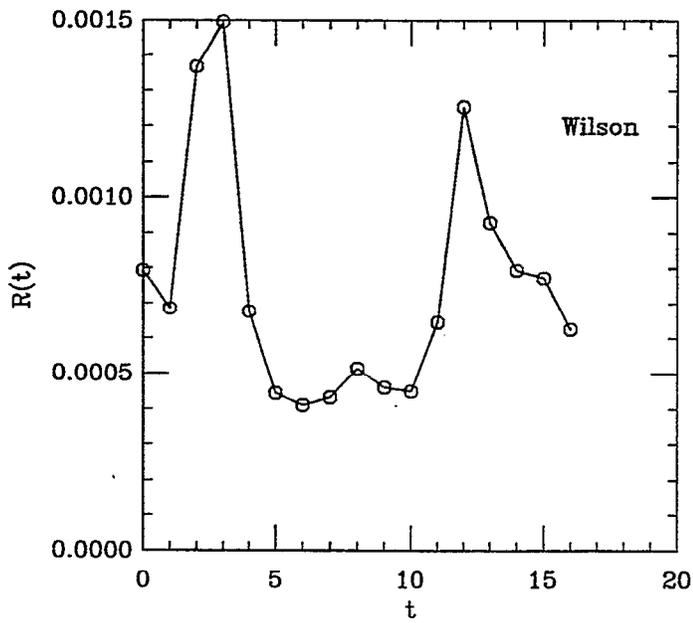
We measured the light hadron spectrum; the residual mass, and the ratio $R(t)$ (defined in the previous page) on $16^3 \times 32$ lattices.

- $a^{-1} \sim 2\text{GeV}$ (from the ρ mass)
Matches the Wilson $\beta = 6.0$
- Bare quark masses 0.02 0.04 and 0.06
- Varied M_5 in the range 1.4 - 2.0
- Varied L_s (8 12 16)
- Gauge actions:
 - 1-loop Symanzik (50 configs)
 - Iwasaki (50 configs one L_s)
 - DBW2 (90 configs)

We also have data for DBW2 at $a^{-1} \sim 1.3\text{GeV}$ $16^3 \times 32$ (Y. Aoki's talk for the spectrum results).

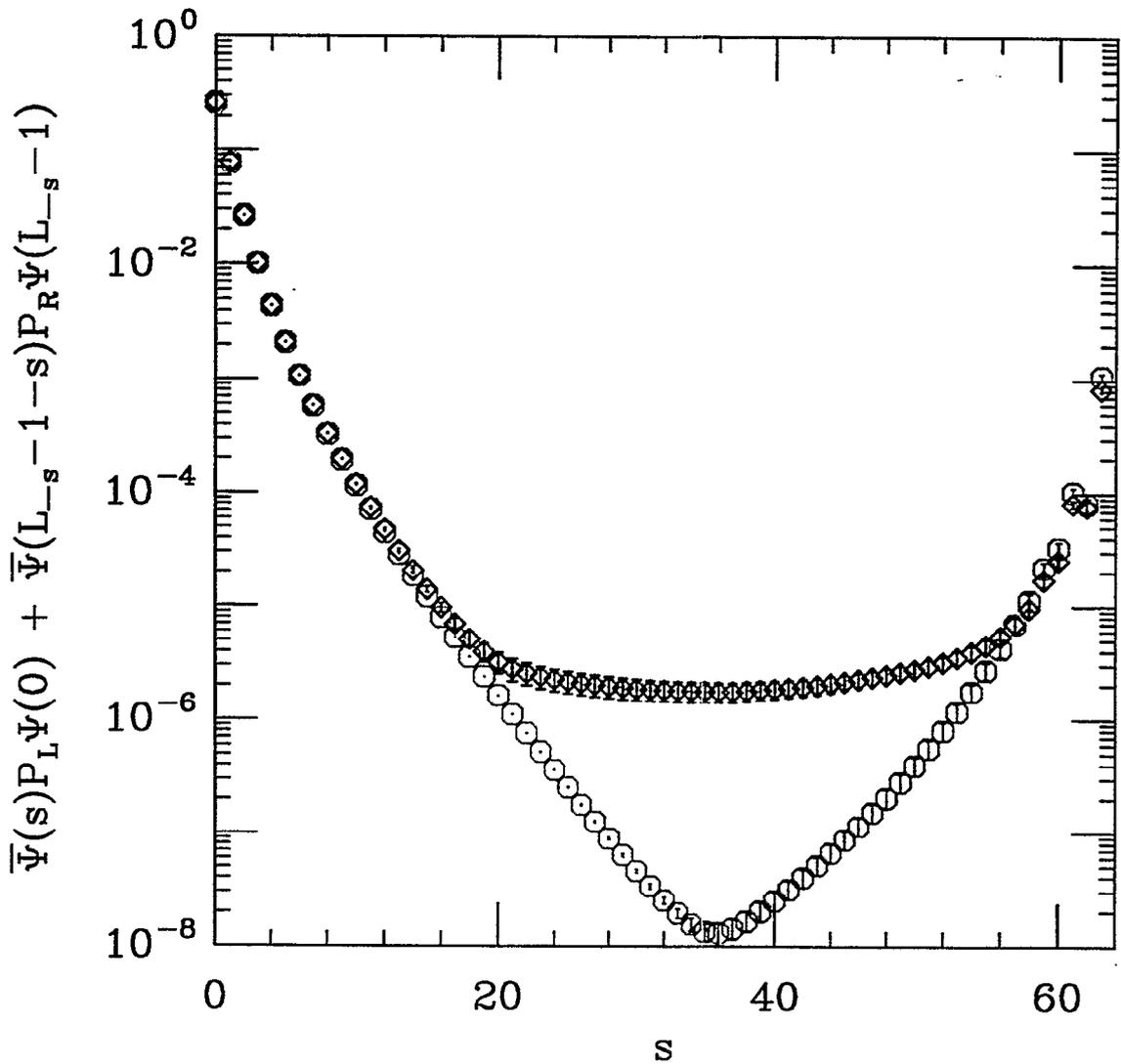


$$R = \sum_t R(t) = \frac{J_{5q}^a(0) J_5^a(t)}{J_5^a(0) J_5^a(t)}$$



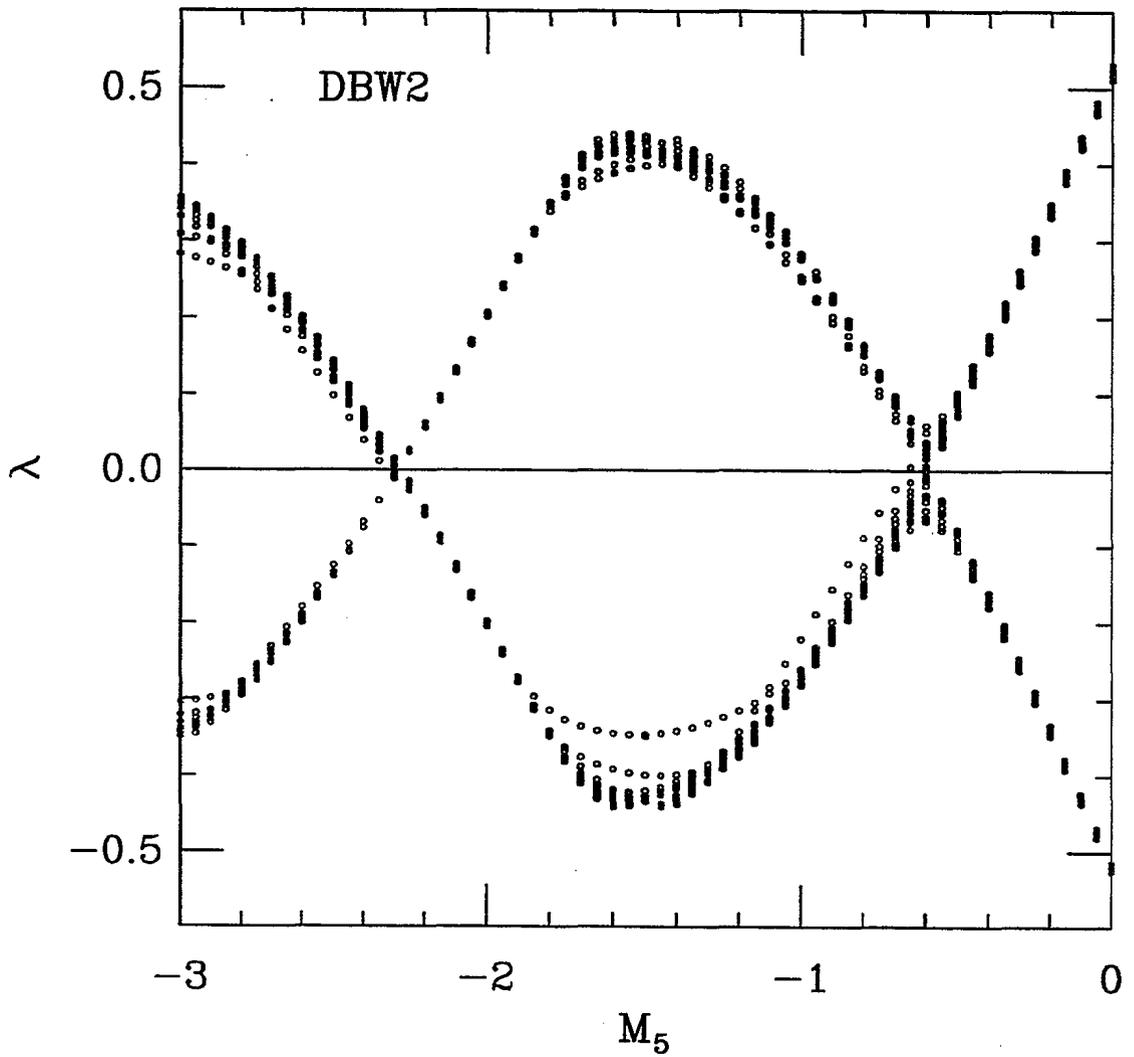
$R(t)$ spikes indicate the localization of the Zero Modes.

The Zero Mode



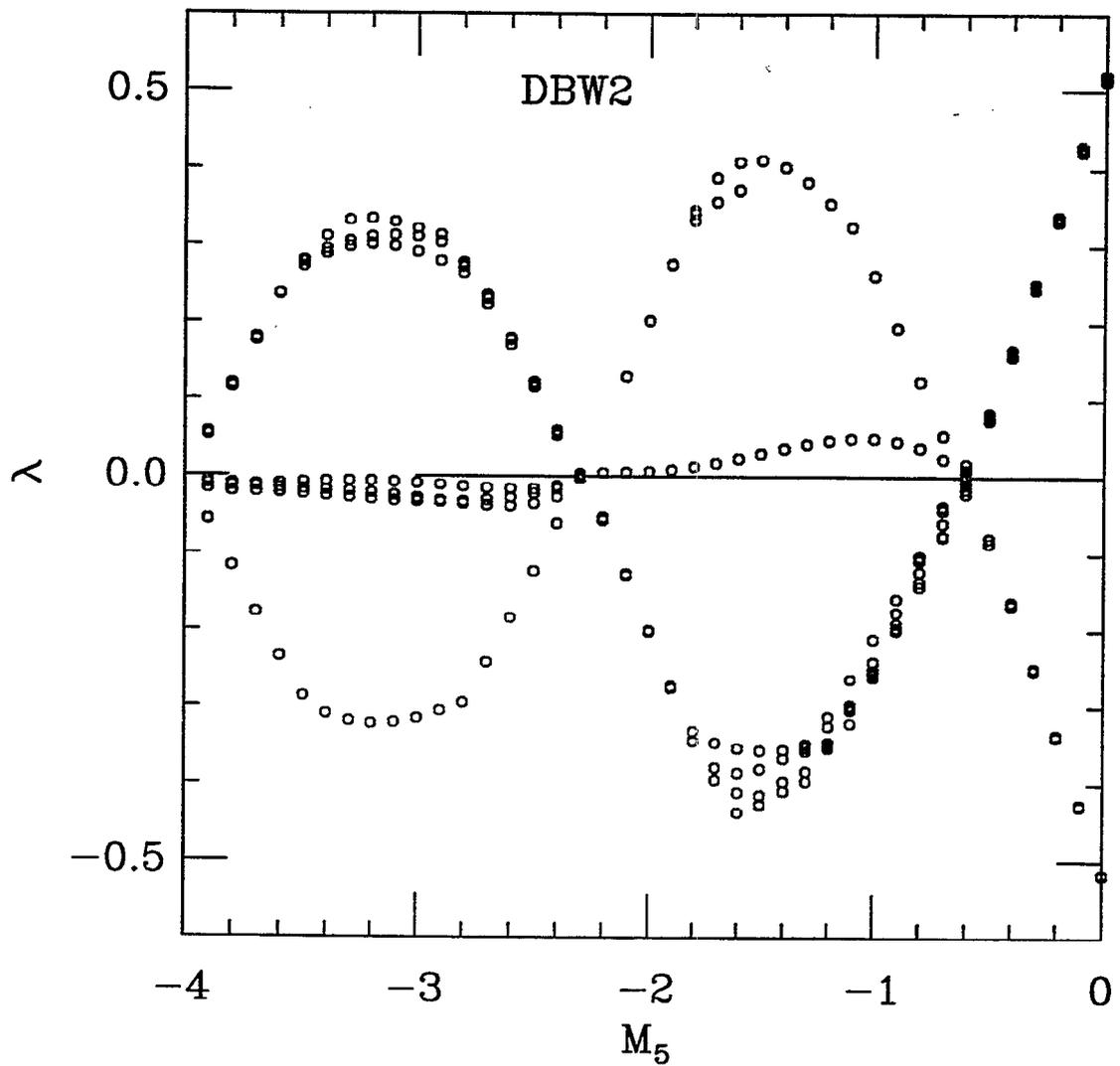
$$\begin{aligned} \bar{\Psi}\Psi(s) &= \bar{\Psi}(s)\frac{1-\gamma_5}{2}\Psi(0) + \\ &+ \bar{\Psi}(L_s-1-s)\frac{1+\gamma_5}{2}\Psi(L_s-1) \end{aligned}$$

Spectral flow



Spectral flow of $\gamma_5 D_w(-M_5)$

[T. Izubuchi talk]



This is the single spike DBW2 has.

(one out of 90 configurations).

[T. Izubuchi talk]

Observations

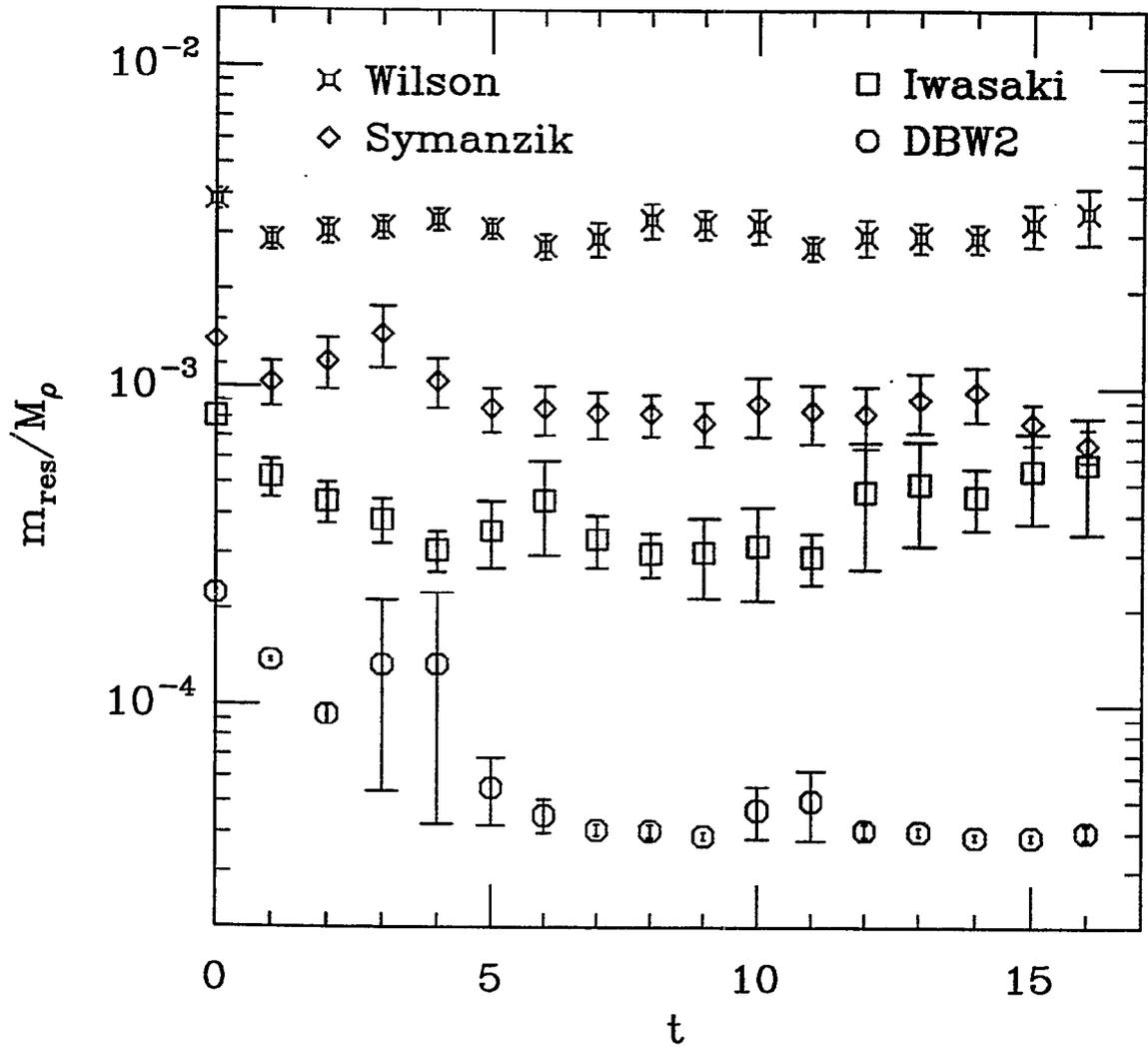
Summary of “Zero Mode” observations:

- They are localized
- They enhance Chirality breaking
- Significantly fewer for Iwasaki and DBW2

Expectation:

- DBW2 improves Chiral Symmetry

m_{res}

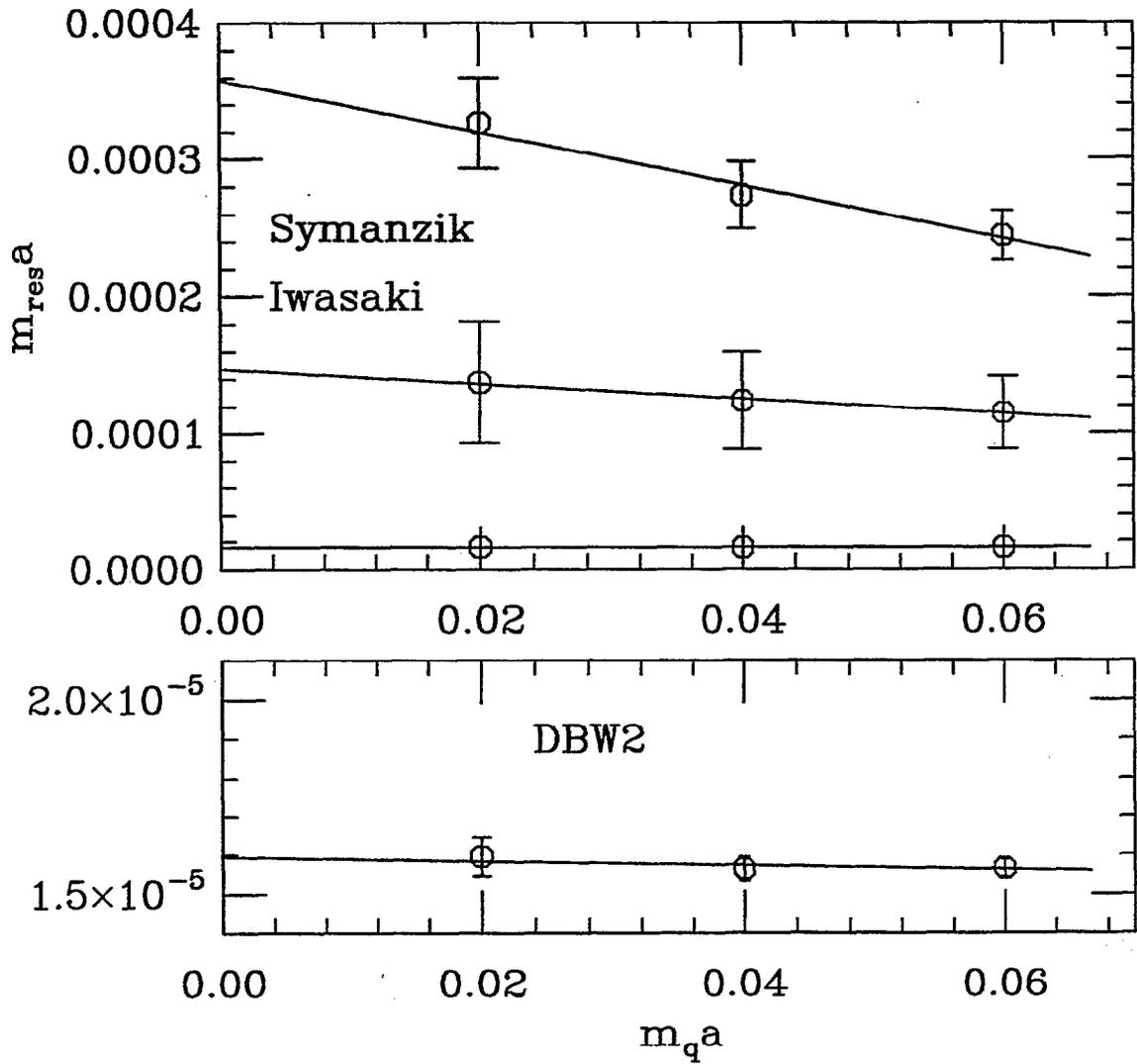


Bare quark mass is 0.020

$L_s = 16$

$M_5 = 1.8$ (for DBW2 $M_5 = 1.7$)

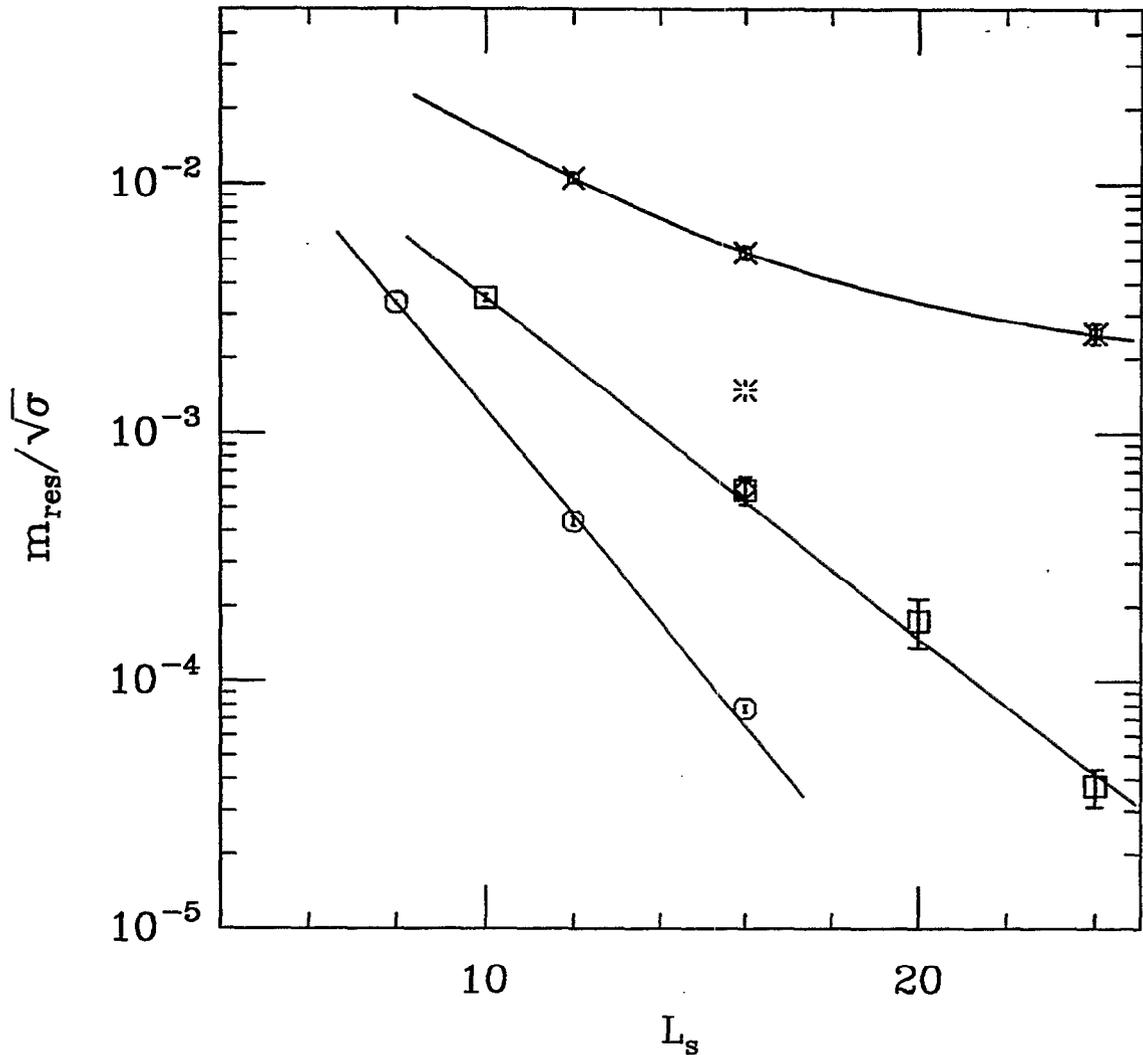
m_{res} VS m_q



$$L_s = 16$$

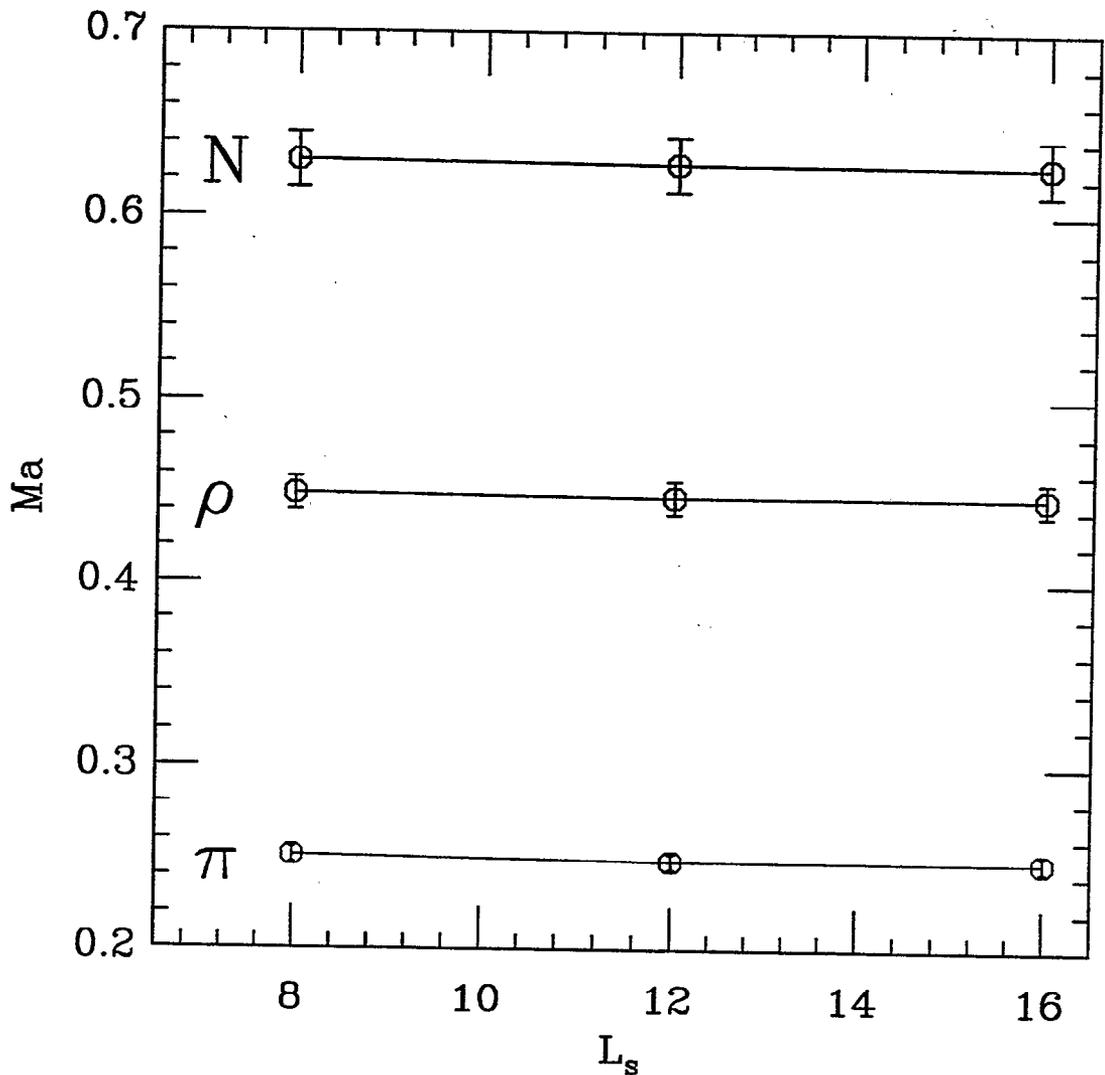
$$M_5 = 1.8 \text{ (for DBW2 } M_5 = 1.7)$$

m_{res} VS L_s



- DBW2 action ($m_{res}(s) \sim q^s$ with $q \sim .6$).
- Iwasaki action [CP-PACS Phys.Rev. D63 (2001)]
- Symanzik action.
- Wilson action [RBC hep-lat/0007038]

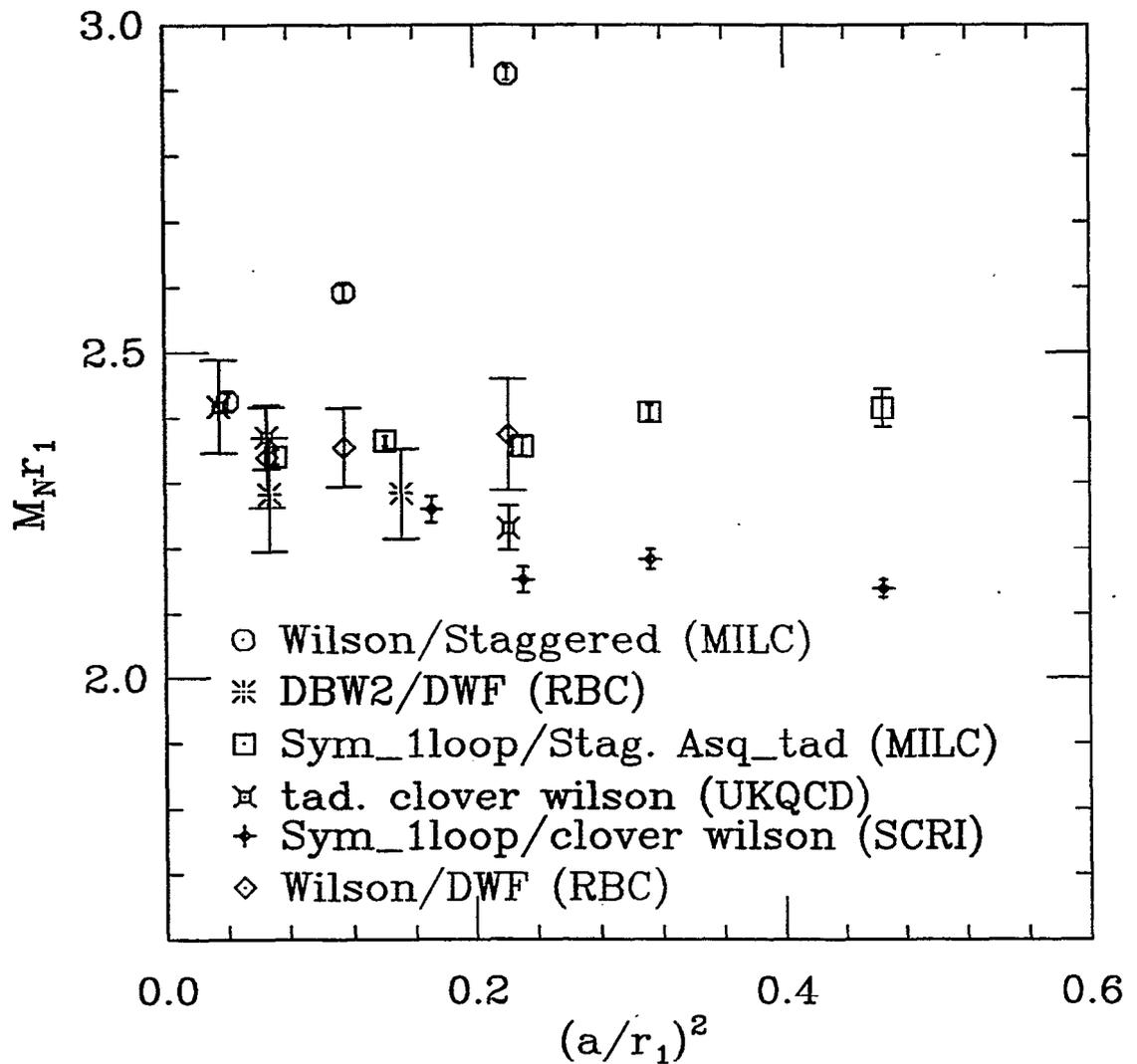
Hadron Masses vs L_s



Action: DBW2 $M_5 = 1.7$, bare $m_q = 0.020$

Masses for $L_s = 12$ and $L_s = 16$ are identical.

Nucleon scaling



Non Domain Wall data published in

[MILC Phys.Rev. D61 (2000)]

[Y. Aoki talk]

What about Topology?

It is believed that:

[Neuberger, Narayanan] [Edwards, Heller, Narayanan]

- Zero Modes \iff Topology change

DBW2 suppresses the number of Zero Modes.

- Does topology change?

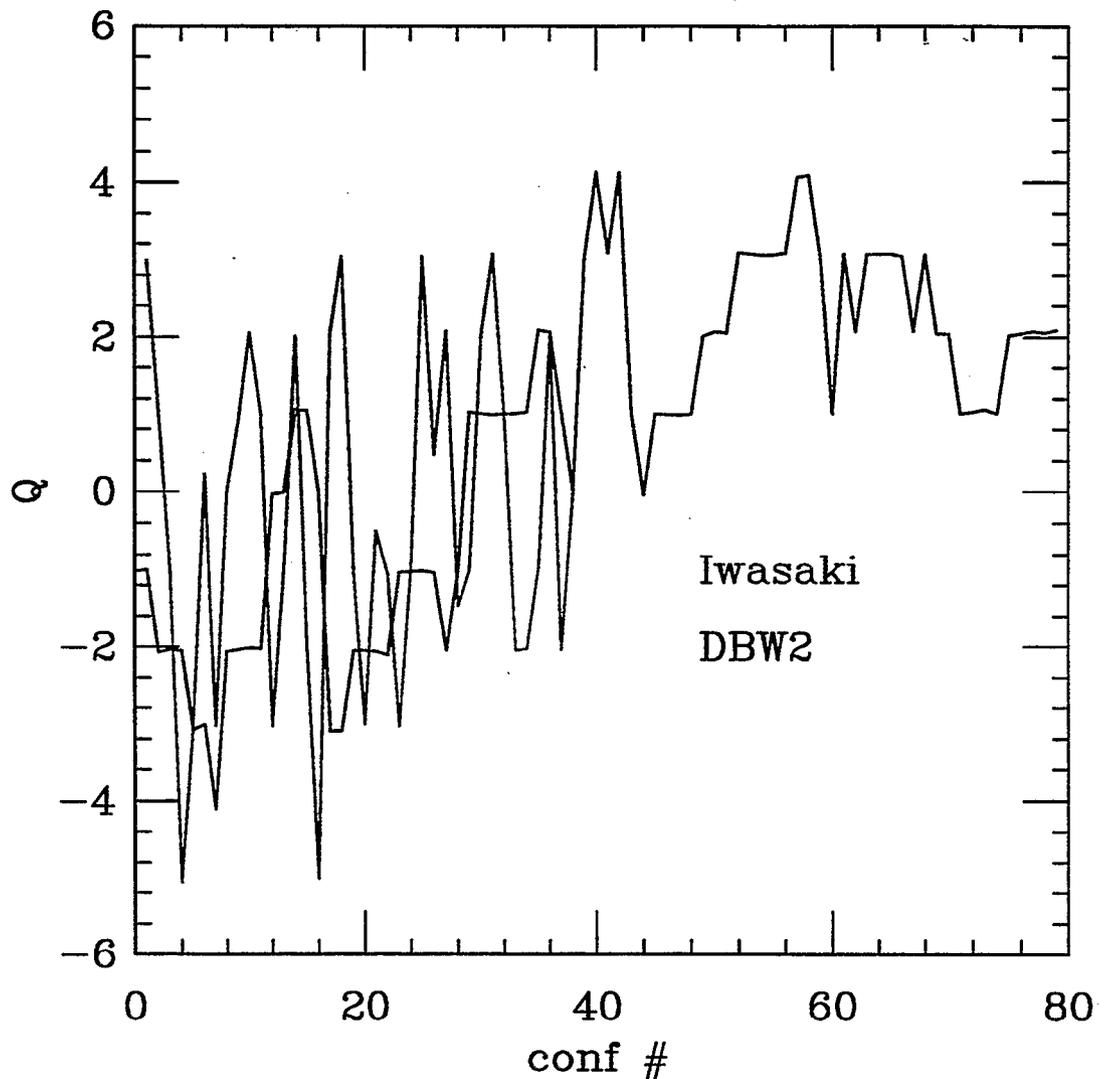
$$S_g[U^I] = 8\pi^2 \left(1 + C \frac{a^2}{\rho^2} + \mathcal{O} \left(\frac{a^4}{\rho^4} \right) \right)$$

$C > 0 \rightarrow$ Stable instantons (Iwasaki/DBW2)

$C < 0 \rightarrow$ Unstable instantons (Wilson/Symanzik)

[Itoh, Iwasaki, Yoshié]

Topological Charge history



Topology tunnels slowly with DBW2.

Topological charge measured using APE smearing and measuring $\int F\tilde{F}$

[DeGrand, Hasenfratz, Kovacs Nucl.Phys. B520 (1998)]

Conclusions

- The RG improved gauge actions significantly improve Chiral Symmetry for Domain Wall Fermions
- The DBW2 gauge action results in a residual mass about a factor of 10 smaller than the Iwasaki at 2GeV. ($L_s = 16$, $m_{\text{res}} \sim 30\text{KeV}$) At 1.3GeV m_{res} is about a factor of 2 smaller than the Wilson action at 2GeV!
- The good scaling of DWF with Wilson action is preserved with DBW2 [Y. Aoki talk]
- The hadron masses seem to reach their asymptotic values at $L_s = 16$.
- The improvement of Chiral symmetry comes from the suppression of $\gamma_5 \not{D}_w(-M_5)$ zero modes. As a result topology fluctuations are significantly reduced
- The DBW2 action should be equally effective in improving the Overlap Fermion convergence.

Hadron Spectrum for Quenched Domain-Wall Fermions With an Improved Gauge Action

Yasumichi Aoki

Hadron spectrum for quenched domain-wall fermions with an improved gauge action

Yasumichi Aoki for RBC collaboration



RIKEN BNL Research Center

RBRC scientific review committee meeting

Nov. 29, 2001

Introduction

- Why Domain Wall Fermion ?
 - Good chiral and flavor symmetry
 - and Good scaling
- Applications
 - B_K , ϵ'/ϵ , proton structure functions
 - Proton decay matrix element (very small mixing).
 $(q^T C P_R q) P_L q \leftarrow (q^T C P_L q) P_L q, (q^T C \gamma_\mu \gamma_5 q) P_L \gamma_\mu q$
- Good chiral symmetry for the fine lattice, (CP-PACS, RBC).
 - Wilson gauge action : good for $a^{-1} \gtrsim 2$ GeV.
 - Iwasaki gauge action : very good for $a^{-1} \gtrsim 2$ GeV.
- Not sufficiently good for coarse lattices.
- Difficult to take continuum limit for demanding calculations, like ϵ'/ϵ .
- Better chirality can we have with further improvement of gauge action ?
 - Yes! DBW2 gauge action provides better chiral symmetry than Iwasaki gauge action.
- Important to check
 - Chiral property at $a^{-1} \simeq 1.3$ GeV.
 - Scaling of spectrum ($a^{-1} \simeq 1.3, 2$ GeV).

Gauge action

$$S_g = \frac{1}{g^2} \left\{ c_0 \sum_{\text{plaquette}} \text{Tr} U_{pl} + c_1 \sum_{2 \times 1 \text{ rectangle}} \text{Tr} U_{rtg} \right\}, \quad \frac{6}{g^2} = \beta$$

$$c_0 + 8c_1 = 1$$

$$c_1 = 0 \rightarrow \text{Wilson action}$$

$$c_1 = -0.331 \rightarrow \text{Iwasaki action}$$

$$c_1 = -1.4069 \rightarrow \text{DBW2 action of QCD-TARO}$$

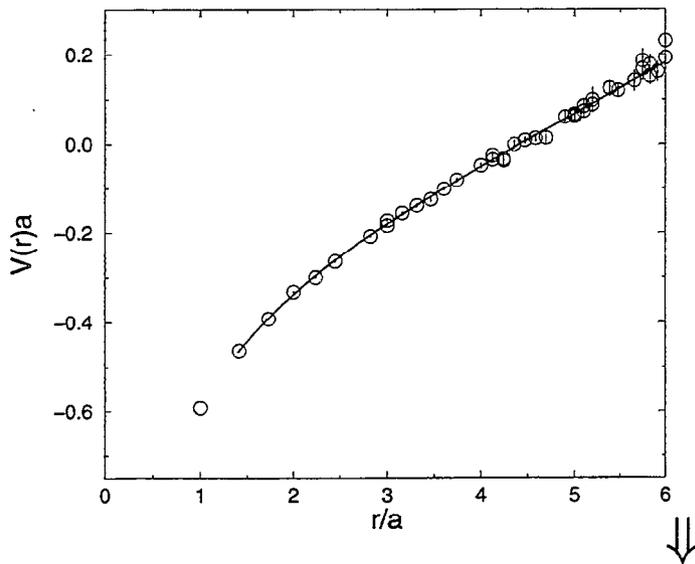
T. Takaishi, Phys. Rev. D54 (1996) 1050;

P. de Forcrand *et al*, Nuc. Phys. B 577 (2000) 263.

Heavy quark potential:

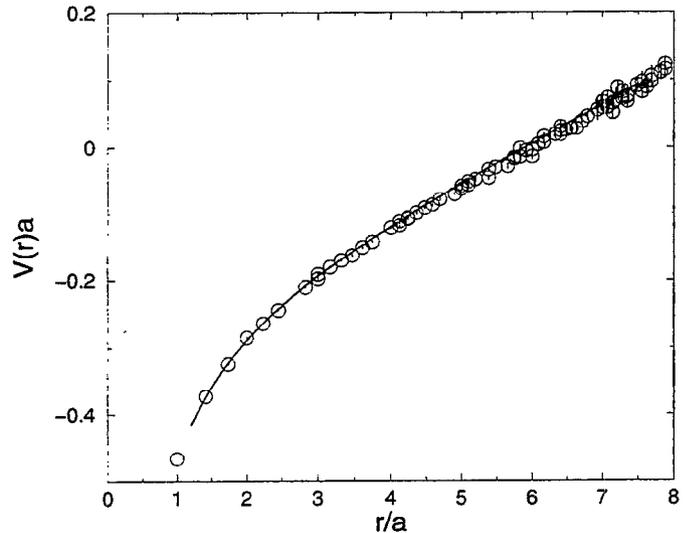
$$\beta = 0.87, \quad (a^{-1} \simeq 1.3 \text{ GeV})$$

beta=0.87, 16³x32



$$\beta = 1.04, \quad (a^{-1} \simeq 2 \text{ GeV})$$

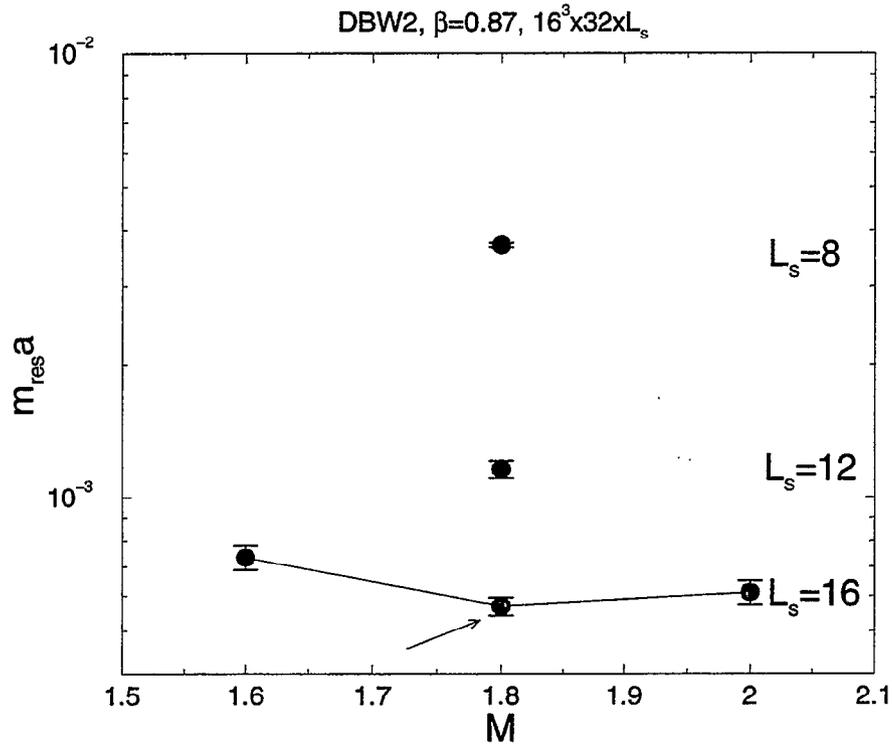
beta=1.04, 16³x32



- Scale determined from gluon dynamics.
 - Sommer parameter r_0 : $F(r_0)r_0^2 = 1.65$; F : force.
 - String tension.

Residual chiral symmetry breaking

$$a^{-1} \simeq 1.3 \text{ GeV}$$

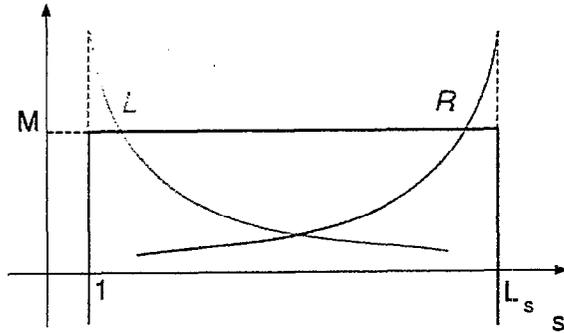


Comparison for same size of fifth dimension $L_s = 16$

- $m_{res}^{DBW2}(a^{-1} \simeq 1.3 \text{ GeV}) \simeq 1 \text{ MeV} < m_{res}^{Wilson}(a^{-1} \simeq 2 \text{ GeV})$
- $m_{res}^{DBW2}(a^{-1} \simeq 2 \text{ GeV}) \simeq 0.03 \text{ MeV} \simeq \frac{1}{10} m_{res}^{Iwasaki}(a^{-1} \simeq 2 \text{ GeV})$.

[\rightarrow talk by K. Orginos]

Residual chiral symmetry breaking



$$\Delta_\mu \mathcal{A}_\mu^a(x) = 2m_f P^a(x) + 2J_{5q}^a(x). \quad \text{“conserved current” (non local)}$$

The Ward-Takahashi identity:

$$\Delta_\mu \langle \mathcal{A}_\mu^a P^b \rangle = 2m_f \langle P^a P^b \rangle + 2 \langle J_{5q}^a P^b \rangle + i \langle \delta^a P^b \rangle$$

Residual quark mass ($t \gg a$):

$$m_{res} = \frac{\langle J_{5q}^a(t) P^b(0) \rangle}{\langle P^a(t) P^b(0) \rangle}.$$



$$m_\pi^2 \propto m_f + m_{res}, \quad m_{res} \rightarrow 0 \quad (L_s \rightarrow \infty).$$

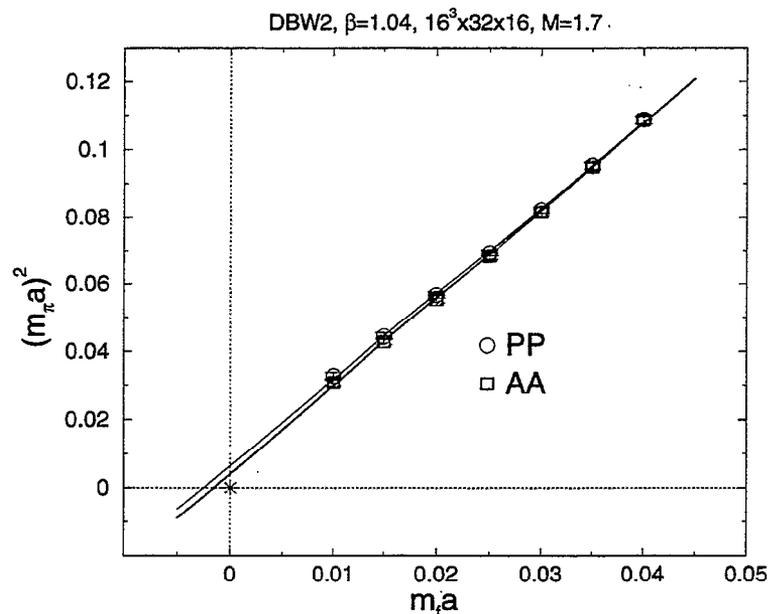
Pion mass

Pion correlator suffers from topological near zero modes in DWF. $\langle PP \rangle$ correlator and $\langle A_0 A_0 \rangle$ correlator have different type of pole from zero modes, all of which vanish in the limit $V \rightarrow \infty$.

$$\langle PP \rangle : \frac{1}{m^2}, \frac{1}{m}$$
$$\langle A_0 A_0 \rangle : \frac{1}{m}$$

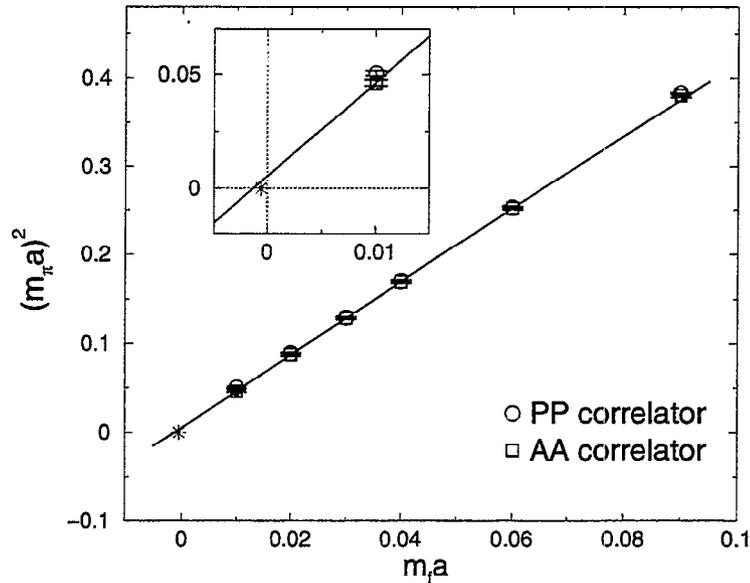
[RBC, hep-lat/0007038]

$\beta = 1.04$, ($a^{-1} \simeq 2$ GeV), $16^3 \times 32 \times 16$, $M = 1.7$.



- Values from two methods are consistent, but trying to deviate each other toward the chiral limit.
- linear extrapolation overshoots $m_f = -m_{res}$.

$\beta = 0.87$, ($a^{-1} \simeq 1.3$ GeV), $16^3 \times 32 \times 16$, $M = 1.8$.



- No difference seen in $0.02 \leq m_f a \leq 0.09$.
- Slight deviation at $m_f a = 0.01$.
- Linear extrapolation overshoots $m_f = -m_{res}$.
 - $\chi^2/dof = 3.4/3$, for PP correlator.
 - $\chi^2/dof = 0.03/3$, for AA correlator.
- with constraint: m_π vanishes at $m_f = -m_{res}$.
 - $m_\pi^2 = A(m_f + m_{res})(1 - \delta \ln(m_f + m_{res}))$
 $\rightarrow \delta = 0.03(2)$, $\chi^2/dof = 0.5/3$ for AA.
 - $m_\pi^2 = A(m_f + m_{res})(1 - \delta \ln(m_f + m_{res})) + B(m_f + m_{res})^2$
 $\rightarrow \delta = 0.09(5)$, $\chi^2/dof = 0.04/3$ for AA.
- Consistent with quenched chiral log.

Pseudoscalar decay constant

$$\frac{f_\pi^2 m_\pi}{Z_A^2} e^{-m_\pi t} = \langle A_0(t) A_0(0) \rangle$$

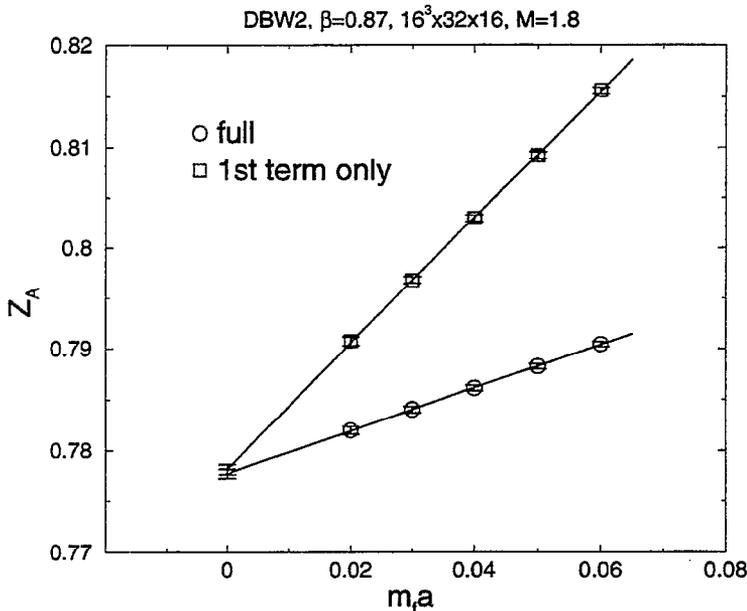
Z_A can be calculated by the ratio of conserved current and local current correlator:

$$C(t + 1/2) = \langle \mathcal{A}_0(t) P(0) \rangle,$$

$$L(t) = \langle A_0(t) P(0) \rangle,$$

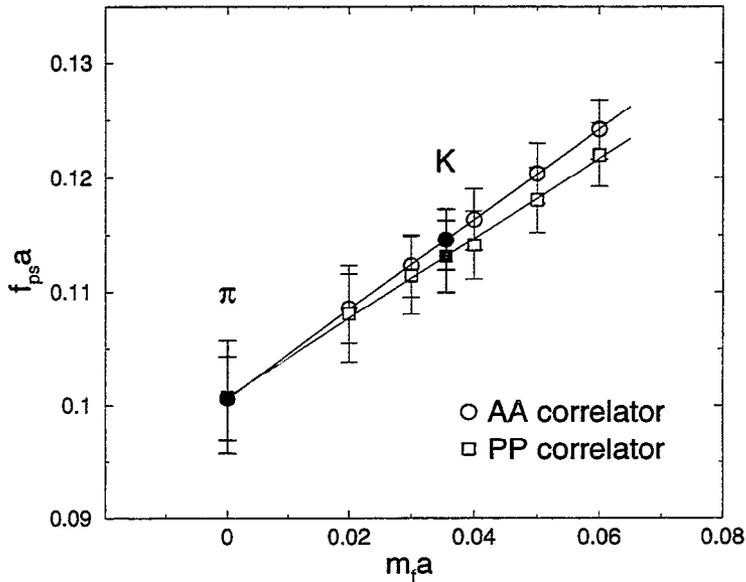
$$Z_A = \frac{1}{2} \left[\frac{C(t + 1/2) + C(t - 1/2)}{2L(t)} + \frac{2C(t + 1/2)}{L(t) + L(t + 1)} \right].$$

$$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$$



- Mild linear dependence on m_f (1-2% in entire region).
- Define Z_A at the chiral limit.

$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$



- Both correlators give the consistent results.



Good chiral property.

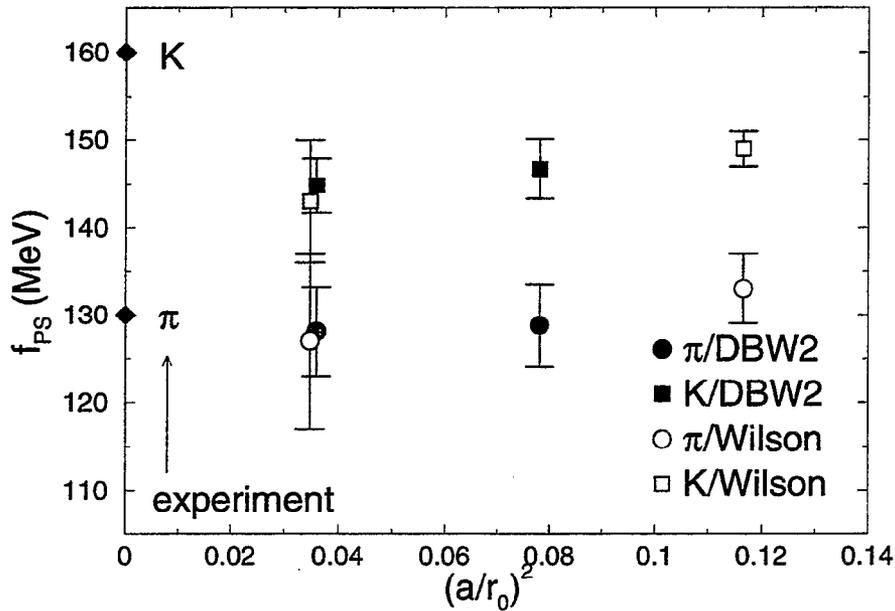
Another method: using

$$\Delta_0 \mathcal{A}_0(t) = 2m_f P(t) + 2J_{5q}(t) = 2(m_f + m_{res})P(t),$$

which holds in low energy matrix amplitude,

$$-\frac{f_\pi^2}{(m_f + m_{res})^2} \frac{m_\pi^3}{8} e^{-m_\pi t} = \langle P(t)P(0) \rangle$$

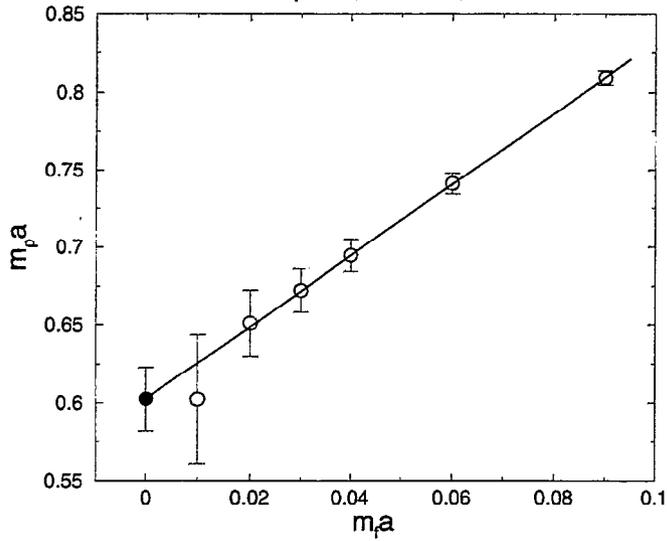
scaling plot of decay constant for DWF



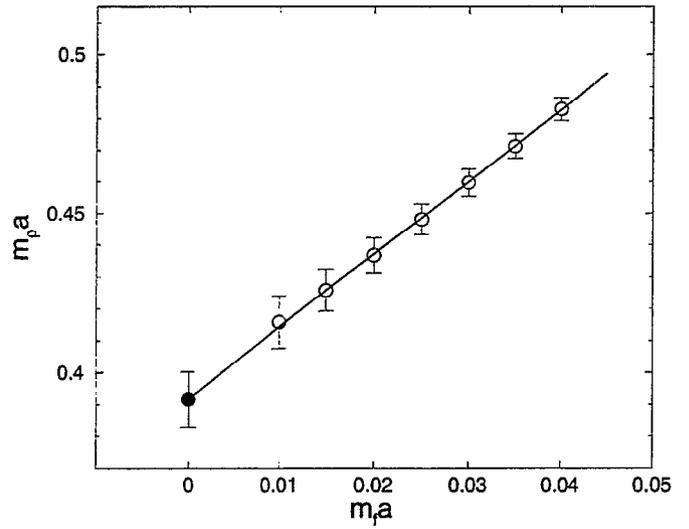
- Good scaling for both f_π and f_K .
- f_π is consistent with experiment.
- f_K is small, expected from quenched chiral perturbation theory [Bernard, Golterman, Phys. Rev. D (1992) 853].

Rho meson mass

$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$
DBW2, $\beta=0.87, 16^3 \times 32 \times 16, M=1.8$

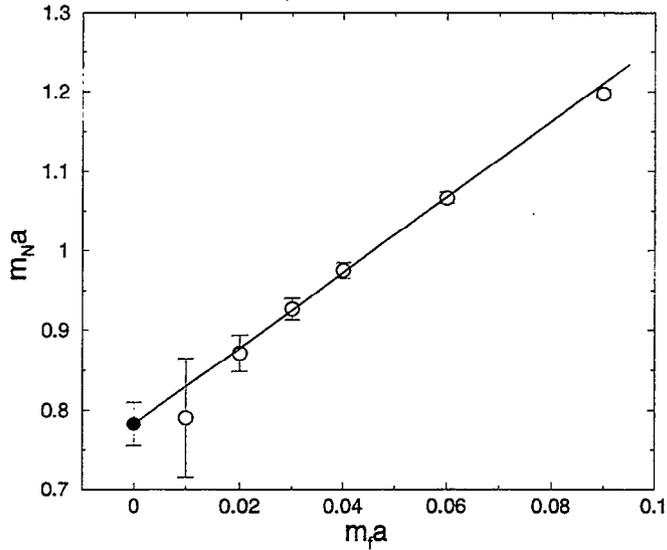


$\beta = 1.04, (a^{-1} \simeq 2 \text{ GeV})$
DBW2, $\beta=1.04, 16^3 \times 32 \times 16, M=1.7$

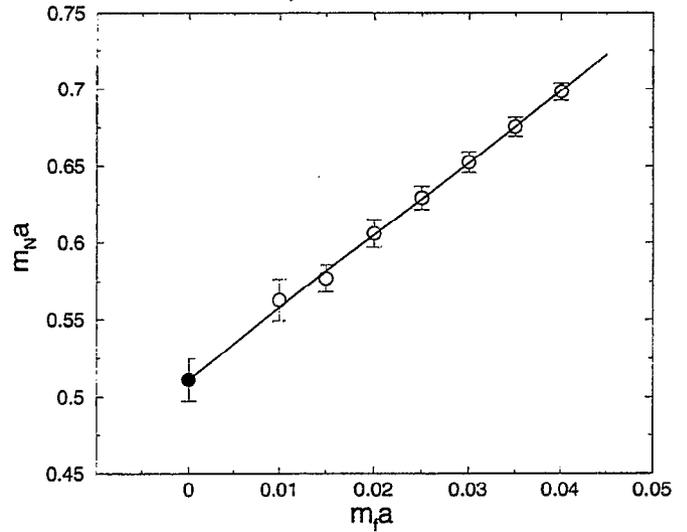


Nucleon mass

$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$
DBW2, $\beta=0.87, 16^3 \times 32 \times 16, M=1.8$

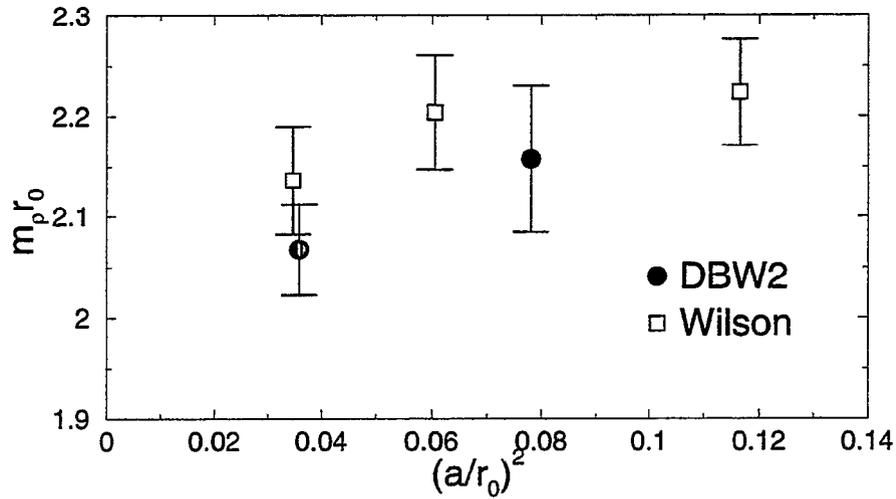


$\beta = 1.04, (a^{-1} \simeq 2 \text{ GeV})$
DBW2, $\beta=1.04, 16^3 \times 32 \times 16, M=1.7$



Scaling properties

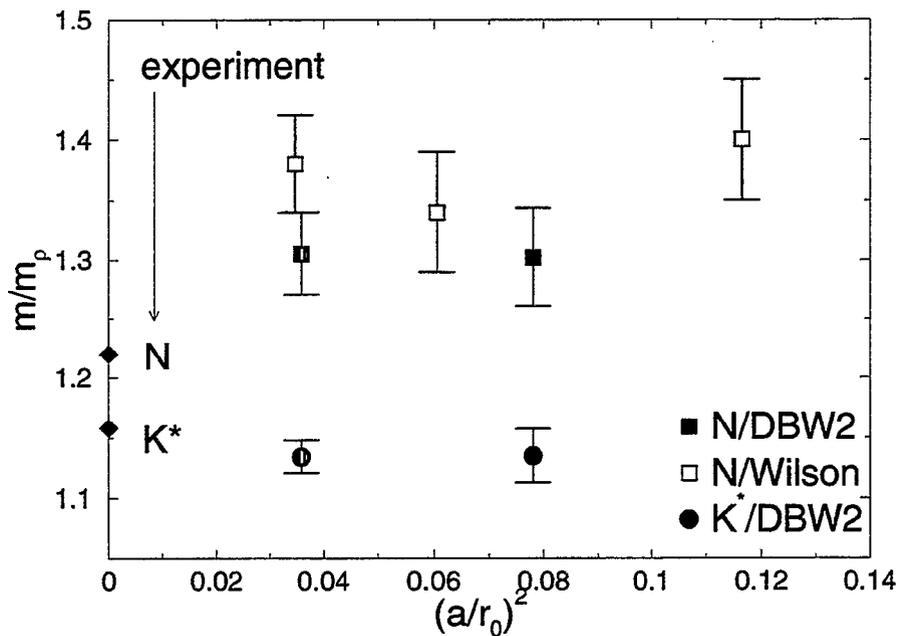
Rho meson mass:



DBW2 : This work

Wilson : RBC, hep-lat/0007038

Nucleon/rho mass ratio and K^* /rho mass ratio:



Summary

Quenched DWF simulation with DBW2 gauge action.

- Chiral properties for $a^{-1} \simeq 1.3 \text{ GeV}$.
 - $m_{res}^{DBW2}(a^{-1} \simeq 1.3 \text{ GeV}) \simeq 1 \text{ MeV} < m_{res}^{Wilson}(a^{-1} \simeq 2 \text{ GeV})$.
 - Pion mass behaves consistent with quenched chiral log, with constraint such that it vanishes at $m_f = -m_{res}$.
 - Pseudoscalar decay constant obtained from different correlator at $a^{-1} \simeq 1.3$ shows consistent results.
- Scaling properties.
 - Rho meson mass gives consistent scale with that from r_0 calculated only by gluon dynamics.
 - Good scaling observed for Nucleon and K^* mass.
 - Pseudoscalar decay constant shows good scaling.
- Ready to be used for applications.

Localization of Chirality for Domain Wall Fermion Eigenvectors

Chris Dawson

Localisation of Chirality for Domain Wall Fermion Eigenvectors.

Chris Dawson, RIKEN-BNL Research Center

[RBC Collaboration]

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G. Liu^b, R. Mawhinney^b, L. Wu^b, Y. Zhestkov^b

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Continuum QCD

- Eigenvalues and Eigenvectors of the Dirac operator, D .

- Eigenvalue spectrum split into two classes

— Zero-modes; $D\Psi_0 = 0$

* Also eigenvector of γ_5

$$[\gamma_5, D] \Psi_0 = 0$$

$$\gamma_5 \Psi_0 = \pm \Psi_0$$

* Chirality ± 1

— Paired modes; $D\Psi_{\pm i\lambda} = \pm i\lambda\Psi_{\pm i\lambda}$

* γ_5 maps between paired modes

$$\gamma_5 \Psi_{\pm i\lambda} = \Psi_{\mp i\lambda}$$

* Chirality Zero

$$\psi^\dagger \gamma_5 \psi = 0$$

Structure of Paired Modes

- How is the global chirality of paired modes zero?
 - Lumps of well defined chirality that cancel
 - * e.g. Instanton Liquid Model
 - Chirality locally zero/small.
 - * e.g. Witten [Nucl. Phys. B149 285 (1979)]

- Can be addressed by studying eigenvectors on the Lattice.

- First studied by Horvath et. al. [hep-lat/0102003]
 - Chirality found to be locally small

- Our study [hep-lat/0105006]using:
 - Weaker coupling (closer to continuum).
 - Domain Wall Fermion Dirac operator (improved chirality).

- Several other groups: [hep-lat/0103002],[hep-lat/0105004],[hep-lat/0105001]and [hep-lat/0107016]

Domain Wall QCD

- Chirality a problem for lattice actions
- Domain Wall Fermions are a solution.
 - [Kaplan, Shamir, Neuberger]
- Add a fifth dimension, S , of length L_S .
 - Localise left- and right-handed components at either end of 5th dimension
 - Couple ends with a mass term m_f .
 - Chirally symmetric when $L_S \rightarrow \infty$.
- Degree of chiral symmetry breaking depends on
 - Gauge Field
 - L_S
- Found to work well in practice for $L_S \approx 10$ with quenched gauge fields. [RBC, CP-PACS]

Our Study

- Solve for lowest 18 eigenvalues and eigenvectors of $5D$ DWF Dirac operator

- $L_s = 16$

- Two gauge actions: Wilson and Iwasaki

Iwasaki Gauge Action	55 configurations $m_f = 0.0005$
Wilson Gauge Action	32 configurations $m_f = 0$

- Quenched approximation.

- 16^4 volume with $a^{-1} \approx 2\text{GeV}$

- DWF has better chirality for Iwasaki action [hep-lat/0007014].
 - provides good check on answer

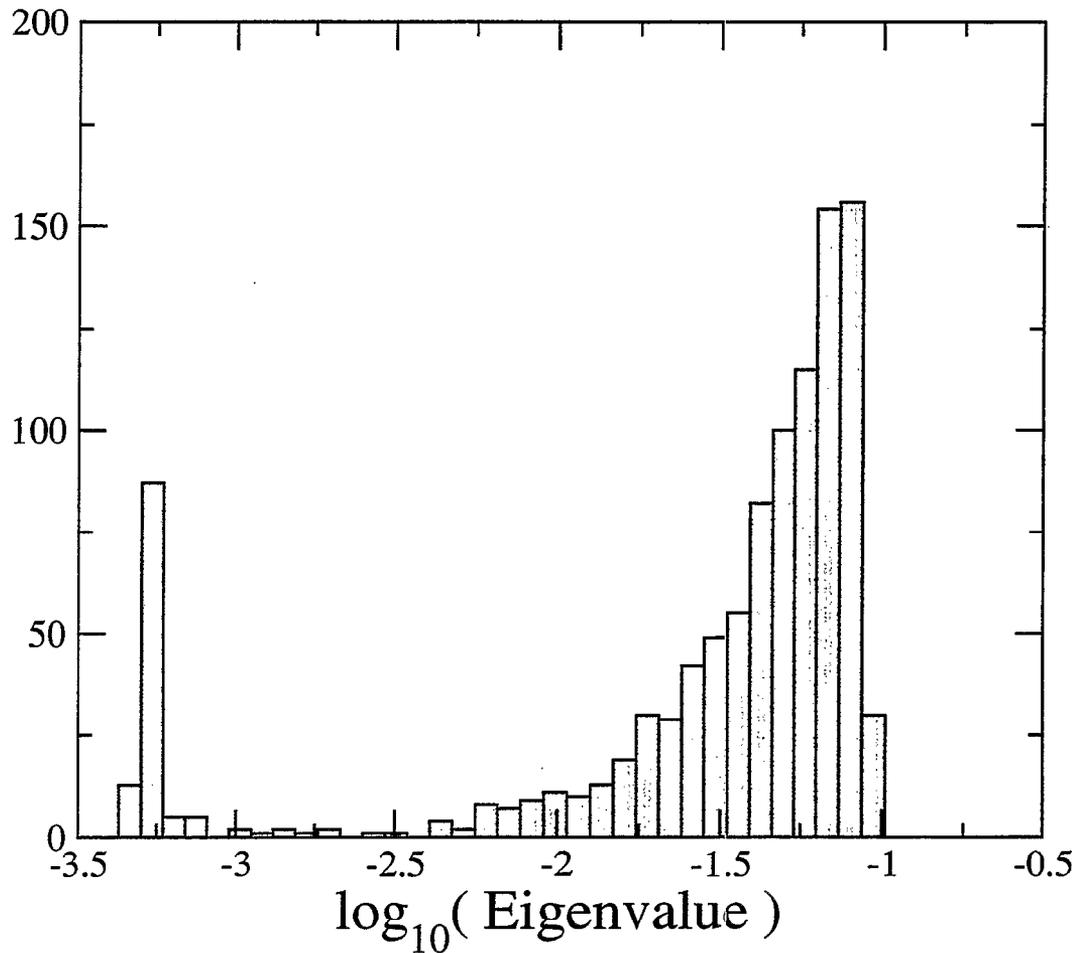
5d to 4d

- From 5D eigenvector Ψ_5 , construct 4D vector

$$\Psi_{4d,LEFT}(x, y, z, t) = \sum_{s=0}^{s < L_s/2} \Psi_{5d}(x, y, z, t, s)$$

$$\Psi_{4d,RIGHT}(x, y, z, t) = \sum_{s=L_s/2}^{s < L_s} \Psi_{5d}(x, y, z, t, s)$$

Eigenvalue Spectrum

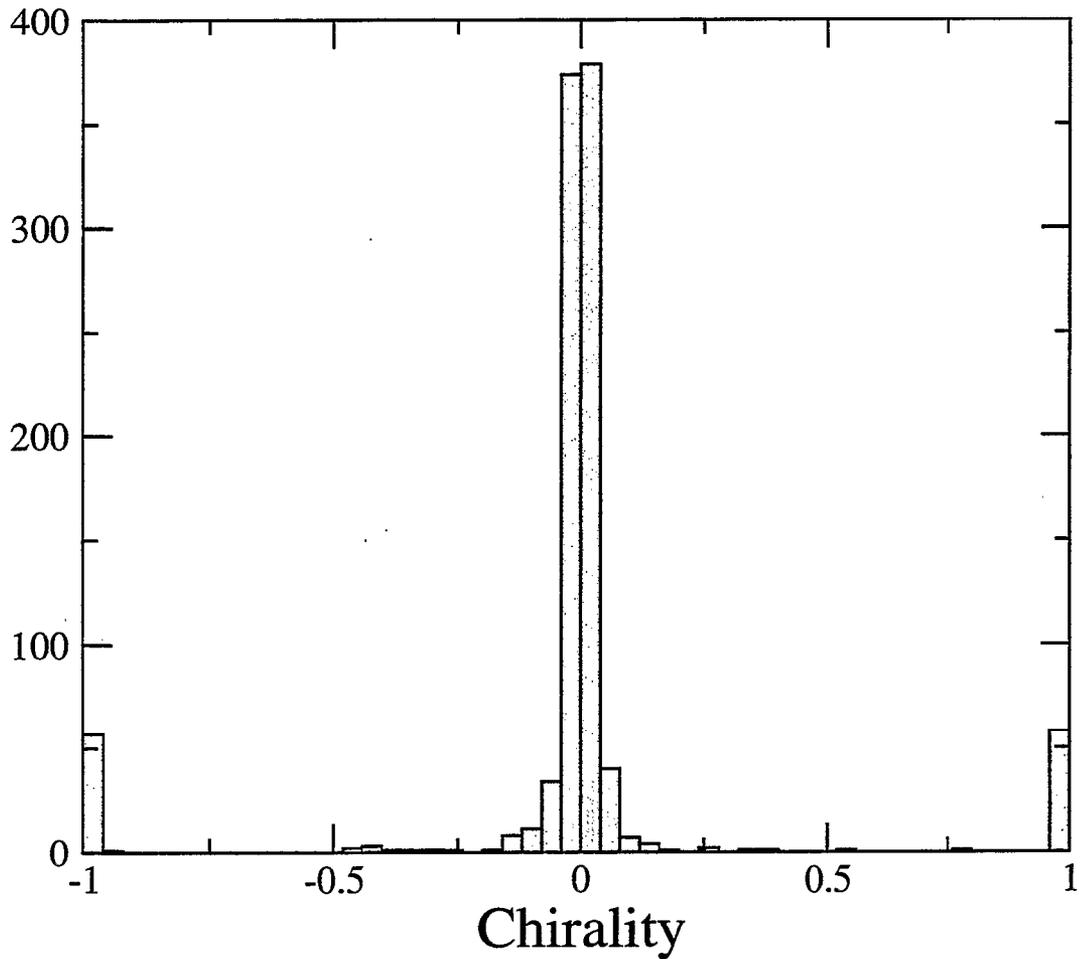


- Eigenvalues span large range ; Histogram

$$\log_{10} (|\lambda|)$$

- Clear signal for zero-mode vs paired modes.

Global Chirality



$$\Psi_{4d}^\dagger \gamma_5 \Psi_{4d}$$

- Histogram chirality of each eigenvector.
- Again clear signal for zero-mode vs paired modes.

γ_5 Plots

$$G_5(i, j) = \Psi_{4d,i}^\dagger \gamma_5 \Psi_{4d,j}$$

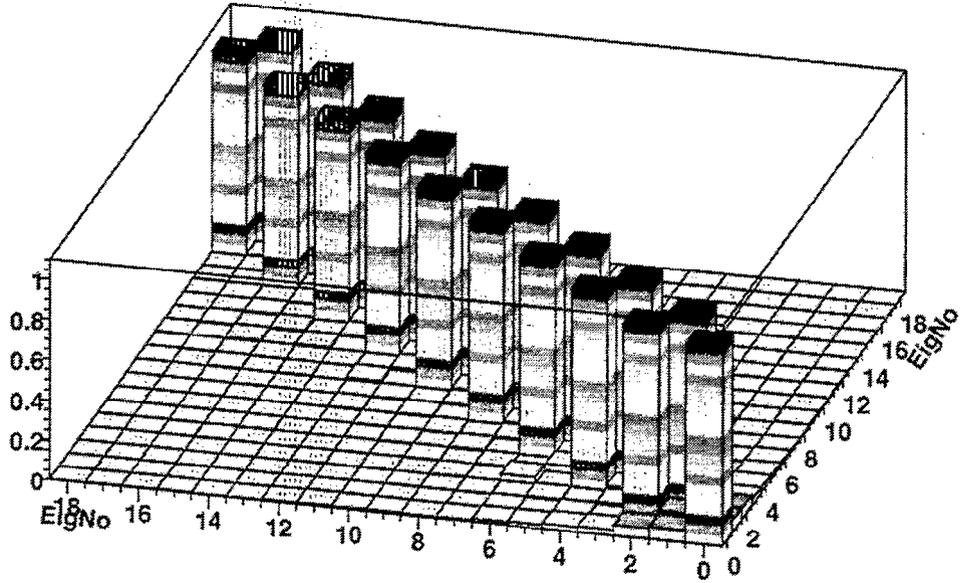
Non-zero if:

- $i = j$ and $\Psi_{4d,i}$ is a zero-mode.
- $i \neq j$ and $\Psi_{4d,i}$ and $\Psi_{4d,j}$ are paired.

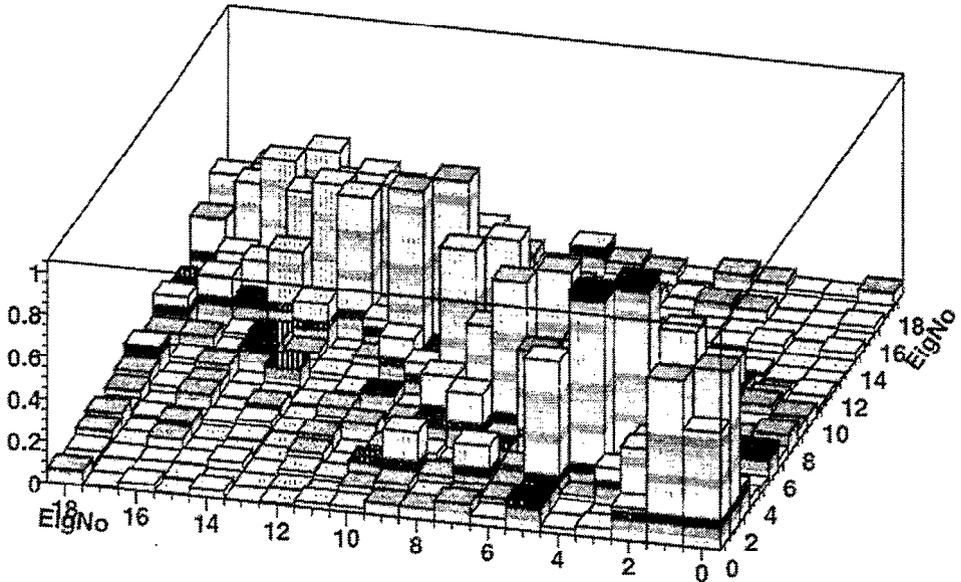
- Simple and “complex” configurations
- Iwasaki ensemble approximately 1 : 10
- Wilson ensemble much worse.

75 Plots

G5(i,j) for Iwasaki configuration 7



G5(i,j) for Iwasaki configuration 2



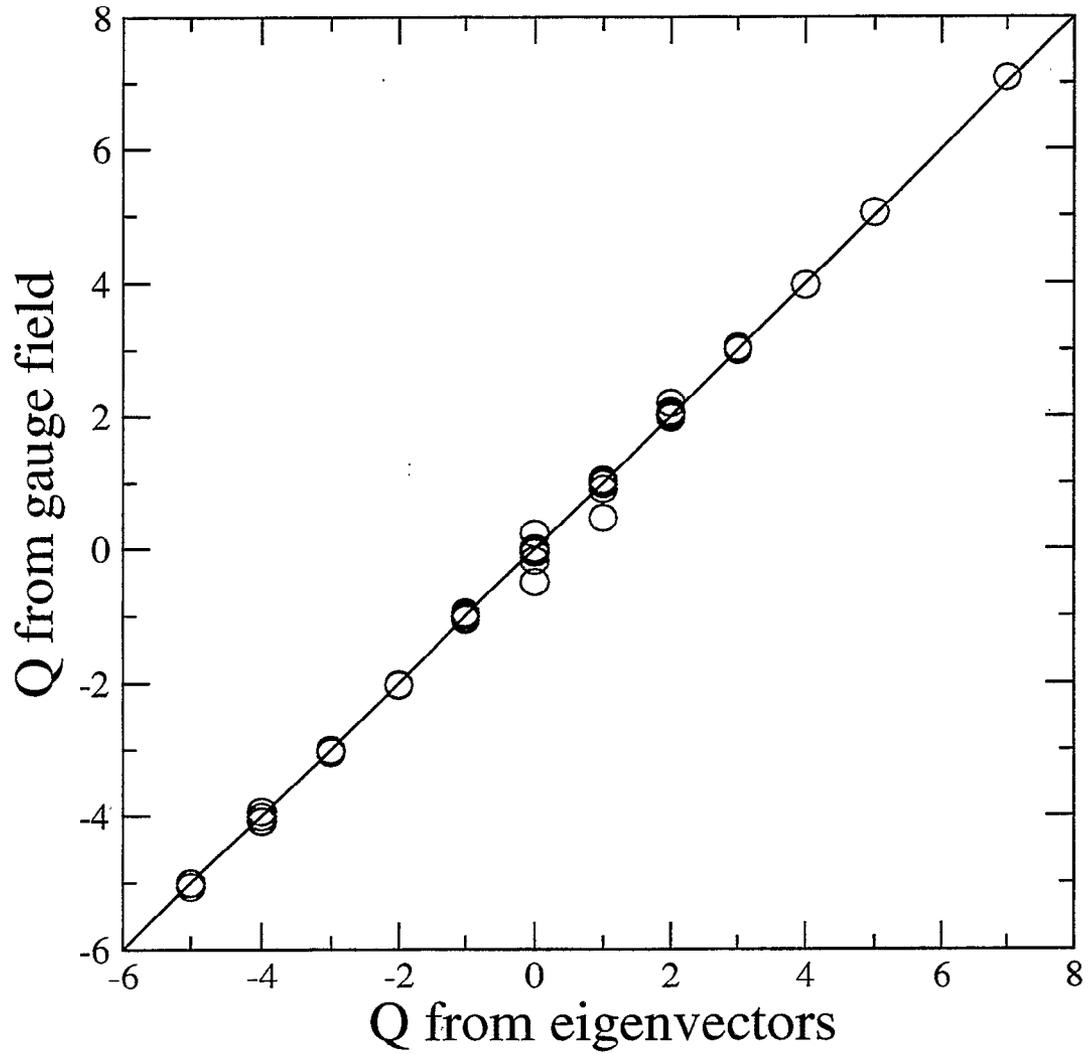
Topological Charge Definition

- Gauge Field definition

$$Q = \frac{1}{32\pi^2} \epsilon_{ijkl} \text{Tr} [F_{ij} F_{kl}]$$

- Calculate this on the lattice by the method DeGrand et. al
- May also calculate the Topological Charge from the number of positive and negative chirality zero-modes.
- Provides a good consistency check.

Topological Charge



- Good agreement between gauge field and fermionic definition of Topological Charge.

Localisation of Chirality

- local norm

$$\Omega_H(x) = \Psi_{4d}^\dagger(x) \Psi_{4d}(x)$$

- local chirality , $L(x)$.

$$X_H(x) = \Psi_{4d}^\dagger(x) \gamma_5 \Psi_{4d}(x)$$

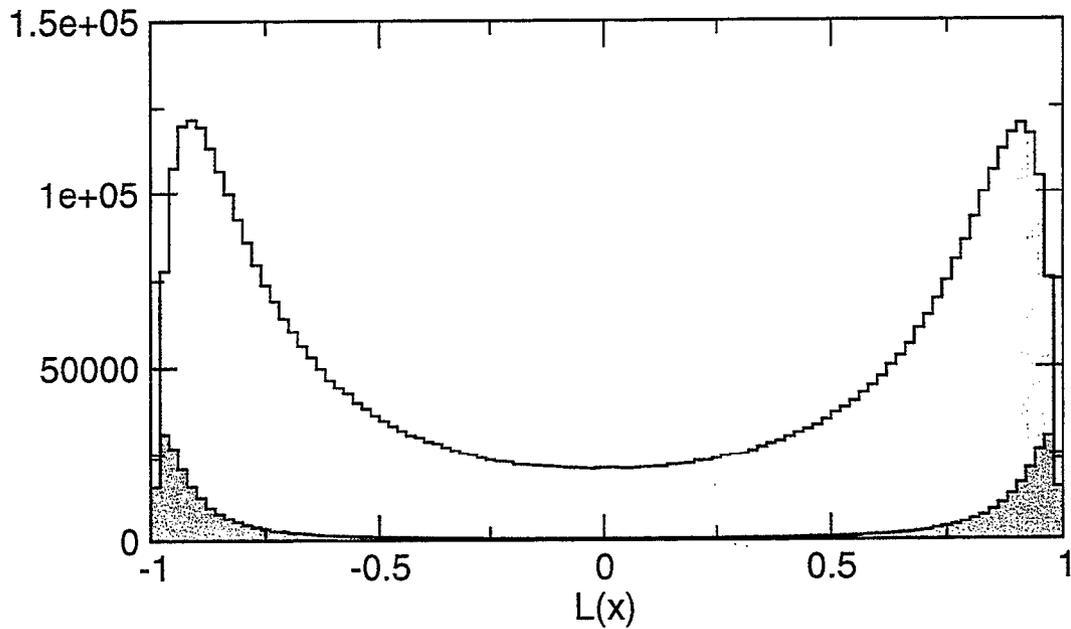
$$L(x) = X_H(x) / \Omega_H(x)$$

- Only want to look at important points

$$\Omega_H > \Omega_{\min}$$

- Histogram $L(x)$.

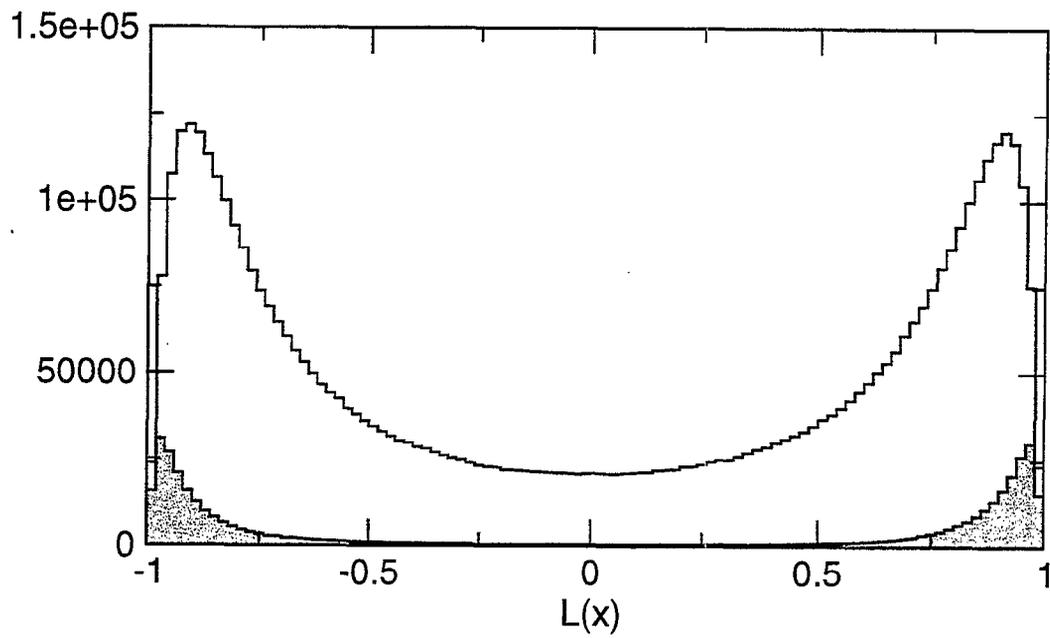
Localisation of Chirality : Iwasaki



- $\Omega_{min} = 8 \cdot 10^{-5}$ allowing 6% of total norm .
- $\Omega_{min} = 3 \cdot 10^{-5}$ allowing 29% of total norm .

- Localisation of chirality favoured.

Localisation of Chirality: Wilson



- Results independent of gauge action.

Spatial Distribution

- Hard to visualise $4D$ data.
- May look a $2D$ section

$$N(x, y) = \sum_z \sum_t \Psi_{4d}^\dagger \Psi_{4d}(x, y, z, t)$$

- Look at left- and right-handed norms separately
 - Localisation of chirality visible.

Spatial Distribution of a Zero-mode

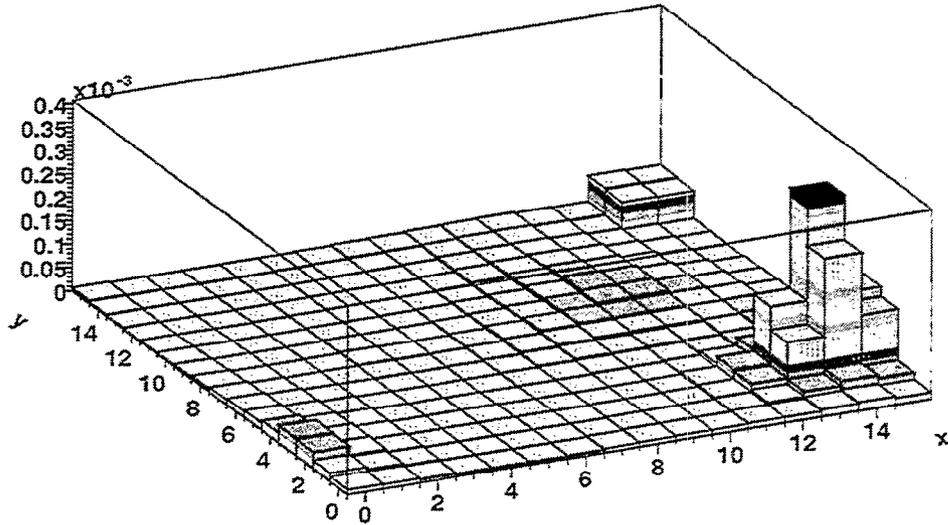


Figure 1: Left-handed component of the local norm summed over z and t for a zero-mode

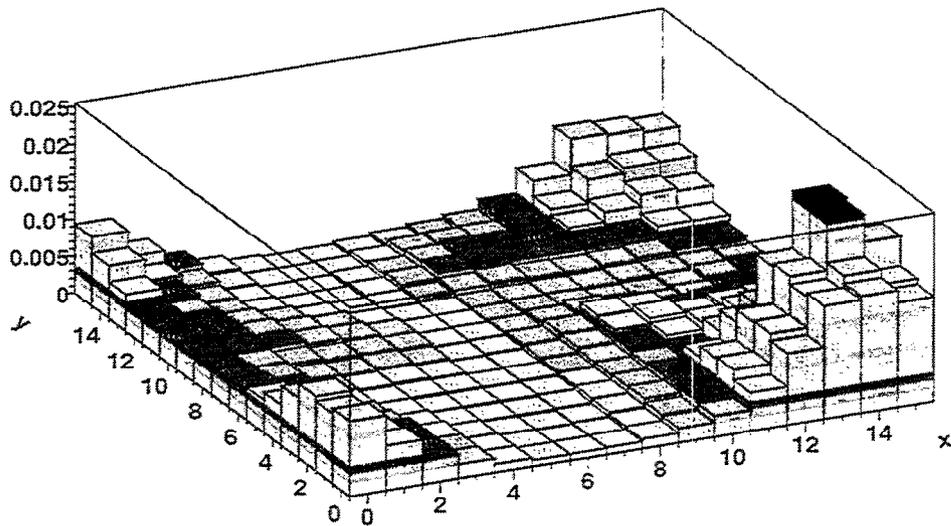


Figure 2: Right-handed component of the local norm summed over z and t for a zero-mode

Spatial Distribution of Paired mode

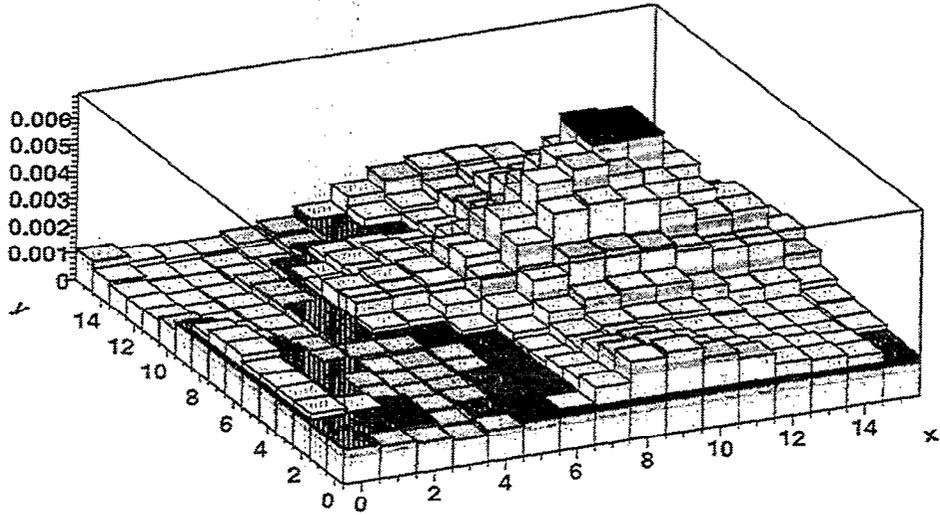


Figure 3: Left-handed component of the local norm summed over z and t for a paired mode

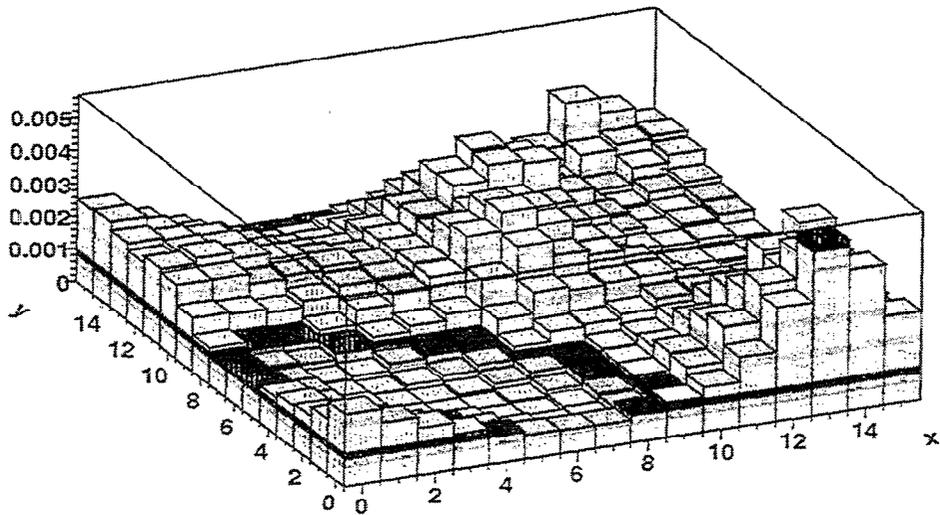


Figure 4: Right-handed component of the local norm summed over z and t for a paired mode

CP Violation in K Decay from Lattice QCD

Thomas Blum

CP Violation in K Decay from Lattice QCD

[T. Blum, et al., (RBC) hep-lat/0110078]

[S. Meakins, et al., (UK-PACS) hep-lat/0108018]

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RIKEN BNL Research Center Review

November 29, 2001

Outline

I. Introduction

II. Results: Physical Amplitudes and the CP violation parameter ϵ'

III. Summary and Outlook

I. Introduction

CP violation in $K \rightarrow \pi\pi$ decays

The long-lived and short-lived neutral kaons are **almost** CP eigenstates, but contain small mixtures of each other

$$|K_S\rangle = |K^{\text{even}}\rangle + \epsilon|K^{\text{odd}}\rangle$$

$$|K_L\rangle = |K^{\text{odd}}\rangle + \epsilon|K^{\text{even}}\rangle$$

$$|K^{\text{even,odd}}\rangle = |K^0\rangle \mp |\bar{K}^0\rangle$$

Indirect CP violation occurs when K_L oscillates into the K^{even} state and decays to the CP -even state $|\pi\pi\rangle$. Loosely speaking, the probability for this is parameterized by the observable $|\epsilon|$.

Direct CP violation occurs when the K_L decays to $|\pi\pi\rangle$ directly from the K^{odd} component. Loosely speaking, the probability for this is parameterized by the observable $|\epsilon'|$.

Long theoretical effort driven by experimental observation

- Summary of CP **violation** found in Nature

- Indirect: ϵ

- 1. Christensen, Cronin, Fitch, Turlay (BNL 1964)

- $2.271(17) \times 10^{-3}$

- Direct: ϵ'/ϵ

- 1. KTeV (FNAL 2001)

- $20.7 \pm 2.8 \times 10^{-4}$

- 2. NA48 (CERN 2001)

- $15.3 \pm 2.6 \times 10^{-4}$

- B factories measure $\sin(2\beta)$

- 1. BaBar (SLAC 2001)

- 0.59 ± 0.14

- 2. Belle (KEK 2001)

- $0.99 \pm 0.14 \pm 0.06$

- $\Delta I = 1/2$ rule for kaon decays: $\frac{A(K \rightarrow \pi\pi (I=0))}{A(K \rightarrow \pi\pi (I=2))} \approx 22$

Use theory + experiment to constrain the Standard Model

Convenient to use QCD eigenstates K^0 and \bar{K}^0 and define the *isospin* decay amplitudes

$$A(K^0 \rightarrow \pi\pi(I)) = A_I e^{i\delta_I}$$

$$A(\bar{K}^0 \rightarrow \pi\pi(I)) = -A_I^* e^{i\delta_I}$$

$$A_I e^{i\delta_I} = \langle \pi\pi(I) | -i\mathcal{H}(\Delta S=1) | K^0 \rangle$$

where $I = 0, 2$

which yields

$$\epsilon' = \frac{ie^{i(\delta_2-\delta_0)} \text{Re}A_2}{\sqrt{2} \text{Re}A_0} \left[\frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right]$$

and

$$(\Delta I = 1/2 \text{ rule}) \rightarrow \frac{\text{Re}A_0}{\text{Re}A_2}$$

The $\Delta S = 1$ Effective Hamiltonian

The Standard Model Hamiltonian: a *short distance expansion* in terms of effective local **four-quark operators** $Q_i(\mu)$ (c.f. Fermi interaction) with **Wilson coefficients** $z_i(\mu)$ and $y_i(\mu)$.

$$\mathcal{H}^{(\Delta S=1)} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[z_i(\mu) - \frac{V_{td} V_{ts}^*}{V_{ud} V_{us}^*} y_i(\mu) \right] Q_i(\mu) \right\}$$

Both depend on an *arbitrary factorization scale* μ . Effective Hamiltonian is **independent** of this scale. Take μ low enough that non-perturbative calculations are practical ($1/a \ll M_W$), but high enough that continuum perturbation theory remains valid.

Key to the OPE is that the full amplitude is divided into low energy (hadronic matrix elements of Q_i) and high energy (Wilson coefficients) parts that can be computed separately.

III. Lattice Calculation of

Hadronic Matrix Elements $\langle \pi\pi | Q_i | K \rangle$

There are three key features of our calculation

- Chiral perturbation theory to obtain $K \rightarrow \pi\pi$
from $K \rightarrow \pi$ and $K \rightarrow 0$
- Non-perturbative renormalization (NPR) of operators
- Domain Wall Fermions (chiral symmetry)

Chiral Perturbation theory

Bernard, *et al.*

Significant technical difficulties associated with $|\pi\pi\rangle$, so use **lowest order** chiral perturbation theory to relate physical $K \rightarrow \pi\pi$ amplitudes to unphysical $K \rightarrow \pi$ and $K \rightarrow 0$ ones calculated on the lattice.

Replace four-quark operators with χPT representatives, $Q_i \rightarrow \Theta_i = \alpha_j^i \tilde{\Theta}_j$:

$$\langle 0 | \Theta^{(8,1)} | K^0 \rangle = \frac{16iv}{f^3} (m'_s - m'_d) \alpha_2^{(8,1)}$$

$$\langle \pi^+ | \Theta^{(8,1)} | K^+ \rangle = \frac{4m_M^2}{f^2} (\alpha_1^{(8,1)} - \alpha_2^{(8,1)})$$

$$\langle \pi^+ | \Theta^{(27,1)} | K^+ \rangle = -\frac{4m_M^2}{f^2} \alpha^{(27,1)}$$

$$\langle \pi^+ | \Theta^{(8,8)} | K^+ \rangle = \frac{12}{f^2} \alpha^{(8,8)}$$

$$\langle \pi^+ \pi^- | \Theta^{(8,1)} | K^0 \rangle = \frac{4i}{f^3} (m_{K^0}^2 - m_{\pi^+}^2) \alpha_1^{(8,1)}$$

$$\langle \pi^+ \pi^- | \Theta^{(27,1)} | K^0 \rangle = -\frac{4i}{f^3} (m_{K^0}^2 - m_{\pi^+}^2) \alpha^{(27,1)}$$

$$\langle \pi^+ \pi^- | \Theta^{(8,8)} | K^0 \rangle = \frac{-12i}{f^3} \alpha^{(8,8)}$$

m_M is a common unphysical meson mass ($m_u = m_d = m_s$), $m'_{d,s}$ are unphysical quark masses, and f is the decay constant $f = f_\pi = f_K$ to lowest order.

Significant approximation, but can be improved by **one-loop** plus $\mathcal{O}(p^4)$ tree-level calculations.

Also complicated by use of the quenched approximation.

Operator renormalization factors, Z_{ij}

- Bare lattice operators are divergent as $a \rightarrow 0$ so must be renormalized at some scale μ (μ dependence cancels with μ dependence of \vec{C} in $\mathcal{H}^{(\Delta S=1)}$ which is RG invariant).
- Non-perturbative renormalization (Rome-Southampton)
- Regularization independent (RI) scheme (c.f. MOM-scheme)

$$\langle q(p) O^{\text{ren}} q(p) \rangle = \langle q(p) Z O q(p) \rangle = \langle q(p) O q(p) \rangle_{\text{tree}}$$

Green's functions calculated in a fixed gauge with off-shell quarks with large Euclidean momenta ($\mu^2 \equiv p^2$).

- No need for difficult perturbative lattice calculations. Can match, using continuum perturbation theory, to other schemes like \overline{MS} .

- $\mathcal{H}^{(\Delta S=1)}$ case is complicated since operators mix with each other and also lower-dimensional ones that are power divergent:

$$O_i^{\text{ren}}(\mu) = \sum_j Z_{ij}(a\mu) \left(O_j^{\text{latt}}(a) + \sum_k c_k^j(a\mu) B_k(a) \right) + \mathcal{O}(a^2)$$

Details of the Simulation

Wilson gauge action, **quenched** $6/g^2 = 6.0 \rightarrow 1/a = 1.922$ GeV,
400 configurations

Lattice size $16^3 \times 32 \rightarrow (1.6 \text{ fm})^3 \times 3.2 \text{ fm}$

Domain wall fermions with $M_5 = 1.8$, $L_s = 16$, and quark masses

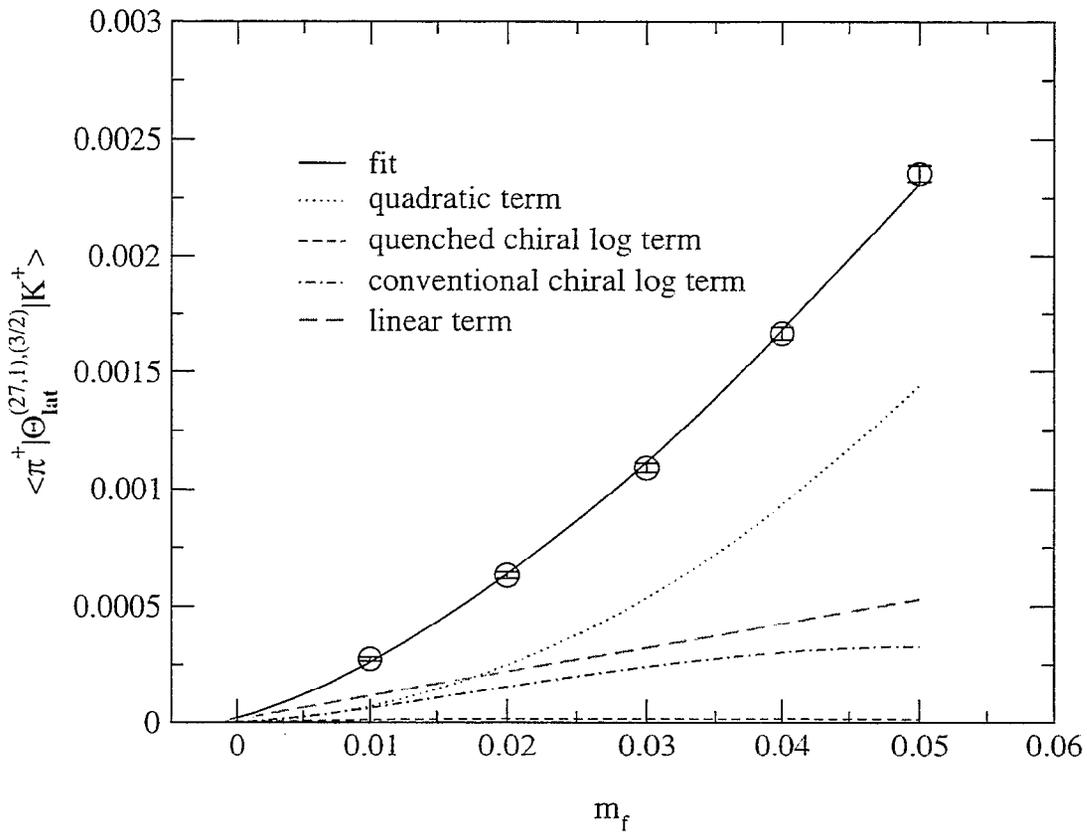
$m_f = 0.01, 0.02, 0.03, 0.04, 0.05$ (in units of lattice spacing). $m_{\text{strange}}^{\text{phys}}$
corresponds to $m_f \approx .02$. $m_c = 0.1, 0.2, 0.3, 0.4$

The non-perturbative renormalization of operators was done with
the same parameters as above except $m_f = 0.01$ only 400 con-
figurations. Checked that results were not significantly affected by
 $m_f \rightarrow 0$ extrapolation on 100 configurations.

Simulations done on the QCDSP supercomputers at *Columbia Uni-
versity* and *RIKEN BNL Research Center*. Matrix element calcula-
tion took roughly 4 months x 0.8 TFlops (peak).

$$\langle \pi^+ | Q_{i,\text{lat}}^{(27,1),3/2} | K^+ \rangle \propto \langle \pi^+ | \Theta_{\text{lat}}^{(27,1),3/2} | K^+ \rangle (i = 1, 2, 9, 10)$$

Higher order effects are **large**. Fit is forced to vanish at $m_f = -m_{\text{res}} = -.00124$. Quenched log is small. Conventional log is large and mimics linear term. *Known coefficients* calculated in $Q\chi\text{PT}$.

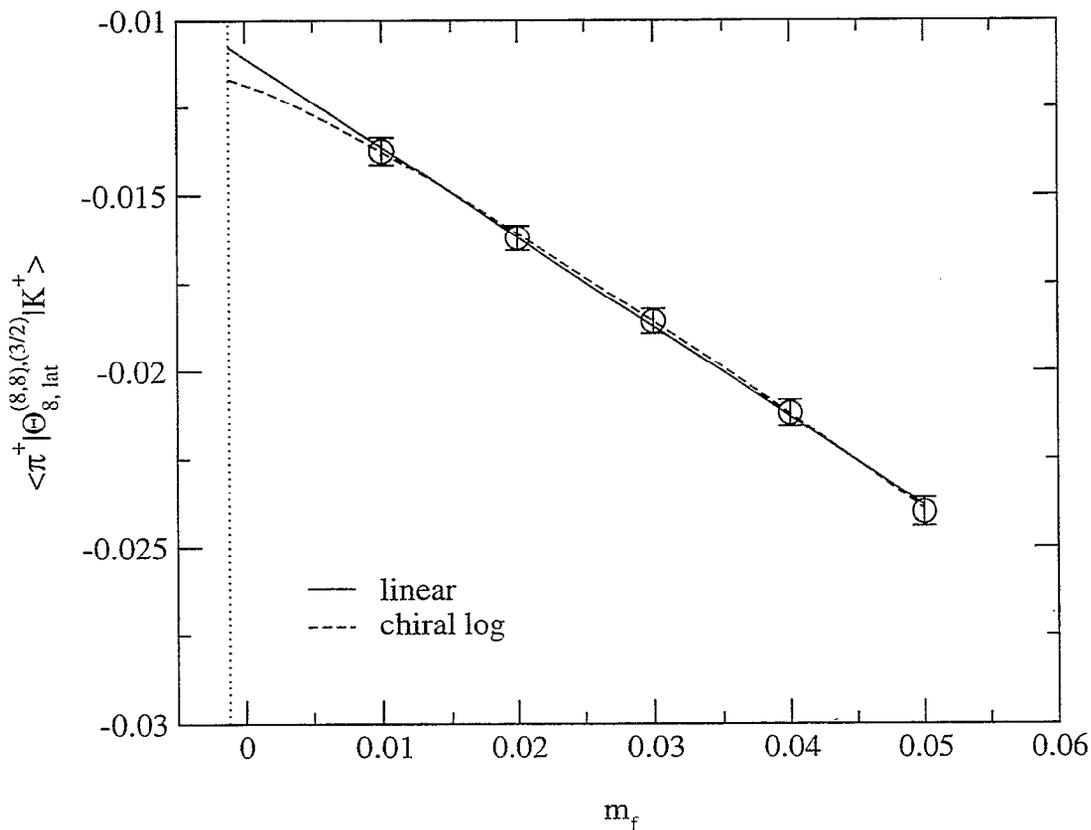


$$\alpha_i^{(27,1),3/2} = -\frac{f^2}{4} \times \text{slope} = (-4.13 \pm 0.18) \times 10^{-6}$$

and gives the lowest order contribution to $\text{Re}\mathcal{A}_2$

Electroweak penguin $\langle \pi^+ | Q_{8,\text{lat}}^{(3/2)} | K^+ \rangle$ (important to ϵ')

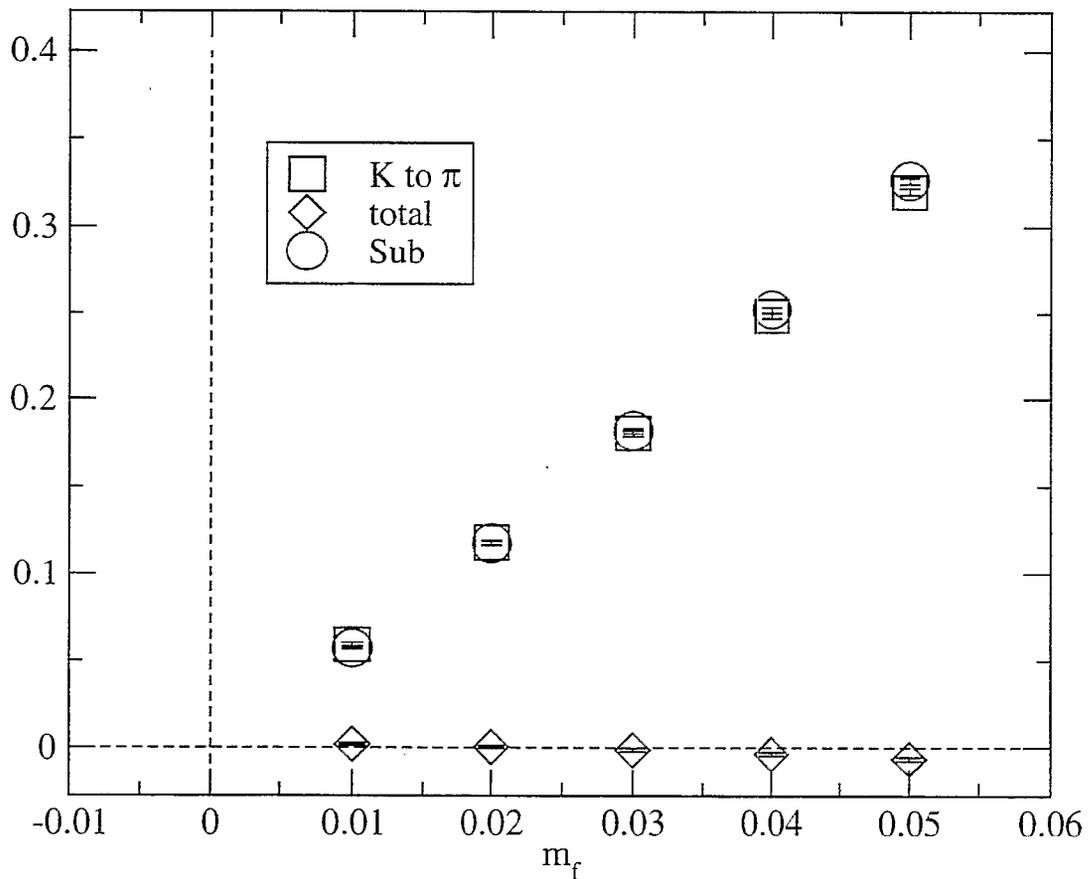
Lowest order contribution is a constant, higher order correction to *this constant* appears **small**. Extrapolate to $m_f = -m_{res} = -.00124$. Quenched log is unknown (ignore). Coefficient of conventional log is also unknown, but fit to it.



$$\alpha_8^{(3/2)} = \frac{f^2}{12} \times \text{intercept} = (-4.96 \pm 0.27) \times 10^{-6}$$

QCD Penguin $\langle \pi^+ | Q_{6,\text{lat}} | K^+ \rangle$ and $2 m_f \eta_6 \langle \pi^+ | \bar{s} d_{\text{lat}} | K^+ \rangle$

Divergent subtraction is almost complete. Physical slope is roughly 50 x smaller than the unsubtracted one

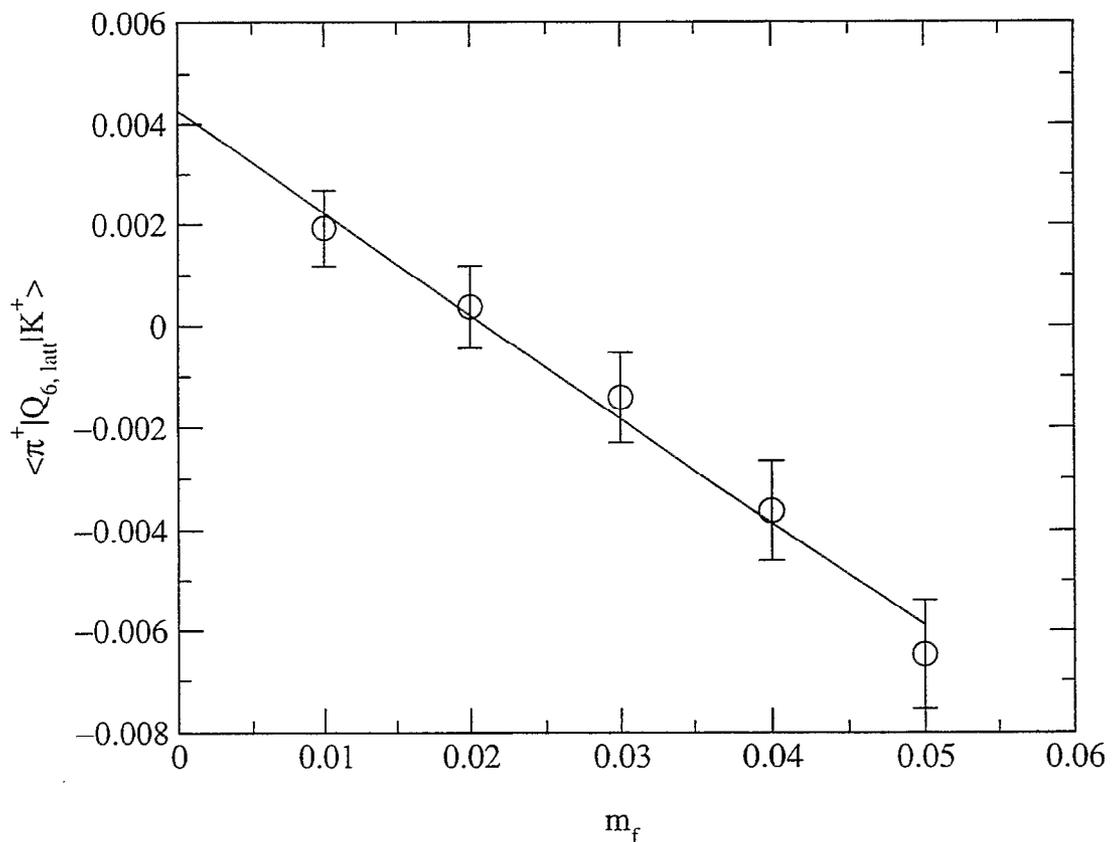


Data are highly correlated!

Subtracted QCD Penguin $\langle \pi^+ | Q_{6,\text{lat}} | K^+ \rangle$ (important to ϵ')

Does not vanish as $m_f \rightarrow -m_{res}$ because valence quark loop is sensitive to **high energy** chiral symmetry breaking effects (mixing between domain walls). Effect is an additive shift in the quark mass, which is eliminated by taking the slope.

$$\alpha_6 = \frac{f^2}{4} \times \text{slope} = (-8.12 \pm 0.98) \times 10^{-5}$$



V. Physical Amplitudes

$$\langle \pi \pi_{(I)} | -i\mathcal{H}^{(\Delta S=1)} | K^0 \rangle = -i\sqrt{\frac{3}{4}} G_F V_{ud} V_{us}^* \sum_{i=1}^{10} \sum_{j=1, j \neq 4}^8 [z_i(\mu) + \tau y_i(\mu)] \hat{Z}_{ij}^{\text{NPR}}$$

$$\times \left\{ \begin{array}{ll} \frac{4i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} \left[1 - \frac{97}{27} L_\chi(m_K) \right] & I = 0, \quad j = 1, 2, 3, 5, 6 \\ \frac{-4\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} \left[1 - \frac{3}{2} L_\chi(m_K) \right] & I = 2, \quad j = 1, 2, 3, 5, 6 \\ \frac{-12i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} a^{-6} [1 - 8.4 L_\chi(m_K)] & I = 0, \quad j = 7, 8 \\ \frac{-12\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} a^{-6} [1 - 2.3 L_\chi(m_K)] & I = 2, \quad j = 7, 8 \end{array} \right.$$

Tree level

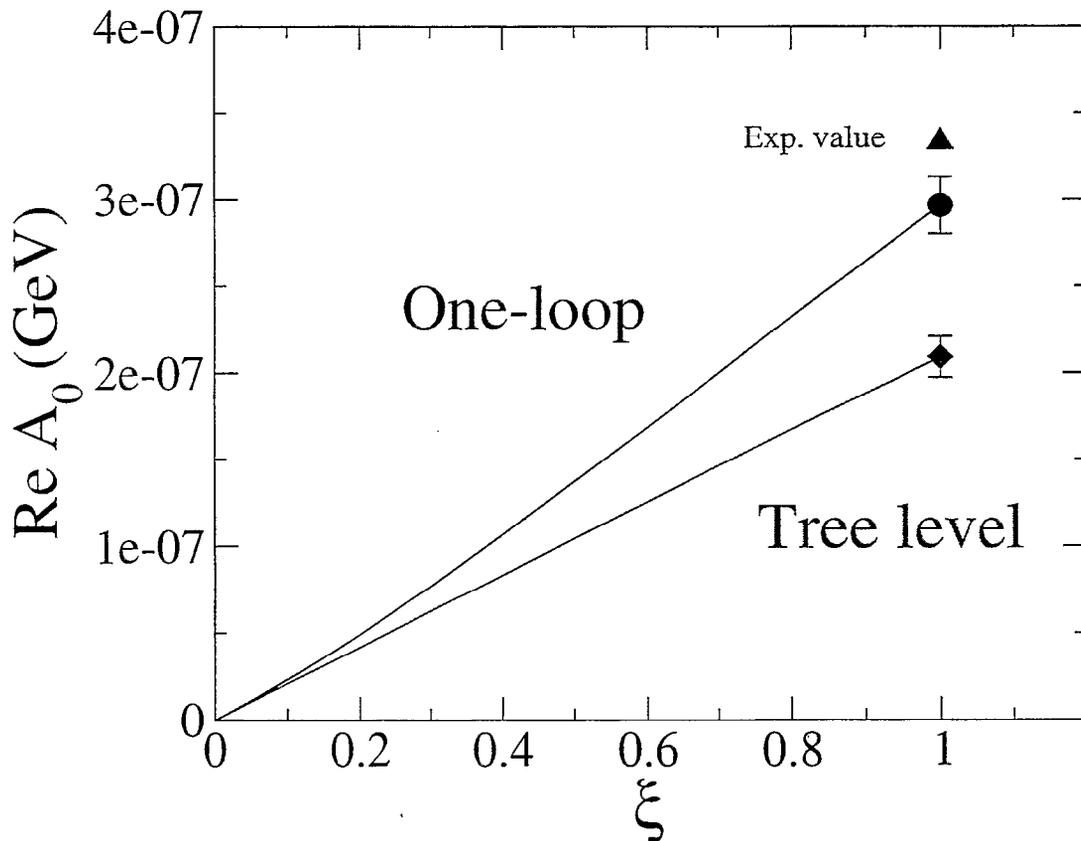
One-Loop, logs only

Real part of A_0

Study “fictional” world with masses $m_{K^0}^2, m_{\pi^+}^2 \rightarrow \xi \times (m_{K^0}^2, m_{\pi^+}^2)$

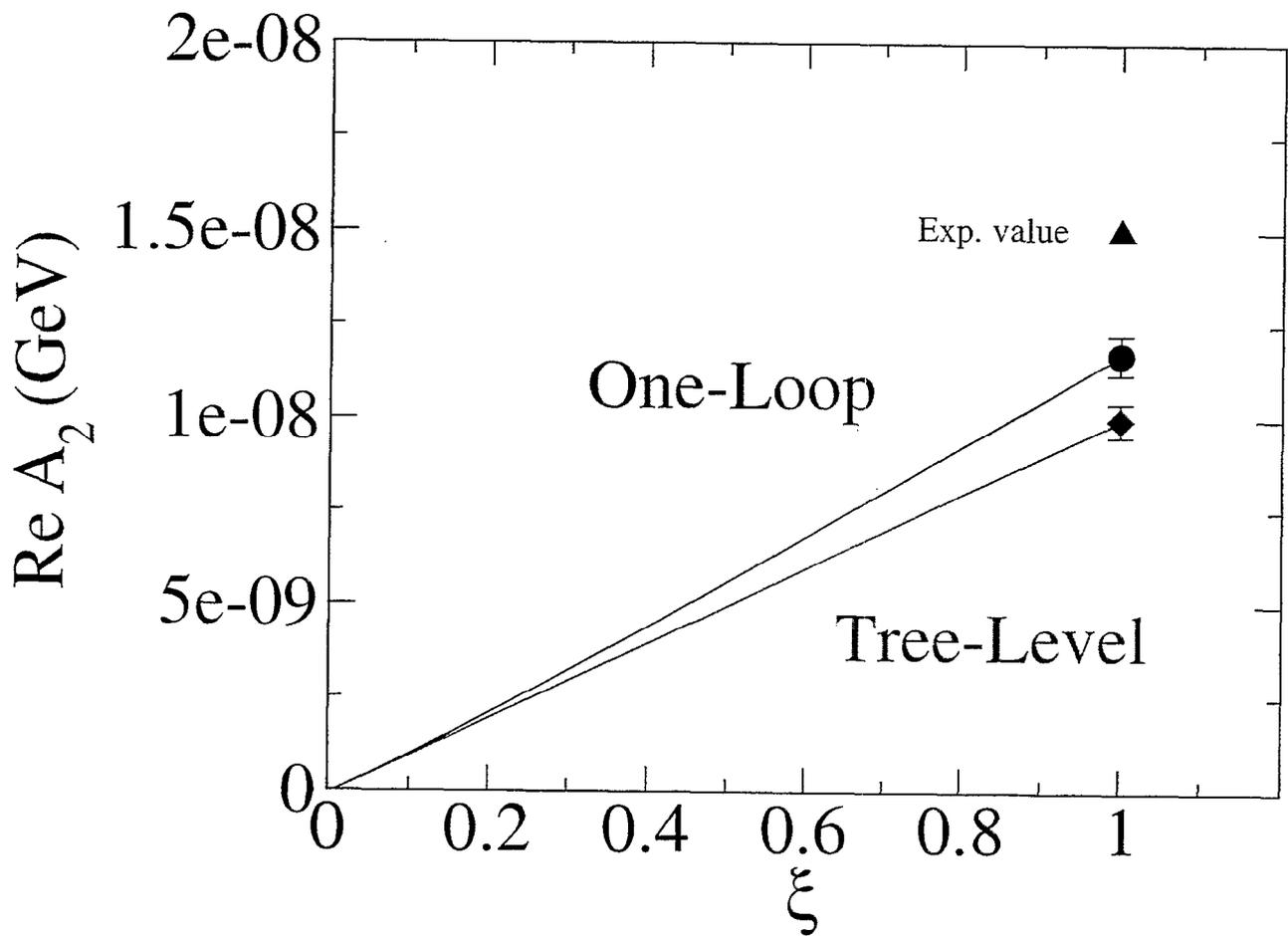
“Tree-Level” = Lowest order chiral perturbation theory

“One-Loop” = Tree-Level + full QCD chiral logs ($K \rightarrow \pi\pi$)



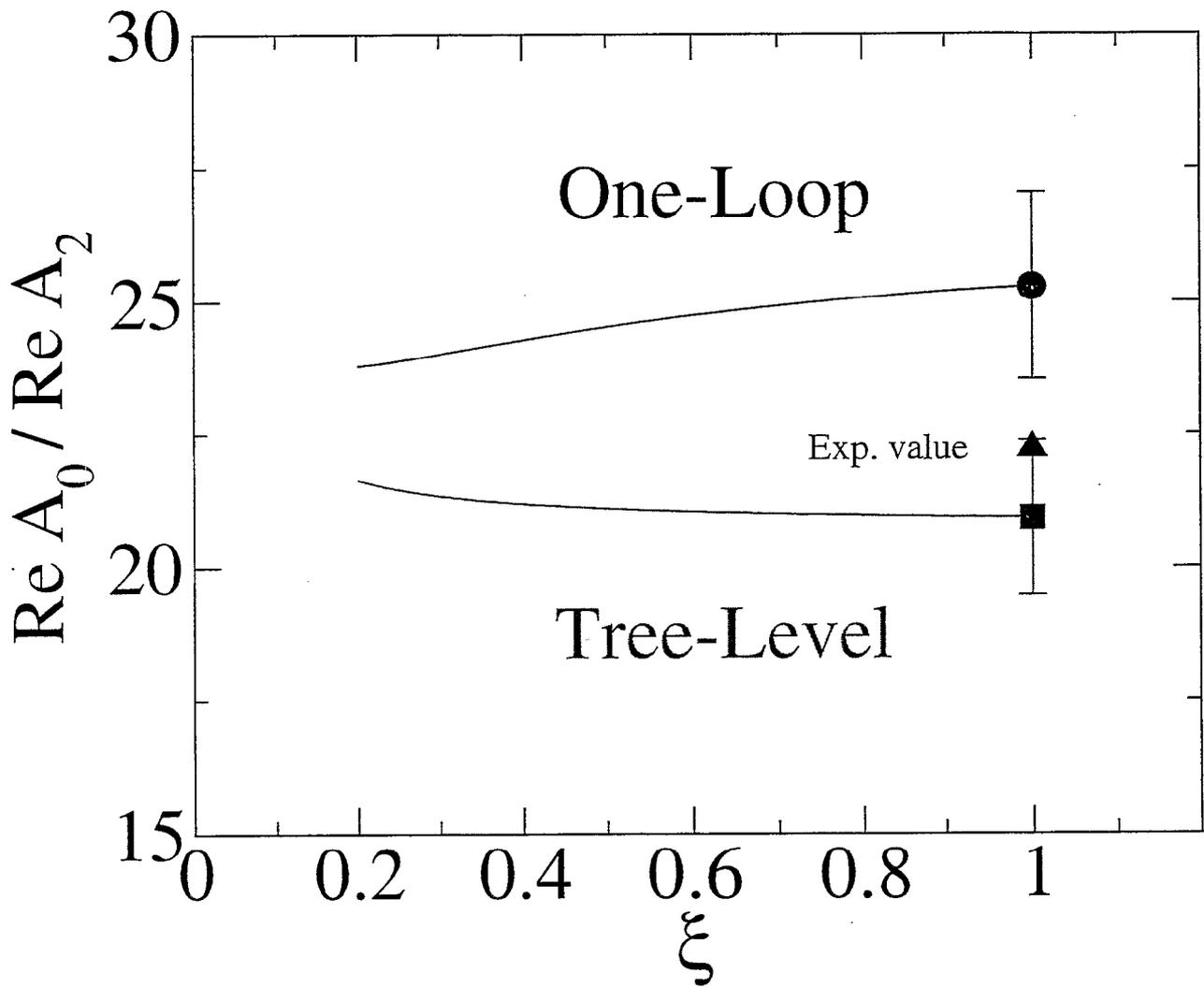
($\mu = 2.13$ GeV)

Real part of A_2



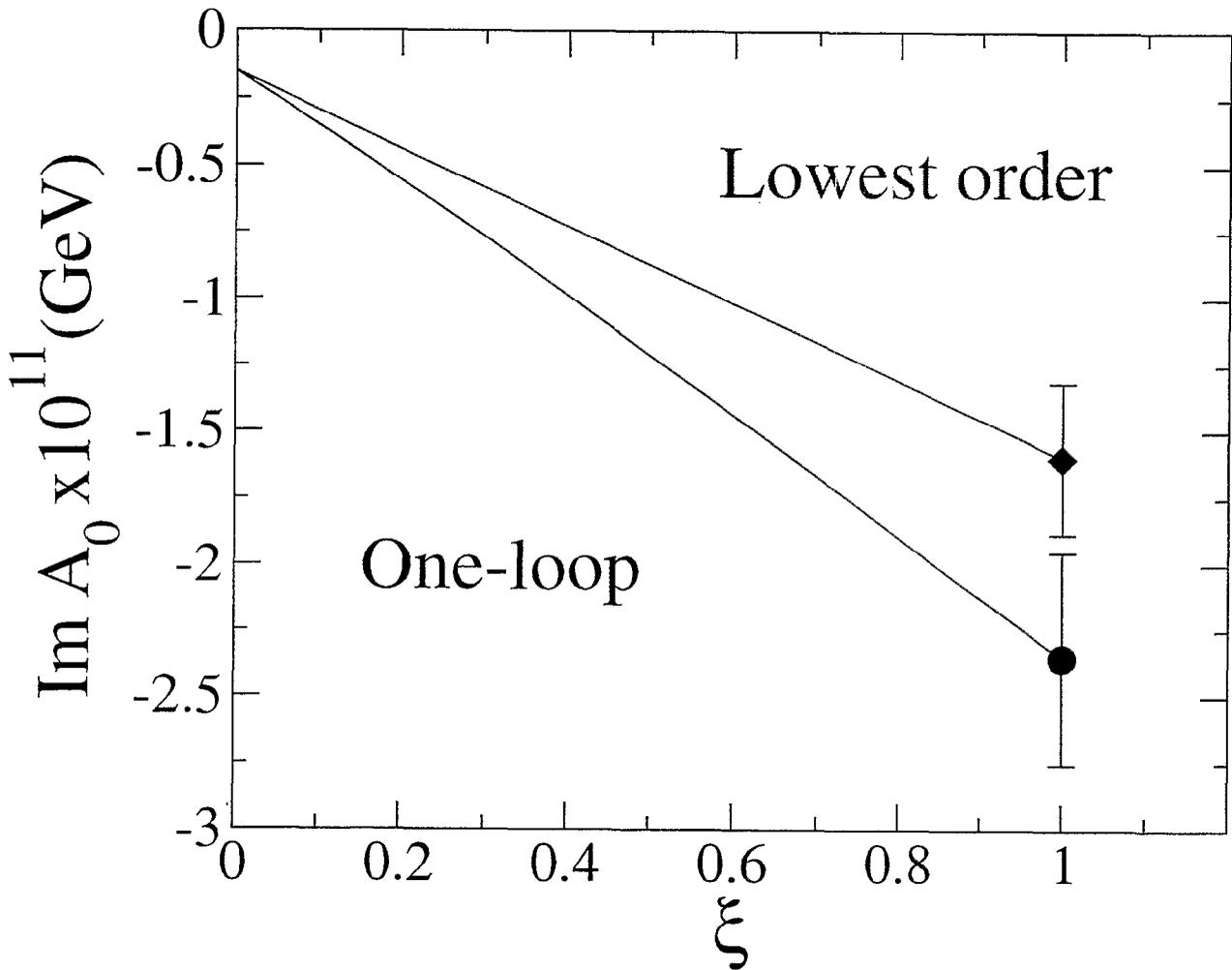
$(\mu = 2.13 \text{ GeV})$

$\Delta I = 1/2$ Rule



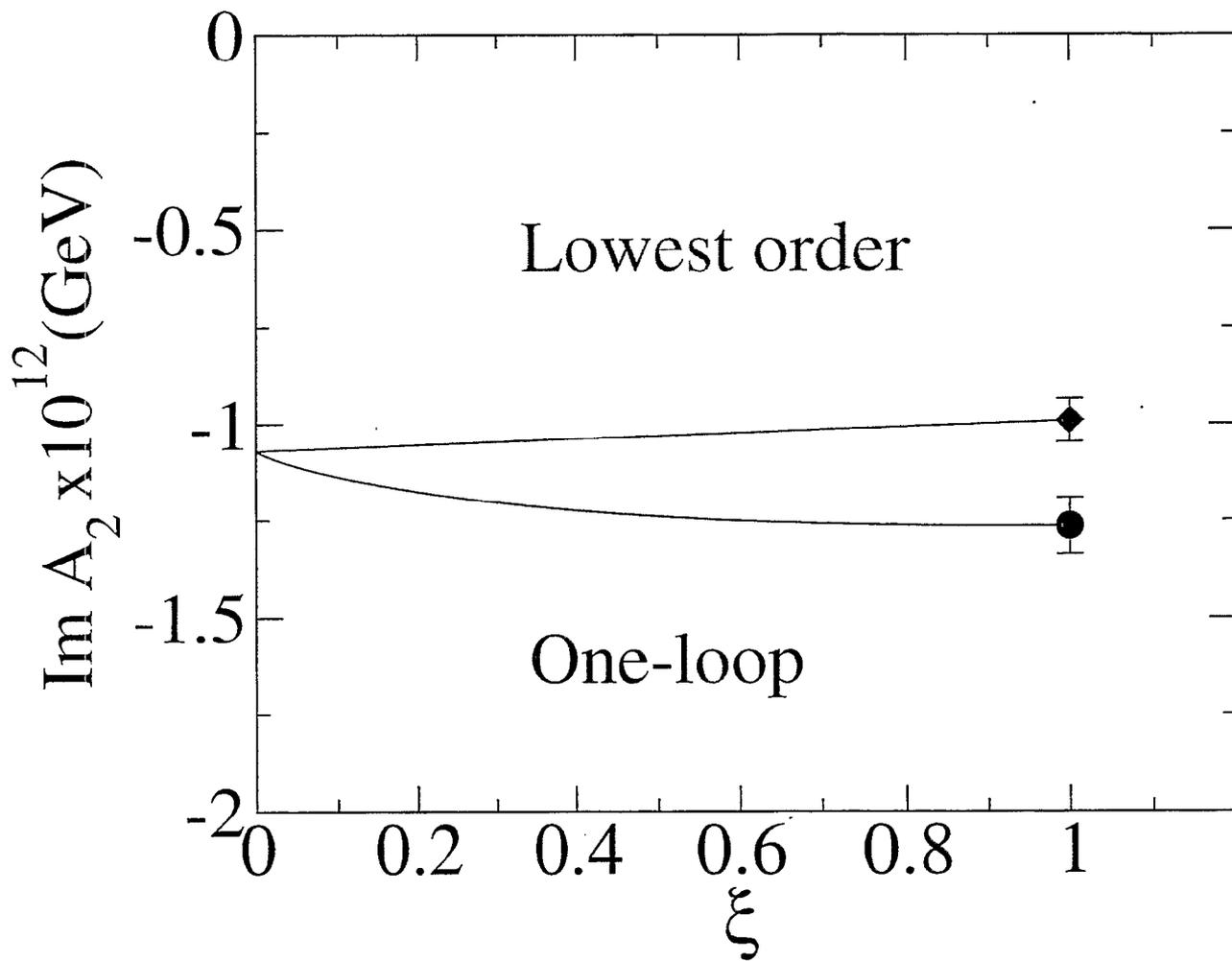
($\mu = 2.13$ GeV)

Imaginary part of A_0



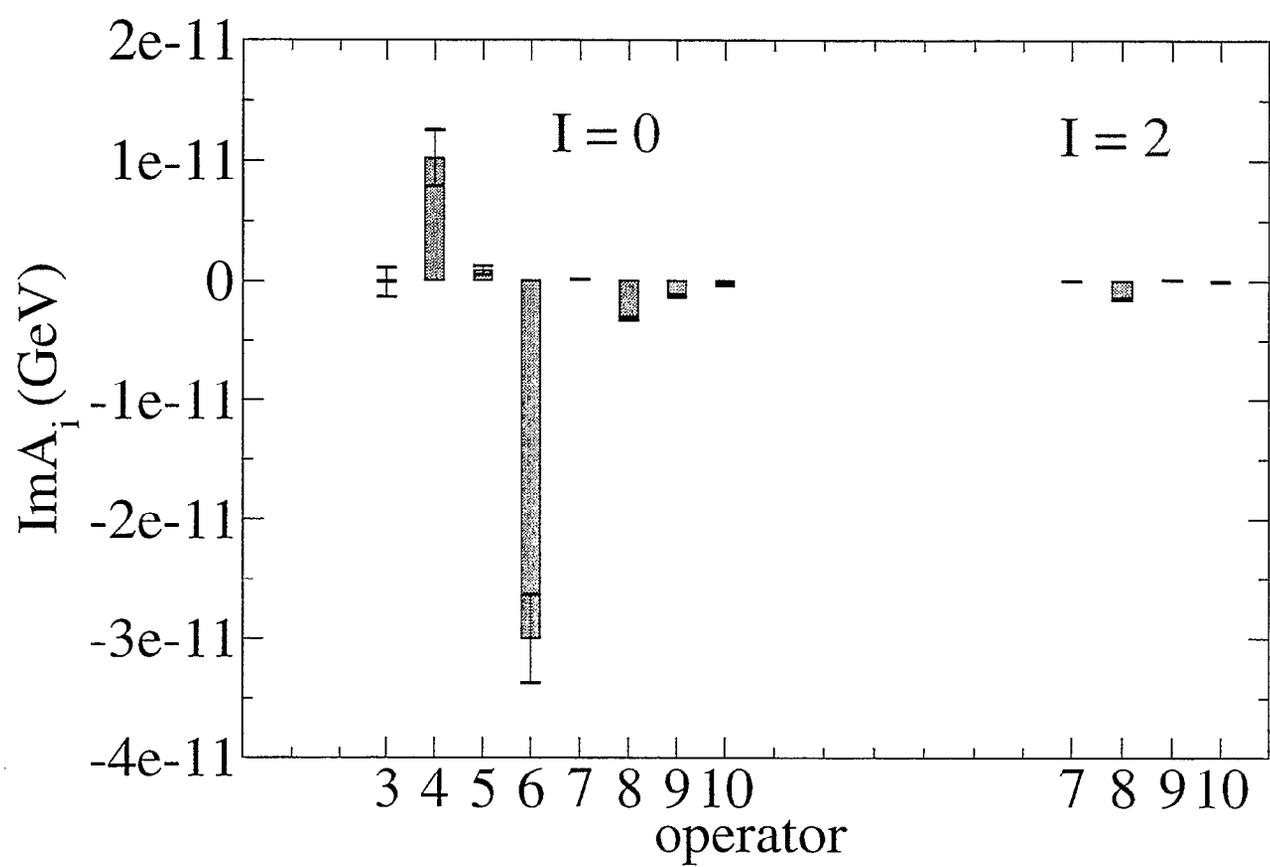
($\mu = 2.13 \text{ GeV}$)

Imaginary part of A_2



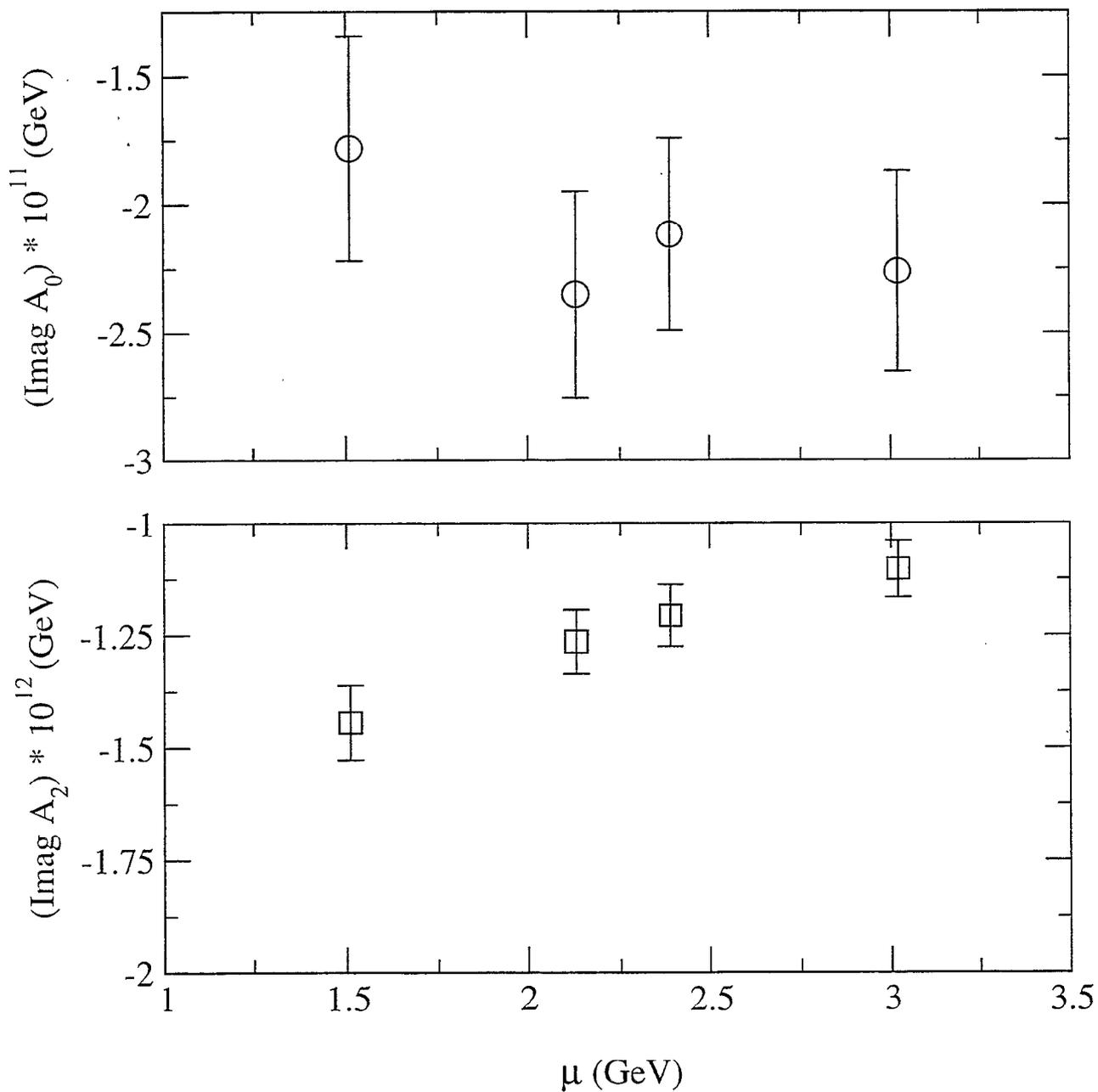
($\mu = 2.13 \text{ GeV}$)

Individual Contributions to $\text{Im}A_{0,2}$



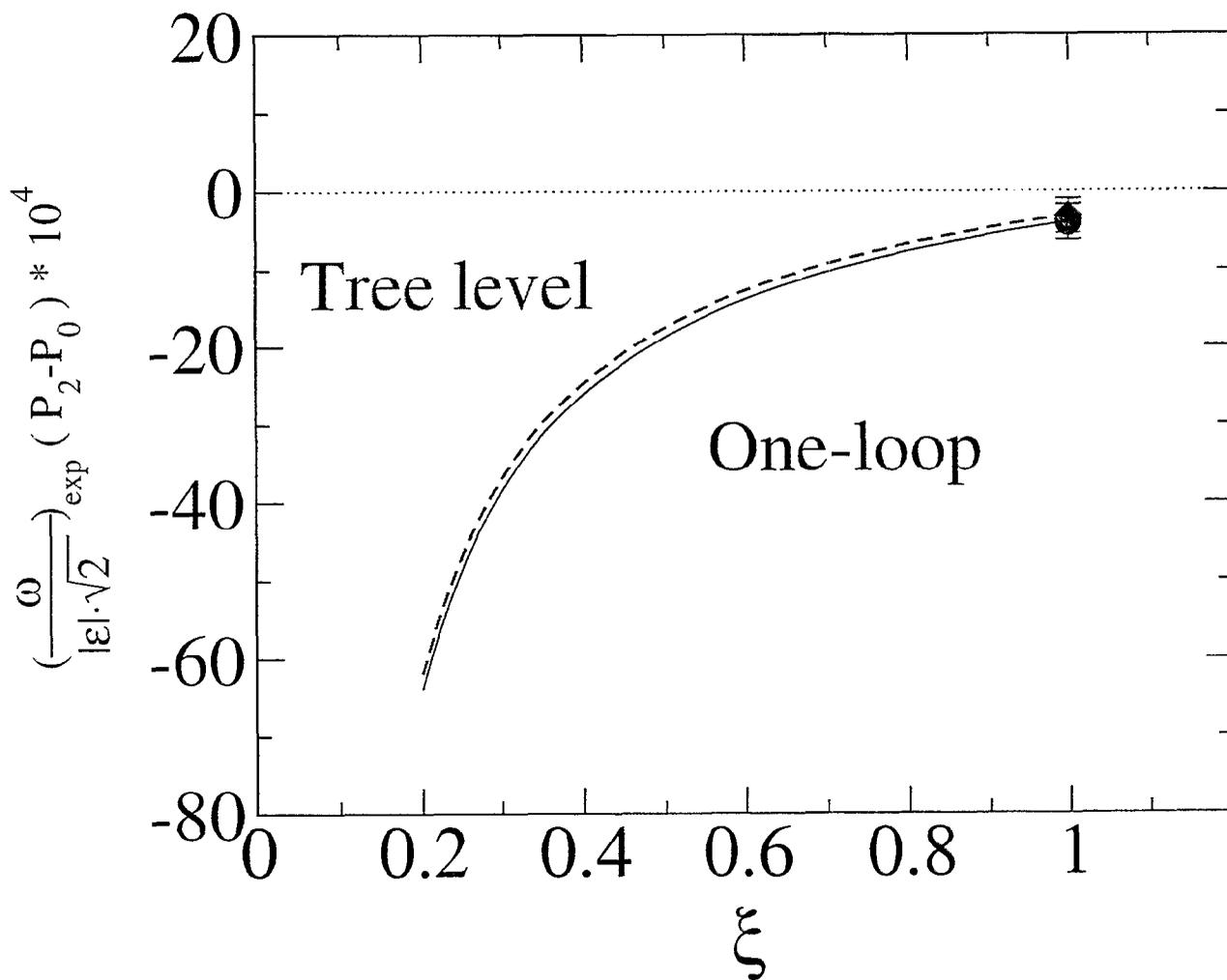
$\mu = 2.13 \text{ GeV}$, One-loop χ PT logs ($\xi = 1$)

Residual Scale Dependence in Imag. Amplitudes



ϵ'/ϵ

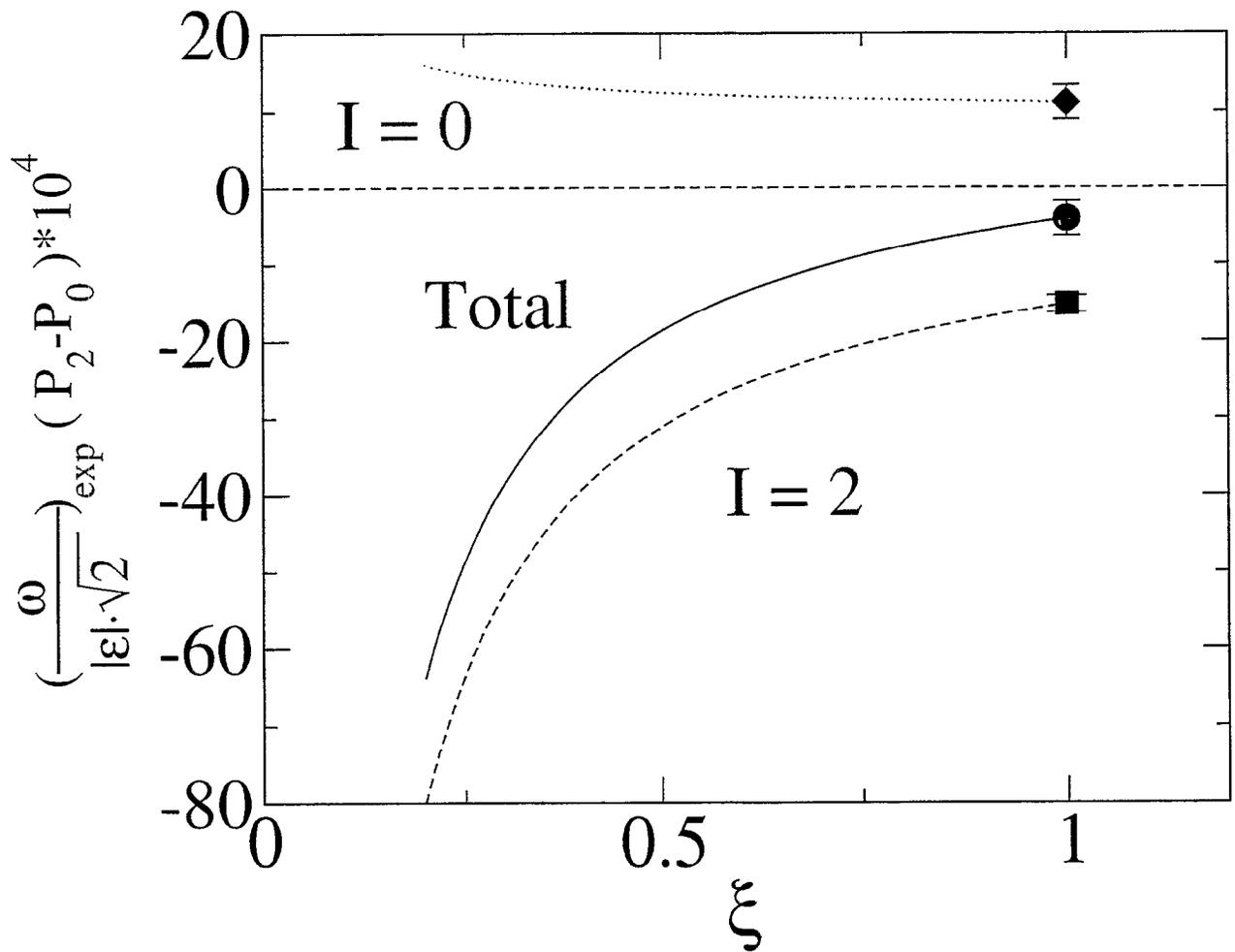
$$\frac{\epsilon'}{\epsilon} = \left(\frac{\omega}{\sqrt{2}|\epsilon|} \right)_{\text{exp}} \left(\frac{\text{Im } A_2}{\text{Re } A_2} - \frac{\text{Im } A_0}{\text{Re } A_0} \right)$$



($\mu = 2.13$ GeV)

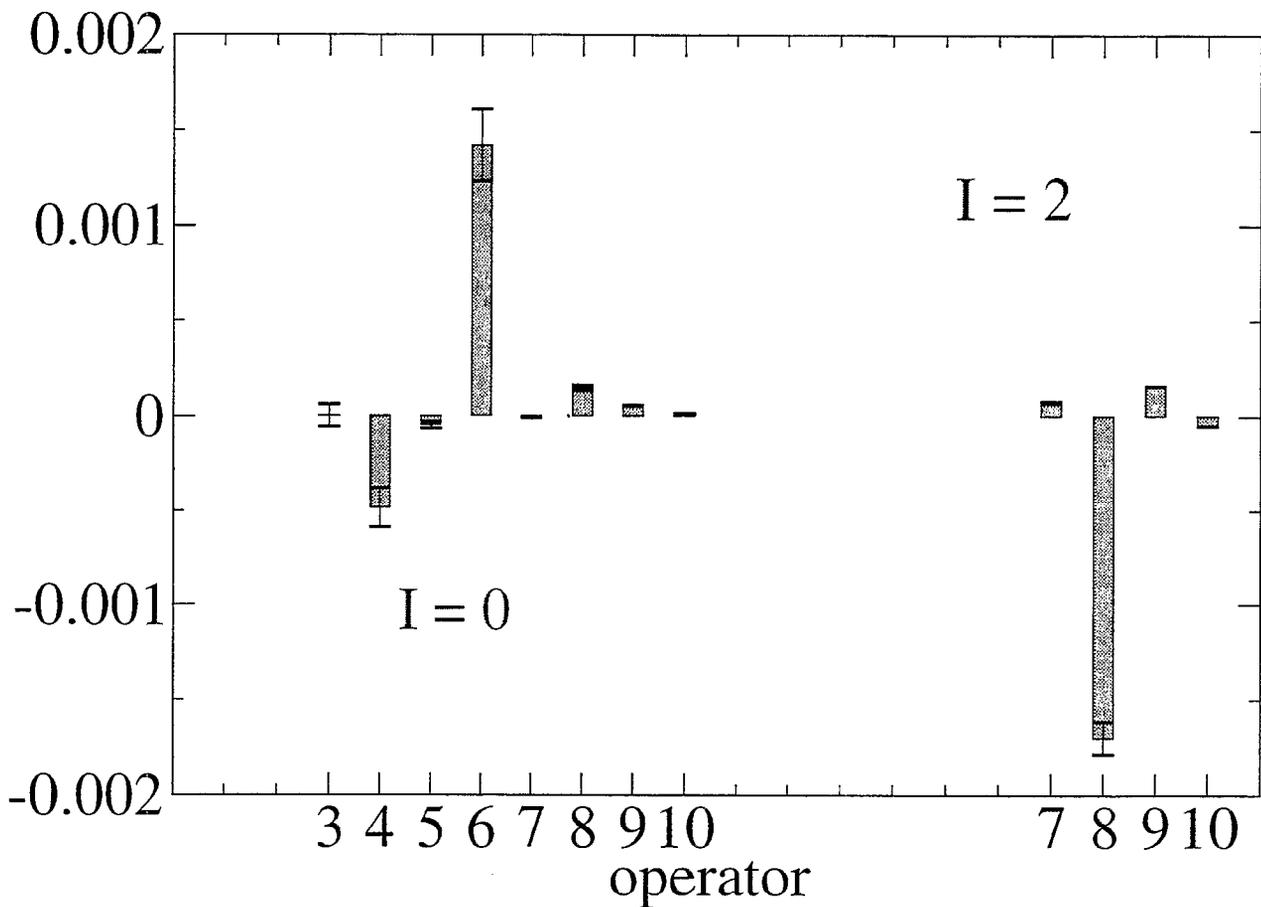
Isospin Breakdown P_0 and P_2

$$P_{0,2} \equiv \frac{\text{Im } A_{0,2}}{\text{Re } A_{0,2}}$$



$\mu = 2.13 \text{ GeV}$, One-loop χ PT logs ($\xi = 1$)

Individual Contributions to ϵ'/ϵ



$\mu = 2.13$ GeV, One-loop χ PT logs ($\xi = 1$)

Final Results

Quantity	Experiment	This calculation (statistical errors only)
$\text{Re } A_0(\text{GeV})$	3.33×10^{-7}	$2.96(17) \times 10^{-7}$
$\text{Re } A_2(\text{GeV})$	1.50×10^{-8}	$1.172(53) \times 10^{-8}$
ω	22.2	25.3(18)
$\text{Re } (\epsilon'/\epsilon)$	$15.3(26) \times 10^{-4}$ (NA48)	$-4.0(23) \times 10^{-4}$
	$20.7(28) \times 10^{-4}$ (KTev)	

$(\mu = 2.13 \text{ GeV}, \text{ One-loop chiral logs})$

Dense and Baryon Rich QCD

Misha Stephanov

Hot and Dense QCD:
*Pion Propagation Near Chiral Phase
Transition*

M.A. Stephanov
(collaboration with D.T. Son)

- Soft pion dispersion relation can be determined from *static* quantities only (\Rightarrow can be measured on Euclidean lattice):

(analogy: spin waves in antiferromagnets)

$$\omega^2 = u^2(\mathbf{p}^2 + m^2) - \text{dispersion relation } (|\mathbf{p}| \ll m_\sigma).$$

u – “velocity” of pions; m – screening mass.

m – from static (zero-frequency) correlator of $\pi^a \equiv i\bar{\psi}\gamma^5\tau^a\psi$:

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \frac{\langle \pi^a(x)\pi^b(0) \rangle}{\langle \bar{\psi}\psi \rangle^2} = \frac{1}{f^2} \frac{\delta^{ab}}{\mathbf{q}^2 + m^2},$$

f – T -dependent static pion “decay constant”.

u – from the ratio of 2 static quantities:

$$\boxed{u^2 = \frac{f^2}{\chi_{I5}},} \quad \text{where}$$

$$\int d\tau dV \langle A_0^a(x)A_0^b(0) \rangle = \delta^{ab}\chi_{I5}, \quad A_0^a \equiv \bar{\psi}\gamma^0\gamma^5\frac{\tau^a}{2}\psi.$$

χ_{I5} – axial isospin susceptibility.

valid for “all” $T < T_c$, (at $T = 0$: $f^2 = \chi_{I5} = f_\pi^2$).

- Derivation using effective Lagrangian method

Microscopic (QCD) Lagrangian:

$$\mathcal{L}_{\text{quark}} = i\bar{\psi}\gamma^\mu D_\mu\psi - (\bar{\psi}_L M \psi_R + \text{h.c.}) + \mu_{I5} A_0^3,$$

$M = \text{diag}(m_u, m_d)$ is the quark mass matrix; μ_{I5} is chem. potential of the axial isospin charge A_0^3 .

Eff. (pion) Lagrangian, the most general allowed by symmetries, to lowest order in momenta:

$$\mathcal{L}_{\text{eff}} = \frac{f_t^2}{4} \text{Tr} \nabla_0 \Sigma \nabla_0 \Sigma^\dagger - \frac{f_s^2}{4} \text{Tr} \partial_i \Sigma \partial_i \Sigma^\dagger + \frac{f_m^2}{2} \text{Re Tr} M \Sigma,$$

from which we derive $\omega^2 = u^2(\mathbf{p}^2 + m^2)$ with

$$u^2 = \frac{f_s^2}{f_t^2} \quad \text{and} \quad m^2 = \frac{m_q f_m^2}{f_s^2}.$$

The (T -dependent) coefficients f_t , f_s and f_m , can be found in terms of microscopic correlators by matching derivatives w.r.t. M and μ_{I5} .

$\mu_{I5} \equiv$ time component of a vector potential for axial isospin \rightarrow local $SU(2)_A$ symmetry \rightarrow

$$\nabla_0 \Sigma \equiv \partial_0 \Sigma - \frac{i}{2} \mu_{I5} (\tau_3 \Sigma + \Sigma \tau_3).$$

Thus, matching 2nd derivative:

$$\chi_{I5} = \frac{\partial^2 \mathcal{P}}{\partial \mu_{I5}^2} = f_t^2.$$

Derivatives w.r.t. M give: $f_m^2 = -\langle \bar{\psi} \psi \rangle$ and $f_s = f$.

Thus: $\boxed{u^2 = f^2 / \chi_{I5}}$ and $f^2 m^2 = -m_q \langle \bar{\psi} \psi \rangle$ (GOR).

- Critical behavior

What happens with u and m when $T \rightarrow T_c$?

Theory of *static* critical phenomena can be used.

Near T_c , but not too close to T_c : $m \ll m_\sigma \ll T$.

In the range of momenta $m \ll |\mathbf{q}| \ll m_\sigma$ we have

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \langle \pi^a(x) \pi^b(0) \rangle = \delta^{ab} \frac{\langle \bar{\psi}\psi \rangle^2}{f^2} \frac{1}{\mathbf{q}^2}.$$

For momenta such that $m_\sigma \ll |\mathbf{q}| \ll T$:

$$\int d\tau dV e^{-i\mathbf{q}\cdot\mathbf{x}} \langle \bar{\psi}\psi(x) \bar{\psi}\psi(0) \rangle \sim \frac{1}{|\mathbf{q}|^{2-\eta}}.$$

In this regime correlators of $\sigma = \bar{\psi}\psi$ and $\pi^a = i\bar{\psi}\gamma^5\tau^a\psi$ are degenerate, since they are related by the $SU(2)_A$ symmetry, which is restored at T_c . Matching at the scale $|\mathbf{q}| \sim m_\sigma$:

$$f^2 = A m_\sigma^{-\eta} \langle \bar{\psi}\psi \rangle^2.$$

$\eta \approx 0.03$ – $O(4)$ universality class in $d = 3$.

Using $m_\sigma \sim t^\nu$ and $\langle \bar{\psi}\psi \rangle \sim t^\beta$, where $t = (T_c - T)/T_c$:

$$f^2 \sim t^{2\beta-\nu\eta} = t^{(d-2)\nu} = t^\nu,$$

$\nu \approx 0.73$ and $\beta \approx 0.38$, $d = 3$.

χ_{I5} is *finite* at $T = T_c$. Thus,

$$u^2 = \frac{f^2}{\chi_{I5}} \sim f^2 \sim t^\nu \rightarrow 0 \text{ at } T_c$$

○ Critical behavior (contd.)

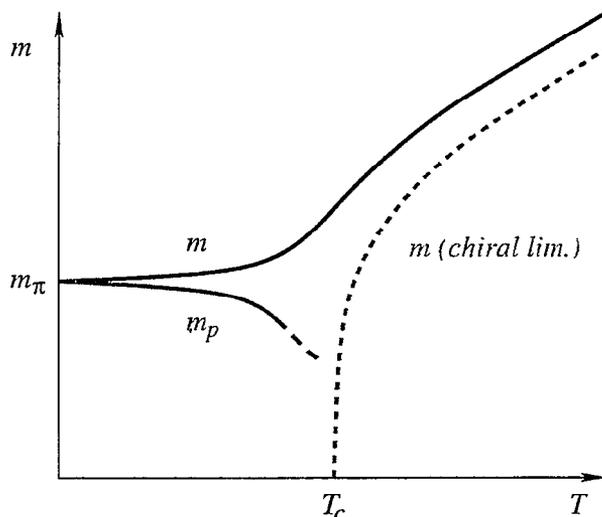
$$m^2 = -\frac{m_q \langle \bar{\psi} \psi \rangle}{f^2} \sim m_q t^{\beta-\nu}.$$

since $\beta < \nu$ — the static screening pion mass *grows* (at fixed $m_q \neq 0$) as $T \rightarrow T_c$.

The *pole* mass of the pion, m_p , scales differently:

$$m_p^2 \equiv u^2 m^2 = -\frac{m_q \langle \bar{\psi} \psi \rangle}{\chi_{I5}} \sim m_q t^\beta.$$

\Rightarrow the pole mass of the pion *drops* as $T \rightarrow T_c$.



● Potentially observable consequences

◇ In statistical models

$\Delta m_p \equiv m_p - m_\pi \approx m_\pi ((m_q/\Lambda_{\text{QCD}})^{1/2\delta} - 1) \approx -0.3m_\pi$
 translates into $\exp(-\Delta m_p/T_{\text{ch}}) \approx 1.3$ enhancement of pion abundance.

◇ $u < 1 \Rightarrow$ Cherenkov radiation of pions by a hard probe.

Gluons Out of Equilibrium

Dietrich Bödeker

Strongly coupled gluons out of equilibrium

Dietrich Bödeker, RBRC and BNL

Small coupling, $g \ll 1$ and large fields,

$$A_\mu \sim \frac{1}{g} \partial_\mu$$

→ non-linearities in Yang-Mills equations become essential, strong coupling

examples:

- magnetic scale gluons ($k \sim g^2 T$) close to thermal equilibrium
- small- x gluons “colored glass condensate”

Non-perturbative calculations for many body systems out of equilibrium, that is, in real time?

quantum field theory: no

classical field theory: yes

classical field theory applies when occupation numbers of (bosonic) fields are large
strongly coupled gluons have occupation number

$$n(k) \sim \frac{1}{g^2} \gg 1$$

typically quantum modes (modes with small occupation number) can not be neglected

idea: try to find effective classical theory by integrating out quantum degrees of freedom

general problem: classical thermal field theory has UV divergences,
non-local for real time

Dynamics of magnetic scale gluons

unequal time correlation functions

$$\mathcal{C}(t) = \langle O(t)O(0) \rangle$$

determined by Langevin equation

$$\frac{3}{m_D^2}(c_1 + \mathbf{v} \cdot \mathbf{D})\mathbf{v} \cdot \mathbf{D} \times \mathbf{B} + (C + v \cdot D)\widetilde{W} = \mathbf{v} \cdot \mathbf{E} + \xi,$$

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$\widetilde{W}(x, \mathbf{v})$ adjoint rep phase space density matrix of plasma particles, C linear collision operator, ξ Gaussian white noise

- no propagating gauge field waves \rightarrow solves problem of non-local UV divergences
- generalizes the leading log effective theory

$$\mathbf{D} \times \mathbf{B} = \sigma \mathbf{E} + \zeta$$

to leading order in g and all orders in $[\log(1/g)]^{-1}$

leading log equation

- for gluon fields only
- UV finite
- single length scale $R \sim (g^2 T)^{-1}$
- single time scale $\tau \sim [g^4 \log(1/g) T]^{-1}$

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leading order equation

- for gluon fields and particle phase space density
- UV divergences
- one length scale $R \sim (g^2 T)^{-1}$ (two if one counts logs)
- two time scales $\tau \sim (g^4 T)^{-1}$, $\tau \sim (g^2 T)^{-1}$

issues to be addressed for leading order equation

- relation to thermodynamics of soft gluons
- expansion in $[\log(1/g)]^{-1}$
- role of “fast” modes with $\tau \sim (g^2 T)^{-1}$
- renormalization

Relation to thermodynamics

Langevin equations generate probability distribution for field configurations $P(\phi, t)$

leading log Langevin equation:

$$P(\mathbf{A}, t) \rightarrow \exp \left[-\frac{H}{T} \right], \quad H = \frac{1}{2} \int d^3x \mathbf{B}^2$$

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for $t \rightarrow \infty \Leftrightarrow$ 3-dimensional chromodynamics, obtained through dimensional reduction and by integrating out A_0

Fokker-Planck equation for $P(\mathbf{A}, \widetilde{W}, t) \Rightarrow$

$$P(\mathbf{A}, \widetilde{W}, t) \rightarrow \exp \left[-\frac{H}{T} \right], \quad H = \frac{1}{2} \int d^3x \left\{ \mathbf{B}^2 + m_D^2 \int_{\mathbf{v}} \widetilde{W}^2 \right\}$$

\widetilde{W} Gaussian free field for thermodynamics \Rightarrow same gauge field thermodynamics as from eq. (3)

\widetilde{W} has non-trivial effect on dynamics

Perturbation theory

- UV behavior: renormalizability, continuum limit?

expansion in $[\log(1/g)]^{-1}$: systematic improvement of leading log Langevin equation

classical field theory can be written as path integral

→ “quantum field theory”, Feynman rules (not Lorentz invariant)

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$$\langle O[A, \widetilde{W}] \rangle_{\text{noise}} = \int [dA][d\widetilde{W}][d\lambda] e^{-S} O[A, \widetilde{W}]$$

$$S = \int_{x, \mathbf{v}} \left\{ \frac{T}{m_D^2} \lambda C \lambda - i\lambda \left[\frac{3}{m_D^2} (c_1 + \mathbf{v} \cdot \mathbf{D}) \mathbf{v} \cdot \mathbf{D} \times \mathbf{B} + (C + v \cdot D) \widetilde{W} - \mathbf{v} \cdot \mathbf{E} \right] \right\}$$

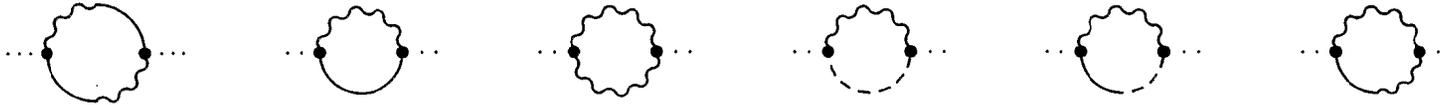
gauge fixing: flow gauge

$$\kappa A_0 = \nabla \cdot \mathbf{A}$$

One loop self-energies

high frequency ($\omega \sim g^2 T$) modes do not decouple

$\lambda\lambda$:



288 λA_0 :



determine color conductivity at next to leading order in $[\log(1/g)]^{-1}$

result is gauge fixing independent and agrees with Arnold, Yaffe

Renormalizability

large momentum behavior of propagators

$$\langle \mathbf{A}_{\text{tr}} \mathbf{A}_{\text{tr}} \rangle \sim \frac{1}{k^5}$$

but

$$\langle \widetilde{W} \widetilde{W} \rangle \sim \langle \widetilde{W} A_0 \rangle \sim \langle A_0 A_0 \rangle \sim \frac{1}{k}$$

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n -point functions for λ have bad UV behavior

$$\sim \int d^4k \frac{1}{k^2}$$

$$\sim \int d^4k \frac{1}{k^3}$$

however, contribution to gauge field dynamics suppressed by powers of g
non-physical, higher loops will contribute at the same order

Gluon Saturation from Small-x Evolution Equation

Kazunori Itakura

Gluon Saturation from

Small- x Evolution Equation

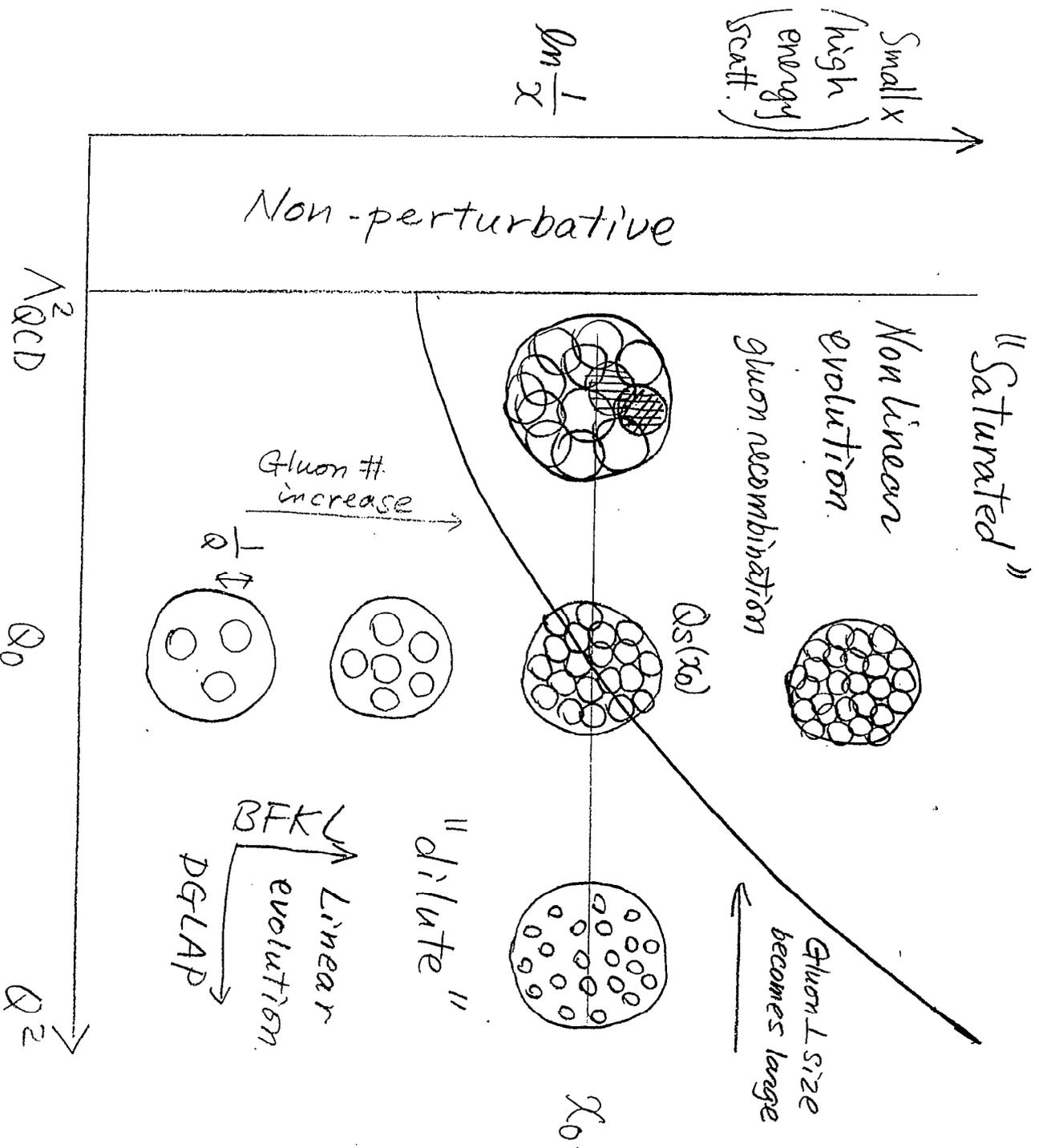
Kazu Itakura (PERC)

Edmond Iancu (Saclay)

Larry McLerran (BNL)

- Gluon Saturation
- Color Glass Condensate
- Evolution Equation
- Approximate Solutions (MFA, RPA)
- Summary

Gluon Saturation



Saturated gluon with $\left\{ \begin{array}{l} \text{high field strength} \\ \text{coherent gluon field} \end{array} \right.$

\Rightarrow "Color Glass Condensate"

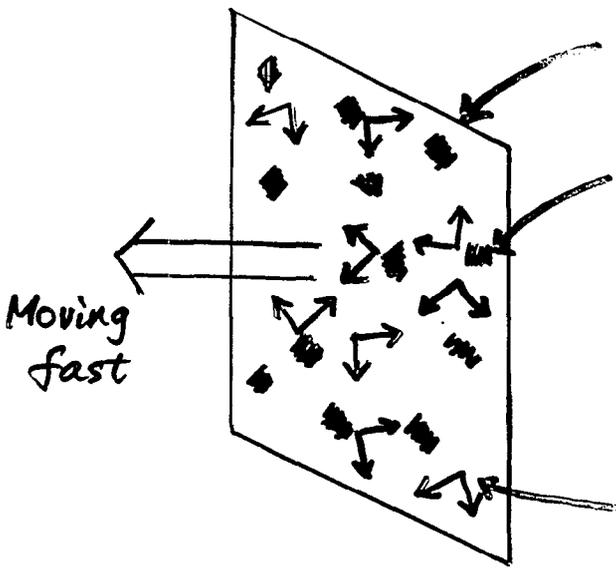
Color Glass Condensate

McLerran-Venugopalan
 Jalilian-Marian, Leonidov
 Kovner, Weigert, ...

Effective theory of saturated gluons

Separation of degrees of freedom

slow { Large x partons \longrightarrow "random" source
 (valence)
 fast { small x partons \longrightarrow classical gluon field
 induced by the random source
 (NonAbelian Weizsäcker-Williams field)



Very thin sheet

valence partons $P(x_1)$

weight function

$$W[P] = \exp \left\{ -\frac{1}{2} \int d^2x_1 \frac{\rho^2(x_1)}{\mu^2} \right\}$$

Gaussian

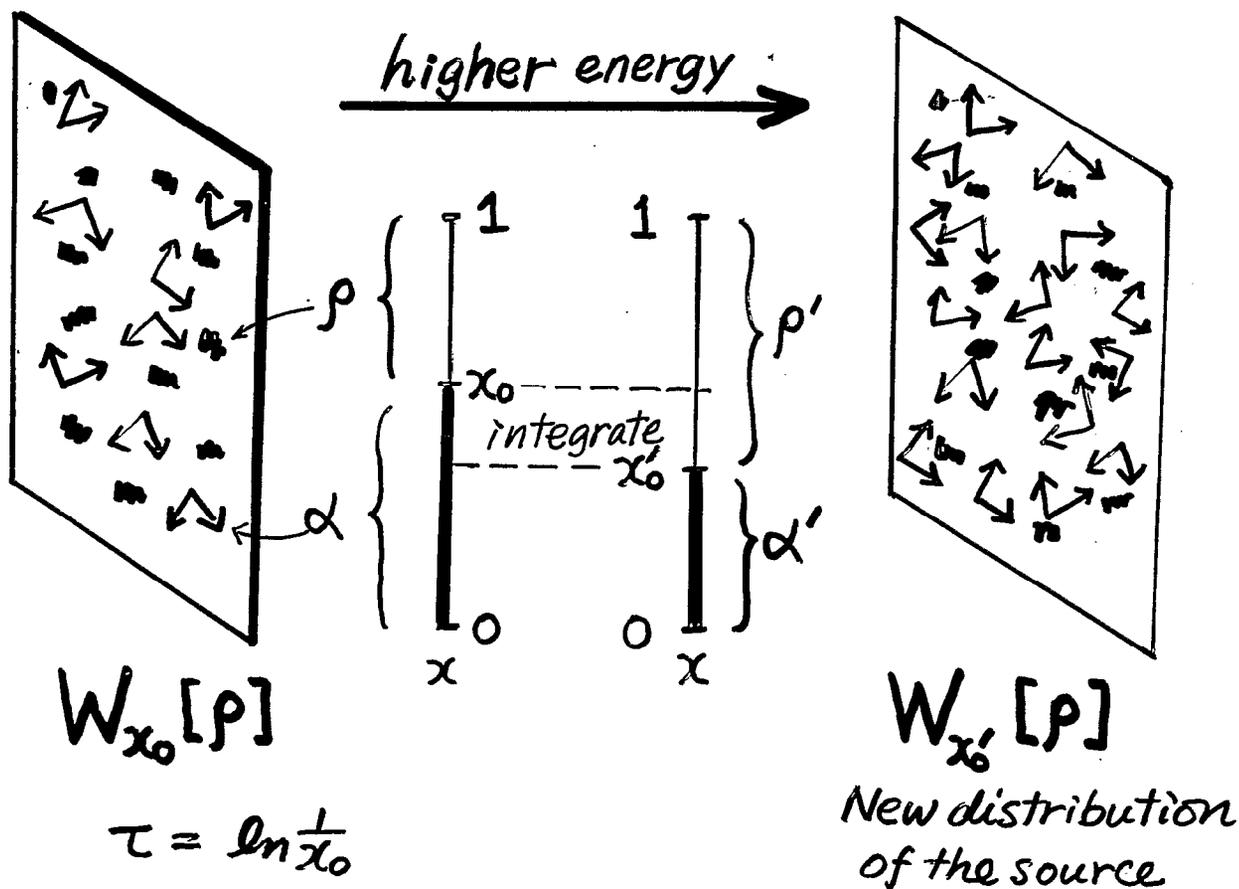
Classical gluon field $A^i(x_1)$

$$A^i(x_1) = \frac{i}{g} U \partial^i U^\dagger$$

$$U^\dagger(x_1) = P \exp \left\{ i g \int^{x_1^-} dz^- A(z^-, x_1) \right\}$$

Evolution Equation

Jalilian-Marian, Leonardov-Koussin
Weigert, Iancu, McLerran, Ferrell



$$\frac{\partial}{\partial \tau} W_\tau[\alpha] = \frac{1}{2} \frac{\delta}{\delta \alpha_\tau^a(x_\perp)} \left[\chi_{x_\perp y_\perp}^{ab} \frac{\delta}{\delta \alpha_\tau^b(y_\perp)} W_\tau[\alpha] \right]$$

$$\chi_{x_\perp y_\perp}^{ab} = \alpha_s \int \frac{d^2 z_\perp}{(2\pi)^2} \frac{z_\perp^i x_\perp^i}{(z_\perp - x_\perp)^2} \frac{z_\perp^i y_\perp^i}{(z_\perp - y_\perp)^2} \left(1 + V_x^+ V_y - V_x^+ V_z - V_z^+ V_y \right)$$

$$V_x^+ = U^+(x^- = e^T \cdot x_\perp)$$

$$\alpha_\tau(x_\perp) = \alpha(x^- = e^T \cdot x_\perp)$$

α is a function of ρ $W[\rho] \rightarrow W[\alpha]$

Solving the Evolution Equation

- functional differential equation
- highly non-linear due to $\chi[\alpha]$

$$\frac{\partial W_\tau[\alpha]}{\partial \tau} = \frac{1}{2} \frac{\delta}{\delta \alpha} \left(\chi[\alpha] \frac{\delta}{\delta \alpha} W_\tau[\alpha] \right)$$

“Mean Field Approximation”

Replace $\chi[\alpha]$ by $\langle \chi[\alpha] \rangle_\tau$

“Random Phase Approximation”

Ignore α dependence of $\chi[\alpha]$

Both lead to

$$\frac{\partial W_\tau[\alpha]}{\partial \tau} = \frac{1}{2} \delta_\tau \frac{\delta^2}{\delta \alpha^2} W_\tau[\alpha]$$

Solution is Gaussian

$$W_\tau[\alpha] \sim e^{-\frac{1}{2} \int \alpha \frac{1}{\delta} \alpha} \sim e^{-\int \frac{p^2}{\mu^2}}$$

Mean Field Approximation

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Self consistency condition

$$\langle \chi[\alpha] \rangle_\tau \equiv \chi_\tau(x_1 - y_1) = \int \mathcal{D}\alpha \underbrace{e^{-\frac{1}{2}\alpha \frac{1}{\delta}\alpha}}_{\text{MFA } W_\tau[\alpha]} \chi[\alpha]$$

$$S_\tau(x_1 - y_1) \equiv \langle \text{tr}(V_x^\dagger V_y) \rangle_\tau \quad \text{dipole scattering amplitude}$$

$$\frac{\partial}{\partial \tau} S_\tau(x - y) = \bar{\alpha}_s \int \frac{d^2 z_1}{(2\pi)} \frac{z_1^i - x^i}{(z_1 - x_1)^2} \frac{z_1^i - y^i}{(z_1 - y_1)^2}$$

$$\times \left(1 + S_\tau(x - y) - S_\tau(x - z) - S_\tau(z - y) \right) S_\tau(x - y)$$

Short distance $|x_1 - y_1| \ll 1/Q_s$

$$S_\tau(x_1 - y_1) \simeq 1 - (x_1 - y_1)^2 \# x G(x, 1/(x - y_1)^2)$$

- Leading log \rightarrow DLA equation
- First nonlinear \rightarrow Mueller-Qiu equation correction
- Saturation scale Q_s

$$Q_s^2(\tau) \propto x G(x, Q_s^2(\tau)) \quad Q_s^2(\tau) \sim e^{4\bar{\alpha}_s \tau} \text{DLA}$$

- Gluon number density per unit trans. area.

$$N_\tau(k_1) = \frac{1}{\pi R^2} \frac{d(x G)}{d^2 k_1} \propto 1/k_1^2$$

Random Phase Approximation

At long distance $|x_1 - y_1| \gg 1/Q_s$

$$\langle V_x^\dagger V_y \rangle \simeq 0$$

We can ignore all the Wilson lines in χ .

$$\chi = \int d^2z_1 K_{xyz} \left(1 + \cancel{V_x^\dagger V_y} - \cancel{V_x^\dagger V_z} - \cancel{V_z^\dagger V_y} \right)$$

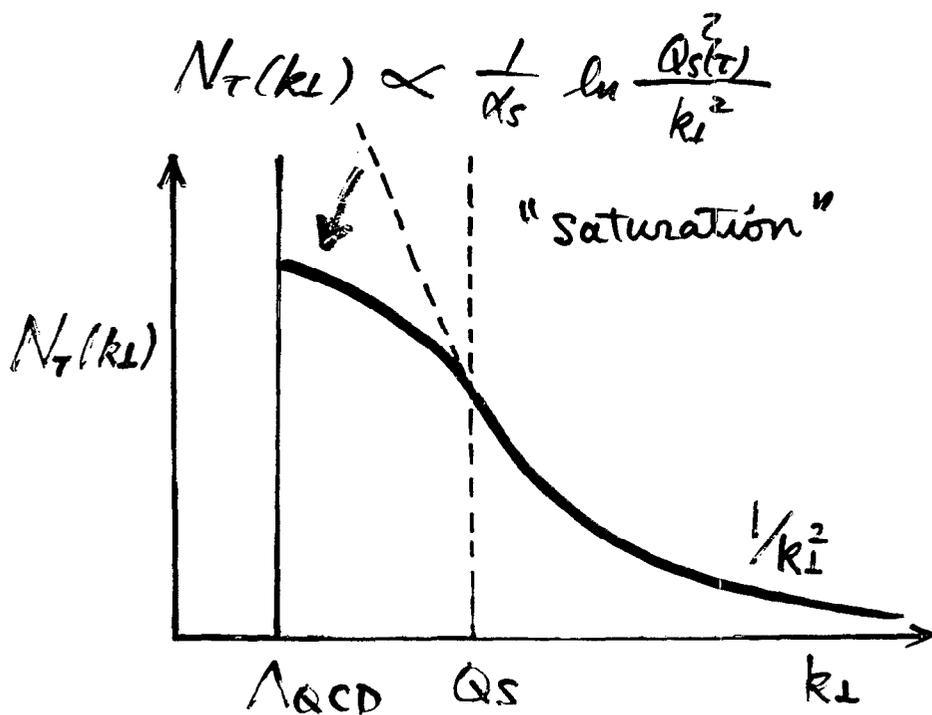
RPA

- Two point function gives a consistent result.

$$\langle V_x^\dagger V_y \rangle \simeq \exp \left\{ -\frac{1}{8} \left[2u(Q_s^2(\tau)(x_1 - y_1)^2) \right]^2 \right\}$$

rapidly decreasing func.

- Gluon # density



Summary

- Color Glass Condensate is the effective theory of saturated gluons at small x .
- Small- x evolution equation for the weight function $W_\tau[\rho]$ is solved by MFA and RPA.
- MFA works well at high momentum region and reproduces DLA and MQ equations.
- RPA works well at low momentum region and leads to gluon saturation.

Renormalization Group Improvement of the Time Dependent Ginzburg-Landau Equation at Finite Temperature

Yukio Nemoto

**Renormalization Group
Improvement
of the Time Dependent
Ginzburg-Landau Equation
at Finite Temperature**

Yukio Nemoto(RBRC)

Teiji Kunihiro (YITP,Kyoto)

Time-Dependent Ginzburg-Landau (TDGL) eq.

Spatial variation of an order parameter of phase transition.

⇒ GL equation

$$-\frac{1}{2m}(\nabla^2 - 2ieA)\Delta + \alpha\Delta + \beta\Delta^3 = 0 \quad (1)$$

An extension to the description of space-time development

⇒ TDGL equation.

$$\gamma_1 \frac{d\Delta}{dt} + \gamma_2 \frac{d^2\Delta}{dt^2} = -\frac{1}{2m}\nabla^2\Delta + \alpha\Delta + \beta\Delta^3 \quad (2)$$

**Various application of the TDGL eq.
Dynamical critical phenomena**

e.g., (for the chiral phase transition)

- Disoriented Chiral Condensate**
- Relativistic Heavy-Ion Collision**
- Color Superconductivity**

Microscopic derivation of the TDGL eq.

BCS \Rightarrow GL eq.

Gor'kov 1959

BCS \Rightarrow TDGL eq.

Abrahams, Tsuneto 1966

two limited cases ($T = 0, T \approx T_C$)

(Otherwise Landau damping terms diverge.)

Chiral effective theory (NJL model) has the same problem.

NJL \Rightarrow TDGL

Eguchi, Sugawara 1974 (for $T = 0$)

Our purpose

We employ the RG equation to the Landau damping which causes divergence. \Rightarrow coarse graining of time scale.

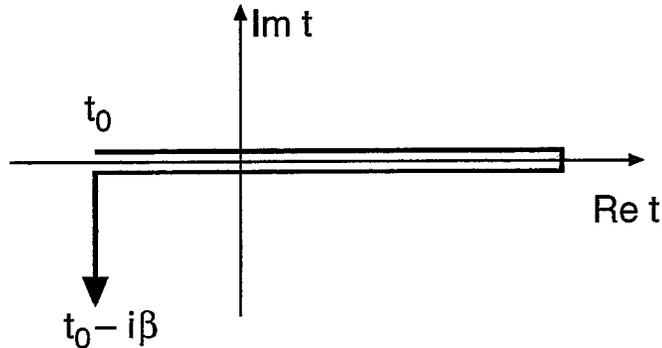
We use the 2-flavor NJL model.

2-flavor NJL model

$$\mathcal{L} = \bar{q}i\not{\partial}q + g[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2] \quad (3)$$

The Green function satisfies the equation

$$(i\not{\partial}_x - M(t_x; t_0))S(x, x') = \delta_c^4(x - x') \quad (4)$$



(closed time path)

Self-consistency condition

$$M(t; t_0) = 2gi\text{Tr}[S(x, x^+)] \quad (5)$$

We neglect the fluctuation of pions, for simplicity.

t_0 : initial time (assumes local equilibrium)

In relative and center-of-mass coordinates,

$$S(t = t_x - t_y, T = (t_x + t_y)/2)$$

t : microscopic variable,

T : macroscopic variable

The lowest order solution (=Hartree)

$$S(t, t^+) = S_0(t, t^+), \quad M(t; t_0) = M(T) \quad (6)$$

The next order

$$\begin{aligned} S(t, t^+) &= S_0(t, t^+) \\ &+ \int_c dt' \int d^3y S_0(t, t') (M(t') - M(T)) \\ &\quad \times S_0(t', t^+) \end{aligned} \quad (7)$$

$M(t')$ is expanded around $t(=T)$

$$M(t') = M(t) + (t' - t) \frac{dM}{dt} + \frac{1}{2} (t' - t)^2 \frac{d^2M}{dt^2} + \dots \quad (8)$$

Each derivative-term is not periodic in the imaginary time direction. (T.S.Evans 1998)

\Rightarrow One cannot perform the naive Fourier transform.

\Rightarrow We compute the time-integral directly.

At the order $O\left(\frac{dM}{dt}\right)$

$$\begin{aligned}
 M(t; t_0) = & 8gN_c \int \frac{d^3k}{(2\pi)^3} \left[\frac{M(T)}{E} (1 - 2f(E)) \right. \\
 & - i \frac{1}{E^2} \frac{E^2 - M(T)^2}{E} \left\{ -e^{2i(t-t_0)E} f(E)^2 \right. \\
 & + e^{-2i(t-t_0)E} (1 - f(E))^2 \\
 & \left. \left. + M(T)^2 \beta (\beta - 2i(t - t_0)) f(E)(1 - f(E)) \right\} \right] \\
 & \times \frac{dM(t)}{dt} \Bigg], \quad E = \sqrt{k^2 + M(T)^2} \quad (9)
 \end{aligned}$$

Note 1: We neglect the variation of the temperature.

Note 2: The Landau damping term is divergent if one performs F.T. in time. This means $t_0 \rightarrow -\infty$.

Note 3: The Landau damping term is finite, but appears as a secular term in our case.

This is similar to the situation of kinetic equations. (Boyanovsky et.al.)

Note 4: The second-derivative term has the same structure.

The initial time t_0 is important!

Treatments of the secular terms
 \Rightarrow Renormalization group approach

t_0 is considered as the macroscopic variable, $t_0 \sim T$.

$$\boxed{\left. \frac{dM(t; t_0)}{dt_0} \right|_{t_0=T}}$$

This means that we extract the slow (macroscopic) motion. Note $\frac{d}{dt} \neq \frac{d}{dT}$.

The result is

$$\frac{dM}{dT} = -2gN_c \int \frac{d^3k}{(2\pi)^3} M(T)^2 \beta^2 f(E)(1-f(E)) \frac{dM}{dt} \quad (10)$$

The t -derivative is written as

$$\frac{dM}{dt} = \left[1 - 8N_c \int \frac{d^3k}{(2\pi)^3} \frac{1}{E} \left\{ \frac{E^2 - M(t)^2}{E^2} (1 - 2f(E)) + M(t)\beta f(E)(1 - f(E)) \right\} \right]^{-1} \quad (11)$$

and finally replaces $t \rightarrow T$.

Comments

- It is straightforward to extend this result to systems at finite density.
- At $T \approx T_c$, the TDGL eq. is diffusion-like in superconductor, while it is wave-like in the NJL model.

Summary

We have derived the TDGL eq. from the NJL model at finite temperature. The important is to set up the (finite) initial time t_0 . The Landau damping terms are then divergence-less and appear as the secular terms. The secular terms are removed by extracting the slow motion of time, whose idea is based on the renormalization group method. (e.g., Ei, Fujii and Kunihiro(2000))

Future works

- Generalization (pion, vector, axialvector fields)
- Derivation: $\text{BCS} \implies \text{TDGL eq.}$
- Applications to various phenomena (DCC etc.)

Domain Walls in High-Density QCD and in Atomic Bose-Einstein Condensates

Dam Thanh Son

CONFINEMENT AND DOMAIN WALLS IN HIGH DENSITY QUARK MATTER

D. T. Son

D. Rischke, DTS, M. Stephanov PRL 87 (2001) 062001
DTS, M. Stephanov, A. Zhitnitsky PRL 86 (2001) 3955

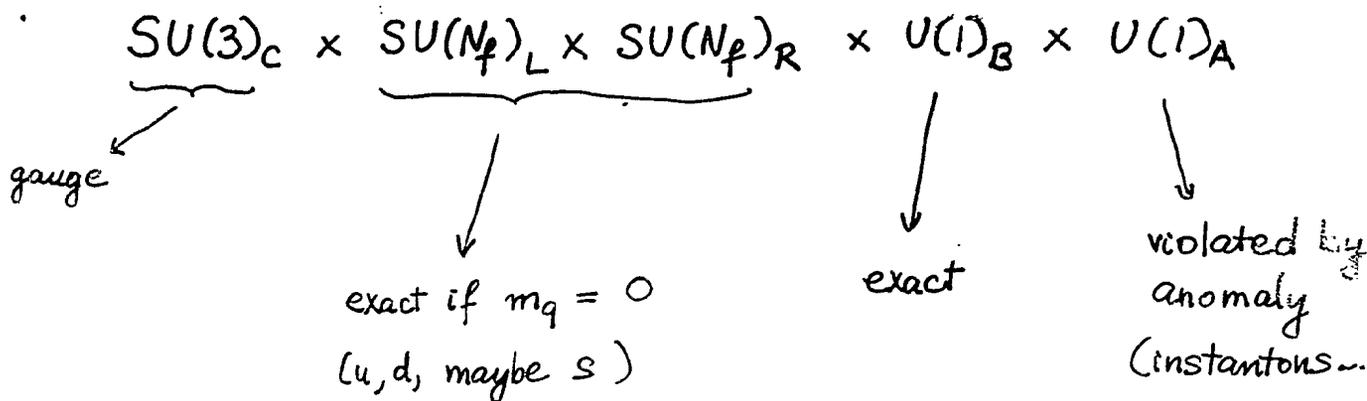
QCD Lagrangian and symmetries

$$L = \bar{q} (i\not{D} - m) q - \frac{1}{4} F_{\mu\nu}^2$$

$$q = \begin{pmatrix} q_L \\ q_R \end{pmatrix}_{ai}$$

$$a = 1, 2, 3$$

$$i = u, d, s, \dots$$



$$SU(3)_C : q^a \rightarrow \Lambda^{ab}(x) q^b$$

$$A_\mu \rightarrow \Lambda A_\mu \Lambda^{-1} + \Lambda \partial_\mu \Lambda^{-1}$$

$$SU(3)_L : q_L^i \rightarrow U^{ij} q_L^j$$

$$SU(3)_R : q_R^i \rightarrow U^{ij} q_R^j$$

$$U(1)_B : q_L \rightarrow e^{i\alpha} q_L \quad q_R \rightarrow e^{i\alpha} q_R$$

$$U(1)_A : q_L \rightarrow e^{i\alpha} q_L \quad q_R \rightarrow e^{-i\alpha} q_R$$

In vacuum : $SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V$

$$\langle \bar{q}_L q_R \rangle \neq 0$$

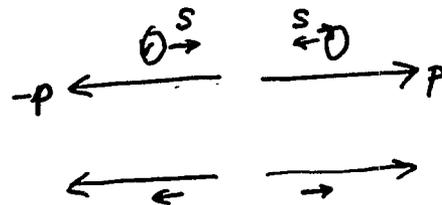
Symmetries at high densities: depends on N_f

• $N_f = 2$ (u, d)

quark pairing

$$\langle q_L q_L \rangle \neq 0$$

$$\langle q_R q_R \rangle \neq 0$$



More precisely:

$$X^a = \epsilon^{abc} \epsilon^{ij} \epsilon^{\alpha\beta} \langle q_{L\alpha}^{bi} q_{L\beta}^{cj} \rangle^*$$

$$Y^a = \epsilon^{abc} \epsilon^{ij} \epsilon^{\alpha\beta} \langle q_{R\alpha}^{bi} q_{R\beta}^{cj} \rangle^*$$

If $X^a \parallel Y^a$: $SU(3)_c \rightarrow SU(2)_c$

Chiral $SU(2)_L \times SU(2)_R$ unbroken ϵ_{ij}

X^a and Y^a are not gauge invariant

but $\Sigma = X^{a*} Y^a$ is gauge invariant

breaks $U(1)_A$ symmetry

$$q_L \rightarrow e^{i\alpha} q_L$$

$$X \rightarrow e^{-2i\alpha} X$$

$$q_R \rightarrow e^{-i\alpha} q_R$$

$$Y \rightarrow e^{2i\alpha} Y$$

$$\Sigma \rightarrow e^{4i\alpha} \Sigma$$

DECONFINEMENT ?

Naively: distance between quarks $\sim \mu^{-1} \ll \Lambda_{\text{QCD}}^{-1}$
quarks become free at high densities

BUT: unbroken $SU(2)_c$ must be confining.
How?

Look at a test charge in plasma

Normal plasma:

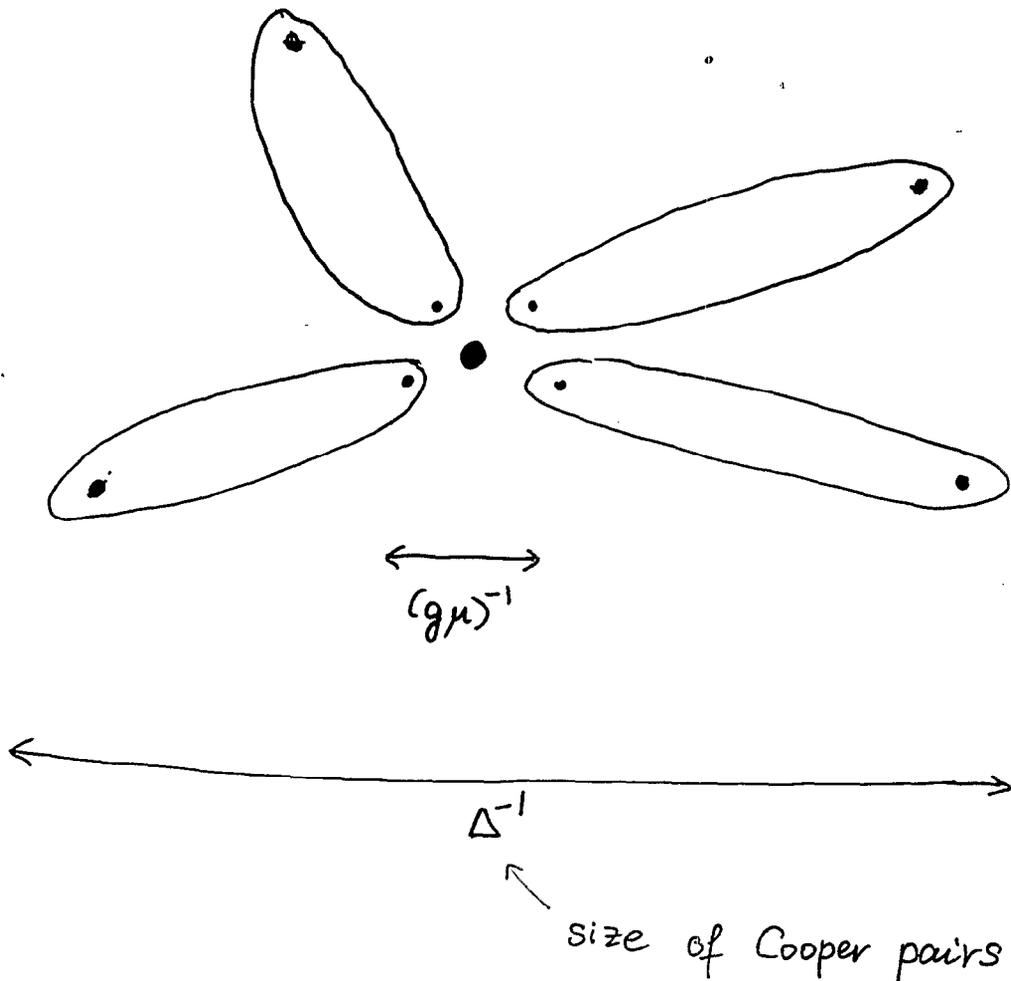


test charge attracts oppositely charged particles
in plasma

\Rightarrow Debye screening

$$m_D \sim g\mu$$

Test $SU(2)_c$ change in color superconductor



Test charge cannot be completely screened at distances larger Δ^{-1} : Cooper pairs are $SU(2)_c$ neutral

But: medium is polarizable

\Rightarrow dielectric constant $\epsilon \neq 1$
↑
color

like water

Confinement:

Effective Lagrangian for gluons (energies below Δ)

$$L = \frac{\epsilon}{2} \vec{E}^a \cdot \vec{E}^a - \frac{1}{2} \vec{B}^a \cdot \vec{B}^a \quad \epsilon = \frac{g^2 \mu^2}{18\pi^2 \Delta^2}$$

2 effects:

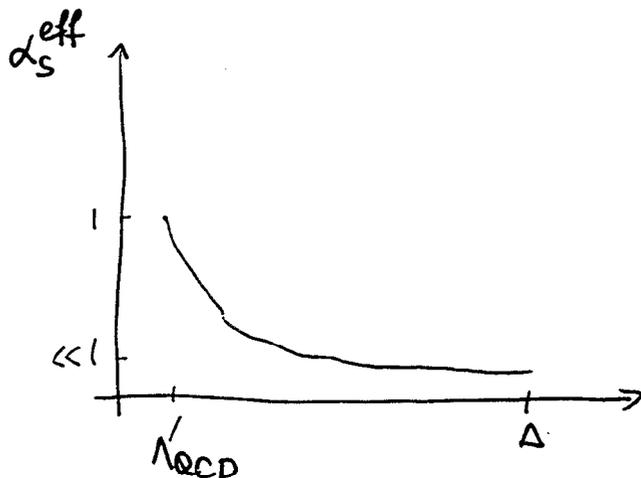
- Coulomb's law $\frac{g^2}{r} \rightarrow \frac{g^2}{\epsilon r}$

$$g_{\text{eff}}^2 = \frac{g^2}{\epsilon}$$

- Gluon velocity $v = \frac{1}{\sqrt{\epsilon}} \ll 1$

$$\alpha_s = \frac{g^2}{4\pi \hbar c} \rightarrow \alpha_s^{\text{eff}} = \frac{g_{\text{eff}}^2}{4\pi \hbar v} = \frac{g^2}{4\pi} \cdot \frac{1}{\sqrt{\epsilon}}$$

\Rightarrow effective strong coupling is very small at scale Δ



$$\Lambda_{\text{QCD}} \sim \Delta \exp\left(-\frac{2\pi}{\beta_0 \alpha_s^{\text{eff}}}\right)$$

$$\sim \Delta \exp\left(-\frac{2\sqrt{2}\pi}{11} \frac{\mu}{g\Delta}\right)$$

depending on Δ
can be from $O(1 \text{ keV})$
to $O(10 \text{ MeV})$

DOMAIN WALLS

Recall: ~~color~~ color superconductivity breaks $U(1)_A$
Spontaneously

Let ϕ be the $U(1)_A$ phase of the condensate

$$\Sigma = |\Sigma| e^{i\varphi}$$

then if $U(1)_A$ was an exact symmetry

$$L_{\text{eff}} = f^2 [(\partial_0 \varphi)^2 - u^2 (\partial_i \varphi)^2]$$

$$= \frac{\mu^2}{8\pi^2}$$

$U(1)_A$ susceptibility

$$= \frac{1}{3}$$

BUT: $U(1)_A$ is explicitly violated by:

- quark masses
- anomaly, instantons

Explicit violation of $U(1)_A$ becomes weaker at
higher density

(instantons become more dilute)

$$L = f^2 [(\partial_0 \varphi)^2 - u^2 (\partial_i \varphi)^2] - V(\varphi)$$

↑ from instantons, quark masses
periodic

$$V(\varphi) = -a \mu^2 \Delta^2 \cos \varphi$$

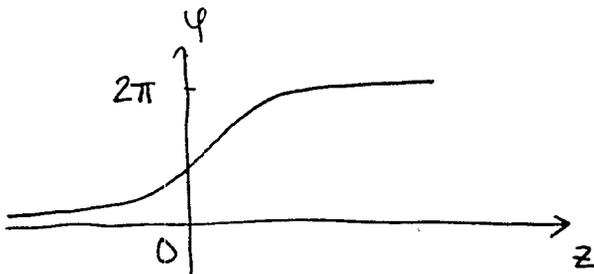
$$a \rightarrow 0$$

$$\mu \rightarrow \infty$$

$$a \sim \underbrace{O\left(\left(\frac{\Lambda_{\text{QCD}}}{\mu}\right)^{29/3}\right)}_{\text{instantons}} + \underbrace{O\left(\frac{m_u m_d}{\mu^2}\right)}_{\text{quark masses}}$$

This is Sine-Gordon theory

which possesses domain wall solution



$$\varphi(z) = 4 \arctan e^{mz/u}$$

$$m = 2\pi \sqrt{a} \Delta$$

mass of pseudoscalar
singlet.

Notes: 1) Needs $m \lesssim 2\Delta$

for effective theory to be effective

2) Ground states on 2 sides of domain wall
are identical

⇒ non-topological domain wall

(similar to $N=1$ axion domain walls)

Chiral Properties of Domain Wall Fermions with Improved Gauge Actions

Kostas Orginos

Chiral properties of Domain Wall Fermions with Improved Gauge actions



K. Orginos

RBC group

- Introduction and Motivation.
 - Chiral properties of DWF.
 - Gauge Actions.
 - Tests and Comparisons.
 - Conclusions.
-

Introduction - Motivation

Domain Wall Fermion Chiral Ward Identity:

[Furman & Shamir Nucl.Phys. B439 (1995)]

$$\begin{aligned}\Delta_\mu \langle \mathcal{A}_\mu^a(x) O(y) \rangle &= 2m_f \langle J_5^a(x) O(y) \rangle \\ &+ 2 \langle J_{5q}^a(x) O(y) \rangle + i \langle \delta^a O(y) \rangle.\end{aligned}$$

$\mathcal{A}_\mu^a(x)$: Axial Current

$J_5^a(x)$: Pseudo-scalar density

$J_{5q}^a(x)$: Anomalous Pseudo-scalar density

$$\lim_{L_s \rightarrow \infty} \langle J_{5q}^a(x) O(y) \rangle = 0$$

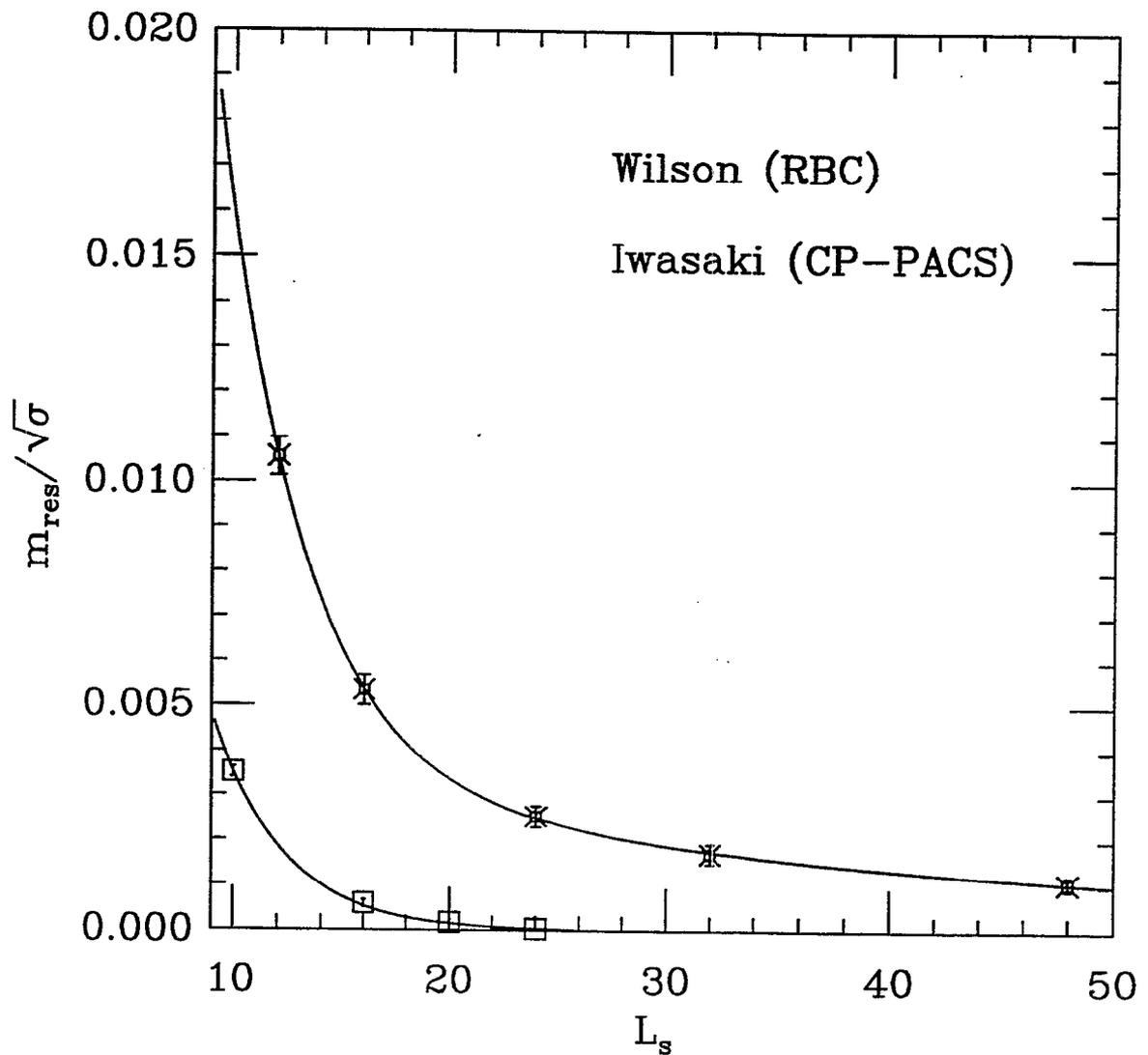
- $L_s \rightarrow \infty$: Exact chiral symmetry
- Finite L_s : Exponentially suppressed breaking

Measure of Chiral Symmetry Breaking:

$$m_{\text{res}} = \frac{\langle J_{5q}^a(0) J_5^a(t) \rangle}{\langle J_5^a(0) J_5^a(t) \rangle} \Big|_{t \gg t_{\text{min}}}$$

Assume at low energy $J_{5q}^a \sim m_{\text{res}} J_5^a$

Data



- Exponential suppression is small.
at $a^{-1} = 2\text{GeV}$ $m_{res} \sim q^{L_s}$
Wilson gauge $q \sim .97$
Iwasaki gauge $q \sim .74$
- m_{res} varies with the Gauge Action.

Objective

Minimize Chiral Symmetry breaking in the space of Gauge Actions.

Actions Tested:

- Wilson: $S_g = \frac{\beta}{3} \text{Re Tr} \left\langle 1 - \text{square} \right\rangle$

- One loop Symanzik:

$$S_g = \frac{\beta}{3} \text{Re Tr} \left[c_0 \left\langle 1 - \text{square} \right\rangle + 2c_1 \left\langle 1 - \text{rectangle} \right\rangle + \frac{4}{3} c_2 \left\langle 1 - \text{pentagon} \right\rangle \right]$$

c_i computed by 1-loop tadpole improved perturbation theory.

[Lüscher & Weisz Phys.Lett. B158 (1985)]

[Alford *et.al.* Phys.Lett. B361 (1995)]

- Iwasaki:

$$S_g = \frac{\beta}{3} \text{Re Tr} \left[(1 - 8c_1) \left\langle 1 - \text{square} \right\rangle + 2c_1 \left\langle 1 - \text{rectangle} \right\rangle \right]$$

With $c_1 = -0.331$ computed by perturbative RG blocking.

[Iwasaki (1983)]

- DBW2: Same as Iwasaki but $c_1 = -1.4067$ computed non-perturbatively by RG blocking.

[Takaishi Phys.Rev. D54 (1996)]

The DBW2 action

Doubly Blocked Wilson 2 [Takaishi Phys.Rev. D54 (1996)]

- Start from Wilson $\beta = 6.3$ on a $32^3 \times 64$ lattice
- Doubly Block by a factor 2 (Swendsen's Blocking)
- Solve the Schwinger-Dyson equations to find the effective action.
- Truncate to the two coupling space:

$$S_g = \beta_{11} \frac{1}{3} \text{ReTr} \langle 1 - \text{square} \rangle + \beta_{12} \frac{1}{3} \text{ReTr} \langle 1 - \text{rectangle} \rangle$$

DBW2 definition:

$$\frac{\beta_{12}}{\beta_{11}} = -0.1148$$

QCD-TARO [Nucl.Phys. B577 (2000)] studied the RG flow on the 2D plane of couplings and showed that DBW2 is approximately RG invariant.

The transfer matrix

Chiral Symmetry breaking is controlled by the nearly unit eigenvalues of the Transfer Matrix \mathcal{T} in the 5th dimension.

[Boriçi hep-lat/9912040]

$$\mathcal{T}^{-1} = \frac{1 + \mathcal{H}_t}{1 - \mathcal{H}_t}$$

with

$$\mathcal{H}_t = \frac{1}{2 + \mathcal{D}_w^\dagger(-M_5)} \gamma_5 \mathcal{D}_w(-M_5)$$

- $\mathcal{H}_t |n\rangle = 0 \Rightarrow \gamma_5 \mathcal{D}_w(-M_5) |n\rangle = 0 \Rightarrow \mathcal{T} |n\rangle = 1$
- $\gamma_5 \mathcal{D}_w(-M_5)$ has a lot of nearly zero eigenvalues.
[Neuberger, Narayanan] [Edwards, Heller, Narayanan]
[Hernandez *et.al.* Nucl.Phys. B552 (1999) ; hep-lat/0007015]
- Their frequency decreases rapidly as the continuum limit is approached.
- Proposals of improvement: “*Just remove them*”

[See above citations]

Improved Chirality \iff Suppressed \mathcal{H}_t Zero modes

We would like to:

- See the signal of \mathcal{H}_t Zero modes
- Chirality Breaking per configuration:

$$R(t) = \frac{J_{5q}^a(0)J_5^a(t)}{J_5^a(0)J_5^a(t)}$$

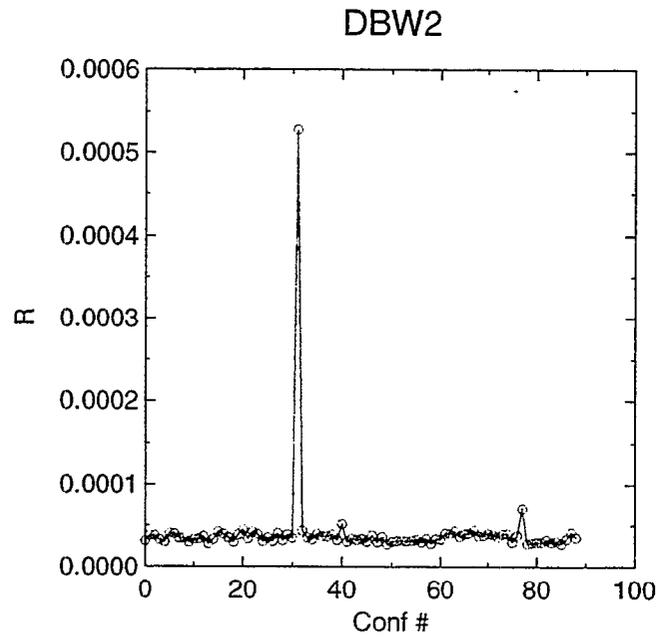
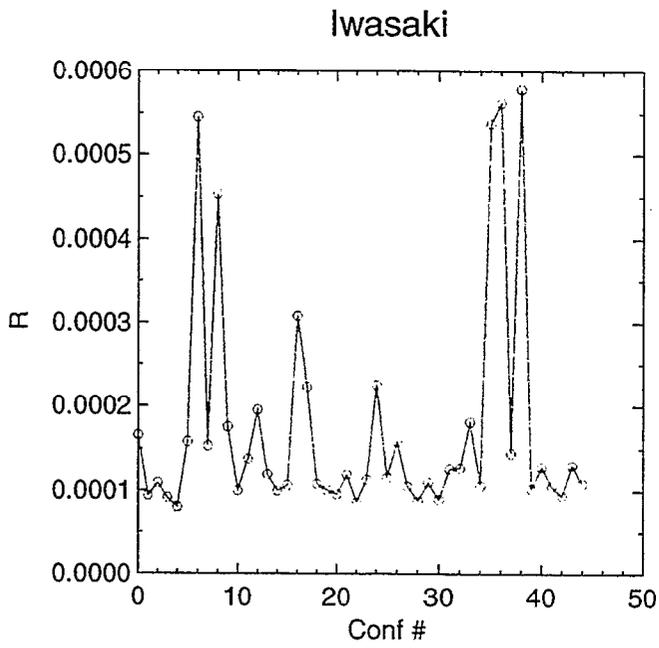
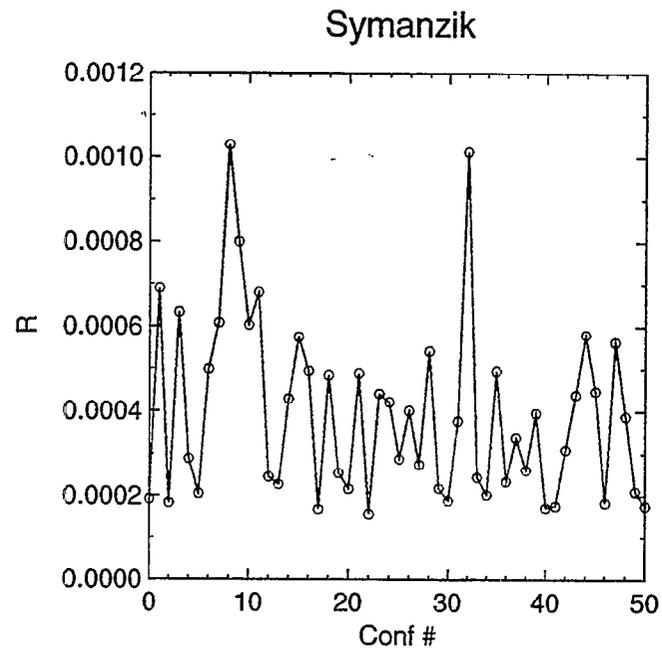
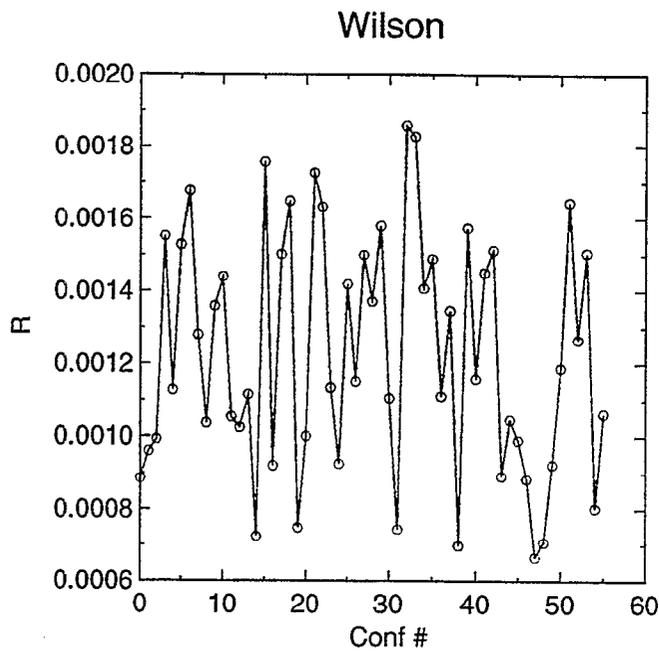
- See how much we can change the number of Zero modes by changing the gauge action, and hence improve Chiral Symmetry

Simulations

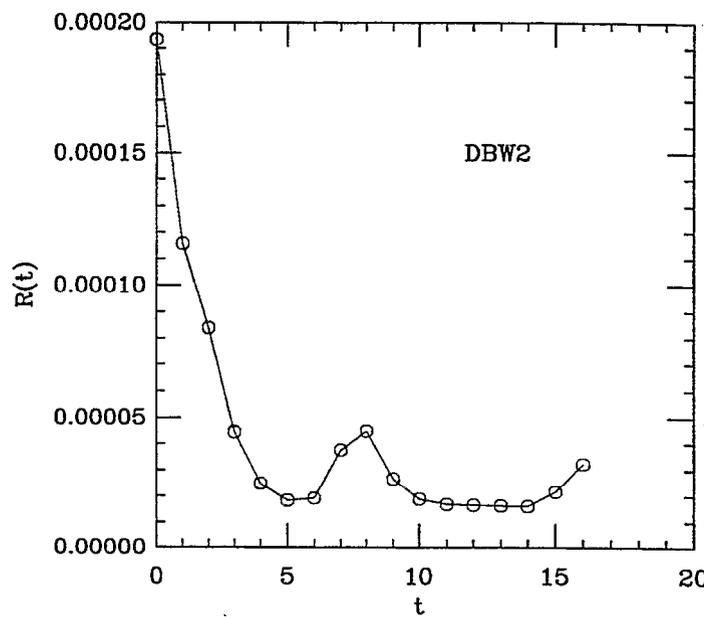
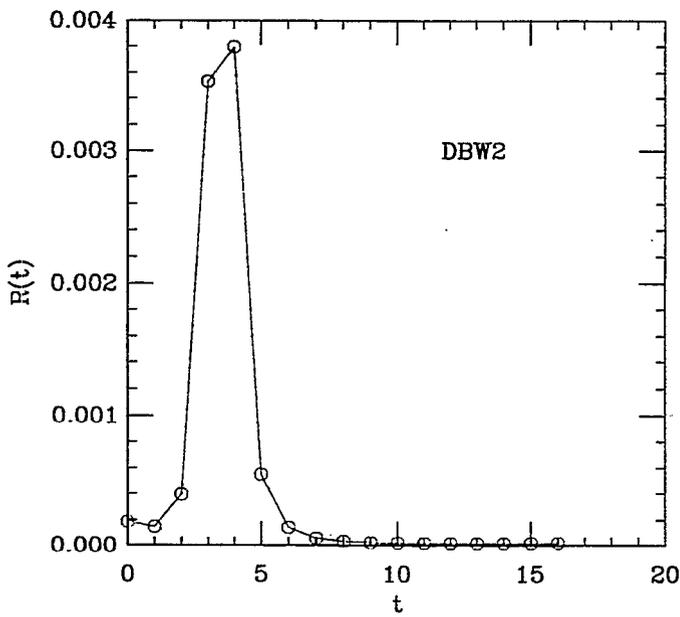
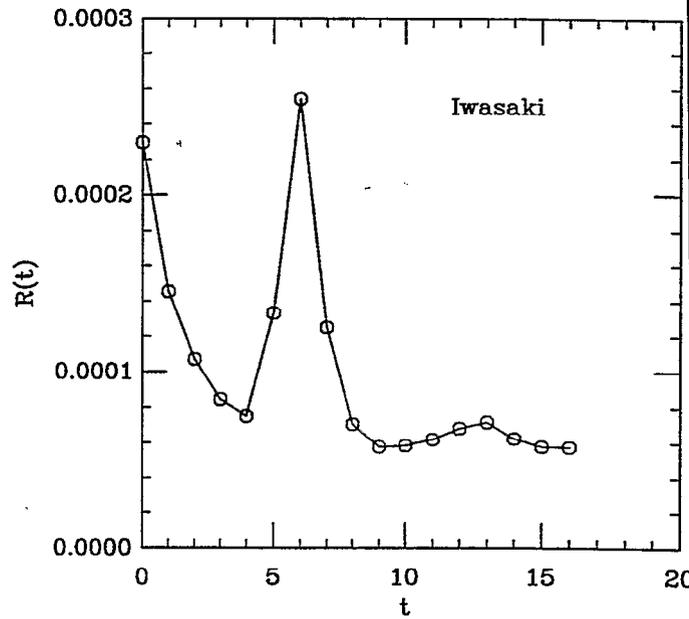
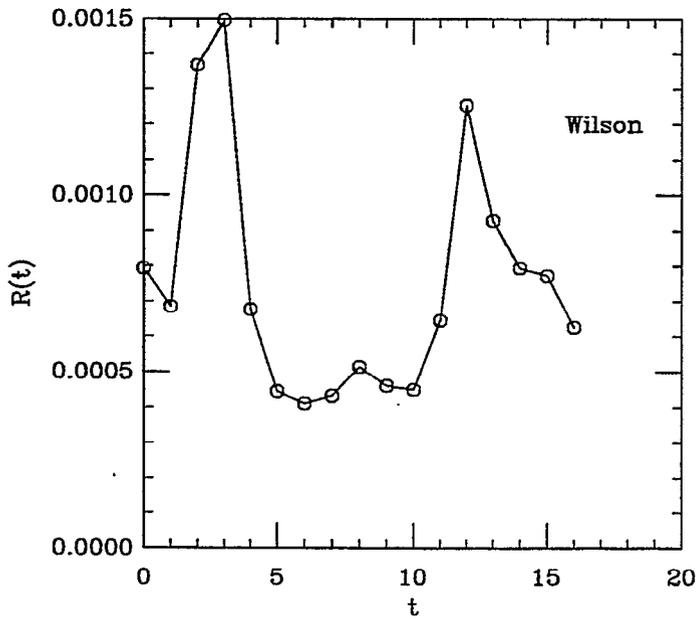
We measured the light hadron spectrum; the residual mass, and the ratio $R(t)$ (defined in the previous page) on $16^3 \times 32$ lattices.

- $a^{-1} \sim 2\text{GeV}$ (from the ρ mass)
Matches the Wilson $\beta = 6.0$
- Bare quark masses 0.02 0.04 and 0.06
- Varied M_5 in the range 1.4 - 2.0
- Varied L_s (8 12 16)
- Gauge actions:
 - 1-loop Symanzik (50 configs)
 - Iwasaki (50 configs one L_s)
 - DBW2 (90 configs)

We also have data for DBW2 at $a^{-1} \sim 1.3\text{GeV}$
 $16^3 \times 32$ (Y. Aoki's talk for the spectrum results).

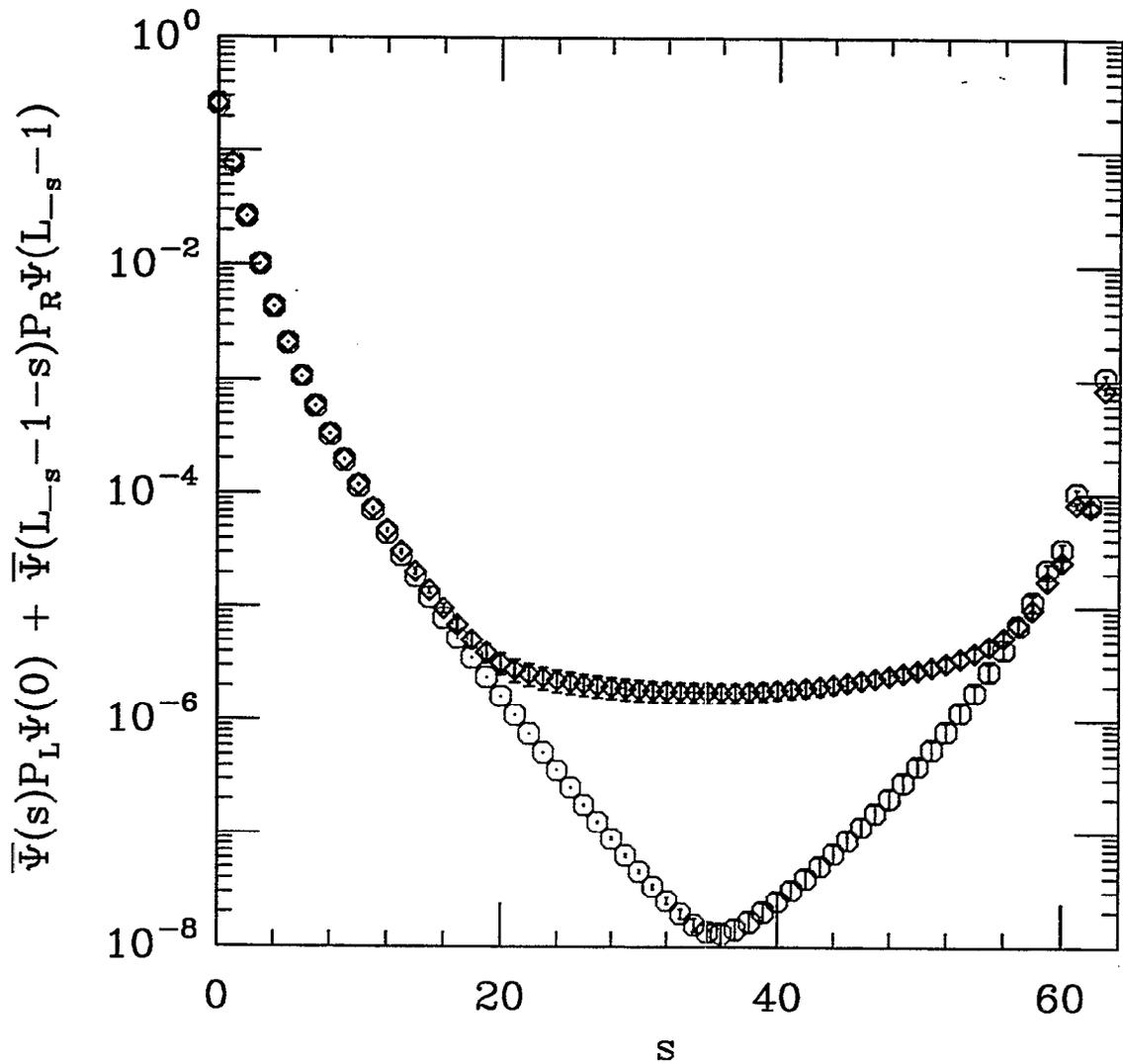


$$R = \sum_t R(t) = \frac{J_{5q}^a(0)J_5^a(t)}{J_5^a(0)J_5^a(t)}$$



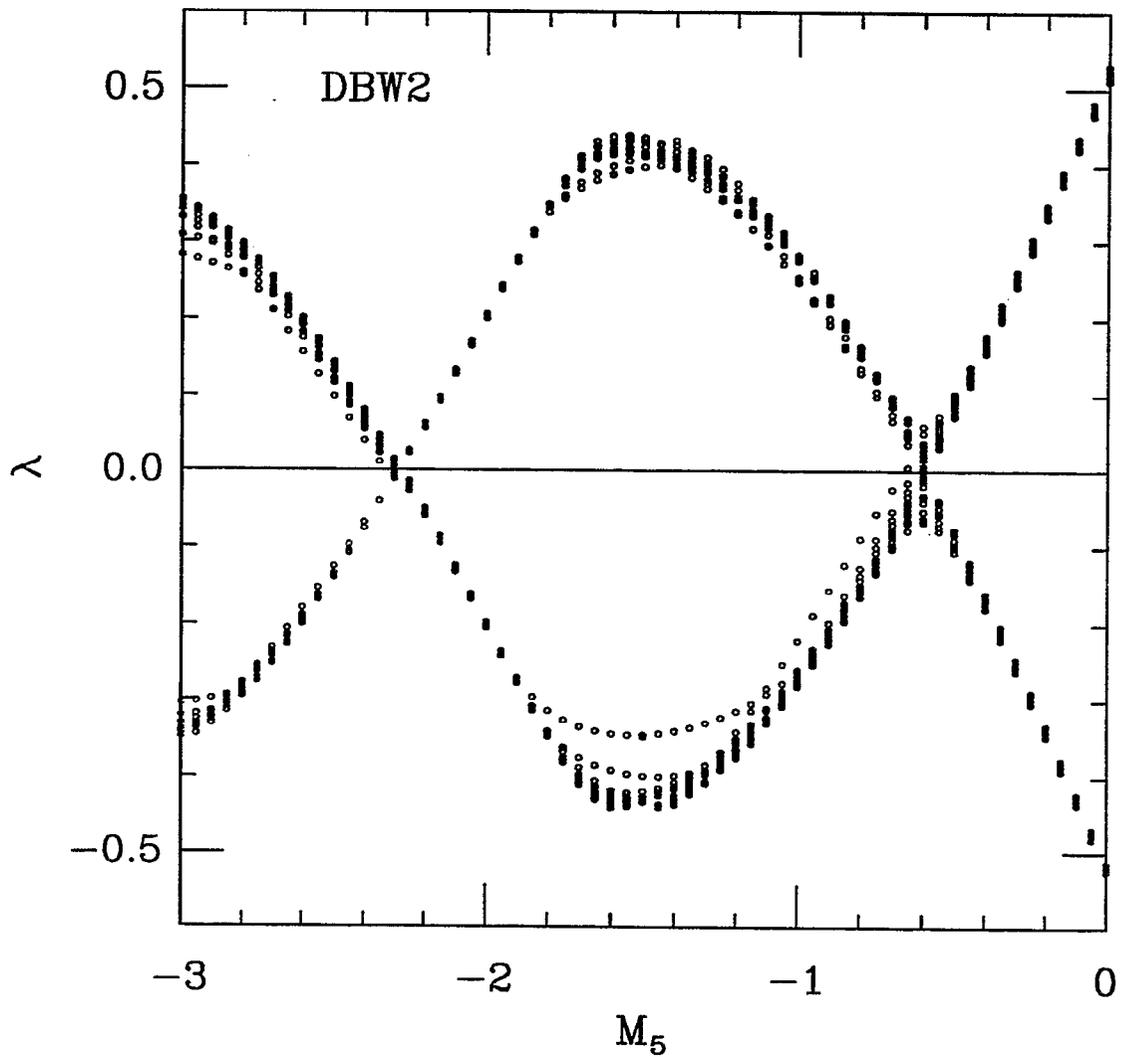
$R(t)$ spikes indicate the localization of the Zero Modes.

The Zero Mode



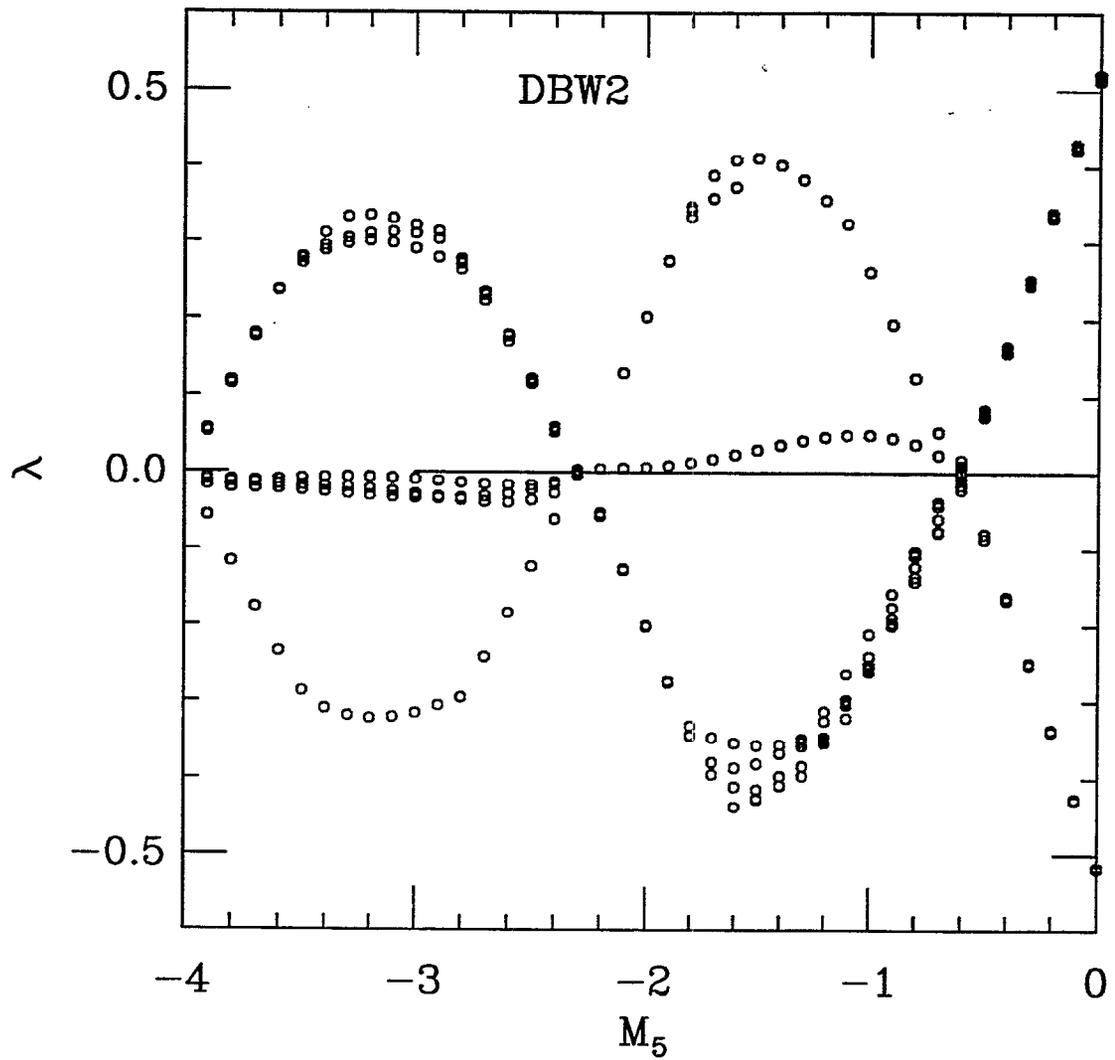
$$\begin{aligned} \bar{\Psi}\Psi(s) &= \bar{\Psi}(s)\frac{1-\gamma_5}{2}\Psi(0) + \\ &+ \bar{\Psi}(L_s-1-s)\frac{1+\gamma_5}{2}\Psi(L_s-1) \end{aligned}$$

Spectral flow



Spectral flow of $\gamma_5 \mathcal{D}_w(-M_5)$

[T. Izubuchi talk]



This is the single spike DBW2 has.

(one out of 90 configurations).

[T. Izubuchi talk]

Observations

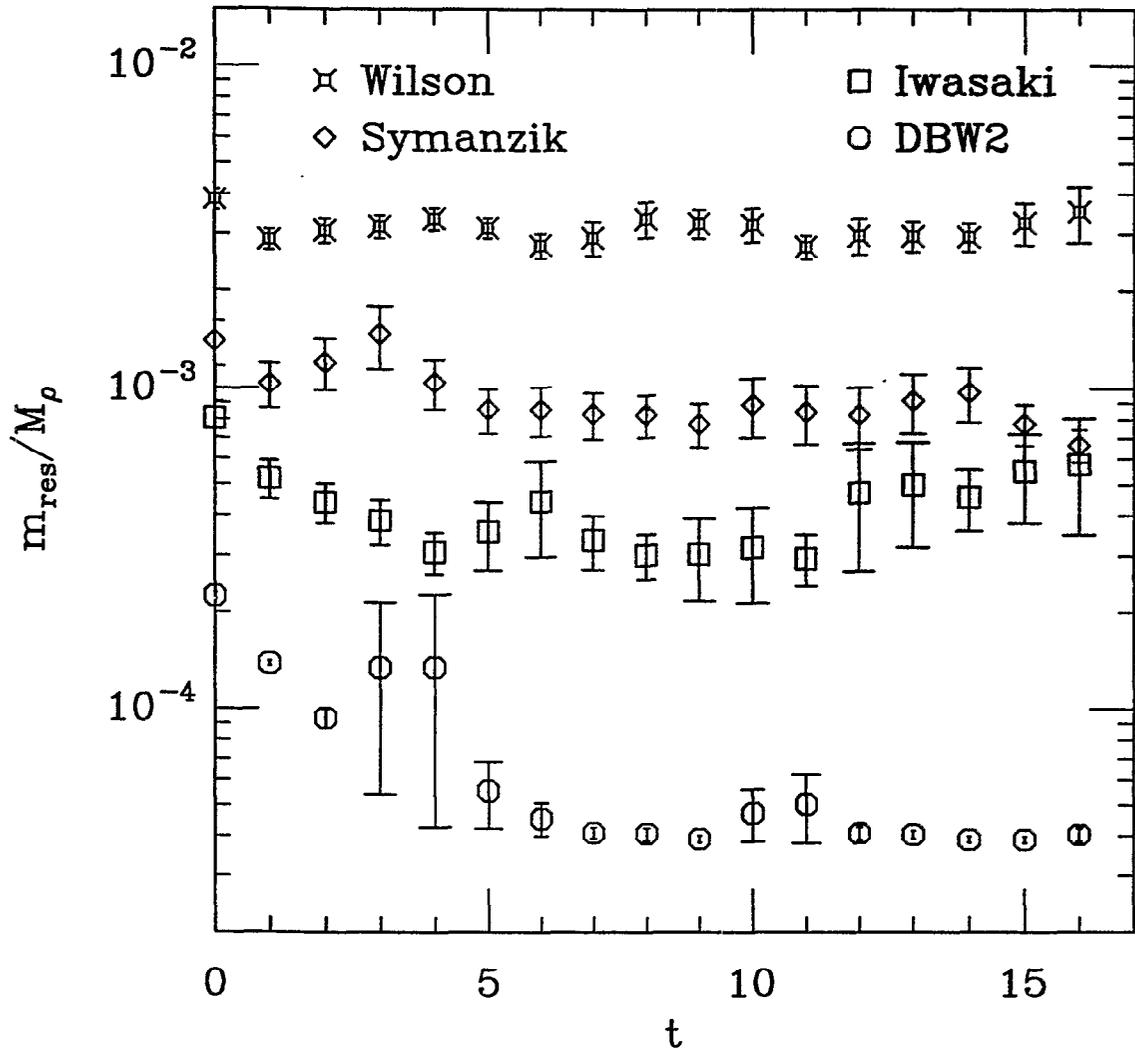
Summary of “Zero Mode” observations:

- They are localized
- They enhance Chirality breaking
- Significantly fewer for Iwasaki and DBW2

Expectation:

- DBW2 improves Chiral Symmetry

m_{res}

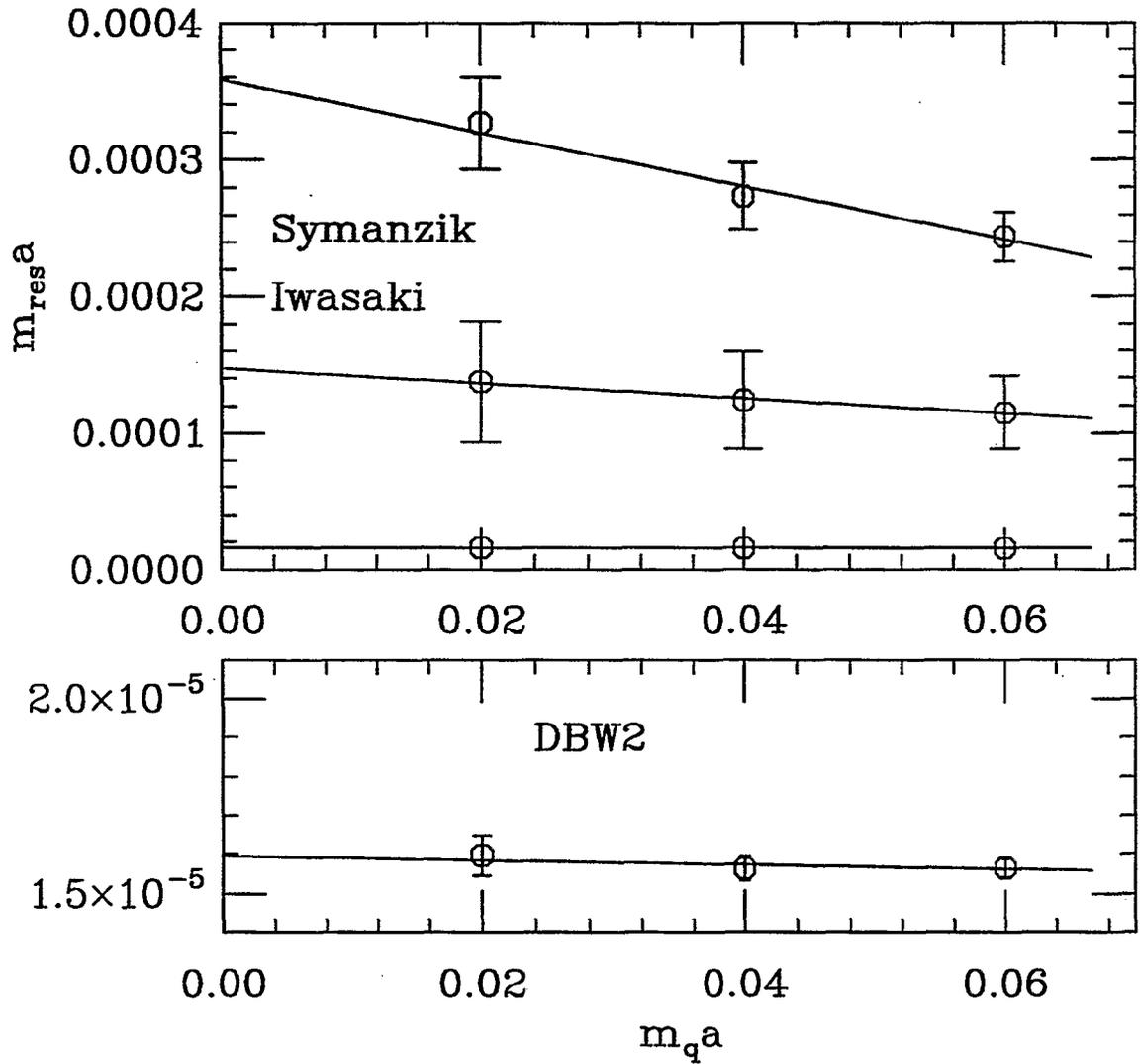


Bare quark mass is 0.020

$L_s = 16$

$M_5 = 1.8$ (for DBW2 $M_5 = 1.7$)

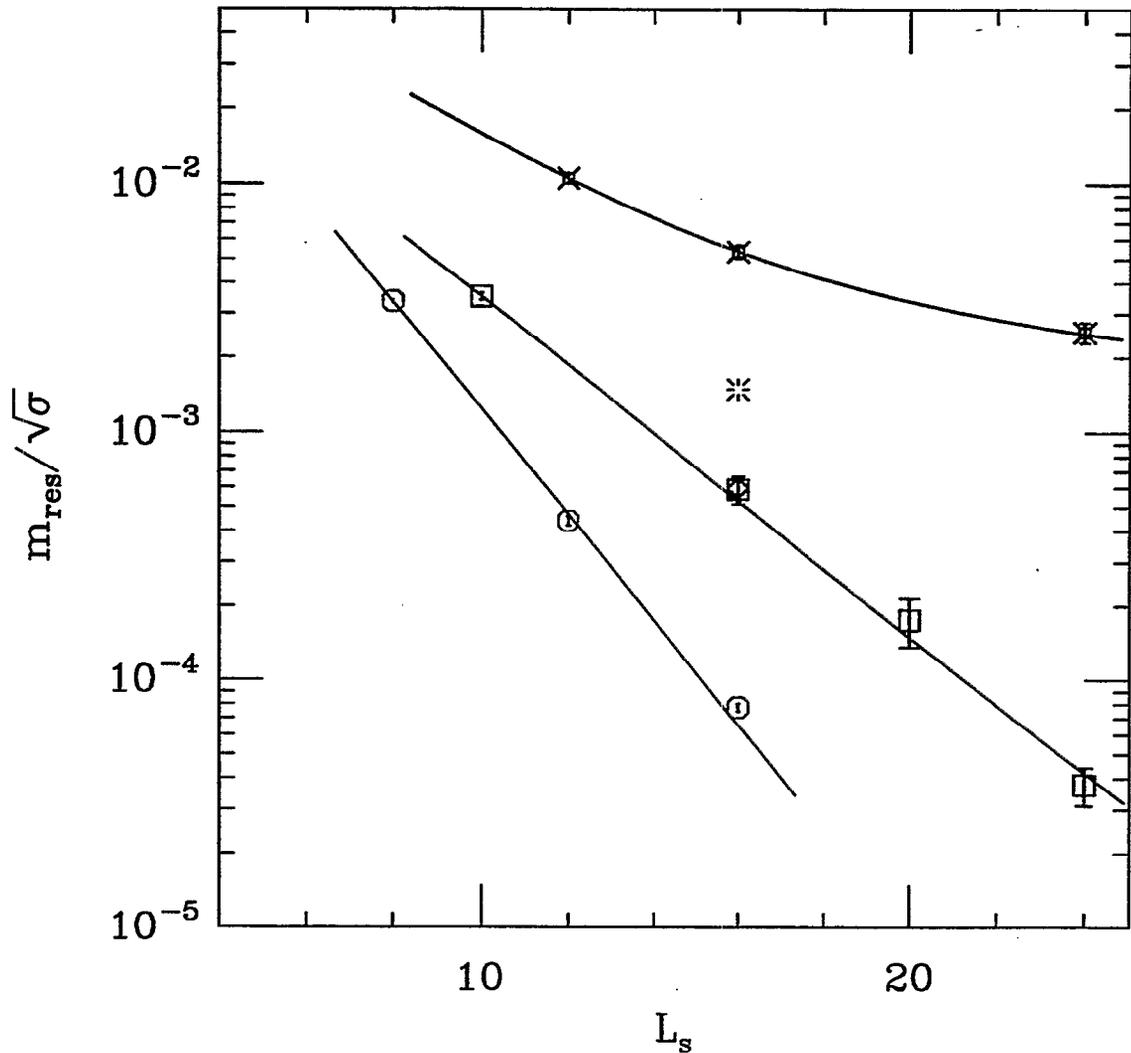
m_{res} VS m_q



$$L_s = 16$$

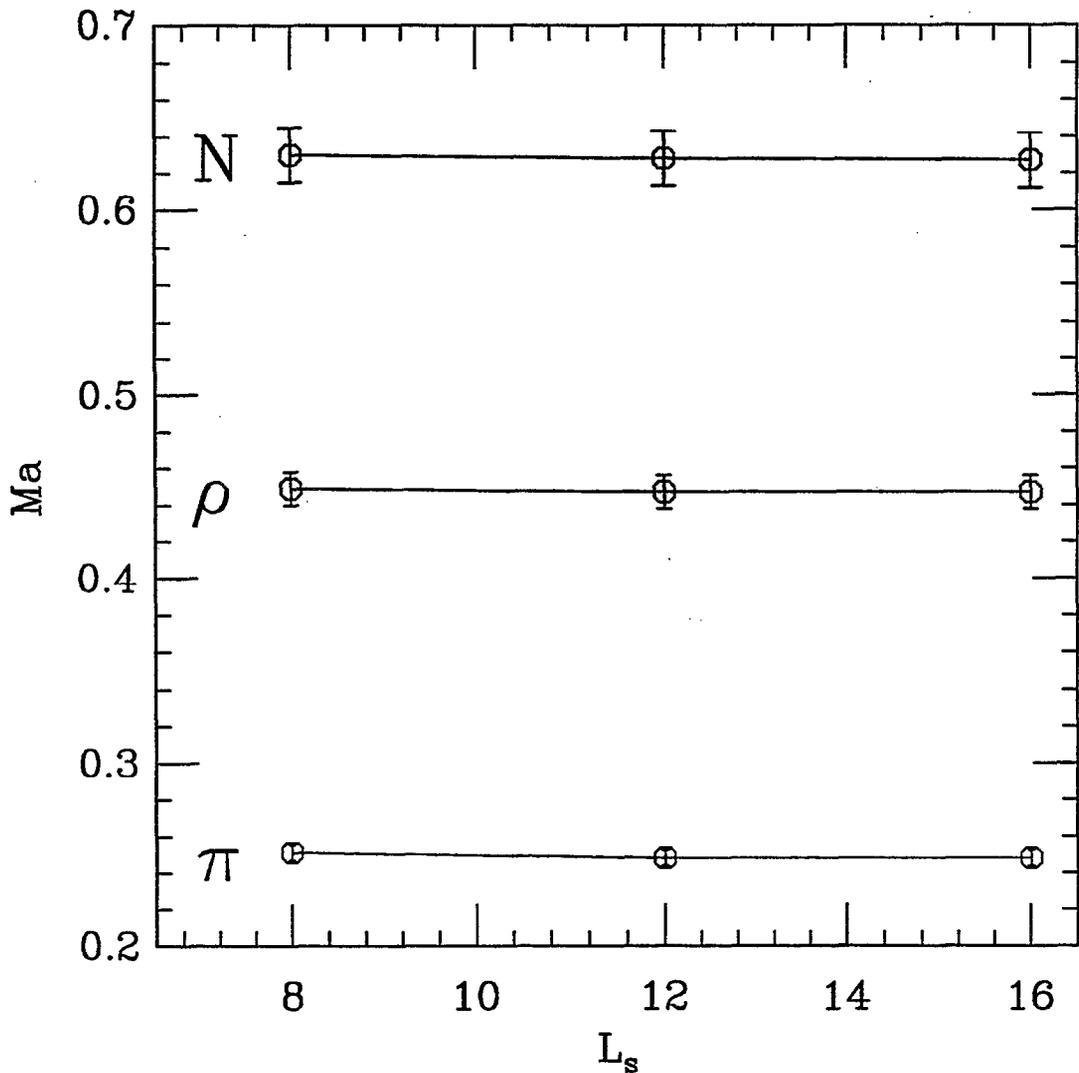
$$M_5 = 1.8 \text{ (for DBW2 } M_5 = 1.7)$$

m_{res} VS L_s



- DBW2 action ($m_{res}(s) \sim q^s$ with $q \sim .6$).
- Iwasaki action [CP-PACS Phys.Rev. D63 (2001)]
- Symanzik action.
- Wilson action [RBC hep-lat/0007038]

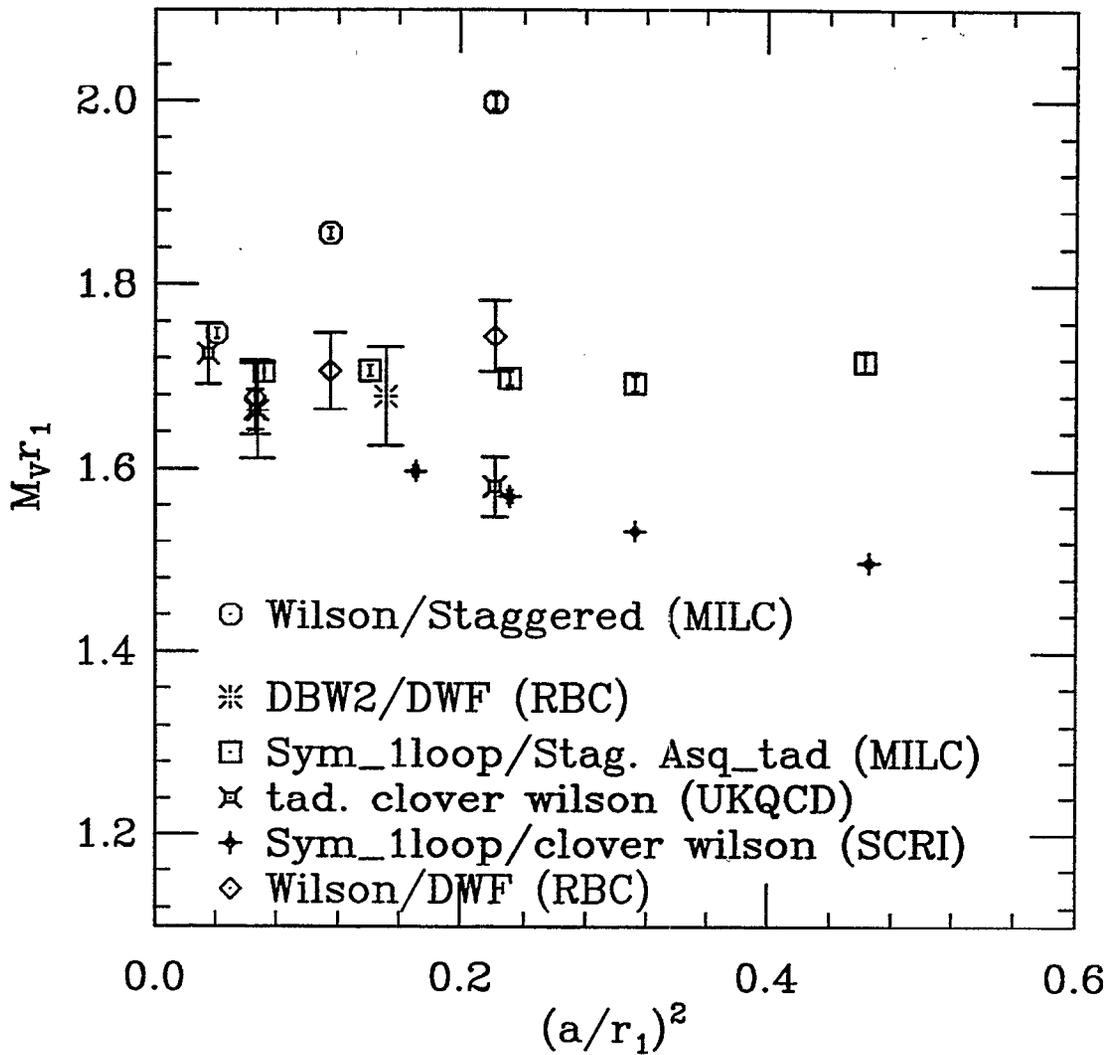
Hadron Masses vs L_s



Action: DBW2 $M_5 = 1.7$, bare $m_q = 0.020$

Masses for $L_s = 12$ and $L_s = 16$ are identical.

Vector meson scaling

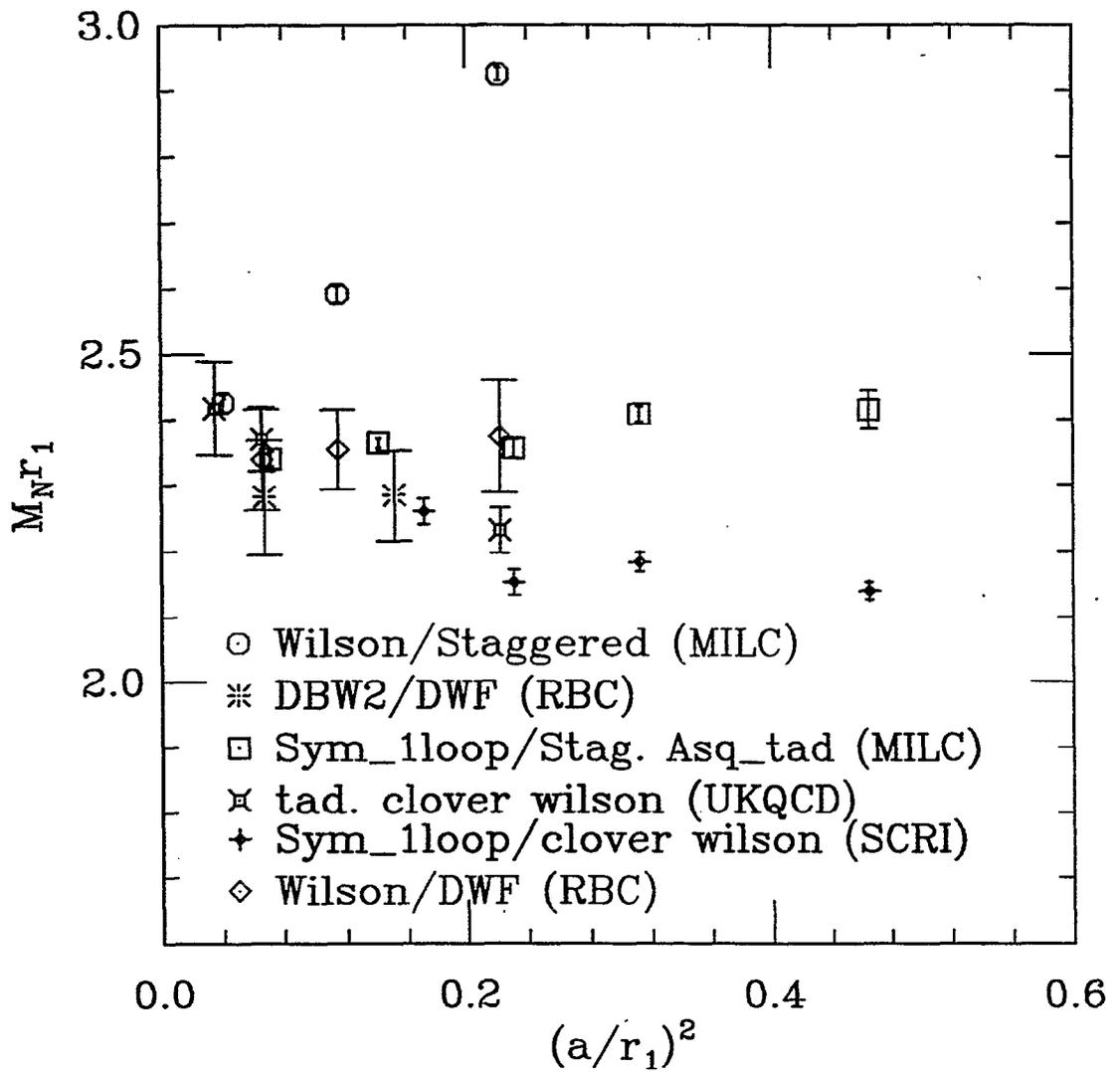


Non Domain Wall data published in

[MILC Phys.Rev. D61 (2000)]

[Y. Aoki talk]

Nucleon scaling



Non Domain Wall data published in

[MILC Phys.Rev. D61 (2000)]

[Y. Aoki talk]

What about Topology?

It is believed that:

[Neuberger, Narayanan] [Edwards, Heller, Narayanan]

- Zero Modes \iff Topology change

DBW2 suppresses the number of Zero Modes.

- Does topology change?

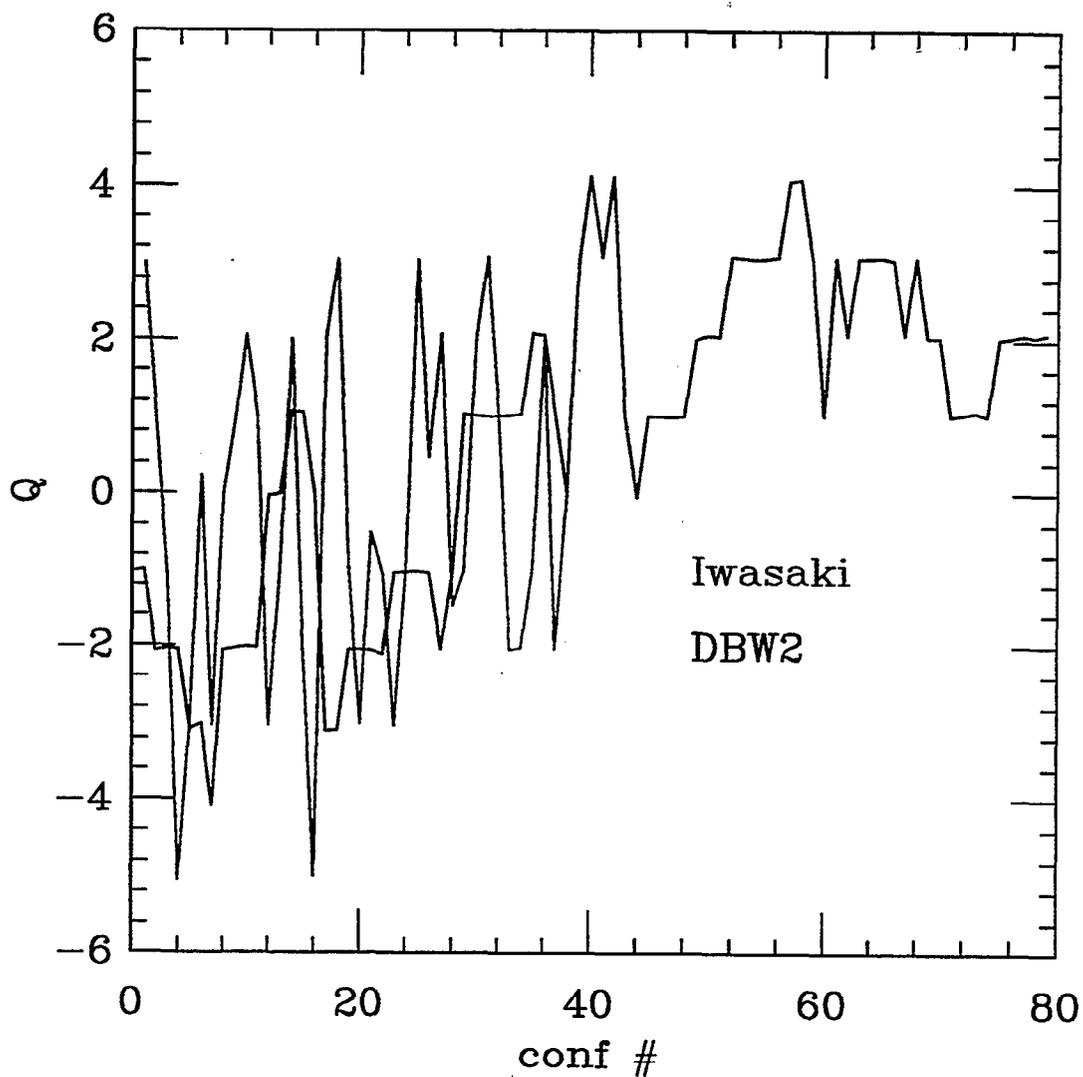
$$S_g[U^I] = 8\pi^2 \left(1 + C \frac{a^2}{\rho^2} + \mathcal{O}\left(\frac{a^4}{\rho^4}\right) \right)$$

$C > 0 \rightarrow$ Stable instantons (Iwasaki/DBW2)

$C < 0 \rightarrow$ Unstable instantons (Wilson/Symanzik)

[Itoh, Iwasaki, Yoshié]

Topological Charge history



Topology tunnels slowly with DBW2.

Topological charge measured using APE smearing and measuring $\int F\tilde{F}$

[DeGrand, Hasenfratz, Kovacs Nucl.Phys. B520 (1998)]

Conclusions

- The RG improved gauge actions significantly improve Chiral Symmetry for Domain Wall Fermions
- The DBW2 gauge action results in a residual mass about a factor of 10 smaller than the Iwasaki at 2GeV. ($L_s = 16$, $m_{\text{res}} \sim 30\text{KeV}$) At 1.3GeV m_{res} is about a factor of 2 smaller than the Wilson action at 2GeV!
- The good scaling of DWF with Wilson action is preserved with DBW2 [Y. Aoki talk]
- The hadron masses seem to reach their asymptotic values at $L_s = 16$.
- The improvement of Chiral symmetry comes from the suppression of $\gamma_5 \not{D}_w(-M_5)$ zero modes. As a result topology fluctuations are significantly reduced
- The DBW2 action should be equally effective in improving the Overlap Fermion convergence.

Hadron Spectrum for Quenched Domain-Wall Fermions With an Improved Gauge Action

Yasumichi Aoki

Hadron spectrum for quenched domain-wall fermions with an improved gauge action

Yasumichi Aoki for RBC collaboration



RIKEN BNL Research Center

RBRC scientific review committee meeting
Nov. 29, 2001

Introduction

- Why Domain Wall Fermion ?
 - Good chiral and flavor symmetry
 - and Good scaling
- Applications
 - B_K , ϵ'/ϵ , proton structure functions
 - Proton decay matrix element (very small mixing).
 $(q^T C P_R q) P_L q \leftarrow (q^T C P_L q) P_L q, (q^T C \gamma_\mu \gamma_5 q) P_L \gamma_\mu q$
- Good chiral symmetry for the fine lattice, (CP-PACS, RBC).
 - Wilson gauge action : good for $a^{-1} \gtrsim 2$ GeV.
 - Iwasaki gauge action : very good for $a^{-1} \gtrsim 2$ GeV.
- Not sufficiently good for coarse lattices.
- Difficult to take continuum limit for demanding calculations, like ϵ'/ϵ .
- Better chirality can we have with further improvement of gauge action ?
 - Yes! DBW2 gauge action provides better chiral symmetry than Iwasaki gauge action.
- Important to check
 - Chiral property at $a^{-1} \simeq 1.3$ GeV.
 - Scaling of spectrum ($a^{-1} \simeq 1.3, 2$ GeV).

Gauge action

$$S_g = \frac{1}{g^2} \left\{ c_0 \sum_{\text{plaquette}} \text{Tr} U_{pl} + c_1 \sum_{2 \times 1 \text{ rectangle}} \text{Tr} U_{rtg} \right\}, \quad \frac{6}{g^2} = \beta$$

$$c_0 + 8c_1 = 1$$

$$c_1 = 0 \rightarrow \text{Wilson action}$$

$$c_1 = -0.331 \rightarrow \text{Iwasaki action}$$

$$c_1 = -1.4069 \rightarrow \text{DBW2 action of QCD-TARO}$$

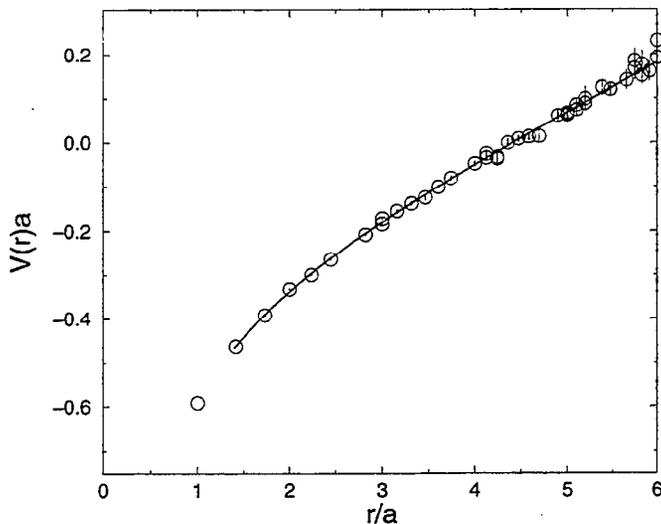
T. Takaishi, Phys. Rev. D54 (1996) 1050;

P. de Forcrand *et al*, Nuc. Phys. B 577 (2000) 263.

Heavy quark potential:

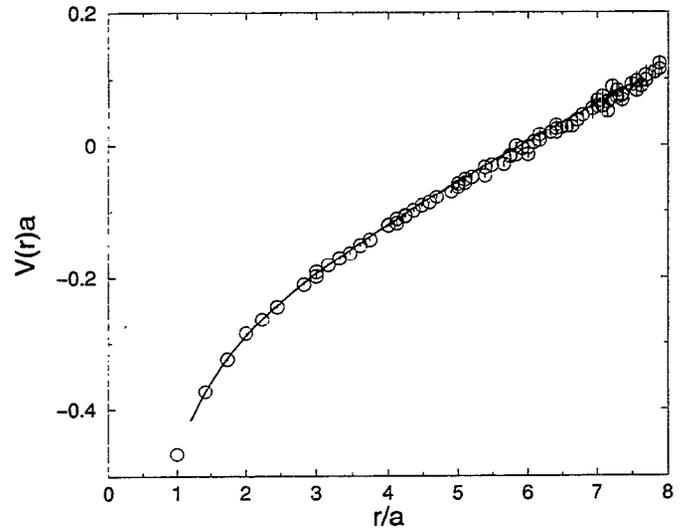
$$\beta = 0.87, \quad (a^{-1} \simeq 1.3 \text{ GeV})$$

beta=0.87, 16³x32



$$\beta = 1.04, \quad (a^{-1} \simeq 2 \text{ GeV})$$

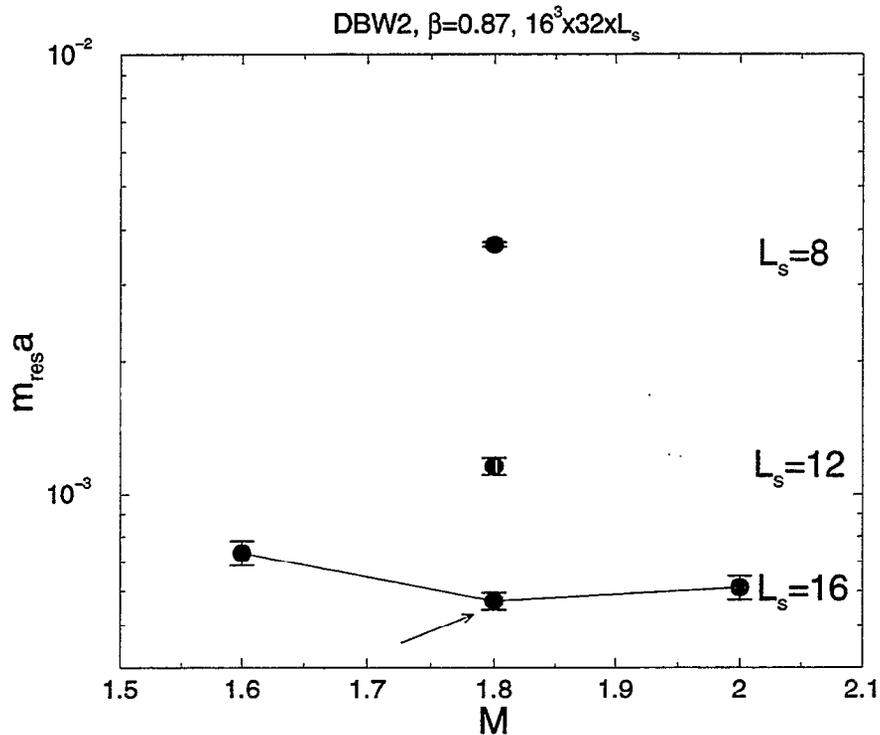
beta=1.04, 16³x32



- Scale determined from gluon dynamics.
 - Sommer parameter r_0 : $F(r_0)r_0^2 = 1.65$; F : force.
 - String tension.

Residual chiral symmetry breaking

$$a^{-1} \simeq 1.3 \text{ GeV}$$

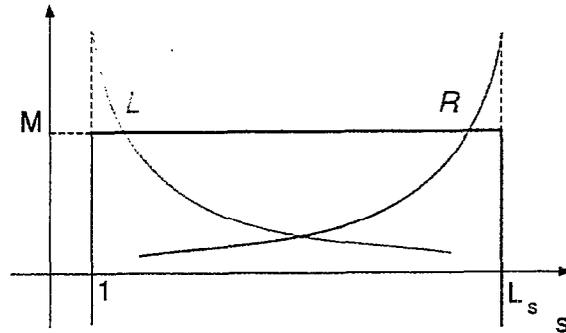


Comparison for same size of fifth dimension $L_s = 16$

- $m_{res}^{DBW2}(a^{-1} \simeq 1.3 \text{ GeV}) \simeq 1 \text{ MeV} < m_{res}^{Wilson}(a^{-1} \simeq 2 \text{ GeV})$
- $m_{res}^{DBW2}(a^{-1} \simeq 2 \text{ GeV}) \simeq 0.03 \text{ MeV} \simeq \frac{1}{10} m_{res}^{Iwasaki}(a^{-1} \simeq 2 \text{ GeV})$.

[→ talk by K. Orginos]

Residual chiral symmetry breaking



$$\Delta_\mu \mathcal{A}_\mu^a(x) = 2m_f P^a(x) + 2J_{5q}^a(x). \quad \text{“conserved current”}$$

(non local)

The Ward-Takahashi identity:

$$\Delta_\mu \langle \mathcal{A}_\mu^a P^b \rangle = 2m_f \langle P^a P^b \rangle + 2 \langle J_{5q}^a P^b \rangle + i \langle \delta^a P^b \rangle$$

Residual quark mass ($t \gg a$):

$$m_{res} = \frac{\langle J_{5q}^a(t) P^b(0) \rangle}{\langle P^a(t) P^b(0) \rangle}.$$



$$m_\pi^2 \propto m_f + m_{res}, \quad m_{res} \rightarrow 0 \quad (L_s \rightarrow \infty).$$

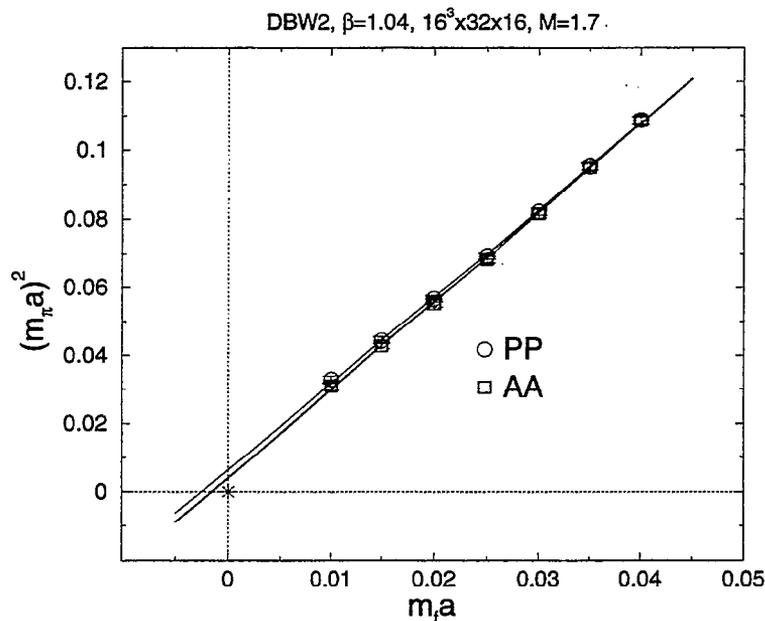
Pion mass

Pion correlator suffers from topological near zero modes in DWF. $\langle PP \rangle$ correlator and $\langle A_0 A_0 \rangle$ correlator have different type of pole from zero modes, all of which vanish in the limit $V \rightarrow \infty$.

$$\begin{aligned}\langle PP \rangle &: \frac{1}{m^2}, \frac{1}{m} \\ \langle A_0 A_0 \rangle &: \frac{1}{m}\end{aligned}$$

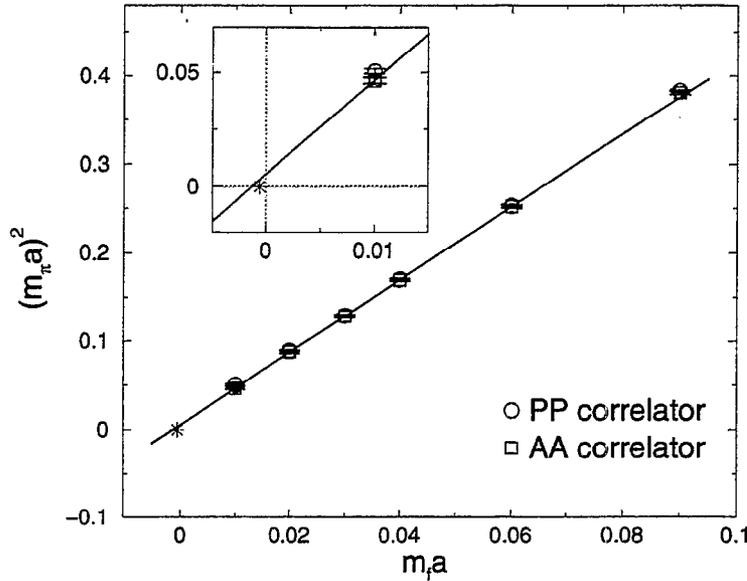
[RBC, hep-lat/0007038]

$\beta = 1.04$, ($a^{-1} \simeq 2$ GeV), $16^3 \times 32 \times 16$, $M = 1.7$.



- Values from two methods are consistent, but trying to deviate each other toward the chiral limit.
- linear extrapolation overshoots $m_f = -m_{res}$.

$\beta = 0.87$, ($a^{-1} \simeq 1.3$ GeV), $16^3 \times 32 \times 16$, $M = 1.8$.



- No difference seen in $0.02 \leq m_f a \leq 0.09$.
- Slight deviation at $m_f a = 0.01$.
- Linear extrapolation overshoots $m_f = -m_{res}$.
 - $\chi^2/dof = 3.4/3$, for PP correlator.
 - $\chi^2/dof = 0.03/3$, for AA correlator.
- with constraint: m_π vanishes at $m_f = -m_{res}$.
 - $m_\pi^2 = A(m_f + m_{res})(1 - \delta \ln(m_f + m_{res}))$
 $\rightarrow \delta = 0.03(2)$, $\chi^2/dof = 0.5/3$ for AA.
 - $m_\pi^2 = A(m_f + m_{res})(1 - \delta \ln(m_f + m_{res})) + B(m_f + m_{res})^2$
 $\rightarrow \delta = 0.09(5)$, $\chi^2/dof = 0.04/3$ for AA.
- Consistent with quenched chiral log.

Pseudoscalar decay constant

$$\frac{f_\pi^2 m_\pi}{Z_A^2 2} e^{-m_\pi t} = \langle A_0(t) A_0(0) \rangle$$

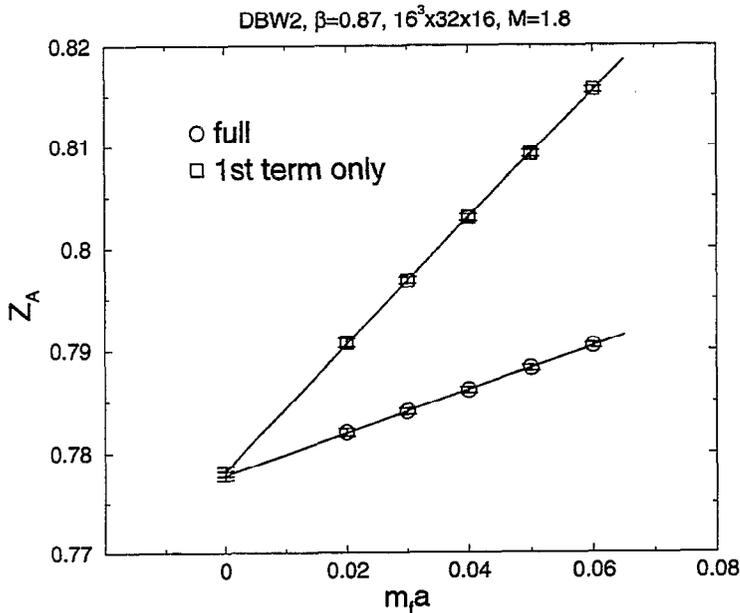
Z_A can be calculated by the ratio of conserved current and local current correlator:

$$C(t + 1/2) = \langle \mathcal{A}_0(t) P(0) \rangle,$$

$$L(t) = \langle A_0(t) P(0) \rangle,$$

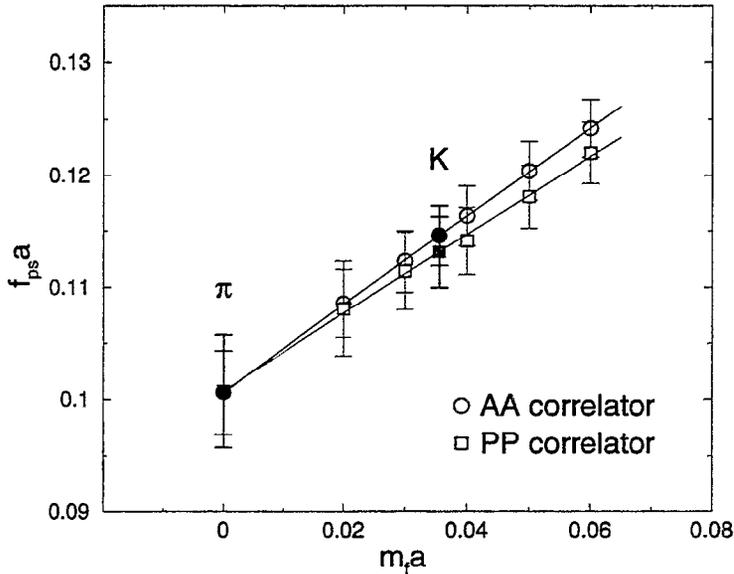
$$Z_A = \frac{1}{2} \left[\frac{C(t + 1/2) + C(t - 1/2)}{2L(t)} + \frac{2C(t + 1/2)}{L(t) + L(t + 1)} \right].$$

$$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$$



- Mild linear dependence on m_f (1-2% in entire region).
- Define Z_A at the chiral limit.

$$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$$



- Both correlators give the consistent results.



Good chiral property.

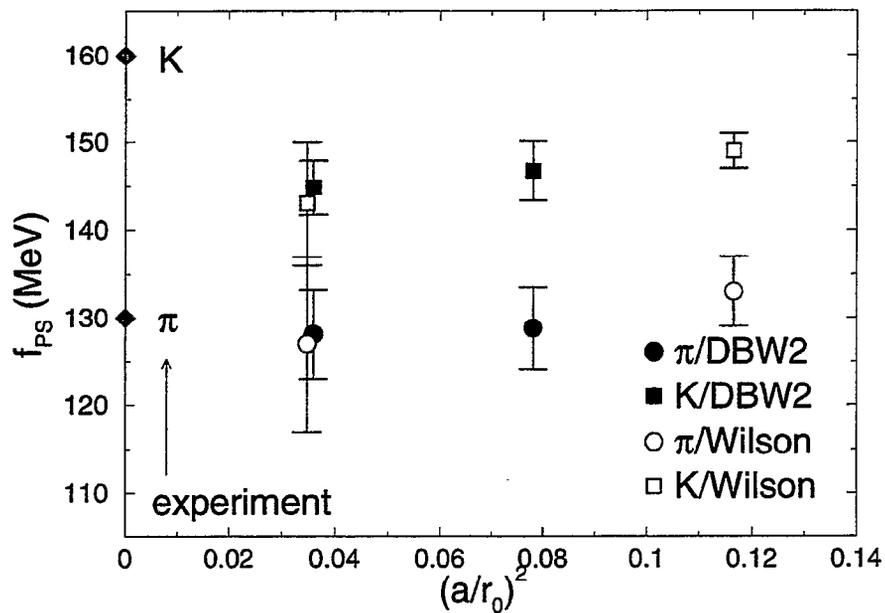
Another method: using

$$\Delta_0 \mathcal{A}_0(t) = 2m_f P(t) + 2J_{5q}(t) = 2(m_f + m_{res})P(t),$$

which holds in low energy matrix amplitude,

$$-\frac{f_\pi^2}{(m_f + m_{res})^2} \frac{m_\pi^3}{8} e^{-m_\pi t} = \langle P(t)P(0) \rangle$$

scaling plot of decay constant for DWF

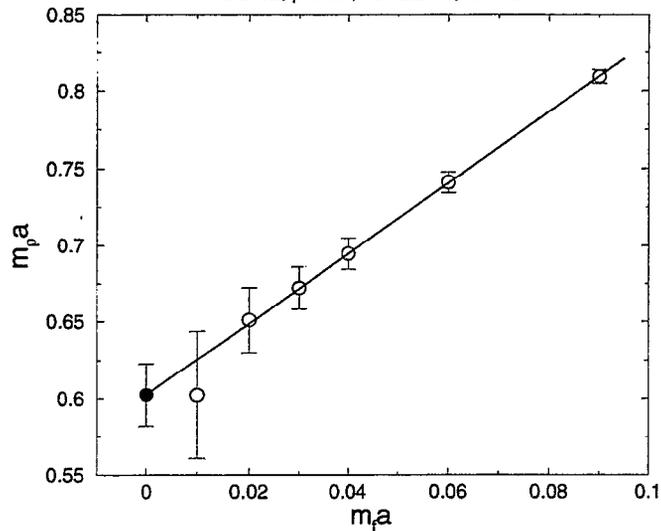


- Good scaling for both f_π and f_K .
- f_π is consistent with experiment.
- f_K is small, expected from quenched chiral perturbation theory [Bernard, Golterman, Phys. Rev. D (1992) 853].

Rho meson mass

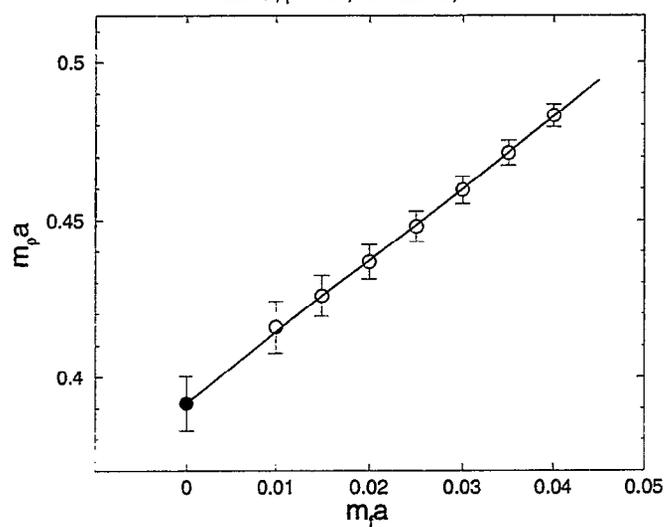
$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$

DBW2, $\beta=0.87, 16^3 \times 32 \times 16, M=1.8$



$\beta = 1.04, (a^{-1} \simeq 2 \text{ GeV})$

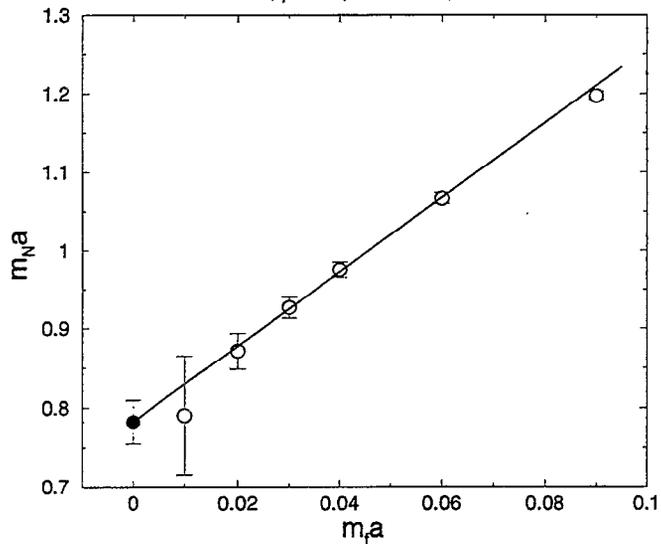
DBW2, $\beta=1.04, 16^3 \times 32 \times 16, M=1.7$



Nucleon mass

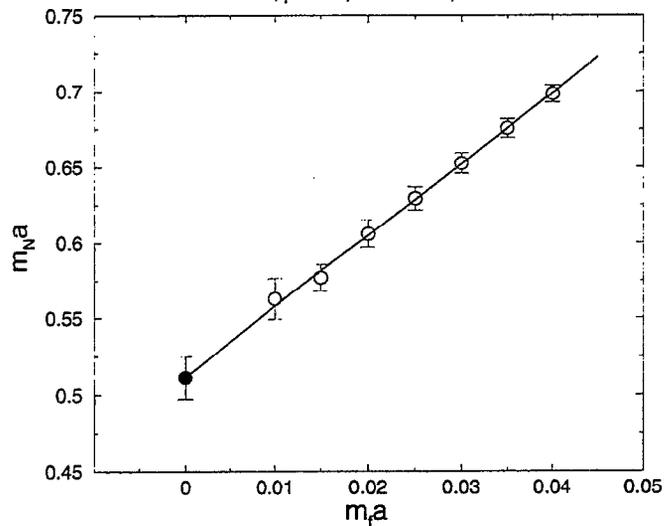
$\beta = 0.87, (a^{-1} \simeq 1.3 \text{ GeV})$

DBW2, $\beta=0.87, 16^3 \times 32 \times 16, M=1.8$



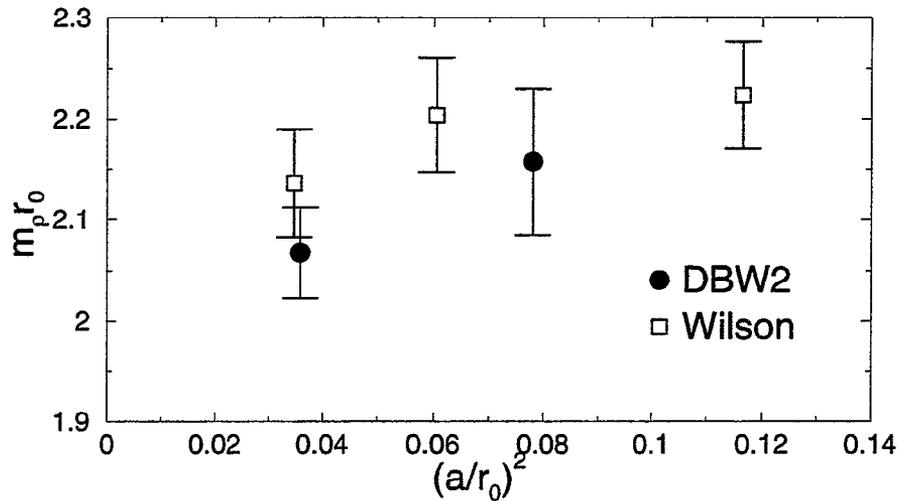
$\beta = 1.04, (a^{-1} \simeq 2 \text{ GeV})$

DBW2, $\beta=1.04, 16^3 \times 32 \times 16, M=1.7$



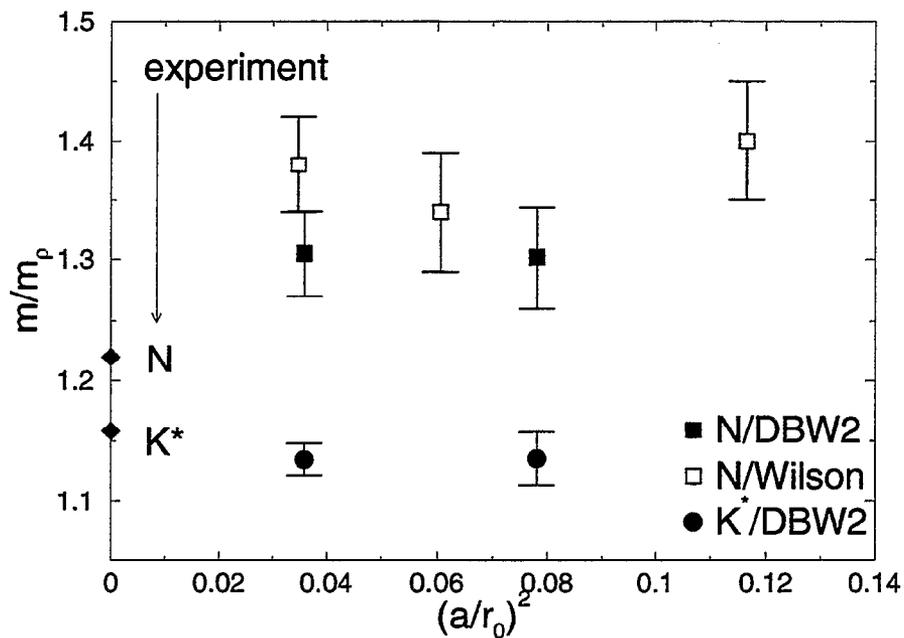
Scaling properties

Rho meson mass:



DBW2 : This work
Wilson : RBC, hep-lat/0007038

Nucleon/rho mass ratio and K^* /rho mass ratio:



Summary

Quenched DWF simulation with DBW2 gauge action.

- Chiral properties for $a^{-1} \simeq 1.3$ GeV.
 - $m_{res}^{DBW2}(a^{-1} \simeq 1.3\text{GeV}) \simeq 1\text{MeV} < m_{res}^{Wilson}(a^{-1} \simeq 2\text{GeV})$.
 - Pion mass behaves consistent with quenched chiral log, with constraint such that it vanishes at $m_f = -m_{res}$.
 - Pseudoscalar decay constant obtained from different correlator at $a^{-1} \simeq 1.3$ shows consistent results.
- Scaling properties.
 - Rho meson mass gives consistent scale with that from r_0 calculated only by gluon dynamics.
 - Good scaling observed for Nucleon and K^* mass.
 - Pseudoscalar decay constant shows good scaling.
- Ready to be used for applications.

Localization of Chirality for Domain Wall Fermion Eigenvectors

Chris Dawson

Localisation of Chirality for Domain Wall Fermion Eigenvectors.

Chris Dawson, RIKEN-BNL Research Center

[RBC Collaboration]

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Continuum QCD

- Eigenvalues and Eigenvectors of the Dirac operator, D .

- Eigenvalue spectrum split into two classes

— Zero-modes; $D\Psi_0 = 0$

* Also eigenvector of γ_5

$$[\gamma_5, D] \Psi_0 = 0$$

$$\gamma_5 \Psi_0 = \pm \Psi_0$$

* Chirality ± 1

— Paired modes; $D\Psi_{\pm i\lambda} = \pm i\lambda \Psi_{\pm i\lambda}$

* γ_5 maps between paired modes

$$\gamma_5 \Psi_{\pm i\lambda} = \Psi_{\mp i\lambda}$$

* Chirality Zero

$$\psi^\dagger \gamma_5 \psi = 0$$

Structure of Paired Modes

- How is the global chirality of paired modes zero?
 - Lumps of well defined chirality that cancel
 - * e.g. Instanton Liquid Model
 - Chirality locally zero/small.
 - * e.g. Witten [Nucl. Phys. B149 285 (1979)]

- Can be addressed by studying eigenvectors on the Lattice.

- First studied by Horvath et. al. [hep-lat/0102003]
 - Chirality found to be locally small

- Our study [hep-lat/0105006]using:
 - Weaker coupling (closer to continuum).
 - Domain Wall Fermion Dirac operator (improved chirality).

- Several other groups: [hep-lat/0103002],[hep-lat/0105004],[hep-lat/0105001]and [hep-lat/0107016]

Domain Wall QCD

- Chirality a problem for lattice actions
- Domain Wall Fermions are a solution.
 - [Kaplan, Shamir, Neuberger]
- Add a fifth dimension, S , of length L_S .
 - Localise left- and right-handed components at either end of 5th dimension
 - Couple ends with a mass term m_f .
 - Chirally symmetric when $L_S \rightarrow \infty$.
- Degree of chiral symmetry breaking depends on
 - Gauge Field
 - L_S
- Found to work well in practice for $L_S \approx 10$ with quenched gauge fields. [RBC, CP-PACS]

Our Study

- Solve for lowest 18 eigenvalues and eigenvectors of $5D$ DWF Dirac operator

- $L_s = 16$

- Two gauge actions: Wilson and Iwasaki

Iwasaki Gauge Action	55 configurations $m_f = 0.0005$
Wilson Gauge Action	32 configurations $m_f = 0$

- Quenched approximation.

- 16^4 volume with $a^{-1} \approx 2\text{GeV}$

- DWF has better chirality for Iwasaki action [hep-lat/0007014].
 - provides good check on answer

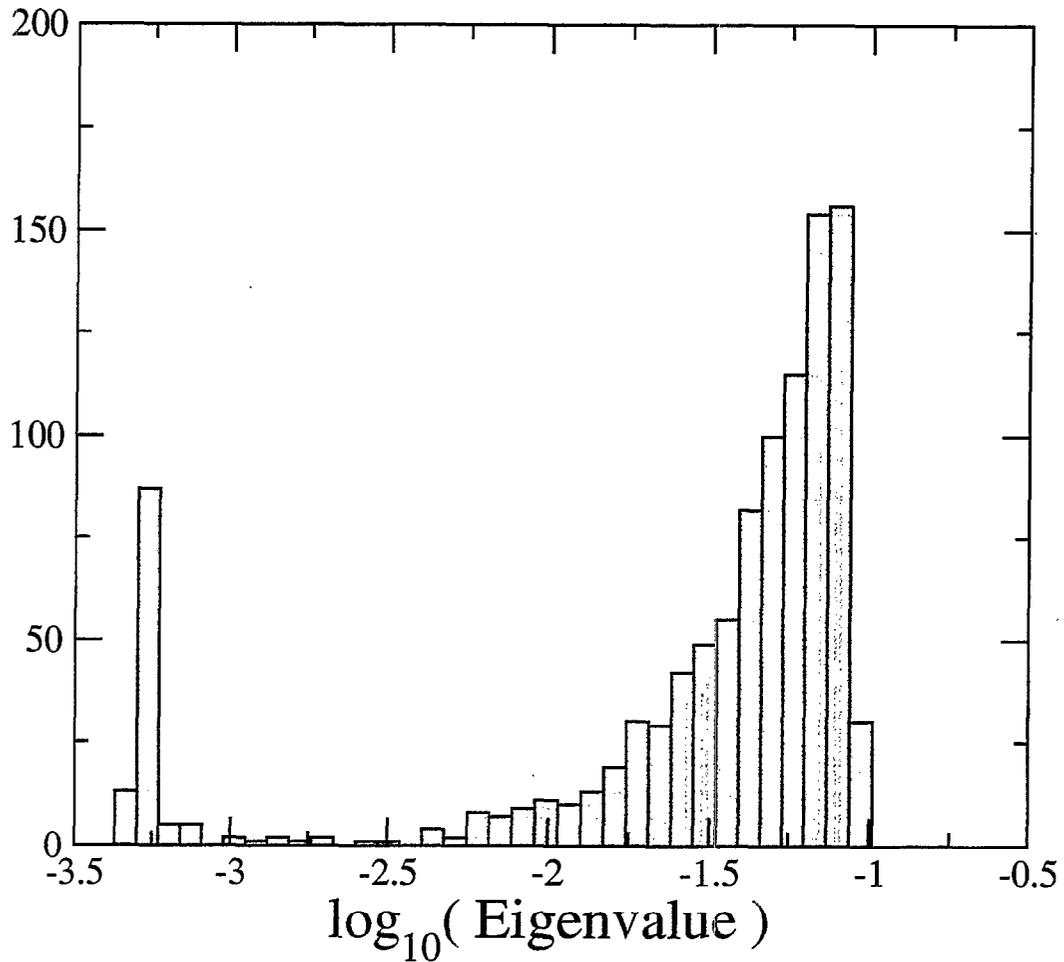
5d to 4d

- From 5D eigenvector Ψ_5 , construct 4D vector

$$\Psi_{4d,LEFT}(x, y, z, t) = \sum_{s=0}^{s < L_s/2} \Psi_{5d}(x, y, z, t, s)$$

$$\Psi_{4d,RIGHT}(x, y, z, t) = \sum_{s=L_s/2}^{s < L_s} \Psi_{5d}(x, y, z, t, s)$$

Eigenvalue Spectrum

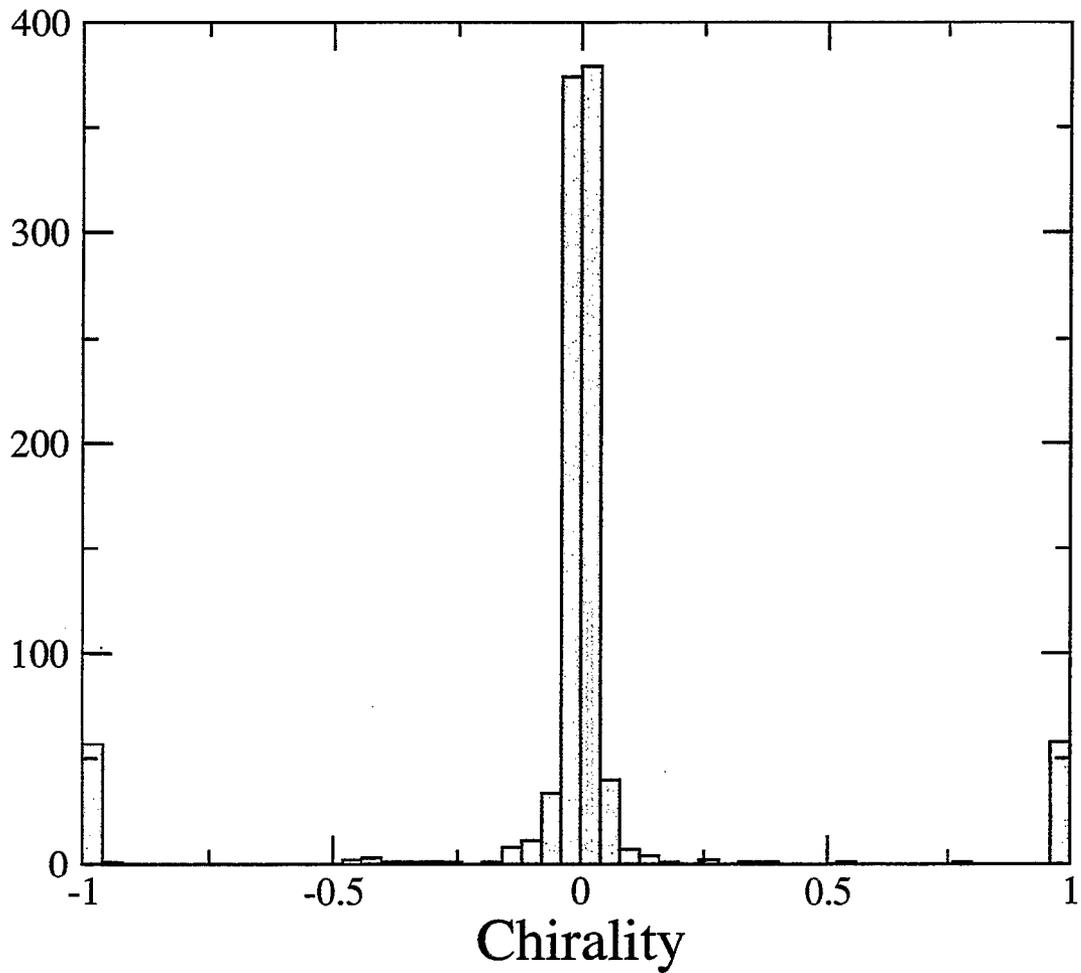


- Eigenvalues span large range ; Histogram

$$\log_{10} (|\lambda|)$$

- Clear signal for zero-mode vs paired modes.

Global Chirality



$$\Psi_{4d}^\dagger \gamma_5 \Psi_{4d}$$

- Histogram chirality of each eigenvector.
- Again clear signal for zero-mode vs paired modes.

γ_5 Plots

$$G_5(i, j) = \Psi_{4d,i}^\dagger \gamma_5 \Psi_{4d,j}$$

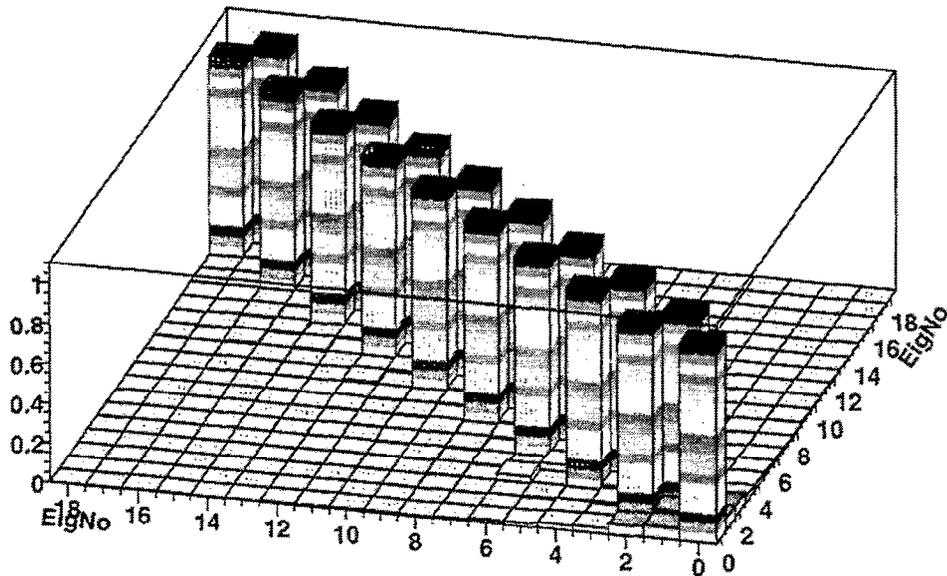
Non-zero if:

- $i = j$ and $\Psi_{4d,i}$ is a zero-mode.
- $i \neq j$ and $\Psi_{4d,i}$ and $\Psi_{4d,j}$ are paired.

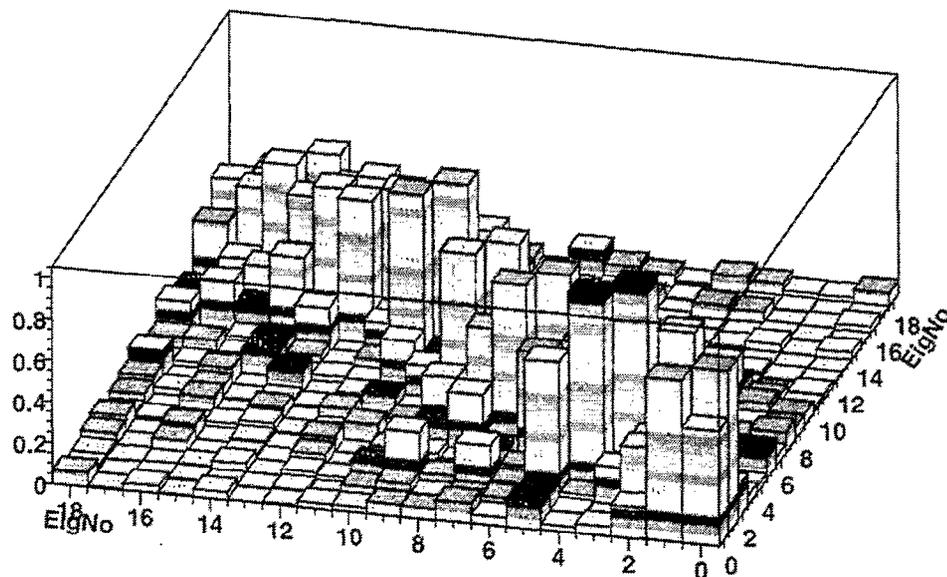
- Simple and “complex” configurations
- Iwasaki ensemble approximately 1 : 10
- Wilson ensemble much worse.

γ_5 Plots

G5(i,j) for Iwasaki configuration 7



G5(i,j) for Iwasaki configuration 2



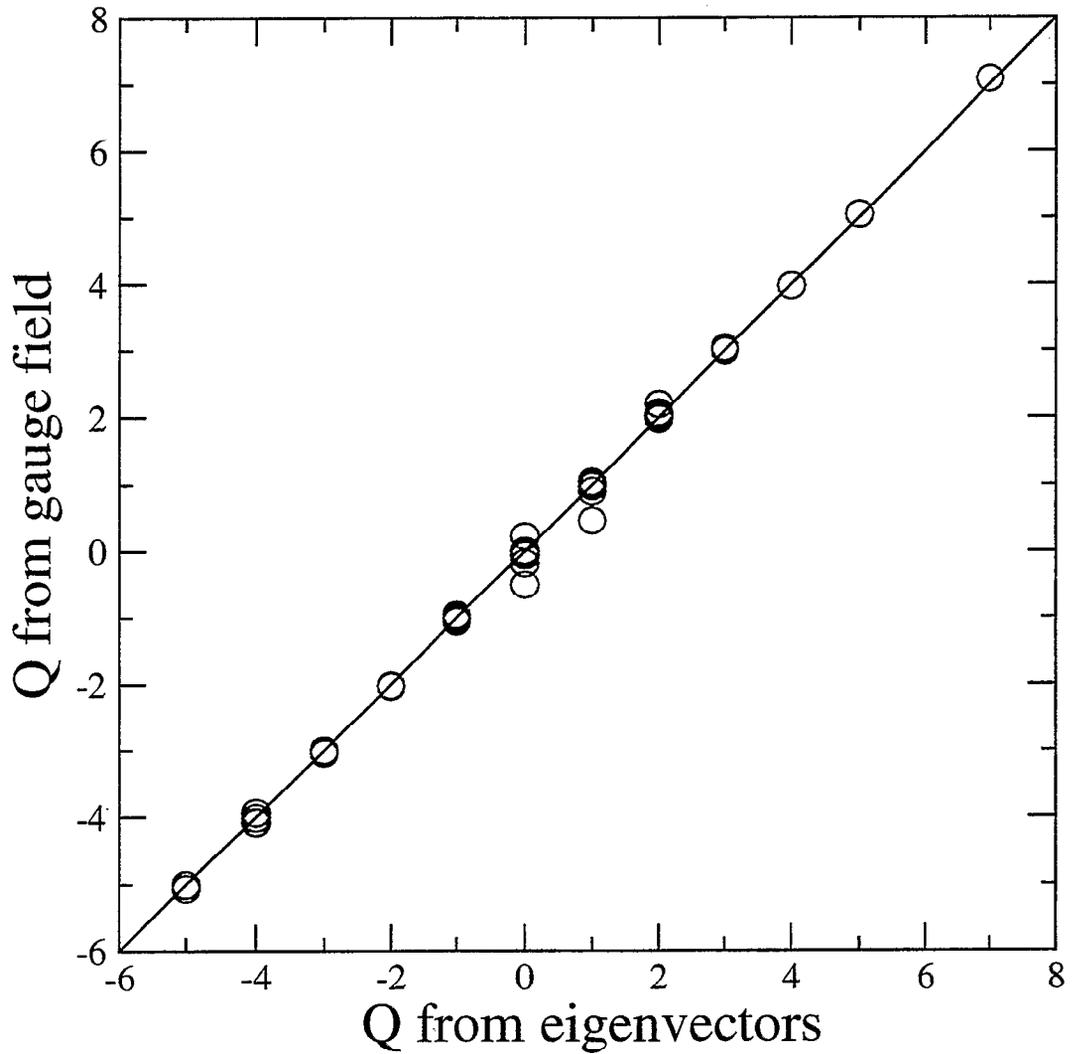
Topological Charge Definition

- Gauge Field definition

$$Q = \frac{1}{32\pi^2} \epsilon_{ijkl} \text{Tr} [F_{ij} F_{kl}]$$

- Calculate this on the lattice by the method DeGrand et. al
- May also calculate the Topological Charge from the number of positive and negative chirality zero-modes.
- Provides a good consistency check.

Topological Charge



- Good agreement between gauge field and fermionic definition of Topological Charge.

Localisation of Chirality

- local norm

$$\Omega_H(x) = \Psi_{4d}^\dagger(x) \Psi_{4d}(x)$$

- local chirality , $L(x)$.

$$X_H(x) = \Psi_{4d}^\dagger(x) \gamma_5 \Psi_{4d}(x)$$

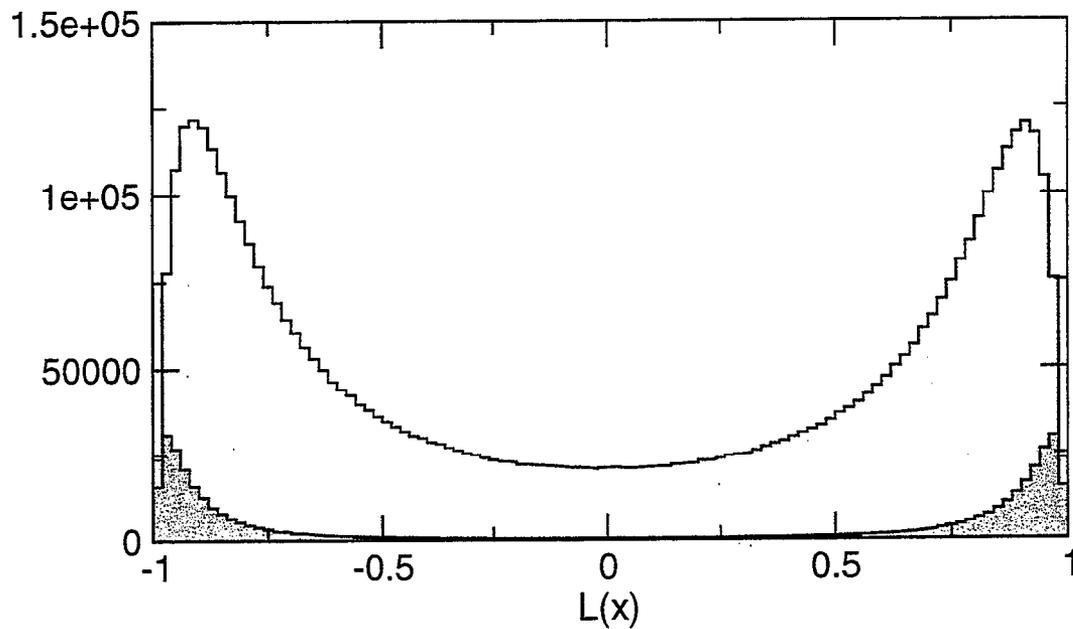
$$L(x) = X_H(x) / \Omega_H(x)$$

- Only want to look at important points

$$\Omega_H > \Omega_{\min}$$

- Histogram $L(x)$.

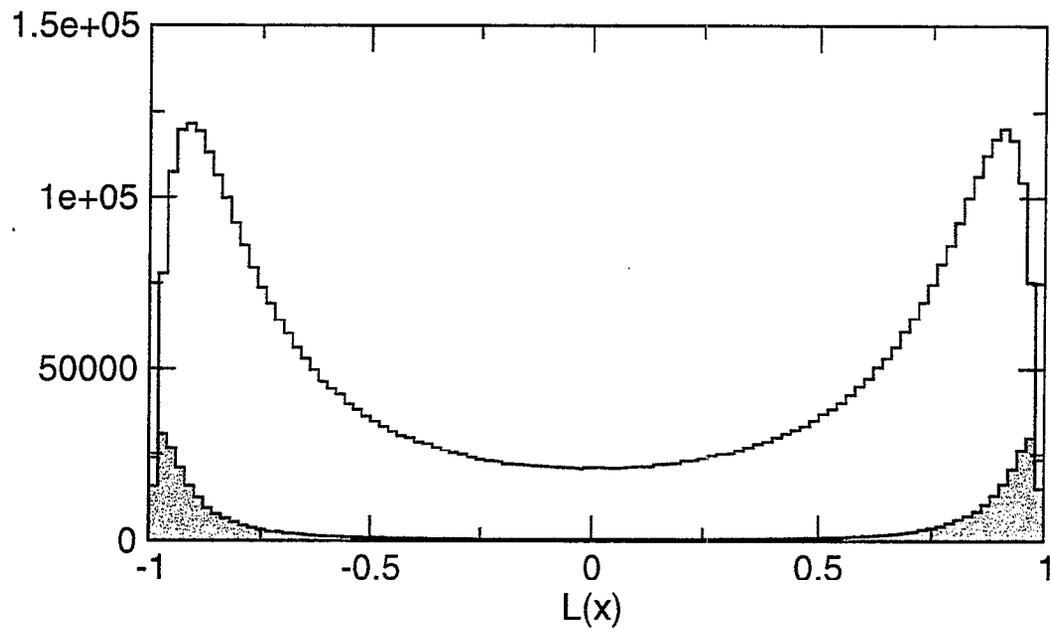
Localisation of Chirality : Iwasaki



- $\Omega_{min} = 8 \cdot 10^{-5}$ allowing 6% of total norm .
- $\Omega_{min} = 3 \cdot 10^{-5}$ allowing 29% of total norm .

- Localisation of chirality favoured.

Localisation of Chirality: Wilson



- Results independent of gauge action.

Spatial Distribution

- Hard to visualise $4D$ data.

- May look a $2D$ section

$$N(x, y) = \sum_z \sum_t \Psi_{4d}^\dagger \Psi_{4d}(x, y, z, t)$$

- Look at left- and right-handed norms separately
 - Localisation of chirality visible.

Spatial Distribution of a Zero-mode

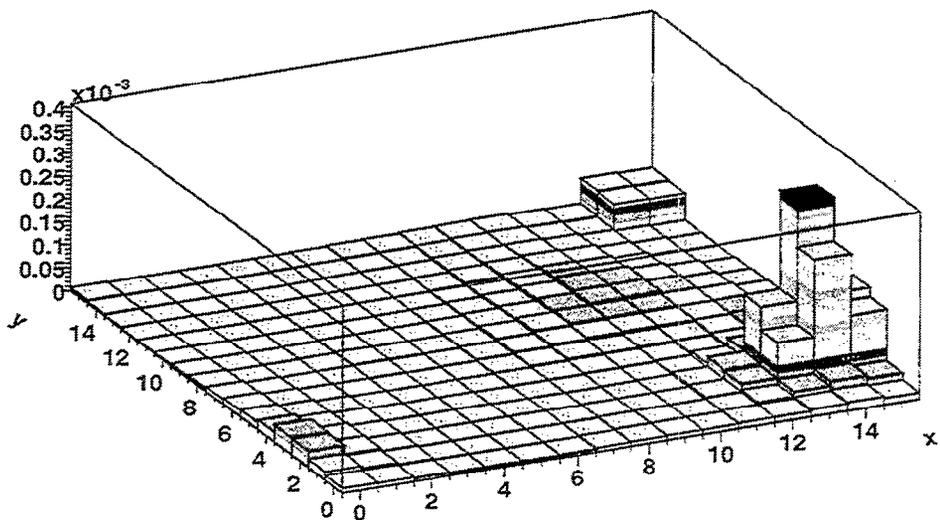


Figure 1: Left-handed component of the local norm summed over z and t for a zero-mode

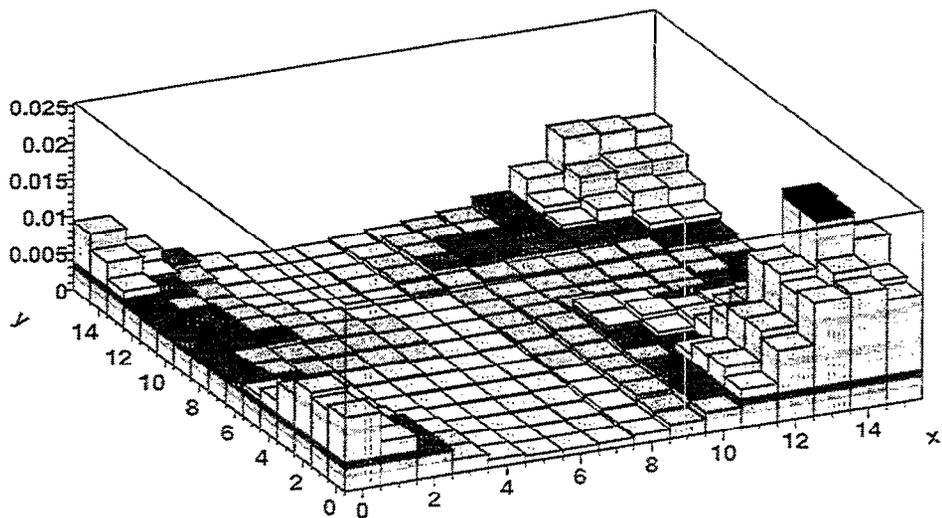


Figure 2: Right-handed component of the local norm summed over z and t for a zero-mode

Spatial Distribution of Paired mode

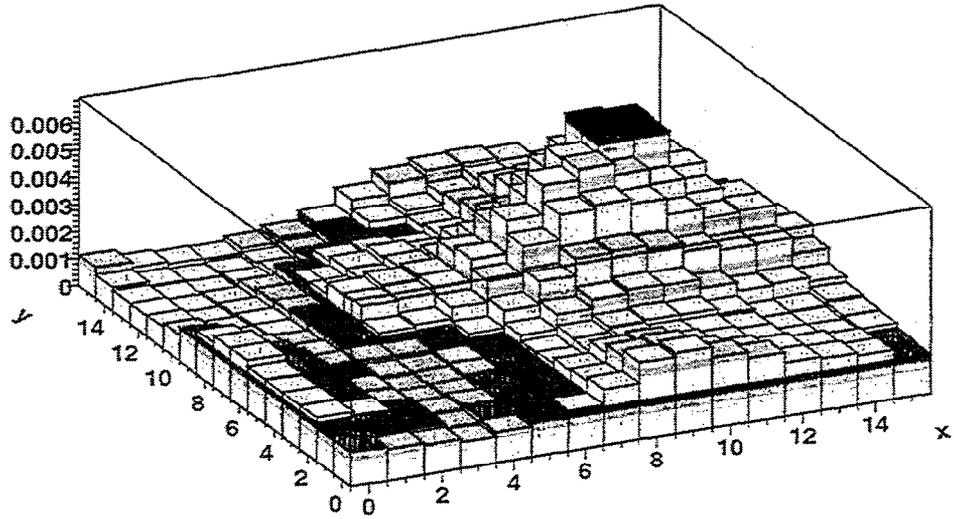


Figure 3: Left-handed component of the local norm summed over z and t for a paired mode

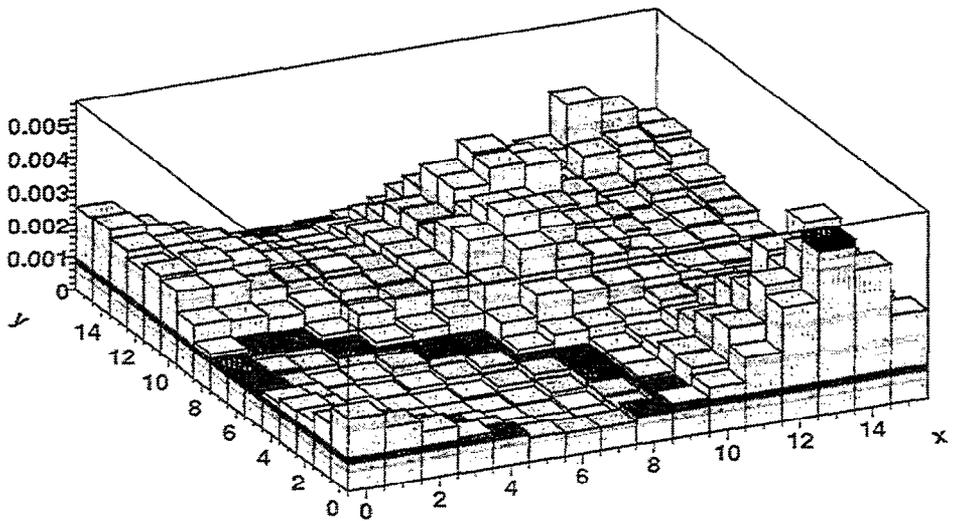


Figure 4: Right-handed component of the local norm summed over z and t for a paired mode

CP Violation in K Decay from Lattice QCD

Thomas Blum

CP Violation in K Decay from Lattice QCD

[T. Blum, et al. (RBC) hep-lat/0110075]

[C. Michael, et al. (CP-PACS) hep-lat/0103013]

Thomas Blum^a

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RIKEN BNL Research Center Review

November 29, 2001

Outline

I. Introduction

II. Results: Physical Amplitudes and the CP violation parameter ϵ'

III. Summary and Outlook

I. Introduction

CP violation in $K \rightarrow \pi\pi$ decays

The long-lived and short-lived neutral kaons are **almost** CP eigenstates, but contain small mixtures of each other

$$|K_S\rangle = |K^{\text{even}}\rangle + \epsilon|K^{\text{odd}}\rangle$$

$$|K_L\rangle = |K^{\text{odd}}\rangle + \epsilon|K^{\text{even}}\rangle$$

$$|K^{\text{even,odd}}\rangle = |K^0\rangle \mp |\bar{K}^0\rangle$$

Indirect CP violation occurs when K_L oscillates into the K^{even} state and decays to the CP -even state $|\pi\pi\rangle$. Loosely speaking, the probability for this is parameterized by the observable ϵ .

Direct CP violation occurs when the K_L decays to $|\pi\pi\rangle$ directly from the K^{odd} component. Loosely speaking, the probability for this is parameterized by the observable ϵ' .

Long theoretical effort driven by experimental observation

- Summary of CP **violation** found in Nature

- Indirect: ϵ

- 1. Christensen, Cronin, Fitch, Turlay (BNL 1964)

- $2.271(17) \times 10^{-3}$

- Direct: ϵ'/ϵ

- 1. KTeV (FNAL 2001)

- $20.7 \pm 2.8 \times 10^{-4}$

- 2. NA48 (CERN 2001)

- $15.3 \pm 2.6 \times 10^{-4}$

- B factories measure $\sin(2\beta)$

- 1. BaBar (SLAC 2001)

- 0.59 ± 0.14

- 2. Belle (KEK 2001)

- $0.99 \pm 0.14 \pm 0.06$

- $\Delta I = 1/2$ rule for kaon decays: $\frac{A(K \rightarrow \pi\pi(I=0))}{A(K \rightarrow \pi\pi(I=2))} \approx 22$

Use theory + experiment to constrain the Standard Model

Convenient to use QCD eigenstates K^0 and \bar{K}^0 and define the *isospin* decay amplitudes

$$A(K^0 \rightarrow \pi\pi(I)) = A_I e^{i\delta_I}$$

$$A(\bar{K}^0 \rightarrow \pi\pi(I)) = -A_I^* e^{i\delta_I}$$

$$A_I e^{i\delta_I} = \langle \pi\pi(I) | -i\mathcal{H}^{(\Delta S=1)} | K^0 \rangle$$

where $I = 0, 2$

which yields

$$\epsilon' = \frac{ie^{i(\delta_2 - \delta_0)} \text{Re}A_2}{\sqrt{2} \text{Re}A_0} \left[\frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right]$$

and

$$(\Delta I = 1/2 \text{ rule}) \rightarrow \frac{\text{Re}A_0}{\text{Re}A_2}$$

The $\Delta S = 1$ Effective Hamiltonian

The Standard Model Hamiltonian: a *short distance expansion* in terms of effective local **four-quark operators** $Q_i(\mu)$ (c.f. Fermi interaction) with **Wilson coefficients** $z_i(\mu)$ and $y_i(\mu)$.

$$\mathcal{H}^{(\Delta S=1)} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} \left[z_i(\mu) - \frac{V_{td} V_{ts}^*}{V_{ud} V_{us}^*} y_i(\mu) \right] Q_i(\mu) \right\}$$

Both depend on an *arbitrary factorization scale* μ . Effective Hamiltonian is **independent** of this scale. Take μ low enough that non-perturbative calculations are practical ($1/a \ll M_W$), but high enough that continuum perturbation theory remains valid.

Key to the OPE is that the full amplitude is divided into low energy (hadronic matrix elements of Q_i) and high energy (Wilson coefficients) parts that can be computed separately.

III. Lattice Calculation of

Hadronic Matrix Elements $\langle \pi\pi | Q_i | K \rangle$

There are three key features of our calculation

- Chiral perturbation theory to obtain $K \rightarrow \pi\pi$
from $K \rightarrow \pi$ and $K \rightarrow 0$
- Non-perturbative renormalization (NPR) of operators
- Domain Wall Fermions (chiral symmetry)

Significant technical difficulties associated with $|\pi\pi\rangle$, so use **lowest order** chiral perturbation theory to relate physical $K \rightarrow \pi\pi$ amplitudes to unphysical $K \rightarrow \pi$ and $K \rightarrow 0$ ones calculated on the lattice.

Replace four-quark operators with χPT representatives, $Q_i \rightarrow \Theta_i = \alpha_j^i \tilde{\Theta}_j$:

$$\langle 0 | \Theta^{(8,1)} | K^0 \rangle = \frac{16iv}{f^3} (m'_s - m'_d) \alpha_2^{(8,1)}$$

$$\langle \pi^+ | \Theta^{(8,1)} | K^+ \rangle = \frac{4m_M^2}{f^2} (\alpha_1^{(8,1)} - \alpha_2^{(8,1)})$$

$$\langle \pi^+ | \Theta^{(27,1)} | K^+ \rangle = -\frac{4m_M^2}{f^2} \alpha^{(27,1)}$$

$$\langle \pi^+ | \Theta^{(8,8)} | K^+ \rangle = \frac{12}{f^2} \alpha^{(8,8)}$$

$$\langle \pi^+ \pi^- | \Theta^{(8,1)} | K^0 \rangle = \frac{4i}{f^3} (m_{K^0}^2 - m_{\pi^-}^2) \alpha_1^{(8,1)}$$

$$\langle \pi^+ \pi^- | \Theta^{(27,1)} | K^0 \rangle = -\frac{4i}{f^3} (m_{K^0}^2 - m_{\pi^+}^2) \alpha^{(27,1)}$$

$$\langle \pi^+ \pi^- | \Theta^{(8,8)} | K^0 \rangle = \frac{-12i}{f^3} \alpha^{(8,8)}$$

m_M is a common unphysical meson mass ($m_u = m_d = m_s$), $m'_{d,s}$ are unphysical quark masses, and f is the decay constant $f = f_\pi = f_K$ to lowest order.

Significant approximation, but can be improved by **one-loop** plus $\mathcal{O}(p^4)$ tree-level calculations.

Also complicated by use of the quenched approximation.

Operator renormalization factors, Z_{ij}

- Bare lattice operators are divergent as $a \rightarrow 0$ so must be renormalized at some scale μ (μ dependence cancels with μ dependence of \vec{C} in $\mathcal{H}^{(\Delta S=1)}$ which is RG invariant).
- Non-perturbative renormalization (Rome-Southampton)
- Regularization independent (RI) scheme (*c.f.* MOM-scheme)

$$\langle q(p) O^{\text{ren}} q(p) \rangle = \langle q(p) Z O q(p) \rangle = \langle q(p) O q(p) \rangle_{\text{tree}}$$

Green's functions calculated in a fixed gauge with off-shell quarks with large Euclidean momenta ($\mu^2 \equiv p^2$).

- No need for difficult perturbative lattice calculations. Can match, using continuum perturbation theory, to other schemes like \overline{MS} .
- $\mathcal{H}^{(\Delta S=1)}$ case is complicated since operators mix with each other and also lower-dimensional ones that are power divergent:

$$O_i^{\text{ren}}(\mu) = \sum_j Z_{ij}(a\mu) \left(O_j^{\text{latt}}(a) + \sum_k c_k^j(a\mu) B_k(a) \right) + \mathcal{O}(a^2)$$

Details of the Simulation

Wilson gauge action, **quenched** $6/g^2 = 6.0 \rightarrow 1/a = 1.922$ GeV,
400 configurations

Lattice size $16^3 \times 32 \rightarrow (1.6 \text{ fm})^3 \times 3.2 \text{ fm}$

Domain wall fermions with $M_5 = 1.8$, $L_s = 16$, and quark masses

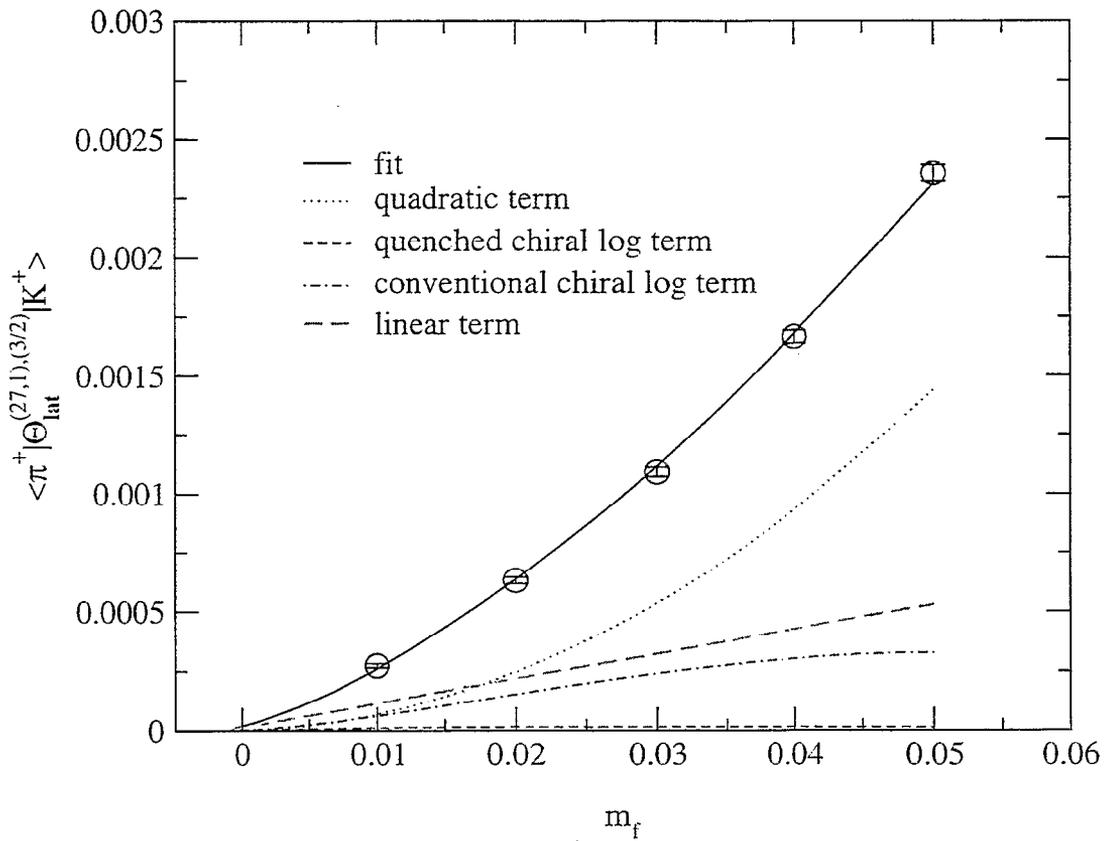
$m_f = 0.01, 0.02, 0.03, 0.04, 0.05$ (in units of lattice spacing). $m_{\text{strange}}^{\text{phys}}$
corresponds to $m_f \approx .02$. $m_c = 0.1, 0.2, 0.3, 0.4$

The non-perturbative renormalization of operators was done with the same parameters as above except $\beta_5 = 1.02$ only 400 configurations. Checked that results were not significantly affected by $\beta_5 \rightarrow$ extrapolation on 200 configurations.

Simulations done on the QCDSF supercomputers at *Columbia University* and *RIKEN BNL Research Center*. Matrix element calculation took roughly 4 months x 0.8 TFlops (peak).

$$\langle \pi^+ | Q_{i,\text{lat}}^{(27,1),3/2} | K^+ \rangle \propto \langle \pi^+ | \Theta_{\text{lat}}^{(27,1),3/2} | K^+ \rangle (i = 1, 2, 9, 10)$$

Higher order effects are **large**. Fit is forced to vanish at $m_f = -m_{\text{res}} = -.00124$. Quenched log is small. Conventional log is large and mimics linear term. *Known coefficients* calculated in $Q\chi\text{PT}$.

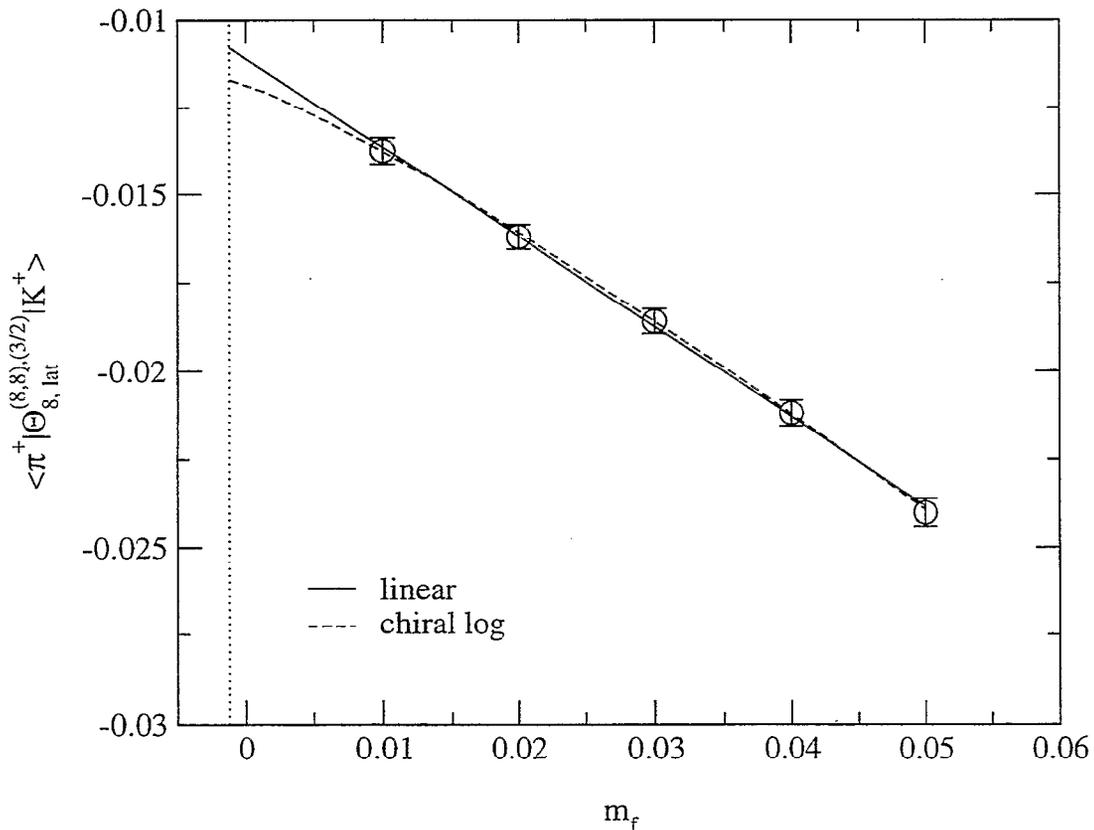


$$\alpha_i^{(27,1),3/2} = -\frac{f^2}{4} \times \text{slope} = (-4.13 \pm 0.18) \times 10^{-6}$$

and gives the lowest order contribution to $\text{Re}\mathcal{A}_2$

Electroweak penguin $\langle \pi^+ | Q_{8,\text{lat}}^{(3/2)} | K^+ \rangle$ (important to ϵ')

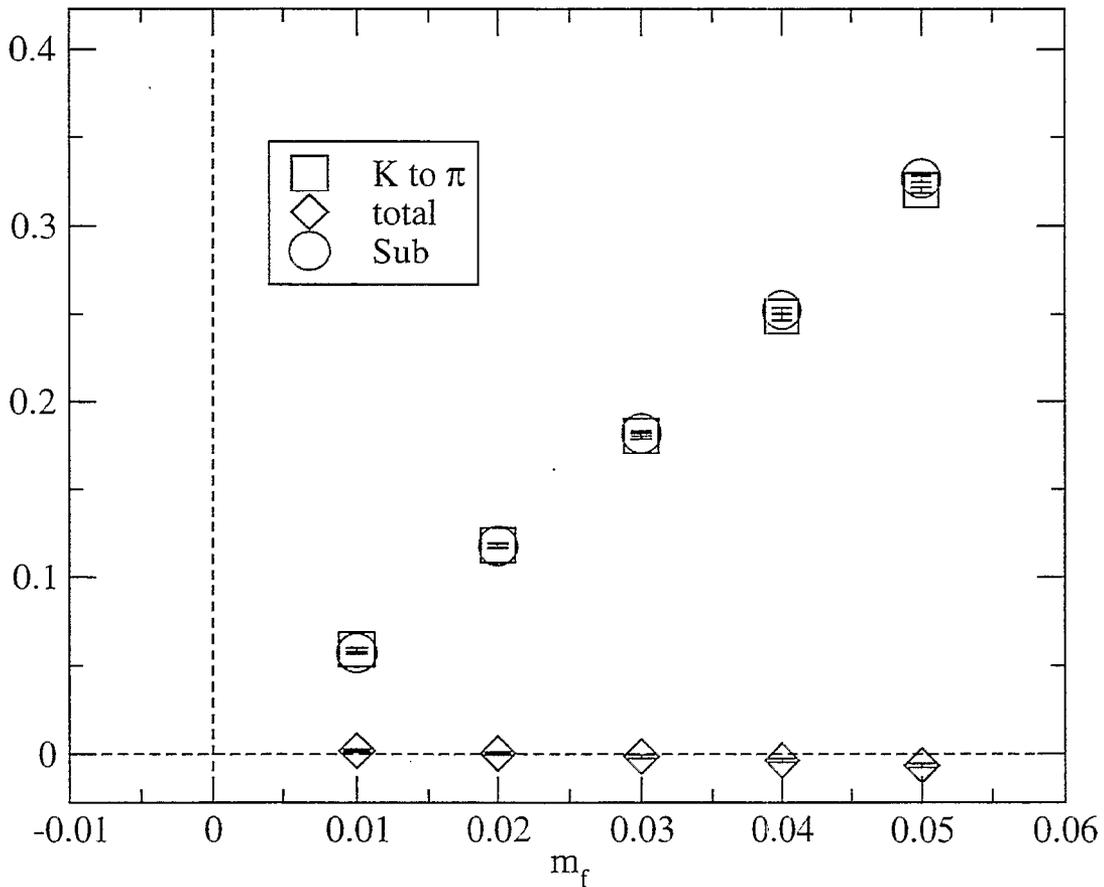
Lowest order contribution is a constant, higher order correction to *this constant* appears **small**. Extrapolate to $m_f = -m_{res} = -.00124$. Quenched log is unknown (ignore). Coefficient of conventional log is also unknown, but fit to it.



$$\alpha_8^{(3/2)} = \frac{f^2}{12} \times \text{intercept} = (-4.96 \pm 0.27) \times 10^{-6}$$

QCD Penguin $\langle \pi^+ | Q_{6,\text{lat}} | K^+ \rangle$ and $2 m_f \eta_6 \langle \pi^+ | \bar{s}d_{\text{lat}} | K^+ \rangle$

Divergent subtraction is almost complete. Physical slope is roughly 50 x smaller than the unsubtracted one

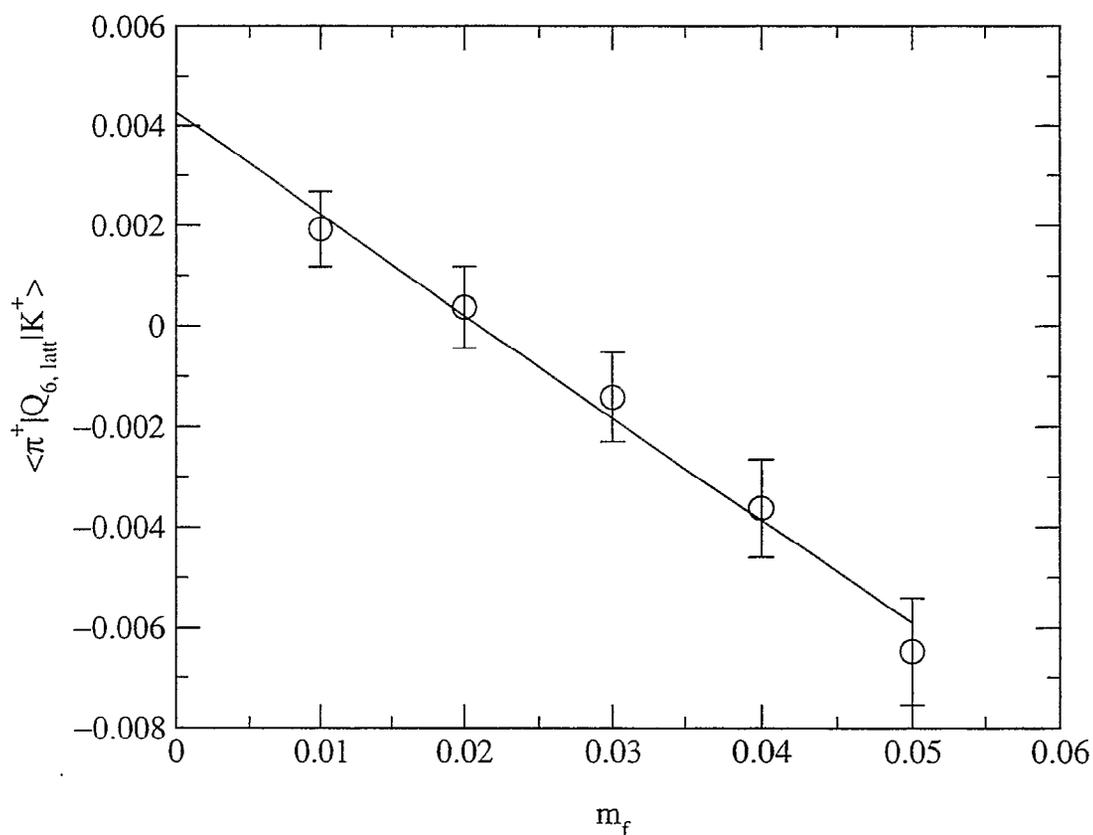


Data are highly correlated!

Subtracted QCD Penguin $\langle \pi^+ | Q_{6, \text{lat}} | K^+ \rangle$ (important to ϵ')

Does not vanish as $m_f \rightarrow -m_{res}$ because valence quark loop is sensitive to **high energy** chiral symmetry breaking effects (mixing between domain walls). Effect is an additive shift in the quark mass, which is eliminated by taking the slope.

$$\alpha_6 = \frac{f^2}{4} \times \text{slope} = (-8.12 \pm 0.98) \times 10^{-5}$$



V. Physical Amplitudes

$$\langle \pi \pi_{(I)} | -i\mathcal{H}^{(\Delta S=1)} | K^0 \rangle = -i\sqrt{\frac{3}{4}} G_F V_{ud} V_{us}^* \sum_{i=1}^{10} \sum_{j=1, j \neq 4}^8 [z_i(\mu) + \tau y_i(\mu)] \hat{Z}_{ij}^{\text{NPR}}$$

$$\times \left\{ \begin{array}{ll} \frac{4i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} \left[1 - \frac{97}{27} L_\chi(m_K) \right] & I = 0, \quad j = 1, 2, 3, 5, 6 \\ \frac{-1\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} \left[1 - \frac{3}{2} L_\chi(m_K) \right] & I = 2, \quad j = 1, 2, 3, 5, 6 \\ \frac{-12i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} a^{-6} [1 - 8.4 L_\chi(m_K)] & I = 0, \quad j = 7, 8 \\ \frac{-12\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} a^{-6} [1 - 2.3 L_\chi(m_K)] & I = 2, \quad j = 7, 8 \end{array} \right.$$

Tree level

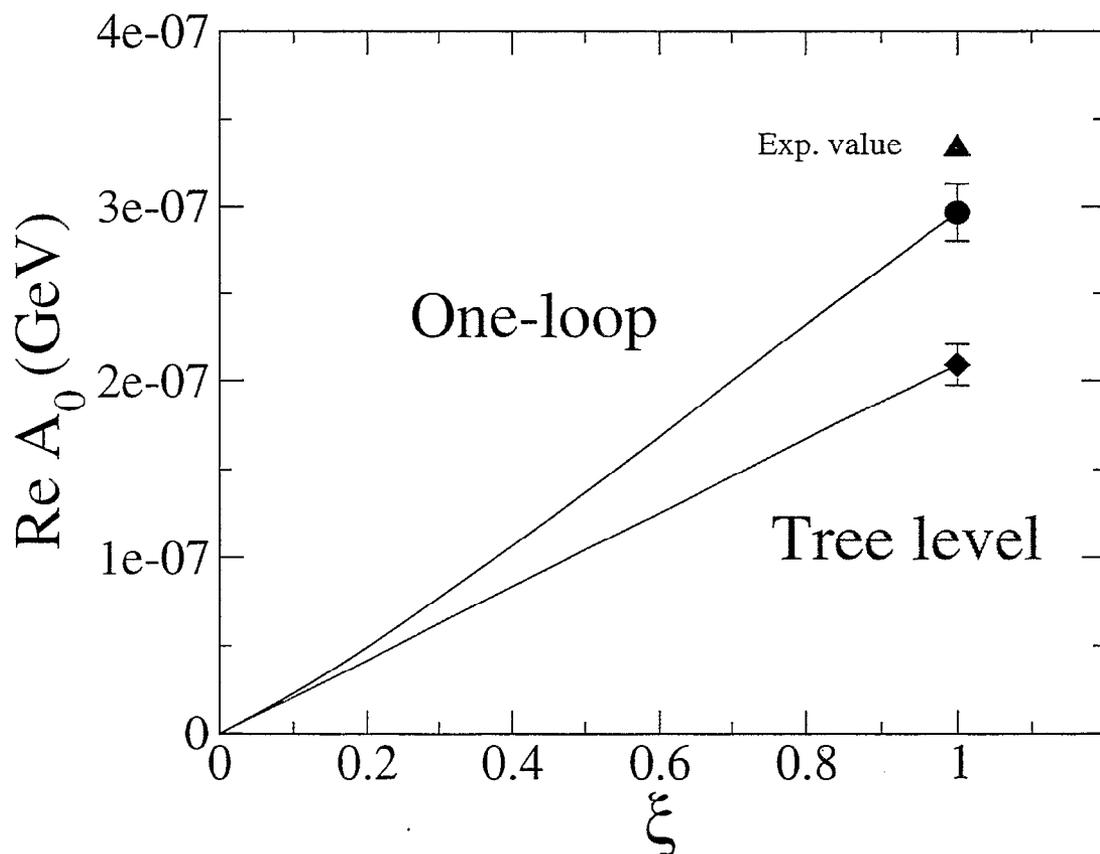
One-Loop, logs only

Real part of A_0

Study “fictional” world with masses $m_{K^0}^2, m_{\pi^+}^2 \rightarrow \xi \times (m_{K^0}^2, m_{\pi^+}^2)$

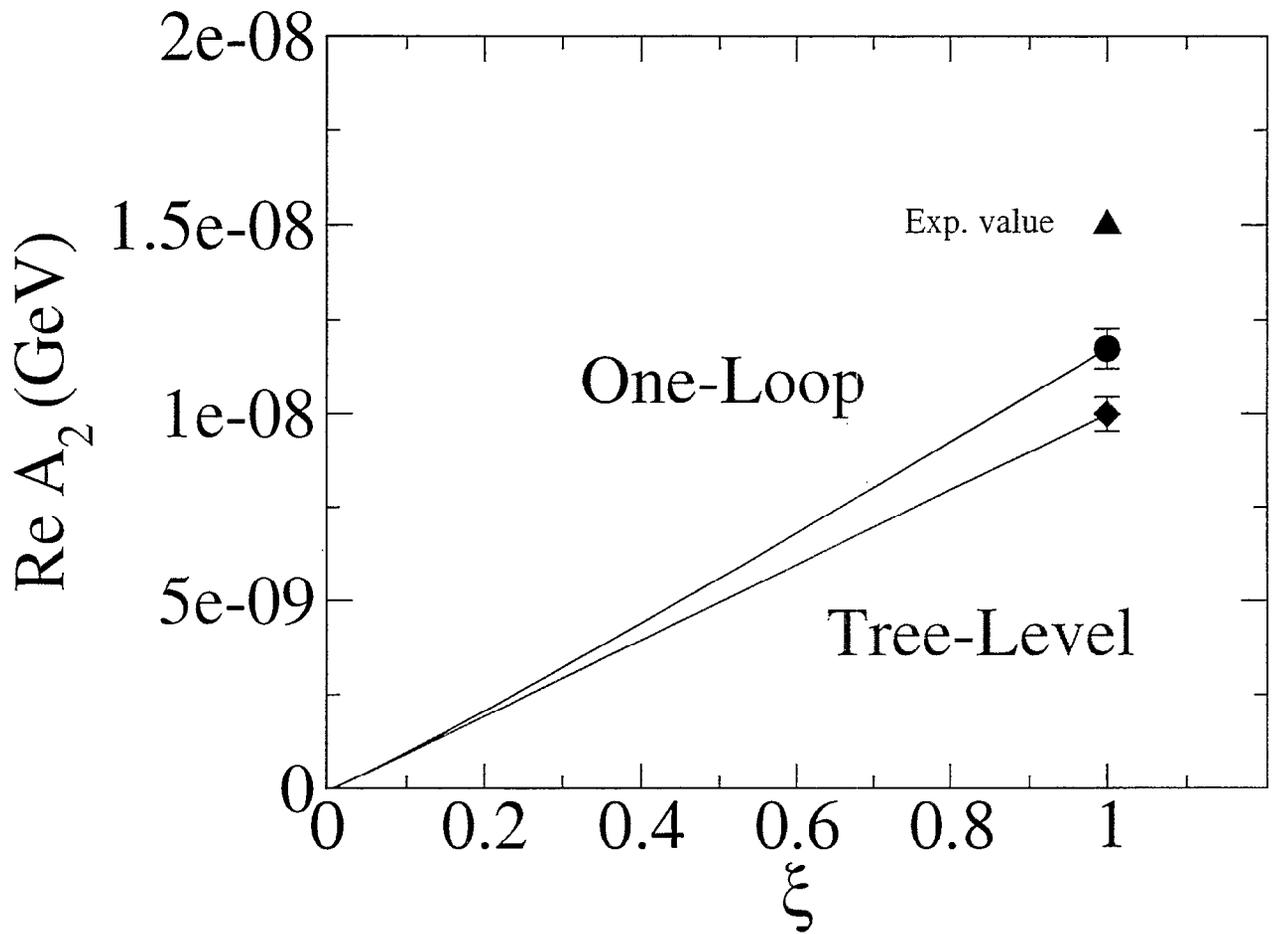
“Tree-Level” = Lowest order chiral perturbation theory

“One-Loop” = Tree-Level + full QCD chiral logs ($K \rightarrow \pi\pi$)



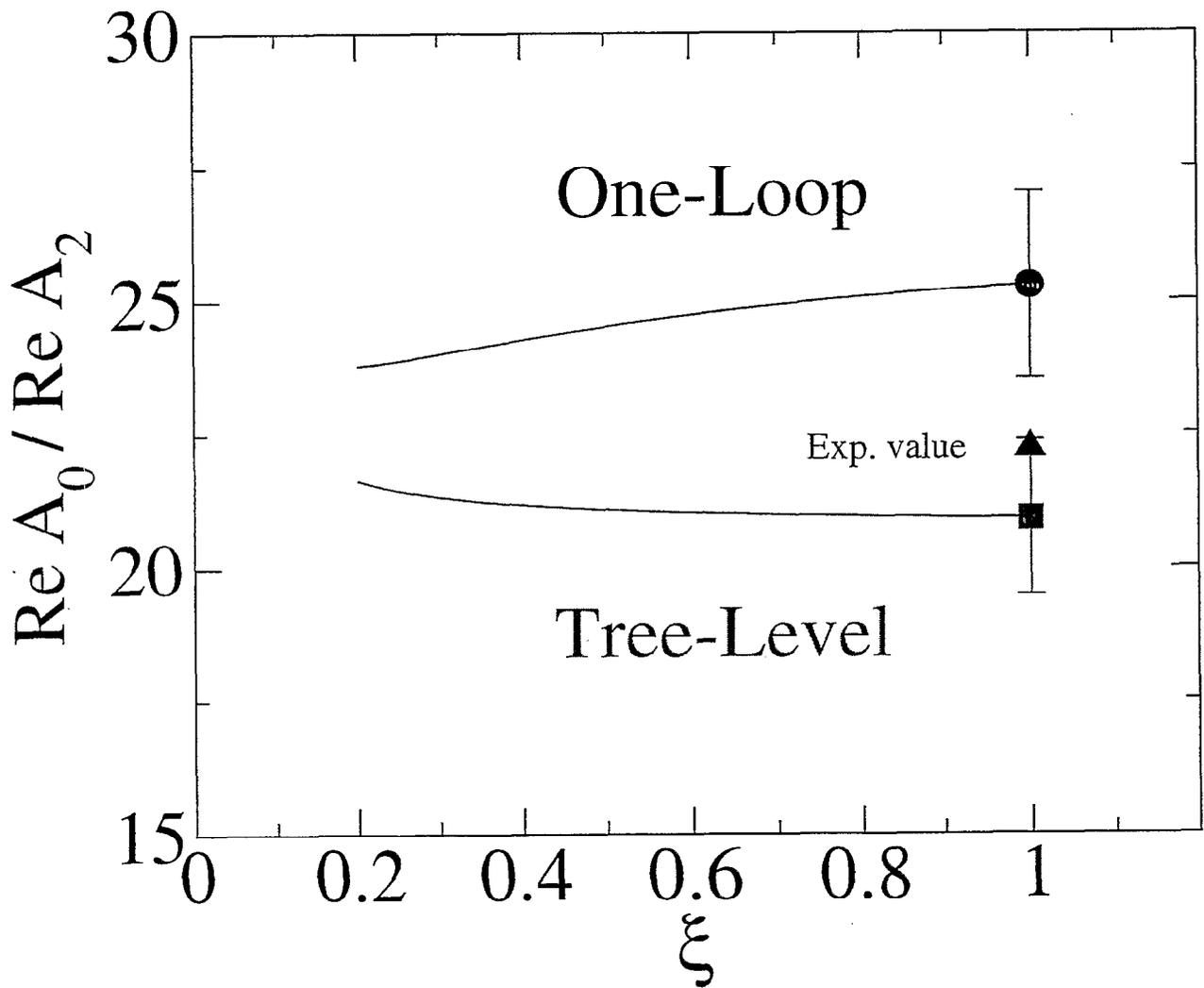
($\mu = 2.13$ GeV)

Real part of A_2



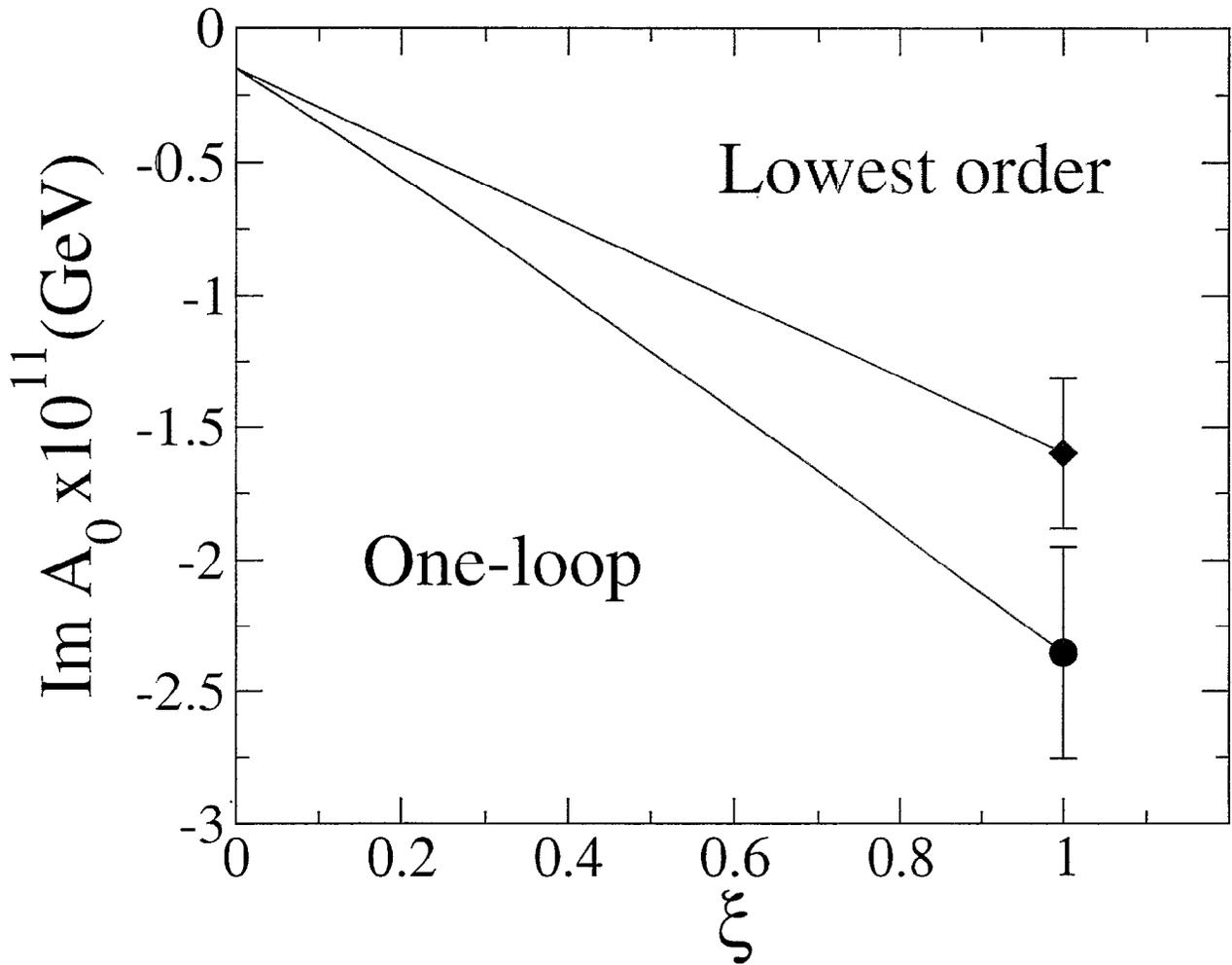
($\mu = 2.13$ GeV)

$\Delta I = 1/2$ Rule



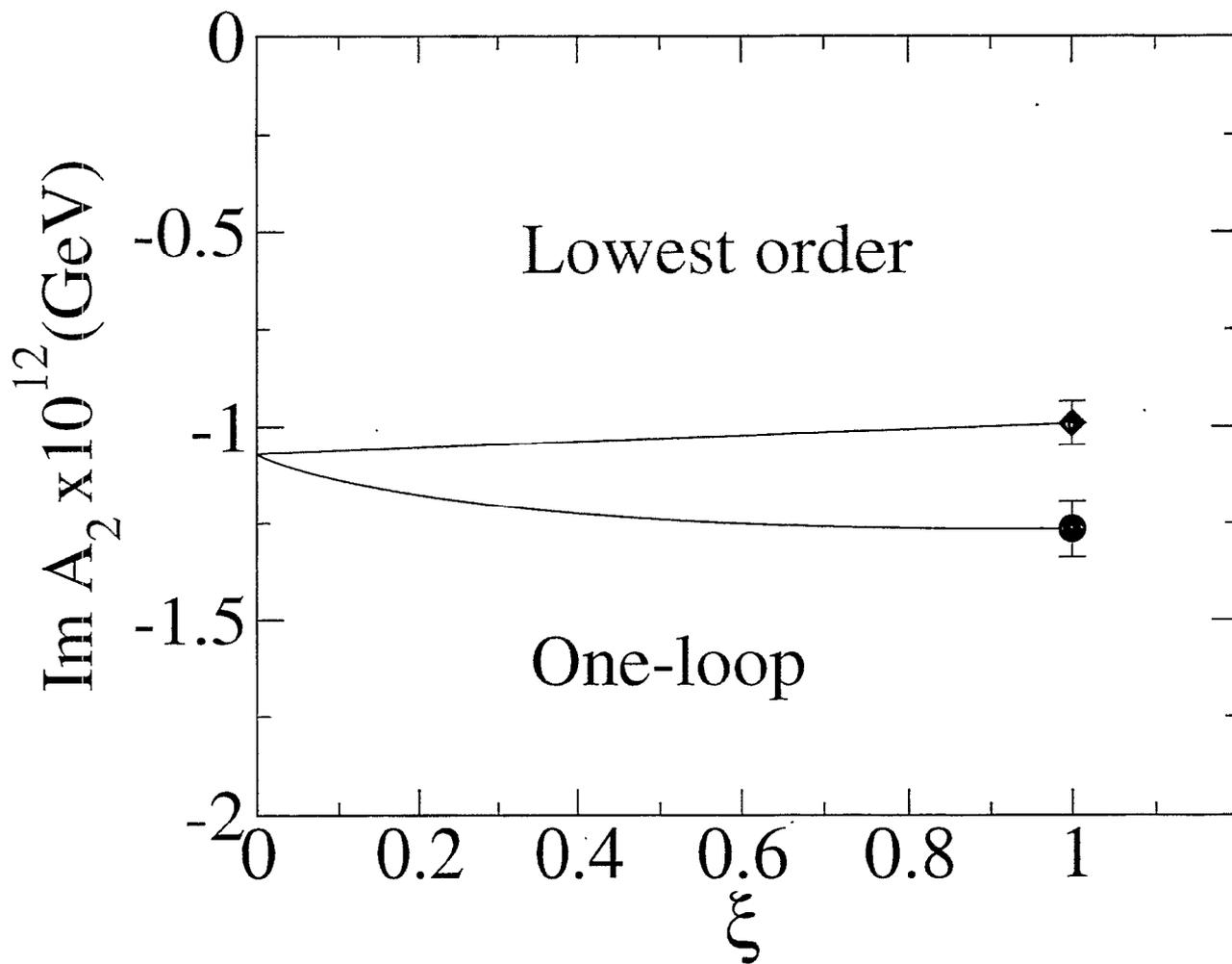
$(\mu = 2.13 \text{ GeV})$

Imaginary part of A_0



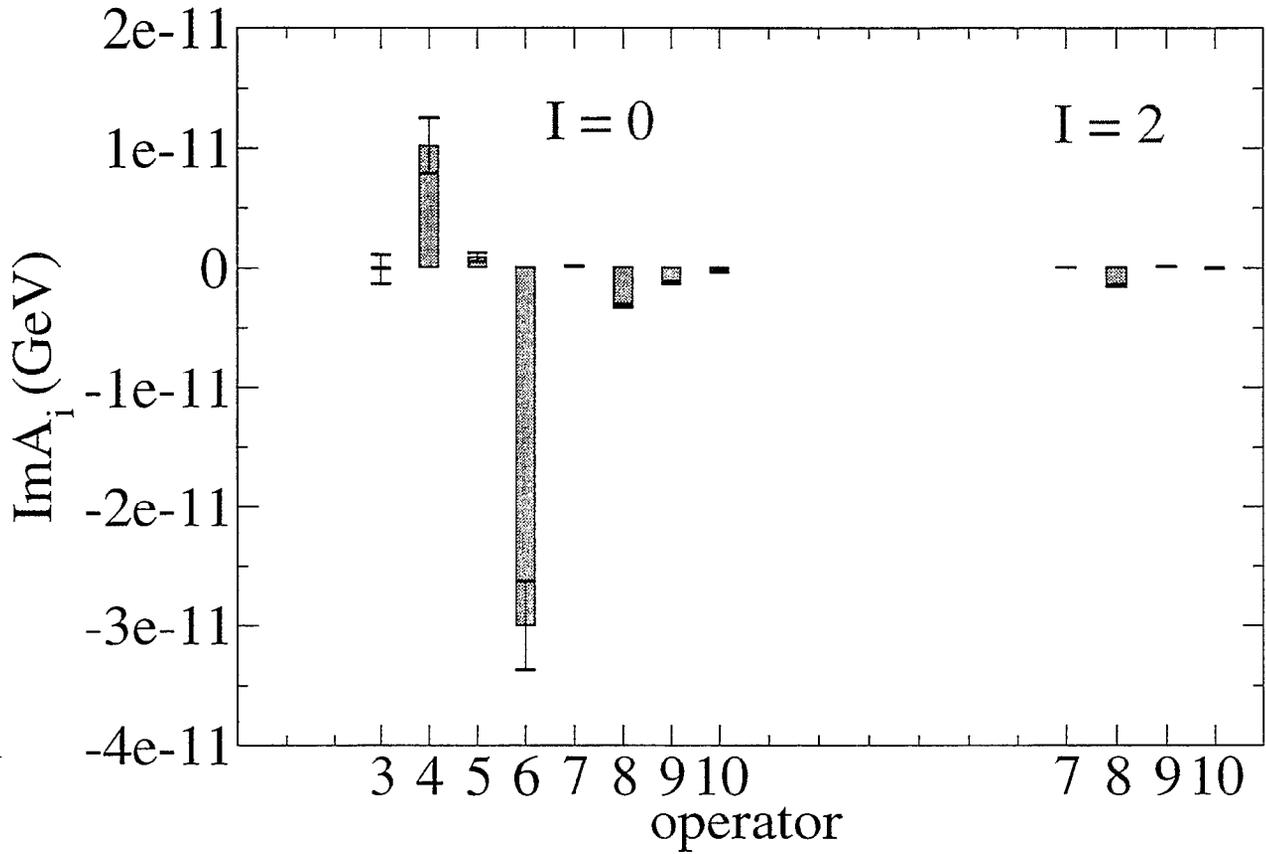
$(\mu = 2.13 \text{ GeV})$

Imaginary part of A_2



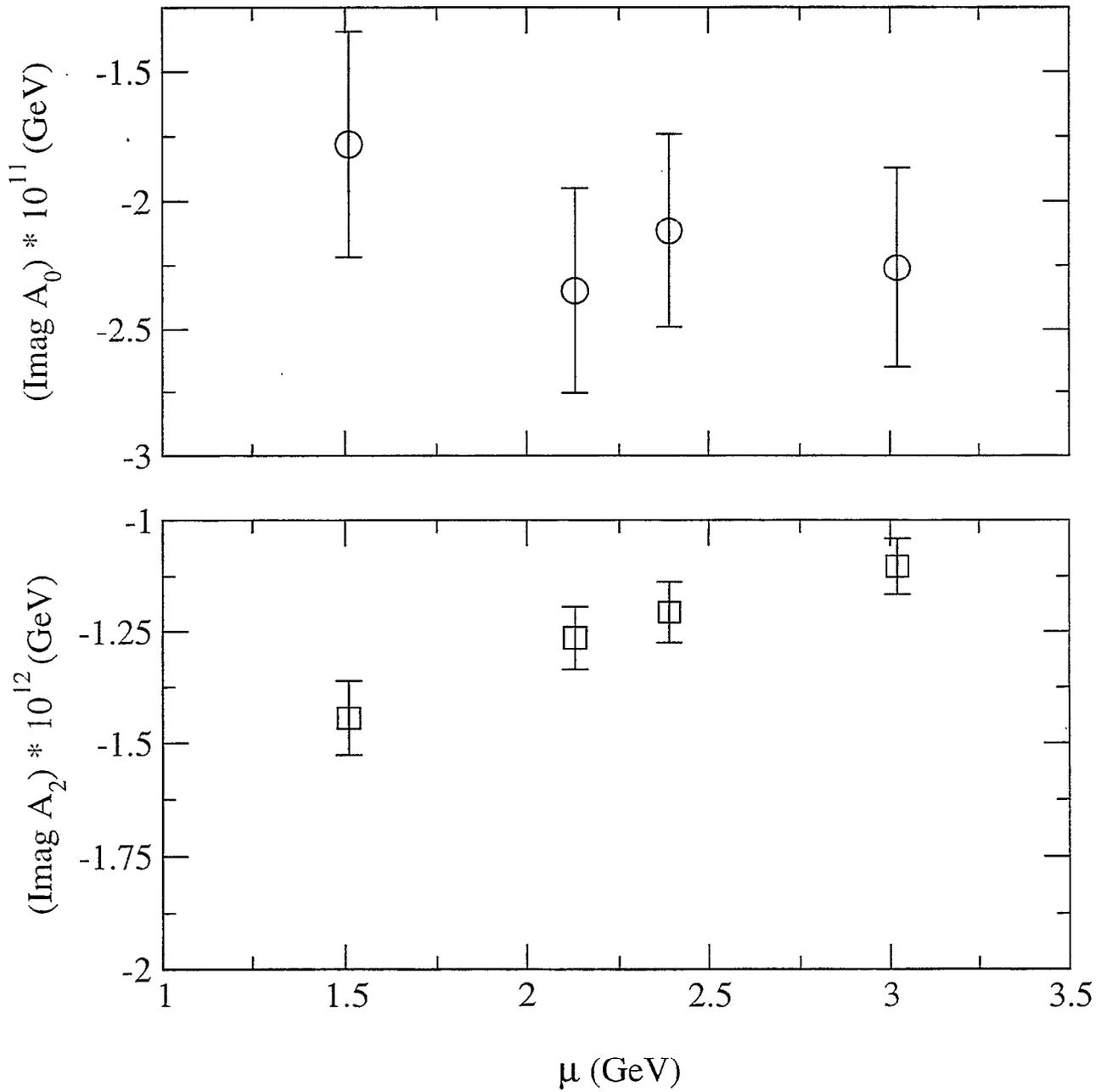
($\mu = 2.13 \text{ GeV}$)

Individual Contributions to $\text{Im}A_{0,2}$



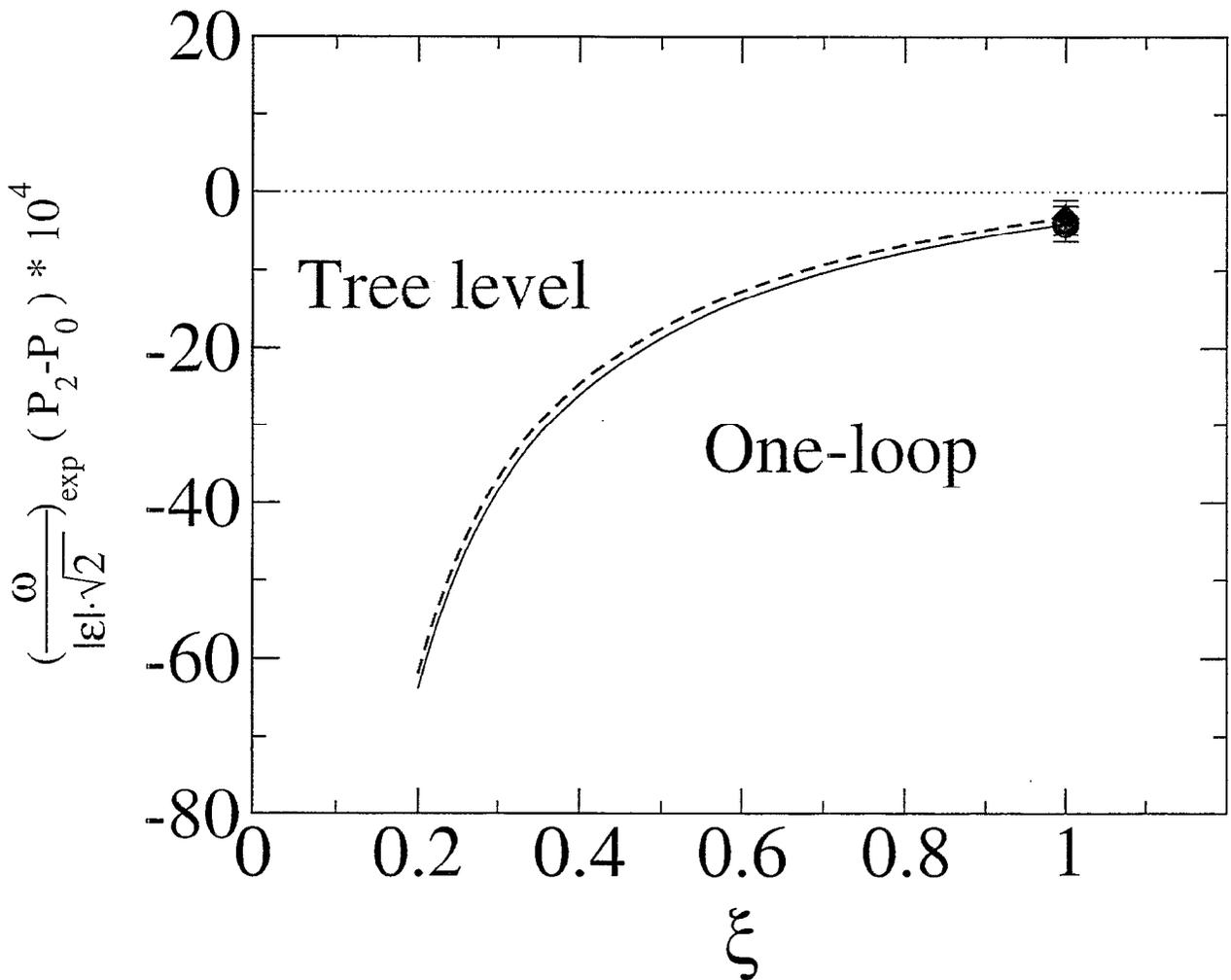
$\mu = 2.13 \text{ GeV}$, One-loop χ PT logs ($\xi = 1$)

Residual Scale Dependence in Imag. Amplitudes



ϵ'/ϵ

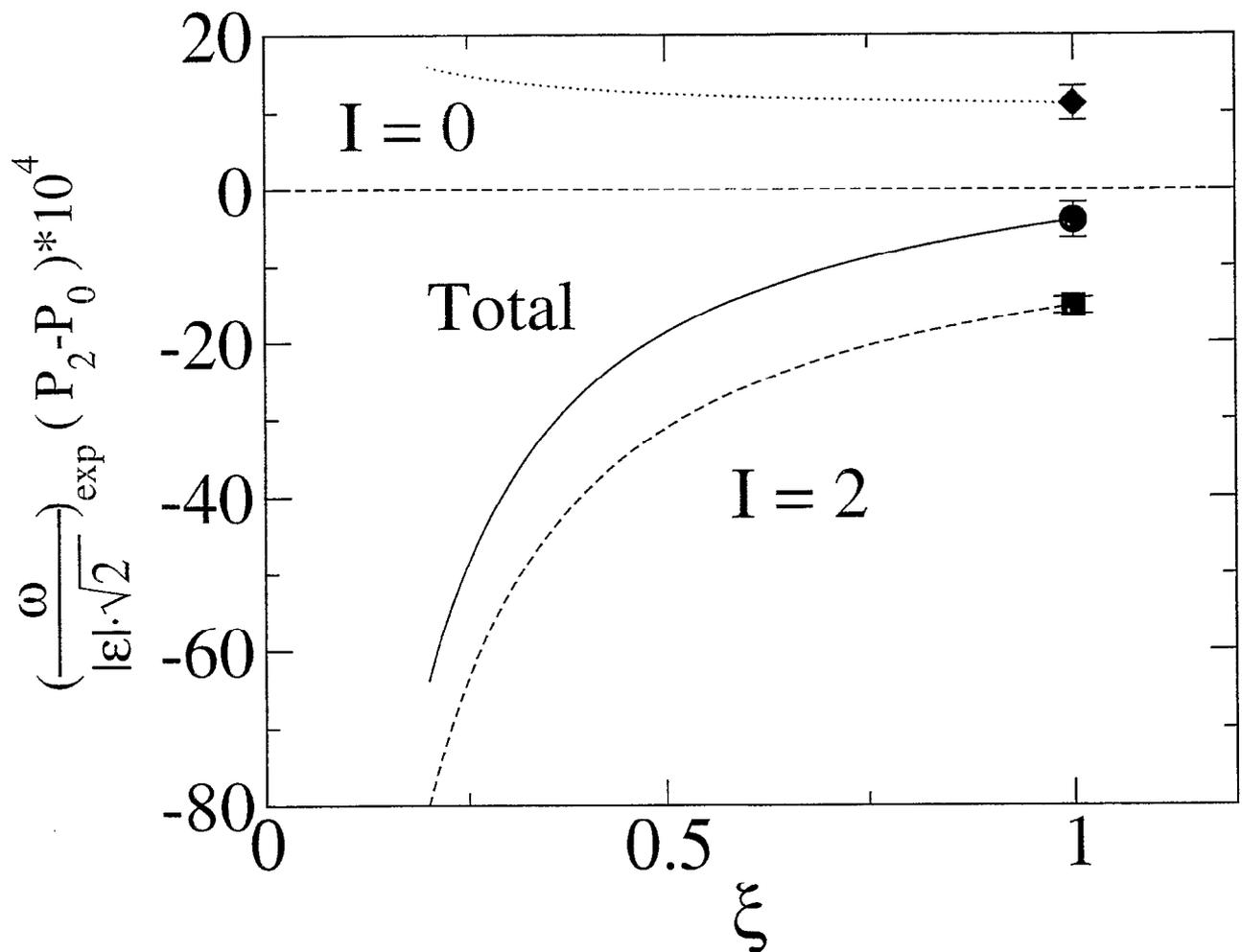
$$\frac{\epsilon'}{\epsilon} = \left(\frac{\omega}{\sqrt{2}|\epsilon|} \right)_{\text{exp}} \left(\frac{\text{Im } A_2}{\text{Re } A_2} - \frac{\text{Im } A_0}{\text{Re } A_0} \right)$$



($\mu = 2.13$ GeV)

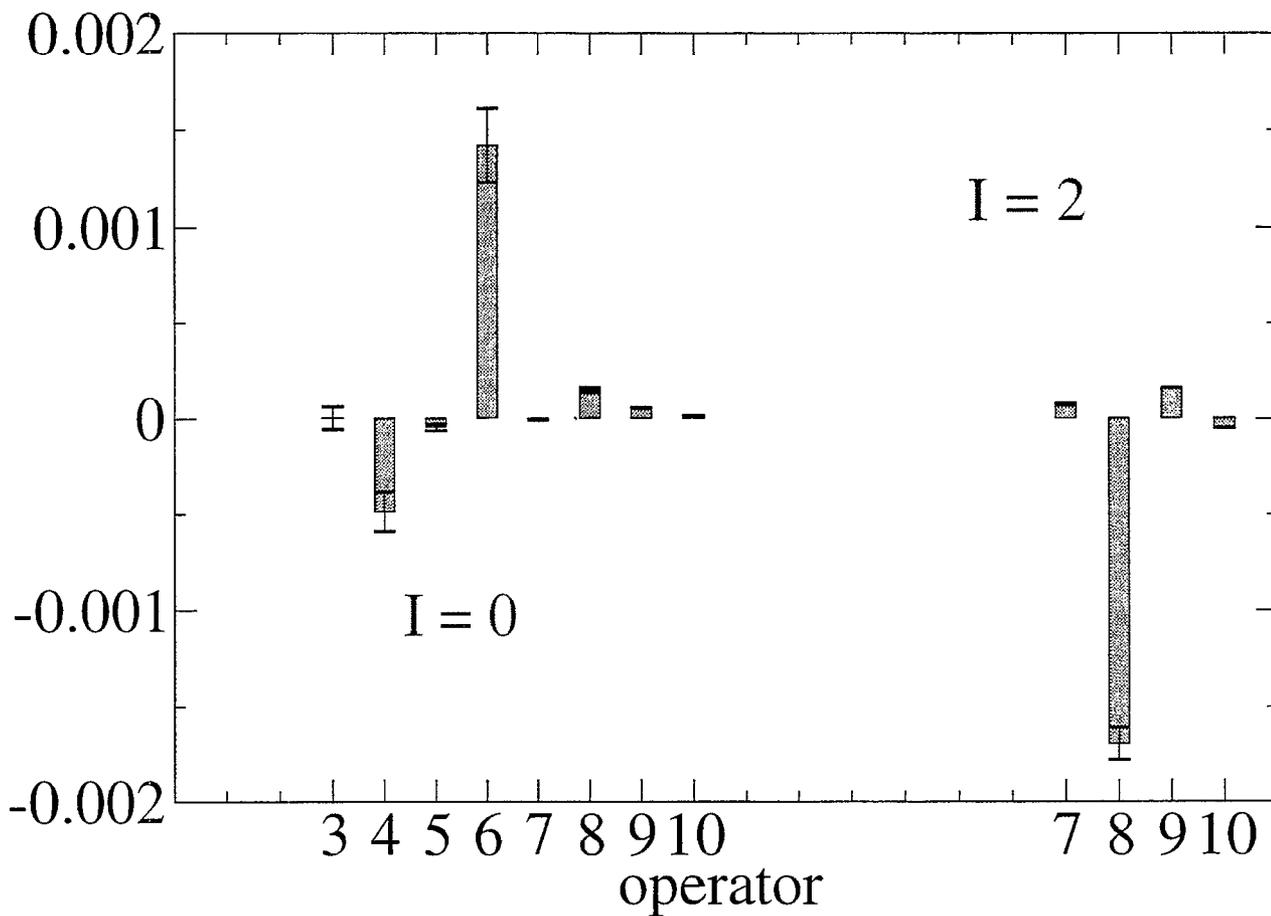
Isospin Breakdown P_0 and P_2

$$P_{0,2} \equiv \frac{\text{Im } A_{0,2}}{\text{Re } A_{0,2}}$$



$\mu = 2.13 \text{ GeV}$, One-loop χ PT logs ($\xi = 1$)

Individual Contributions to ϵ'/ϵ



$\mu = 2.13$ GeV, One-loop χ PT logs ($\xi = 1$)

Final Results

Quantity	Experiment	This calculation (statistical errors only)
$\text{Re } A_0(\text{GeV})$	3.33×10^{-7}	$2.96(17) \times 10^{-7}$
$\text{Re } A_2(\text{GeV})$	1.50×10^{-8}	$1.172(53) \times 10^{-8}$
ω	22.2	25.3(18)
$\text{Re } (\epsilon'/\epsilon)$	$15.3(26) \times 10^{-4}$ (NA48)	$-4.0(23) \times 10^{-4}$
	$20.7(28) \times 10^{-4}$ (KTev)	

($\mu = 2.13$ GeV, One-loop chiral logs)

Approximations in this Calculation of ϵ'/ϵ

1. Use of quenched QCD (Golterman and Pallante).
2. Use of chiral perturbation theory
 - (a) Unknown values for (8,1) and (8,8) conventional chiral logarithms ($m_M^2 \ln(m_M^2)$) in quenched $K^+ \rightarrow \pi^+$ matrix elements.
 - (b) Unknown $\mathcal{O}(p^4)$ counter terms in full and quenched QCD
3. Charm is not treated as an active flavor
4. Reliance on continuum perturbation theory down to $\mu = 1.3$ GeV in the calculation of the Wilson coefficients.

A 25 % error in each, “added linearly”, could produce a much different final result.

Summary and Outlook

- Domain wall fermions + non-perturbative renormalization: calculation of $K \rightarrow \pi$ matrix elements of $\mathcal{H}^{(\Delta S=1)}$ in quenched QCD under very good control.
- Given relatively good agreement with experiment for **Real** amplitudes, **small, negative** result for ϵ' may seem surprising. However, cancellation $P_0 - P_2$ complicates ϵ' .
- Outlook is good for **systematic** improvement of the calculation:
 - Treat charm as an active flavor
(matrix elements, Z^{NPR} , Wilson coefficients calculated, but analysis not complete.)
 - Higher order terms in chiral perturbation theory
 - Dynamical simulations (QCDOC)
 - Direct calculation of on-shell $K \rightarrow \pi\pi$ matrix elements
(Lüscher and Lellouch, Rome-Southampton)

**Calculation of Non-Leptonic Kaon Decay Amplitudes
from $K \rightarrow \pi$ Matrix Elements in Quenched Domain-Wall
QCD**

Junichi Noaki

Calculation of Non-Leptonic Kaon Decay Amplitudes from $K \rightarrow \pi$ Matrix Elements in Quenched Domain-Wall QCD*

Jun-Ichi Noaki

for CP-PACS Collaboration :

S. Aoki, Y. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita,
S. Hashimoto, N. Ishizuka, Y. Iwasaki, T. Izubuchi,
K. Kanaya, T. Kaneko, Y. Kuramashi, V. Lesk,
K.-I. Nagai, M. Okawa, Y. Taniguchi, A. Ukawa
and T. Yoshié

*hep-lat/0108013

I. Introduction

- Calculation of $K \rightarrow \pi\pi$ Decay Amp.

- $\Delta I = 1/2$ Rule
- Direct CP (ϵ'/ϵ)

- χ PT Reduction [Bernard *et al.*, 1985]

$$K \rightarrow \pi\pi \text{ HME} \underset{\text{LO}\chi\text{PT}}{\iff} K \rightarrow \pi \text{ HME on the lattice}$$

Requires chiral symmetry on the lattice

- We Use

- Domain-Wall fermion \Rightarrow Good chiral properties
- RG-improved gluon \Rightarrow Better chiral properties

cf. T. Blum's talk

- This Talk

- Description of the method
- Details of our quenched numerical simulation
- Results of $\Delta I = 1/2$ rule and ϵ'/ϵ

II. χ PT Reduction

- Effective Hamiltonian (OPE)

$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} W_i(\mu) \cdot \underline{Q_i(\mu)}$$

$$\text{local operators : } Q_i = \underset{\uparrow}{Q_i^{(0)}} + \underset{\uparrow}{Q_i^{(2)}}$$

$$\Delta I = 1/2, \quad 3/2$$

- Reduction Formulae (LO)

$$\boxed{Q_1 - Q_6, Q_9, Q_{10}}$$

$$\langle \pi\pi | Q_i^{(0)} | K \rangle = \frac{m_K^2 - m_\pi^2}{\sqrt{2} f_\pi m_\pi^2} \langle \pi | Q_i^{(0)} - \alpha_i Q_{\text{sub}} | K \rangle + \mathcal{O}(m^2)$$

$$\langle \pi\pi | Q_i^{(2)} | K \rangle = \frac{m_K^2 - m_\pi^2}{\sqrt{2} f_\pi m_\pi^2} \langle \pi | Q_i^{(2)} | K \rangle + \mathcal{O}(m^2)$$

$$\boxed{Q_7, Q_8} \quad I = 0, 2$$

$$\langle \pi\pi | Q_i^{(I)} | K \rangle = \frac{-1}{\sqrt{2} f_\pi} \langle \pi | Q_i^{(I)} | K \rangle + \mathcal{O}(m^2)$$

III. Details of Numerical Simulation

● Simulation Parameters

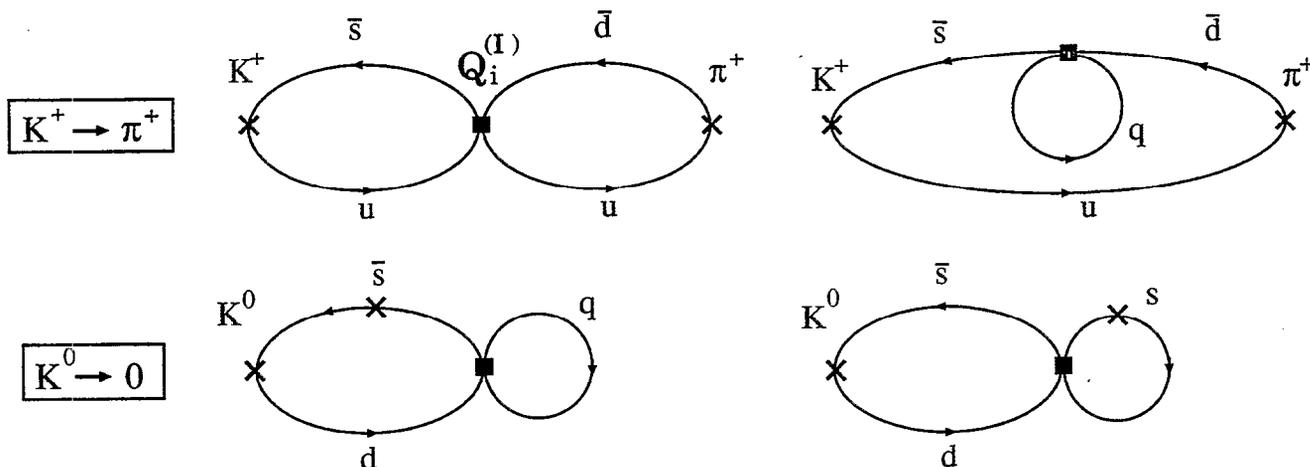
- Two lattice sizes $16^3 \times 32, 24^3 \times 32$
- Domain-Wall fermion $M = 1.8, N_5 = 16$
- RG improved gluon $\beta = 2.6, a^{-1} = 1.94 \text{ GeV}$

\Rightarrow better chiral property than plaquette action
[CP-PACS Collab., 2000]

- Independent gauge confs.

# confs. ($m_f = m_{u,d,s}$)					
m_f	0.02	0.03	0.04	0.05	0.06
$16^3 \times 32$	407	406	406	432	435
$24^3 \times 32$	432	200	200	200	200

● Contractions

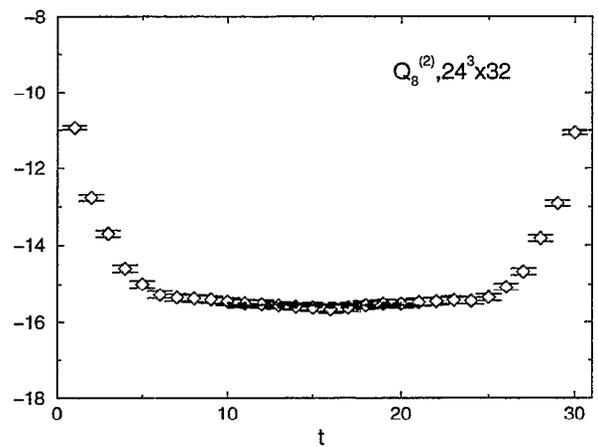
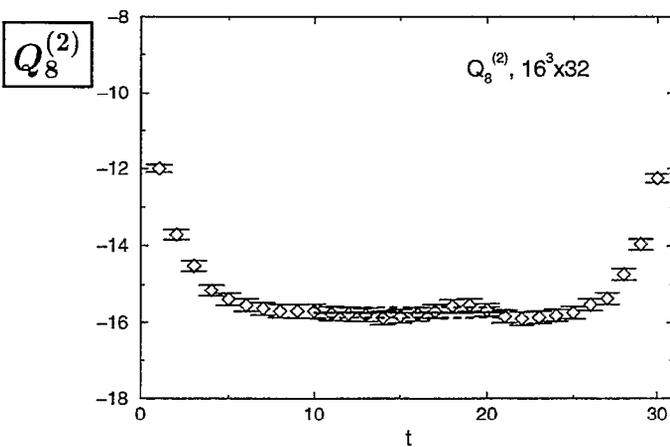
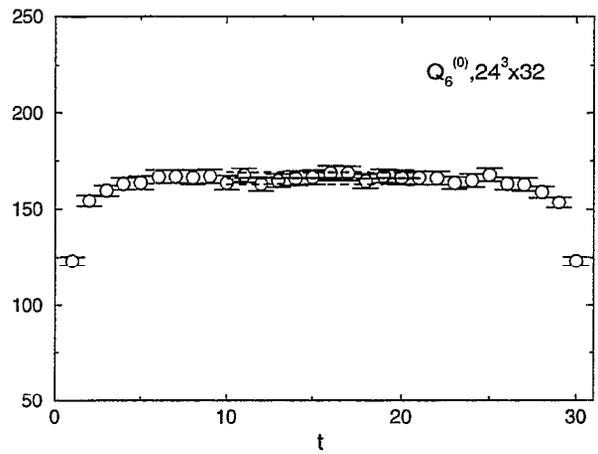
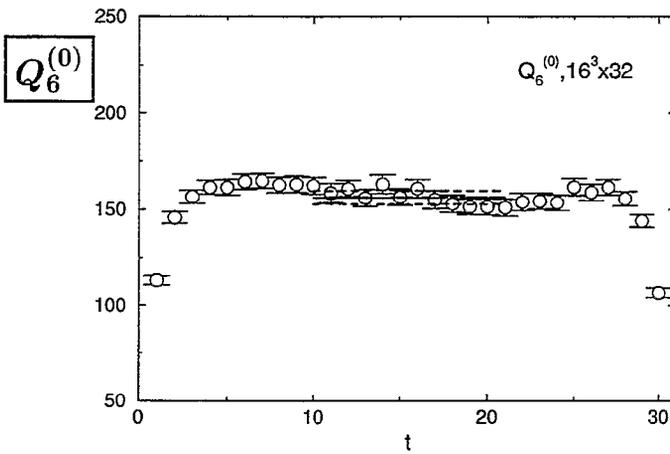


• Qualities of Data (time dependence)

$$\frac{\langle \pi | Q_i^{(I)} | K \rangle}{\langle \pi | A_4 | 0 \rangle \langle 0 | A_4 | K \rangle} \Rightarrow \text{Plateau}$$

$m_f = 0.03, 16^3 \times 32$

$24^3 \times 32$



IV. Chiral Properties of $K^+ \rightarrow \pi^+$ HME

$$\langle \pi^+ | Q_i^{(I)} | K^+ \rangle = a_0 + a_1 m_M^2 + a_2 (m_M^2)^2 + a_3 (m_M^2)^2 \ln m_M^2 + a_4 (m_M^2)^3 + \dots$$

- Three Types of Fit Function

quadratic $a_0 + a_1 m_M^2 + a_2 (m_M^2)^2$

chiral log $a_1 m_M^2 + a_2 (m_M^2)^2 + a_3 (m_M^2)^2 \ln m_M^2$

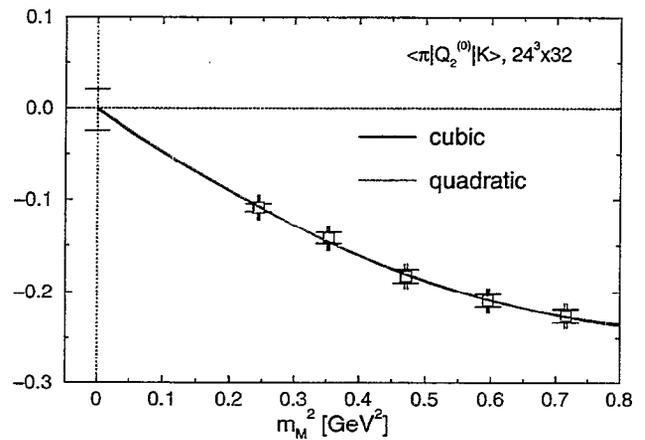
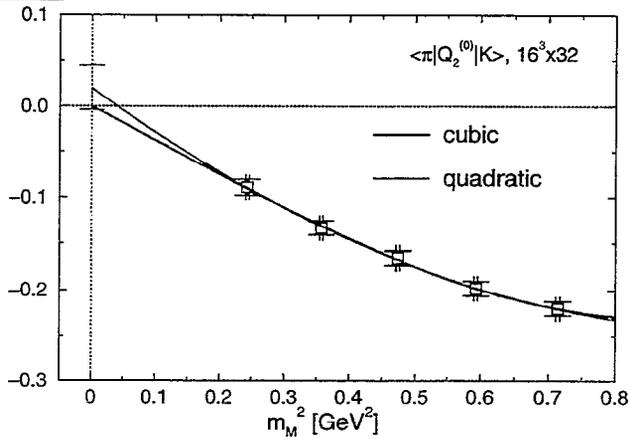
cubic $a_1 m_M^2 + a_2 (m_M^2)^2 + a_4 (m_M^2)^3$

$I = 0$

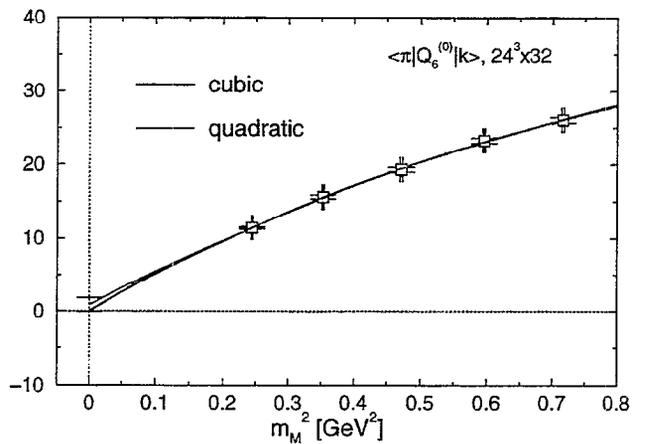
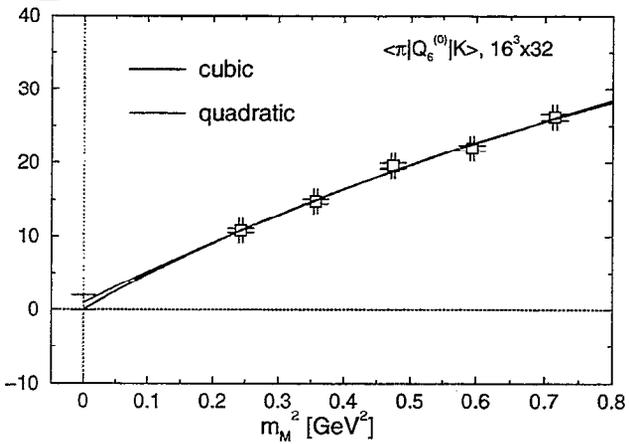
$Q_2^{(0)}$

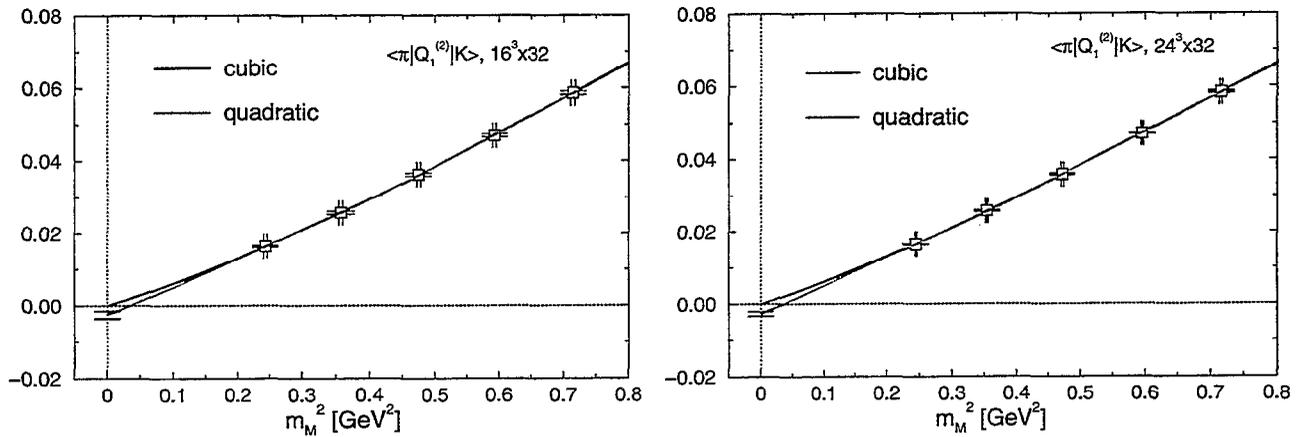
$16^3 \times 32$

$24^3 \times 32$



$Q_6^{(0)}$



$I = 2$ $Q_1^{(2)}$ $16^3 \times 32$ $24^3 \times 32$ Reasonable vales of $\chi^2/\text{d.o.f.}$

● Effect of Chiral Log.

Quenched χPT : [Golterman & Pallante, 2000]

$$a_3/a_1 = -\frac{3}{8\pi^2 f_\pi^2} = -2.18 \text{ GeV}^{-2}$$

Our data (24^3): -0.58 GeV^{-2} Only about 25%

V. Physical Results

- Procedures

1. Renormalization at $q^* = 1/a$

$$Q_i^{\overline{\text{MS}}}(1/a) = Z_{ij}^{\text{latt}} Q_j^{\text{latt}}$$

Z^{latt} : perturbation at 1-loop level

[S. Aoki, Izubuchi, Kuramashi and Taniguchi, 1999 ; 2000]

2. RG running to $\mu = m_c = 1.3 \text{ GeV}$

$$Q_i^{\overline{\text{MS}}}(m_c) = U(m_c, 1/a)_{ij} Q_j^{\overline{\text{MS}}}(1/a)$$

$U(m_c, 1/a)$: at NLO with $N_f = 3$

[Buras, *et al.*, 1992]

3. Chiral extrapolation

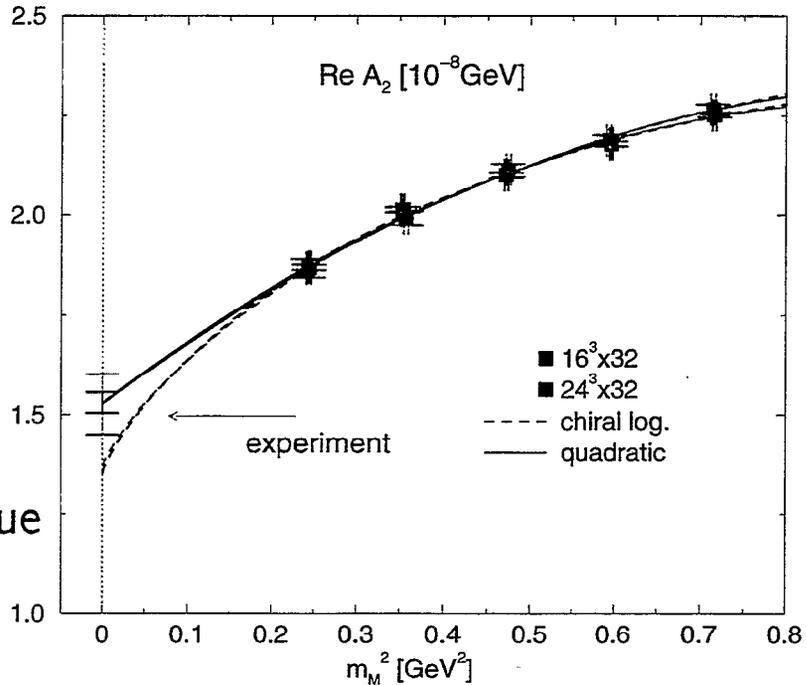
$\mathcal{O}(m_M^2 \rightarrow 0)$: the values in $\text{LO}\chi\text{PT}$

● Decay Amplitudes

$$A_{0,2} = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} W_i(\mu) \langle \pi \pi_{(I=0,2)} | Q_i(\mu) | K^0 \rangle$$

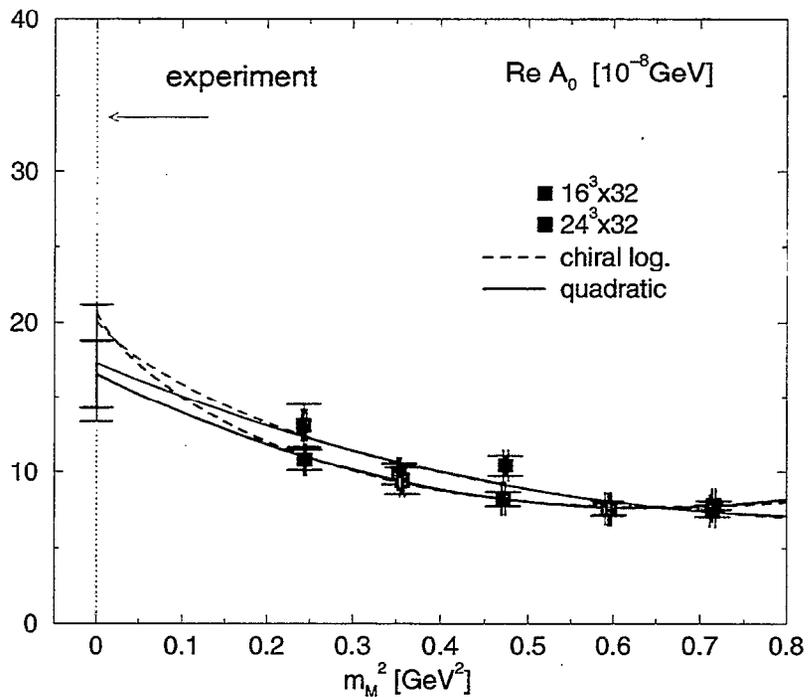
$\text{Re}A_2$
[10^{-8} GeV]

consistent
with exp. value



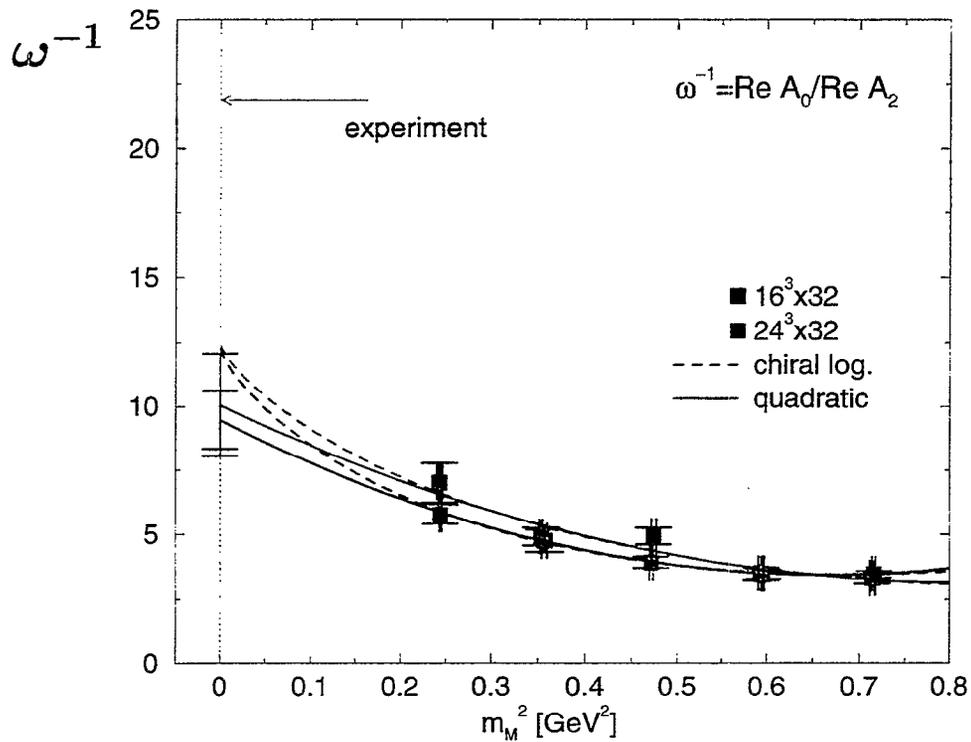
$\text{Re}A_0$
[10^{-8} GeV]

$\approx 50\%$
of exp. value



• $\Delta I = 1/2$ Rule

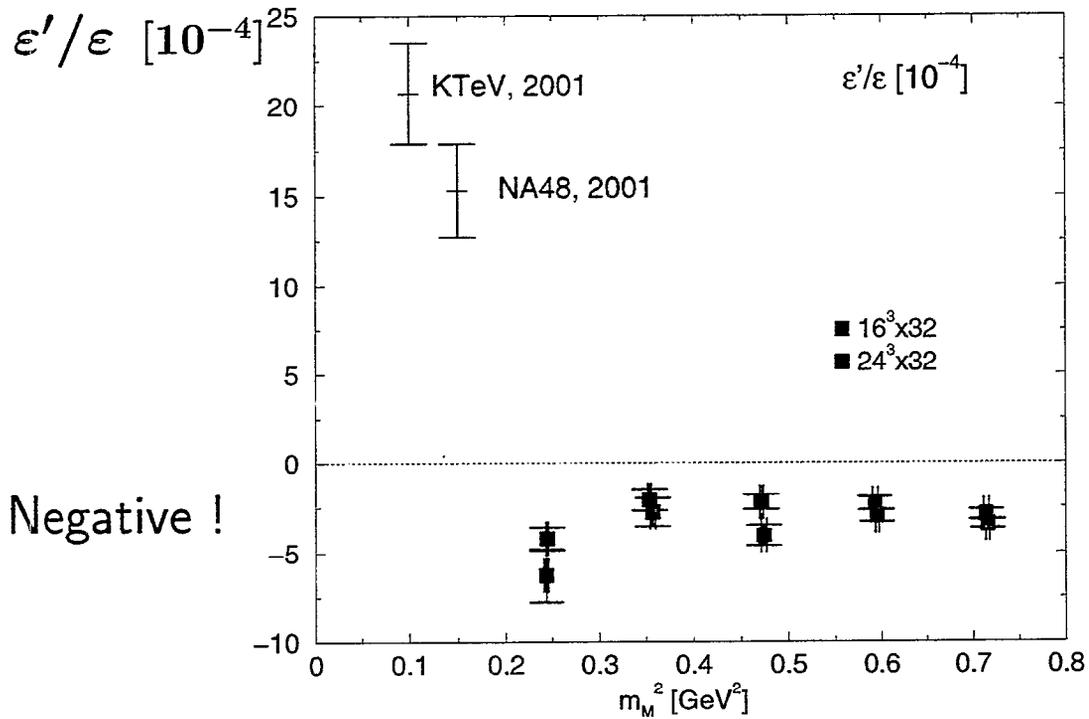
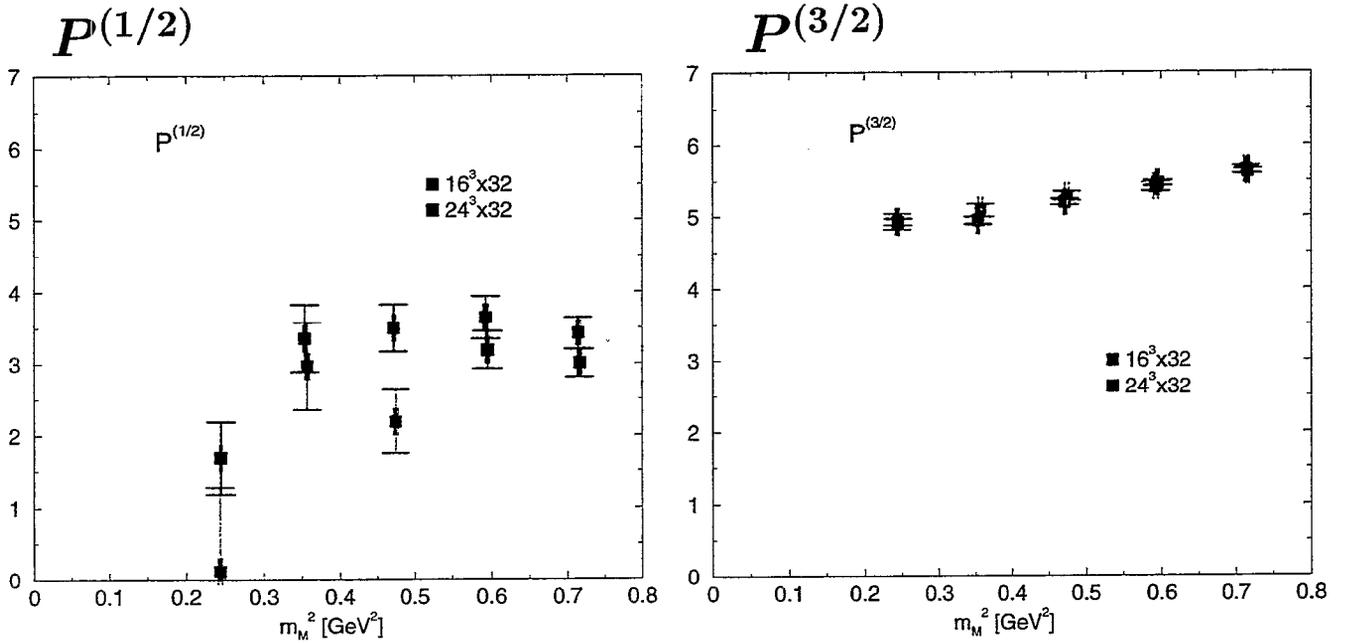
$$\omega^{-1} = \text{Re}A_0/\text{Re}A_2 \approx 22$$



$\approx 50\%$ of exp. value at chiral limit

● Direct CP Violation

$$\epsilon'/\epsilon \simeq \text{Im}(V_{ts}^* V_{td}) [P^{(1/2)} - P^{(3/2)}]$$



VI. Discussion

- Sources of Error ?

- : Chiral properties (DW fermion+ RG-imp. gluon)

- Finite size effect ($V = 16^3$ v.s. 24^3)

- △ : Scaring violation

- Perturbative Z -factors

- Quenching effect

- ? : Higher order effect of χ PT

- Insufficiency of the χ PT reduction

- We have to fight them.

QCDSP/QCDOC: PHYSICS RESULTS AND PROSPECTS/PROJECT STATUS

RBRC Lattice QCD

Norman H. Christ

RBRC LATTICE QCD

PRESENTATION TO RBRC REVIEW COMMITTEE

November 30, 2001

Norman H. Christ
Robert Mawhinney

- **Status of QCDOC Project**
 - **Hardware** (NHC)
 - **Software** (RDM)
- $K \rightarrow \pi\pi$ (RDM)
- **Physics Overview** (NHC)

TECHNOLOGY STRATEGY: BUILD UPON *QCDS*

- Focus maximum computing resources on a single problem
 - 10K processors with fast, low-latency communications.
 - $16^3 \times 32$ lattice on a 8K node, 4 Tflops (sustained) partition (2^4 local volume).
- Homogeneous/modular approach
 - Mesh communications, no central communications switch.
 - Add two extra dimensions for software partitioning: 4-D \rightarrow 6-D
- Target a small, cool processor
 - Fastest, hottest processor does not provide optimum cost performance.
 - Reduced power consumption lowers operating costs.
 - Cooling, packaging and reliability are essential for a large machine.

QCDOC ARCHITECTURE

- **IBM-fabricated, single-chip node.**
[50 million transistors, 1-2 Watt, $\approx 1\text{cm} \times 1\text{cm}$ die]
- **PowerPC 32-bit processor**
 - 1 Gflops, 64-bit IEEE FPU.
 - Memory management.
 - GNU compiler.
- **4 Mbyte on-chip memory.**
- **Extra 2.0 Gbyte/node with DIMM card.**
- **500 MHz serial communications:**
6-D, LVDS, bidirectional.
- **100 Mbit/sec, Fast Ethernet**
 - JTAG/Ethernet boot hardware.
 - Host-node OS communication.
 - Disk I/O.
 - RISCWatch debugger.

QCDOC COLLABORATION

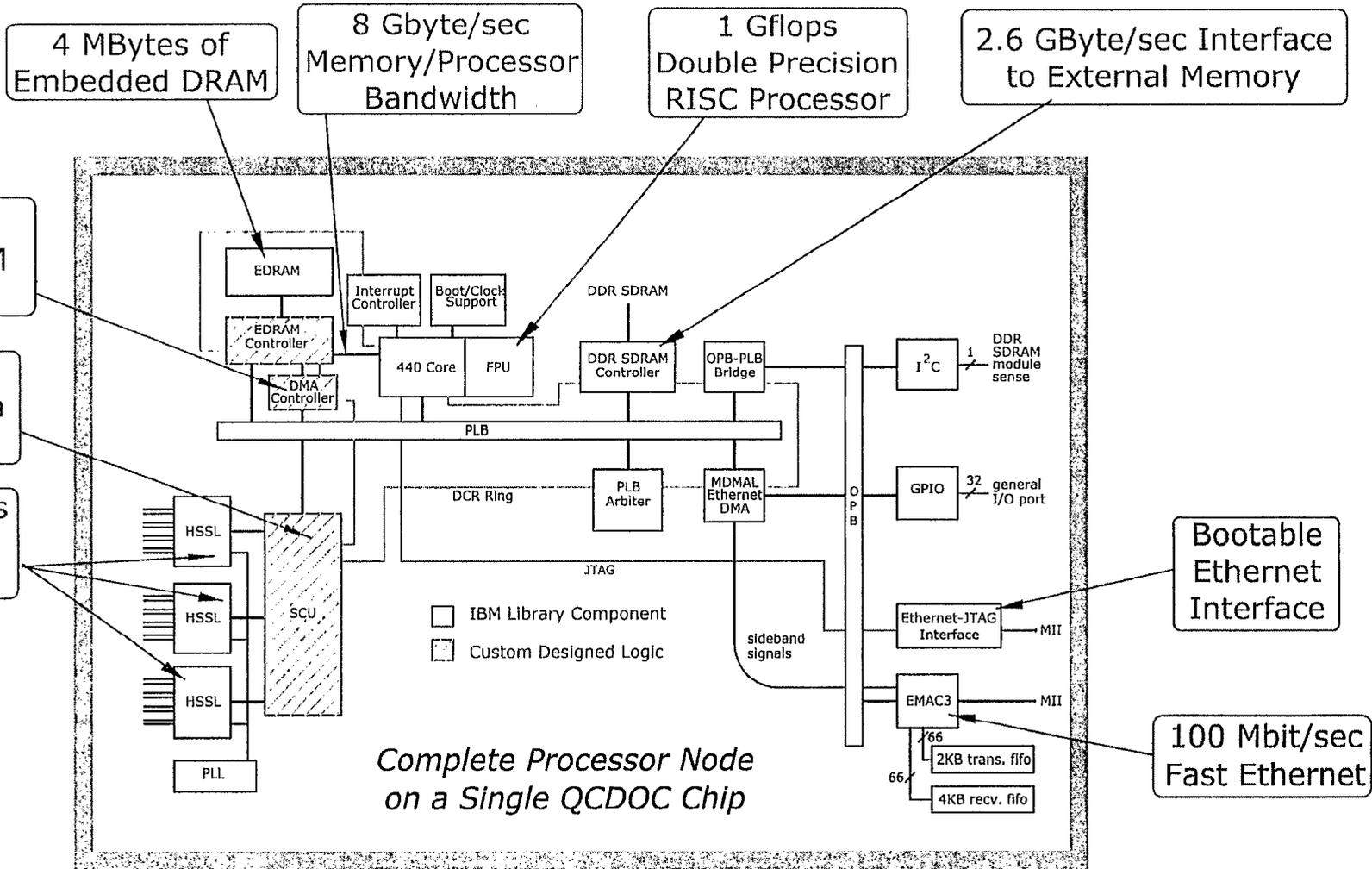
Columbia: Norman Christ
Calin Cristian
Zhihua Dong
Changhoan Kim
Ludmilia Levkova
Xiaodong Liao
Guofeng Liu
Robert Mawhinney
Azusa Yamaguchi

IBM: Dong Chen
Alan Gara

KEK/RBRC: Shigemi Ohta

UKQCD: Peter Boyle
Balint Joo

Yale/RBRC: Tilo Wettig



ASIC Design Status

- **IBM library integration**

- People: Tilo Wettig, Changhoan Kim.
- Subsystems: 440 PowerPC+FPU, DDR controller, DDR memory model, EMAC3, MCMAL8, GPIO, I²C, PLB.
- Status: Essentially finished.

- **Serial Communications Unit**

- People: Norman Christ, Guofeng Liu, Azusa Yamaguchi.
- Status: Most pieces finished, not integrated.

- **DMA controller with PLB master**

- People: Dave Krolak, Matthew Tubbs, IBM/Rochester.
- Status: Tests beginning.

- **Bootable Ethernet/JTAG interface**

- People: Dave Hill, Michelle Rouse, IBM/Rochester.
- Status: Passes elaborate simulation.

- **PEC and PLB slave**

- People: Al Gara, Ben Nathanson, Minhua Lu, IBM/Watson.
- Status: 500 hours of random simulation.

ASIC SCHEDULE

- Full analysis net list Sep 24, 2001
- Floor planning net list Dec 1, 2001
- Preliminary net list Jan 2, 2002
- Final net list Mar 1, 2001
- Release to manufacturing May 1, 2001
- Prototype chips available Jun 15, 2001

PERFORMANCE/COST/SCHEDULE

- We expect to sustain $\approx 50\%$ of peak, even for small volumes/node.
- Cost performance below \$1/Mflops: 10 \times enhancement over QCDSP.
- **Schedule** (peak speeds):

Prototype hardware	06/02
UKQCD/Columbia/U.S pilot machine (7 Tflops)	12/02
RBRC (10 Tflops)	2003
UKQCD in Edinburgh (10 Tflops)	
BNL LGT Center (20 Tflops)	

RBRC-BNL-CU (RBC) Collaboration

- RIKEN-BNL Research Center:

Visiting Faculty: Shigemi Ohta (KEK)

Fellows: Tom Blum, Chris Dawson

Postdoc: Yasumichi Aoki, Jun-Ichi Noaki, Yukio Nemoto,
Kostas Orginos,

Former Postdoc: Shoichi Sasaki, Matthew Wingate

- BNL:

Faculty: Mike Creutz, Amarjit Soni

Visiting Faculty: Taku Izubuchi (Kanazawa)

Postdoc: Saša Prelovšek

- BNL/Columbia:

Postdoc: Chulwoo Jung (SciDAC)

- Columbia:

Faculty: Norman Christ, Robert Mawhinney

Current Postdoc: Thomas Manke, Azusa Yamaguchi

Former Postdoc: Pavlos Vranas, Tim Klassen,
Gabi Siegert

Student: Calin Cristian, Changhoan Kim,

Xiaodong Liao, Ludmila Levkova, Guofeng Liu

Former Student: P. Chen, G. Fleming, C. Jung,

A. Kaehler, Y. Luo, C. Malureanu, C. Sui, L. Wu,
Y. Zhestkov

Talks at Lattice 2001

- Weak Matrix Elements

1. Lattice Values for the Low Energy Constants of $K \rightarrow \pi\pi$ Matrix Elements, [R. Mawhinney]
2. $\text{Re}A_0$ and $\text{Re}A_2$ from Quenched Lattice QCD, [C. Cristian]
3. $\text{Im}A_0$, $\text{Im}A_2$ and ϵ' from Quenched Lattice QCD, [T. Blum]

- Heavy Quarks

1. Relativistic Bottomonium Spectrum from Anisotropic Lattices, [X. Liao and T. Manke]

- Thermodynamics

1. Study of 3-flavor QCD Finite Temperature Phase Transition with Staggered Fermions, [X. Liao]
2. Anisotropic Lattices and Dynamical Fermions, [L. Levkova]
3. The QCD Phase Transition with Domain Wall Fermions, [N. Christ and L. Wu]

- Finite Density

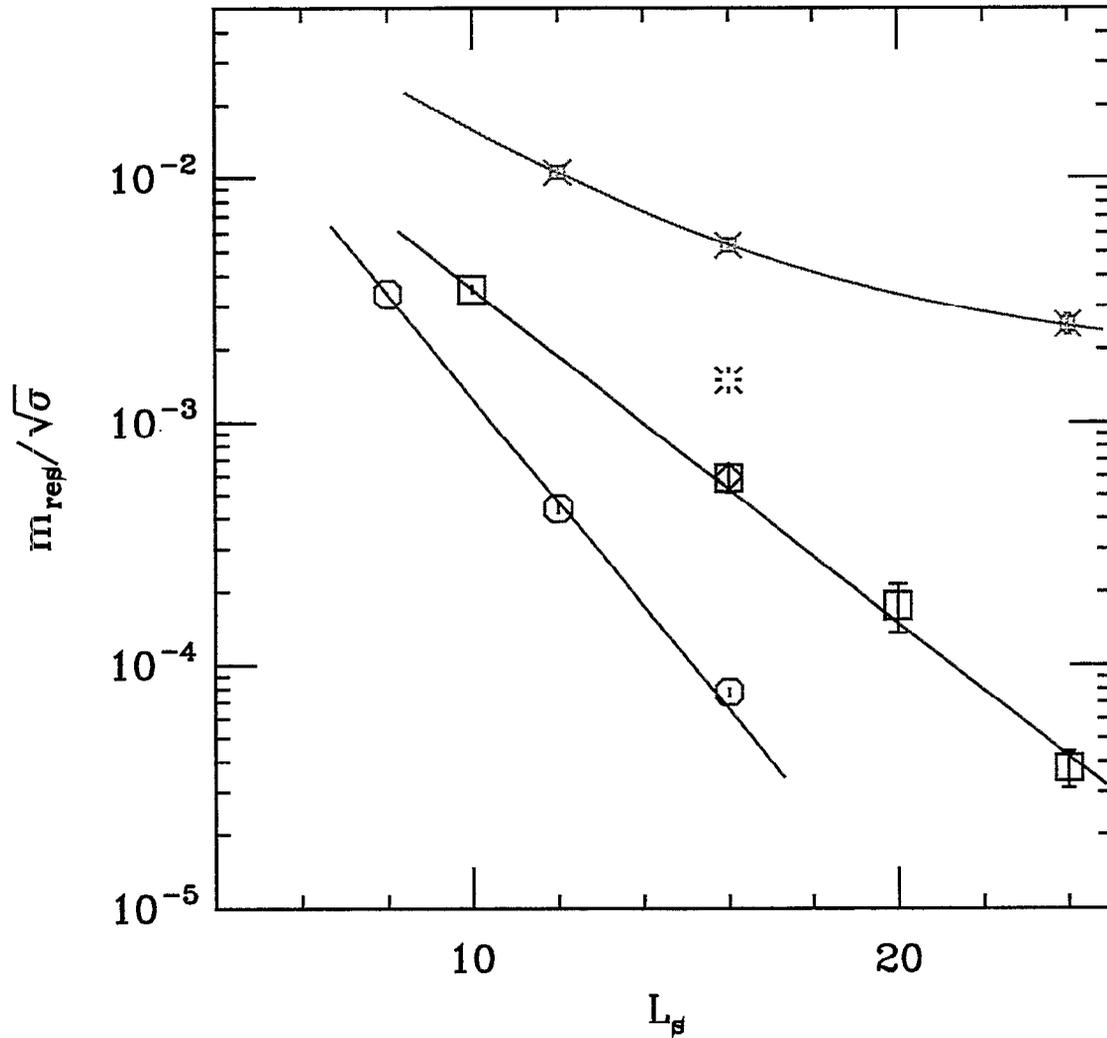
1. Finite Baryon Number Simulations in the Static Limit, [A. Yamaguchi]

- DWF Properties
 1. Improving Full QCD Calculation using Domain-Wall Fermions, [T. Izubuchi and C. Dawson]
 2. Localisation of Chirality for Domain Wall Fermion eigenvectors, [C. Dawson]
 3. Low-lying Dirac Eigenmodes from Domain Wall Fermions, [G. Liu]
 4. Chiral Properties of Domain Wall Fermions with improved gauge actions, [K. Orginos]
- Quenched DWF Hadronic Properties
 1. Hadron spectrum for quenched domain-wall fermions with DBW2 gauge action, [Y. Aoki]
 2. Nucleon axial charge from quenched lattice QCD with domain wall fermions and improved gauge action, [S. Sasaki]
- The QCDOC Machine
 1. The QCDOC Project, [T. Wettig]
 2. Summary of QCDOC, [N. Christ]
- Plenary Discussion
 1. Dynamical Fermion Simulations, [N. Christ]

PHYSICS OVERVIEW

- **Improve DWF method (quenched)** [Y. Aoki, K. Orginos]
 - DBW2 action reduces m_{res} 100 X
 - Collecting $a^{-1} = 1.3$ GeV and 2.0 GeV lattices.
- **Exploit DWF for new physics (quenched)**
 - Install QCDSF disks and standardize propagator storage. [G. Liu]
 - Nucleon axial current matrix elements. [T. Blum, S. Ohta, S. Sasaki]
 - Nucleon structure functions. [K. Orginos]
 - Proton decay matrix elements. [Y. Aoki]
 - Mass of the η' . [T. Izubuchi]
- **Extend anisotropic technique to QCD Thermodynamics.** [L. Levkova, T. Manke]
- **Enhance $K \rightarrow \pi\pi$ calculation**
 - Include charm quark in simulation. [T. Blum, C. Calin, N. Christ, R. Mawhinney, A. Soni]
 - Explore direct $\pi\pi$ final state simulation. [T. Blum, N. Christ, C. Kim, A. Soni]
 - Explore full QCD simulation. [Next slide]

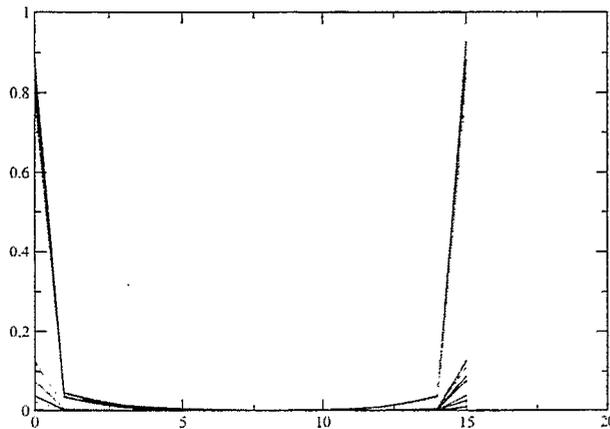
L_s dependence of m_{res} for various actions



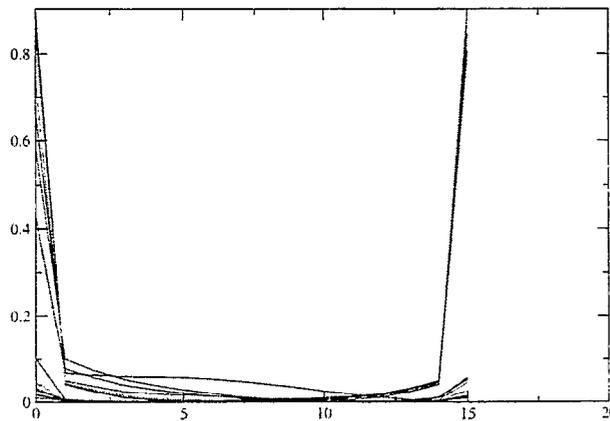
Yellow: Wilson action. Blue: Iwasaki action.
Red: DBW2. Burst: Symanzik.

s -dependence of low-lying Dirac eigenmodes for heavy quarks

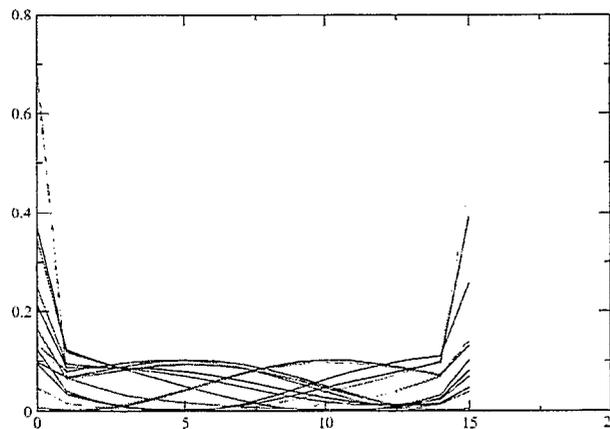
$m_f = 0.1$
(≈ 250 MeV)



$m_f = 0.2$
(≈ 500 MeV)



$m_f = 0.3$
(≈ 750 MeV)



Dynamical DWF Simulations?

- Improve HMC algorithm
 - Explore small L_s guide Hamiltonian. [C. Dawson, R. Mawhinney]
 - Coherent fermion and Pauli-Villars force term. [C. Dawson]
- Add $\det(D_{W-4D} + M_5 + i\gamma^5\epsilon)$ to suppress zero-crossings. [T. Izubuchi]
- Develop Iwasaki/DBW2 variant for full QCD [C. Dawson, T. Izubuchi]
 - Use Schwinger-Dyson conditions to determine equivalent gauge action.
 - Use $a^{-1} = 2.0$, a $T \approx 200\text{MeV}$, $8^3 \times 16 \times 8$ lattice and $m_{\pi\text{-screen}}$ for numerical tests.

**Kaon Matrix Elements and CP Violation from
Quenched Lattice QCD**

Robert D. Mawhinney

Kaon Matrix Elements and CP violation from Quenched Lattice QCD

RBC Collaboration

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RBRC Review

November 30, 2001

Software Projects

Software system	People	Projects
QCDSP OS	2	Parallel disk system
QCDSP CPS	15	Anisotropy, improved actions, more matrix elements, improved evolution alg.
QCDOC OS	5	Boot and Run Kernels Host-side OS Disks, queueing system
QCDOC CPS	7	Portability SciDAC standard
QCDOC ASIC	7	High performance kernels Design verification

Many personnel are involved in more than one software project.

CPS is the Columbia Physics System

$K^0 - \bar{K}^0$ CP Violation Experiments

Two parameters:

- ϵ CP violation from mixing
- ϵ' CP violation from decays

Two amplitudes:

$$\eta_{+-} = \frac{A(K_L^0 \rightarrow \pi^+ \pi^-)}{A(K_S^0 \rightarrow \pi^+ \pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = \frac{A(K_L^0 \rightarrow \pi^0 \pi^0)}{A(K_S^0 \rightarrow \pi^0 \pi^0)} = \epsilon - 2\epsilon'$$

Measurements of 2 real numbers needed:

$$|\epsilon|$$

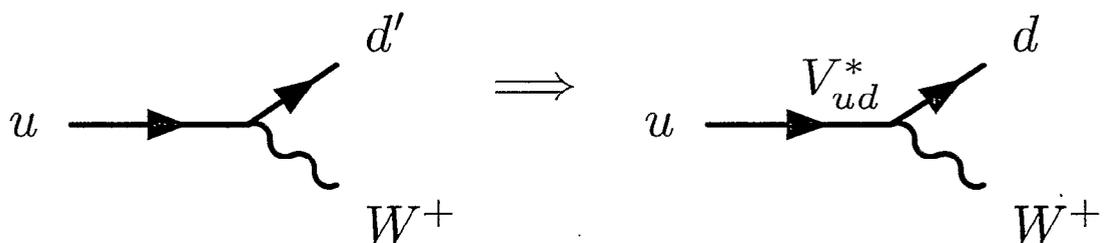
$$|\eta_{00}/\eta_{+-}|^2 \approx 1 - 6 \operatorname{Re}(\epsilon'/\epsilon) \approx 1 - 6 \epsilon'/\epsilon$$

CP Violation in the Standard Model

quark electroweak eigenstates \neq quark mass eigenstates

$$\text{QCD: } m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s + \dots$$

$$\text{Weak: } d' = V_{ud}d + V_{us}s + V_{ub}b$$



Cabbibo-Kobayashi-Maskawa (CKM) matrix relates these eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(X) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - X) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin \theta_C = 0.2237, \quad X = \rho + i\eta, \quad A, \rho, \eta \text{ real.}$$

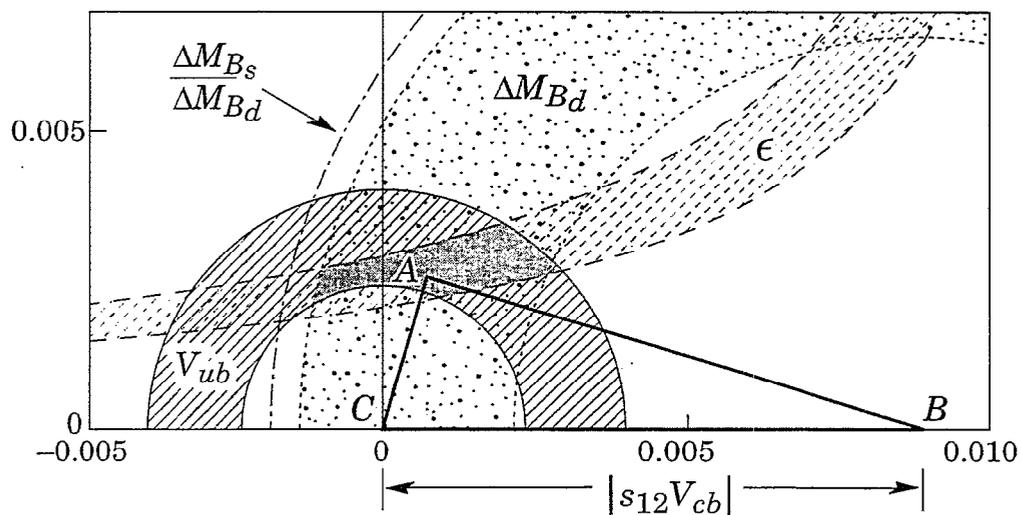
One real parameter (η) in CKM matrix controls CP violation in the standard model.

11.30.01-4

Unitarity Triangle

CKM mixing matrix

Particle Data Group, C. Caso et. al.



Definitions of Experimental Quantities

- Need $K \rightarrow \pi\pi$ matrix elements of CP-violating operators which produce decays.
- Scale of physics in $K \rightarrow \pi\pi$ system is ~ 500 MeV.
- Defining $A(K^0 \rightarrow \pi\pi(I)) = A_I e^{i\delta_I}$ gives

$$\epsilon' = \frac{ie^{i(\delta_2 - \delta_0)}}{\sqrt{2}} \left(\frac{\text{Re } A_2}{\text{Re } A_0} \right) \left(\frac{\text{Im } A_2}{\text{Re } A_2} - \frac{\text{Im } A_0}{\text{Re } A_0} \right)$$

- There is the $\Delta I = 1/2$ rule

$$\omega \equiv \frac{\text{Re } A_0}{\text{Re } A_2} \simeq 22$$

- We also define

$$P_2 \equiv \frac{\text{Im } A_2}{\text{Re } A_2} \quad P_0 \equiv \frac{\text{Im } A_0}{\text{Re } A_0}$$

From the SM to the Lattice

Continuum

Lattice

$$\mathcal{L}^{\text{EW}}$$

$$\Downarrow$$

$$\sum_i C_i(M_W) O_i$$

$$\Downarrow$$

$$\sum_i C_i(\mu, m_t, \dots) O_i$$

$$\Downarrow$$

$$\langle q(p) | O_i | q(p) \rangle_{\text{tree}}$$

$$\overset{\text{fix}}{\Rightarrow} Z$$

$$Z_{ij} \langle q(p) | O_j^{\text{lat}} | q(p) \rangle_{p^2 = -\mu^2}$$

$$\langle \pi\pi | O_i | K \rangle$$

$$\overset{\text{use}}{\Leftarrow} Z$$

$$Z_{ij} \langle \pi\pi | O_j^{\text{lat}} | K \rangle$$

$$\Uparrow$$

$$\langle \pi\pi | O_i^{\text{lat}} | K \rangle$$

$$\Uparrow$$

$$\langle \pi | O_i^{\text{lat}} | K \rangle$$

$$\langle 0 | O_i^{\text{lat}} | K \rangle$$

$K \rightarrow \pi\pi$ in 3-flavor Effective Theory

- Hamiltonian for 3-flavor Effective Theory

$$\mathcal{H}^{(\Delta S=1)} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left\{ \sum_{i=1}^{10} [z_i(\mu) + \tau y_i(\mu)] Q_i \right\}$$

- Ten four-quark operators Q_i , only 7 independent

$SU(3)_L \times SU(3)_R$ irrep.	Number	Isospin
(27,1)	1	$I = 1/2, 3/2$
(8,1)	4	$I = 1/2$
(8,8)	2	$I = 1/2, 3/2$

- $K \rightarrow \pi\pi$ from lattice calculations and chiral perturbation theory

Irrep.	$K^+ \rightarrow \pi^+$	$K^0 \rightarrow \pi^+ \pi^-$
(27,1)	$-\frac{4m_M^2}{f^2} \alpha_1^{(27,1)}$	$-\frac{4i}{f^3} m_{K^0}^2 \alpha_1^{(27,1)}$
(8,8)	$-\frac{12}{f^2} \alpha_2^{(8,8)}$	$-\frac{12i}{f^3} \alpha_2^{(8,8)}$
(8,1)	$\frac{4m_M^2}{f^2} (\alpha_1^{(8,1)} - \alpha_2^{(8,1)})$	$\frac{4i}{f^3} m_{K^0}^2 \alpha_1^{(8,1)}$

- (8,1) requires determining $\alpha_2^{(8,1)}$ from $K \rightarrow |0\rangle$

Master Formula for $K \rightarrow \pi\pi$ Matrix Elements

$$A(K \rightarrow (\pi\pi)_I) = -i\sqrt{\frac{3}{4}}G_F V_{ud}V_{us}^* \sum_{i=1}^{10} \sum_{\substack{j=1 \\ j \neq 4}}^8 \left[z_i(\mu) + \tau y_i(\mu) \right] \hat{Z}_{ij}^{\text{NPR}}(\mu)$$

$$\times \left\{ \begin{array}{ll} \frac{4i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} & I = 0, \quad j = 1, 2, 3, 5, 6 \\ \frac{-4\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} (m_{K^0}^2 - m_{\pi^+}^2) a^{-4} & I = 2, \quad j = 1, 2, 3, 5, 6 \\ \frac{-12i}{f^3} \alpha_{j,\text{lat}}^{(1/2)} a^{-6} & I = 0, \quad j = 7, 8 \\ \frac{-12\sqrt{2}i}{f^3} \alpha_{j,\text{lat}}^{(3/2)} a^{-6} & I = 2, \quad j = 7, 8 \end{array} \right.$$

CKM matrix elements from experiment

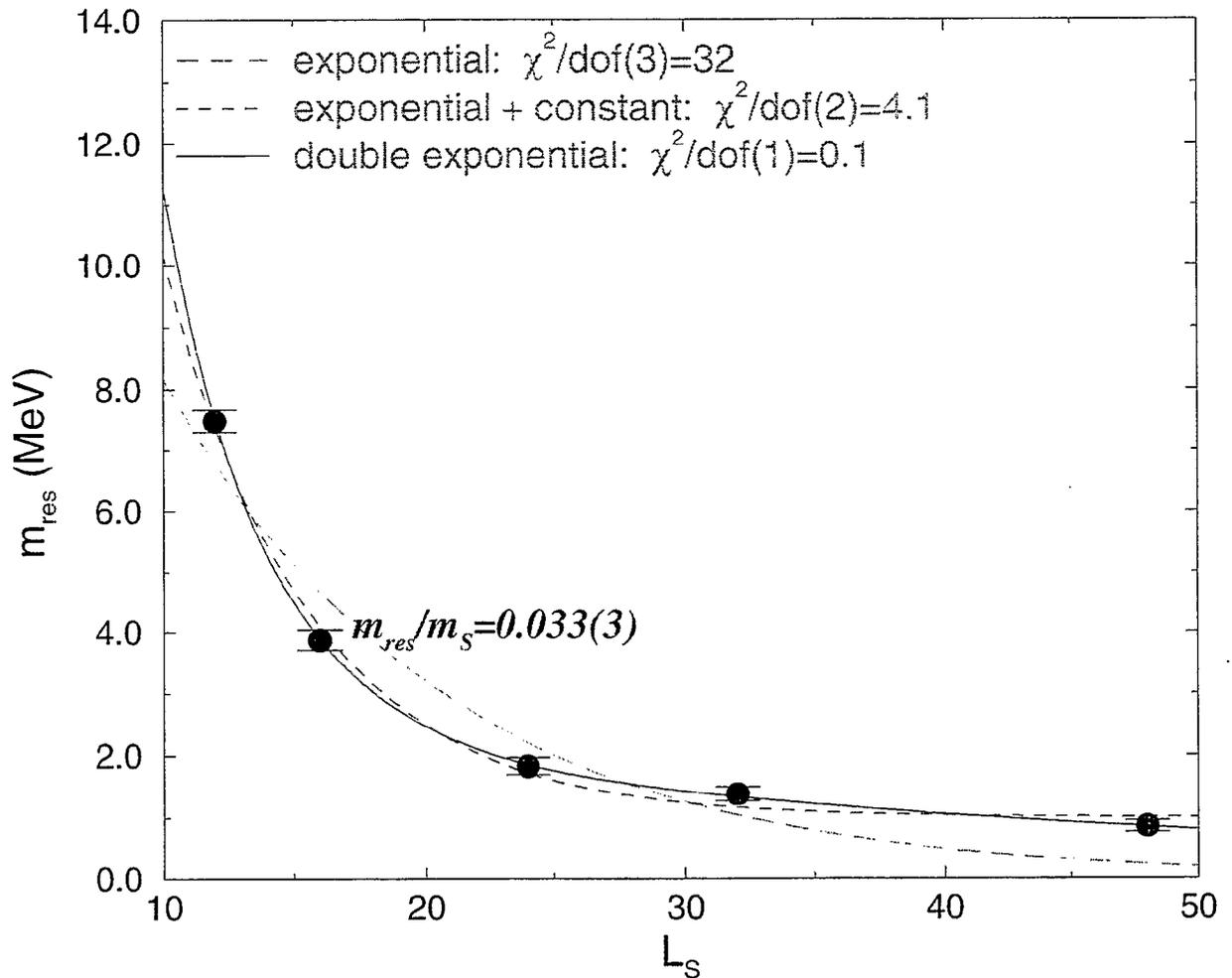
Wilson coefficients from continuum perturbation theory

Non-perturbative renormalization factors from quenched lattice QCD

Parameters from $K \rightarrow \pi$ and $K \rightarrow 0$ in quenched lattice QCD.

Residual Mass for $\beta = 6.0$

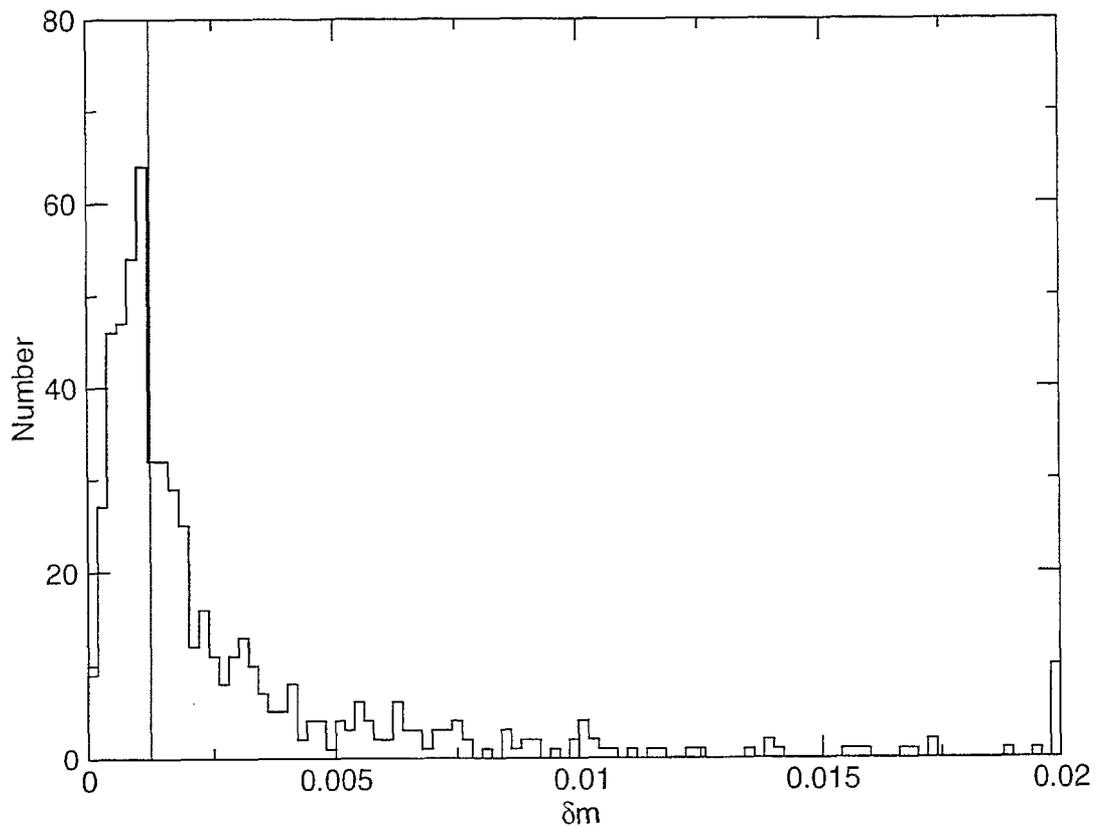
For $\beta = 6.0$ with Wilson gauge action, $m_{\text{res}} = 0.00124$.
Plotted versus L_s in $\overline{\text{MS}}$ scheme at $\mu = 2$ GeV, using
NPR determined Z_s .



Symmetry Breaking per Eigenvalue, δm_i

Connect eigenvalues $\Lambda_{H,i}$ of hermitian DWF operator to 4-dimensional eigenvalue λ_i and symmetry breaking for this eigenvalue, δm_i through

$$\Lambda_{H,i}^2 = n_{5,i}^2 (\lambda_i^2 + (m_f + \delta m_i)^2) + \dots$$



RBC Collaboration, hep-lat/0007038

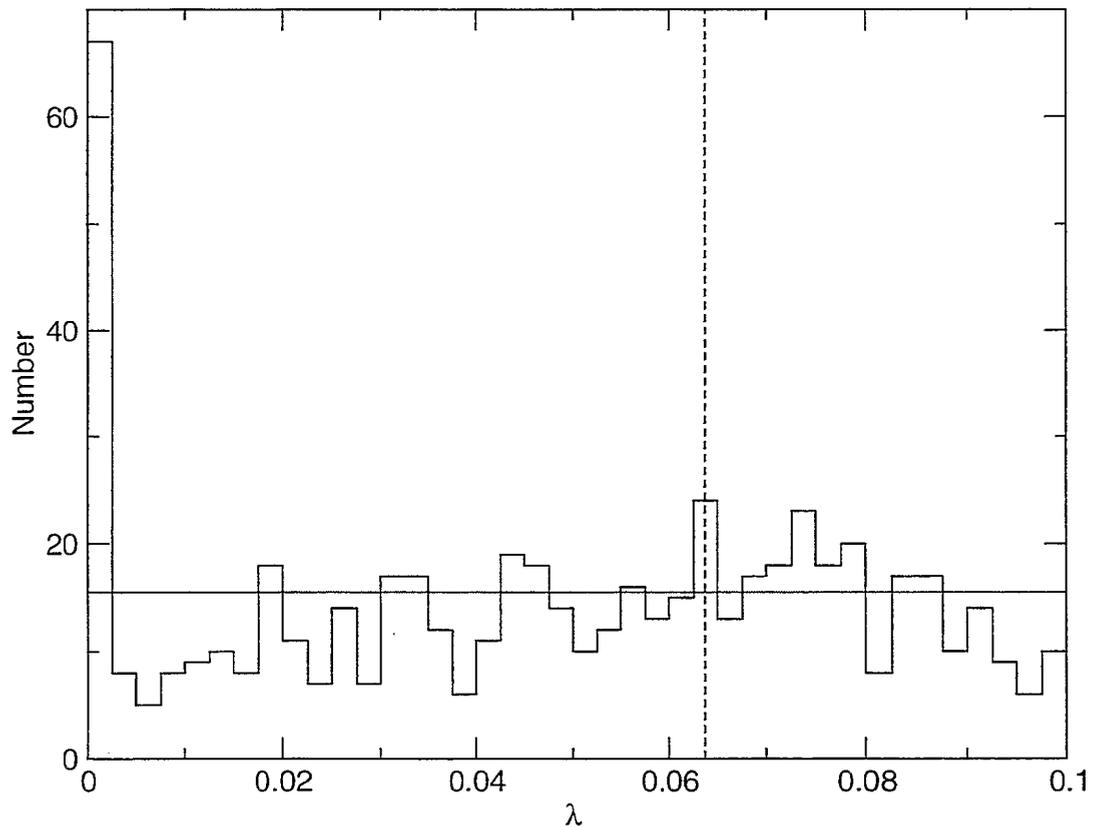
11.30.01-11

Density of Eigenvalues from DWF

Determine $\rho(\lambda)$ for eigenvalues λ of $D^{(4)}$. from $\beta = 6.0$ with Wilson gauge action, $16^4 \times 16$ lattices.

Red line is $\rho(0)$ from $-\langle \bar{\psi}\psi \rangle$.

Blue line is minimum over lattices of largest λ per

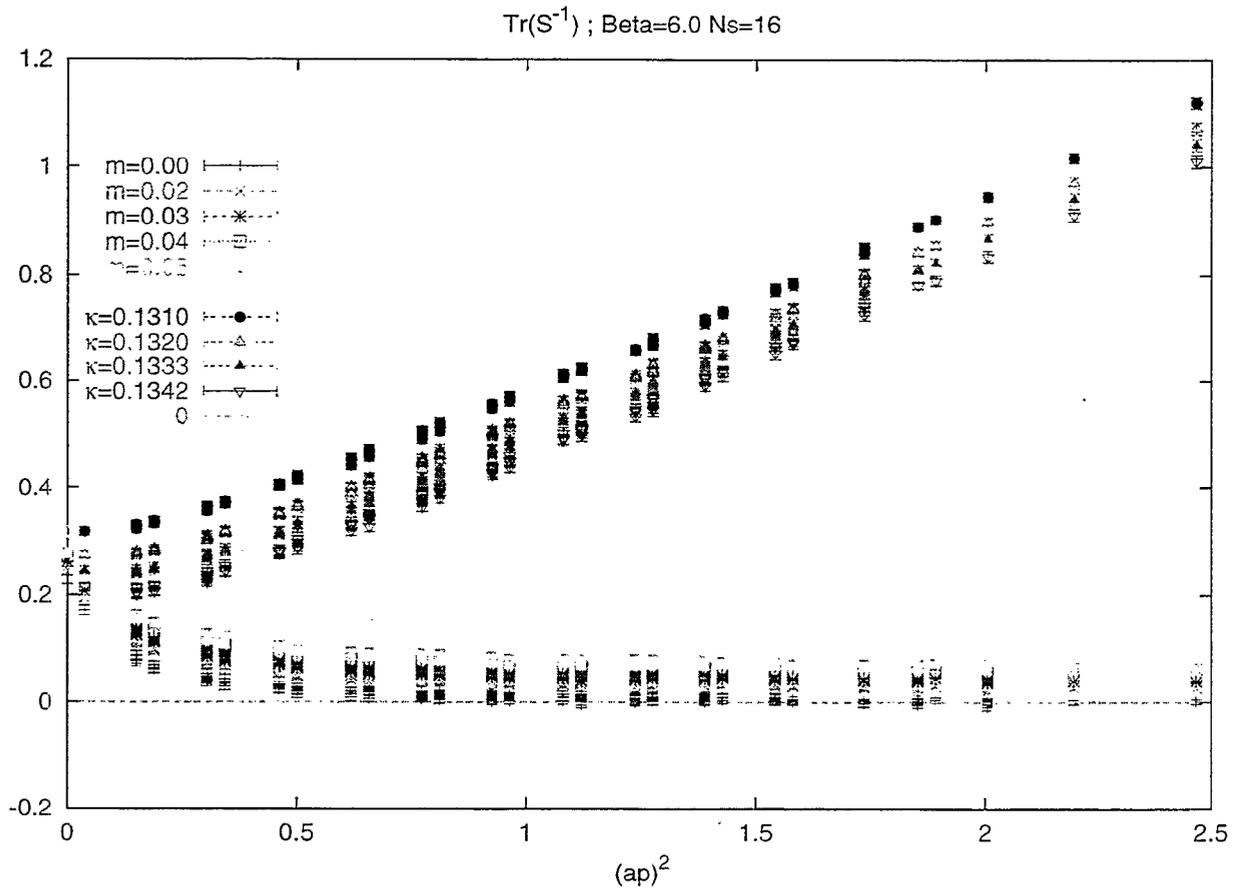


Guofeng Liu, Lattice 2001

11.30.01-12

Renormalization of Quark Mass

$$M_{RI} = \frac{1}{Z_q} \frac{\text{Tr} S^{-1}(p^2)}{12} = Z_m m$$



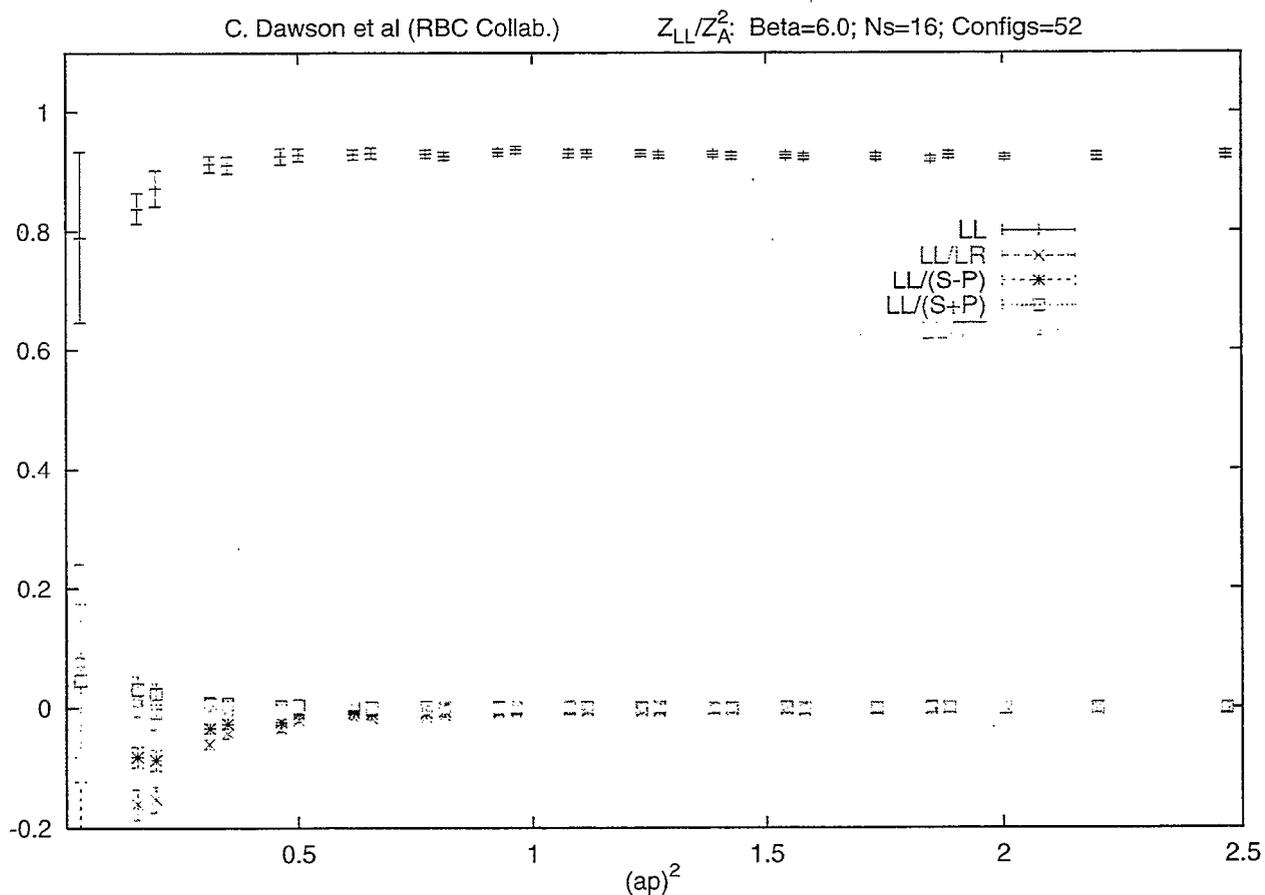
Chris Dawson, Lattice 1999

Operator Mixing for $\Delta S = 2$

Calculate mixing between

$$O_{VV+AA} = \bar{s}\gamma_\mu\gamma_5d\bar{s}\gamma_\mu\gamma_5d + \bar{s}\gamma_\mu d\bar{s}\gamma_\mu d$$

and O_{VV-AA} , O_{SS-PP} , O_{SS+PP} and O_{TT} .



Chris Dawson, Lattice 1999

11.30.01-14

Comparing B_K

Current RBC result using NPR and DWF.

$a^{-1} = 1.922(40)$ GeV, from m_ρ . $16^3 \times 32 \times 16$ lattice,
Wilson gauge action.

$$B_K(2 \text{ GeV}) = 0.513(11)$$

CP-PACS (hep-lat/0105020) result using perturbative matching and DWF. $a^{-1} = 1.875(56)$ GeV, from m_ρ .
 $16^3 \times 40 \times 16$ lattice, RG-improved gauge action.

$$B_K(2 \text{ GeV}) = 0.564(14) \quad q^* = 1/a$$

Using two scales, CP-PACS also quotes a result in the $a \rightarrow 0$ limit of $0.5746(61)(191)$, where the errors are (statistical) and (scaling).

Scaling for B_K

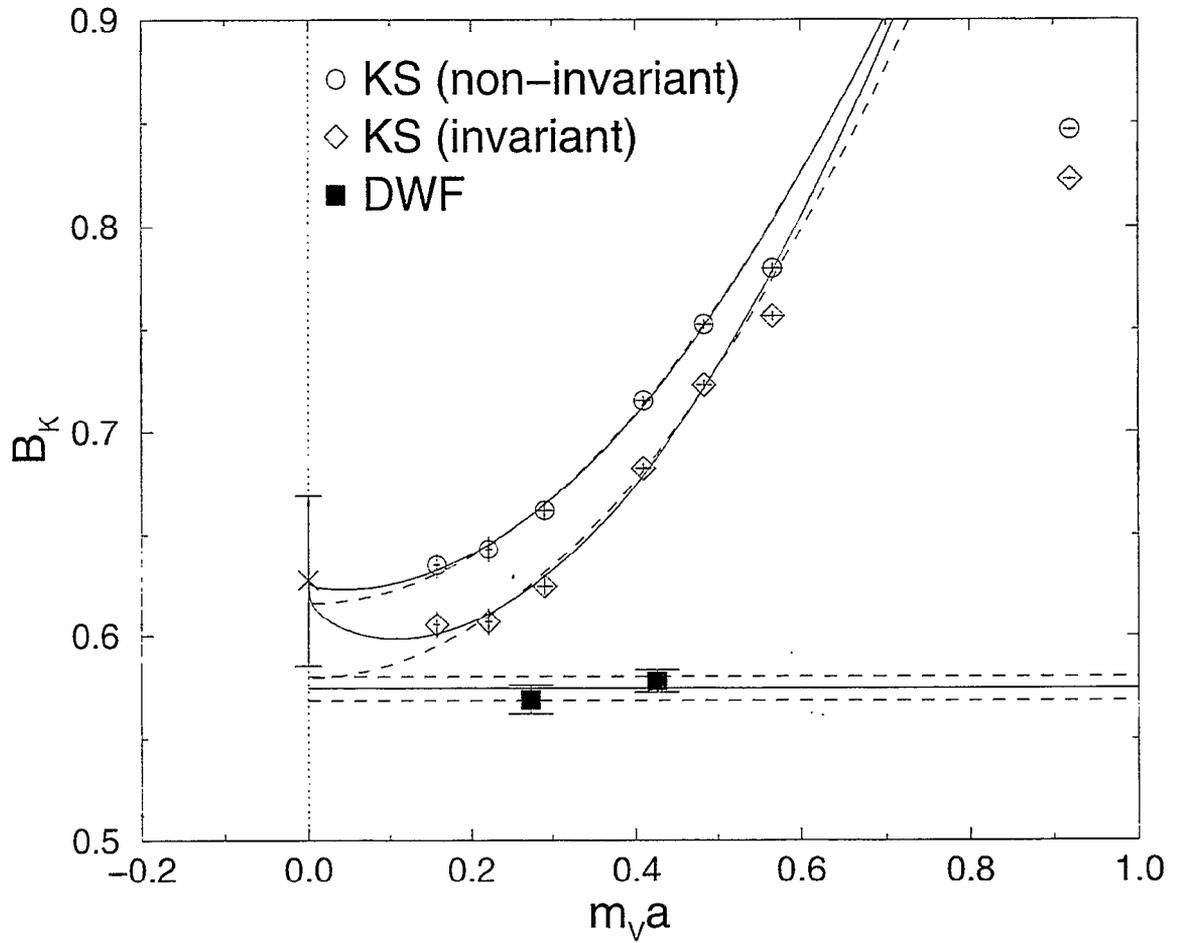
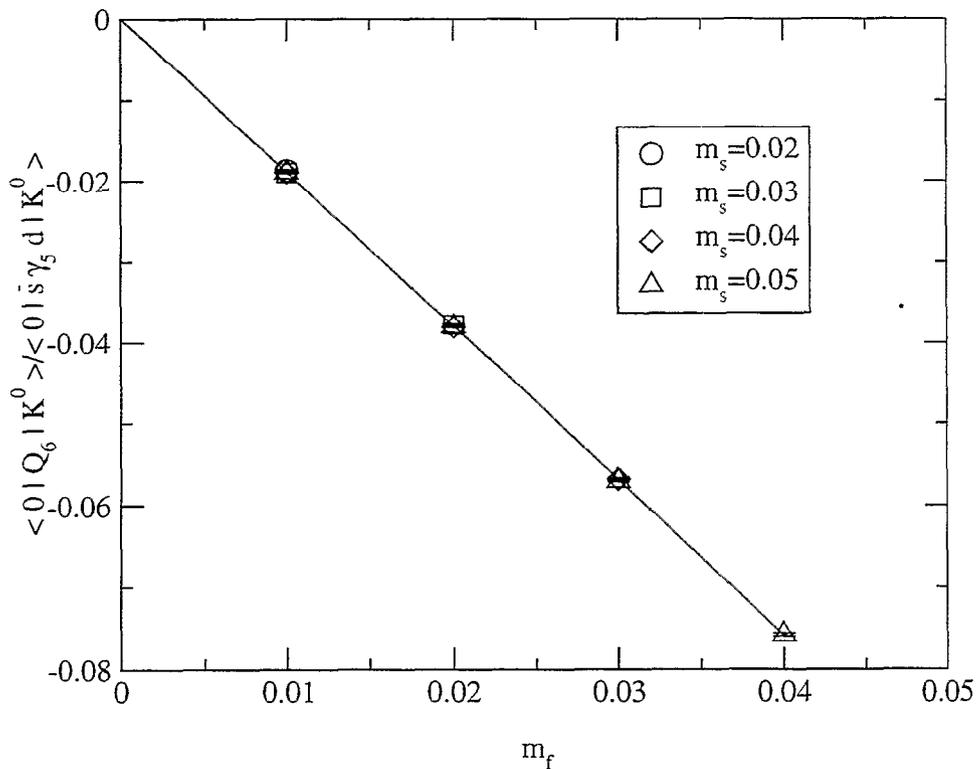


Figure from CP-PACS collaboration, hep-lat/0105020

Determining the Subtraction

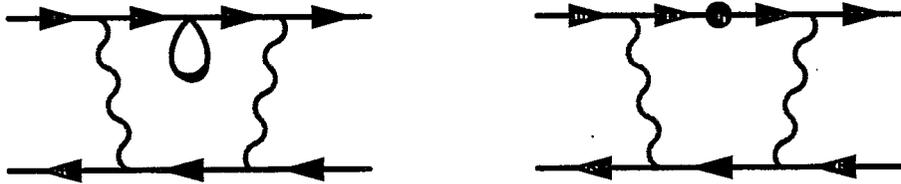
Divergent part of $K \rightarrow |0\rangle$ graph should have the same non-linearities as $\bar{s}\gamma_5 d$

$$\frac{\langle 0|Q_{i,\text{lat}}|K^0\rangle}{\langle 0|(\bar{s}\gamma_5 d)_{\text{lat}}|K^0\rangle} = \eta_{0,i} + \eta_{1,i} (m'_s - m'_d) \left\{ 1 + \dots \right\}$$

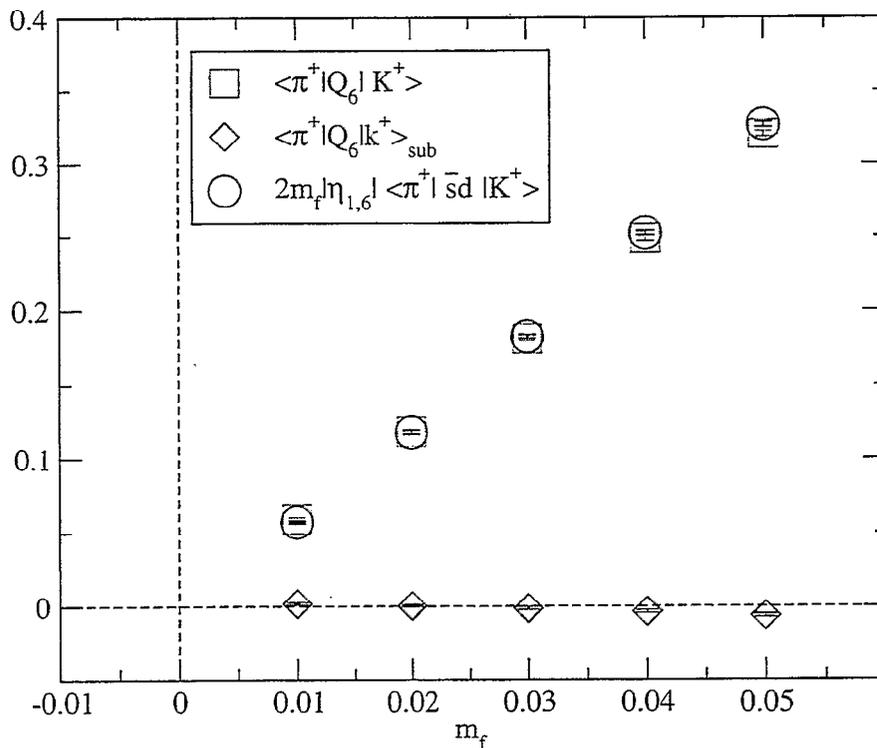


Zero Modes and Chiral Logs in Operator Subtraction

Divergent part of 4-quark operator should have the same non-linearities as $\bar{s}d$



$$\langle \pi^+ | Q_{i,\text{lat}}^{(1/2)} | K^+ \rangle + \eta_{1,i}(m_s + m_d) \langle \pi^+ | (\bar{s}d)_{\text{lat}} | K^+ \rangle$$



Subtracted Q_6 Matrix Element

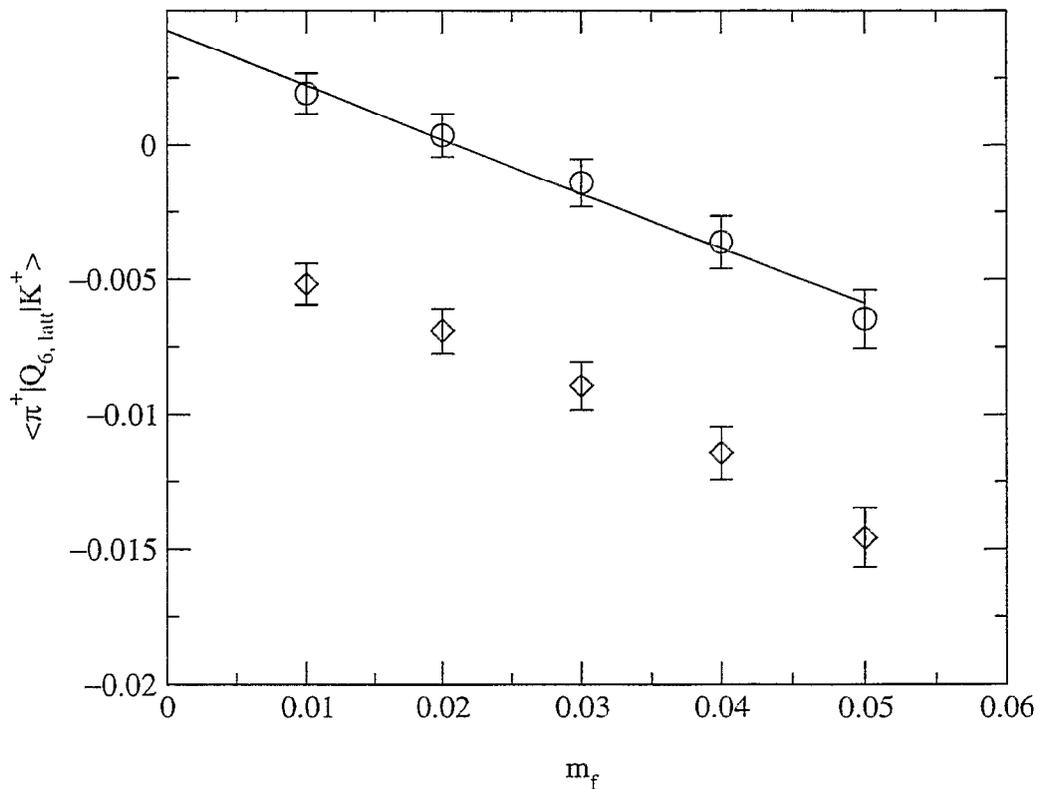
Because of correlated fluctuations in $\langle \pi^+ | Q_6 | K^+ \rangle$ and $\langle \pi^+ | \bar{s}d | K^+ \rangle$ subtracted operator still has small errors.

Upper points use $(m_s + m_d)$ in subtraction.

Lower points use $(m_s + m_d + 2m_{\text{res}})$ in subtraction.

Neither vanish at $m_f = 0$, but slope is all we need.

Subtraction of $O(m_{\text{res}})$ makes matrix element vanish at $m_f = 0$.



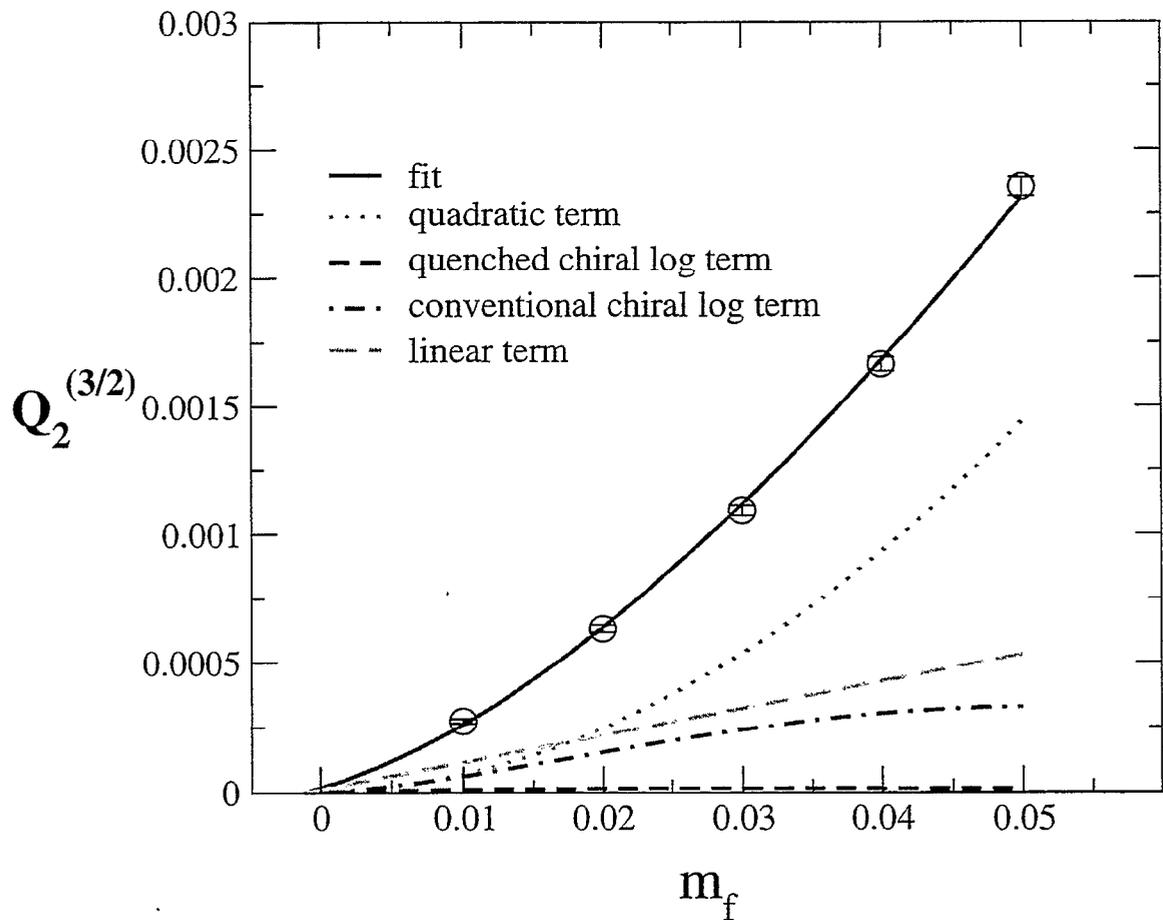
Results for Real A_2

Lattice determination from $K^+ \rightarrow \pi^+$:

1. Uses known chiral logarithm in quenched theory

$$1 - \frac{6m_M^2}{(4\pi f)^2} \ln(m_M^2/\Lambda^2)$$

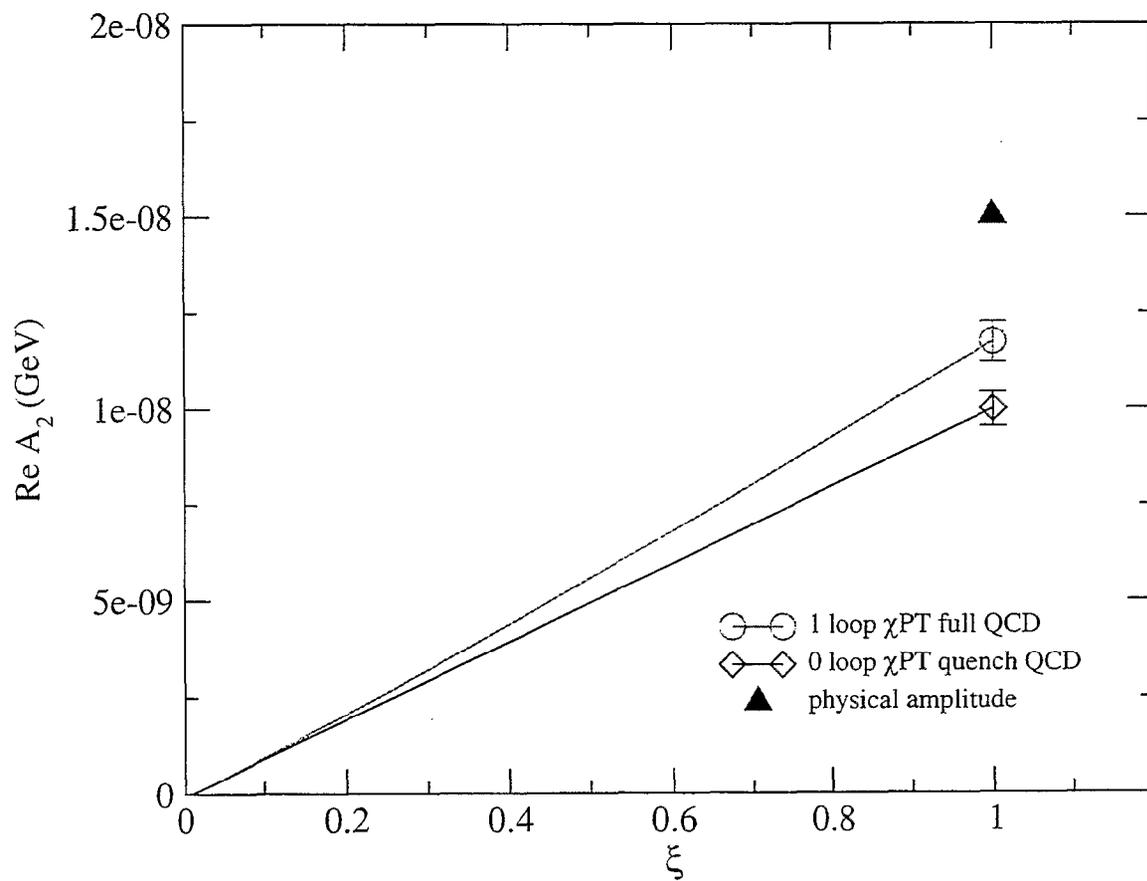
2. Fit gives m_M^4 terms



Physical result

1. 0-loop chiral extrap. in quenched continuum QCD
2. 1-loop chiral extrap. in full continuum QCD

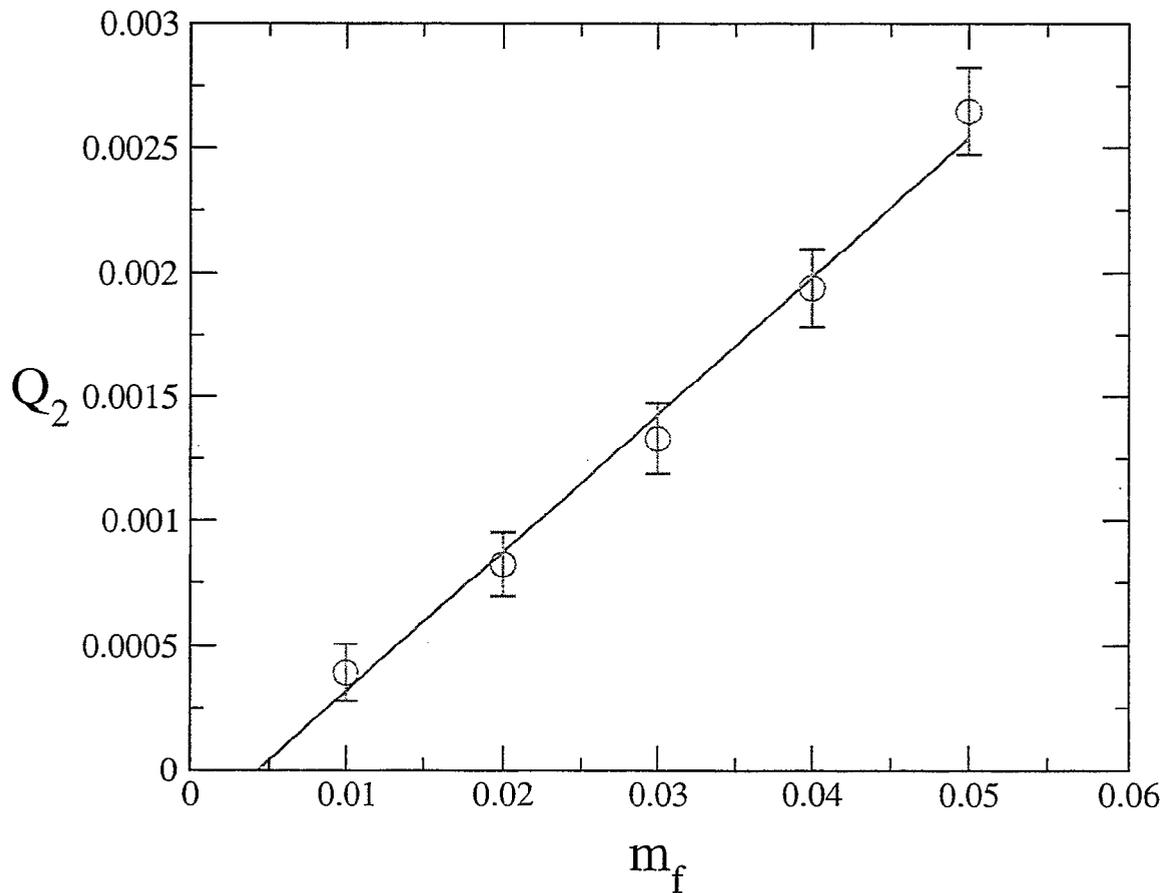
$$1 - \frac{3m_K^2}{2(4\pi f)^2} \ln(m_K^2/\Lambda^2)$$



Results for Real A_0

Lattice determination from $K^+ \rightarrow \pi^+$ involves subtraction of power divergent contribution.

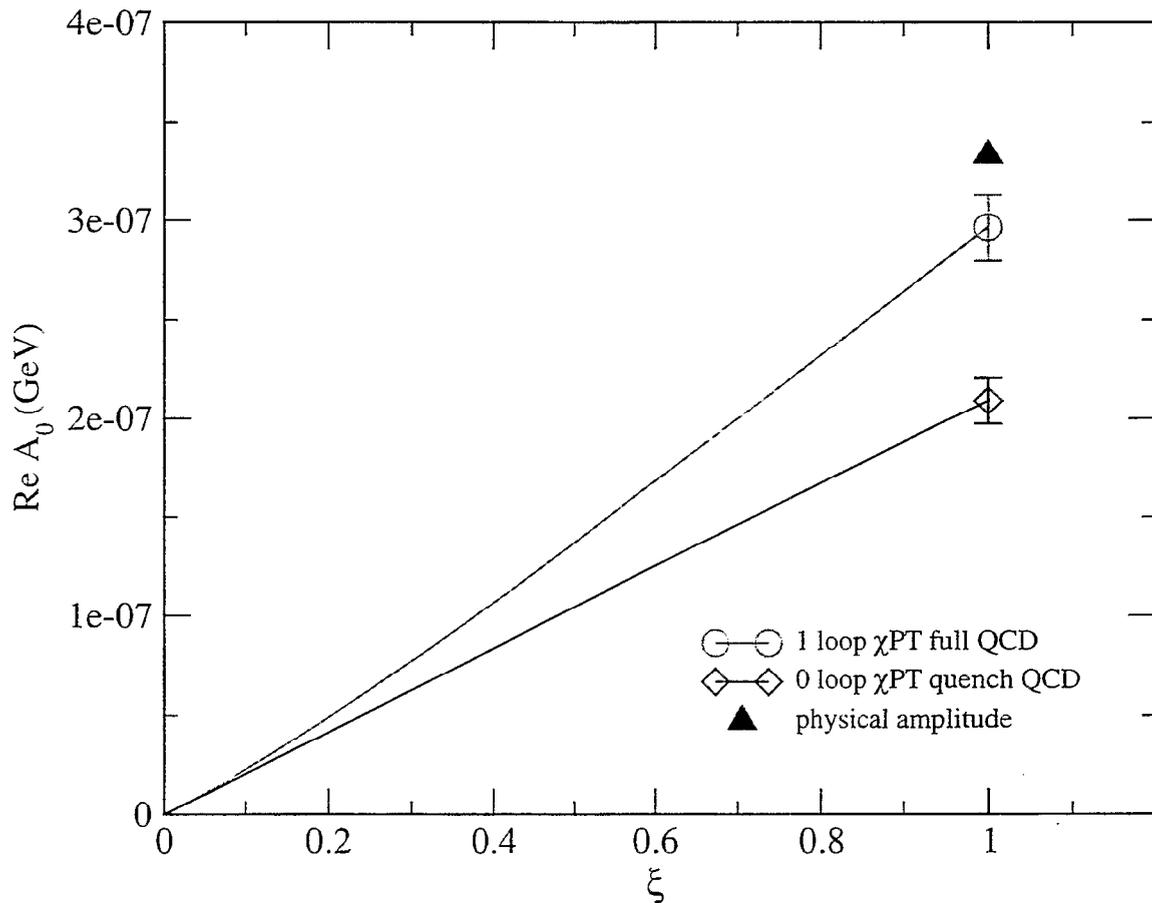
Chiral logarithm in quenched theory unknown



Physical result

1. 0-loop chiral extrap. in quenched continuum QCD
2. 1-loop chiral extrap. in full continuum QCD

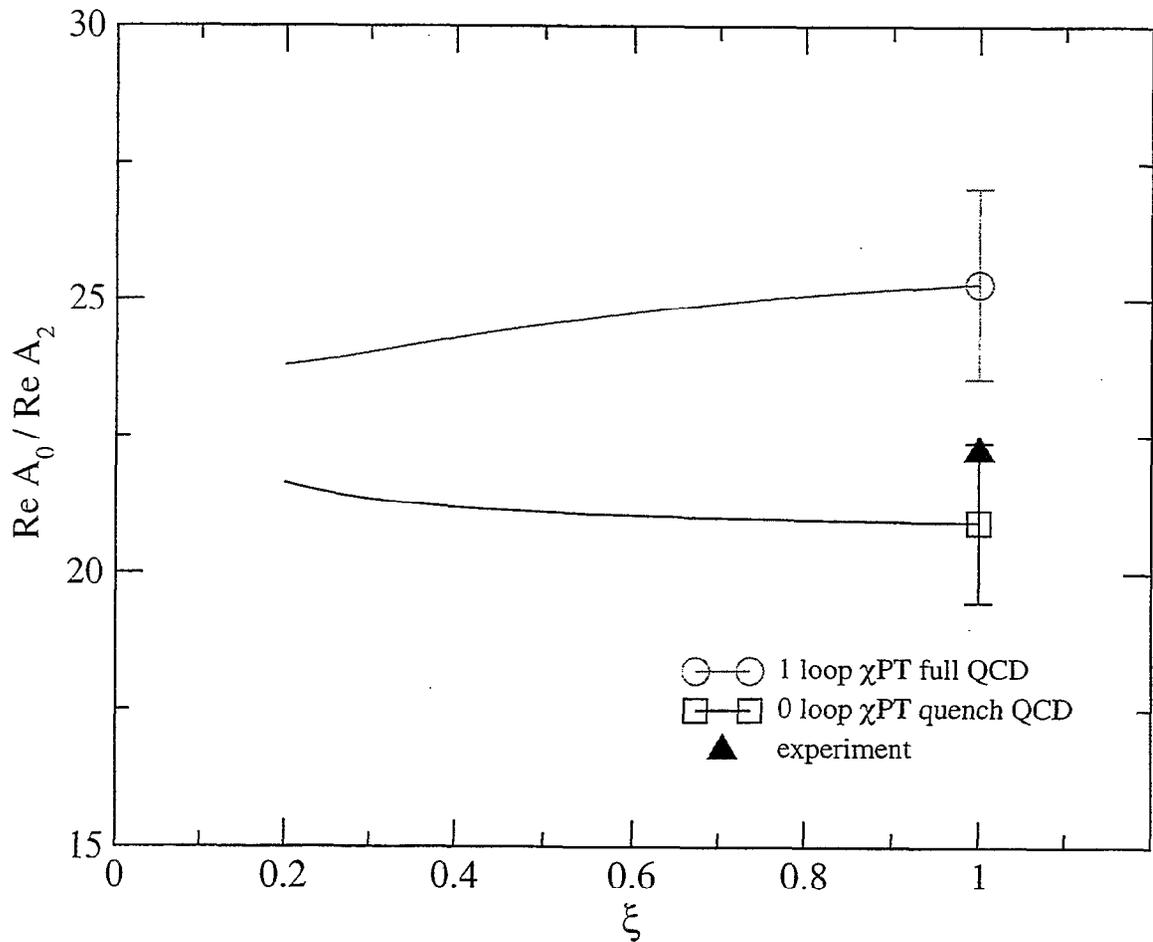
$$1 - \frac{97m_K^2}{27(4\pi f)^2} \ln(m_K^2/\Lambda^2)$$



Results for (Real A_0 / Real A_2)

Physical result

1. 0-loop chiral extrap. in quenched continuum QCD
2. 1-loop chiral extrap. in full continuum QCD

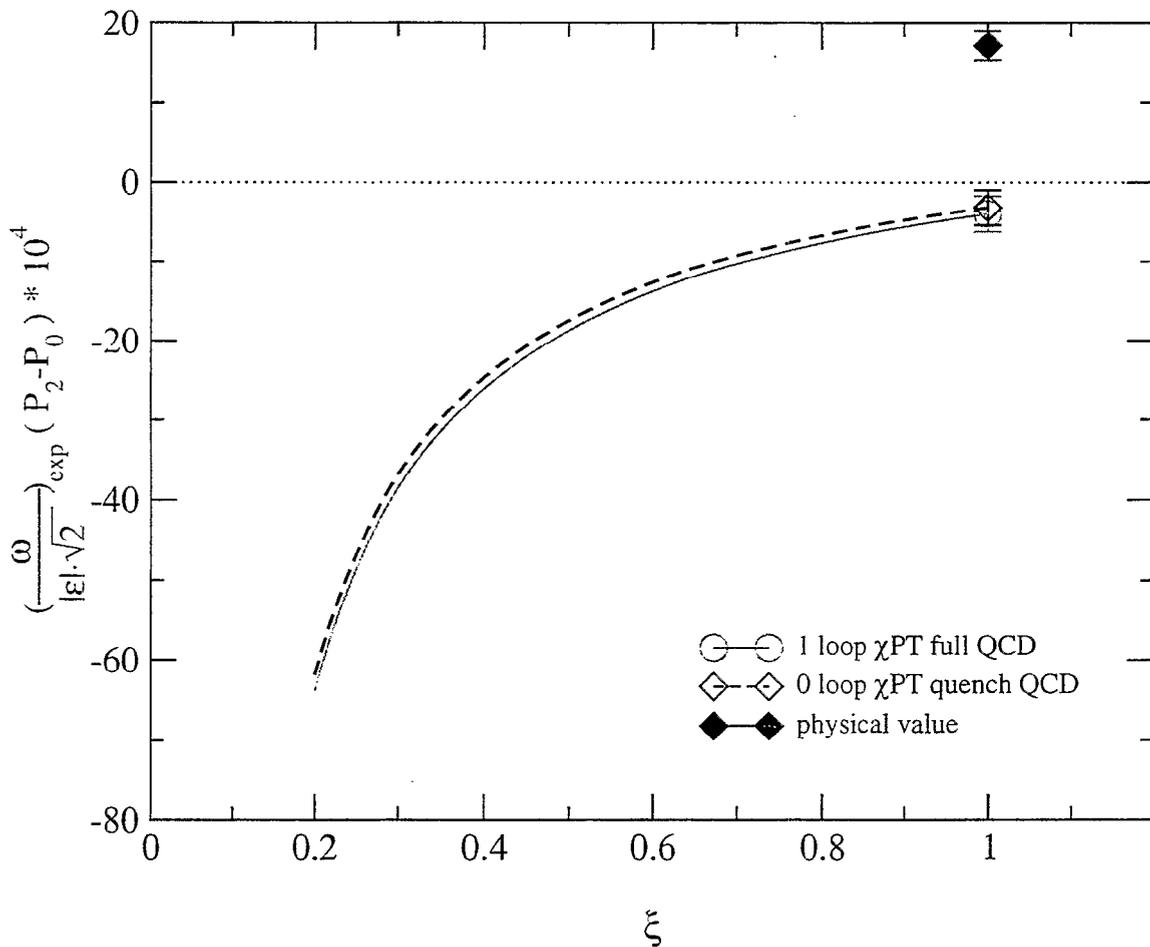


Results for ϵ'/ϵ

$$\epsilon'/\epsilon = \left[\frac{\omega}{|\epsilon| \cdot \sqrt{2}} \right]_{\text{exp.}} (P_2 - P_0)$$

Physical result:

1. 0-loop chiral extrap. in quenched continuum QCD
2. 1-loop chiral extrap. in full continuum QCD

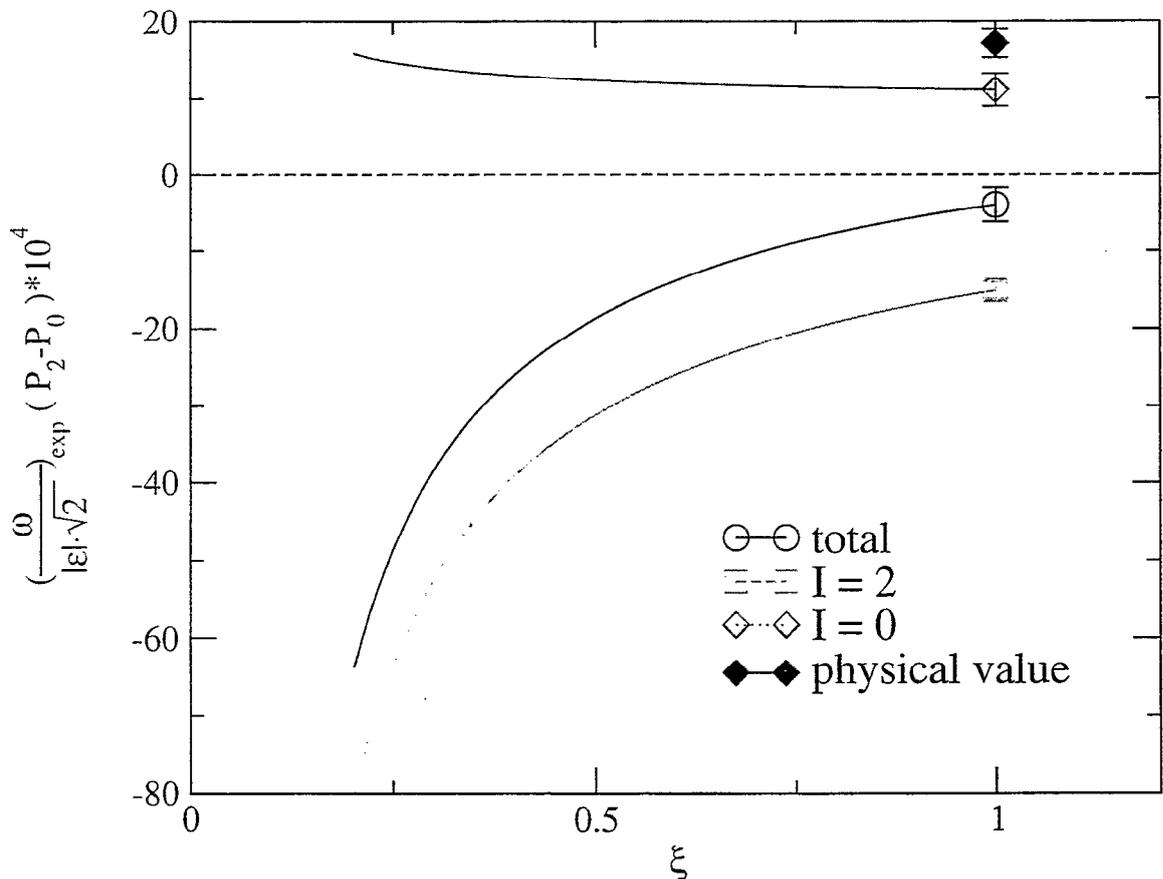


P_2 and $-P_0$ contributions to ϵ'/ϵ

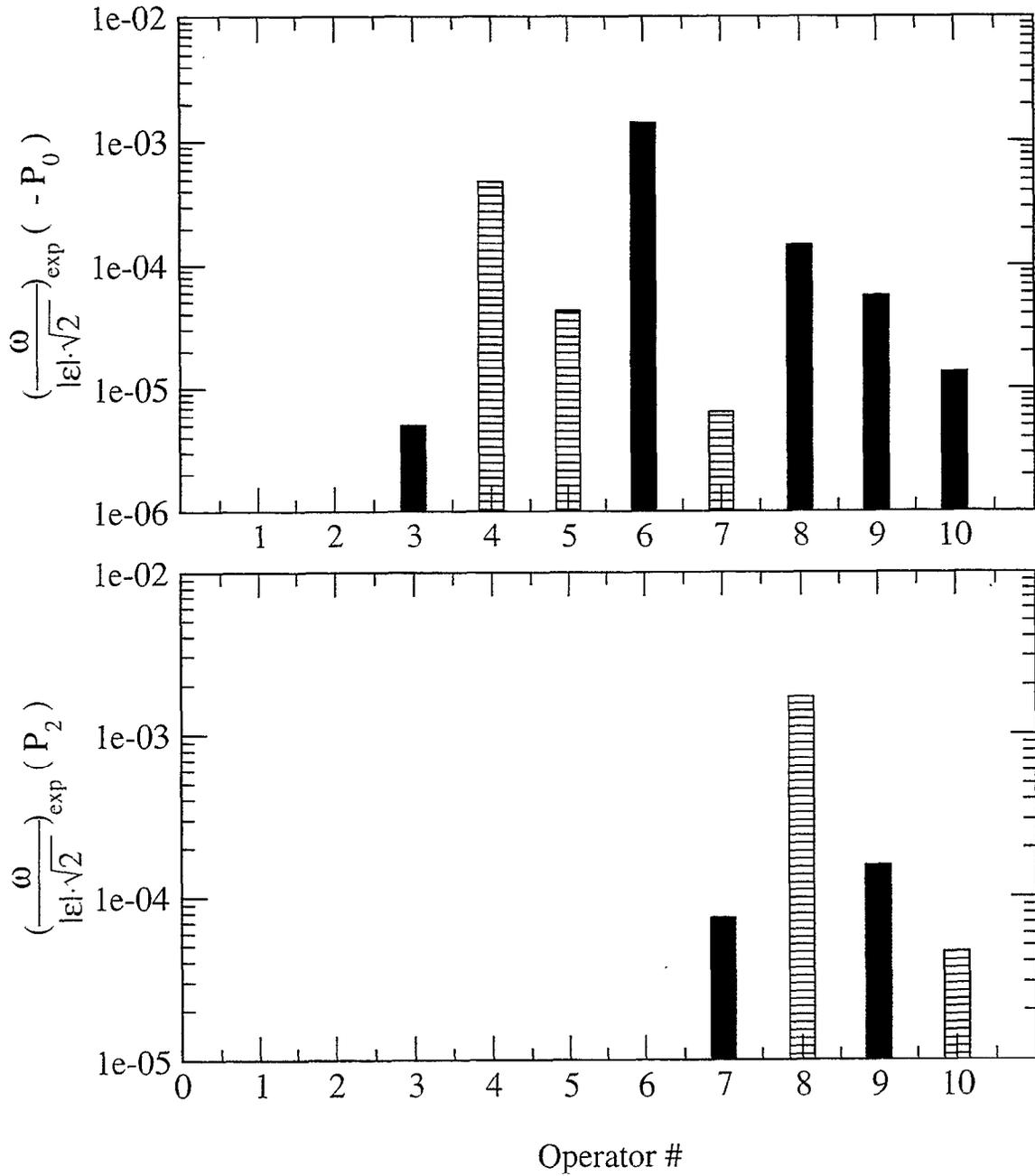
$$P_2 \equiv \frac{\text{Im}A_2}{\text{Re}A_2}$$

$$P_0 \equiv \frac{\text{Im}A_0}{\text{Re}A_0}$$

- P_2 decreases as $\xi \rightarrow 1$, since $\text{Re}A_2$ increases
- P_0 constant for $\xi \sim > 0.4$.
- Almost complete cancellation for physical masses.



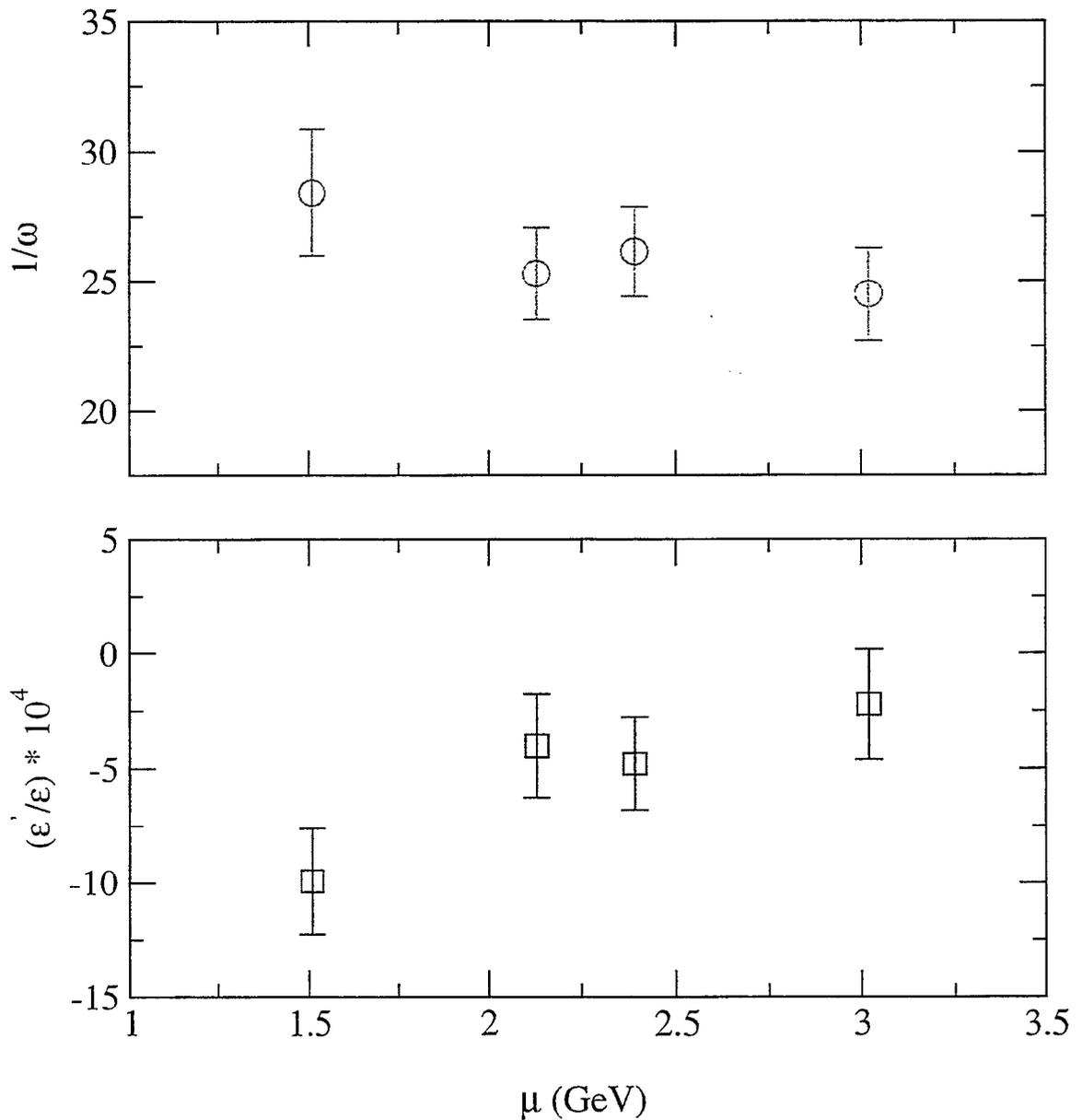
Individual Operator Contributions to ϵ'/ϵ



μ dependence of ω and ϵ'/ϵ

Plot variation of physical results with μ , the scale where matching between the continuum and lattice is done.

$1/\omega$ and ϵ'/ϵ



Comparison with Experimental Results

Quantity	Experiment	This calculation (statistical errors only)
Re A_0 (GeV)	3.33×10^{-7}	$2.96(17) \times 10^{-7}$
Re A_2 (GeV)	1.50×10^{-8}	$1.172(53) \times 10^{-8}$
ω	22.2	25.3(18)
Re (ϵ'/ϵ)	$15.3(26) \times 10^{-4}$ (NA48) $20.7(28) \times 10^{-4}$ (KTev)	$-4.0(23) \times 10^{-4}$

Given the general agreement with the experimental values for real $K \rightarrow \pi\pi$ amplitudes and the relatively small statistical error on ϵ'/ϵ , the difference between the current calculation for ϵ'/ϵ and experiment is surprising. Most of the approximations in the current calculation could individually produce $\sim 25\%$ changes in the individual $K \rightarrow \pi\pi$ amplitudes. Cumulatively, these could markedly alter ϵ'/ϵ , but there is currently no identified single approximation that could easily explain the discrepancy.

Conclusions

- We have calculated $K \rightarrow \pi\pi$ matrix elements using
 - Chiral perturbation theory
 - Quenched QCD
 - Domain wall fermions
 - Non-perturbative renormalization
 - Single lattice spacing
- Within these approximations, we have encountered no technical barriers.
- Lattice matrix elements + NPR + Wilson coefficients + standard model parameters yield physical results
 - Real amplitudes in general agreement with experiment
 - $\text{Re}(A_0)$ showing large enhancement from matrix element.
 - Large cancellation between $I = 0$ and $I = 2$ contributions to ϵ'/ϵ
- Consistency of these approximations with the physical world is unknown.

RESEARCH SUMMARIES

Progress Report and Project Proposal

Steffen A. Bass

1 Progress Report and Project Proposal for Steffen A. Bass:

Project for 2001: Probing the QGP equation of state with two-particle interferometry

Bose-Einstein correlations in multiparticle production processes [1] provide valuable information on the space-time dynamics of fundamental interactions [2]. In particular, lattice QCD calculations predict the occurrence of a phase transition at high temperature. A first order phase transition leads to a prolonged hadronization time as compared to a cross-over or ideal hadron gas with no phase transition, and has been related to unusually large Hanbury-Brown-Twiss (HBT) radii [3]. The phase of coexisting hadrons and QGP reduces the “explosivity” of the high-density matter before hadronization, extending the emission duration of pions [3]. This phenomenon should then depend on the hadronization (critical) temperature T_c and the latent heat of the transition.

In our study, we have calculated the Gaussian radius parameters of the pion-emitting source in high energy heavy ion collisions [4], assuming a first order phase transition from a thermalized Quark-Gluon-Plasma (QGP) to a gas of hadrons. Our calculations have been performed in the framework of a hybrid macro/micro transport approach, utilizing hydrodynamics for the early, dense, QGP phase of the reaction and microscopic transport theory for the later, dilute, hadronic reaction phase [5]. Such a model leads to a very long-lived dissipative *hadronic* rescattering phase which dominates the properties of the two-pion correlation functions. Figure 1 shows that if the dissipative hadronic phase is taken into account, the radii as well as the R_{out}/R_{side} ratio are found to depend only weakly on the thermalization time τ_i , the critical temperature T_c (and thus the latent heat), and the specific entropy of the QGP. The dissipative hadronic stage enforces large variations of the pion emission times around the mean. Therefore, the model calculations suggest a rapid increase of R_{out}/R_{side} as a function of K_T if a thermalized QGP were formed.

Extending our analysis from pions to kaons ⁶ we find that the kaon radii as well depend only weakly on the thermalization time τ_i , the critical temperature T_c (and thus the latent heat), and the specific entropy of the QGP. However, kaons are less distorted by decays of (long-living) resonances. The predicted increase in the R_{out}/R_{side} ratio with K_T is rather moderate compared to pions.

At high transverse momenta $K_T \sim 1 \text{ GeV}/c$, however, direct emission from the phase boundary becomes important (approx. 30% of the kaons are then emitted directly from the phase-boundary). The emission duration signal, i.e., the R_{out}/R_{side} ratio, and its sensitivity to T_c (and thus to the latent heat of the phase transition) are enlarged (see figure 2). Moreover, the QGP+hadronic rescattering transport model calculations do not yield unusual large radii ($3 \leq R_i \leq 9 \text{ fm}$). Finite momentum resolution effects have a strong impact on the extracted HBT parameters (R_i and λ) as well as on the ratio R_{out}/R_{side} .

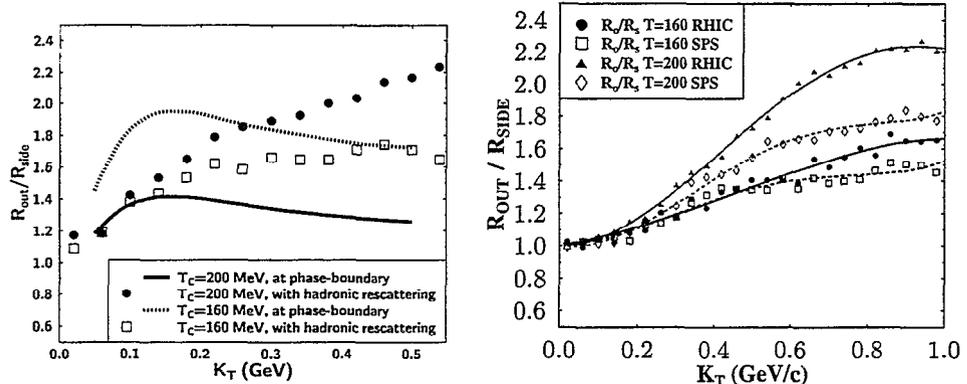


Figure 1: Left: R_{out}/R_{side} for pions at RHIC initial conditions, as a function of K_T at freeze-out (symbols) and at hadronization (lines). Right: R_{out}/R_{side} for kaons at RHIC (full symbols) and at SPS (open symbols), as a function of K_T for critical temperatures $T_c \simeq 160$ MeV and $T_c \simeq 200$ MeV, respectively. The lines are to guide the eye.

1.1 Proposed Project for 2002:

The Parton Cascade Model (PCM) [7] was developed to explore the reaction dynamics of deconfined colored quanta in relativistic heavy-ion collisions. Over the past half year, we have undertaken a thorough revision of the original PCM implementation (the VNI code). Although the new revision is not yet quite complete, we anticipate that it will be available to us for applications to nucleus-nucleus calculations in the RHIC energy domain in the very near future. The following topics will constitute our main areas of research:

1.1.1 Thermal and chemical parton equilibration

What are the time-scales for thermal and chemical parton equilibration? Does the PCM dynamics actually predict the creation of a thermalized system of quarks and gluons? To what extent does the full transport QCD theory confirm the notion of a “bottom-up thermalization” of the quark-gluon plasma [8]? Can flavor saturation actually be achieved during the life-time of the partonic phase [9]? A number of calculations performed in the past (utilizing hydrodynamics as well as an early version of the PCM model [10]) indicated thermal equilibration, but incomplete strangeness saturation. In view of importance of these issues for the interpretation of the emerging RHIC data we intend to tackle these questions by means of a state-of-the-art calculation.

1.1.2 Parton energy loss: Confined vs. deconfined matter

Jet-quenching, i.e. a suppression in the high- p_t component of hadronic momentum spectra due to the energy loss of a partonic jet traversing a zone of deconfined matter, has been suggested as a QGP signature and as a tool for

probing the properties of deconfined matter [11]. However, certain ambiguities remain - namely whether the energy loss is dominated by the partonic phase or whether interactions among formed hadrons in the later reaction stages may contribute significantly to a suppression of the high momentum component of the spectra [12]. The PCM approach, coupled with a hadronic model of the final state transport such as UrQMD [13] takes both effects into account and is thus well suited to determine the relative weights of partonic and hadronic mechanisms of jet energy loss.

1.1.3 Event-by-event fluctuations: Effects of hadronization and final state interaction

The size of the average fluctuations of net baryon number and electric charge in a finite volume of hadronic matter differs widely between the confined and deconfined phases. These differences have been suggested as indicators of the formation of a quark-gluon plasma in relativistic heavy-ion collisions, based on the assumption that fluctuations created in the initial state survive until freeze-out due to the rapid expansion of the hot fireball [14]. Although some studies of hadronic final-state effects on these fluctuations by means of microscopic transport models have been made [15], these calculations have not used dynamical models of the full time-evolution of a relativistic heavy-ion collision. We will use the PCM, coupled with a cluster hadronization algorithm and a hadronic final state transport model, to explore how fluctuations develop in the deconfined phase and to probe whether these fluctuations actually survive hadronization and subsequent final state interactions.

1.1.4 Elliptic and radial flow

Collective flow is a prime observable sensitive to the pressure present within the dense matter that is created in a relativistic heavy ion collision. Elliptic flow has been suggested as a probe for the buildup of pressure in the early reaction stage [16]. Radial flow, on the other hand, is expected to receive contributions from both, early and late, reaction stages [17]. First RHIC data shows strikingly large values for both types of collective flow – compatible with hydrodynamic calculations. The question is whether a microscopic approach such as the PCM is able to create as much pressure and flow as is observed at RHIC. Coupled with a cluster hadronization algorithm and a hadronic final state transport model the PCM can be used to perform a detailed study on the different time scales associated with elliptic and radial flow. The flavor dependence of collective flow is another topic which is difficult to address in a hydrodynamical calculation, but which can be easily investigated in the framework of a microscopic transport theory.

1.1.5 Dileptons and photons as probes of deconfinement

Dileptons and direct photons can carry information on the thermodynamic state of the deconfined medium at the moment of production – since they interact

only electromagnetically they can leave the hot and dense reaction zone basically undistorted.

The most prominent process for the creation of direct (thermal) photons in a QGP are $q\bar{q} \rightarrow \gamma g$ (annihilation) and $gq \rightarrow \gamma q$ (Compton scattering). The production rate and the momentum distribution of the photons depend on the momentum distributions of quarks, anti-quarks and gluons in the plasma. Infrared singularities occurring in perturbation theory are softened by screening effects [18]. If the plasma is in thermodynamic equilibrium, the photons may carry information on this thermodynamic state at the moment of their production [19]. If a very hot plasma is formed (e.g. at RHIC or LHC energies) a clear photon signal might be visible at transverse momenta in the range between 2 and 5 GeV/c [20]. The lower p_t range (1–2 GeV/c) is dominated by the mixed phase; separated contributions of the different phases are difficult to see due to transverse flow effects [21].

Analogously to the formation of a real photon via a quark - anti-quark annihilation, a virtual photon may be created in the same fashion which subsequently decays into a l^+l^- pair (a *dilepton*). Also bremsstrahlung of quarks scattering off gluons can convert into dileptons.

The parton cascade model is ideally suited to predict the production rates and spectra of photons and dileptons without any assumptions on equilibrium conditions (which are present in hydrodynamical calculations). These rates as well as the resulting dilepton and photon spectra will then be compared to those stemming from hydrodynamical calculations in order to estimate non-equilibrium contributions from the early reaction phase.

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Progress Report
Alexander Kusenko

Progress Report for Alexander Kusenko

Over the last year Kusenko performed research in elementary particle physics and astrophysics. He presented his results in several scientific publications, as well as invited talks at international conferences, departmental colloquia (UCSD, U. Washington), and seminars.

0.1 Non-topological solitons (NTS) as candidates for dark matter

In a recent paper [Phys. Rev. Lett. **87**, 141301, 2001], Kusenko and P. Steinhardt of Princeton University explored the possibility that dark matter is in the form of NTS and has strong self-interactions. Interactions between dark-matter particles could resolve the discrepancy between some recent observations and the predictions of cold dark matter (CDM) models. For example, CDM without a significant self-interaction would yield galactic halos with cuspy profiles and much more structure on small scales than what is observed.

The cross section of self-interaction that could resolve the discrepancies must be large. The requisite ratio of the cross section to mass is required to be as high as $\sigma/m \sim 10^{-24} \text{cm}^2 \text{GeV}^{-1}$. It can be easily shown that, based on unitarity alone, particle candidates cannot satisfy this criterion unless they have masses of a few GeV or lower. However, unitarity does not prevent NTS from having a large enough cross section. This makes NTS an interesting candidate for dark matter, as Kusenko and Steinhardt have pointed out.

0.2 Ultrahigh-energy cosmic rays and neutrinos

0.2.1 Cross section measurements at 10^{11} GeV

Future detectors of ultrahigh-energy cosmic rays (UHECR) expect to detect ultrahigh-energy neutrinos from (1) interactions of cosmic rays with the background photons, (2) astrophysical sources, *e.g.*, active galactic nuclei, (3) hypothetical sources invoked to explain UHECR. The detection strategy relies on the knowledge of neutrino-nucleon cross section at energies far beyond those accessible in experiment. These cross sections have been calculated based on a plausible extrapolation of parton distribution functions and the Standard Model parameters to energies of 10^{11} GeV ($\sqrt{s} \sim 10^6 \text{GeV}$). While this is a sensible approach, there remains an uncertainty in the magnitude of the cross section. A lower-than-expected cross section could stymie the detection of neutrinos via horizontal air showers.

Kusenko and Tom Weiler (Vanderbilt University), in a paper [hep-ph/0106071] submitted to Phys. Rev. Lett., pointed out that, fortunately, the planned experiments can adopt a new strategy that will make them less vulnerable to the uncertainties in the neutrino-nucleon cross section. If the cross section is smaller than was previously thought, the rate of horizontal air showers diminishes. However, at the same time, the Earth becomes more transparent to high-energy neutrinos. UHE neutrinos can go through the Earth and produce a charged lepton below the Earth's surface. The lepton can then originate an up-going air shower which can be detected by Pierre Auger, EUSO, or OWL. While the rate of horizontal air showers (HAS) due to neutrino interactions in the atmosphere is proportional to $\sigma_{\nu N}$, the rate of up-going air showers (UAS) is inversely proportional to $\sigma_{\nu N}$. Thus, the total rate remains unchanged, fortunately for the future experiments.

In addition, by comparing the HAS and UAS rates, one can measure the neutrino-nucleon cross section at the unprecedented energies of 10^{11} GeV or higher. Furthermore, the angular distribution of UAS depends on the cross section and can also be used for measuring $\sigma_{\nu N}$.

0.2.2 Sources of ultrahigh-energy cosmic rays

Together with a UCLA student Marieke Postma, Kusenko described a signature in the neutrino spectrum that could indicate the presence of sources of UHE photons at high red shift [Phys.Rev.Lett. **86**, 1430 (2001)].

If decays of superheavy relic particles in the galactic halo are responsible for ultrahigh-energy cosmic rays, these particles must be clustered to account for small-scale anisotropy in the AGASA data. Kusenko and Kuzmin (INR, Moscow) showed in a recent paper [JETP Lett. **73** (2001) 443] that the masses of such clusters are large enough for them to gravitationally lens stars and galaxies in the background. They proposed a general strategy that can be used to detect such clusters via gravitational lensing, or to rule out the hypothesis of decaying relic particles as the origin of highest-energy cosmic rays.

0.2.3 Neutrino production in the background with time-dependent density

Kusenko and Postma have studied the conceptually interesting phenomenon of neutrino production in matter with time-dependent density [hep-ph/0107253]. Both the ordinary matter and the nuclear matter of neutron stars have a net isospin. As a result, neutrinos can be produced through standard electroweak interactions if the matter density changes with time.

0.3 Baryogenesis in the wake of inflation

It is well known that the usual “thermal” electroweak baryogenesis in the Standard Model cannot account for the observed baryon asymmetry of the Universe. This is probably the strongest evidence so far for physics beyond the Standard Model.

One of the conditions for a successful baryogenesis, the departure from thermal equilibrium, is naturally achieved at the stage of preheating after inflation. J. García-Bellido, D. Grigoriev, M. Shaposhnikov, and Kusenko [Phys. Rev. **D59**, 123001 (1999)] showed that the baryon asymmetry of the Universe could be generated through the electroweak sphalerons in this highly non-equilibrium state even if the reheating temperature is too low for the electroweak symmetry to be restored.

In a recent paper [hep-ph/0106127, Phys. Rev. **D**, in press], Grigoriev, Cornwall, and Kusenko showed that the necessary CP violation can be supplied by the time-dependent background solutions during preheating.

Phases of Matter at High Baryon Density

Thomas Schaefer

**Phases of Matter
at high Baryon Density**

Thomas Schaefer

SUNY Stony Brook

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1 Hadronic Matter at high baryon density

At very high baryon density we expect that attractive interactions between quarks lead to color superconductivity. Estimates suggest that the corresponding gaps are quite substantial, on the order of $\Delta = 100$ MeV. Current work focuses on the phase structure in the realistic case of unequal masses and non-zero electron chemical potential, the application of effective field theory techniques at high baryon density, and implications for neutron star interiors.

Phase Structure at finite strange quark mass and electron chemical potential

Early work on color superconductivity in QCD focused mostly on idealized worlds with N_f flavors of massless quarks and no external fields. But in order to understand the matter at the core of real neutron stars the effects of non-zero masses and electron chemical potential clearly have to be taken into account. Schäfer and Wilczek (IAS, Princeton) [3], as well as Alford, Berges and Rajagopal [4], realized that there is a first order phase transition at a critical strange quark mass $m_s \sim \sqrt{p_F \Delta}$ which separates the three flavor color-flavor locked phase (CFL) from the two flavor color superconducting phase (2SC). Bedaque (LBL) and Schäfer analyzed the situation in more detail [5, 6]. They were interested, in particular, in the structure of the CFL phase for values of the strange quark mass and electron chemical potential that are smaller than the critical values for the transition to a 2SC phase. They argue that in this regime the system responds by forming Bose condensates of pions or kaons. The critical μ_e and $m_s^2/(2p_F)$ are on the order of $\sqrt{m_u m_s}(\Delta/p_F)$, which is much smaller than the gap.

Spectrum of Excitations in the Kaon Condensed Phase

Schäfer, Son (Columbia), Stephanov (UIC), Toublan (UIUC), and Verbaarschot analyzed the spectrum in the kaon condensed phase. Kaon condensation provides an unusual realization of Goldstone's theorem. The symmetry breaking pattern is $SU(2)_I \times U(1)_Y \rightarrow U(1)_Q$. Both isospin and hypercharge are broken, the only unbroken symmetry corresponds to electric charge. This means that there are three broken generators. On the other hand, we find only two Goldstone bosons, the K^0 and the K^+ . This result is consistent with Goldstone's theorem in the case of broken Lorentz symmetry [7]. The discrepancy between the number of broken generators and the number of Goldstone bosons is related to the fact that the K^0 is a normal Goldstone mode with $\omega \sim p$ whereas the K^+ is an anomalous Goldstone boson with dispersion relation $\omega \sim p^2$.

High density effective theory

At very high baryon density the ground state and the spectrum of excitations of baryonic matter can be studied in perturbative QCD. However, these calculations require resummation

and the structure of the perturbative expansion is far from obvious. The calculations can be vastly simplified by using a hierarchy of effective theories. In [8] we study the structure of the expansion in the quark mass. This problem is relevant to the determination of the Goldstone boson masses and the structure of the effective potential for the order parameter.

2 Nonperturbative QCD

Lattice simulations continue to provide strong support for the instanton liquid picture of chiral symmetry breaking and the structure of light hadrons.

Analysis of tau lepton decay data

Schäfer and Shuryak analyzed the vector and axial-vector meson spectral functions obtained by the ALEPH collaboration at CERN and studied implications for non-perturbative QCD [9]. They compared these results to predictions from the instanton model and from the operator product expansion (OPE). Schäfer and Shuryak observe that the correlation functions are best analyzed by focusing on the linear combinations vector (V) \pm axial-vector (A). The difference $V - A$ is sensitive to chiral symmetry breaking and described perfectly by the instanton liquid at all distances. The OPE, on the other hand, only describes the data for distances less than 0.3 fm. The sum $V + A$ is sensitive to perturbative effects at small and intermediate distances and there is a (10-20)% discrepancy as compared to the instanton model. The OPE describes the data at short distance but the theoretical prediction is dominated by perturbative effects, and there is no evidence that the gluon condensate can be extracted from the data. Schäfer and Shuryak also emphasize that one can combine the instanton prediction with the data in the $V + A$ channel in order to obtain an improved estimate of higher order perturbative effects. This allows us to observe the evolution of α_s out to distances much larger than otherwise available.

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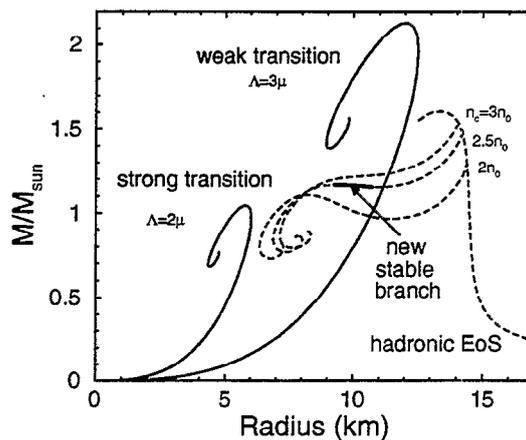
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High Density QCD - Quark Stars

Jürgen Schaffner-Bielich

High Density QCD - from Quark Stars to Scaling at RHIC

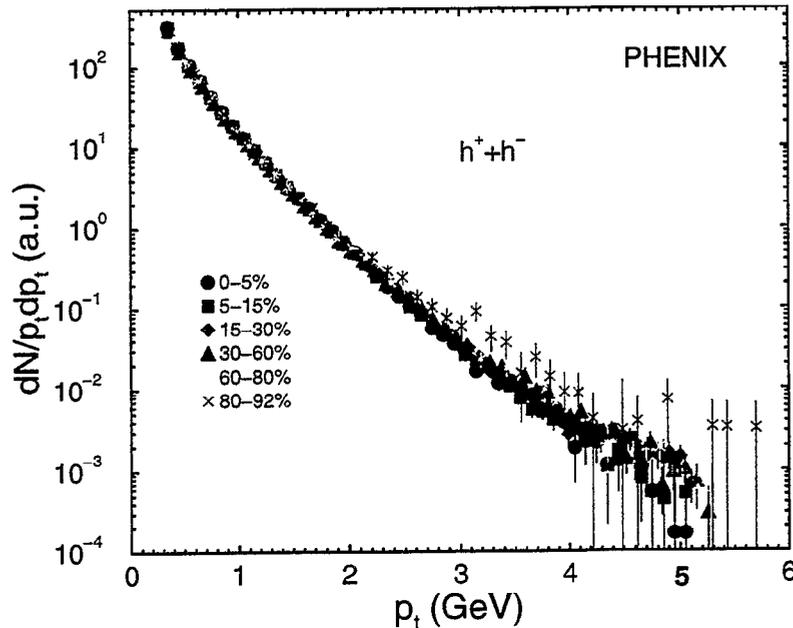
Jürgen Schaffner-Bielich



- Quark Stars: use perturbative QCD to second order in α_s to describe the high density quark equation of state
- solution of the TOV equations generates small and dense quark stars with radii $R \sim 6$ km and maximum masses of $M \sim 1M_\odot$
- matching to low-density hadronic equation of state generates a new family of compact stars (quark stars) besides neutron stars and white dwarfs
- mass-radius relation is compatible with a recent (first) determination of the mass *and* radius of an isolated neutron star



High Density QCD - Scaling at RHIC



- Scaling at RHIC: color glass condensate (CGC) predicts scaling relations for the initial state in ultrarelativistic heavy-ion collisions
- similar scaling relations seems to be preserved during the evolution and the deconfinement transition and show up in the hadron spectra
 - generalized m_t scaling: hadrons of different flavor are following one universal curve in m_t
 - m_t spectra of different centralities can be rescaled into each other
 - the rescaling parameters (transverse area and the saturation momentum) follow the centrality dependence as expected from a CGC

L. McLerran and JSB: PL B514, 29 (2001); JSB, D. Kharzeev, L. McLerran, R. Venugopalan: nucl-th/0108048



List of Publications for 2001

1. E. S. Fraga, R. D. Pisarski, J. Schaffner-Bielich: “*New Class of Compact Stars at High Density*”, nucl-th/0110077
2. J. Schaffner-Bielich, D. Kharzeev, L. McLerran, R. Venugopalan: “*Generalized scaling of the transverse mass spectrum at the Relativistic Heavy-Ion Collider*”, nucl-th/0108048, submitted to Phys. Lett. B
3. A. Ramos, J. Schaffner-Bielich, J. Wambach: “*Kaon Condensation in Neutron Stars*”, nucl-th/0011003, Springer Lecture Notes in press
4. D. Zschesche, P. Papazoglou, S. Schramm, J. Schaffner-Bielich, H. Stöcker, W. Greiner: “*Hadrons in Dense Resonance-Matter: A Chiral SU(3) Approach*”, Phys. Rev. **C63**, 025211-1–10 (2001)
5. D. Zschesche, L. Gerland, S. Schramm, J. Schaffner-Bielich, H. Stöcker, W. Greiner: “*Critical Review of Quark-Gluon Plasma Signals*”, Nucl. Phys. **A681**, 34–40 (2001)
6. J. Schaffner-Bielich: “*Effects of In-Medium Properties on Heavy-Ion Collisions*”, J. Phys. **G27**, 337–347 (2001)
7. J. Schaffner-Bielich: “*Strange Dibaryons in Neutron Stars and in Heavy-Ion Collisions*”, Nucl. Phys. **A691**, 416–422 (2001)
8. L. McLerran and J. Schaffner-Bielich: “*Intrinsic Broadening of the Transverse Momentum Spectra in Ultrarelativistic Heavy-Ion Collisions?*”, Phys. Lett. **B514**, 29–32 (2001)
9. E.S. Fraga, R.D. Pisarski, J. Schaffner-Bielich: “*Small, Dense Quark Stars from Perturbative QCD*”, Phys. Rev. **D63**, 121702(R)-1–5 (2001)



Nuclear Effective Field Theory

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Nuclear Effective Field Theory

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Abstract

I review some of past year's developments in the formulation of the nuclear effective field theories (EFTs) of QCD, and discuss future directions of this research.

1 Recent developments

For the last few years Effective Field Theory (EFT) has emerged as a useful framework in which to describe nucleon dynamics consistently with QCD. The most general Lagrangian involving low-energy degrees of freedom (such as low-momentum nucleons) and the symmetries of QCD (in particular, chiral symmetry) is constructed, and interactions are ordered according to an expansion in powers of momenta. During the last year, developments took place regarding several issues.

1.1 Power counting in the two-nucleon system

A critical issue has been the power counting of pion interactions in the EFT applicable to momenta $Q \sim m_\pi < M_{QCD} \sim m_\rho$. Naive dimensional analysis suggests that one-pion exchange should be iterated to all orders in nuclear amplitudes, together with two-momentum-independent contact interactions. However, arguments from perturbation theory apparently indicate that this procedure introduces spurious cutoff dependence, which could be avoided only by treating pion interactions as perturbative corrections to short-range effects. For a review, see [1].

On the other hand, it was discovered recently that the renormalization of a non-perturbative problem can be dramatically different from the renormalization of its perturbative series [2]. It is therefore possible that perturbative arguments do not hold for the resummed series.

In the chiral limit ($m_\pi \rightarrow 0$), the relevant interaction is the $1/r^3$ tensor potential, so the problem boils down to the old, unresolved issue of the renormalization of singular potentials. Using EFT techniques, we have recently shown that a central $1/r^n$ potential can indeed be renormalized by a short-range interaction containing a single parameter [3].

The extension to the relevant case of pion interactions in the 1S_0 and 3S_1 - 3D_1 two-nucleon channels has also been carried out [4]. We were able to show that the two momentum-independent contact parameters can be varied in such a way that the remaining cutoff dependence is taken care of by smaller operators that appear in higher orders. Away from the chiral limit, we confirmed perturbative results that implied that explicit chiral-symmetry-breaking terms should, and can, be treated in perturbation theory [4].

The power counting that arises is one in which only the chiral-symmetric part of one-pion exchange is treated in leading order together with chiral-symmetric, momentum independent contact interactions, while interactions with more powers of Q and m_π^2 are treated in perturbation theory.

1.2 Parity-violating electron-deuteron scattering

The (parity-violating) longitudinal asymmetries in polarized quasi-elastic electron scattering on the proton and deuteron have recently been measured [5]. The asymmetries are sensitive to the nucleon's strange magnetic and axial form factors. If other effects are under control, the two measurements can be used to determine the values of the form factors at $|Q^2| = 0.1 \text{ GeV}^2$. Neglecting two-nucleon current effects, the results are in disagreement with theoretical estimates, in particular for the axial contribution [5]. It is unlikely that this discrepancy can be attributed to the anapole form factor of the nucleon [6], so a better understanding of two-nucleon effects is desirable.

Using power-counting arguments, we identified the leading contributions to the longitudinal asymmetry in quasi-elastic electron-deuteron scattering [7]. They include not only previously estimated one-nucleon currents and parity-violating effects in the wave functions, but also meson exchange currents. We have calculated the asymmetry due to electromagnetic and weak neutral one- and two-nucleon currents, using deuteron and pn scattering-state wave functions from solutions of a Schrödinger equation with the Argonne v_{18} potential. The results indicate that two-body contributions to the asymmetry are small ($\simeq 0.2\%$) around the quasi-elastic peak, but become relatively more significant ($\simeq 3\%$) in the high-energy wing of the peak [7].

1.3 Pion production in nucleon-nucleon collisions

Data for near-threshold pion production in nucleon-nucleon collisions have defied theoretical understanding (for a review, see [8]). Although EFT can in principle account for the observed cross section, different approximations for the kinematics have been employed in calculations that yield widely different results.

We developed a toy model that reproduces some of the features of EFT calculations of this process [9]. Within this model, we calculated the production amplitude and examined some common approximations. We found that only the fixed kinematics approximation (for both propagator and vertex) is appropriate for the final-state interaction, while in the initial-state interaction the contribution of the πNN cut is very important and has to be taken into account properly, which is not done in the commonly used approximations.

2 Future directions

In the near future, I intend to further study some of the issues discussed above.

The new, proposed power counting for the pionful EFT needs to be better examined. Other two-nucleon channels (P and higher waves) are currently under investigation. We plan to follow this up with a rigorous analysis of renormalization in the three- and four-nucleon systems. This will be an extension of the analysis [10] carried out in the pionless theory, limited to momenta $Q < m_\pi$.

The power counting can be also applied to the weak two-nucleon force. A global analysis of parity-violating processes involving nuclei shows that the standard meson-exchange (“DDH”) framework cannot explain the existing data [11]. This standard framework ignores certain contributions that appear in the EFT power counting at the same order as contributions that are kept. Among those ignored contributions, the most relevant is the weak two-pion exchange potential, which we are currently calculating in a way analogous to the strong two-pion exchange potential [12].

One important advantage of EFT over conventional nuclear models is that processes with different number of nucleons are treated consistently. In some cases, this allows the extraction of nucleon parameters from data on nuclear targets. One such case is Compton scattering on the deuteron. We have already studied this process to $O(Q^3)$ in the pionful EFT [13]. We are currently extending the calculation to $O(Q^4)$. Because we can calculate all two-nucleon effects, we will be able to fit the only unknowns, the neutron electric and magnetic polarizabilities, to existing data.

The longer-term goal is to improve our understanding of nuclear EFTs, so as to be able to systematically describe the hadronic phase of the QCD phase diagram [14].

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Progress Report and Research Plans

Tilo Wettig

RBRC Scientific Review Committee Meeting

November 29-30, 2001

Progress report for the past year

Tilo Wettig

My work in the past year has focused on two rather different yet complementary aspects of Quantum Chromodynamics: first, the study of the QCD Dirac operator using low-energy effective theories and lattice QCD, and second, the design of the next generation of massively parallel computers for lattice QCD.

As for the first aspect, I have extended my studies of the QCD Dirac operator in several directions. We now know that in a finite volume (a situation relevant for lattice simulation) there are several important energy scales that characterize the applicability of various effective theories. These are

- the magnitude and spacing of the lowest Dirac eigenvalues, $\lambda_{\min} \sim \pi/V\Sigma$,
- the QCD equivalent of the Thouless energy, $E_c \sim f_\pi^2/\sqrt{V}\Sigma$, and
- the mass of the lightest non-Goldstone particle, m_ρ .

(Here Σ denotes the absolute value of the chiral condensate.) For energies or momenta below m_ρ , QCD can be described by an effective chiral theory. This theory is usually treated in perturbation theory (chiral perturbation theory or chPT), which breaks down on the scale λ_{\min} since on this scale non-perturbative effects, which are responsible for the spontaneous breaking of chiral symmetry, become important. (The essential point is that in this case the group integral over the zero-momentum modes of the Goldstone fields has to be computed exactly, which is not done in chPT.) On the other hand, chiral random matrix theory (chRMT) gives an exact description of the QCD Dirac operator below the Thouless energy, i.e. also in the regime where the zero-momentum modes dominate. In the region between λ_{\min} and E_c (the overlap region), the predictions of chPT and chRMT coincide.

While my previous work has focused on the regime below the Thouless energy, I have now, in collaboration with the group of Andreas Schäfer at the University of Regensburg in Germany, extended the analytic description of the Dirac spectrum to the third region in the above picture, between E_c and m_ρ . Our main interest was to compare our theoretical results to data obtained in lattice gauge simulations. Since we were using staggered fermions away from the continuum limit, we had to construct a version of chPT applicable to this particular situation. Because the symmetries of staggered fermions at finite lattice spacing are different from those of continuum fermions, the number of Goldstone bosons and therefore the number of degrees of freedom of the theory is different. Also, there is no massive η' particle since the U(1) symmetries are all non-anomalous. In addition, as one approaches the continuum limit, one must carefully take into account the effects of the 15 doublers. Our theoretical work, as well as the comparison with lattice data, has been published in Ref. [1].

We have also started to study the eigenvectors of the QCD Dirac operator on the lattice (again for staggered fermions). In particular, we concentrated on the localization properties of the eigenvectors in the vicinity of the deconfinement phase transition. Above the critical temperature T_c , the Z_3 symmetry of the gauge action is spontaneously broken so that one must distinguish the three Z_3 -sectors labeled by the phase of the expectation value of the Polyakov loop (this is important in the quenched case which we were studying). The localization of the eigenvectors is very different in the Z_3 -sectors, and studying these characteristic differences allowed us to obtain semiclassical properties of the underlying gauge field configurations without any cooling. In particular, we found isolated modes with definite handedness that show localization in space but not in time and can therefore be associated with caloron configurations. This work has been published in Ref. [2] and presented at LATTICE 2001 in Berlin, Ref. [3].

Now to the second aspect mentioned above. In collaboration with other members of the RIKEN BNL Research Center as well as Columbia University, IBM Research (Yorktown Heights), and the UKQCD collaboration (Edinburgh), I am working very hard on the QCDOC project. The name QCDOC stands for QCD On a Chip. We are designing an application-specific integrated circuit (ASIC) combining existing IBM technology and custom-designed logic specially optimized for lattice QCD (of particular importance here is the nearest-neighbor communications unit that sends and receives data to and from neighboring chips). While I am contributing to all aspects of this project through weekly design meetings, my main responsibility is the overall integration of the ASIC. We are currently finishing the ASIC design and will then concentrate on designing the other parts of the machine (motherboards, daughterboards, etc.). A first account of this project has been published in Ref. [4], and I have presented the current status at LATTICE 2001 in Berlin, Ref. [5].

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RBRC Scientific Review Committee Meeting

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Research plans for the coming year

Tilo Wettig

One of the major efforts in my research work for the coming year will again be the QCDOC project mentioned in my progress report. I am heavily involved in many aspects of this project, including the design of the ASIC, test strategies, and the design of the other parts necessary to complete the machine (daughterboards, motherboards, ethernet switches, etc.). We are getting close to completing the ASIC design and will then concentrate on synthesizing the design to meet all timing requirements. While contributing to the ASIC logic by writing VHDL myself, I am also coordinating the efforts of the other developers, integrating their work into the overall design. QCDOC is a big team effort involving five major institutions, and we are planning to have the first prototype machines available in the second half of 2002.

I am also interested in a particular problem in mathematical physics, a transformation recently introduced by Zirnbauer in the context of condensed matter physics. This transformation reads

$$\begin{aligned} \int_{U(N)} dU \exp \left(\bar{\psi}_{+a}^i U^{ij} \psi_{+a}^j + \bar{\psi}_{-b}^j \bar{U}^{ij} \psi_{-b}^i \right) \\ = \int D\mu_N(Z, \tilde{Z}) \exp \left(\bar{\psi}_{+a}^i Z_{ab} \psi_{-b}^i + \bar{\psi}_{-b}^j \tilde{Z}_{ba} \psi_{+a}^j \right). \end{aligned}$$

In the language of QCD, ψ denotes a (super) tensor carrying “color” (i, j) and “flavor” (a, b) indices. The remarkable feature of this transformation is that the integral over the “gluon fields” U is traded for an integral over (super) matrices Z, \tilde{Z} that live in flavor space and can be thought of as meson degrees of freedom. The color degrees of freedom are completely decoupled on the right-hand side.

While this “color-flavor transformation” represents a remarkable step forward in the theory of disordered systems for which it was originally derived, it is not immediately applicable to (lattice) QCD. The major obstacles are:

1. The transformation only addresses the fermionic action which contains terms linear in the gauge field. The Yang-Mills action contains higher-order terms in the gauge field that have to be taken into account as well.
2. The fermion doubling problem that one encounters on the lattice is still present in this approach.
3. The transformation needs to be adapted to gauge group $SU(N)$ with $N = 3$ for QCD.

As for item 1., we note that the plaquette term on the lattice is of the general form $\text{tr} UUUU$. As already hinted at by Zirnbauer, terms of this form could be generated by coupling heavy fermionic ghosts to the gauge field via $\bar{\psi}U\psi$.

As for item 2., the doubling problem has recently been solved in a variety of ways based on the Ginsparg-Wilson relation. Therefore, we have some guidance as to how it can be tackled in this new method. At first sight it seems as if the domain-wall fermion approach might be the most suitable candidate.

Item 3. is perhaps the most complicated task. First steps in this direction have been taken recently in a note by Budcziec and Shnir, but the results are not yet complete. Alternatively, one could first solve the problem for gauge group $SU(2)$. This is possible because of the accidental isomorphism $SU(2) \simeq Sp(2)$ and because the original color-flavor transformation also works for $Sp(2N)$.

If all three obstacles can be overcome, one would accomplish a radically new and very promising formulation of lattice QCD. This would be interesting both from a theoretical and from an algorithmic point of view. It is of course too early to tell how a fermionic algorithm based on this new formulation would look like, but perhaps the technical problems resulting from very light dynamical quark masses may not even be present in this approach. In any event, the importance of lattice QCD simulations with realistic light quark masses and the performance problems of current algorithms such as Hybrid Monte Carlo certainly justify steps in new, unexplored directions.

Finally, I have an interest in the sign problem that plagues lattice QCD at nonzero chemical potential. It is now understood that the various reweighting methods that have been suggested over time will fail if the volume becomes too large. Recently, Adami and Koonin have suggested that the complex Langevin algorithm might be a suitable candidate to tackle the problem. I plan to test this suggestion, first in the framework of a chiral random matrix model where analytical results can be obtained as well. The obvious advantage of knowing the analytical results is that one can tell immediately whether or not the algorithm works. Also, they might give us hints as to how the algorithm could be improved in case it doesn't work right away.

CURRICULA VITAE

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Visiting Assistant Professor, Michigan State University, 1999
•RHIC Physics Fellow/Assistant Professor--RBRC/Duke,
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Thomas C. Blum **Birthplace:** USA **DOB:** December 27, 1962
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Research Associate, University of Minnesota, 1994-5
Research Associate, University of Heidelberg, 1995-8
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Basic and Highlights in Fundamental Physics, Erice, Italy,
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Associate Research Scientist, Yale University, 1994-2000
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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,
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Weis Prize, University of Washington, 1990

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Assistant Scientist, Physics Department, BNL - October 1998
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Research Associate, Institute for Theoretical Physics, Technical University of Munich; External Scientific Associate, Max-Planck-Institute for Nuclear Physics, Heidelberg
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PUBLICATIONS

11/15/01

RIKEN BNL Research Center
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Publication List

RBRC/#

1. H. Fujii and H. Shin, "Dilepton Production in Meson Condensed Matter," *Prog. Theor. Phys.* 98, 1139 (1997).
2. K. Bora, and R. L. Jaffe "The Double Scattering Contribution to $b_1(x, Q^2)$ in the Deuteron," [hep-ph/97113213]; *Phys. Rev. D* 57, 6906 (1998).
3. R. L. Jaffe, X. Jin and J. Tang, "Interference Fragmentation Functions and Valence Quark Spin Distributions in the Nucleon," [hep-ph/9710561, BNL-66451]; *Phys. Rev. D* 57, 5920 (1998).
4. R. L. Jaffe, "Can Transversity Be Measured"? [hep-ph/9710465] to appear in the *Proceedings of Deep Inelastic Scattering off Polarized Targets: Theory Meets Experiment*, DESY, Zeuthen, September 1997.
5. R. L. Jaffe, X. Jin and J. Tang, "Interference Fragmentation Functions and the Nucleon's Transversity," *Phys. Rev. Lett.* 80, 1166 (1998).
6. D. Kharzeev, "Charmonium Suppression in Nuclear Collisions," *Proceedings of the Quark-Gluon Plasma School, Hiroshima*, Eds. M. Asakawa, T. Hatsuda, T. Matsui, O. Miyamura and T. Sugitate; *Progress of Theoretical Physics Supplement No. 129*, 73-81 (1997).
7. D. Kharzeev, "Quarkonium Production in Nuclear Collisions," to appear in the *Proceedings of the Color Transparency Workshop, Grenoble, France, 1997*, p. 45, Eds. J.-F. Mathiot and E. Voutier.
8. D. Kharzeev, "The Charm of Nuclear Physics," in *Proceedings of Non-Equilibrium Many Body Dynamics*, Eds. M. Creutz and M. Gyulassy, RIKEN BNL Research Center, 1997, p. 37.
9. D. Kharzeev, "Theoretical Interpretations of J/ψ Suppression, A Summary," *Proceedings of Quark Matter '97, Tsukuba, Japan, Nucl. Phys.* A638, 279c-290c (1998).

RBRC/#

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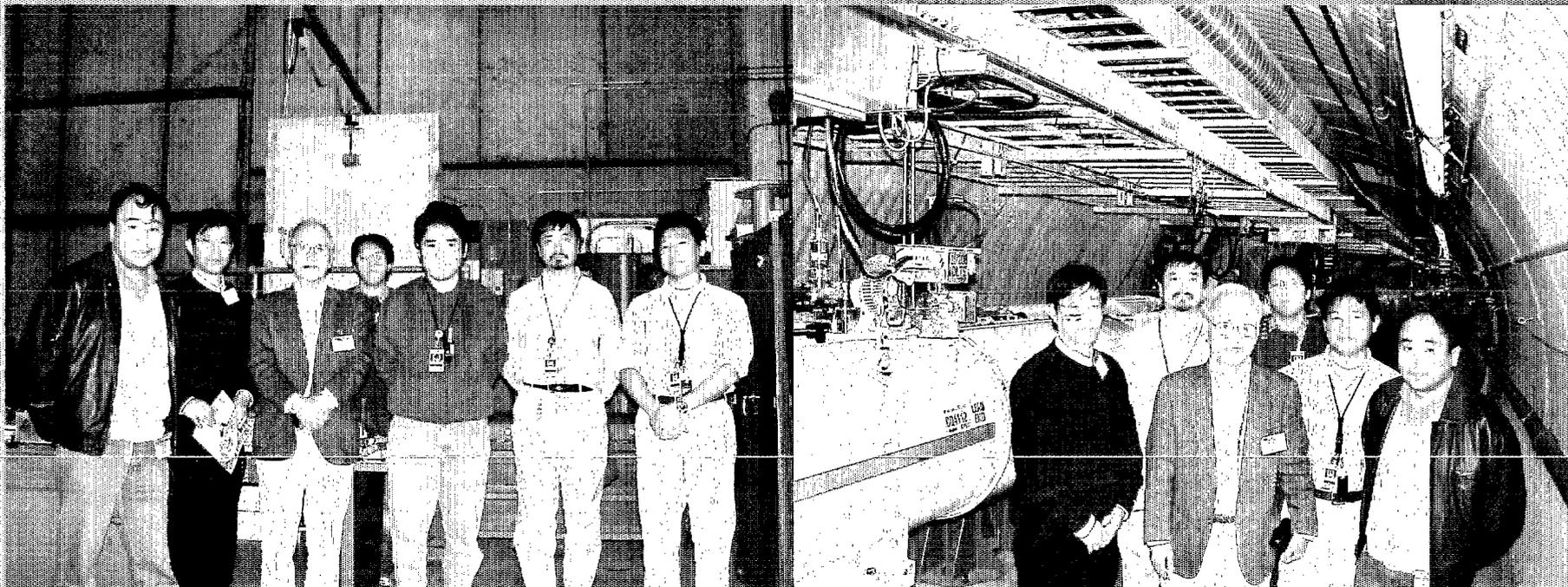
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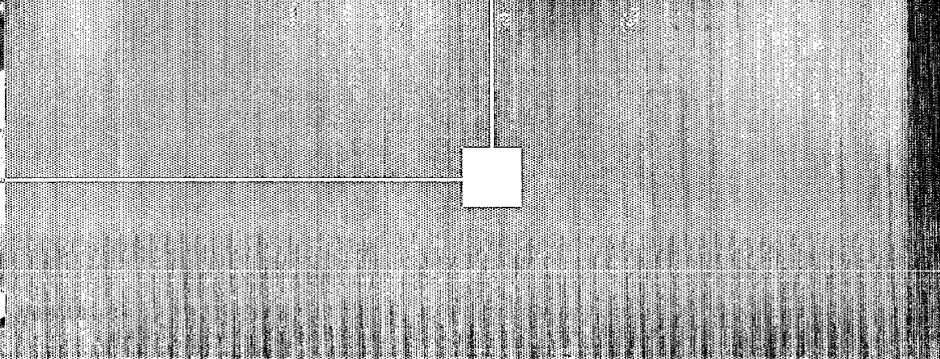
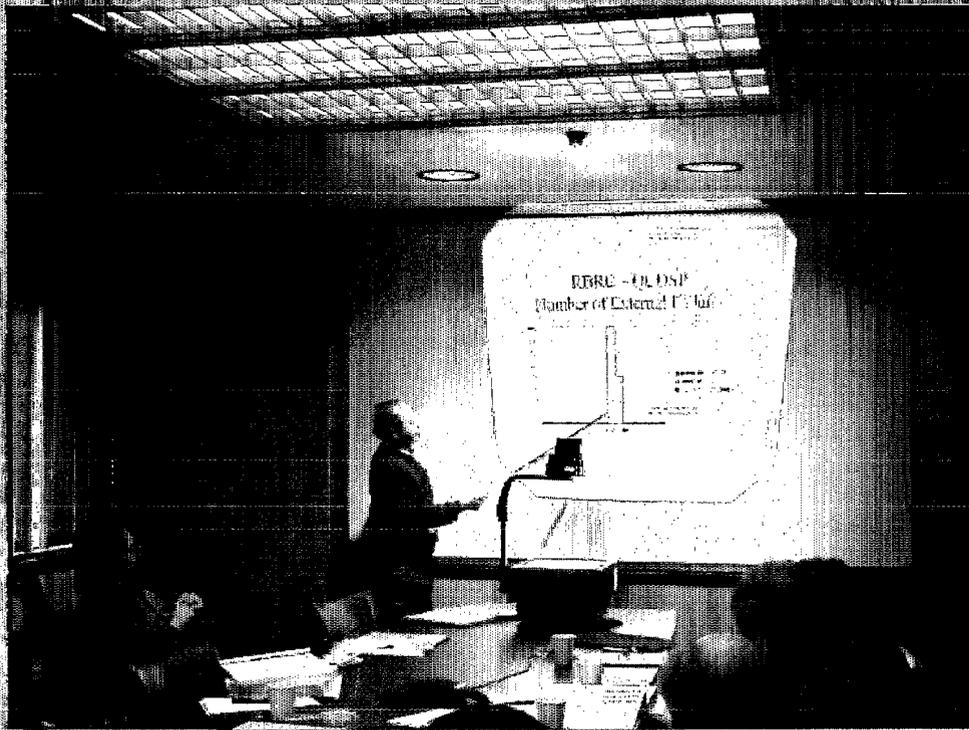
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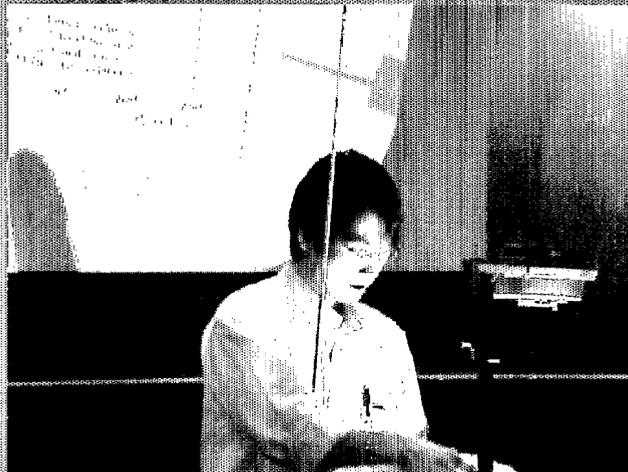


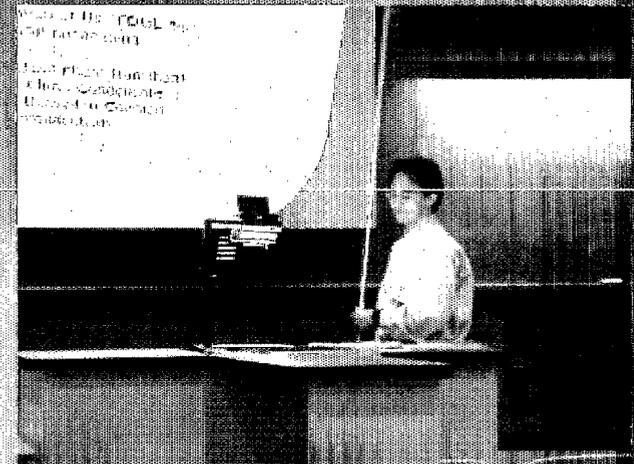
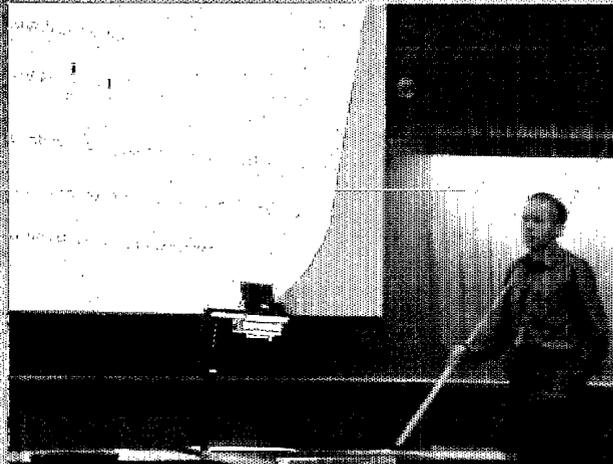
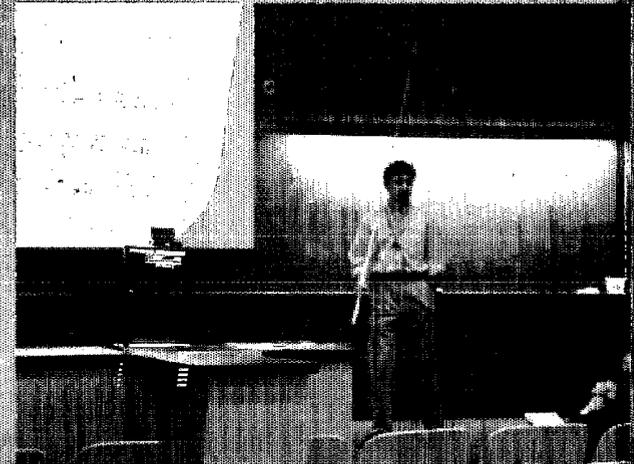
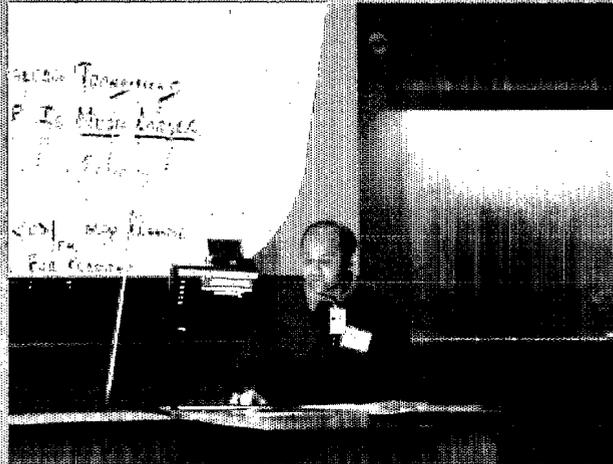


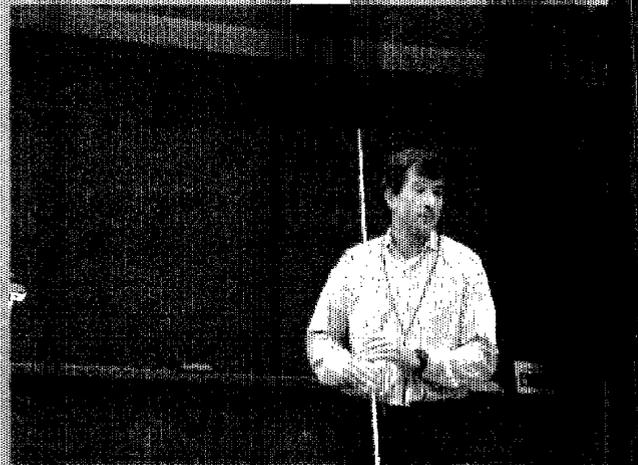
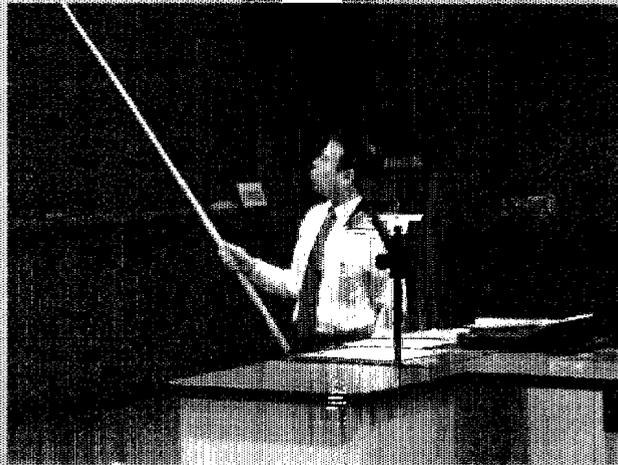
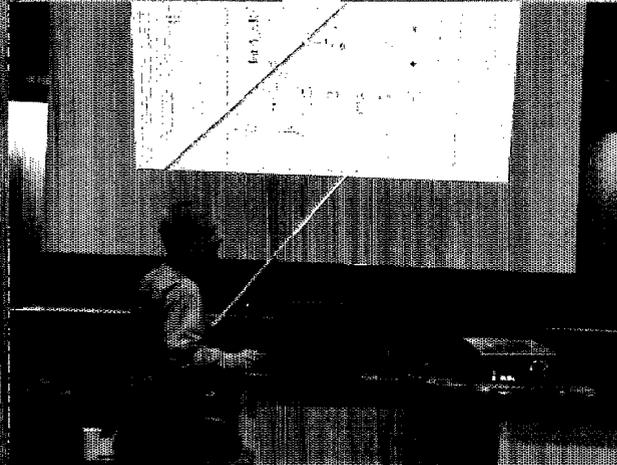
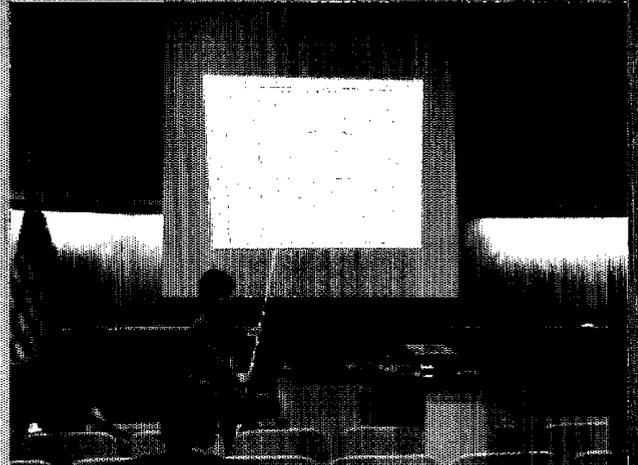
















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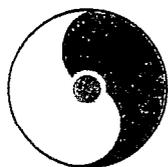
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RIKEN BNL RESEARCH CENTER

RBRC Scientific Review Committee Meeting

November 29-30, 2001



Li Keran

Nuclei as heavy as bulls

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Through collision

Generate new states of matter.

T.D. Lee

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