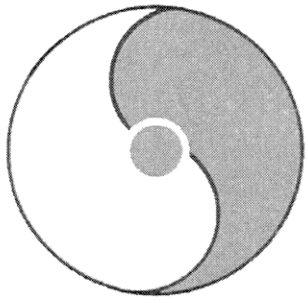
BNL-79570-2007
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 87

RBRC Scientific Review Committee Meeting

November 5 - 6, 2007



Organizer:

N.P. Samios

RIKEN BNL Research Center

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

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Preface to the Series

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

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

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

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. 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 eighty-three proceeding volumes available.

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

N. P. Samios, Director
March 2007

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

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RBRC Scientific Review Committee Meeting

November 5-6, 2007

Brookhaven National Laboratory, Upton, NY 11973

The ninth evaluation of the RIKEN BNL Research Center (RBRC) took place on Nov. 5-6, 2007, at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC) were Dr. Jean-Paul Blaizot, Dr. Wit Busza, Dr. Akira Masaike, Dr. Alfred Mueller, Dr. Charles Young Prescott (Chair) and Dr. Akira Ukawa. We are pleased that Dr. Yasushige Yano, the Director of the Nishina Institute of RIKEN, Japan participated in this meeting both in informing the committee of the activities of the Nishina Institute and the role of RBRC and as an observer of this review.

In order to illustrate the breadth and scope of the RBRC program, each member of the Center made a presentation on his/her research efforts. This encompassed three major areas of investigation, theoretical, experimental and computational physics. In addition the committee met privately with the fellows and postdocs to ascertain their opinions and concerns.

Although the main purpose of this review is a report to RIKEN Management (Dr. Ryoji Noyori, RIKEN President) on the health, scientific value, management and future prospects of the Center, the RBRC management felt that a compendium of the scientific presentations are of sufficient quality and interest that they warrant a wider distribution. Therefore we have made this compilation and present it to the community for its information and enlightenment.

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

N. P. Samios

RIKEN BNL Research Center

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

Agenda

Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510
Large Seminar Room
November 5 and 6, 2007
Open Sessions

Committee Members

Jean-Paul Blaizot	C.E.A. - Saclay
Wit Busza	MIT
Akira Masaike	JSPS, Washington, D.C.
Alfred Mueller	Columbia U
Charles Prescott, Chair	SLAC
Akira Ukawa	U. of Tsukuba

Monday, November 5, 2007

8:00 AM - 9:00 AM *Open Executive Session & Working Breakfast (Room 2-160)*
(Presentations by RIKEN/RBRC Administration)

THEORY GROUP PRESENTATIONS
LARRY MC LERRAN, CHAIR
LARGE SEMINAR ROOM, BLDG 510

Talks by Fellows

9:00 AM - 9:15 AM Sinya Aoki: *Nuclear force from lattice QCD*

9:15 AM - 9:30 AM Shigemi Ohta: *Nucleon structure from lattice QCD with 2+1 dynamical domain wall fermions*

9:30 AM - 9:45 AM Yasumichi Aoki: *Hadronic matrix elements with 2+1 flavor domain fermions*

9:45 AM - 10:00 AM Taku Izubuchi: *Lattice QCD with Theta Terms*

10:00 AM - 10:15 AM Derek Teaney: *Quark Energy Loss*

10:15 AM - 10:30 AM Kirill Tuchin: *Scale anomaly in QCD at zero and finite temperature*

10:30 AM	-	10:45 AM	Denes Molnar: Determining the shear viscosity of dense QCD matter at RHIC
10:45 AM	-	11:00 AM	Break
11:00 AM	-	11:15 AM	Rainer Fries: *Probing Hot and Cold Nuclear Mater*
11:15 AM	-	11:30 AM	Feng Yuan: *Spin structure functions*
11:30 AM	-	11:45 AM	Cecilia Lunardini: *Neutrino Astrophysics*

THEORY GROUP PRESENTATIONS
ANTHONY BALTZ, CHAIR
LARGE SEMINAR ROOM, BLDG 510

Talks by Postdocs

11:45 AM	-	12:00 PM	Tomomi Ishikawa: *Phase structure of twisted large N reduced model*
12:00 PM	-	12:15 PM	Agnes Mocsy: Heavy quark bound states at finite temperature
12:15 PM	-	12:30 PM	Adam Lichtl: *Excited resonance physics from the lattice*
12:30 PM	-	12:45 PM	Yoshimasa Hidaka: *Real time behavior of the Quark Gluon Plasma*
12:45 PM	-	1:00 PM	Cyrille Marquet: *Particle production in dA collisions*
1:00 PM	-	2:00 PM	SRC Executive Session - Working Lunch (Room 2-160)

EXPERIMENTAL GROUP PRESENTATIONS
HIDETO EN'YO, CHAIR
LARGE SEMINAR ROOM, BLDG 510

2:00 PM	-	2:15 PM	Abhay Deshpande - *Gluon's spin in the proton: recent results from PHENIX and the path forward*
2:15 PM	-	2:30 PM	Kensuke Okada: *Direct photon measurements*
2:30 PM	-	2:45 PM	Patricia Liebing: *Delta G from open charm production*

2:45 PM	- 3:00 PM	David Kawall: *Development of a trigger for high p_T charged pions for PHENIX*
3:00 PM	- 3:15 PM	Itaru Nakagawa: *Muon trigger upgrade for W boson detection*
3:15 PM	- 3:30 PM	Atsushi Taketani: *Vertex detector for PHENIX*
3:30 PM	- 4:00 PM	Break
		EXPERIMENTAL GROUP PRESENTATIONS **GERRY BUNCE, CHAIR** **LARGE SEMINAR ROOM, BLDG 510**
4:00 PM	- 4:15 PM	Matthias Grosse Perdekamp: *QCD and Transverse Spin - Future Studies*
4:15 PM	- 4:30 PM	Yuji Goto: *Very Forward Neutron Asymmetry at RHIC*
4:30 PM	- 4:45 PM	Wei Xie: *PHENIX Reaction Plane Detector and its Physics Input*
4:45 PM	- 5:00 PM	Yasuyuki Akiba: *Heavy Ion Physics at PHENIX*
7:00 PM		**Dinner - Three Village Inn, Stony Brook**

Tuesday, November 6, 2007

8:00 AM	- 9:00 AM	*Executive Session & Working Breakfast (Room 2-160)*
		COMPUTING PRESENTATIONS **N.P. Samios, CHAIR** **SMALL SEMINAR ROOM, BLDG 510**
9:00 AM	- 9:30 AM	Norman Christ: *RBRC lattice QCD program and the Next Computer Project*
9:30 AM	- 10:00 AM	Robert Mawhinney: *K meson physics with domain wall fermions in the chiral limit*
10:00 AM	- 10:30 AM	Peter Petreczky: *The QCD phase transition and equation of state: toward physical quark masses and vanishing lattice spacing*
10:30 AM	- 12:00 PM	INTERVIEWS (Experimental) - Meetings with Individual RBRC Staff (Room 2-78) INTERVIEWS (Theory) - Meetings with Individual RBRC Staff (Room 2-160)
12:00 PM	- 1:00 PM	Executive Session - Working Lunch (Room 2-160)
1:00 PM	- 3:00 PM	INTERVIEWS (Experimental) - Meeting with Individual RBRC Staff (Room 2-78) INTERVIEWS (Theory) - Meetings with Individual RBRC Staff (Room 2-160)
3:00 PM	- 4:15 PM	Executive Session
4:15 PM	- 5:00 PM	Closeout

RBRC Scientific Review Committee Membership 2007

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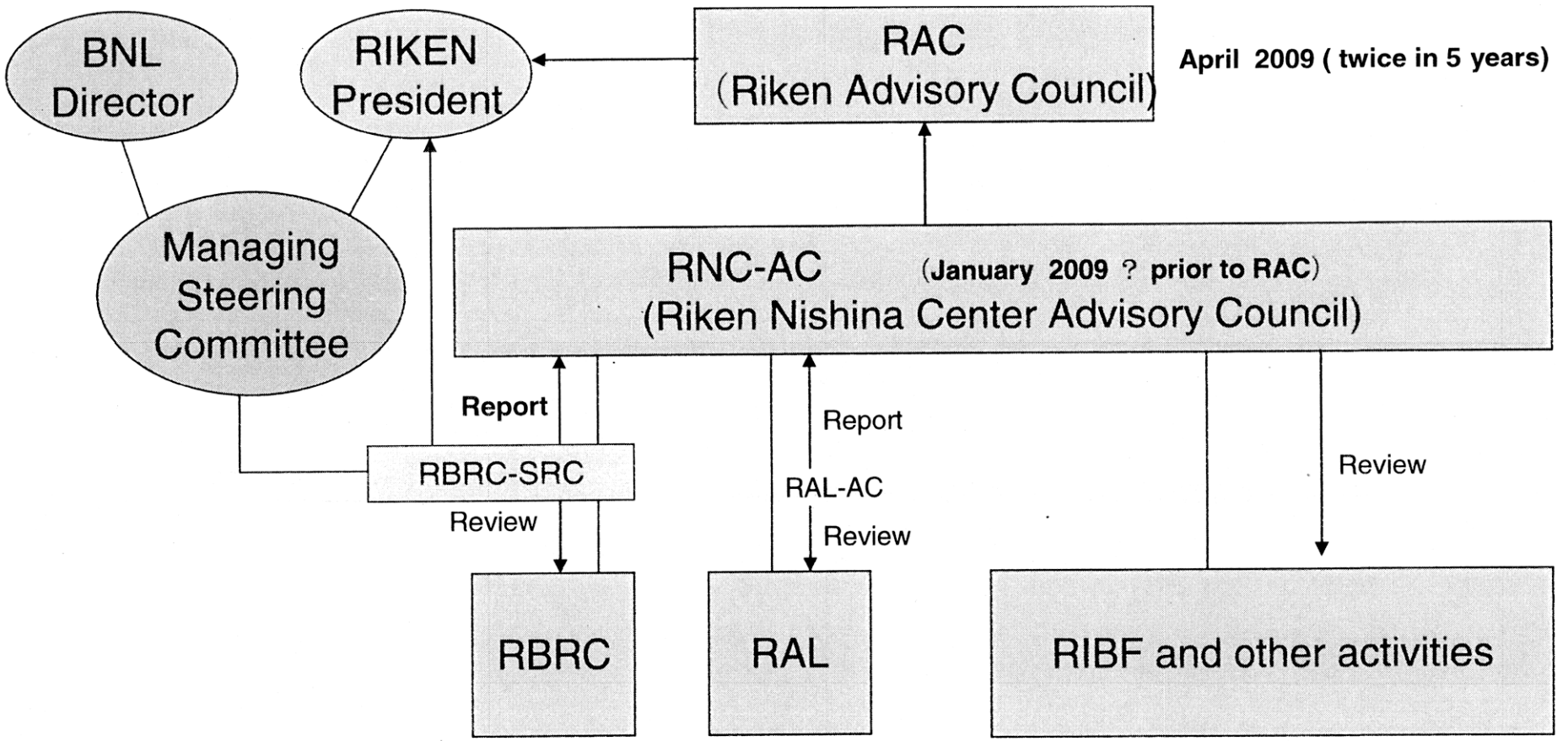
E-mail: ukawa@ccs.tsukuba.ac.jp

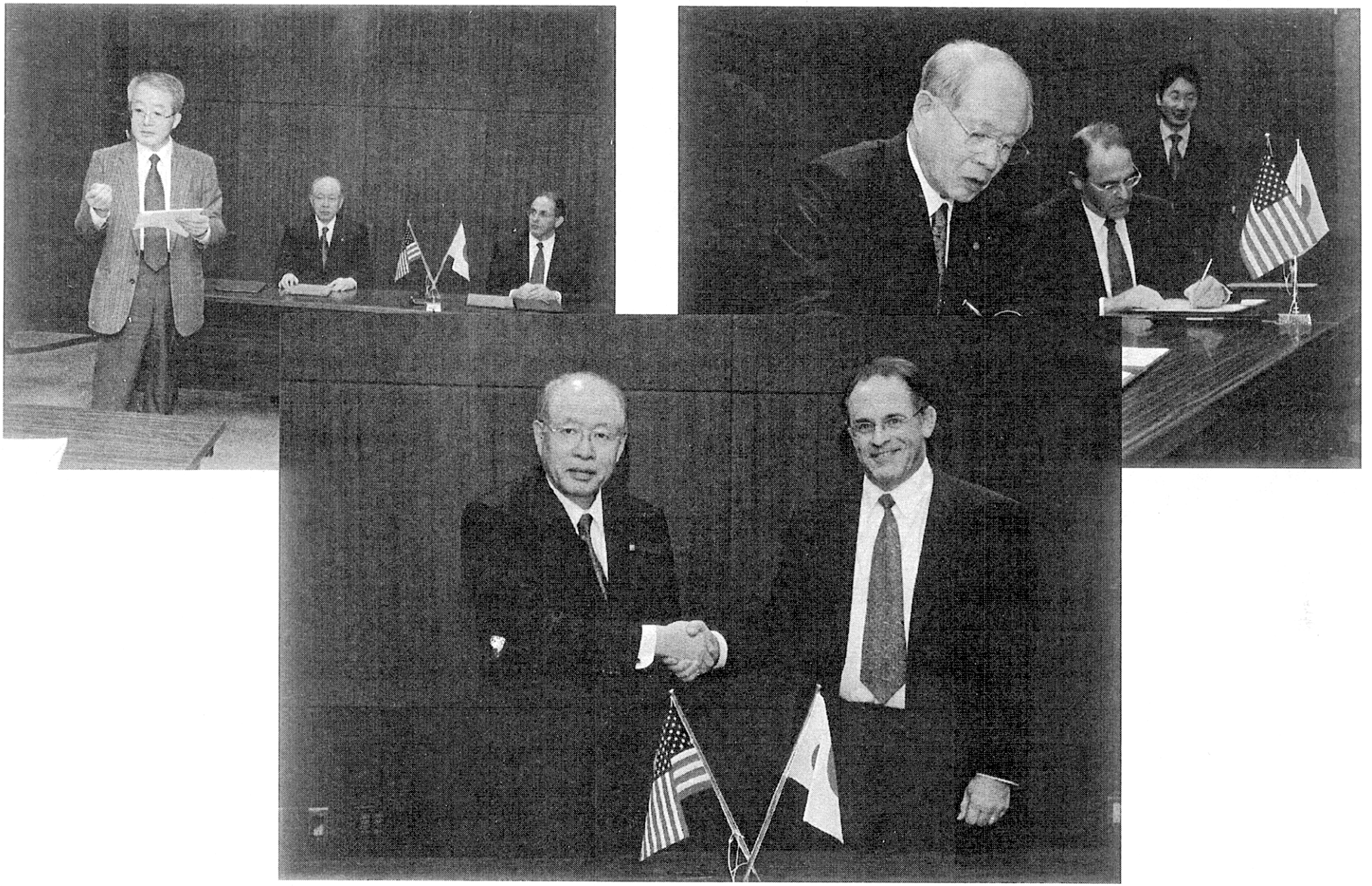
RBRC Administration Presentations

RIKEN Review System and Schedule

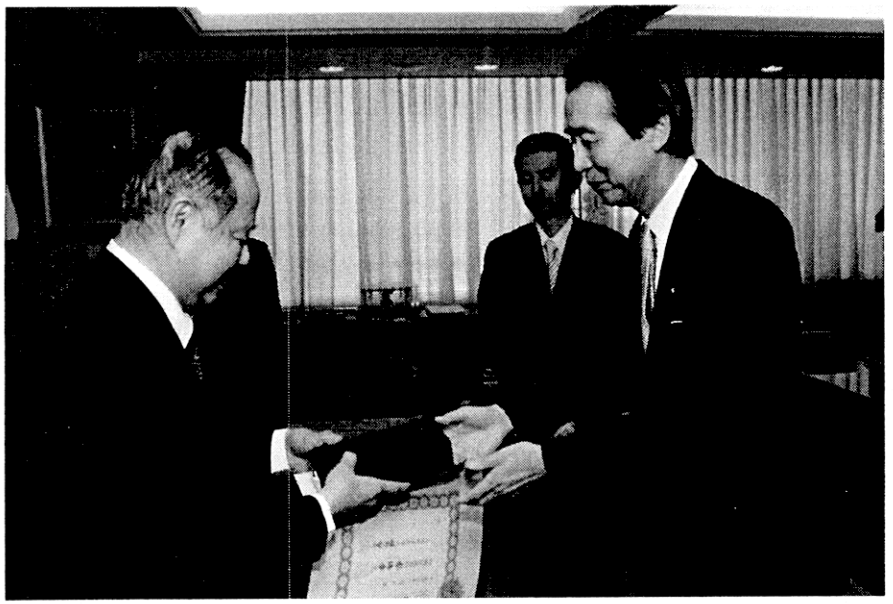


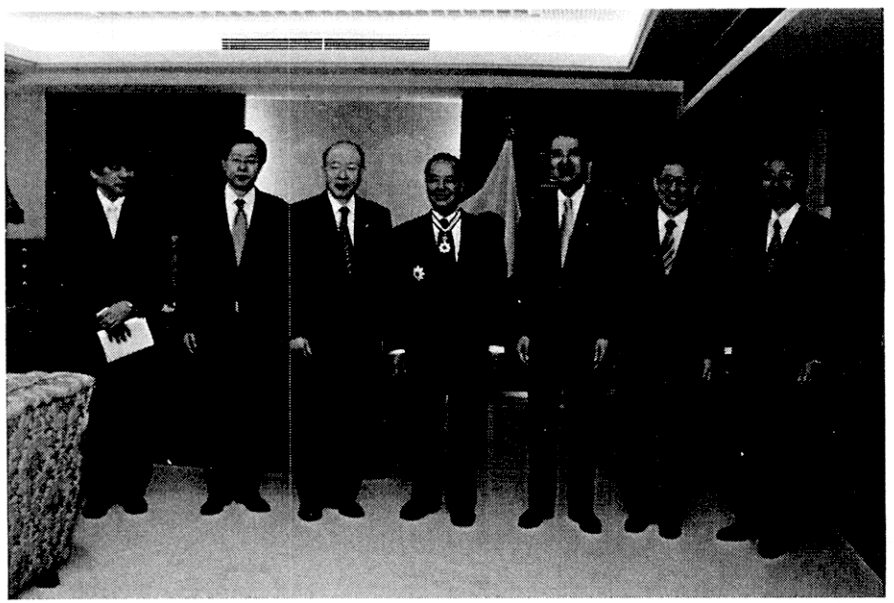
RBRC-SRC
(Nov. 5,6 2007)
(Nov. 2008?)

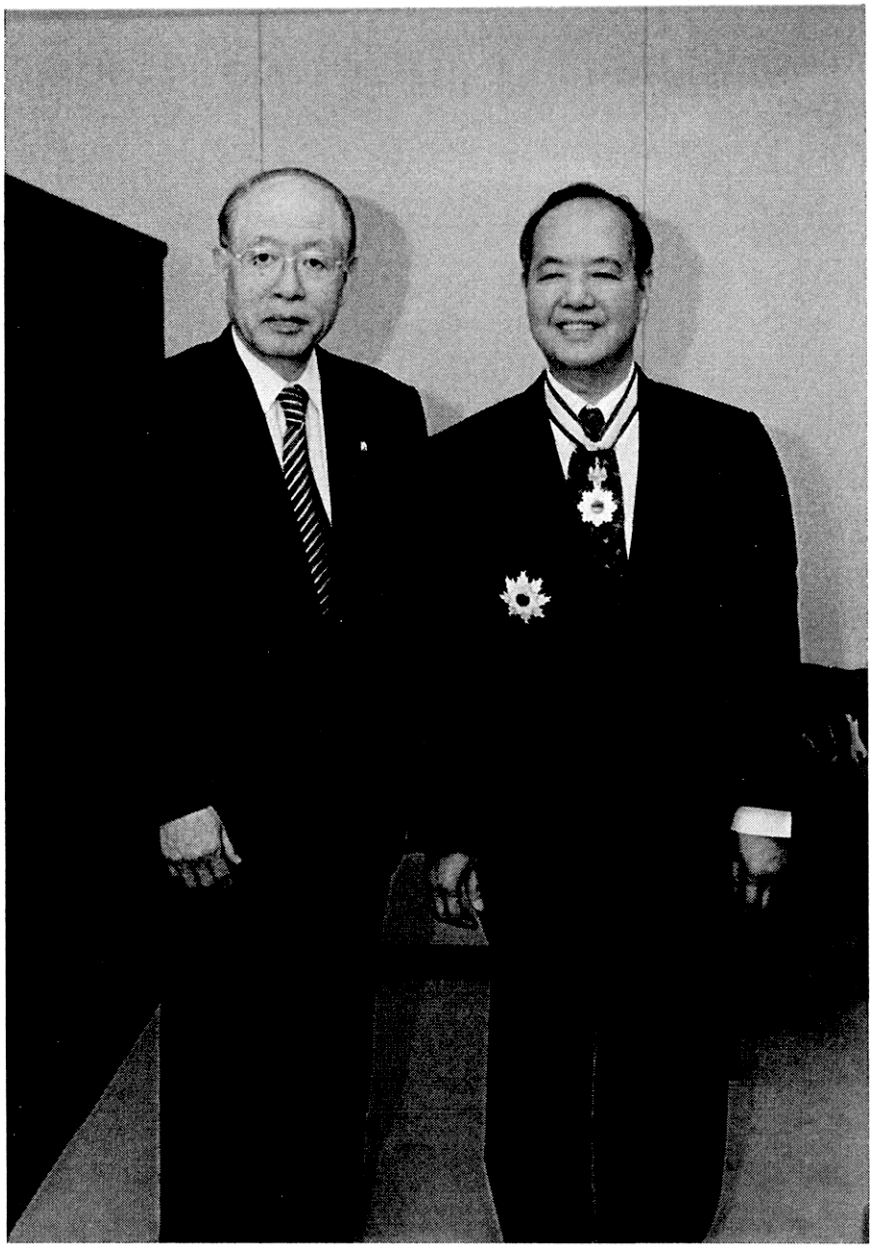
RAL-AC
(Nov. 26,27 2007)



The signature ceremony for the revision of MoU between RIKEN and BNL







The award ceremony for Professor T. D. Lee (15 January 2007)
(The order of the rising sun, gold and silver star:旭日重光章)

RBRC Scientific Review Committee Meeting

RBRC Overview

Nicholas P. Samios

Nov. 5, 2007

Brookhaven National Laboratory

Activities

- October 10-12, 2005
- RBRC Scientific Review Committee Mtg.

BNL

- Oct. 12, 2005
  RBRC Proposal for 5 year extension of the RIKEN BNL Collaboration MOU beyond

2007

Committee augmented with Nakai and Ukawa

- Dec. 1, 2005
  RBRC – Extension Request for RBRC

- Jan. 19, 2006
  Chief Scientist Assembly – RIKEN
  Samios and En'yo Presentation

Wako

- Jan. 2006
  RIKEN Executive Director Board
  Recommendation to MEXT
- June 29, 2006
  12th Management Steering Committee Meeting

Video

- Jan. 15, 2007

  T.D. Lee – Recipient of
  Order of the Rising Sun

  Gold & Silver Star

  Tokyo

- Jan. 16, 2007

  13th Management Steering Committee

  Tokyo

- Jan. 16, 2007

  MOE Extended 5 years – RIKEN-BNL

  Concerning the collaboration on the
  Spin Physics Program at RHIC

  Noyori/RIKEN Aronson/BNL

Physics: Major Inputs in 2006

Quark Matter 2006 Shanghai, China

RHIC Dominated

Plenary Talk by RBRC Personnel

Present & Past

Hatsuda
Kharzeev
Mc Lerran
Grosse Perdekamp
Samios
Son
Wiedemann

Plenary Talks by RBRC Scientific Review Committee

Present & Past

Blaizot
Stoecker

Spin 2006

Kyoto, Japan
Plenary RBRC Speaker
Deshpande
Invited Parallel Session Speakers
Bunce
Liebing
Vogelsang
Yuan

Lattice Gauge 2007

International Conference on Lattice Gauge

Regensburg, Germany
Organized by T. Wettig (RBRC Graduate)
Major Plenary Talk
RBRC UK Collaboration

RBRC Major Physics Interests

Spin Structure of the Proton
High Energy Density Matter
SQGP
Color Glass Condensate
Critical Point
Lattice Gauge Calculation
QCDOC; Domain Wall Fermions

Major Result for Run 6 Spin

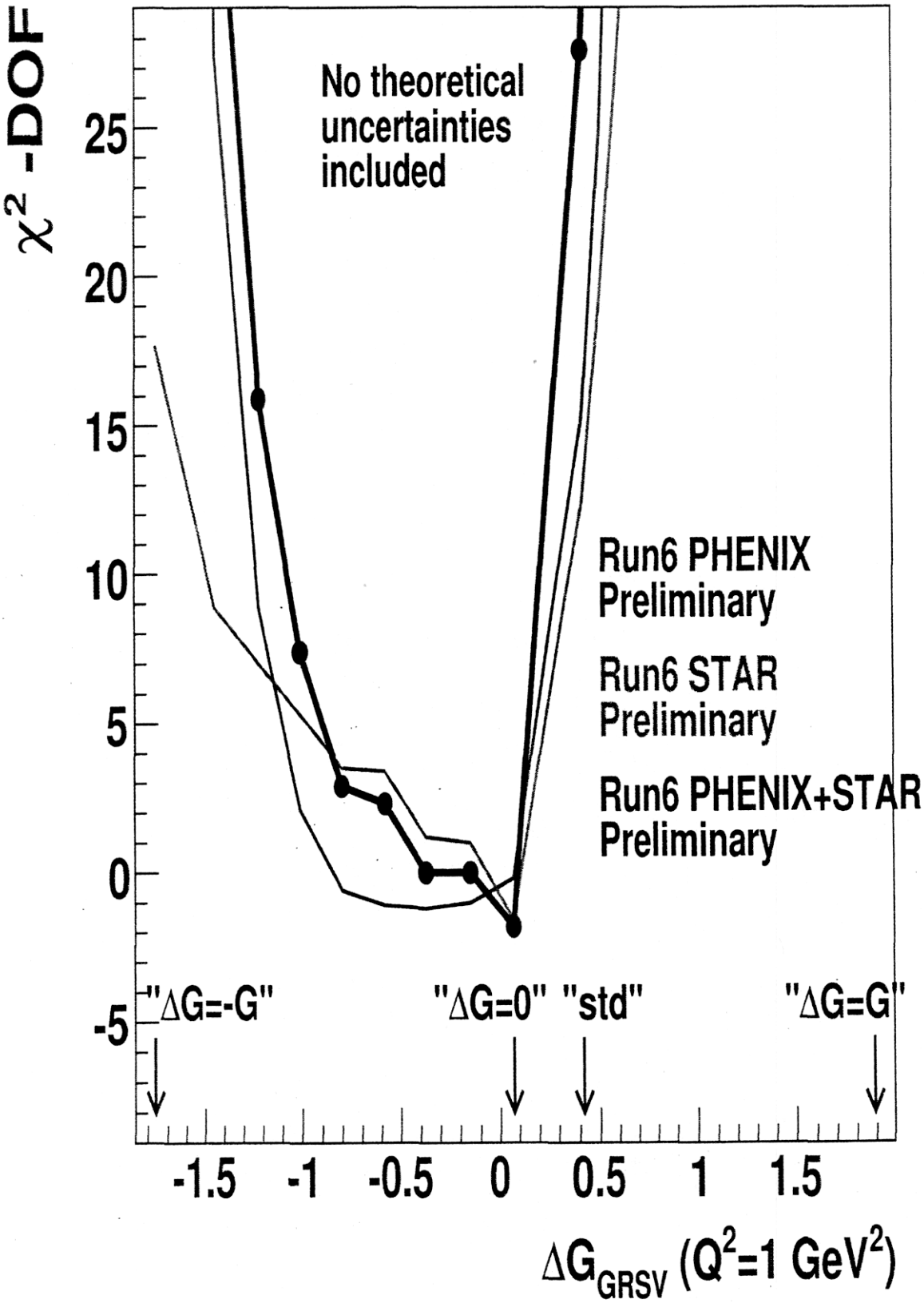
Spin Content of the Proton
Gluon Contribution ΔG
Plot $\chi 2$ vs ΔG

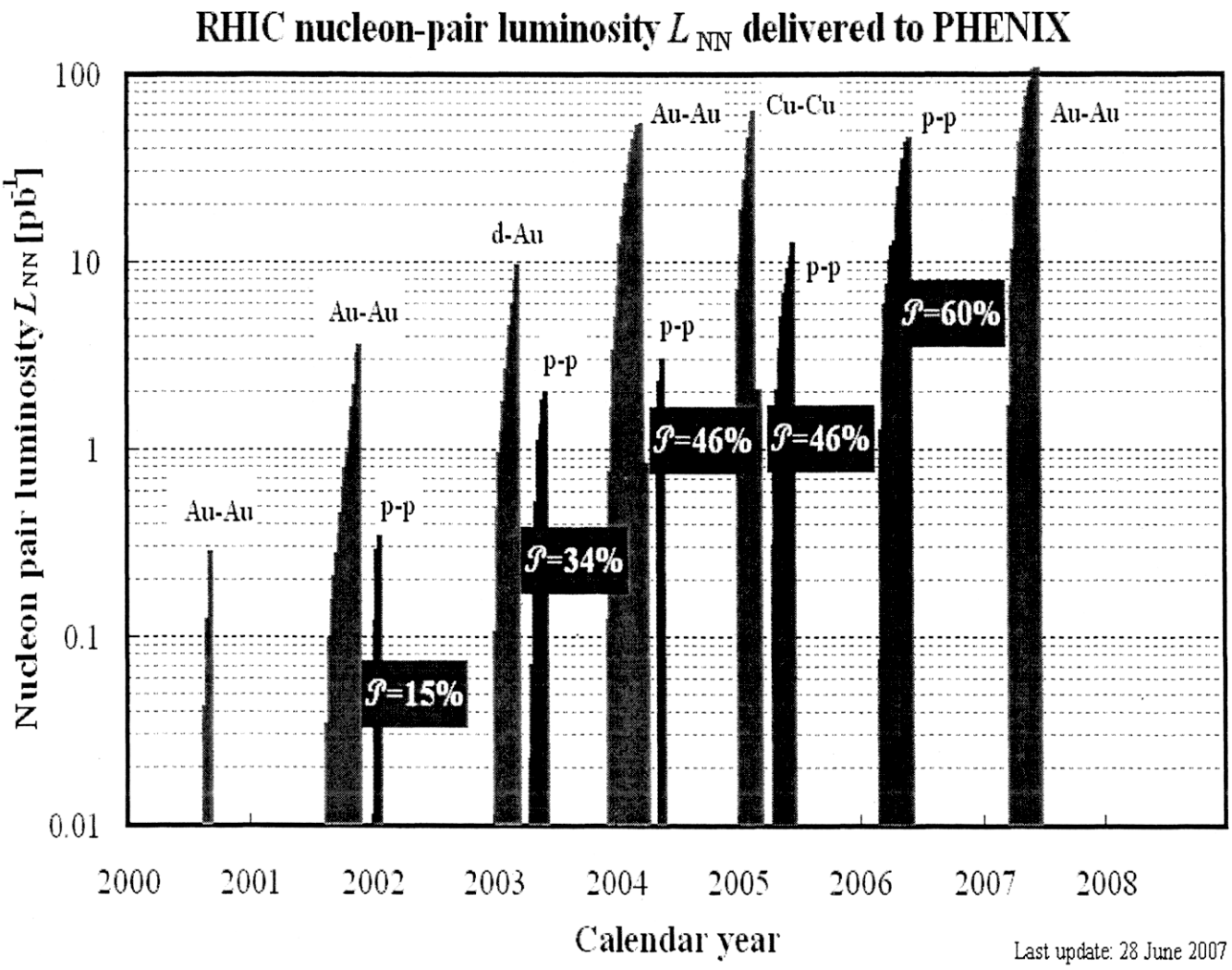
R&D Next Lattice Gauge Computer

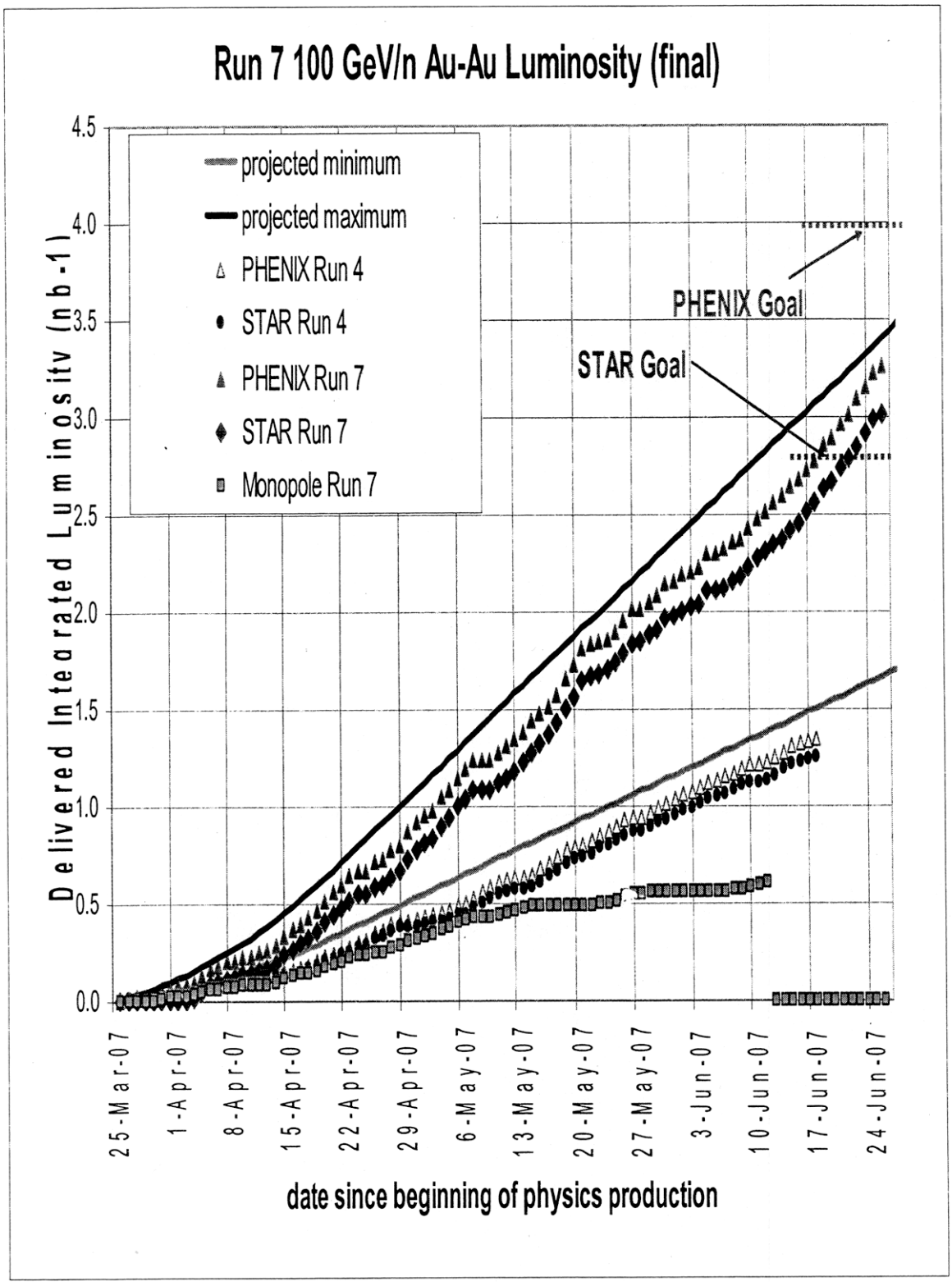
Columbia, IBM, RIKEN, UK
Hired Post doc

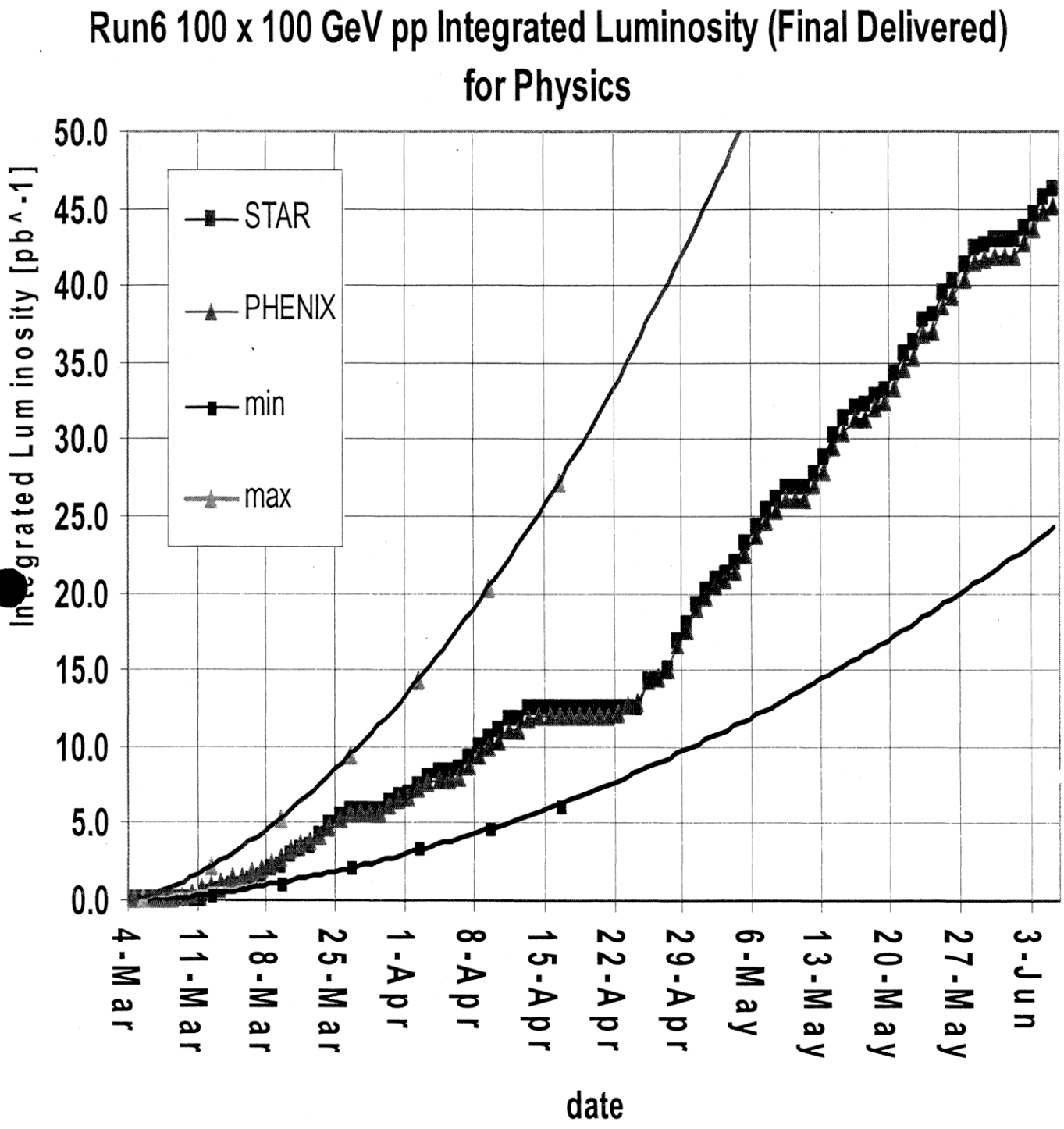
Computing: World Ranking LINPAC

Year	QCDOC(8Tf)	NY Blue (100Tf)
2006	152	3
2007	398	5

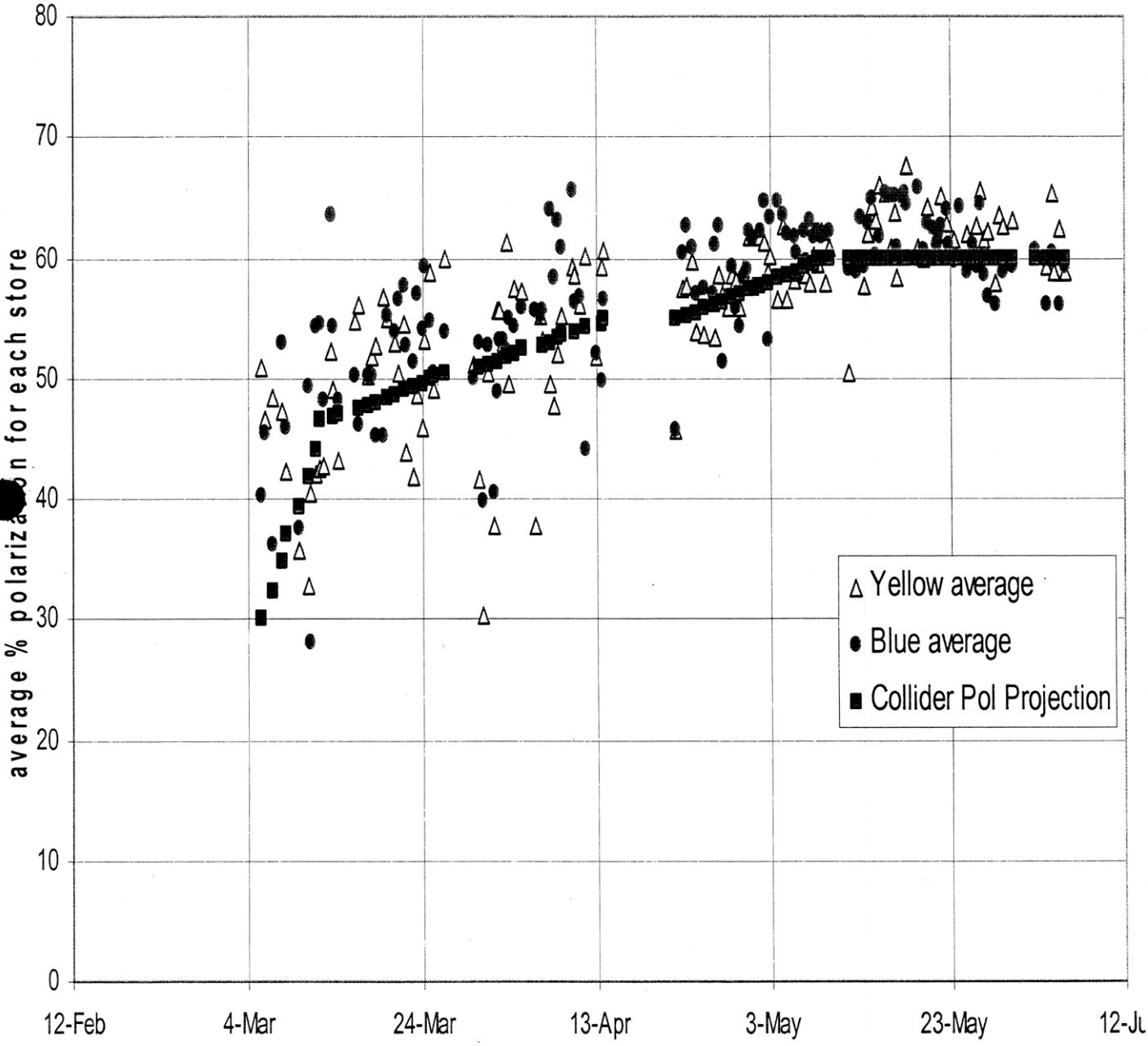

χ^2 -DOF
No theoretical uncertainties included
Run6 PHENIX Preliminary
Run6 STAR Preliminary
Run6 PHENIX+STAR Preliminary
"ΔG=-G"
"ΔG=0"
"std"
"ΔG=G"
25
20
15
10
5
0
-5
-1.5
-1
-0.5
0
0.5
1
1.5
ΔG_{GRSV} (Q^2=1 GeV^2)


RHIC nucleon-pair luminosity L_{NN} delivered to PHENIX
Nucleon pair luminosity L_{NN} [pb^{-1}]
100
10
1
0.1
0.01
Au-Au
p-p
$\mathcal{P}$=15%
Au-Au
d-Au
p-p
$\mathcal{P}$=34%
Au-Au
p-p
$\mathcal{P}$=46%
Cu-Cu
p-p
$\mathcal{P}$=46%
p-p
$\mathcal{P}$=60%
Au-Au
2000
2001
2002
2003
2004
2005
2006
2007
2008
Calendar year
Last update: 28 June 2007


Run 7 100 GeV/n Au-Au Luminosity (final)
projected minimum
projected maximum
PHENIX Run 4
STAR Run 4
PHENIX Run 7
STAR Run 7
Monopole Run 7
PHENIX Goal
STAR Goal
Delivered Integrated Luminosity (nb-1)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
25-Mar-07
1-Apr-07
8-Apr-07
15-Apr-07
22-Apr-07
29-Apr-07
6-May-07
13-May-07
20-May-07
27-May-07
3-Jun-07
10-Jun-07
17-Jun-07
24-Jun-07
date since beginning of physics production


Run6 100 x 100 GeV pp Integrated Luminosity (Final Delivered) for Physics
Integrated Luminosity [pb^-1]
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
STAR
PHENIX
min
max
4-Mar
11-Mar
18-Mar
25-Mar
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
date

Polarization for Run 6, 100x 100 GeV - final



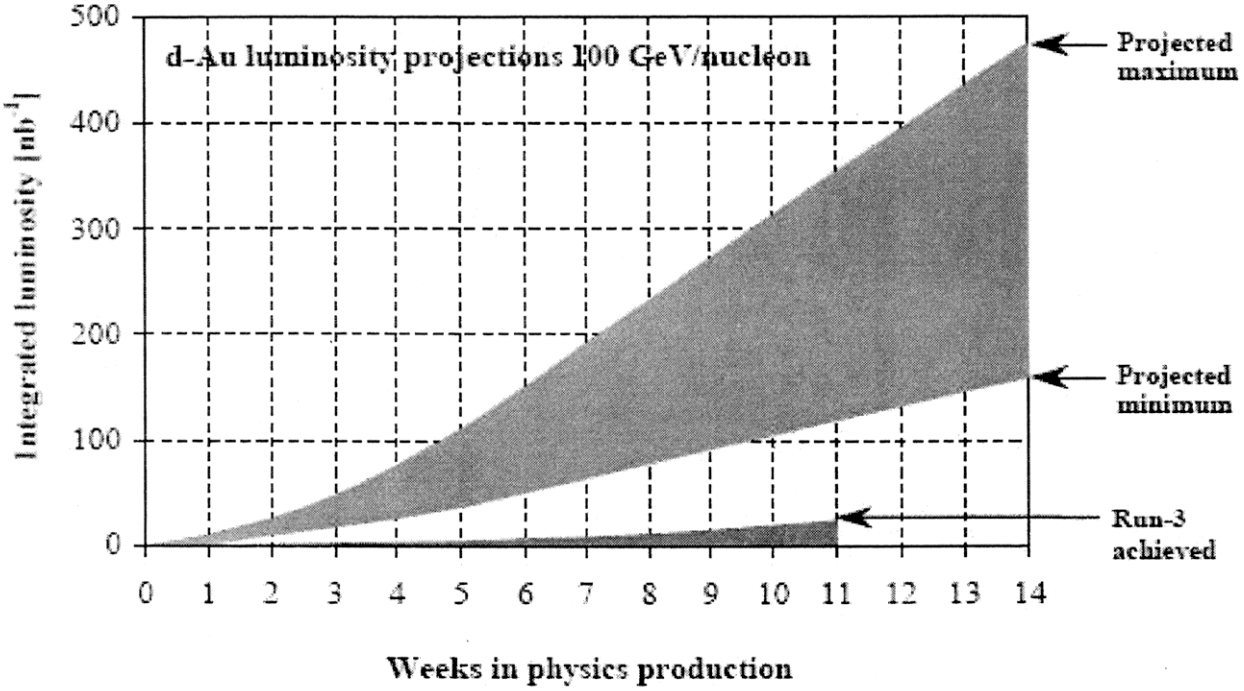


Figure 2: Projected minimum and maximum integrated luminosities for deuteron-gold collisions at 100 GeV/nucleon beam energy, assuming linear weekly luminosity ramp-up in 6 weeks.

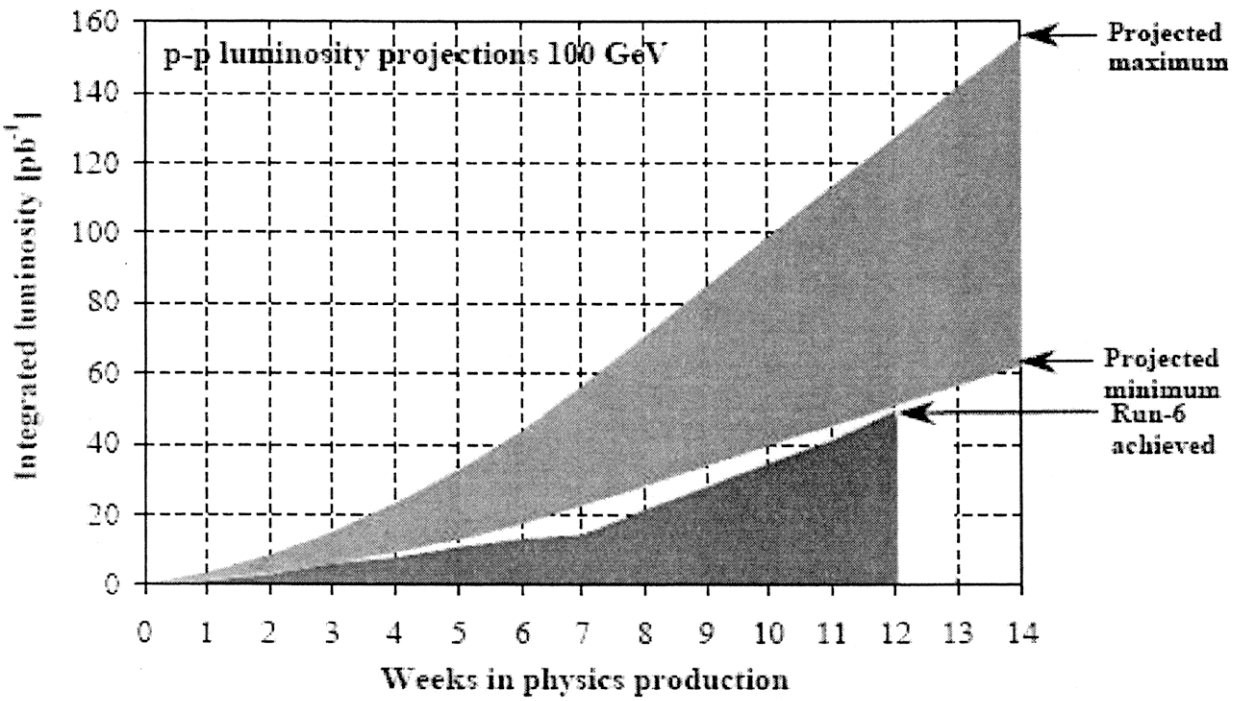


Figure 3: Projected minimum and maximum integrated luminosities for polarized proton collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 8 weeks. An average store polarization of 65% is expected.

RBRC

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

Theory Advisory Committee

- L. Mc Lerran (Chair)
- A. Baltz
- M. Creutz
- F. Karsch
- M. Gyulassy
- R. Pisarski

Experimental Advisory Committee

- A. Masaike
- K. Imai
- Y. Makdisi

QCDOC Advisory Committee

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

Personnel

Granted Tenure Since Last Meeting

Theory

S. Jean	Mc.Gill
S. Bass	Duke

Experiment

D. Fields	U. of New Mexico
M. Grosse Perdekamp	U. of Illinois

New Appointments (Fellows)

D. Molnar	Purdue	9/05
K. Tuchin	Iowa Sate	9/05
U. Wiedemann	Stony Brook 1/06 – 6/06 Tenure CERN	
S. Aoki	Tsukuba	8/06
Y. Aoki	BNL	8/06
R. Fries	Texas A&M	10/06
C. Lunardini	Arizona State	10/07
D. Teaney	Stony Brook	10/07
F. Yuan	LBNL	10/07

Graduates to Tenure Track Positions

C. Dawson	U. of Virginia
W. Xie	Purdue
T. Izibuchi	Kanizawa
K. Fukushima	Kyoto

New RBRC Postdocs

A. Mocsy	10/05
P. Liebing	1/06
C. Marquet	10/06
A. Lichtl	10/06
T. Ishikawa	10/06

Outstanding Junior Investigator Awards

RBRC

2000	D. Son
2001	M. Stephanov
2001	U. van Kolck
2002	T. Schaefer
2003	S. Bass
2005	T. Blum
2007	K. Orgenos (William & May) (RBRC/RA 10/2000 – 8/2003)
2007	D. Teaney Arkansas/Stony Brook (RBRC Fellow 10/7 – present)

Workshops

- Dec. 12-14, 2005
  Heavy Flavor Production and
  Hot/Dense Quark matter
  Akiba, Huang,
  Rapp, Tuchin, Xie

- Feb. 24-26, 2006
  Parton Orbital Momentum
  Bunce, Fields, Vogelsang
- March 9, 10, 2006
  Can we discover the QCD
  Critical Point at RHIC?

  Ludlam, Mc Lerran
- June 18-23, 2006
  RHIC Physics in the Context of the
  Standard Model

  Deshpande, Kharzeev,
  Venugopalan, Vogelsang

  RBRC Reunion

  Talks by RBRC Alumni, Present
  Staff, and other Distinguished
  Physicists

- July 31 – Aug. 2, 2006
  QCD in Extreme Conditions
  Datta, Pisarski, Petreczky, Schmidt
- March 15-17, 2007
  Domain Wall Fermions at Ten Years
  Blum, Soni

- Aug. 26-27, 2007
  Parity Violating Spin Asymmetry at RHIC-BNL
  Grosse Perdekamp, Surrow, Vogelsang
- Oct. 8, 2007
  Global Analysis of Polarized Partons Distributions in the RHIC Era
  Deshpande, Vogelsang
- Volumes 78-86
  Four Workshops in Planning Stage

- Oct. – Dec, 2006
  Joint Doctoral Training Program
  ECT and RBRC
  Trento, Italy

Other:

Publications:

Theory:	124
Experimental:	50

Seminars:

Weekly	
Tuesday	Spin
Wednesday	Joint RBRC/BNL-HE
Thursday	RBRC Lunch
	Presentation by RBRC Physicists
Friday	Joint RBRC/BNL-NP

Looking Ahead

Proton Spin: Complicated
ΔG, Angular Momentum
500 Gev, W'S
Hire 3-4 Physicists

Heavy Ions: d-A Colored Glass Condensate
AA Heavy Flavors
Direct Photons
Critical Point

RHIC II Higher Luminosity
Stochastic Cooling

eRHIC polarized cP
e A

Computing Utilizing: QCDOC
New York Blue
R&D Next Computer

RBRC Experimental Group Overview

RBRC Scientific Review Committee

5th Nov. 2007

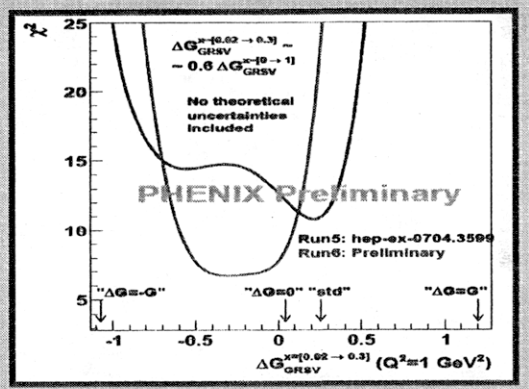
Hideto En'yo

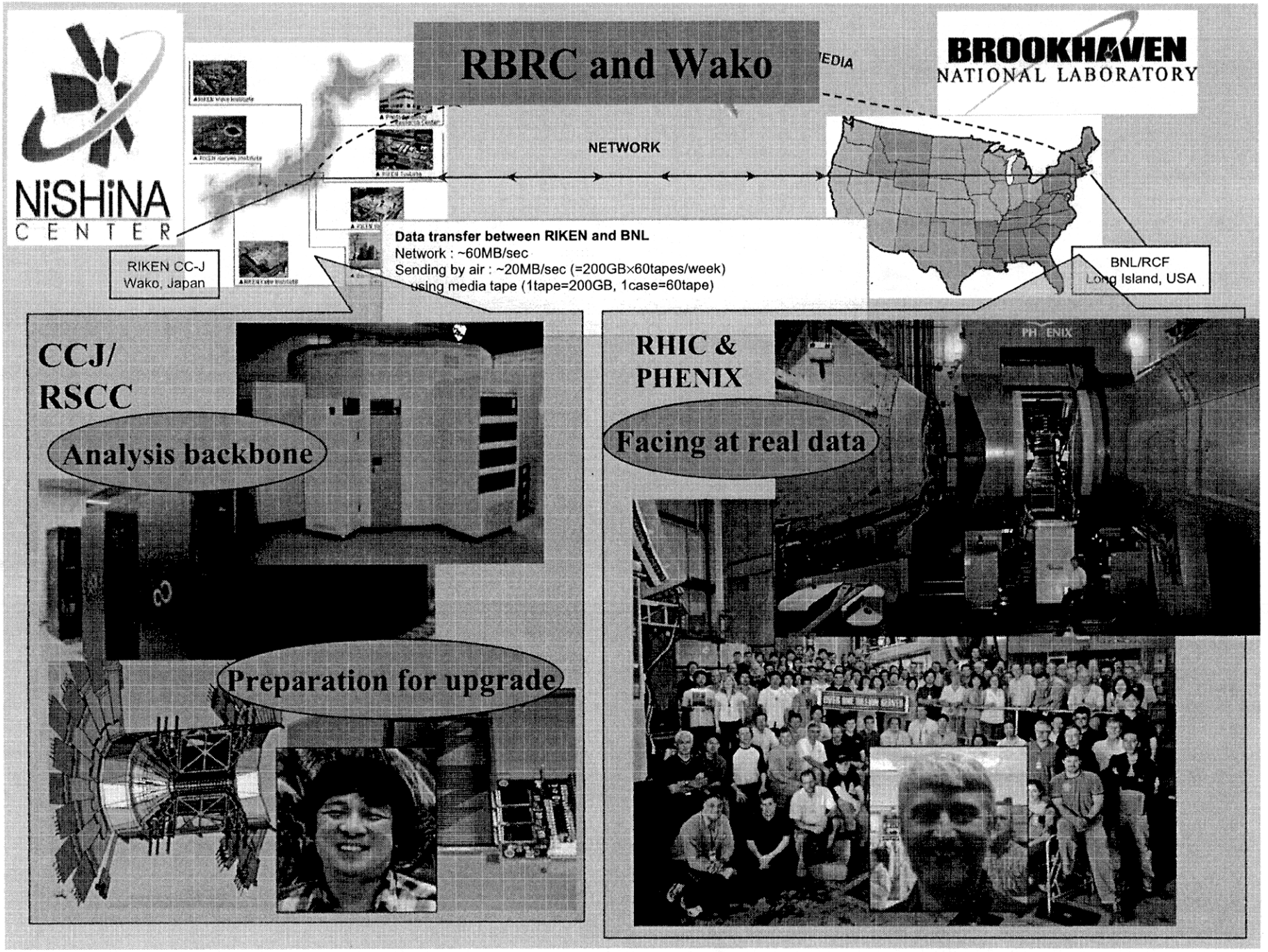
We are now in the 3rd MoU period

- Objective with the first stage of the RHIC spin program and the BNL-RIKEN collaboration
  - to prepare the tools to probe the spin structure of the proton at RHIC,
  - to make the first sensitive measurements of the gluon polarization in the proton.

  This objective has been accomplished.

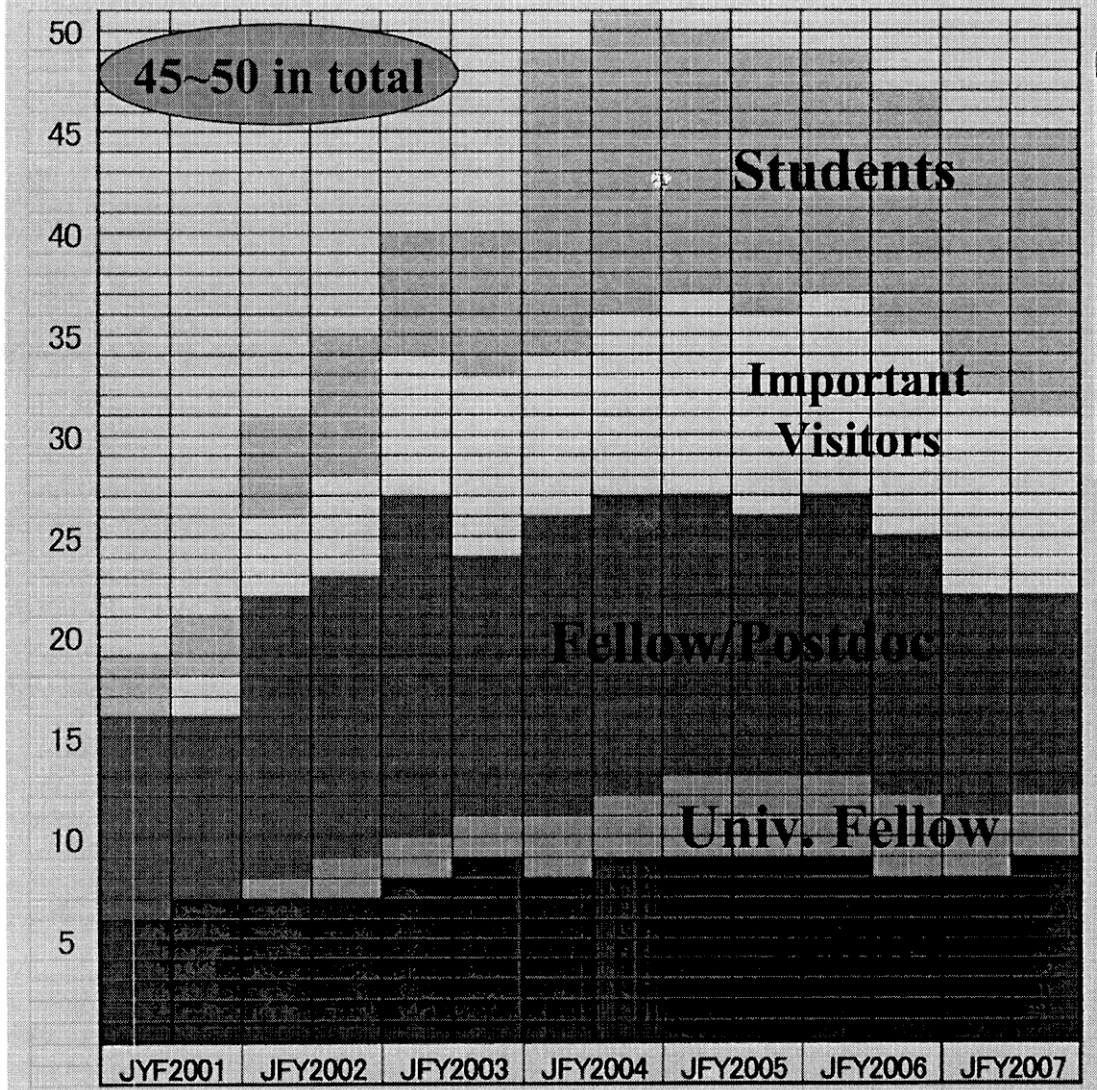
- This new MOU period we aim
  - to investigate the contribution of antiquarks to the proton spin,
  - to investigate the contribution from orbital angular momentum.
  - to perform precise measurements of the gluon polarization over a large range of gluon momenta in the proton.

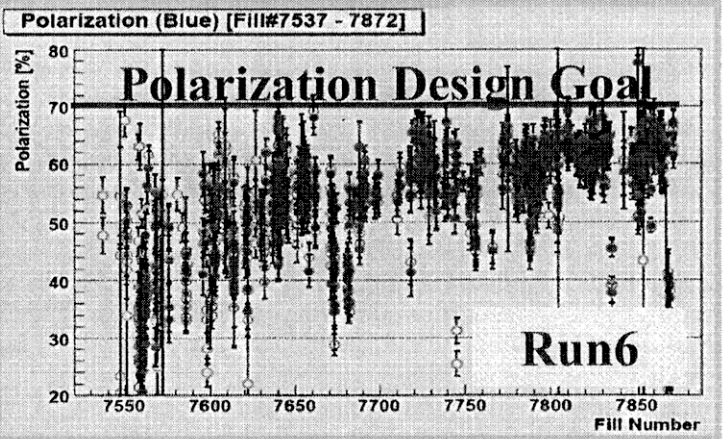


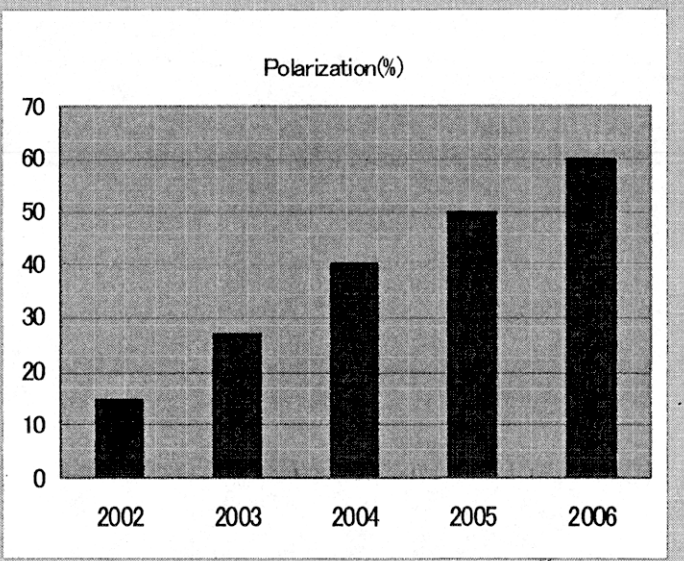

NiSHiNA
CENTER
RBRC and Wako
BROOKHAVEN
NATIONAL LABORATORY
NETWORK
Data transfer between RIKEN and BNL
Network : ~60MB/sec
Sending by air : ~20MB/sec (=200GB×60tapes/week)
using media tape (1tape=200GB, 1case=60tape)
RIKEN CC-J
Wako, Japan
BNL/RCF
Long Island, USA
CCJ/
RSCC
Analysis backbone
Preparation for upgrade
RHIC &
PHENIX
Facing at real data
PHENIX

B.Jacak (SUNY)
Spokes person
E.Obreien (BNL)
OP manager
RBRC in PHENIX
R.Seto(UCR), M.Perdecamp (RBRC),
Y.Akiba(RBRC/RIKEN)
Deputy Spokes persons
PHENIX Experiment
15 Nations, 60 Institutes
500 Physicists
Wako
RadiationLab

RHIC matured, We matured







the Bulletin

BROOKHAVEN NATIONAL LABORATORY

Vol. 58 - No. 11 April 2, 2004

AGS Beam P... Through ... Goal

50 percent p...

J. Takano
Built the Snake when he was Master Student,
Stayed Main Control Room for 2+ years as RIKEN JRA
Now in Tenure Post at KEK accelerator division

Get to Know Snakes, Polarized Protons

Snakes

Snake magnets get their name from the snake-like undulation of the beam as it travels through the helical, or twisting, form of the magnet. The original idea of snake

ing G... (AGS). Designed by Masahiro Okamura of RIKEN and Junpai Takano of the Tokyo Institute of Technology, and built by the Takano Original Magnet Company in Japan, the magnet's

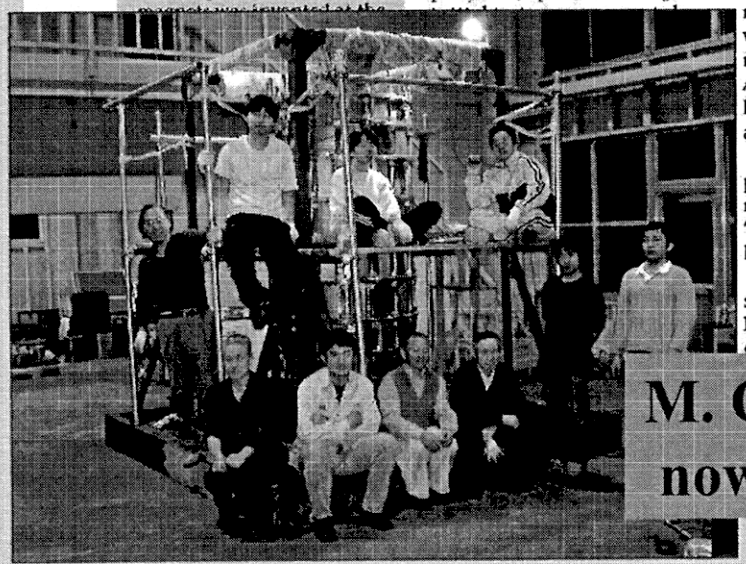
building the snake. The new helical snake was expected to minimize the depolarization from coupling resonances as the beam of polarized protons accelerated around the AGS ring before entering RHIC. It would replace the older solenoidal snake magnet in the AGS, which also promoted polarization, but had other disadvantages.

"Then, RIKEN designed and produced the final product in record time," said MacKay. "The magnet was delivered to BNL at the end of October."

The snake magnet was first set up in the Superconducting Magnet Division, where a detailed series of measurements

Roger Stadlenburgh DO98CB4

Pictured with the new warm helical Siberian snake magnet is Junpai Takano of the Tokyo Institute of Technology, who designed the magnet with Masahiro Okamura of RIKEN. Built by the Takano Original Magnet Company in Japan, the new snake was funded by RIKEN.



M. Okamura, supervising Takano
now BNL Physicist

...f the orbit, if
... AGS are not

...t well.
...ly, we have
...asurements

Postdoc/Fellows career path at RHIC
After the first contract with RIKEN

RIKEN	NOW	NAME	sum	Tenure%	
RBRC	TENURE & Tenure Track	M. Perdekamp	10	91% (76%)	81% (63%)
		A. Deshpande			
		D. E. Fields			
		A. Bazilevski			
		D. Kawall			
		M. Kaneta			
		O. Jinnnouchi			
		K. Kurita			
		Y. Gòto			
		X. Wei			
	Termed	K. Okada	1		
	Left	B. Fox	2		
		F. Messor			
Wako	TENURE	T. Kawabata	7	70% (50%)	
		J. Murata			
		H. Ohnishi			
		J. Tojo			
		T. Chujo			
		J. Hauser			
		S. Yokkaichi			
	Termed	H. Torii	3		
		A. Kiyomichi			
		H. Okada			
	Left	H. Kobayashi	4		
		T. Tabaru			
		K. Hasuko			
		J. Asai			
		H. Kano			

Fellow & Shared Post

How we are doing for doctor students at RBRC

Current Stuation	Names		Figure of Merit ?
Tenure Post	J.Tojo J.Takano	2	83%
Postdoc at RHIC	H.Torii, K.Fujiwara, N.Kamihara, M.Togawa, Y.Fukao, H.Okada	6	
Postdoc elsewhere	T.Horaguchi, T.Isobe	2	
Left Physics	H.Sato, T.Hachiya	2	
Still Student	K.Nakano, T.Sakashita. K.Aoki, K.Shoji, Karatsu, Dairaku, R.Han, Y.Tsuchimoto, M.Ouchida, F.Kajihara, Y.Yamaguhci, K.Miki	12	---

Where they are, What are they doing

Affliation	Type	Name	Spin			Heavy Ion			Upgrade/CCJ		
			BNL	Wako	Else	BNL	Wako	Else	BNL	Wako	Else
RBRC	Admin	H.Enyo		○							
		G.Bunce	○								
	Fellow	M.Perdecamo	○								
		A.Deshpande	○								
		D. Kawall	○								
		K.Okada	○								
	RA	P.Liebing	○								
	RSP	N.Saito			○						
		D.E.Fields			○						
	Visiting	A.Bazilevski	○								
	Researc	K.Kurita									
	her	A.Ogawa			○						
		Z.Li									
		K.Tanida			○						
		R.Seidl			○						
Wako	Tenure	T.Ichihara									
		Y.Watanabe									
		A.Taketani									
		Y.Goto	○								
		Y.Akiba				○			○		
		I. Nakagawa	○								
		S.Yokkaichi								○	
	RA	N.Kamihara		○							
		Y.Fukao		○							
		M.Togawa		○							
		Y.Onuki								○	
		S.Kametani								○	
		R.Ichimiya								○	
		K.Fujiwara								○	
		M.Kurosawa								○	
STUDENT	TIT	K.Nakano	○								
		T.Sakashita	○								
	Kyoto	K.Aoki	○								
		S.Kohei	○								
		Dairaku									○
		Karatsu									
	Hiroshim	M.Ouchida				○					
	TokyoU	F.Kajihara				○					
		Y.Yamaguchi				○					
	Rikkyo	Kasai								○	
		Kawashima									
	Tsukuba	K. Miki				○					
TOTAL		41	22			5			16		

22 in BNL
16 in Wako
7 in Elsewhere

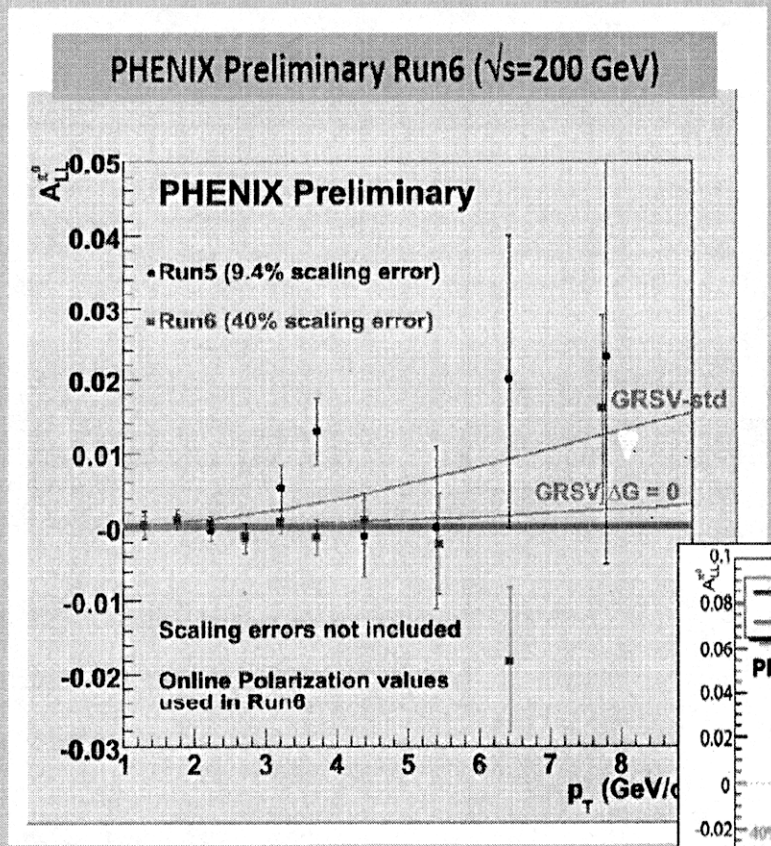
BNL	Wako	Else	Total
19	16	7	42

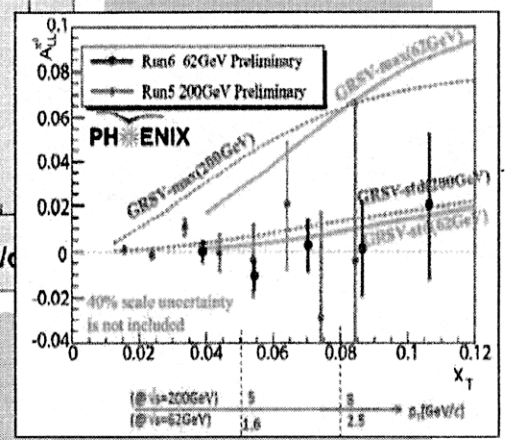
Recent Movements (RBRC-exp & Wako)

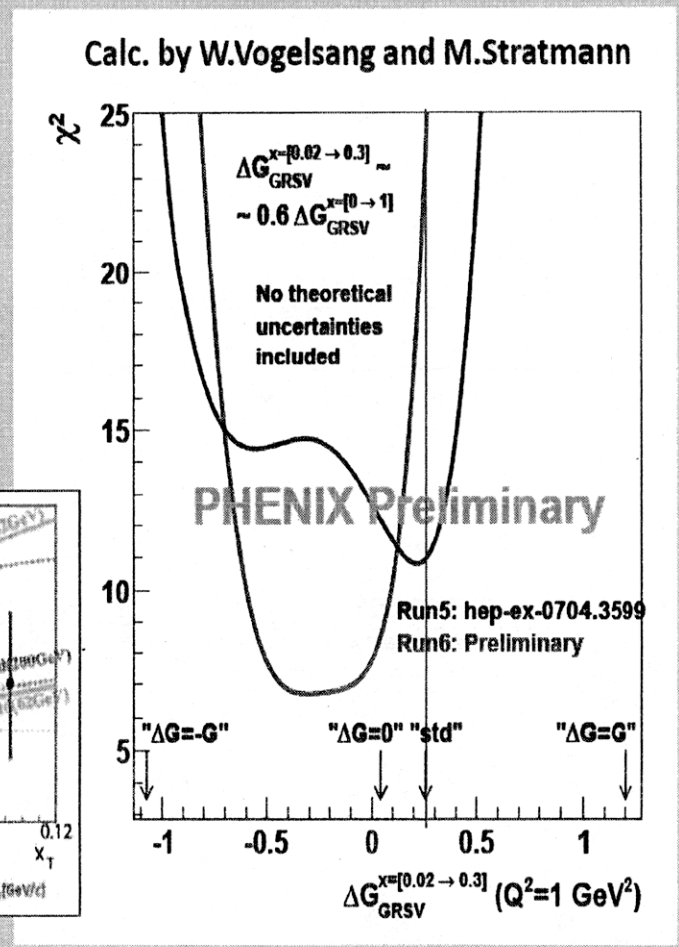
- **Masahiro Okamura moved to BNL-CAD in August '06 (Head hunt)**
- **Kiyoshi Tanida Moved to Kyoto-U in March '06 (tenure to tenure)**
- **X. Wei left (Fellow to tenure track post)**
- **M. Perdekamp (to tenure post)**
- **Vladimir Rykov moved to Wayne State Univ. '06 (retire)**
- **Hisa Torii moved to Hiroshima-U in March '06 (postdoc to postdoc)**
- **Junji Tojo moved to KEK in March '06 (postdoc to tenure)**
- **Takuma Horaguchi moved to CNS-U-Tokyo (student to postdoc)**

- **New RA in RBRC, Patricia Liebing (but leaving soon)**
- **New Fellow Kensuke Okada (from RA, promoted)**
- **Yoshi Fukao became Special doctoral fellow in April '06 (student to postdoc)**
- **Manabu Togawa became Special doctoral fellow in April '07 (student to postdoc)**
- **Hiromi Okada became RIKEN postdoc in April '06 (students to postdoc)**
  - **Then moved to BNL Postdoc (STAR!!)**
  - **Awarded for "RHIC/AGS Thesis Award"**
- **Ryo Ichimiya join us in April '06 (students to postdoc)**
- **Maki Kurosawa join us in April '06 (students to postdoc)**
- **New JRA Students, Y. Yamaguchi (U. Tokyo), M. Ouchida (Hiroshima U), K. Miki (Tsukuba U)**

Spin Crisis Again ?







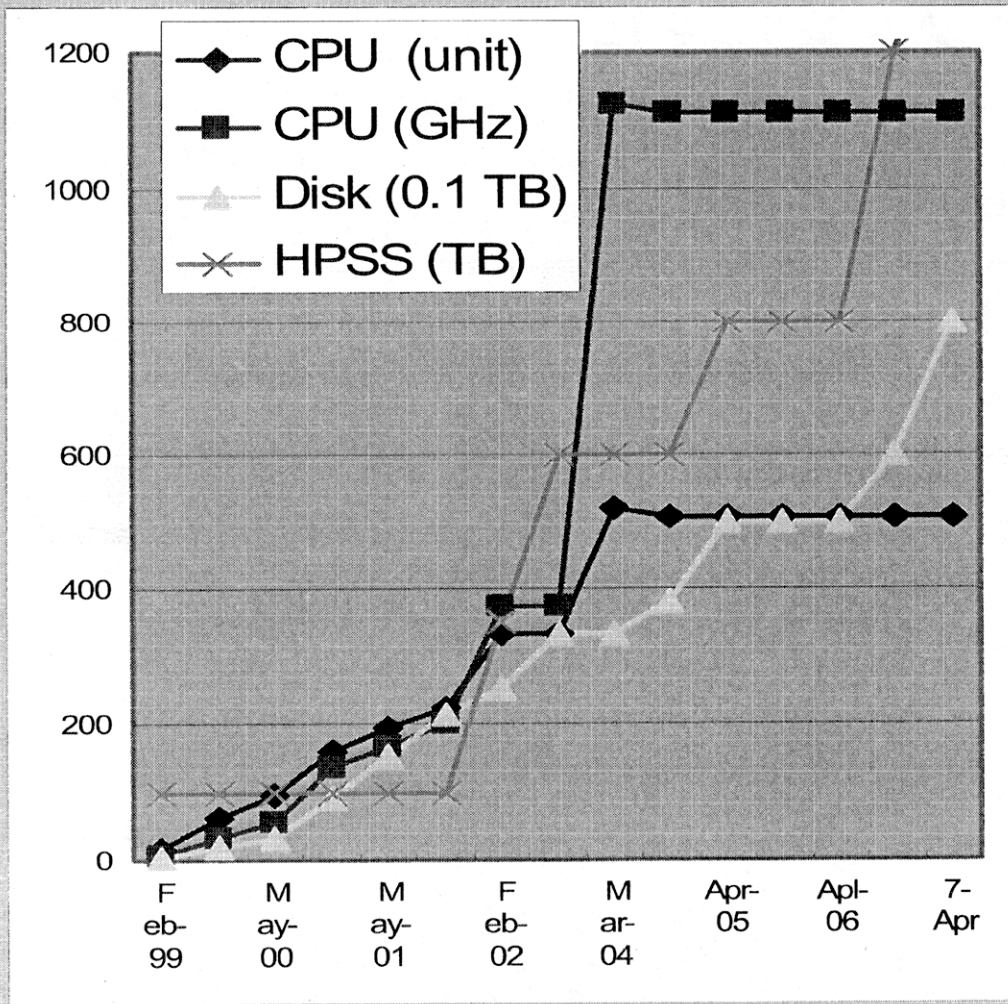
Abhay Deshpande—
Gluon's spin in the proton:
Recent results from PHENIX and the path forward

Activities along the scope for coming years, and presentations prepared

Physics	Observable	New Tools		Comments
anti-quark polarization flavor separated	W boson @500GeV	Muon trigger upgrade I. Nakagawa (2008/2009)	Nose Cone Calorimeter	World New Measurements
Precise ΔG	π, γ heavy quarks K.Okada P. Liebing	Vertex detector A. Taketani (2007/8) D. Kawall	Nose Cone Calorimeter	$\Delta G(x)$ mapped out x range expanded γ+Jet
angular momentum (or Transversity)	A_N (LR asym.) M.Perdecamp Fwd neutron Y. Goto Jet k_T	Any Muon Piston Calorimeter	Nose Cone Calorimeter	Discovery of finite Collins function (Belle). Theoretical help needed.

Wei Xie—PHENIX Reaction Plane Detector and its Physics Input
Yasuyuki Akiba—Heavy Ion Physics at PHENIX

Cooperation of CCJ with Riken Super Combined Cluster (RSCC)



Analyses

- **Run-6 raw data transfer(~300TByte)**
- **Run-5/6 DST production @ RSCC**
- **Physics Analysis for Year-2/3/4/5 experiments @ CCJ**
  - **New 6 large physics analysis project started**

Management

- **HPSS (tape storage system) used 1.2 PByte**
  - **Added new tapes (0.2PByte), Total 1.4PB**
  - **Installed new tape drive**
  - **The total capacity became possible to increase up to 3PByte**
- **RAID (hard disk drive) used 40TByte out of 80TB**

Plan for coming years

JFY	Spin Weeks	CME (GeV)	Pol.	Integrated. Luminosity	Remarks
2007	0				No spin run due to unfortunate budget problem
2008	10	200	0.7	88pb^{-1}	Direct gamma May start 500 GeV run
2009	10	200	0.7	106pb^{-1}	Direct gamma with new vertex detector
2010	5 5	200 500	0.7 0.7	35pb^{-1} 180pb^{-1}	Complete 200GeV program Muon trigger upgrade completed
2011	10	500	0.7	266pb^{-1}	Nose cone calorimeter completed *W* physics (direct gamma continues)
2012	10	500	0.7	266pb^{-1}	*W* physics
2013	10	500	0.7	266pb^{-1}	Complete 500GeV program

This MoU

Theoretical Physics at RIKEN-BNL Center

Strong Interactions and QCD

How are strongly interacting particles made from fundamental constituents?

How do fundamental interactions of QCD produce mass and confinement?

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

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

All issues intertwined!
Require understanding and computation.

Current Interests in RIKEN-BNL Center

Lattice Gauge Theory

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

Structure of Hadrons

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

Color Glass Condensate and Quark Gluon Plasma

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

Accomplishments and Goals of Lattice Gauge Theory at RBRC

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

The weak interactions in strongly interacting particles

CP violation in kaon decays

Spectra of exotic hadronic states, such as pentaquark

Low energy matrix elements

QCD Thermodynamics

Accomplishments and Goals in Study of Spin and Perturbative QCD

Achievements:

Developed GRSV Spin Structure Functions

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

Used GRSV for analysis at RHIC

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

QCD soft gluon resummations

Single spin asymmetries in DIS and polarized pp

Goals

Extract gluon spin from RHIC experiments

Understand hard processes in larger program

Accomplishments and Goals in Study of High Energy Density Matter

Accomplishments:

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

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

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

Goals:

Turn study of high energy density matter into a precise science

Understand from first principles in QCD, the high energy limit

Why is BNL a Good Place to Study QCD?

RHIC
QCDOC

Strong theory groups:
BNL, Columbia, Stony Brook

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

Supportive atmosphere for young people

Relations

QCDOC and Lattice Gauge Theory

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

Spin and pQCD

Vogelsang was RBRC
Larry Trueman in HEP

RHIC Physics

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

RBRC-BNL University Fellows Program (Theory)

University pays 1/2 of academic year salary

University selects candidates

Must be approved by Theory Advisory Committee

Current Theory Fellows:

S. Aoki (Tsukuba)

Y. Aoki, (BNL)

T. Blum, Connecticut

T. Izubuchi (Kanazawa)

R. Fries, Texas A&M

D. Molnar, Purdue

P. Petreczky, BNL

K. Tuchin, Iowa State

New Theory Fellows:

C. Lunardini, Arizona State

D. Teaney, Stony Brook

F. Yuan, LBNL

Tenured Graduates:

S. Bass, Duke

D. Bodeker, Bielefeld

K. Iida, Kochi

S. Jeon, McGill

D. Kharzeev, BNL

A. Kusenko, UCLA

D. Rischke, Frankfurt

S. Sasaki, Tokyo

T. Schaefer, N. Carolina

M. Stephanov, Illinois

D. Son, Washington

R. Venugopalan, BNL

U. Van Kolck, Arizona

W. Vogelsang, BNL

U. Weidemann, CERN

T. Wettig, Regensburg

09

Workshops:

Broad based coverage of topics related to areas of interest.

Must have an RBRC members as one of the proposers

Spin and Pert. QCD 39

Lattice and Computing 11

Quark Gluon Plasma 8

High Energy QCD 2

Jets and Hard Processes at RHIC 4

Flow, Hydrodynamics and Event Simulation 4

Hadron Physics and QCD 4

Color Glass Condensate 3

New Discoveries at RHIC 1

RBRC Theory Postdocs who have received faculty Faculty Jobs:

Recent Examples:

K. Itakura (KEK) (CGC)

T. Hirano (Tokyo) (RHIC Phenomenology)

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

Yoshi Hatta (Tsukuba*) (CGC)

S. Sasaki (Tokyo U.) (Lattice)

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

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

C. Orginos (William and Mary) (Lattice)

M. Wingate (Cambridge) (Lattice)

Theory Presentations

Nuclear force from lattice QCD

Sinya Aoki
RBRC Fellow
Riken BNL Research Center and University of Tsukuba

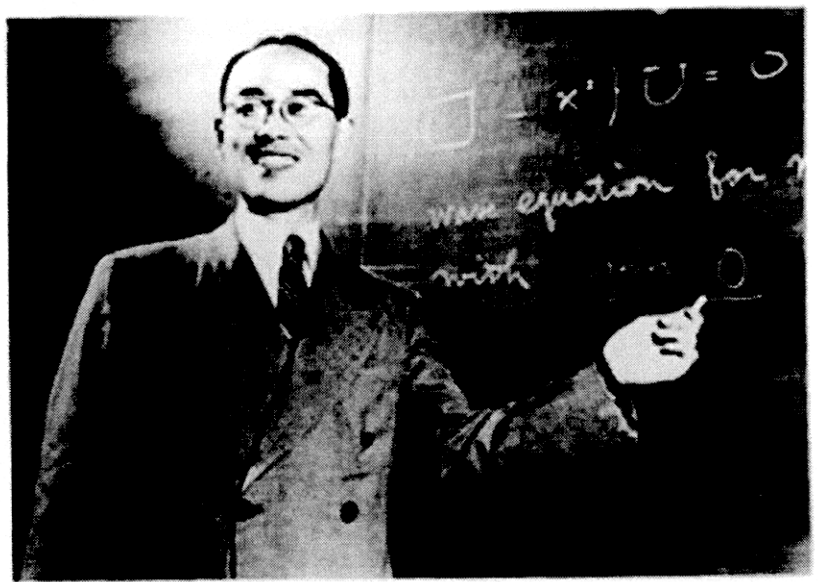
Based on the work in collaboration with
N. Ishii and T. Hatsuda
Phys.Rev.Lett. 90(2007)0022001

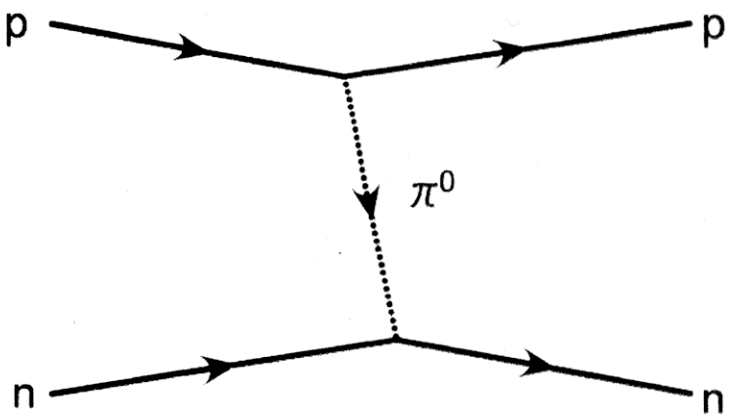
Force between Nucleons(The nuclear force)

1935 H. Yukawa

The nuclear force ⇔ exchange of virtual particles between nucleons

mesons



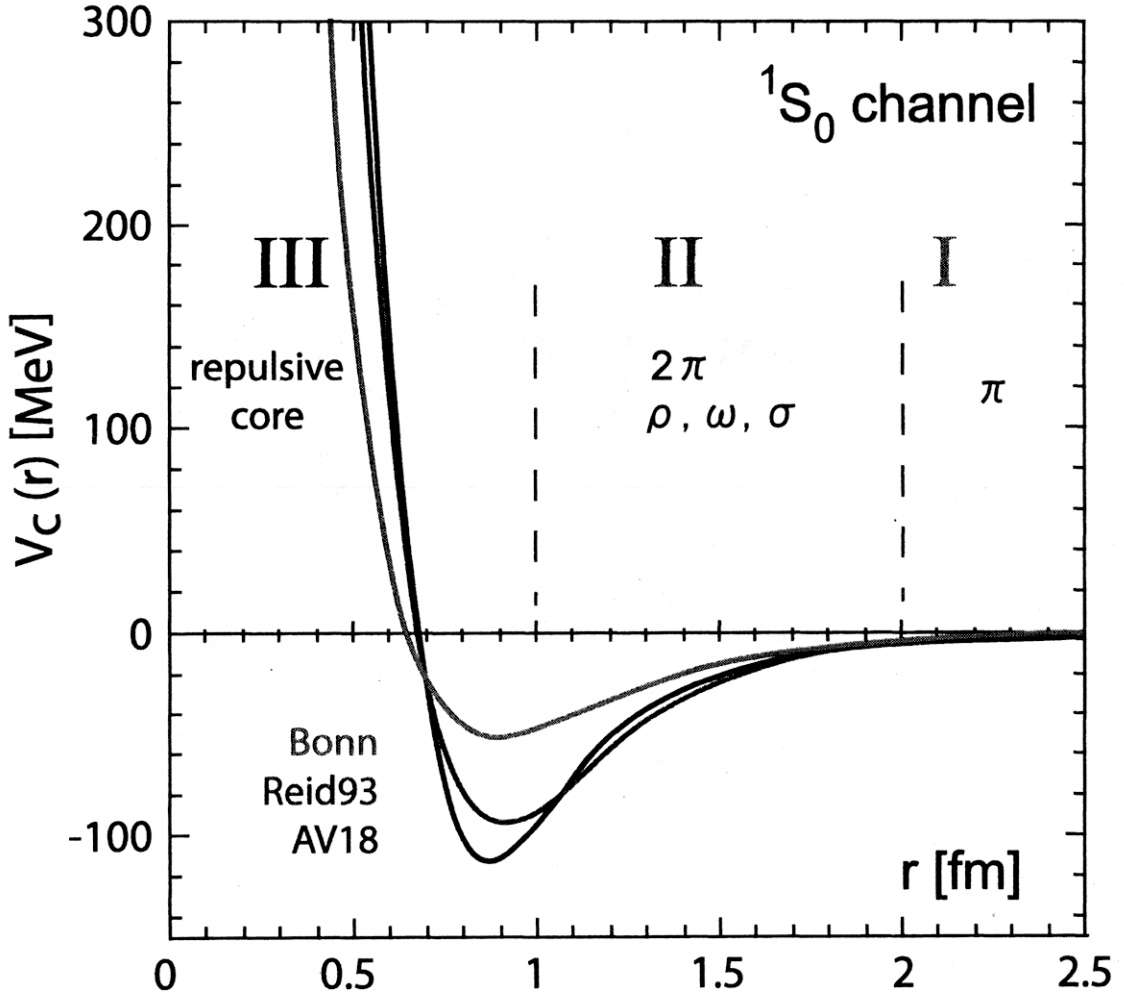


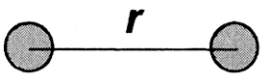
Yukawa potential

$$( ) = \frac{2}{4\pi} \frac{-m_\pi r}{\qquad}$$

1949 Nobel prize

Modern nucleon-nucleon potential





I Long range part

one pion exchange potential (OPEP)

II Medium range part

σ, ρ, ω exchange

2π exchange

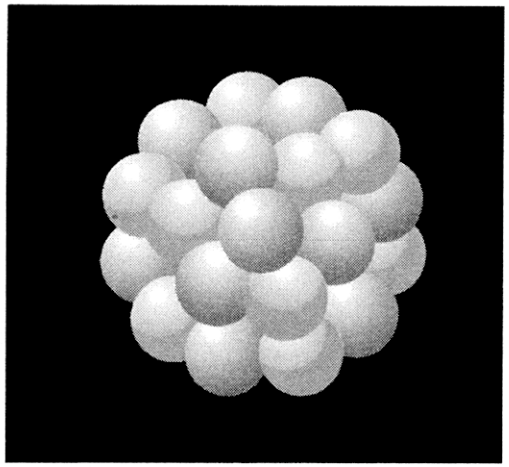
III Short range part

repulsive core (RC)
quark ?

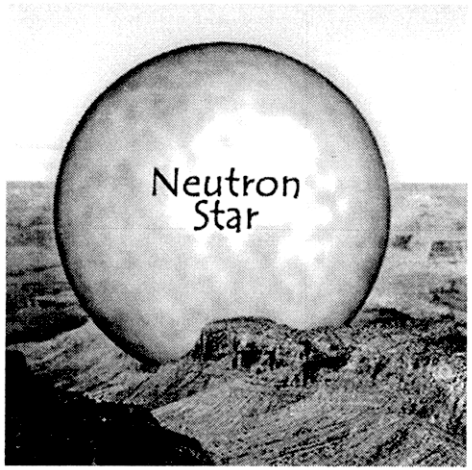
Bonn: Machleidt, Phys.Rev. C63('01)024001
Reid93: Stoks et al., Phys. Rev. C49('94)2950.
AV18: Wiringa et al., Phys.Rev. C51('95) 38.

Importance of repulsive core

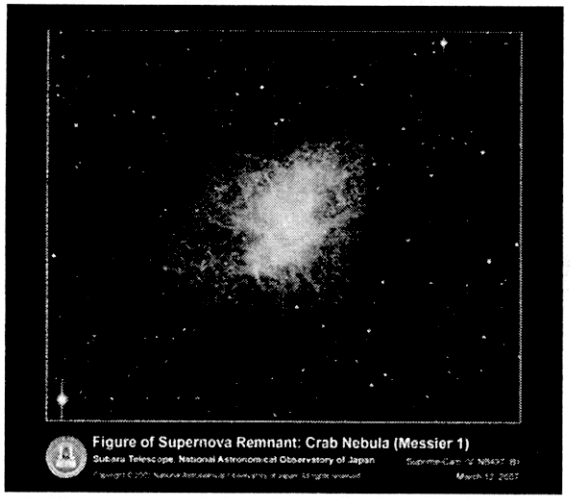
stability of nuclei



neutron star

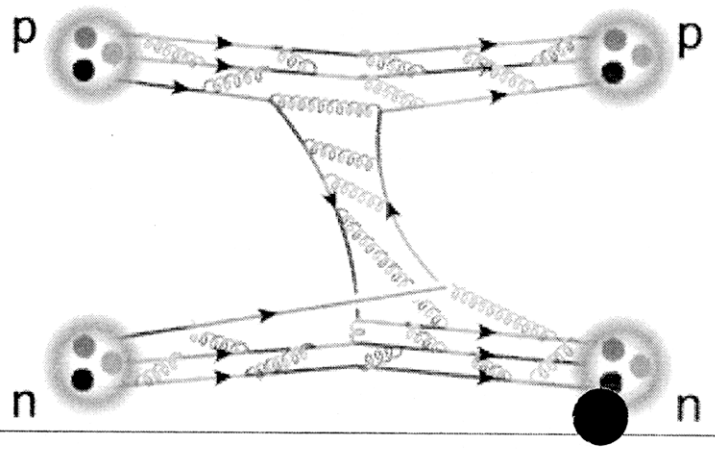


supernova explosion



Origin of RC: “The most fundamental problem in Nuclear physics.”

Lattice QCD can explain ?



Our strategy

1. define and calculate "wave function" $\varphi_E(\mathbf{x})$ with energy

2. define a potential through Scrödinger equation

$$[\quad_0 + \quad(\mathbf{x})]\varphi_E(\mathbf{x}) = \quad \varphi_E(\mathbf{x}) \qquad H_0 = \frac{-\nabla^2}{2\mu}$$

reduced mass

3. extract a potential as

$$(\mathbf{x}) = \frac{(\quad - \quad_0)\varphi_E(\mathbf{x})}{\varphi_E(\mathbf{x})}$$

Simulation details

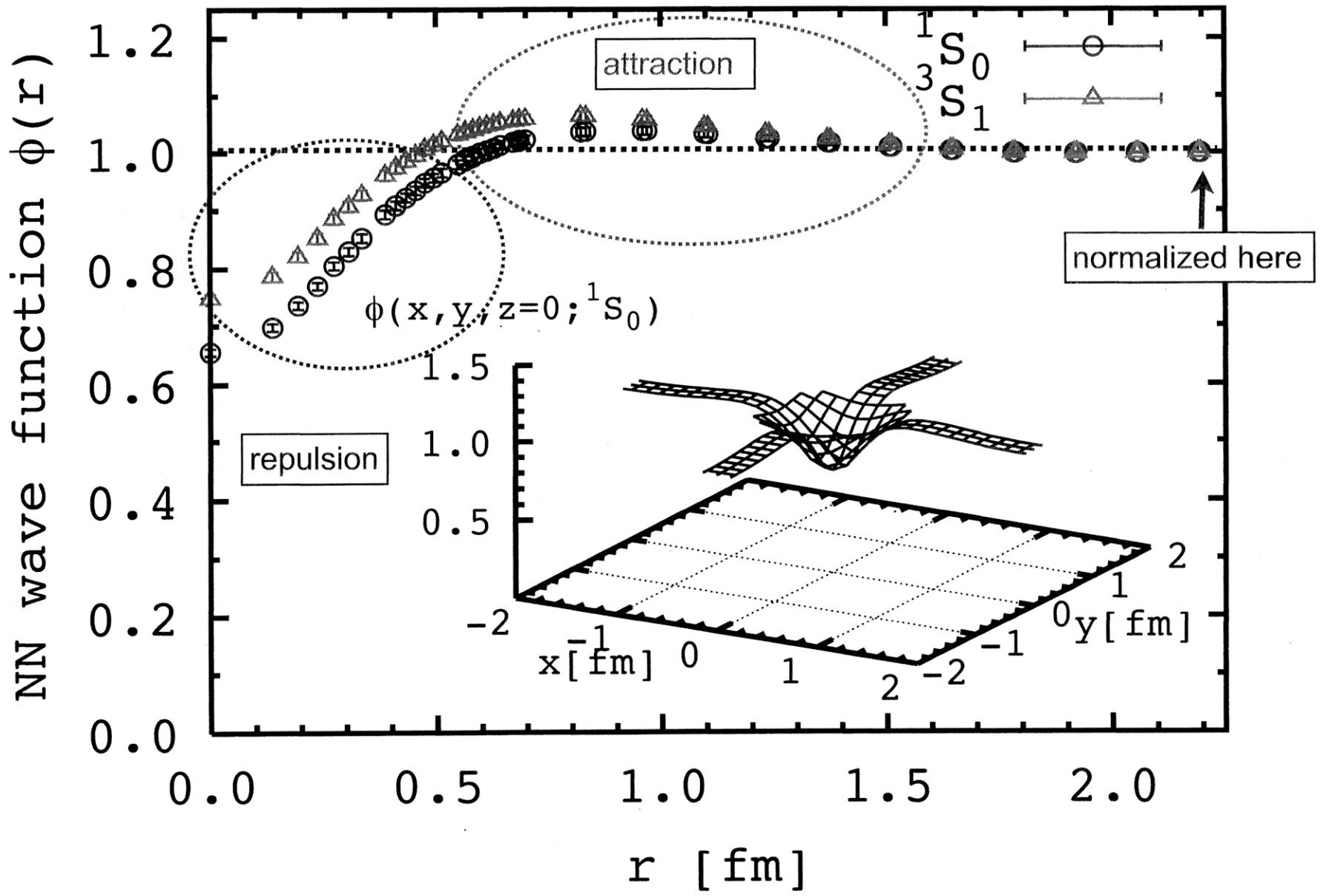
- plaquette gauge action at β=5.7(quenched) on 32^4 lattice
  - a=0.137 fm from ρ meson mass ⇒ physical size: $(4.4\ \mathrm{fm})^4$
- Wilson quark action
  - 3 quark masses $m_\pi = 370\ \mathrm{MeV}(2000\ \mathrm{conf}),\ m_\pi = 527\ \mathrm{MeV}\ (2000\ \mathrm{conf})$
    $m_\pi = 732\ \mathrm{MeV}(1000\ \mathrm{conf})$
- Blue Gene/L @ KEK (57.3TFlops peak)

Singlet (S=0) $^1S_0$ Triplet (S=1) $^3S_1$

NN wave function

$m_\pi \simeq 0.53$ Ge

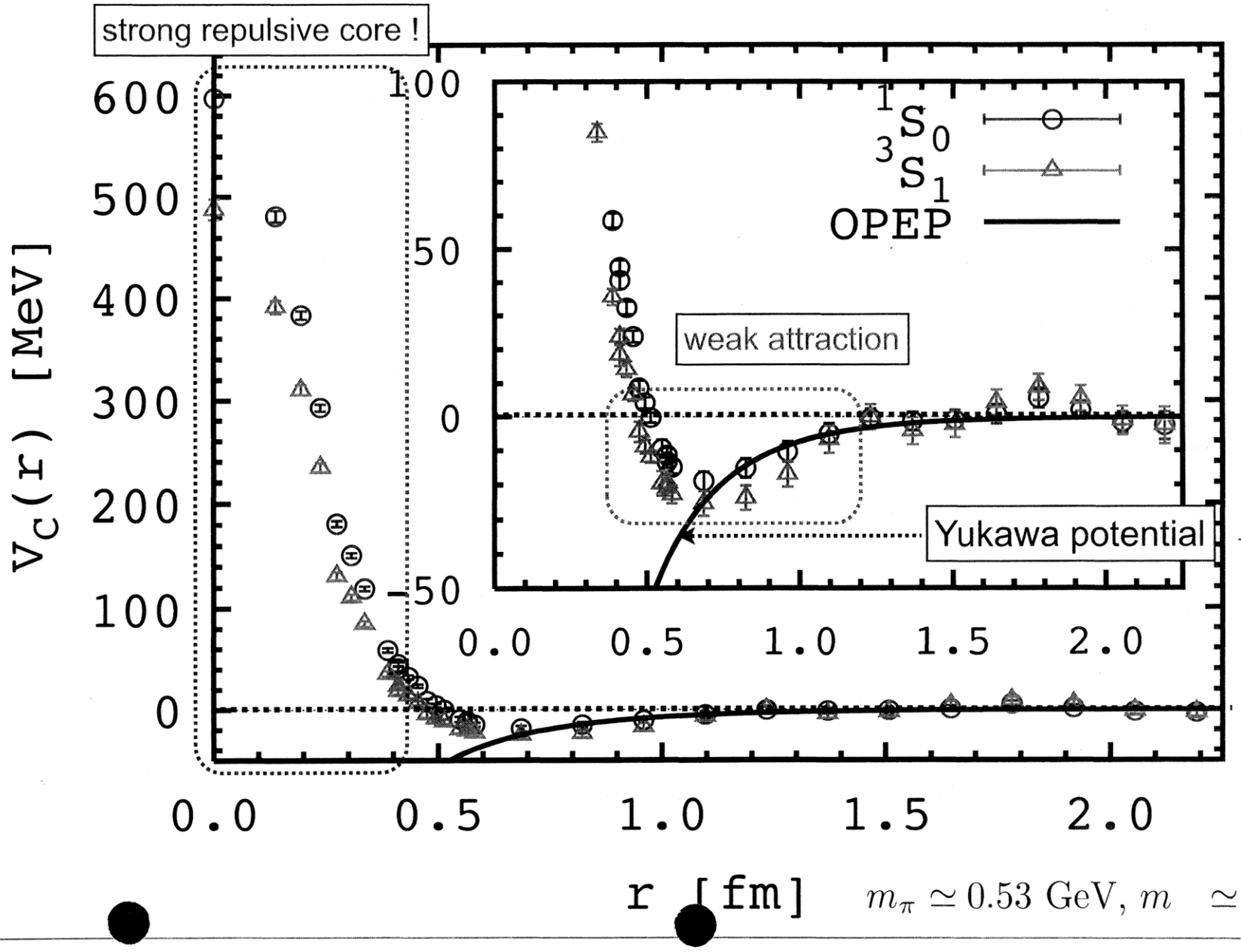
$t - t_s = 6$



NN (effective) central potentials

$m_\pi \simeq 0.53$ GeV

$t - t_s = 6$

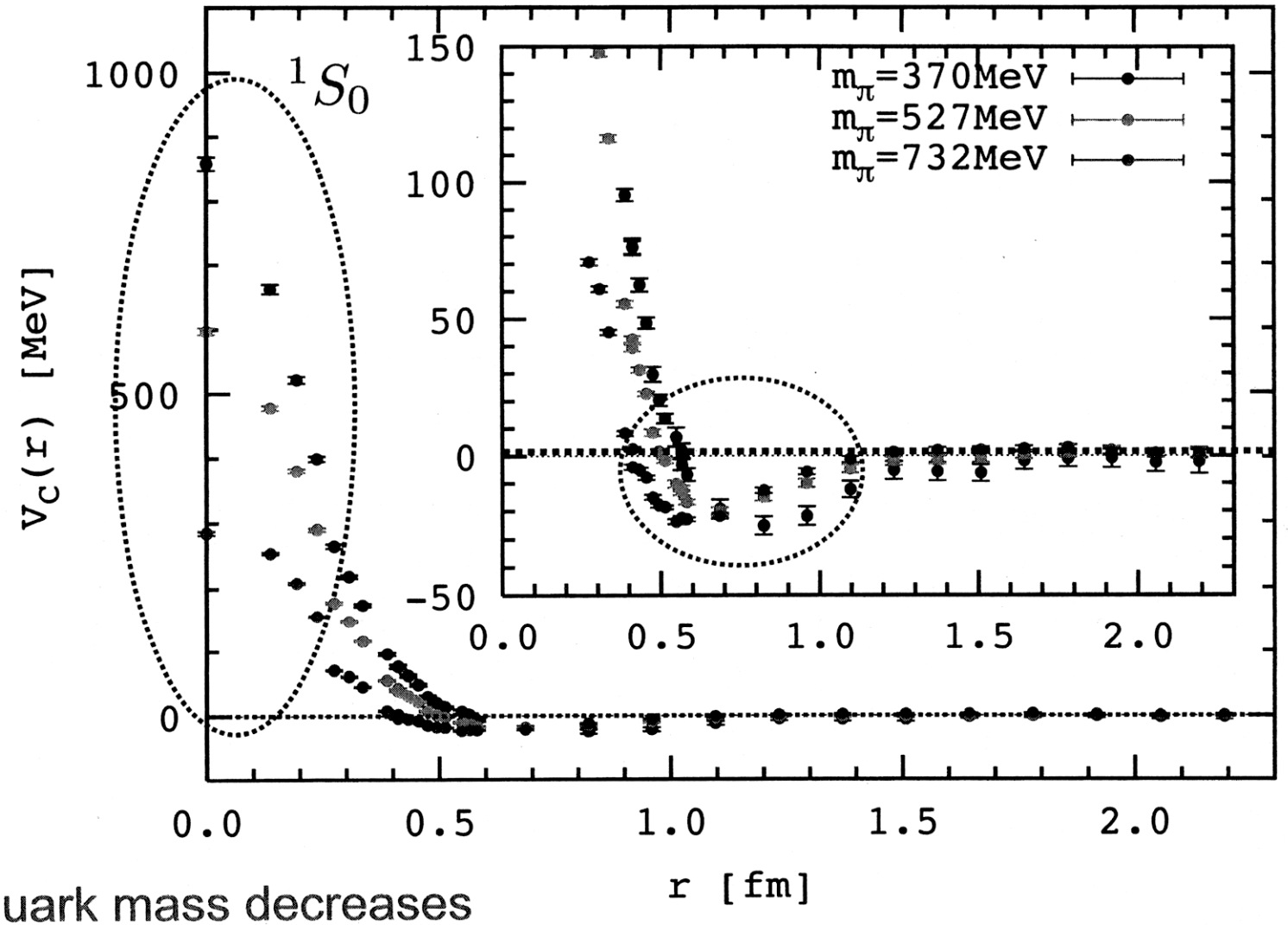


$\frac{2}{\frac{\pi}{4\pi}} \simeq 14.0$

$m_\pi \simeq 0.53$ GeV, $m \simeq 1.34$ GeV

Quark mass dependence

Preliminary



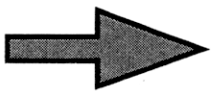
as quark mass decreases

stronger repulsive core at short distance

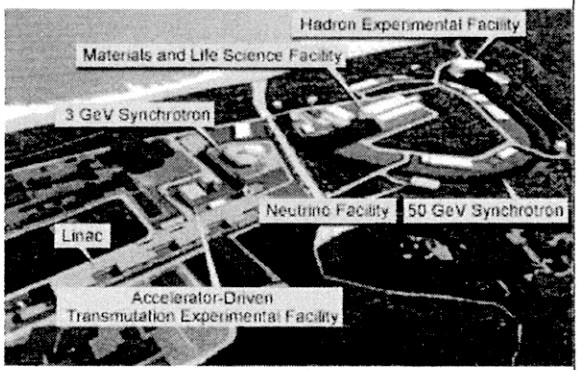
a little stronger attraction at intermediate distance

Application: Hyperon-Nucleon(Hyperon) interaction

Almost no information from experiments

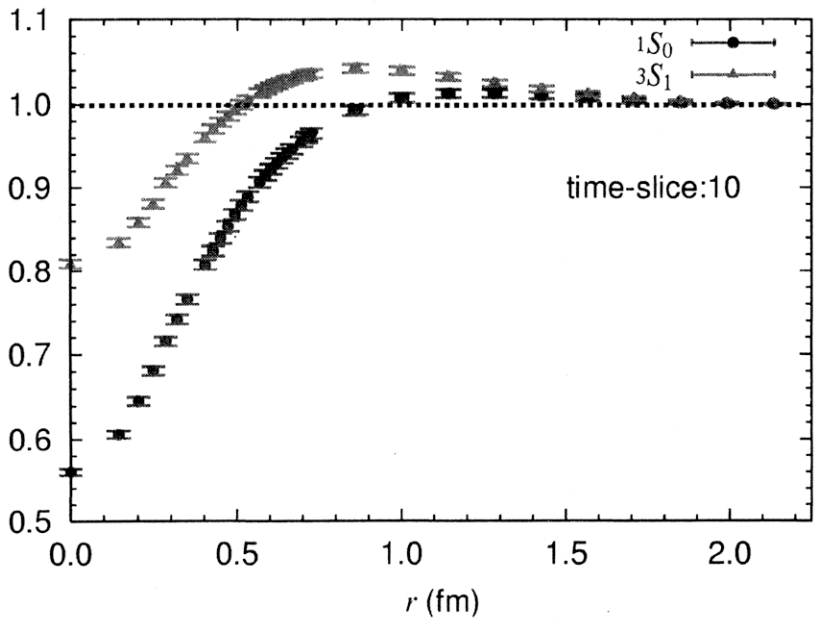


J-PARC

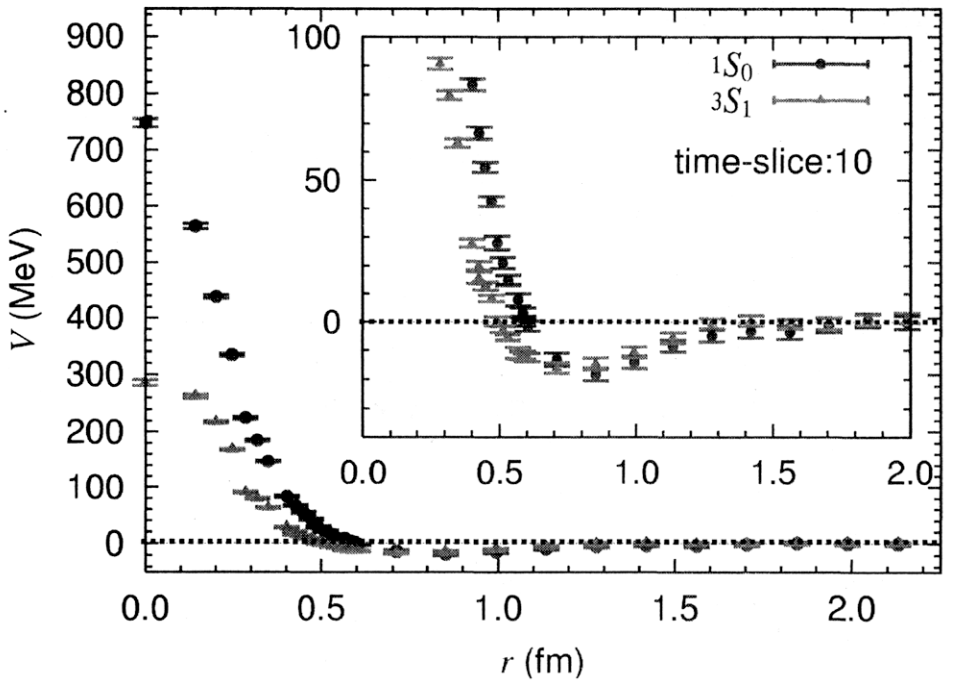


I N Ξ

Nemura, Ishii, Aoki, Hatsuda



Wave function



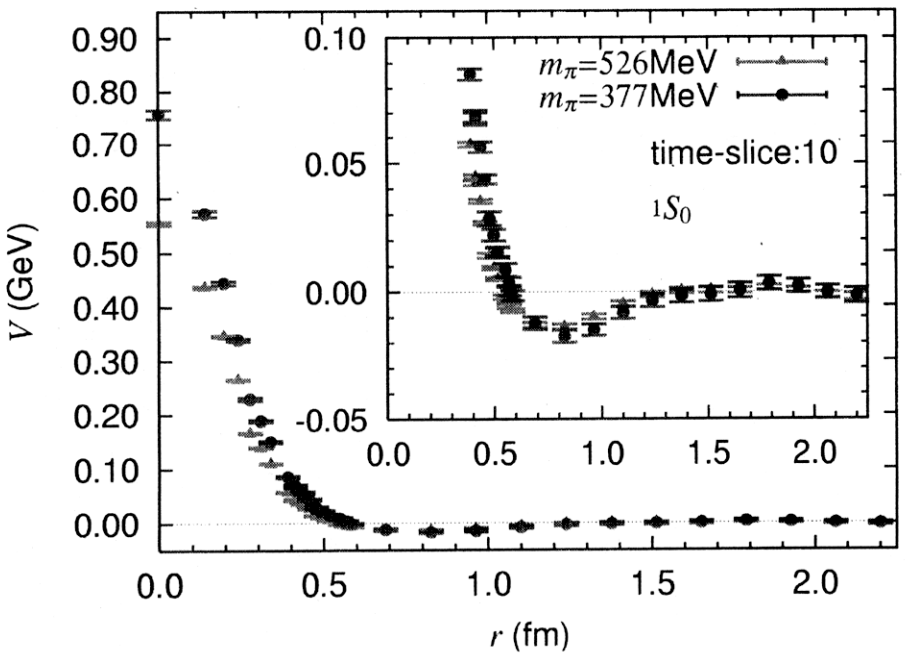
"potential"

Quark mass dependence

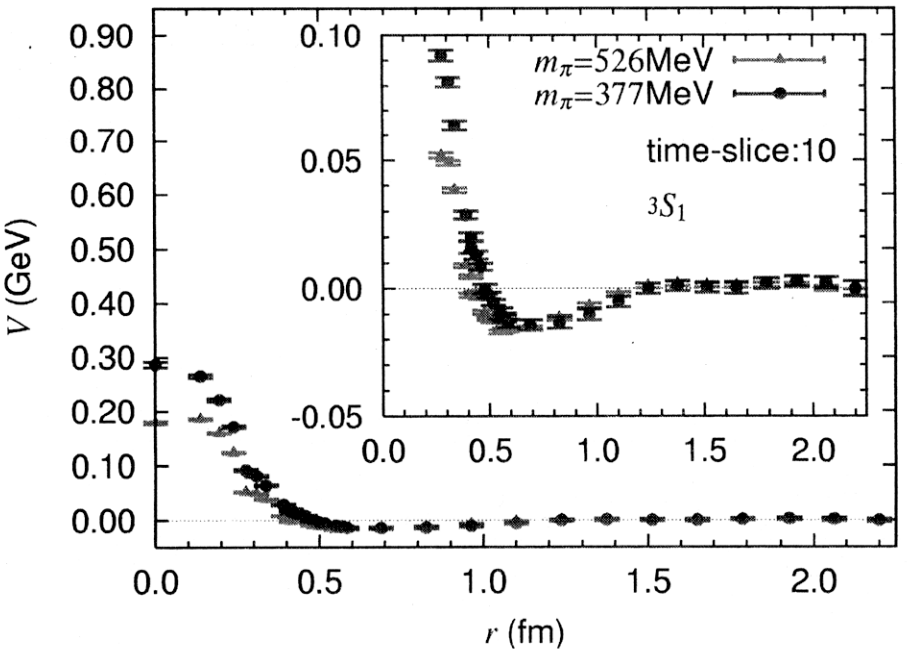
Preliminary

I N Ξ

$^1S_0$



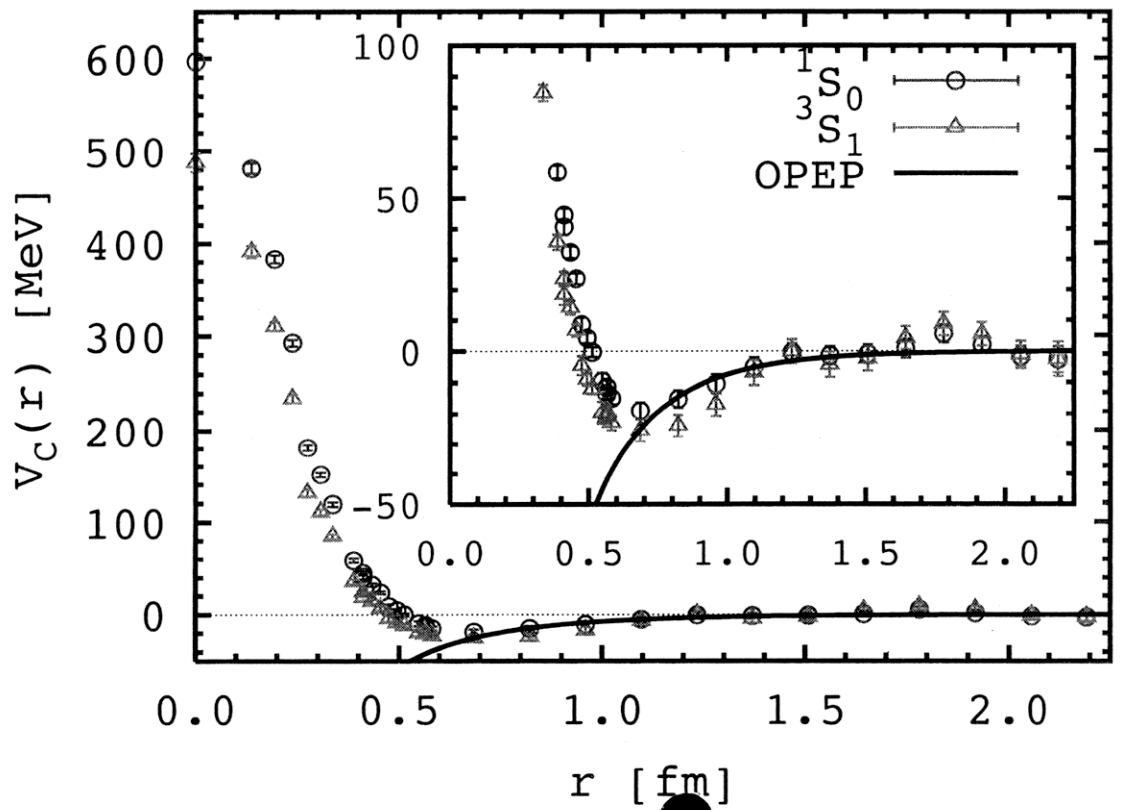
$^3S_1$



Of course, we will have to do

- chiral extrapolation
- continuum extrapolation
- full QCD

New era of nuclear physics using lattice QCD now begins !



Nucleon structure with $N_f = 2 + 1$ dynamical domain-wall fermions

Shigemi Ohta *†‡ [RBC and UKQCD DWF intercollaboration]

RIKEN-BNL Research Center Scientific Review, November 5, 2007

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

- $24^3 \times 64 \times 16$, $16^3 \times 32 \times 16$,
- Iwasaki gauge action, $\beta = 2.13$,
- Domain-Wall Fermions (DWF) quarks, $M_5 = 1.8$,
- $m_{\text{strange}} a = 0.04$, $m_{\text{ud}} a = 0.03$, 0.02, 0.01 and 0.005,

Here we report isovector form factors and some lowest moments of nucleon structure functions: these are calculated by Takeshi Yamazaki, Huey-Wen Lin, Shoichi Sasaki, Tom Blum, ...

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

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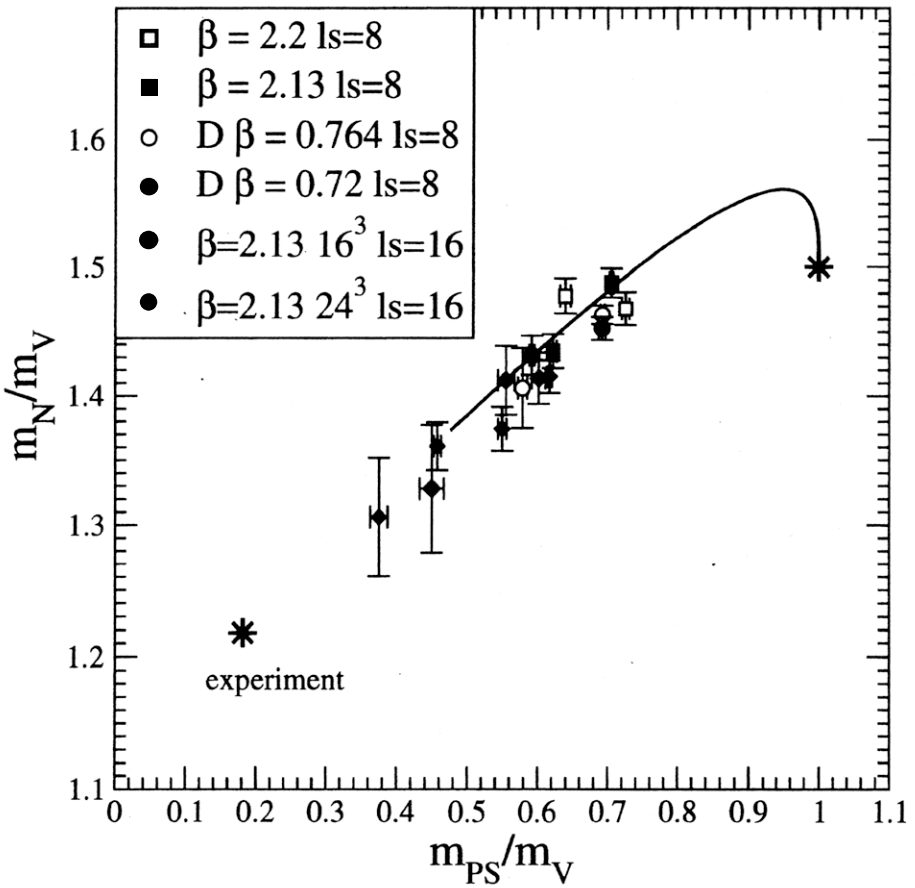
†Physics Department, Sokendai Graduate University of Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan
‡RIKEN BNL Research Center, Upton, NY 11973, USA

Residual mass $m_{\text{residual}}a = 0.00315(2)$. From Ω^- and K masses we estimate

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



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

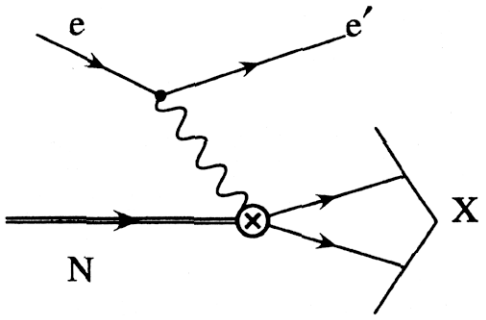
The isovector form factors are defined in the following:

$$\begin{aligned}\langle p|V_\mu(0)|p\rangle &= \overline{u}_p\left[\gamma_\mu F_1(q^2)+\sigma_{\mu\nu}q_\nu F_2(q^2)/2m_N\right]u_p,\\ \langle p|A_\mu(0)|p\rangle &= \overline{u}_p\left[\gamma_\mu\gamma_5 G_A(q^2)+iq_\mu\gamma_5 G_P(q^2)\right]u_p,\end{aligned}$$

where $V_\mu=\overline{u}\gamma_\mu u-\overline{d}\gamma_\mu d$ and $A_\mu=\overline{u}\gamma_\mu\gamma_5 u-\overline{d}\gamma_\mu\gamma_5 d$ are isovector vector and axial vector currents.

Nucleon structure functions are measured in deep inelastic scatterings (and RHIC/Spin):

- DIS



$$\left|\frac{\mathcal{A}}{4\pi}\right|^2=\frac{\alpha^2}{Q^4}l^{\mu\nu}W_{\mu\nu},\ W^{\mu\nu}=W^{[\mu\nu]}+W^{\{\mu\nu\}}$$

  - unpolarized: $W^{\{\mu\nu\}}(x,Q^2)=\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right)F_1(x,Q^2)+\left(P^\mu-\frac{\nu}{q^2}q^\mu\right)\left(P^\nu-\frac{\nu}{q^2}q^\nu\right)\frac{F_2(x,Q^2)}{\nu},$
  - polarized: $W^{[\mu\nu]}(x,Q^2)=i\epsilon^{\mu\nu\rho\sigma}q_\rho\left(\frac{S_\sigma}{\nu}(g_1(x,Q^2)+g_2(x,Q^2))-\frac{q\cdot SP_\sigma}{\nu^2}g_2(x,Q^2)\right),$

  with $\nu=q\cdot P$, $S^2=-M^2$, $x=Q^2/2\nu$.

- The same structure functions appear in RHIC/Spin and Drell-Yang, which may also provide $\langle 1\rangle_{\delta q}$ or $\langle P,S|\bar{\psi}i\gamma_5\sigma_{\mu\nu}\psi|P,S\rangle$.

Moments of the structure functions are accessible on the lattice:

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

- c_1, c_2, e_1, and e_2 are the Wilson coefficients (perturbative),
- $\langle x^n\rangle_q(\mu)$, $\langle x^n\rangle_{\Delta q}(\mu)$ and $d_n(\mu)$ are forward nucleon matrix elements of certain local operators,
- so is $\langle x^n\rangle_{\delta q}(\mu)$ which may be provided by polarized Drell-Yang and RHIC Spin.

Unpolarized (F_1/F_2): on the lattice we can measure: $\langle x\rangle_q$, $\langle x^2\rangle_q$ and $\langle x^3\rangle_q$.

$$\frac{1}{2}\sum_s \langle P,S|\mathcal{O}^q_{\{\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = 2\langle x^{n-1}\rangle_q(\mu)[P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{trace})]$$

$$\mathcal{O}^q_{\mu_1\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n-1}\gamma_{\mu_1}\overleftrightarrow{D}_{\mu_2}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{trace})\right]q$$

Polarized (g_1/g_2): on the lattice we can measure: $\langle 1\rangle_{\Delta q}$ (g_A), $\langle x\rangle_{\Delta q}$, $\langle x^2\rangle_{\Delta q}$, d_1, d_2, $\langle 1\rangle_{\delta q}$ and $\langle x\rangle_{\delta q}$.

$$-\langle P,S|\mathcal{O}^{5q}_{\{\sigma\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{2}{n+1}\langle x^n\rangle_{\Delta q}(\mu)[S_\sigma P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{5q}_{\sigma\mu_1\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n}\gamma_5\gamma_\sigma\overleftrightarrow{D}_{\mu_1}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})\right]q$$

$$\langle P,S|\mathcal{O}^{[5]q}_{[\sigma\{\mu_1]\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{1}{n+1}d^q_n(\mu)[(S_\sigma P_{\mu_1} - S_{\mu_1}P_\sigma)P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{[5]q}_{[\sigma\mu_1]\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^{n}\gamma_5\gamma_{[\sigma}\overleftrightarrow{D}_{\mu_1]}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})\right]q$$

and transversity (h_1):

$$\langle P,S|\mathcal{O}^{\sigma q}_{\rho\nu\{\mu_1\mu_2\cdots\mu_n\}}|P,S\rangle = \frac{2}{m_N}\langle x^n\rangle_{\delta q}[(S_\rho P_\nu - S_\nu P_\rho)P_{\mu_1}P_{\mu_2}\cdots P_{\mu_n} + \cdots - (\text{traces})]$$

$$\mathcal{O}^{\sigma q}_{\rho\nu\mu_1\mu_2\cdots\mu_n} = \bar{q}[\left(\frac{i}{2}\right)^{n}\gamma_5\sigma_{\rho\nu}\overleftrightarrow{D}_{\mu_1}\cdots\overleftrightarrow{D}_{\mu_n} - (\text{traces})]q$$

Higher moment operators mix with lower dimensional ones: Only $\langle x\rangle_q$, $\langle 1\rangle_{\Delta q}$, $\langle x\rangle_{\Delta q}$, d_1, and $\langle 1\rangle_{\delta q}$ can be measured with $\vec{P} = 0$.

Our formulation follows the standard one:

- Two-point function: $G_N(t) = \mathrm{Tr}[(1+\gamma_t)\sum_{\vec{x}}\langle TB_1(x)B_1(0)\rangle]$, using $B_1 = \epsilon_{abc}(u_a^T C\gamma_5 d_b)u_c$ for proton.
- Three-point functions: appropriate operator inserted between source and sink.
- Source and sink are separated by 12 lattice spacings. 4 source positions.
- Gaussian smearing is employed to enhance ground-state signals.
- All the matrix elements except d_1 are iso-vector.

Number of configurations and pion mass

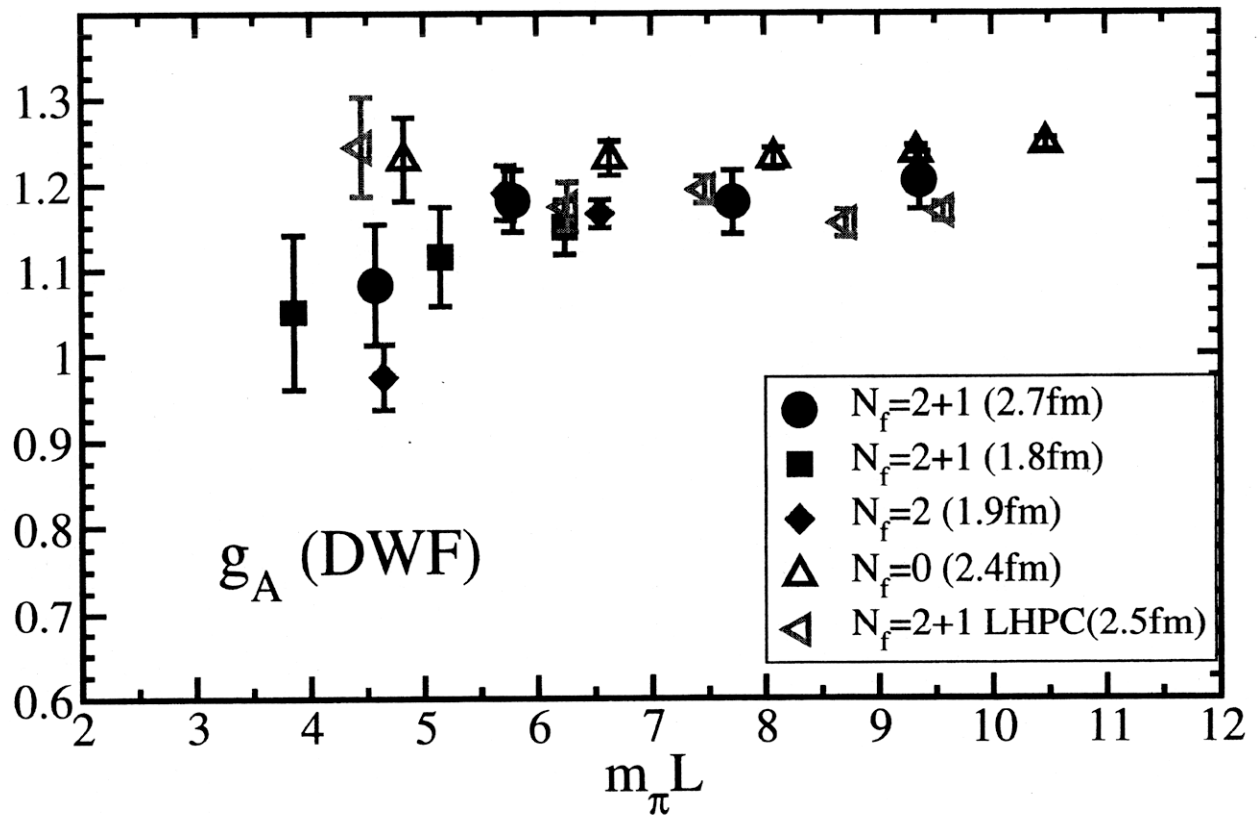
$m_f a$	# of config.'s	meas. interval	N_{sources}	m_π (GeV)	m_N (GeV)
0.005	360	10	4	0.33	1.15
0.01	356	10	4	0.42	1.22
0.02	98	20	4	0.56	1.39
0.03	106	20	4	0.67	1.55

Good chiral and flavor symmetries of DWF help:

- negligible unwanted mixings,
- straight-forward non-perturbative renormalization (eventually/soon).

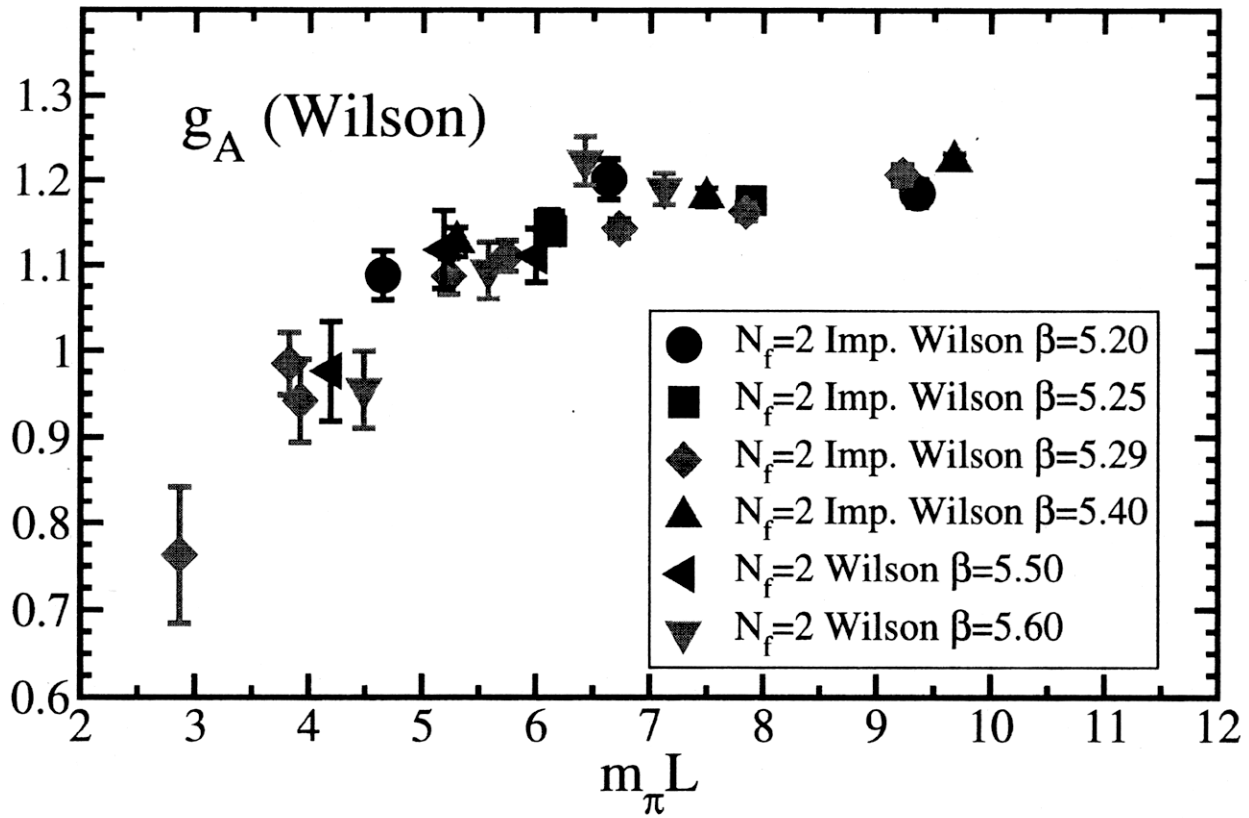
In particular, ratios such as g_A/g_V or $\langle x\rangle_{u-d}/\langle x\rangle_{\Delta u-\Delta d}$ are naturally renormalized.

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



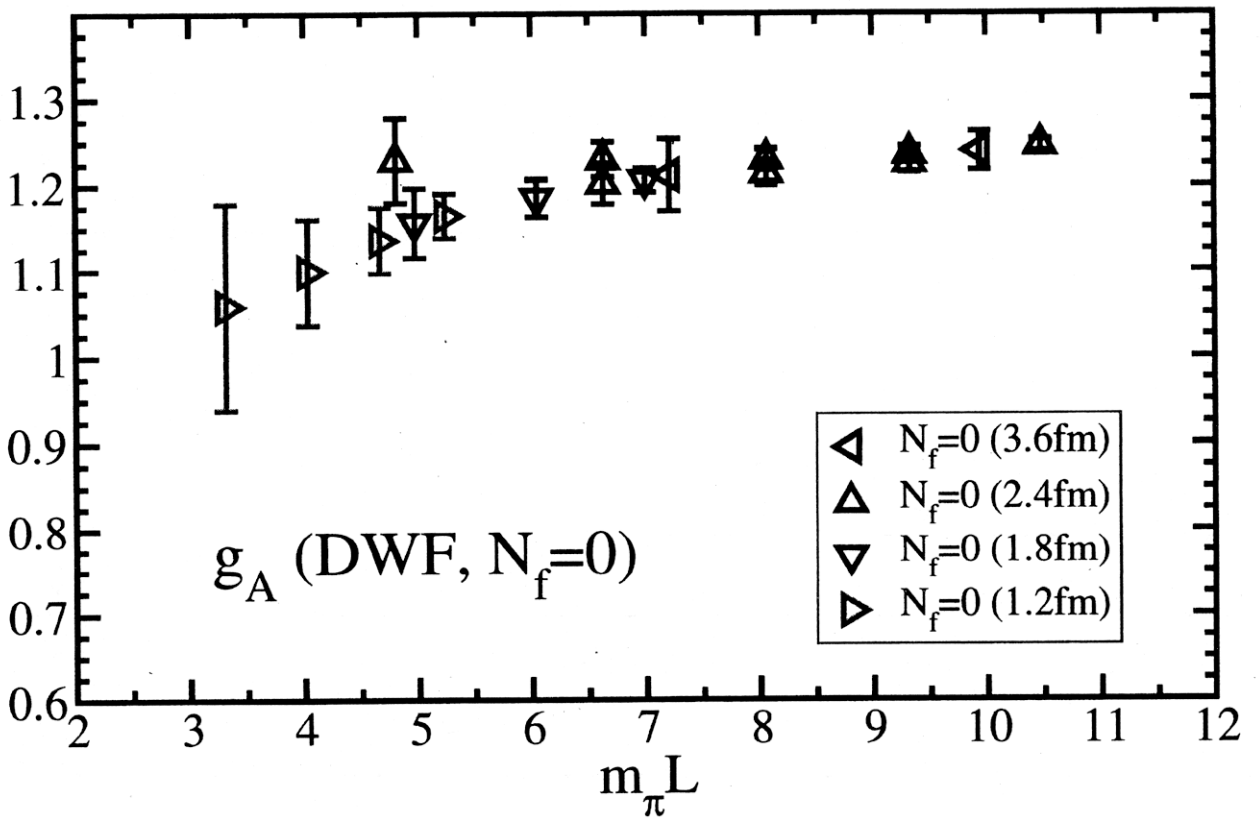
Heavier quarks: consistent with experiment, no discernible quark-mass dependence.
Lighter quarks: finite-size sets in as early as $m_\pi L \sim 5$, and suggests scaling in $m_\pi L$.
(Our DWF on quenched and LHPC DWF on MILC calculations are presented for comparison.)

Axial charge:



2-flavor dynamical Wilson results show similar finite-size and scaling-like behavior.

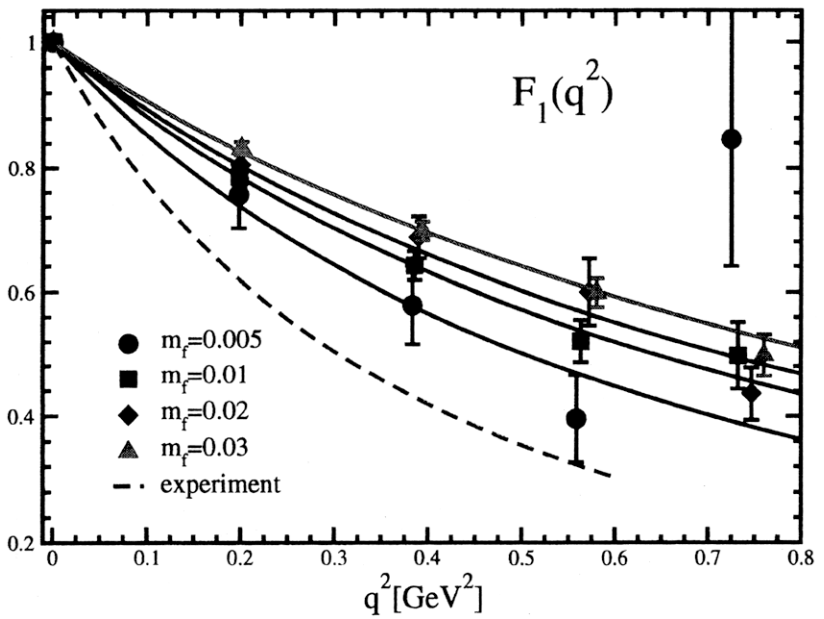
Axial charge:

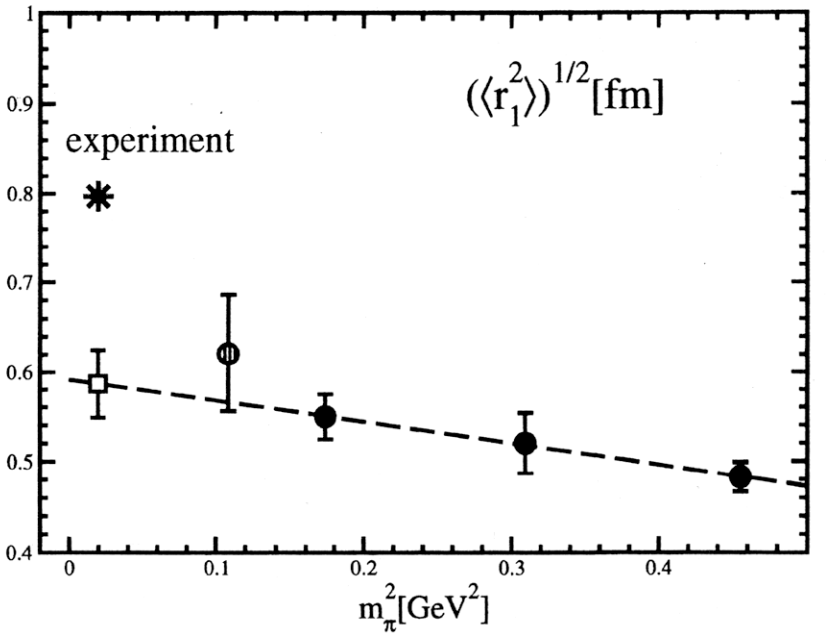


May suggest there are two, large- and small-volume, scaling curves.

Isovector Dirac form factor: isovector part of charge radius, fit by dipole form

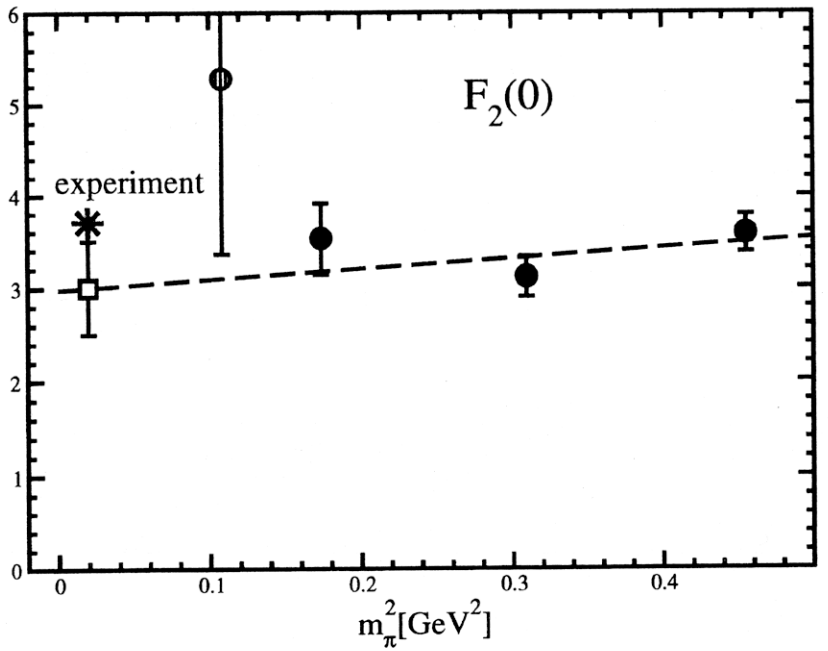
fit by dipole form, $F_1(q^2) = 1/(1 + q^2/M_1^2)^2$, and compared with experiment, $M_1 = 0.857(8)$ GeV.

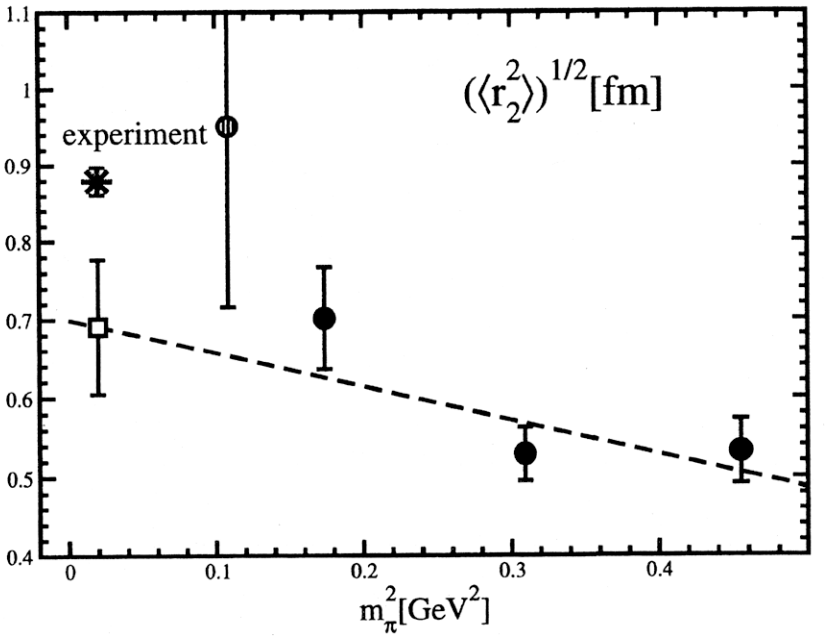




Nucleon beginning to swell at the lightest point?

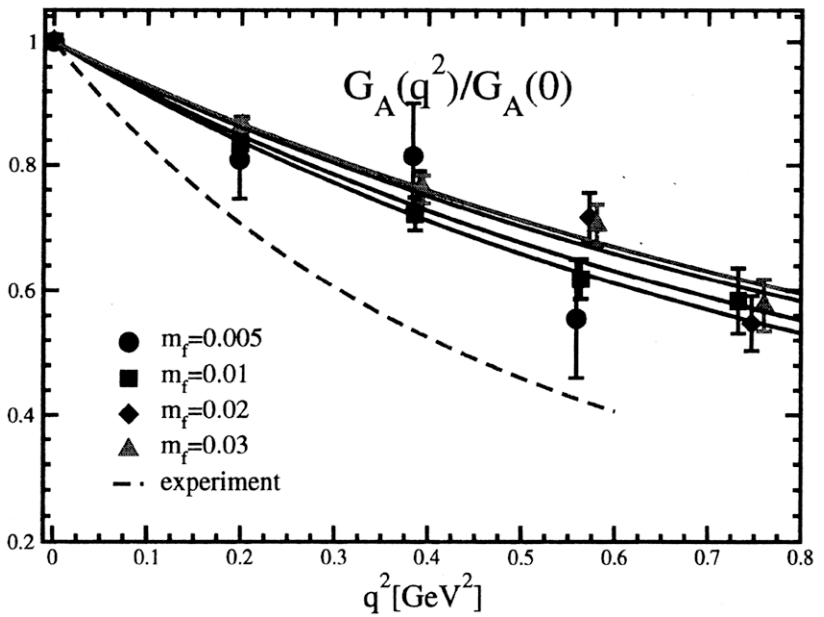
Isovector Pauli form factor: isovector part of magnetic moment, fit by dipole form

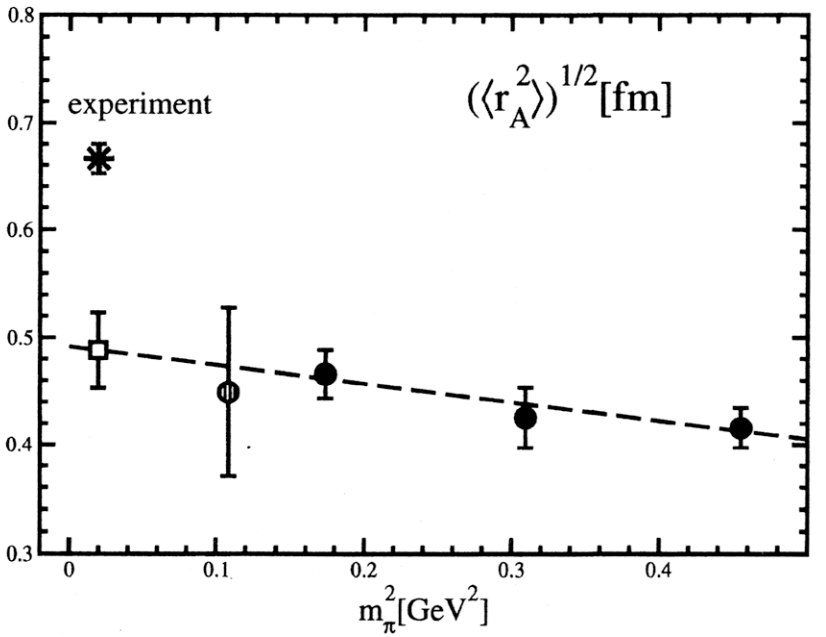




Magnetic moment broadly in agreement with experiment.
Nucleon beginning to swell at the lightest point?

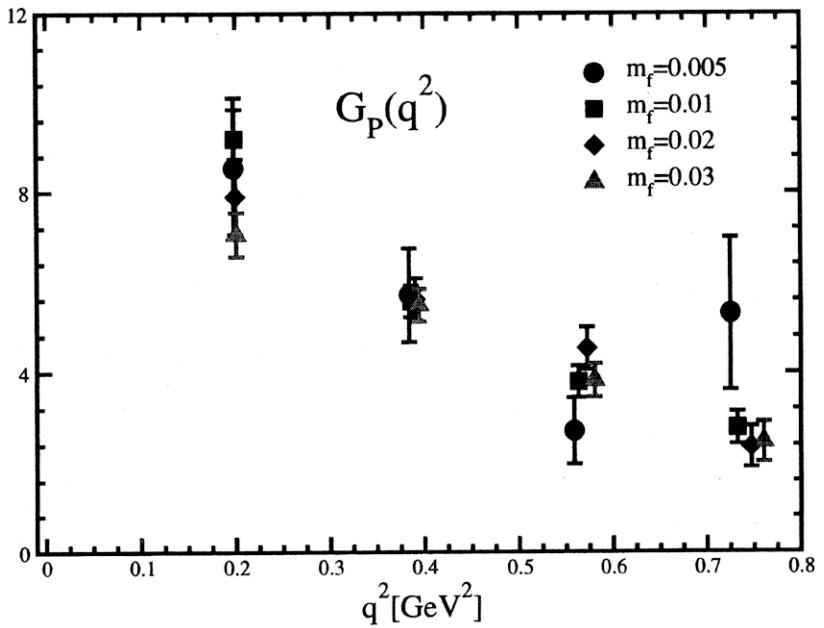
Isovector axialvector form factor: fit by dipole form, but not so well,

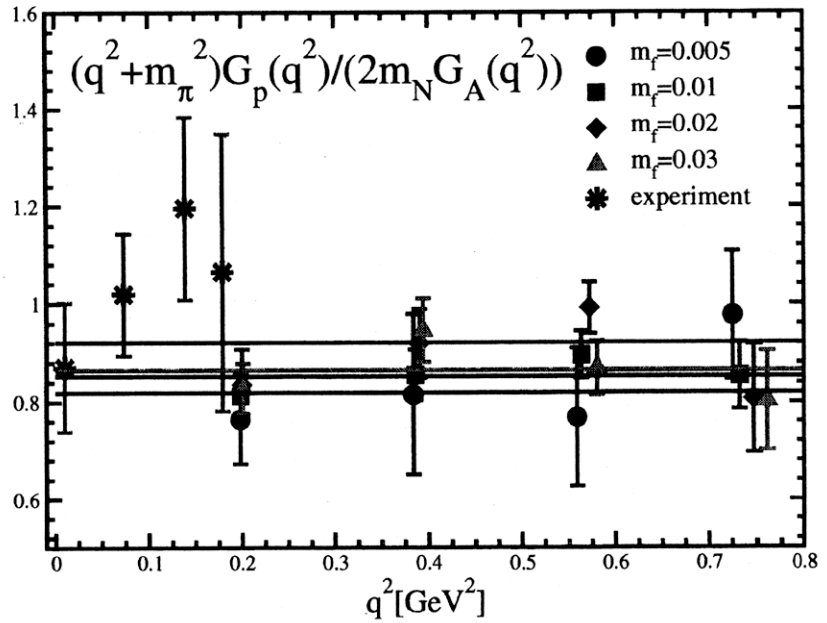




Isovector induced pseudoscalar form factor:

Should be affected by the pion pole.

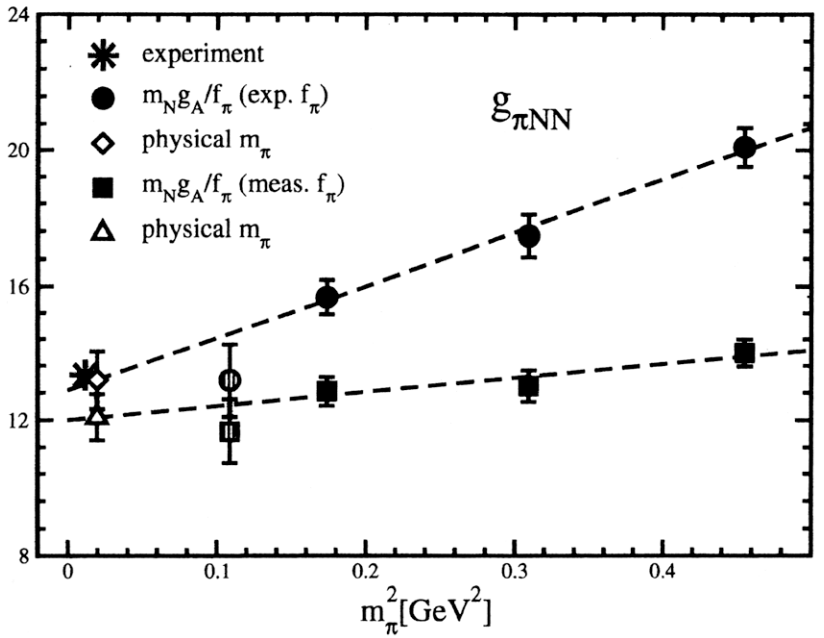


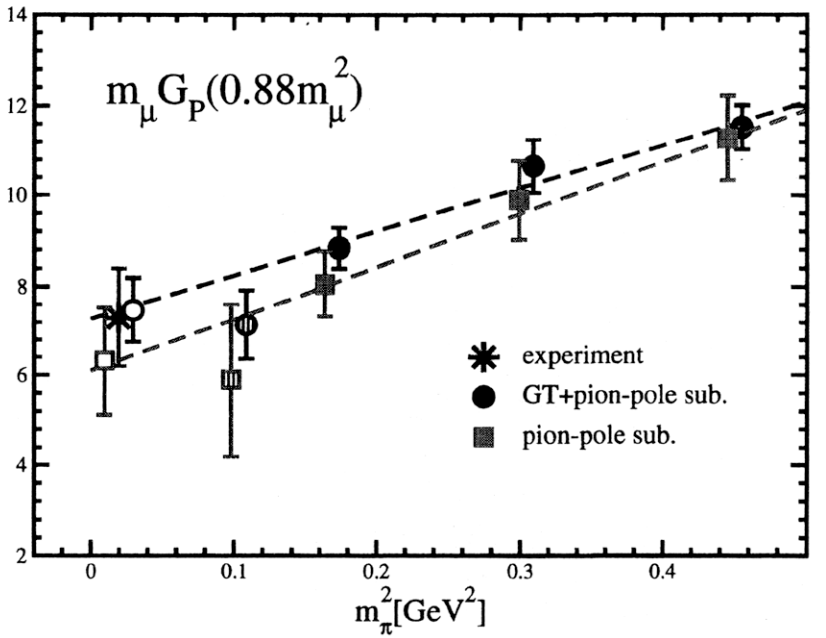


Pion pole seen (left).

Goldberger-Treiman relation seems satisfied within statistics (right).

Isovector induced pseudoscalar form factor: πNN coupling from GT and muon-capture G_P

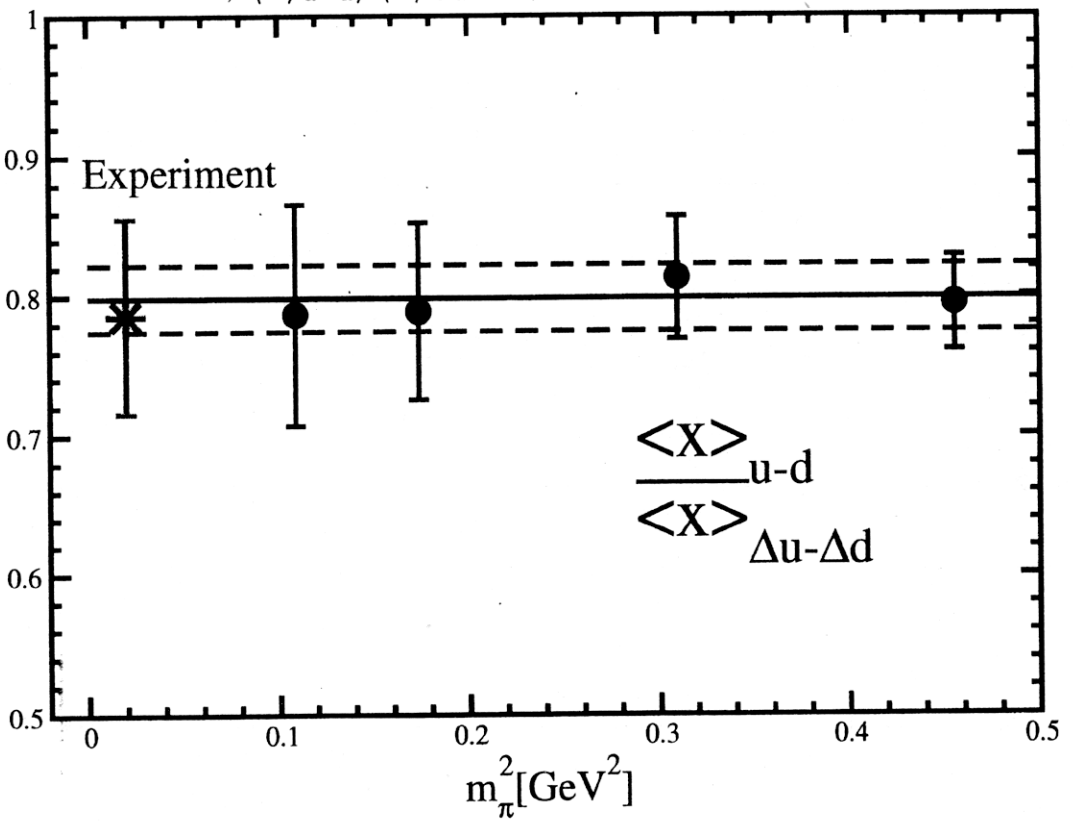




RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, $a^{-1} = 1.73(2)$ GeV, $m_{\rm res} = 0.00315(2)$, $m_{\rm strange} = 0.04$,

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

Renormalized ratio, $\langle x \rangle_{u-d} / \langle x \rangle_{\Delta u - \Delta d}$, of momentum and helicity fractions,



consistent with experiment, no discernible quark-mass dependence.

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

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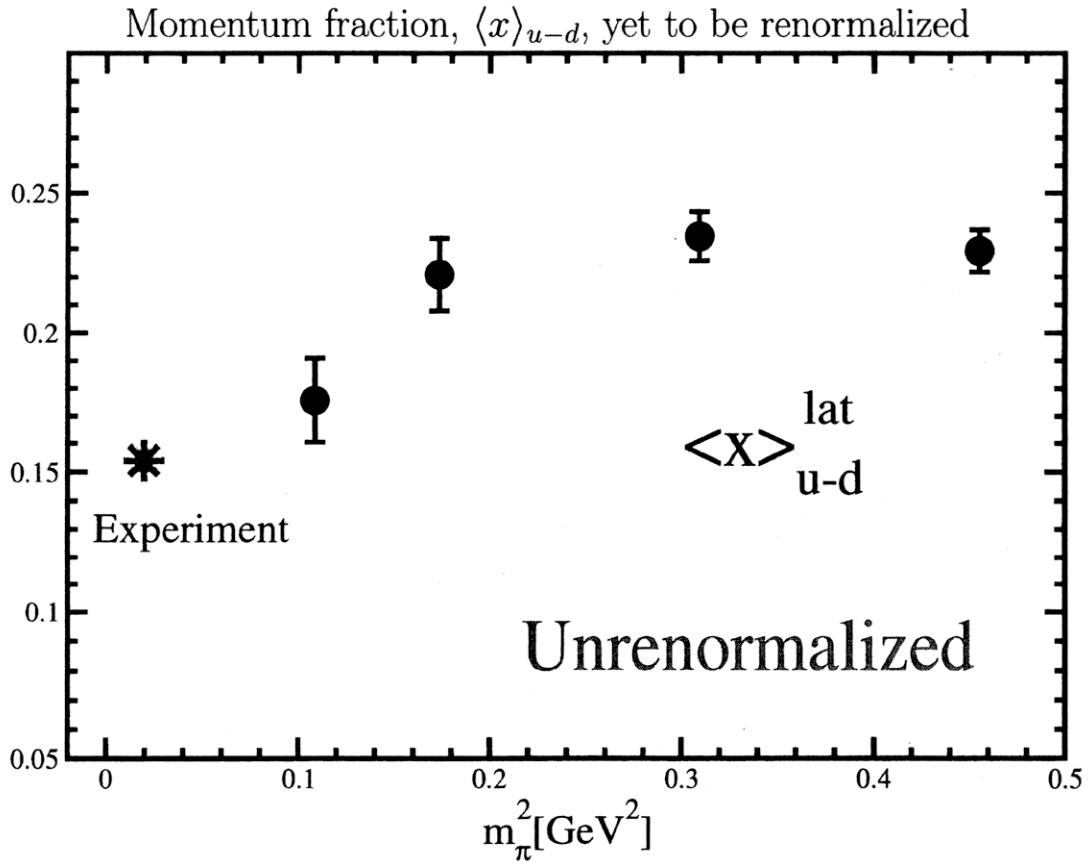
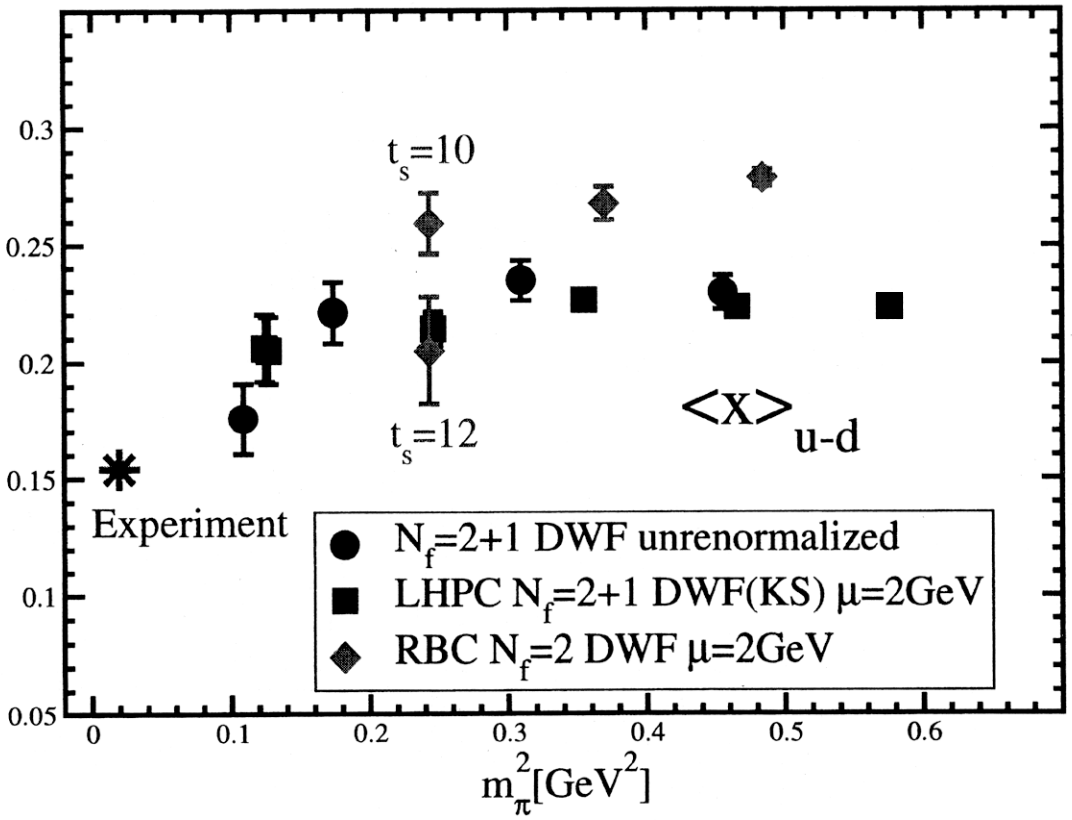


Absolute values seem to have improved, trending to the experimental values, but yet to be renormalized (typically 10% effect at these cuts off).

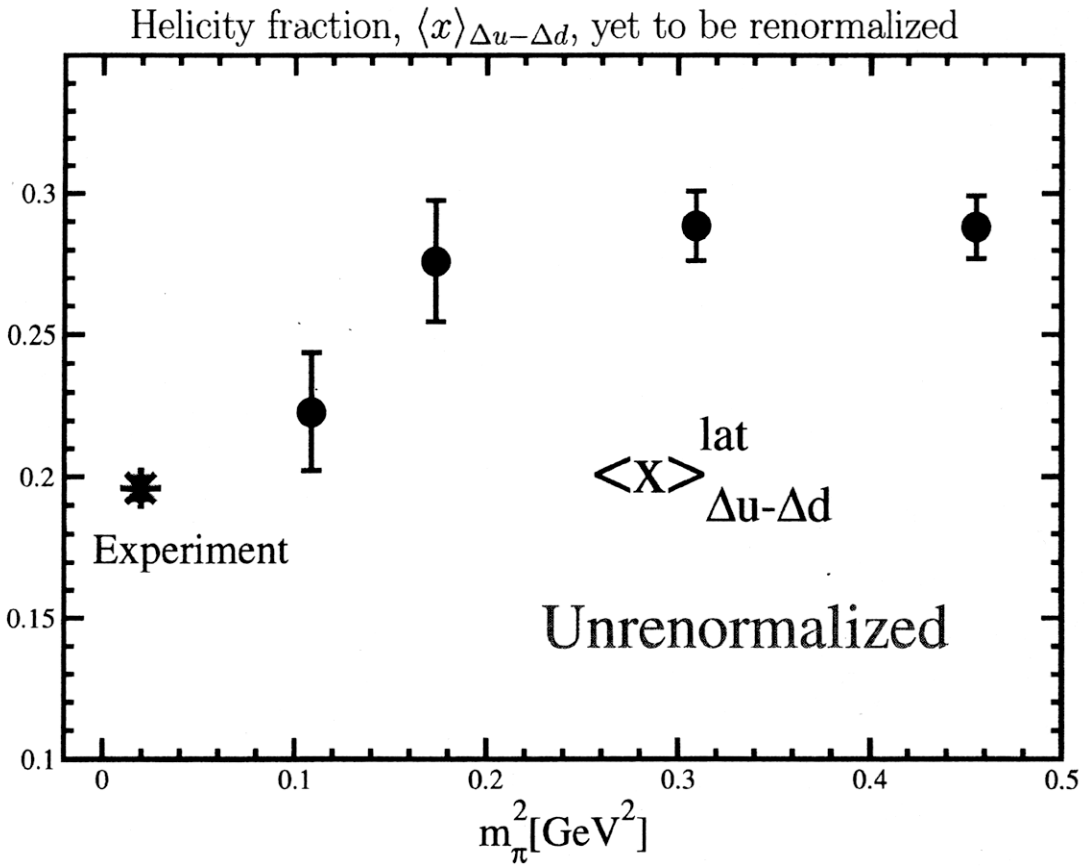
RBC/UKQCD (2+1)-flavor, Iwasaki+DWF dynamical, compared with with LHPC/MILC 2+1f and RBC 2f



- Renormalization close to 1?
- Light sea quarks are important.
- Light valence quarks are important: otherwise cannot share much momentum with sea quarks and gluons.
- Finite-volume effect beginning at $m_\pi L \sim 4.5$? Not necessarily.

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

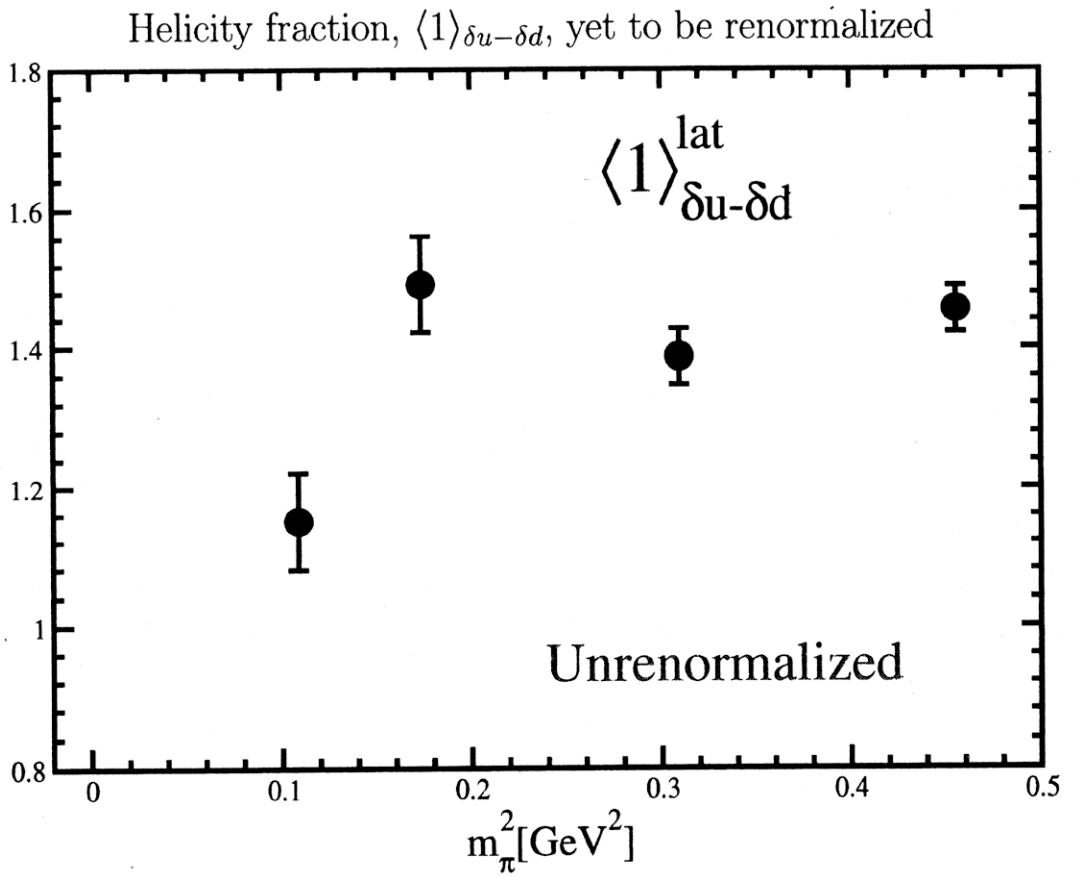
- $m_\pi = 0.67$, 0.56, 0.42 and 0.33 GeV; $m_N = 1.55$, 1.39, 1.22 and 1.15 GeV,



Absolute values seem to have improved, trending to the experimental values, but yet to be renormalized (typically 10% effect at these cuts off).

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

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



Yet to be renormalized (typically 10% effect at these cuts off).

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

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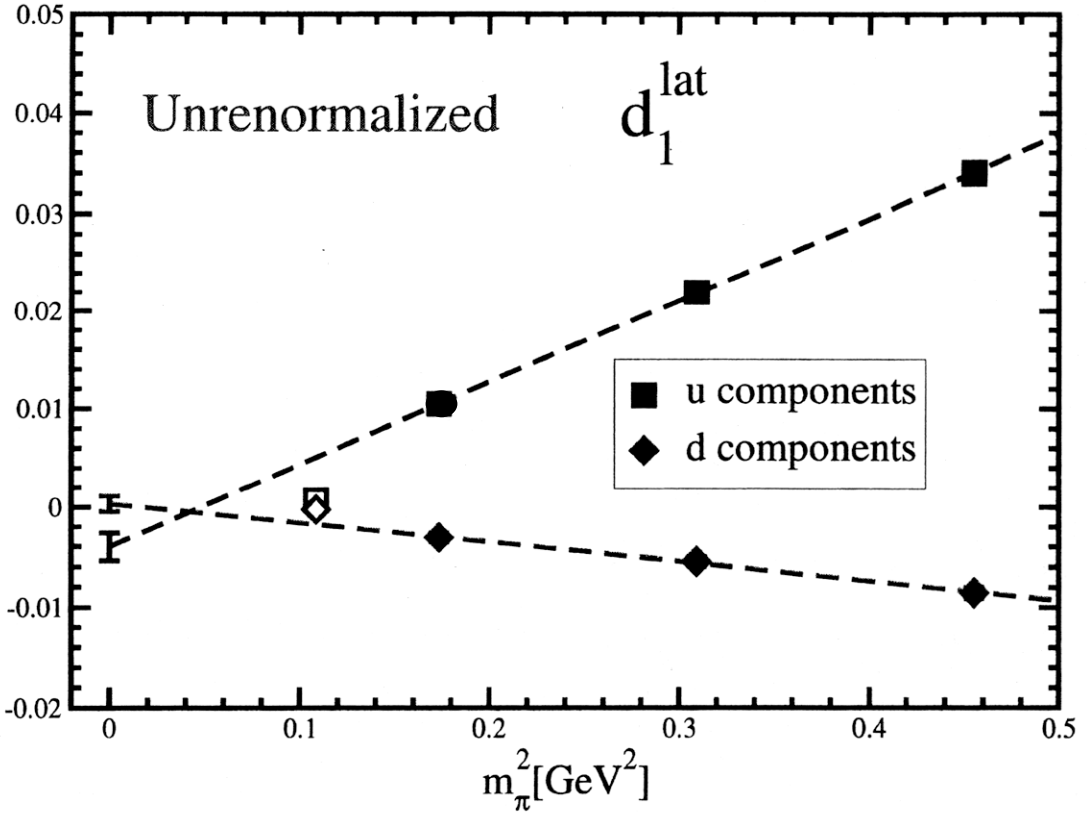
Twist-3, d_1, yet to be renormalized



Chirally well-behaved, small, and in consistency with Wandzura-Wilczek relation.

Conclusions

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

- Isovector axial charge, g_A, at heavier quark mass is consistent with experiment with little mass dependence;
  - a large finite-size effect seen as early as $m_\pi L \sim 5$, and may scale in $m_\pi L$.
- Momentum-transfer dependence of all the isovector form factors are studied:
  - some already can meaningfully compared with experiments.
- Momentum to helicity fraction ratio, $\langle x \rangle_{u-d} / \langle x \rangle_{\Delta u - \Delta d}$, is consistent with experiment,
  - without any discernible quark-mass dependence.
- Lightest point shows an encouraging trend toward experiments in both momentum and helicity fractions.
- Transversity moment is obtained.
- Twist-3 moment, d_1, is chirally well-behaved, small, and consistent with Wandzura-Wilczek relation.

Structure function renormalizations will be available very soon (typically 10 % effect).

Calculations at finer lattice ($\beta = 2.23$, 2.1-2.2 GeV) with about the same volume (32^3) are on-going.

Hadronic matrix elements with 2+1 flavor domain fermions for the standard model and beyond

Yasumichi Aoki

RIKEN BNL Research Center

RBRC scientific review committee meeting, 11/5/07

Hadronic matrix elements

First principle calculation with lattice QCD

- $\langle f|\mathcal{O}|i\rangle_{QCD}$
  - $i =$ a hadron, $f = 0$
    - ★ decay constants
  - $i =$ a hadron, $f =$ a hadron
    - ★ $Kl3$ form factor
    - ★ $K^0 - \overline{K^0}$ mixing
    - ★ $B^0 - \overline{B^0}$ mixing
    - ★ proton decay matrix elements
  - necessary to determine parameters in Standard Model and beyond by comparing with experiment.
- domain wall fermions
  - preserve chiral symmetry
    - ★ continuum QCD like property
    - ★ simple structure of operator mixing
    - ★ small systematic error: mild dependence on the lattice spacing a
  - Rome-Southampton non-perturbative renormalization works well for light flavors.

Systematic improvements in lattice calculation

- number of dynamical flavors:
  - $N_f = 0 \to 2 \to 2+1$
    - ★ $2+1$ flavor: u, d, s.
- light quark masses
  - $m_{ud}^{sim} \lesssim m_s/5$ in the latest RBC/UKQCD simulations
    - ★ $m_{ud}^{phys} \simeq m_s/28$
    - ★ chiral extrapolation needed
    - ★ but already in the chiral regime
  - all these are possible thanks to QCDOC
- lattice spacing dependence
  - some tested in $N_f = 0$ case, small as expected.
  - yet to be done in $N_f = 2+1$.

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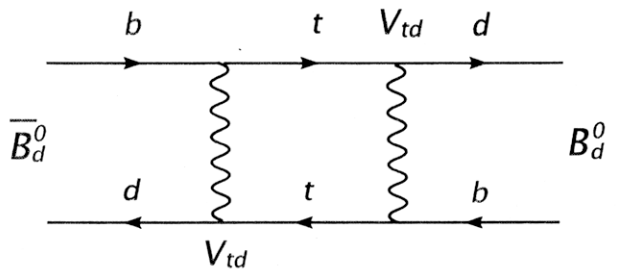
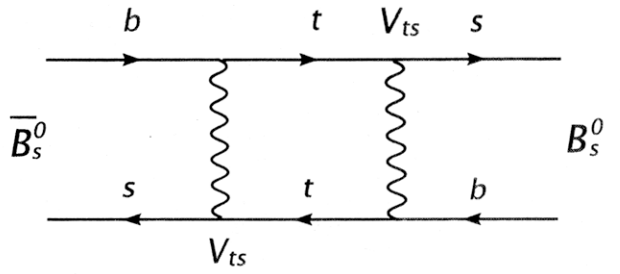
B^0–$\overline{B^0}$ mixing in the Standard Model





$\Delta m_d = 0.507(5)\text{ps}^{-1}$ PDG $\Delta m_s = 17.77(12)\text{ps}^{-1}$ CDF

- B^0_q–$\overline{B^0_q}$ oscillation frequency ($q = d, s$)

$$\Delta m_q = (\text{known factor}) \cdot |V_{tb} V^*_{tq}|^2 \mathcal{M}_q,$$

- B^0_q–$\overline{B^0_q}$ mixing matrix elements

$$\mathcal{M}_q = \left\langle \bar{B}^0_q \right| [\bar{b}\gamma^\mu(1-\gamma_5)q][\bar{b}\gamma_\mu(1-\gamma_5)q] \left| B^0_q \right\rangle .$$

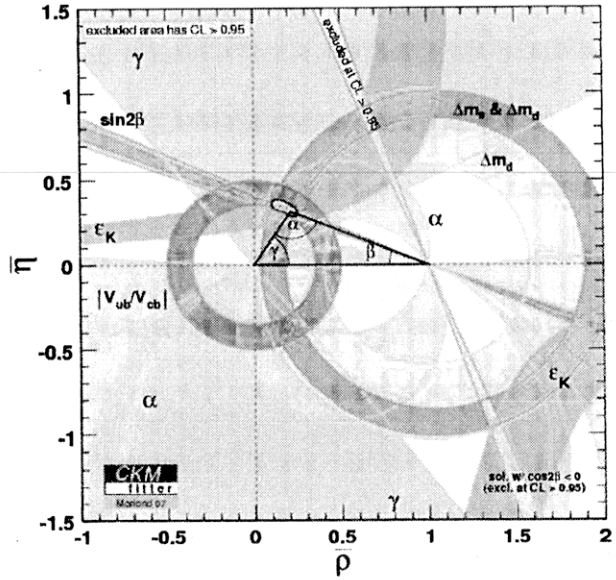
- $SU(3)_f$ breaking ratio:

$$\xi \propto \sqrt{\frac{\mathcal{M}_s}{\mathcal{M}_d}} \to \left|\frac{V_{td}}{V_{ts}}\right| = \frac{1}{\xi}\frac{\Delta m_s}{\Delta m_d}\frac{m_{B_d}}{m_{B_s}}$$

  - Large fraction of statistical, systematic errors cancel in the ratio ξ.

B^0–$\bar{B}^0$ mixing

- $\left|\frac{V_{td}}{V_{ts}}\right|$: $\longrightarrow$ unitarity triangle
  - error of $\frac{\Delta m_s}{\Delta m_b}$ [experiment] is tiny
  - error of $\xi \propto \sqrt{\frac{\mathcal{M}_s}{\mathcal{M}_d}}$ [lattice] dominates $\longrightarrow$ orange band
  - So far full $2+1$ flavor lattice calculation of ξ has not been done!

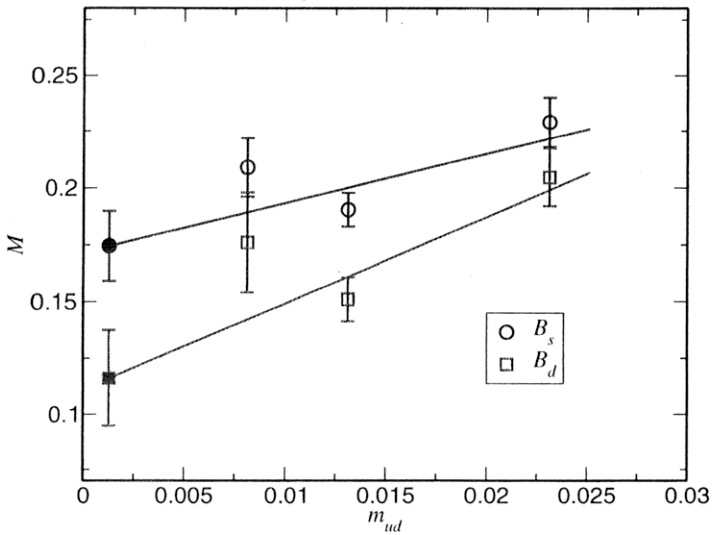


- Our approach for $\mathcal{M}_d$ and $\mathcal{M}_s$
  - Discretized Heavy Quark Effective Theory for for b quark
    - ★ $m_b \to \infty$ limit
    - ★ useful as the reference point
    - ★ good approximation as $m_b \gg \Lambda_{QCD}$
  - Dynamical domain wall fermions for the u, d, s quarks.
    - ★ simple operator mixing structure like continuum theory
    - ★ - $O(a)$ improvement yet to be done
  - Mean field improved lattice perturbation theory for matching

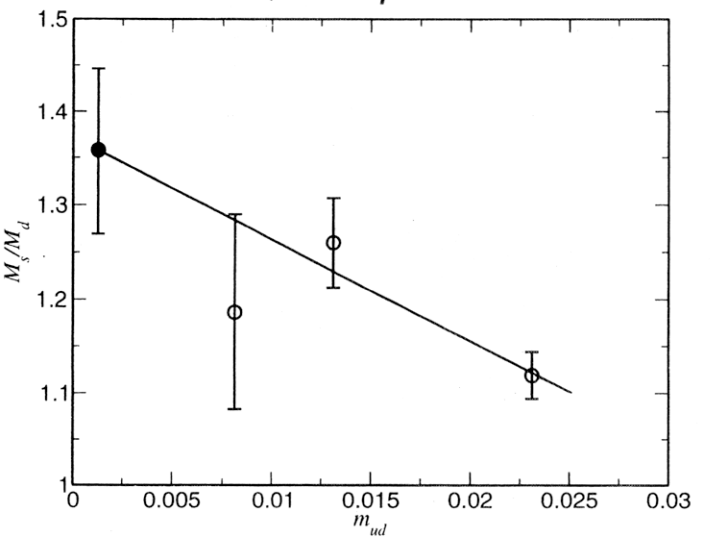
B^0–$\overline{B^0}$ mixing matrix elements

with 2 + 1 flavor domain wall fermions

$\mathcal{M}_q$ vs m_{ud}



$\mathcal{M}_s/\mathcal{M}_q \propto \xi^2$



- $\xi = 1.16(4)$ stat. error only
- Lightest m_{ud} has poor statistics, should be increased.
- Taking partially quenched points will lead to better constraint on the chiral extrapolation.
- New technique will be useful
  - Low mode average and all to all propagator
  - Deflation

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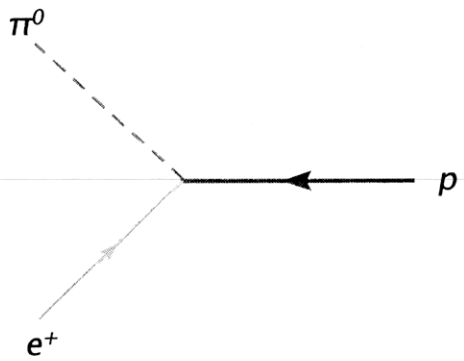
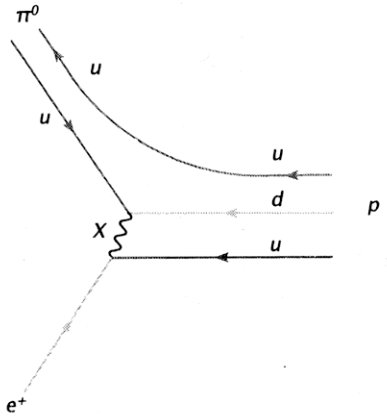
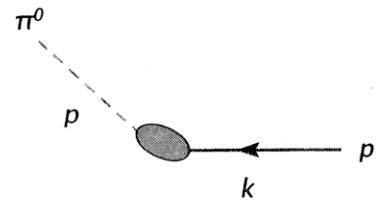
Proton decay







- Smoking gun evidence of Beyond SM
  (B is conserved in SM.)
- Natural in GUT
- Dominant mode in non-SUSY GUT
  $p \to \pi^0 + e^+$
- At standard model energy scale
  $\mathcal{L} = \mathcal{L}_{SM} + C_{\not B}\mathcal{O}_{\not B}$
  $\mathcal{O}_{\not B} = (ud)_{R/L}(ue)_{R/L}$
  $C_{\not B} \propto 1/m_X^2$
- Need the relevant form factor W_0 for
  $\Gamma(p \to PS + \bar{l}) = (\text{kinematic factor}) \cdot |C_{\not B} W_0|^2$

$q = k - p$: momentum transfer
$\to$ momentum of e^+

$$\langle \pi^0; \vec{p}|(ud)u_L|p; \vec{k}, s\rangle = P_L[W_0(q^2) - \frac{i\not{q}}{m_p} W_q(q^2)]u_p(\vec{k}, s)$$

How to calculate W_0

- direct method: exact but unconventional as cumbersome and expensive
  - direct measurement through 3- and 2-point functions
- indirect method: approximation, conventional
  - Chiral Perturbation + Low Energy Constants evaluated on the lattice
  - $\mathcal{L}_B^\chi(f, g_A, , ,) + \mathcal{L}_{\not B}^\chi(\alpha, \beta)$,
  - On the lattice, measure α and β

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

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

  - Reduction formula for $p \to \pi^0$:

$$W_0(\langle \pi^0|(ud)_R u_L|p\rangle) = \alpha(1 + g_A)/\sqrt{2}f,$$

$$W_0(\langle \pi^0|(ud)_L u_L|p\rangle) = \beta(1 + g_A)/\sqrt{2}f$$

  - Reduction formula available for all the matrix elements [Claudson-Wise-Hall, JLQCD].
  - These are only the lowest order approximations. As the pion has large momentum $|\vec{p}| \simeq m_p/2$, the applicability is questionable.

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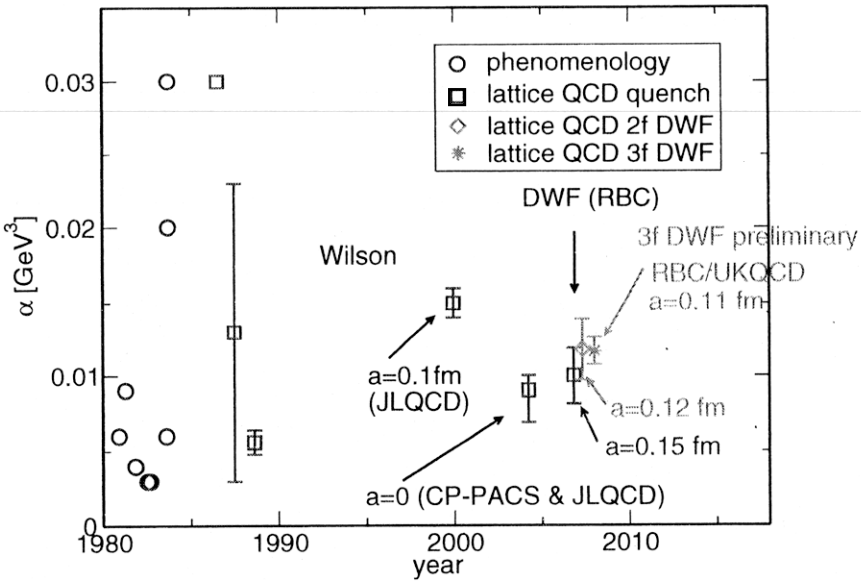
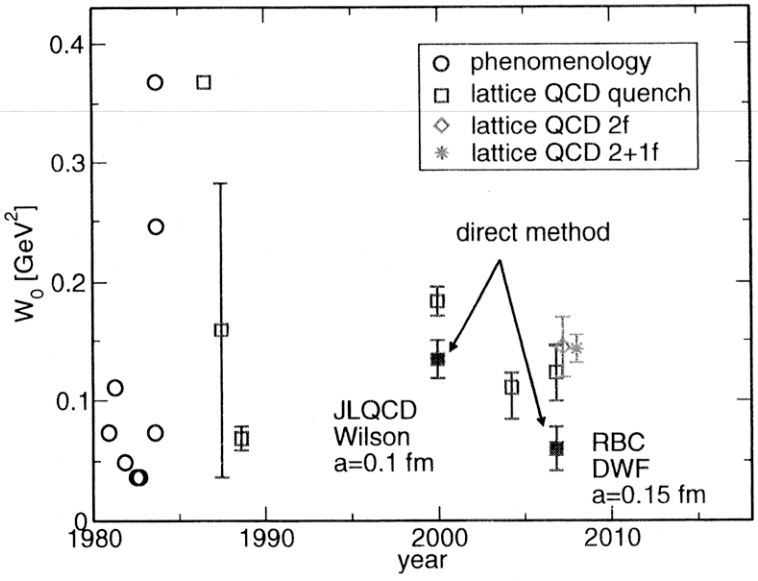
Proton decay matrix elements

α vs published year



$W_0(\langle\pi^0|(ud)_R u_L|p\rangle)$

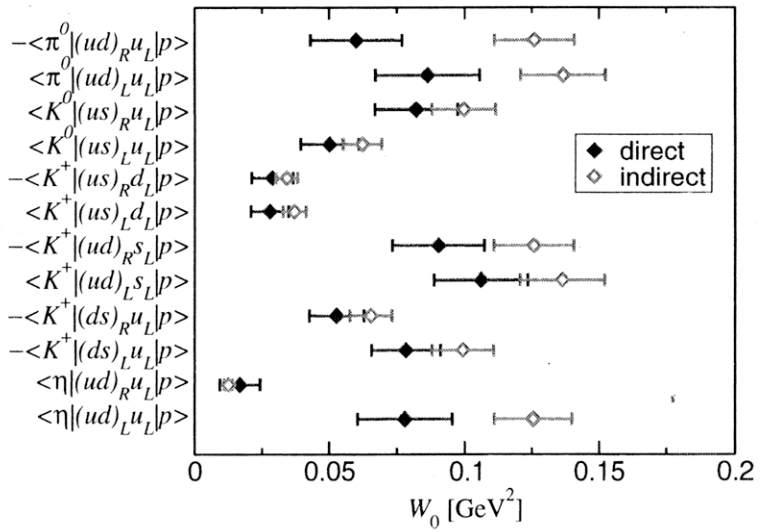


- $N_f = 2 + 1$ preliminary.
- $\alpha = 0.01$ GeV^3 may be a representative value.
- $(\beta \simeq -\alpha)$.
- so far so good.
- But the story does not end....

- only $N_f = 0$ for direct method
- Large difference: $W_0(\text{indirect}) \simeq 2W_0(\text{direct})$
- indirect method underestimate partial lifetime by factor 4.
  - indirect method unreliable

W_0 summary at $N_f = 0$

comparison of direct and indirect methods



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- Indirect method tends to overestimate W_0, results in underestimating proton lifetime. Note: $\tau \propto 1/W_0^2$
- Largest difference observed for $p \to \pi$ decay.
  - $\tau(\text{direct})/\tau(\text{indirect}) = 2 - 4$.
- Similar pattern has been observed by JLQCD with $a = 0.1$ fm, Wilson Fermion. Direct-indirect diff is larger here.
- Need to perform direct calculation with $N_f = 2 + 1$ domain wall fermions, which is in preparation

Lattice QCD simulations with

θ terms : Neutron EDM and η'

Taku Izubuchi

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Kanazawa Univ.

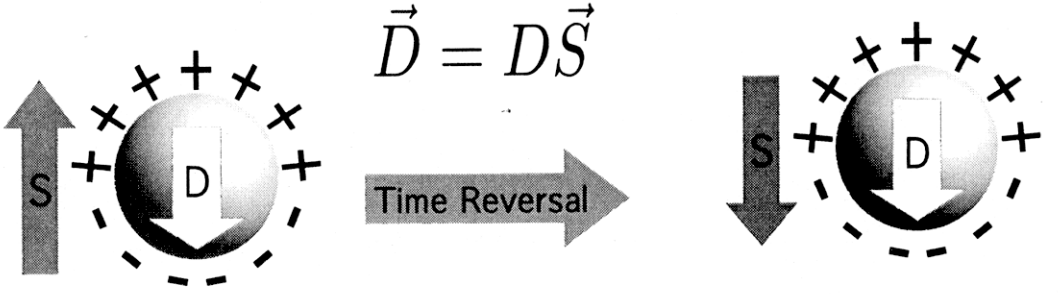
- 05 K. Hashimoto & RBC
- 06 S. Aoki, T. Blum, and T. Doi
- 07 S. Aoki, K. Hashimoto, Y. Nakamura, T. Sekido, and G. Schierholz

RBRC Scientific Review Committee Meeting, 2007-11-5,6

$\theta\,\theta\,\theta$

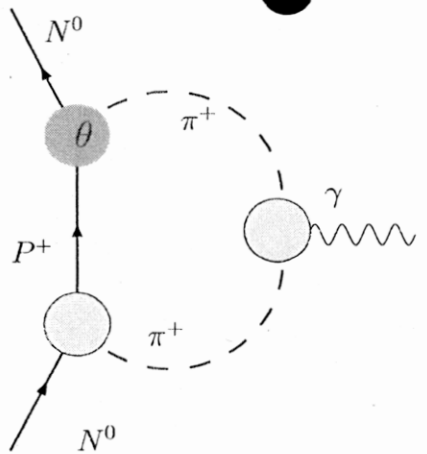
Electric Dipole Moment (EDM)

- Permanent EDM is a signature of T (Time reversal symmetry) violation.



- various candidates of T (= CP) violations :
  - Electro Weak (CKM phase in quark mass matrix) : very small (Neutron: 10^{-4} smaller than exp. limit)
  - New Physics (SUSY, left-right, multi Higgs)
  - Strong CP: vacuume angle θ

Strong CP problem



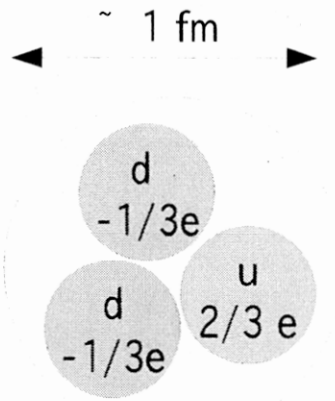
- CP odd Lagrangians in QCD are perfectly allowed.

$$S_\theta = i\theta \frac{1}{32\pi^2} \int d^4x F_{\mu\nu}(x)\widetilde{F}_{\mu\nu}(x) = i\theta Q_{\rm top}$$

Qtop is (classically) integer counting winding number of gluon field (net number of instanton). θ is an angle of complex phase assoc. each topological sectors: θ vacuume.

- Neutron's Electric Dipole Moment, NEDM (CP odd) is experimentally very small,

$$D_n \leq 3.0 \times 10^{-13} [\text{e fm}] \quad \text{(06, Grenoble grp.)}$$



- Model estimates (Bag model, ChPT, Large Nc)

$$D_n = (9, 17, -4 \sim -7) \times 10^{-3} \times \theta \ [\text{e fm}]$$

(79 Baluni, 79 Crewther et.al., 92 Aoki-Hatsuda, 02 Pospelov-Ritz)

$$|\bar{\theta}| = |\theta + \theta_{\rm EW}| \leq 10^{-10}$$

- One of the most prominent unnaturalness in the nature.

Proposed solutions

- theta term is U(1) ABJ Anomaly: changes the path integral measure

$$\psi \to e^{i\theta'\gamma_5}\psi, \qquad \overline{\psi} \to \overline{\psi}e^{i\theta'\gamma_5}$$

$$\mathcal{D}\psi\mathcal{D}\overline{\psi} \to \mathcal{D}\psi\mathcal{D}\overline{\psi}e^{i\frac{N_f}{32\pi^2}\theta' F_{\mu\nu}\tilde{F}_{\mu\nu}}$$

and also quark mass terms

$$m\overline{\psi}\psi \to m\overline{\psi}\psi\cos(2\theta') + im\overline{\psi}\gamma_5\psi\sin(2\theta')$$

- if up(/down) quark is massless (m=0) then vacuum angle can be rotated away, which is less consistent with spectrum results.
- A very light, neutral, weakly coupled pseudoscalar, axion, which is (would-be) NG-boson of the Peccei-Quinn Symmetry

$$\left(\theta - \frac{a(x)}{f_A}\right) F_{\mu\nu}\tilde{F}_{\mu\nu}$$

- Another field theoretical solutions ?

Lattice QCD

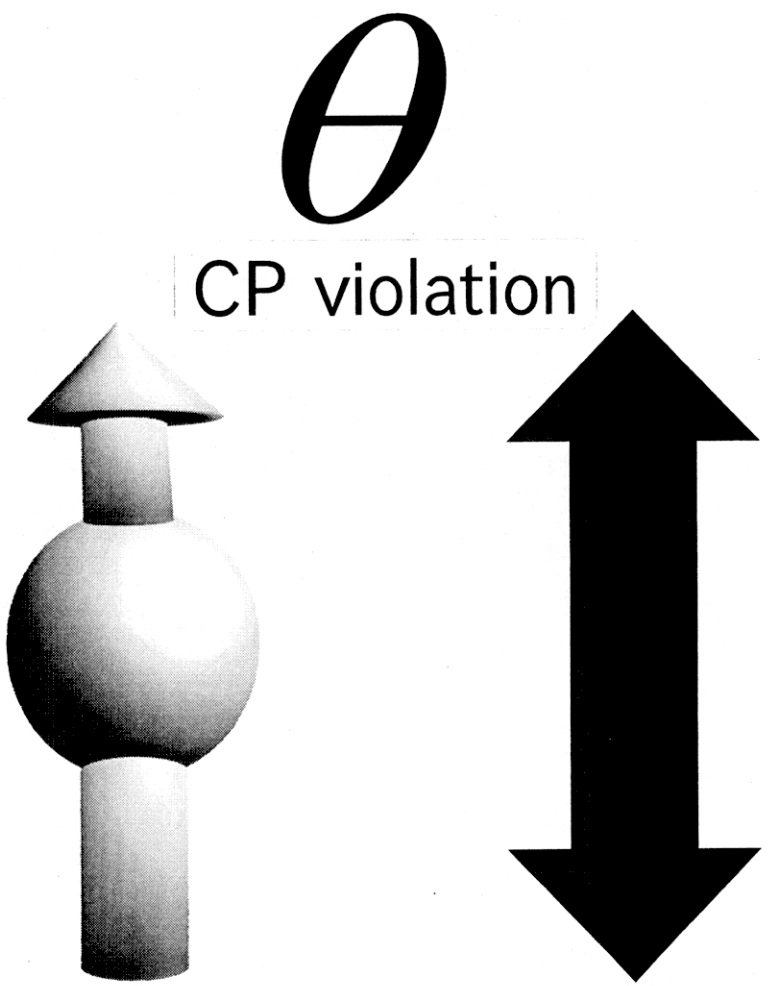
- 18 years of Nucleon Electric Dipole Moment, NEDM on lattice : two methods so far

89 Aoki-Gocksch	Nf=0 Wilson	Electric field
04 Berruto et. al.	Nf=0 DWF	3pt
05 Berruto et. al.	Nf=2 DWF	3pt
06 Shintani et. al. (CP-PACS)	Nf=0 DWF	3pt
06 Shintani et. al. (CP-PACS)	Nf=0 DWF,Nf=2 clover	Electric field
06 QCDSF	Nf=0 overlap	3pt
06 Blum, TI, & Doi	Nf=2 DWF	Electric field
06 Shintani et. al. (CP-PACS)	Nf=2 clover	Electric field

(c.f. experiments: 10^{-6} progress for last ~50 years)

- Dynamical Simulation (including sea quark pair creation/annihiration effect) becomes easier. NEDM is very sensitive to sea quark mass; zero at chiral limit (and valence quark theta is to be rotated away)

NEDM (as a spectrum)



- Three ingredients
  - Uniform Electric Field
  - source of CP violation,
  - Polarized Nucleaon
- Measure a spin splitting of energy

(89 Aoki-Gocksch)

$$m_{N\theta}(\mathsf{E},\uparrow) - m_{N\theta}(\mathsf{E},\downarrow) = 2i\theta d_N \mathsf{S}\cdot\mathsf{E} + \mathcal{O}(\mathsf{E}^2,\theta^2)$$

External Field method

- External electric field method,
  - Usual U(1) (not Minkowskian used by Aoki-Gocksch, CP-PACS)
  - Weak to avoid E^2 contaminations
  - Uniform to avoid a boundary effect

Weak and Uniform E(M) field

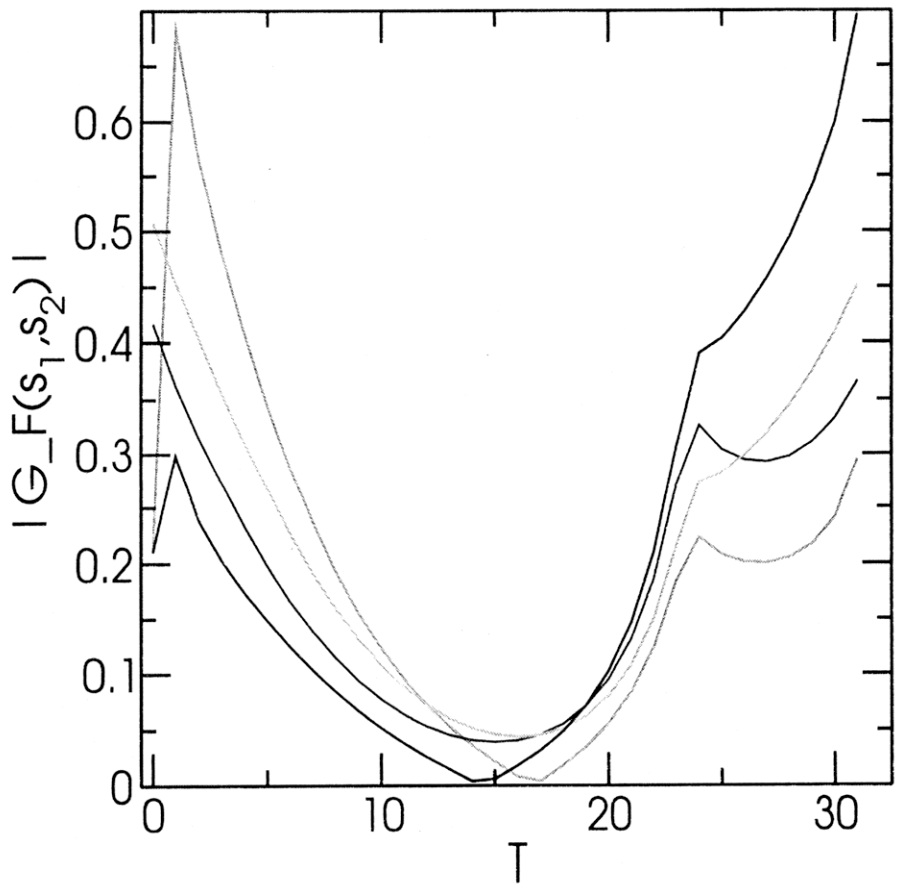
- 98 U. Heller, 64 E. Brown construct an EM field on torus which keeps translational invariance, $U_{\Box,zt} = e^{iEz}$ is constant everywhere, equiv. to a "twistier" boundary condition

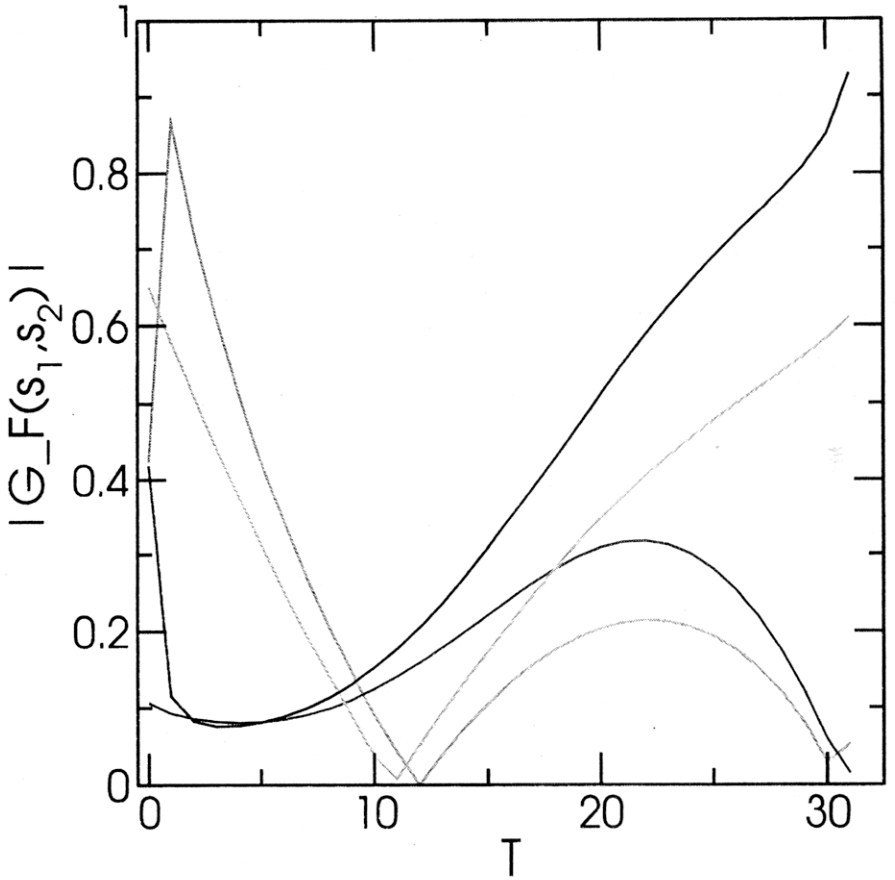
$$\psi(z, t + N_t) = \exp(iEN_x z)\psi(z, t)$$

The discretization unit is small $E_z^{(\text{unit})} = \dfrac{2\pi}{N_z N_t} \sim 0.01$

- No strong negative field at the boundary, which could skew the energy and/or larger excited state contamination (c.f. delta function potential in QM)
- Could also apply to MDM, Polarizability calcs.

Free case





- Tsrc=8
- T-> T-8

- E=E(unit) x n

Dynamical QCD with θ

- Source of CP violation : $S_\theta = i\frac{\theta}{32\pi^2}\sum \tilde{F}F = i\theta Q_{\rm top}$
- In previous calculations, $\theta = 0$ ensemble were generated (Nf=0,2), then each configuration were reweighted by topological charge : $\left\langle \mathcal{O} \right\rangle_\theta = \left\langle \mathcal{O} e^{i\theta Q} \right\rangle_0$
- Alternatively, one could put θ term into the ensemble probability, rather than observable, if θ is analytically continued to pure imaginary.

$$\theta \longrightarrow -i\theta$$

- Spin splitting becomes <u>real:</u>

$$m_{N^\theta}(\mathrm{E}\,,\uparrow) - m_{N^\theta}(\mathrm{E}\,,\downarrow)$$
$$= 2i\theta d_N S\cdot E \longrightarrow -2\theta d_N S\cdot E$$

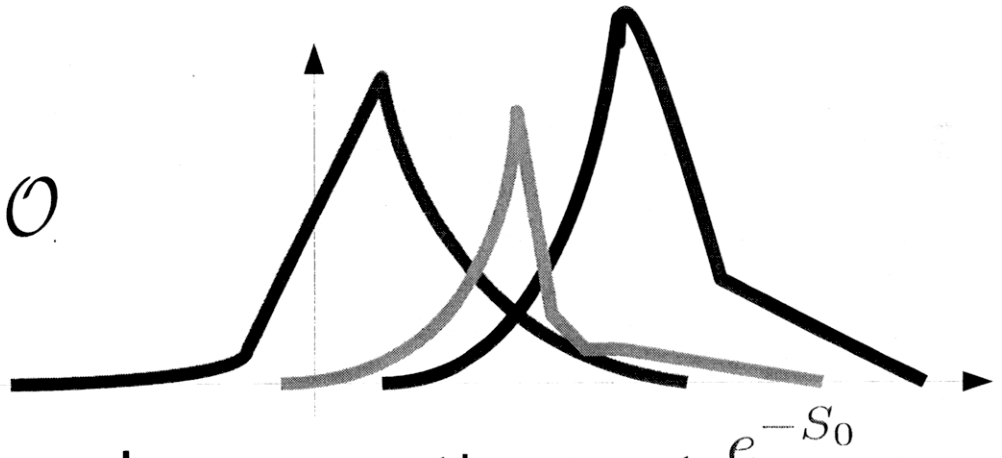
previously done by Minkowskian E .

- 85 Bhanot-David, 02 Azcoiti et. al
  06 Imachi-Yoneyama et.al.
  (CP^N model with imaginary theta)
- 02 de Forcrand-Philipsen,
  03 D'Elia-Lombardo (chem. pot.)

more loyal to the MC philosophy

- Important sampling:
  Concentrate on points (configuration) where the integrand is large

$$\langle \mathcal{O} \rangle = \int [DU] e^{-S_0} e^{-S_\theta} \mathcal{O}$$



- In usual QCD simulation only $\theta = 0$ action part, e^{-S_0} is used for generating vacuume ensemble, and later the "observable" part, $e^{-S_\theta}\mathcal{O}$, is measured.
- important sampling not only for action but also for the measurement. Justifiable for difficult problems ?

Simulation with imaginary θ term

- two choices
  - gluonic $S_\theta = \frac{1}{32\pi^2}\theta\sum \tilde{F}F(x)$ needs smearing/cooling
  - fermionic: by using anomalous chiral WT relation

    $\psi \longrightarrow e^{\theta\gamma_5}\psi$

    $\bar{\psi} \longrightarrow \bar{\psi}e^{\theta\gamma_5}$ (flavor-singlet "chiral" rotation)

    $\mathcal{D}\psi\mathcal{D}\overline{\psi} \rightarrow \mathcal{D}\psi\mathcal{D}\overline{\psi}\ e^{S_\theta}$

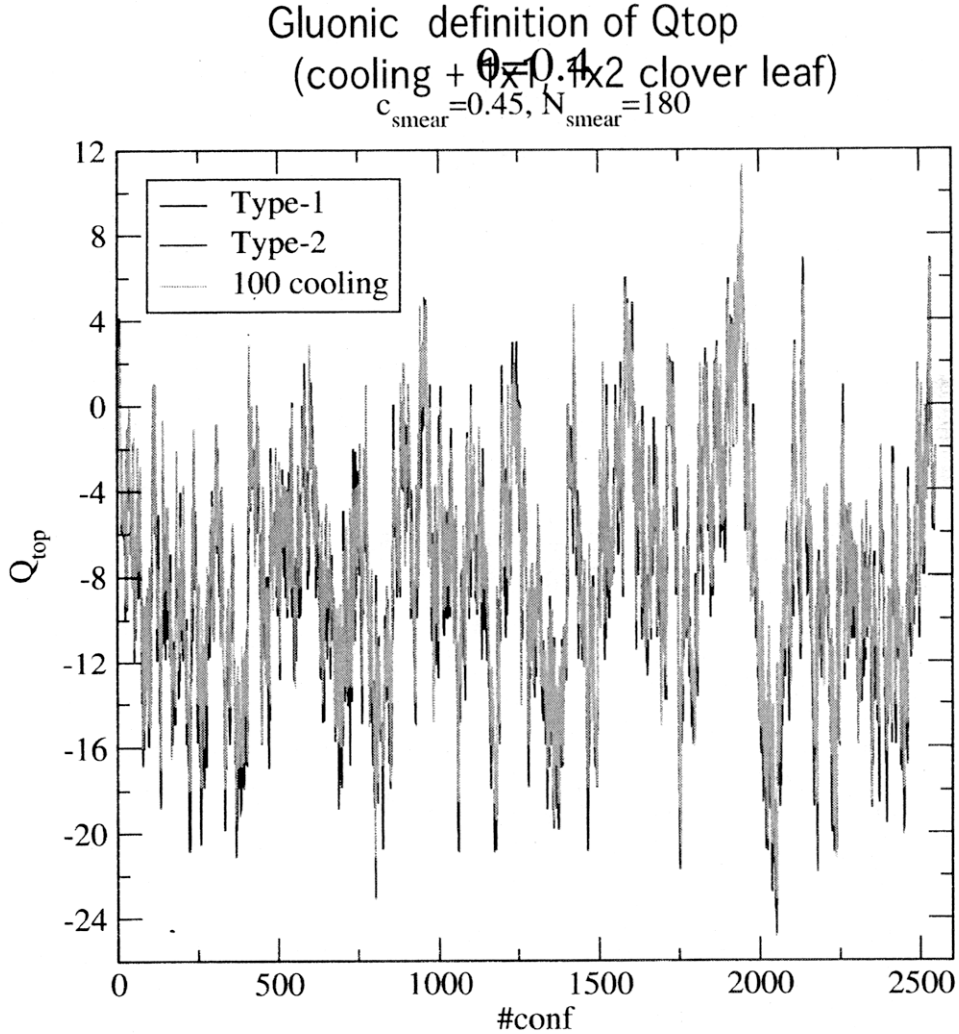
    $\mathcal{L}_\theta = \frac{m\theta}{2}\overline{\psi}\gamma_5\psi$
- Nf=2 dynamical clover fermion
  - fast $\psi(D_W + m + ia\frac{c_{SW}}{4}\sigma_{\mu\nu}F_{\mu\nu})\psi(x)$
  - θ term into the clover term's implementation

$$\begin{pmatrix} \frac{\theta''}{2} + \sigma\cdot B - \sigma\cdot E & 0 \\ 0 & \frac{-\theta''}{2} + \sigma\cdot B + \sigma\cdot E \end{pmatrix} \quad \theta'' = \left[1 - \frac{\kappa}{\kappa_c(\beta)}\right] Z_P\theta$$

  - DWF/GW is nicer, definitely.

Progress report of EDM calculation

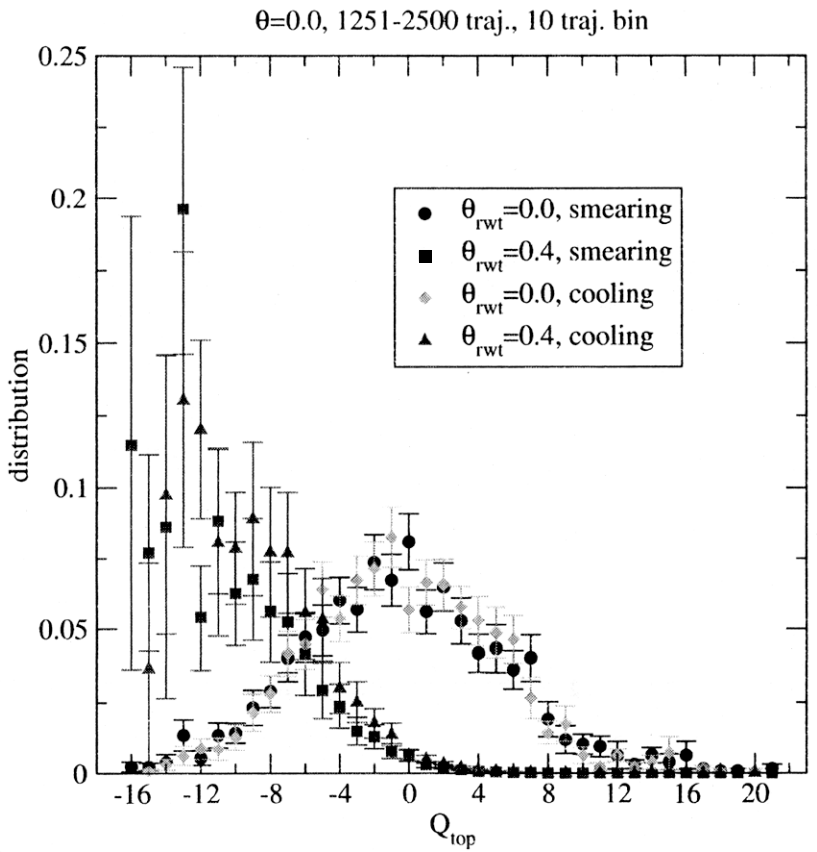
- Nf=2 clover fermion
- 16^3 x 32
- beta=2.1 Iwasaki
  1/a = 2 GeV
- kappa = 0.1357
  mPS/mV = 0.85
- theta = 0.4, 0.0
- tau= 1 x 2,500 trajs.
- CPS++ & DESY code
  Sexton-Weingarten & Hasenbush accel.



$$Q_{\rm top} = \frac{1}{32\pi^2} \sum \tilde{F} F(x)$$

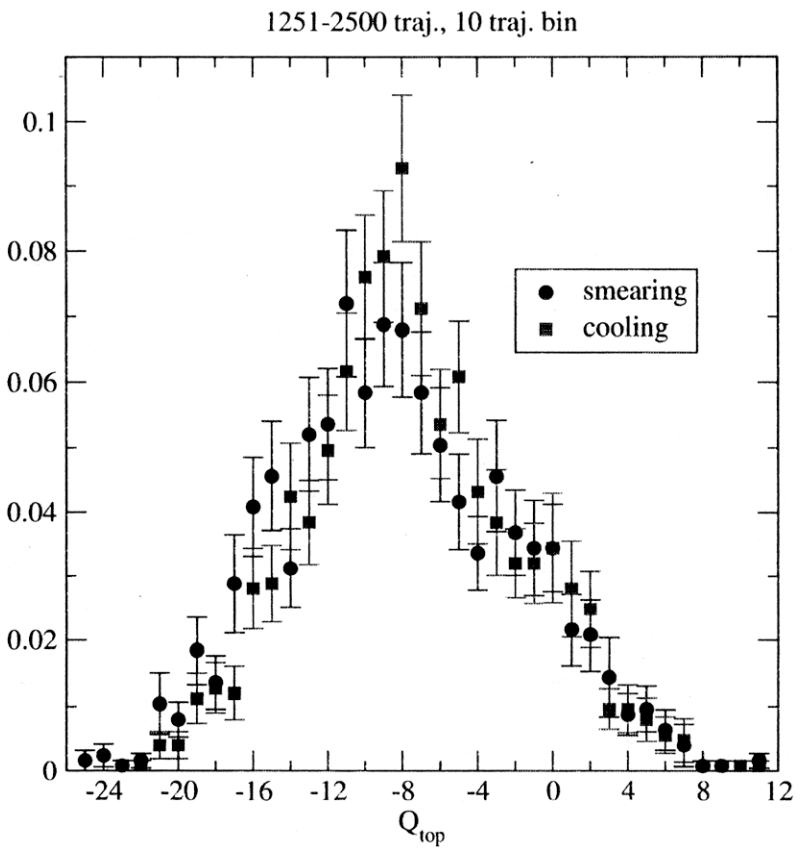
Qtop distribution (from Bosonic definition)

- θ=0.0



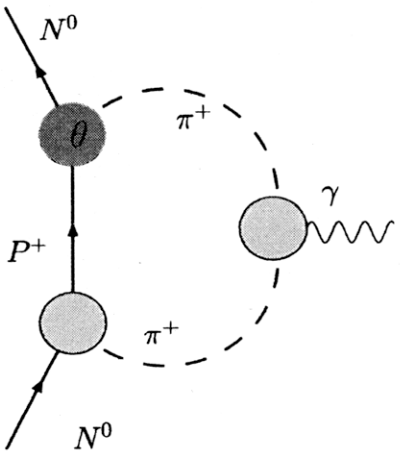
- <Q>=-0.6
- width = 5.8

- θ=0.4



- <Q>=-7.9
- width = 6.0

Preliminary results of NEDM



- The third smallest Uniform Electric field

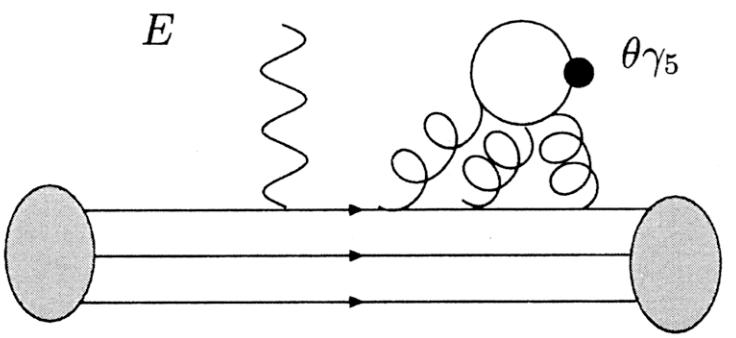
$$E_Z = \frac{2\pi}{N_z N_t} \times 3 \simeq 0.0368$$

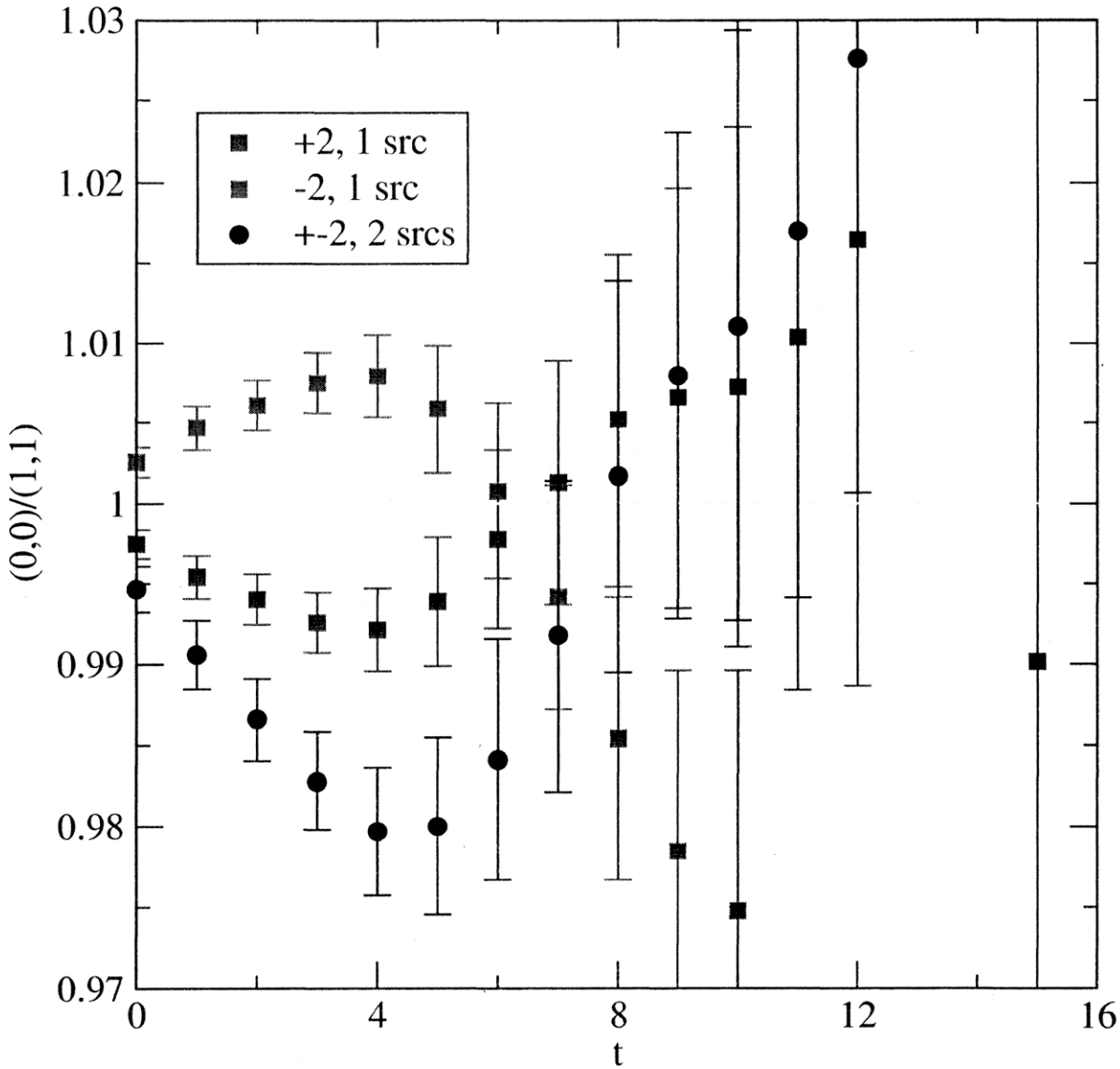
- quark charges = {+,-} 1, 2 x { 2/3, -1/3 }
- tsrc = 0, 16, Nucleon 2pt corr. func. (4x4)

$$\frac{\langle N_\uparrow(t)\overline{N}_\uparrow(t_{src})\rangle}{\langle N_\downarrow(t)\overline{N}_\downarrow(t_{src})\rangle} \to c\, e^{\Delta m t}$$

$$\Delta m = m_{N^\theta}(\mathsf{E},\uparrow) - m_{N^\theta}(\mathsf{E},\downarrow)$$

$$= -2\theta d_N \mathsf{S}\cdot\mathsf{E}$$





- Spin splitting of the Nucleon propagator

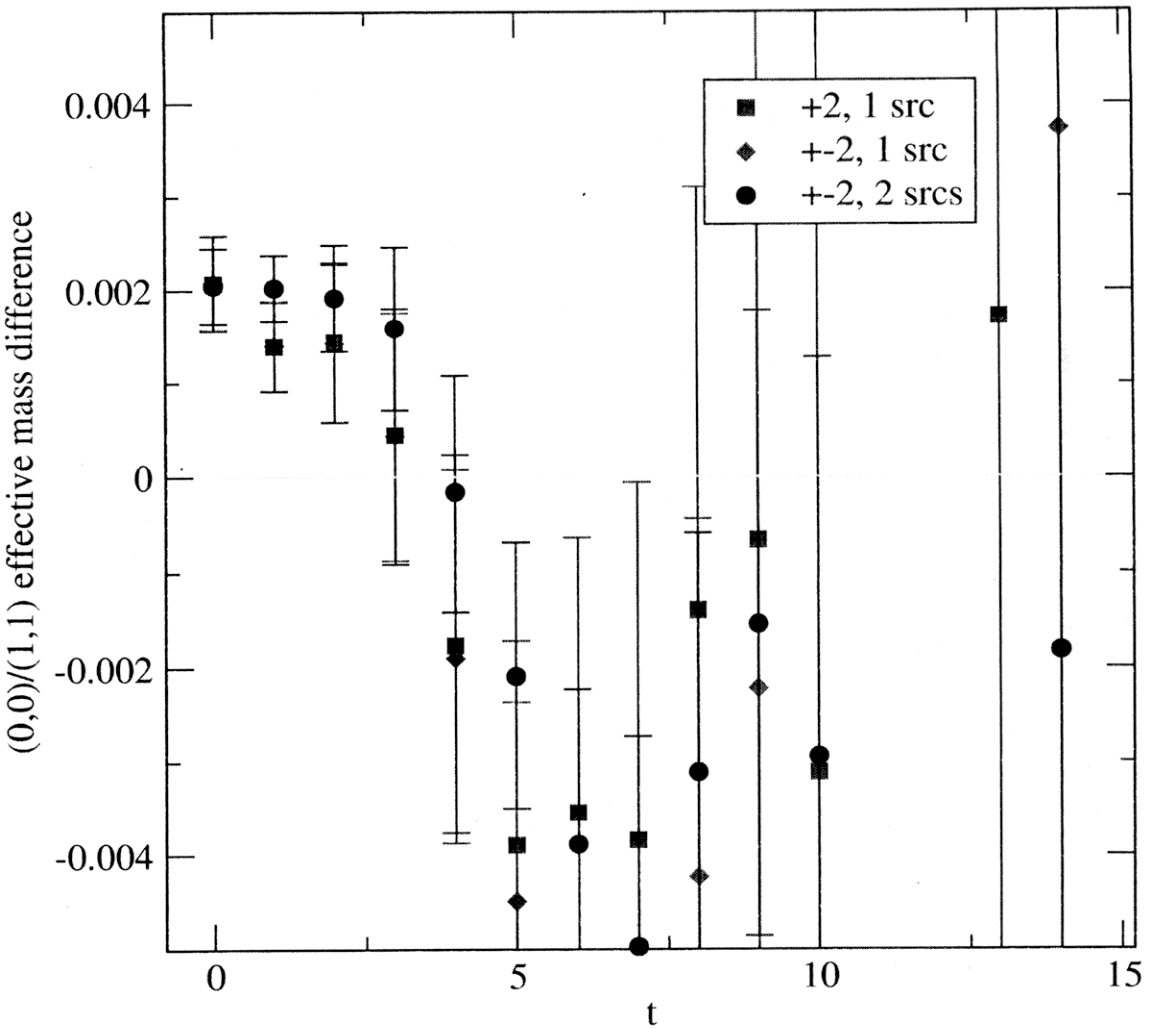
$$c \exp(\Delta m t)$$

$$\simeq c(1 + \Delta m t)$$

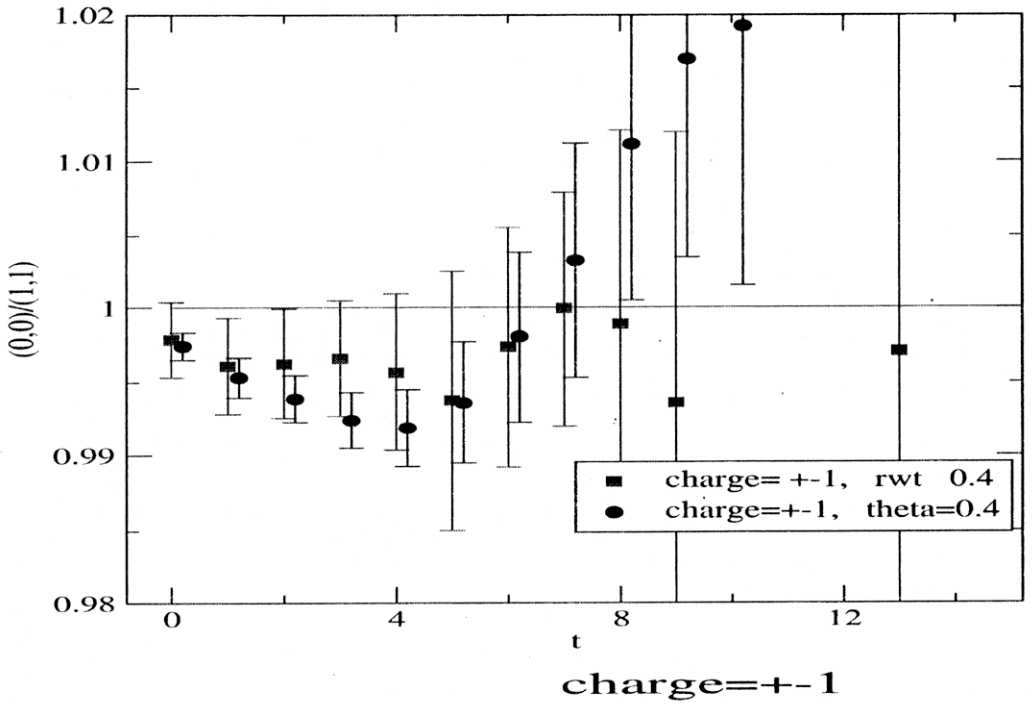
- +/- charge, two sources help
- signal at t < 5
- excited state contamination should be checked

effective energy splitting

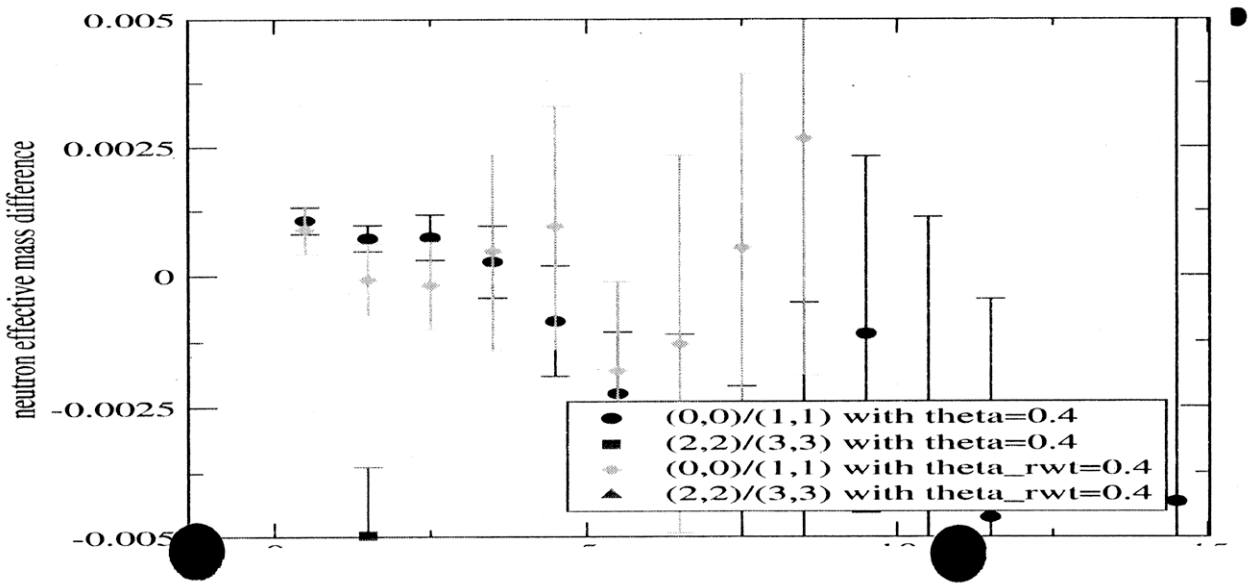
- average t, Nt-t at propagator level
- numbers are comparable to the previous estimations
- need to be checked by F_3



comparison with reweighting method

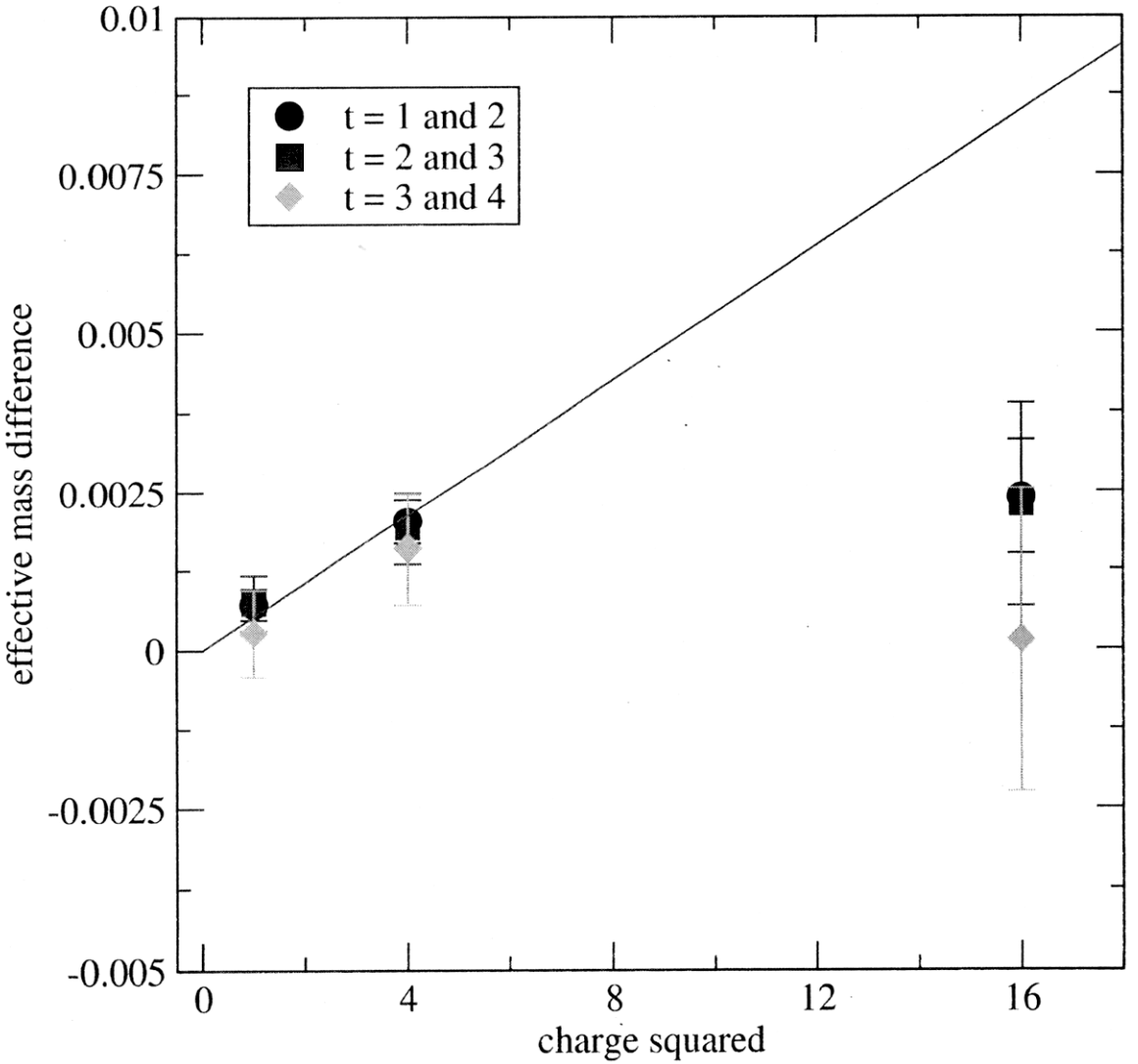


charge=+-1



- charge= +/- 1
- reweighting method has larger error bar
- Further nested ratio ?
  - G(theta=0)
  - G(mag)

Electric charge dependence

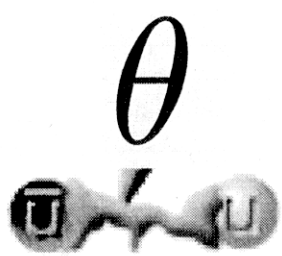


- Consistent with charge squared scaling for smaller two charges.
- Higher order effects is seen for Q = 4

effective value of theta

- fermionic θ needs calibration just like mass does.
  - clover to continuum matching of $im\theta \times \overline{\psi}\gamma_5\psi$
- We could define renormalized theta by $Q(\theta)$ which gives rougly 0.6(1) of bare value
- One could also check the effect of θ in other hadronic observable (most notably in PS mesons).
  - 03 Brower et.al, 07 Aoki et.al,

$$M_\pi^2(\theta) = M_\pi^2(0)\cos(i\theta/N_f)$$



  - Mps(th=0) : 0.6279(17) t in [9,16]
  - Mps(th=0.4): 0.6327(21) t in [9,16]
  - gives

$$\theta\,(\text{chpt}) = 0.35\begin{pmatrix}+12\\-19\end{pmatrix} = 0.4\times 0.88\begin{pmatrix}+30\\-48\end{pmatrix}$$

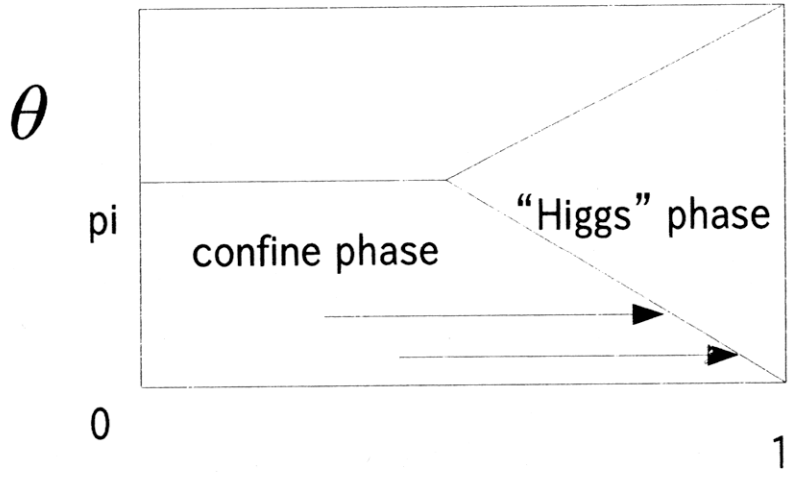
renormalization of θ ?

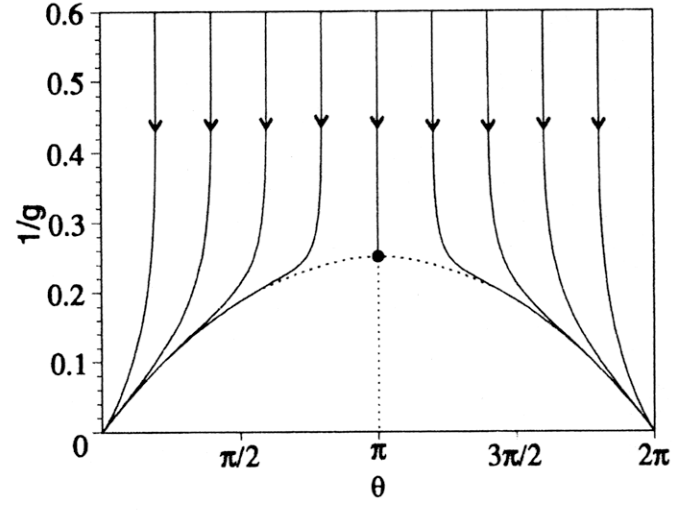
(despite of Adler-Bardeen ?)

- '94 Schierholz argued an interesting possibility that CP(n) & QCD may not be confined in the continuum limit when

$$\theta \neq 2\pi \times N$$

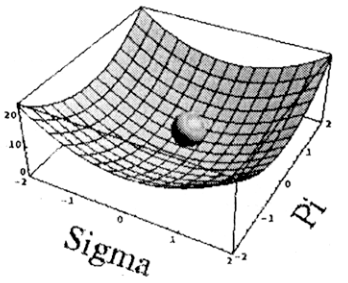
- '06,'07 Apenko : estimations of RG flow of theta in Quantum ring.
- '07 Gurosoy, Kiritsis, Nitti, in Holographic QCD, suggest the possibility that the non-perturbatively renormalized theta runs strongly into zero at IR.





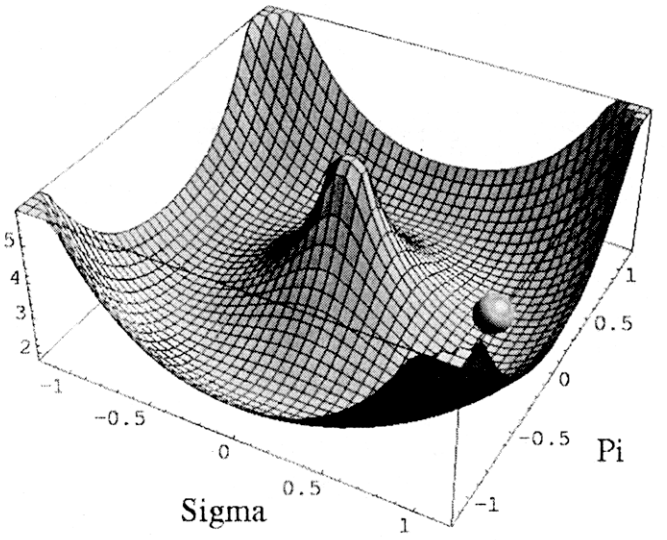
$m_\pi = 135\mathrm{MeV}$
$m_K = 498\mathrm{MeV}$
$m_{\eta'} = 958\mathrm{MeV}$

Strong U(1)$_A$ puzzle



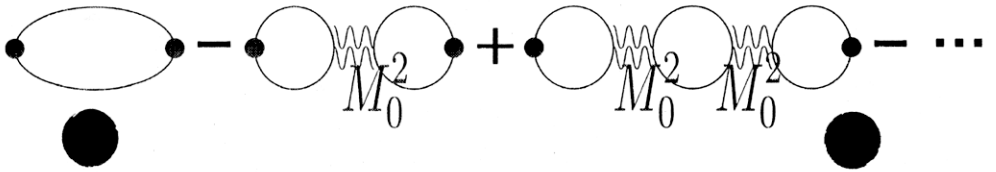
- psuedoscalar (PS) mesons are light as it would be NG-boson in quark (u,d,s) massless limit, where the spontaneous chiral symmetry breaking occurs : $SU(3)_V \times SU(3)_A \to SU(3)_V$
- But flavor singlet PS, η' , is special as U(1)$_A$ current is broken by quantum anomaly.

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

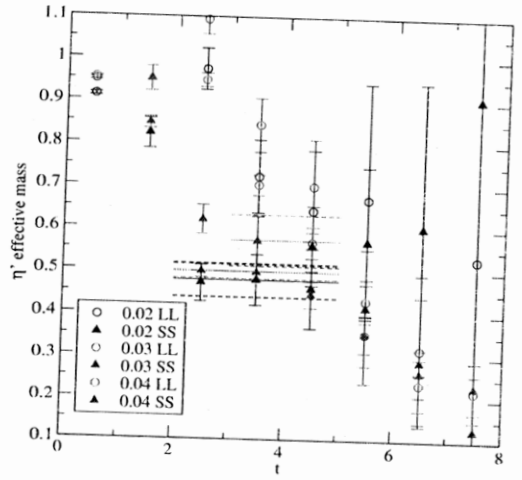


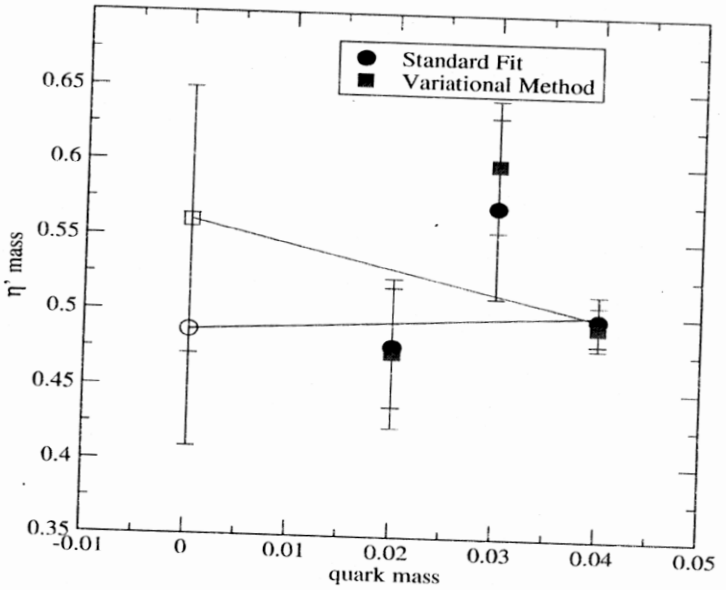
- DWF is an ideal fermion to investigate this puzzle along with WV formula:

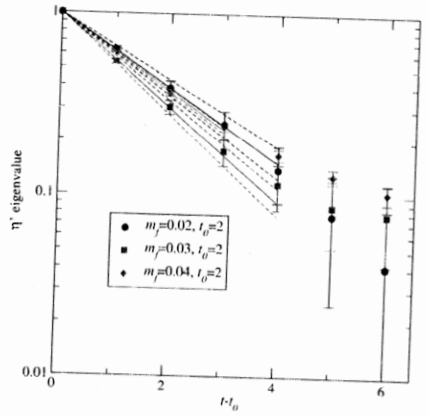
$$M_0^2 = m_{\eta'}^2 - m_\pi^2 = \frac{2N_f}{f_\pi}\frac{\langle Q^2_{top} \rangle}{V}$$



Preliminary eta' using DWF (Nf=2)





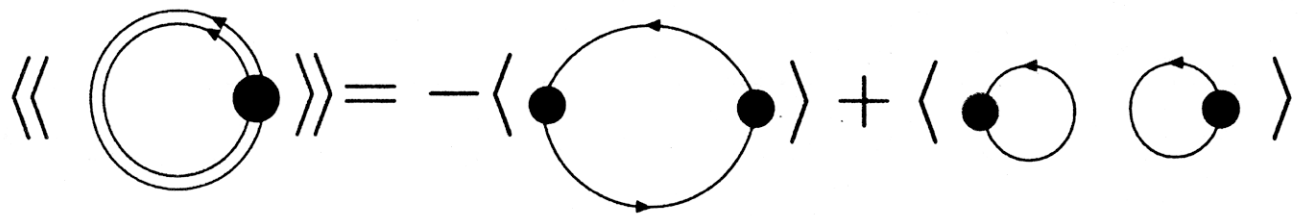


- 2 fm box, PS/V = 0.5, 0.60, 0.65
- 500-1,000 conf x {1~3} noise
- Gaussian src/snk
- variational method
- non-NG chiral extrap.

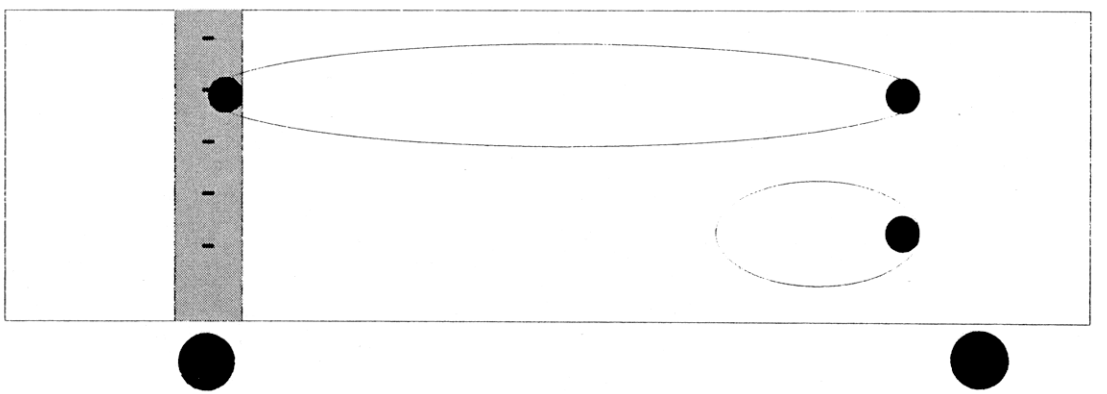
θ simulation for disconnected quark loop

- Restrict θ to a time slice, call it λ_s.
- Measure PS 1pt function with λ_v at the time.
- By using an identity, $\partial_\lambda D^{-1} = -D^{-1}(\partial_\lambda D)D^{-1}$

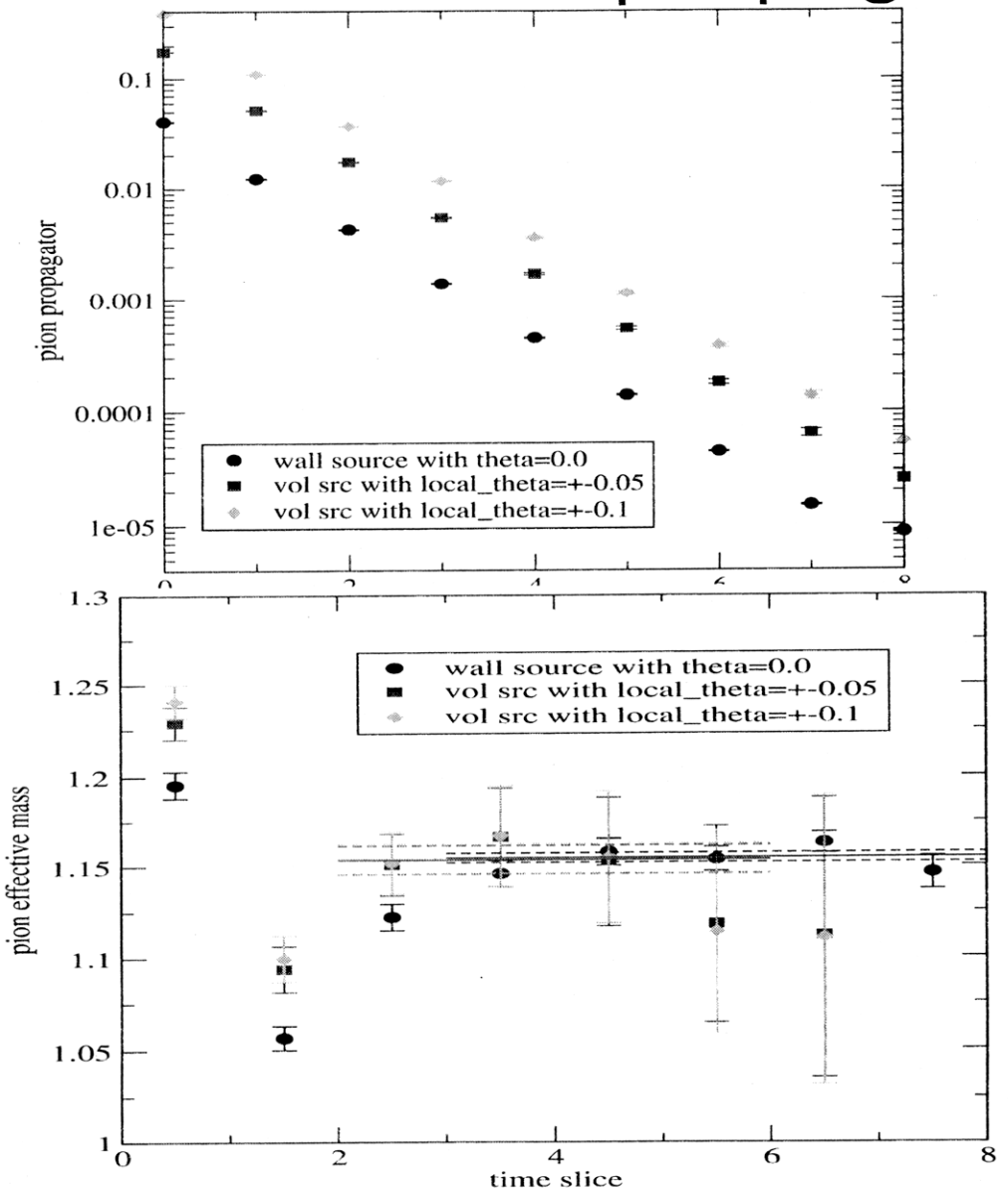
$$\langle \mathrm{Tr}\gamma_5 {D_{\lambda_v}}^{-1}(t,t)\rangle_{\lambda_s} = -\lambda_v \langle \mathrm{Tr}\gamma_5 D^{-1}(t,t_{src})\gamma_5 D^{-1}(t_{src},t)\rangle_0 + N_F\lambda_s \langle \mathrm{Tr}\gamma_5 D^{-1}(t,t)\mathrm{Tr}\gamma_5 D^{-1}(t_{src},t_{src})\rangle_0$$



- Similar to Ising with localized magnetic source

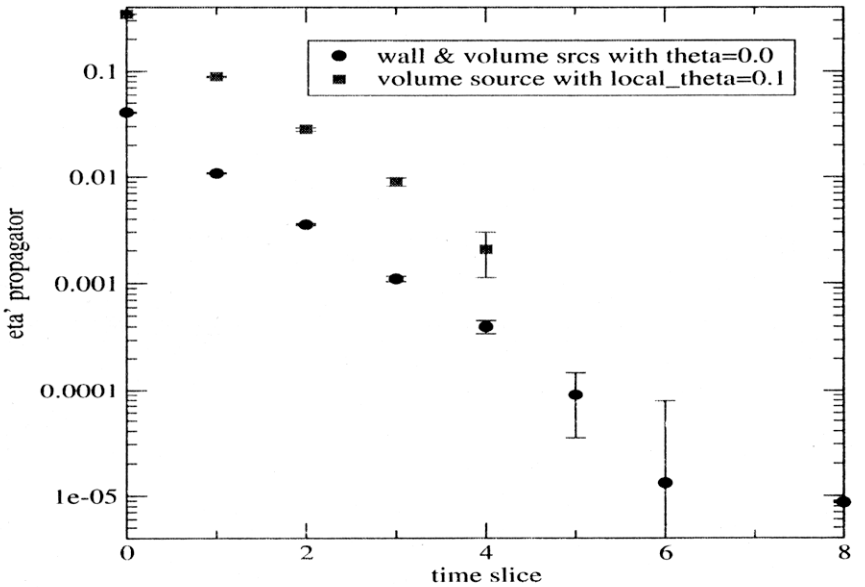


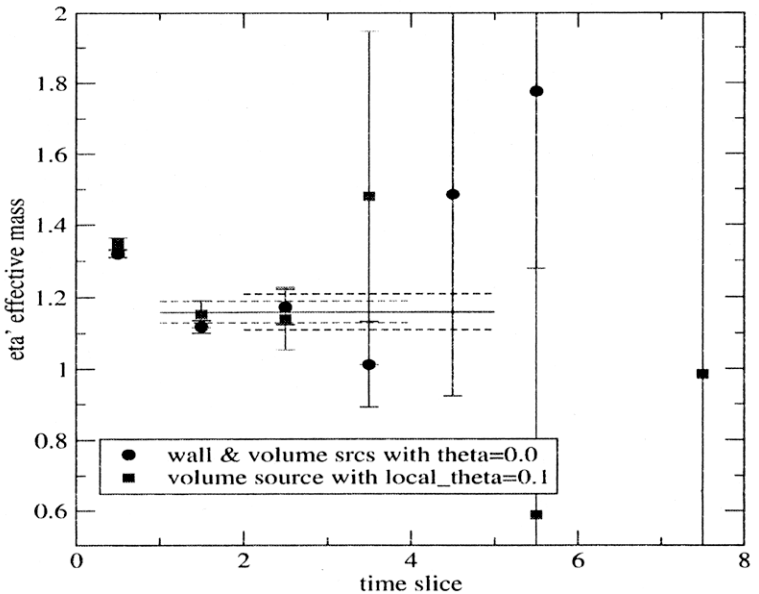
Connected propagator on theta=0



- As a test, a comparison of usual pion spectrum with that using valence theta is made
- 8^3 x 16, a = 0.2 fm x 1000 confs
- The new method using a 1PT while the traditional method calculate 2PT correlation functions
- Signal, so far, seems to be better for the conventional method.

Very preliminary η' on θ lattice





- Traditional method : calculate two 2PT correlators, connected & disconn.
- New method: just one 1PT correlators with both valence and sea θ terms
- statistical error is larger for new method, so far.....
- Lattice CP transformation helps ?

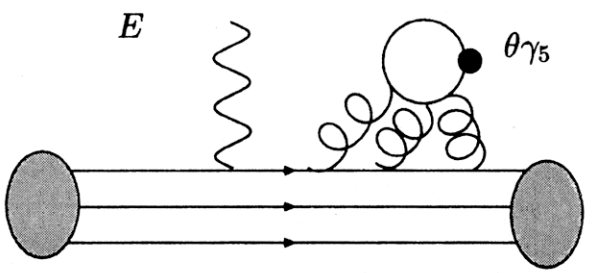
Summary & Discussions

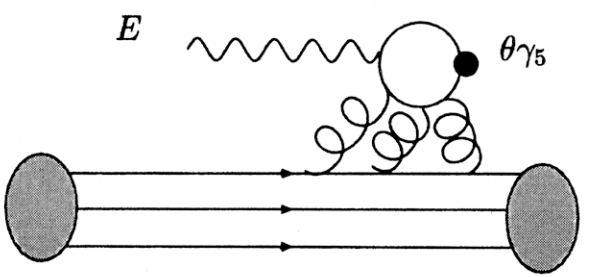
- Weak & Uniform {E,M} field is useful to avoid boundary effects.
- Dynamical simulation with imaginary θ term could control topology distribution of QCD ensemble.
  (one could put very large/small Qtop on small lattice)
- It may provide better/correct statistics in the sense of the important sampling than putting it in the valence; ensemble dedicated for a certain class of applications.
  (c.f. Schroedinger Functional)
- More careful studies on larger statistics are needed to conclude whether this method is worth trying .
- The renormalization of θ is needed, at least, on lattce.
- Disconnected diagrams calculation, so far, were not improved by the new method using the local θ term .

Future prospects

- Improving current calculation
  - More statistics
  - Form factor $F_3(q^2)$ calculation
  - several θ values to check $\mathcal{O}(\theta^2)$
  - quark mass dependence, $d_N \to 0$
- NEDM needs another disconnected quark loop contribution.

(07 Shintani et.al.)





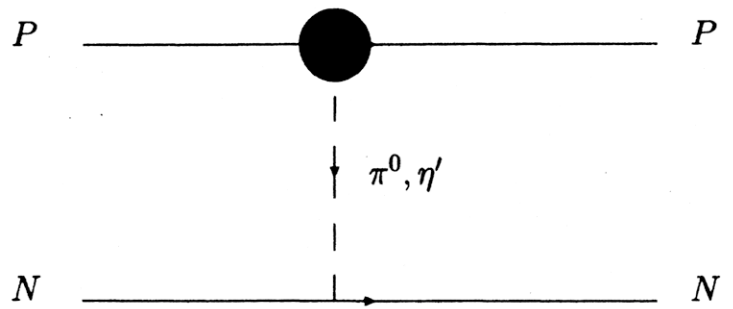
Future prospects (cont.)

- Quark (C)EDM on lattice ?

  ('03 Hisano-Shimizu, Nagai et. al.)

  - $i\frac{d_q^C}{2}\overline{\psi}\sigma_{\mu\nu}\gamma_5 F_{\mu\nu}\psi$ may be doable by $d_q^C \to -id_q^C$
  - mixing with other operator would be hard

- Study of Deutron, Hg ...'s EDM ?
  measuring CP-violating couping



Acknowledgments

- Nf=2 DWF is generated by the RBC collaboration.
- We are grateful for authors/maintainers of DESY code and CPS++, which are used for ensemble generation and measurements.
- We thank for computational resources supported by the Large Scale Simulation Program No. 07-14 (FY2007) of High Energy Accelerator Research Organization (KEK), the RIKEN Super Combined Cluster (RSCC), and QCDOC at RBRC & Columbia University.

Too much reweighting is dangerous

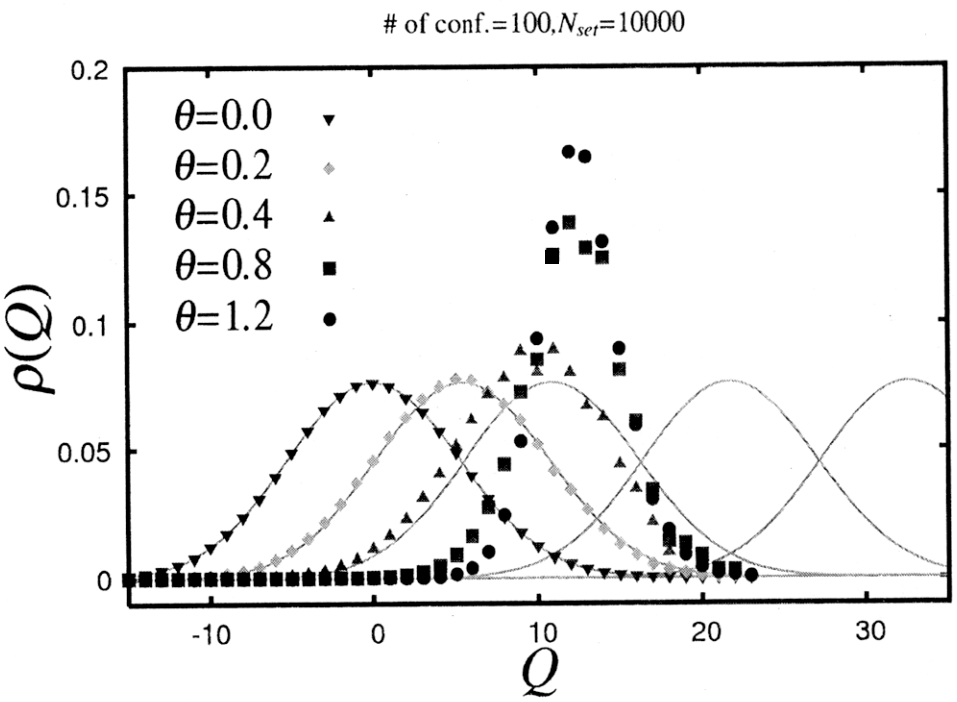
- An observable

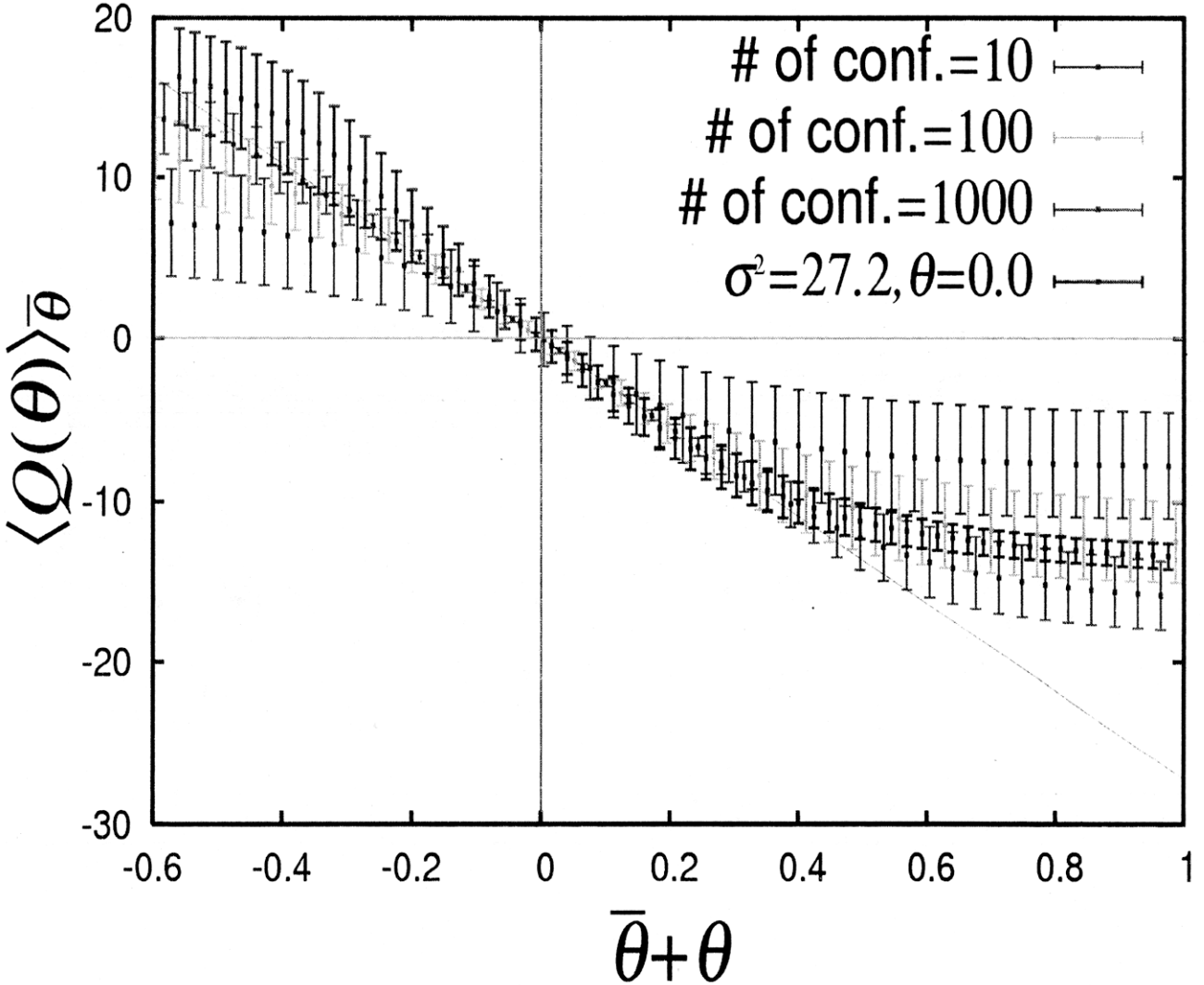
$$\langle Q e^{\theta Q} \rangle$$

always breaks the central limit theorem for large enough θ with fixed statistics.

- Gaussian mock-up data

- Nconf=100





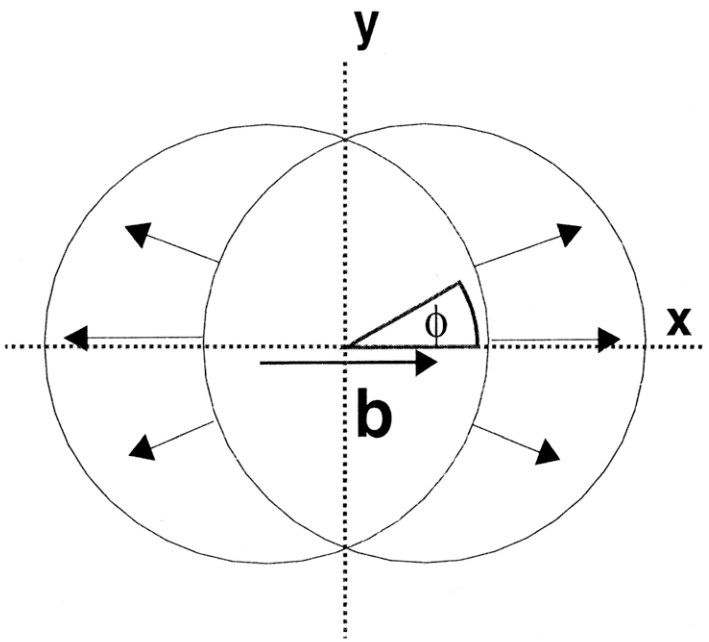
- Large enough reweighting gives biased results and underestimated error.
- Compared to theta=0.0 real simulation data result (red), we could get a hint of # of independent configuration, ~ 100 might be appropriate.

Understanding Transport in Heavy Ion Collisions

Derek Teaney

SUNY Stonybrook and RIKEN-BNL Research Center

Observation:



There is a large momentum anisotropy:

$$v_2 \equiv \frac{\left\langle p_x^2 - p_y^2 \right\rangle}{\left\langle p_x^2 + p_y^2 \right\rangle} \approx 20\%$$

Interpretation

- The medium responds as a fluid to differences in X and Y pressure gradients

Ideal Hydro models "work"

How to probe this picture?

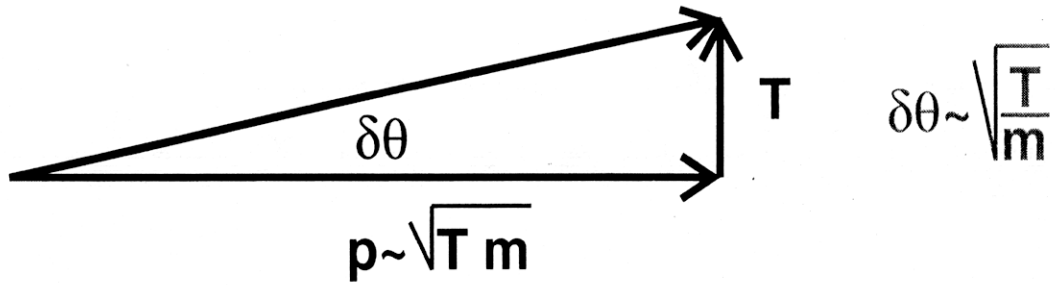
- Study the equilbration of heavy quarks
  - Model the interaction of heavy quarks with the medium
  - Understand transport at strong coupling using AdS/CFT.
    - Heavy Quark energy loss
    - Heavy Quark fluctuations
    - Quarkonium Drag (in progress)
- Viscous Hydrodynamics.
  - Last week with K. Dusling: nucl-th/0710.5932
  - A summary of work that I've been talking about for a long time
  - I won't discuss this today.

Modelling Heavy Quarks interacting with Medium

Goal: to illustrate how I started studying AdS/CFT

Estimate of transport times with Heavy Quarks

- Put a heavy quark in this medium

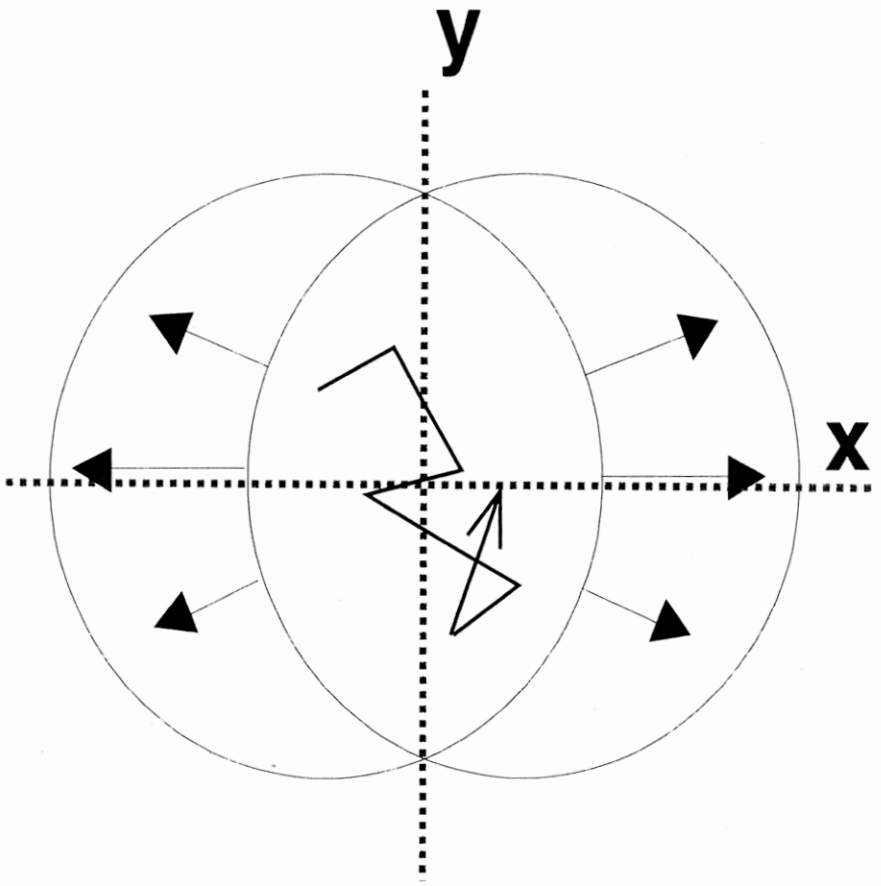


- The charm quark undergoes a random walk suffering many collisions
- The relaxation time of the heavy quark is:

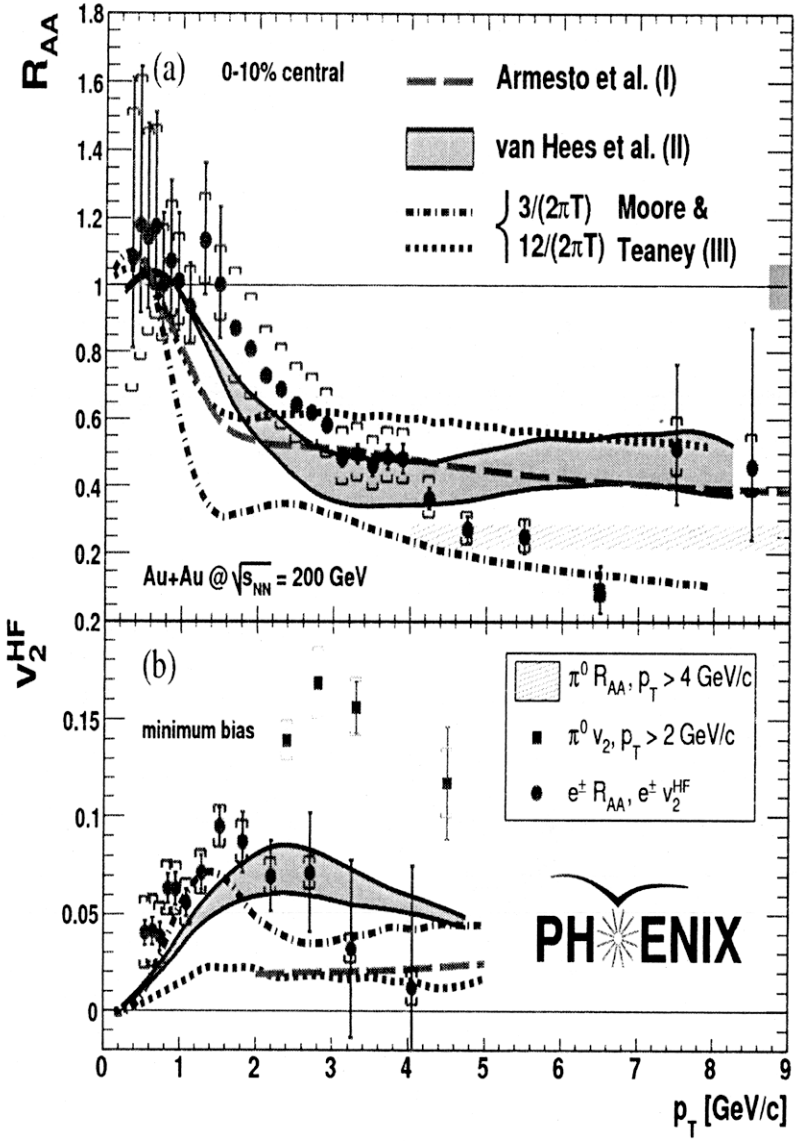
$$\tau_R^{\text{charm}} \sim \frac{M}{T}\tau_R^{\text{light}}$$

If you think you know the relaxation time you should be able to compute the charm spectrum.

Hydro + Brownian Heavy Quarks



The heavy quarks will either relax to the thermal spectrum and show the same v_2 as all thermal particles or not depending on the Drag/Diffusion coefficients and p_T.



Summary

1. Suppression and Elliptic Flow are intimately related.
2. From the suppression pattern, we estimate that

$$D \lesssim \frac{12}{2\pi T}$$

With this diffusion coefficient, I can't produce enough elliptic flow.

AdS/CFT and Heavy Quark Transport

1. Heavy Quark Diffusion

Matching Langevin to a Microscopic Theory

- Heavy Quarks are Quasi Classical

$$\lambda_{\text{de Broglie}} \sim \frac{\hbar}{\sqrt{MT}} \ll \frac{\hbar}{T}$$

- Compare the Langevin process to the microscopic theory

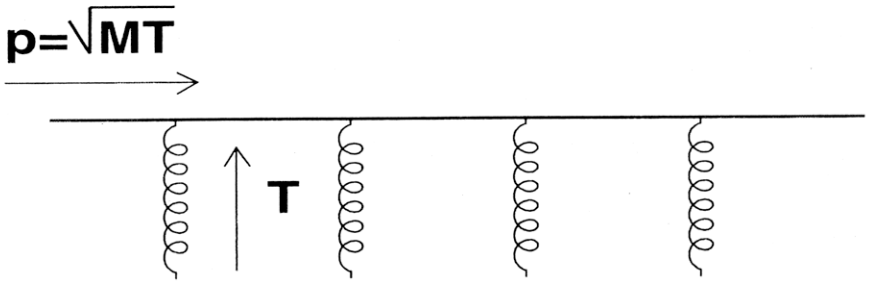
Langevin	Microscopic Theory
$\frac{dp}{dt} = -\eta_D p + \xi(t)$	$\frac{dp}{dt} = qE(t, \mathbf{x})$

- Match the Langevin to the Microscopic Theory

Langevin	Microscopic Theory
$\kappa = \int dt \, \langle \xi(t) \, \xi(0) \rangle$	$\kappa = q^2 \int dt \, \langle E(t, \mathbf{x}) E(0, \mathbf{x}) \rangle$

Diffusion Coefficient $\leftrightarrow$ Electric Field Correlator

QCD and Color: Heuristic Derivation



- Use Wong equations for a classical color charge

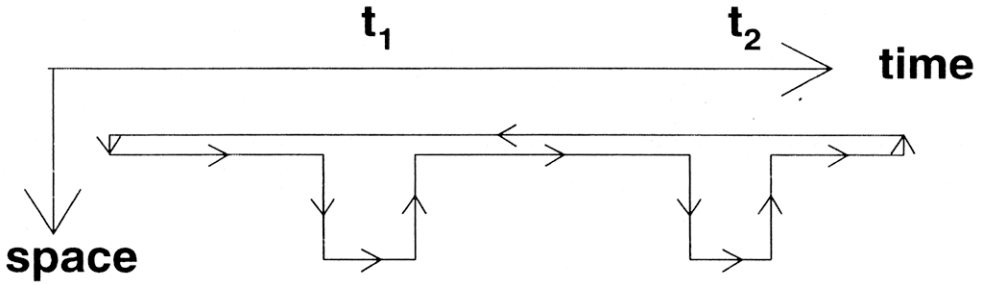
Langevin	Microscopic Theory
$\frac{dp}{dt} = -\eta_D p + \xi(t)$	$\frac{dp}{dt} = \mathrm{Tr}\,[Q\,E(t,\mathbf{x})]$
	$\partial_t Q = \underbrace{-i[Q, A_0(t,\mathbf{x})]}_{\text{Color Precession}}$

- Then compare to the microscopic theory:

$$\kappa = \frac{C_R}{d_A} \int dt \, \left\langle E^a(t,\mathbf{x})\, U_{ab}(t)\, E^b(0,\mathbf{x}) \right\rangle$$

Wilson Lines and the Diffusion Coefficient:

- Variations of Wilson Lines give electric field correlators

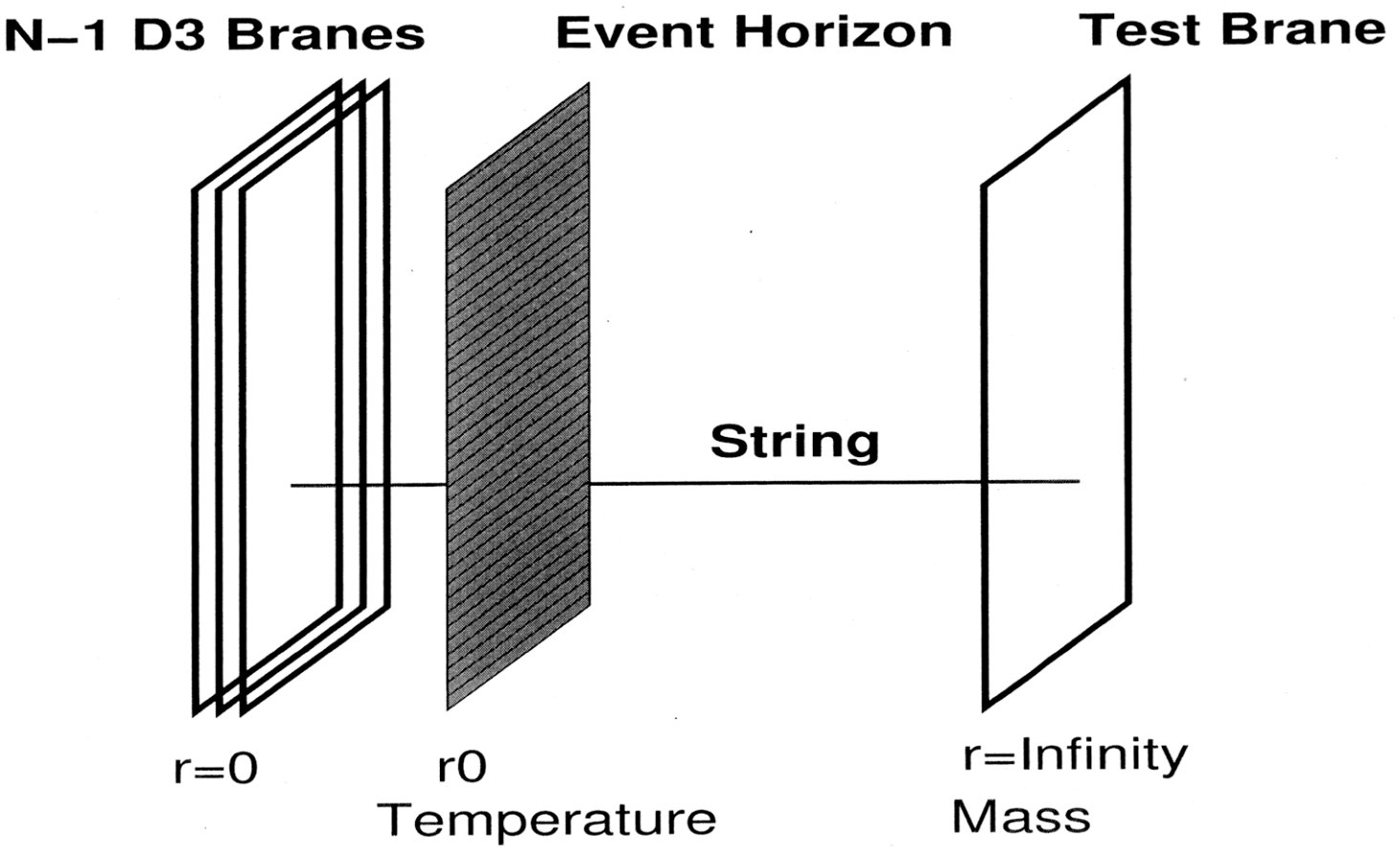


$$\left\langle \frac{1}{i^2} \frac{\delta^2 W[\delta x]}{\delta x(t_1)\, \delta x(t_2)} \right\rangle \sim \langle\, T\,[\, E(t_2) E(t_1)\,]\,\rangle$$

- Put the Wilson line along the Schwinger-Keyldish contour.

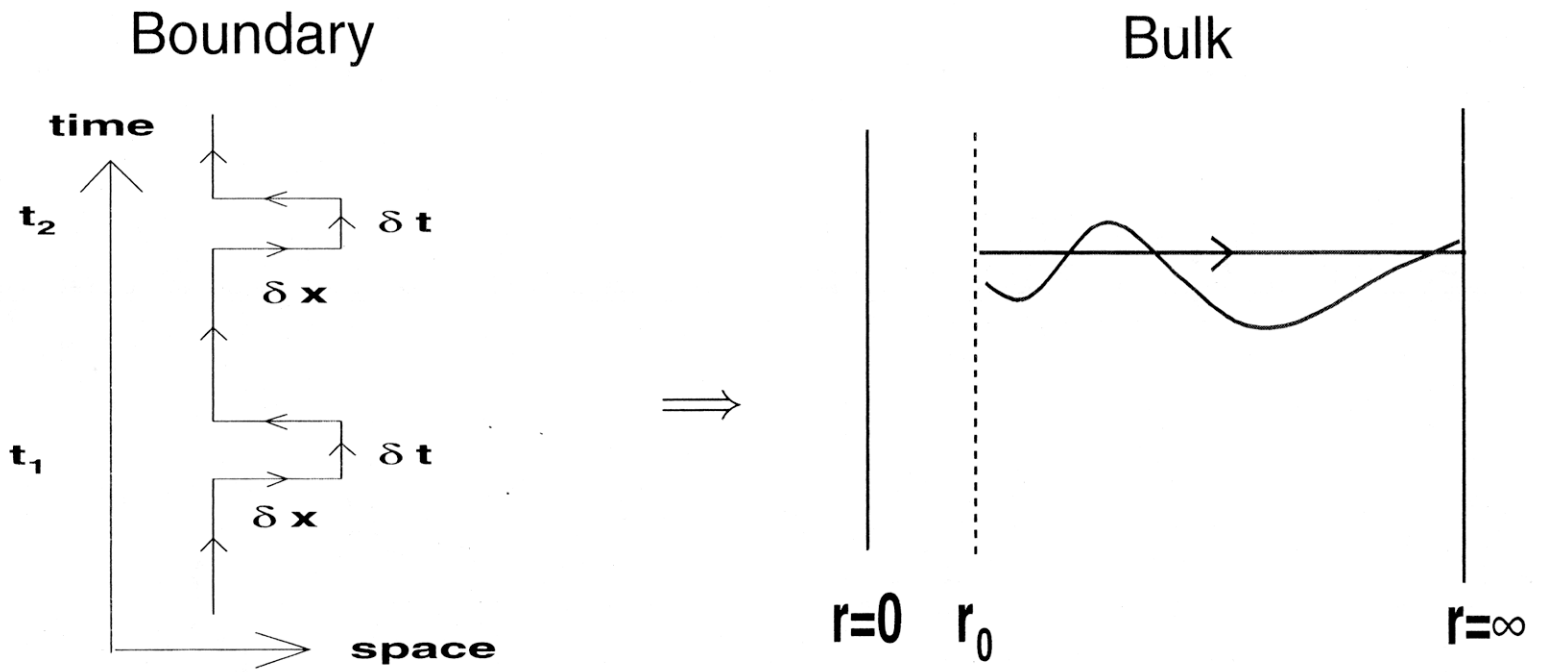
$$\kappa = \frac{1}{3} \lim_{\omega \to 0} \int dt\, e^{+i\omega t} \left\langle \frac{1}{i^2} \frac{\delta^2 W[\delta x]}{\delta x_2(t)\, \delta x_1(0)} \right\rangle$$

The AdS/CFT correspondence and the Wilson Line – Maldacena, S.Rey



Measure the diffusion of the heavy boson with the dynamics of the string

Testing the string dynamics:



$W[\delta x]$ $\qquad\qquad$ $S_{cl}[\delta x]$

$$\frac{1}{\langle W_C[0]\rangle}\,\langle W_C[\delta y]\rangle = \frac{1}{e^{iS_{cl}[0]}}\,e^{iS_{cl}[\delta y]}$$

Summary of Technical Steps

- Fluctuate the end point of a string at $r = \infty$ at very small frequencies: $u = 1/r^2$

$$S_{NG} = \frac{R^2}{2\pi\ell_s^2} \int \underbrace{dt\, dr}_{\text{Area}} \Bigg[1 - \underbrace{\frac{1}{2}\left(\frac{\dot{y}_\parallel^2}{f} - 4fu\left(y_\parallel'\right)^2 \right)}_{\text{Quadratic Fluctuations}} \Bigg]$$

- Solve for the waves along the string in the $AdS_5 \times S_5$ metric
  - Impose incoming boundary conditions for retarded propagator .
- Differentiating twice with respect to δy yields the retarded force force correlator

$$\langle E(t)E(0)\rangle \sim \frac{\delta^2}{\delta y(t)\delta y(0)} \langle W[\delta y]\rangle \sim \frac{\delta^2}{\delta y(t)\delta y(0)} e^{iS_{NG}[\delta y]}$$

κ is the imaginary part of the retarded correlator

Results:

- Mean Squared momentum Transfer

$$\kappa = \pi \underbrace{\sqrt{\lambda}}_{\text{Large } g^2 N_c} \times \underbrace{T^3}_{\text{dimension}}$$

- Answer:

$$\begin{aligned} D &= \frac{2T^2}{\kappa} \\ &= \frac{2}{\sqrt{\lambda}\pi T} \end{aligned}$$

QCD Guesses: Strong Coupling

- Strong Coupling: $\mathcal{N} = 4$ SUSY. $\lambda \approx 5 \leftrightarrow 20$

$$D = \frac{1}{\sqrt{g_{YM}^2 N_c}} \frac{4}{2\pi T} \quad \longrightarrow \quad D \simeq \frac{1.0 \leftrightarrow 2.0}{2\pi T}$$

- Weak coupling (Aleski Vuorinnen)

  2 gluons + 6 scalars + 8 fermions $\neq$ 2 gluons

$$\frac{D_{QCD}}{D_{SYM}} = \frac{6}{1 + \frac{N_f}{2N_c}} \approx 4$$

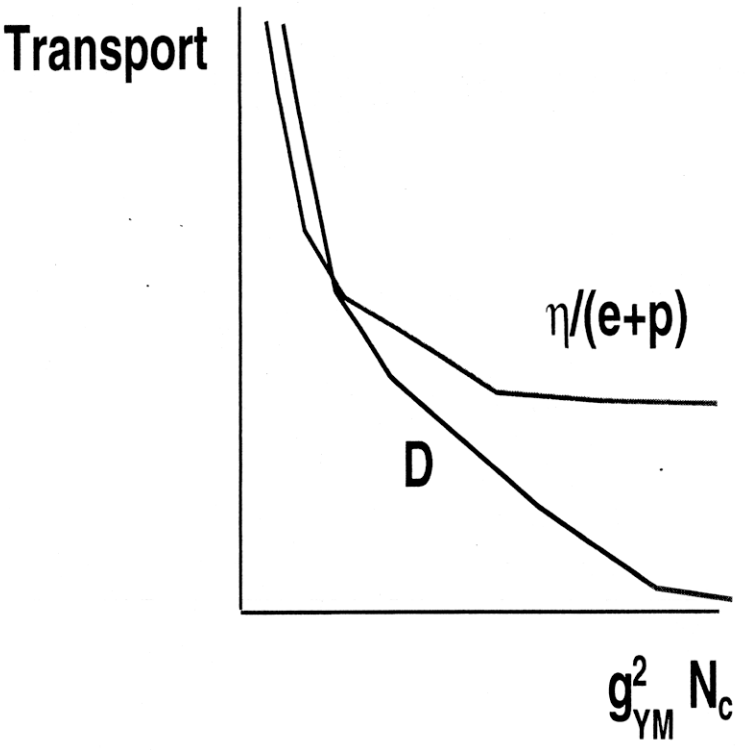
- Best guess for QCD from strong coupling

$$D \approx \frac{4.0 \leftrightarrow 8.0}{2\pi T}$$

Compare to weak coupling best guess $D \approx 6/(2\pi T)$

Heavy Quark Diffusion is Parametrically Small

$$D = \frac{1}{\sqrt{g_{YM}^2 N_c}} \frac{4}{2\pi T} \qquad \frac{\eta}{e+p} = \frac{1}{4\pi T}$$



Constraint On The Heavy Quark Mass

- To treat the heavy quark as a quasi-classical quasi-particle we need

$$\tau_R \gg \frac{\hbar}{T}$$

- Then we have

$$\tau_R \sim \frac{M}{T} D \qquad\qquad D = \frac{2}{\sqrt{\lambda}\pi T}$$

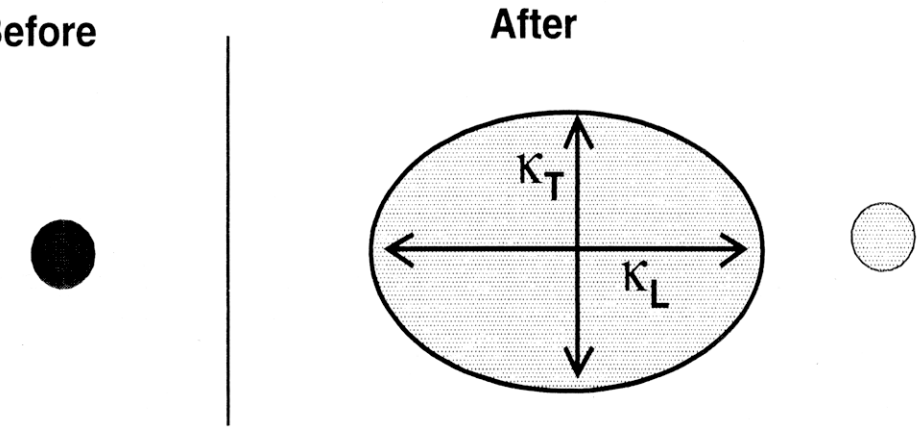
- This leads to a constraint on Mass/String Length

$$M \gg \frac{\pi T}{2}\sqrt{\lambda} \qquad\qquad L \gg r_o$$

- Substituting numbers we have

$$M \gg 1.7\text{GeV}\left(\frac{T}{0.250\,\text{GeV}}\right)\left(\frac{\alpha_{SYM}N}{1.5}\right)^{1/2}$$

Generalize to Relativistic Heavy Quarks



- Average Energy Loss

$$\frac{d\bar{p}}{dt} = -\eta(p)\bar{p} \tag{1}$$

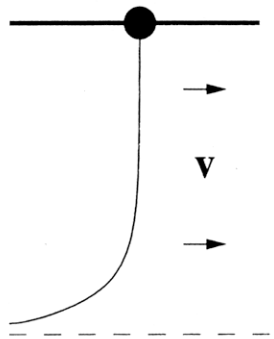
- Transverse Momentum Broadening of a heavy quark (analagous to $\hat{q}$)

$\kappa_T(v)$ = Mean squared transverse momentum transfer per unit time

$\kappa_L(v)$ = Mean squared longitudinal momentum transfer per unit time

Moving Heavy Quarks (HKKKY and S. Gubser)

- Turn on an electric field to accelerate the quark



- Find a quasi-steady state
- Calculate the momentum flow out of the string

$$\frac{dp}{dt} = -\underbrace{\eta_D}_{\text{Constant!}} p$$

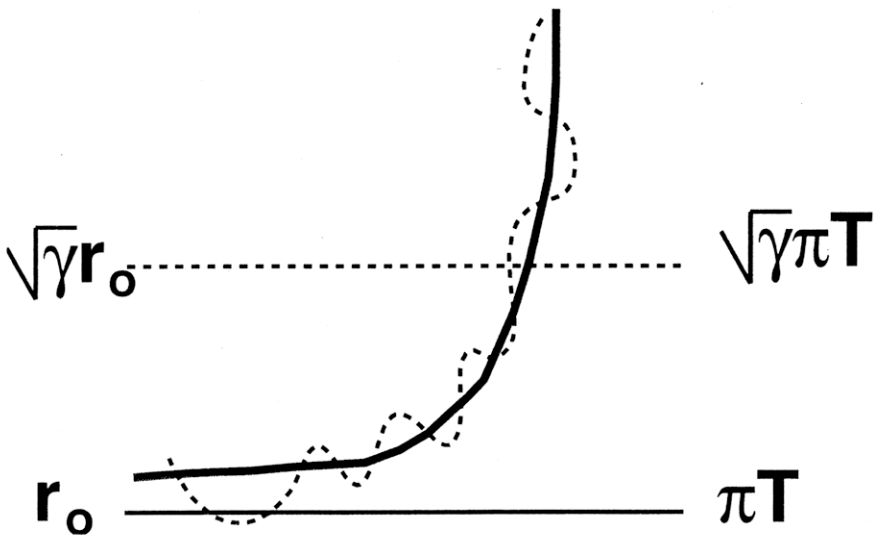
  - Drag is independent of momentum!

AdS/CFT and Heavy Quark Transport

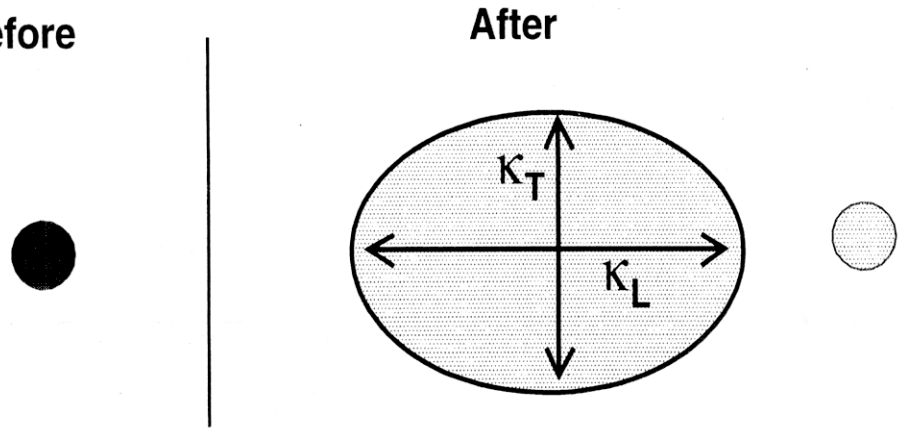
1. Heavy Quark Diffusion

2. Fast Heavy Quarks, fluctuations

Fluctuating the String (J. Casalderrey, DT; S. Gubser)



Results Relativistic Heavy Quarks



- Transverse Momentum Broadening of a heavy quark (analgous to $\hat{q}$)

$$\kappa_T(v) = \underbrace{\sqrt{\lambda}\,\pi\,T^3}_{\text{Non-relativistic result}} \times \sqrt{\gamma}$$

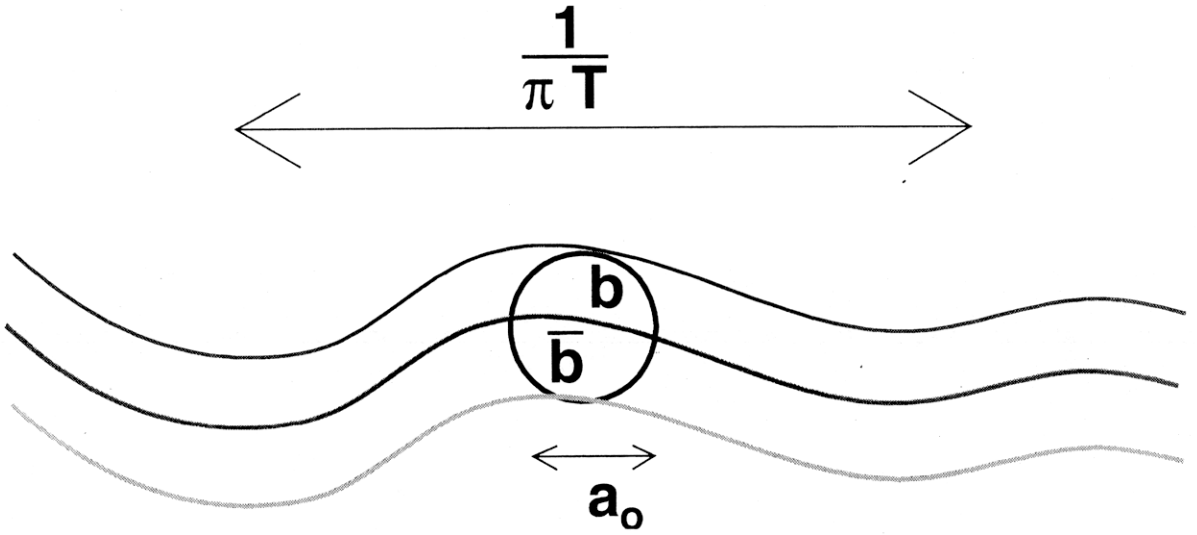
$$\kappa_L(v) = \underbrace{\sqrt{\lambda}\,\pi\,T^3}_{\text{Non-relativistic result}} \times \gamma^{5/2}$$

The strong dependence on the energy could have important phenomenological consequences and theoretical implications.

AdS/CFT and Heavy Quark Transport

1. Heavy Quark Diffusion
2. Fast Heavy Quarks – fluctuations
3. Quarkonia (in progress)

Quarkonia:



- Gluons probe the structure of the quarkonium system when:

$$(\pi T)\, a_o \sim 1$$

- For bottomonium we have:

$$\pi T a_o = 0.7 \left(\frac{T}{.240\,\text{GeV}}\right) \left(\frac{a_0}{1.1\,\text{GeV}^{-1}}\right)$$

Dipole approximation seems marginal – but $(\pi T a_o)^3 \simeq 0.33$

Dipole Interactions:

- Dipole moment $\propto \mathcal{E}$

$$\mathbf{p} = \alpha_{\mathcal{E}} \mathcal{E} \qquad U_I = -\frac{1}{2} \alpha_{\mathcal{E}} \mathcal{E}^2$$

- Effective Lagrangian:
  - Write down the lowest dimension gauge invariant terms (Manohar '94)
  - higher dimension Ops suppressed by small size: $(\pi T a_o)^3$

$$\mathcal{L} = \phi_v \partial_t \phi_v + \frac{1}{2} \alpha_{\mathcal{E}} \mathcal{E}^2 \phi_v^\dagger \phi_v + \frac{1}{2} \alpha_{\mathcal{B}} \mathcal{B}^2 \phi_v^\dagger \phi_v + \dots$$

  - From Gravity perspective we will write this as

$$\mathcal{L} = \phi_v \partial_t \phi_v + c_1 \underbrace{T^{00}}_{\frac{1}{2}(\mathcal{B}^2+\mathcal{E}^2)} + c_2 \underbrace{F^2}_{\frac{1}{2}(\mathcal{B}^2-\mathcal{E}^2)}$$

Determining the Polarizability with the Mass Shift

- Leading order perturbation theory

$$\begin{aligned} \delta M &= \langle H_I \rangle \\ &= -\frac{1}{2} \underbrace{\alpha_{\mathcal{E}}}_{\sim a_B^3/N^2} \underbrace{\left\langle \mathcal{E}^2 \right\rangle}_{\sim N^2 T^4} \end{aligned}$$

- Finite at Large N

Calculation of Drag and Diffusion

- κ is the mean squared momentum transfer per unit time

$$\kappa = \int dt \, \langle \mathcal{F}(t, \mathbf{x}) \mathcal{F}(0, \mathbf{x}) \rangle$$

- For the force on the dipole we have

$$\mathcal{F} = -\nabla U = \frac{1}{2} \alpha_{\mathcal{E}} \nabla \mathcal{E}^2$$

- Then the force force correlator is

$$\kappa = \alpha_{\mathcal{E}}^2 \times \underbrace{\frac{1}{4} \int dt \, \left\langle \nabla \mathcal{E}^2(t, \mathbf{x}) \nabla \mathcal{E}^2(t, \mathbf{x}) \right\rangle}_{\text{Computable in AdS}}$$

Summary

- For the Strong Coupling we have

$$\kappa = \underbrace{\#}_{\sim 1} \frac{41.29}{N^2} \pi T^3 \times \left[\frac{\pi T}{M_J}\right]^6$$

- Drag and diffusion Heavy Meson – Perturbative

$$\kappa = \frac{41.29}{N^2} \pi T^3 \times [\pi T a_0]^6$$

- For Both Weak and Strong Coupling we have

$$\kappa = (\delta M)^2 \ \pi T \ \frac{1280}{3N^2} \ \times \#$$

Summary

- AdS/CFT is a useful foil to perturbation theory
- Its a wild theory!
- Many Questions (suitably posed) can be answered.
- My goal: find something computable in AdS/CFT in wild contradiction with data.

Scale anomaly in QCD at zero and finite temperature

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Nuclei as heavy as cars through collision generate new states of matter

RBRC Review, Nov 5-6, 2007, BNL

Scale anomaly in vacuum

- QCD Lagrangian is confromally invariant. In particular, it is invariant under the scale transformation $x \to \lambda x$.
- The corresponding "dilatational" current is conserved in the massless limit:

$$\partial_\mu j^\mu_D = \theta^\mu_\mu = m\bar{q}q$$

- However, quantum fluctuations break the scale symmetry by introducing the mass scale Λ_{QCD} and inducing the scale anomaly

$$\partial_\mu j^\mu_D = \theta^\mu_\mu = \frac{\beta(g)}{2g} F^a_{\mu\nu} F^{a\mu\nu} + m\bar{q}q$$

- Although the scale invariance is broken there is a residual symmetry due to the Renormalization Group invariance of physical quantities.

Low-energy theorems (LET) in vacuum

Novikov, Shifman, Vainshetein, Zakharov 1981

- Conformal symmetry of QCD is broken by vacuum fluctuations. However, there is still a certain unbroken symmetry which manifests itself as a set of LET. Consider an operator of canonical dimension d:

$$\langle O \rangle_v \sim \left[M_0 e^{-\frac{8\pi}{b\, g^2(\mu)}} \right]^d \qquad \text{(by RGE)}$$

- On the other hand, <O> can be represented as a functional integral:

$$\langle O \rangle_v = \int \mathcal{D}\tilde{A}^\mu_a \, O \, \exp\left(-i \frac{1}{4g^2} \int d^4x \, \tilde{F}^a_{\mu\nu} \tilde{F}^{a\mu\nu} \right) \qquad \tilde{F} = gF$$

- Coupling *g* enters the lagrangian of Gluodynamics only as a pre-factor. Thus, differentiating with respect to (-1/4 g^2) we get

$$i \int dx \, \langle T[O(x), \tilde{F}^2(0)] \rangle = -\frac{d}{d(-1/4g^2)} \langle O \rangle_v$$

LET in vacuum (cont.)

$$i \lim_{q \to 0} \int dx\, e^{iqx} \langle T[O(x), \frac{\beta(\alpha_s)}{4\alpha_s} F^2(0)] \rangle = (-d) \langle O \rangle_v$$

- Using the trace of energy-momentum tensor for O: $\theta^\mu_\mu = \frac{\beta(g)}{2g} F^a_{\mu\nu} F^{a\mu\nu}$
- we derive $\boxed{i \int dx \langle T\, \theta^\mu_\mu(x), \theta^\nu_\nu(0) \rangle_{\text{connected}} = \langle \theta^\mu_\mu(0) \rangle (-4)}$
- Differentiating n times we can derive LET for Green's function of n'th order.

$$i^n \int dx_1 \dots dx_n \langle T\, \theta^{\mu_1}_{\mu_1}(x), \dots, \theta^{\mu_n}_{\mu_n}(x_n), \theta^\nu_\nu(0) \rangle_{\text{connected}} = \langle \theta^\mu_\mu(0) \rangle (-4)^n$$

Note: Coupling constant does not explicitly appear in LET →
LET contain a non-perturbative information about the correlation functions.

Effective Dilaton Lagrangian

- LET can be saturated by a single scalar field χ

Migdal, Shifman, 1982

$$L = \frac{|\epsilon_v|}{m^2}\frac{1}{2}e^{\chi/2}(\partial_\mu\chi)^2 + |\epsilon_v|e^{\chi}(1-\chi)$$

$$\theta^\mu_\mu = -4|\epsilon_v|e^{\chi}$$

- The field χ is referred to as the *dilaton*. In gluodynamics it corresponds to the scalar glueball. In the real world, it mixes up with light quarks to produce the σ-meson.

Scale anomaly and confinement

Kharzeev, Levin, KT 2001-2007

$$L = \frac{|\epsilon_v|}{m^2}\frac{1}{2}e^{\chi/2}(\partial_\mu\chi)^2 + |\epsilon_v|\,e^{\chi}(1-\chi) - \frac{1}{4}(F^a_{\mu\nu})^2 + e^{\chi}(1-\chi)\frac{1}{4}(F^a_{\mu\nu})^2$$

- Extremizing this Lagrangian with respect to χ yields

$$\chi\, e^{\chi}\left(|\epsilon_{\rm v}| - \frac{1}{4}(F^a_{\mu\nu})^2\right)|_{\rm min} = 0$$

  i.e. the minimum of the Lagrangian is at $F^2=4|\epsilon_v|$.

- In the quasi-Abelian gauge $\phi(r) = -\frac{\alpha_s}{r} + |\vec{E}_{\rm vac}|\, r$

This is the result of broken scale invariance!

- Expanding near χ=1 were the effective theory matches onto pQCD we can see that the dilaton becomes massless.

Kubo formula for bulk viscosity

$$\eta(\omega)\left(\delta_{il}\delta_{km}+\delta_{im}\delta_{kl}-\frac{2}{3}\delta_{ik}\delta_{lm}\right)+\zeta(\omega)\delta_{ik}\delta_{lm}=\frac{1}{\omega}\lim_{\mathbf{k}\to\mathbf{0}}\int\int_0^\infty e^{i(\omega t-\mathbf{kr})}\langle[\theta_{ik}(t,\mathbf{r}),\theta_{lm}(0)]\rangle dt d^3x$$

where $\theta_{ik}(x)$ is the operator of the stress tensor.

Contracting *i,k* and *l,m* (*i=1,2,3)* we get in the static limit

$$\zeta=\frac{1}{9}\lim_{\omega\to0}\frac{1}{\omega}\int_0^\infty dt\int d^3r\, e^{i\omega t}\,\langle[\theta_{ii}(x),\theta_{kk}(0)]\rangle$$

In terms of the 4-dim trace:

$$\zeta=\frac{1}{9}\lim_{\omega\to0}\frac{1}{\omega}\int_0^\infty dt\int d^3r\, e^{i\omega t}\,\langle[\theta^\mu_\mu(x),\theta^\nu_\nu(0)]\rangle=-\frac{1}{9}\lim_{\omega\to0}\frac{1}{\omega}\,\mathrm{Im}G^R(\omega,\vec{0})$$

Indeed $\langle[\int d^3x\,\theta_{00},O]\rangle_{\mathrm{eq}}=\langle[H,O]\rangle_{\mathrm{eq}}=i\left\langle\frac{\partial O}{\partial t}\right\rangle_{\mathrm{eq}}=0$

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Euclidean Green's function

- It is convenient to use the Euclidean Green's function. First, introduce the spectral density $\rho(\omega,\vec{p}) = -\frac{1}{\pi}\,\mathrm{Im}G^R(\omega,\vec{p})$
- Kramers-Kronig relation: $G^R(\omega,\vec{p}) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\mathrm{Im}G^R(u,\vec{p})}{u-\omega-i\epsilon}\,du = \int_{-\infty}^{\infty}\frac{\rho(u,\vec{p})}{\omega-u+i\epsilon}\,du$

- The retarded Green's function $G^R(\omega,p)$ of a bosonic excitation is related to the Euclidean Green's function $G^E(\omega,p)$ by analytic continuation

$$G^E(\omega,\vec{p}) = -G^R(i\omega,\vec{p})\,, \quad \omega > 0$$

- Using $\rho(\omega,p)=-\rho(-\omega,p)$ we get the following sum rule

$$G^E(\omega\to 0,\vec{0}) = 2\int_0^{\infty}\frac{\rho(u,\vec{0})}{u}\,du$$

Can be calculated from LET!

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LET at finite temperature

Ellis, Kapusta, Tang 1998
Shushpanov, Kapusta, Ellis 1999

- At finite temperature there is an additional dimensional parameter T. The grand potential Ω per unit volume can be written in imaginary time formalism as

$$\Omega = -T \ln Z = -T \ln \int \mathcal{D}\tilde{A}^{\mu}_{a} \exp\left(-\frac{1}{4g^2} \int_0^{1/T} d\tau \int d^3x \, \tilde{F}^2_{\mu\nu} \tilde{F}^{a\mu\nu} \right)$$

- Dimensional analysis: $\langle O \rangle \sim \Lambda^d f(\Lambda/T)$ with $\Lambda \sim M_0 \, e^{-\frac{8\pi}{b\, g^2(\mu)}}$

- Differentiating with respect to (-1/4 g^2) we obtain

$$\left(T\frac{\partial}{\partial T} - d \right)^n \langle O \rangle = \int_0^{1/T} d\tau_n \int d^3x_n \ldots \int_0^{1/T} d\tau_1 \int d^3x_1 \, \langle \theta^{\mu_n}_{\mu_n}(\tau_n, x_n) \ldots \theta^{\mu_1}_{\mu_1}(\tau_1, x_1) \, O(0,0) \rangle_{\text{connected}}$$

- In particular,

$$\int_0^{1/T} d\tau \int d^3x \langle \theta^{\nu}_{\mu}(x), \theta^{\nu}_{\nu}(0) \rangle_{\text{connected}} = \left(T\frac{\partial}{\partial T} - 4 \right) \langle \theta^{\mu}_{\mu}(0) \rangle$$

$$\mathcal{E} - 3P$$

$$G^E(\omega \to 0, \vec{0}) = 2 \int_0^{\infty} \frac{\rho(u, \vec{0})}{u} \, du$$

Sum rule for the spectral density

Kharzeev, KT 2007

✳ Note, that on the lattice one computes not $\langle\theta_{\mu\mu}\rangle_T$ but, $\langle\theta_{\mu\mu}\rangle_T - \langle\theta_{\mu\mu}\rangle_0$ (subtracting the vacuum expectation value), i.e.

$$(\mathcal{E} - 3P)_{\rm LAT} = \langle\theta^\mu_\mu\rangle_T - \langle\theta^\mu_\mu\rangle_0$$

✳Denote $\langle\theta^\mu_\mu\rangle_0 = -4|\epsilon_v|$

- The following exact sum rule holds

$$2\int_0^\infty \frac{\rho(u,\vec{0})}{u}\,du = -\left(4 - T\frac{\partial}{\partial T}\right)\langle\theta\rangle_T = T^5\frac{\partial}{\partial T}\frac{(\mathcal{E}-3P)_{\rm LAT}}{T^4} + 16|\epsilon_v|$$

Extracting the bulk viscosity

- In order to extract bulk viscosity we need an ansatz for the spectral density ρ

  ✳ In pQCD (high frequencies) $\rho(\omega) \sim \alpha_s^2 \omega^4$. This divergent part is subtracted on both sides of the sum rule.

  ✳ At small frequencies we assume the following functional form which is odd in ω and has correct $\omega \to 0$ limit:

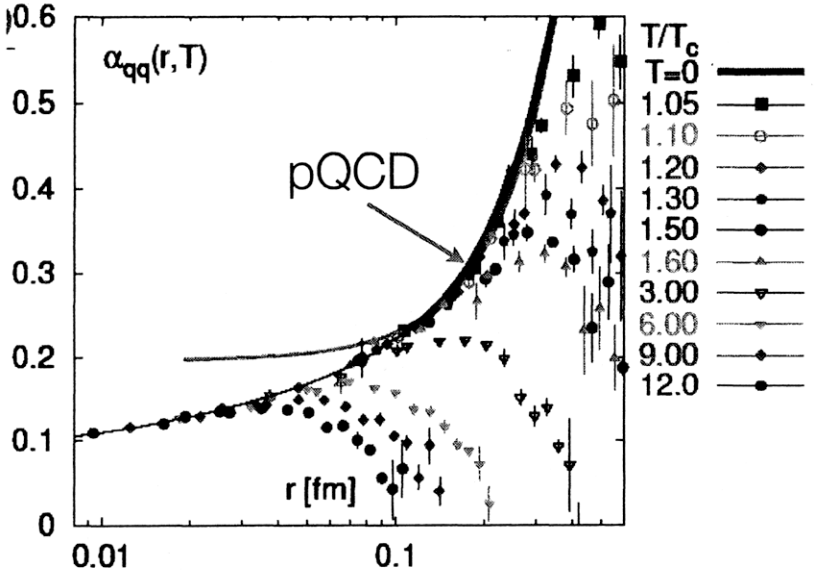
$$\frac{\rho(\omega, \vec{0})}{\omega} = \frac{9\,\zeta}{\pi} \frac{\omega_0^2}{\omega_0^2 + \omega^2}$$

- We have

$$\zeta = \frac{1}{9\,\omega_0} \left\{ T^5 \frac{\partial}{\partial T} \frac{(\mathcal{E} - 3P)_{\rm LAT}}{T^4} + 16 |\epsilon_v| \right\}$$

Extracting the bulk viscosity (cont.)

- Parameter ω_0 is a scale at which the perturbation theory becomes valid.

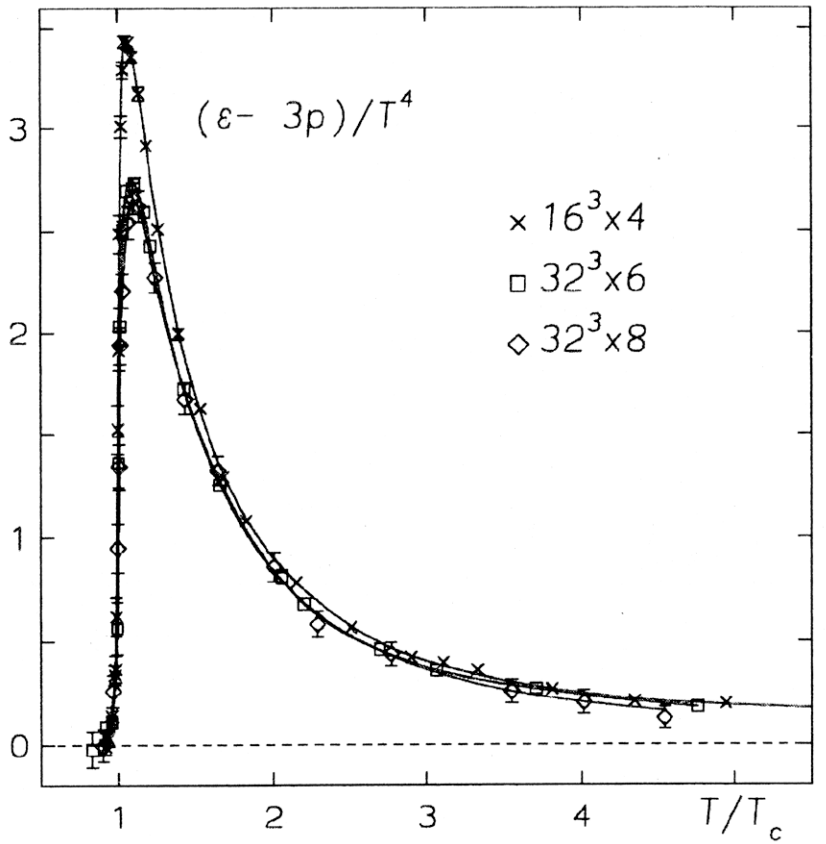


Kaczmarek, Karsch, Zantow, Petreczky, 2004

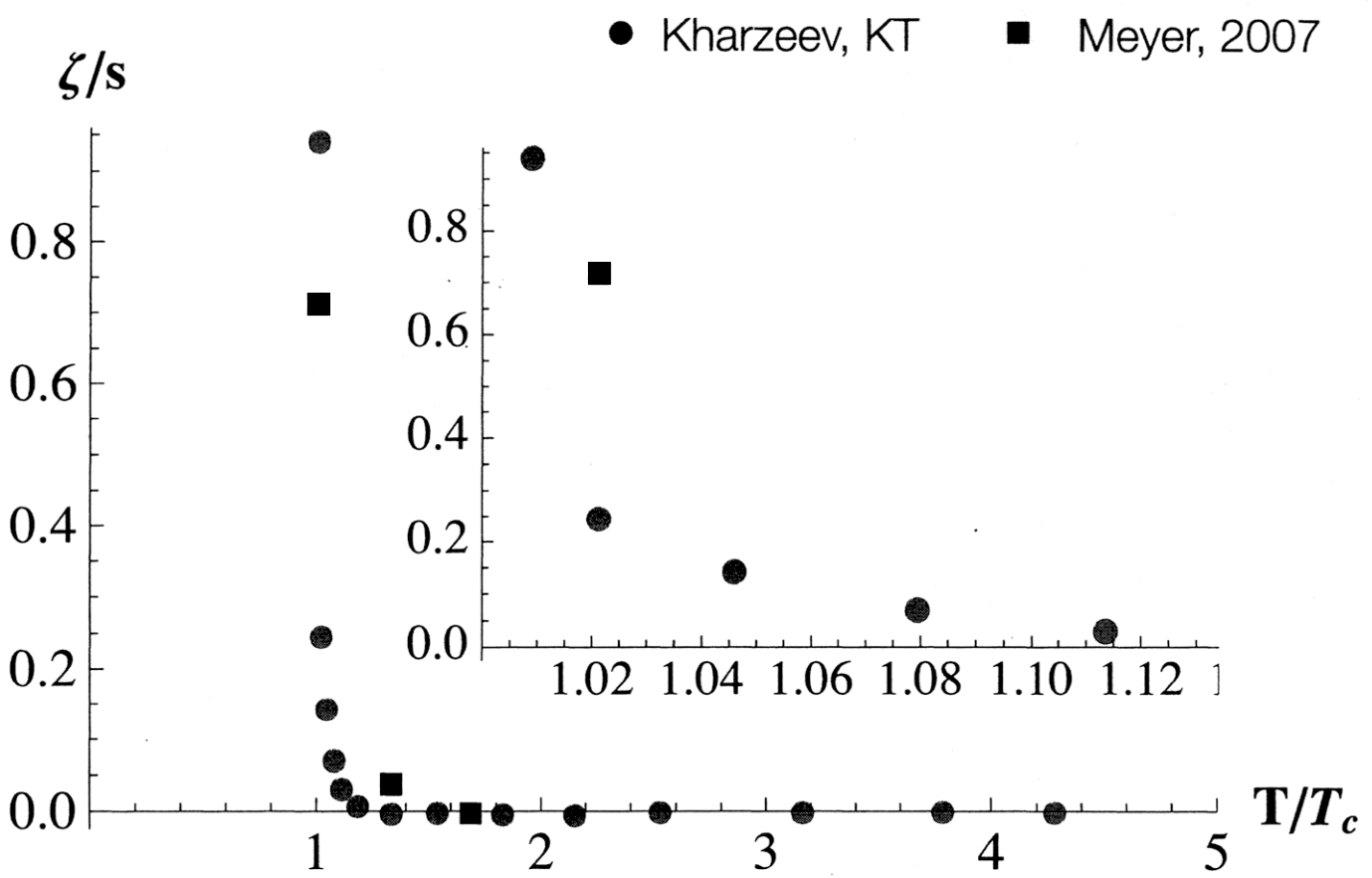
- In the region $1< T/T_c <3$ we find $\omega_0 \approx (T/T_c)$ 1.4 GeV
- T_c=0.28 GeV; $|\epsilon_v|$=0.62 T_c^4.

Lattice data

Boyd et al (Bielefeld) , 1996



Bulk viscosity on the lattice



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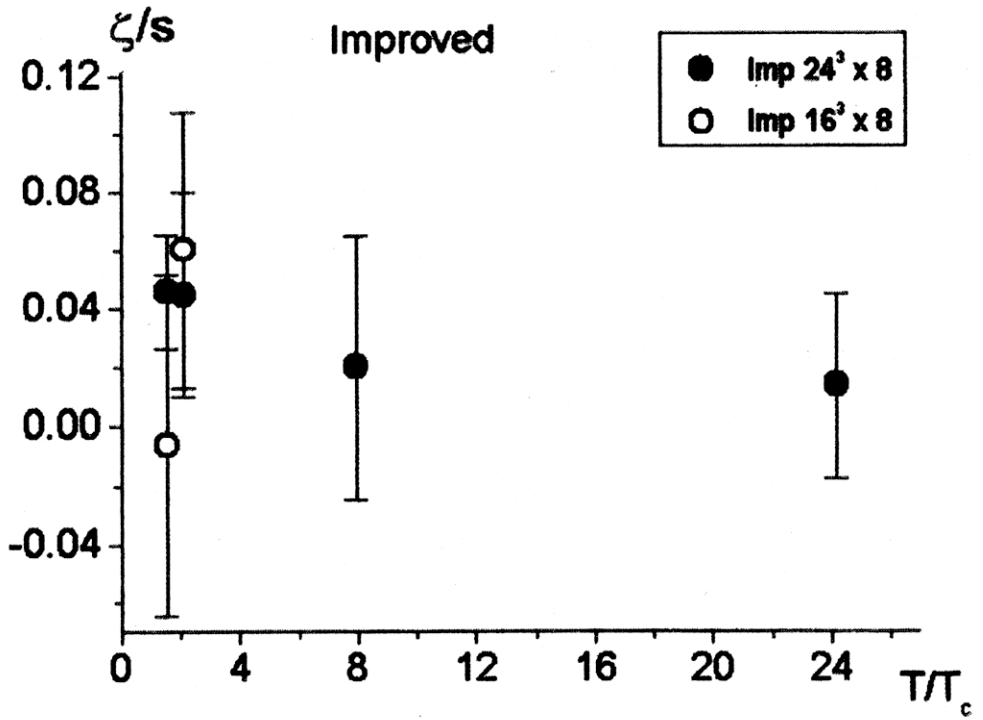
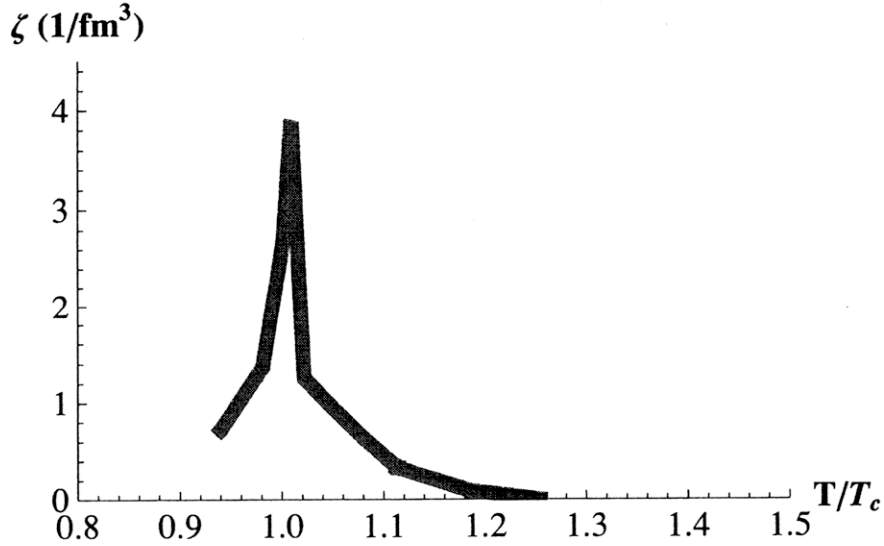
Bulk viscosity on the lattice



Sakai, Nakamura 2007

Bulk viscosity from the lattice



Bulk viscosity is

- small at $T>>T_c$ in accord with expectations from pQCD.
- small at $T<<T_c$ due to a derivative interactions

$$\theta^\mu_\mu = -\partial_\mu \pi^a \, \partial^\mu \pi^a + 2m_\pi^2 \pi^a \pi^a + \cdots$$

- large at $T \approx T_c$ where it becomes the dominant correction to the ideal hydrodynamics.

see also Paech, Pratt, 2006

Summary

- Bulk viscosity increases near $T=T_c$ by 3 orders of magnitude.
- This growth is directly related to the appearance of massless dilaton which is in turn related to the color confinement.
- Large bulk viscosity = large entropy production.
- The effects of bulk viscosity on hydrodynamical calculation deserves a serious study.

Determining the shear viscosity of dense QCD matter at RHIC

Denes Molnar

RIKEN/BNL Research Center & Purdue University

for RBRC Annual Review

Nov 5-6, 2007, RIKEN BNL Research Center, Upton, NY

- Introduction - hydrodynamics and elliptic flow
- Viscosity - covariant transport and dissipative hydrodynamics
- Extracting shear viscosity from heavy-ion data

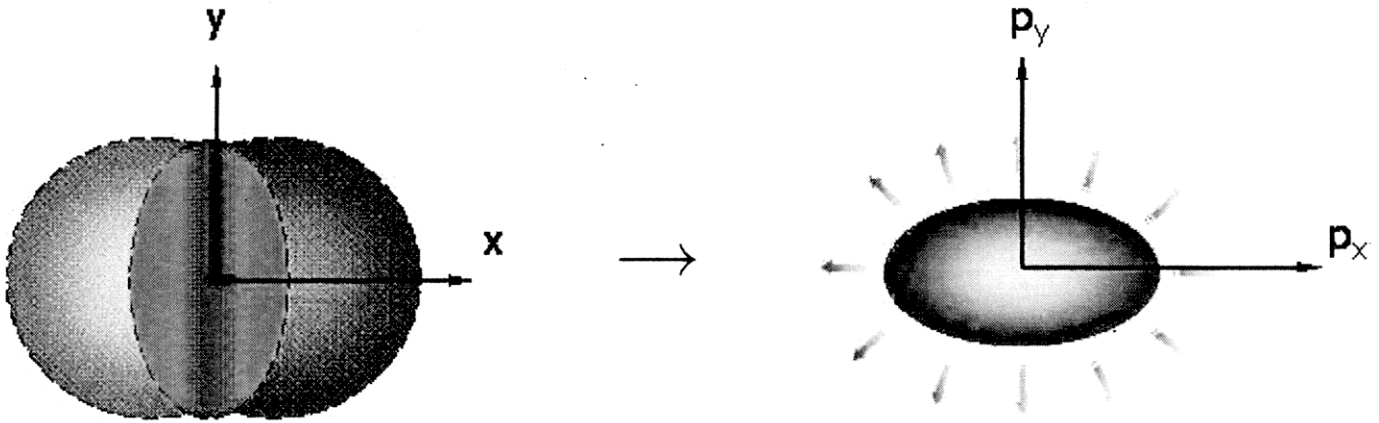
Relativistic Heavy Ion Collider: **Au,Cu,..**

Au,Cu,

hot & dense nuclear matter

- **a good observable - "elliptic flow"** (v_2)

spatial anisotropy $\rightarrow$ **final azimuthal momentum anisotropy**



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

sensitive to speed of sound $c_s^2 = \partial p / \partial e$ **, and also viscosity**

Ideal (Euler) hydrodynamics

local, macroscopic variables: **energy density** $e(\vec{x},t)$
pressure $p(\vec{x},t)$
baryon density $n(\vec{x},t)$
flow velocity $u^\mu(\vec{x},t)$ $\quad (u^\mu u_\mu = 1)$

energy-momentum and charge conservation:

$$\partial_\mu T^{\mu\nu}(x) = 0, \qquad \partial_\mu N^\mu(x) = 0$$

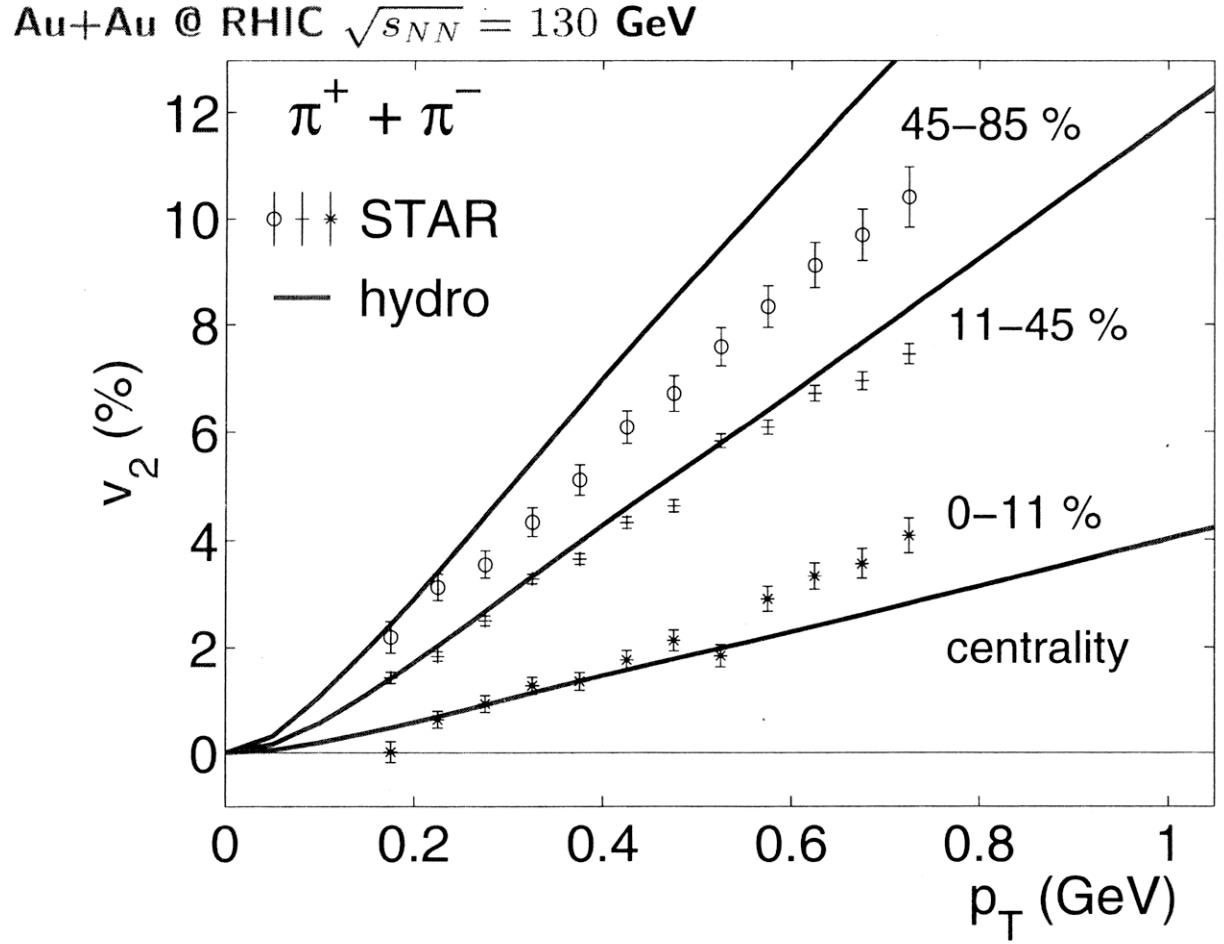
local equilibrium:

$$T^{\mu\nu}_{LR} = diag(e,p,p,p) \quad , \quad N^\mu_{LR} = (n,\vec{0}) \qquad \textbf{in fluid rest frame}$$

matter characterized by: **equation of state** $p(e,n)$

$$\Rightarrow \textbf{speed of sound } c_s^2 = \partial p/\partial e$$

conserves entropy, NO dissipation



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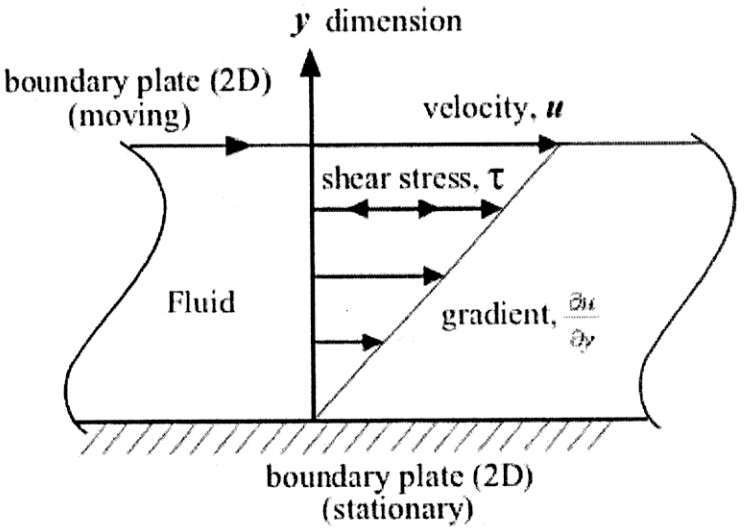
potential causes for deviations:
- **lack of equilibrium in late stages**
- **equation of state differs from Nature**
- **imprecise initial density profile**

a natural candidate: lack of dissipation

Shear viscosity

Newton:

$$T_{xy} = -\eta \frac{\partial u_x}{\partial y}$$



acts to reduce velocity gradients

quantum mechanics: $\Delta E \cdot \Delta t \geq \hbar/2$

+ kinetic theory: $T \cdot \lambda_{MFP} \geq \hbar/3$ Gyulassy & Danielewicz, PRD 31 ('85)

$\eta \approx 4/5 \cdot T/\sigma_{tr}$, **entropy** $s \approx 4n$

gives minimal viscosity: $\eta/s = \frac{\lambda_{tr} T}{5} \geq \hbar/15$

recently from string theory: $\eta/s \geq \hbar/4\pi$ Policastro, Son, Starinets, PRL87 ('02)
Kovtun, Son, Starinets, PRL94 ('05)

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Could viscosity be important at RHIC??

Can we constrain it from data?

Two options to study minimal viscosity effects:

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- covariant transport

Israel, de Groot,... Zhang, Gyulassy, DM, Pratt, Xu, Greiner...

- causal viscous hydrodynamics

Israel, Stewart; ... Muronga, Rischke; Teaney; Romatschke et al; Heinz et al...

Covariant transport

Boltzmann ..., Israel, Stewart, de Groot, ... Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, Xu, Greiner ...

Causal, stable, nonequil. approach - **formulated in terms of local rates.**

$$\Gamma_{2\to 2}(x) \equiv \frac{dN_{scattering}}{d^4x} = \sigma v_{rel} \frac{n^2(x)}{2}$$

mean free path:

$$\lambda(x) \equiv \frac{1}{\textbf{cross section} \times \textbf{density}(\mathbf{x})}$$

- **Ideal fluid limit $\lambda \to 0$: local equilibrium, entropy conserved**

- **for small spatial gradients near local equil.: Chapman-Enskog expansion**

  $\Rightarrow$ **dissipative Navier-Stokes hydro** Chapters V & IX of De Groot, "Relativistic kinetic theory"

$$e.g., \quad \textbf{shear viscosity } \eta \approx 0.8 \frac{T}{\sigma_{tr}}$$

Viscous hydrodynamics

relativistic Navier-Stokes hydro: **add small corrections linear in gradients**

$$T^{\mu\nu}_{NS} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha$$

$$N^\mu_{NS} = N^\mu_{ideal} - \frac{n}{e+p}\kappa\nabla^\mu T$$

where $\Delta^{\mu\nu} \equiv u^\mu u^\nu - g^{\mu\nu}$, $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$

η, ζ **shear and bulk viscosities,** κ **heat conductivity**

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two problems:

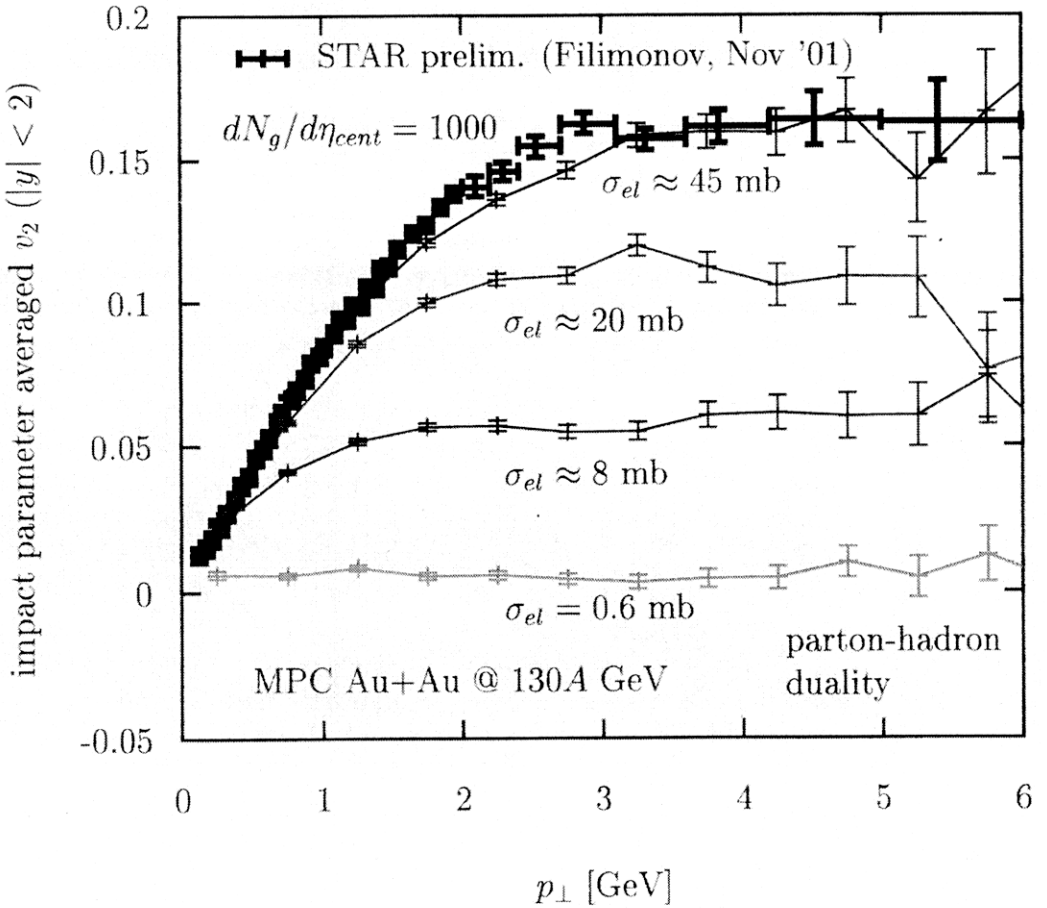
parabolic equations $\rightarrow$ **acausal** Müller ('76), Israel & Stewart ('79) ...

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

must use a causal formulation $\rightarrow$ **hydro algorithms being developed**

Muronga & Rischke, Teaney, Heinz & Song, Romatschke et al, Kodama et al, DM et al...

DM & Gyulassy, NPA 697 ('02): **opacity @ RHIC from $v_2(p_T)$, $2 \to 2$ transport**



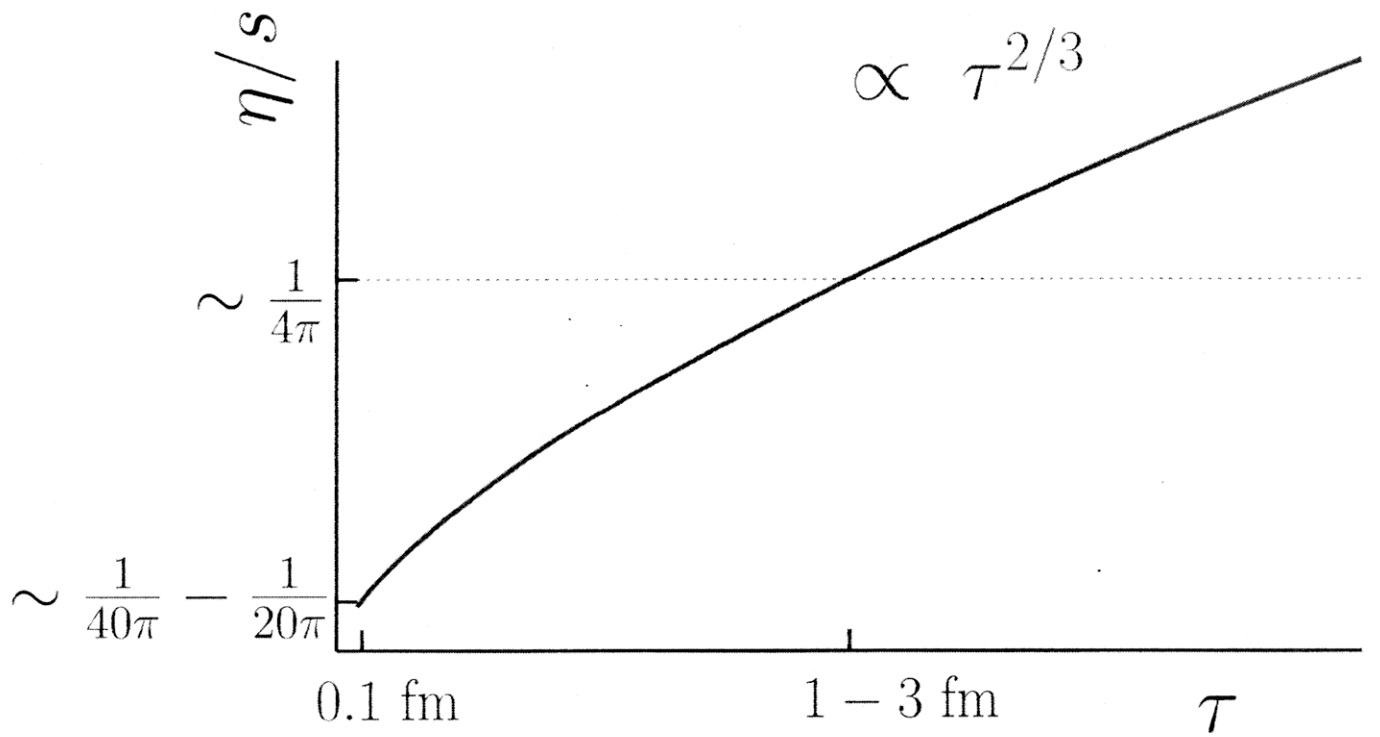
puzzle: need $\sigma_{gg \to gg} \approx 45$ mb $\to$ $15\times$ higher than perturbative QCD rates

open question: radiative $ggg \leftrightarrow gg$ - probably helps by factor $\sim 3-5$ [Xu&Greiner, PRC71 ('05)]

$\sigma \approx 45$ **mb result for RHIC corresponds to**

$\eta/s \sim \lambda_{tr} T \sim 1/(\sigma T^2)$

$T \sim \tau^{-1/3}$ **cooling**



$\eta/s = const$ **needs <u>growing</u>** $\sigma(\tau) \propto 1/T^2 \propto \tau^{2/3}$

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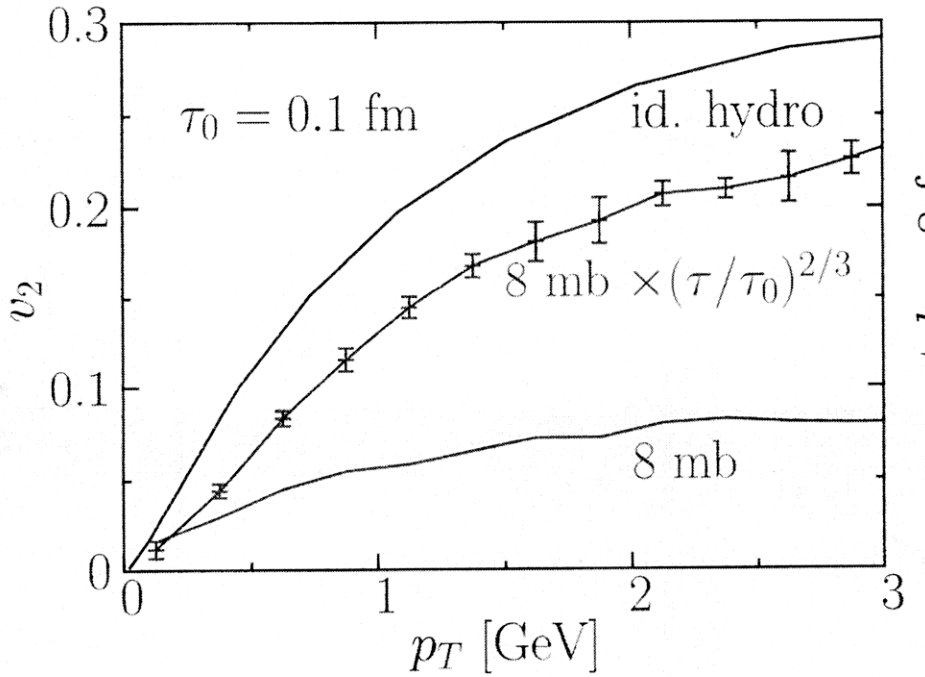
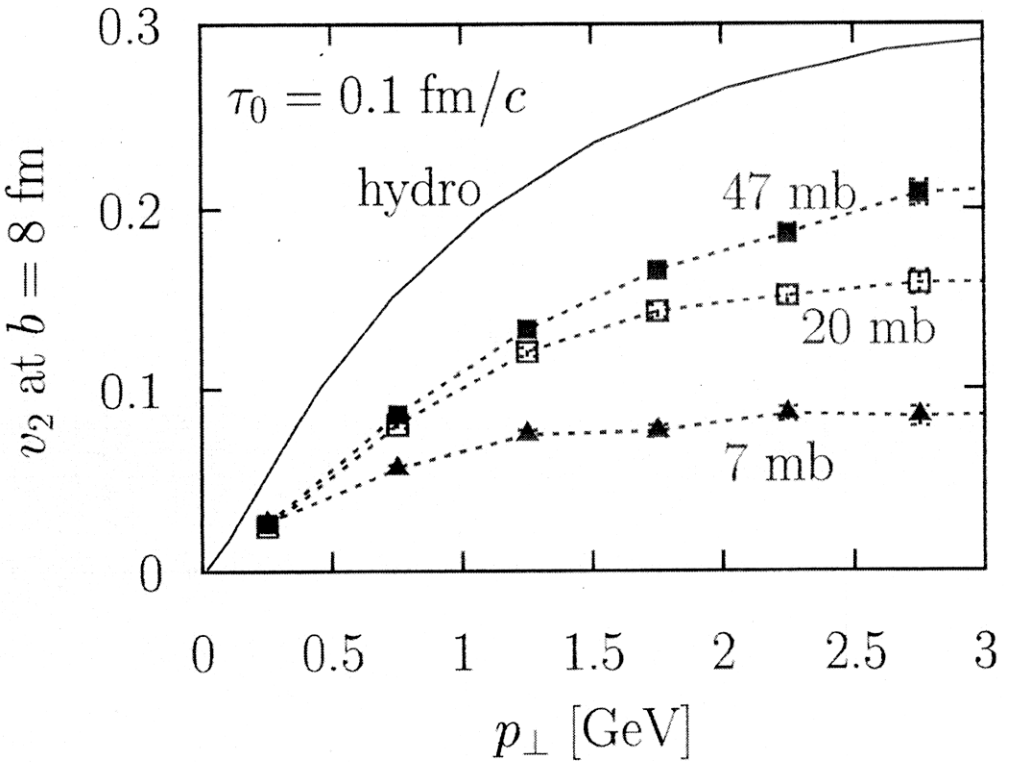
Au+Au at $b = 8$ fm from transport:

DM '06-'07: $\eta/s \approx 1/(4\pi)$ **vs** $\sigma_{gg} = const$ DM & Huovinen, PRL94 ('05)





$\eta/s \approx 1/(4\pi)$ **almost same as** $\sigma_{gg} = 47$ **mb, which described the RHIC** v_2 **data**

$\Rightarrow \quad \eta/s \sim 1/(4\pi)$ **within factor of** $1.5 - 2$ **at RHIC**

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Conclusions

We can use covariant transport to extract the shear viscosity from heavy-ion data. The RHIC $v_2(p_T)$ data indicate $\eta/s \approx 0.05 - 0.12$, which is compatible with $\eta/s = 1/(4\pi)$ conjectured minimum. (statistical/fitting error only, can be reduced with more computing)

Caveats: - only $2 \to 2$ processes

- massless $e = 3p$ equation of state (no phase transition)
- missing local spatial variations in σ to set a precise η/s

Next steps: - cross-check with other data (e.g., centrality dependence of v_2)

- check result from causal viscous hydrodynamics
  - $\to$ first make sure hydrodynamics is applicable
  - $\to$ if yes, use realistic equation of state

Probing Hot and Cold Nuclear Matter

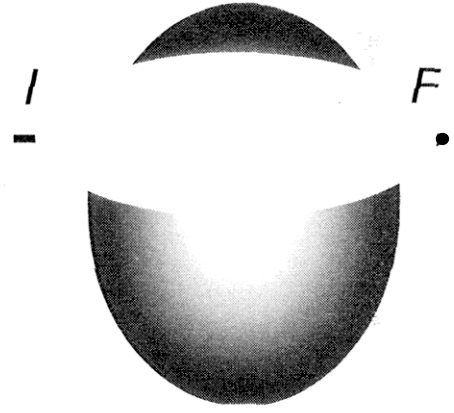
Rainer Fries

Texas A&M University & RIKEN BNL

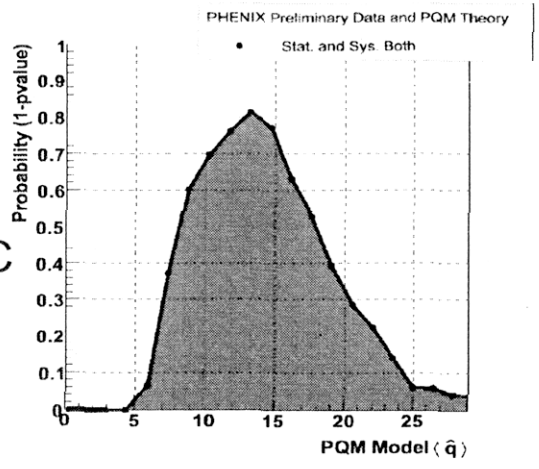
RIKEN Review, Brookhaven National Lab
November 5, 2007

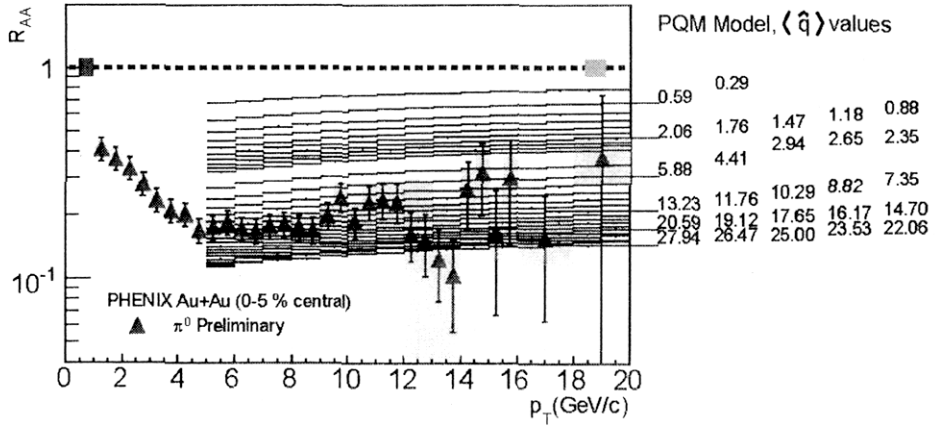
QCD Tomography

- What are the properties of the QCD state found at RHIC?
  - Equation of state, transport properties, phase transitions
- How can we understand final state interactions in e+A collisions (e.g. at a future EIC)?
- Precision probes:
  - External hard probes interacting with the medium
  - QCD jets & electromagnetic radiation
- Tomography precision? Not yet …



$\hat{q}$ from RHIC R_{AA} data





The Next Step

- Many open questions
  - Energy loss: collisional vs radiative, perturbative vs non-perturbative
  - New phenomena: ridge, cone, …
  - Collective medium response? Which modes?
  - (Partial) jet thermalization?
  - Heavy quark suppression

- Observables available to us currently or in the near future
  - Suppression of inclusive spectra, R_{AA}
  - Path dependence: v_2 , R_{AA} vs reaction plane
  - Electromagnetic radiation from jets
  - Hadron-hadron, photon-hadron, photon-jet correlations
  - Jet flavor chemistry

Increasingly higher resolution

- Still much work to do for theory.

What You Will Hear About Today

– some past, current and future projects –

- Interaction of a jet with a nuclear medium from collinear factorization
  - Enhanced higher twist
  - Resummation and photon production
- Electromagnetic Probes and correlations with photons
  - Jets from photons, photon v_2
  - Opportunity for photons from γ-h correlations; need for NLO
- Medium induced conversion of hard probes
  - Parton flavor
  - Photons

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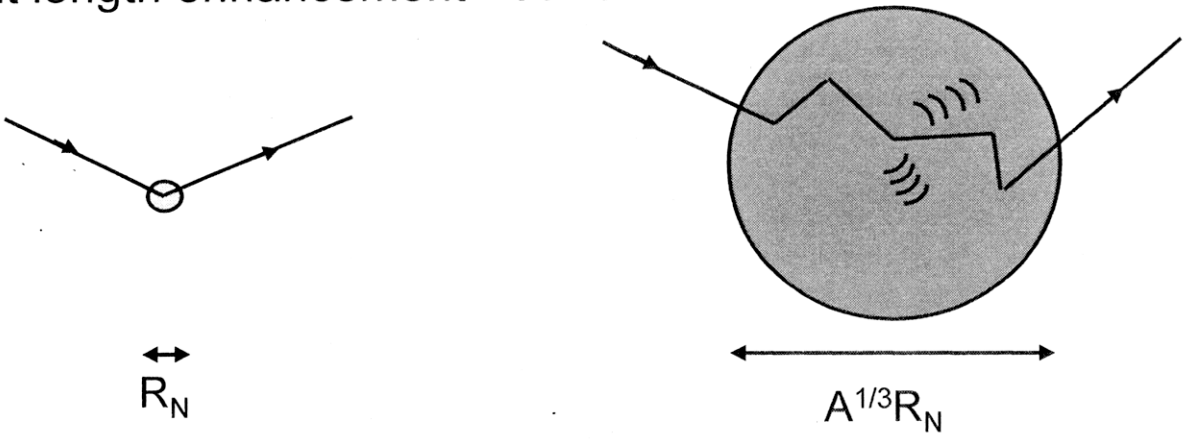
Jet + Medium

Perturbative QCD + Multiple Scattering

- Multiple scattering in collinear factorization:
  - Described by a class of higher twist operators
  - Some of them exhibit length enhancement ~ $A^{1/3}$.

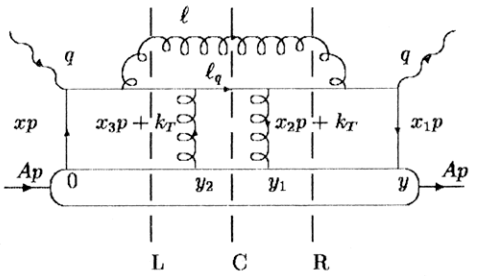


- Qiu + Sterman:
  - Focus on maximal enhancement $A^{n/3}$ (for n-scattering)
  - Very few operators contribute; most have a simple probabilistic interpretation, e.g.

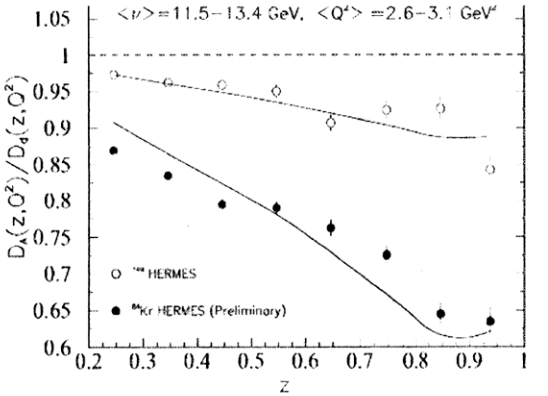
$$T_{qg}^{\mathrm{SH}}(x) = \int dz_4^- \frac{dz_3^-}{2\pi}\frac{dz_1^-}{2\pi}\Theta(z_1^- - z_3^-)\Theta(-z_4^-)\,\mathrm{e}^{ixP^+z_1^-}\,\frac{1}{2}\left\langle P\left|F^{\omega+}(z_4^-)\bar{q}(0)\gamma^+ q(z_1^-)F_\omega^+(z_3^-)\right|P\right\rangle$$

$$\left\langle \bar{q}q\right\rangle \longleftrightarrow^{R_A} \left\langle FF\right\rangle$$

Higher Twist at Work

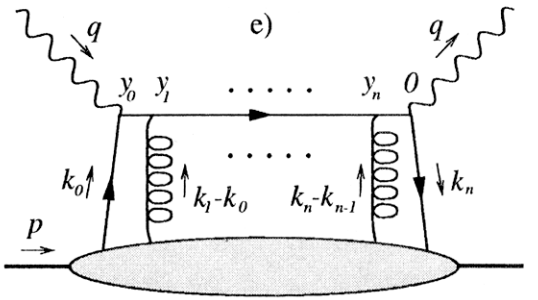


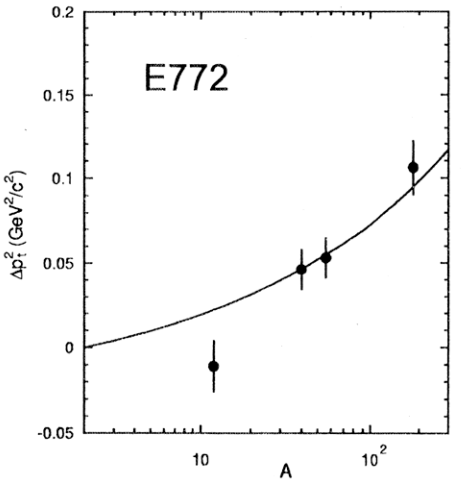
- Application to energy loss:
  - Medium-modified fragmentation in DIS [Guo, E.Wang, X.N.Wang]
  - Single rescattering with gluon radiation
  - Also applied to jets in other systems incl. HIs



- Momentum broadening of DIS jets & DY pairs
  - Resummation of arbitrary twist operators with maximal enhancement [RJF (2003)]
  - Multiple rescattering w/o radiation
  - Computed moments of transverse momentum q_T:

$$\left\langle q_T^{2n} \right\rangle \sim \frac{1}{n!}\left(\frac{4\pi\alpha_s}{N_c} A^{1/3} \langle FF \rangle \right)^n$$





McGaughey, Moss, Peng (1999)

Transport Properties

- Recent development:
  - Earlier result for HT resummation w/o radiative correction confirmed [Majumder, Müller (2006)]
  - New insight: final momentum distribution $\phi(q_T)$ obeys diffusion equation!

$$\nabla_L \phi = D \nabla^2_{q_T} \phi \qquad D = \frac{4\pi\alpha_s}{N_c} \rho \langle FF \rangle$$

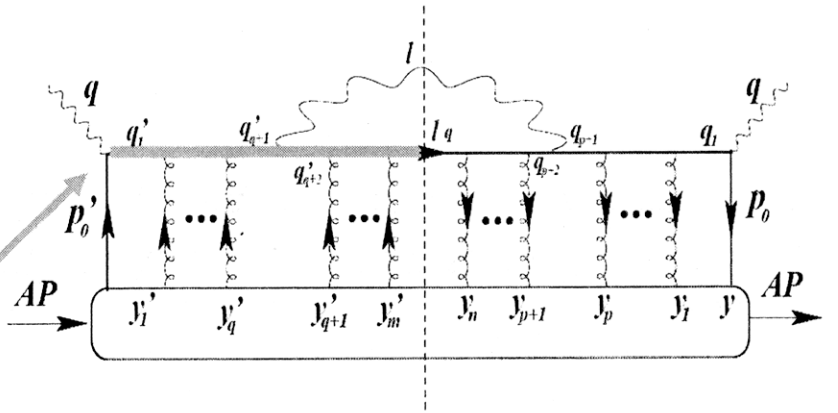
L = distance traveled on light cone
ρ = nuclear density

  - Transport picture derived from collinear factorized pQCD!

- Our motivation for further study:
  - Is there a simple transport picture behind other processes as well?
  - Attempt resummation with radiation (first photon for simplicity).
  - Eventually radiative energy loss in the thick medium limit ??
  - Generalization to hot nuclear matter ??
  - Consistent NLO jet quenching scheme ??

Photon Radiation off a Jet in nDIS I

- Resum graphs of the following type:



- Effective fermion propagator for photon attached at position q:

$$\frac{l_\perp - yK_{q\perp}}{\left(l_\perp - yK_{q\perp}\right)^2} \times \text{Phases}$$

y = momentum fraction of photon wrt to quark
$K_{q\perp}$ = transverse momentum inserted by gluons up to position q

- Photon position can be resummed e.g. in the small y limit

$$\frac{d\sigma}{dy d^2q_\perp dl_\perp^2} = \sigma_0 \sum_q Q_q^4 \frac{1}{l_\perp^2} \frac{\alpha_{em}}{2\pi} P_\gamma(y) \left[f_q(x_B + x_L) + y \frac{E(x_B, x_L)}{2DL} \left(1 + \frac{\vec{l}_\perp \cdot \vec{q}_\perp}{l_\perp^2} \right) \right] \phi\left(L, \vec{q}_\perp - \vec{l}_\perp\right)$$

Photon splitting function can be factored out

Leading term for $y \to 0$

NLO term for $y \to 0$

Transverse momentum diffusion as before, but initial value shifted to $q_\perp = l_\perp$

[Majumder, Fries, Müller, to be submitted]

Photon Radiation off a Jet in nDIS II

- Resummed cross section in the small *y* limit

$$\frac{d\sigma}{dyd^2q_\perp dl_\perp^2} = \sigma_0 \sum_q Q_q^4 \frac{1}{l_\perp^2} \frac{\alpha_{em}}{2\pi} P_\gamma(y) \left[f_q(x_B + x_L) + y \frac{E(x_B, x_L)}{2DL} \left(1 + \frac{\vec{l}_\perp \cdot \vec{q}_\perp}{l_\perp^2} \right) \right] \phi(L, \vec{q}_\perp - \vec{l}_\perp)$$

Leading term for $y \to 0$:

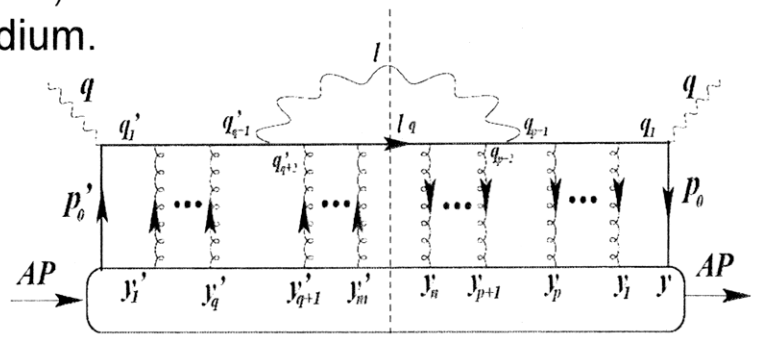
Complete destructive interference of photon emission points, only q=0 contributes (deep LPM limit!)

Quark shifted off-shell by $x_L = \frac{l_\perp^2}{y(1-y)2P \cdot q}$

NLO term for $y \to 0$:

Destructive interference incomplete, photon emission point arbitrary on one side of the diagram, adjacent gluon acquires finite momentum fraction x_L.

E ~ $\langle qqFF \rangle$ non-trivial correlation function in the medium.



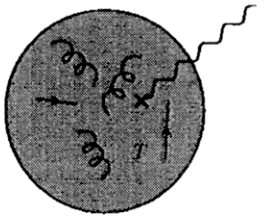
- To do:
  - Large *y*; phenomenology
  - Comparison to other calculations
  - Gluon radiation

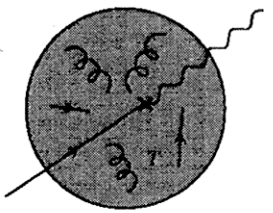
[Majumder, Fries, Müller, to be submitted]

Photons & Correlations

E&M Probes

- Photons + dileptons carry information from deep inside the fireball and/or early times
  - Access temperature via *thermal emission* and *jet-photon conversion*
  - Not yet well constrained from single inclusive measurements.

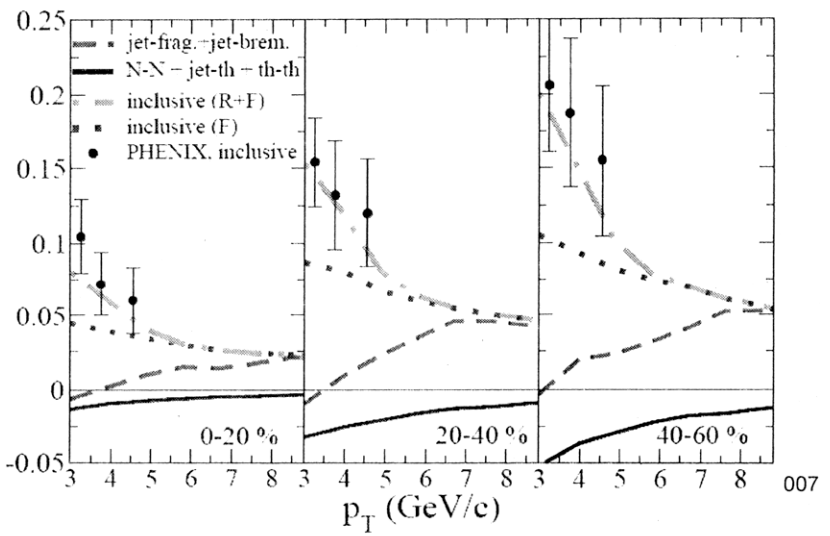




[RJF, Müller, Srivastava (2003)]
[Zakaharov (2004)]

- Need less inclusive observables
  - γ-hadron, γ-jet correlations
  - v_2: jet-medium photons negative (!)

[Turbide, Gale, RJF (2006)]



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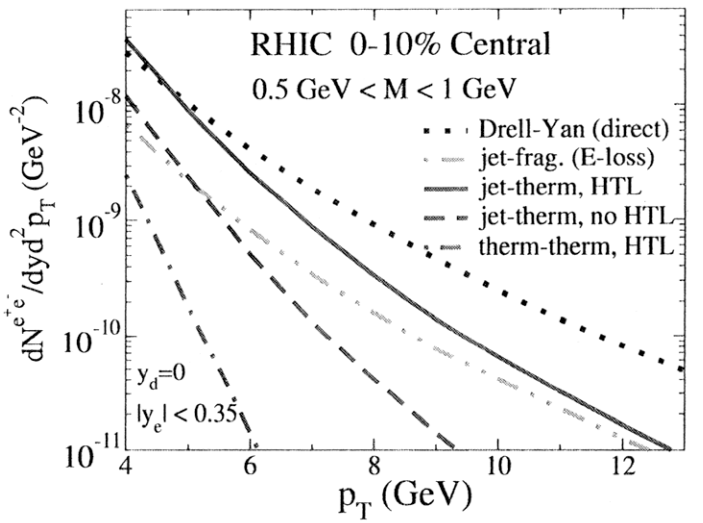
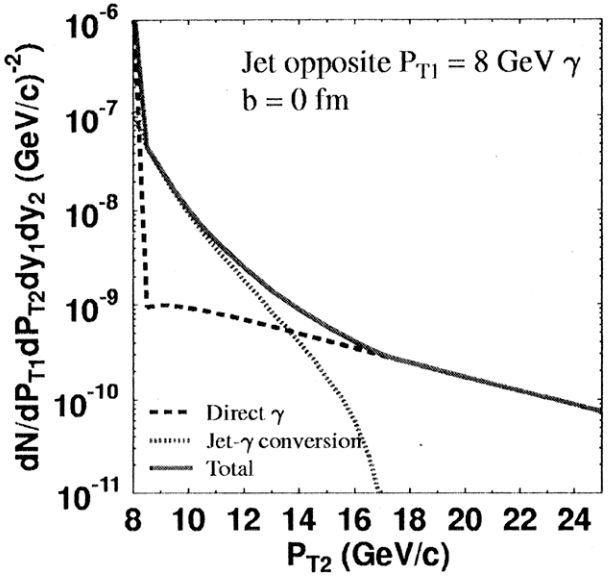
Dilepton spectrum



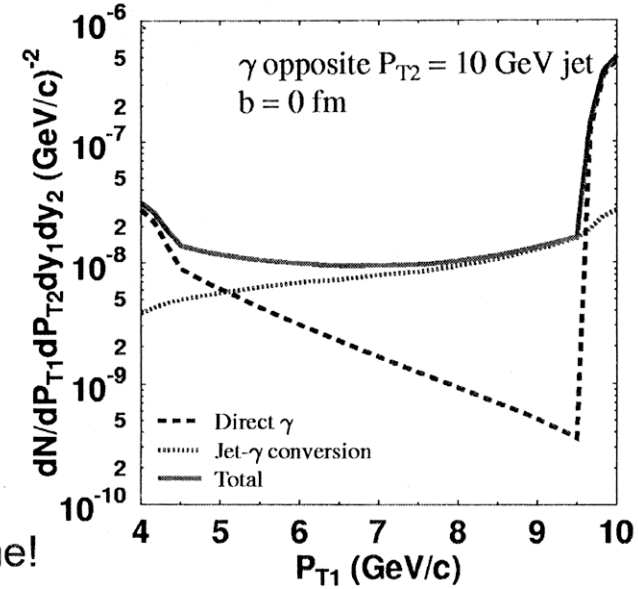
[Turbide, Gale Srivastava, RJF (2006)]

Correlations with Photons

- Improve sensitivity by using correlations/triggered yields: h-h, γ-h, γ-jet
  - Back-to-back γ-h: gold-plated measurement for energy loss [Wang et al.]
  - Caveat: 3-jet events, jet-medium photons $\rightarrow$ washed-out signal !
  - Turn this into a strength: use γ-h, γ-jet to disentangle photon sources!
- We ought to build a more precise theory framework for hard probes
  - Underlying hard perturbative process at NLO
  - Challenge: how to implement jet quenching?
- Preliminary LO studies:



[RJF (APS 2004)]

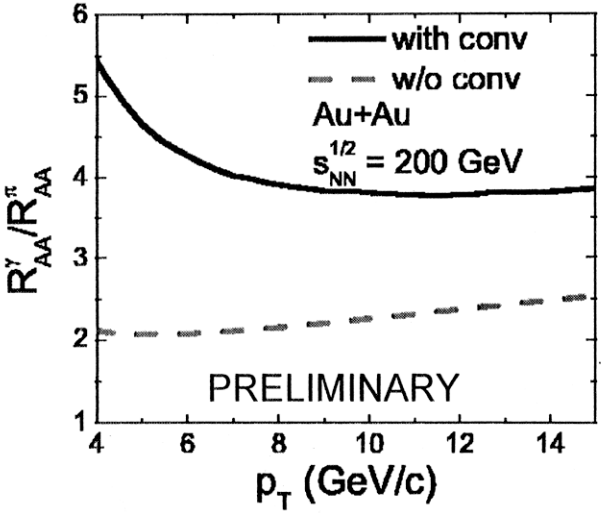


More to come!

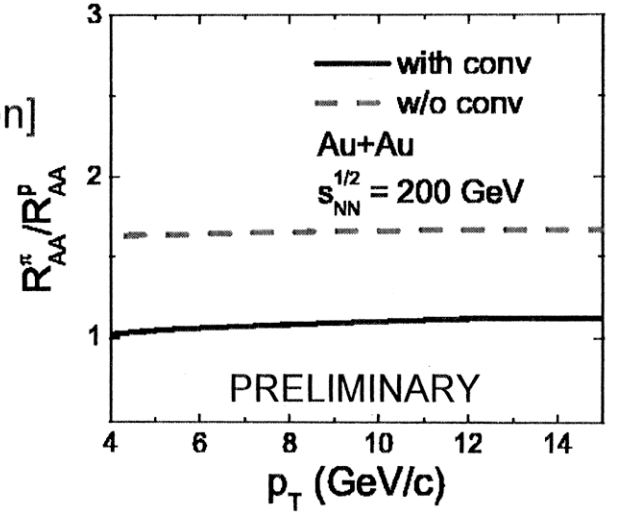
Jet Chemistry

Flavor Conversion

- Jet interaction with the medium can change the flavor of the leading parton (quark $\leftrightarrow$ gluon $\leftrightarrow$ photon)
  - Ko + Liu (2006): effect of q $\leftrightarrow$ g conversion on the p/π ratio.
  - RJF et al.: q, g $\rightarrow \gamma$ conversion is important photon source.
- Importance of flavor changing processes
  - Connection between the conversion processes
  - Predictions about the size (e.g. perturbative vs non-perturbative?)
  - Identify sensitive observables
- R_{AA} double ratios calculated in one consistent framework



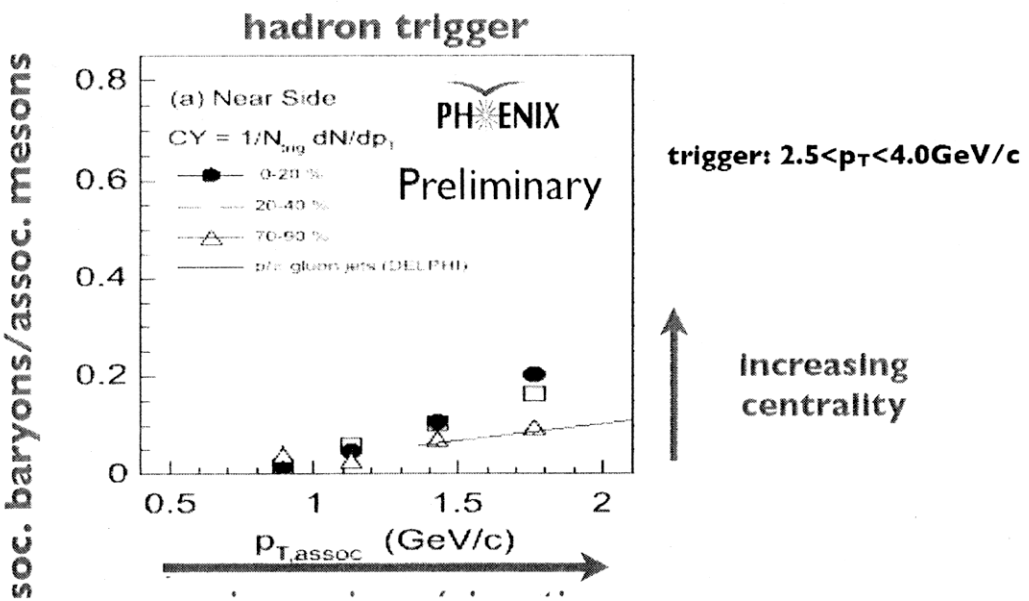
[Liu, Fries, in preparation]

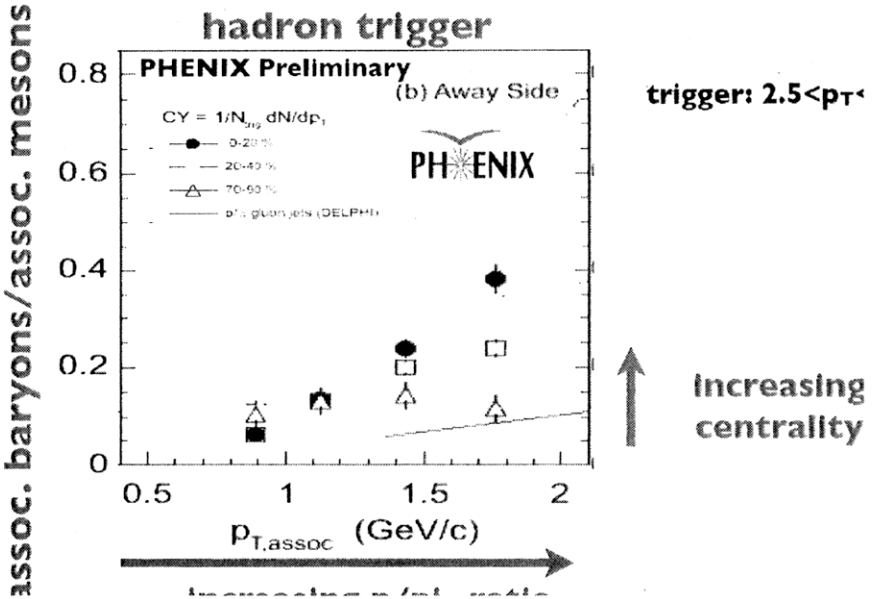


Medium Influence on Jet Chemistry

- At lower P_T: many hadrons from jets that have interacted heavily with the medium; (partial) thermalization of jets.
- Lesson from the baryon anomaly and recombination:
  - Baryon/meson ration is a good measure for the the ratio of hadrons coming from the medium vs vacuum fragmentation
  - PHENIX data: B/M ration increased on away-side vs near-side
- Effects can be understood in a recombination + jet fragmentation picture

[Fries, Nonaka, in preparation]



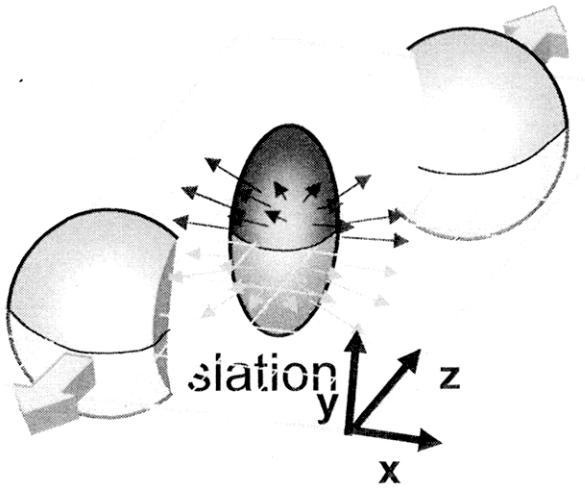


Summary & Outlook

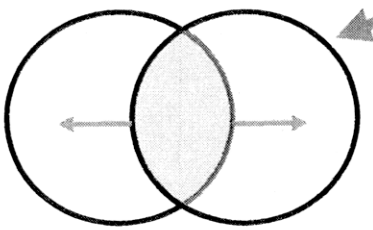
- Progress on understanding of rescattering a in a collinear factorization framework
  - Make connections with transport properties
  - Next: gluon radiation + energy loss
- Electromagnetic Probes
  - Photons from jets: no hard experimental evidence yet; negative v_2
- Correlations with photons:
  - Get NLO calculations ready
  - Use correlations as a filter for photon sources
- Chemistry with jets
  - Flavor conversions in the medium might be important
  - Check partial thermalization with B/M ratios

Elliptic Flow v_2

- Finite impact parameter $b > 0$:
  - Spatial anisotropy in the initial state
  - Momentum anisotropy in the final state
- Space $\leftrightarrow$ momentum space

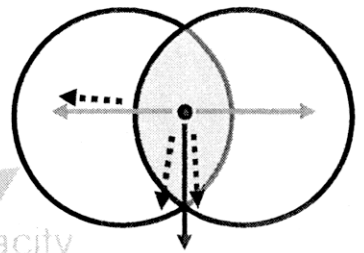


Bulk/soft particles

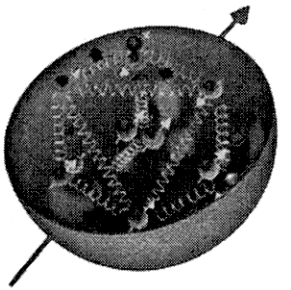


$Force = -\nabla P$

Hard particles + Photons



$\Delta E \propto L$



Spin-Orbital Correlation and Structure Function at large-x

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Nuclear Science Division, Lawrence Berkeley Laboratory

RBRC, Brookhaven National Laboratory

RIKEN BNL Research Center

RIKEN/BNL Research Center Review 11/05/07

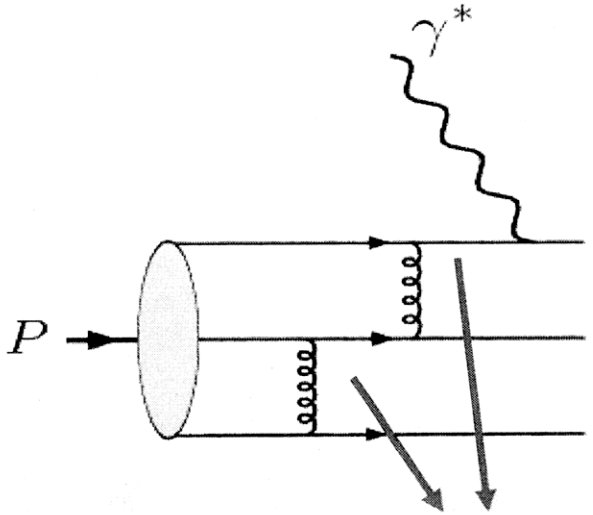
Summary of 2007

- Transverse spin physics
  - Single-Transverse Spin Asymmetry in Dijet Correlations at Hadron Colliders, Bomhof, Mulders,Vogelsang,F.Yuan, **PRD75:074019, 2007**
  - Asymmetric Di-jet Production in Polarized Hadronic Collisions Qiu,Vogelsang,F. Yuan, **Phys.Lett.B650, 373 (2007)**
  - Single Transverse-Spin Asymmetry in Hadronic Dijet Production, Qiu,Vogelsang,F. Yuan, **PRD76:074029, 2007**
  - Azimuthal Asymmetric Distribution of Hadrons Inside a Jet at Hadron Collider, F. Yuan, **arXiv:0709.3272 [hep-ph]**
- Factorization in hard scattering
  - Hadronic Dijet Imbalance and Transverse-Momentum Dependent Parton Distributions, Vogelsang,F.Yuan, **arXiv:0708.4398 [hep-ph]**
- Power counting at large-x
  - Effect of Orbital Angular Momentum on Valence-Quark Helicity Distributions, Avakian,Brodsky,Deur,F.Yuan, **PRL99, 082001 (2007).**

Physics Motivation for large-x

- Global fit for the PDFs
- New Physics at Tevatron and LHC
- Precision Test of EW physics at Colliders
- ...
- Itself is very interesting to study QCD effects, such as resummation; and nucleon structure, such as **quark orbital angular momentum**,...

Why Perturbative calculable



All propagators are far off-shell: $k_t^2/(1-x) >> \Lambda_{QCD}^2$

Spectator power counting

Power counting of Large x structure

- Drell-Yan-West (1970)

$$F_1(q^2) \xrightarrow[q^2 \to -\infty]{} (-1/q^2)^n \longleftrightarrow \nu W_2(x) \xrightarrow[x \to 1]{} (1-x)^{2n-1}$$

- Farrar-Jackson (1975)

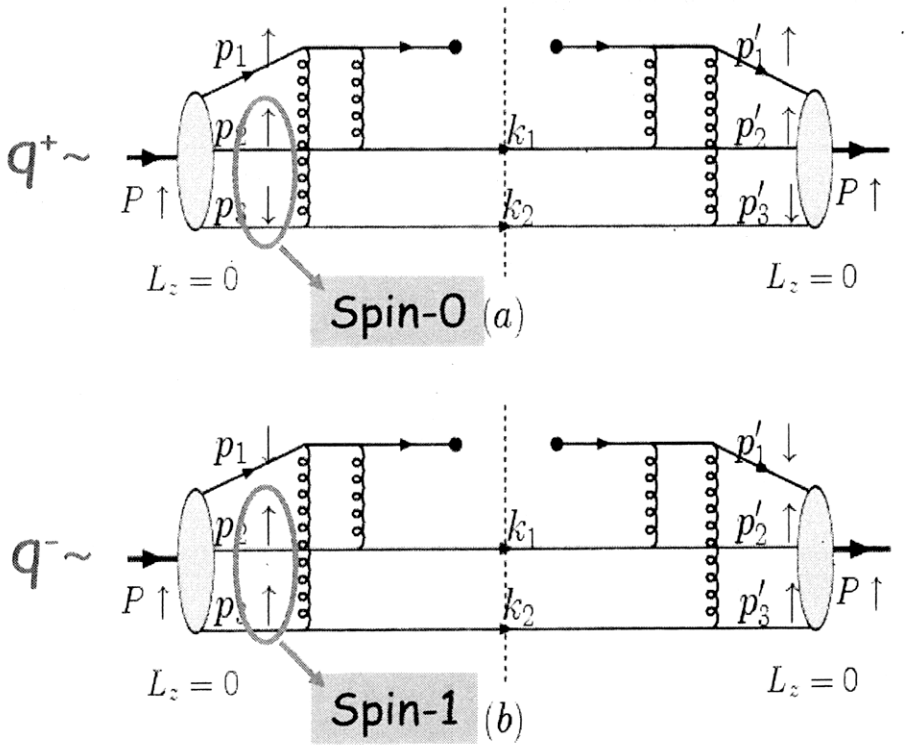
$$\nu W_2^{\pi} \sim (1-x)^2 \quad \text{and} \quad \nu W_2^{p} \sim (1-x)^3$$

- Brodsky-Lepage (1979)

$$G_{q\uparrow/p\uparrow} \sim (1-x)^{\cdot} \quad ; \quad G_{q\downarrow/p\uparrow} \sim (1-x)^{\cdot}$$

- Brodsky-Burkardt-Shmidt (1995) fit the polarized structure functions.

Power counting from L_z=0



- Spectator two quarks with spin-1 configuration will be suppressed by $(1-x)^2$ relative to spin-0
  - $q^-\sim (1-x)^2 q^+$

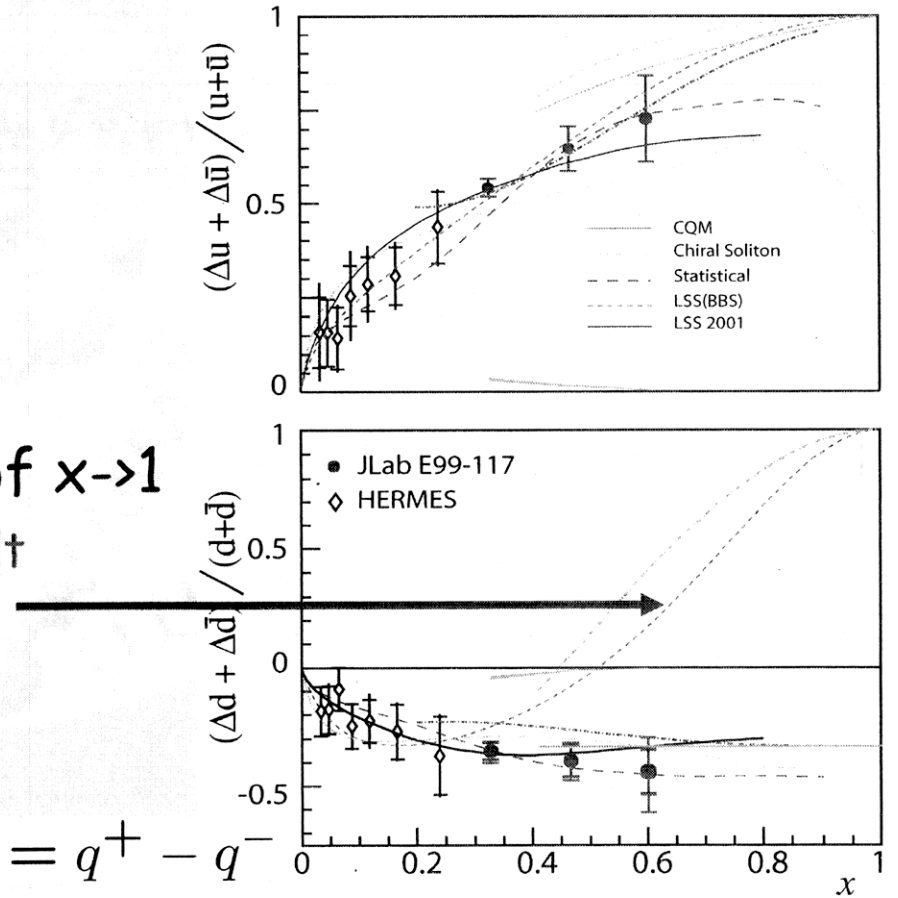
Quark polarization at large-x

- Power counting rule:

  $q^+ \sim (1-x)^3$, $q^- \sim (1-x)^5$

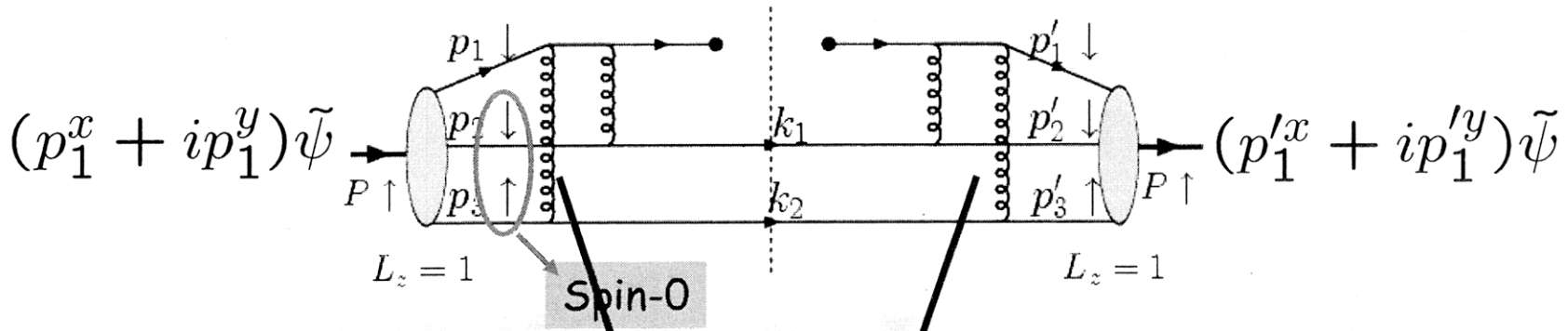
- The ratio of $\Delta q/q$ will approach 1 in the limit of x->1
  - Brodsky-Burkardt-Shmidt (1995)

JLab Hall A, PRL04



$$\Delta q = q^+ - q^-$$

L_z=1 contributions to q^-



- No suppression from the partonic scattering part
- Intrinsic pt expansion will lead to power suppression

$$\approx \frac{\beta(1-x)}{y_3 k_{2\perp}^2}\left(1 - \frac{\beta(1-x)}{y_3 k_{2\perp}^2} 2p_{3\perp}\cdot k_{2\perp}\right)$$

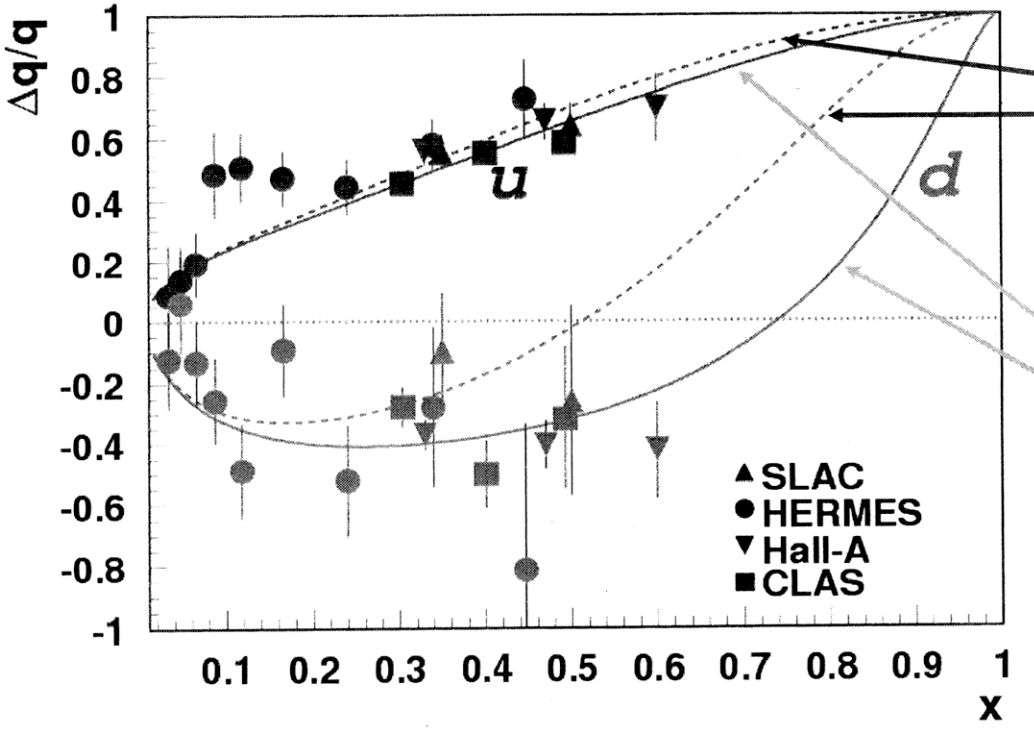
- Total suppression factor will be

$$\frac{(1-x)^2}{y_3 y_3'}$$

Orbital angular momentum contribution

- It does not change the power counting
  - $q^- \sim (1-x)^5$
- It introduces double logarithms to q^-
  - $q^- \sim (1-x)^5 \log^2(1-x)$
  - Coming from additional factor $1/y_3 y_3'$ in the intrinsic pt expansion
  - $q^-/q^+ \sim (1-x)^2 \log^2(1-x)$ at $x \to 1$

Quark orbital angular momentum contribution at large-x



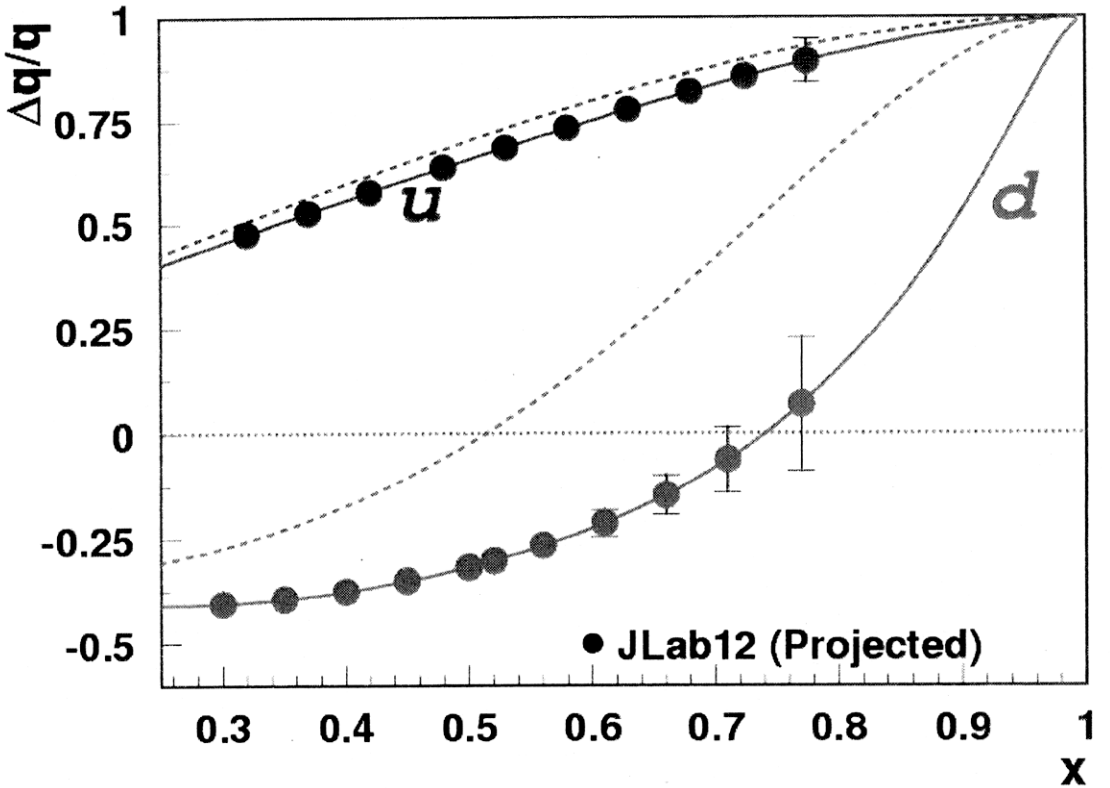
Power counting rule
Brodsky-Burkardt-Schmidt 95
Leader-Sidorov-Stamenov 98
$q^-/q^+ \sim (1-x)^2$

Quark-orbital-angular Momentum contribution
Avakian-Brodsky-Deur-Yuan,07
$q^-/q^+ \sim (1-x)^2 \log^2(1-x)$

More precise determination of these contributions requires a NLO global fit with all experimental data

Can be further tested at Jlab-12GeV and future EIC experiments

Jlab-12GeV projections



Summary of my three years at RBRC

- 28 publications (17 journal papers + 8 conference proceedings + 3 on my desk)
- 43 talks (31 conference talks and lectures + 12 seminars)
- I am really grateful to RBRC for all the support

Thank You Very Much!!

Neutrino astrophysics

Cecilia Lunardini

Arizona State University – Asst. prof.

RBRC - Fellow

The RBRC – ASU partnership

How RBRC is supporting ASU

- A ***new*** faculty position in ASU's Department of Physics
  - increases Nuclear/particle physics
  - Begins ASU's strategic area of nuclear/particle astrophysics
  - Rejuvenates the nuclear/particle group
  - Increases diversity at ASU

- The RBRC fellowship enhances research
  - Allows 50% of time for research only
  - Offers resources at BNL (interaction, workshops, …)
  - Increases opportunities for travel

Neutrino astrophysics

After solar neutrinos: new challenges

- Understanding core collapse supernovae (SN) with ν:
  - Dominate the energetics
  - Participate in the synthesis of heavy elements
  - Contribute to powering the explosion

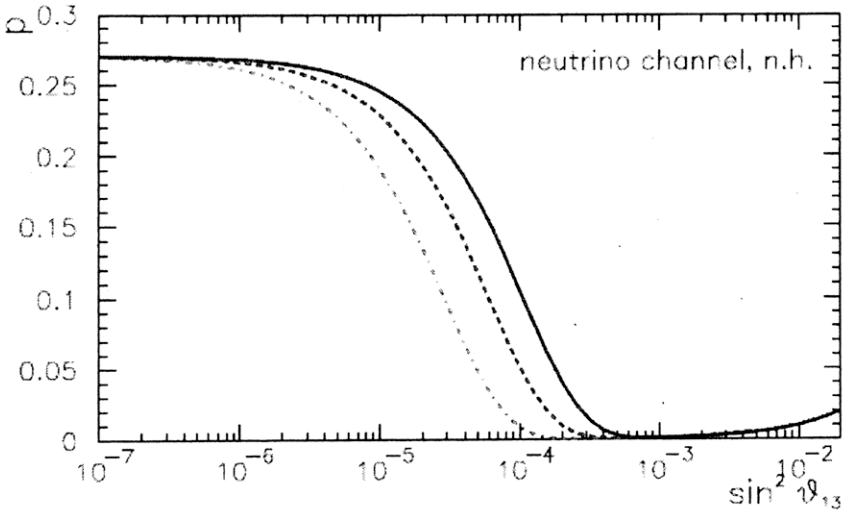
- Exploring and understanding the sky at high energy (>TeV)
  - Origin of cosmic rays: ν from baryonic jets (Gamma Ray Bursts)
  - High energy ν from exotica (decay of heavy relics, ..)

- Ongoing tests of ν properties: using stars as ν factories

Themes of my research

MeV – TeV ν from core collapse supernovae (SN)

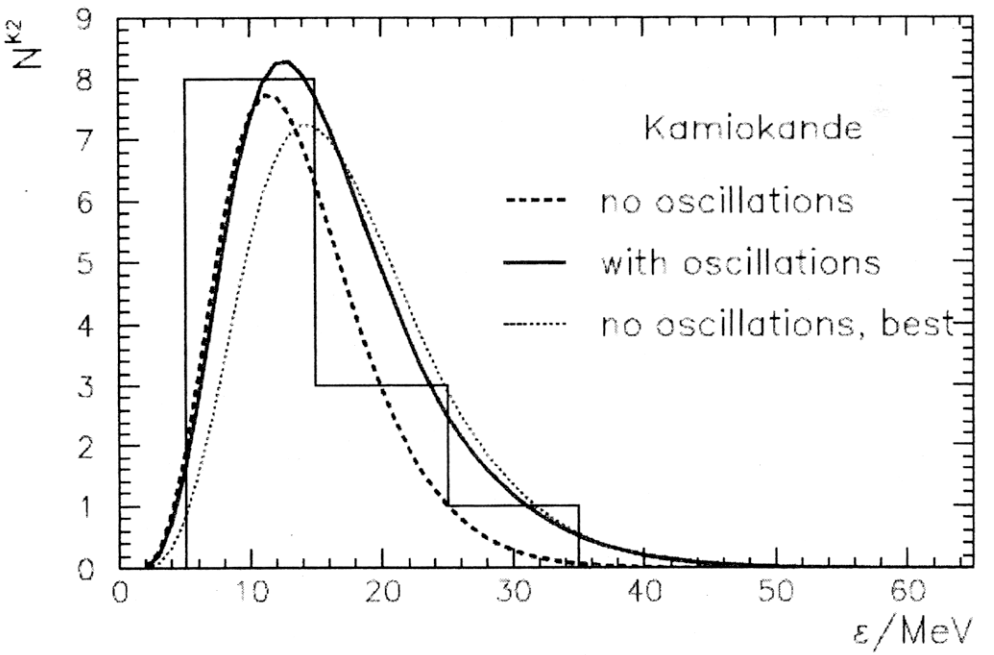
Learning from a nearby supernova

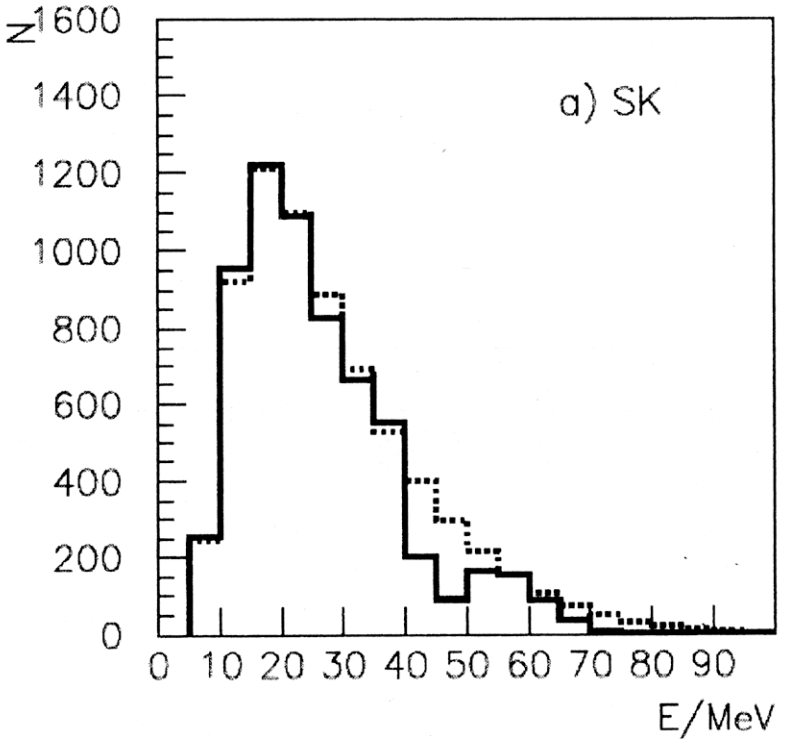


- Conversion probabilities in SN distinguish $\sin^2 \theta_{13}$ down to 10^{-5} !

Lunardini & Smirnov, JCAP 0306 (2003) 0,
Astropart. Phys. 21 (2004) 703–720

- Oscillations are a reality. They change the interpretation of SN1987A dramatically
  - $\langle E_{\nu_e} \rangle$ ~ 11 MeV no oscill.
  - $\langle E_{\nu_e} \rangle$ ~ 8 MeV oscill.

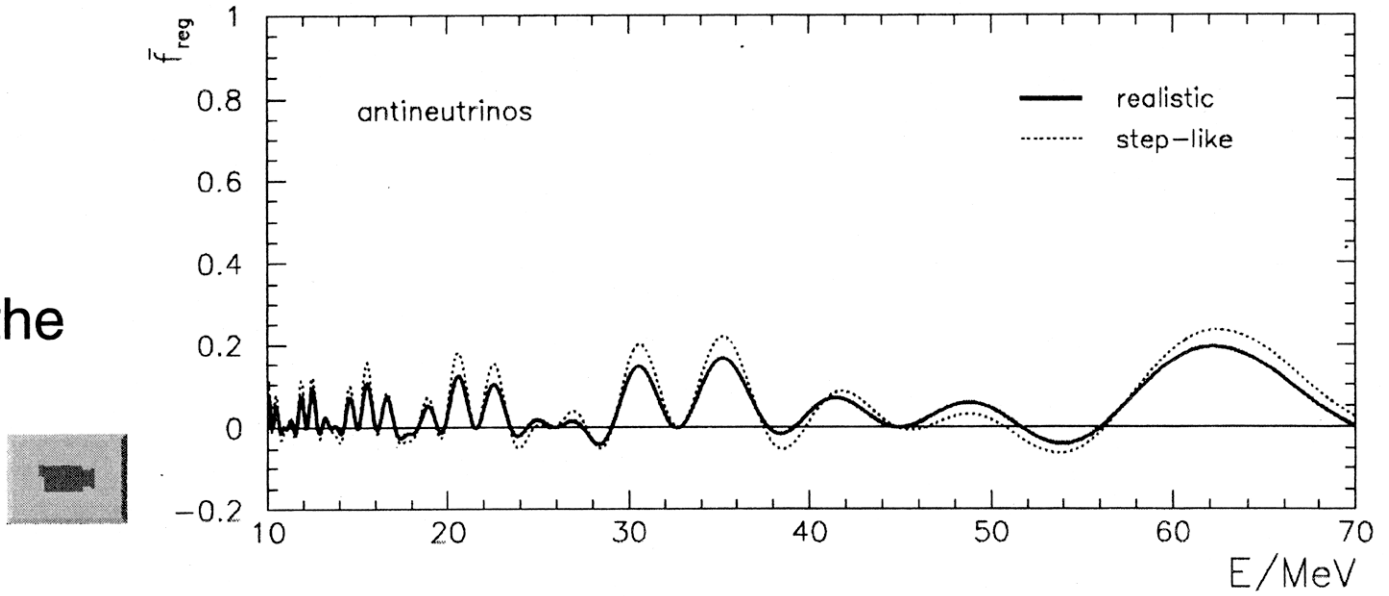




- Oscillations in the Earth are a robust signature
  - Can tell ordering of ν mass spectrum and θ_{13}

Lunardini & Smirnov,
Nucl. Phys. B616 (2001) 307–348
JCAP 0306 (2003) 0

- They might appear *late*, marking the passage of the shockwave



Next:

- Three-neutrino oscillations in a neutrino background
  - Neutrino-neutrino effects change the picture

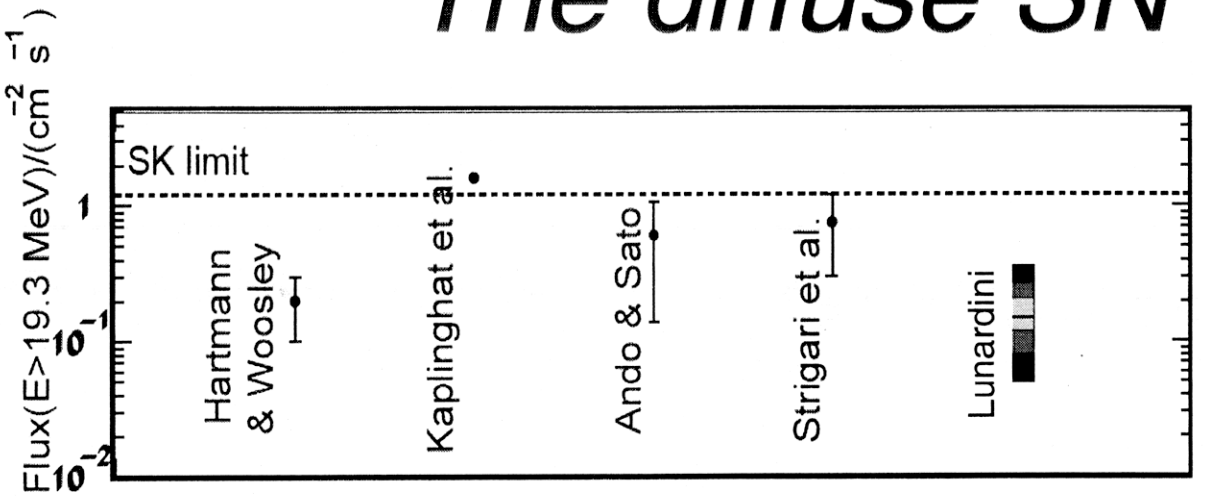
    Duan, Fuller, Carlson and Qian, Phys. Rev. D74 (2006) 105014

- Learning about the star: ONeMg supernovae
  - Different density profile → different oscillations

- Late time effects
  - Transition to ν-transparent core: observable?

- What detectors do we need?
  - After SNO, no large ν_e detector available!

The diffuse SN ν flux



- *Predict anti-ν_e flux with SN direct data:* SuperK limit is *not* testing the SN rate

- *Calculate event rates:* Megaton size necessary for *likely* detection

	UNO/HyperK: Water, 0.4 Mton fiducial, E_ν > 19.3 MeV	GADZOOKS Water+Gd, 20 Kt fiducial, E_ν>11.3 MeV
Anti-ν_e + p Events/4 yr (99% CL, from SN1987A)	7 - 60	1.1 - 6.4

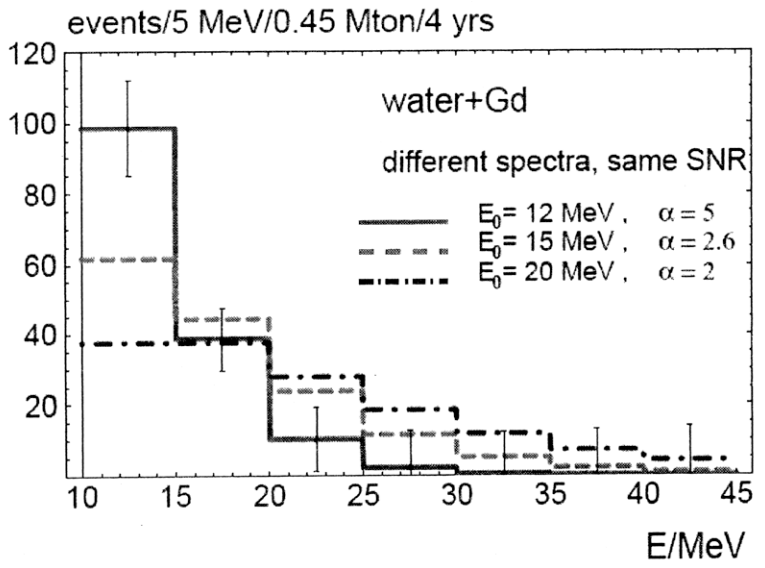
C. Lunardini, Astropart. Phys. 26 (2006) 190–201

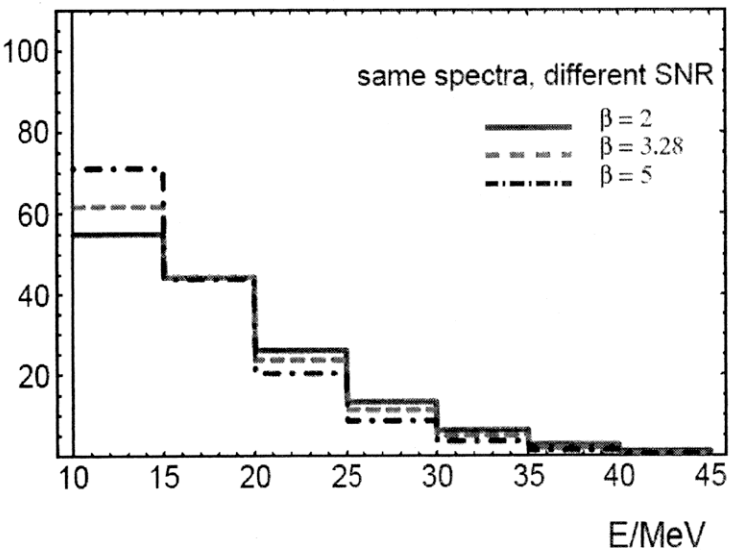
- Best limit on ν_e component from SuperK anti-ν_e search + oscillations:

$$\Phi_{\nu_e}(E < 19.3\ \mathrm{MeV}) < 5.5\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad \text{at } 98\%\ \mathrm{C.L.}\ .$$

C. Lunardini, Phys. Rev. D73 (2006) 083009

- What can be learned? Original ν spectrum
  - Supernova rate z-dependence below sensitivity





C. Lunardini, Phys. Rev. D75 (2007) 073022

Next:

- Including individual differences
  - 20-50% differences in ν flux depending on star's mass

    M. Liebendoerfer et. al., Nucl. Phys. A719 (2003) 144–152

- Physics potential: do we need a galactic supernova?
  - What observables absolutely need high statistics?

- Ratio of SuperNova Rate and Star Formation Rate
  - SNR from ν + SFR from astronomy → measure minimum mass required for core collapse

High energy ν from deep jets in SN

- γ-Ray Bursts are from *very few* SNe with ultrarelativistic jets

- *Slow* (Γ ~ few) jets could be very common in SNe → *~ TeV flux of ν from SNe!*

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

- Slow jet can be deep → *matter-affected oscillations*
  - Tomography of star
  - Test of CP-violating phase

  O. Mena, I. Mocioiu and S. Razzaque, Phys. Rev. D75 (2007) 063003

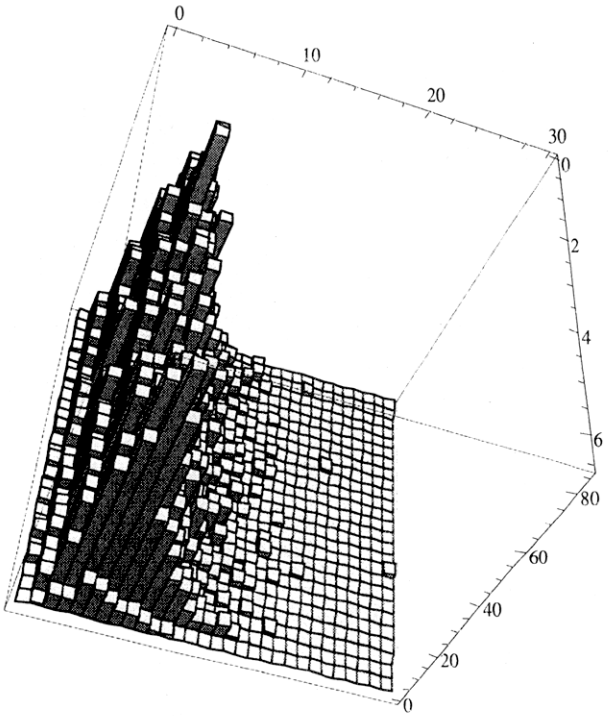
Geochemical signatures of SN

- ^{97}Tc in Molybdenum rocks counts prehistoric ν_e
  - ^{97}Tc lifetime: 2.6 10^6 yrs: not primordial!
  - SN contribution ~ 40% of solar
  - Only ν_e SN data! Already available!

Haxton & Johnson, Nature 333 (1988) 325–329.

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

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



- Modern version of the idea
  - Include oscillations
  - Updated galactic distribution of SNe
  - Calculated cross sections
  - Known solar ν flux

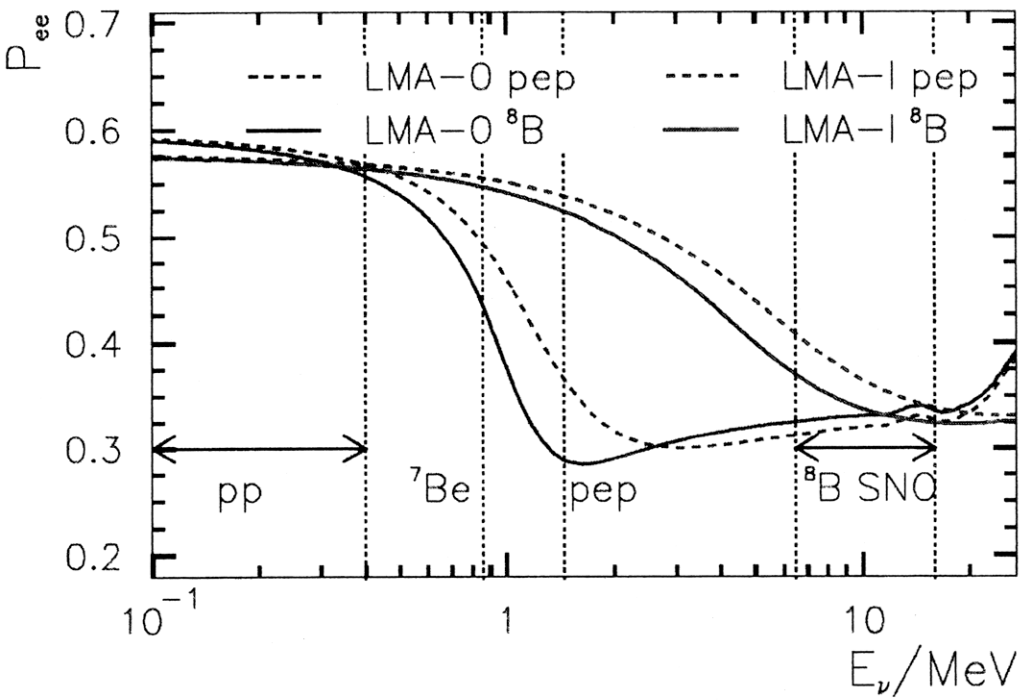
Non-astro ν research

- Studied non-standard neutrino-matter interactions

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R)$$

- Solar ν:
  - Standard
  - With NSI

- Strong effects in *long baseline* ν beams!



Friedland, Lunardini & Pena Garay, Phys.Lett.B594:347,2004

Phase structure of twisted large-N reduced model

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

The RBRC Scientific Review Committee Meeting
BNL, November 5 and 6, 2007

based on collaboration with
Tatsuo Azeyanagi (Kyoto University, Japan)
Masanori Hanada (RIKEN, Nishina Center, Japan)
Tomoyoshi Hirata (Kyoto University, Japan)

Reference
- PoS (LATTICE2007) 054 [arXiv:0710.2919].

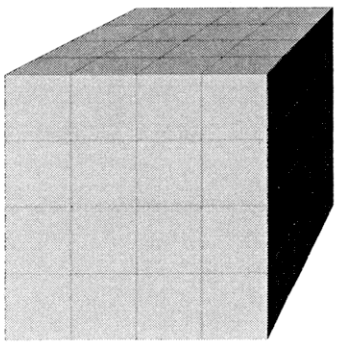
Large-N and Eguchi-Kawai equivalence

Large-N

- 't Hooft proposed in 1974 to use the dimensionality of the gauge group SU(N) as an expansion parameter, which is called the 1/N expansion.
- At large-N, the theories are simplified while preserving essential features of QCD.
- Strongly connected to the string theory

Eguchi-Kawai equivalence (Eguchi and Kawai, PRL48(1982)1063)

- At the large-N limit, the SU(N) YM theory lose volume dependence.



L^D dimensional reduction $=$ 1^D

with periodic b.c.

$$S_{\mathrm{EK}} = -N\beta \sum_{\mu \neq \nu} \mathrm{tr}\left[U_\mu U_\nu U_\mu^\dagger U_\nu^\dagger\right]$$

- Needed assumption: Z_N^D symmetry is not broken.

$$U_\mu \to e^{i\theta_\mu} U_\mu, \quad e^{i\theta_\mu} \in Z_N$$

Large-N and Eguchi-Kawai equivalence

Failure of the equivalence (D>2)

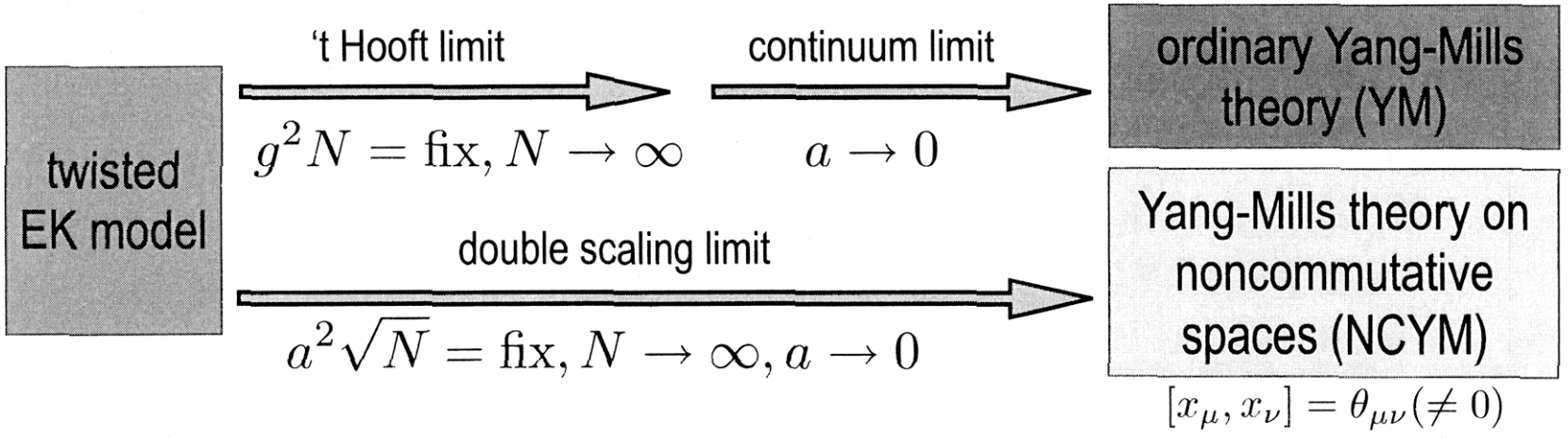
- Z_N^D symmetry in the weak coupling region
  - D=2 ⟹ unbroken
  - D>2 ⟹ spontaneously broken in weak coupling region

(Bhanat, Heller, Neuberger, PLB113(1982)47)

Twisted Eguchi-Kawai model

(Gonzalez-Arroyo and Okawa, PLB120(1983)174)

- Twisted b.c. $U_\mu(L\hat{\nu}) = \Gamma_\nu U_\mu(0)\Gamma_\nu^\dagger, \quad \Gamma_\nu \in SU(N)$
- Z_N^D symmetry is manifestly preserved in the weak coupling limit.
- This model can describe two kind of theories.



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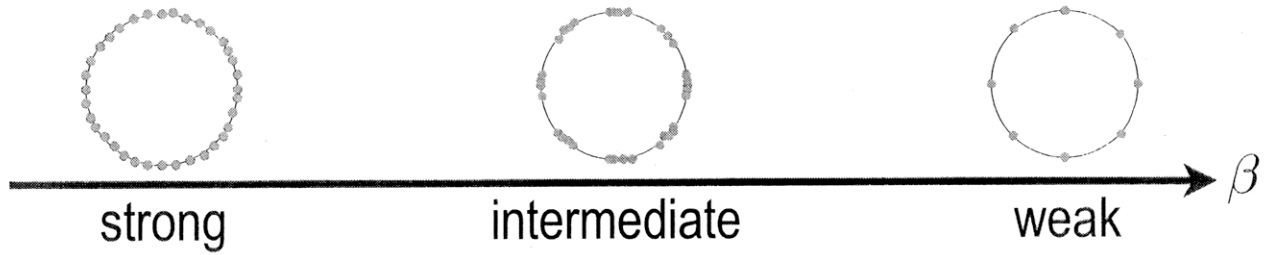
Intermediate coupling region (D=4)

There is no guarantee to maintain the Z_N^D symmetry throughout the whole coupling region.

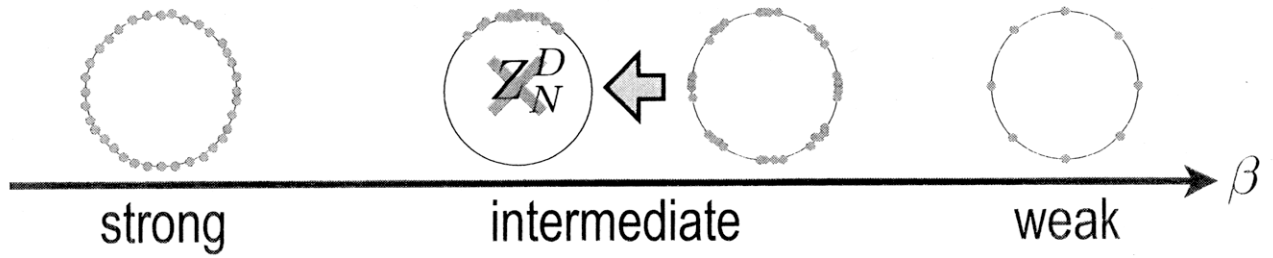
Situation in 80s

- numerical simulation (small N) : maintain throughout the whole coupling region



Recent claim (Teper and Vairinhos, PLB652(2007)359)

- numerical simulation (larger N) : not maintain in the intermediate coupling region



related works:
Bietenholtz et al.,
JHEP 0610(2006)042:
T.I and Okawa, talk in
JPS meeting (2002).

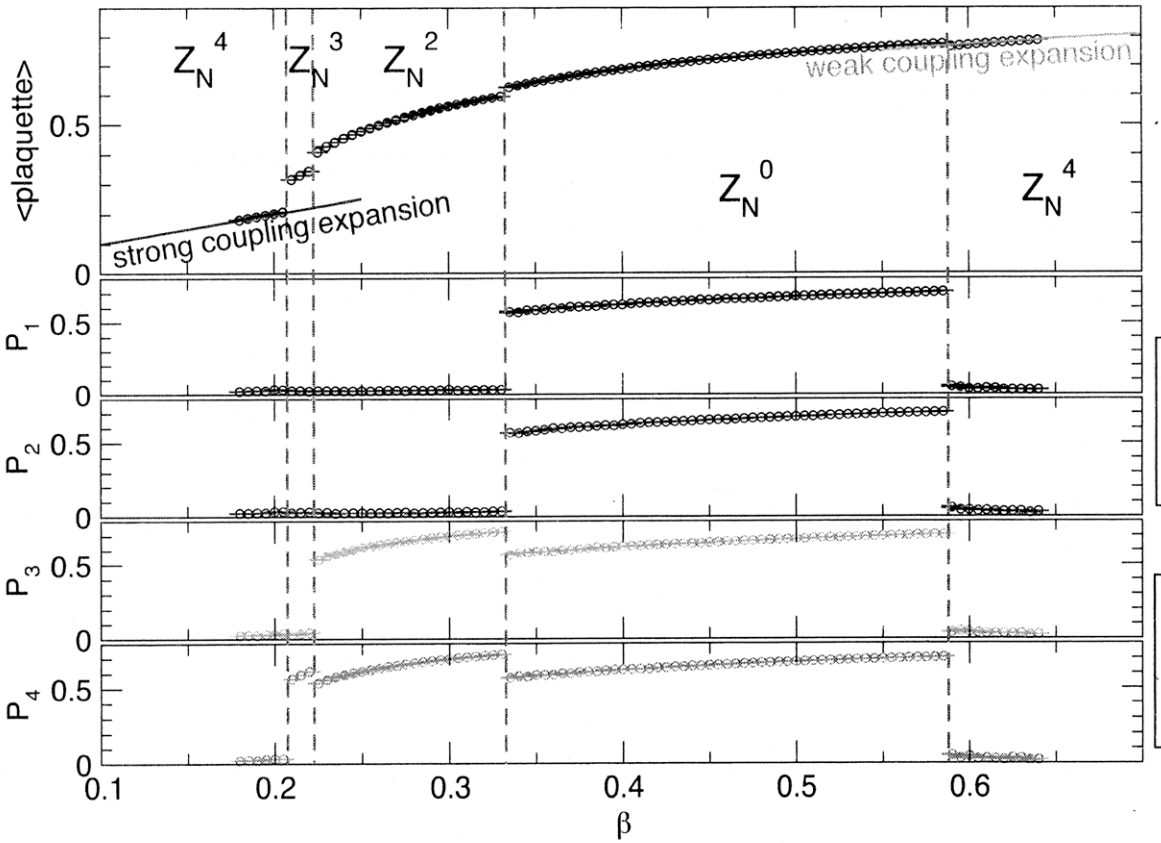
This work

We address whether the continuum limit can be taken or not both as the YM and as the NCYM.

Breaking behavior from the simulation

Example

- N=100, minimal twist $N = L^2, \;\; n_{\mu\nu} = L\epsilon'_{\mu\nu}$, cold start

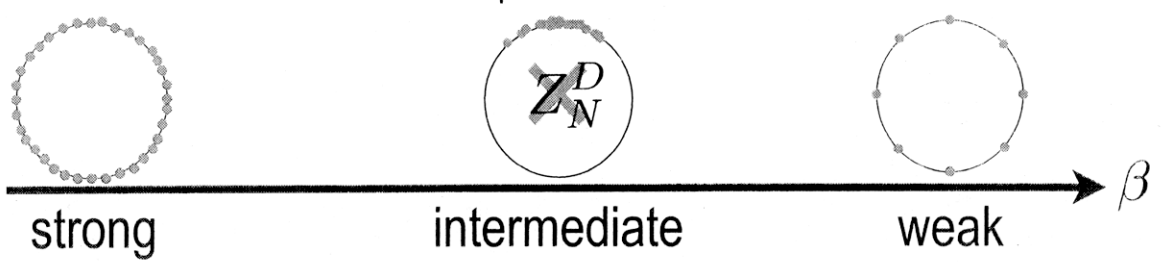


Polyakov line

$$P_\mu = \left\langle \frac{1}{N} \mathrm{tr} U_\mu \right\rangle$$

$$P_\mu = 0 \; (Z_N : \text{unbroken})$$
$$U_\mu \to e^{i\theta_\mu} U_\mu : P_\mu \to P_\mu$$

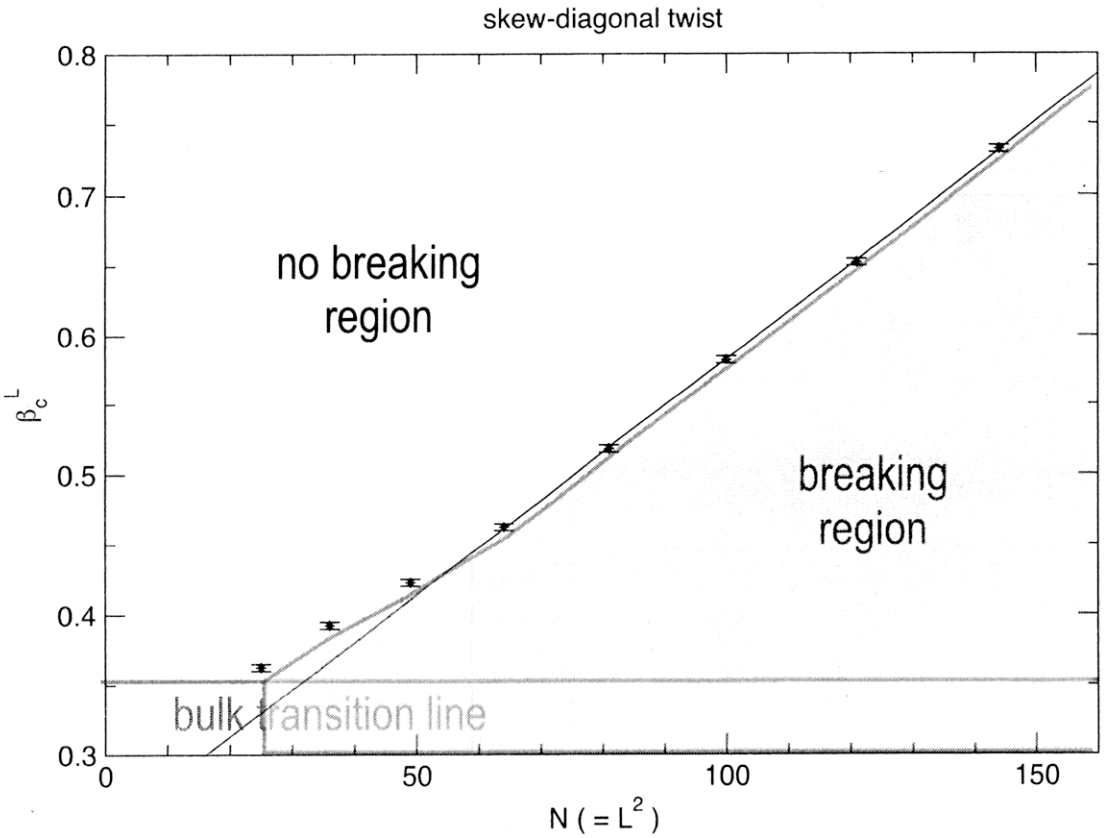
$$P_\mu \neq 0 \; (Z_N : \text{broken})$$
$$U_\mu \to e^{i\theta_\mu} U_\mu : P_\mu \to e^{i\theta_\mu} P_\mu$$



Breaking behavior from the simulation

Expansion of the breaking region

- minimal twist $N = L^2, \;\; n_{\mu\nu} = L\epsilon'_{\mu\nu}$



The linear behavior can also be obtained by theoretical estimation.

clear linear growth in larger N region

$$\beta_c(N) = 0.0034N + 0.25 \qquad (N \geq 64)$$

Continuum limit

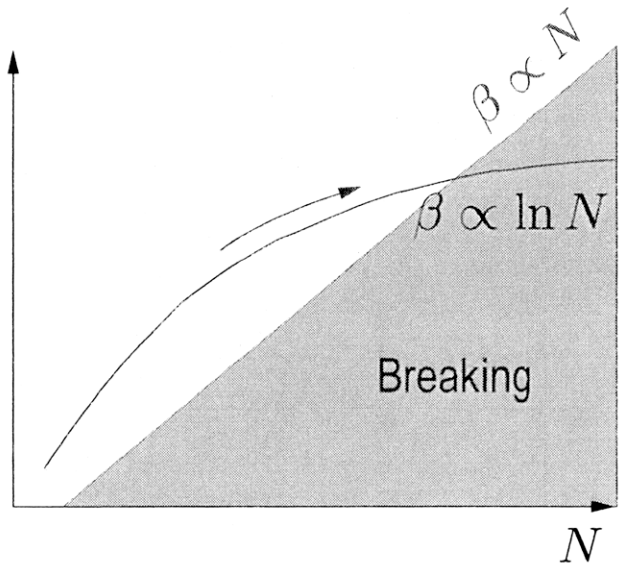
Continuum limit as the YM

- Near the continuum limit

$$\beta = \frac{1}{g^2 N} = -\frac{22}{3(4\pi)^2}\ln(a\Lambda) \quad \text{one-loop perturbation}$$

$$= \frac{22}{3(4\pi)^2}\left(\frac{1}{2}\ln N - \ln(l\Lambda)\right) \longleftarrow l = aL = a\sqrt{N} \text{ (minimal twist)}$$

- Continuum limit cannot be taken as the YM.



Continuum limit as the NCYM

- The beta function is essentially same as that of the YM. (Minwalla et.al., JHEP 0002(2000)020)
- The scaling is logarithm of N.
- Continuum limit cannot be taken as the NCYM.

The simple twisted Eguchi-Kawai model is fried up.

Summary and Outlook

Z_N^4 symmetry breaking in the twisted EK model

- Confirmation of the claim in the paper by Teper and Vairinhos
- Expansion of the breaking region

  clear linear behavior $\beta_c \sim N$

Continuum limit

- The breaking grows faster than $\log N$.

  Continuum limit cannot be taken both as the YM and as the NCYM.

  The simple twisted Eguchi-Kawai model is fried up.

Some possible directions

- Introduction of fermions can alter the phase structure.
- Improved action
- Imposition of quotient conditions in the NCYM context

RBRC Review Meeting, Brookhaven, November 5-6 2007

Heavy Quark Bound States at Finite Temperature

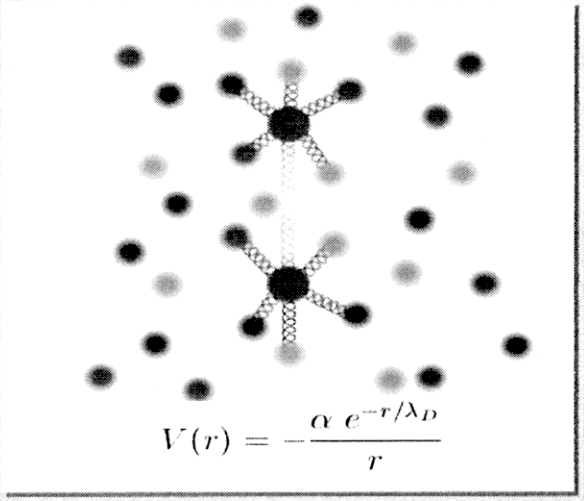
Ágnes Mócsy

Á. Mócsy, P. Petreczky, 0706.2183[hep-ph] (to appear in PRL)
0705.2559[hep-ph] (to appear in PRD)
0710.5125[hep-ph] (to appear in Eur Phys J.)
Phys. Rev. D 73, 074007, 2006
Eur. Phys. J. C 43, 77, 2005

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Deconfinement at high temperatures

Chromo-electric screening



Matsui-Satz argument:

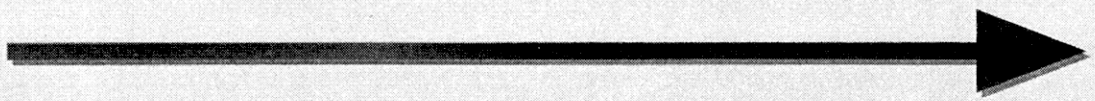
binding in quarkonium reduced,
dissociation for $\lambda_D < r_{Quarkonium}$

"Unambiguous signature of QGP formation"

Quarkonia melting as QGP thermometer

Sequential suppression

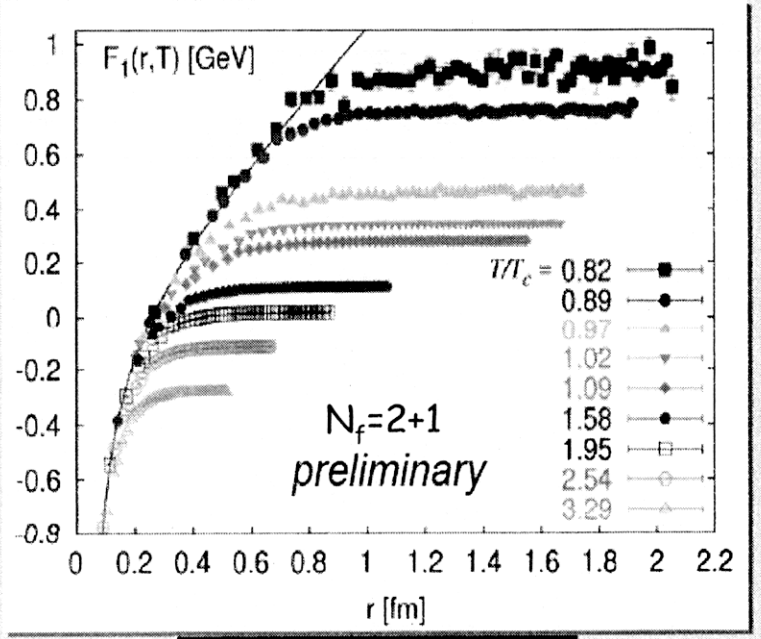
$\Psi'(2S)$	$\chi_c(1P)$		$J/\psi(1S)$	
	$\Upsilon''(3S)$	$\chi_b'(2P)$	$\chi_b(1P)$	$\Upsilon(1S)$
0.9 fm	0.7 fm		0.4 fm	0.2 fm



Quarkonia at Finite Temperature

Strong screening

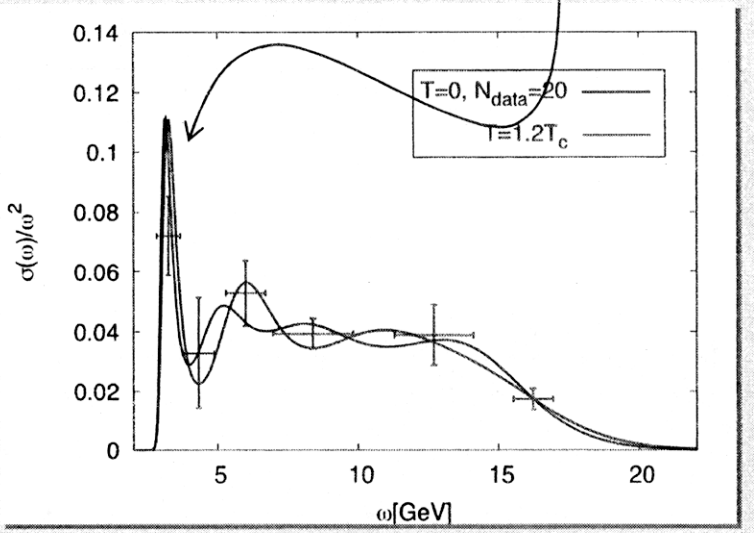
Free energy of a static Q-antiQ



RBC-Bielefeld Coll.07

Charmonium spectral function

Common interpretation:
1S ground state survives above T_c



Jakovác et al 07

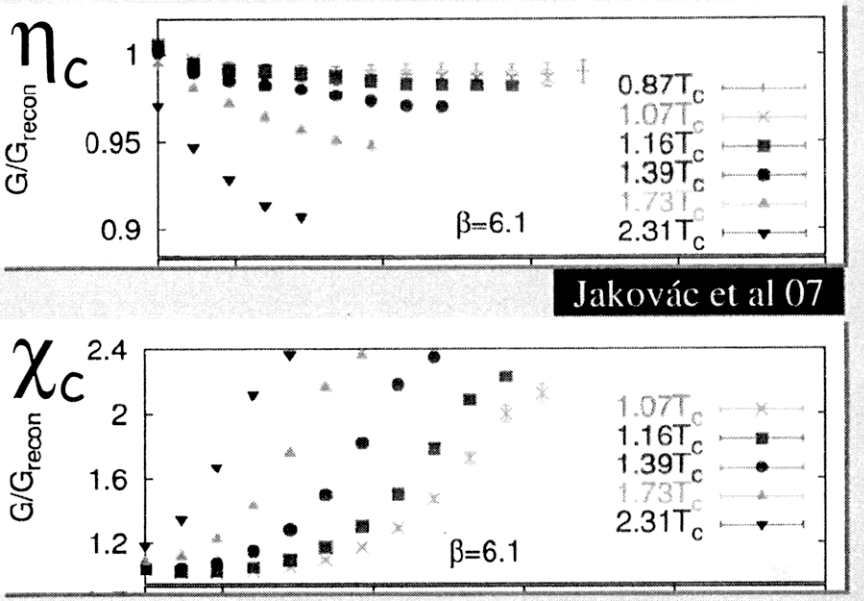
Strong screening seen, yet still some quarkonium states would survive unaffected in the QGP ?

Lattice QCD at T≠0

Directly calculated **Euclidean-time correlators** of mesonic currents

T-dependence of correlators

$$\frac{G(\tau,T)=\int\sigma(\omega,T)K(\tau,\omega,T)d\omega}{G_{rec}(\tau,T)=\int\sigma(\omega,T=0)K(\tau,\omega,T)d\omega}$$



Initial interpretation:

= 1 ⇒ unchanged spectral function = quarkonium survival

≠ 1 ⇒ modified spectral function ⇒ $T_{dissociation}$

⇒ "Lattice reported" J/ψ and η_c survive up to 1.5-2T_c
χ_c melts by 1.1 T_c

Lattice Correlators

Our Approach:

Assume potential model works at finite T

Construct a finite T potential

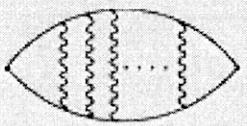
Constrained by lattice data

Assume to share general features with the free energy

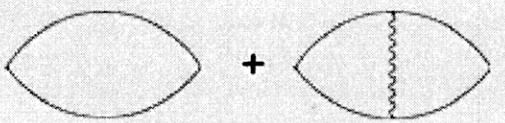
Calculate the spectral function

Unified treatment of bound-, scattering states, threshold effects

NR Green's function + pQCD



$$\left[-\frac{1}{m}\nabla^2 + V(\vec{r}) + E\right] G^{NR}(\vec{r},\vec{r}',E) = \delta^3(\vec{r}-\vec{r}')$$



$$\sigma(E) = \frac{2N_c}{\pi}\,\mathrm{Im}G^{NR}(\vec{r},\vec{r}',E)_{r=\vec{r}'=0}$$

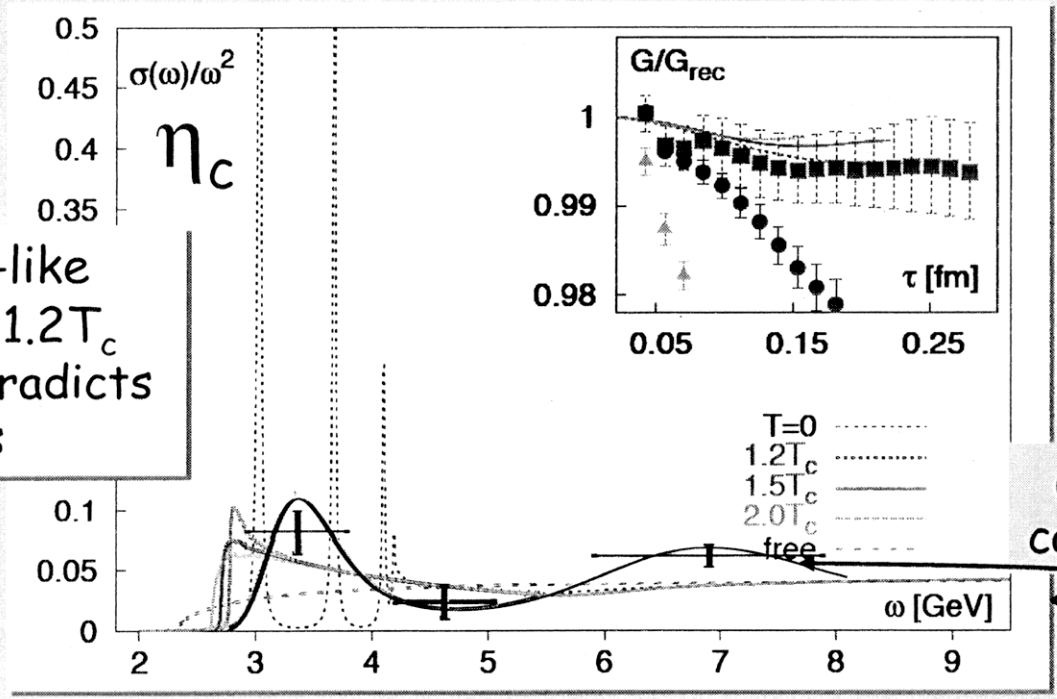
$$\sigma_{pert} \equiv \omega^2 \frac{3}{8\pi}\left(1+\frac{11}{3\pi}\alpha_s\right)$$

Determine the correlator ratio G/G_{rec}

compare to lattice data

Potential Models

Pseudoscalar Charmonium



No resonance-like structures at $1.2T_c$ seemingly contradicts previous claims

Correlators agree with lattice data within few %

details on lattice cannot be resolved

Jakovác et al 07

Threshold enhancement above free propagation indicates correlation

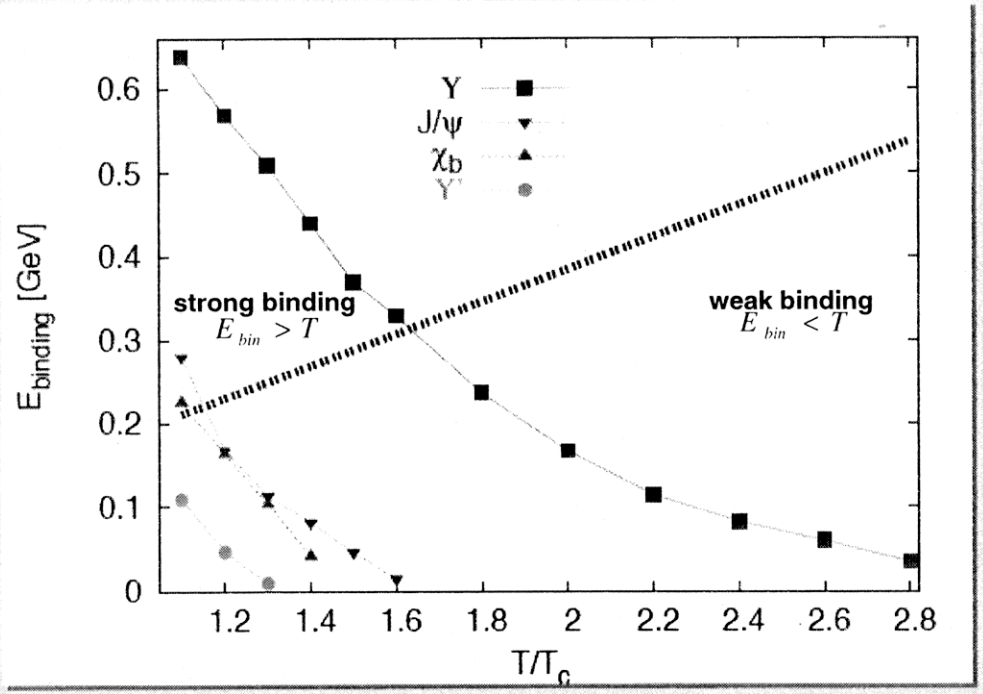
Lattice consistent with threshold enhancement

Note: Spectral function may show peak but binding energy is small

S-wave Charmonium

Find the upper limit for binding

with most confining potential still consistent with lattice



Thermal fluctuations can destroy the weakly bound states

Binding Energy Upper Limits

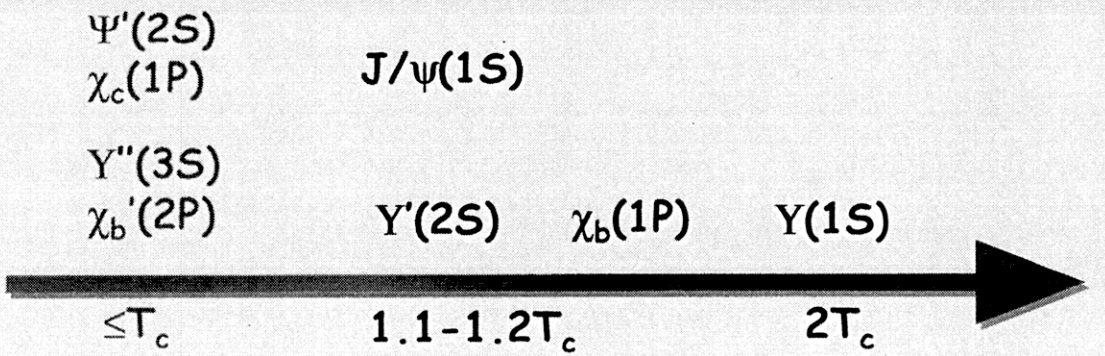
Upper bounds on dissociation temperatures

dissociation condition: thermal width > 2x binding energy

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

New calibration of the QGP thermometer

Implications for heavy ion phenomenology...



Dissociation Temperatures

Agreement to few% between potential model and lattice correlators for all states - First Time

Lattice data consistent with charmonium dissolution just above T_c

Conclusions

****The END****

Excited Resonance Physics From the Lattice

2007 RBRC Review

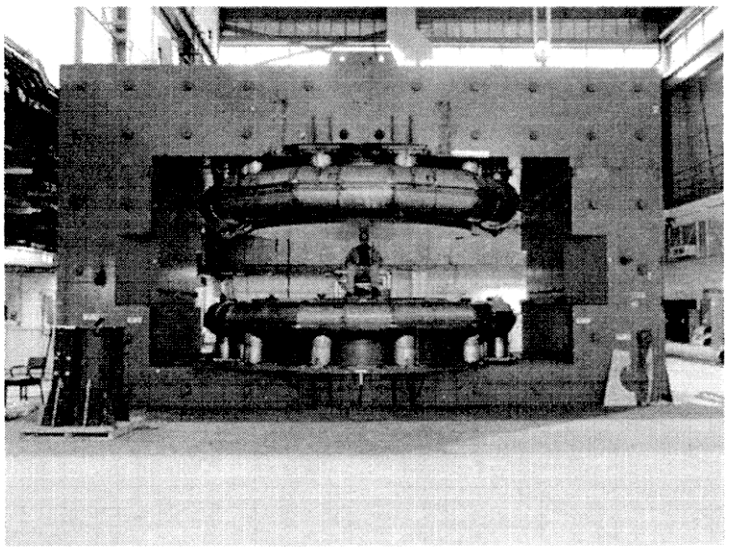
Adam C. Lichtl
RIKEN BNL Research Center

Brookhaven National Laboratory

Monday, November 5, 2007

Historical context

- Chicago Cyclotron (1952)
- H. Anderson, E. Fermi, E.A. Long, and D.E. Nagle
- Looked at pion-nucleon elastic scattering:
  - $\pi^+ p \longrightarrow \pi^+ p$
  - $\pi^- p \longrightarrow \pi^- p$



When they measured the cross sections

- The $\pi^+ p$ cross section is enhanced around 1232 MeV.
- Doubly-charged resonance: Δ^{++}

Experimentally measured cross section data

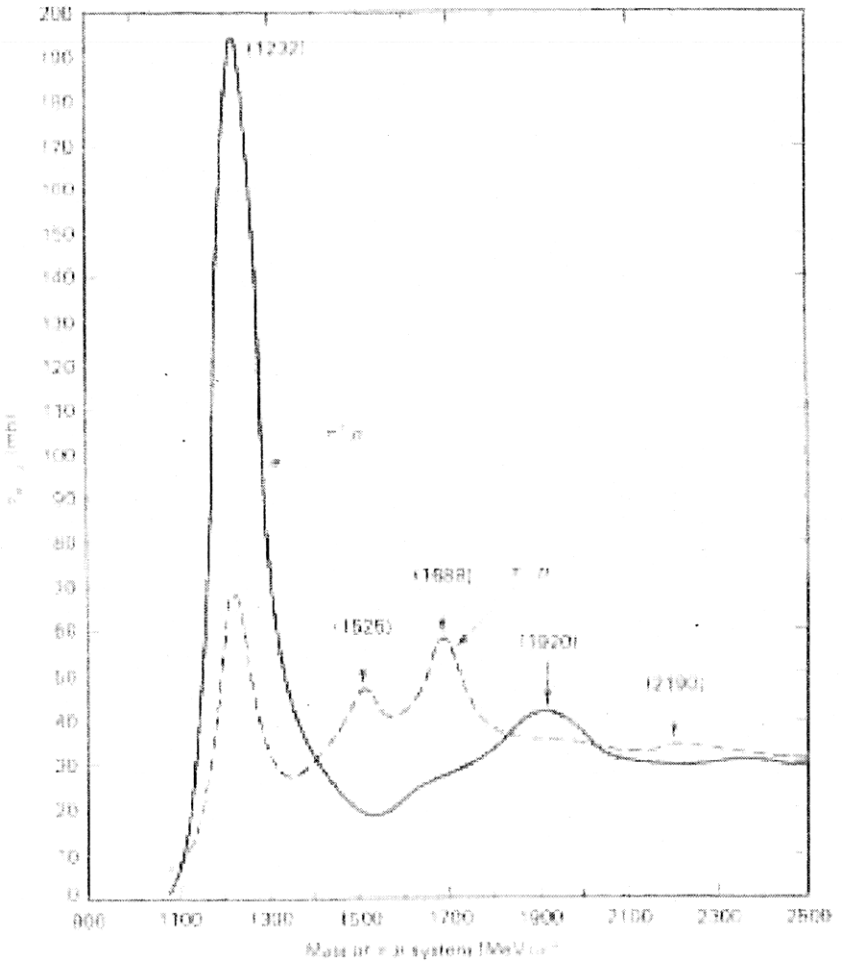


Figure 4.6 Total cross sections for $\pi^+ p$ (solid line) and $\pi^- p$ (dashed line) scattering. (Source: S. Gasiorowicz, *Elementary Particle Physics* (New York: Wiley, copyright © 1966, page 294. Reprinted by permission of John Wiley and Sons, Inc.)

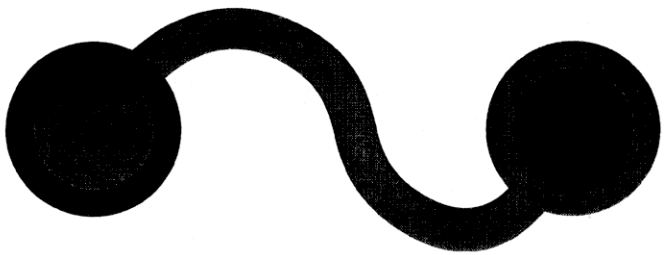
Particle zoo

- Since then, particle physicists have discovered over 200 resonances
- Wolfgang Pauli:

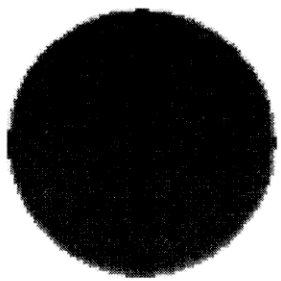
"If I had known this was going to happen, I would have gone into botany."

Motivation - Why calculate the hadron spectrum?

- Can QCD reproduce the observed hadron spectrum and explain missing resonances?
- When do the gluonic degrees of freedom begin to play a role in the spectrum?
- What are the masses and other properties of hybrid hadronic resonances?



Hybrid mesons: $Q\bar{Q}$
+(excited glue)

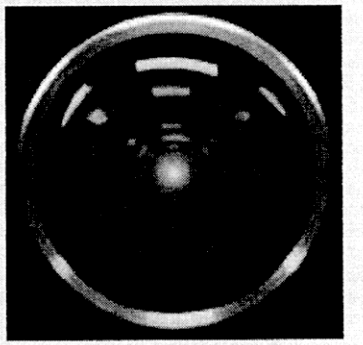


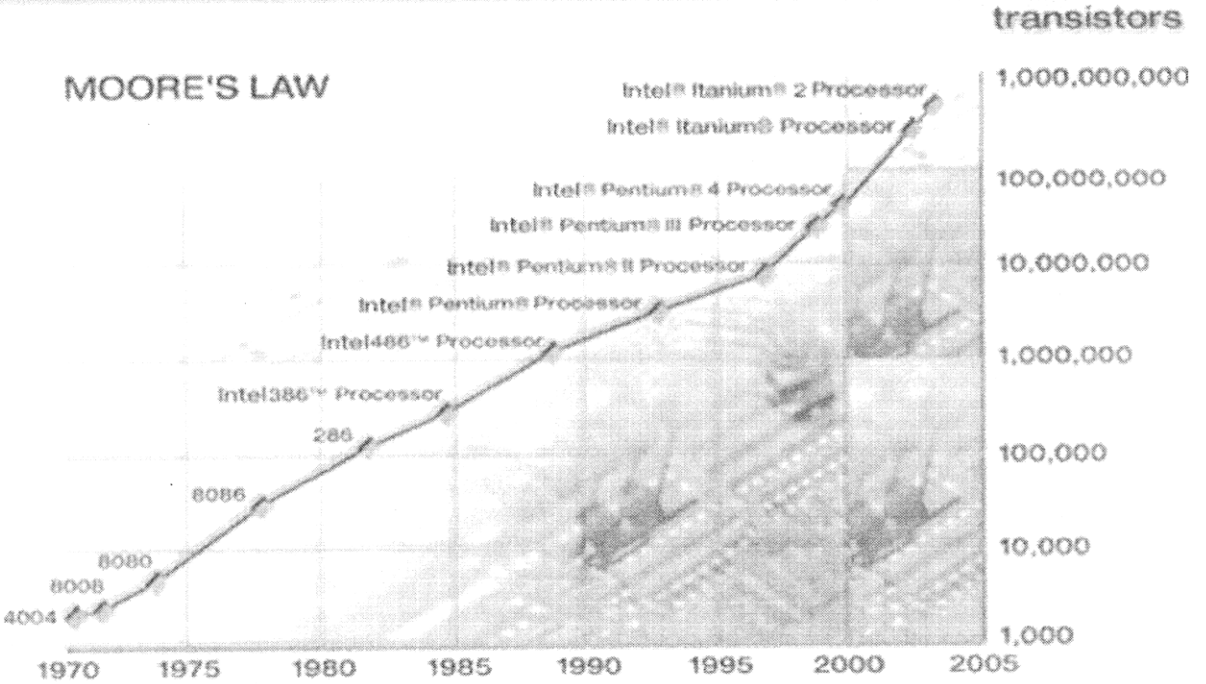
Glueballs: bound states
of pure glue

Perspective

Moore's Law

- Computing power doubles every 18 months
- (Normalized) price halves every 18 months
- The lattice has become *the* tool for non-perturbative QCD calculations





Overview

1. Formalism
2. Operator construction
3. The variational method for excited states
4. Excited Nucleon spectrum results

Part I

Formalism

Spectral representation of two-point functions

- Correlation functions allow us to probe a theory's spectrum

$$\begin{aligned} C(\tau) \equiv \langle \mathcal{O}(\tau)\overline{\mathcal{O}}(0)\rangle &\equiv \langle 0|\mathcal{O}e^{-H\tau}\overline{\mathcal{O}}|0\rangle \\ &= \langle 0|\mathcal{O}\sum_{k=0}^{\infty}|k\rangle\langle k|e^{-H\tau}\overline{\mathcal{O}}|0\rangle \\ &= \sum_{k=1}^{\infty}|\langle k|\overline{\mathcal{O}}|0\rangle|^2 e^{-E_k\tau}, \qquad \langle 0|\overline{\mathcal{O}}|0\rangle = 0 \end{aligned}$$

- Definition: effective mass function:

$$M_{\mathcal{O}}(\tau) \equiv \ln[C(\tau)/C(\tau + a_\tau)] \overset{\tau\to\infty}{\to} a_\tau E_0$$

- My research goal: extract the nucleon spectrum $\{E_k\}$

Part II

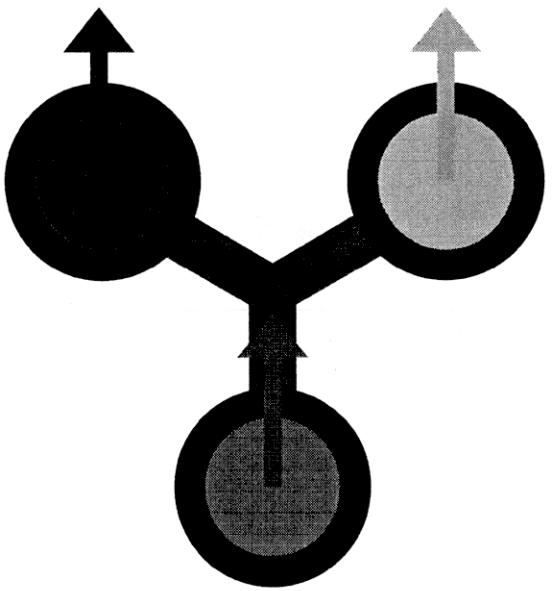
Nucleon operator construction

Extended operators

- Baryon constituents determine total angular momentum J

$$\vec{J} = \vec{S}_q + \vec{S}_g + \vec{L}$$

- $J_{max} = 3/2$ for a localized operator with unexcited glue ($\vec{S}_g = \vec{L} = 0$)



- Extended operators are used to generate angular momentum $\vec{L}$
  $\longrightarrow$ can access higher J quantum numbers $(5/2, 7/2, \ldots)$

Spin and parity on the lattice

- Cubic spatial lattice: breaks full rotational symmetry down to octahedral point group O_h
- Three double-valued (spinorial) irreducible representations G_1, G_2 (2-dim), and H (4-dim)
- Even (odd) parity labeled by subscript g (u)
- Specialized Dirac structure prevents mixing

$$\overline{\mathcal{O}}_p = \sum_{\mu\nu\lambda} \Gamma^{(G_{1g})}_{\mu\nu\lambda} \bar{u}_\mu \bar{u}_\nu \bar{d}_\lambda$$

- High-dimensional continuum spin irreps project onto degeneracy patterns in lattice spectra

J	$n^J_{G_1}$	n^J_H	$n^J_{G_2}$
$\frac{1}{2}$	1	0	0
$\frac{3}{2}$	0	1	0
$\frac{5}{2}$	0	1	1
$\frac{7}{2}$	1	1	1
$\frac{9}{2}$	1	2	0
$\frac{11}{2}$	1	2	1
$\frac{13}{2}$	1	2	2
$\frac{15}{2}$	1	3	1
$\frac{17}{2}$	2	3	1

Part III

The variational method for excited states

Using the variational method to extract excited states

- Instead of one operator $\overline{\mathcal{O}}$, use a broad selection of operators $\{\overline{\mathcal{O}}_a\}$

$$C(\tau) \equiv \langle 0|\mathcal{O}_a e^{-H\tau}\overline{\mathcal{O}}_b|0\rangle$$

- We may define a trial basis of states, and form linear combinations

$$|\mathcal{O}_a(\tau_0)\rangle \equiv e^{-H\tau_0/2}\overline{\mathcal{O}}_a|0\rangle, \quad |\Theta_k(\tau_0)\rangle \equiv \sum_a |\mathcal{O}_a(\tau_0)\rangle v_{ak}$$

- Use the variational method to diagonalize the transfer matrix within the subspace of trial states

$$\frac{\langle\Theta_k(\tau_0)|e^{-H(\tau-\tau_0)}|\Theta_k(\tau_0)\rangle}{\langle\Theta_k(\tau_0)|\Theta_k(\tau_0)\rangle} = \frac{v_k^\dagger C(\tau) v_k}{v_k^\dagger C(\tau_0) v_k}$$

Generalized eigenvalue problem

- We may find the extrema of

$$\frac{v_k^\dagger C(\tau) v_k}{v_k^\dagger C(\tau_0) v_k},$$

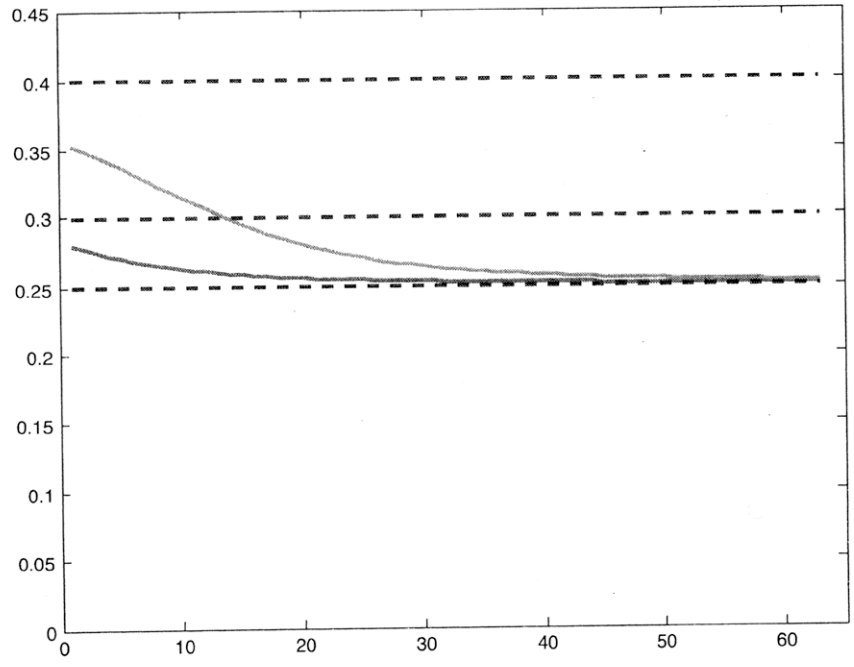
- By solving the generalized Hermitian eigenvalue problem:

$$C(\tau) v_k(\tau;\tau_0) = \lambda_k(\tau;\tau_0) C(\tau_0) v_k(\tau;\tau_0)$$

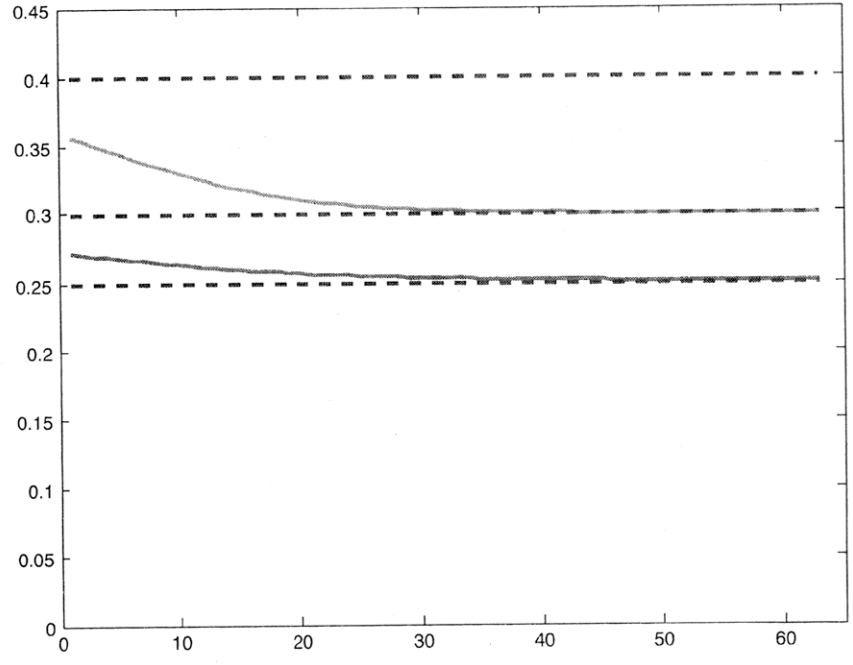
- The eigenvalue solutions $\lambda_k(\tau;\tau_0)$ are called *principal correlators*, and each is asymptotically dominated by a unique energy level E_k
- This requires good estimates of the elements of $C(\tau_0)$ and $C(\tau)$ (limited by finite statistics and finite temporal extent)

Orthogonalization illustrated: three-level toy-model

- For fixed τ_0, the different eigenvector solutions v_k are orthogonal
- Consider a toy theory with three energy states
- Use two operators to form the correlator matrix
- Effective mass results: $M_k(\tau) \equiv \ln[\lambda_k(\tau)/\lambda_k(\tau + a_\tau)] \overset{\tau \to \infty}{\to} a_\tau E_k$:



Original operators

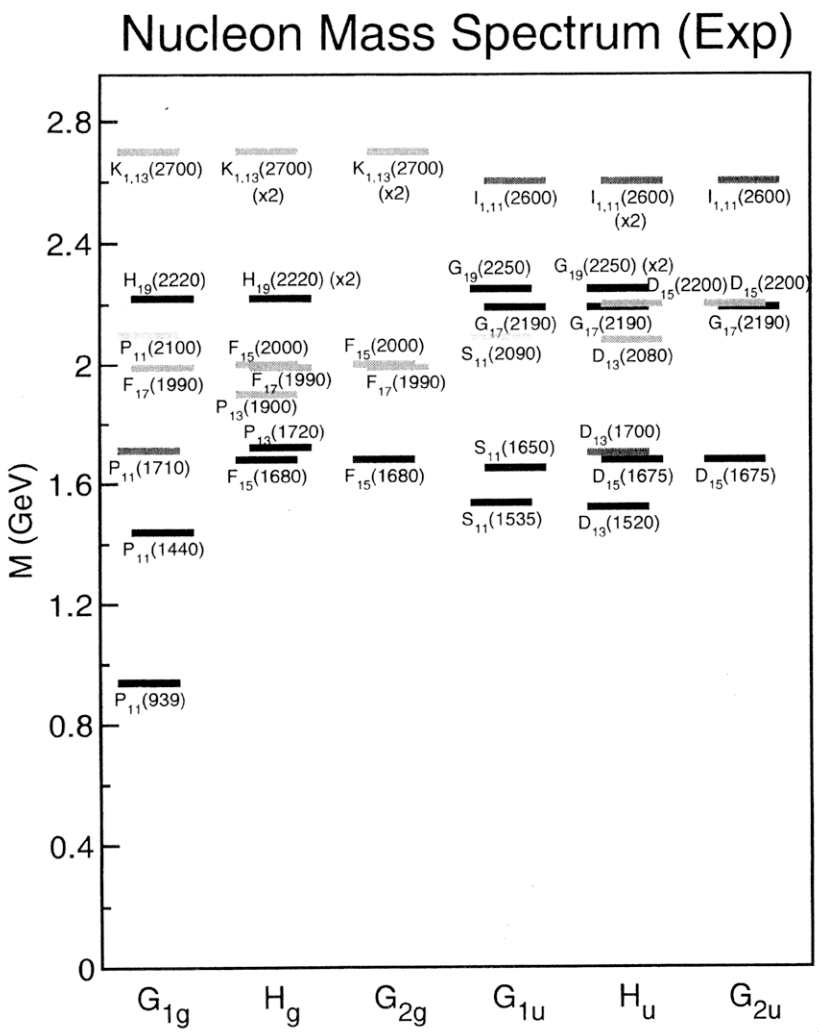


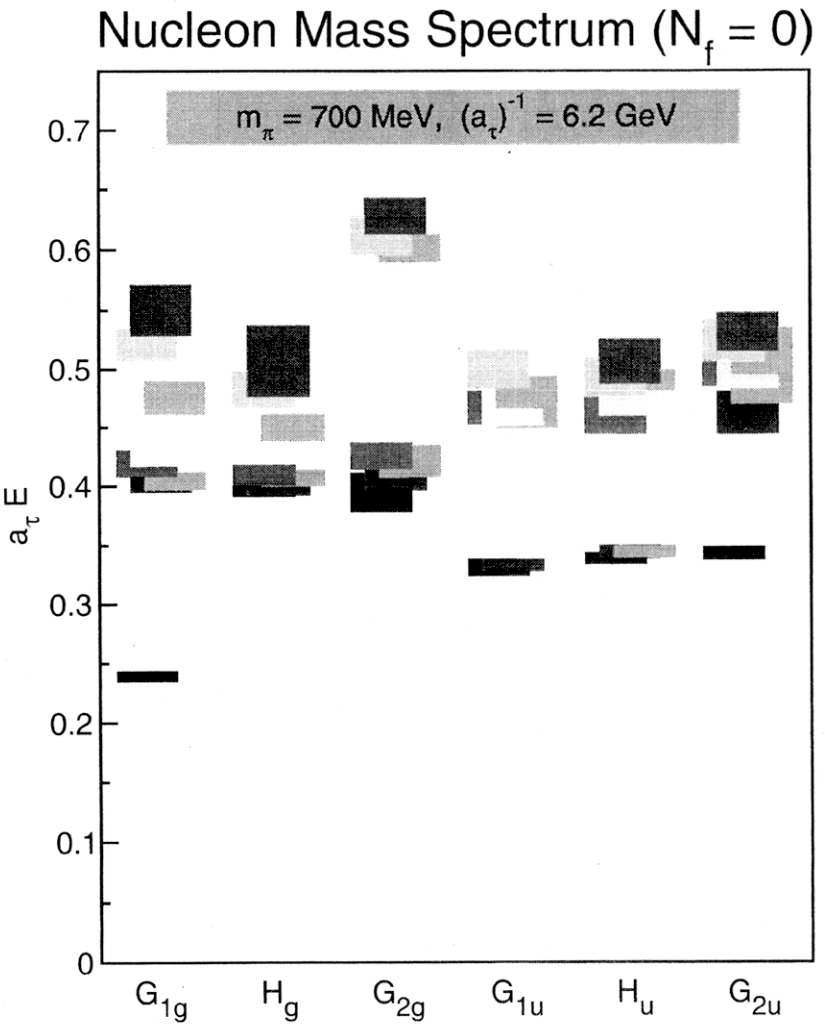
Variational operators

Part IV

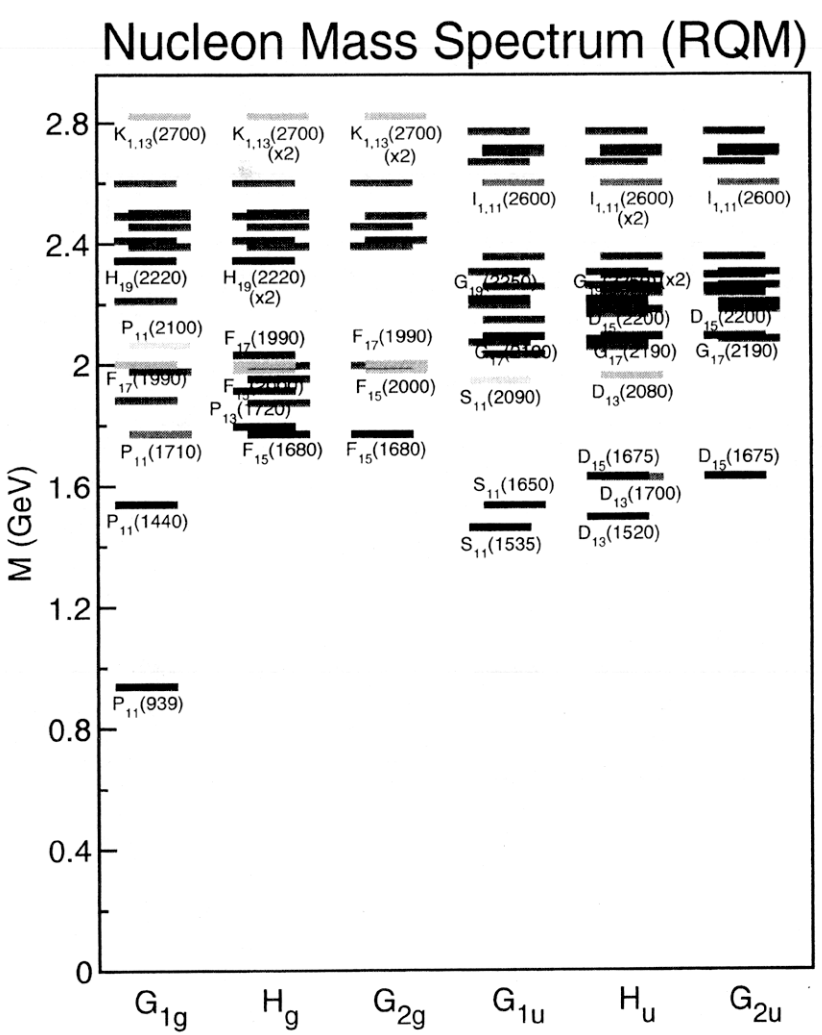
Excited Nucleon spectrum results

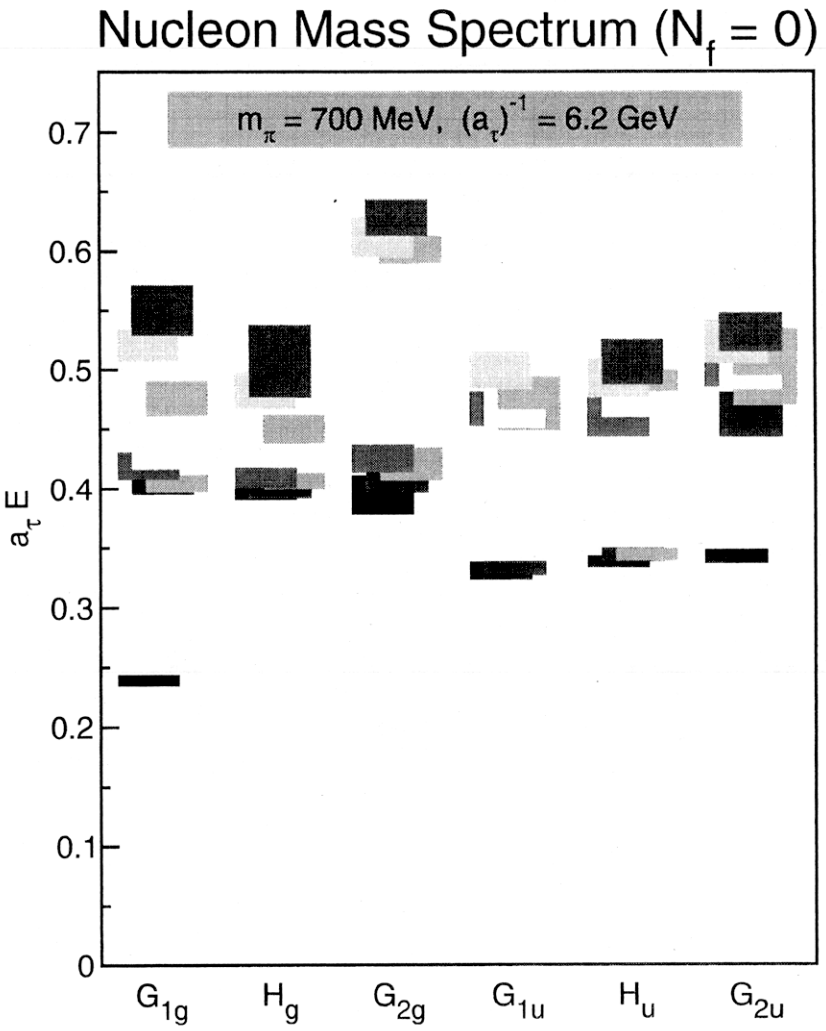
Experiment vs. Lattice: Quenched



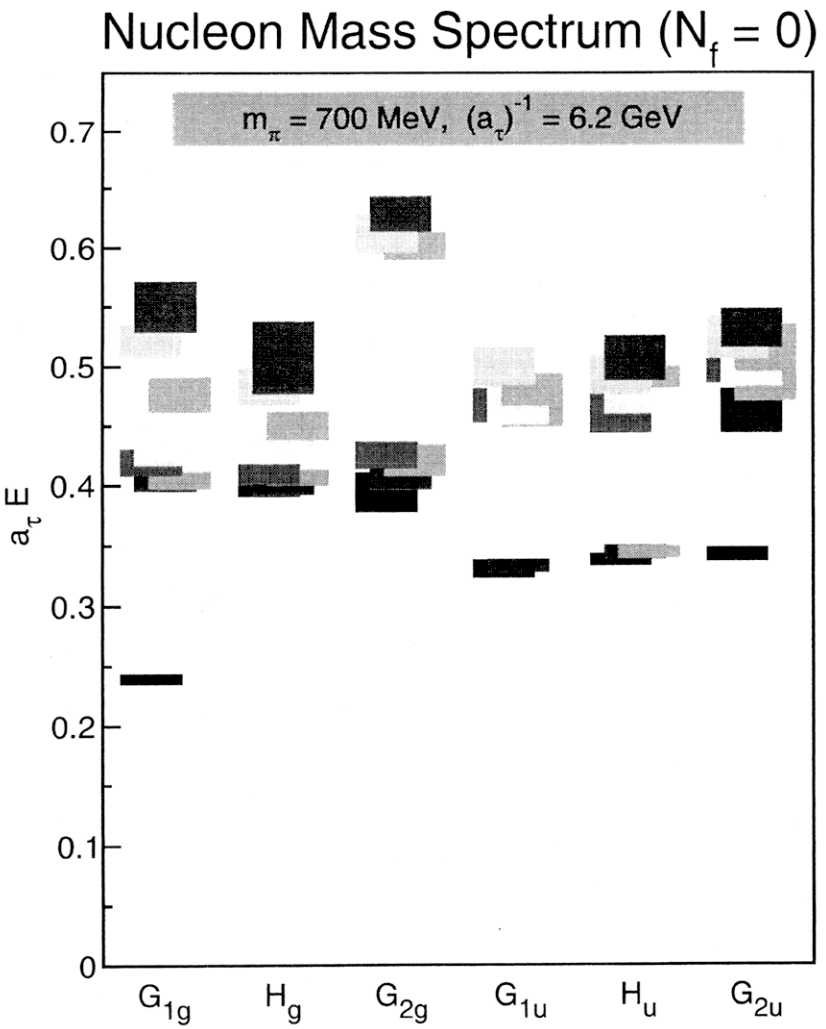


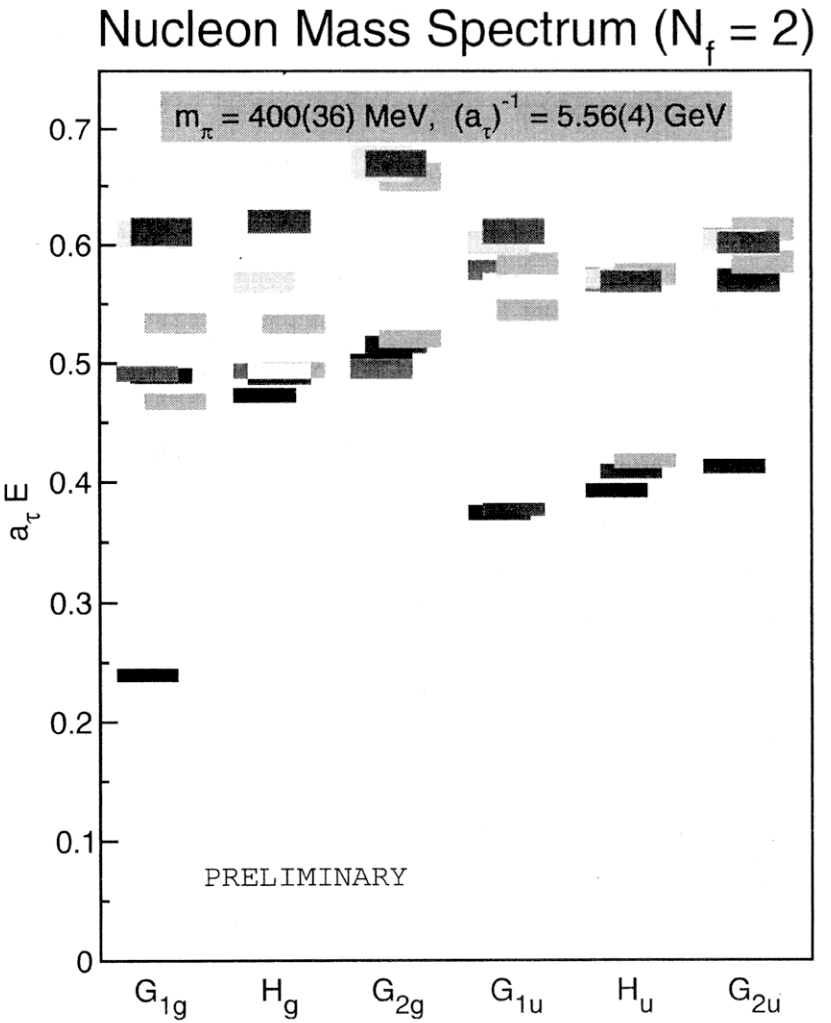
RQM vs. Lattice: Quenched



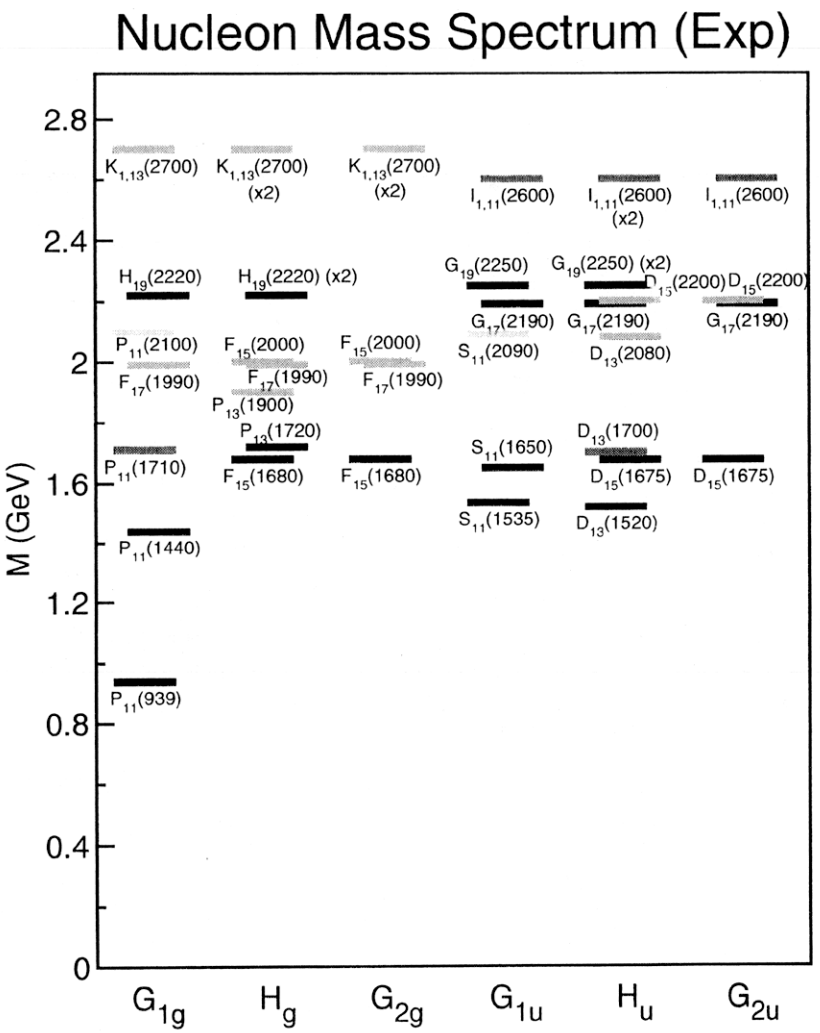


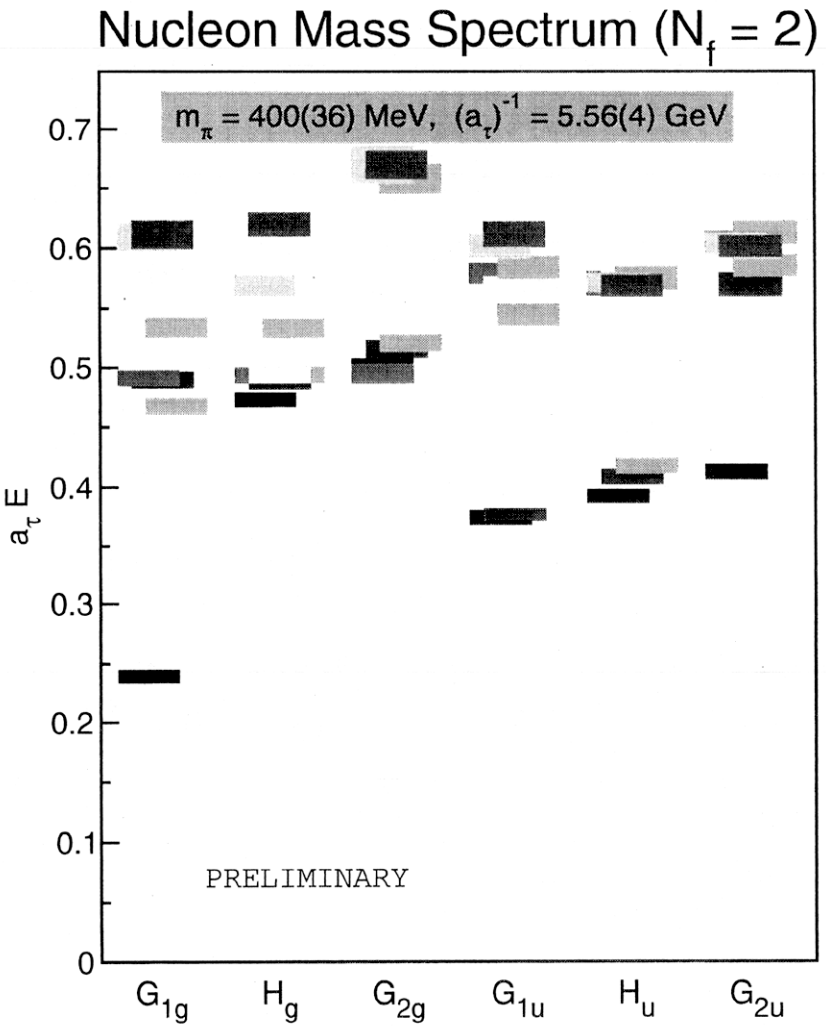
Quenched vs. Dynamical



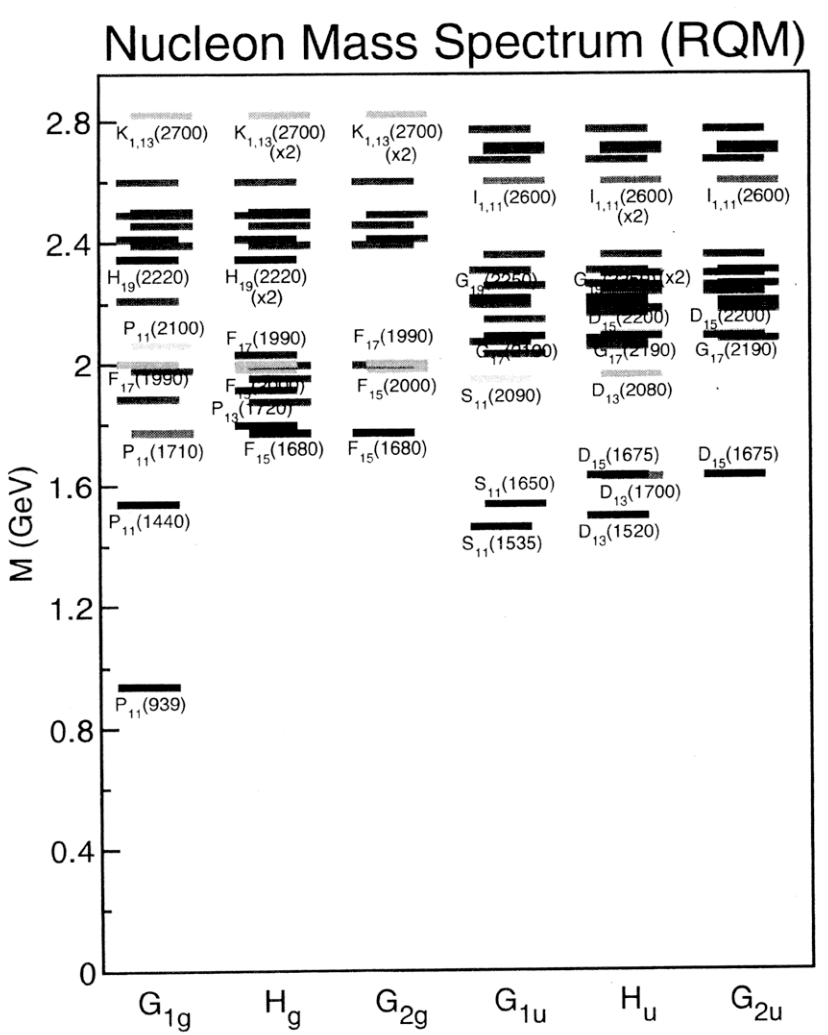


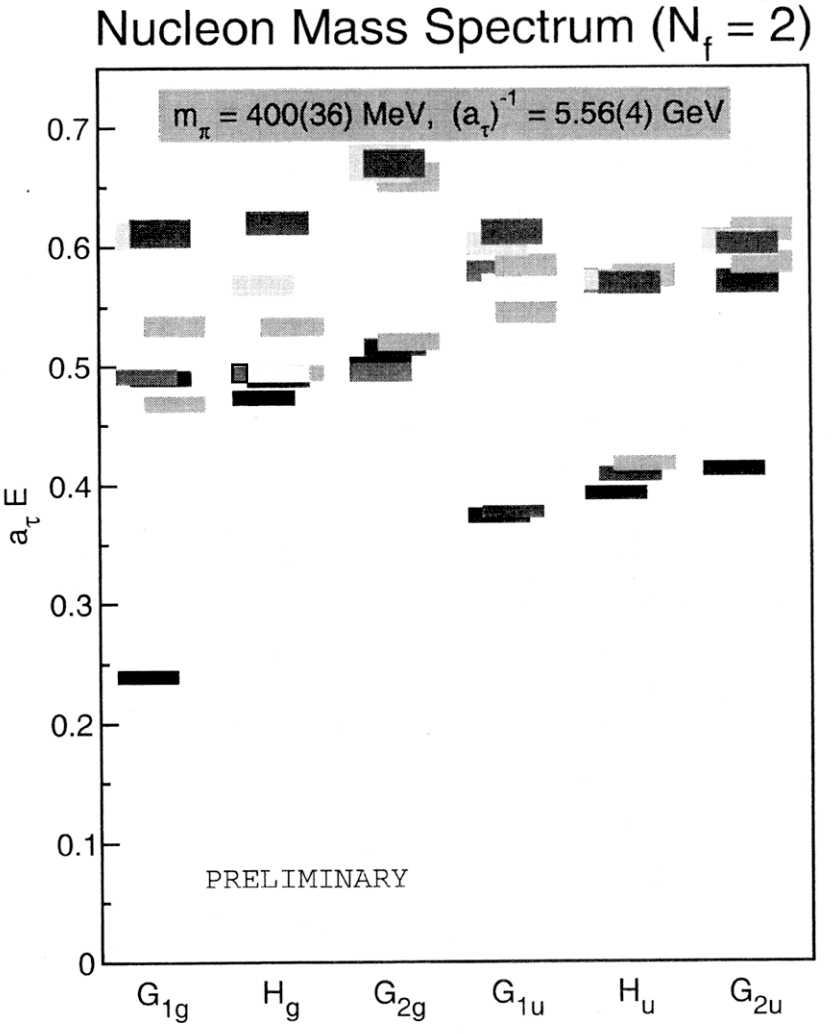
Experiment vs. Lattice: Two-flavor





RQM vs. Lattice: Two-flavor





Part V

Conclusion

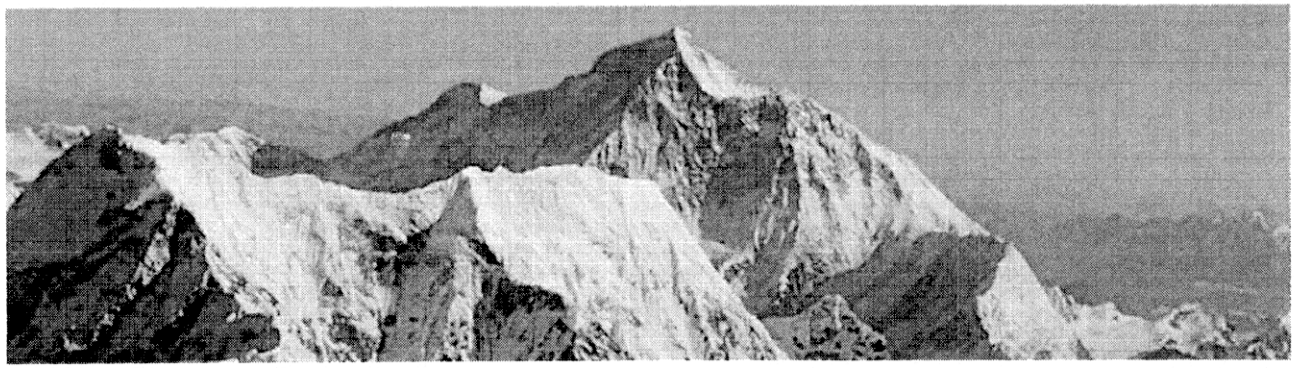
Benefits of this project

- Quantum operator technology
  1. Smearing
  2. Group theory
  3. Variational method
- Data analysis tools for the RBRC code repository
  1. Uncorrelated and correlated fitting
  2. Data visualisation
  3. Batch fitting
- Significant interaction with the experimental community

Outlook

Looking forward

- Calculating the QCD hadron spectrum is rapidly becoming a reality
- This long-term effort is beset on all sides by challenges
- Careful work *will* overcome these difficulties
- Once the spectrum is calculated, it can be used
  1. to check QCD against low-energy experiments
  2. to guide experimental explorations (missing resonance couplings, hybrids)
  3. to provide inputs to model builders



Any Questions?

Real time behavior of the Quark Gluon Plasma

Yoshimasa Hidaka (RBRC)

collaboration with Rob. Pisarski (BNL)

Static and real time properties

Micro Quantum Chromodynamics

Statistical mechanics

Kubo Formula
Boltzmann equation

Macro

Static

- Pressure P
- Entropy S
- Susceptibilities χ

$\vdots$

Real time near thermal equilibrium

- Hydrodynamics
  - Transport coefficients
    - Shear viscosity η
    - Bulk viscosity ζ
    - Conductivities σ
- Damping rates γ
- Particle production

Properties in real time automatically include many body dynamics.

Viscosities

shear viscosity

bulk viscosity

Perturbation theory $\alpha_s \ll 1$

$$\eta \sim \frac{T^3}{\alpha_s^2 \log[1/\alpha_s]}$$

Hosoya, Sakagami and Takao ('84);Hosoya and Kajantie ('85);Baym, Monien, Pethick and Ravenhall ('90), ('91); Arnold, Moore and Yaffe ('00), ('03)

$$\zeta \sim \frac{\alpha_s^2 T^3}{\log[1/\alpha_s]}$$

Arnold, Dogan and Moore ('06)

$\mathcal{N} = 4$ Super Yang-Mills

$N_c \to \infty$

$\alpha_s N_c \to \infty$

Policastro, Son and Starinets ('01)
Kovtun, Son and Starinets ('04)

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

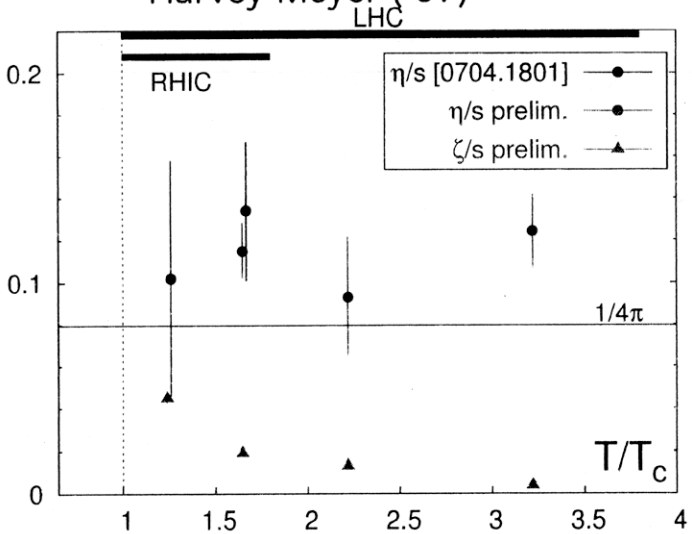
$$\frac{\zeta}{s} = 0$$ conformal

s: entropy density

Lattice

Karsch and Wyld('87);
Sakai and Nakamura('04);
Meyer ('07)

Harvey Meyer ('07)



Partial deconfinement

High temperature

T

pQGP

$\sim 3T_c$

sQGP

T_c

Static

Perturbative calculation

3D effective theory

Lattice simulation

Real time

Hard thermal loop resummation

Real time effective theory

We want to construct an effective theory with large A_0.

Complete deconfinement

$$\left\langle \frac{1}{N_c} \mathrm{tr} L \right\rangle \simeq 1$$

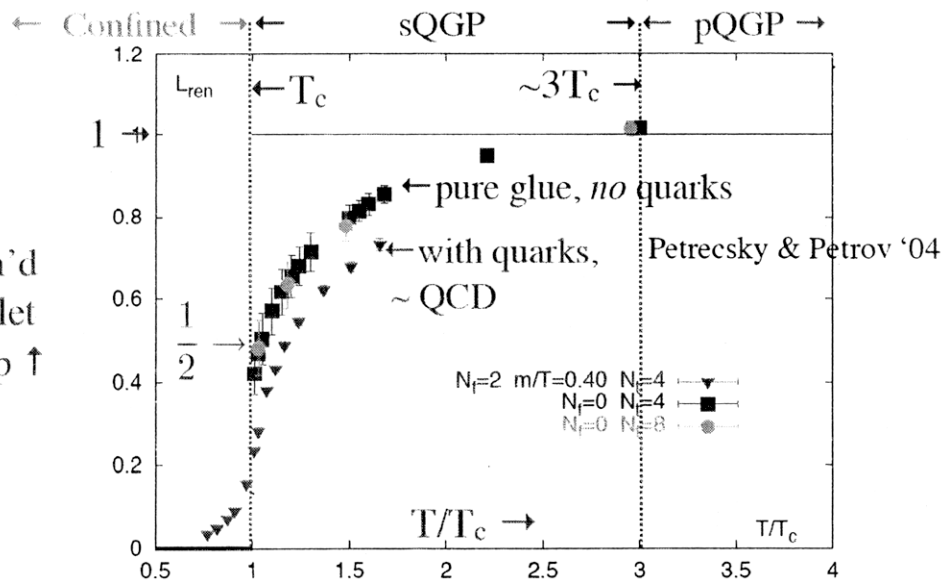
Partial deconfinement

$$\left\langle \frac{1}{N_c} \mathrm{tr} L \right\rangle < 1$$

Confinement

$$\left\langle \frac{1}{N_c} \mathrm{tr} L \right\rangle = 0$$

partial deconfinement



Polyakov loop

$$L = \frac{1}{N_c} \exp[ig \int_0^\beta d\tau A_0]$$

A_0 is decomposed to classical and quantum parts

$$A_0 = A_0^{\mathrm{cl}} + A_0^{\mathrm{qu}}$$

Assumption

- Coupling is small $g \ll 1$
- Background gauge field is large $A_0^{\mathrm{cl}}/T \sim 1/g \gg 1$
- Slowly changing $\partial A_0^{\mathrm{cl}}/T^2 \sim 1$

⇩

can use derivative expansion.

Analytical continuation

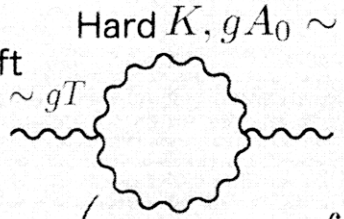
Relation between imaginary time A_0^{cl} and real time A_0^{cl} is non trivial.

$$i\omega_n + igA_0^{\mathrm{cl}} \to p_0 \pm i\epsilon$$

ω_n :Matsubara frequency

Two point function

Hard Thermal Loop approximation: $\delta\mathcal{L}_{\rm eff} = \frac{1}{2} A_\mu \Pi^{\mu\nu} A_\nu$

$\Pi^{\mu\nu}(P) =$ 

$+$ Tadpole, ghost diagrams

$$= (m_D^2)^{ab} \left(\delta^{\mu 0}\delta^{\nu 0} - \int \frac{d\Omega}{4\pi} \frac{(P)^0 \hat{K}^\mu \hat{K}^\nu}{P\cdot\hat{K}} \right) - i f^{ab}{}_c \langle (J^c)^0 \rangle \int \frac{d\Omega}{4\pi} \frac{\hat{K}^\mu \hat{K}^\nu}{P\cdot\hat{K}}$$

Ordinary HTL approx. term
The thermal mass is modified

vanishes in homogeneous system

Debye mass $[m_D^2(A_0^{\rm cl})]^{ab} = m_D^2 \times h^{ab}(A_0^{\rm cl})$

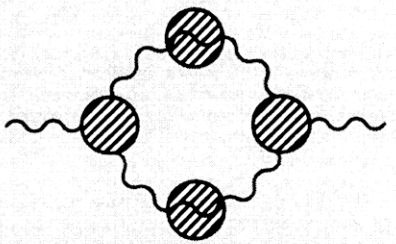
Completely deconfined phase $h^{ab} = \delta^{ab}$

Partially deconfined phase $h^{ab} < 1$

Confined phase $h^{ab} \sim 0$ because background is neutral.

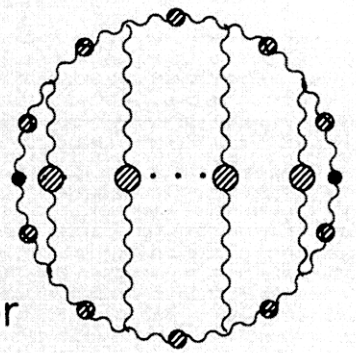
Damping rates and Viscosities

Gluon damping rate

$\gamma =$ Im 

Viscosity

Kubo formula

$\eta \sim \langle T_{12} T_{12} \rangle =$ 

$T_{\mu\nu}$:Energy-momentum tensor

:effective propagator

Summary

- We have constructed an effective Lagrangian in real time for large A_0.
- Debye mass changes in the partially deconfined phase.
- Next step: Viscosity!

Forward particle production in d-Au collisions

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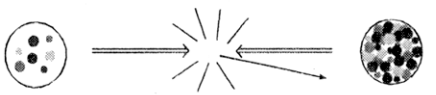
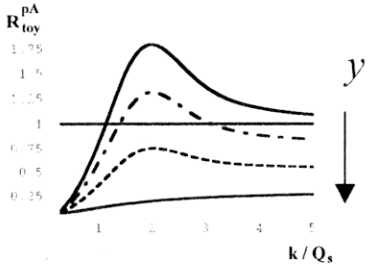
Outline and Motivation

- after the first d-Au run at RHIC, there was a lot of new results on single inclusive particle production at forward rapidities d Au → h X



the spectrum $\frac{d\sigma^{dAu\to hX}}{d^2k dy}$ and

the modification factor $R_{dA} = \frac{1}{N_{coll}} \frac{dN^{dA\to hX}}{d^2k dy} \Big/ \frac{dN^{pp\to hX}}{d^2k dy}$ were studied



y increases

the suppressed production ($R_{dA} < 1$) was predicted in the Color Glass Condensate picture of the high-energy nucleus

- but single particle production probes limited information about the CGC (only the 2-point function)

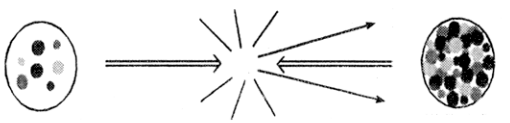
to strengthen the evidence, we need to study more complex observables to be measured with the next d-Au run

- my calculation: two-particle production at forward rapidities

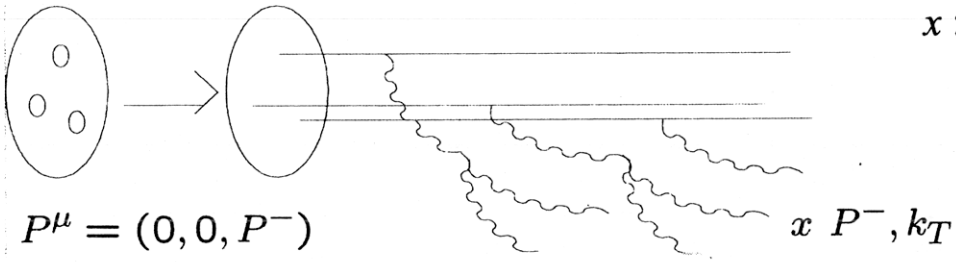
I computed $\frac{d\sigma^{dAu\to h_1 h_2 X}}{d^2k_1 dy_1 d^2k_2 dy_2}$ C. Marquet, NPA 796 (2007) 41

(probes up to a 6-point function)

d Au → h_1 h_2 X



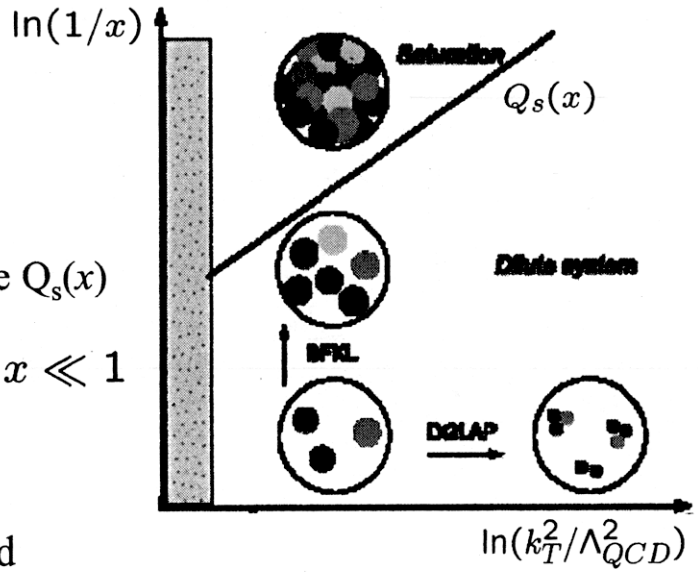
Gluon saturation and the CGC



x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a dilute hadron)
BFKL evolution to smaller x (and a dense hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

CGC evolution into the saturation regime

there the hadron is dressed with many gluons responsible for a large color field $\alpha_c = A_c^- \sim 1/g_s$ which can be treated as a classical field and one can use an effective theory

McLerran and Venugopalan (1994)

weakly-coupled regime

$k_T \gg \Lambda_{QCD} \quad \alpha_s \ll 1$

$$|\text{hadron}\rangle = |qqq\rangle + |qqqg\rangle + \ldots + |qqq.....ggggg\rangle \quad \Rightarrow \quad |\text{hadron}\rangle = \int D\alpha\ \Phi_x[\alpha]|\alpha\rangle \equiv |\text{CGC}\rangle$$

The CGC wavefunction $\left|\Phi_x[\alpha]\right|^2$

- obeys the JIMWLK equation: $\dfrac{d}{d\ln(1/x)}\left|\Phi_x[\alpha]\right|^2 = H^{JIMWLK}\otimes\left|\Phi_x[\alpha]\right|^2$

Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

a functional equation for the small-x evolution of $\left|\Phi_x[\alpha]\right|^2$

- is used to compute physical observables: $\left\langle S\right\rangle_x^{CGC} = \int D\alpha\ \left|\Phi_x[\alpha]\right|^2 S[\alpha]$

the x evolution of the cross-sections is encoded in the x evolution of $\left|\Phi_x[\alpha]\right|^2$

functions of Wilson lines, describing the scattering of partons off the CGC

$$W_F[\alpha](\mathbf{x}) = \mathcal{P}\exp\left\{ig_s\int dz^+ T^c\alpha_c(z^+,\mathbf{x})\right\}$$

we will use this formalism to compute forward particle production

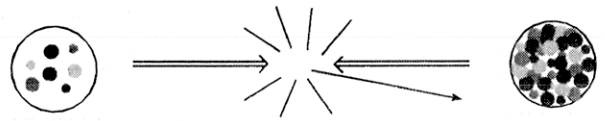
- the most common average is the 2-point function $\left\langle Tr(W_F^+(\mathbf{y})W_F(\mathbf{x}))\right\rangle_x$
  - it is often called the dipole scattering amplitude
  - (at large Nc) it obeys the Balitsky-Kovchegov (BK) equation

when only the two-point function enters in the formulation of a cross-section, the so-called k_T-factorization is applicable

(it is used in many CGC calculations without precaution)

Forward particle production

single inclusive particle production :



final state: transverse momentum k and rapidity y

the partons probed in the process have $x_d = \dfrac{k\,e^{y}}{\sqrt{s}} \approx 0.5$ and $x_A = \dfrac{k\,e^{-y}}{\sqrt{s}} \approx 10^{-4}$

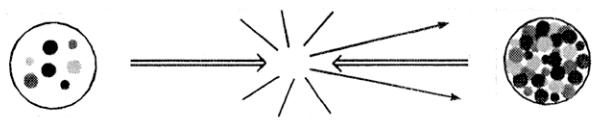
$\dfrac{d\sigma^{dAu\to hX}}{d^2k\,dy}$ involves $\left\langle \mathrm{Tr}\left(W_F(\mathbf{x})W_F^{\dagger}(\mathbf{x}')\right)\right\rangle_{x_A}$

high energies and forward rapidities are needed to probe small values of x

many derivations (in momentum or coordinate space, in different gauges, …):

Kovner and Wiedemann (2001), Kovchegov and Tuchin (2002), Dumitru and McLerran (2002)
Blaizot, Gélis and Venugopalan (2004), Marquet (2005), Gélis and Mehtar-Tani (2006)

inclusive two-particle production :



final state : $k_1, y_1 \quad k_2, y_2$

C. Marquet, NPA 796 (2007) 41

$$x_d = \frac{k_1\,e^{y_1} + k_2\,e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\,e^{-y_1} + k_2\,e^{-y_2}}{\sqrt{s}}$$

$\dfrac{d\sigma^{dAu\to h_1h_2X}}{d^2k_1dy_1d^2k_2dy_2}$ involves 2-, 4- and 6- point functions

no k_T factorization

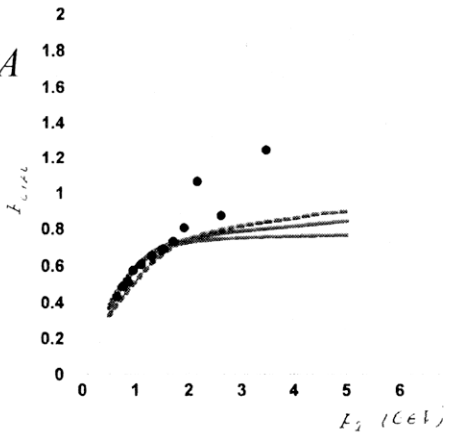
probes more information about the CGC

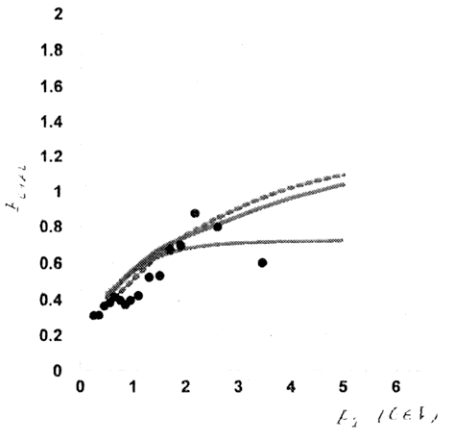
R_{dA} and forward pion spectrum

R_{dA}

first comparisons to data:

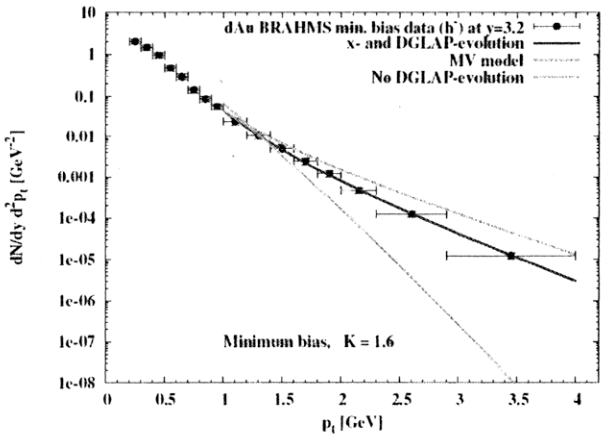
Kharzeev, Kovchegov and Tuchin (2004)
Kharzeev, Levin and Nardi (2005)





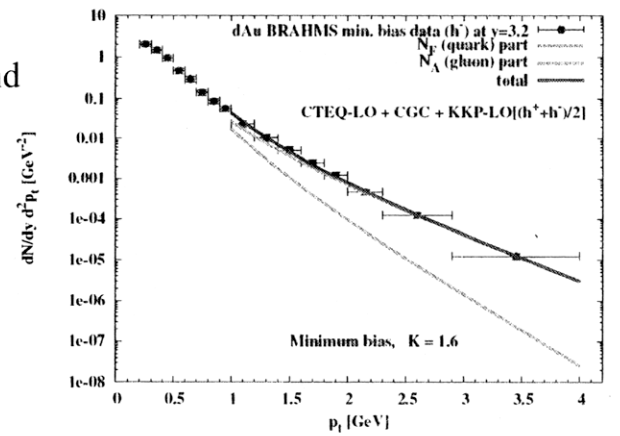
more recent work:

from qualitative to quantitative agreement



Dumitru, Hayashigaki and Jalilian-Marian (2006)

p_T - spectrum



shows the importance of both evolutions:

x_A (CGC) and x_d (DGLAP)

shows the dominance of the valence quarks of the deuteron

Two particles at forward rapidities

to compute the correlators, and include the small-x QCD evolution:

- use a Gaussian CGC wavefunction: $|\Phi_{x_A}[\alpha]|^2 = \exp\left(-\int d^2x d^2y dz^+ \frac{\rho_c(z^+,\mathbf{x})\rho_c(z^+,\mathbf{y})}{2\mu^2_{x_A}(z^+,\mathbf{x}-\mathbf{y})}\right)$

at large Nc, one can obtain $\mu^2_{x_A}$ from the BK equation $-\nabla^2\alpha_c^-(z^+,\mathbf{z}) = \rho_c(z^+,\mathbf{z})$

Fujii, Gélis and Venugopalan (2006)

the 6-point function is a new result, although here it is not the most general one

- in practice I use the McLerran-Venugopalan initial condition at $x_0 = 0.01$:

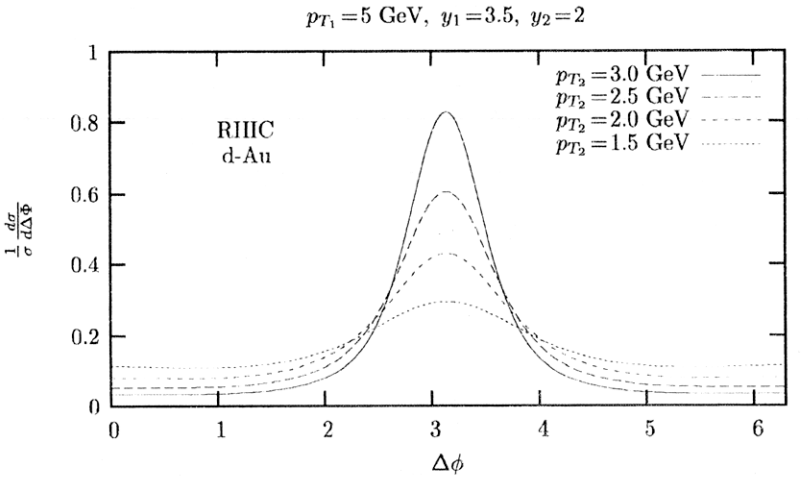
$\mu^2_{x_0}(z^+,\mathbf{x}) = \delta(\mathbf{x})\mu^2_{x_0}(z^+)$ with $Q^2_{s0} \propto \left(\int dz^+ \mu^2_{x_0}(z^+)\right) = 2\ \mathrm{GeV}^2$ the initial saturation scale

some results for $(1/\sigma)\, d\sigma/d\Delta\Phi$:

$k_1 = 5\ \mathrm{GeV},\ y_1 = 3.5,\ y_2 = 2$

k_2 is varied from 1.5 to 3 GeV

as k_2 decreases, it gets closer to Q_S and the correlation in azimuthal angle is suppressed



for these kinematics, the spectrum does not get completely flat

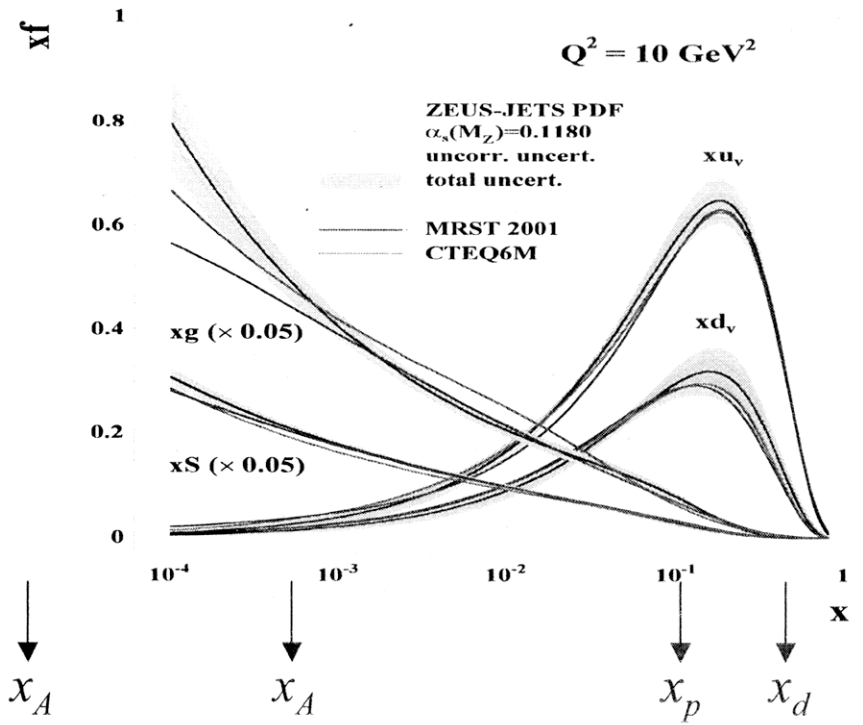
RHIC vs LHC

the CGC picture would be even better tested:

value of x_A at LHC << RHIC

but at RHIC, one has $x_h \sim 0.5$, and the dominant partonic process is

$$q \longrightarrow qg$$



the value of x_d at the LHC is slightly smaller than at RHIC

including the gluon-initiated processes $g \longrightarrow q\bar{q}$ and $g \longrightarrow gg$ in the calculation will be needed

Conclusions and Outlook

- I obtained CGC predictions (MV model + BK evolution) for the two-particle spectrum, when both particles are produced at forward rapidities

  $\Rightarrow$ need to include hadron fragmentation for final results

- my predictions for the fully differential spectrum are not directly comparable with the data (unless fully differential spectra can be measured)

  $\Rightarrow$ need integrations over the experimental y and p_T ranges

future measurements:

- at RHIC another d-Au run

- at the LHC p-Pb?

both STAR and PHENIX will improve their rapidity coverage

Experimental Presentations

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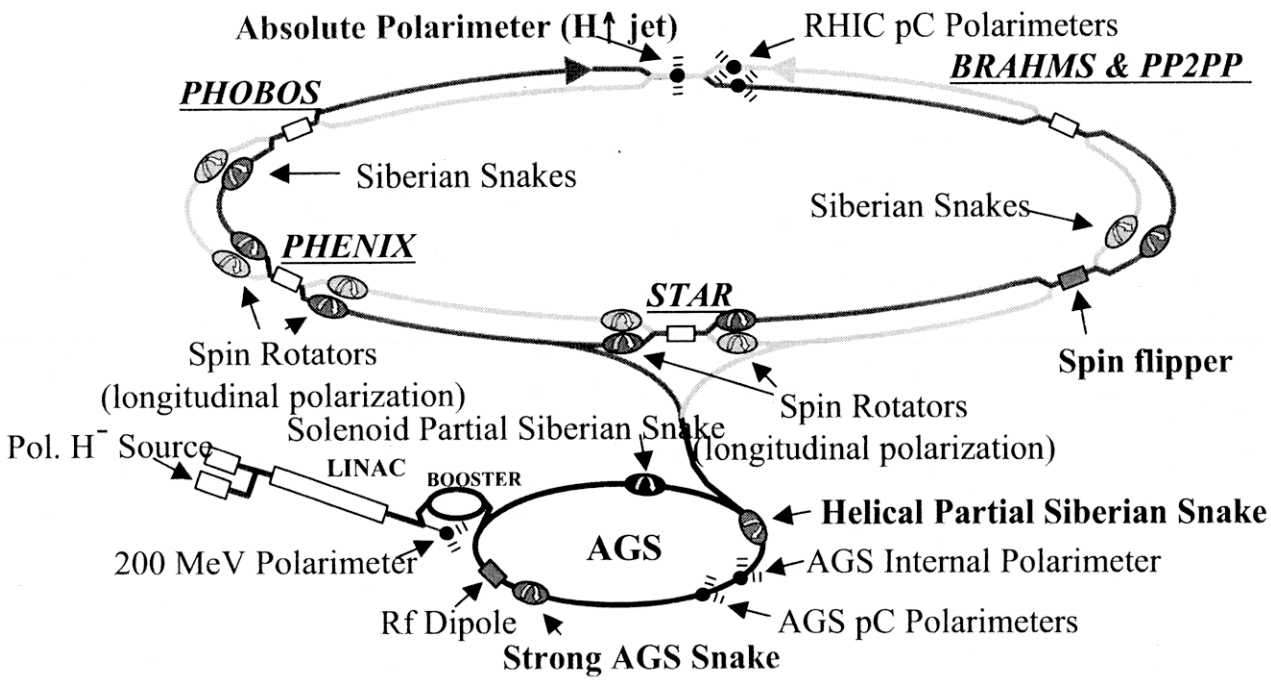
Gluon polarization in proton: Recent results from PHENX & the path forward...



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RHIC Spin Physics Program

- ***Direct measurement*** of polarized gluon distribution *using multiple probes: Measure double spin asymmetry A_{LL} in*
  - ***gg,qg $\longrightarrow \pi^{0,+,-}$ + X (inclusive pion production)***
  - ***gg → c-cbar, b-bbar + X (open heavy quark production)***
  - ***gq → γ+X (direct photon production)***

- Direct measurement of ***anti-quark polarization*** using parity violating production of $W^{+/-}$ in single spin A_L
  - **u + dbar → W^+ + ν_l and ubar + d → W^- + ν_l**

- **Transverse spin:** Transversity & transverse spin effects: possible connections to orbital angular momentum?

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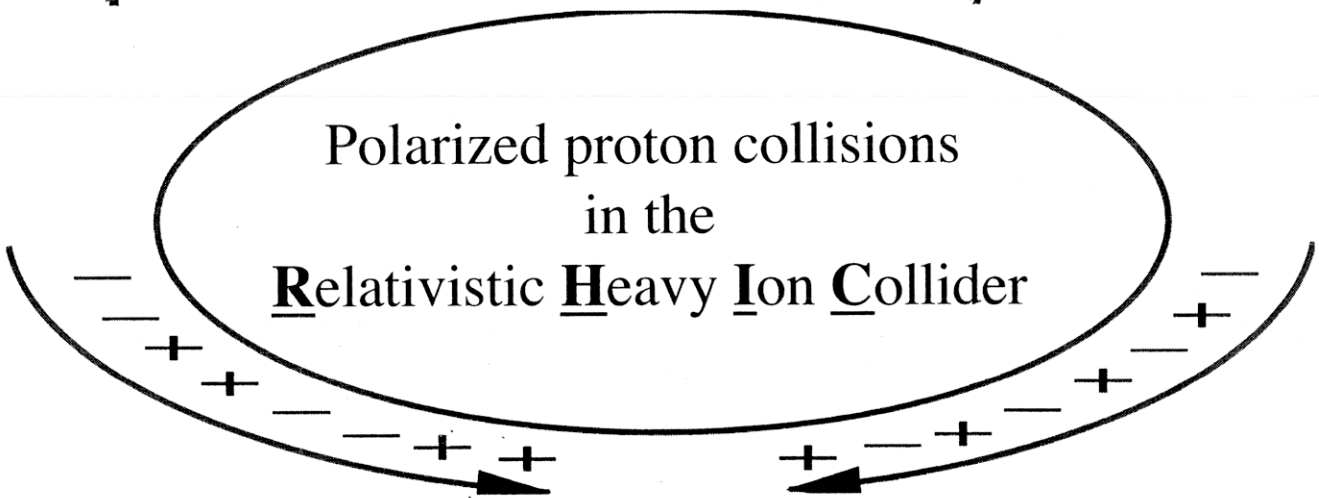
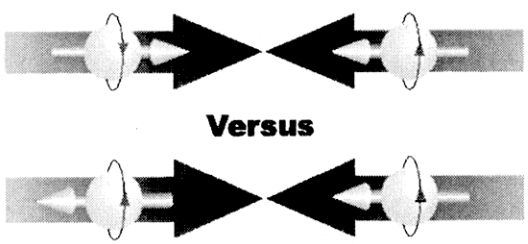
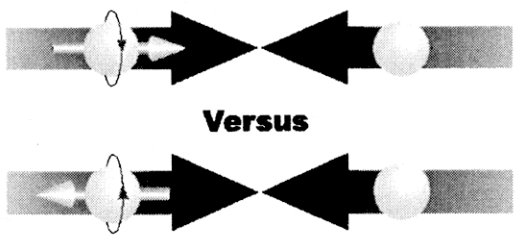
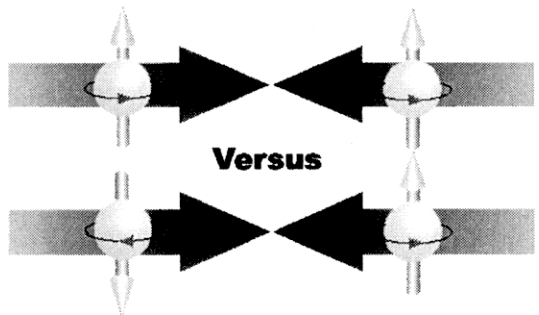
Exquisite Control of Systematics



Flexibility & Spin Manipulation at RHIC: Access to different physics







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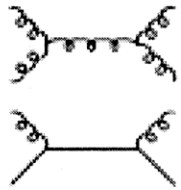
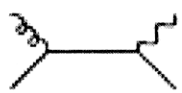
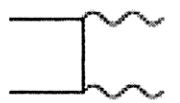
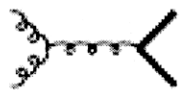
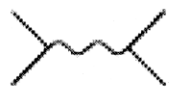
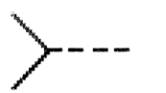
Polarized Collider: Status

Parameter	Unit	2002	2003	2004	2005	**2006**	Design
No. of bunches	--	55	55	56	106	**111**	**111**
bunch intensity	10^{11}	0.7	0.7	0.7	0.9	**1.4**	**2.0**
store energy	GeV	100	100	100	100	**100**	**100 250**
β^*	m	3	1	1	1	**1**	**1**
peak luminosity	$10^{30}cm^{-2}s^{-1}$	2	6	6	10	**35**	**80**
average luminosity	$10^{30}cm^{-2}s^{-1}$	1	4	4	6	**20**	**60**
Collision points	--	4	4	4	3	**2**	**2**
average polarization, store	%	15	35	46	47	**60-65**	**70**

RHIC Spin Physics

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$	Δg Δg	
$\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{\bar{q}} \to \gamma\gamma$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'q \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

Now

> 2009

> 2009

Si VTX upgrade

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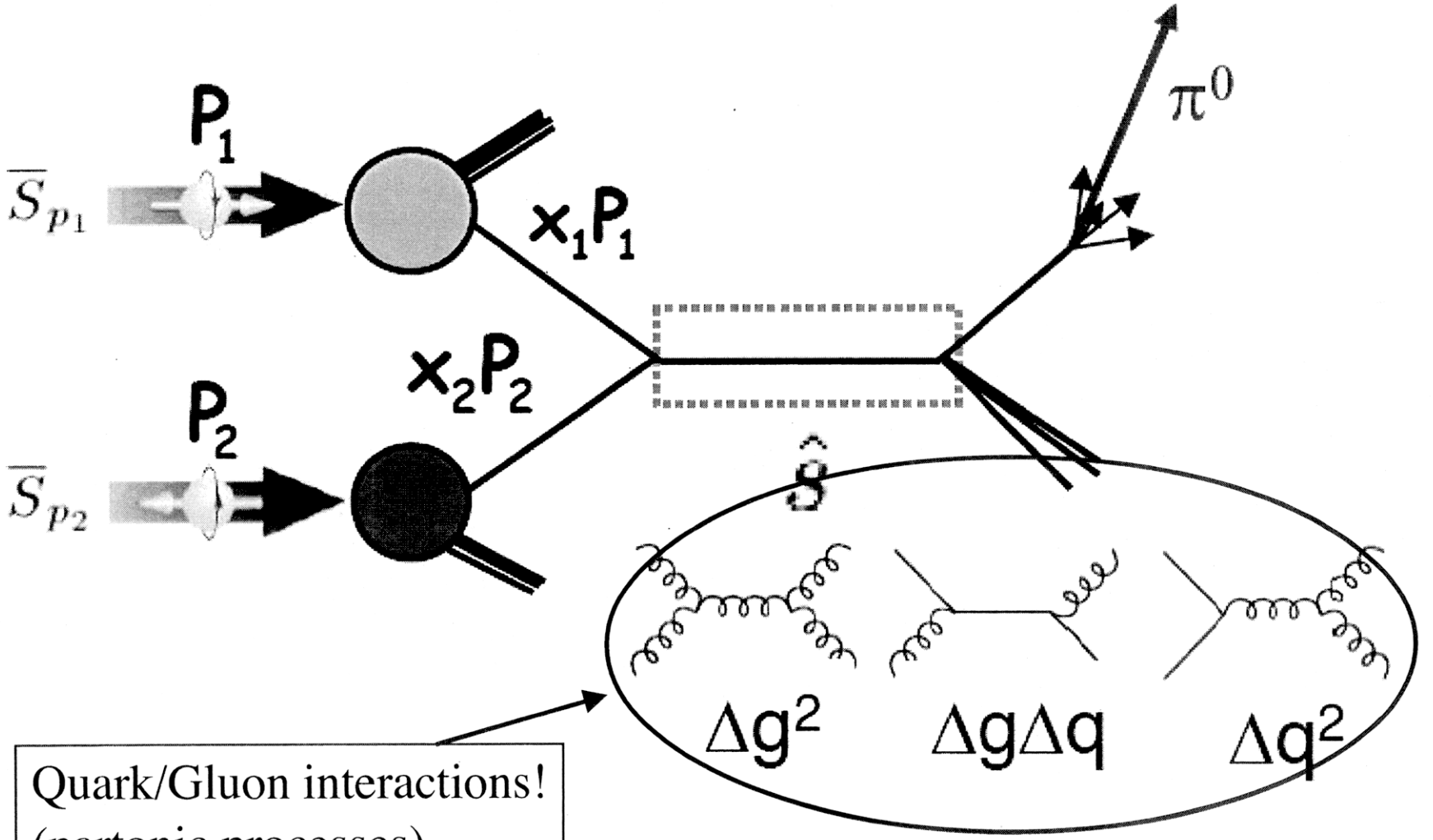
Neutral pion produced in pp collisions: "Our Probe"



Quark/Gluon interactions!
(partonic processes)

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Calibration of our probes...

- Measurement of a cross section involves:
  - **Detailed understanding of the luminosity**
  - **Detailed understanding of the detector**
- Comparison of the data with state of the art theory calculations tests:
  - **Whether the theoretical framework used for the calculation applicable?**
  - **Double spin asymmetry measured this way could be interpreted in terms of polarized gluon distributions**

Next-to-leading Order pQCD calculations must match the measured cross section for the physic process

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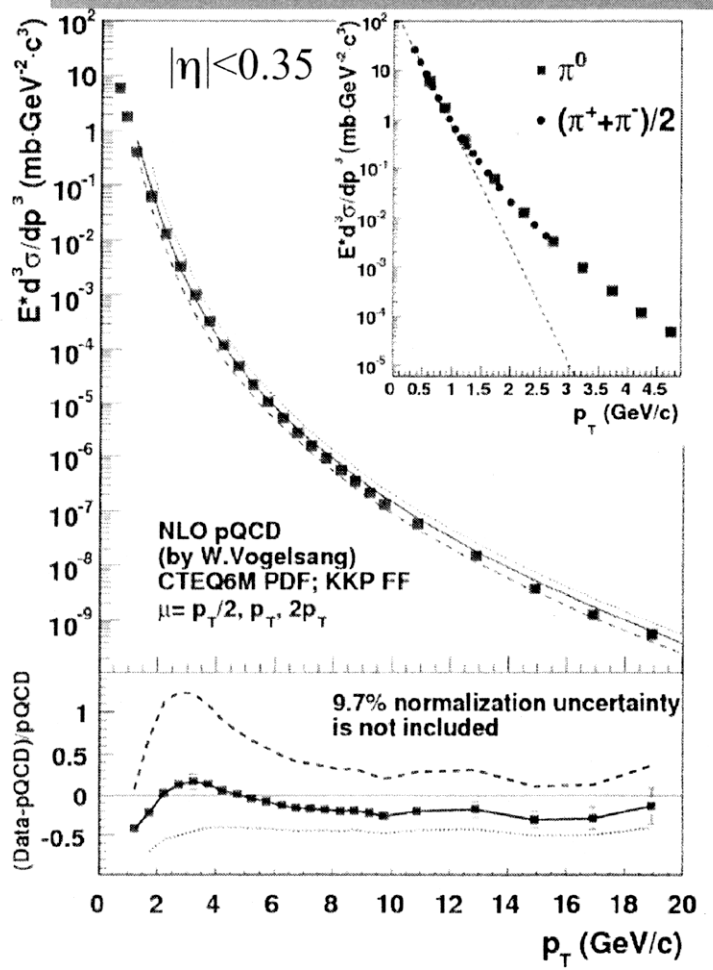
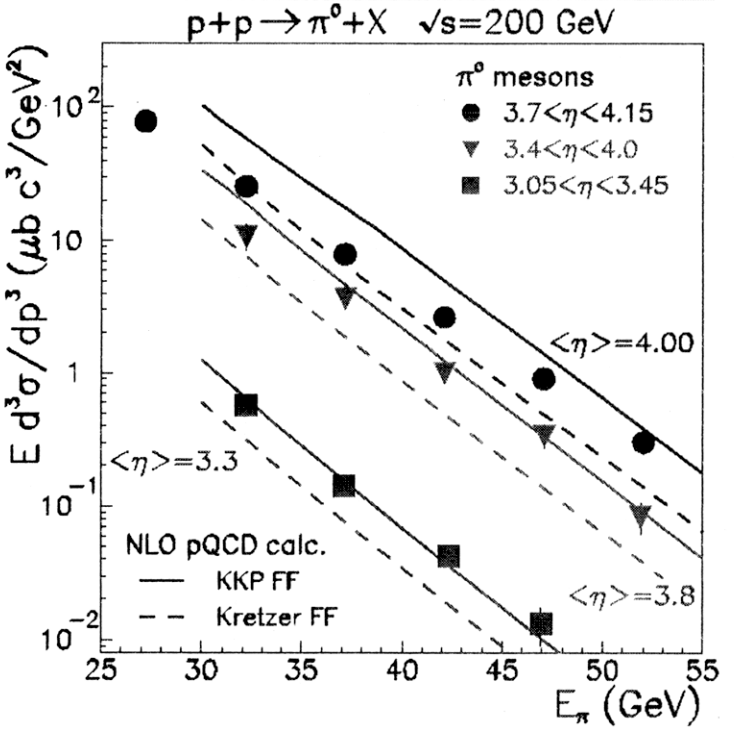
Un-polarized Cross Section in *pp*

PHENIX: π^0 mid-rapidity
hep-ex-0704.3599

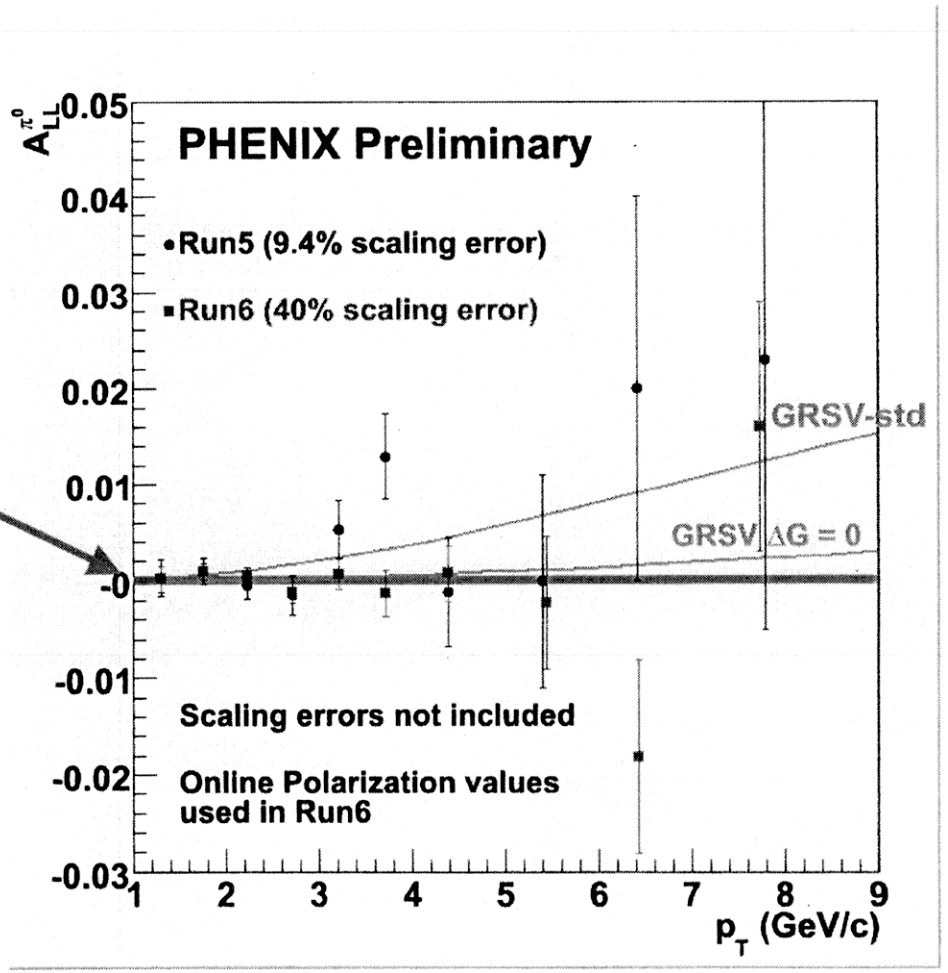


STAR: π^0 forward rapidity
PRL 97, 152302



Run5 & 6 π^0 A_{LL}

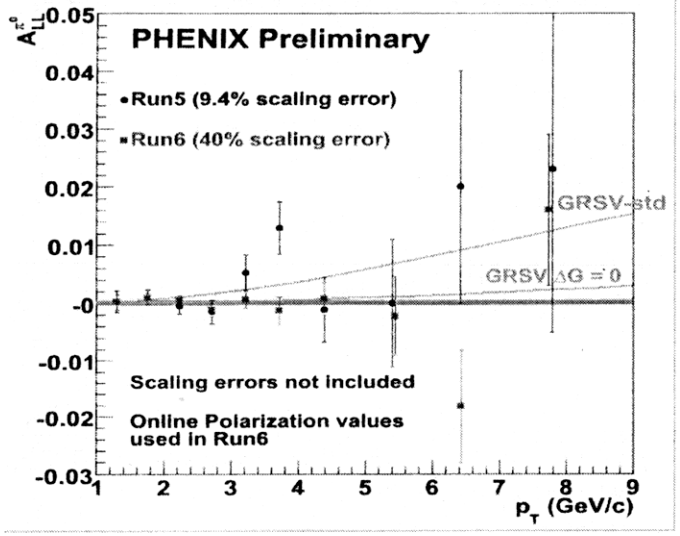
- Run6 scaling error based on online polarization values. Final scaling error expected to be ~10%
- Systematic uncertainty due to Relative Luminosity (it is p_T independent): Grey band
- Run6 Data favor "GRSV $\Delta G=0$" over "GRSV-std" both at $Q^2=1$ GeV^2

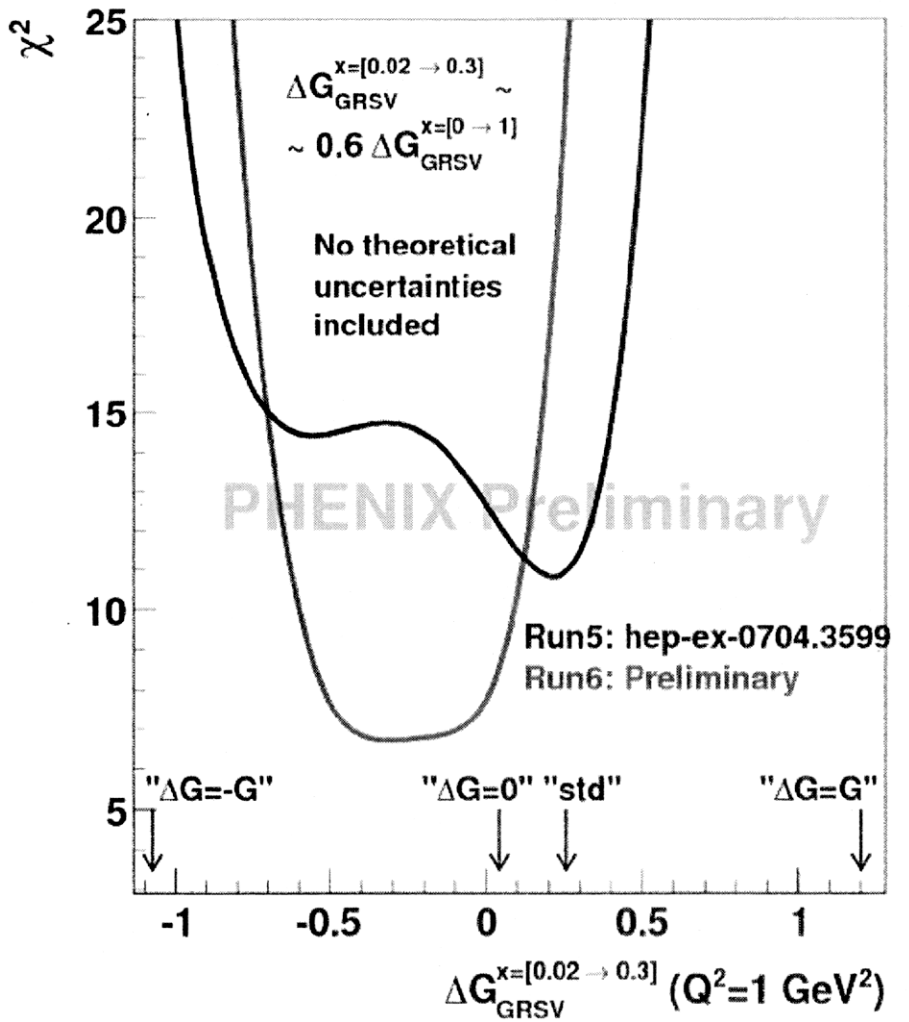


Theory	χ^2/NDF	CL(%)
GRSV-std $\Delta G=0.4$	23.8/8*	0.25
GRSV $\Delta G=0$	7.9/8*	44

*Theoretical uncertainties not included

From A_{LL} to ΔG (with GRSV)





"std" scenario,
$\Delta G(Q^2=1\text{GeV}^2)=0.4$, is excluded by data with >3-σ since
$\chi^2(\text{std})-\chi^2_{\text{min}}>9$

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The path forward.... For ΔG

- More data through higher luminosity & *different energy*
  - In addition to neutral pions, direct photons, heavy quarks
  - 62 GeV CM already at hand:
    - Results indicate small contribution to higher energy
- Detector upgrades: Si VTX tracker & new high-η detectors will explore wider x regions
  - crucial to measure ΔG(x) integral
- Last but not the least, all present and future RHIC Spin data need to be analyzed together with the fixed target DIS data in order to extract the best possible polarized PDFs
  - A Global Analysis of the CTEQ/MRST kind in unpolarized PDFs is needed
  - A new effort towards that was just initiated starting from a recent RBRC workshop, October 2007

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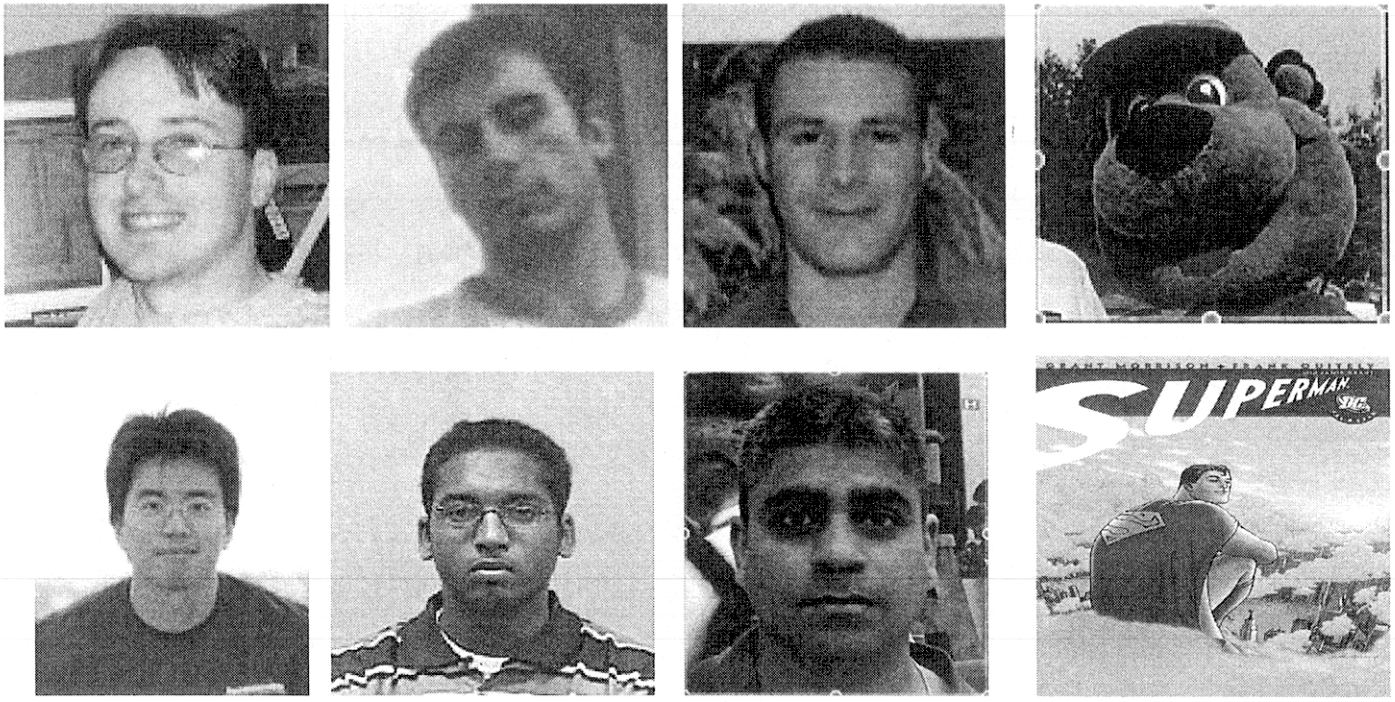
Global Analysis

- Theoretical tools to accomplish this now exists thanks to many theoretical groups: but in particular:
  - D. deFlorian (UBA), R. Sassot (UBA), M. Stratman (RIKEN) & W. Vogelsang (BNL), S. Kumano (KEK)
- Large amount of experimental data are being produced by Hermes, COMPASS, ***PHENIX, STAR***
- **Aim: to produce a set of polarized parton distributions and their uncertainties due to *theoretical as well as experimental* sources**
- An informal collaboration of experimentalists and theorists is formed:
  - Students & post doctoral fellows from experiments and theory will work together
  - Coordinators: W. Vogelsang(BNL) and AD (Stony Brook/RBRC)
    - First post doctoral fellow: Dr. Swadhin Taneja (Stony Brook)
    - Students expected to join the effort soon
- Will put in place a structure for incorporating future data

STONY BROOK
STATE UNIVERSITY OF NEW YORK

The SBU Spin group



Top L-to-R: Kieran Boyle (GS), Robert Bennett (GS), Nathan Means (GS), Andrew Manion (GS)

Bottom L-toR: Sang Wan Lee (UG), Kevin Jagdipsingh (UG), Dr. Swadhin Taneja (Post Doc), Christopher Perkins (GS)

GS: Graduate Student, UG: Undergraduate Student

Abhay Deshpande (not shown) joined Stony Brook U. in January 2004

Direct photon measurements

Kensuke Okada

RBRC review

November 5, 2007

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Motivation

Direct photon production process is important.

- ***p+p* collisions**
  - One of the simplest processes
  - Test on pQCD calculation

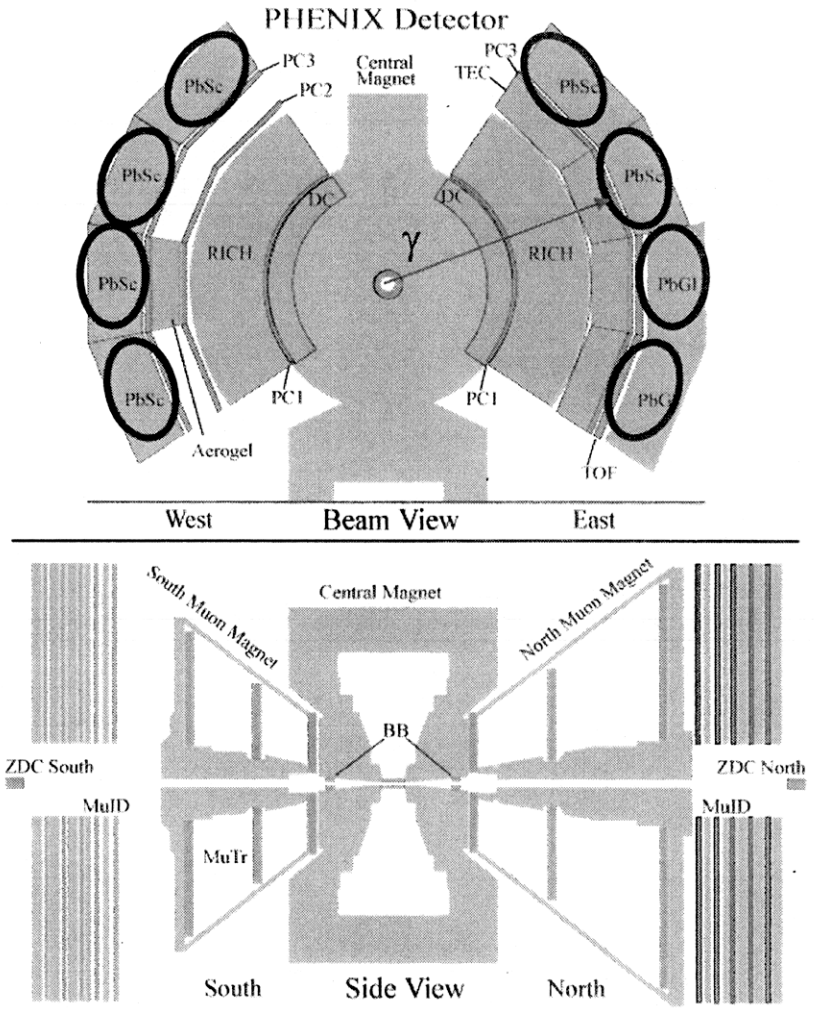
- ***N+N* collisions**
  - Electromagnetic probe for the media
  - Brings information of the initial state

- **Polarized *p+p* collisions**
  - Probe for gluon polarization via gluon Compton scattering.

I mainly worked on *p+p*.

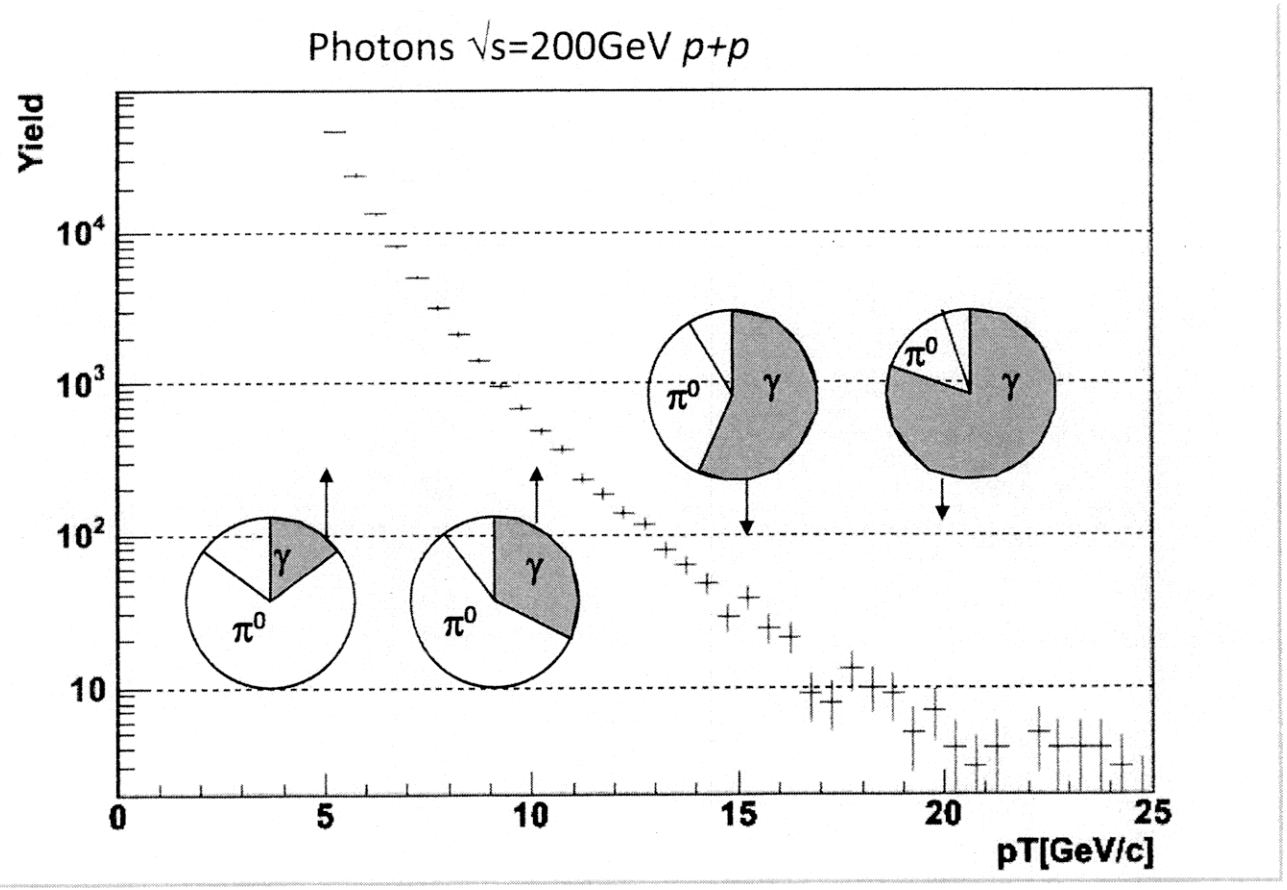
The PHENIX detector

- **Electromagnetic calorimeter (EMCal)**
  - Mid-rapidity region
  - photon detection
    - coverage:
      - $0.5\pi * 0.7 * 2$arms
    - segmentation:
      - $d\phi * d\eta = 0.01 * 0.01$
- **Beam-beam counters (BBC)**
  - Luminosity measurement
  - Vernier scan
    - (beam size measurement)



Background photons

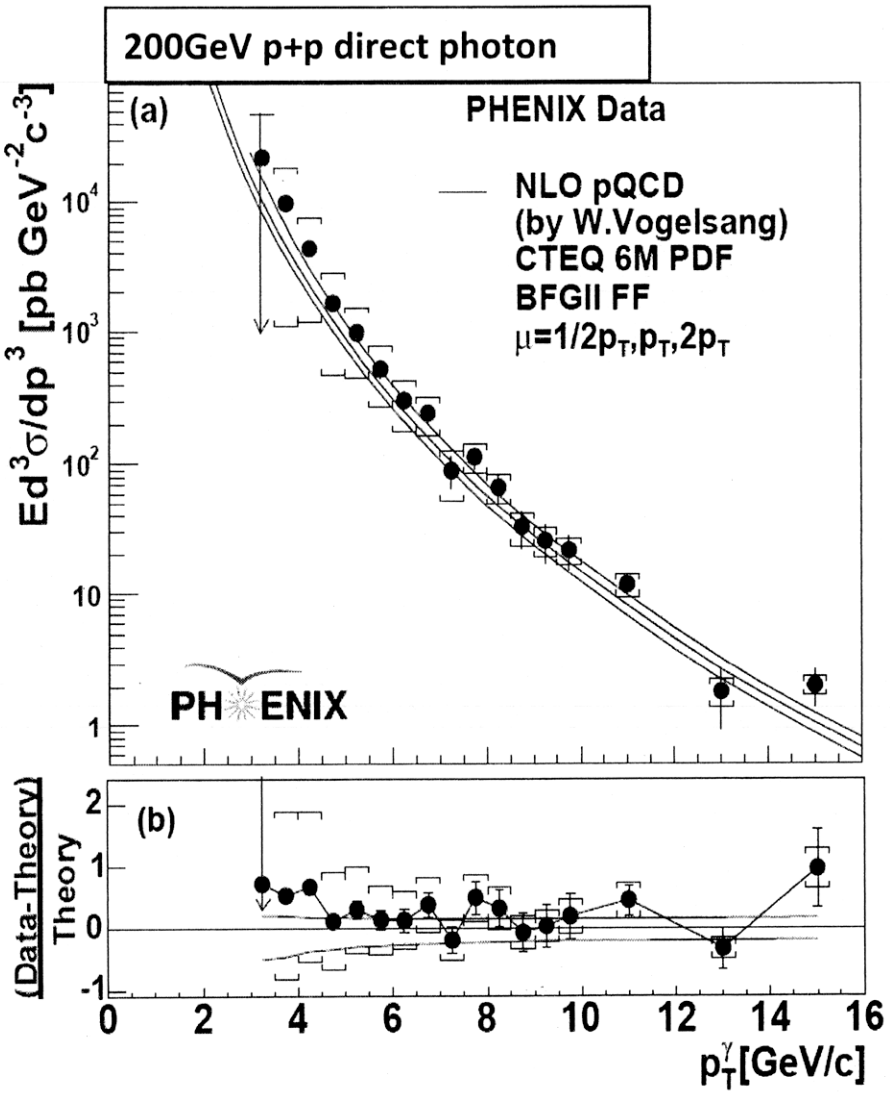
Clusters from other sources (hadronic decays, albedos)



Small S/N

π^0 2γ into one tower

Direct photon spectra



PRL 98, 012002 (2007)

2 results are combined

TABLE I: Relative systematic uncertainties of the direct photon spectra.

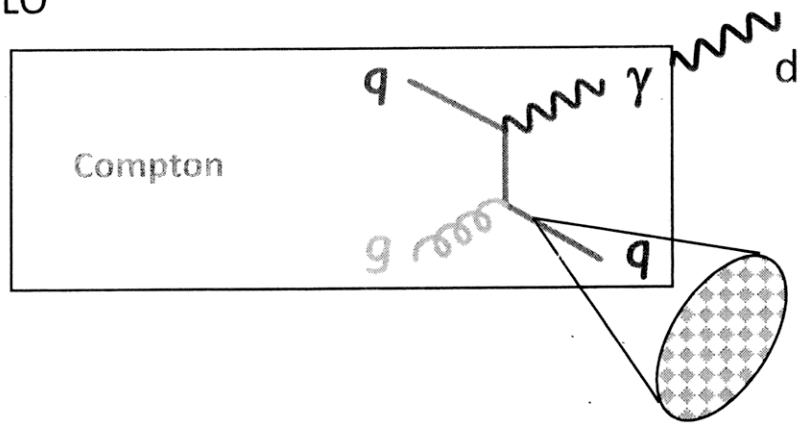
p_T [GeV/c]	4.5-5	7.5-8	10-12
Signal fraction	9%	27%	49%
(a) Global	16.8%	14.9%	14.9%
(b) Inclusive photons	12.3%	4.7%	3.1%
(c) Photons from π^0	30.1%	10.7%	6.5%
(d) Other hadrons	21.4%	6.7%	3.8%
(e) Non-linearity (+ remaining)			
(e_1) π^0 tagging	42.7%	6.8%	5.4%
(e_2) cocktail	69.5%	20.4%	13.4%
Total	71.6%	25.2%	19.8%

pQCD describes the result well.

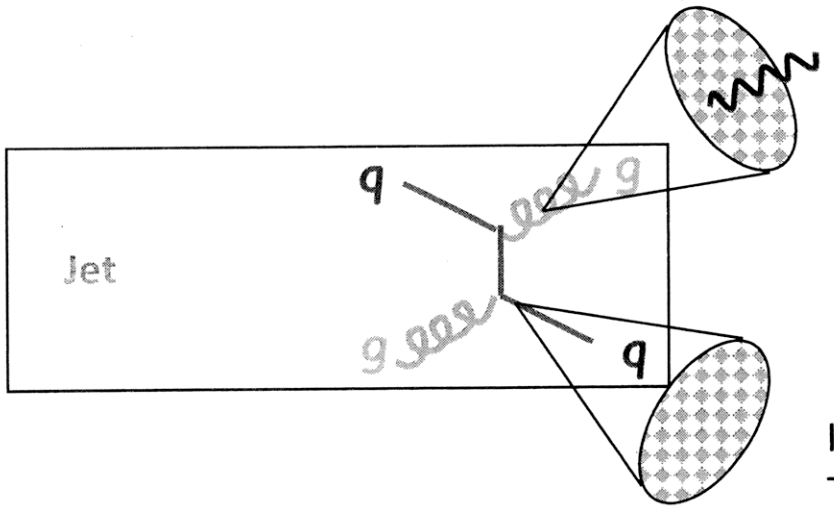
(It's not sensitive to the uncertainty of gluon PDF yet.)

Direct photon event structure

In LO



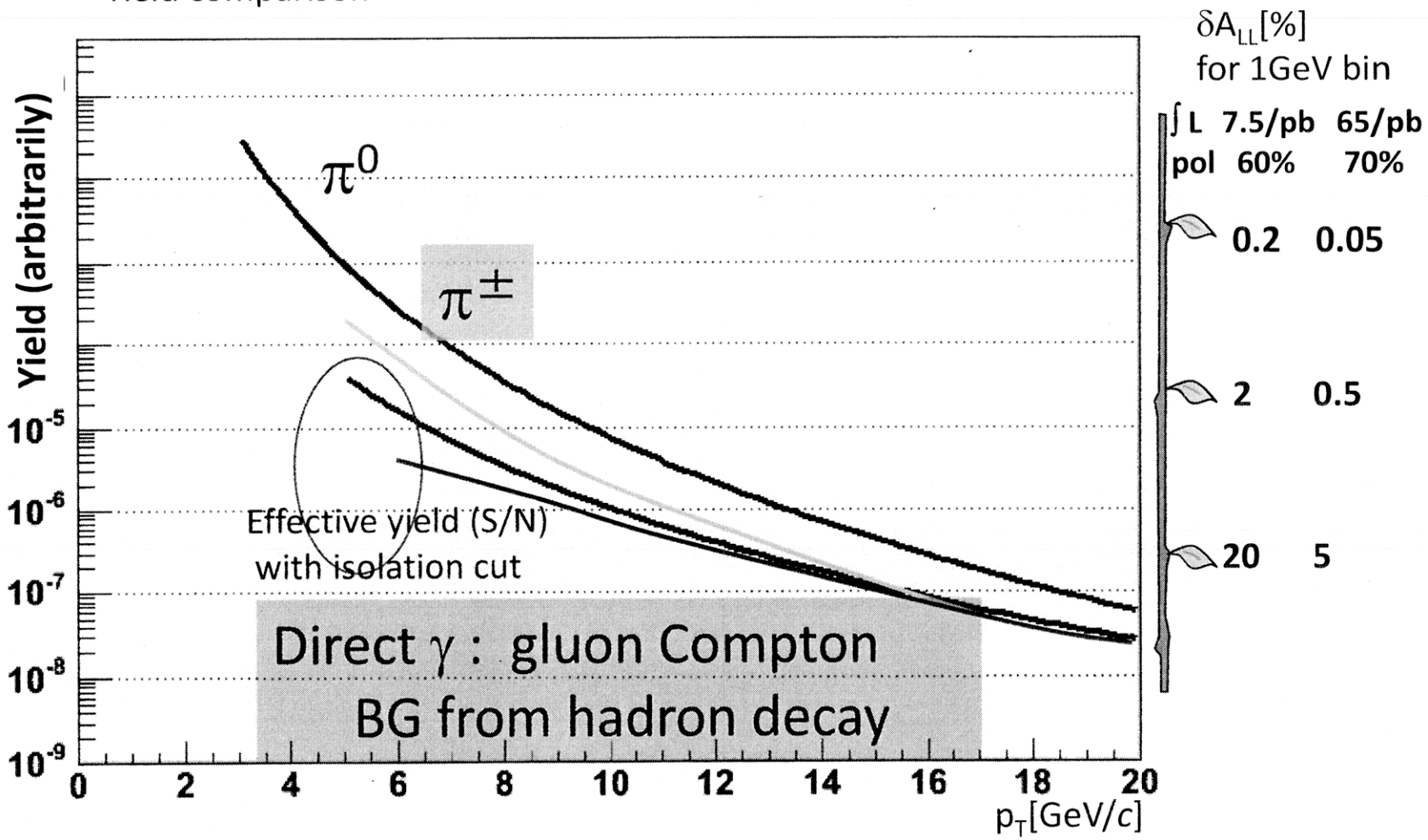
They should look different !



In the paper, we applied an isolation cut.
The signal photons are isolated particularly in high pT region.

Double Spin Asymmetry (A_{LL})

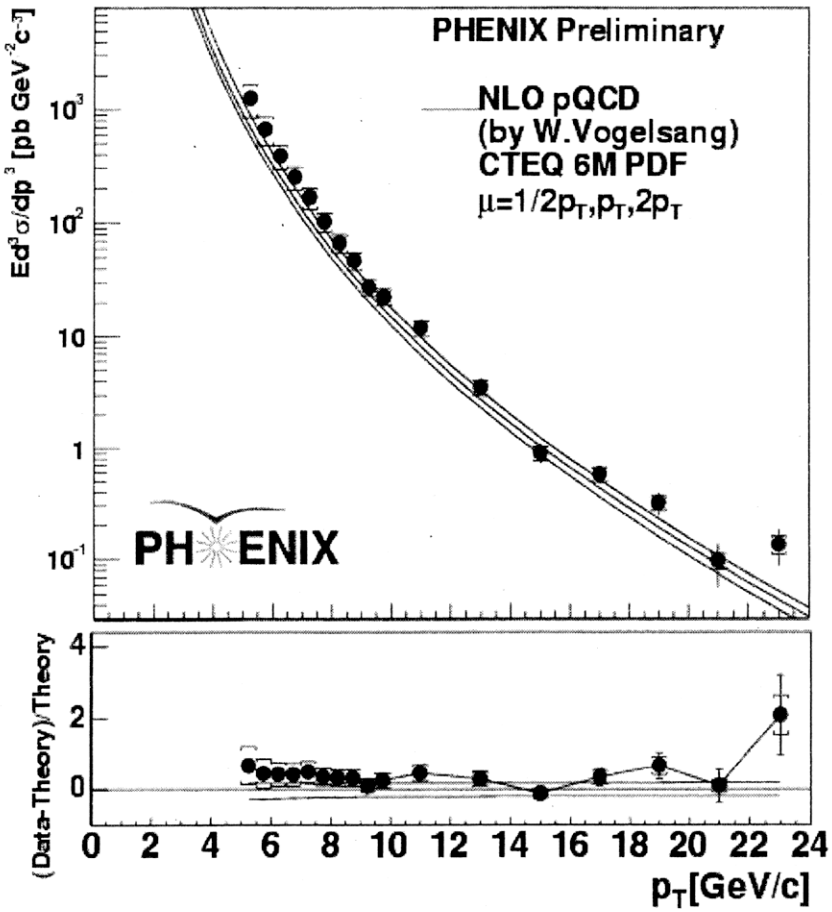
(PHENIX Central Arm)



High LP^4 for precise A_{LL}

Run3 (L=0.25/pb)
Cross section
published
P=35%

Run5 (L=2.5/pb), P=50%



Run6 long. Pol.
(L<7.5/pb)
P=60%

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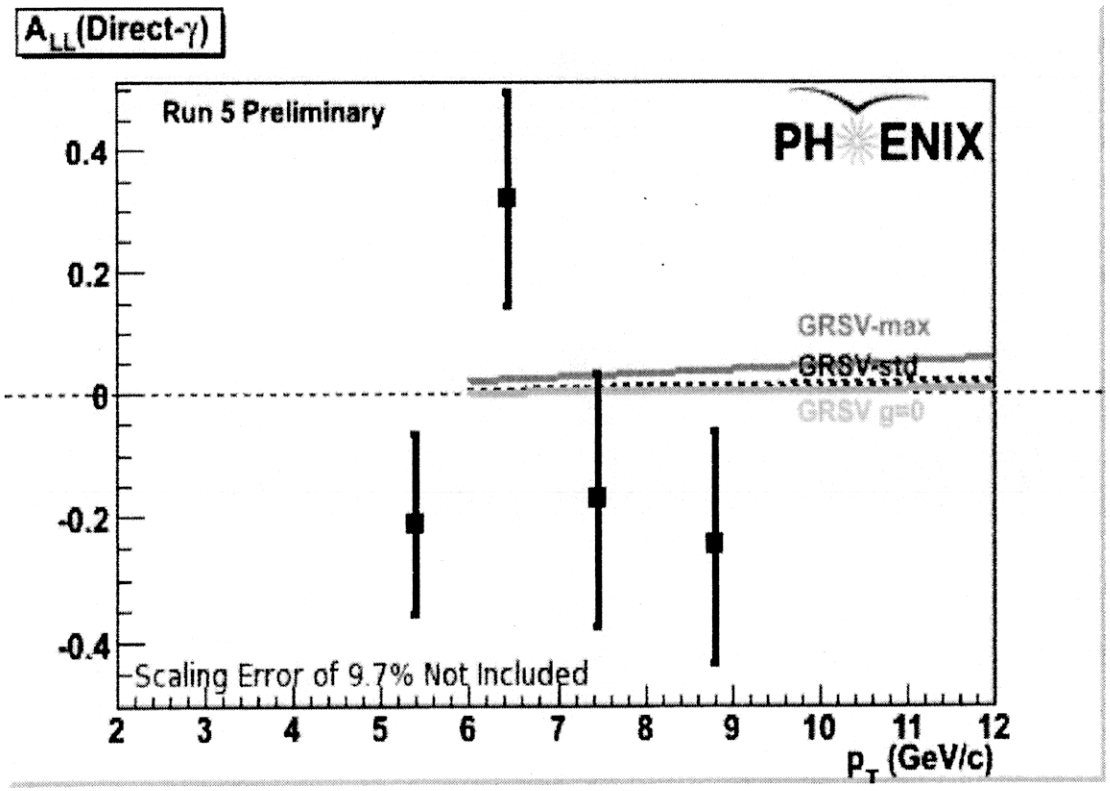
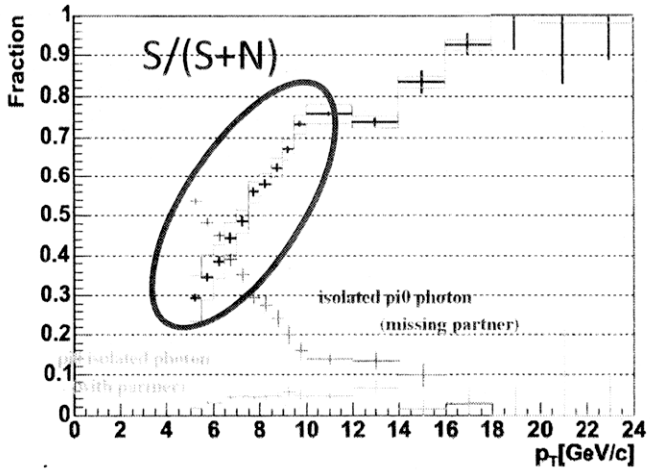
Direct photon A_{LL}

- An isolation cut is applied.
- Background A_{LL} is corrected.
  - (Assuming it is represented by the isolated π^0 photon)





- Background A_{LL} estimation can be improved.
  Low S/N is the main issue in this region.

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High x_T?

- $x_T \equiv 2p_T/\sqrt{s}$

  A representative of x_{gluon}

- If we assume the shape of polarized gluon distribution as

  $$\delta g(x,\mu^2) \propto x^{\alpha}(1-x)^{\beta} g(x,\mu^2) \qquad \alpha>0$$

  The A_{LL} is expected to be large in high x_T, since it is proportional to $\delta g/g$.

- To go to higher x_T

  More statistics ($p_T\uparrow$)
  Lower the collision energy ($\sqrt{s}\downarrow$)

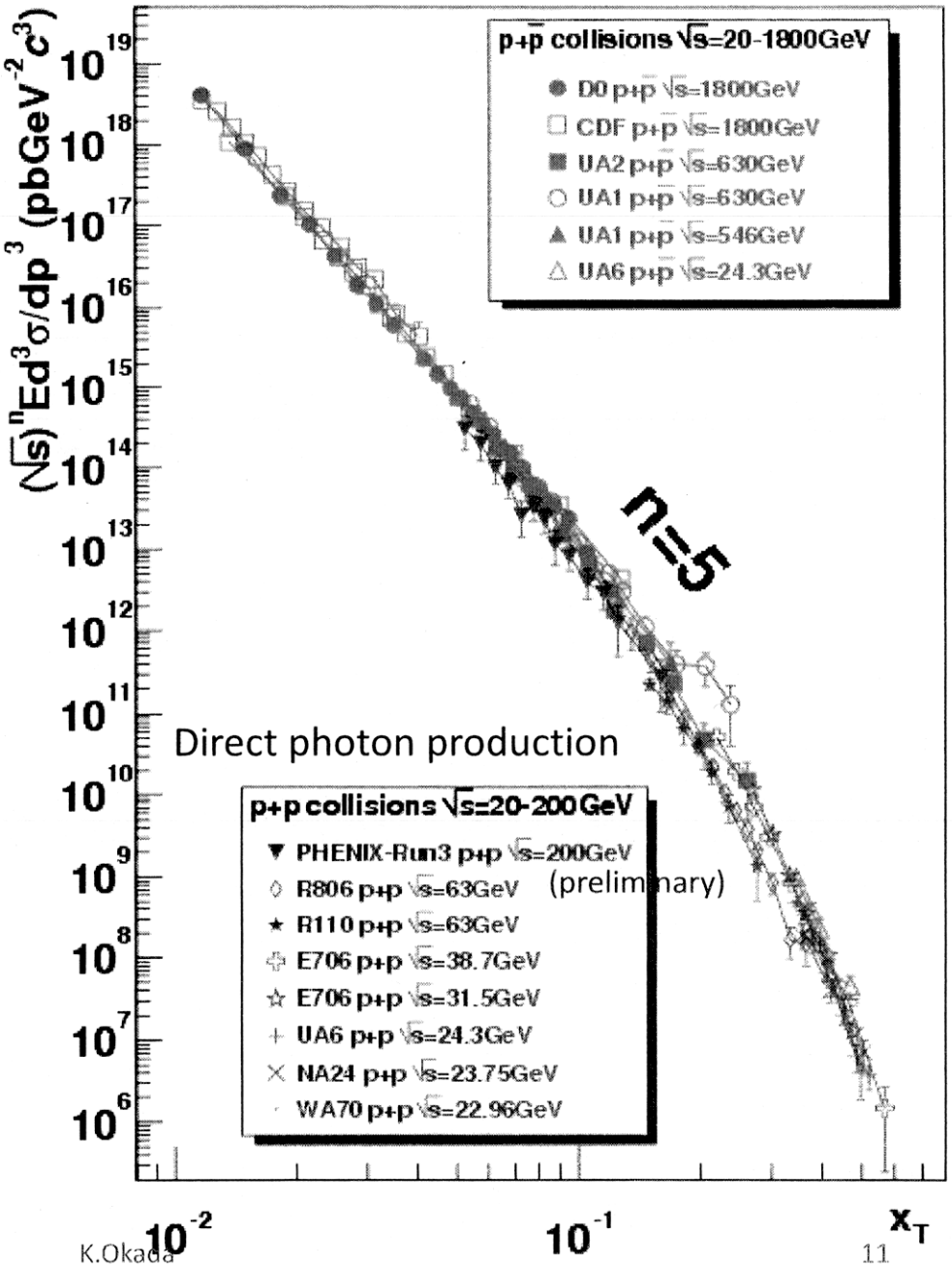
Extrapolation to another collision energy.

- When this scaling is applied,

  $\sqrt{s}$=200GeV $\rightarrow$ 62.4GeV
  $\times$33 production rate in the same x_T.
  $\times$ 0.1 Luminosity

  = $\times$3 statistics / unit time

- With Run6 62.4GeV data,
  we start to check
  the yield and background ratio.



Summary (direct photon)

- Cross section measurement with Run3 data is published.
- The first result of double spin asymmetry from Run5 data.
- Run6 data analyses are on going.

  High p_T (200GeV)
  Low collision energy (62.4GeV) $\longrightarrow$ High x_T

Heavy Flavor Asymmetries from Inclusive Electrons

P. Liebing, RBRC Review,
November 5, 2007

Motivation

- Δg from open charm via semileptonic D decay
- Signal: $gg \rightarrow cc \ldots \rightarrow D^{0,*,\pm,\ldots} \rightarrow e^{\pm} \nu \sim \Delta g \, \Delta g$
- Scale: $\approx 2m_c$ (no p_T cut $\Rightarrow$ $\langle x \rangle$ smaller)
- Background: $\pi^0 \rightarrow \gamma e^+ e^-$, $\gamma \rightarrow e^+ e^-$, $(\pi^0, \eta, \gamma, \ldots)$, $K^{0,\pm} \rightarrow e\pi\nu$ (K_{e3}), $\rho, \omega, \varphi, \ldots \rightarrow e^+ e^-$
- Background large at low $p_T < 2$ GeV
- At high $p_T > 3$ GeV: $gg \rightarrow bb$

Run Selection

- Reject all runs with relative lumi/polarization problems
- Cuts to ensure run good quality
  - Relative luminosity, yields, efficiencies
- Exclude converter runs and runs with known hardware problems

Outline

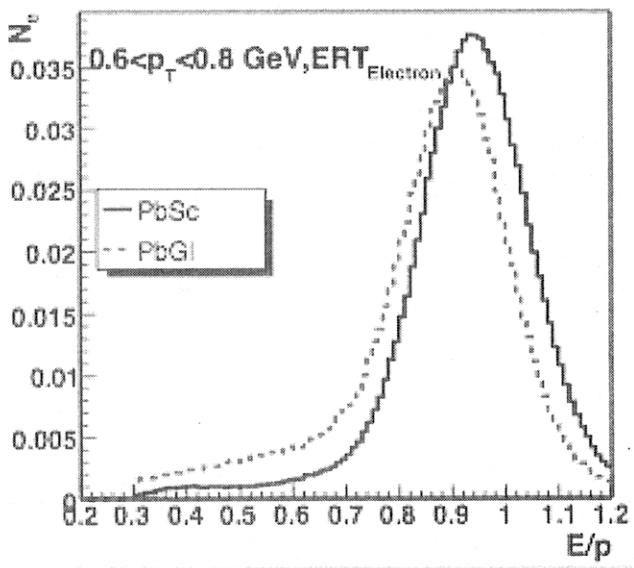
- Data selection
- Inclusive Electron Asymmetries
- Background Estimate And Subtraction
- Further Up On The Road?

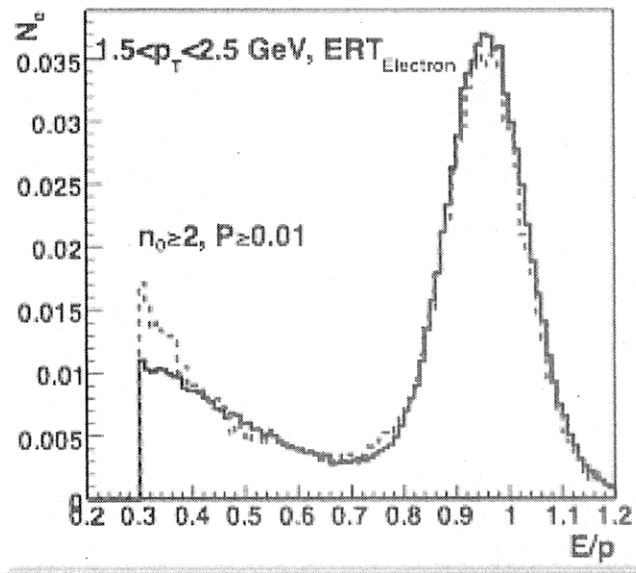
Event/Kinematic Cuts

- Trigger: MB, $ERT_{Electron}$, ERT_{4x4c}
- Event: $|z|<20$ cm
- Good track quality
- MVD service pipe (reduce conversion)
- Track matching (reduce bkgd. from wrongly reconstructed tracks):
  - $\sqrt{\Delta^2 z/\sigma_z^2+\Delta^2\varphi/\sigma_z^2}<4.2$ (EMC, PC3)

PID Cuts

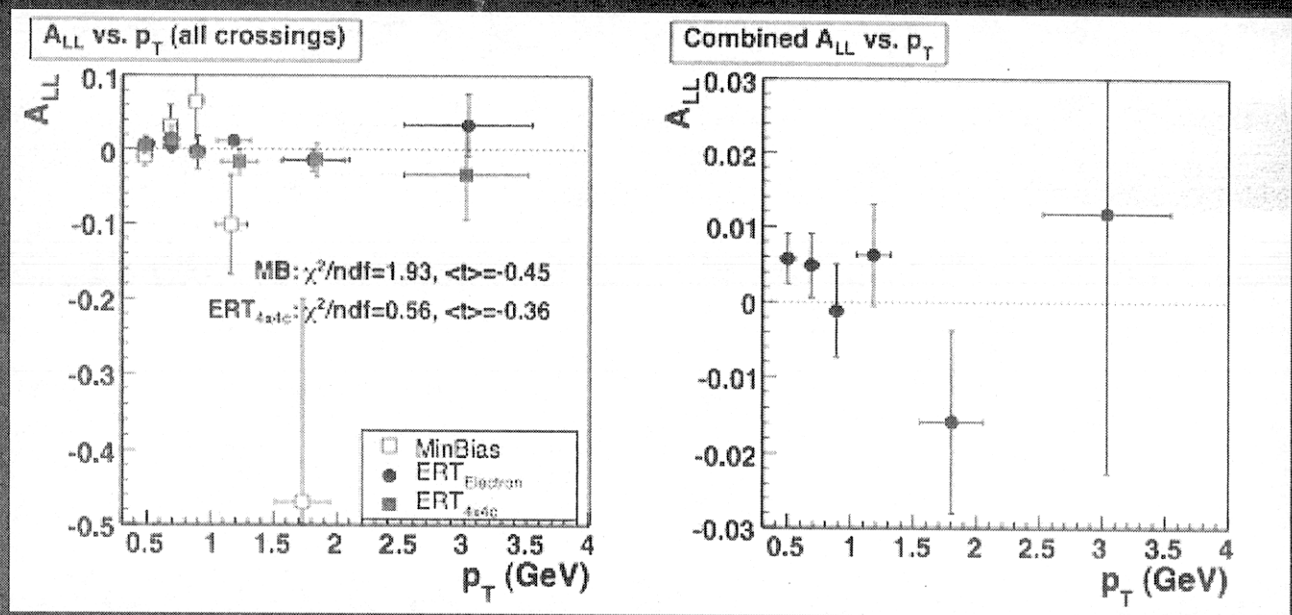
- $n_0 \geq 2$ (Ring between $R_1 = 3.4$ and $R_2 = 8.4$ cm around track)
- $E/p > 0.7$ ($p_T < 0.6$ GeV)
- $E/p > 0.75$ ($0.6 < p_T < 0.8$ GeV)
- $E/p > 0.8$ ($0.8 < p_T < 5$ GeV)
- EM Shower probability>0.01





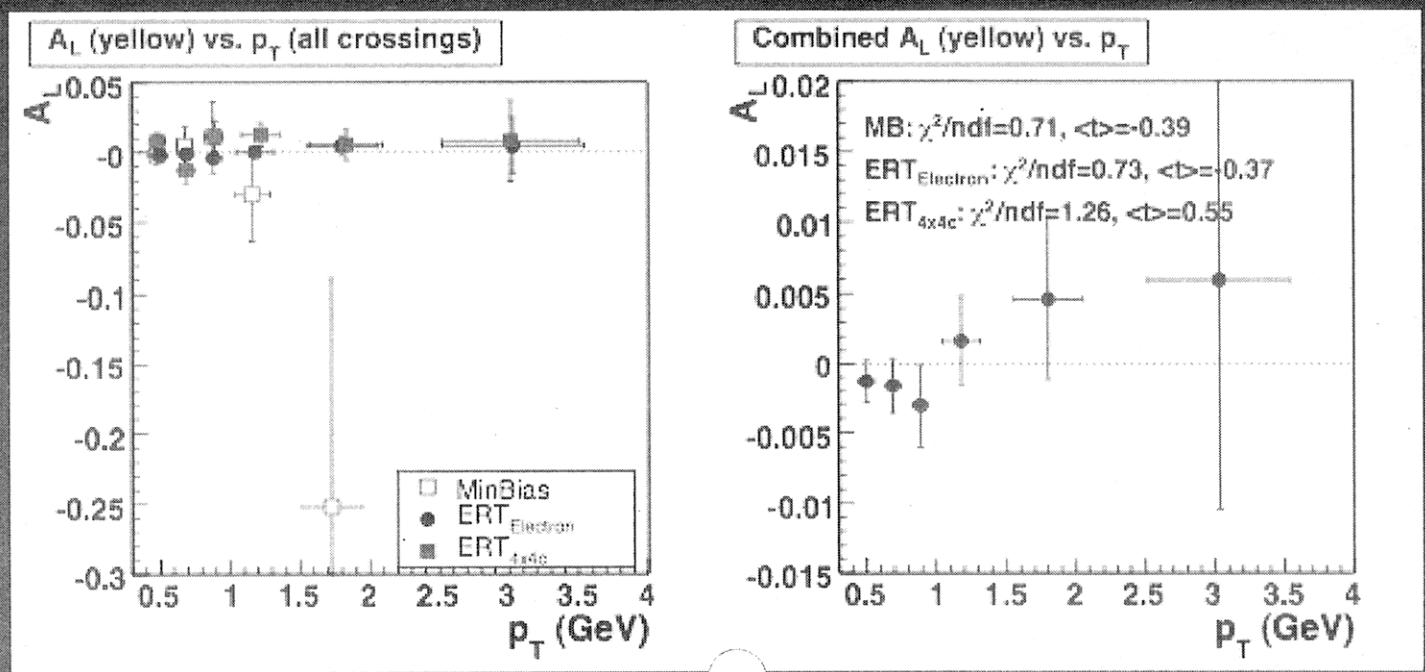
Asymmetries

- MB, ERT_Electron, ERT_4x4c



Parity Violating Asymmetries

- Systematic check for false asymmetries
  - Physics single helicity asymmetry $\approx 10^{-5}$
- Single Spin Asymmetries
  - $\rightarrow$ zero (within statistics)

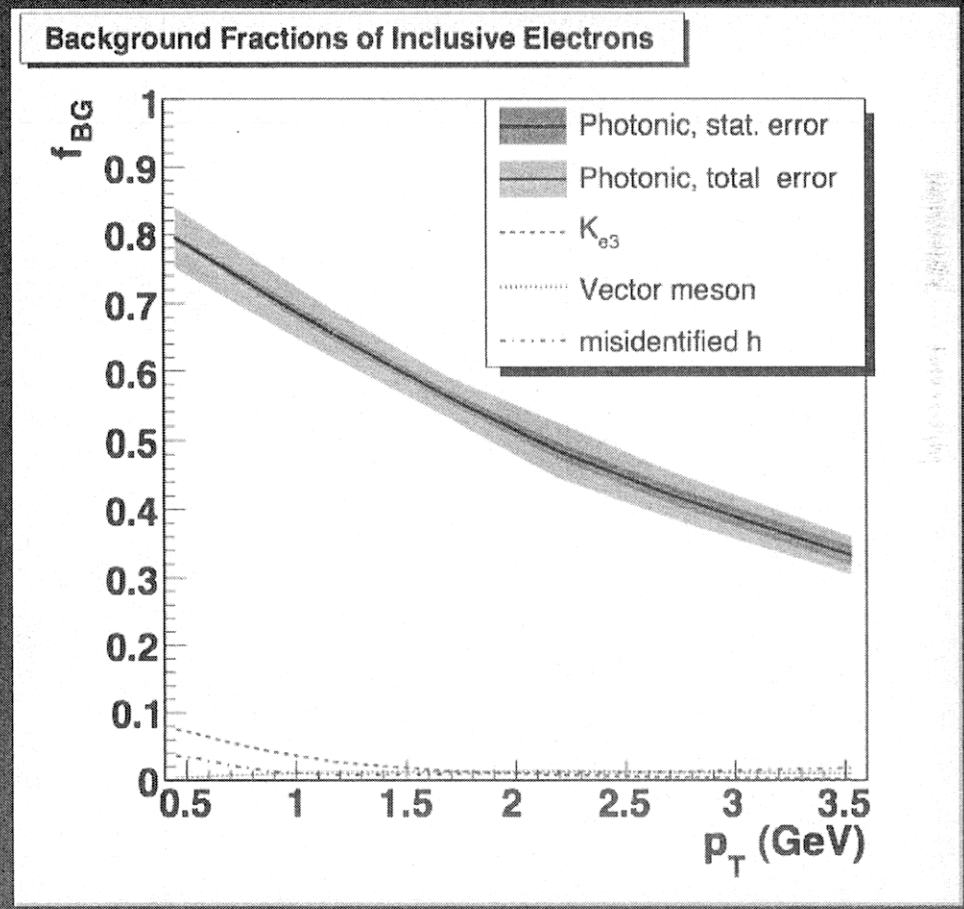


Background

- $A^e = f_{BG} A_{BG} + f_{sig} A_{sig}$
- f_{BG}: From PPG65 analysis
- A_{BG}: dominant contribution from electrons originating from π^0 and kaons
- $A^e = f_\pi A_\pi + f_K A_K + f_{sig} A_{sig}$
  - f_π contains contributions from photonic-, VM decay background and hadron misidentification
  - $A_{\pi,K}$ need assumptions on p_T distributions of electrons

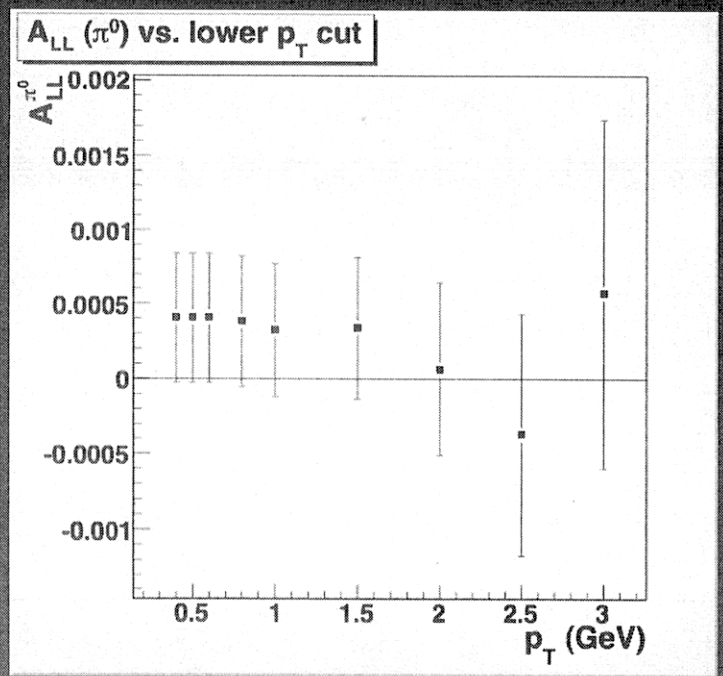
Background

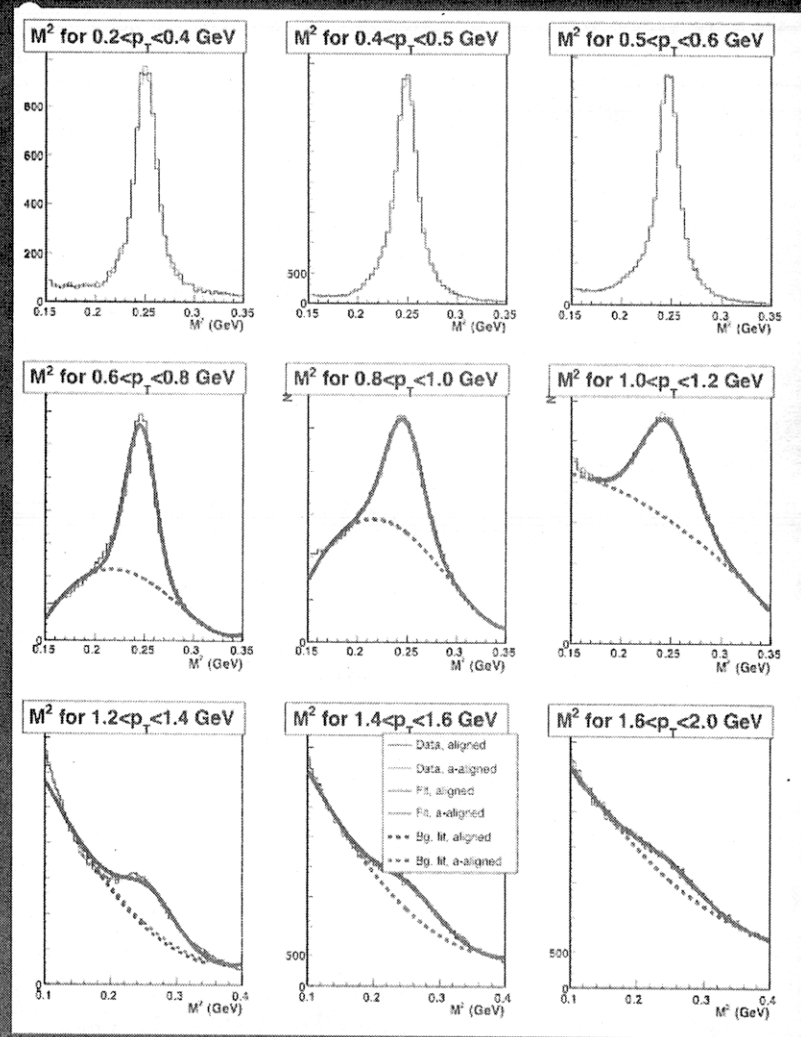
- Photonic BG:
  - Fit to PPG65 converter ratio data for $p_T<2$ GeV
  - Fit to PPG65 cocktail (MC) for $p_T>2$ GeV
- Nonphotonic BG:
  - From PPG65 analysis



Background Asymmetries

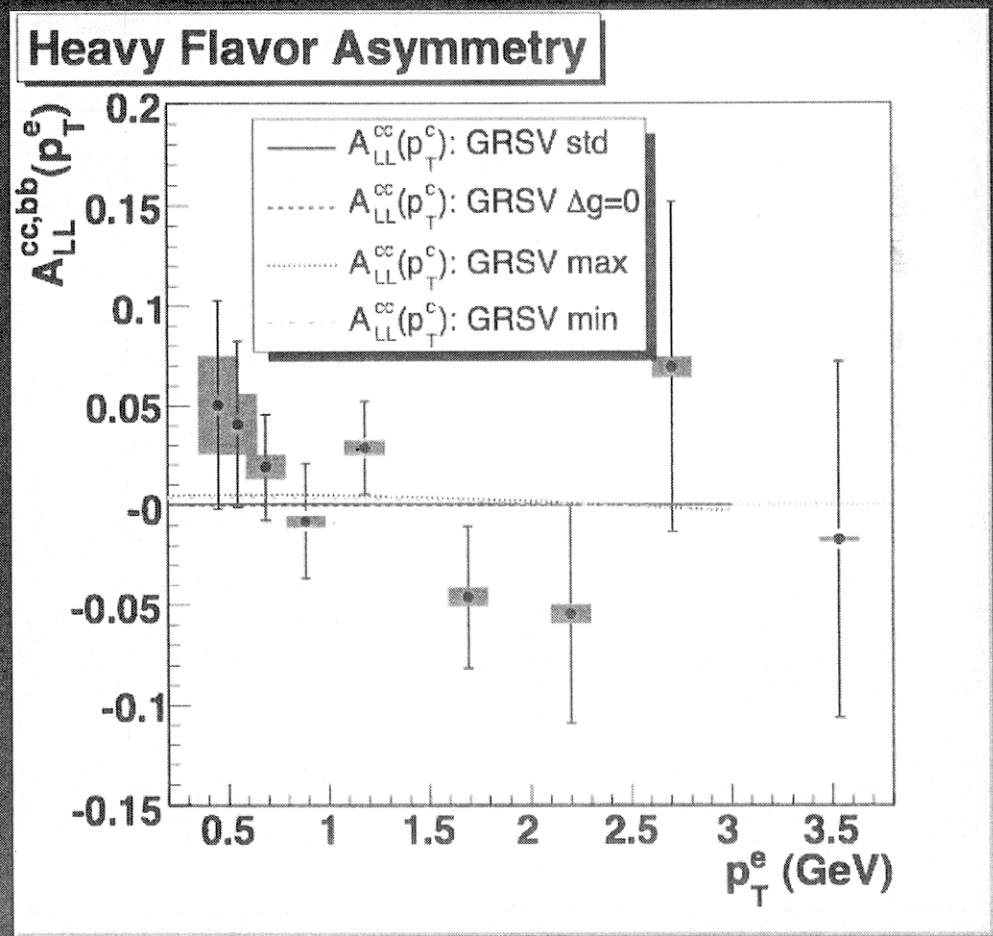
- π^0 Asymmetry from Run 5 (p_T<1 GeV) and Run 6 (p_T>1 GeV)
- Integrate from p_{Tmin}=low edge of electrons bin





Heavy Flavor Asymmetry

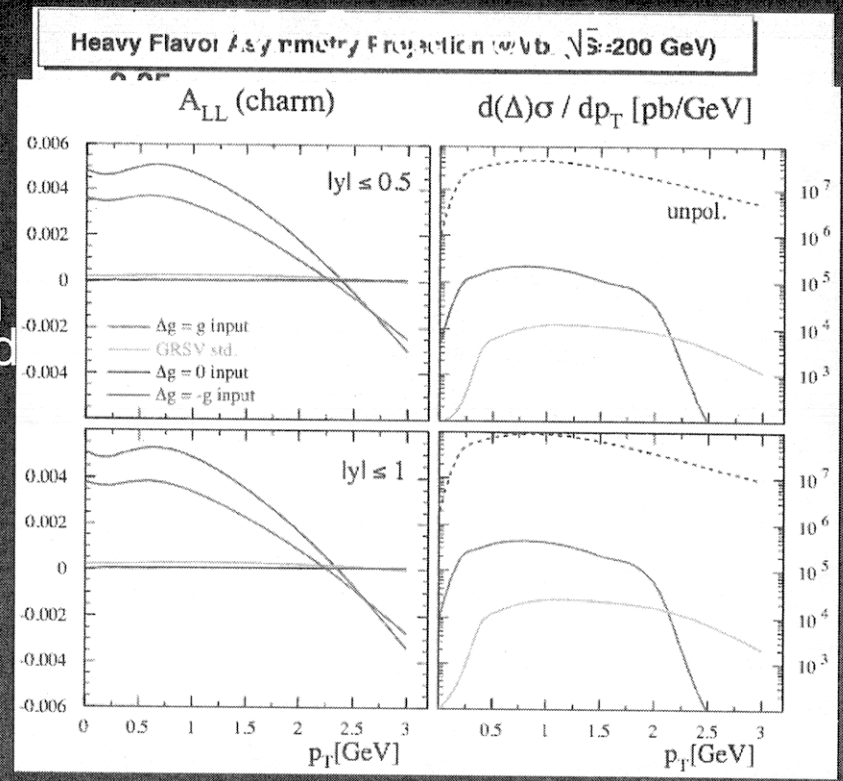
- Systematics are from systematic error on R_{NP}, and statistical errors on R_{NP}, A_π, A_K
- Run 6 will not change the picture
  - Might be worse because of HBD?



Some Outlooks

- Si-Vtx detector:
  - Use vertex measurement to reduce BG
  - Cut on DCA excludes tracks originating at vertex=0 (Dalitz), and at large vertex (conversion at beam pipe)
  - Match tracks between central arm and VTX to exclude K_{e3} decay and conversion in DC
- Extrapolation of N_e (this analysis), S/B from Run5 to projected good lumi (21.6/pb) and S/B from VTX proposal
  - With DCA>200μm cuts (2*resolution)
  - Cuts can be optimized

Predicted NLO Asymmetry of *charm quarks*



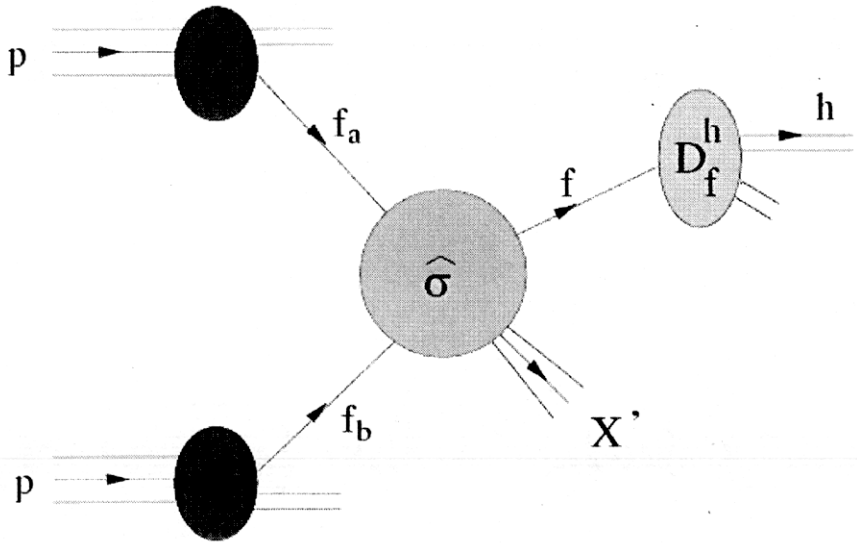
Summary

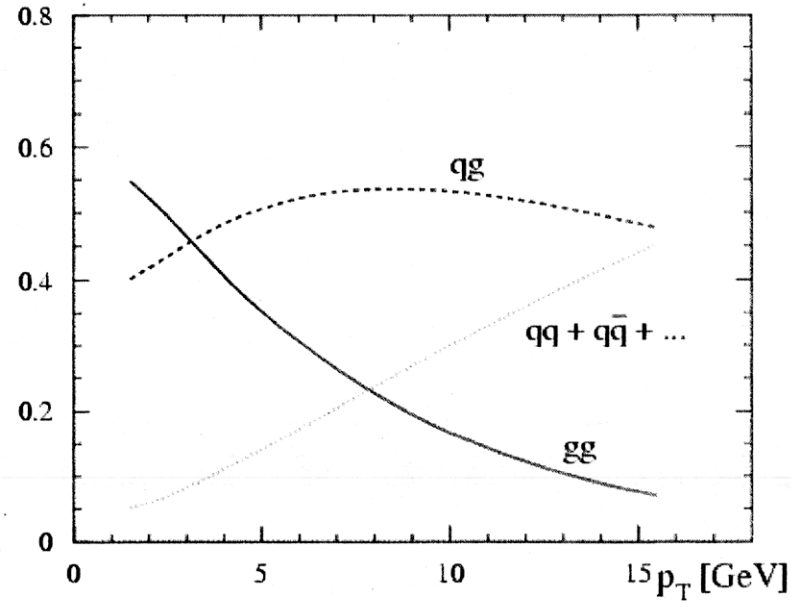
- Heavy flavor (open charm and bottom) asymmetry extracted from single electron asymmetry of Run 5 using PPG65 results on S/B
- Current statistics do not reveal systematically different asymmetries of background and signal
- With current detector setup A_{LL}(heavy flavor) in central arm has no sensitivity to $\Delta g/g$
- Difficult measurement even with VTX upgrade, due to small predicted asymmetries (few 10^{-4})
  - Bottom/charm separation w/VTX

Development of a Trigger for High p_T Charged Pions at PHENIX

D. Kawall, RBRC and Univ. of Massachusetts

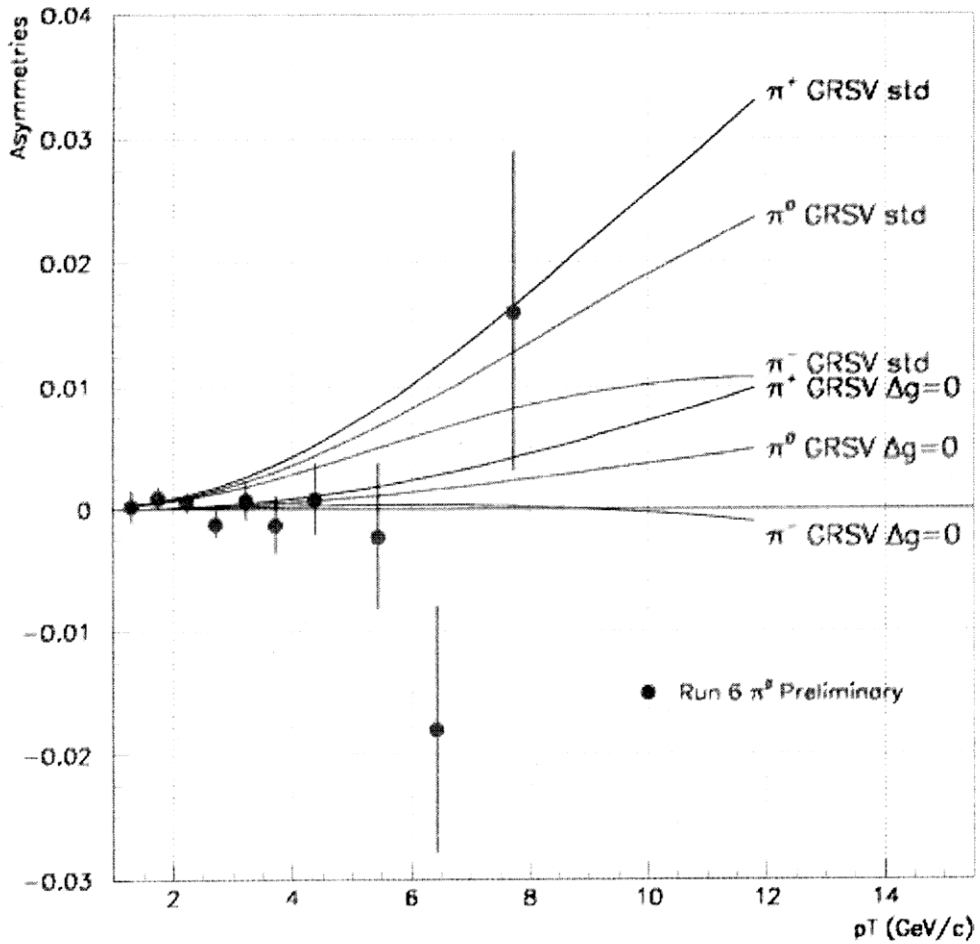
- PHENIX has measured unpolarized $\sigma(pp \to \pi^0 X)$ and asymmetry $A_{LL}(pp \to \pi^0 X)$
- Unpolarized cross section σ well described by pQCD $\Longrightarrow$ use pQCD to interpret asymmetries





- quark-gluon scattering starts to dominate for $p_T \geq 5$ GeV/c
- $A_{LL}^{\pi} \propto \Delta g \, (\Delta u D_u^{\pi} + \Delta d D_d^{\pi})$
- Asymmetry measurement important because it is sensitive to Δg

Motivation for a Trigger for High p_T Charged Pions



- $A_{LL}^{\pi} \propto \Delta g \, (\Delta u D_u^{\pi} + \Delta d D_d^{\pi})$
- $\Delta u > 0, \;\; \Delta d < 0, \;\; |\Delta d / \Delta u| < 1$
- $D_u^{\pi^+} > D_d^{\pi^+}, \;\; D_u^{\pi^-} < D_d^{\pi^-}$

- $A_{LL}^{\pi+} \propto \Delta g \, (\, \Delta u D_u^{\pi+})$
- $A_{LL}^{\pi-} \propto \Delta g \, \big(\, \Delta u D_u^{\pi-} + \Delta d D_d^{\pi-} \approx 0 \big)$

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

Run 5 Yields, 2 pb^{-1}			
p_T (GeV/c)	π^+	π^-	π^0
5-6	9600	9300	93000
6-7	9100	7600	28000
7-10	7400	5900	>15000

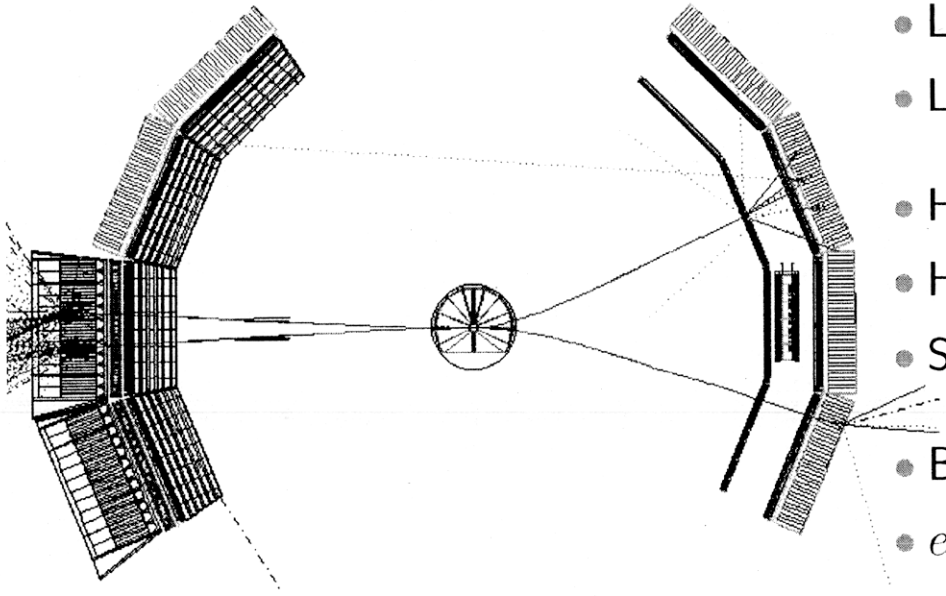
- Charged pion yields $\ll$ neutral pion yields because we lack a dedicated trigger

How can we Implement a High p_T Charged Pion Trigger at PHENIX?

$\Rightarrow$ Form a coincidence between the RICH and Hadron Blind Detector (HBD)

- RICH uses CO_2 at 1 atm., Cherenkov threshold for $\pi^{\pm}$ about 4.8 GeV/c
- HBD uses CF_4 at 1 atm., Cherenkov threshold for $\pi^{\pm}$ about 4.5 GeV/c

$\Rightarrow$ Pions above $\approx$ 5 GeV/c will fire both detectors

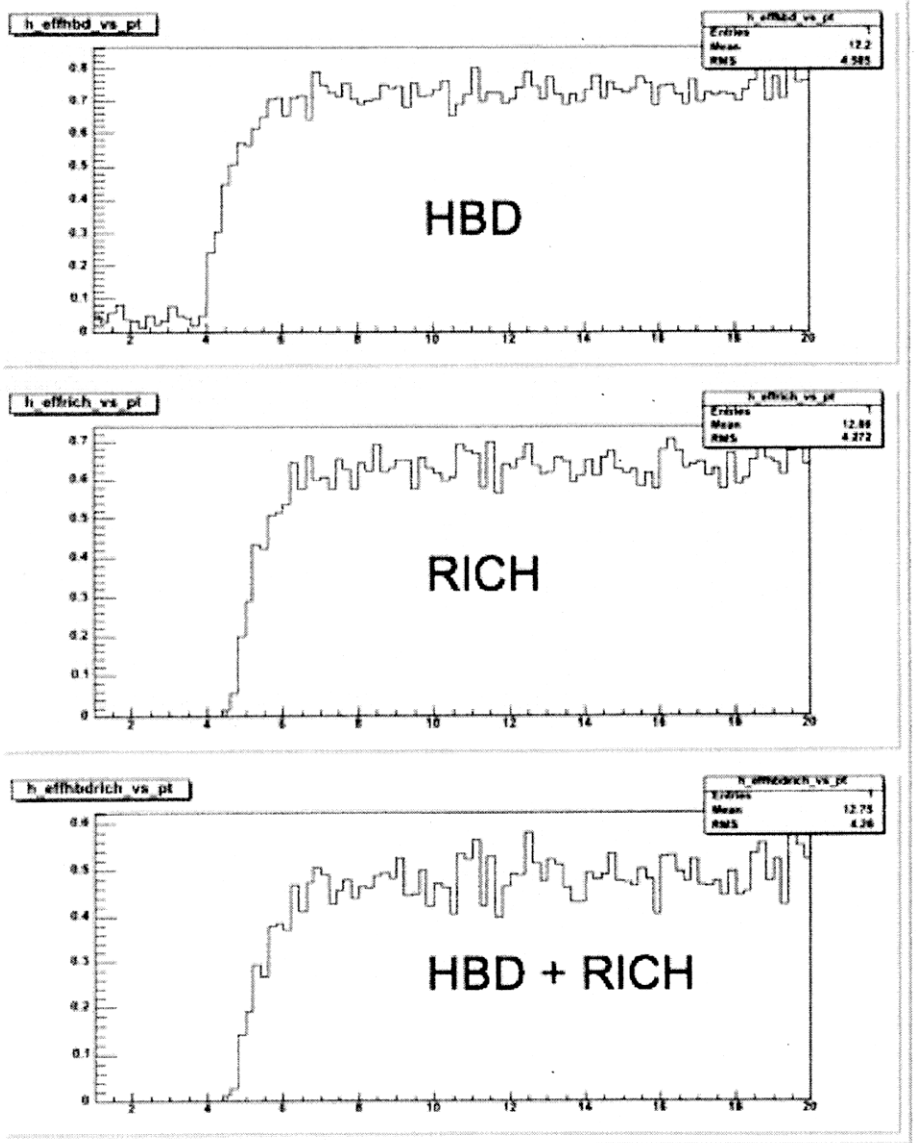


- Low p_T $\pi^{\pm}$ bend significantly in the $\mathbf{B}$ field
- Low p_T $\pi^{\pm}$ will not fire RICH or HBD
- High p_T $\pi^{\pm}$ bend less in $\mathbf{B}$ field
- High p_T $\pi^{\pm}$ fire RICH and HBD
- Small $\Delta\phi$ between hits in HBD and RICH
- Background from conversion of $\gamma \rightarrow e^+e^-$
- $e^{\pm}$ fire HBD and RICH, but large $\Delta\phi$

- Trigger LUT associates each of the 1152 HBD pads/arm with subset of the 128 RICH trigger tiles/arm (each pad maps to $\approx$ 16 RICH tiles)
- Check each event to see if HBD and RICH hits correspond to high p_T $\pi^{\pm}$

Will this Trigger be Efficient?

Efficiency vs p_T



- HBD efficiency is threshold dependent
- $70\%+$ efficiency reasonable
- HBD also sensitive to ionization signal from $\pi^{\pm}$
- Leads to a response below Cherenkov threshold

- RICH efficiency limited by masked-off trigger tiles
- Expect efficiency of $> 60\%$

$\Rightarrow$ Should be $\approx$ 50% efficient (factor 3 improvement)

Is this Trigger Sufficiently Discriminating?

- As we approach design luminosity, minimum bias (MB) trigger rate >500 kHz
- Rate of $\pi^{\pm}$ >5 GeV/c into acceptance < 20 Hz!
- Need to keep the <20 Hz signal, reject the 500 kHz background
- Realistically, need to keep false trigger rate to 1 in 500 or so

Can we Achieve this?

- East arm of HBD will fire in $\approx 1/6$ MB events
- East arm of RICH will fire in $\approx 1/20$ MB events
- Will get a coincidence in either arm in 1/60 MB events
- Chance HBD and RICH hits will overlap in ϕ about 1/8
- This predicts false trigger rate about 1 in 480
- Improve by increasing threshold in HBD, eliminating elements of LUT which fire rarely

$\Rightarrow$ Rejection factor of 1 in 500 realistic

Work Required to Implement this Trigger

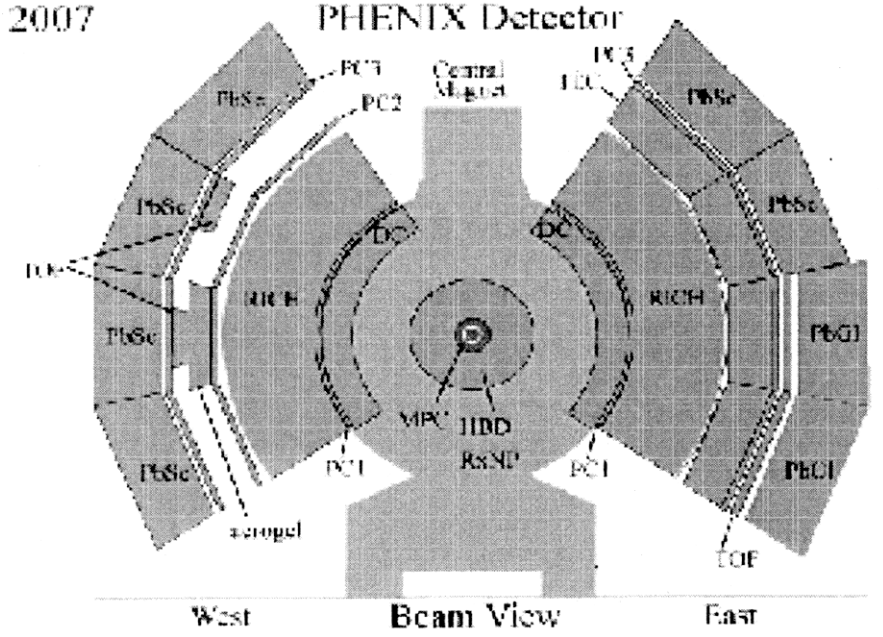
(1) Complete simulation work - finalize lookup table, determine rejection factors and thresholds

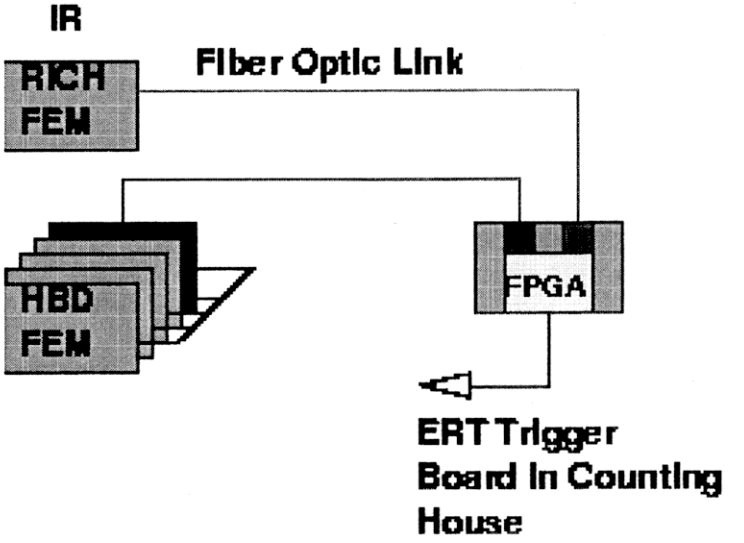
(2) Reprogram FPGAs on Front-End-Modules of HBD to see which pads above threshold

(3) Develop new board to combine pad information into trigger bits, send by optical fiber to ERT trigger boards

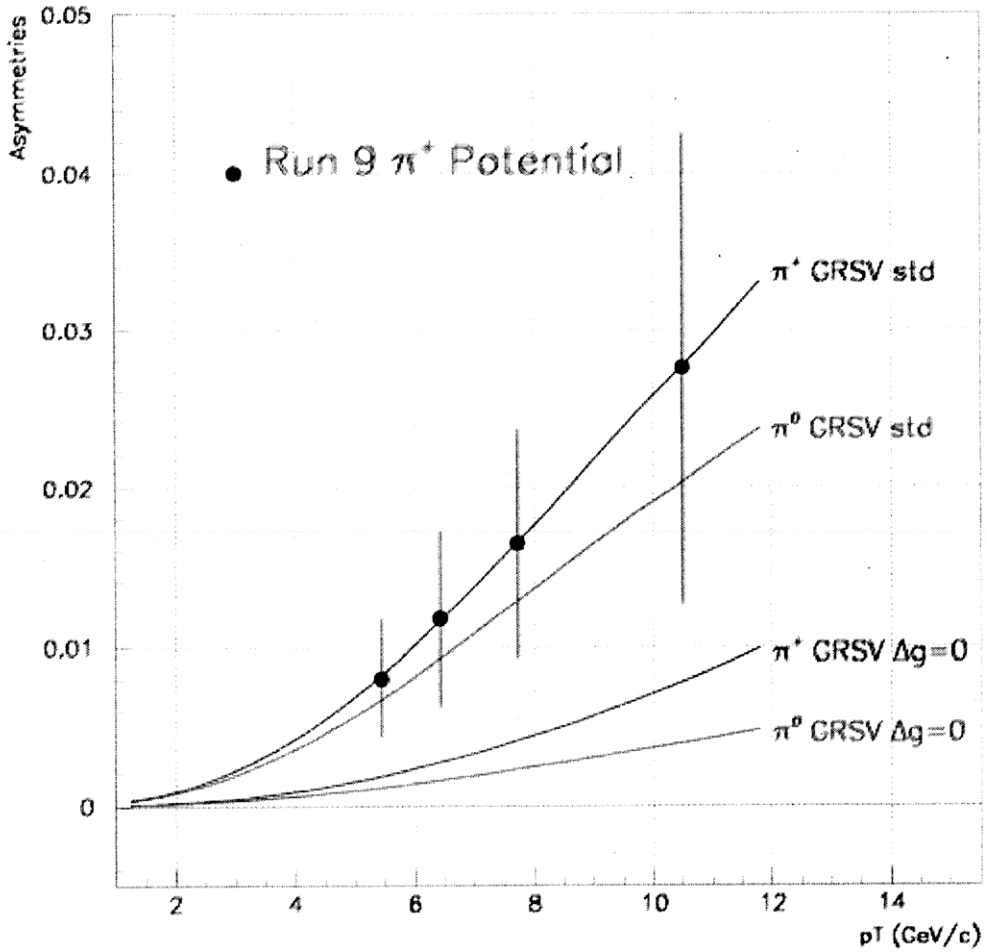
(4) Add new optical transceiver to ERT trigger boards to accept HBD trigger bits

(5) Reprogram trigger board FPGA to compare RICH+HBD trigger bits with lookup table





- Goal is to have trigger in place for Fall 2008, in time for Run 9
- Success would result in π^+ and π^- yields roughly 80% of π^0 yield
- CAD projects $\mathcal{L}_{\rm ave}^{\rm Run9} \approx 6 \times 10^{31}$ cm^{-2}s^{-1} (3 × Run 6) $\Rightarrow$ few million $\pi^{\pm}$!

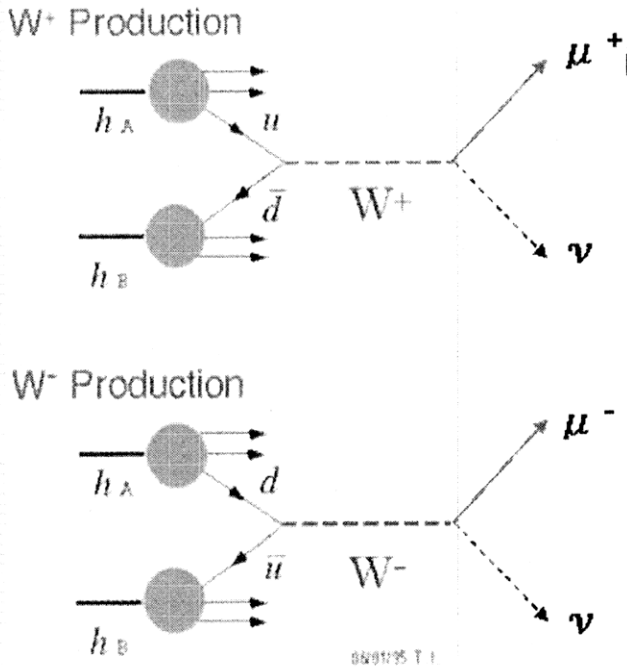


- Underappreciated point : Recall
  $A_{LL}^{\pi} \propto \Delta g\,(\Delta u D_u^{\pi} + \Delta d D_d^{\pi})$
- For π^+, $(\Delta u D_u^{\pi} + \Delta d D_d^{\pi})$ acquires maximum value
- $A_{LL}^{\pi^+}$ > has greater analyzing power for Δg than $A_{LL}^{\pi^0}$
- This trigger would be helpful for central-forward correlation measurements

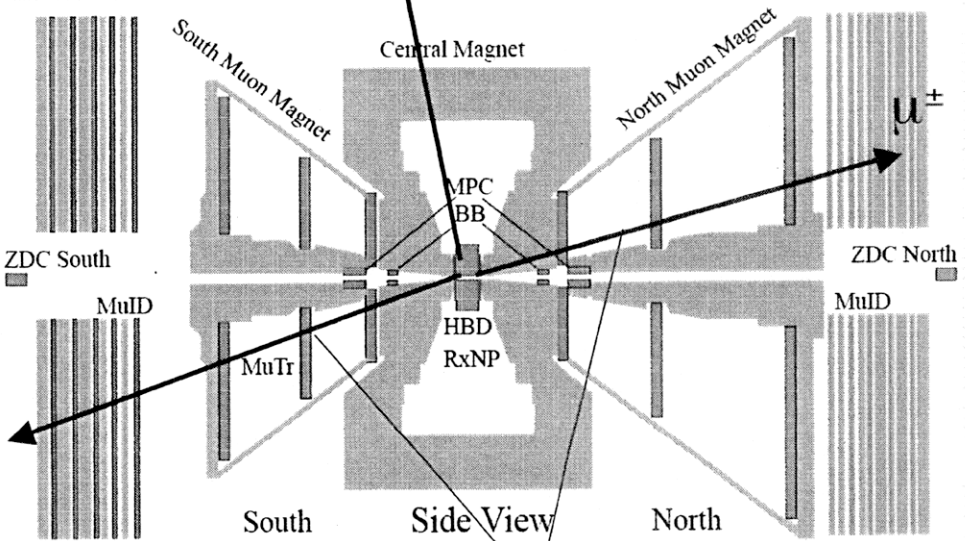
Muon Trigger Upgrade for W Boson Detection

Itaru Nakagawa
RIKEN/RBRC
On behalf of MuTrig Collaboration

sqrt(s)=500 GeV @ RHIC



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

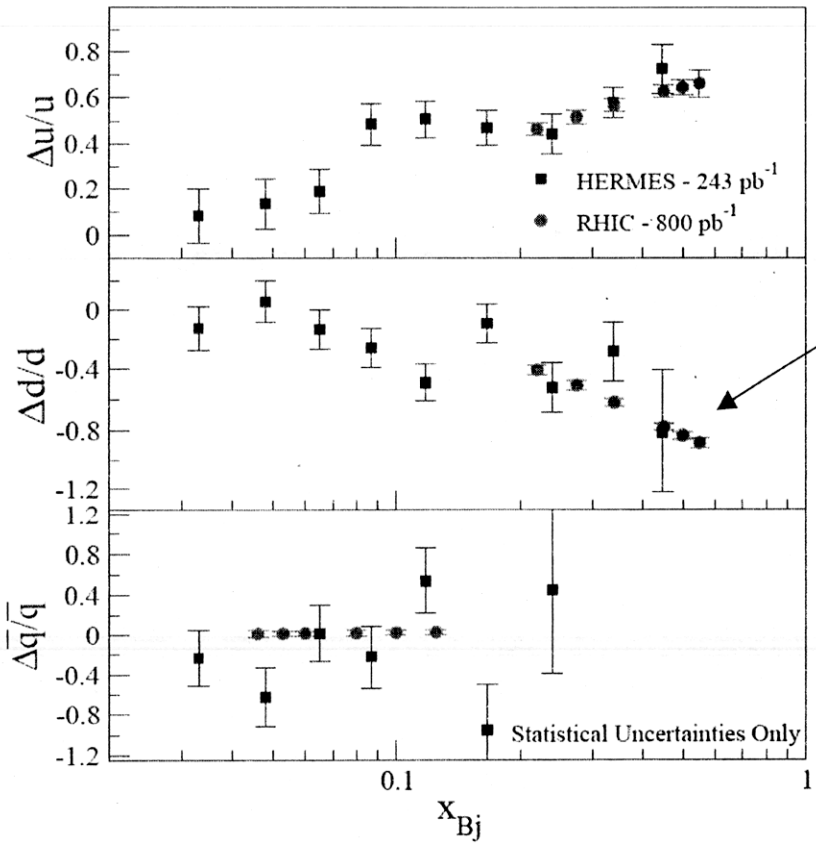


Clean flavor separation
w/o fragmentation uncertainty

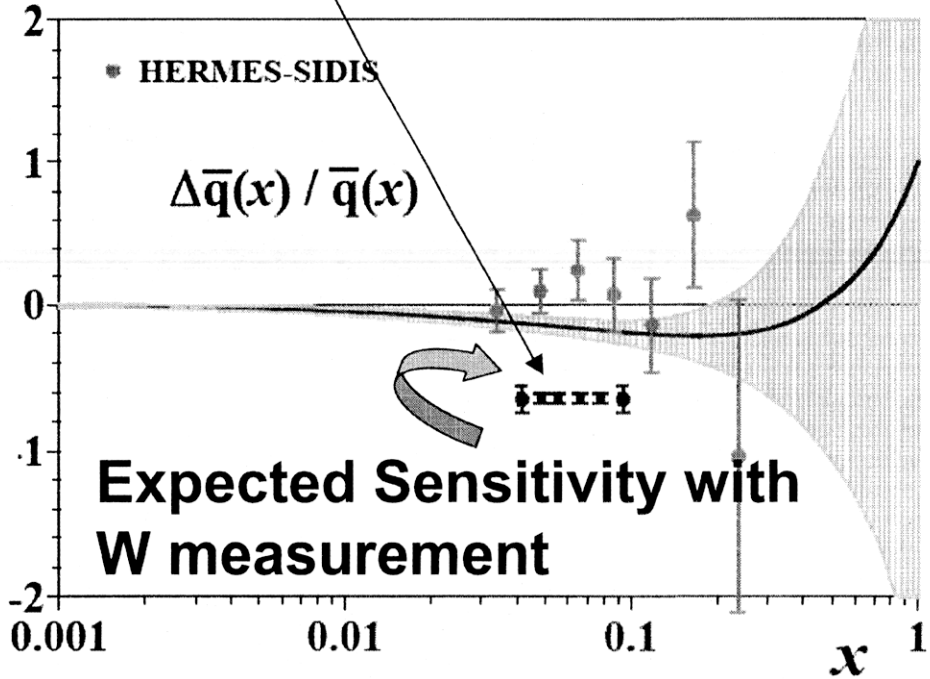
$$A_L^{W^+} \approx \frac{\Delta u(x_1, M_W^2)}{u(x_1, M_W^2)}, \quad x_1 > x_2 \quad (y_W >> 0)$$

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

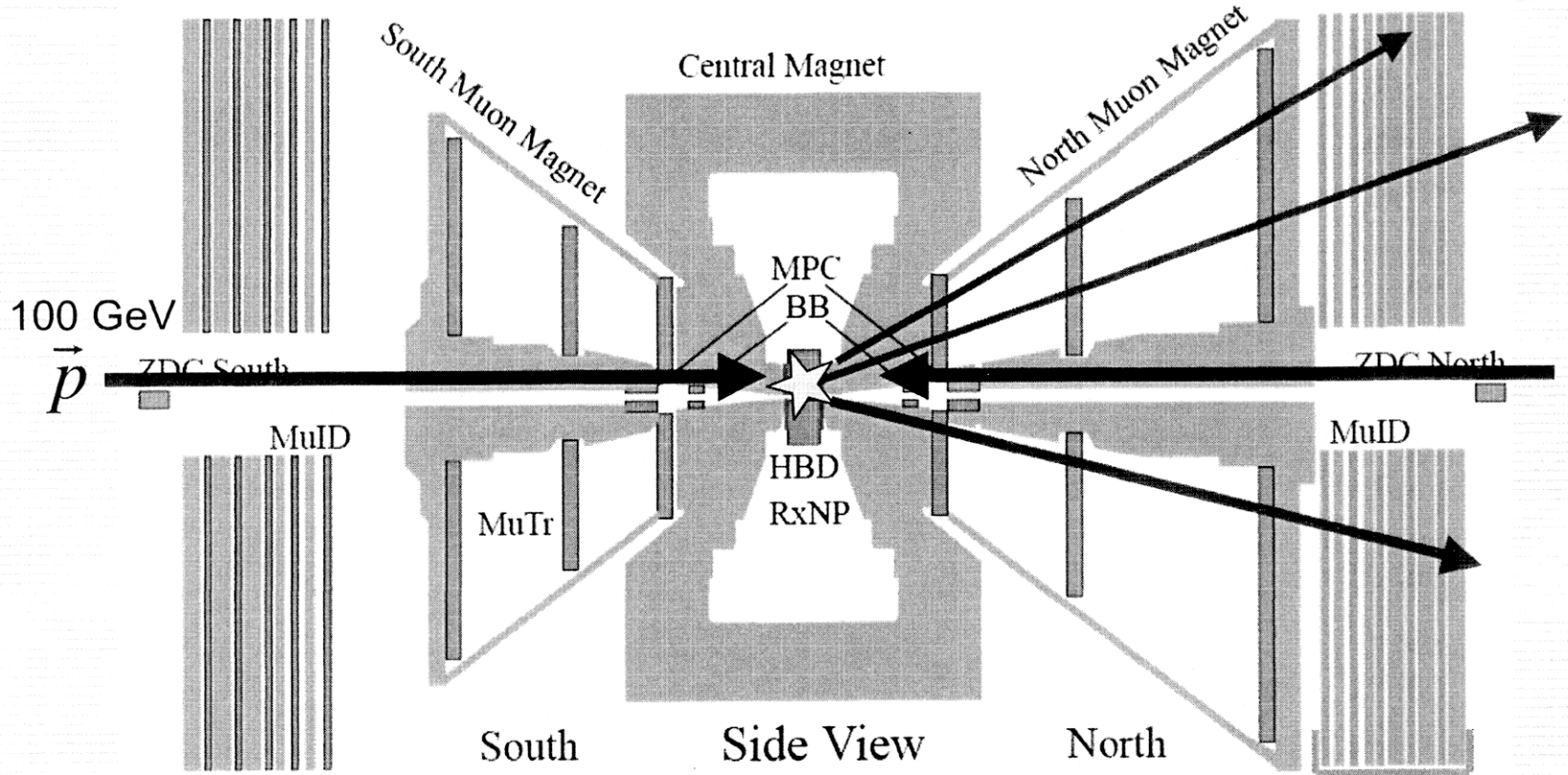
Flavor Separation by $A_L^{W+/-}$



∫Ldt=800pb^{-1}, P=0.7
projected @500GeV

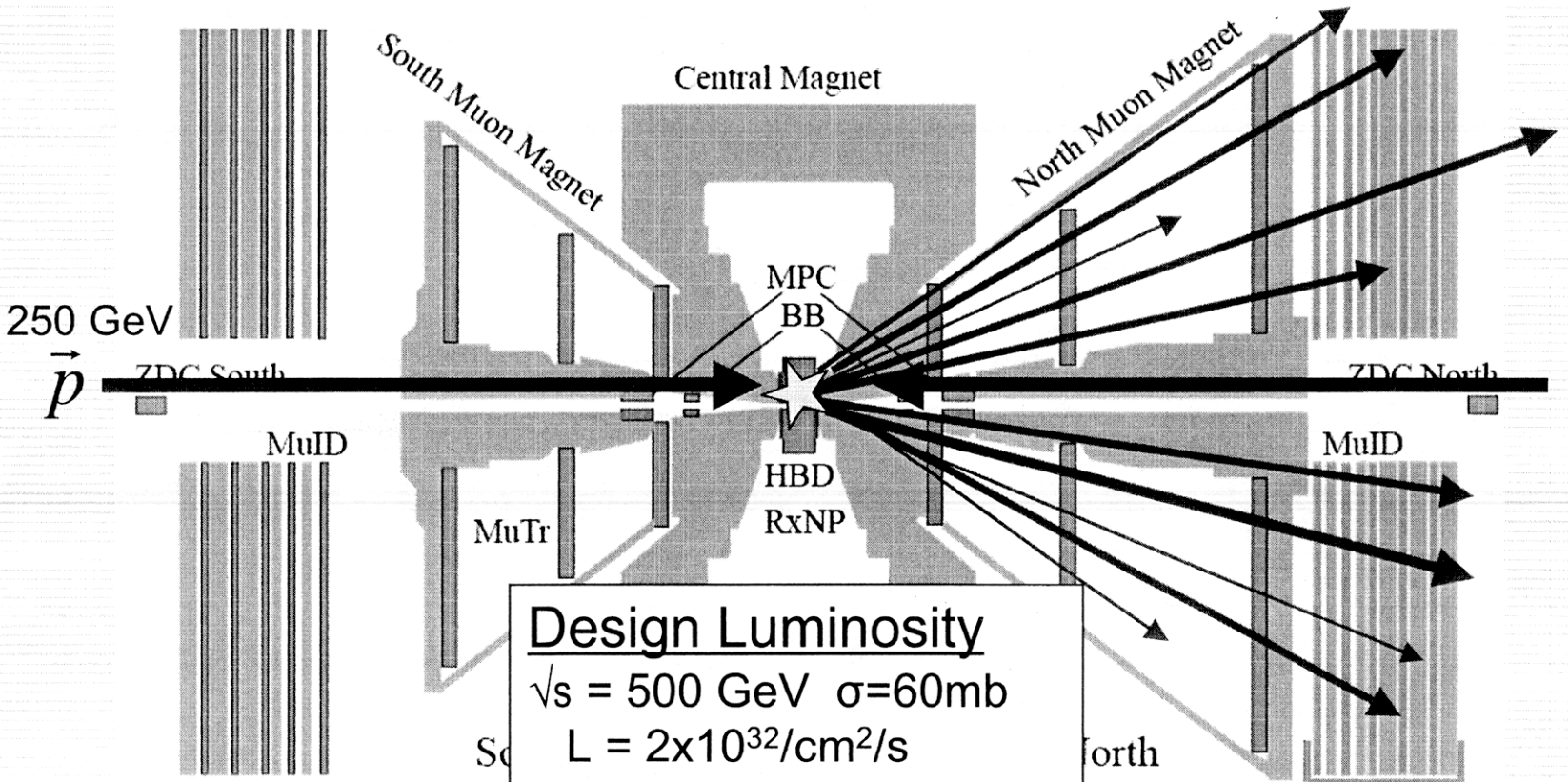


Trigger Rate @ sqrt(s) = 200 GeV



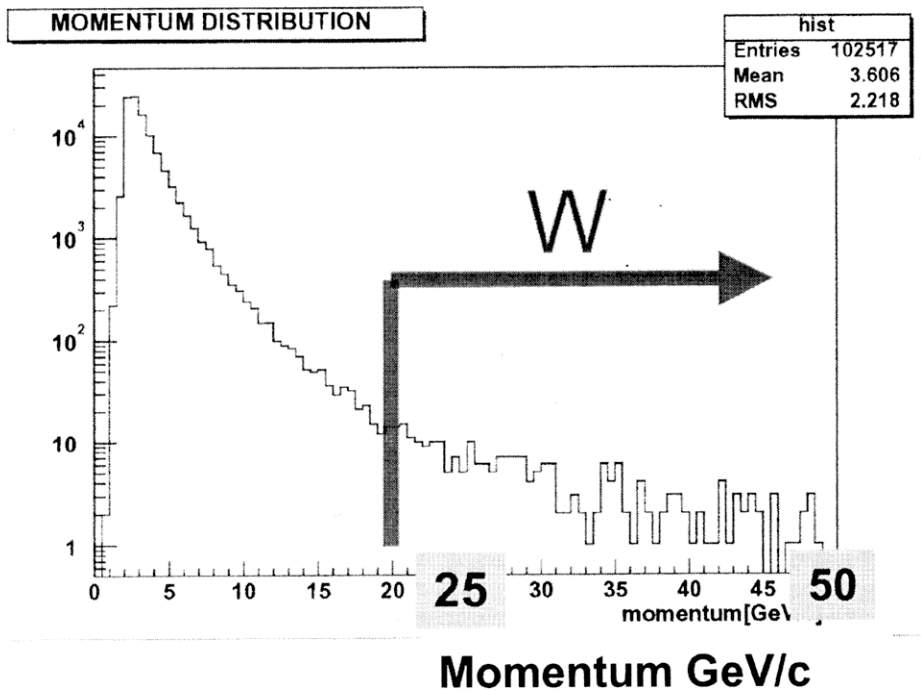
μ-Trigger Rate < 2 kHz

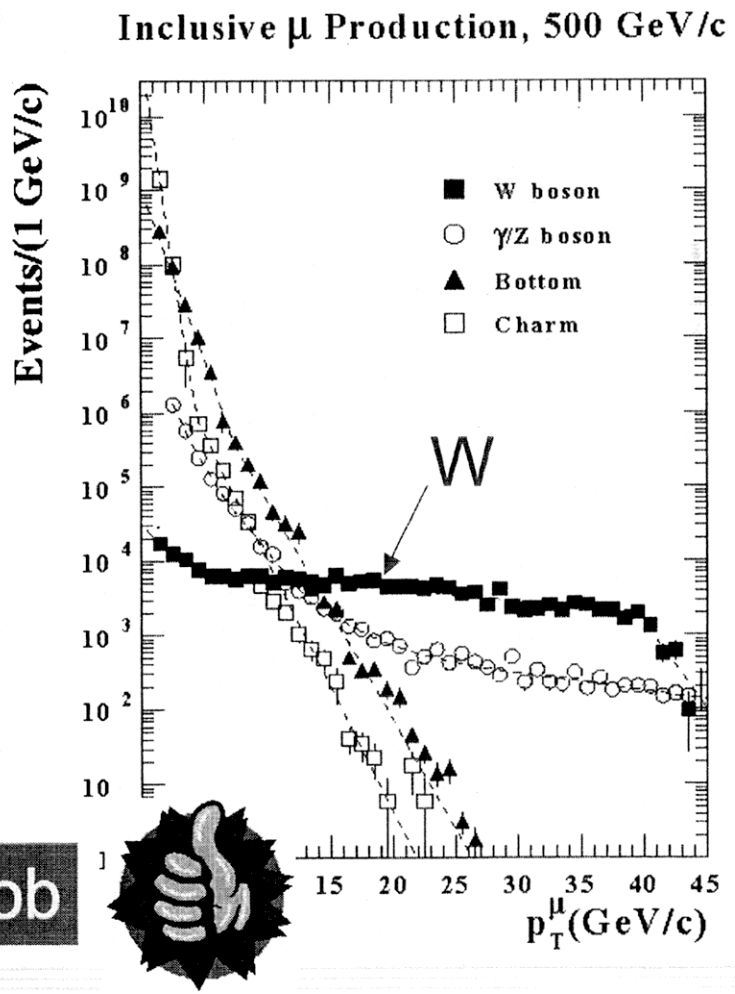
Trigger Rate @ sqrt(s) = 500 GeV



Rejection Factor ~ **10000** ← Rate ~ 12 MHz !!

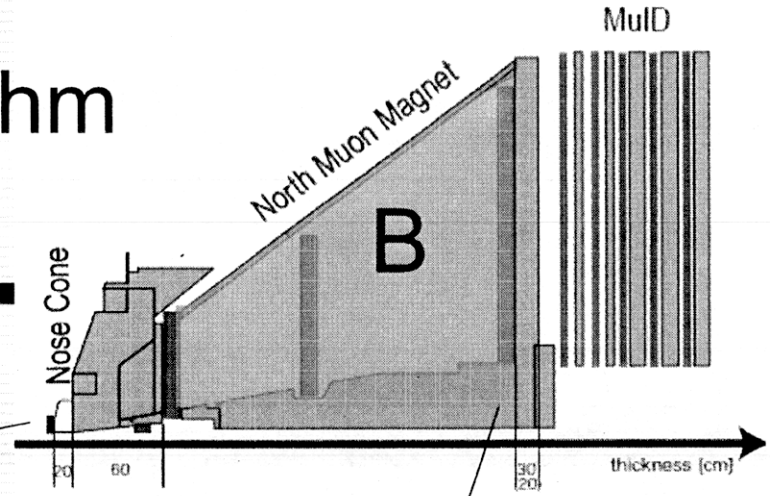
Rejection Power : Approach



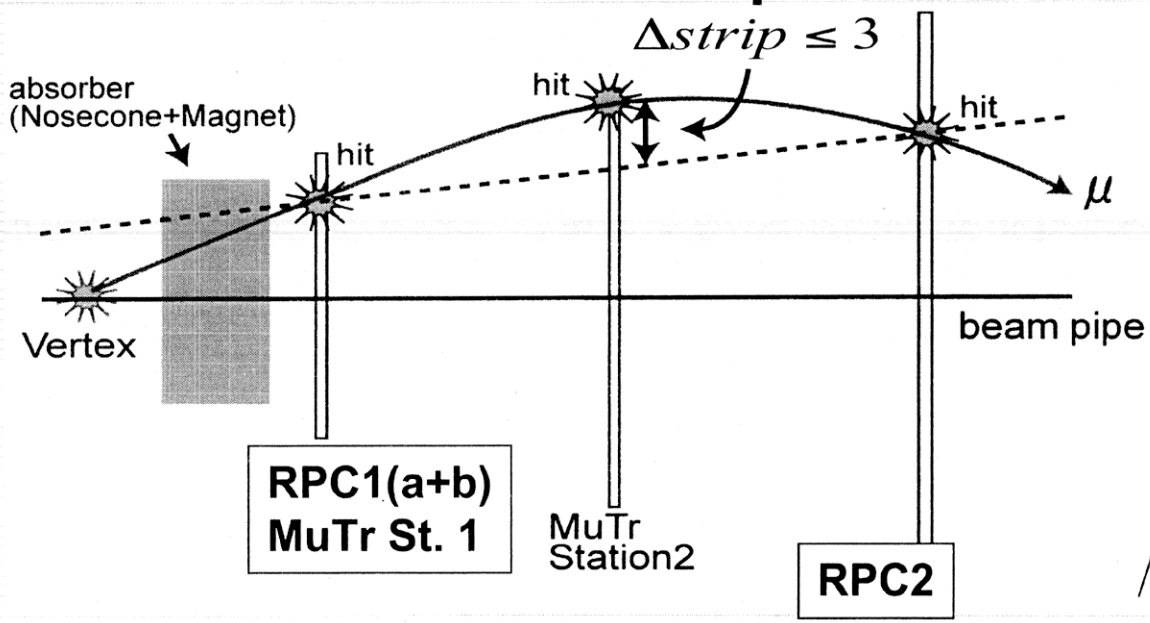


P_T Sensitive Trigger Does The Job

High - P_T Trigger Algorithm



Trigger Logic



PHENIX Muon Trigger Upgrade

(I) Three d
RPC sta
design)

R1(a,b): ~

R2: ~5.4m

R3: ~6.0m

(Trigger only – off

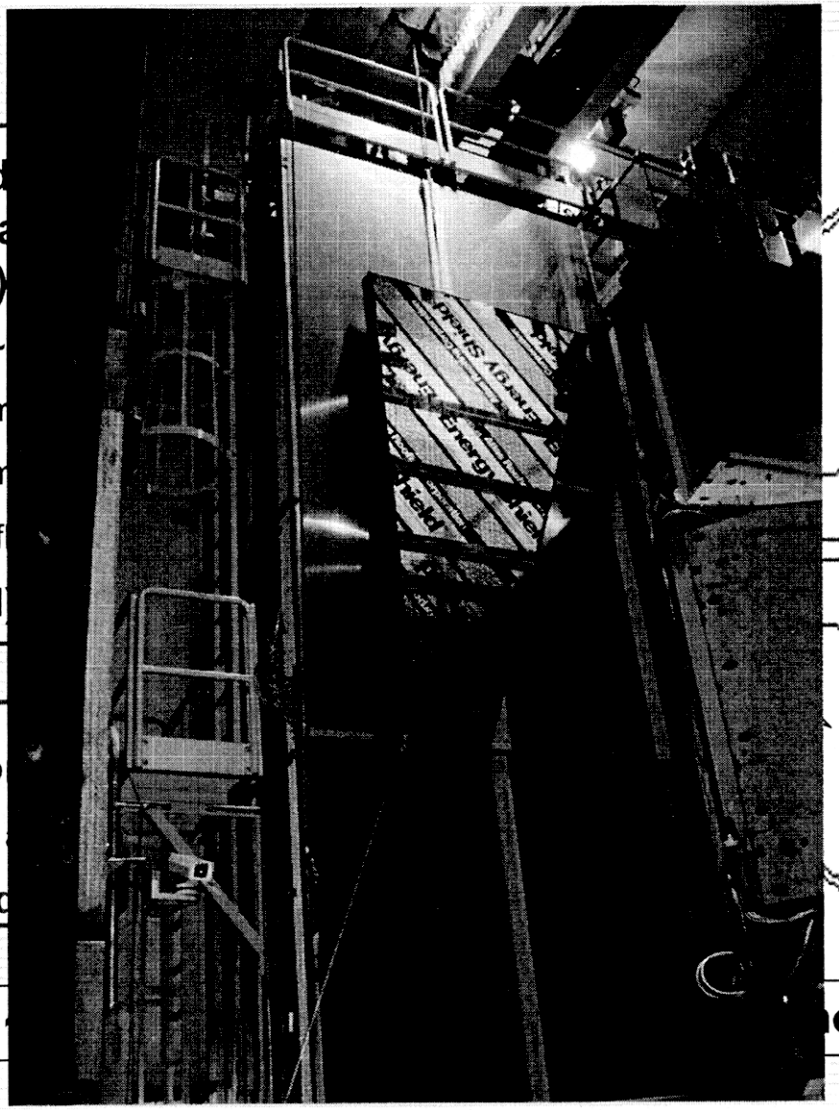
NSF (Funded)

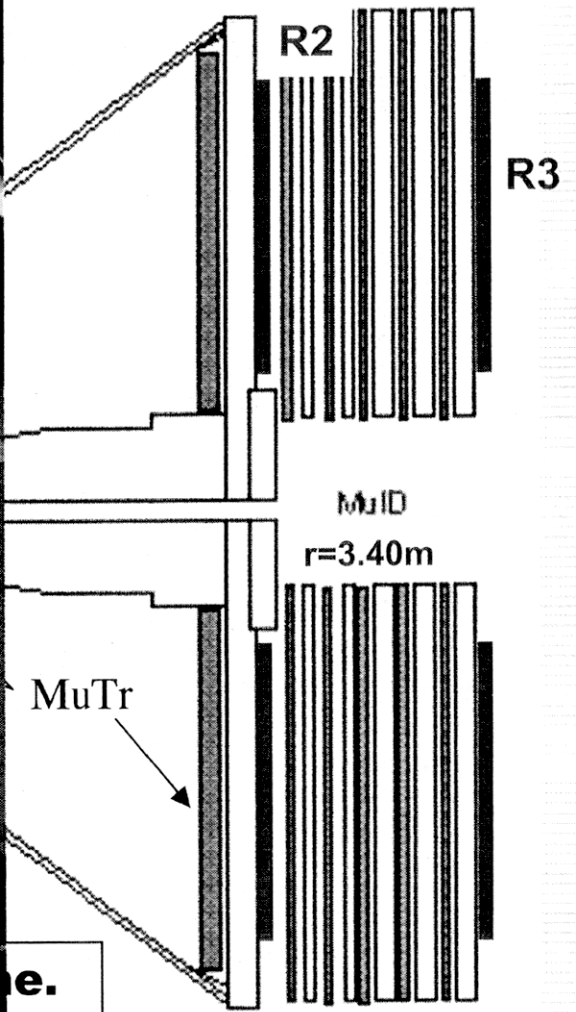
(II) MuTr fro

Upgrade to

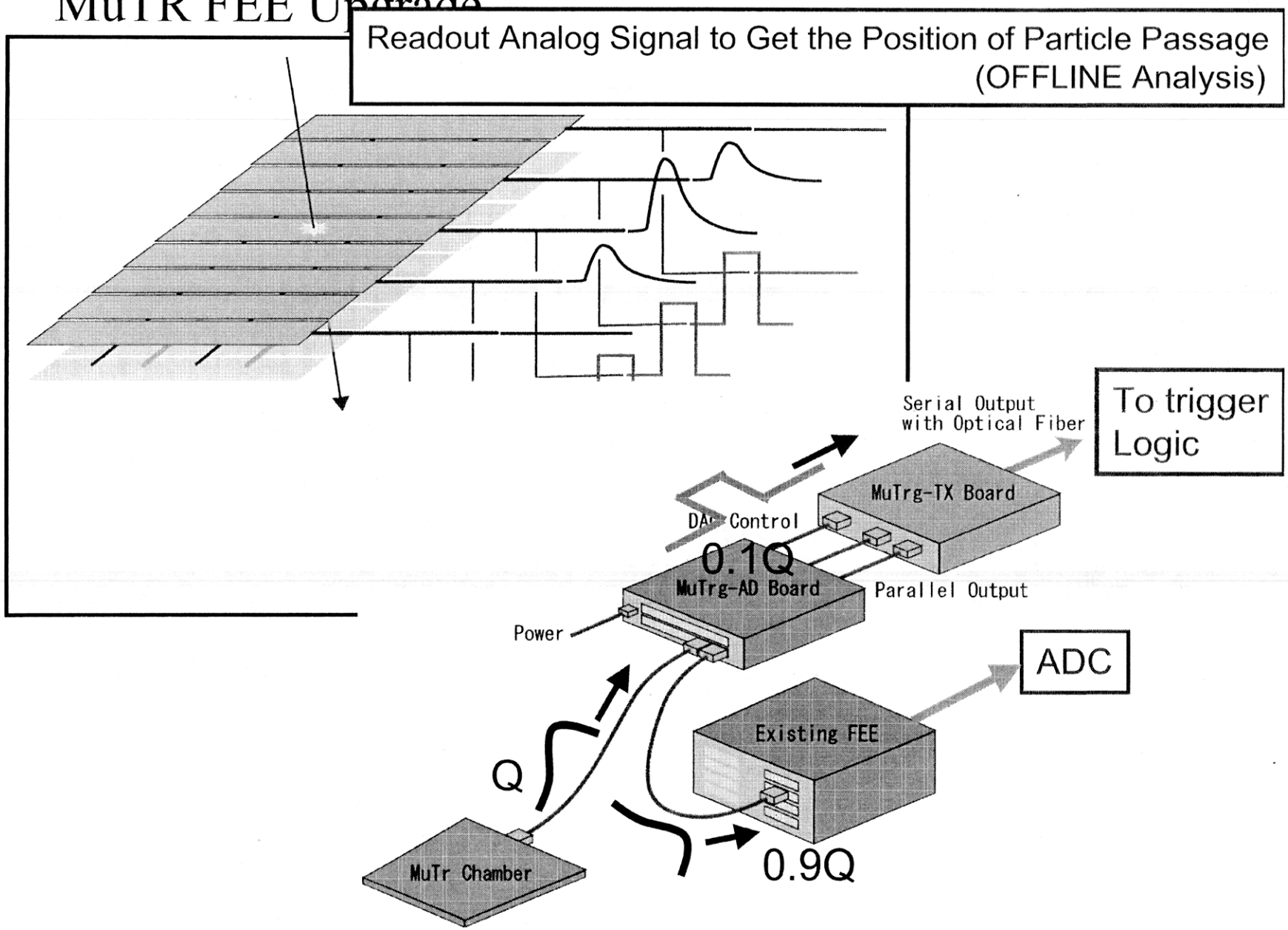
JSPS (Funded

Rejection e.

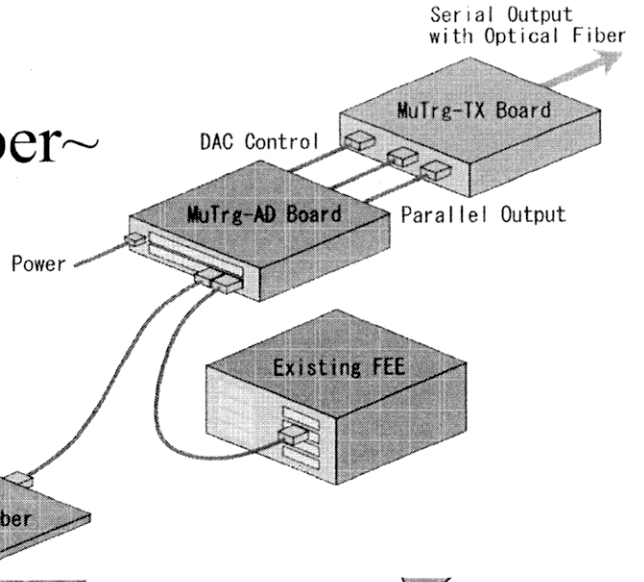




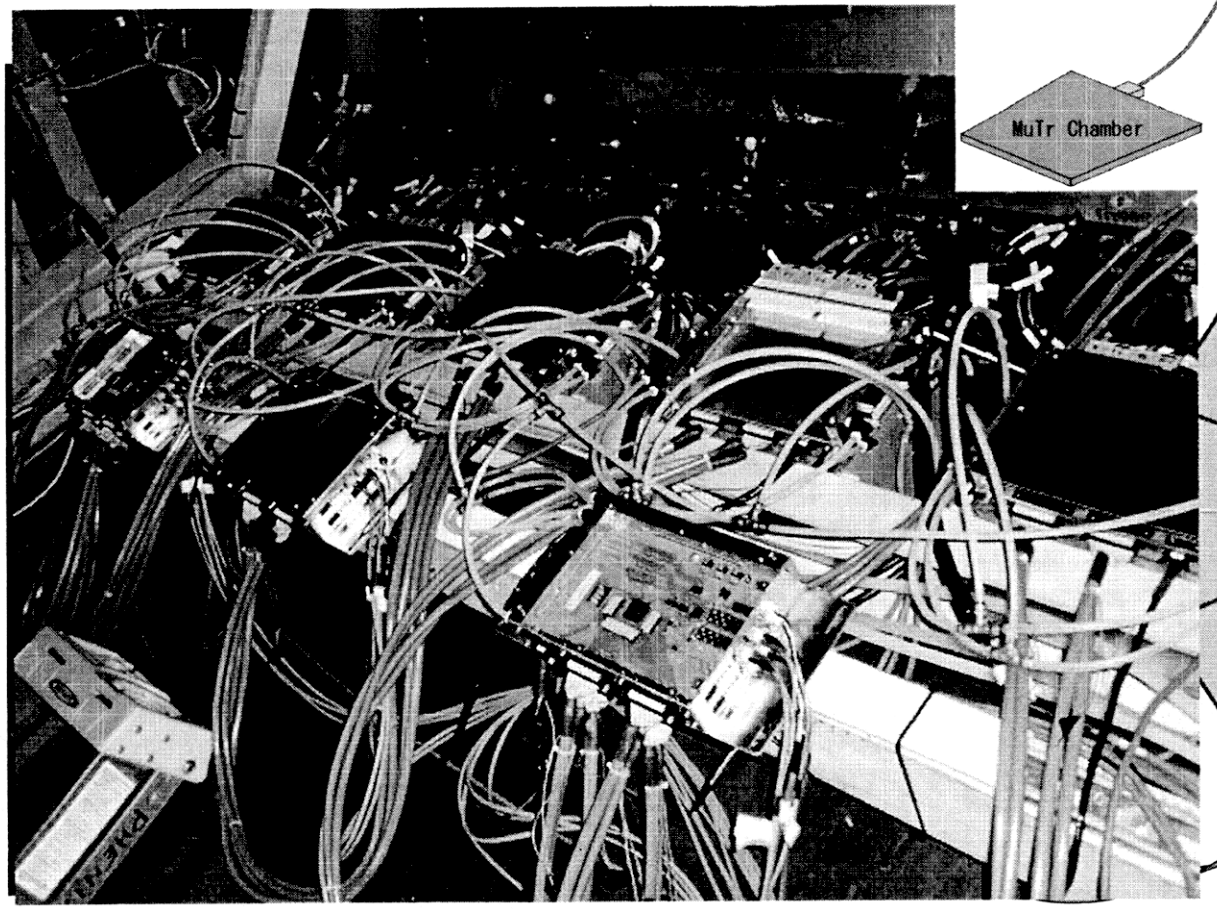
MuTR FEE Upgrade

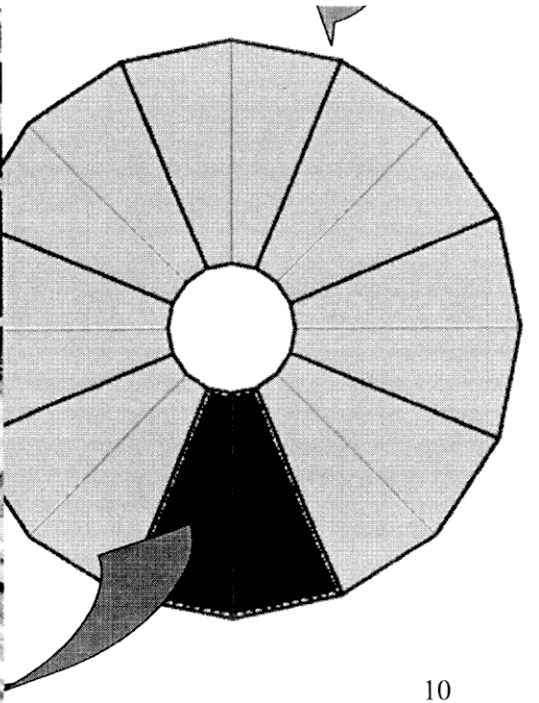


Prototype Test SetUp ~2007 September~



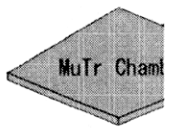
MuTR (Station-2)

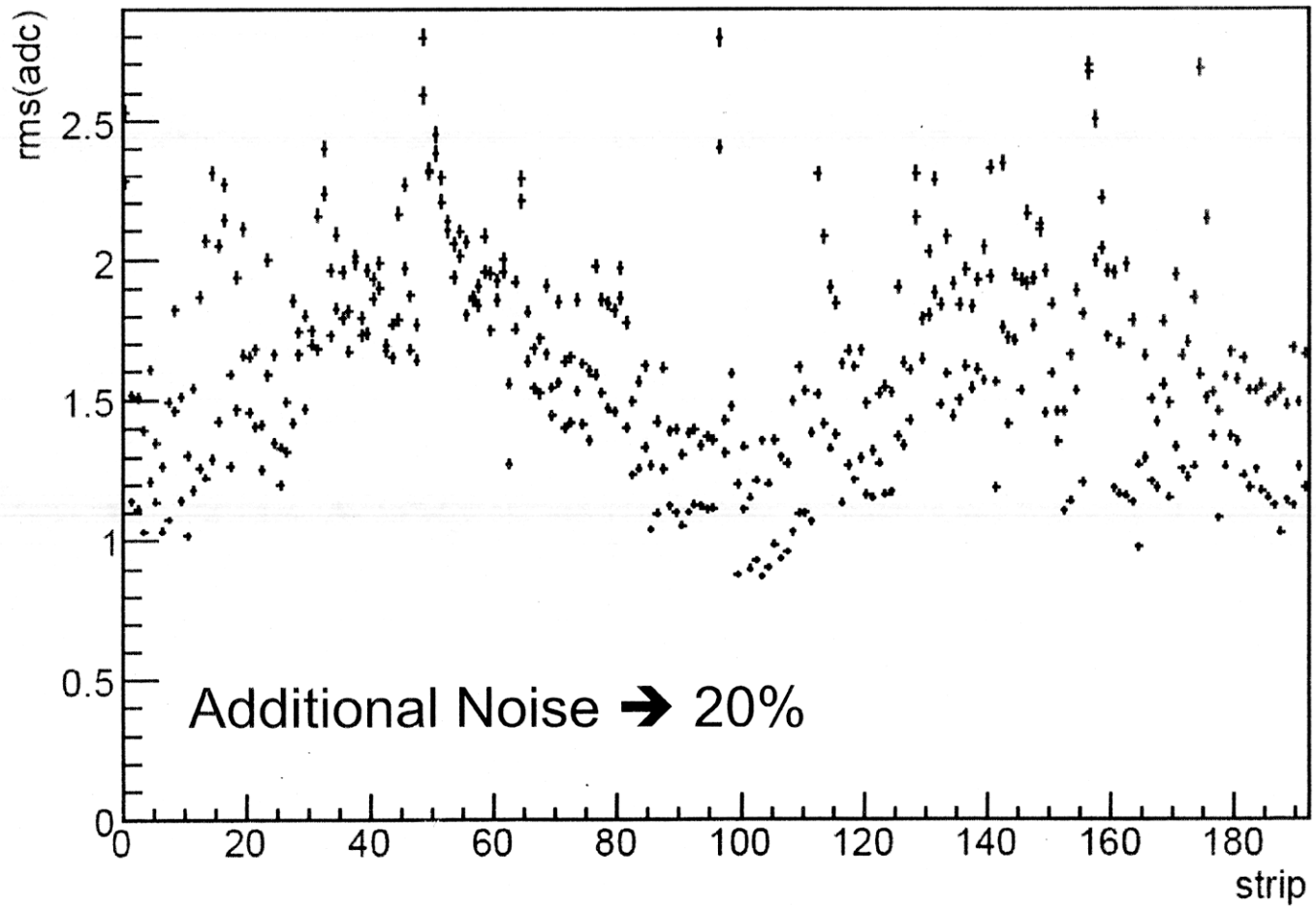




Noise Performance

Pedestal RMS : All sample



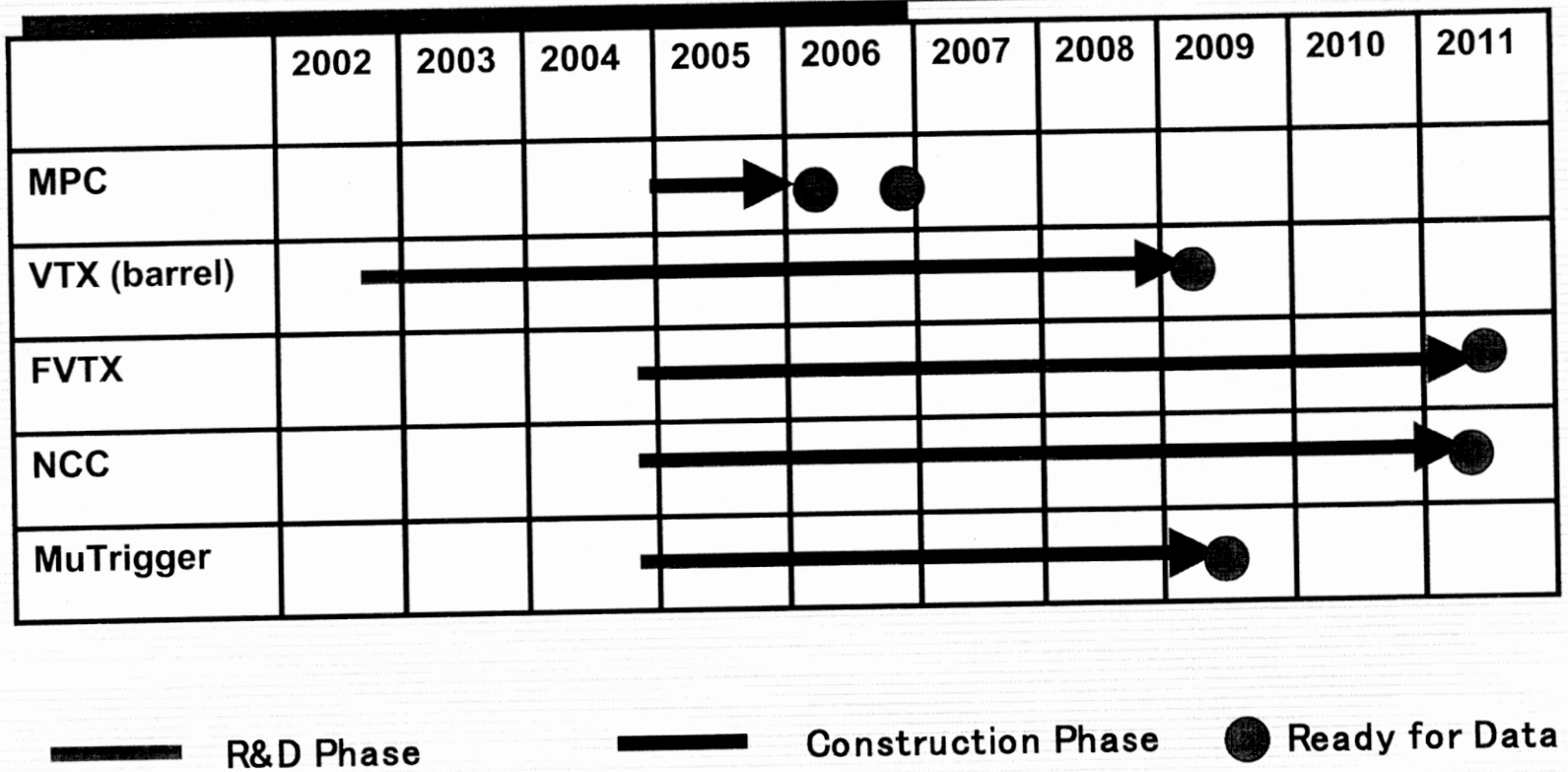


Summary

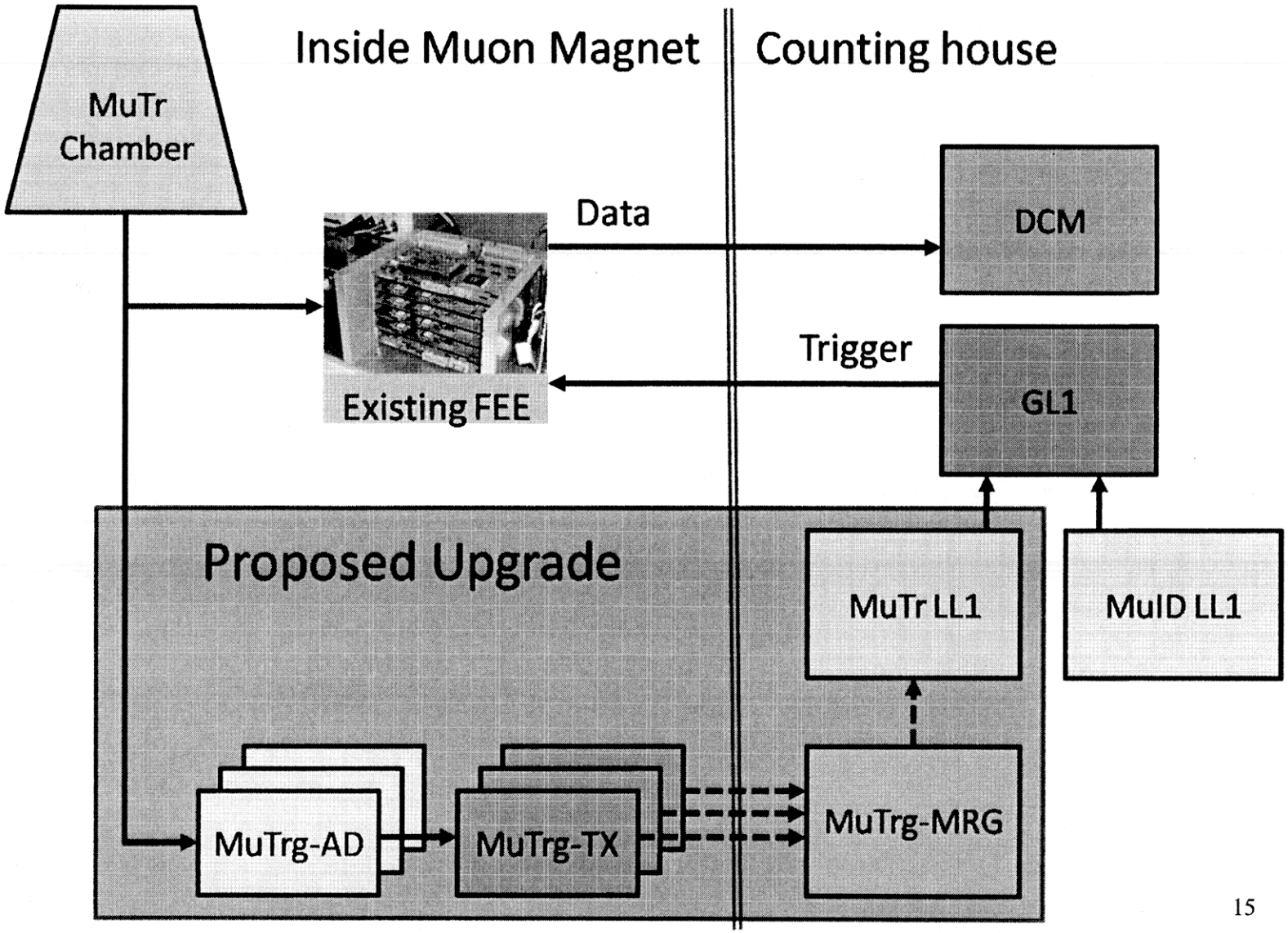
- μ-Trigger Upgrade Necessary for W Detection
- P_T Sensitive Trigger → Factor 10000 Rejection
- RPC(NSF) and FEE-Upgrades (JSPS) Funded
- Prototype Test in Sep. 2007 @ PHENIX
- Performance:
  - Additional Noise ~ 20%
  - Gain ?
  - Efficiency ?
  - Stability ?
  - …

Backup Slides

Upgrade Schedule



System overview



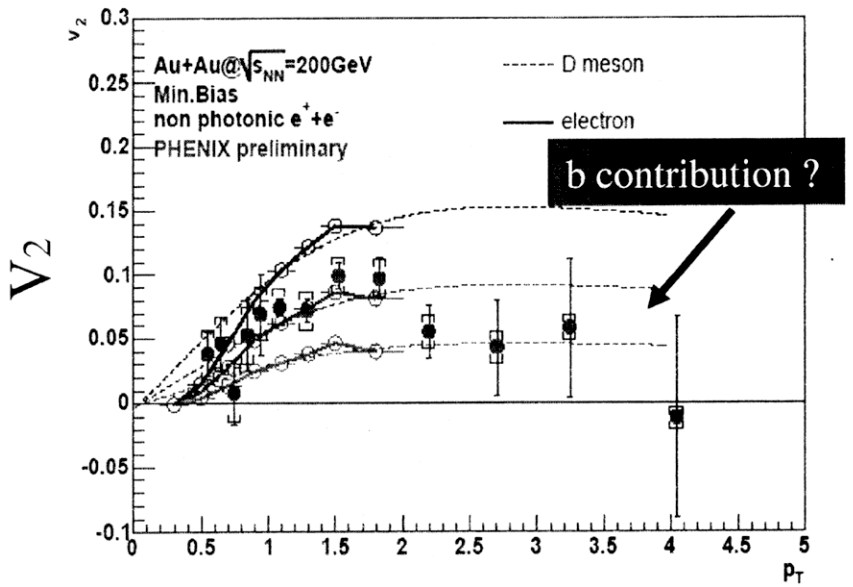
Vertex Detector for PHENIX

Atsushi Taketani

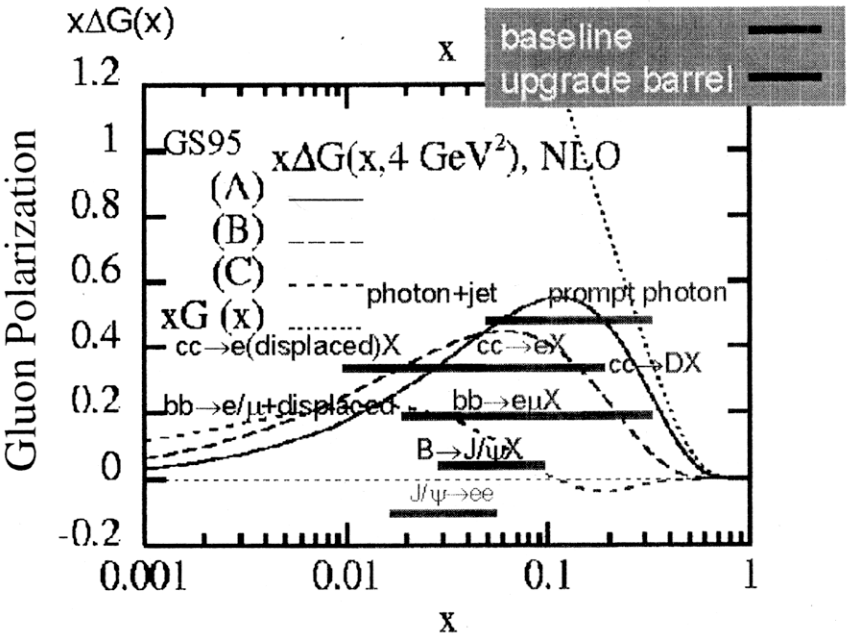
1. Physics Goal
2. Vertex Detector
3. PIXEL
4. STRIP
5. Personnel
6. Plan and Summary

Physics Goal

Heavy Ion Program

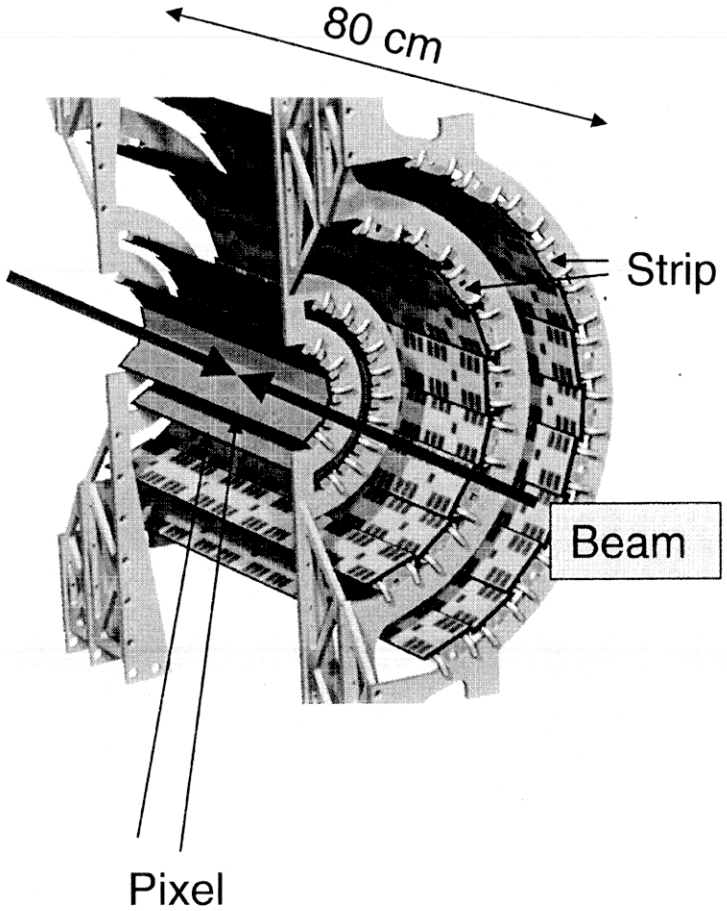


Spin Program



- **Charm and bottom identification by displaced vertex**
- **Jet identification with larger acceptance**

Vertex Detector

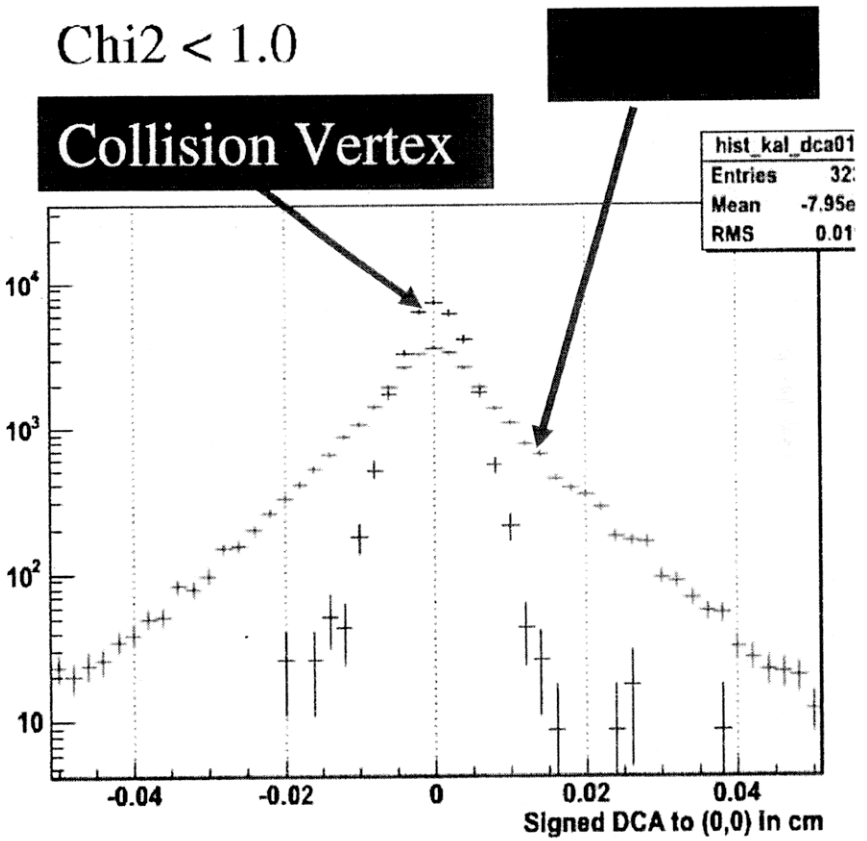


- Pixel R=2.5cm and 5cm
  - ✓Real 2 dim sensor with 50*425 μm pixel
  - ✓High granularity for 1700 tracks in Central Au-Au collsiion.
  - ✓Binary readout
  - ✓Trigger capability
- Strip R=10cm and 14cm
  - ✓Single sided 1+1 dim. Readout
  - ✓Strip size 50μm*3cm
- Expected Performance
  - ✓50μm resolution for distance closest approach.
  - ✓Momentum resolution: $\sigma/P \sim 5\%*P$

Expected Performance

Layer	radius	Sensor	Occupancy	
Layer 1	2.5 cm	Pixel	**0.53 %**	
Layer 2	5.0 cm	Pixel	**0.16%**	
Layer 3	10.0 cm	Strip	**4.5 %** (x-strip)	**4.7 %** (u-strip)
Layer 4	14.0 cm	Strip	**2.5 %** (x-strip)	**2.7 %** (u-strip)

Expected occupancy at Au-Au 200GeV most central event

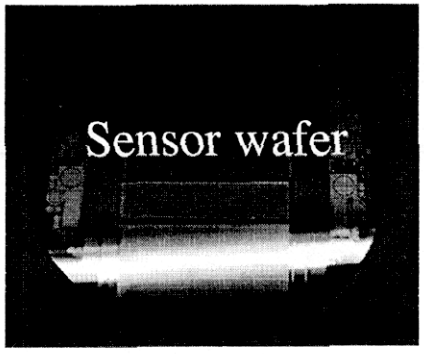


Distance to the Closest Approach [cm]

380

Pixel sensor module

A pixel sensor

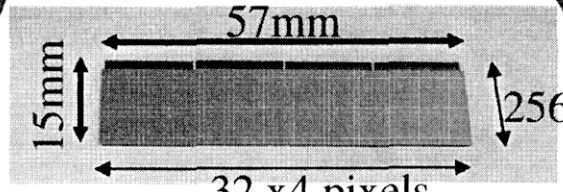


•Thickness : 200μm

•Pixel size:50μm(f)x450μm(Z)

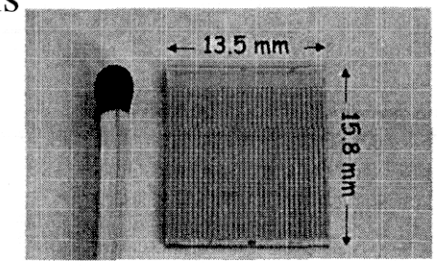
•Number of Pixel:8192x4

A pixel sensor module



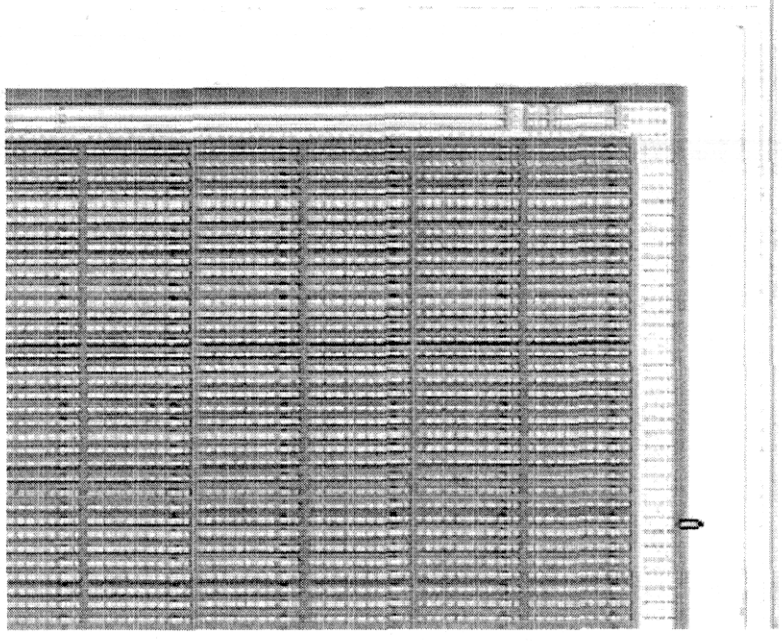
Bump bonding with
a pixel sensor
& 4 ALICE chips

ALICE1LHCb r/o chip

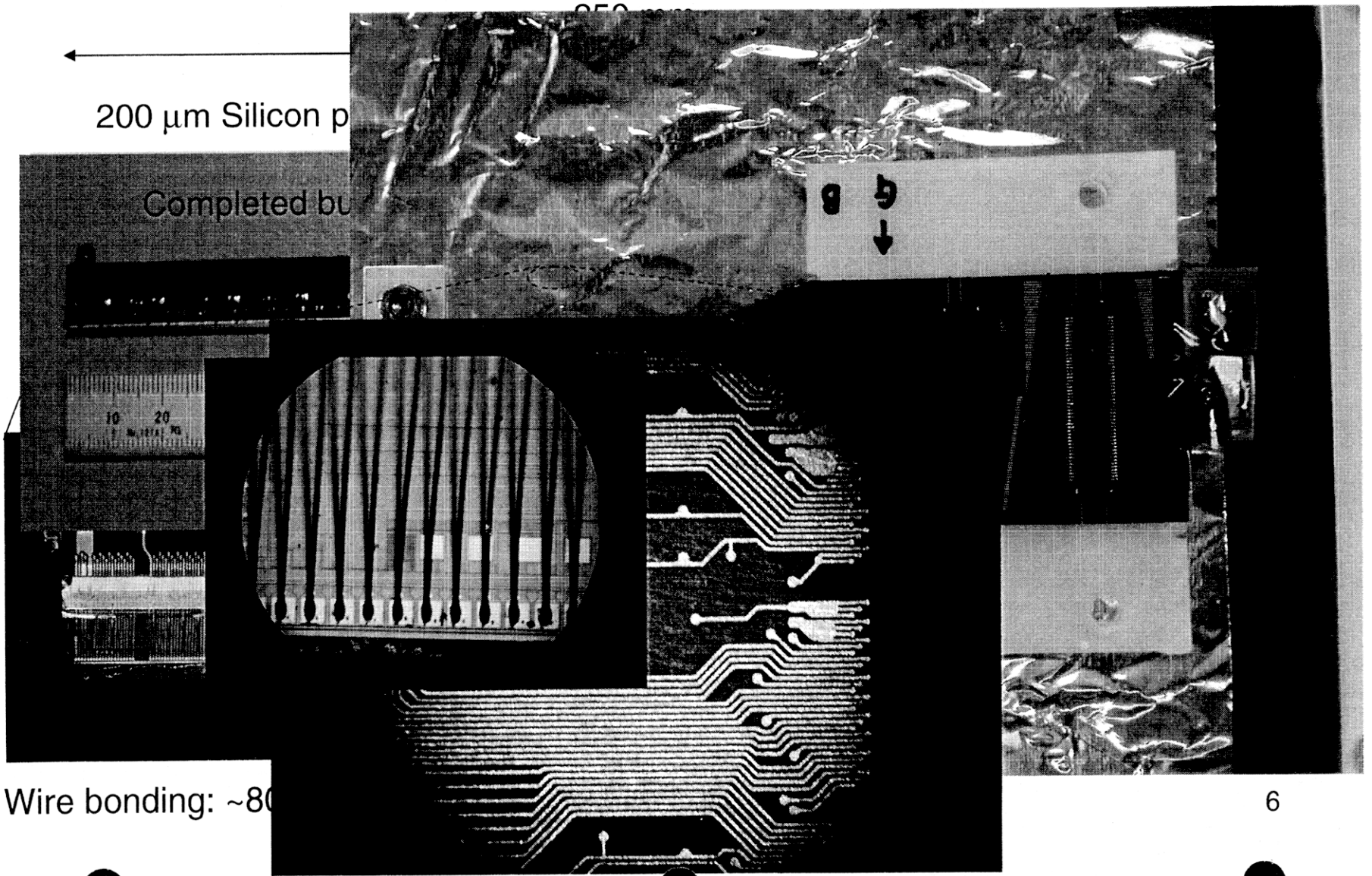


• Radiation Hardness:~30Mrad

•8192 binary readout channels



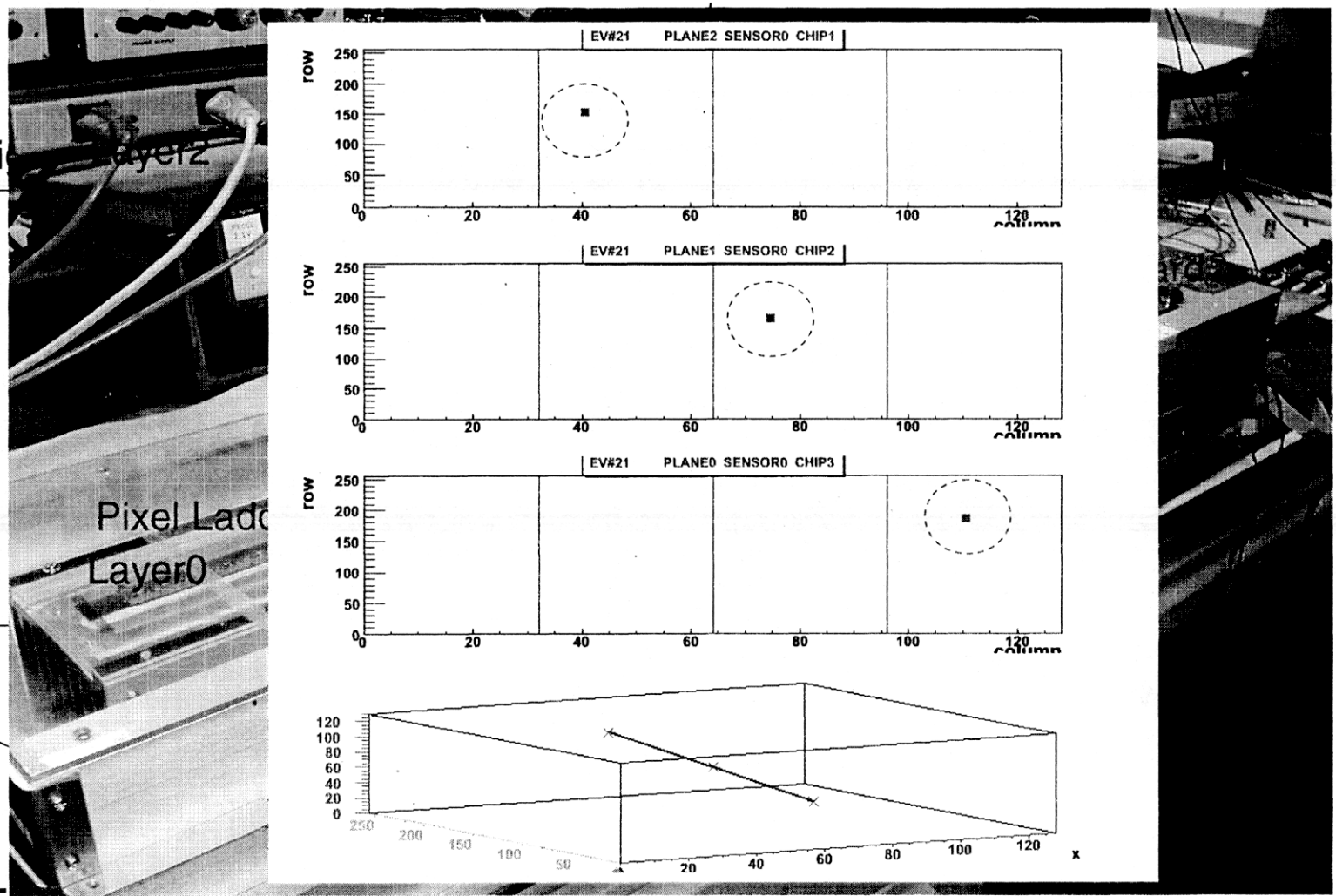
Prototype pixel ladder



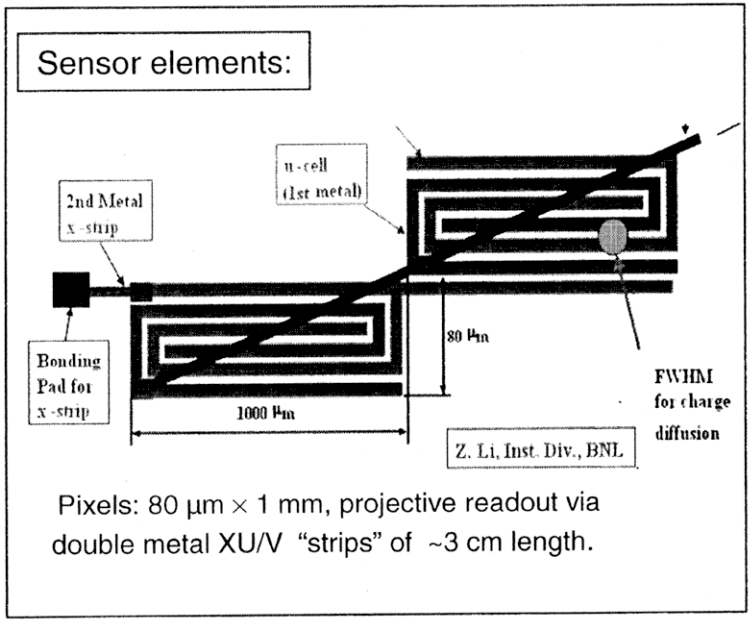
Wire bonding: ~80

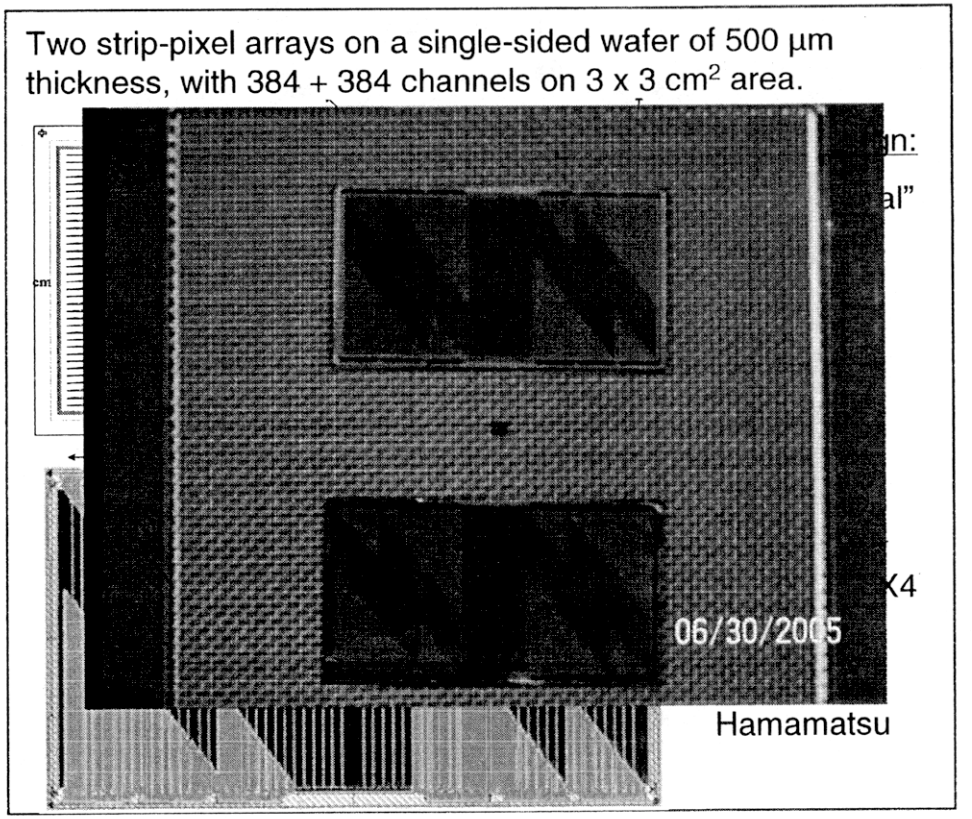
Chain test with cosmic-ray

- Pixel telescope with prototype half pixel ladder and two test ladders.
- The telescope consist of 3 layers.



Strip layer





Developed at BNL Instrumentation Gr.

✓Single sided

✓1+1 dimensional readout

(X and U direction)

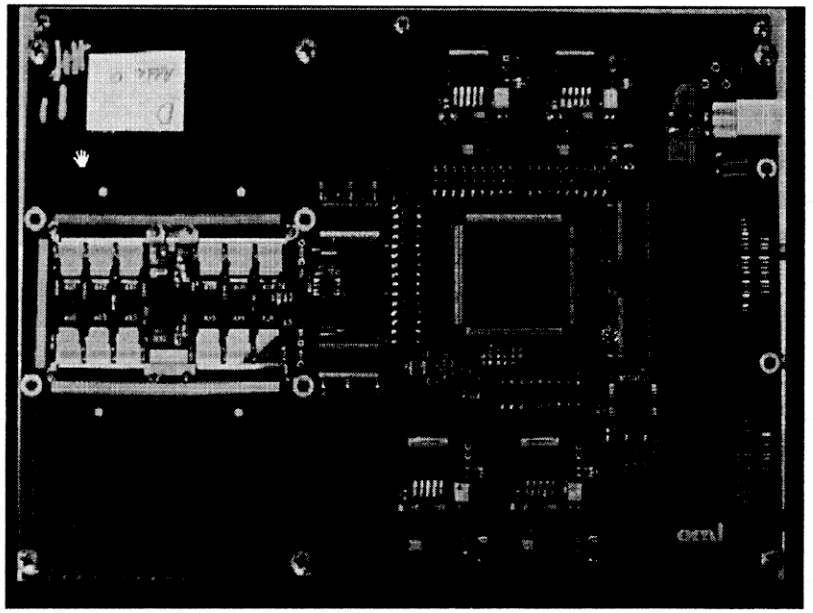
✓3cmξ3cm sensor ξ2 / chip

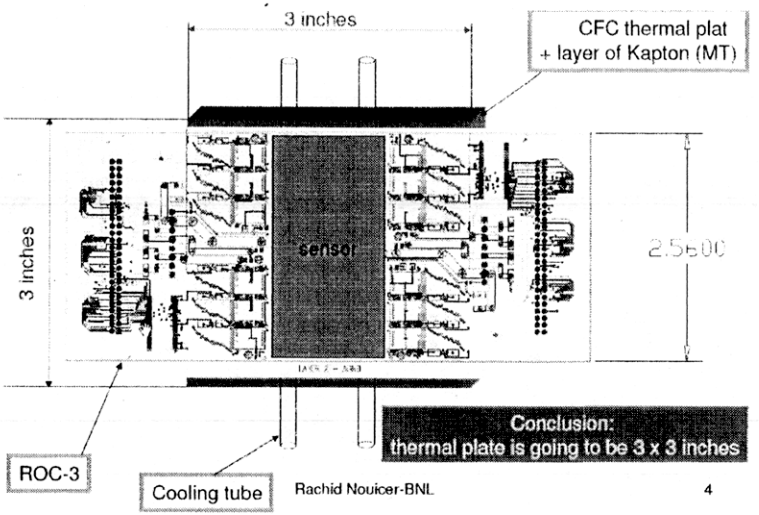
✓768 X strip and 768 U strips/chip

Position resolution is 25μm by test beam

384

STRIP





Read out card V2 with sensor

6 SVX4 readout ASIC by FERMILAB

Board was fabricate by ORNL and assembled by RIKEN

Read out card V 3

With better noise performance

Cooling

Board by ORNL,

Assembled by BNL/FERMILAB

Personnel

- RIKEN Wako

A.Taketani (Pixel subsystem manager)

Posdoc: K.Fujiwara, Y.Onuki, R.Ichimiya, M.Kurosawa, M.Togawa

Rikkyo : K.Kurita, M.Kawashima, M.Kasai

KEK: M.Sekimoto

Tokyo Met. Tech. Aero Eng. : S.Watanabe and his students.

- RBRC

Y. Akiba(VTX manager)

A. Despande (Strip subsystem manager)

Plan and Summary

- PHENIX VTX will enhance new PHYSICS in both SPIN and HI.
- RBRC has major role in this project.
- Pixel and Strip sensors are well proceeded.
- We may install VTX partially in 2009 summer.
- Fully installed at 2010 summer.

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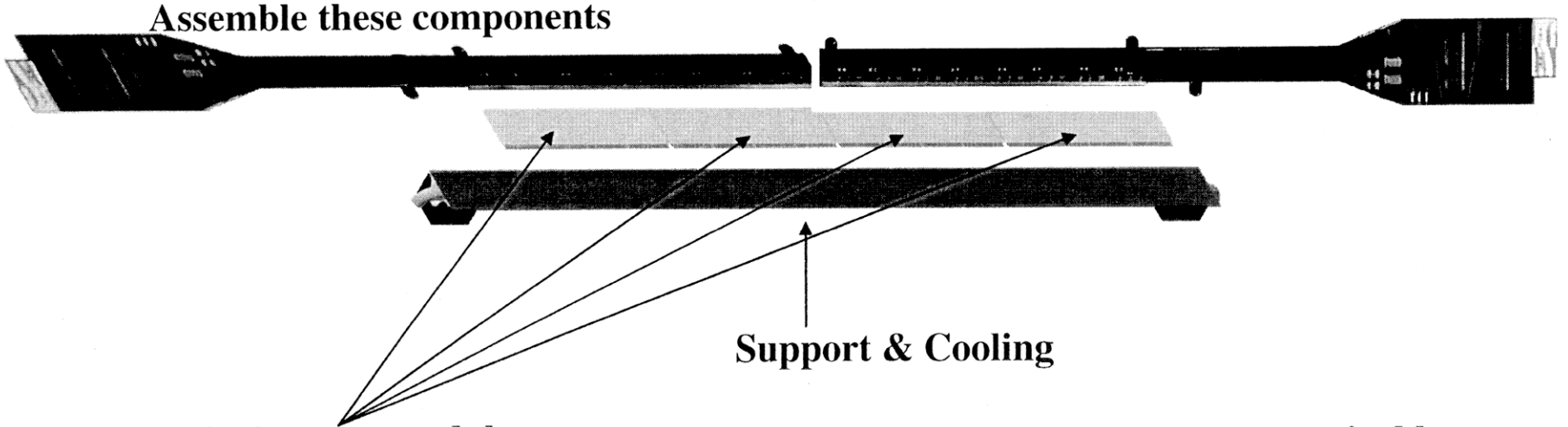
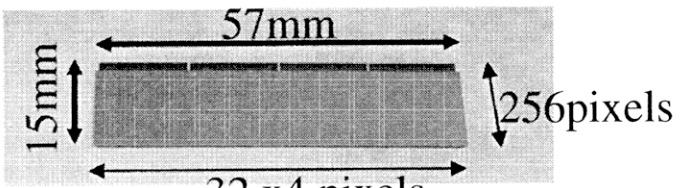
Pixel full ladder



A pixel sensor module



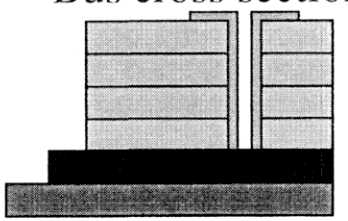
Bump bonding with
a pixel sensor
& 4 ALICE chips

A Al-Cu-Kapton pixel bus

4 Cu signal layers
1 Al VDD layer
1 Al GND layer

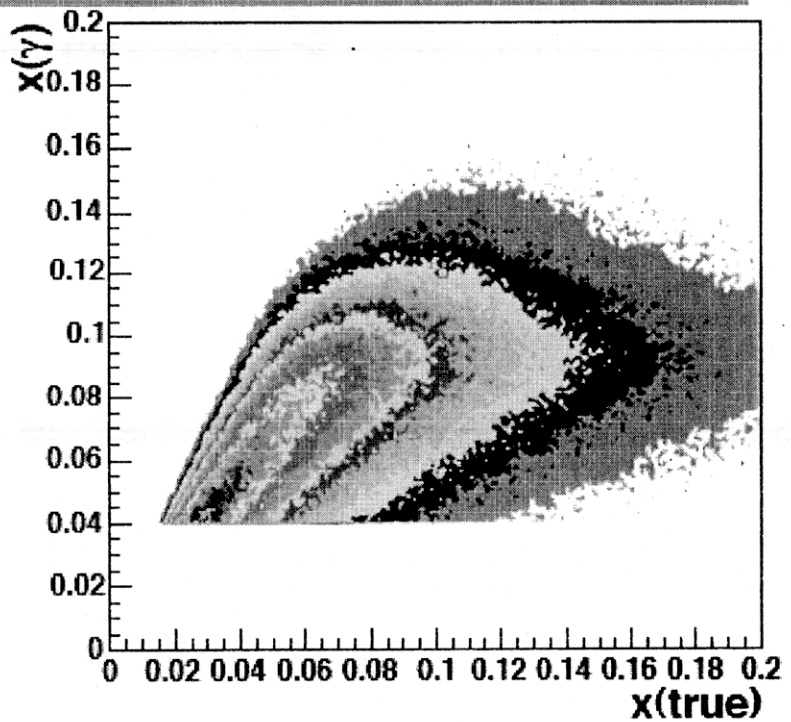
400μm

Bus cross section

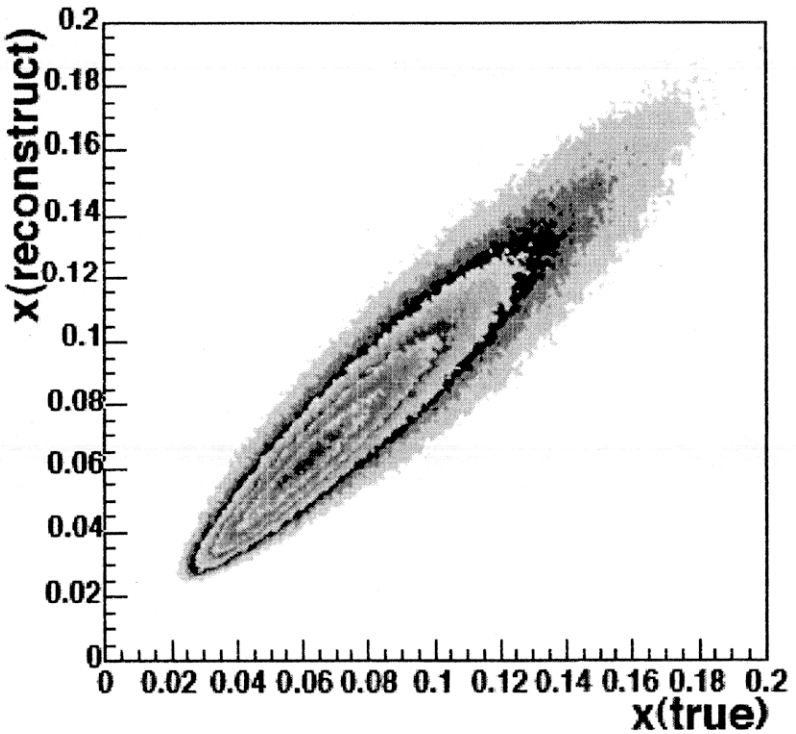


Spin performance
parton X reconstruction by γ + Jet

Using only Photon information



Photon + 2π VTX tracker



Great improvement with VTX

2002-2007 Many Thanks from Illinois to RBRC for Support and Collaboration !
John Koster, New York
Young Jin Kim, Seoul
Ruizhe Yang, Beijing
Martin Leitgab Vienna
Dave Northacker, New York
Beau Meredith, Illinois
Patricia Francisconi Vienna
Nick Mudia Illinois
Tyler Natoli Illinois
John Blackburn, Illinois
Matthias Perdekamp, Freiburg
Ralf Seidl, Erlangen

UIUC-group activities: Analysis + Physics

Belle Fragmentation Function Analysis:	
Collins + Interference Fragmentation	Ralf Seidl
High precision measurement of spin-averaged Hadron ragmentation functions	Martin Leitgab
Extraction of gluon fragmentation function from a QCD analysis of BELLE and LEP data	Patricia Francisconi
PHENIX Analysis:	
Interference fragmentation asymmetries.	Ruizhe Yang
A_{LL} for forward neutral pions (MPC)	Aaron Veicht
A_{LL} for di-hadrons (MPC + central arm)	John Koster
Forward neutral pions in d+A (MPC)	Young Jin Kim
New Physics Topics	
Parity violating asymmetries at RHIC	Beau Meredith, Ralf Seidl
Single transverse spin asymmetries in Drell Yan	Beau Meredith

UIUC-group activities: Instrumentation

RPC muon level-1 trigger spectrometer for W-physics - completion 10/2010 :

Collaboration: ACU, Colorado, Columbia, GSU, ISU, Korea University, Kyoto, Muhlenberg, PKU, RBRC, UCR, UIUC.

Funding: $2.0M NSF MRI (UIUC led)
$0.3M institutional contributions

Muon piston calorimeter for forward physics - completion 10/2007 :

Collaboration: Amherst, BNL, Colorado, Hiroshima, Kurchatov, ORNL, RIKEN, Stony Brook, UCR, UIUC

Funding: UIUC, NSF and UCR , DOE
PbWO4 crystals from Kurchatov
50% of APDs from Hiroshima

Young Jin Kim, Naomi Makins, Beau Meredith, Jen-Chieh Peng, Matthias Perdekamp, Ralf Seidl, Ruizhe Yang, and 4 undergraduate students

John Koster, Jen-Chieh Peng, Matthias Perdekamp, Aaron Veicht

Technical staff: Dave Northacker, John Blackburn and Eric Thorsland

QCD and Transverse Spin
Future Studies

Matthias Grosse Perdekamp, UIUC

- Ab Initio Calculations in QCD at high energies
- Transversity, Sivers and Boer Mulders
- Future Sivers Measurements in Drell Yan

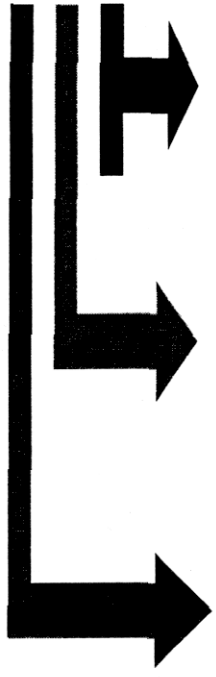
Ab Initio Calculations in QCD at High Energies

factorization + universality

higher order pQCD

soft gluon resummation

gauge link formalism



e-p :
extract pdfs ➔ quark spin
predict sum rules

p-p :
extract pdfs ➔ gluon spin
calculate cross sections

Transverse spin:
extract k_T dependent pdfs
➔ quark spin
➔ L_z (?)

Expand range of applicability for ab initio calculations in QCD!

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Theory Frame Work: Sum Soft Initial and Final State Gluon Interactions in Gauge Link Integrals

S. J. Brodsky, D. S. Hwang, and I. Schmidt, *Phys. Lett.* B 530 (2002) 99–107, hep-ph/0201296

J. C. Collins, *Phys. Lett.* B 536 (2002) 43–48, hep-ph/0204004

S. J. Brodsky, D. S. Hwang, and I. Schmidt, *Nucl. Phys.* B 642 (2002) 344–356, hep-ph/0206259

A. V. Belitsky, X. Ji, and F. Yuan, *Nucl. Phys.* B 656 (2003) 165–198, hep-ph/0208038

A. Metz, *Phys. Lett.* B549 (2002) 139–145

J. C. Collins and A. Metz, *Phys. Rev. Lett.* 93 (2004) 252001, hep-ph/0408249

D. Boer, *Nucl. Phys.* B 603 (2001) 195–217, hep-ph/0102071

X.-d. Ji and F. Yuan, *Phys. Lett.* B 543 (2002) 66–72, hep-ph/0206057

X.-d. Ji, J.-p. Ma, and F. Yuan, *Phys. Rev.* D 71 (2005) 034005, hep-ph/0404183

X.-d. Ji, J.-P. Ma, and F. Yuan, *Phys. Lett.* B 597 (2004) 299–308, hep-ph/0405085

A. Idilbi, X.-d. Ji, J.-P. Ma, and F. Yuan, *Phys. Rev.* D 70 (2004) 074021, hep-ph/0406302

A. Idilbi, X.-d. Ji, and F. Yuan, *Phys. Lett.* B 625 (2005) 253–263, hep-ph/0507196

C. J. Bomhof, P. J. Mulders, and F. Pijlman, *Phys. Lett.* B 596 (2004) 277–286, hep-ph/0406099

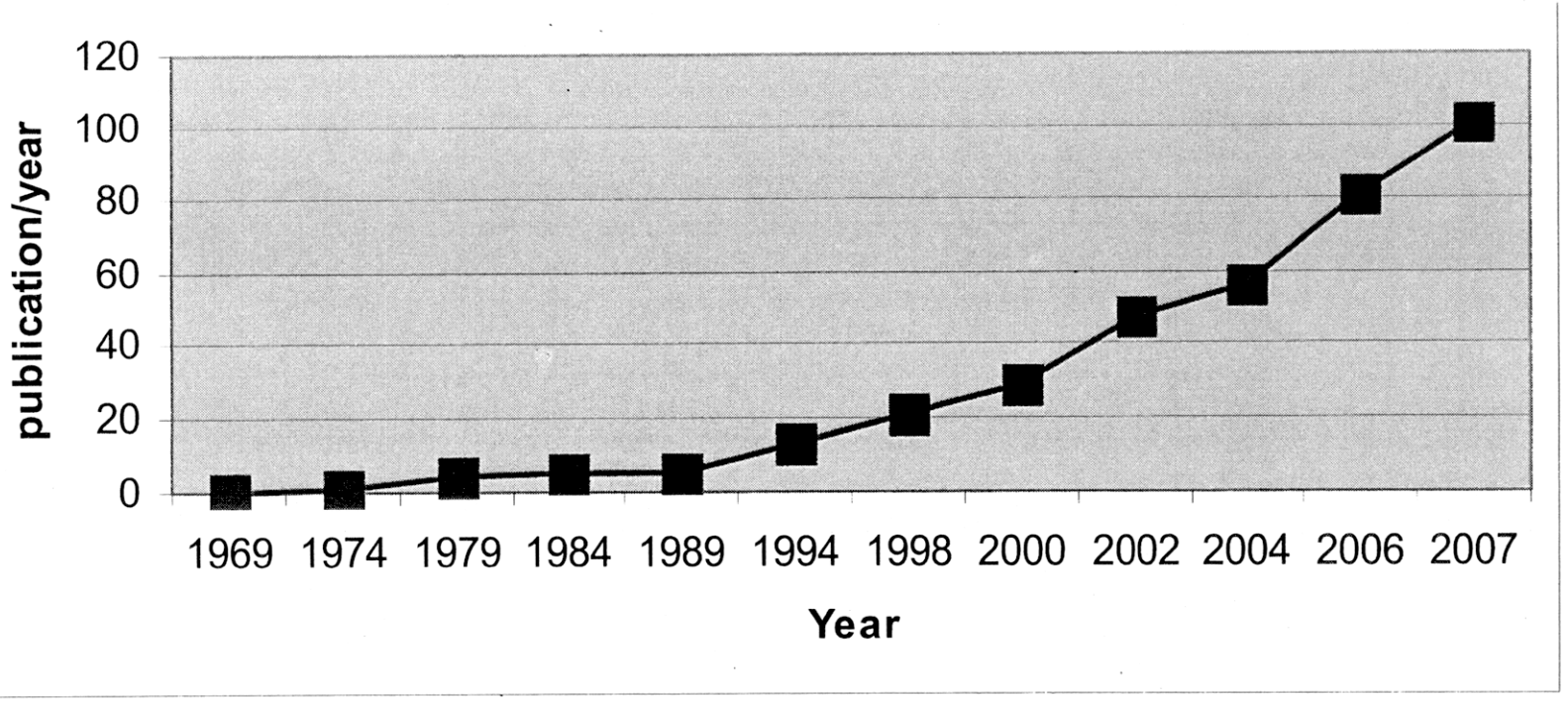
A. Bacchetta, C. J. Bomhof, P. J. Mulders, and F. Pijlman, *Phys. Rev.* D 72 (2005) 034030, hep-ph/0505268

C. J. Bomhof, P. J. Mulders, and F. Pijlman, *Eur. Phys. J.* C47 (2006) 147–162, hep-ph/0601171

D. Boer, S. J. Brodsky, and D. S. Hwang, *Phys. Rev.* D 67 (2003) 054003, hep-ph/0211110

Theory Interest in Transverse Spin vs Time

Annual number of publications on transverse spin in SPIRES vs time. The total number of pulications is about ~750, about 15% are experimental.



Transverse Spin Drell Yan at RHIC

- Prediction from gauge link formalism:
  Sivers function is non-universal.
  Sign change for the Sivers function between Drell Yan and SIDIS

- Can be tested at RHIC with high luminosity (~ 250 pb^{-1}) in either STAR or PHENIX. [For comparison we expect ~950 pb^{-1} delivered for operations at 500 GeV.]

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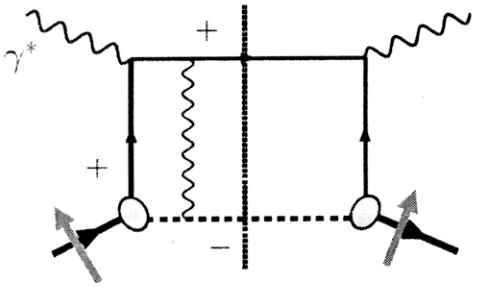
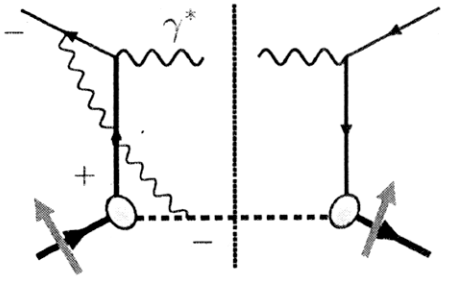
Non-universality of Sivers Asymmetries: Unique Prediction of Gauge Theory !

Courtesy
Werner Vogelsang
BNL

Simple QED example:

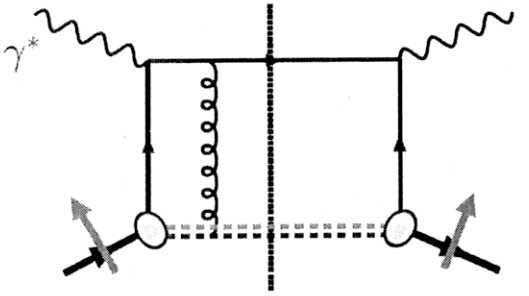


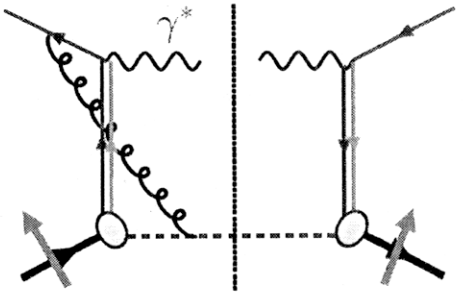
DIS: attractive



Drell-Yan: repulsive

Same in QCD:



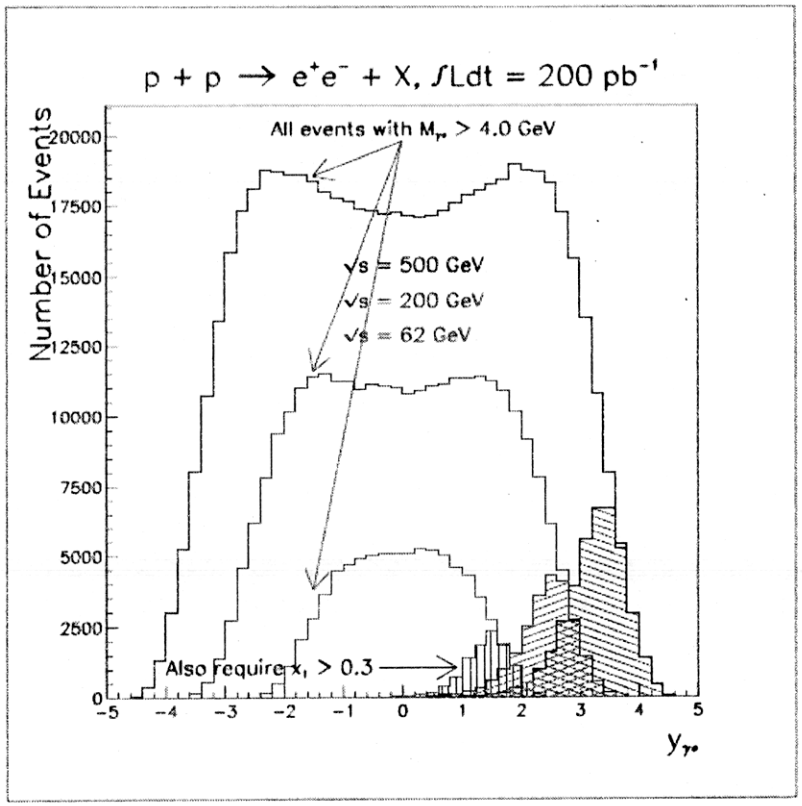


As a result:

$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Drell Yan at RHIC

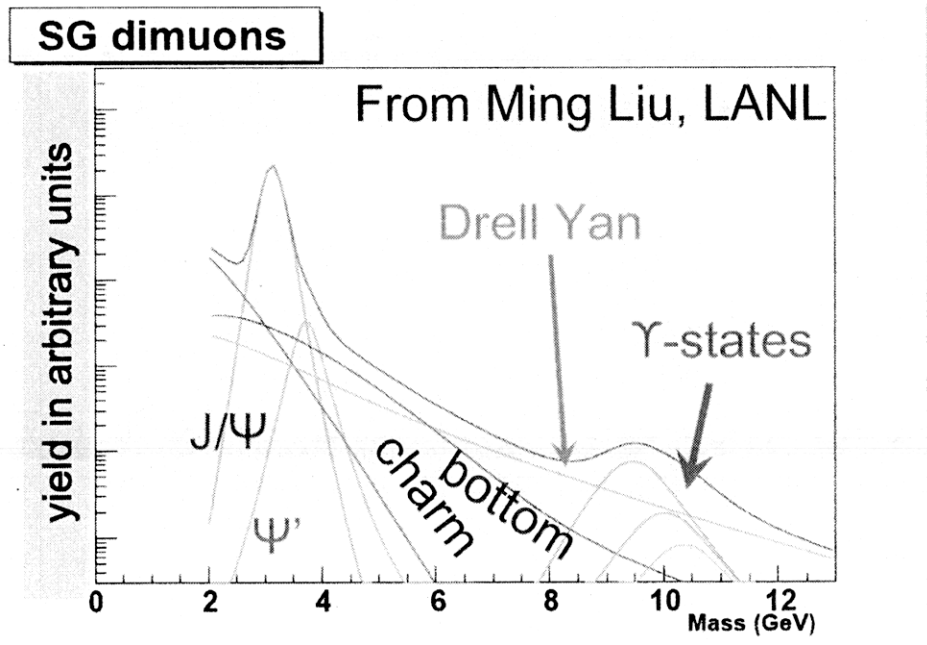
From Les Bland, BNL



➔STAR: endcap EMC + FMS

➔ PHENIX: muon spectrometers

Example: Drell Yan with the PHENIX muon spectrometers and a new forward silicon detector (FVTX).



FVTX enables DY measurement by rejecting heavy flavor background:

➔Measurement: 4 GeV < Q < 10 GeV

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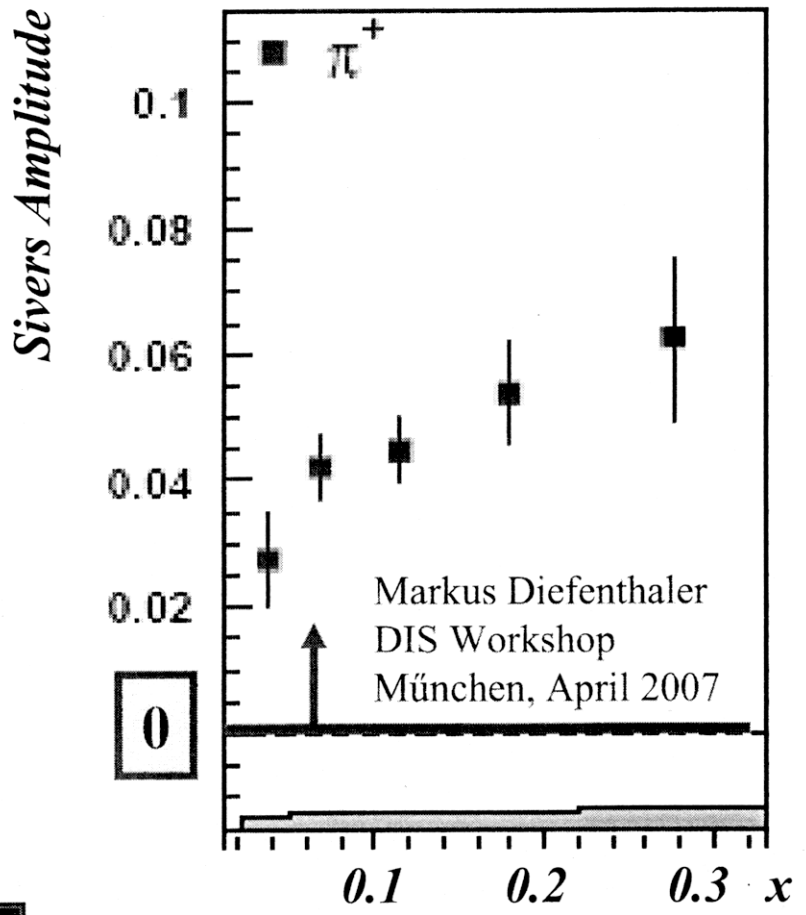
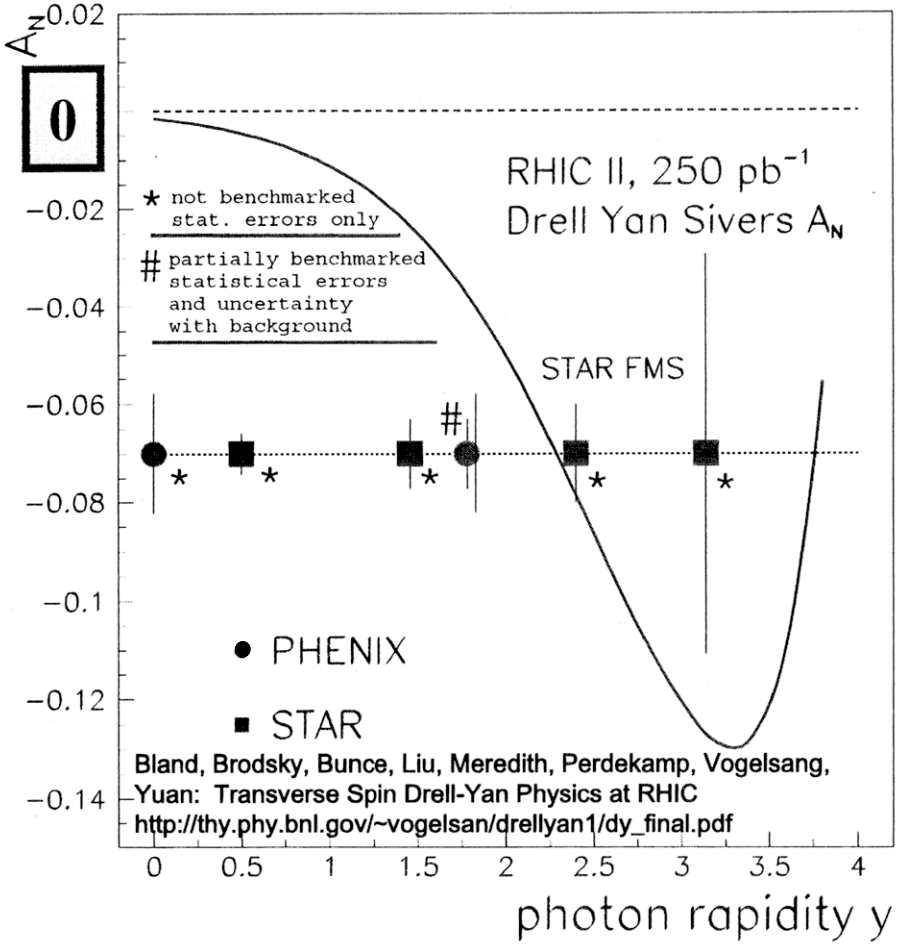
Experiment SIDIS vs Drell Yan: $\text{Sivers}|_{DIS} = -\text{Sivers}|_{DY}$
*** Test QCD Prediction of Non-Universality ***

HERMES Sivers Results



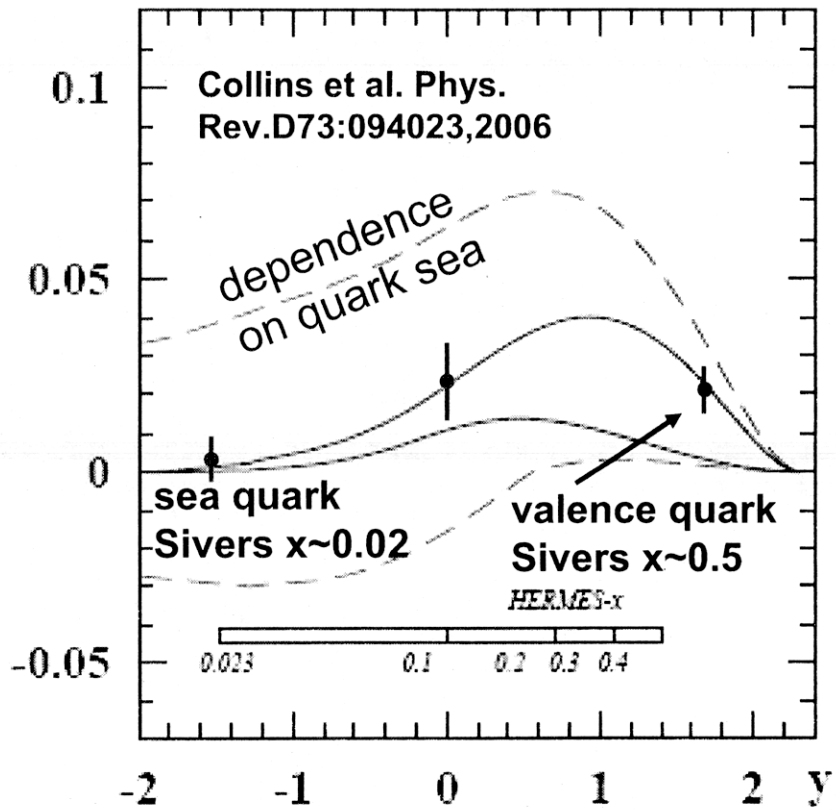
RHIC II Drell Yan Projections



Unique Sensitivity at RHIC to Sivers Effect for Anti-Quarks

Collins, Efremov, Goeke, Grosse Perdekamp, Menzel, Meredith, Metz, Schweitzer et al. Phys.Rev.D73:094023,2006

$A_{UT}^{\sin(\phi - \phi_S)}$ *in* $p^{\uparrow}p \to l^{+}l^{-}X$ *at RHIC Q=20GeV*



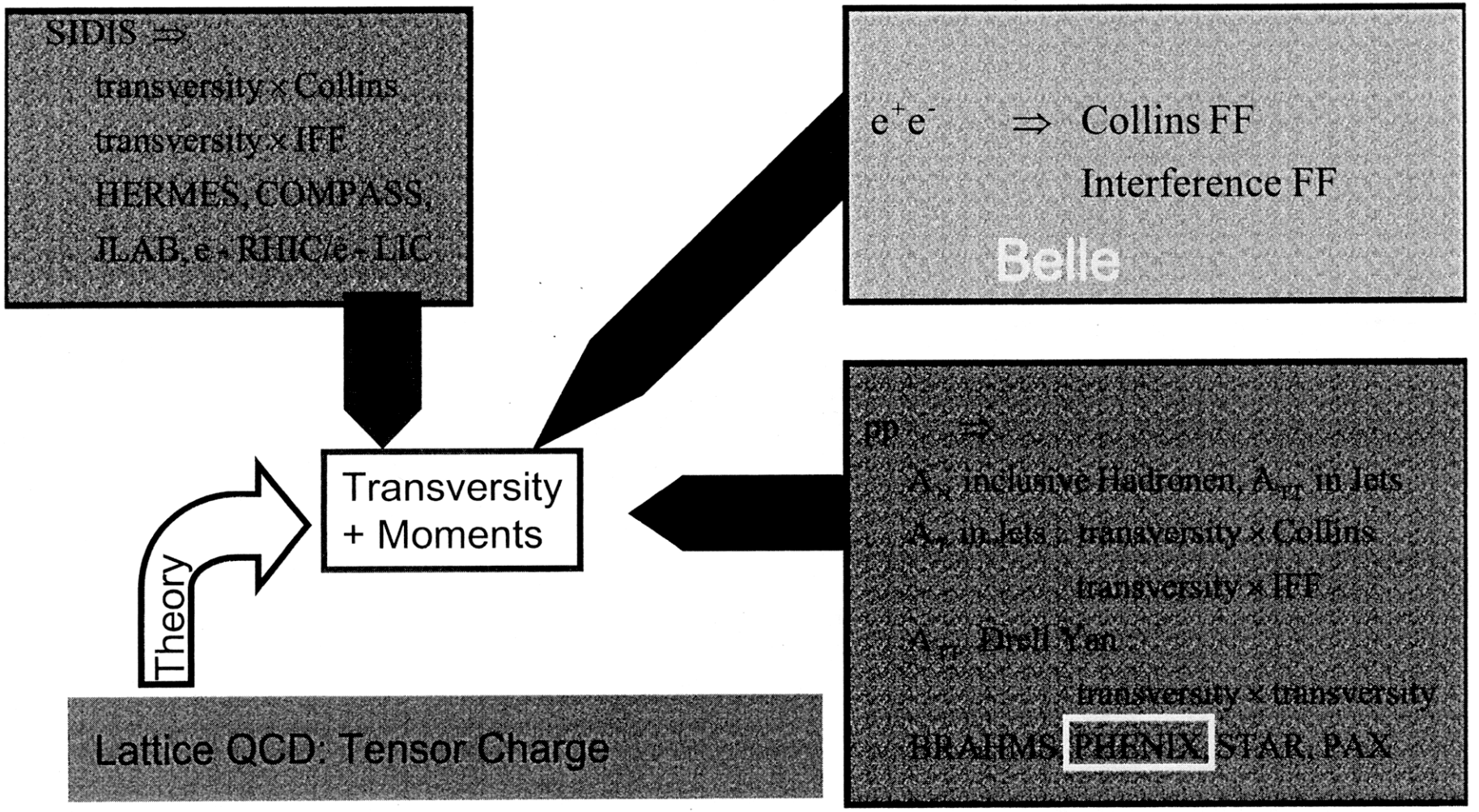
Sensitive to valence quark Sivers at large x and sea quark Sivers distributions at small x.

$$f_{1T_{\rm DY}}^{\perp(1)\bar{q}}(x) = \epsilon(x)\ f_{1T_{\rm DY}}^{\perp(1)q}(x)\ ,$$

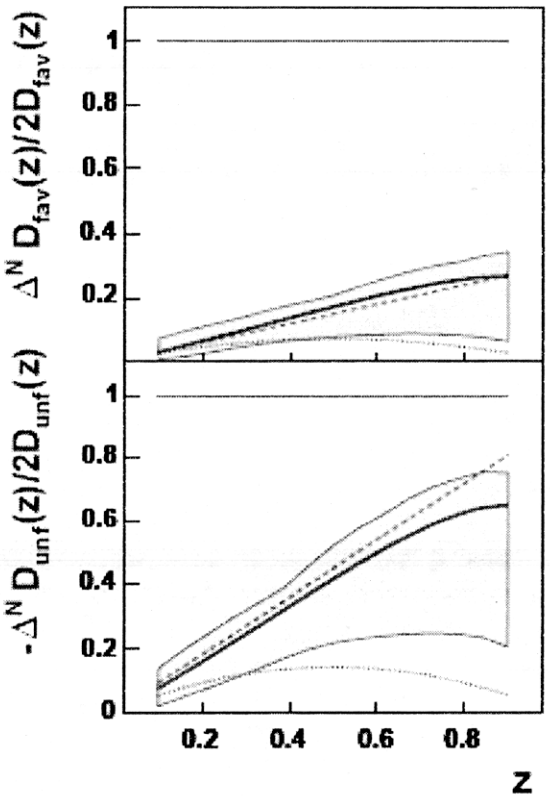
$$\epsilon(x) = \pm \begin{cases} 0.25 = \text{const} & \text{model I} \\ \dfrac{(f_1^{\bar{u}} + f_1^{\bar{d}})(x)}{(f_1^{u} + f_1^{d})(x)} & \text{model II} \end{cases}$$

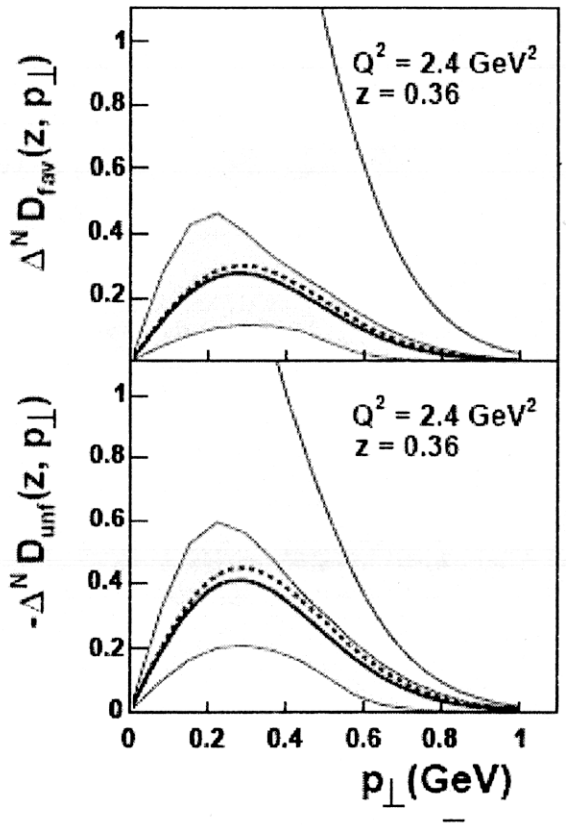
A Plan for the Extraction of Transversity Distributions and the Tensor Charge

RBRC Workshop, 9-2000 (Daniel Boer, MGP)



First Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-





Fit includes:

HERMES SIDIS

+ COMPASS SIDIS

+ Belle e^+e^-

→ transversity dist.

+ Collins FF

Anselmino,Boglione,D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:05032,2007

Italian theory support !

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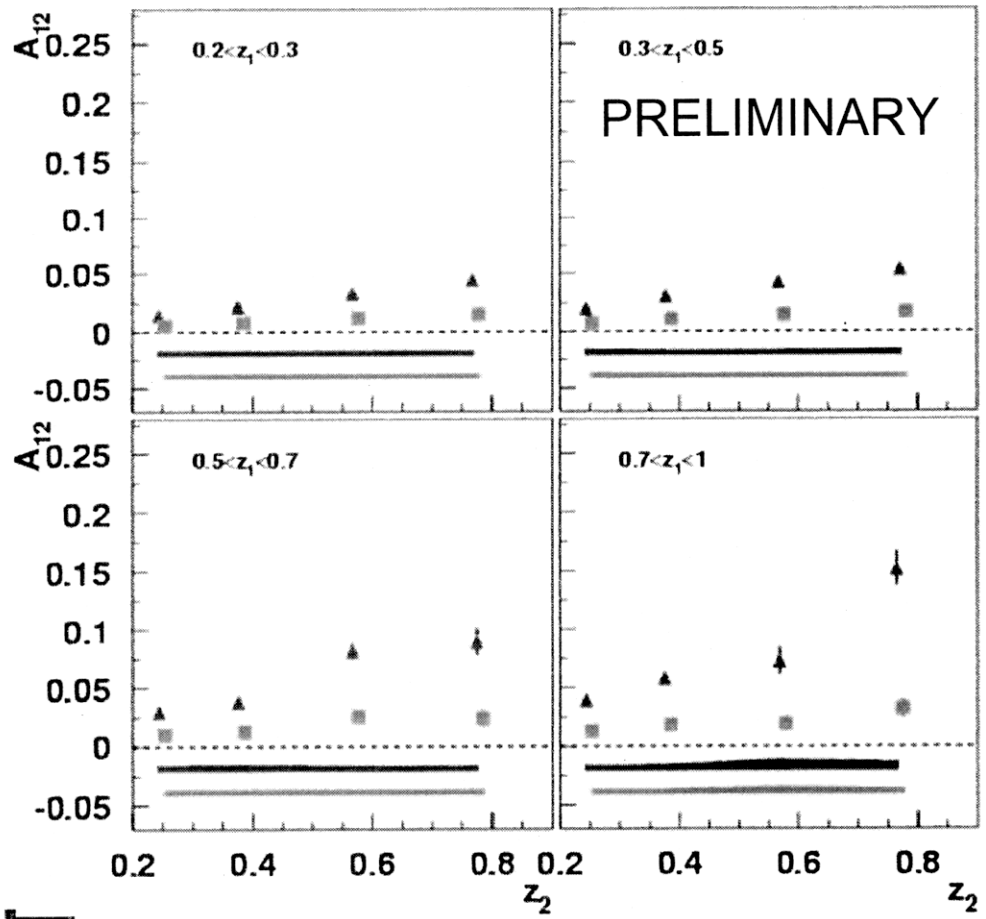
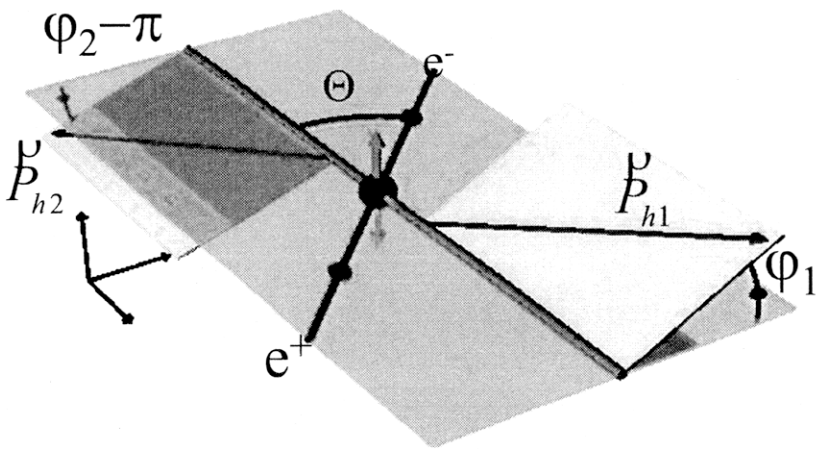
Improved Measurement of Collins Asymmetries
$29fb^{-1} \rightarrow 547\ fb^{-1}$ (on resonance)



Collins Asymmetries in e^+e^- annihilation into hadrons

$e^+ + e^- \rightarrow \pi^+ + \pi^- + X$

$\sim Collins(z_1) \times Collins(z_2)$



$A_{12} \cos(\phi_1 + \phi_2)$

Summary

White paper: "Transverse Spin Drell-Yan Physics at RHIC"
http://thy.phy.bnl.gov/~vogelsan/drellyan1/dy_final.pdf

Gauge link formalism makes it possible to describe k_T-dependent phenomena in a rigorous QCD framework

A fundamental test of this framework is possible measuring single transverse spin asymmetries in Drell Yan at RHIC.

The extraction of quark transversity distributions will come from a global QCD analysis of single transverse spin asymmetries from SIDS, pp and e+e-.

Very Forward Neutron Asymmetry at RHIC

RBRC SRC Meeting at BNL

November 5, 2007

Yuji Goto

Introduction

- One of the main goals of RHIC experiments is to determine polarized parton distributions by measuring double helicity asymmetries (A_{LL})
  - A_{LL} measurements need longitudinally polarized proton-proton collisions
  - At RHIC, protons are stored with transverse polarization
  - spin rotator magnets rotate the proton polarization into the longitudinal direction at PHENIX and STAR collision points
- Polarimeter at the collision point is necessary to confirm that beams are longitudinally polarized
  - monitored by the **local polarimeter** by using physics processes with left-right asymmetry (A_N)

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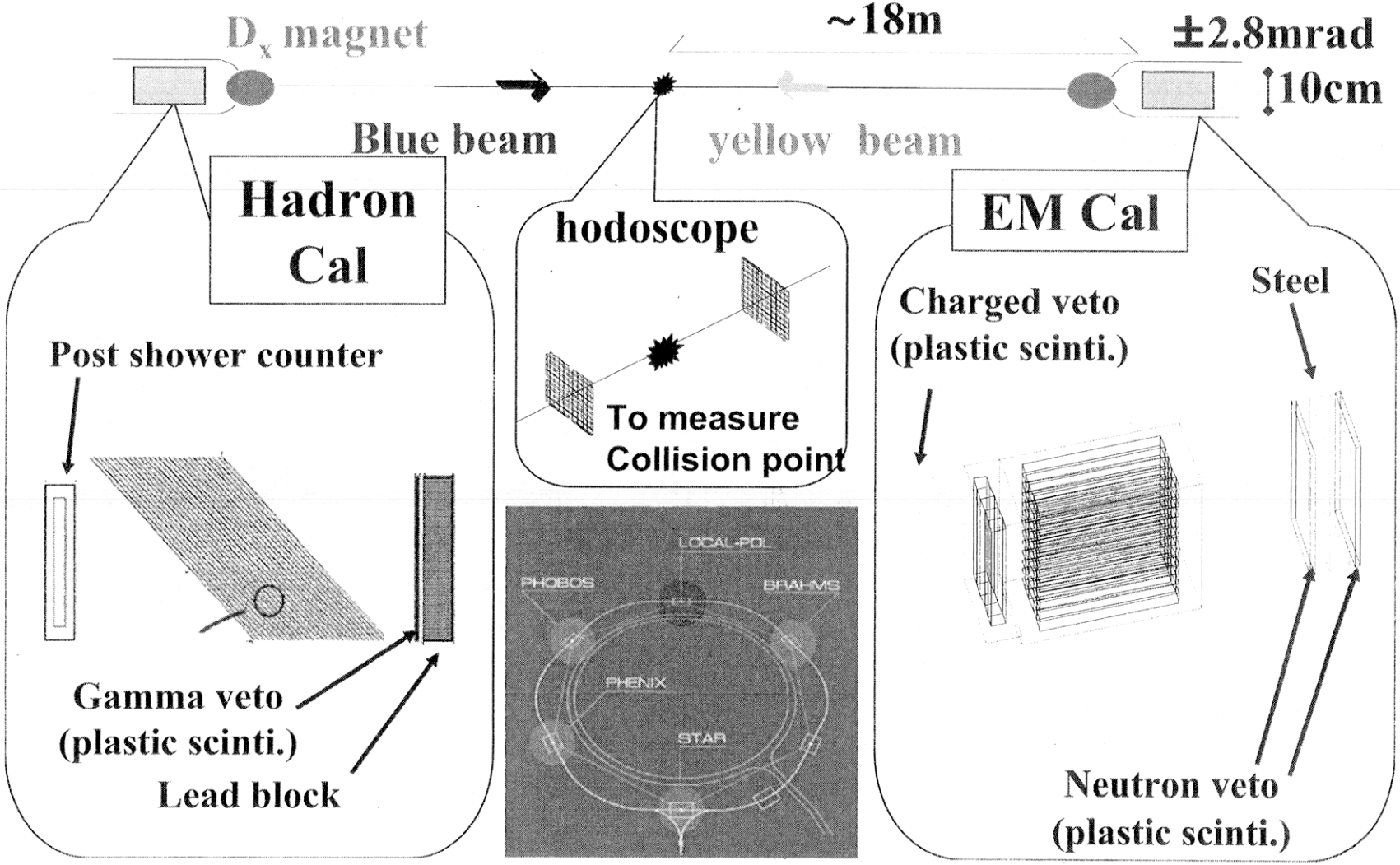
IP12 experiment

- performed in 2001-2002 with $\sqrt{s}$ = 200 GeV polarized proton collisions at the 12 o'clock collision point



Results

- **Phys. Lett. B 650 (2007) 325.**
  - large negative asymmetry in very forward neutron production

$$A(\phi) = \frac{1}{P_B} \frac{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} - \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}}{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} + \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}} = A_N \sin(\phi - \phi_0)$$

    - EMCal result $A_N = -0.090 \pm 0.006 \pm 0.009$
    - HCal result $A_N = -0.135 \pm 0.018$
    - consistent at the 2σ-level
  - π^0 and photon
    - A_N consistent with zero
  - backward asymmetries
    - A_N consistent with zero

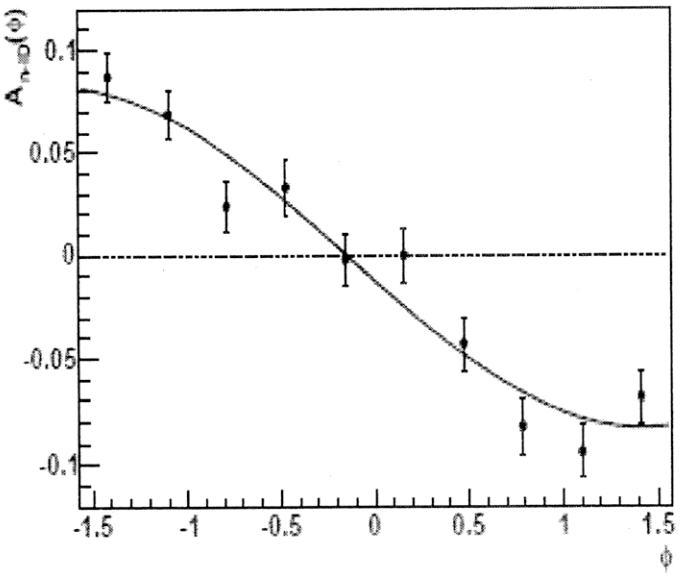


FIG. 4: Azimuthal dependence of asymmetry for the n-ID sample produced forward with respect to the polarized proton direction, based on the east detector. The error bars are statistical.

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RIKEN Research Highlights

- http://www.rikenresearch.riken.jp/research/313/
- **Looking forward at proton collisions**
  - Asymmetry in neutrons produced by proton collisions makes a good detector for spin-polarized protons

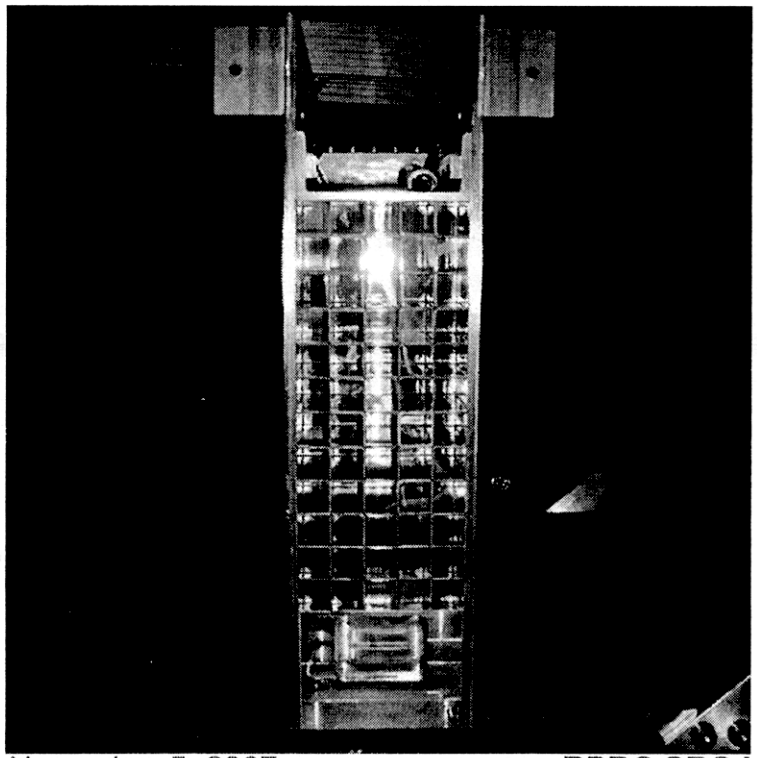

Figure 1: Photo of the calorimeter used to measure the asymmetry in neutron production of high-energy proton collisions.

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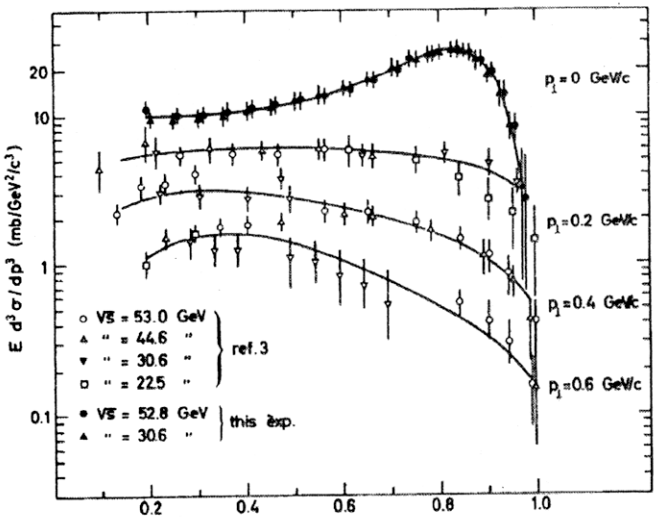
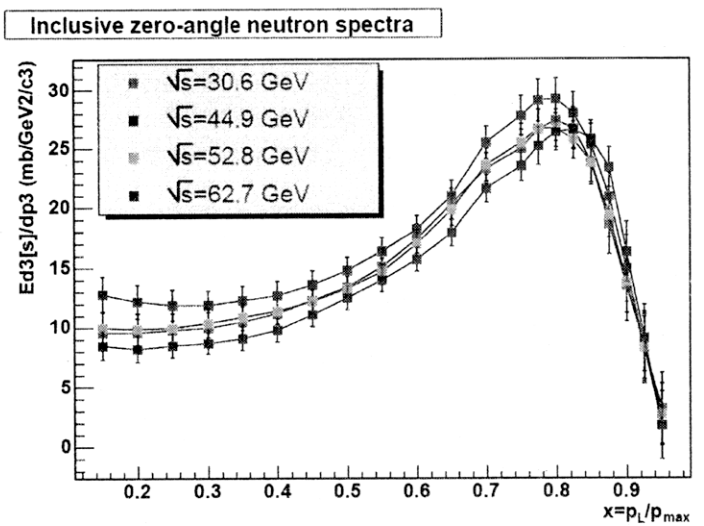
Neutron production in the forward region

- ISR experiments
  - p+p collisions at $\sqrt{s}$ = 30~63 GeV
  - cross section of forward neutron production (p_T~0) has a peak at high x_F ~ 0.8
  - scaled by x_F, $\sqrt{s}$ independent
- Well described by the One Pion Exchange (OPE) model



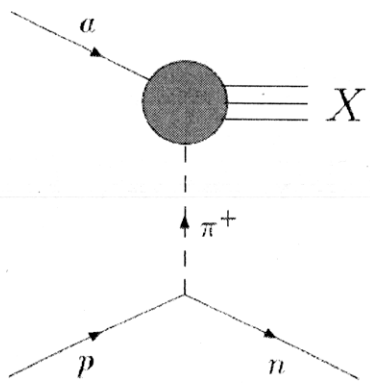
Nucl. Phys. B109 (1976) 347-356



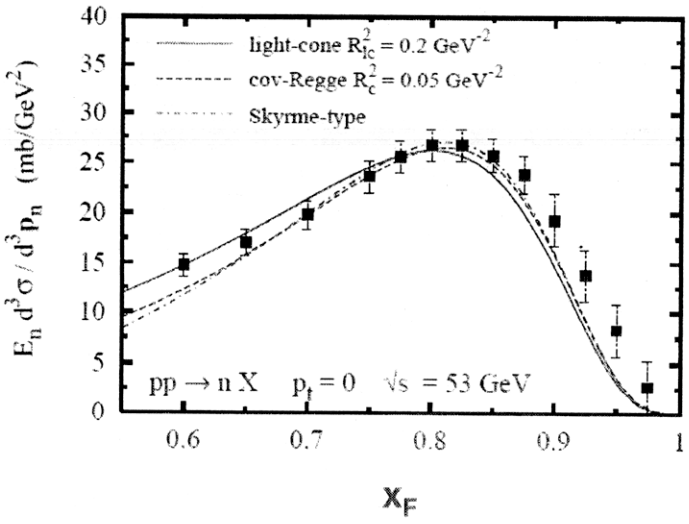
Neutron production in the forward region

- Well described by the One Pion Exchange (OPE) model
- H1 and ZEUS experiments
  - *e*+*p* collisions at $\sqrt{s}$ = 300 GeV
  - having a forward peak, too
  - pion structure function study
- x_F scaling at RHIC energy?

Eur.Phys.J.A7:109-119,2000



OPE model calculation



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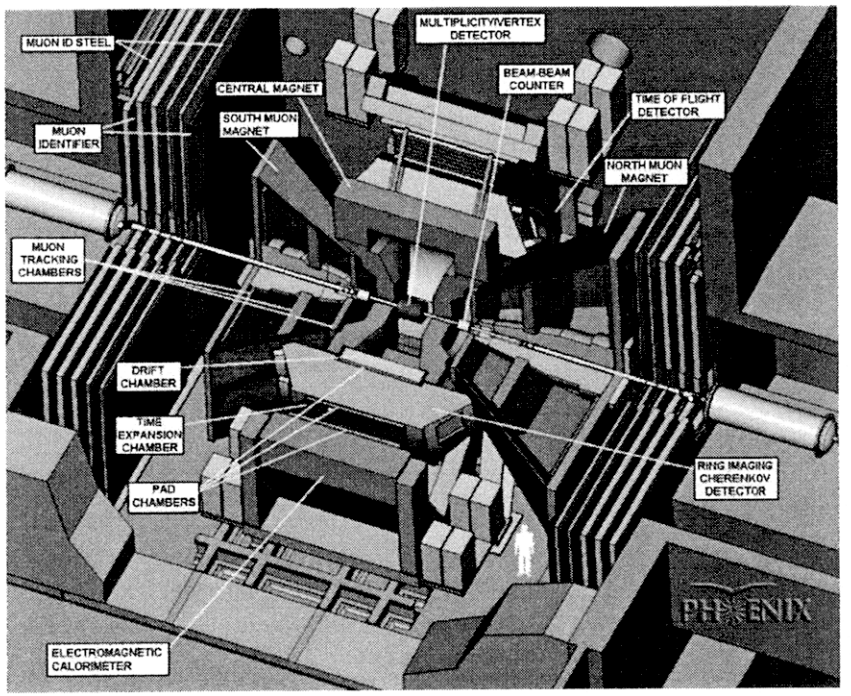
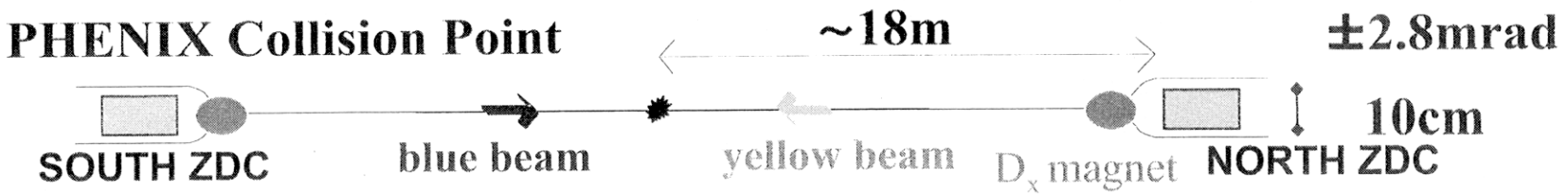
PHENIX local polarimeter

- There have existed ZDCs (Zero Degree Calorimeter) to detect neutrons at PHENIX
- SMDs (Shower Maximum Detector) were added to measure the hit position of neutrons

ZDC

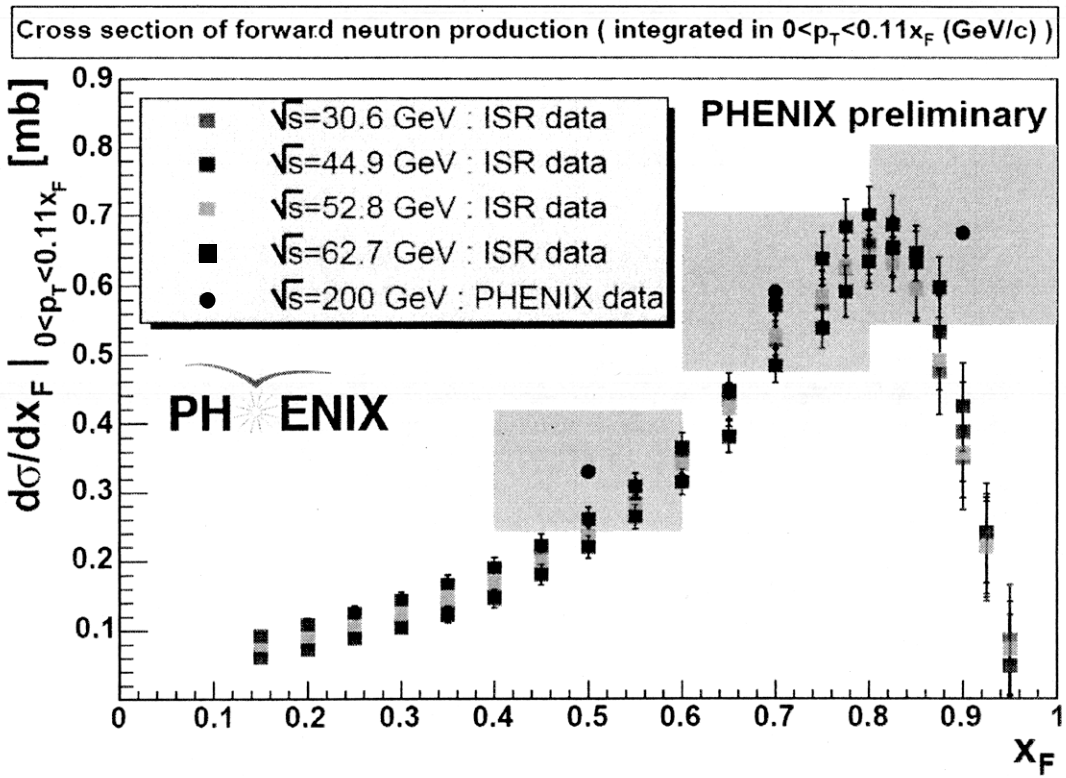


ZDC
@ 18m away
from the IP



Cross section

- Coarse cross section result is consistent with ISR data
- No indication of violation of x_F scaling at higher energy
  - integrated p_T region: $0 < p_T < 0.11\ x_F$ GeV/c in each point
  - p_T distribution assuming the ISR result



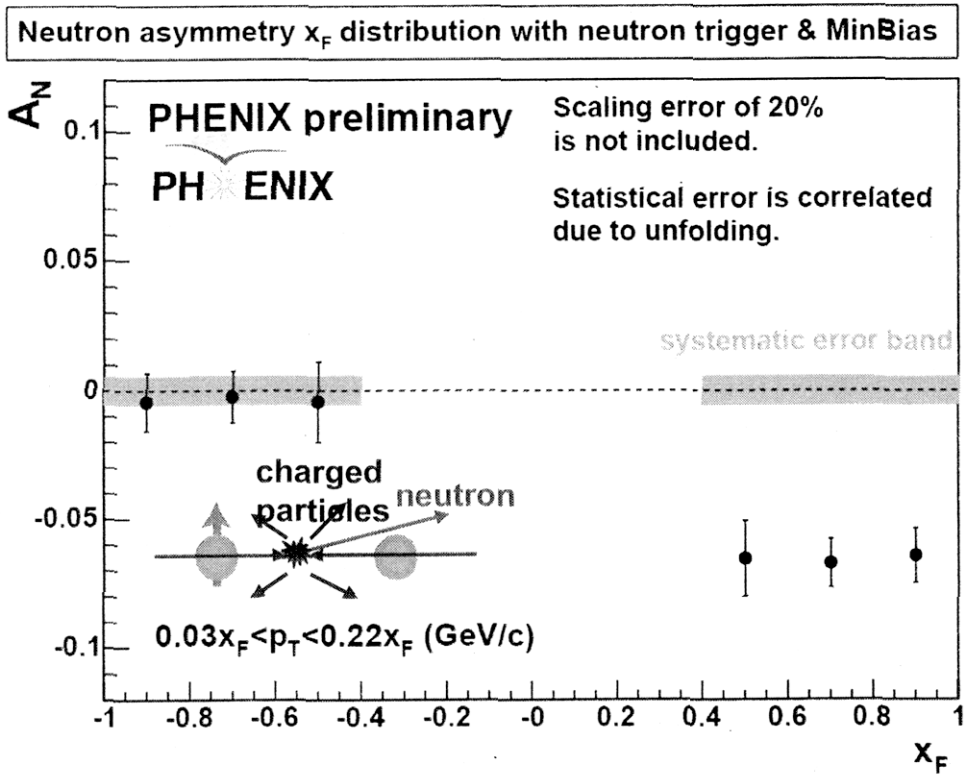
by Manabu Togawa

x_F-dependence of A_N

- Smearing effect is evaluated by simulation.
- For asymmetry calculation, square root formula is used.

$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx \frac{1}{Pol.} \frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}$$

Pol.~48%



Expected mean p_T are estimated by simulation assuming ISR p_T distribution.

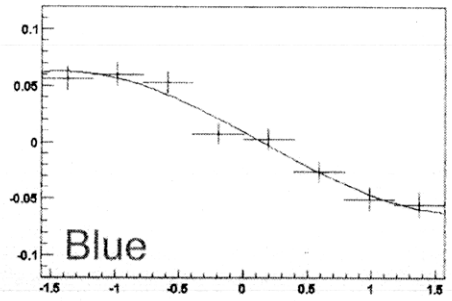
x_F	Expected mean p_T (GeV/c)
0.4~0.6	0.088
0.6~0.8	0.118
0.8~1.0	0.144

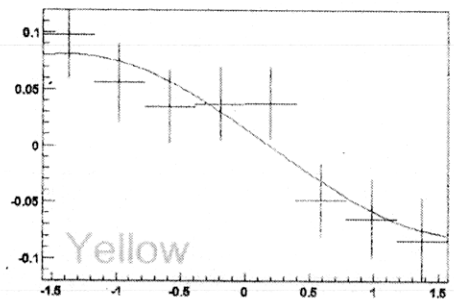
by Manabu Togawa

Spin rotator commissioning in 2003 run

Spin Rotators OFF

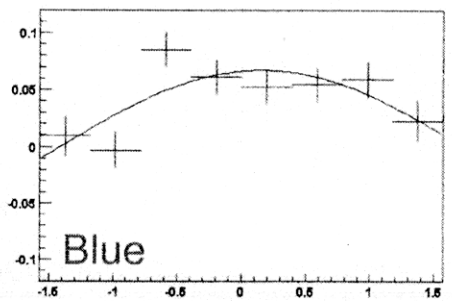
transversely-polarized proton collisions

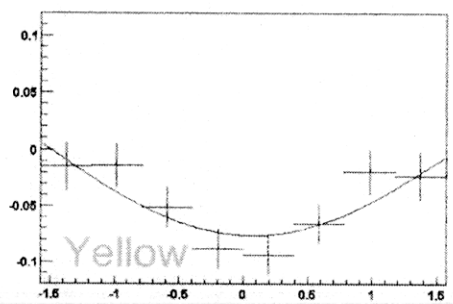




Spin Rotators ON
Current Reversed

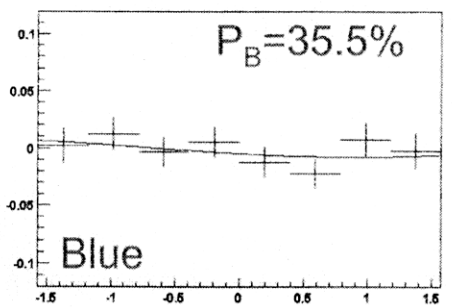
radially-polarized proton collisions

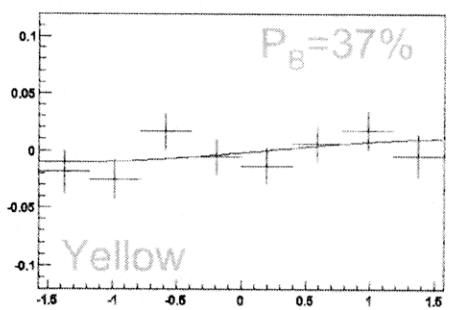




Spin Rotators ON
Correct Current !

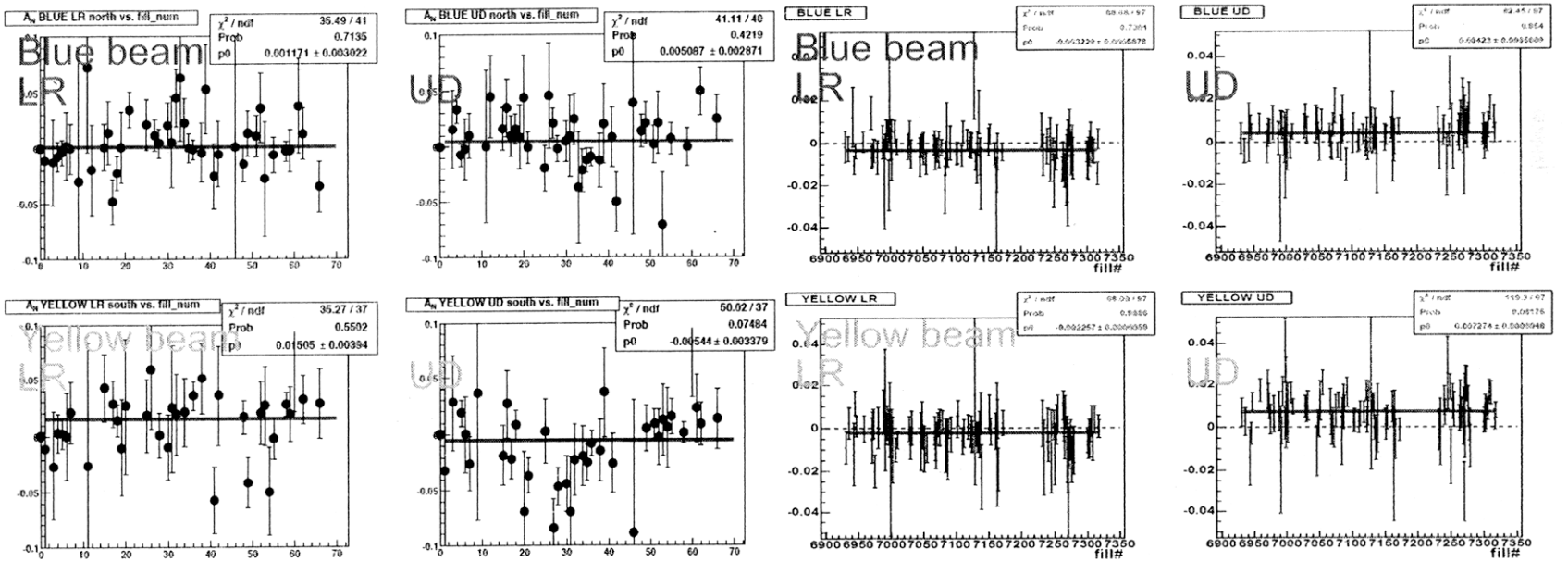
longitudinally-polarized proton collisions





Remaining transverse component of the longitudinally polarized beam

- evaluated by measuring a small remaining A_N
- fill-by-fill analysis and fitting



Run3 (2003)

Run5 (2005)

$$\langle p_L / p \rangle_{Blue} = 99.3^{+0.5+0.0}_{-1.4-0.9}\%$$

$$\langle p_L / p \rangle_{Yellow} = 97.4^{+1.3+0.1}_{-3.2-0.9}\%$$

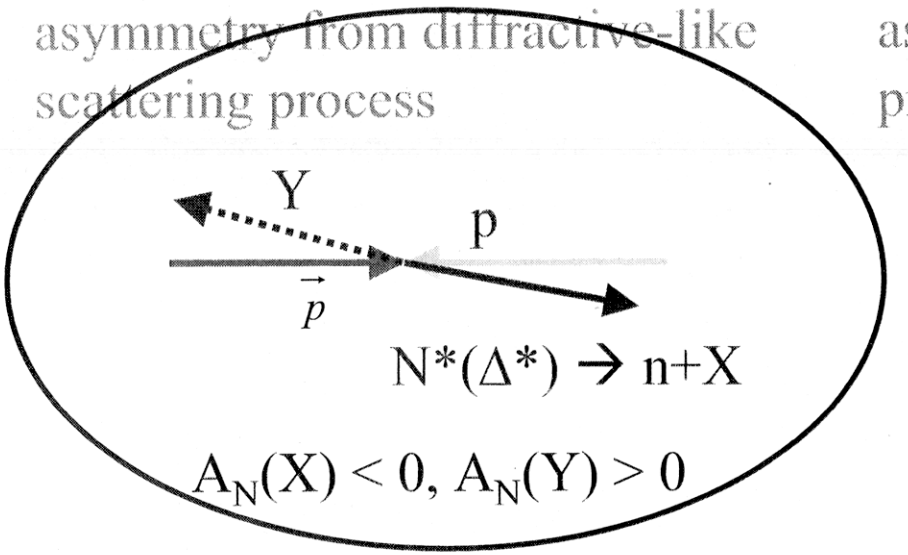
$$\langle p_L / p \rangle_{Blue} = 99.48 \pm 0.12 \pm 0.02\%$$

$$\langle p_L / p \rangle_{Yellow} = 98.94 \pm 0.21 \pm 0.04\%$$

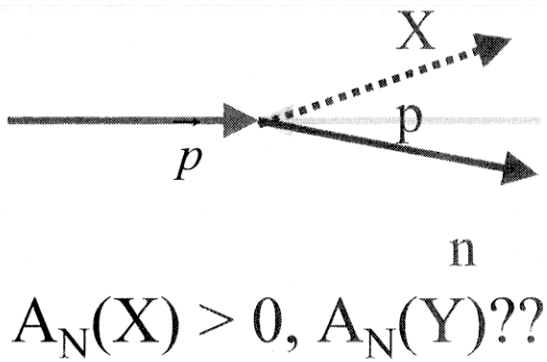
BBC asymmetry with neutron production

- Forward neutron, forward BBC, left-right
  - $(-4.50\pm0.50\pm0.22)\times10^{-2}$
- Forward neutron, backward BBC, left-right
  - $(2.28\pm0.55\pm0.10)\times10^{-2}$
- No significant asymmetry in backward neutron tagged data or in top-bottom asymmetry.
  - systematic error doesn't include A_N^{CNI} error

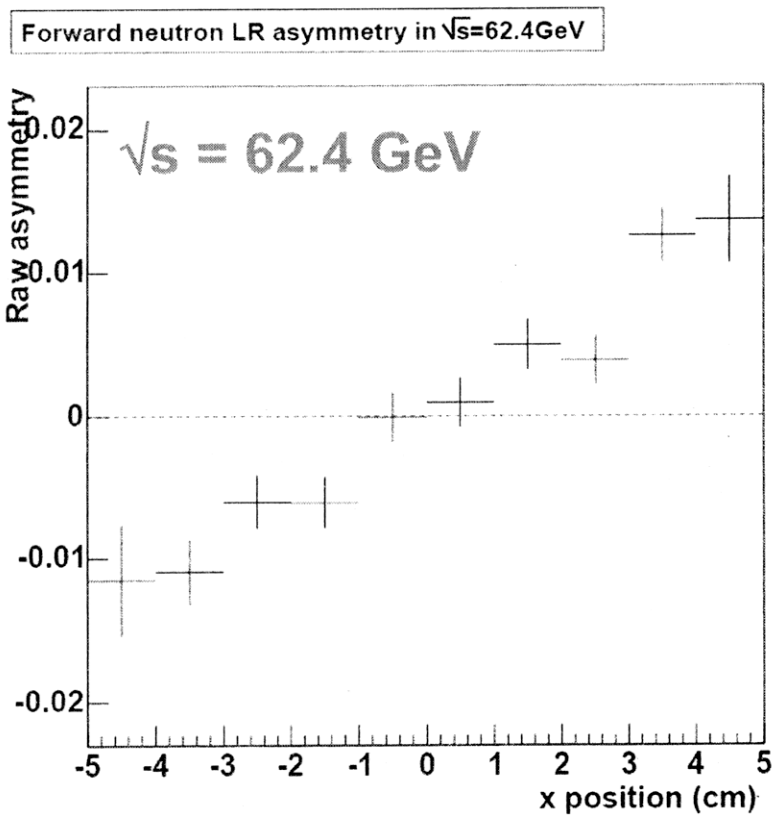
asymmetry from diffractive-like scattering process

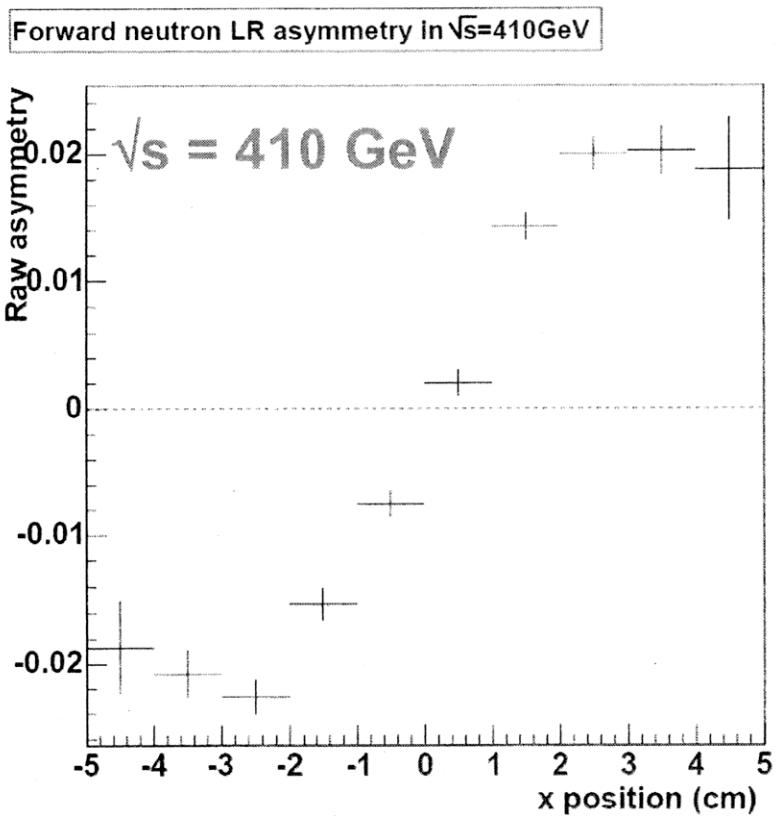


asymmetry from fragmentation process (kick-out/recoil picture)



Neutron asymmetries at 62.4 GeV and 410 GeV





by Manabu Togawa

Summary

- We discovered a large neutron single spin asymmetry ($A_N \sim -10\%$) in forward production of p+p collision at IP12 experiment (2001-2002)
- PHENIX local polarimeter is configured by ZDC for neutron detection and SMD for hit position measurement
- Local polarimeter have successfully been monitoring how well the proton beam is longitudinally polarized at the collision point by measuring the neutron asymmetry at PHENIX
- We are measuring x_F dependence of cross section and asymmetries to understand the production mechanism of the forward neutron
- BBC asymmetry with forward neutron production is also interesting for the local polarimeter and to understand the production mechanism

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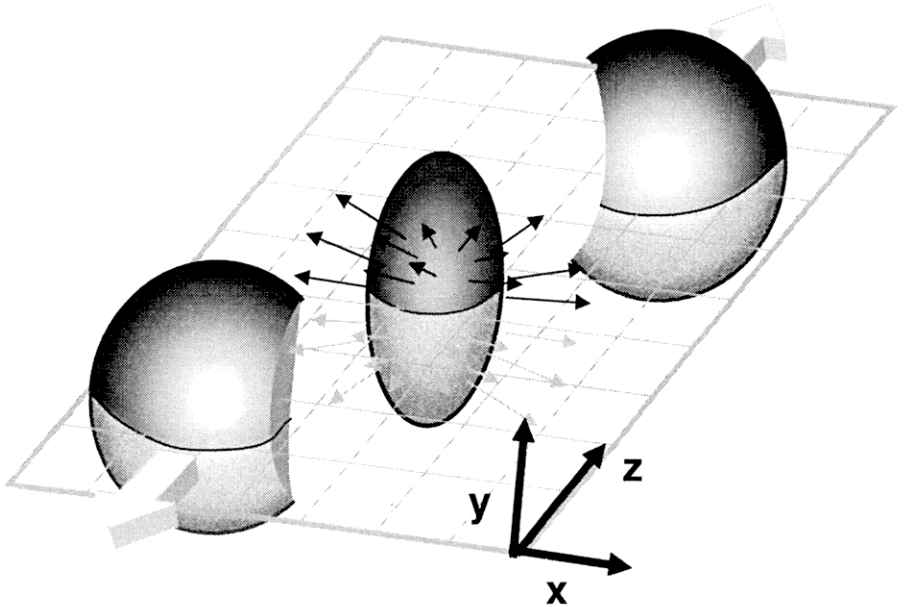
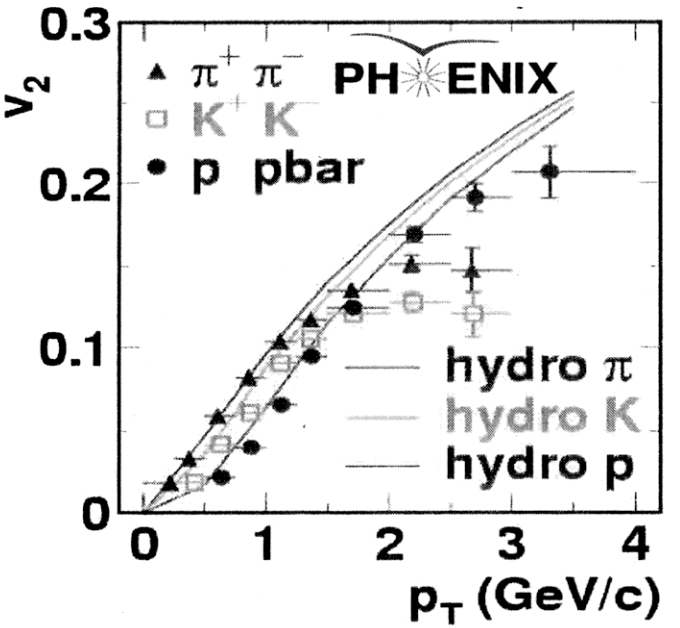
PHENIX Reaction Plane Detector and its Physics Input

Wei Xie
Purdue University

Physics Motivation

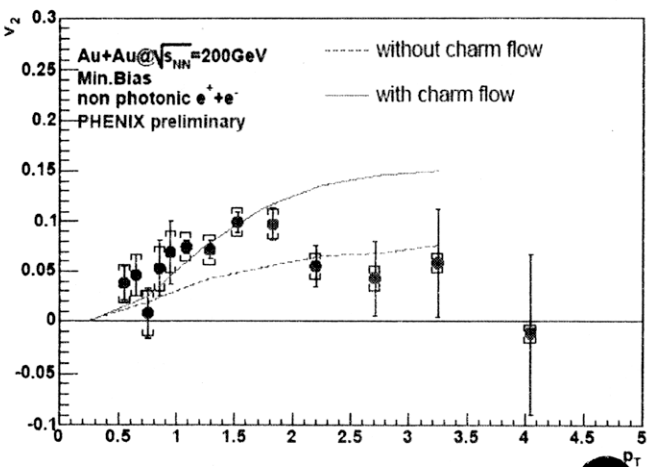
Large elliptic flow is one of the critical observation to support the discovery of the "perfect fluid"





$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r))),$$

$$v_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$$



Effect of Reaction Plane Resolution on Flow Measurement

The relation between the observed $v2$ (raw) and the correct $v2$:

$$v2 \text{ (raw)} = v2 \text{ (true)} * \langle \cos 2\Delta\psi \rangle$$

Here $\langle \cos 2\Delta\psi \rangle$ is the correction factor of the reaction plane resolution, and sometimes it is simply called as "reaction plane resolution".

$$\delta v2 \text{ (raw)} \sim 1/\text{sqrt(Nsignal)}.$$

$$\delta v2 \text{ (true)} = \delta v2 \text{ (raw)} / \langle \cos 2\Delta\psi \rangle \sim (1/\langle \cos 2\Delta\psi \rangle) * 1/\text{sqrt(Nsignal)}$$

the statistical power of the measurement is reduced by a factor of $(1/\langle \cos\Delta\psi \rangle)^2$ due to the reaction plane resolution.

Determination of reaction plane resolution

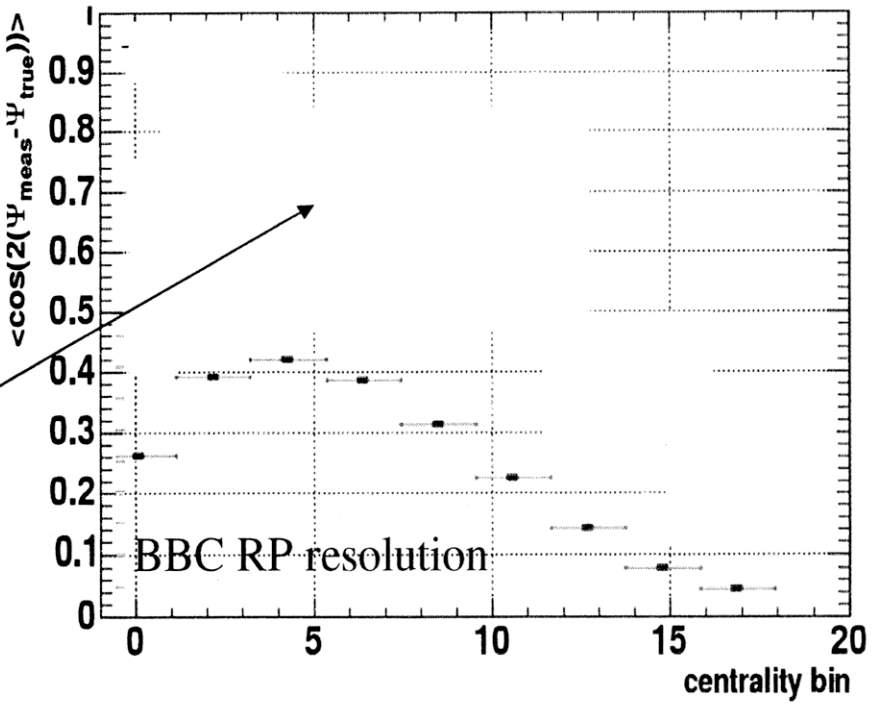
The resolution in any 2-pi detector basically depends on two things:

- The number of secondaries that are produced headed toward that detector
- The strength of the anisotropy among those particles, usually the v_2 for eta ranges of the BBC and inward.

The detector need to:

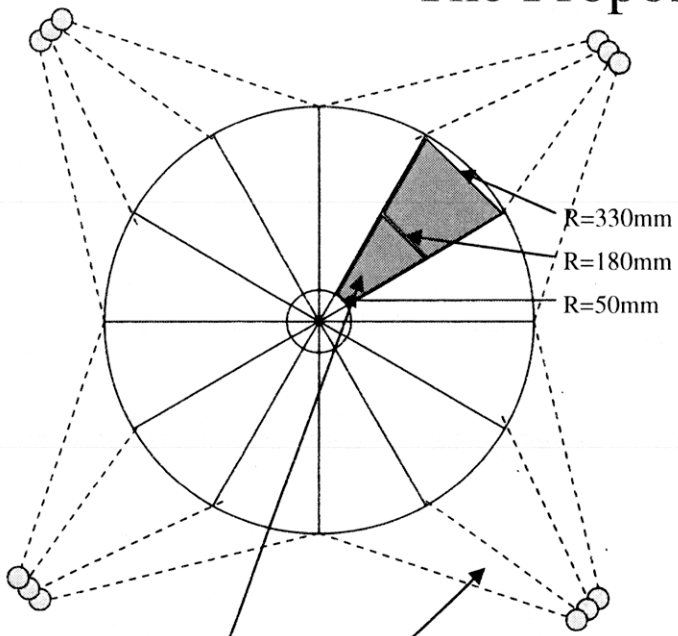
- have a larger acceptance and/or
- sitting in a region with larger anisotropy

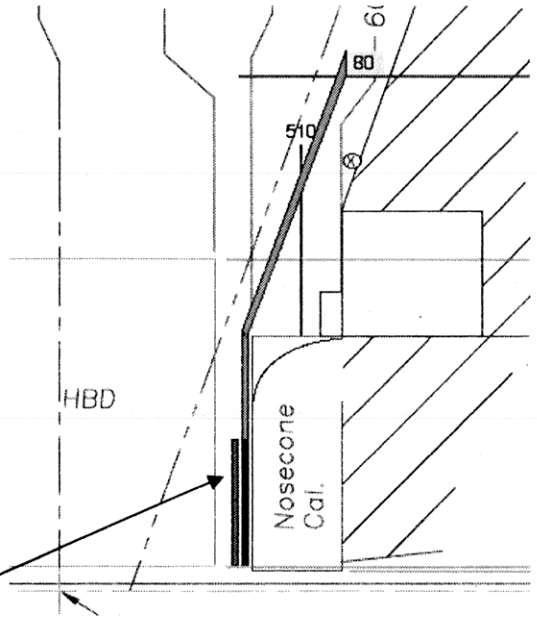
A scintillator detector covering the nosecone with a converter in front will have the resolution: ~0.7 at mid-central region



Equivalent to a factor of 3 increase in terms of luminosity

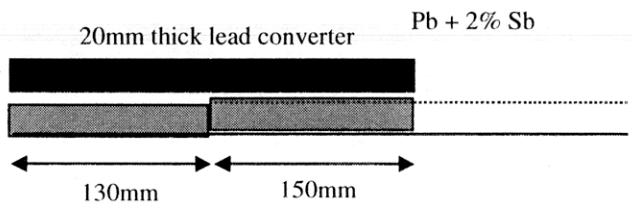
The Proposed Scintillator Detector

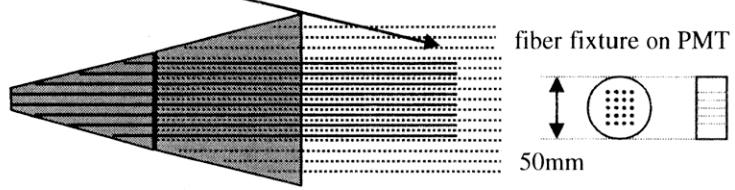




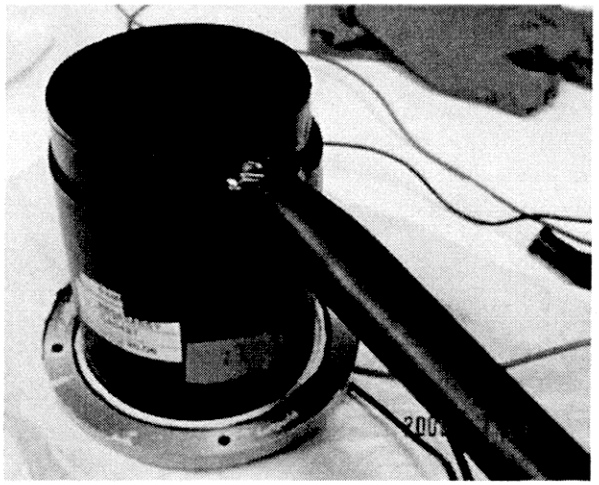
- 2cm thick scintillator + 2cm thick lead converter
  - Enhance RP resolution via adding neutral particles
- fiber light guide
  - flexibility of mechanical structure.
- 12 segments in phi and 2 segments in eta@(1.0, 2.8)
  - Detector stable against dead channel
  - help removing auto-correlation effect.
- Hamamtsu fine mesh PMT for light readout
  - Good dynamic range and work in high field.
- EMCal FEE for electronic readout.
  - good dynamic range.

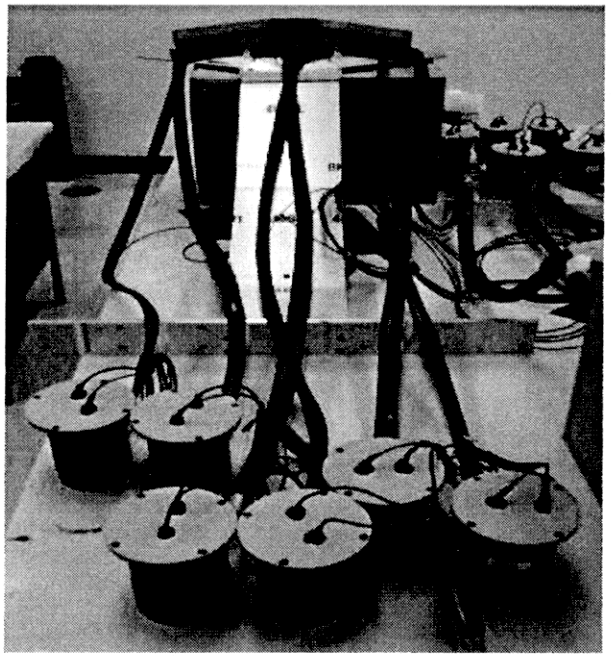
outer painting on the converter surface
or stainless steel case with lead inside

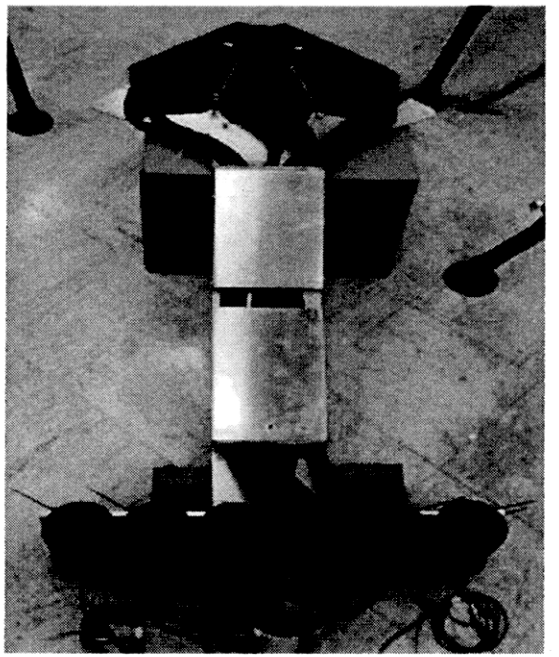


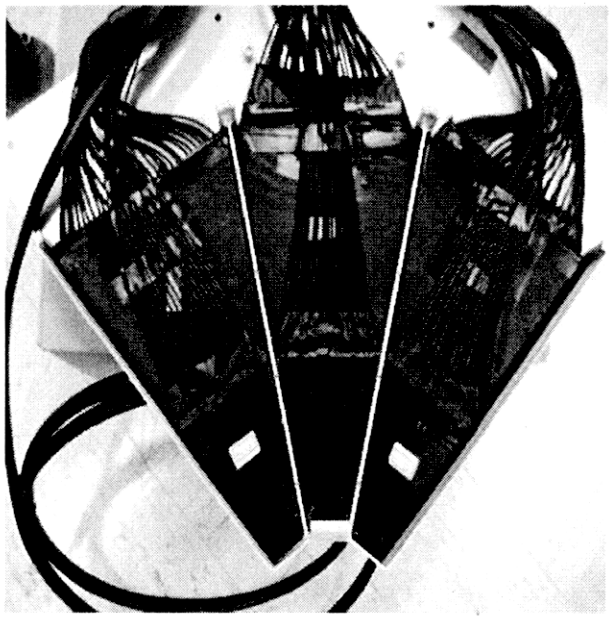


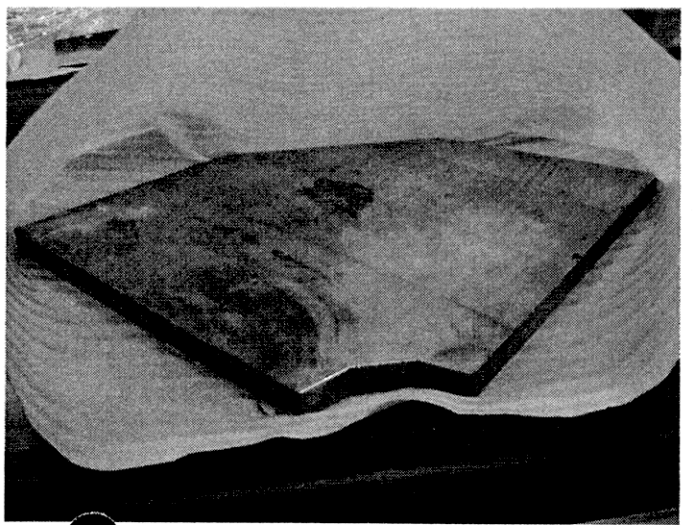
Real Detector Assembly



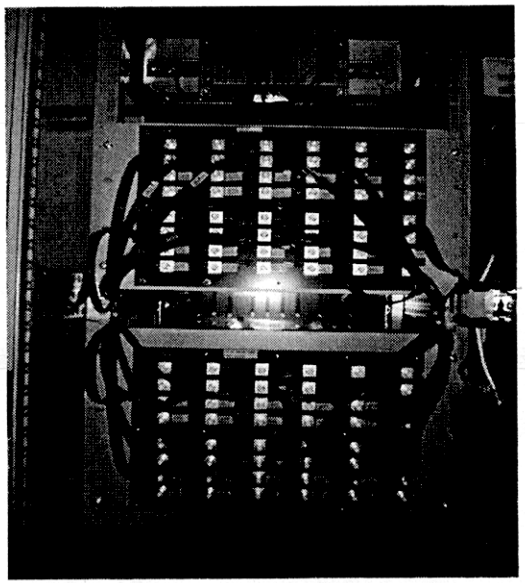


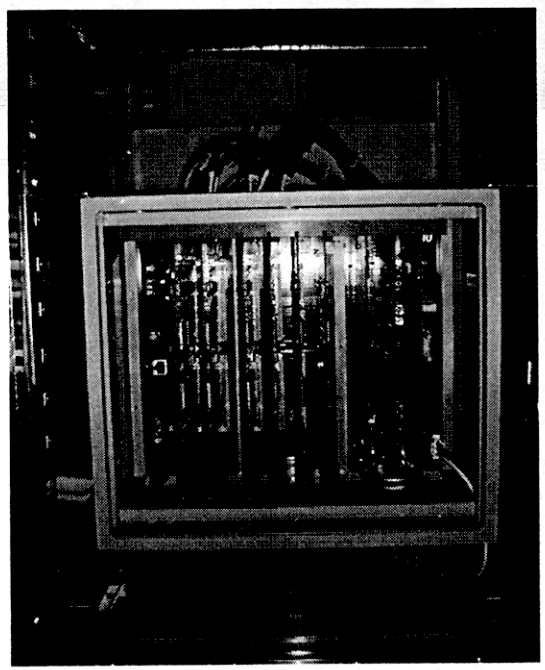


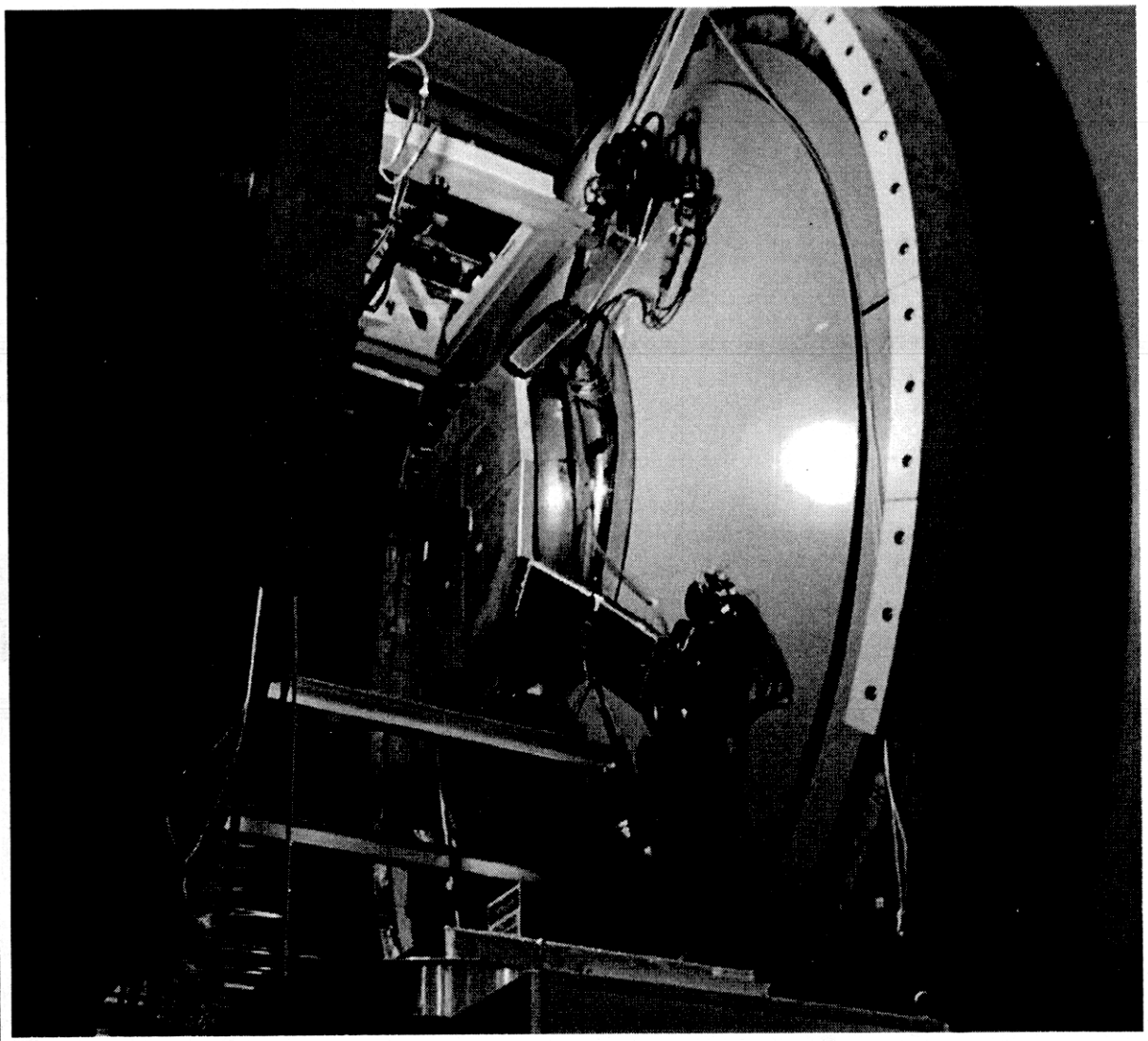




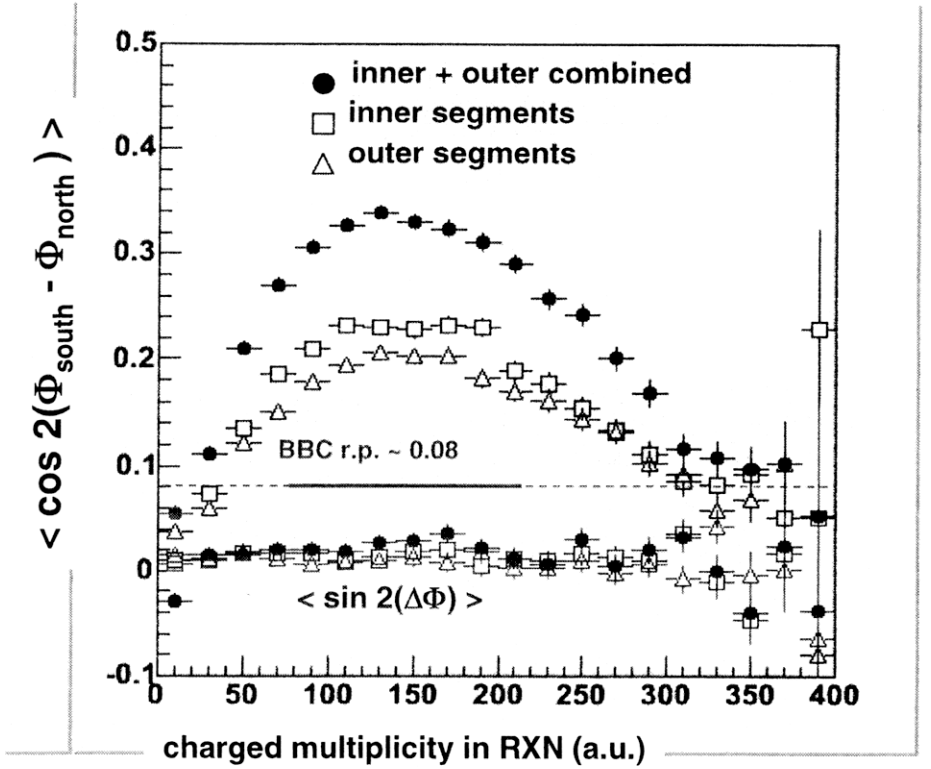
The Complete Reaction Plane Detector

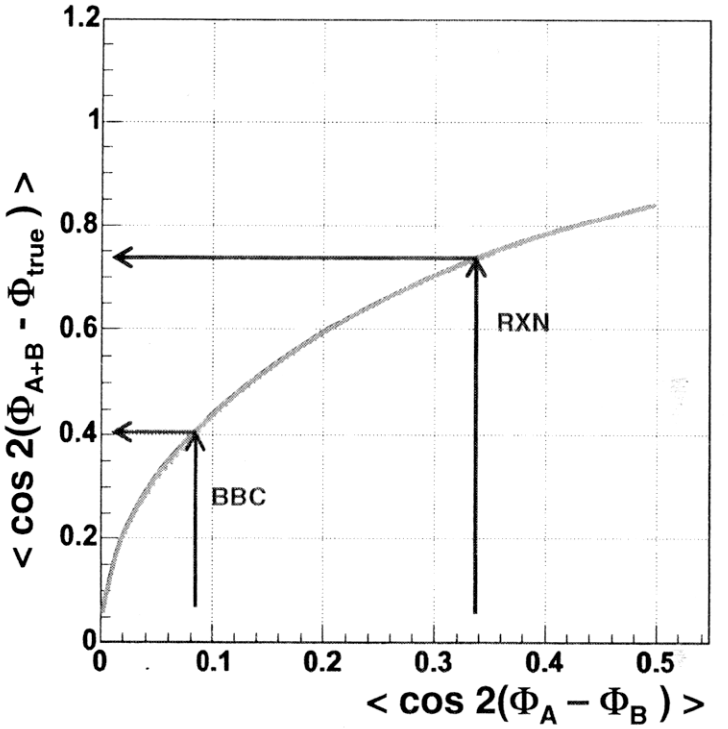






Performance: A declaration of Victory

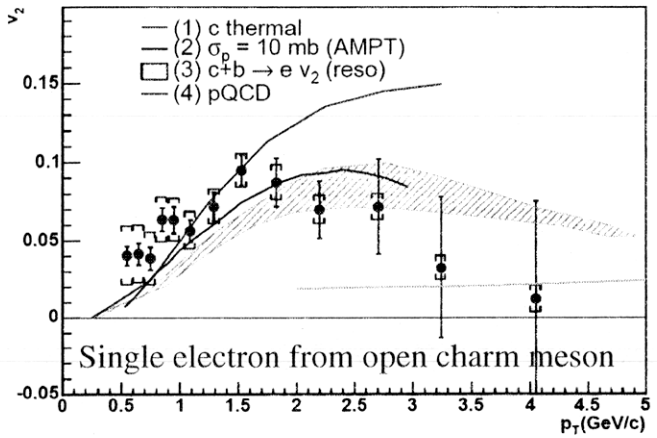




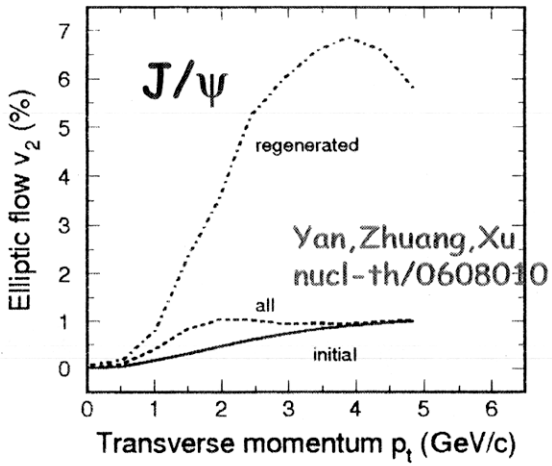
Comparing the RP resolution of 0.4 using BBC alone:

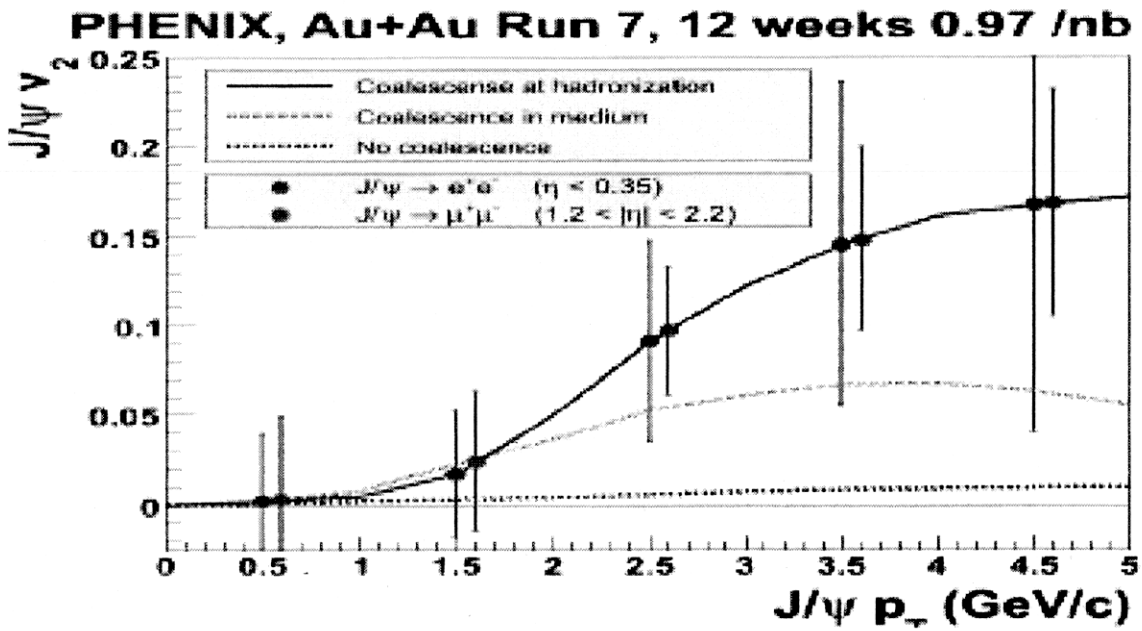
- The N&S combined resolution is 0.75, i.e. the same as the design goal.
- The N&S inner ring reach 0.6, i.e. the same as the design goal.

The Near Term Physics Output from The Detector



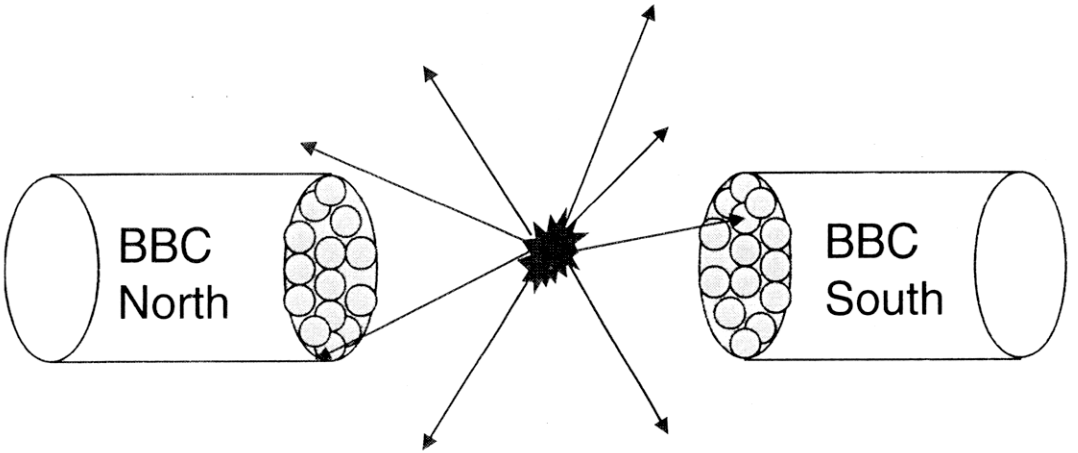
- Charm flows. If recombination is correct, J/Psi should also flow.
- PHENIX accomplished in run7 with higher luminosity (x~4) and better (~sqrt(2.5)) reaction plane resolution.



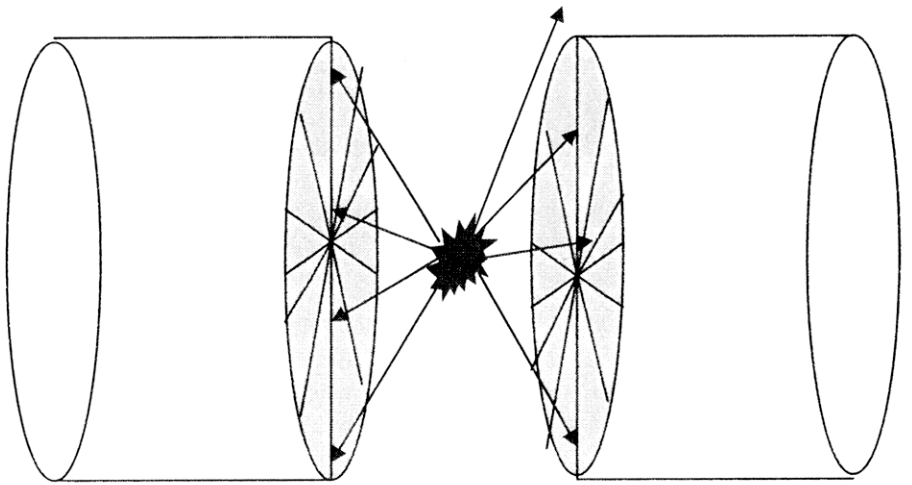


For the first time at RHIC, it will be possible to measure the J/psi elliptic flow.

A Bonus: Trigger on Low Energy Au+Au run



At sqrt(s) = 10GeV run, BBC see 10% of the collision occur in PHENIX inner region



Reaction Plane Detector has much larger phase space coverage.

At sqrt(s) = 10GeV run, it see 95% of the collision occur in PHENIX inner region

The new Minimum-bias trigger is successfully commissioned using run7 the 200GeV Au+Au collisions

RxNP Collaboration

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Heavy Ion Physics at PHENIX

Y. Akiba

RBRC Review
2007/11/05

Heavy Ion Physics at RHIC

- RHIC has produced high density partonic matter
  - Strong suppression of high p_T hadrons in Au+Au (*jet quenching*)
  - *Absence of suppression* in d+Au
  - *Strong elliptic flow* in Au+Au
  - → In 2005, RHIC experiments have concluded *formation of dense partonic matter at RHIC*
- Next step: Detailed study of the newly discovered matter
  - Is the matter de-confined?
  - What is the viscosity of the matter?
  - How hot and dense is the matter?
  - → Measurements of "penerating probes" such as J/ψ, heavy quark, and direct photon

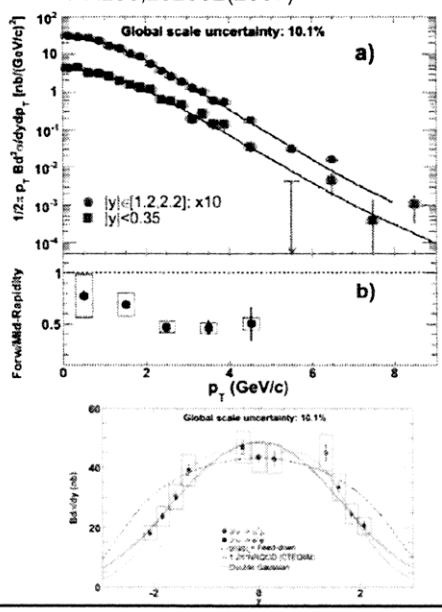
PHENIX heavy-ion/unpolarized pp results with major RBRC/RIKEN contribution

- J/ψ measurements
  - p+p: high statistics study of J/ψ production
  - Au+Au: First measurement of J/ψ suppression at RHIC
- Heavy flavor measurement via Single Electrons
  - p+p: NLO pQCD works
  - Au+Au: Energy loss and flow of charm and bottom quarks
- Direct photons at high pT
  - p+p : pQCD works (→ Okada)
  - Au+Au: probe of the initial state of collision
- Low pT direct photon via internal conversion
  - p+p: baseline
  - Au+Au: excess?

These are most important results in the study of dense matter formed at RHIC

J/ψ in p+p

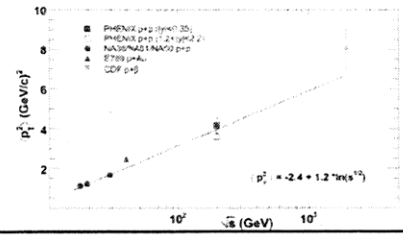
PRL98,232002(2007)



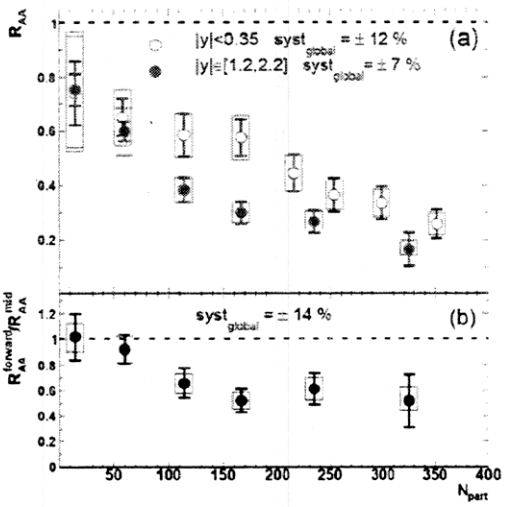
- Order of magnitude higher statistics than the previous measurement by PHENIX
- Pt and rapidity distribution are determined
- Baseline for J/ψ suppression in A+A

J/ψ→ee

Xie We, YA



J/ψ suppression in Au+Au



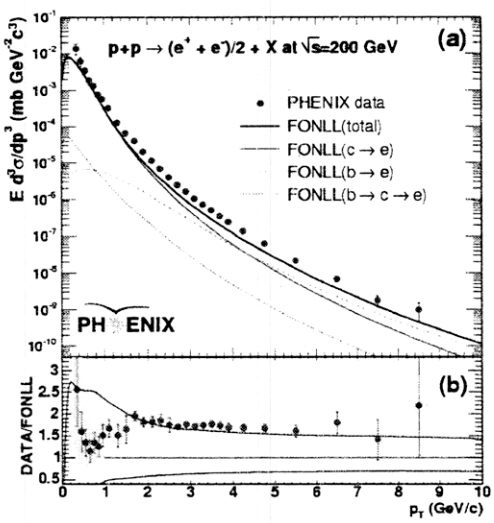
PRL98,232301(2007)

- High statistics measurement of J/ψ in AuAu in wide rapidity range
  - Mid-rapidty J/ψ → ee
  - Forward rapidty J/ψ→μμ
- Strong suppression of J/ψ is observed
  - Consistent with the prediction that J/ψs are destroyed in de-confined matter
- Surprisingly, the suppression is stronger at forward rapidity than in mid-rapidity
  - J/ψ formation by recombination of charm pairs in deconfined matter?

Xie Wei, YA

Heavy flavor production in pp

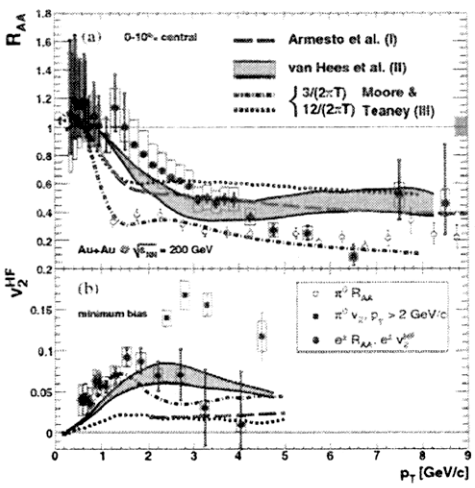
Phys. Rev. Lett 97,252002 (2006)



- Single electrons from heavy flavor (charm/bottom) decay are measured and compared with pQCD theory
- The new data extends the p_T reach to 9 GeV/c
- FONLL pQCD calculation agree with the data

YA, F. Kajihara (JRA,Tokyo)

Heavy quark energy loss and flow



- Measurement of single electrons from charm/bottom decay in Au+Au for wide pT range (0<pT<9 GeV/c)
- Strong suppression of heavy-flavor single electrons at high pT is observed
  → Evidence of large energy loss of heavy quark in the dense matter
- Strong elliptic flow of heavy-flavor electrons
  → Evidence for rapid thermalization of heavy quarks in the dense matter
- The data are consistent with small viscosity/entropy ratio

PRL98,172301(2007)

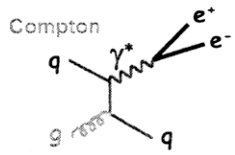
F.Kajihara(JRA,Tokyo), YA

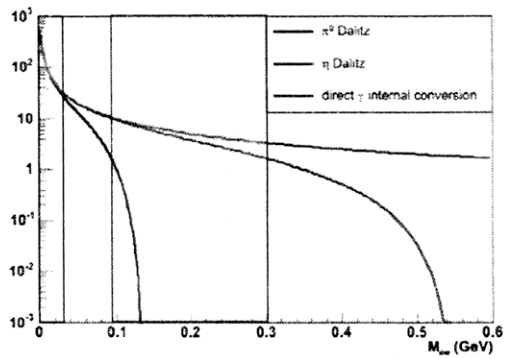
Search for direct photon via Virtual Photon Analysis

Any source of 'real' photon should emits 'virtual' photon with very low mass.

□ Shape of the inv.mass spectrum is given by Kroll-Wada formula.

$$\frac{1}{N_\gamma}\frac{dN}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}\left(1-\frac{M_{ee}^2}{M^2}\right)^3\left|F\left(M_{ee}^2\right)\right|^2$$

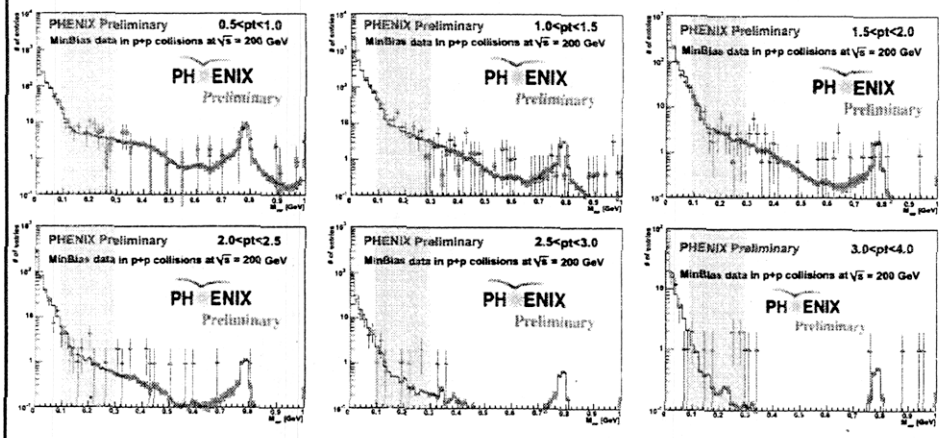




Baisic Idea:
If one measure Mee > Mpi0, contribution from pi0 decay (~85% of hadronic decay photon) can be eliminated

PHENIX preliminary results in Au+Au (RUN4) using this method suggests excess for 1<pT < 3 GeV/c, but so far there is no p+p baseline.

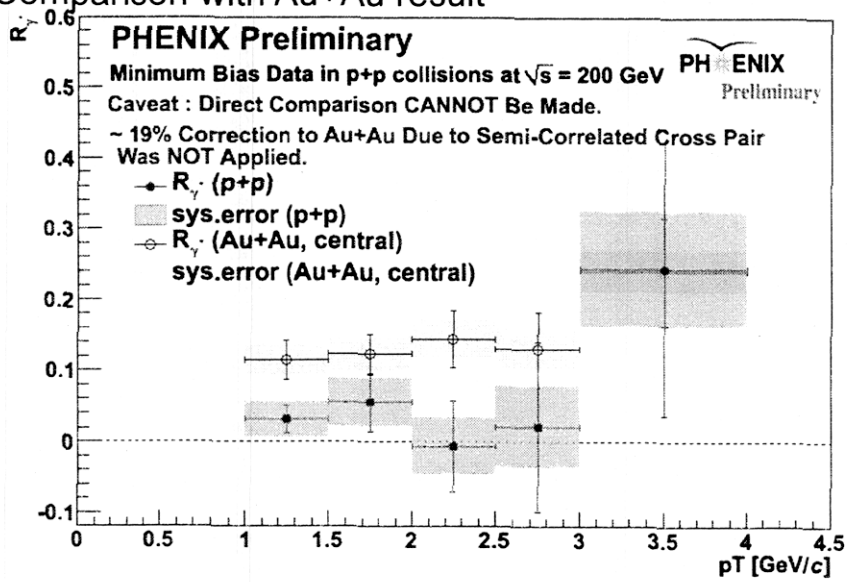
Search for "excess" in p+p collisions at 200 GeV



The same method is applied for p+p data to search for virtual direct photon. Good agreement between the data and the cocktail; there is little excess.

Y. Yamaguchi (JRA, Tokyo), YA

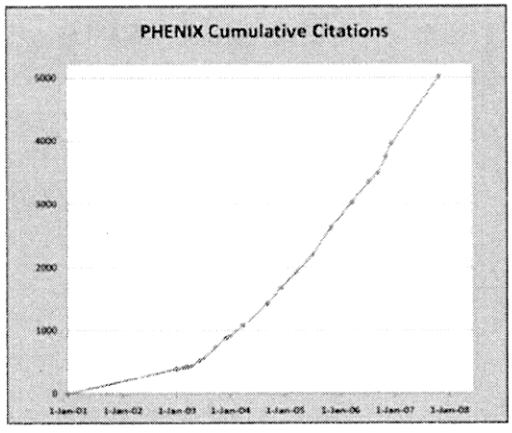
Comparison with Au+Au result



Y. Yamaguchi (JRA, Tokyo), YA

PHENIX publications

- 63 papers published since 2001
  - Phys. Rev. Lett. 41
  - Phys. Rev. C 15
  - Phys. Rev. D 4
  - Phys. Letter B 2
  - Nucl. Phys. A 1 (white paper)
- Total citation: >5000
  - Topcite 250+ 5
  - 100-250 11
  - 50-100 12
- 25 (8) papers submitted since January 2006
  - 21(8) published, 4(0) in review
  - PRL 12 (6)
  - PRC 5 (0)
  - PRD 3 (2)
  - Phy. Lett. 1 (0)



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

Summary

- A new form of dense matter is created in heavy ion collision at RHIC
- Many new measurements that probes the property of the newly discovered matter
  - J/ψ suppression / recombination
  - Heavy Flavor energy loss and flow
  - Direct photon
- RIKEN and RBRC plays very important role in this rapidly evolving field of phyiscs

QCDSP/QCDOC
Physics Results And Prospects/Projects Status

RBRC lattice QCD program and the Next Computer Project

November 6, 2007

Norman H. Christ

RBRC Lattice QCD Program

9:00 - 9:30	RBRC lattice QCD program and the Next Computer Project	Norman Christ
9:30 -10:00	K meson physics with domain wall fermions in the chiral limit	Robert Mawhinney
10:00 -10:30	The QCD phase transition and equation of state: toward physical quark masses and vanishing lattice spacing.	Peter Petreczky

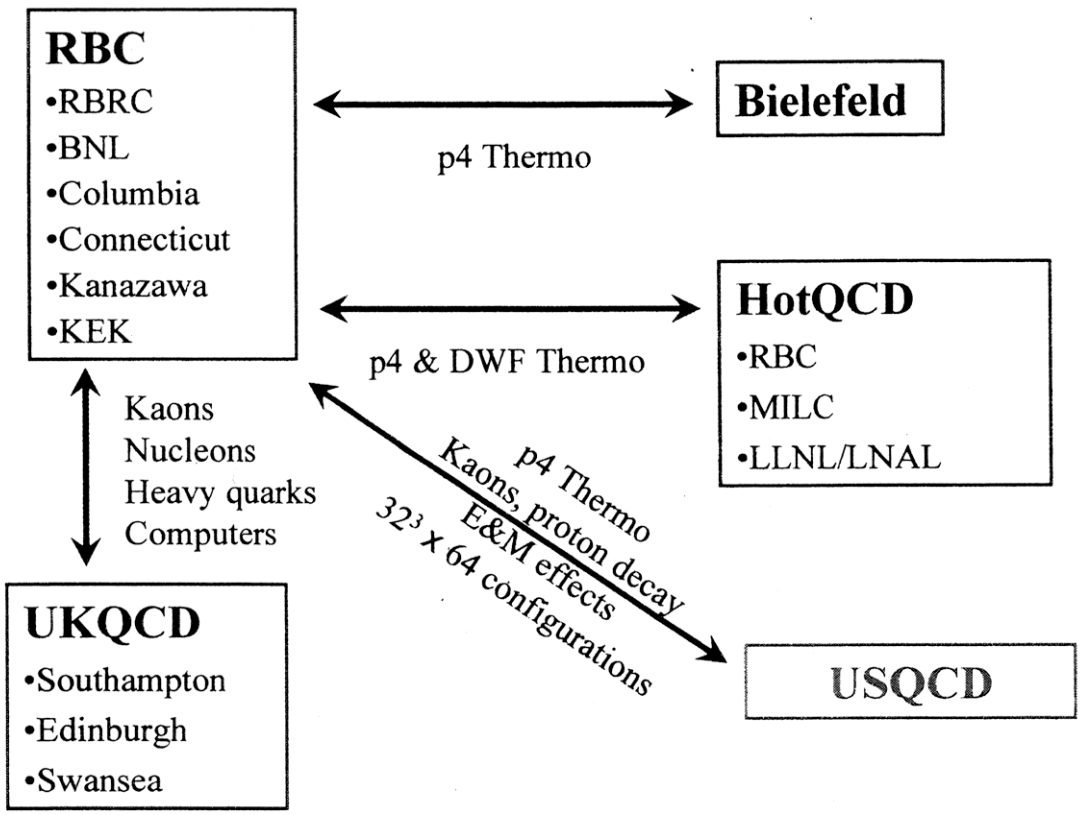
Outline

- RBRC Lattice QCD
  - Collaboration
  - Computer infrastructure
- Physics overview
- Domain wall fermions
- Configuration generation
- Physics results
  - Nucleon physics
  - Heavy quarks
  - $T \neq 0$, domain wall fermions
- The Next Computer Project

Collaborations

RBRC Review - Nov. 6, 2007 (4)

Collaborations



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  - Taku Izubuchi (Kanazawa)
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  - Takeshi Yamazaki (Connecticut)
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  - Saumen Datta
  - Shinji Ejiri
  - Chulwoo Jung
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  - Changhoan Kim
  - Min Li
  - Sam Li
  - Matthew Lightman
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  - HueyWen Lin (JLab)
  - Oleg Loktik (Goldman Sachs)
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  - Takashi Umeda (Tsukuba)

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  - Alistair Hart
  - Chris Kelly
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  - Richard Kenway
  - Chris Maynard
  - Brian Pendleton
  - Robert Tweedie
  - Jan Wennekers
  - Azusa Yamaguchi
  - James Zanotti
- Southampton
  - Michael Donellan
  - Jonathan Flynn
  - Andreas Juettner
  - Jun Noaki
  - Chris Sachrajda
- Swansea
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  - Aurora Trivini

Computers

RBRC Review - Nov. 6, 2007 (8)

QCDOC Collaboration

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  - Ludmila Levkova
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  - Guofeng Liu
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  - Shu Li
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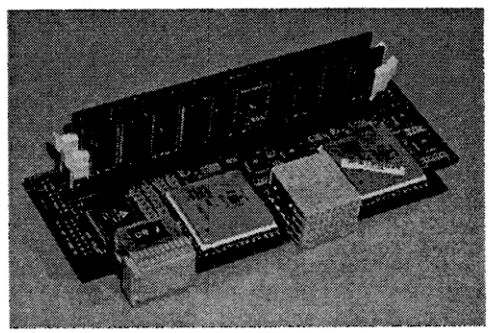
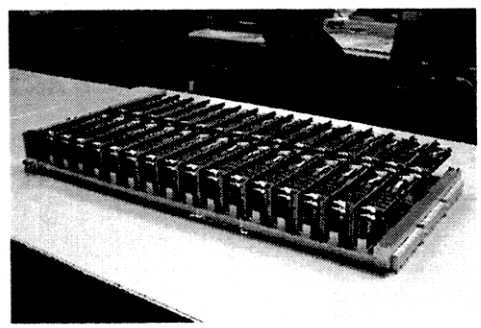
  - Chulwoo Jung
  - Konstantin Petrov
  - Stratos Efstathiadis
- UKQCD (PPARC)
  - Peter Boyle
  - Mike Clark
  - Balint Joo
- RBRC (RIKEN)
  - Shigemi Ohta
  - Tilo Wettig
- IBM
  - Dong Chen
  - Alan Gara
  - Design groups:
    - Yorktown Heights, NY
    - Rochester, MN
    - Raleigh, NC

QCDOC

- 6-D torus
- Double precision
- 0.3 Gflops sustained/node
  (~40% efficiency)
- Completed spring 2005
- 30 Tflops (peak) installed
- Parent of BlueGene
  (*Overview of the QCDSP and QCDOC computers*, IBM Research Journal, Vol 49, No. 2/3, p 351 (2005))

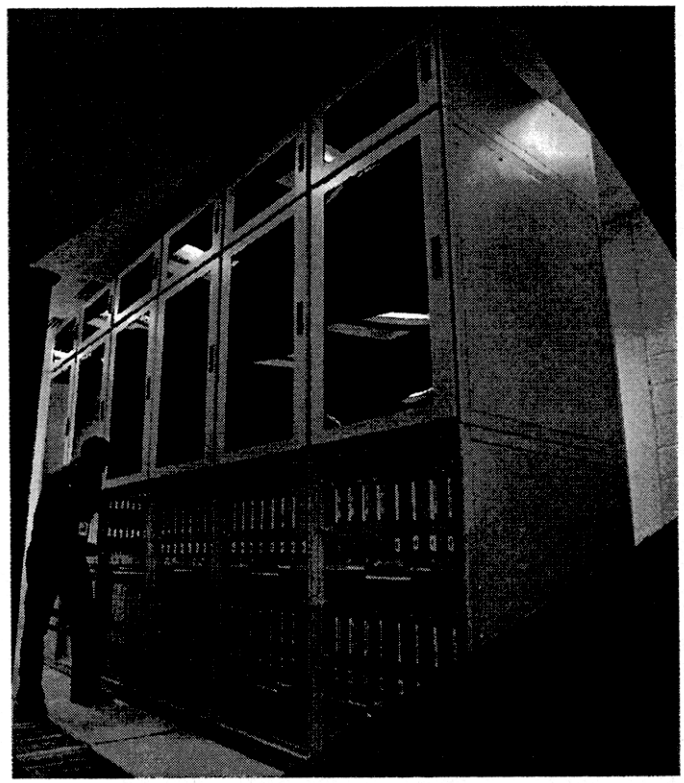




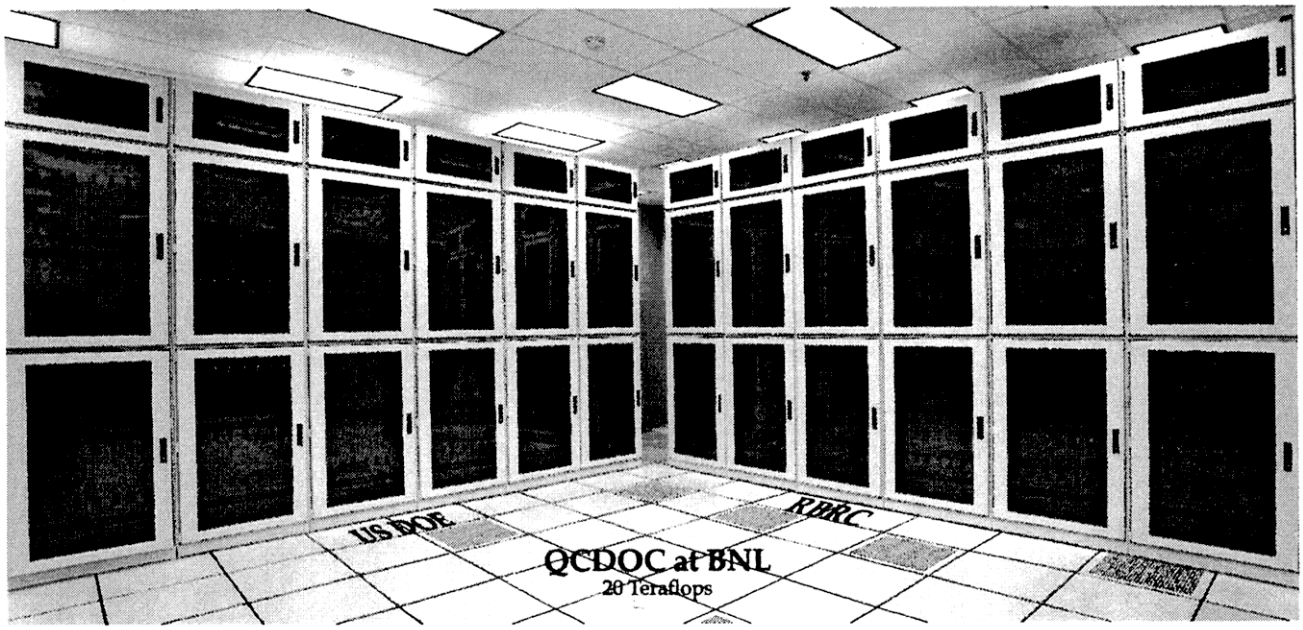
UKQCD Machine (12,288 nodes/10 Tflops)

UKQCD / Edinburgh

- 13K nodes
- Installed Dec. 2004

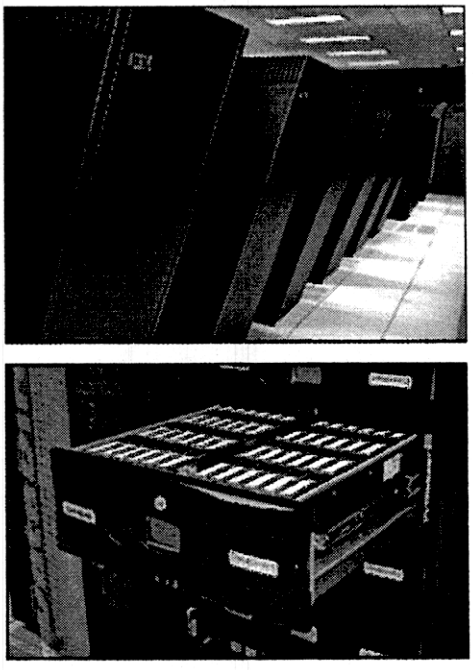


RBRC - US DOE / Brookhaven



- 24K nodes
- Installed May 2005

New York Blue



- IBM BlueGene
- 100 teraflops
- 18-rack configuration
- 36,864 processors

Computer Summary

Computer	Location	Sustained throughput
QCDOC	RBRC	4 Teraflops
	Edinburgh	4 Teraflops
	DOE	2 Teraflops *
BlueGene	NewYork Blue	[6 Teraflops *]
	LLNL	4 Teraflops *

* RBRC allocation

Physics Overview

Physics Overview

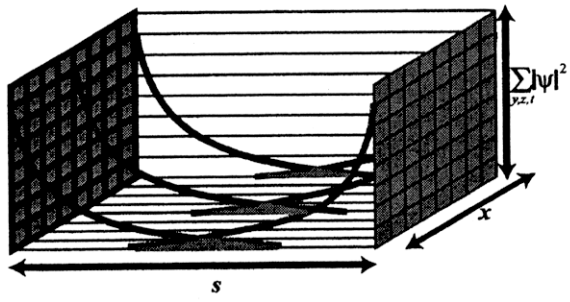
- Zero temperature
  - Domain wall fermions (10-year effort)
  - Kaon physics - Standard Model tests
  - Nucleon physics --- Tests of QCD
  - Heavy quarks - Standard Model tests
- Finite temperature
  - p4 action (T_c, EOS, $\mu > 0$, charm, transport coef's)
  - Domain wall fermions (exploration).

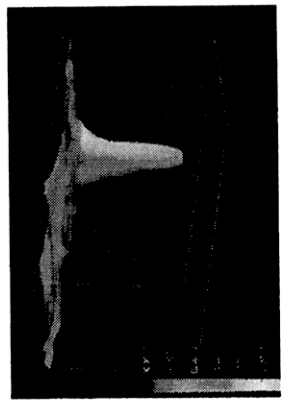
Domain Wall Fermions

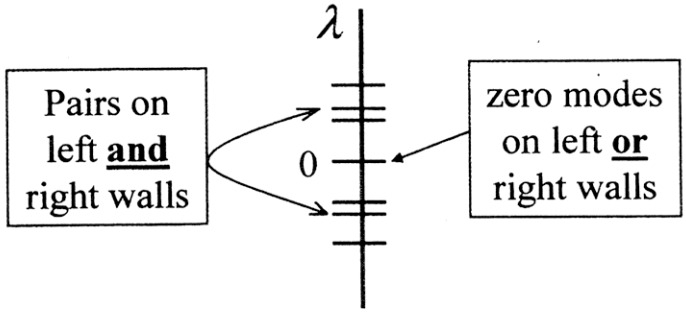
RBRC Review - Nov. 6, 2007 (18)

Domain Wall Fermions

- 5-D theory with 4-D, chiral surface states.
- Typical 5-D extent of 16.
- Excellent chiral symmetry.
- "Revolution" in the lattice treatment of fermions: Pioneered by the RBC and Tsukuba







Lattice Chiral Symmetry Breaking

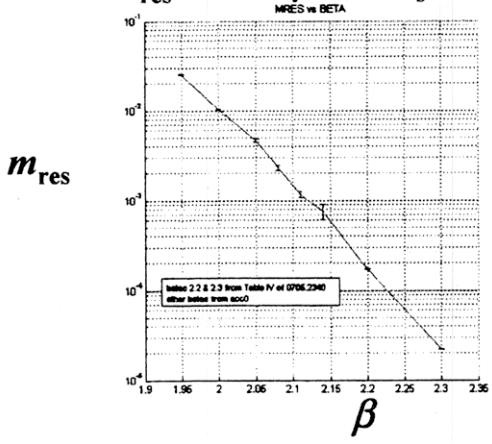
- Described by a "residual" mass: m_{res}

$$m_{\text{res}}(L_s) = c_1 \frac{e^{-\lambda_c L_s}}{L_s} + c_2 \frac{1}{L_s}$$

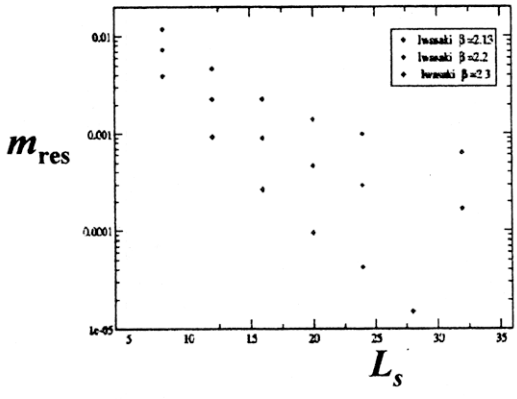
Standard 5-D states with $\lambda \sim$ lattice cutoff.

Localized states created by changing topology.

m_{res} versus β for $L_s = 32$



m_{res} versus L_s



2+1 Flavor DWF Ensembles

RHMC + Hasenbusch
(Mike Clark)

- Multi-time step
- Omelyan integrator
- Multi-mass preconditioning
- Rational Hybrid Monte Carlo
- Fractional power force reduction

Achieve > 6 overall speed up for large DWF calculations.

Optimization

(Peter Boyle, Mike Clark, Bob Mawhinney, Brian Pendleton)

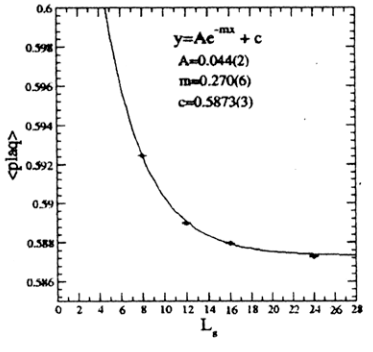
- For $N_f = 2+1$ simulations use m_s for preconditioning:

$$\mathcal{D}(m) \;=\; D^{\dagger}_{DWF}(m)\, D_{DWF}(m)$$

$$\frac{\det \mathcal{D}(m_l)\;\; \det \mathcal{D}(m_s)^{1/2}}{\det \mathcal{D}(1)^{3/2}} \;=\; \det\left[\frac{\mathcal{D}(m_l)}{\mathcal{D}(m_s)}\right] \cdot \det\left[\frac{\mathcal{D}(m_s)}{\mathcal{D}(1)}\right]^{1/2} \cdot \det\left[\frac{\mathcal{D}(m_s)}{\mathcal{D}(1)}\right]^{1/2} \cdot \det\left[\frac{\mathcal{D}(m_s)}{\mathcal{D}(1)}\right]^{1/2}$$

$$\det\left[\mathcal{D}(m_l)\right]^{\frac{1}{2}} = \int d[\phi] d[\phi^*] e^{-\phi^{\dagger}\left[\frac{1}{\mathcal{D}(m_l)}\right]^{\frac{1}{2}}\phi} = \int d[\phi] d[\phi^*] e^{-\sum_{n=1}^{N} \phi^{\dagger}\left[\frac{r_n}{c_n + \mathcal{D}(m_l)}\right]\phi}$$

- Use a "ratio" force term from numerator and denominator together.
- Use multiple step sizes.
- 75% acceptance.
- **The light quark requires only 10% of the computer time!**



2+1 Flavor DWF ensembles

- Compare: DBW2 and Iwasaki gauge actions, 16^3 x 32, $L_s = 8$. (**hep-lat/0612005**)
- Choose Iwasaki and $L_s = 16$: (**hep-lat/0701013**)
- $L = 2$ Fermi, $m_\pi \geq 390$ MeV, $L\, m_\pi \geq 3.8$

$a = 0.123$ Fermi, $1/a$=1.62 GeV, 16^3 x 32, $L_s = 16$			
ml/ms	m_π **(GeV)**	**HMC Time**	**Tflops x days**
0.767	619.5	4,000	13.69
0.535	517.1	4,000	14.12
0.302	388.8	4,000	15.20

- Available on the web: **http://lattices.qcdoc.bnl.gov/**

2+1 Flavor DWF ensembles

- Next generate larger volume: 24^3 x 64, $L_s = 16$.
- Same gauge action and lattice spacing.
- $L = 2.8$ Fermi, $m_\pi \geq 326$ MeV, $L\, m_\pi \geq 4.5$

$a = 0.115$ Fermi, $1/a$=1.73 GeV, 24^3 x 64, $L_s = 16$			
ml/ms	m_π **(GeV)**	**HMC Time**	**Tflops x days**
0.767	661	2813	70
0.535	552	2850	74
0.302	415	5040	148
0.186	326	7000	225

2+1 Flavor DWF ensembles

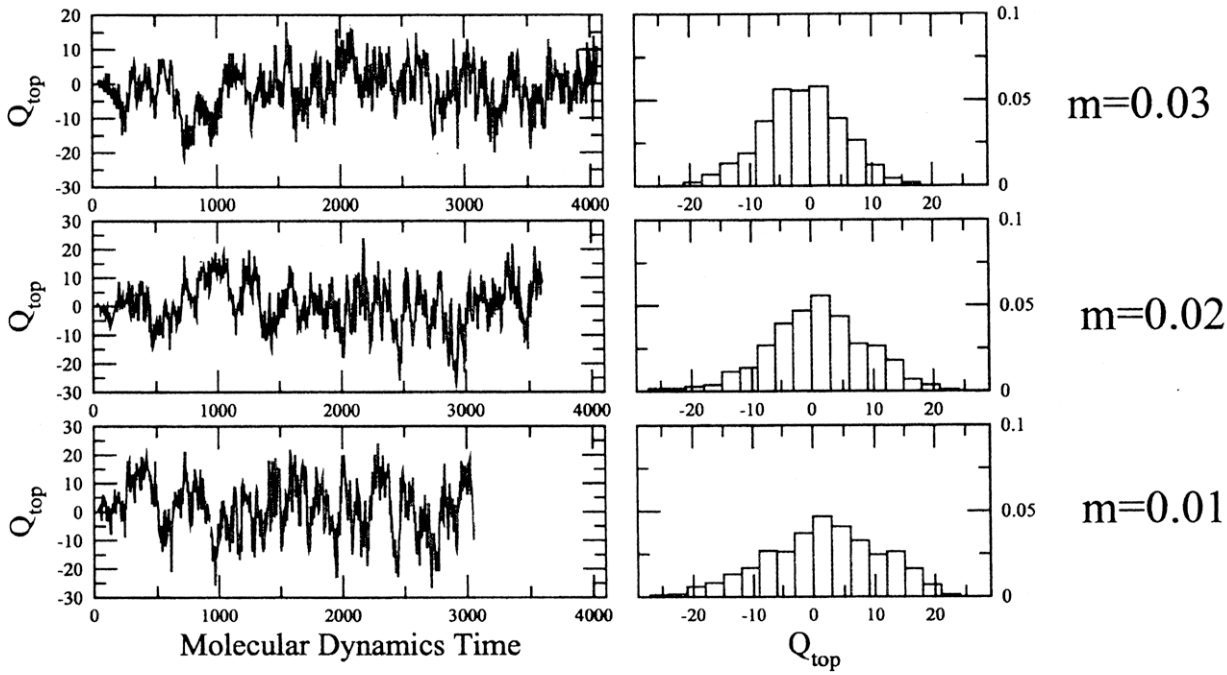
- Start a smaller lattice spacing:

  $1/a$ = 1.73 GeV → 2.2 GeV

- 24^3 x 64 → 32^3 x 64
- Same gauge action and $L_s = 16$.
- L = 3 Fermi, $m_\pi \geq 270$ MeV, $L\, m_\pi \geq 3.9$

a = 0.091 Fermi, $1/a$=2.2 GeV, 32^3 x 64, $L_s = 16$			
ml/ms	m_π **(GeV)**	**HMC Time**	**Tflops x days**
0.22	323	1604	150
0.15	270	2000	222

Topological charge evolution



Physics Results

Physics Projects ($T = 0$)

- $K - \bar{K}$ mixing (ε)
- $Kl3$ decays
- Direct CP violation (ε'/ε), ΔI=1/2 rule
- Nucleon decay
- Hyperon decay
- Neutron electric dipole moment
- Nucleon charges and form factors
- Nucleon structure functions
- Mass of η'
- Electromagnetic mass splittings
- Quark masses: m_s, m_u and m_d
- Charm spectroscopy with NPR Fermilab action
- B-B mixing B_d and B_s in with static + DWF with 1-loop lattice PT → NPR?

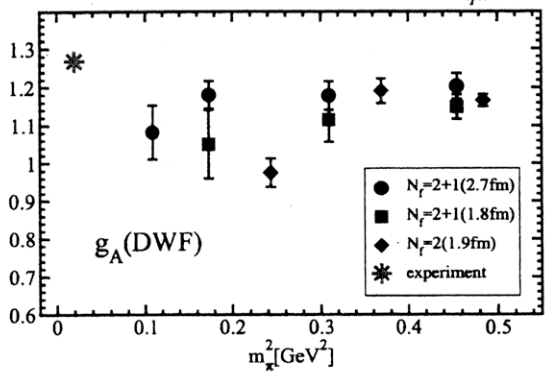
Nucleon Structure

(Yasumichi Aoki, Tom Blum, HueyWen Lin,Shigemi Ohta, Shoichi Sasaki, Takeshi Yamazaki)

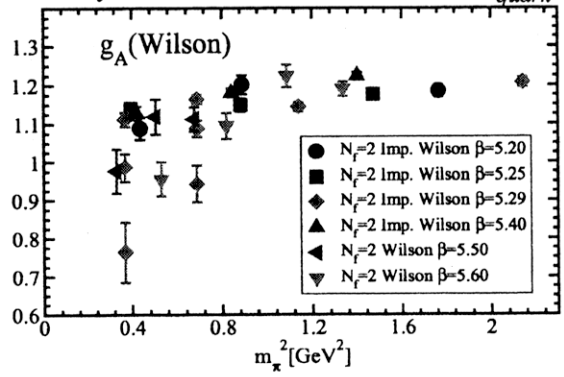
- Axial charge, g_A
- Ground and excited state masses
- Axial and vector form factors
- Low moments of nucleon structure functions
- Nucleon decay matrix elements
- Important result on volume effects

Volume dependence of g_A

Dynamical DWF – versus m_{quark}

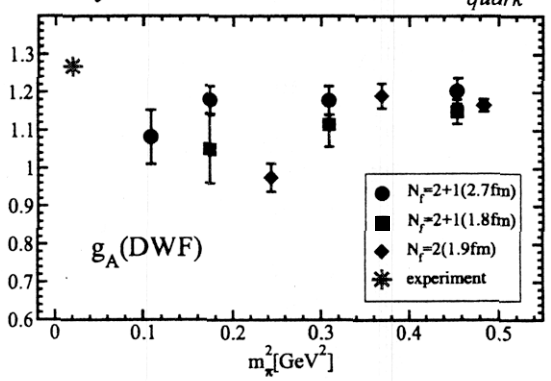


Dynamical Wilson – versus m_{quark}

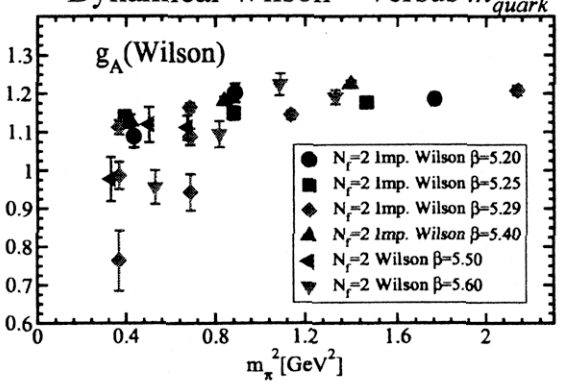


Volume dependence of g_A

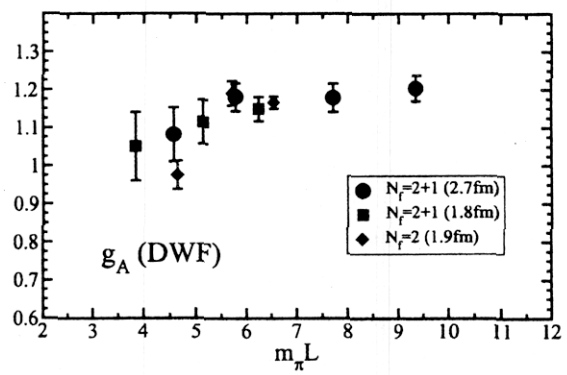
Dynamical DWF – versus m_{quark}



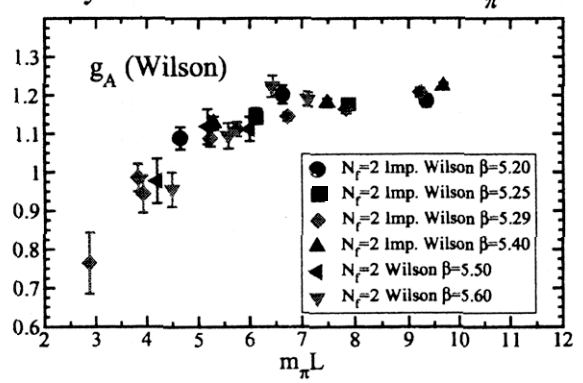
Dynamical Wilson – versus m_{quark}



Dynamical DWF – versus $m_\pi L$

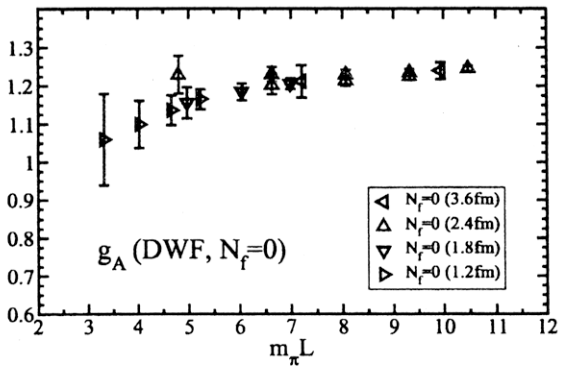


Dynamical Wilson – versus $m_\pi L$

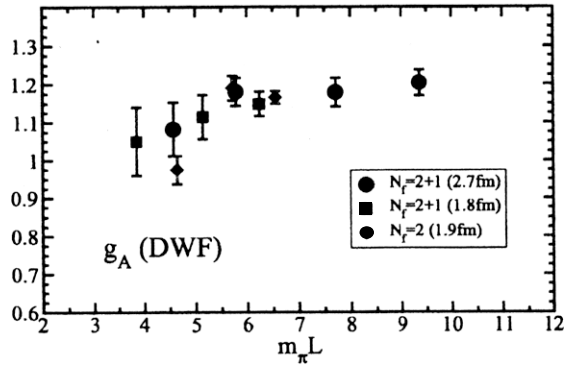


Volume dependence of g_A

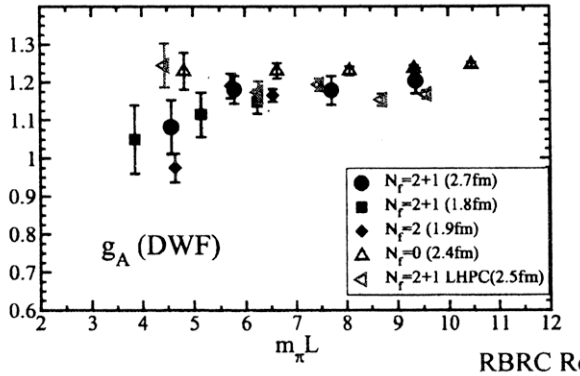
Quenched



Dynamical DWF



Dynamical DWF + Quenched



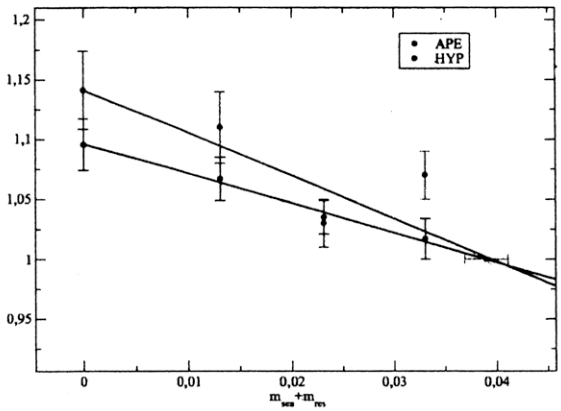
Heavy quarks and lattice QCD

- Static approximation
  - Lattice version of HQET
  - Calculate f_B, f_{B_s}, B_B and B_{B_s}
  - Use two static link smearings and perturbative renormalization
- Fermilab/Tsukuba action
  - 3-parameter effective action, removes all $(ma)^n$ errors
  - Determine all heavy-heavy and heavy-light charm states in terms of one new parameter, c_P
  - Independent determination of lattice spacing

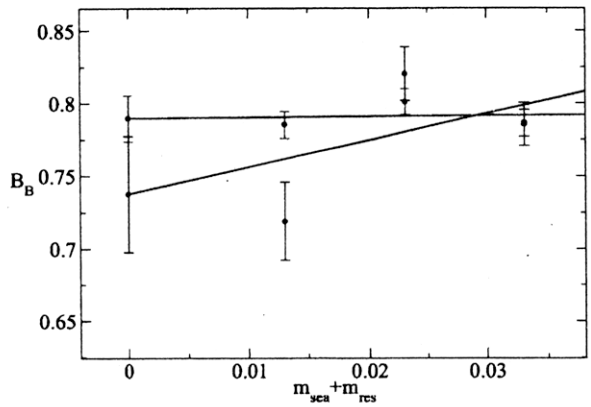
Static: f_B, and B_B

(Yasumichi Aoki, Thomas Dumitrescu, Jonnathan Flynn,
Tomomi Ishikawa, Taku Izubuchi, Oleg Loktik, Yan Wennekers)

f_{B_S}/f_B



B_B



Large $O(a)$ errors and insufficient statistics?

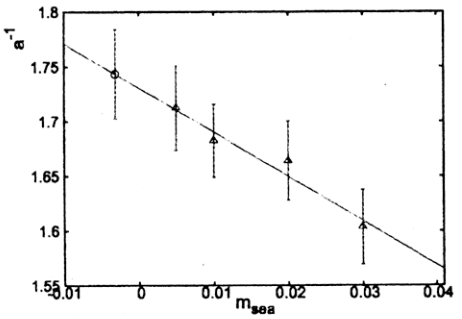
RHQ: Determine lattice spacing

(Min Li and Huey-Wen Lin)

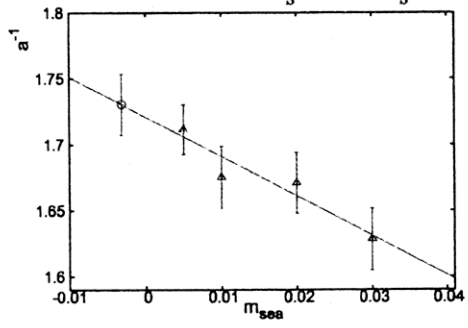
- J/ψ and $\eta_c \rightarrow m_0$ and c_P
- Use experimental χ_{c0} and χ_{c1} masses and fit for *a*.
- Gives $1/a$ = 1.743(41) GeV
- Ω^- mass implies: $1/a$ = 1.73(3) GeV
- Using the D_s and D_s^* which can be more accurately calculated: 1/a = 1.730(23)

m_0	c_P	ζ	$1/a$ (GeV)
0.247(38)	2.083(65)	1.241(10)	1.730(23)

$1/a$ from χ_{c0} and χ_{c1}



$1/a$ from D_s and D_s^*



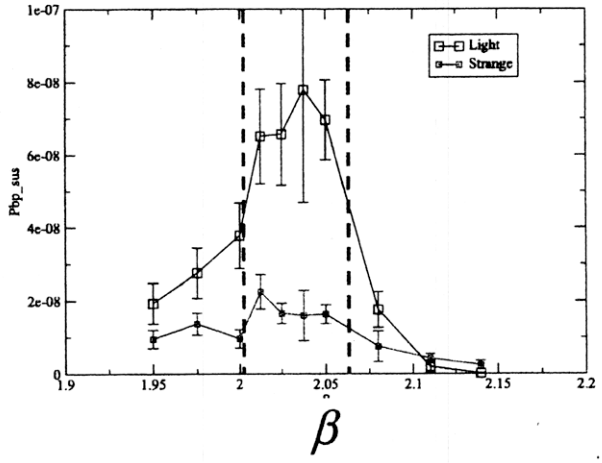
QCD Phase Transition with DWF!

- Most finite temperature studies use staggered quarks.
- DWF calculation provides an important test.
- Good chiral symmetry may be important for a chiral transition?
- Large lattice spacings of $T>0$ calculations make DWF challenging.

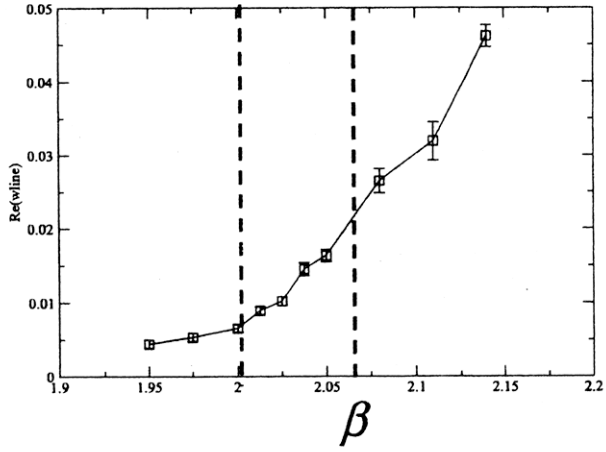
Clear signal for T_c

(Michael Cheng, Dwight Renfrew)

$\langle\bar{q}q\rangle$ susceptibility



Wilson line



- 16^3 x 8, 2+1 flavor, $L_s = 32$
- Increase $L_s = 32 \rightarrow 64$?
- Add $\det\{(D+M_5+i\delta\gamma^5)/(D+M_5+i\Delta\gamma^5)\}$ to suppress dislocations. (Vranas/KEK)

The Next Computer Project

RBRC Review - Nov. 6, 2007 (39)

Next Computer Project

- Technology
  - Reduction in feature size → 128 FPU's on a chip.
  - Target $0.01/Mflops (100 x enhancement) in 2010.
    (100 x from 2005 → 2010 is 10 x better than Moore's law.)
  - Complex design and $4-5M NRE costs.
- Strategy
  - ~~More QCD-specialized architecture~~ ?
  - Work with IBM team at Watson Research!
  - Columbia-Edinburgh-IBM design collaboration.
  - Plan a ~300 (sustained) Teraflops computer.
  - Prototype of possible IBM system.
  - This and equal UK machine constructed at BNL.
- Status
  - Design document passed internal review.
  - VHDL design to begin in 2-3 weeks.

Conclusion

- Exciting physics program --- important physics problems are being solved.
- Large and varied group of physicists --- many opportunities to learn.
- Next computer project offers a new level of research potential.
  - Accurate control of chiral limit
  - Treat 2-particle states ($K \rightarrow \pi\pi$)
  - Do nucleon physics on 6 Fermi box.
  - Use step-scaling to decrease α_s in perturbative matching: $\alpha_s \sim 1/N_{\text{steps}}$
  - Explore new field theories, supersymmetry, large N_c, large N_f, higher dimensions....

Results from 2+1 flavor domain wall fermion QCD

Robert Mawhinney
Columbia University

RBRC Review
November 6, 2007

- Low energy hadronic observables and chiral perturbation theory
- Indirect CP violation in kaons: B_K
- Direct CP violation in kaons: ε'/ε

Basics of Lattice QCD

- Sample phase space for Feynman path integral for QCD using importance sampling

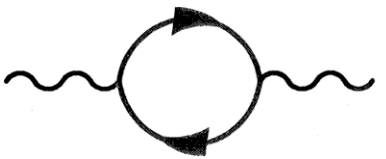
$$\begin{aligned} Z &= \int [dU]\, \Pi_i [d\psi_i]\, [d\bar{\psi}_i]\, \exp\left\{ \sum_n \left[-\beta S_g + \sum_i \bar{\psi}_i (\not{D} + m) \psi_i \right] \right\} \\ &= \int [dU]\, \Pi_i \det(\not{D} + m_i) \exp\left\{ \sum_n (-\beta S_g) \right\} \end{aligned}$$

- Numerically evaluate n-point functions for QCD. Example is 2-point pion correlator:

$$\langle (\overline{\psi}\gamma_5 \tau^a \psi)_x\ (\overline{\psi}\gamma_5 \tau^b \psi)_y \rangle$$

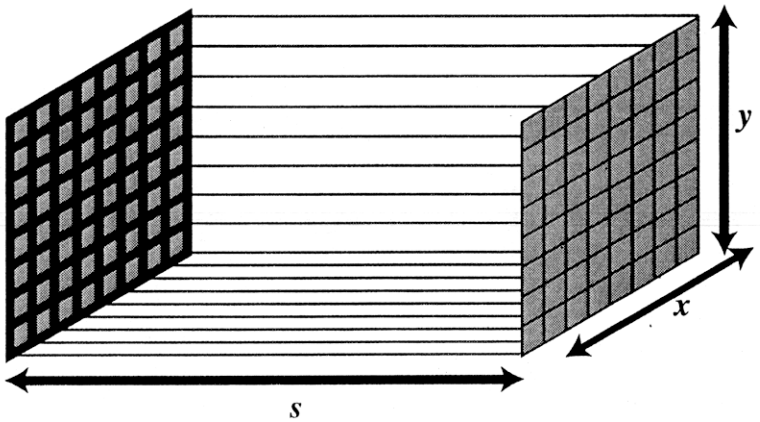
$$= \frac{1}{Z} \int [dU]\, \Pi_i \det(\not{D}+m_i) \exp\left\{ \sum_n (-\beta S_g) \right\} \mathrm{Tr}\left[\gamma_5 \tau^a ((\not{D}+m)^{-1}_{x,y} \gamma_5 \tau^b (\not{D}+m)^{-1}_{y,x} \right]$$

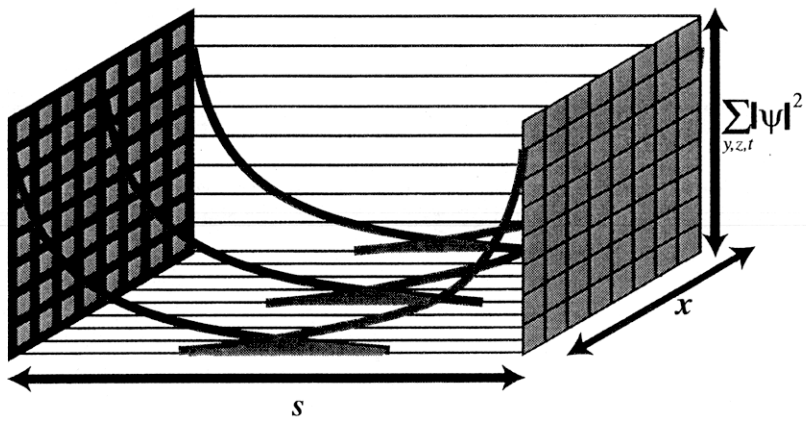
$\Updownarrow$ m_{dyn} $\quad$ $\Updownarrow$ m_{val} $\quad$ $\Updownarrow$ m_{val}

- Leaving out $\det(\not{D} + m)$ is quenching, which removes 

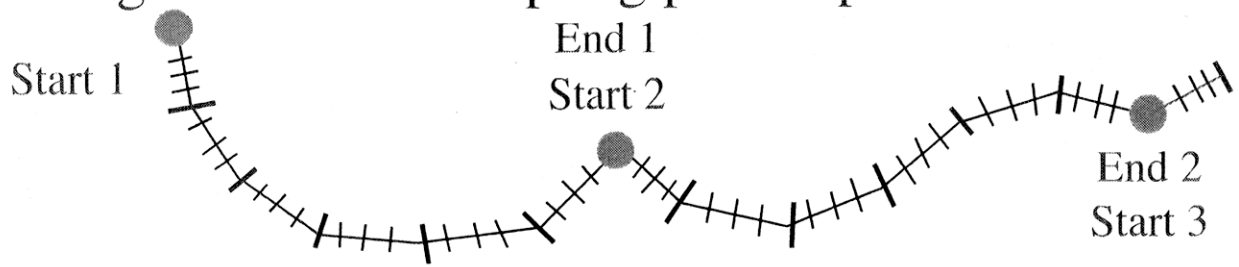
Improvements in Lattice Calculations

- Better lattice fermion formulations, particularly domain wall fermions





- Improved algorithms for sampling phase space



- Faster computers: QCDOC, BG/L, BG/P, ...

→ two light quarks and one strange quark in simulations

24^3 Ensembles: Scale and Quark Masses

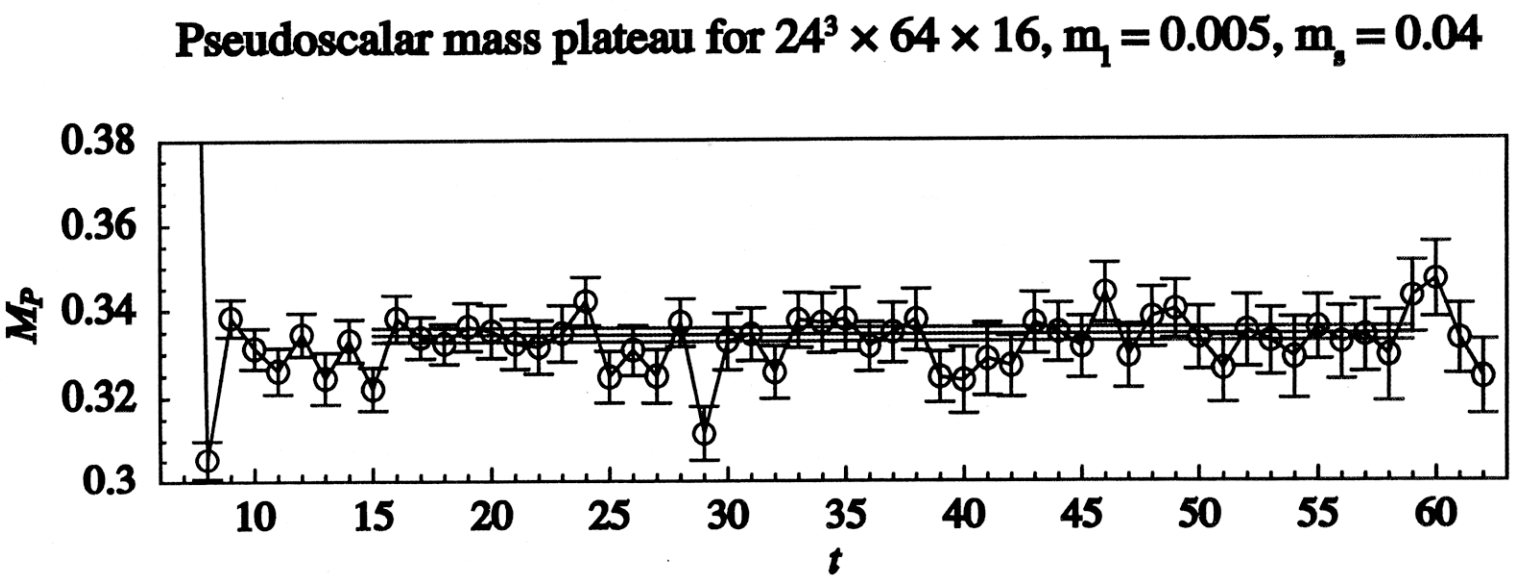
Input m_π, m_K, and m_Ω; results are at single lattice spacing; stat. errors only

Quantity	Value	MILC (2006) (a→0)	Experiment
$m_l^{\overline{MS}}(2\ GeV)$	3.72(16) MeV	3.3(0)(2)(2)(0) MeV	
$m_s^{\overline{MS}}(2\ GeV)$	107.3(4.5) MeV	90(0)(5)(4)(0) MeV	
f_π	124.1(3.6) MeV	128.6(0.4)(3.0) MeV	130.7±0.1±0.36 MeV
f_K	149.6(3.6) MeV	155.3(0.4)(3.1) MeV	159.8±1,4±0.44 MeV → 155 MeV
m_s/m_l	28.8(4)	27.2(0)(4)(0)(0)	
$m_{res}^{\overline{MS}}(2\ GeV)$	9.03(4) MeV		
f_K/f_π	1.205(13)	1.208(2)(+7 -14)	

MILC errors: statistics, simulation systematics, pert. theory, E&M

24^3 Ensembles and light pseudoscalars

- Need to set scale and determine quark masses
- Requires ability to extrapolate from simulation masses to physical masses
- Good statistics for light pseudoscalars (π, K) from long time extent
- Individual masses have errors of 0.2-0.6%, decay constant 0.5-0.9%



Chiral Perturbation Theory

- Expansion in powers of

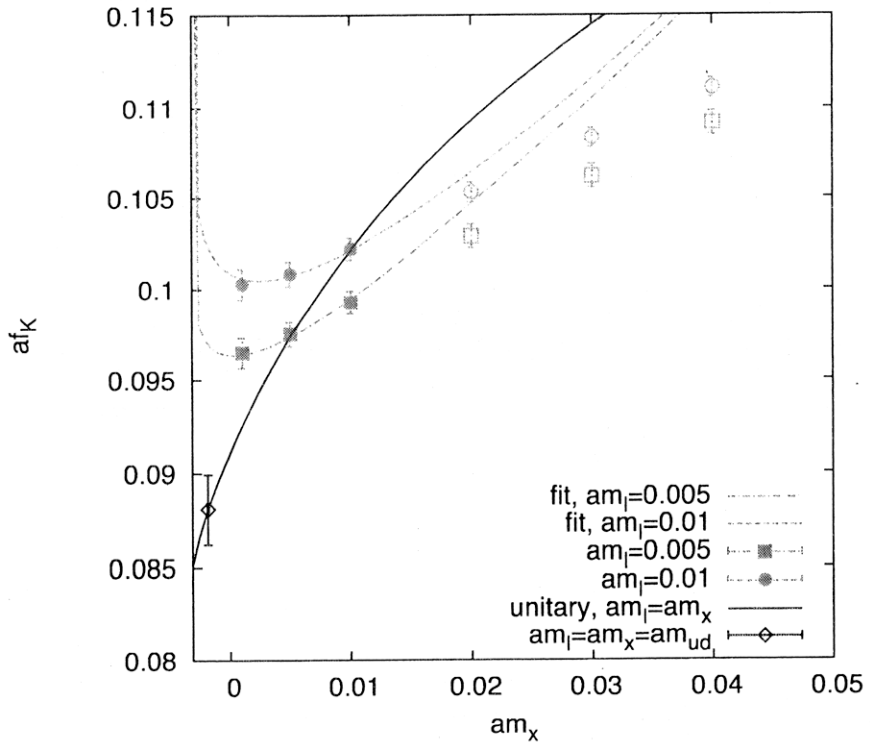
$$\frac{m_{PS}^2}{(4\pi f)^2} \qquad \frac{p^2}{(4\pi f)^2}$$

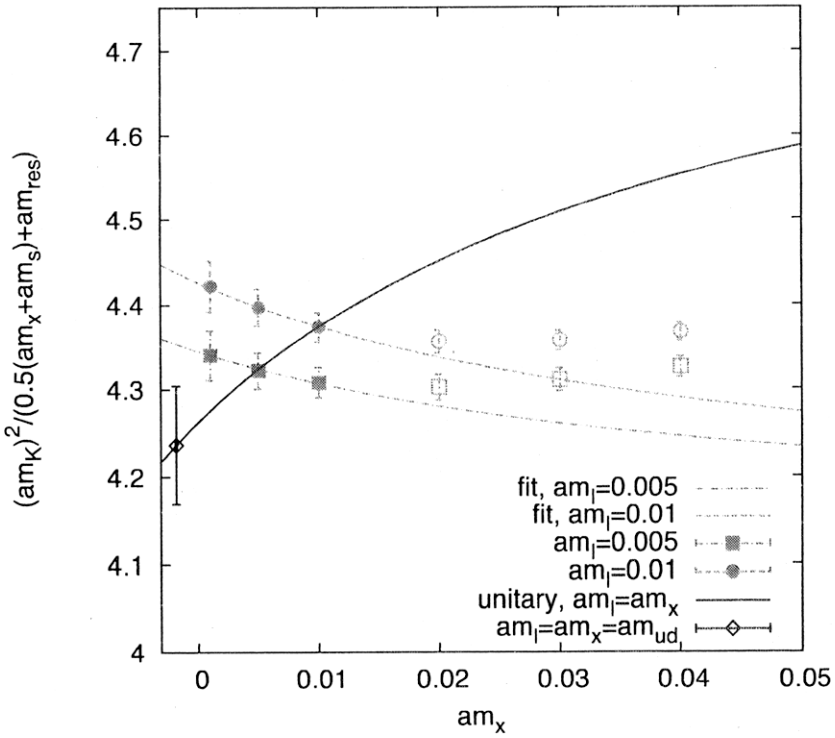
- SU(2) ChPT: m_l is light and only pion masses enter in logs
- SU(3) ChPT: m_l and m_s are considered light, and both enter logs
- SU(3) example (Sharpe and Shoresh, 2000) with six free parameters

$$\begin{aligned}
m_P^2 &= \chi_V \left\{ 1 + \frac{48}{f^2}(2L_6 - L_4)\bar{\chi} + \frac{16}{f^2}(2L_8 - L_5)\chi_V \right. \\
&\quad + \frac{1}{24 f^2 \pi^2}\left[\frac{2\chi_V - \chi_l - \chi_s}{\chi_V - \chi_\eta}\chi_V \log\chi_V - \frac{(\chi_V - \chi_l)(\chi_V - \chi_s)}{(\chi_V - \chi_\eta)^2}\chi_V \log\chi_V \right. \\
&\quad \left. \left. + \frac{(\chi_V - \chi_l)(\chi_V - \chi_s)}{\chi_V - \chi_\eta}(1 + \log\chi_V) + \frac{(\chi_\eta - \chi_l)(\chi_\eta - \chi_s)}{(\chi_V - \chi_\eta)^2}\chi_\eta \log\chi_\eta \right] \right\} \\
f_P &= f\left\{ 1 + \frac{8}{f^2}(3L_4\bar{\chi} + L_5\chi_V) \right. \\
&\quad \left. - \frac{1}{16\pi^2 f^2}\left[(\chi_V + \chi_l)\log\frac{\chi_V + \chi_l}{2} + \frac{\chi_V + \chi_s}{2}\log\frac{\chi_V + \chi_s}{2} \right] \right\} \\
\chi_i &= 2B_0(m_i + m_{\rm res})
\end{aligned}$$

24^3 Ensembles - SU(2) chiral fits

- SU(2) does not require kaon to be considered as light
- Only use pseudoscalar masses below 350 MeV
- Interpolate in valence m_s to physical value (dynamical m_s unchanged)

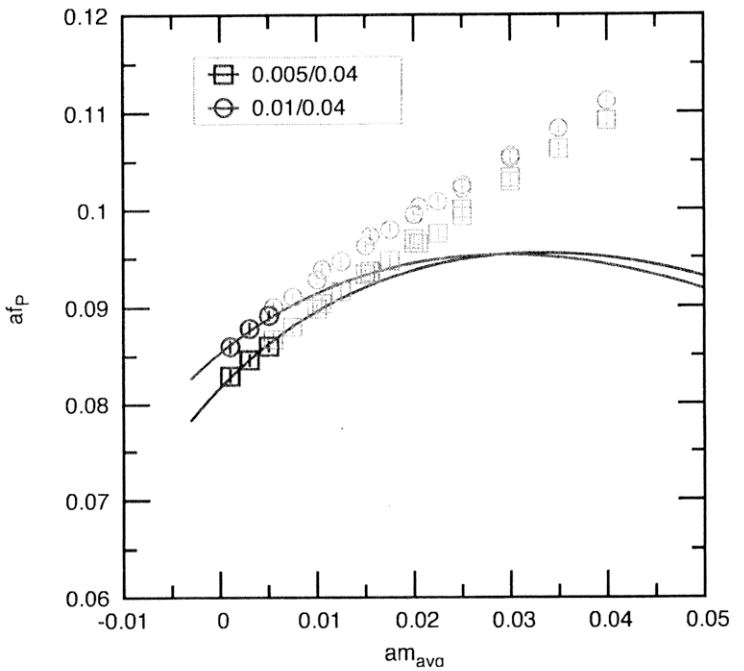


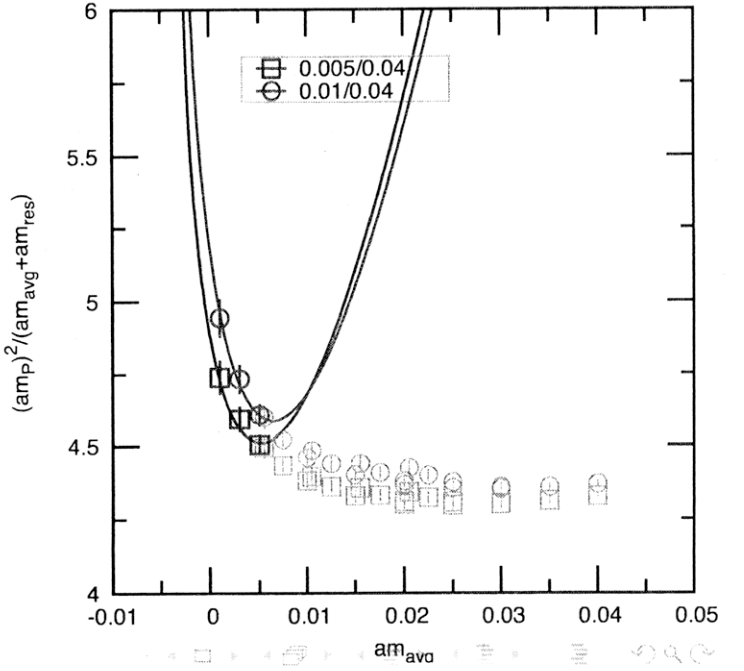


24^3 Ensembles: SU(3) Chiral Perturbation Theory

- Fit continuum NLO ChPT with quark masses shifted by m_{res}
- Simultaneous fit to m_π and f_π with 6 free parameters and 12 points
- Good agreement between data and theory provided $m < \approx 400$ MeV
- Yields values for 4 low energy constants. At $\Lambda = 770$ MeV find:

	$10^4(2L_8 - L_5)$	$10^4(2L_6 - L_4)$	$10^4 L_4$	$10^4 L_5$	$10^4 L_8$
RBC-UKQCD	2.47(45)	-0.02(42)	1.36(80)	8.62(99)	5.54(40)
Bijnens	2.3	0	0	9.7(11)	6.0(18)



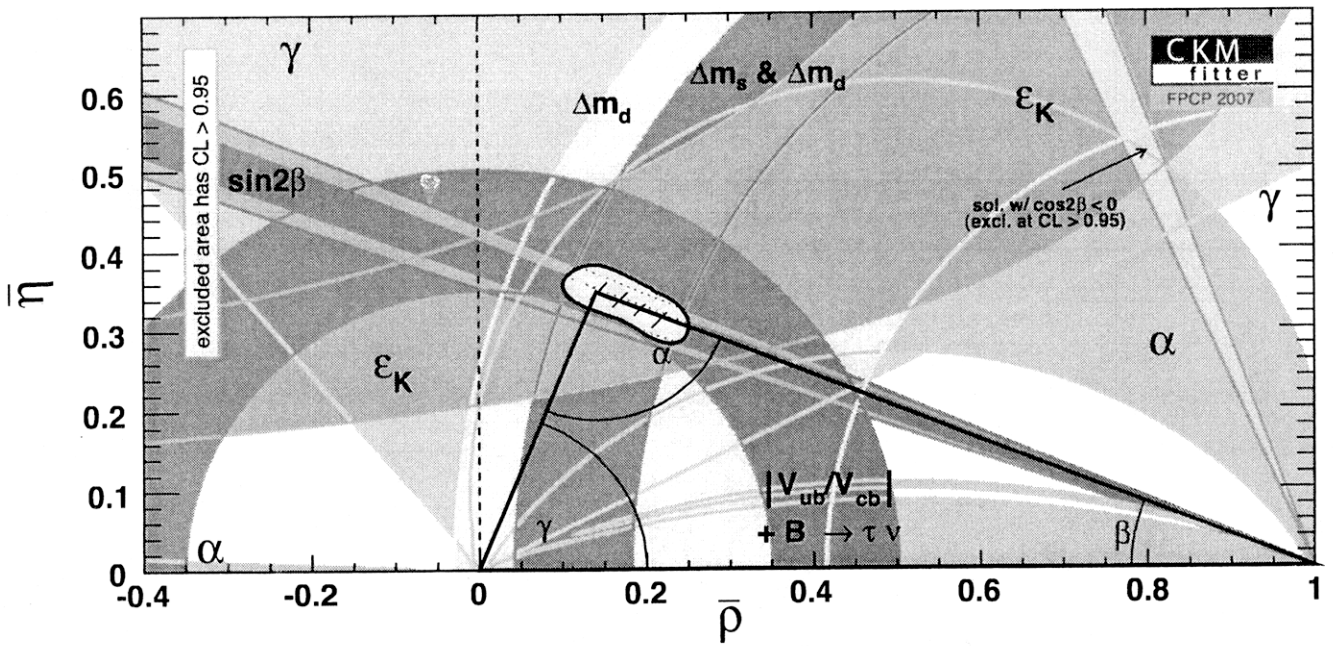


CP Violation Measurements

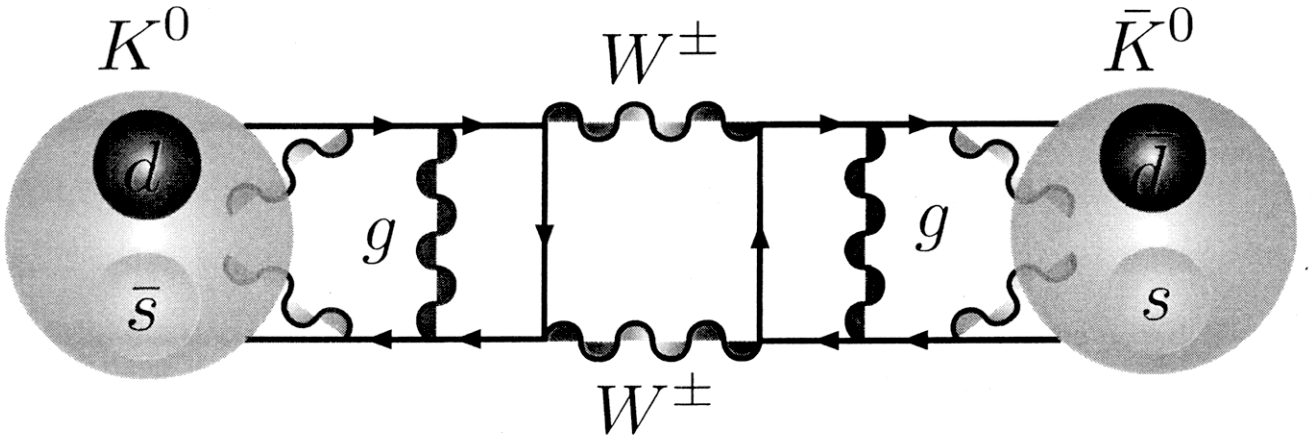
- In kaons, both direct and indirect CP violation observed

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \qquad \eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

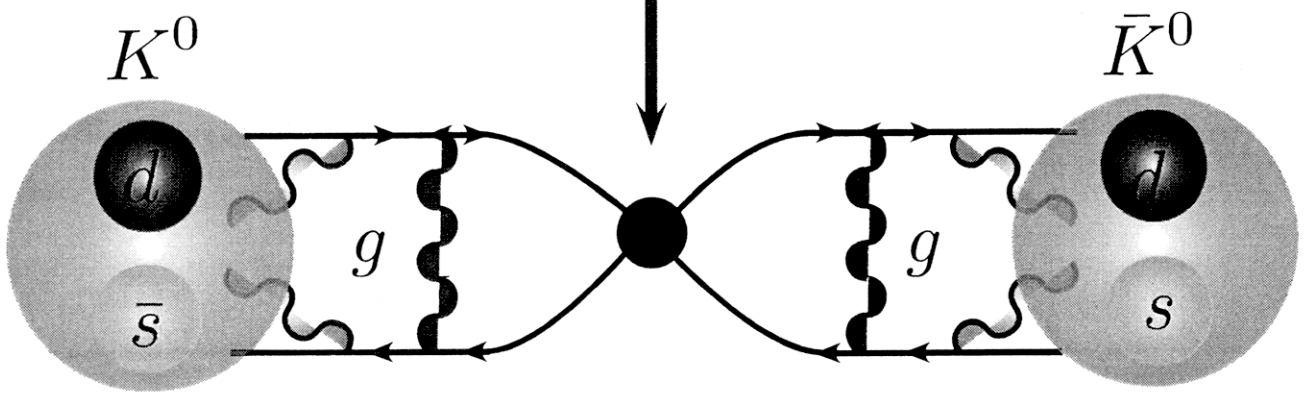
- Need QCD simulations to compare CP violation in kaons and B mesons
- Single CKM parameter (η) is dominant source of CP violation in SM



Low Energy Standard Model Diagrams for B_K



Electroweak process at high energy scales reduce to a single 4-fermion operator at low energies



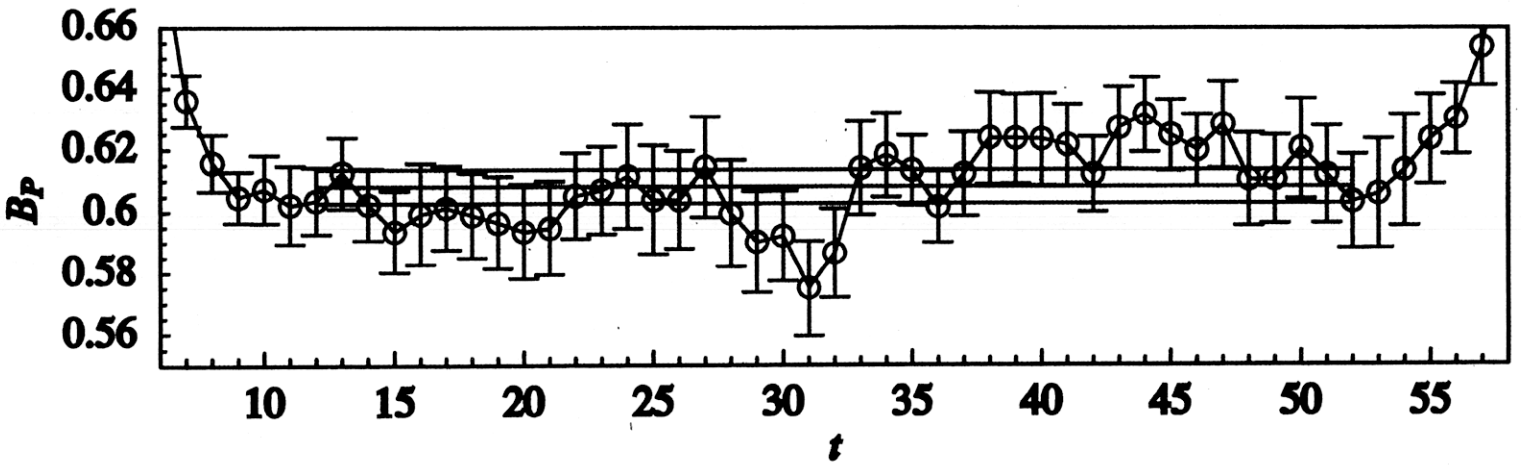
Need correctly normalized value of the $Q^{\Delta S=2}$ operator in kaon states.

$$\epsilon = \hat{B}_K \, \mathrm{Im}\lambda_t \, \frac{G_F^2 f_K^2 m_K M_W^2}{12\sqrt{2}\pi^2 \Delta M_K} \left\{ \mathrm{Re}\lambda_c \left[\eta_1 S_0(x_c) - \eta_3 S_0(x_c, x_t) \right] - \mathrm{Re}\lambda_t \, \eta_2 S_0(x_t) \right\} \exp(i\pi/4)$$

$$\langle \overline{K}^0 | Q^{(\Delta S=2)}(\mu) | K^0 | \rangle \equiv \frac{8}{3} B_K(\mu) f_K^2 m_K^2$$

From Lattice Values for B_K to Continuum

- Long time extent of lattices produces good volume averaging



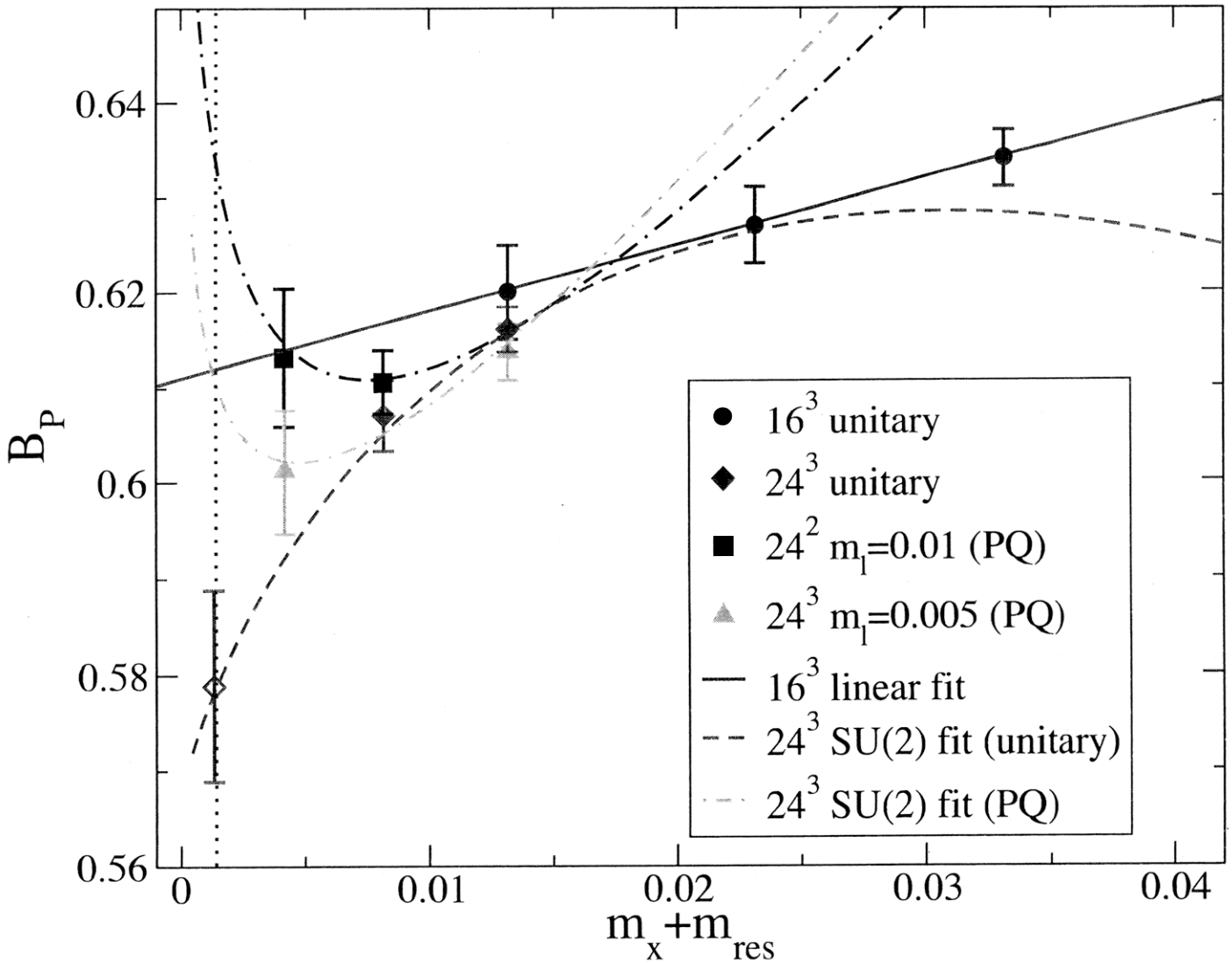
- Domain wall fermions control operator mixing and allow non-perturbative renormalization

$$Z_{B_K}^{\rm RI}(2\ {\rm GeV}) \quad = \quad 0.910(5)(13)$$

- Convert to $\overline{\rm MS}$ using NLO pert. theory (2% effect), adding 2% sys. error

$$Z_{B_K}^{\overline{\rm MS}}(2\ {\rm GeV}) \quad = \quad 0.928(5)(23)$$

Light Quark Chiral Limit for B_K using SU(2) ChPT

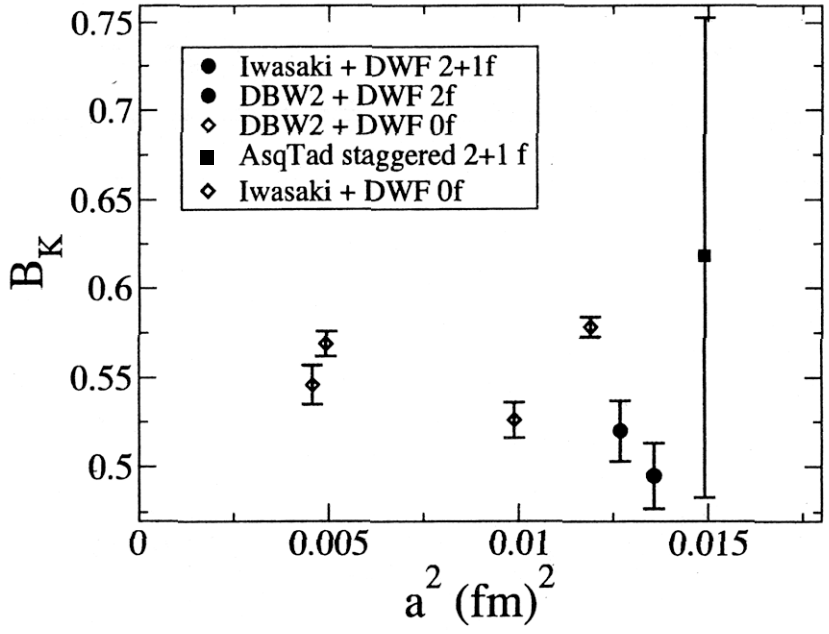


Result for B_K

- Calculation at a single lattice spacing, but estimate a –› 0 error as 4%

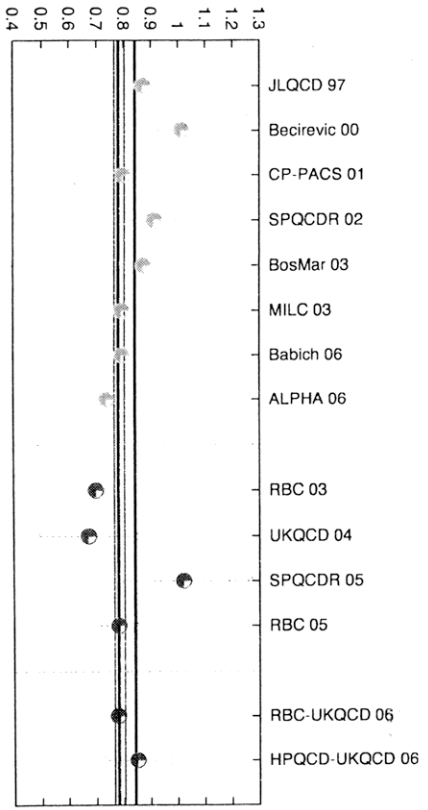
$$B_K^{\overline{\rm MS}}(2\ {\rm GeV}) = 0.524(10)(21)(18)$$

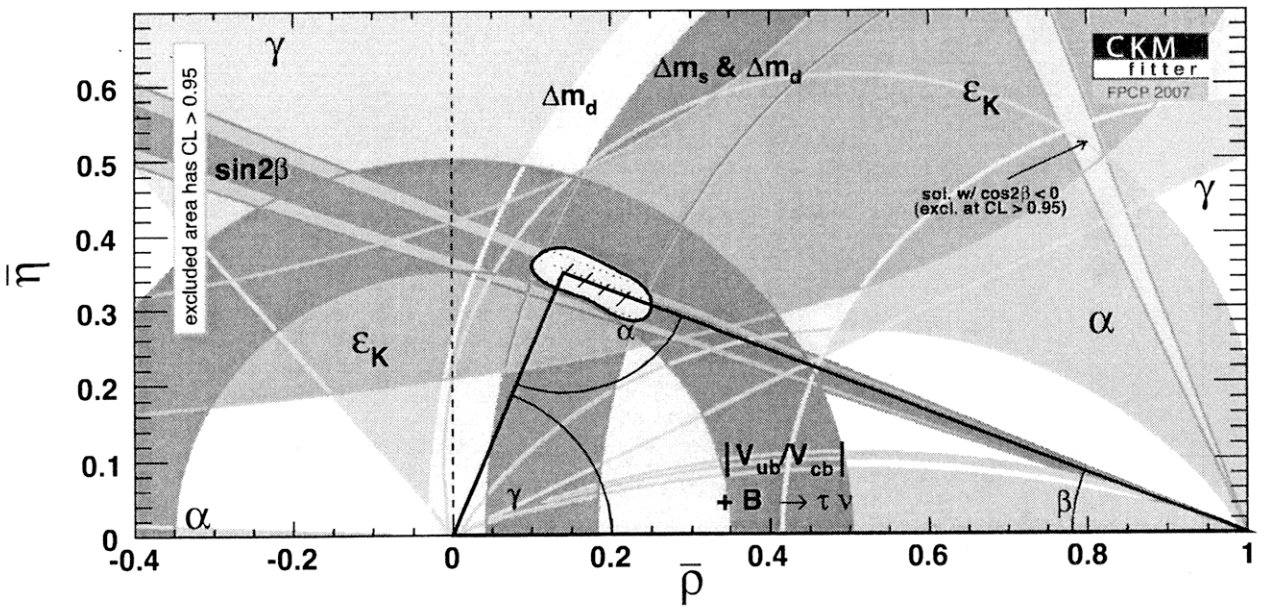
- Errors are statistical (2%), single finite lattice spacing (4%), and other systematics (2% ChPT fit, 2% renormalization, 1% m_s, 1% finite volume).
- World average (without our result) was 0.58(3)(6)



B_K and the Unitarity Triangle

- RG invariant result from RBC and UKQCD (hep-ph/0702042): 0.720(13)(37)
- CKM Fitter (2007) uses: 0.79(2)(9)

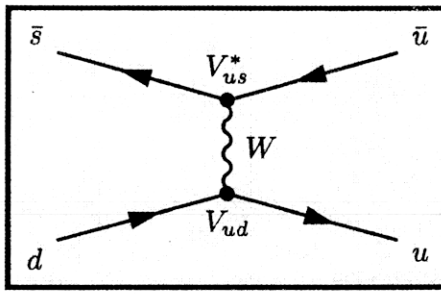




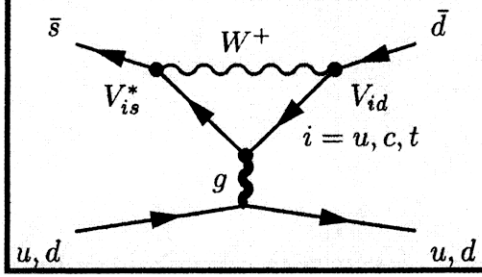
Tantalo, hep-ph/0703241, CKM 2006

Standard Model Diagrams for ε´/ε

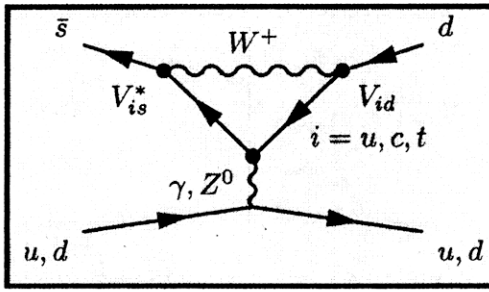
$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \qquad \eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$



→ Exchange diagrams
$Q_1 + Q_2$
These should dominate ΔI = 1/2 rule at μ = 2 GeV



→ Gluonic penuins
$Q_3 + Q_4 + Q_5 + Q_6$
Q_6 should dominate ΔI = 1/2 contribution to ε´/ε at μ = 2 GeV

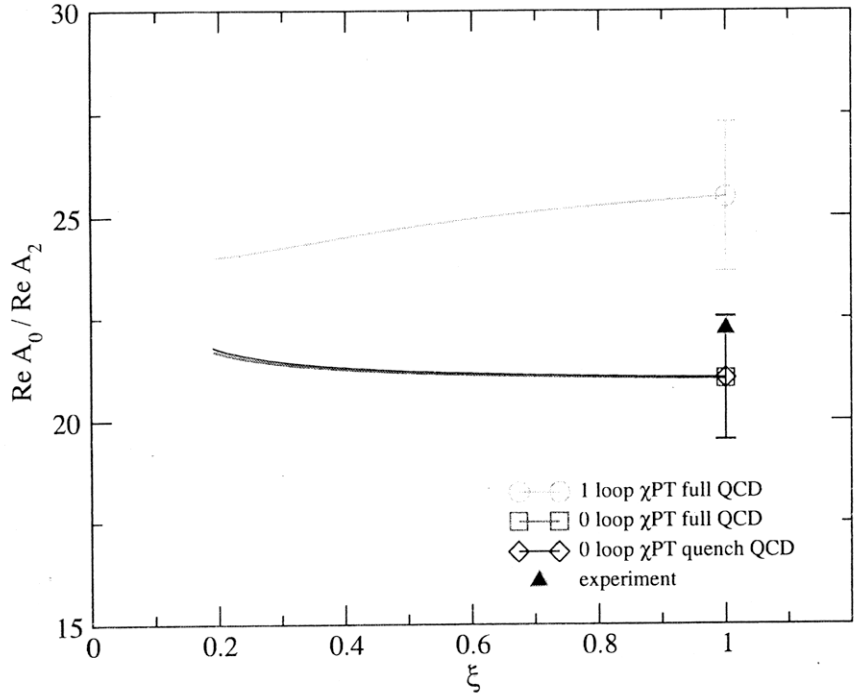


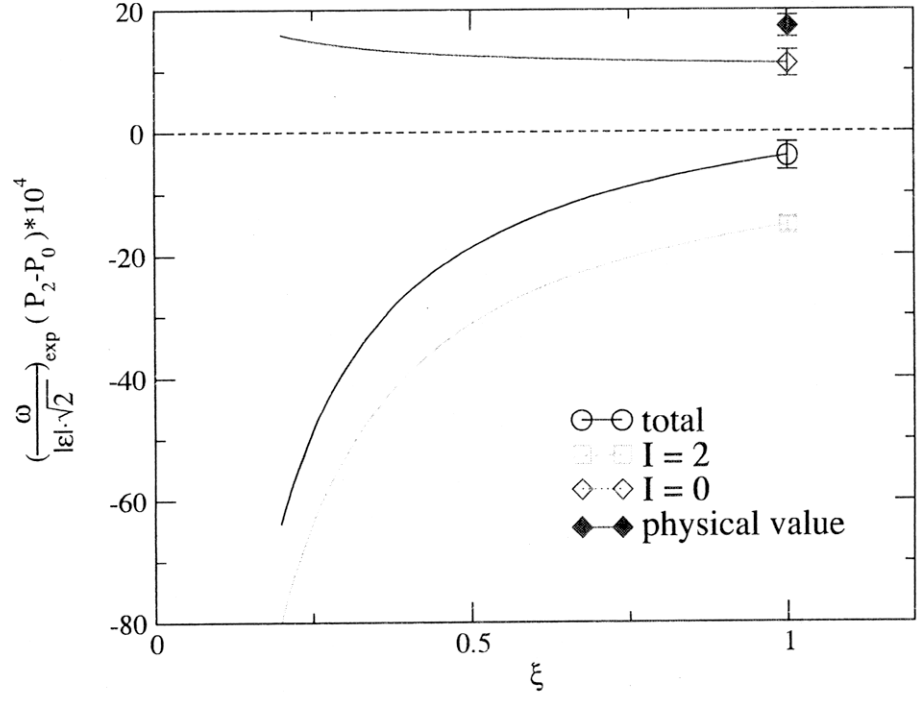
→ Electroweak penguins
$Q_7 + Q_8 + Q_9 + Q_{10}$
Q_8 should dominate ΔI = 3/2 contribution to ε´/ε at μ = 2 GeV

$$A(K^0 \to \pi\pi(I)) \equiv A_I e^{(i\delta_I)} \qquad \omega \equiv \frac{\mathrm{Re}\, A_0}{\mathrm{Re}\, A_2} \approx 22 \qquad \epsilon' = \frac{i e^{i(\delta_2 - \delta_0)}}{\sqrt{2}\omega}\left(\frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} - \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0}\right)$$

Previous Quenched Results

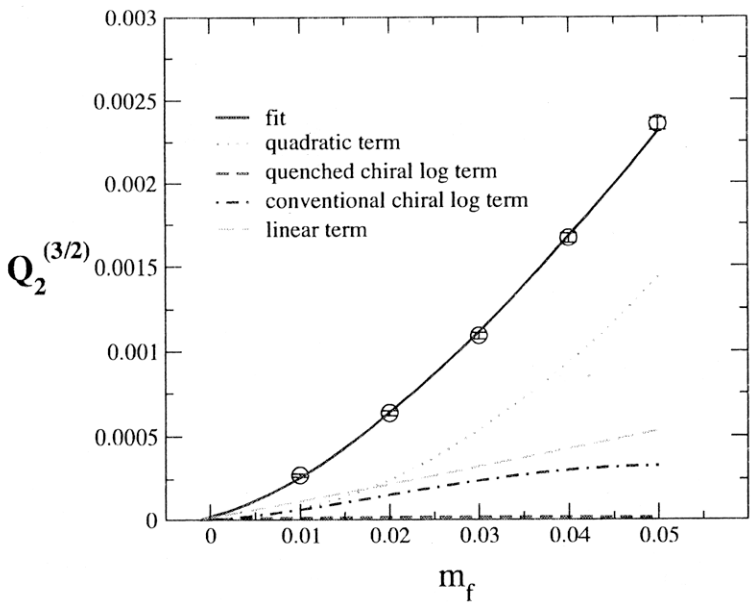
- Direct K –› ππ calculations not yet possible; calculate K –›π and K–› 0
- Then use chiral perturbation theory
- Earlier quenched calculations showed statistics under control
- Calculation now underway, with correct dynamical quark content



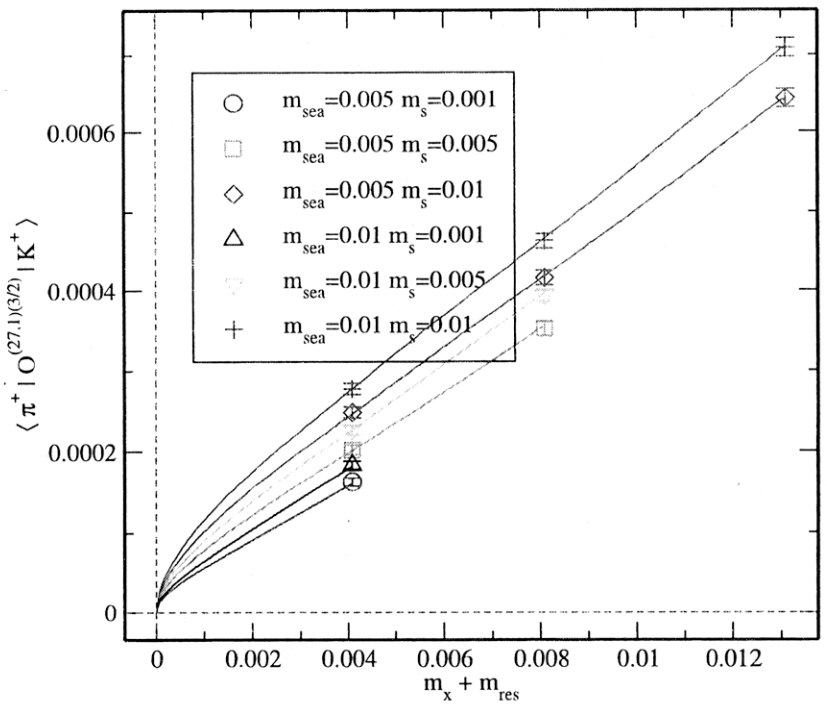


ChPT fits to (27,1) I=3/2

- PQ ChPT formula exist and we're beginning to fit to the data
- Much smaller range of quark masses for 2+1 flavor compared to quenched
- Stability of fits still being investigated.



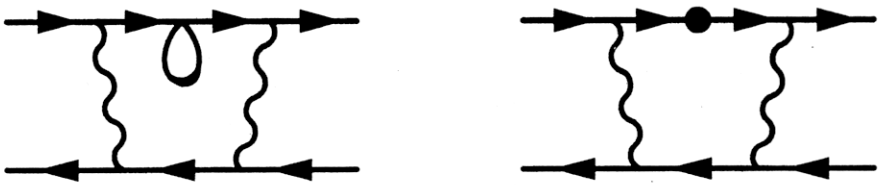
Previous quenched results



Current 2+1 flavor results

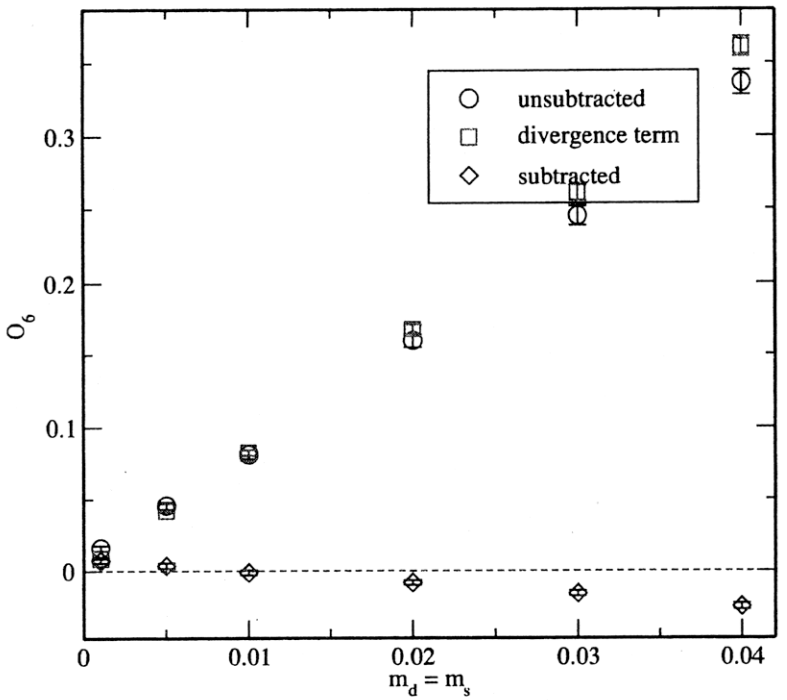
Chiral Behavior of Subtracted Operators

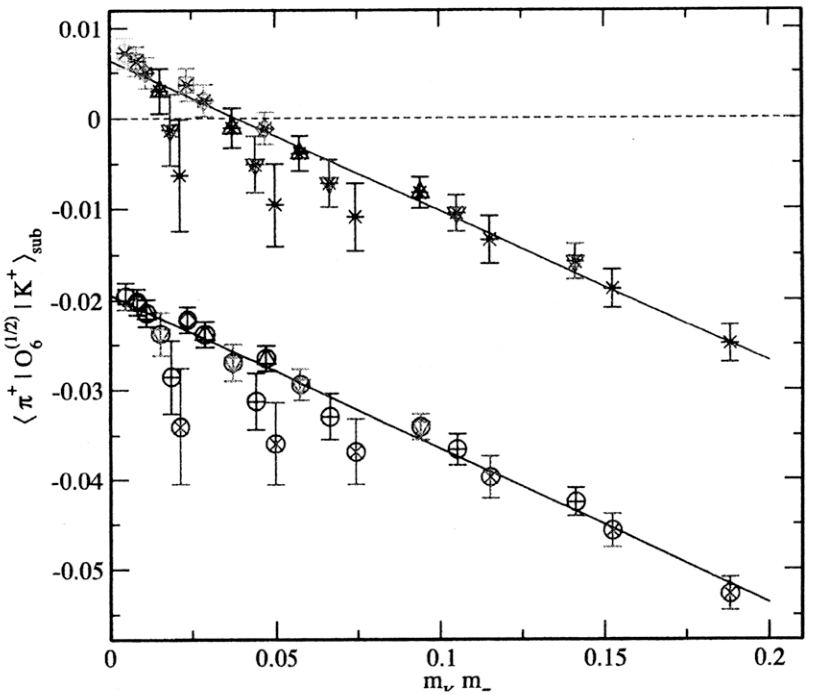
- $\Delta I = 1/2$ amplitudes must be subtracted



$$\langle \pi^+ | Q^{(1/2)}_{i,\mathrm{lat}} | K^+ \rangle_{\mathrm{sub}} = \langle \pi^+ | Q^{(1/2)}_{i,\mathrm{lat}} | K^+ \rangle + \eta_{1,i}(m_s + m_d) \langle \pi^+ | (\bar{s}d)_{\mathrm{lat}} | K^+ \rangle$$

$$= \frac{4\alpha_{i,1}}{f^2} m_K m_\pi + \text{chiral logs} + \cdots$$





Collaboration Members

RBC members:

Y. Aoki, C. Aubin, T. Blum, M. Cheng, N. Christ, S. Cohen, C. Dawson, T. Doi, K. Hashimoto, T. Ishikawa, T. Izubuchi, C. Jung, M. Li, S. Li, M. Lightman, H. Lin, M. Lin, O. Loktik, R. Mawhinney, S. Ohta, S. Sasaki, E. Scholz, A. Soni, T. Yamazaki

UKQCD members:

C. Allton, D. Antonio, K. Bowler, P. Boyle, M. Clark, J. Flynn, A. Hart, B. Joo, A. Juettner, A. Kennedy, R. Kenway, C. Kim, C. Maynard, J. Noaki, B. Pendleton, C. Sachrajda, A. Trivini, R. Tweedie, J. Wennekers, A. Yamaguchi, J. Zanotti

Conclusions

- Large volume 2+1 flavor DWF ensembles at one lattice spacing exist, second lattice spacing well underway
- Can use continuum ChPT formula at NLO for chiral fits, requiring many fewer parameters
- Single lattice spacing values for f_π and f_K are within a few percent of experiment, implying good scaling
- DWF allows non-perturbative renormalization - important for operators
- 2+1 flavor DWF B_K noticably reduces errors on world average
- Direct CP violation under active study, using ChPT
- Direct $K \rightarrow \pi\pi$ measurements being explored
- These lattices being used for nucleon physics, K13 decays, vector meson form factors, charm physics,....

The QCD transition and equation of state : toward the physical quark masses and vanishing lattice spacing

Peter Petreczky (RIKEN-BNL and Physics, BNL)

RBC-Bielefeld collaboration :

Huebner, Ejiri, Karsch, Jung, Petreczky, Pica, Schmidt, Soeldner (BNL)

Cheng, Christ, Mawhiney (Columbia), Datta (Mumbai), Petrov (NBI), Umeda (Tsukuba)

van der Heide, Kaczmarek, Laermann, Liddle, Miao (Bielefeld)

Cheng et al, PRD 74 (2006) 054507
Cheng et al, PRD 75 (2007) 034506
Cheng et al, Eur. Phys. J. C51 (2007) 875
Cheng et al, arXiv:0710.0354 [hep-lat], to be published in PRD

Lattice 2007 (8 talks) :

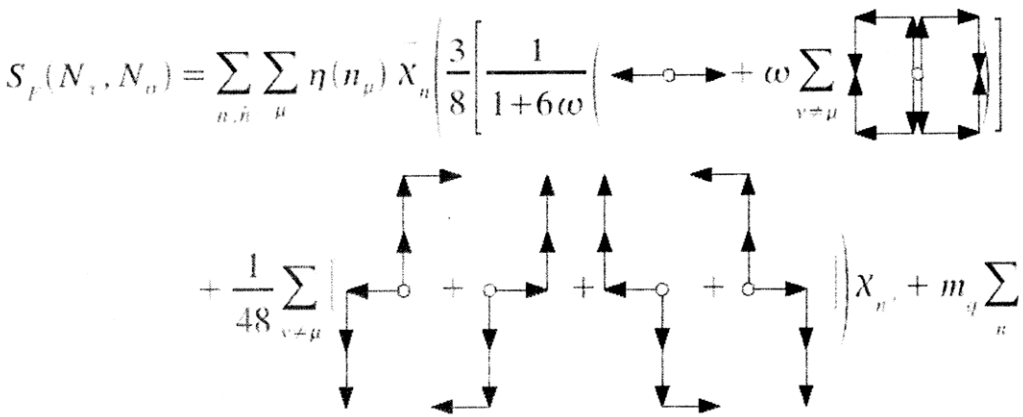
F. Karsch, plenary, PoS(LATTICE 2007)015
Cheng, for RBC-Bielefeld Collaboration, arXiv:0710.4357
van der Heide for RBC-Bielefeld Collaboration PoS(LATTICE 2007)234
Huebner for RBC-Bielefeld Collaboration, arXiv:0709.1467
J. Liddle, for RBC-Bielefeld Collaboration , arXiv:0710.2011
Miao, Schmidt for RBC-Bielefeld Collaboration, arXiv:0710.4312
S. Mukherjee for RBC-Bielefeld Collaboration , arXiv:0710.0963
K. Petrov, for RBC-Bielefeld Collaboration, arXiv:0710.4237

11 invited talks at non-lattice conferences in 2007 !

Physics goal of the thermodynamics project

- Transition temperature and nature of the QCD transition
- Equation of state
- Static screening lengths at high temperatures
- Thermodynamics at finite baryon density, critical end-point, fluctuations of conserved charges
- Meson properties T>0, density-density correlations

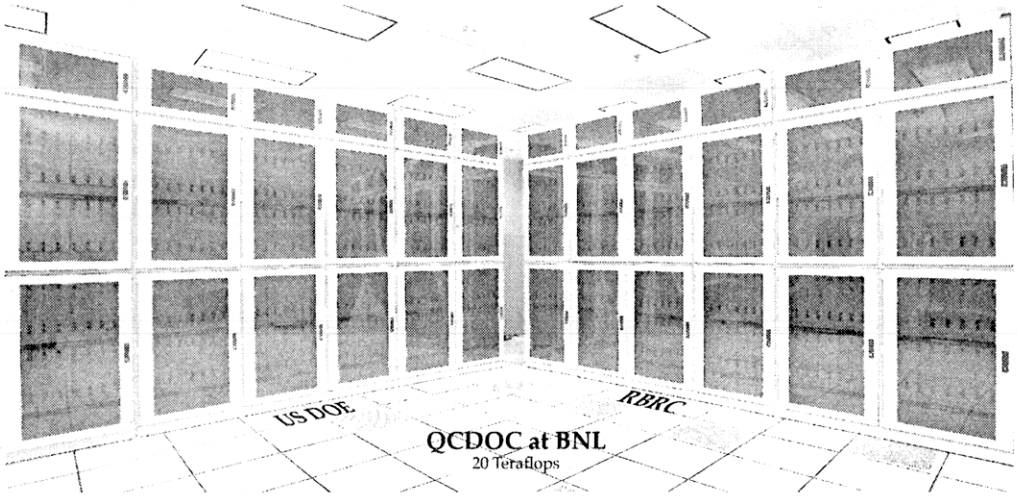
Computational costs $\sim a^{-10} \sim N_\tau^{10}$ ⇨ improved actions



p4fat3 action

RHMC algorithm :
x 20 speedup at small *m*

Computational resources

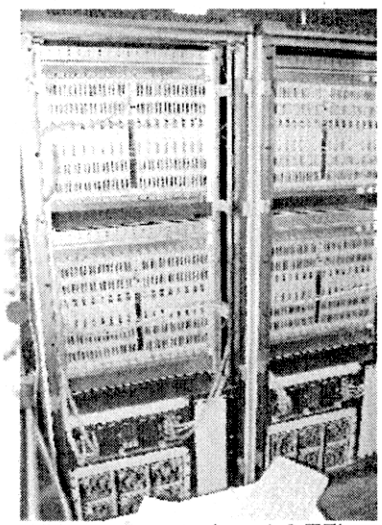


3.5 racks of RBRC QCDOC: 2.87Tflop

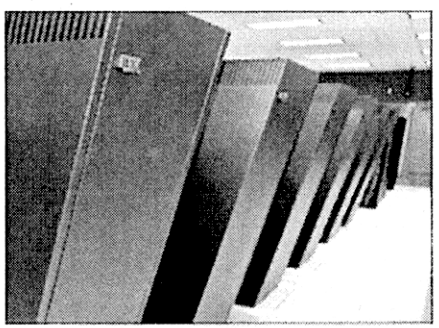
3 racks of RBRC QCDOC: 2.46Tflop

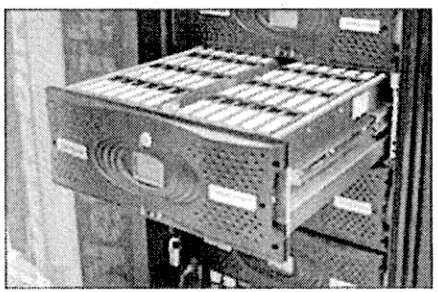
BI – apeNEXT

5.000.000.000.000 ops/s



NYBlue at BNL



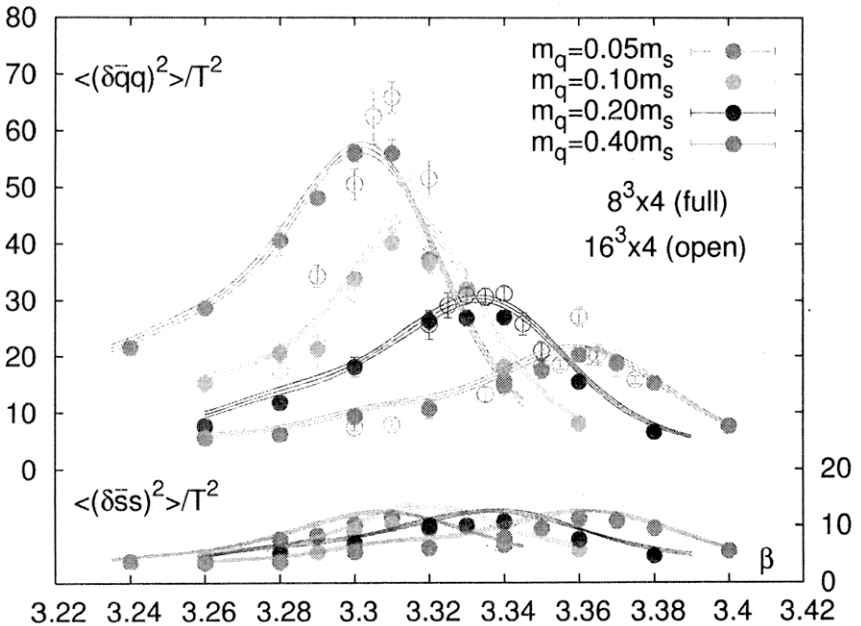


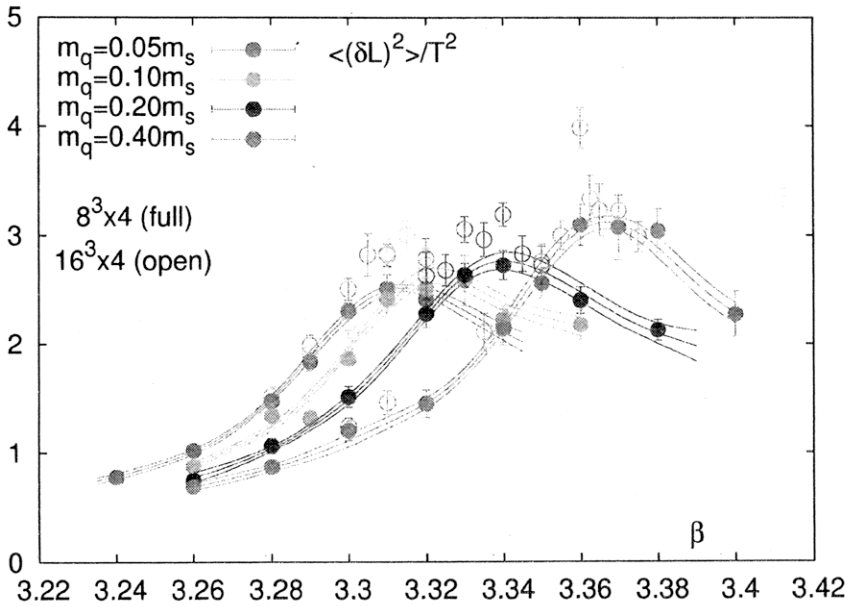
Determining the transition temperature

$$T = 1/(N_\tau a), \quad a = a(\beta) \iff \beta = \frac{6}{g^2}$$

$$\frac{\chi_{\psi\bar{\psi}}}{T^2} = N_\sigma^3 \left(\langle (\psi\bar{\psi})^2 \rangle - \langle \psi\bar{\psi} \rangle^2 \right) = \langle (\delta\bar{\psi}\psi)^2 \rangle$$

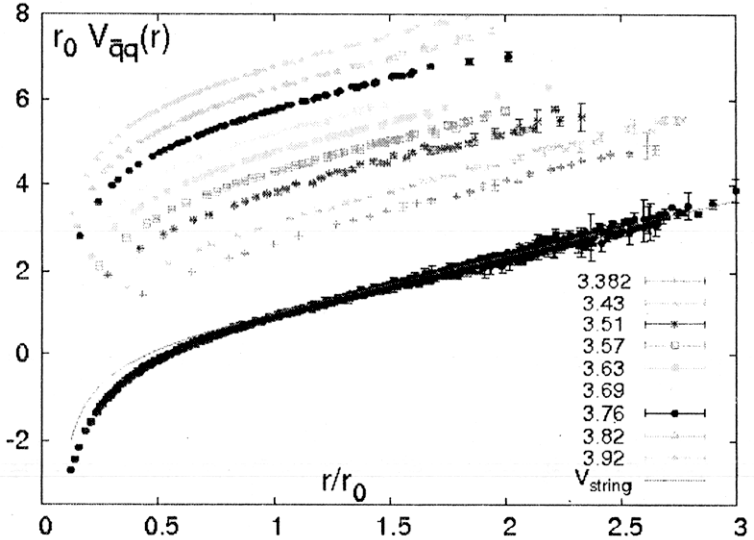
$$\frac{\chi_L}{T^2} = N_\sigma^3 \left(\langle L^2 \rangle - \langle L \rangle^2 \right) = \langle (\delta L)^2 \rangle$$





- the peak position in $\chi_{\psi\bar{\psi}}$ and χ_L is the same withing errors:
  deconfinement and chiral transition happen at the same temperature

- no large volume dependence of the peak position
  (inconsistent with 1st order transition)



$$T_c = 1/(N_\tau a(\beta_c))$$

Sommer scale:

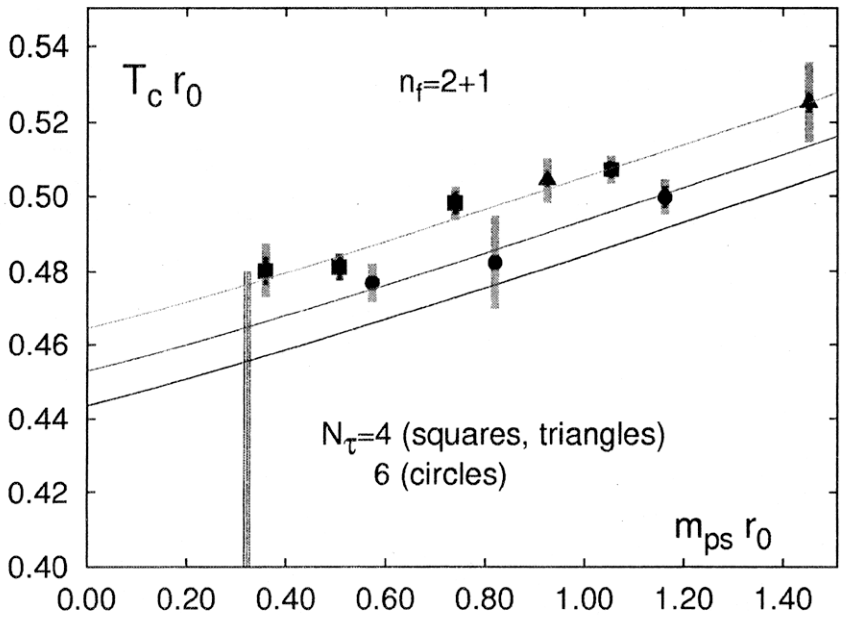
$$r^2 \frac{dV}{dr}|_{r=r_0} = 1.65$$

quarkonia spectroscopy:

$r_0 = 0.469(11)(4)$ fm $\rightarrow \sqrt{\sigma} \simeq 460$ MeV

Gray et al, PRD 72 (2006) 094507

Cheng et al, PRD 74 (2006) 054507 (cited 68 times)



Combined m_q – N_τ extrapolation

$$r_0 T_c(m_\pi, N_\tau) = (r_0 T_c)^{chiral}_{cont} + b(m_\pi r_0) + c/N_\tau^2$$

$$\boxed{T_c = 192(7)(4) \text{ MeV}}$$

Flavor dependence is weak :

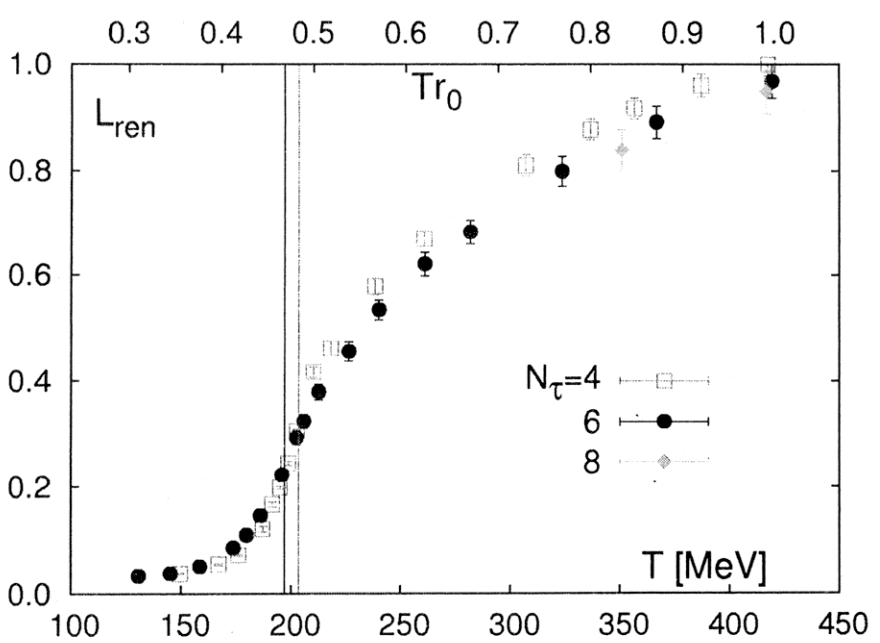
(2+1)-flavor $T_c/\sqrt{\sigma} = 0.398(6)^{+10}_{-1}$

3-flavor theory $T_c/\sqrt{\sigma} = 0.391(9)$

(Cheng et al, PRD 75 (07) 034506)

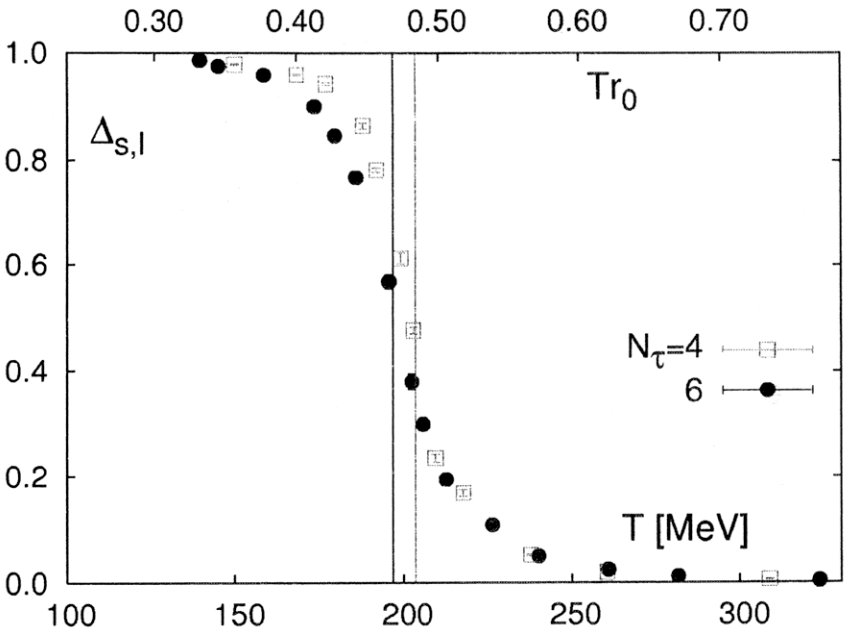
$\frac{T_c}{\sqrt{\sigma}} = 0.425(15), \quad N_f = 2$ Karsch et al, NPB (01) 605

Deconfinement and chiral transition



Polyakov loop

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



Renormalized chiral condensate

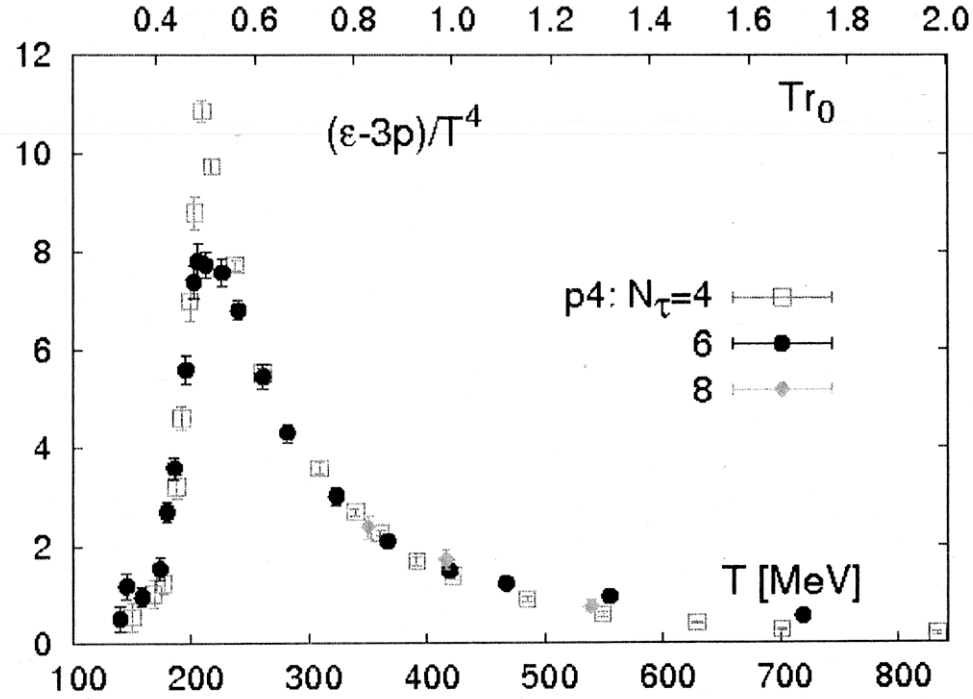
$$\Delta_{s,l}(T) = \frac{\langle\bar{q}q\rangle_T - \frac{m_q}{m_s}\langle\bar{s}s\rangle_T}{\langle\bar{q}q\rangle_{T=0} - \frac{m_q}{m_s}\langle\bar{s}s\rangle_{T=0}}$$

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

Lattice results on trace anomaly

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

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



$$R_\beta(\beta) = -\frac{d\beta}{da},\ \beta = 6/g^2$$

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

$$\frac{p(T)}{T^4} - \frac{p(T_0)}{T_0^4} = \int_{T_0}^{T} dT' \frac{\Theta^{\mu\mu}(T')}{T'^5}$$

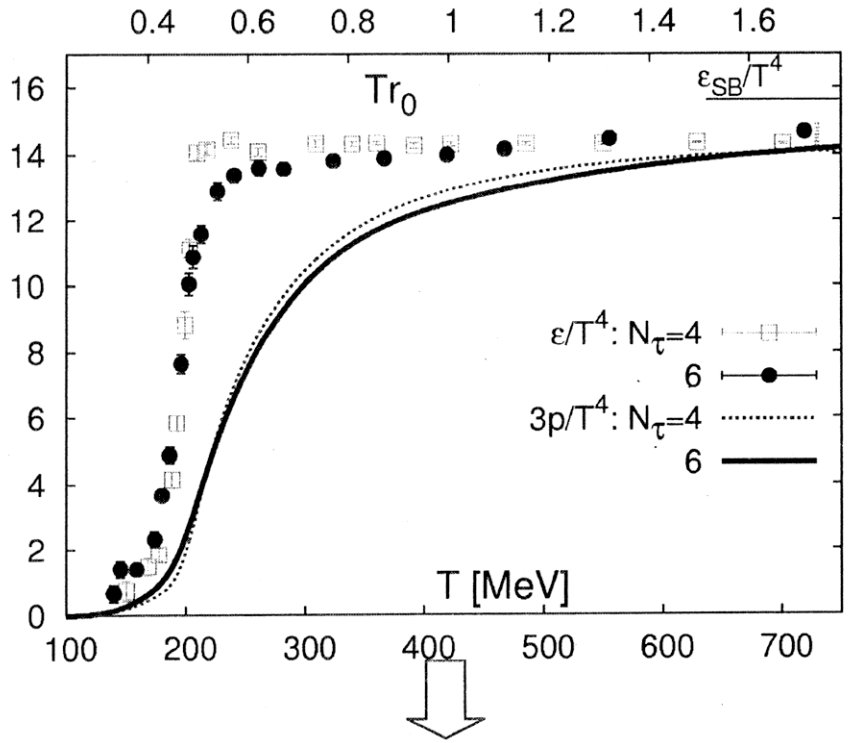
$$s(T) = (\epsilon + p)/T$$

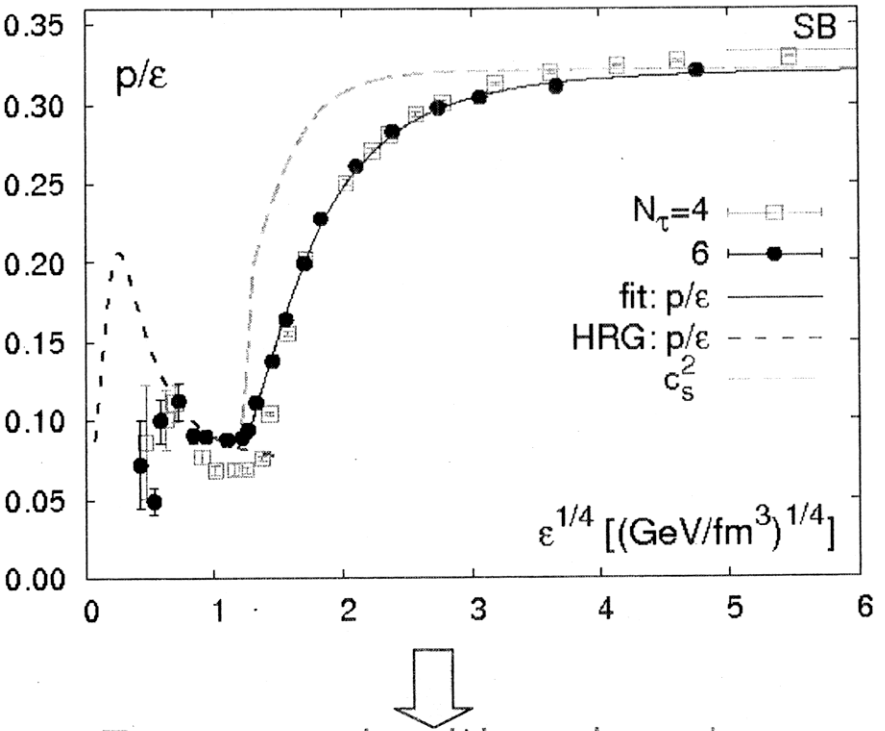
huge peak in the interaction measure @$1.06T_c$

⇩

large increase in bulk viscosity at the transition: Kharzeev, Tuchin, arXiv:0705.4280
(see talk by Tuchin)

Pressure, energy density and speed of sound





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

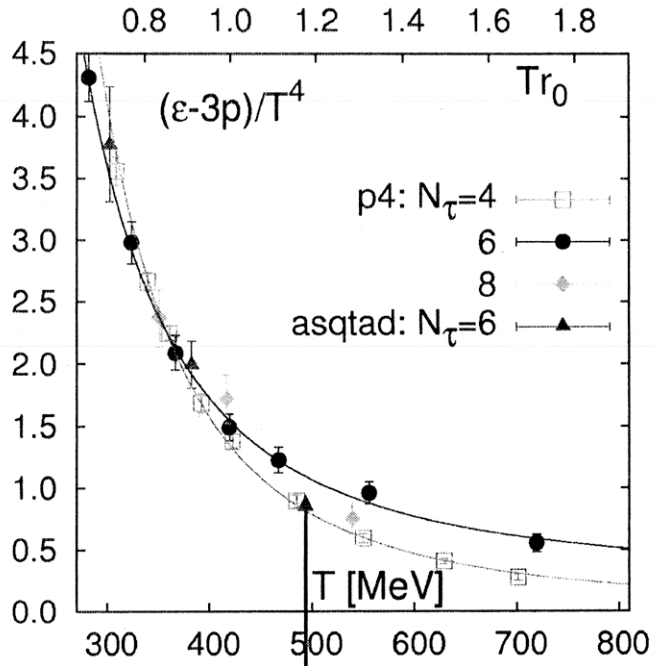
10% deviation from the ideal gas limit

lattice discretization errors are small

For energy densities relevant for RHIC speed of sound is smaller than $1/\sqrt{3}$

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

Equation of State at high T

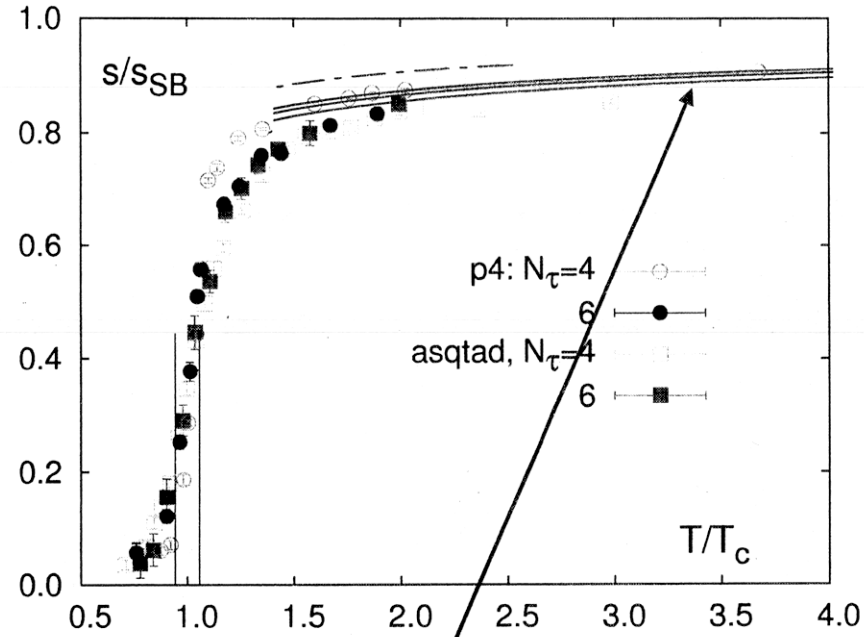


Compatible with perturbative estimate

$$\frac{\epsilon - 3p}{T^4} = \frac{27}{4}\alpha_s + \frac{b}{T^2} + \frac{4B}{T^4}$$

$$\alpha_s \simeq 0.18$$

at high T



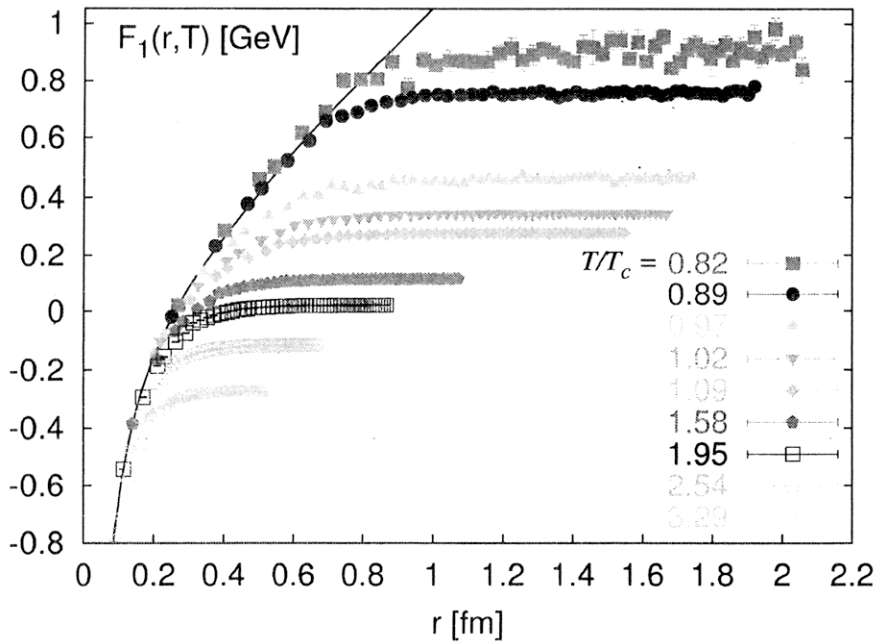
Resummed perturbative calculations from : Blaizot, Iancu, Rebhan, hep-ph/0303185

Lattice data on pressure and entropy density at high temperatures can be described by re-summed perturbation theory

Spatial correlators at T>0

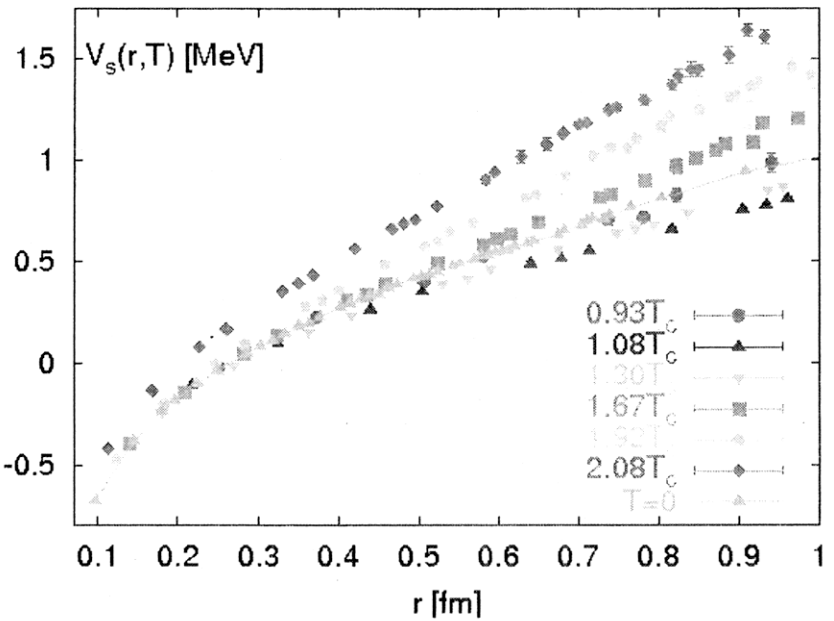
chromo-electric screening

$$\langle L(r)L^{\dagger}(0) > |_{r\to\infty}$$
$$\sim \exp(-m_D r) + F_{\infty}(T)$$



chromo-magnetic screening

$$W(r(x,y),z) = \exp(-V_s(r,T))|_{z\to\infty}$$
$$W(r(x,y),z) \sim \exp(-\sigma_s(T)\cdot r\cdot z)$$
$$\sigma_s(T) \simeq \sigma(T=0),\ T < T_c$$



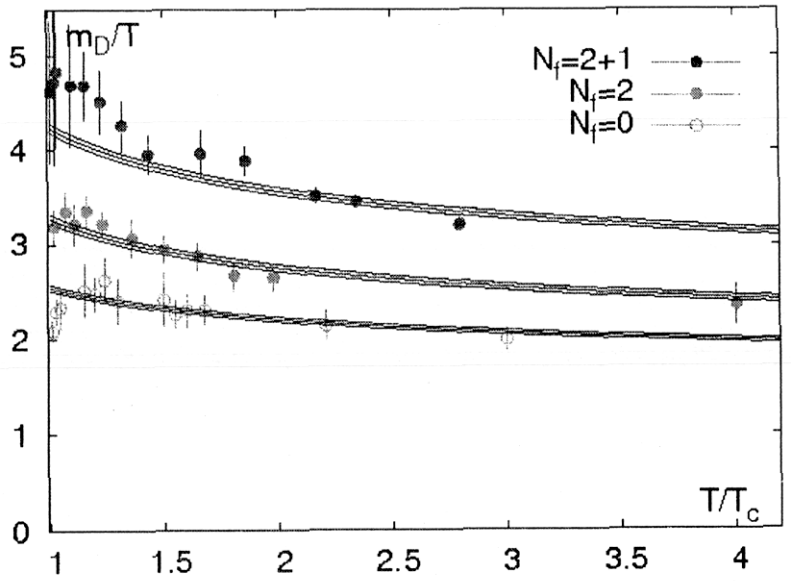
quarkonium properties at T>0
Mocsy, P.P, arXiv:0706.2183, PRL 2007
to be published
(see talk by Agnes)

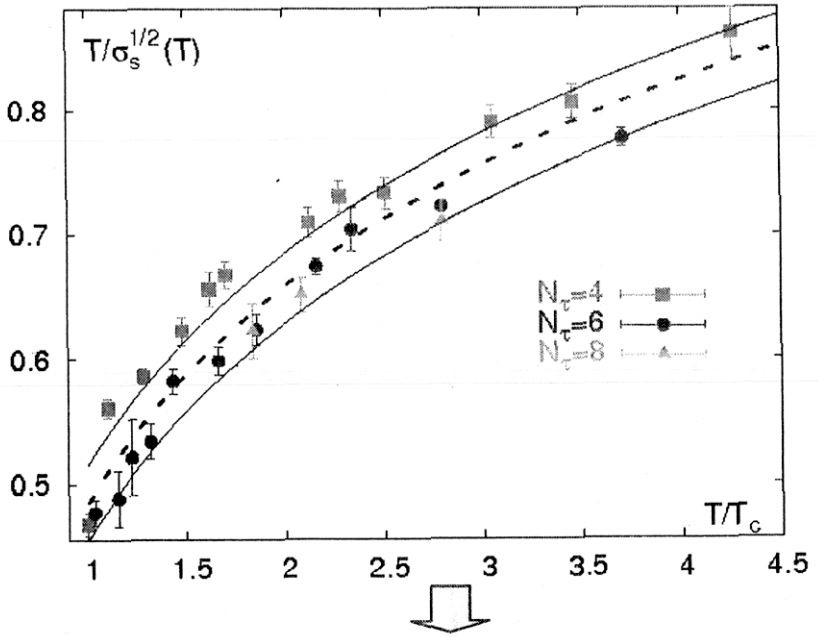
dimenisonal reduction :

$$\sigma_s(T) = \#g^4(T)T^2, T \gg T_c$$

magnetic screening length

Electric and magnetic correlation lengths





dimensional reduction works down to T_c

$\alpha_s(T_c) \sim 0.16$

$$m_D(T) = A\sqrt{1+\frac{N_f}{3}}g^{2\text{-loop}}(T)T$$

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

non-perturbative pre-factor

$m_D \simeq 1.4 m_D^{LO}$

$$g_3^2(T) = g^2(T)T(1 + c_1(N_f, T)g^2(T) + ...)$$

flavor and temperature dependence of static electric magnetic correlation length are given by perturbation theory

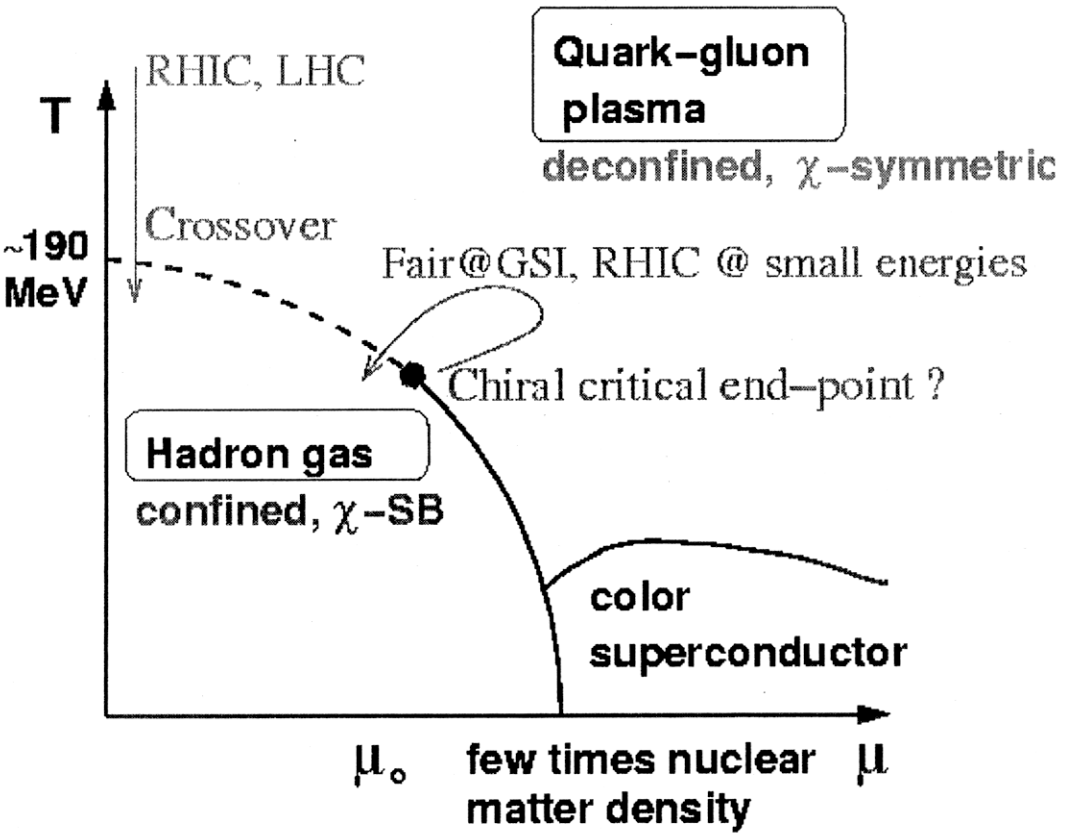
QCD at finite baryon density

At physical quark masses the transition is likely a rapid crossover for $\mu = 0$

MILC, PRD 71 (04) 034504, RBC-Bielefeld, PRD 74 (06) 054507,Aoki et al, Nature 443 (06) 675

There should a critical end-point at some $\mu = \mu_c$ where the transition turns from crossover to 1st odrer. Where it is located ?

Lattice QCD methods to estimate μ_c : re-weighting, Taylor expansion

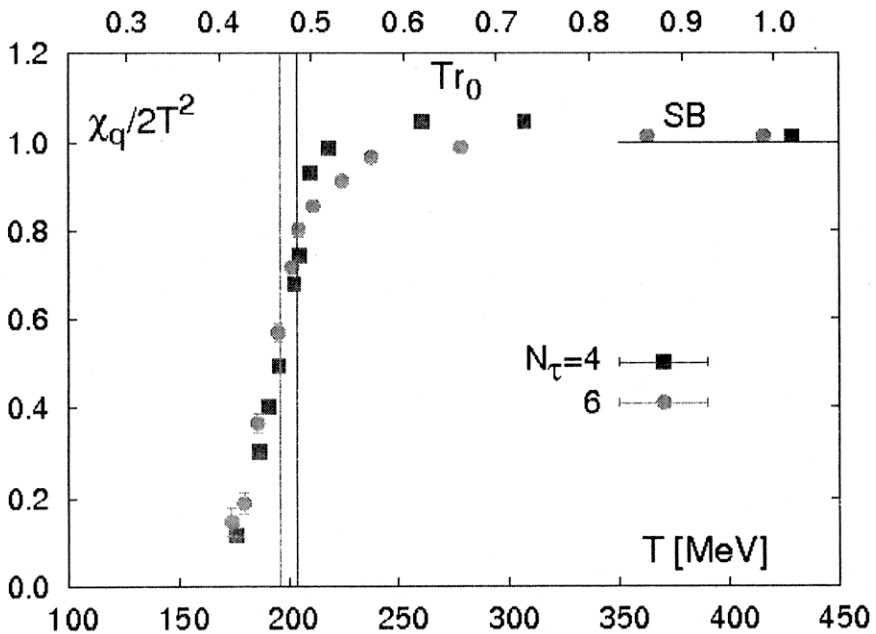


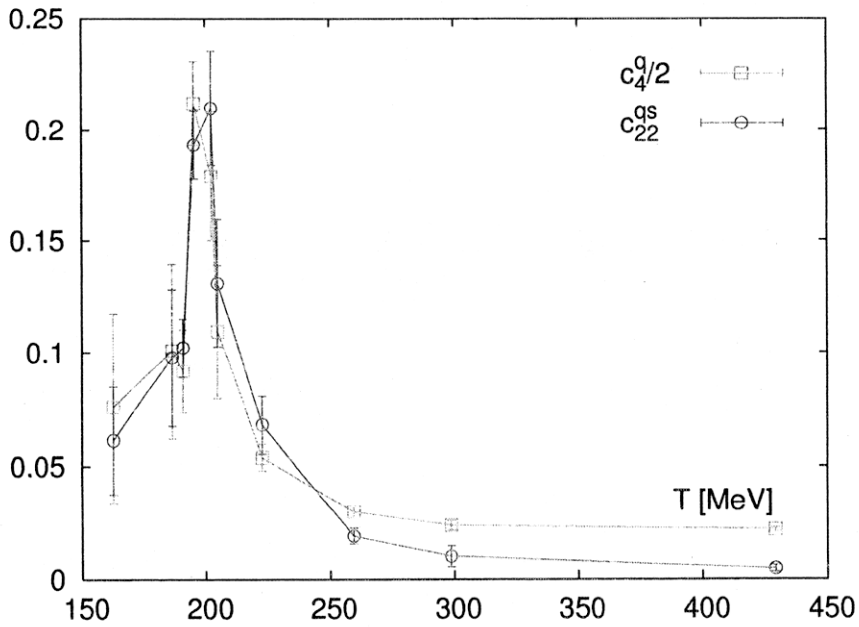
Quark number and strangeness fluctuations

$$\frac{p}{T^4} = \sum_{i,j} c_{i,j} \hat{\mu}_q^i \mu_s^j, \quad c_{i,j} = \frac{1}{i!j!} \frac{\partial^i}{\partial \hat{\mu}_q^i} \frac{\partial^j}{\partial \hat{\mu}_s^j} \frac{1}{VT^3} \ln Z(T,V)$$

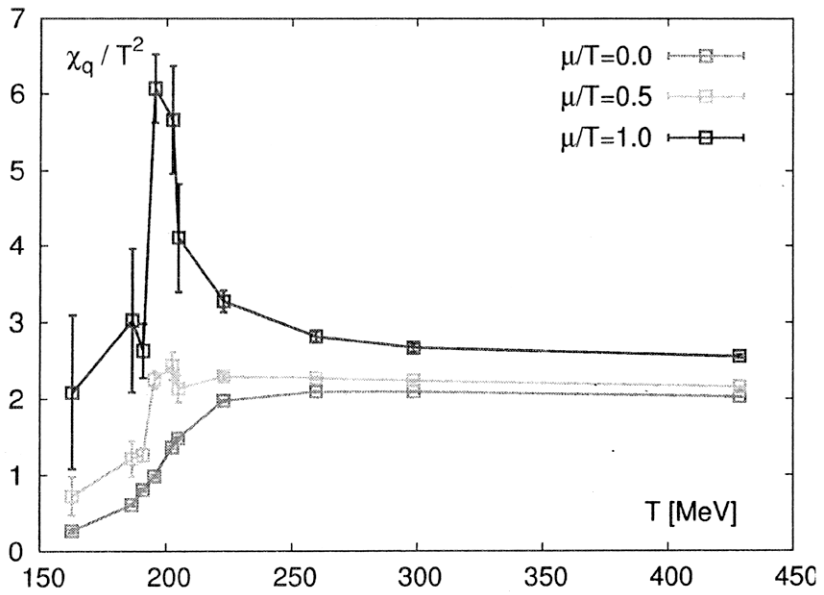
Quark number fluctuations: $c_{20} = \langle q^2 \rangle - \langle q \rangle^2$

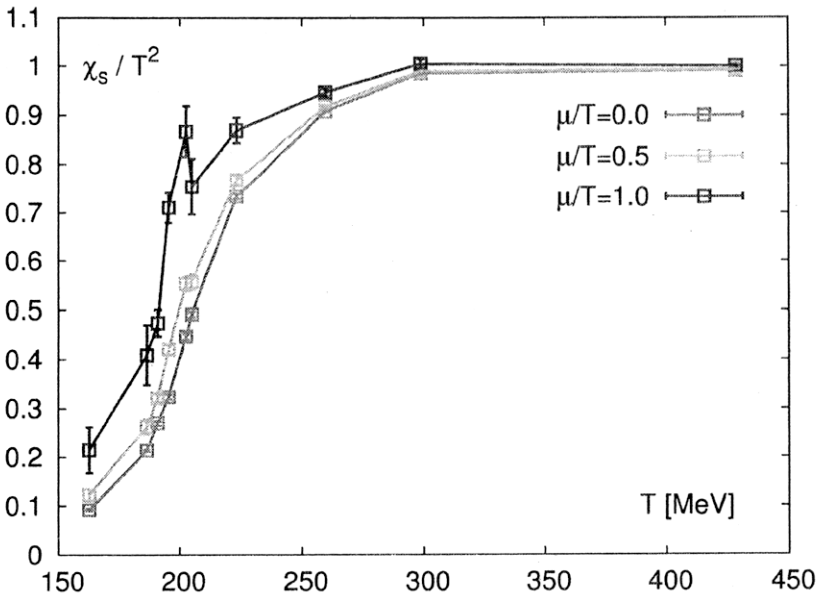
Strangeness fluctuations: $c_{02} = \langle S^2 \rangle - \langle S \rangle^2$





Quark number and strangeness fluctuations





significant enhancement of baryon and strangeness fluctuations at finite baryon density near the transition region

event-by-event fluctuations at RHIC ?

Conclusions and Outlook

Thermodynamics observables like the transition temperature, EoS, electric and magnetic correlation lengths have been calculated at zero net baryon density controlling discretization errors

Important implications for RHIC : quarkonium suppression, increase of bulk viscosity
reduced speed of sound (softest point)

lattice data consistent with wQGP picture for $T > 2T_c$

deconfinement and chiral transition occur roughly at the same temperature

calculations using $N_\tau = 8$ is in progress => better control over the continuum limit

Extension of the lattice calculations to non-zero baryon density via Taylor expansion is in progress :

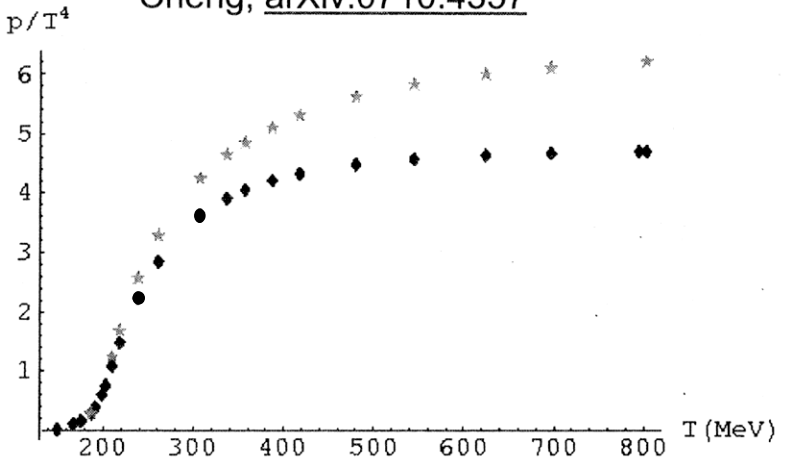
enhancement of strangeness and baryon fluctuations at finite density

estimate of location of the end-point from the convergence radius (future)

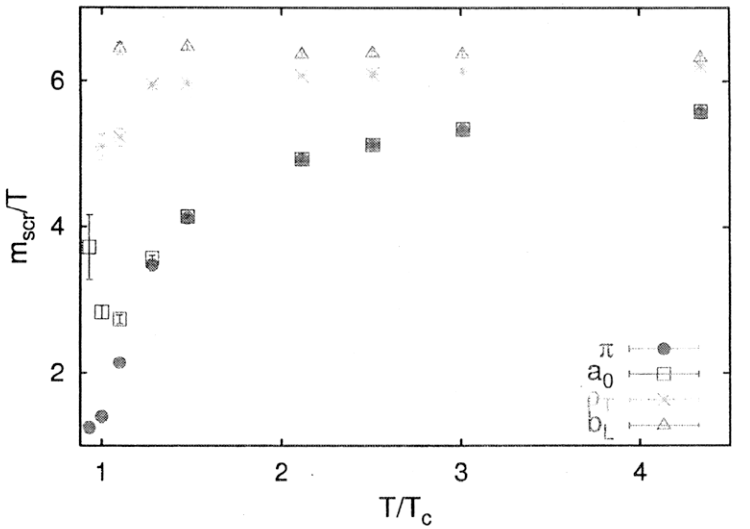
Ongoing investigations :

charm contribution to EoS

Cheng, arXiv:0710.4357

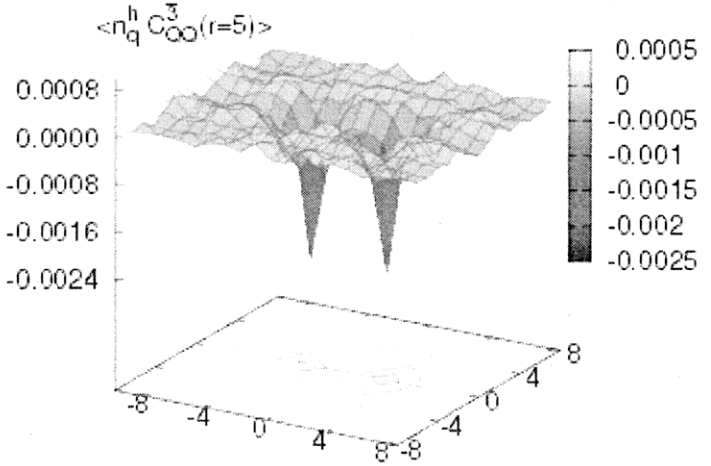


Meson screening masses

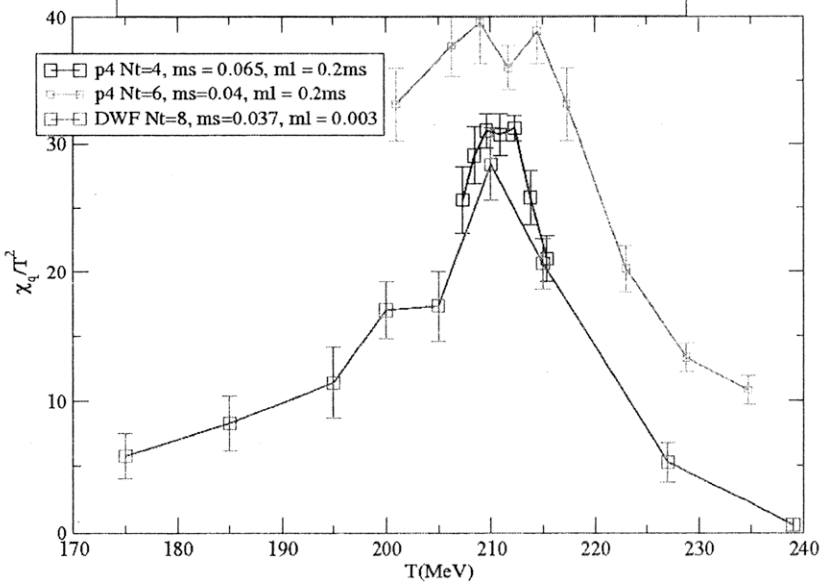


Density correlations

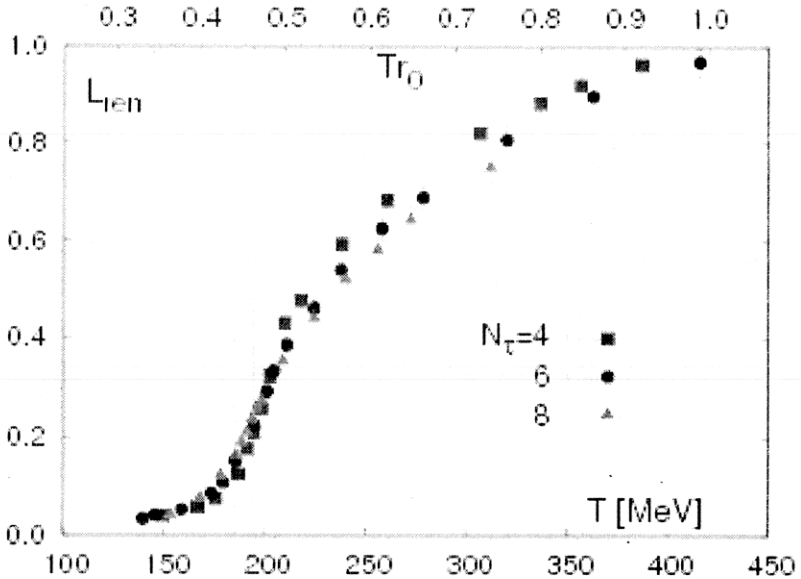
Huebner, arXiv:0709.1467

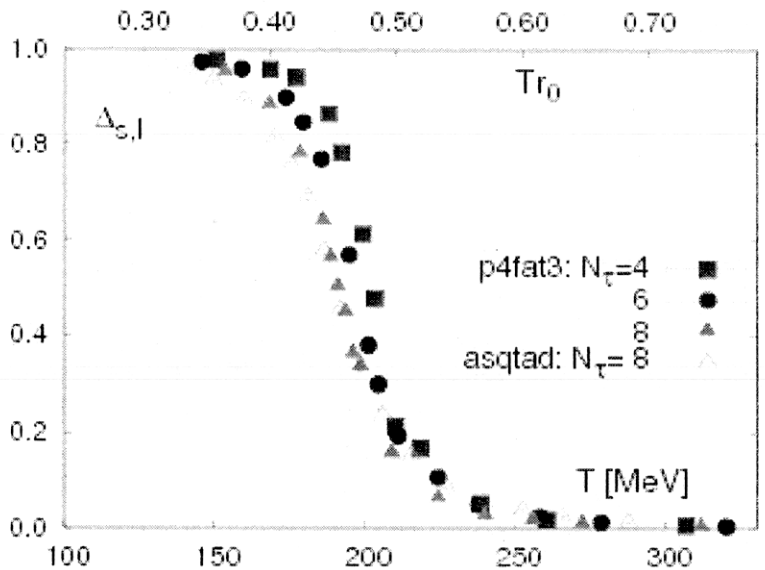


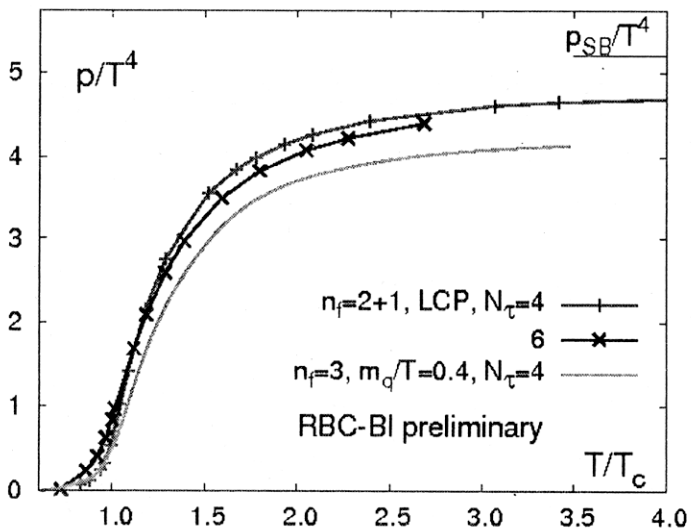
QCD transition with DWF



Backup slide







Curricula Vitae Summary

CURRICULA VITAE - SUMMARY
CURRENT RBRC FELLOWS/RESEARCH ASSOCIATES/RESEARCHERS

Yasuyuki Akiba **Birthplace:** Tokyo, Japan **DOB:** October 20, 1959
D.S. 1988, University of Tokyo
Experience: Research Associate, Institute for Nuclear Study, University of Tokyo, March 1988 – March 1997;
Research Associate, High Energy Accelerator Research Organization (KEK), April 1997 – March 2003;
Senior Research Scientist, RIKEN, April 2003 – July 2003;
Senior Researcher, RIKEN, August 2003 – present;
RIKEN Spin Program Researcher, RBRC-E, November 2003 – present
Deputy Spokesperson for PHENIX, 2004 - present.

Sinya Aoki **Birthplace:** Tokyo, Japan **DOB:** May 16, 1959
D.S. 1987, University of Tokyo
Experience: Research Associate, Brookhaven National Laboratory, 1987-1989
Post-Doctoral Fellow, SUNY at Stony Brook, 1989-1991
Assistant Professor, U. of Tsukuba, Japan
Lecturer, U. of Tsukuba, 1993-1994
Associate Professor, U. of Tsukuba, 1994-2001
Professor, U. of Tsukuba, April 2001 – present
Visiting Fellow, joint position with RBRC Theory Group and Tsukuba University, April 1, 2004 – present.
Awards and Honors: Fellowships of the Japan Society for the Promotion of Science for Japanes Junior Scientists, at Physics Department, U. of Tokyo, Japan;
First (FY 2004) JSPS Prize Award, Mathematics; Physical Sciences; Chemistry; Engineering Sciences.

Yasumichi Aoki **Birthplace:** Gunma, Japan **DOB:** January 7, 1968
Ph.D. 1996, University of Tsukuba, Japan
Experience: COE Research Fellow at the Center for Computational Physics University of Tsukuba;
Assistant (3 year research position) at the Center for Computational Physics, University of Tsukuba
Research Associate, RIKEN BNL Research Center, May 1, 2000 – April 30, 2003.
RBRC Visiting Scientist, with Columbia University, May 1 to July 31, 2003.
Research Associate, University of Wuppertal, Germany, August 2003-September 2006;
RIKEN Fellow, RIKEN BNL Research Center (Theory), October 1, 2006 - present.

Thomas C. Blum **Birthplace**: USA **DOB**: December 27, 1962
Ph.D. 1995, University of Arizona, Tucson, AZ
Experience: Postdoctoral Fellow, High Energy Theory Group, BNL
RIKEN BNL Fellow, October 1, 1998 – September 30, 2003;
Associate Physicist, Brookhaven National Laboratory, October 2003 – Dec. 2003.
•RHIC Physics Fellow/Assistant Professor—RBRC/U. of Connecticut, Storrs, January 1, 2004 - present.
Awards and Honors: DOE-GANN Fellowship: August 1990 - May 1993;
Year 2005 Department of Energy Outstanding Junior Investigator Award, High Energy Physics.

Christopher Dawson **Birthplace**: Preston, Lancashire, UK **DOB**: July 6, 1973
Ph.D. 1998, University of Southampton, UK
Experience: Research Associate, High Energy Theory Group, BNL
RIKEN BNL Fellow, October 1, 2001 – present

Abhay L. Deshpande **Birthplace**: Mumbai/Bombay, India **DOB**: March 21, 1965
Ph.D. 1994, Yale University
Experience: Visiting Scientist, BNL, 1989-1994 (Member of the BNL-E851 Collaboration)
Visiting Scientist, CERN, 1994-1999 (Member of the SMC Collaboration)
Visiting Scientist, DESY, 1998-Present (Member of the ZEUS Collaboration)
Associate Research Scientist, Yale University, 1994-2000
RIKEN BNL Fellow (Experimental Group), February 2000 – December 31, 2003.
•RHIC Physics Fellow/Assistant Professor-RBRC-E, SUNY, Stony Brook, January 1, 2004 – present.
Awards and Honors: Gibbs Prize in Physics, University of Bombay, 1985.

Takumi Doi **Birthplace**: Hiroshima, Japan **DOB**: November 16, 1976
Ph.D. 2004, Tokyo Institute of Technology, Japan
Experience: Fellowships: The Japan Scholarship Foundation, Department of Physics, Tokyo Institute of Technology, 1999-2001, JSPS Research Fellowships for Young Scientists, Department of Physics, Tokyo Institute of Technology, 2001-2004;
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2004 – present.
Awards and Honors: Fellowships: JSPS Fellowship, The Iwakuni Foundation for Scholarship, Tokyo University, 1995-1999; Awards: The Tejima Memorial Research Award for Ph.D. Thesis.

Douglas Fields: **Birthplace**: U.S.A. **DOB**: July 2, 1963
Ph.D. 1991, Indiana University, Bloomington
Experience: Postdoctoral Research Associate, Los Alamos National Laboratory, 1992-1995
Research Associate Professor, University of New Mexico, 1995-2001
Member of the PHENIX Collaboration, BNL, 1995-present
•RHIC Physics Fellow/Assistant Professor—RBRC-E, University of New Mexico,

September 1, 2001 – present

Rainer Fries: **Birthplace**: Regensburg, Germany **DOB**: Aug.10, 1971
Ph.D 2001, University of Regensburg
Experience: Assistant Professor, Texas A&M University 2006-
RHIC Fellow, RIKEN/BNL 2006-
Assistant Professor, University of Minnesota, 2005-2006
Research Associate, University of Minnesota, 2003-2005
Research Associate, Duke University, 2002-2003
Awards and Honors: Fellowship for Outstanding Students, Government of Bavaria, 1991-1996
Feodor Lynen Fellow, Alexander von Humboldt Foundation, 2002-2003
IUPAP Young Scientist Prize 2007

Yoshinori Fukao **Birthplace**: Aichi, Japan **DOB**: April 5, 1978
B.S. 2001, Kyoto University, Kyoto, Japan
Master Course Student, 2002 – present
Experience: RBRC Young Researcher, Experimental Group, 2002 – 2003.
RIKEN Junior Research Associate, RBRC, Experimental Group, April 1, 2003 – present.

Kenji Fukushima **Birthplace**: Tokyo, Japan **DOB**: January 29, 1975
Ph.D. . 2002, University of Tokyo, Komaba
Experience: Research Fellow of the Japan Society for the Promotion of Science (JSPS), University of Tokyo, Japan, April 1999 to August 2003; Visiting Scientist, Massachusetts Institute of Technology, Department of Physics, September 2003 - March 2005; RSP Research Associate, RBRC Theory Group, April 2005 - present.
Awards and Honors: JSPS Fellowship; Enrico Fermi Junior Grant, School of Subnuclear Physics, Erice, Italy, awarded September 2005.

Yuji Goto **Birthplace**: Shizuoka, Japan **DOB**: November 25, 1965
Ph.D 1996, Kyoto University, Kyoto, Japan
Experience: Research Fellow of the Japan Society for the Promotion of Science, 1994-1996
Postdoctoral Fellow, RIKEN, Japan, 1996-1999
RIKEN BNL Fellow, November 1999 – March 31, 2002
Scientist, RIKEN, April 2002 to March 2003;
Senior Research Scientist, RIKEN, April 2003 – present.
RIKEN Spin Program Researcher, RBRC, April 1, 2002 – present.

Matthias Grosse-Perdekamp
Birthplace: Schwenningen, Germany **DOB**: December 1, 1963
Ph.D. 1995, University of California at Los Angeles
Experience: Associate Research Scientist, Yale University 1995-1998
Research Scientist, Mainz University, 1998-1999

RIKEN BNL Fellow, January 1999 – August 31, 2002.
Member of the PHENIX and BELLE Collaborations;
RHIC Physics Fellow/Assistant Professor—RBRC-E; University of Illinois, Urbana Champaign, September 1, 2002 – present.
Deputy Spokesperson for PHENIX, 2004 – present.

Awards and Honors: Foreign Scholar Award, UCLA, 1990; Gustav Mie Preis, Freiburg University, 1991.

Koichi Hashimoto **Birthplace**: Fukui, Japan **DOB**: December 20, 1979
M.Sci. 2003, Kanazawa University
Experience: Visiting Student, RBRC, September-October 2003.
RIKEN Spin Program Young Researcher, RBRC Theory Group, April 2004 – March 2005; RIKEN Jr. Research Associate, April 1, 2005 - March 31, 2006.

Yoshitaka Hatta **Birthplace**: Kyoto, Japan **DOB**: August 5, 1976
Ph.D. 2004, Kyoto University, Department of Physics
Experience: RBRC Young Researcher, Theory Group, RBRC, Spring 2002 – 2003.
RIKEN Junior Research Associate (Theory), 2002 - 2004.
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2004 – September 30, 2006.

Yosimasa Hidaka **Birthplace**: Fukuoka, Japan **DOB**: September 18, 1977
Doctor of Science 2005, University of Tokyo, Graduate School of Science
Experience: Research Fellow, Theory Group, KEK, Japan, April 2005 to January 2006;
Research Fellow, Theoretical Nuclear Physics Group, Tokyo Institute of Technology
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2006 – present.

Tetsufumi Hirano **Birthplace**: Kanagawa, Japan **DOB**: September 17, 1972
Ph.D. 2001, Waseda University, Japan
Experience: Research Associate, Waseda University, Japan, April 1999 to March 2001
Postdoctoral Fellow at University of Tokyo, Japan, April 2001 to March 2003.
RIKEN Spin Program Research Associate, RBRC Theory Group, March 24, 2003 – August 31, 2004.
Visiting Scientist RBRC/Columbia University, September 1, 2004 – present.
Awards and Honors: JPS Theory Award for Distinguished Young Researchers in Nuclear Physics (2002).

Takuma Horaguchi **Birthplace**: Iwate, Japan **DOB**: September 29, 1977
Graduate School: Tokyo University of Science, Japan
Experience: RBRC Young Researcher, Experimental Group, RBRC, Spring 2002 – 2003.
RIKEN Junior Research Associate (Experiment), April 1, 2003 – present.

Takashi Ichihara **Birthplace**: Japan **DOB**: February 22, 1958

Ph.D. 1987, Kyoto University, Japan
Experience: Research Scientist, RIKEN, Japan, 1987-1995
Senior Research Scientist, RIKEN, Japan, 1995-1998
Assistant Chief Scientist, RIKEN, Japan, 1998
Researcher, RBRC Experimental Group, 1998
RIKEN Spin Program Researcher, November 1999- present

Kei Iida **Birthplace**: Aomori, Japan **DOB**: July 28, 1970
Ph.D. 1998, University of Tokyo
Experience: Postdoctoral Research Fellow, JSPS, U. of Tokyo, April 1998– March 2001;
Visiting Postdoctoral Research Associate, U. of Illinois at Urbana-Champaign, September 1999-March 2001.
RIKEN Special Postdoctoral Researcher, April 2001-March 2004.
RIKEN Fellow, RBRC Theory Group, April 2004-March 31, 2006
RBRC Visiting Scientist, April 1, 2006 - present.
Awards and Honors: Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists, April 1996-March 1998 and April 1998-March 2001.
RIKEN Special Postdoctoral Grant, April 2001-2004.

Tomomi Ishikawa **Birthplace**: Tottori, Japan **DOB**: December 25, 1971
Ph.D. 2002, Hiroshima University, Japan
Experience: Researcher, Hiroshima University, April 2002 to March 2003;
Institute Researcher, University of Tsukuba, Center for Computational Sciences, April 2003 - September 2006;
Research Associate, RIKEN BNL Research Center (Theory), October 1, 2006 - present.

Taku Izubuchi **Birthplace**: Tokyo, Japan **DOB**: February 15, 1970
Ph.D. 1997, University of Tokyo
Experience: Postdoc, Tsukuba University, April 1997-November 1999.
Research Associate (with tenure), Department of Physics, Kanazawa University, December 1999 – February 2001
Brookhaven National Laboratory, High Energy Theory Group, March 2001 – February 2003
Research Associate (with tenure), Department of Physics, Kanazawa University, March 2003 – present.
RBRC Visiting Fellow with Kanazawa University, April 1, 2003 – present.
Awards and Honors: Japan Society for the Promotion of Science (JSPS), Research Fellowship for Doctor Course, 1994-1997; André Lagarrigue Scholarship at the International School of Subnuclear Physics, Erice, Italy, 1995; JSPS Research Fellowship for Post Doctor, 1997-1999; JSPS Research Fellowship for Research Abroad, 2001-2003.

Nobuyuki Kamihara **Birthplace**: Yokohama, Japan **DOB**: June 29, 1974
M.Sci. 2002, Master Course of Fundamental Physics, Tokyo Institute of Technology

Experience: Graduate student at Tokyo Institute of Technology/Student Trainee at RIKEN, 2002 - present
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David M. Kawall **Birthplace**: Glasgow, UK **DOB**: April 13, 1965
Ph.D. 1996, Stanford University
Experience: Associate Research Scientist, Yale University, Physics Department, 1995-2004.
RIKEN BNL Fellow, RBRC Experimental Group, June 1, 2004 – January 2005.
RHIC Physics Fellow, RBRC Experimental Group/Assistant Professor, University of Massachusetts, Amherst, January 2005 - present
Awards and Honors: G. David Scott Scholarship in Physics, Trinity College Scholarship, Faculty Scholar, Varsity Fund National Admission Scholarship, William R. Hossack Memorial Scholarship in Mathematics and Physics

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Ph.D. 2005, Kyoto University, Japan
Experience: JSPS, Japan Society for the Promotion of Science Postdoctoral Fellow, Kyoto University, Yukawa Institute for Theoretical Physics, April 2005 - March 2006;
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2006 – present.

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Ph.D. 1999, University of Dortmund
Experience: Visiting Research Associate at Michigan State University, 2000-2002
Research Associate, Brookhaven National Laboratory, October 2002 –present;
Research Associate, Joint RBRC/Nuclear Theory Group, BNL, April 2003 to January 19, 2006.
Awards and Honors: Associate of the Graduiertenkolleg: Erzeugung und Zerfälle von Elementarteilchen of the Deutsche Forschungsgemeinschaft (DFG) Scholarship, 1996-2000.

Zheng Li **Birthplace**: China **DOB**:
Ph.D. 1986, Pennsylvania State University, University Park
Experience: Physicist, Brookhaven National Laboratory, Instrumentation Division, November 1986 - present.
RIKEN Spin Program Visiting Scientist, Experimental Group, May 2003 to present
Awards and Honors: Davey Fellowship, 1981, The Pennsylvania State University; Award for Excellent Academic Performance, 1977-1981, Peking University; Visiting Professor, Beijing Institute of Semiconductors, 1998-present; Dual Professor, Xiangtan University, China, 1999-present; Science and Technology Award, Brookhaven National Laboratory, 2005.

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Ph.D. 2006, Carnegie Mellon University, Pittsburgh, PA
Experience: Research Associate, RIKEN BNL Research Associate (Theory); October 2006 to present.

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Ph.D. 2004, University of Hamburg, Germany
Experience: Postdoc, Max Planck Institut für Physik for the MAGIC and EUSO Experiments
Research Associate, RIKEN BNL Research Center (Experiment),
February 1, 2006 - present

Cecilia Lunardini **Birthplace**: Piacenza, Italy **DOB**: March 27, 1974
Ph.D. 2001, SISSA-ISAS, Trieste, Italy
Experience: 2001 - 2004 Post-doctoral fellowship at the Institute for Advanced Study (IAS), School of Natural Sciences, Princeton. Funds from the National Science Foundation (NSF) and the Keck Foundation.
2004 - 2007 Five years fellow at the Institute for Nuclear Theory of Seattle and research assistant professor at the Physics Department of the University of Washington, Seattle.
2007 - Assistant professor at Arizona State University of Tempe, AZ and fellow at the RIKEN BNL Research Center (RBRC) October 2007 to present.
Awards and Honors: January 2003: Prize "Giorgio Gamberini" issued by Scuola Normale in Pisa (Italy) for a PhD thesis in Theoretical Physics.
December 2006: Selected as plenary speaker for the major conference "Neutrino 2006"(XXII International Conference on Neutrino Physics and Astrophysics) in Santa Fe, New Mexico from June 13-19, 2006.

Cyrille Marquet **Birthplace**: Boulogne-Billancourt, France **DOB**: September 23, 1980
Ph.D. 2006, University of Paris VI, France
Experience: Research Associate, RIKEN BNL Research Center (Theory)
October 2, 2006 - present

Ágnes Mócsy **Birthplace**: Romania **DOB**: September 10, 1971
Ph.D. 2001, University of Minnesota, Minneapolis
Experience: Adjunct/Post Doc, The Niels Bohr Institute, Copenhagen, Denmark, October 2001 to September 2003; Post Doc/Humboldt Research Fellow, Theoretical Physics Institute and Frankfurt Institute for Advanced Studies J. W. Goethe University, Frankfurt, Germany, October 2003 to September 2005;
Research Associate, RBRC Theory Group, October 1, 2005 - present.
Awards and Honors: Merit Scholarship, Babes-Bolyai University, Cluj-Napoca, Romania, 1990-1994; Study Scholarship, Eötvös University, Budapest, Hungary, 1993; NORDPLUS Award Scholarship, The Niels Bohr Institute, Copenhagen, Denmark, 1995-1996; Louise T. Dosdall Fellowship, University of Minnesota, Minneapolis,

2000-2001; Alexander von Humboldt Research Fellowship, J. W. Goethe University, Frankfurt, Germany 2004-2005.

Dénes Molnár **Birthplace**: Debrecen, Hungary **DOB**: June 24, 1974
Ph.D. 2002, Columbia University, New York
Experience: Postdoctoral Fellow, Nuclear Theory Group, The Ohio State University, Columbus, 2002-2003;
Postdoctoral Researcher, Nuclear Theory Group, The Ohio State University, 2003-2005;
•RHIC Physics Fellow, RBRC Theory Group/Assistant Professor, Purdue University, West Lafayette, IN, September 2005 to present
Awards and Honors: Graduate Research Fellowship, Columbia University, 1997-2002;
Postdoctoral Fellowship, The Ohio State University, 2002-2003;
Klaus Kinder-Geiger Award for Best Talk at Hot Quarks 2004 Intl. Workshop, Taos, New Mexico, 2003

Itaru Nakagawa **Birthplace**: Japan **DOB**: October 5, 1969
Ph.D. 1999, Graduate School of Tohoku University, Sendai, Japan
Experience: Postdoctoral Associate of the Laboratory for Nuclear Science, Massachusetts Institute of Technology, Nov. 1999 to Nov. 2002; Postdoctoral Associate of Department of Physics and Astronomy, University of Kentucky, Dec. 2002 - Nov. 2003; Research Assistant Professor of the Department of Physics and Astronomy, University of Kentucky, December 2003-November 2004;
Scientist RIKEN, December 2004 - present;
RIKEN SPIN Program Researcher, RBRC Experimental Group, December 2004 - present.
Awards and Honors: Japan Ikueikai Scholarship, 1989-1994 and 1995-1999; The Peter T. Demos Award for the outstanding Ph.D. thesis in MIT-Bates Laboratory, 2000; Award for outstanding young physicists in Experimental Nuclear physics, Japanese Physics Society, 2003.

Ken'ichi Nakano **Birthplace**: Hiroshima, Japan **DOB**: May 24, 1980
B.S. 2003, Tokyo Institute of Technology
Master Course Student, Tokyo Institute of Technology
Experience: RBRC Young Researcher, RBRC Experimental Group, July 1, 2004 – March 2005.
RIKEN Jr. Research Associate, April 1, 2005 - present.

Akio Ogawa **Birthplace**: Japan **DOB**: September 6, 1969
Ph.D. 1997, Nagoya University, Japan
Experience: Research Associate, September 2002 and Assistant Scientist, April 2003, Brookhaven National Laboratory (BNL), STAR Experiment;
RIKEN Spin Program Visiting Scientist, Experimental Group, Belle Collaboration, KEK, January 1, 2002 - present.

Kensuke Okada **Birthplace**: Japan **DOB**: November 20, 1970
Ph.D. 2001, Nagoya University
Experience: Contract Researcher at RIKEN, Wako, Japan, June 2001-March 31, 2002
Research Associate, RIKEN BNL Research Center (Experiment),
April 1, 2003 – March 31, 2006;
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April 1, 2006 - present.

Peter Petreczky **Birthplace**: Uzsgorod (Ungvar), Ukraine **DOB**: February 17, 1973
Ph.D. 1999, Eötvös University, Budapest, Hungary
Experience: Research Fellow, Bielefeld University, Germany, 1999-2002
Goldhaber Fellow, Brookhaven National Laboratory, October 2002 – Sept. 2005;
RIKEN BNL Fellow, RBRC Theory Group joint with Nuclear Theory
October 1, 2003 – September 30, 2005; RIKEN BNL Fellow/Assistant Physicist joint with Lattice Gauge Group, October 1, 2005 to present.
Awards and Honors: Goldhaber Fellowship, 2002.

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Ph.D. 1995, Kyoto University, Japan
Experience: 1993 July, Research Fellow, Kyoto University, Japan
1995 April, RIKEN Special Post Doctoral Fellow
RIKEN/RBRC Researcher, 1996 April to March 2001
RIKEN Spin Program Researcher, April 1, 2001 – March 31, 2002;
Visiting Scientist, Experimental Group, RBRC, with Kyoto University, Japan, Spring 2002 – present.
Awards and Honors: Fellowship: Japan Society for the Promotion of Science, 1993-1995

Shoichi Sasaki **Birthplace**: Tokyo, Japan **DOB**: May 31, 1968
Ph.D. 1997, Osaka University, Japan
Experience: Research Fellow of JSPS, Yukawa Inst. Theor. Physics, Kyoto U., Japan, April 1997 to August 31, 1998;
RIKEN BNL Research Associate, September 1998 to September 30, 2000;
Assistant Professor, University of Tokyo, October 2000 – present.
RIKEN Fellow, RIKEN BNL Research Center, Theory Group, October 1, 2004 to September 30, 2006.
Awards and Honors: Fellowship: Japan Society for the Promotion of Science, 1997-1998;
JPS Best Paper Award from Japan Physical Society, 1999.

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Ph.D. 2004, University of Erlangen-Nürnberg and DESY, Hamburg, Germany
Experience: Working Visit, Hermes Group at Tokyo Institute of Technology, Japan, granted by DFG/JSPS, October 2003; Hermes Experiment at DESY, Hamburg, Germany, 2002-2004; Postdoctoral Researcher, University of Illinois at Urbana-Champaign;
Visiting Scientist, RBRC Experimental Group, May 15, 2005 to present

Tsuguchika Tabaru **Birthplace**: Ehime, Japan **DOB**: July 31, 1971
Ph.D. 2001, Kyoto University
Experience: Research Fellow of the Japan Society for the Promotion of Science, April 1996 – March 1999;
Contract Researcher of RIKEN, April 2001 – March 2002
RIKEN Special Postdoctoral Researcher, RIKEN Spin Program (RSP) Research Associate, RIKEN BNL Research Center, Experimental Group, April 2003 – January 31, 2006.

Atsushi Taketani **Birthplace**: Ako, Japan **DOB**: February 26, 1963
Ph.D. 1990, Hiroshima University, Japan
Experience: Research Associate, Fermi National Accelerator Laboratory, Batavia, IL, 1990-1994
Researcher, RIKEN, 1994-1999
Senior Research Scientist, RIKEN, 1999- present
RIKEN Spin Program Researcher, April 1, 2001 – present.

Kiyoshi Tanida **Birthplace**: Japan **DOB**: February 8, 1974
Ph.D. 2000, University of Tokyo
Experience: JSPS Special Research Fellow, University of Tokyo, January 2000 – March 2000;
JSPS Postdoctoral Research Fellow, University of Tokyo, April 2000 – September 2001;
Researcher, RIKEN, October 2001 – present;
RIKEN Spin Program Researcher, November 2003 – present.

Derek Teaney **Birthplace**: New York, NY **DOB**: Sept. 26, 1972
Ph.D. 2001, SUNY at Stony Brook
Experience: Postdoctoral Research Fellow, Brookhaven National Laboratory, October 2001 – 2004
Postdoctoral Research Fellow, SUNY at Stony Brook, July 2004 – July 2006
Assistant Professor, Arkansas State University, July 2006 – present
Awards and Honors: T.A. Pond Prize for Distinction on the Qualifying Exam, SUNY at Stony Brook, 1996
Anthony D. Stanley Memorial Prize for Excellence in Mathematics, Yale University, 1995

Hisayuki Torii **Birthplace**: Japan **DOB**: June 6, 1973
Ph.D. 2003, Kyoto University
Experience: Junior Research Associate, RIKEN, Japan, April 1999 – March 2002;
RIKEN Spin Program (RSP) Research Associate, RIKEN BNL Research Center, Experimental Group, April 2003 – present.

Kirill Tuchin **Birthplace:** Makeevka, Ukraine **DOB:** August 11, 1973
Ph.D. 2001, Tel-Aviv, Israel
Experience: Postdoctoral Research Associate, Institute for Nuclear Theory, University of Washington, 2001-2003; Postdoctoral Research Associate, Nuclear Theory Group, Brookhaven National Laboratory;
•RHIC Physics Fellow, RBRC Theory Group/Assistant Professor, Iowa State University, Ames
Awards and Honors: Prize for research achievements from the School of Physics and Astronomy, Tel Aviv University, 2000.

Werner Vogelsang **Birthplace**: Dortmund, Germany **DOB**: October 6, 1965
Ph.D. 1993, University of Dortmund, Germany
Experience: Postdoctoral Researcher in Theoretical Particle Physics, U. of Dortmund, Nov. 1993 - Sept. 1994
Research Associate in Theory Group of the Rutherford Appleton Laboratory, Didcot, England, Oct. 1994-Dec. 1996
Fellow in Theory Division, CERN, Geneva, Switzerland, Jan. 1997-Dec. 1998
Post-doctoral Researcher at the Institute for Theoretical Physics at State University of New York, Stony Brook, January 1999 to March 2000
RIKEN BNL Fellow, April 1, 2000 – September 30, 2003.
•RHIC Physics Fellow/Associate Physicist/RBRC/BNL,
October 1, 2003 to March 31, 2006; Awarded Tenure at BNL on June 1, 2005.
Awards and Honors: Scholar of the "Studienstiftung des Deutschen Volkes, 1984-1990

Yasushi Watanabe **Birthplace**: Tokyo, Japan **DOB**: February 12, 1961
Ph.D. 1993, University of Tokyo, Japan
Experience: Scientific Researcher, RIKEN, 1991
Research Collaborator, PHENIX/RBRC
Scientific Researcher, RIKEN, RBRC, 1998-2001
RIKEN Spin Program Researcher, April 1, 2001 – present

Wei Xie **Birthplace**: Hei Meng Gu, P.R. China **DOB**: April 5, 1970
Ph.D. 1997, Institute of High Energy Physics, Beijing, P.R. China
Experience: Postdoctoral Fellow at Department of Particle Physics, Weizmann Institute of Science, Israel, CERES/NA45 Experiment at CERN, PHENIX at BNL, October 1997 – March 2000.
Postdoctoral Research Associate at Physics Department, University of California, Riverside, PHENIX at BNL, March 2000 to January 2004;
RIKEN BNL Fellow, RBRC Experimental Group, January 2004 – present.
Awards and Honors: Guan Hua Fellowship for outstanding students at Shandong University, P.R. China, 1988; Feinberg Fellowship at Weizmann Institute of Science in Israel, 1998-2000;

Takeshi Yamazaki **Birthplace**: Chiba, Japan **DOB**: September 1, 1976
Doctor of Science: 2004, University of Tsukuba, Japan
Experience: Research Associate, RIKEN BNL Research Center, Theory Group, April 1, 2004 – present.
Awards and Honors: Award Medal by the Japanese Theoretical Particle Physics Group for Outstanding Presentation at Biannual Meeting of the Physical Society of Japan, 2004.

Satoshi Yokkaichi **Birthplace**: Iwamizawa, Hokkaido, Japan **DOB**: Dec. 10, 1966
Ph.D. 2000, Kyoto University, Japan
Experience: Research Fellow of the Japan Society for the Promotion of Science, 1995-1997
Research Fellow of the Department of Physics, Kyoto University, 1998-2000; Special Postdoctoral Researcher, RIKEN, 2000-2001
RIKEN Spin Program Research Associate, April 1, 2001 – present
Awards and Honors: Fellowship: Japan Society for the Promotion of Science, 1995-1997

Hiroshi Yokoya **Birthplace**: Tokyo, Japan **DOB**: March 25, 1978
Master Sc. 2002, Hiroshima University
Experience: RIKEN SPIN Program Young Researcher, RIKEN BNL Research Center, Theory Group, May 2003 – March 2005.

Feng Yuan **Birthplace**: Huangmei, China **DOB**: March 10, 1972
Ph.D. 2000, Peking University, P.R. China
Experience: Postdoctoral Research Associate, U. of Heidelberg, Germany, September 2000 to February 2002; Postdoctoral Research Associate, U. of Maryland, College Park, March 2002 to August 2004;
Research Associate, RIKEN BNL Research Center, Theory Group, September 1, 2004 – present.
Awards and Honors: National Outstanding Ph.D. Thesis, Chinese Ministry of Education, 2002.

RBRC Publications

RBRC/#

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RIKEN BNL Research Center
Theory Group
Publication List

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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. D57, 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. D57, 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).

10. D. Kharzeev, "Production of Heavy Mesons," in *Proceedings Quarks and Gluons in the Nucleon*, Wako, Japan, eds. T. Shibata and K. Yazaki, RIKEN BNL Research Center, 1997, p. 67.

11. S. E. Vance, Y. Csörgo, and D. Kharzeev," Observation of Partial $U_A(1)$ Restoration from Two-Pion Bose-Einstein Correlation," [nucl-th/9802074]; Phys. Rev. Lett. 81, No. 11, 2205-2208 (1998).

12. R. D. Mawhinney, "The QCD Hadron Spectrum and the Number of Dynamical Quark Flavors," Nucl. Physics 63A-C (*Proc. Suppl*), 212 (1998).

13. R. D. Mawhinney and C. Jung, "An Investigation of Semiclassical and Monopole Confinement Mechanisms," Internal Report.

14. D. Rischke, "Instabilities and Inhomogeneities in the Early Stage of Ultrarelativistic Heavy-Ion Collisions," in *Proceedings of Non-Equilibrium Many Body Dynamics*, Eds. M. Creutz and M. Gyulassy, RIKEN BNL Research Center, p. 47, 1997.

15. J. Kodaira, T. Nasuno, H. Tochimura, K. Tanaka, and Y. Yasui, "Renormalization of the Twist-3 Flavor Singlet Operators in a Covariant Gauge," to appear in the *Proceedings of Deep Inelastic Scattering off Polarized Targets: Theory Meets Experiment*, DESY, Germany, 1997.

16. J. Kodaira, T. Nasuno, H. Tochimura, K. Tanaka and Y. Yasui, "Renormalization of Gauge-Invariant Operators for the Structure Function $g_2(x, Q^2)$," Prog. Theor. Phys. 99, 315 (1998).

17. D. H. Rischke, "Forming Disoriented Chiral Condensates Through Fluctuations," [nucl-th/9806045]; Phys. Rev. C58, 2331 (1998).

18. A. Dumitru, D. H. Rischke, "Collective Dynamics in Highly

Relativistic Heavy-Ion Collisions," [nucl-th/9806003]; Phys. Rev. C59, 354-63 (1999).

19. D. H. Rischke, "Fluid Dynamics for Relativistic Nuclear Collisions," [nucl-th/9809044], *Proc. of the 11 Chris Engelbrecht Summer School in Theoretical Physics: Hadrons in Dense Matter and Hadrosynthesis,* Cape Town, South Africa, Feb. 4-13, 1998, Lecture Notes in Physics, Eds. Jean Cleymano, H.B. Geiger, F. G. Scholtz, Springer, pp. 21-70, 1999.

20. D. H. Rischke, "Dynamics of Classical Yang-Mills Fields in Ultrarelativistic Nuclear Collisions," *Proceedings of the Conference on Continuous Advances in QCD 1998 [Workshop dedicated to the memory of V. N. Gribov. Minneapolis, April 16-19, 1998],* 440-450, Editor: A. V. Smilga, World Scientific, Singapore, 1998.

21. S. Kim and S. Ohta, "Quenched Staggered Light Hadron Spectroscopy from $48^3 \times 64$ at $\beta = 6.5$*," *Proc. "Lattice '97,"* Edinburgh, UK, 1997, [hep-lat/9712014], Eds. C.T.H. Davies et al; Nuclear Physics B (Proc. Suppl.) 63, 185-187 (1998).

22. T. D. Lee, "Generalization of Soluble Gauge Model with Gribov Copies," *Proceedings of the Conference on Continuous Advances in QCD 1998 [Workshop dedicated to the memory of V. N. Gribov. Minneapolis, April 16-19, 1998],* xxii-xlvi, Editor: A. V. Smilga, World Scientific, Singapore, 1998.

23. Tom Blum, Amarjit Soni, and Matthew Wingate, "Light Quark Masses Using Domain Wall Fermions," [hep-lat/9809065], *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98,* Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 201-203 (1999).

24. H. Fujii and D. Kharzeev, "Long-range Interactions of Small Color Dipoles," [hep-ph/9807383]; *Proceedings of the Conference on Continuous Advances in QCD 1998 [Workshop dedicated to the memory of V. N. Gribov. Minneapolis, April 16-19, 1998],* 167-178, Editor: A. V. Smilga, World Scientific, Singapore, 1998.

25. T. D. Lee, "Locality and Beyond," Symposium on the occasion of Sid Drell's retirement as Professor and Deputy Director at SLAC, SLAC Auditorium, Stanford University, July 31, 1998. Presentations published on SLAC website: http://www.slac.Stanford.edu/conf/drell98.

26. C. Bernard, T. DeGrand, C. DeTar, Steven Gottlieb, Urs M. Heller, J. E. Hetrick, N. Ishizuka, C. McNeile, R. Sugar, D. Toussaint, and M. Wingate (MILC Collaboration), "Lattice Determination of Heavy-Light Decay Constants," [hep-ph/9806412], Phys. Rev. Lett. 81, 4812-4815 (1998).

27. T. Blum, "Domain Wall Fermions in Vector Gauge Theories," [hep lat/9810017], *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 167-179 (1999).

28. Shigemi Ohta and Matthew Wingate, "SU(4) Pure-gauge String Tensions," [hep-lat/9808022]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 435-437 (1999).

29. C. Bernard, T. DeGrand, C. DeTar, Steven Gottlieb, Urs M. Heller, J.E. Hetrick, N. Ishizuka, C. McNeile, R. Sugar, D. Toussaint, and M. Wingate (MILC Collaboration), "Heavy-Light Decay Constants: Conclusions from the Wilson Action," [hep-lat/9809109] *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 372-374 (1999).

30. S. Kim and S. Ohta, "Chiral Limit of Light Hadron Mass in Quenched Staggered QCD," [hep-lat/9809184]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 195-197 (1999).

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).

32. D. Kharzeev, R. D. Pisarski, and M. Tytgat, "Parity-odd Bubbles in Hot QCD," [hep-ph/9808366]; *Proceedings of the Conference on Continuous Advances in QCD 1998 [Workshop dedicated to the memory of V. N. Gribov. Minneapolis, April 16-19, 1998]*, 451-459, Editor: A. V. Smilga, World Scientific, Singapore, 1998.

33. D. Kharzeev, "Workshop on Quarkonium Production in Nuclear Collisions: Summary," [hep-ph/9812214]; *Proc. Quarkonium Production*, Seattle, May 11-15, 1998, pp 180-189.

34. A. J. Baltz, "Exact Dirac Equation Calculation of Ionization Induced by Ultrarelativistic Heavy Ions, Phys. Rev. A 61, 042701 (2000).

35. S. Sasaki and O. Miyamura, "Lattice Study of $U(1)_A$ Anomaly: The Role of QCD-Monopoles," [hep-lat/9810039, BNL-66443]; Phys. Lett. B443, 331-337 (1998).

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37. A. J. Baltz and L. McLerran, "Two Center Light Cone Calculation of Pair Production Induced by Ultrarelativistic Heavy Ions," Phys. Rev. C58, 1679 (1998).

38. E. Farhi, N. Graham, P. Haagensen, R. L. Jaffe, "Finite Quantum Fluctuations About Static Field Configurations," [hep-th/9802015], Phys. Lett. B427, 334-342 (1998).

39. D. Chen, P. Chen, N. Christ, R. Edwards, G. Fleming, A. Gara, S. Hansen, C. Jung, A. Kaehler, A. Kennedy, G. Kilcup, Y. Luo, C. Malureanu, R. Mawhinney, J. Parsons, C. Sui, P. Vranas, Y. Zhestkov, "Status of the QCDSP Project," [hep-lat/9810004]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 898-900 (1999).

40. P. Chen, N. Christ, G. Fleming, A. Kaehler, C. Malureanu, R. Mawhinney, G. Siegert, C. Sui, P. Vranas, Y. Zhestkov, "Quenched QCD with Domain Wall Fermions," [CU-TP-915, hep-lat/9811026]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 204-206 (1999).

41. P. Chen, N. Christ, G. Fleming, A. Kaehler, C. Malureanu, R. Mawhinney, G. Siegert, C. Sui, P. Vranas, Y. Zhestkov, "The Anomaly and Topology in Quenched, QCD above T_c" [CU-TP-913]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 405-407 (1999).

42. P. Chen, N. Christ, G. Fleming, A. Kaehler, C. Malureanu, R. Mawhinney, G. Siegert, C. Sui, P. Vranas, Y. Zhestkov, "The Domain Wall Fermion Chiral Condensate in Quenched QCD," [CU-TP-913, hep lat/9811013]; *Proc. of the XVI International Symposium on Lattice Field Theory, Lattice '98*, Boulder, Colorado, July 13-18, 1998, Eds. T. DeGrand, C. DeTar, R. Sugar and D. Toussaint; Nuclear Physics B (Proc. Suppl.) 73, 207-209 (1999).

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44. D. Kharzeev, "Quarkonium as a Probe of QCD Matter," to appear in *Proc. Intl. Phys. Conf.*, Paris, 1998, Nucl. Phys. A.

45. D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovjev, "J/ψ Photoproduction and the Gluon Structure of the Nucleon," [hep-ph/9901375], Dec. 1998, Nucl. Phys. A661, 568-572 (1999).

46. D. Kharzeev and J. Ellis, "The Glueball Filter in Central Production and Broken Scale Invariance," [hep-ph/9811222], CERN-TH-98-349, 9 pp, November 1998.

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48. J. T. Lenaghan and D. Rischke, "The O(N) Model at Finite Temperature: Renormalization of the Gap Equations in Hartree and

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RIKEN BNL RESEARCH CENTER

RBRC Scientific Review Committee Meeting

November 5-6, 2007

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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