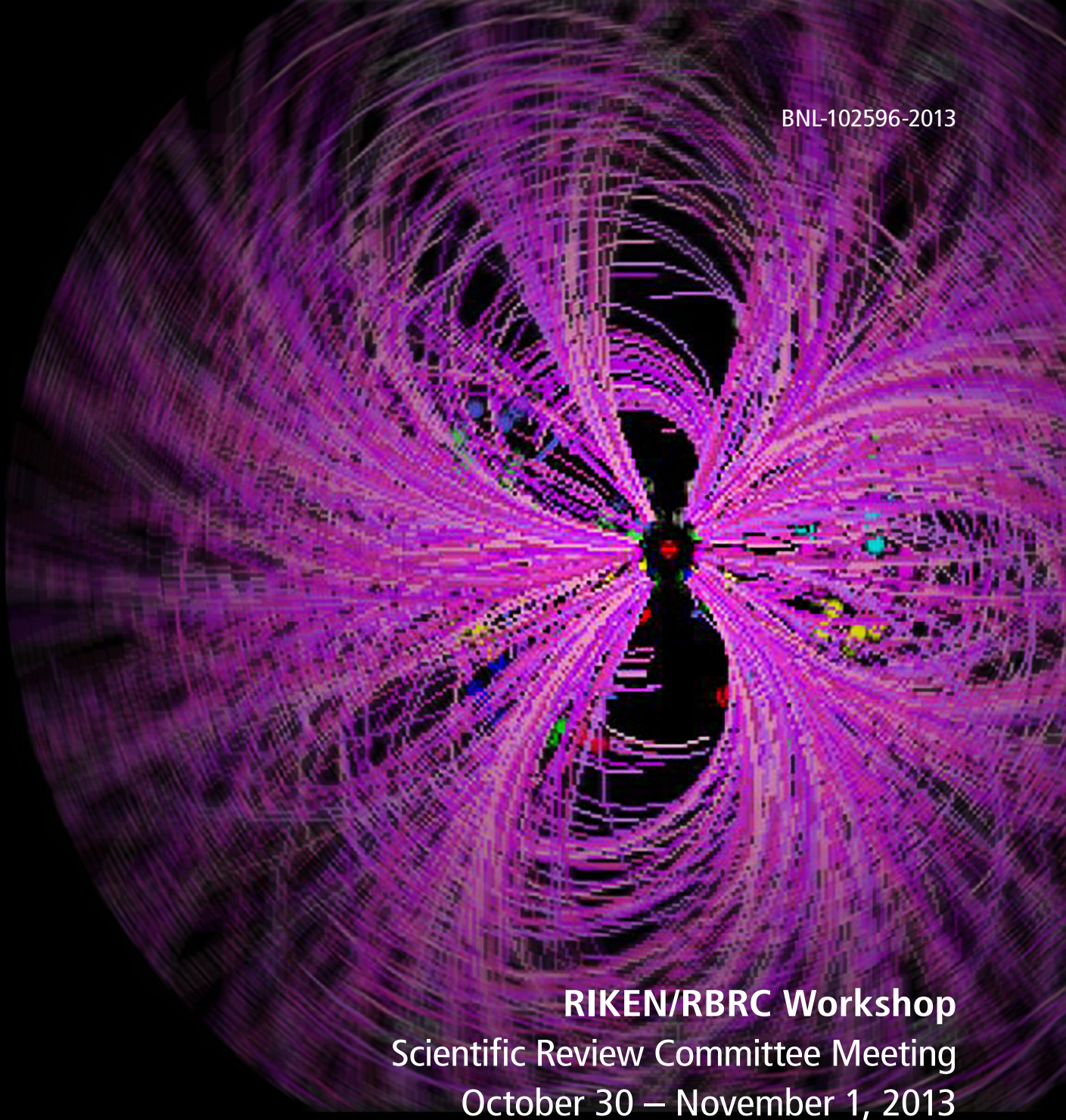
BNL-102596-2013



RIKEN/RBRC Workshop

Scientific Review Committee Meeting

October 30 – November 1, 2013

Proceedings of RIKEN BNL Research Center Workshop

Volume 116

Organizer: Samuel H. Aronson

RBRC

RIKEN BNL Research Center

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Ethan Neil

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RBRC Scientific Review Committee Final Report

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 and the U. S. Department of Energy's Office of Science.

The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002, 2007 and 2012.

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.

In April 2013, Dr. Samuel Aronson was named Director of the Center, preceded by Nicholas Samios and T.D. Lee

The RBRC has theory, lattice gauge computing and experimental components. It is presently exploring the possibility of an astrophysics component being added to the program. The RBRC Theory, Computing and Experimental Groups comprise a total of 42 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 institutions. To date, RBRC has over 101 graduates (Fellows and Post-docs) of whom approximately 67 have already attained tenure positions at major institutions worldwide.

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

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. To date there are over 125 proceedings volumes available.

A series of high performance computers has been designed and built by individuals from Columbia University, IBM, BNL, RBRC, and University of Edinburgh, with the U.S. DOE Office of Science providing infrastructure support at BNL. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center in February 1998, was completed in August 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled on May 26, 2005. QCDOC was decommissioned in May 2012. The next generation computer in this sequence, QCDCQ (600 Teraflops), is currently operational and is producing important simulations of fundamental processes in nuclear and particle physics. Recent $K^0 \rightarrow pp$ results were awarded the Ken Wilson Prize in 2012.

Samuel H. Aronson, Director
November 2013

***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

October 30 – November 1, 2013

Brookhaven National Laboratory, Upton, NY 11973

The thirteenth scientific evaluation of the RIKEN BNL Research Center (RBRC) took place at the Physics Building #510 at Brookhaven National Laboratory.
The members of the Scientific Review Committee (SRC), present at the meeting, were:
Prof. Sinya Aoki, Prof. Peter Braun-Munzinger, Prof. Kenichi Imai, Prof. Tetsuo Matsui, Prof. Richard Milner (Chair), Prof. Alfred Mueller, Prof. Charles Young Prescott, and Prof. Akira Ukawa.
We are pleased that Dr. Hideto En'yo, the Director of the Nishina Institute of RIKEN, Japan, participated in this meeting both in informing the committee of the activities of the RIKEN Nishina Center for Accelerator-Based Science 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 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.

Samuel Aronson

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

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RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Physics Dept, Bldg 510, Rm 2-160
October 30 – November 1, 2013
AGENDA

Committee Members:

Aoki, Sinya	saoki@yukawa.kyoto-u.ac.jp
Braun-Munzinger, Peter	p.braun-munzinger@gsi.de
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Mueller, Alfred	amh@phys.columbia.edu
Prescott, Charles Young	prescott@slac.stanford.edu
Ukawa, Akira	ukawa@ccs.tsukuba.ac.jp

WEDNESDAY, OCTOBER 30, 2013

06:30 - 09:30 *Executive Dinner (Chachama Grill, Patchogue)*
http://www.chachamagrill.com/Chachama/Directions.html

THURSDAY, OCTOBER 31, 2013

Executive Session – Physics Room 2-160

08:00 - 08:30 *SRC Executive Session & Working Breakfast (Room 2-160)*
08:30 - 08:40 Welcome ..... Doon Gibbs
08:40 - 08:55 RIKEN Overview ..... Hideto En'yo
08:55 - 09:10 RBRC Overview ..... Samuel Aronson

Open Session – Physics Large Seminar Room

09:15 - 10:35 EXPERIMENTAL GROUP PRESENTATIONS –YASUYUKI AKIBA, CHAIR

09:15 - 09:35 Experimental Group Overview ..... Yasuyuki Akiba
09:35 - 09:55 W → mu Measurement in PHENIX ..... Ralf Seidl (remote)
09:55 - 10:15 Studying the Medium Properties in dAu via Two Particle Correlation ..... John Chen
10:15 - 10:35 Operation and Current Status of Silicon Pixel Detector ..... Maki Kurosawa
10:35 - 10:45 *BREAK*

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10:45 - 12:05 EXPERIMENTAL GROUP PRESENTATIONS – ANNE SICKLES, CHAIR

10:45 - 11:05 Overview of Current Spin Physics Program and Future Plans in PHENIX....Abhay Deshpande
11:05 - 11:25 Spin Measurement with FVTX.....Xiaorong Wang
11:25 - 11:45 fsPHENIX Detector and Physics Program .....Joe Seele
11:45 - 12:05 Letter of Intent for the ePHENIX Detector .....Kieran Boyle
12:05 - 01:00 *SRC Executive Session - Working Lunch (Room 2-160)*

01:00 - 03:10 THEORY GROUP PRESENTATIONS—DIMITRI KHARZEEV, CHAIR

01:00 - 01:20 Theory Overview.....Robert Pisarski
01:20 - 01:40 The Higgs Field as an Inflaton.....Fedor Bezrukov
01:40 - 02:00 Strongly Interacting Matter In and Out of Equilibrium .....Jinfeng Liao
02:00 - 02:20 Triangle Anomaly in Quark-gluon Plasma .....Ho-Ung Yee
02:20 - 02:40 Extending QCD Transport to NLO.....Derek Teaney
02:40 - 02:50 Instabilities Near the QCD Phase Transition in Holographic Models .....Shu Lin
02:50 - 03:00 Phase Structure and Hosotani Mechanism in QCD-like Gauge Theory.....Koji Kashiwa
03:00 - 03:10 Fluidity of the Quark-gluon Plasma in Heavy Ion Collisions.....Akihiko Monnai
03:10 - 03:20 Comments on Particle Production in pp and pA Collisions .....Adam Bzdak
03:20 - 03:30 Transverse Single-spin Asymmetries and the "Sign Mismatch" Crisis .....Daniel Pitonyak

03:30 - 03:40 *BREAK*

03:40 - 04:40 COMPUTING GROUP PRESENTATIONS— NORMAN CHRIST, CHAIR

03:40 - 04:00 Computing Overview.....Taku Izubuchi
04:00 - 04:20 Kaon Program.....Bob Mawhinney
04:20 - 04:40 Muon g-2 on Lattice.....Thomas Blum

04:40 - 05:00 EXPERIMENTAL GROUP PRESENTATIONS – SAMUEL ARONSON, CHAIR

04:40 - 05:00 Charged Hadron Measurements with the PHENIX VTX Detector .....Stefan Bathe

05:00 - 06:30 *SRC Executive Session (Room 2-160)*
06:30 - 07:00 *Travel to Reception and Dinner*
07:00 - 10:00 *Reception and Dinner (The Oar Restaurant, Patchogue)*
http://www.theoar.com/ordereze/Directions.aspx

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FRIDAY, NOVEMBER 1, 2013

08:00 - 09:00 *SRC Executive Session and Continental Breakfast (Room 2-160)*

Open Session – Physics Large Seminar Room

09:00 - 10:20 ASTROPHYSICS/THEORY GROUP PRESENTATION - ROBERT PISARSKI, CHAIR

09:00 - 09:40 Cosmology/Astrophysics and RBRC.....Toru Tamagawa
09:40 - 10:00 Spatial Wilson Loops in Heavy-ion Collisions .....Adrian Dumitru
10:00 - 10:20 Scattering Amplitudes and Recursion Relations in Light Front Perturbation Theory.....Anna Stasto
10:20 - 10:50 *BREAK*

10:50 - 12:10 COMPUTING GROUP PRESENTATIONS -TAKU IZUBUCHI, CHAIR

10:50 - 11:10 Nuclear Physics.....Brian Tiburzi
11:10 - 11:30 New Theories, New Physics, and Lattice Simulations .....Ethan Neil
11:30 - 11:50 B Physics on the Lattice.....Tomomi Ishikawa
11:50 - 12:00 Kaon Hadronic Decay .....Christopher Kelly
12:00 - 12:10 Nucleon Structure .....Sergey Syritsyn

12:10 - 01:00 *SRC Executive Session and Working Lunch (Room 2-160)*

01:00 - 03:00 Meetings with Individual RBRC Staff
Theorists .....(Room 2-160)
Experimentalists.....(Room 2-78)

Room 2-160

03:00 - 04:20 BNL Future Plan - RAJU VENUGOPALAN, CHAIR

03:00 - 03:20 BNL, RHIC, e-RHIC Future Plan .....Berndt Mueller
03:20 - 03:40 Future Detector Upgrades to RHIC and eRHIC.....Thomas Ludlam
03:40 - 04:00 Why eRHIC is Theoretically Interesting .....Yuri Kovchegov
04:00 - 04:20 Future Prospects of Computing.....Taku Izubuchi & Norman Christ
04:20 - 05:30 *SRC Executive Session with Coffee Break (Room 2-160)*
05:30 - 06:00 *Closeout/Adjourn (Room 2-160)*

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RBRC Scientific Review Committee Membership 2013

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FAX: 212-932-3169
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E-mail: ukawa@ccs.tsukuba.ac.jp

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Executive Session

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STATUS of RIKEN & Nishina Center

Hideto En'yo

31th Oct, 2013

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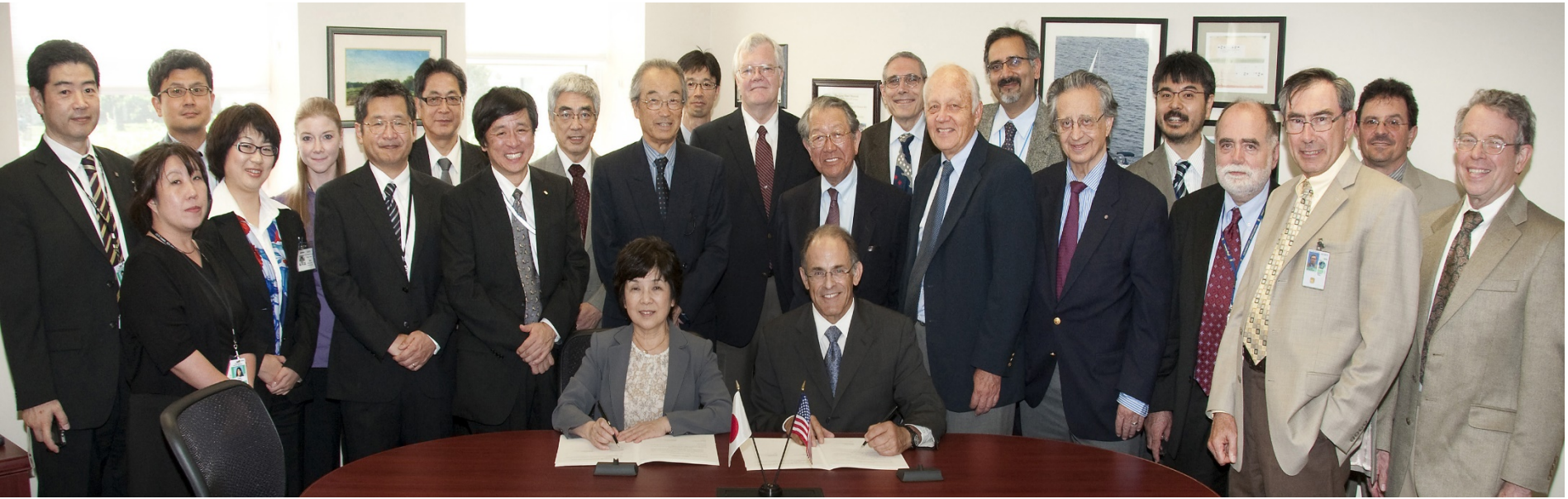
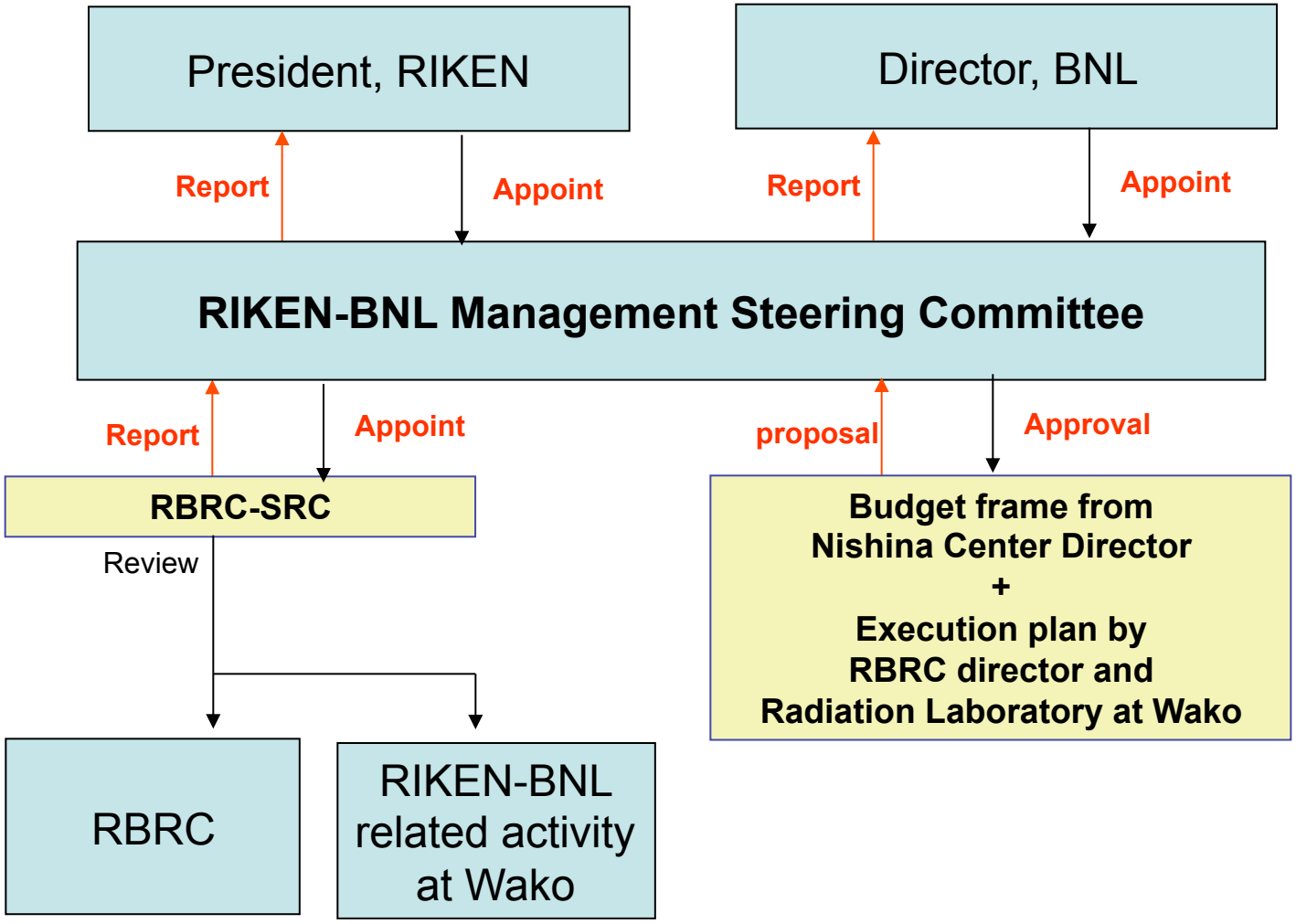
- Many Thanks to Dr. Aronson and Dr. Samios
- Review Structure and Terms of Reference
- Status of RIKEN & Nishina Center



RIKEN Review System and Schedule (General)



RIKEN Institutes and Centers, And their Directors



Director
Akihiro
Fujita

RIKEN Research Cluster for Innovation

Biomass Engineering Program



Director
Dr. Kazuo Shinozaki

Program for Drug Discovery and Medical Technology Platforms



Director
Dr. Toshio Goto

Preventive Medicine & Diagnosis Innovation Program



Director
Dr. Yoshihide Hayashizaki

Headquarters



President
Dr. NOYORI Ryoji

Executive Directors



Mr. Minoru Yonekura



Mr. Teruo Furuya



Dr. Maki Kawai



Dr. Kenji Oeda



Dr. Hiroshi Tsuboi

Wako Campus



Director
Dr. Tomo Ogawa

Center for Advanced Photonics



Director
Dr. Katsumi Midorikawa

Center for Emergent Matter Science



Director
Dr. Yoshinori Tokura

Center for Developmental Biology



Director
Dr. Masatoshi Takeichi

Center for Life Science Technologies



Director
Dr. Yasuyoshi Watanabe

HPCI Program for Computational Life Sciences



Director
Dr. Toshio Yanagida

Yearly Budget

900 M$

Personnel

3,500

FY2012

Nishina Center for Accelerator-Based Science



Director
Dr. Hideto Enyo

Brain Science Institute

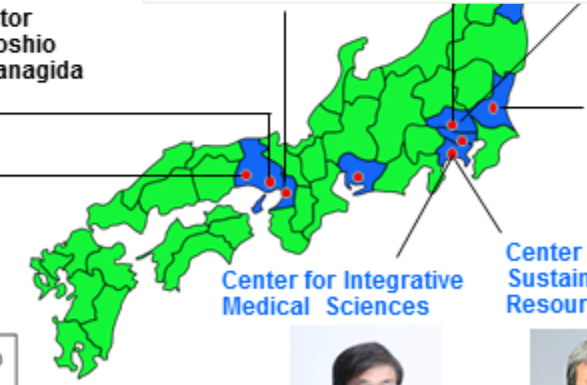


Director
Dr. Susumu Tonegawa

Bio Resource Center



Director
Dr. Yuichi Obata



Advanced Institute for Computational Science



Director
Dr. Kimihiko Hirao

Spring-8 Center



Director
Dr. Tetsuya Ishikawa

Center for Integrative Medical Sciences



Director(Acting)
Dr. Shigeo Koyasu

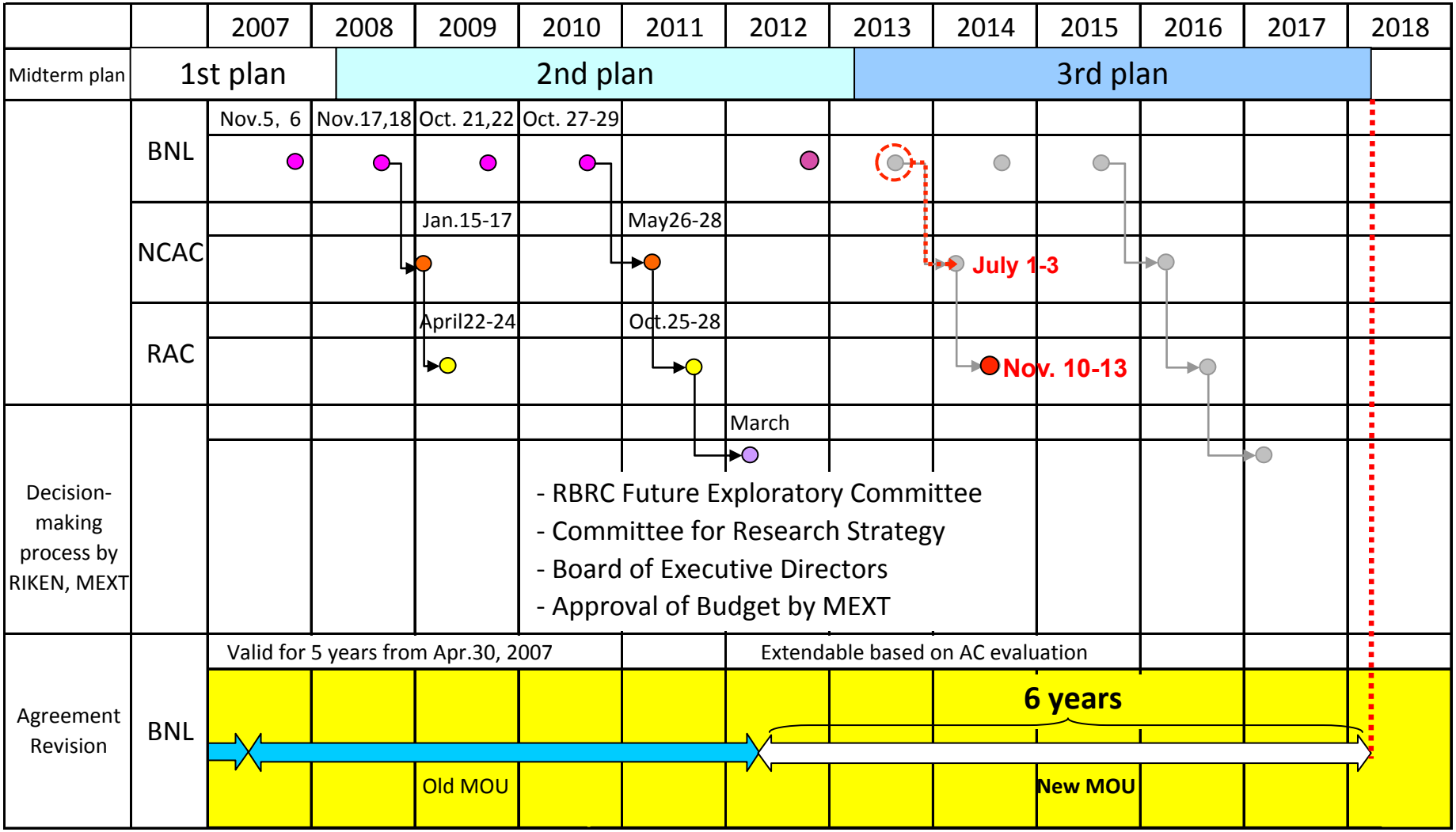
Center for Sustainable Resource Science



Director
Dr. Kazuo Shinozaki

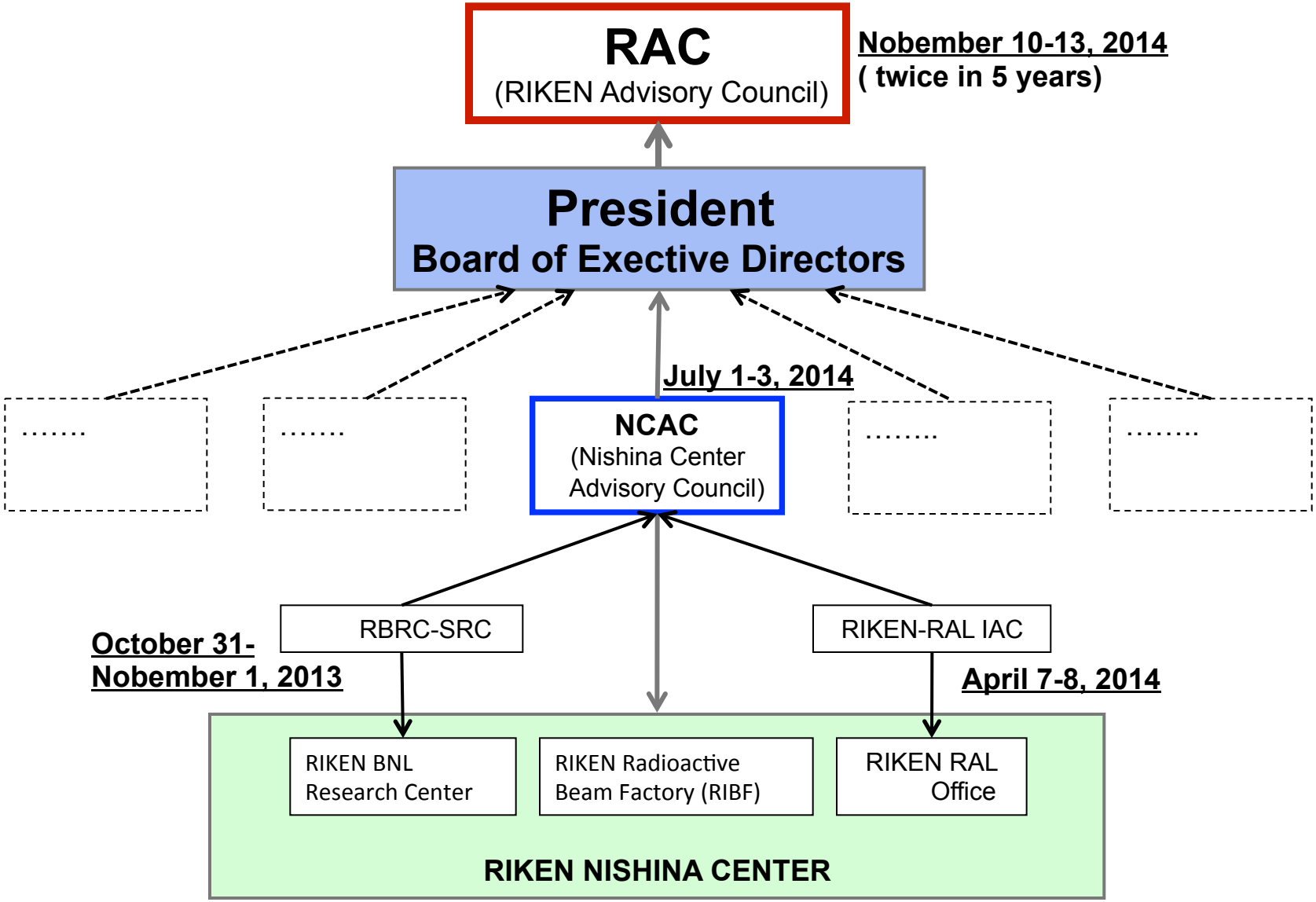
<Overseas>
RAL-RIKEN (UK)
BNL-RIKEN (USA)
Beijing Representative Office (China)
Singapore Representative Office

Schedule of Nishina Center Advisory Coucil and BNL-SRC, RNC-AC, when run with RAC(RIKEN AC).

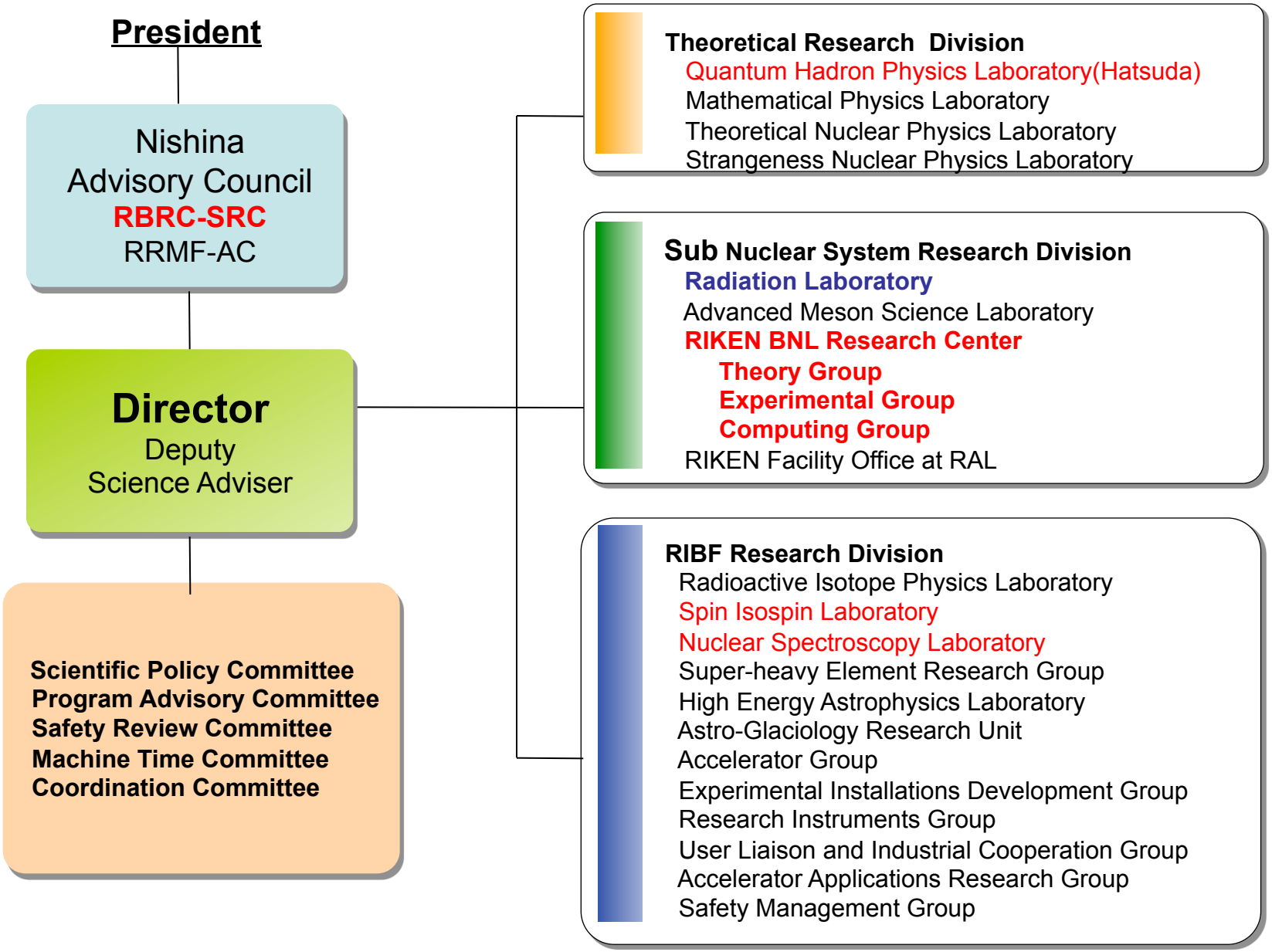


*Extendable based on AC evaluation and Decision Making Process by RIKEN

RIKEN Review System and Evaluation of RBRC



Present Organization of RNC



The terms of reference

NOYORI to RAC	NOYORI to NCAC	EN'YO to NCAC/SRC
Evaluate RIKEN's response to the proposals made by the 8th RAC.		Evaluate RBRC's response to the proposals made by the last SRC.
Evaluate how well the key concept of the Third Five-Year Term "mobilizing RIKEN's overall strength for problem-solving research" is functioning to promote cross-disciplinary research among RIKEN's centers.	Evaluate how the new structure is functioning to promote cross-disciplinary research in between RNC, and other center in RIKEN. Are RNC's research output and personnel up to international standards? Is RNC a world-leading center in its field?	Are RNC's research output and personnel up to international standards? Is RBRC a world-leading center in its field?
Propose the direction RIKEN should take in planning for its Fourth Five-Year Term.		Propose the direction RBRC should take in planning for its Fourth Five-Year Term and beyond.
Address the issue of the directions RIKEN should take in those fields in which its centers are approaching their ten-year review.	RNC will be subject to the 10 year review as an entity integrated in 2006.	Address the issue of the directions RBRC should take in its research fields.
Make proposals for attracting international human resources. Make reference to any items that need to be further strengthened.		Recommend any items that need to be further strengthened to attract (international) human resources.

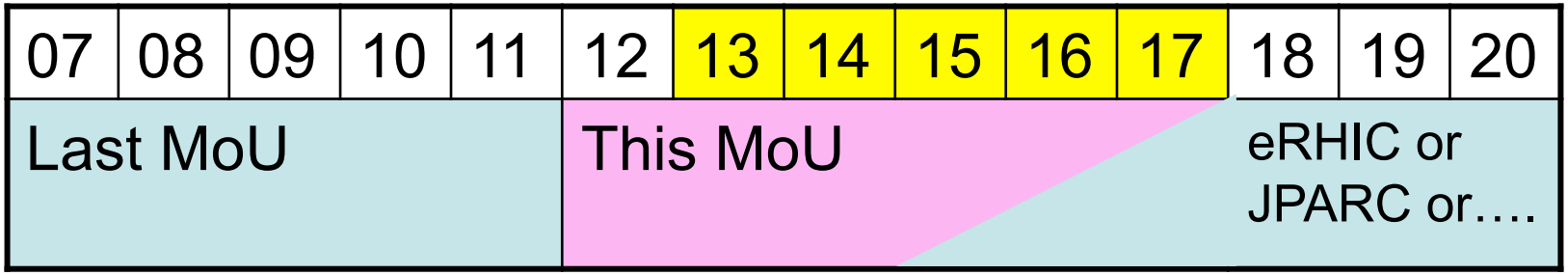
NCAC2014 Review members

Name	Affiliation
Robert Tribble (Chair)	Distinguished Professor, Texas A & M University
Juha Äystö	Director, Helsinki Institute of Physics
Angela Bracco	Professor, The University of Milan
Masaki Fukushima	Professor, ICRR-University of Tokyo
Kinichi Imai	Group Leader, JAEA
Marek Lewitowicz	Deputy Director, GANIL
Lia Merminga	Division Head of Accelerator, TRIUMF
Richard Milner (Chair, RBRC-SRC)	Professor, MIT
Witold Nazarewicz	Professor, University of Tennessee
Matthias Schädel	Group leader, ASRC-JAEA / Visiting Researcher, GSI
Susumu Shimoura	Professor, CNS-University of Tokyo
Jun Sugiyama	Principal Research Scientist, Toyota Central R&D Labs
GuoQing Xiao	Director, IMP-CAS
Akira Yamamoto	Professor, KEK
Wolfram Weise	Director, ECT*
Hirokazu Tamura (Chair, Scientific Policy Committee)	Professor, Tohoku University
Andrew Taylor (Chair, RAL-IAC)	Director, ISIS
Muhsin Harakeh (Chair, NP-PAC)	Emeritus Professor, University of Groningen
+ Chair, ML-PAC	

Some remarks for THIS and the NEXT review

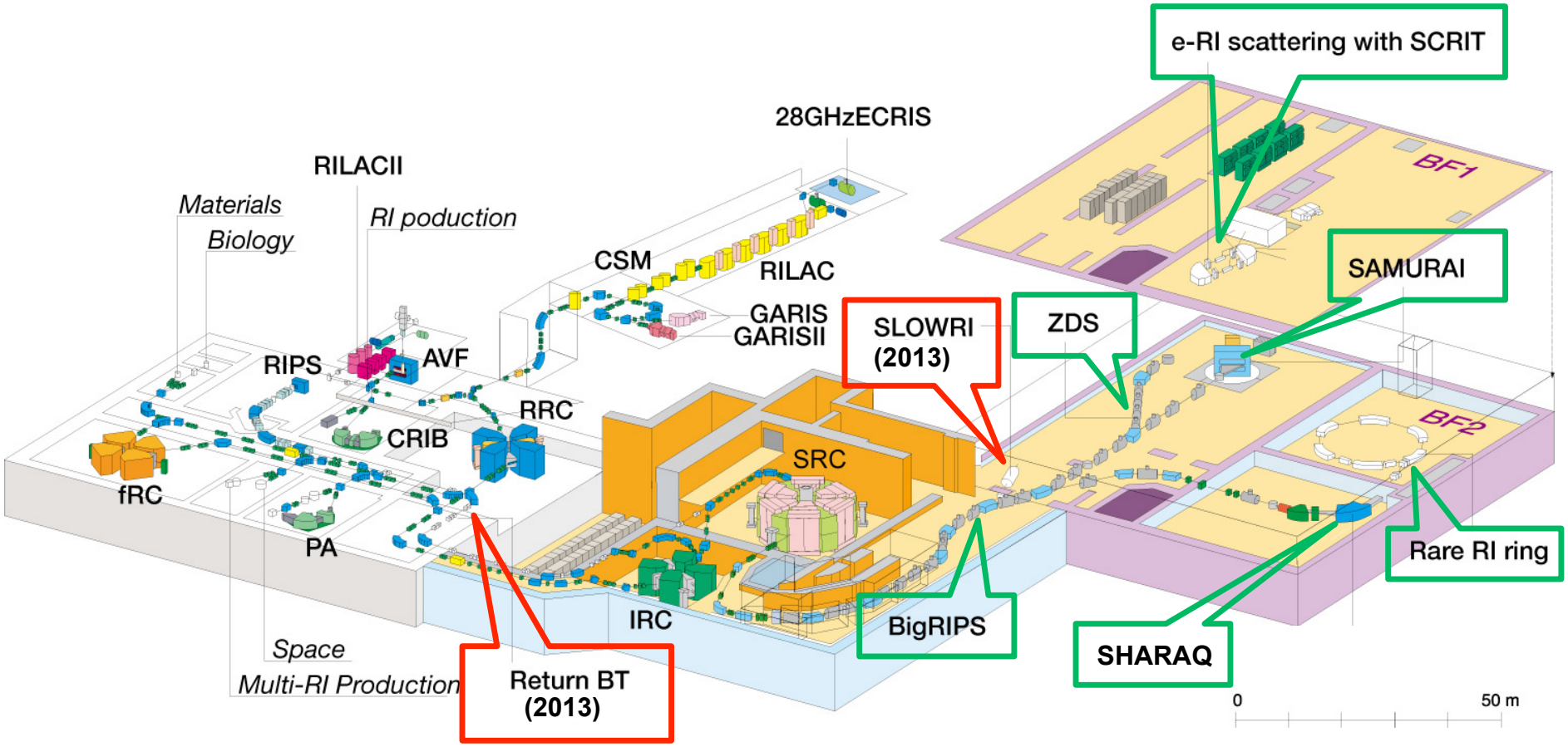
- This MoU runs until JFY2017(RIKEN's mid term cycle 2013-17).
- Within this MoU period, the primary goal of the present RHIC will be accomplished. And new project, sPHENIX, ePHENIX and eRHIC will emerge significantly by 2017. (closure of present RIKEN detectors)

- Next MoU will be for the new project to cover ePHENIX+ePHENIX era. Or, an extended MoU to close RIKEN-BNL Research Center.



- RIKEN-RAL collaboration will be concluded at the end of 2017 also. There will be a big discussion on the international activity of Nishina Center in the next NCAC. (Also for the continuation of Nishina Center)
- Hideto En'yo will step down from chief scientist in 2 years or so).
- We plan to combine SRC (also RAL-AC) and NCAC in the next cycle in JFY2016 at Wako JAPAN. So please be prepared.

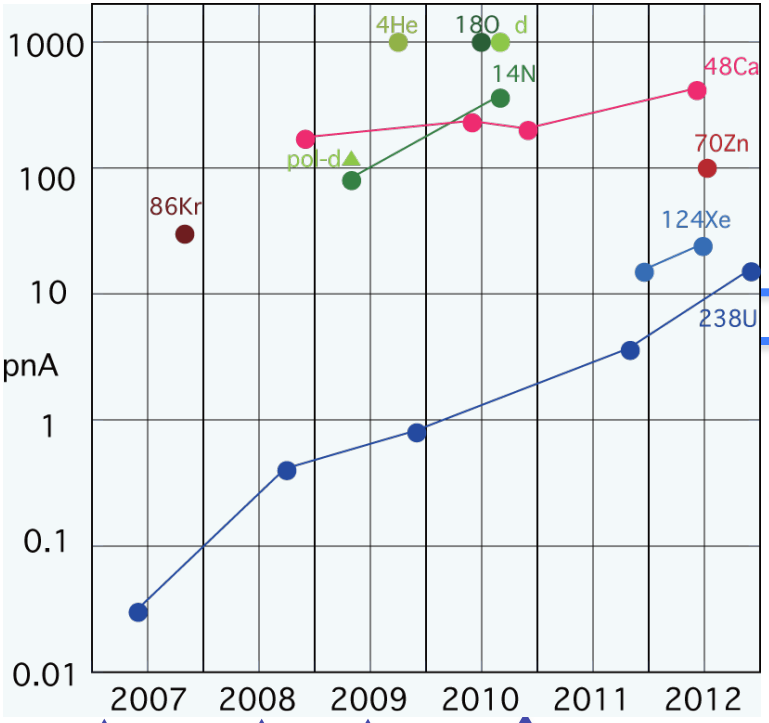
RIKEN Nishina Center is in Good Shape except for Budget.

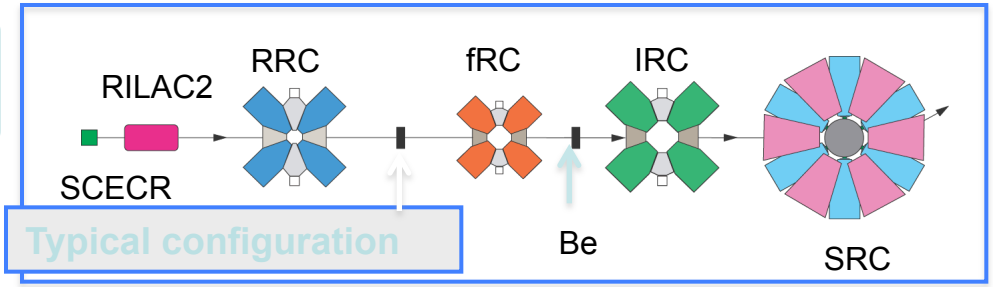


- Elecricity cost has been raised by ~50% since the Fukushima disaster.
- Doller/yen rate is up by 2% since the last year

RIBF beam improvements

Uranium beam intensity reached 1000 times compared to the beginning.

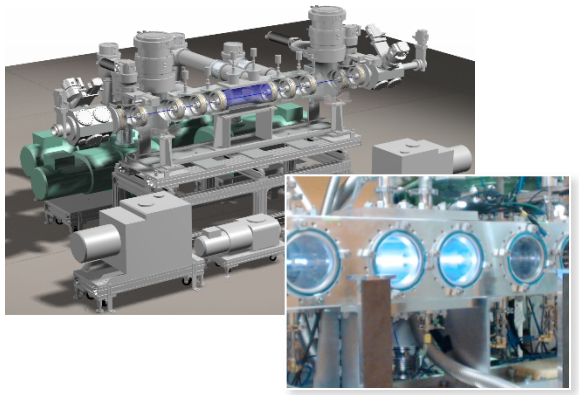




RIBF Goal (U)

RIBF present

GSI present

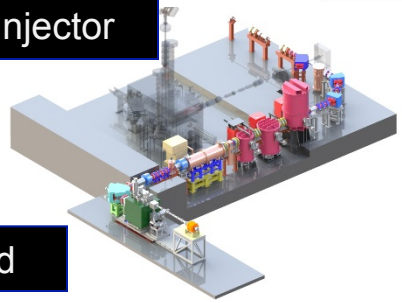


RIBF Start

Improvement on Transmission & Stability

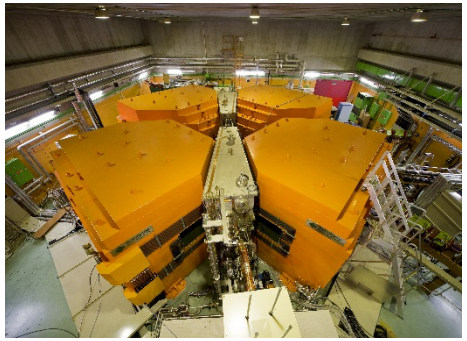
SC-ECR introduced

New Injector



He gas charge Stripper

fRC modification (K570=>K700)

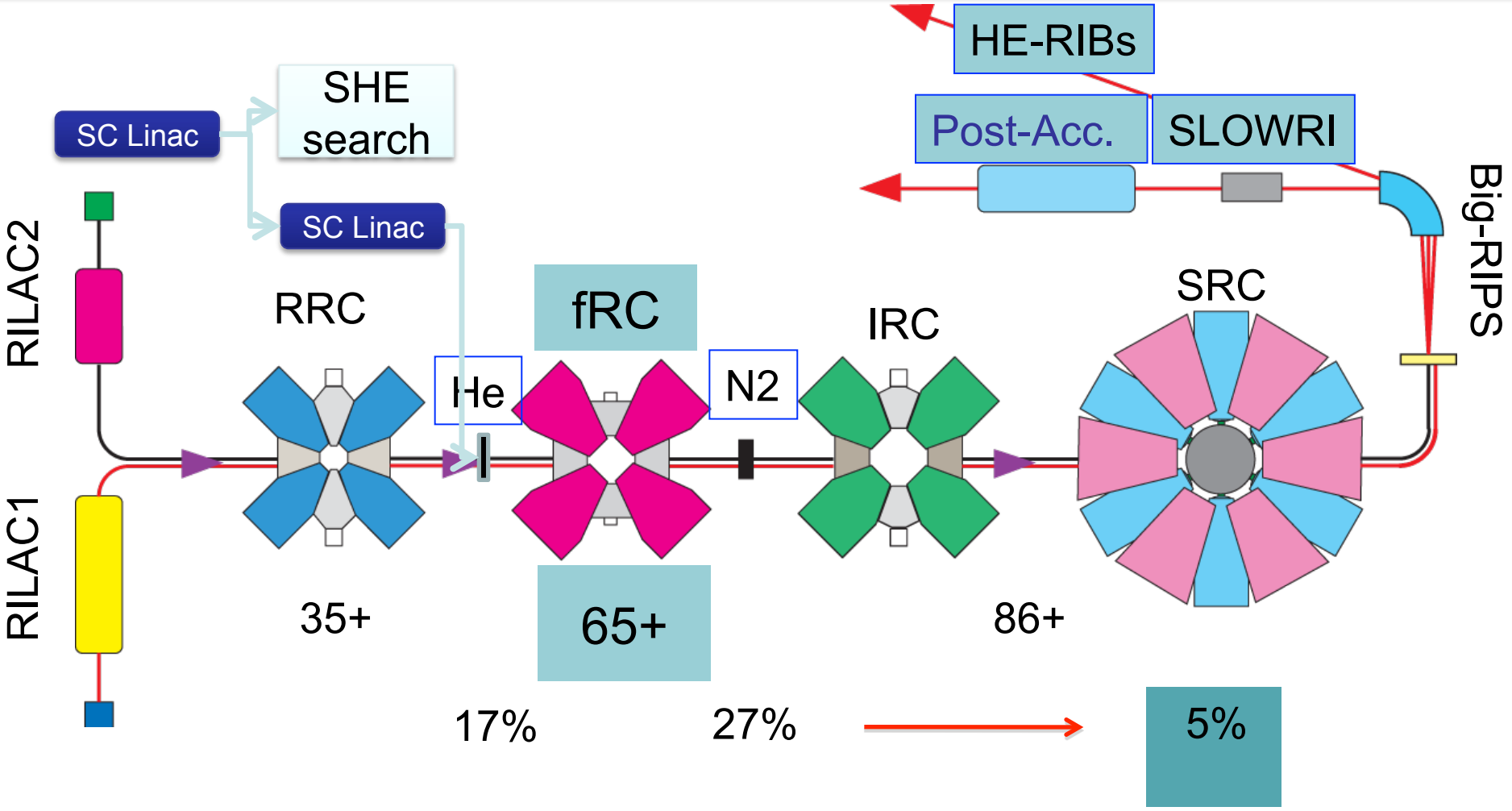


RIBF Upgrade Options – Long-term plan, after 5 years.

Option 0: ISOL or PF+ Post Acceleration (more exotic beams)

Option 1: Super Conducting fRC(stripper 2->1)

Option 2: SC-Linac (1st section: 5MeV-SHE, 2nd section 11MeV-fRC)



Projects -- time line ---

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Fair	Const.								Exp		Complt										
Jparc			Exp						1MW												
RHIC														eRHIC							
LHC				Exp												HL-LHC					
JLAB	Operating(old)								12GeV Exp												
NICA																					

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
RIBF	Exp					Complete								RIBF2 ???							
GSI	Const.								Exp		Complt										
FRIB							Const.						Exp								
ARIEL		Const					Exp		Complt												
GANIL		Const						Exp		RIB Complt											
SPES						Const				Exp											
ISOLDE								2	10 MeV												
EURISOL																					
RISP							Const.				Exp										
HIRFL	Operating								Upgrade?					HIAF ???							
BRIEF	Const						Exp						CARIF?								

RBRC

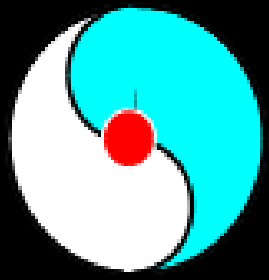
SCIENTIFIC REVIEW COMMITTEE

RBRC OVERVIEW

Sam Aronson

October 31, 2013

Brookhaven National Laboratory



CONTENTS

Administration, Organization Chart

Scientific Personnel

Performance

Future

Budget

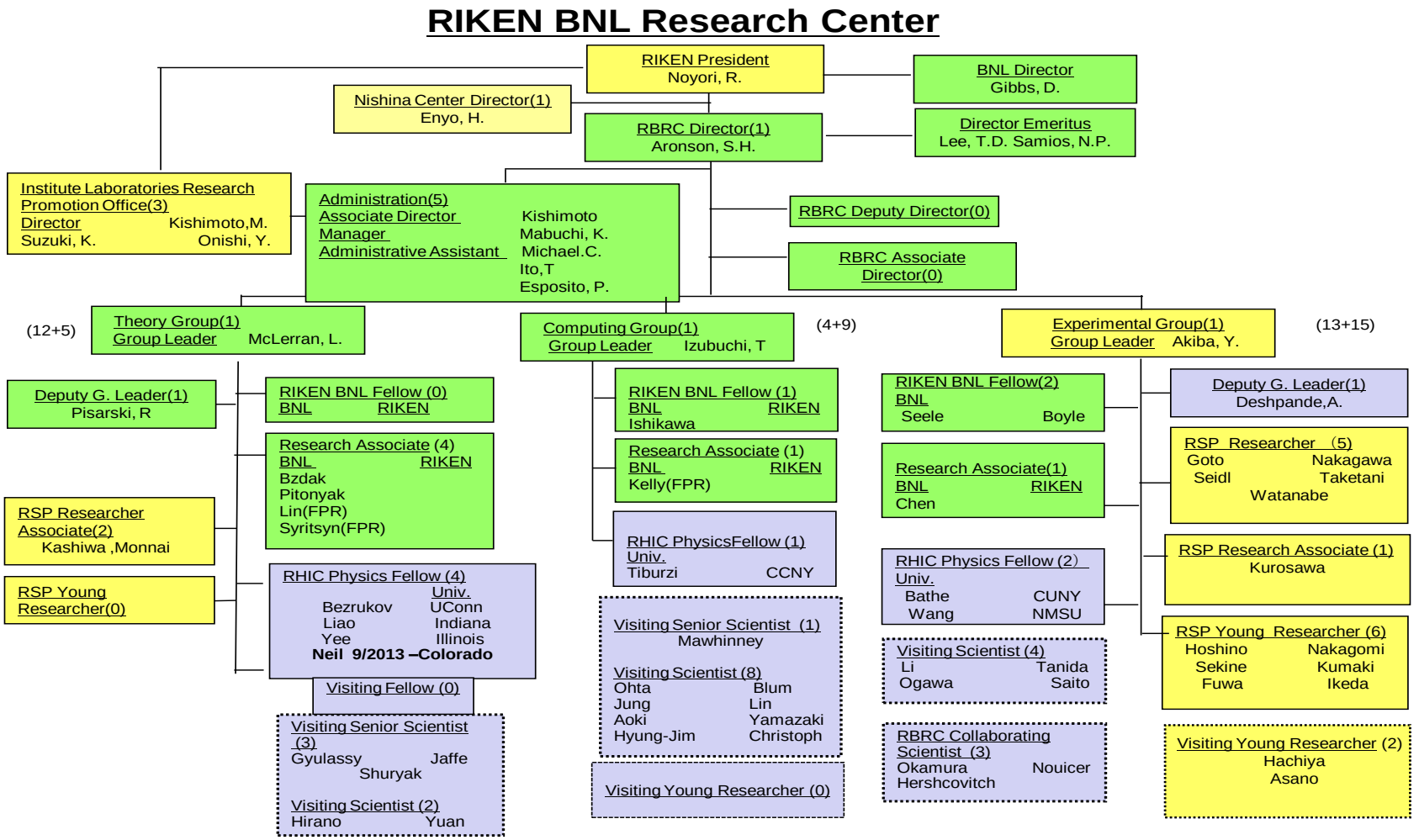


ADMINISTRATION

Directors Emeritus	T. D. Lee, N. P. Samios
Director	S. H. Aronson
Deputy Director	R. Pisarski
Theory Group Leader	L. McLerran
Deputy Theory Group Leader	R. Pisarski
Experimental Group Leader	Y. Akiba
Deputy Exp. Group Leader	A. Deshpande
Computing Group Leader	T. Izubuchi



ORGANIZATION CHART



SCIENTIFIC PERSONNEL: FUTURE FELLOWS

Expressions of Interest in Fellow Positions from:

Theory/Computing

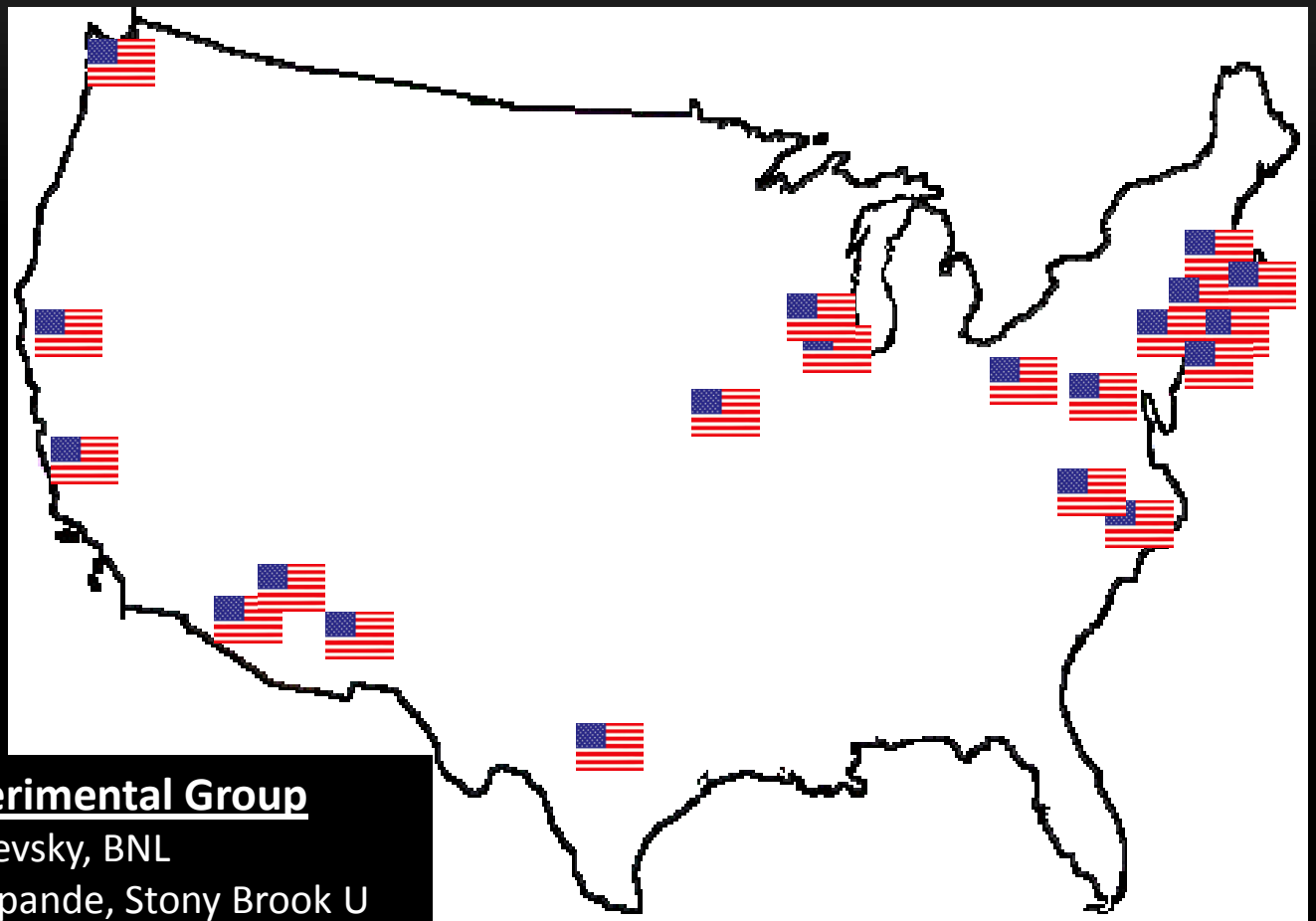
- University of Arizona
- UMass-Amherst
- Lawrence Berkeley National Laboratory
- University of Texas at El Paso
- University of Iowa

Experiment

- University of New Mexico
- Georgia State University
- McGill University



RBRC Graduates Have Tenured Positions In The U.S.



Experimental Group

Bazilevsky, BNL
Deshpande, Stony Brook U
Fields, U New Mexico
Grosse-Perdekamp, U Illinois

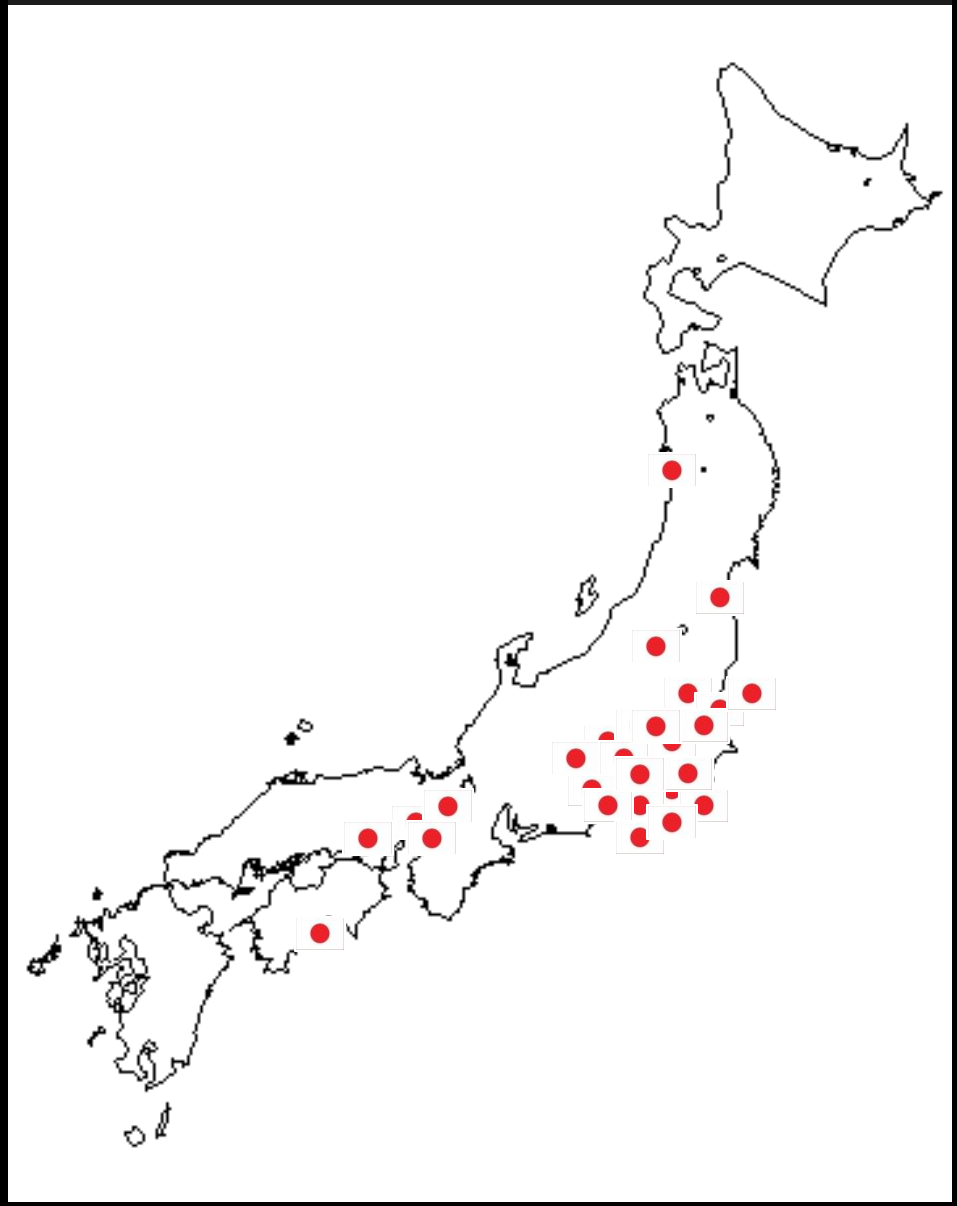
Theory Group

Bass, Duke U
Blum, U of Connecticut
Dumitru, Baruch
Fries, Texas A&M
Kharzeev, BNL/SBU
Kusenko, UCLA
Lunardini, Arizona State
Mocsy, Pratt
Molnar, Purdue
Orginos, William & Mary
Petreczky, BNL
Son, U of Chicago
Schaefer, NCSU
Stasto, Penn State
Stephanov, U of Illinois
Teaney, Stony Brook
Tuchin, Iowa S U
Van Kolck, U of Arizona
Venugopalan, BNL
Yuan, Berkeley

RBRC Graduates Have Tenured Positions In Japan

Theory & Computing Groups

Iida, Kochi U
Kitazawa, Osaka U
Fujii, U of Tokyo
Itakura, KEK
Nemoto, St. Mariannna U
Sasaki, U of Tokyo
Yamada, KEK
Yasui, Tokyo Management
Hirano, U of Tokyo
Fukushima, Keio
Doi, RIKEN
Hidaka, RIKEN
Nara, Akita Int. U
Aoki, Nagoya
Hatta, Kyoto U
Hirono, Sophia U
Fukushima, U of Tokyo
Sasaki, Tohoku U



Experimental Group

Goto, RIKEN
Saito, KEK
Seidl, RIKEN
Kawabata, Kyoto U
Murata, Rikkyo U
Togawa, Osaka U
Tojo, KEK
Yokkaichi, RIKEN
Jinnouchi, Titech
Kaneta, Tohoku U
Kurita, Rikkyo U
Hayashi, JAEA
Nakano, Titech
Onishi, RIKEN
Okada, Spring-8 (JASRI)

RBRC Graduates Have Tenured Positions World-Wide



Theory Group

Bodeker, Bielefeld U

Jeon, McGill U

Rischke, FIAS

Vogelsang, Tubingen U

Wettig, U of Regensburg

Boer, U of Groningen

Schaffner-Bielich, U of Frankfurt

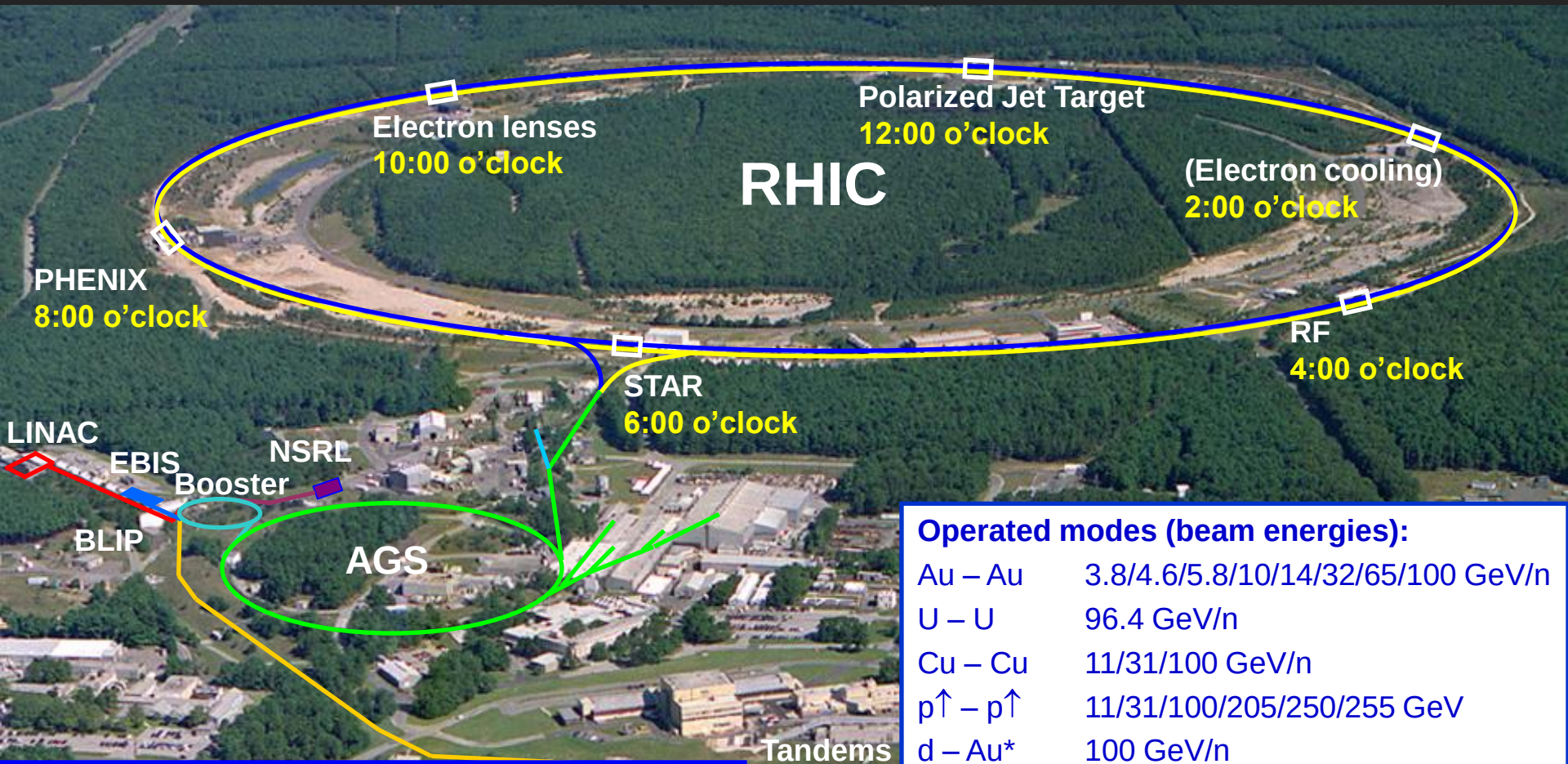
Wingate, U of Cambridge

Wiedemann, CERN

Experimental Group

Heuser, GSI

RHIC – A HIGH LUMINOSITY (POLARIZED) HADRON COLLIDER



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	238×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	493×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

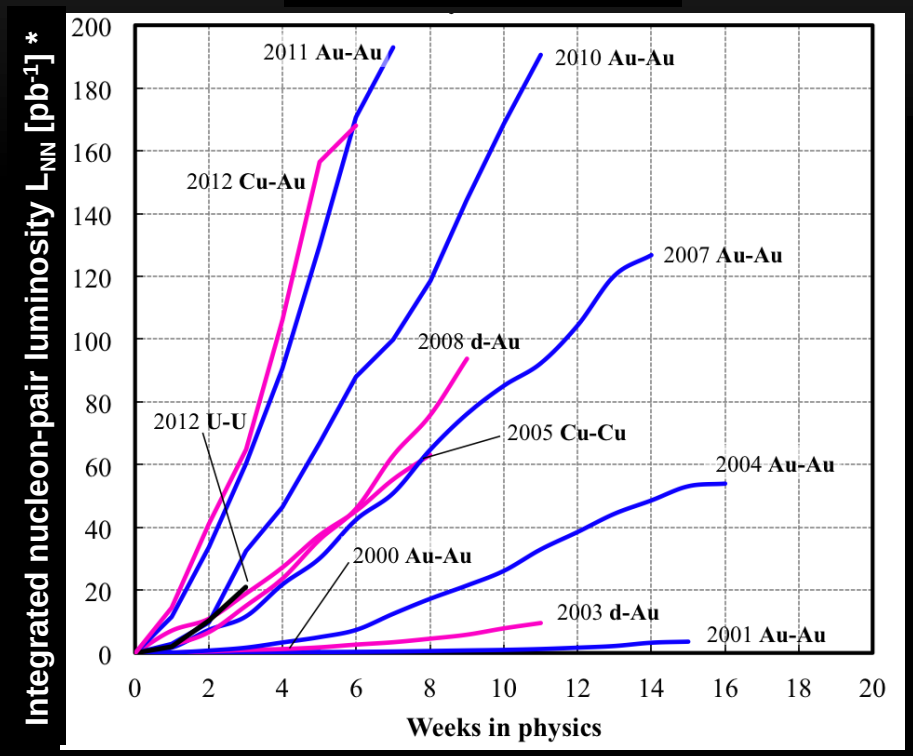
Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – A*	100 GeV/n (A = Au, Cu, Al)
^{3}He – A*	100 GeV/n (A = Au, Cu, Al)
p↑ – ^{3}He↑*	166 GeV/n

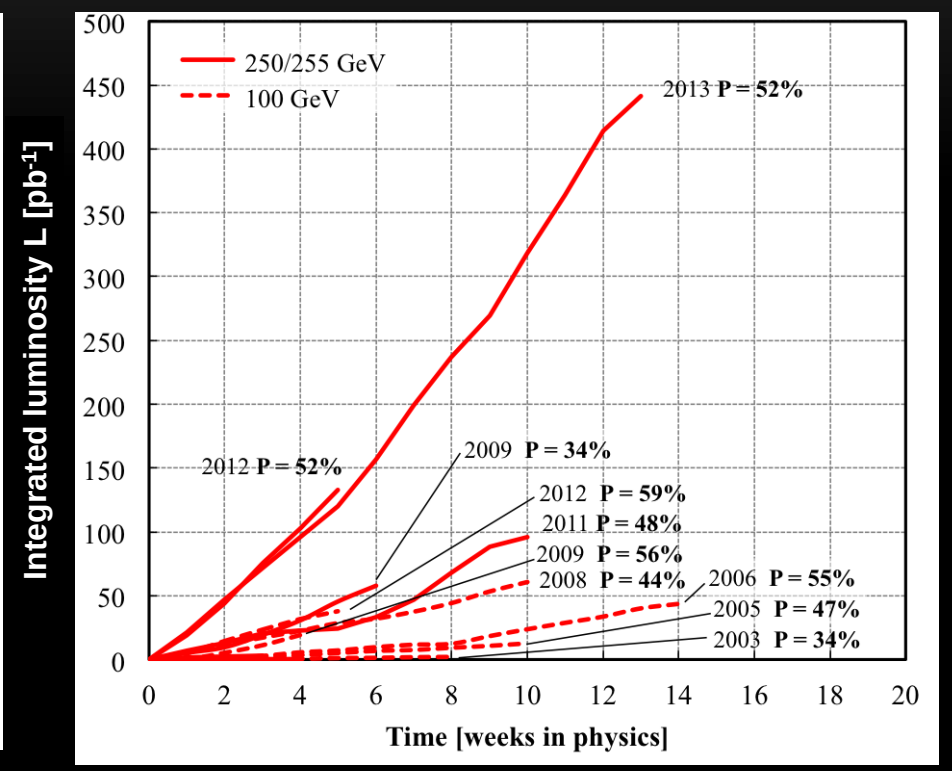
(*asymmetric rigidity)

RHIC INTEGRATED LUMINOSITY AND POLARIZATION (RHIC II PERFORMANCE!)

Heavy ion runs



Polarized proton runs



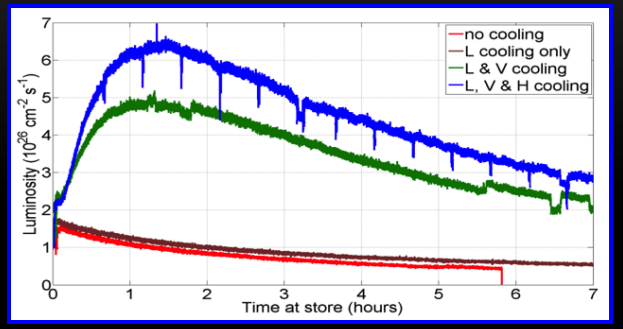
- Run-13: 510 GeV polarized proton collisions with record peak beam polarization (55 – 60 %) and record peak luminosity (2.1×10^{32} cm^{-2} s^{-1})

* Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

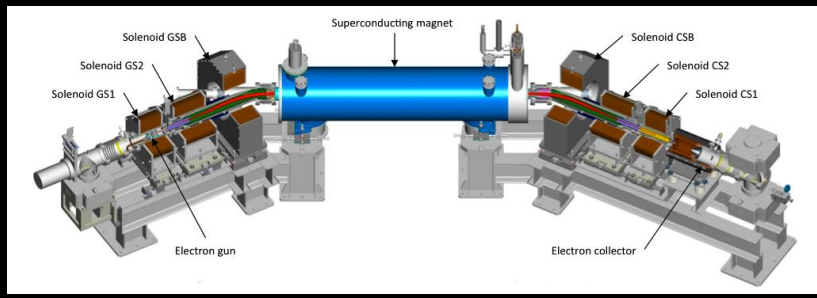
PROGRESS ON RHIC UPGRADE PROJECTS

- 3-D stochastic cooling successfully completed during run-12 with further improvements installed for run-14
- Successful commissioning and first operation with new Optically Pumped Polarized Ion Source (OPPIS) during run-13 with improved polarization and intensity
- Engineering tests of RHIC electron lenses during run-13 and commissioning during run-14
- New 56 MHz storage cavity for shorter vertex length to be installed for commissioning during run-14
- Physics design for RHIC low energy cooling started, completion planned for run-18

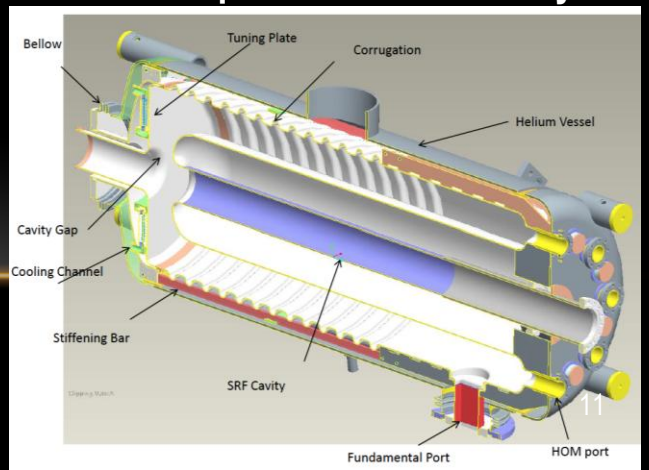
U-U luminosity with 3-D cooling



Electron lens



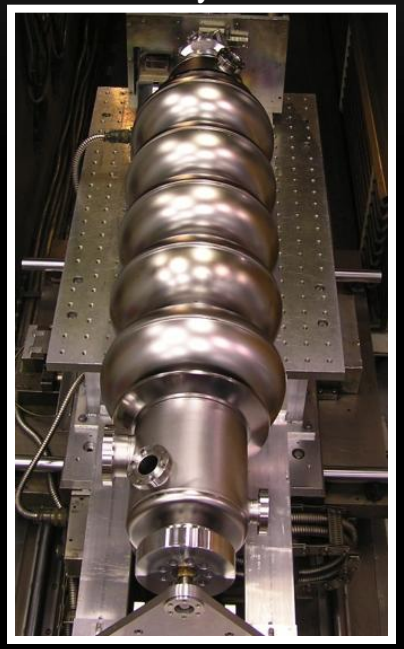
56 MHz quarterwave srf cavity



PROGRESS OF ACCELERATOR R&D (MAINLY eRHIC)

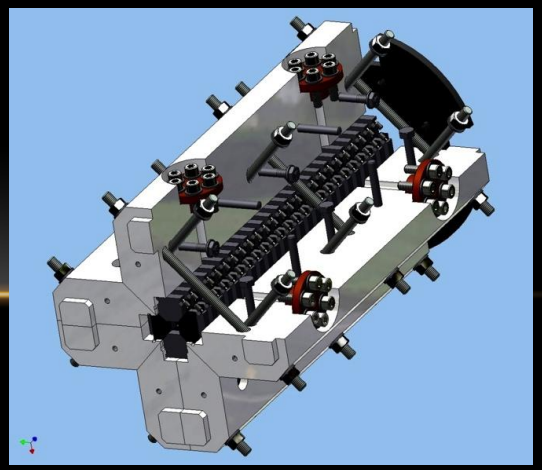
- eRHIC design for 5 GeV electron beam and 10^{32} cm^{-2} s^{-1} luminosity for $550M (FY12$) completed, R&D underway for 10 GeV and 10^{33} cm^{-2} s^{-1} luminosity
- R&D on high intensity polarized electron gun (Gatling gun) progressing well; results with 2 cathodes in 2014
- High intensity test ERL nearing completion: first beam from gun in December 2013, first circulating beam in 2014
- First test of Coherent electron Cooling in RHIC planned for run-15: gun installation at 2 o'clock in summer 2013 and beam transport and undulator installation during summer 2014.

High intensity srf accel. cavity



High power srf electron gun

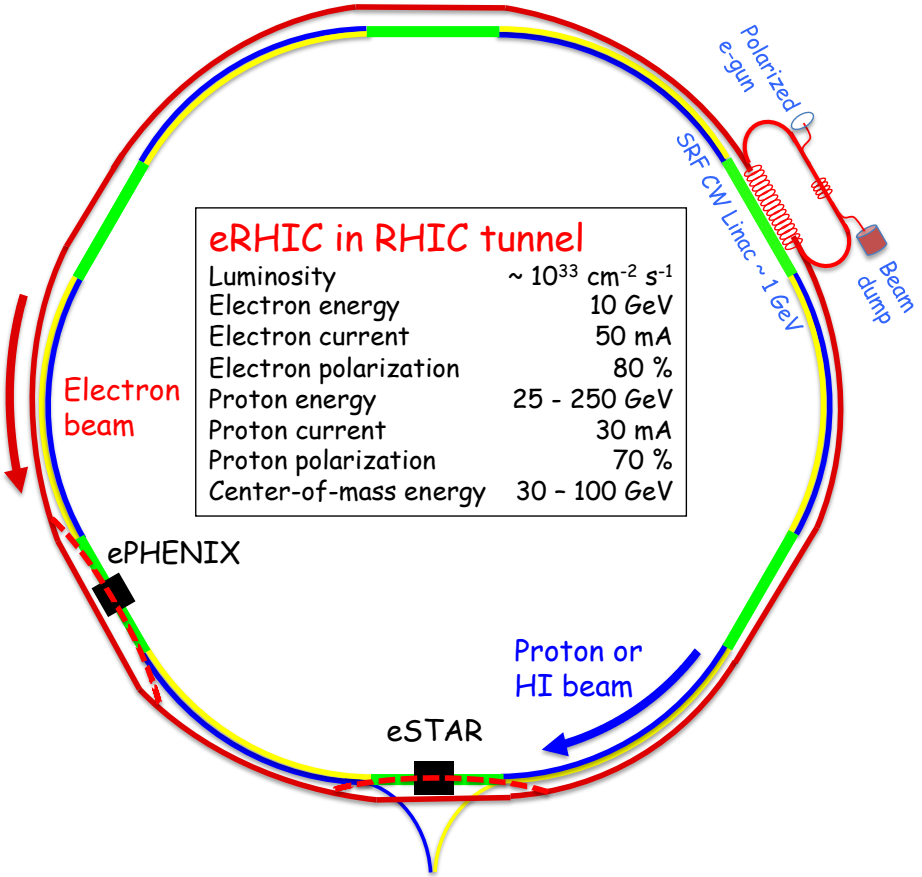




Helical wiggler prototype

ERHIC

- 10 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single pass allows for large collision disruption of electron bunch, giving high luminosity (~ 10^{34} cm^{-2} s^{-1}) and full ele
- Accelerator R&D for highest luminosity
  - High current (50 mA) pol. electron
  - Multi-pass high average current E
  - Coherent electron cooling of hadron beam
- Initial configuration:
  10 GeV e-beam, 10^{33} cm^{-2} s^{-1}



THEORY

Glasma: getting to the QGP

Glasma = coherent colored fields

T. Lappi & L. McLerran '06 Nucl Phys A772(2006)200

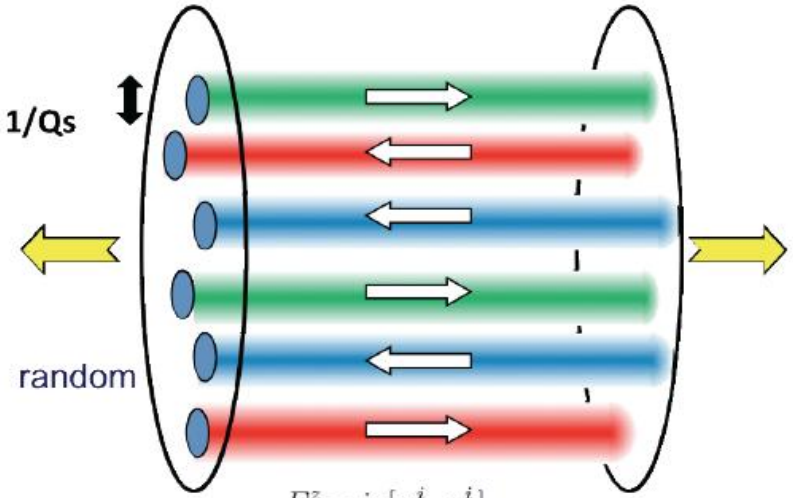
Stringlike along beam direction

Stochastic transverse to beam

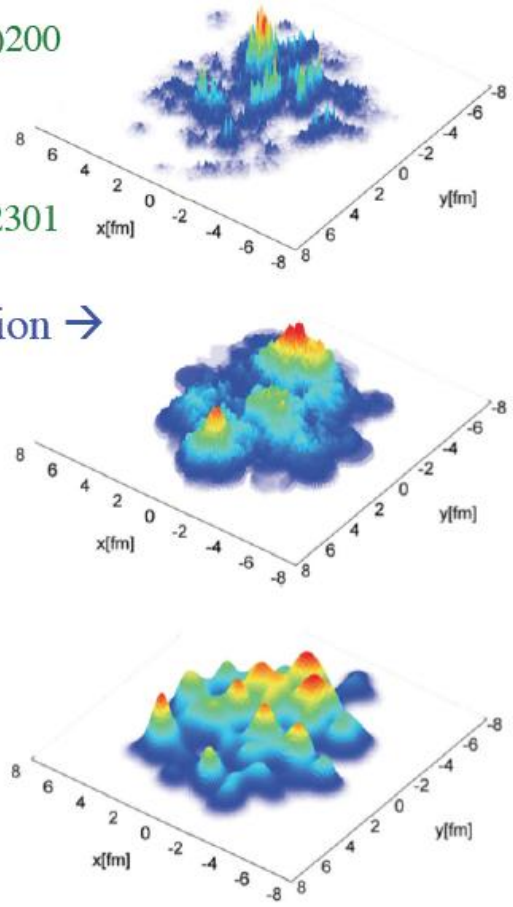
Schenke, Tribedy, & Venugopalan PRL 108 (2012) 252301

Multiplicity: negative binomial distribution

Right: evolve from lumpy to smooth distribution →



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$



Typical configuration of an event just after collision

THEORY

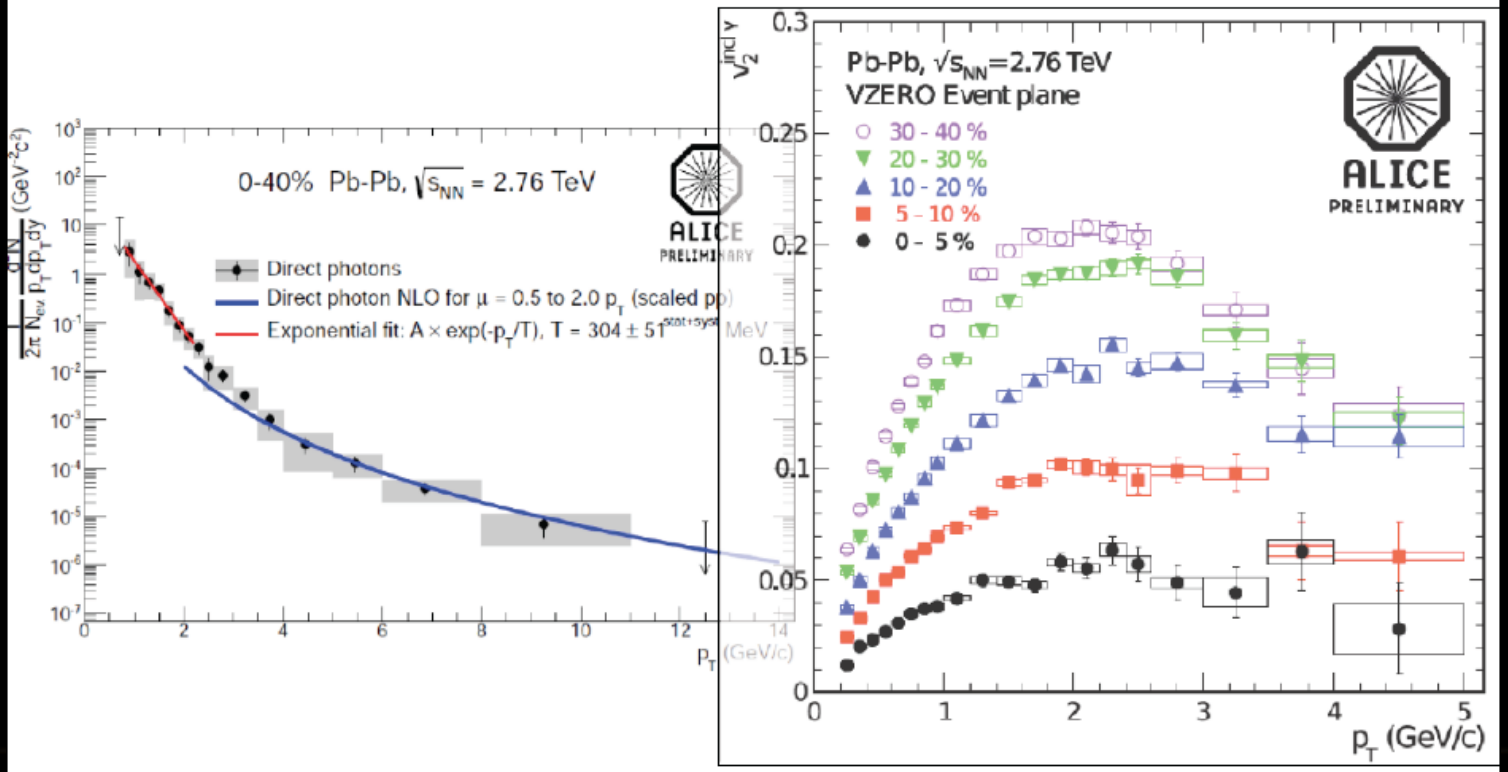
Rainer Fries: photons from heavy ion collisions

R. Fries et al: Hot Quarks 2012, J. Phys. Conf. Ser. 446 (2013)

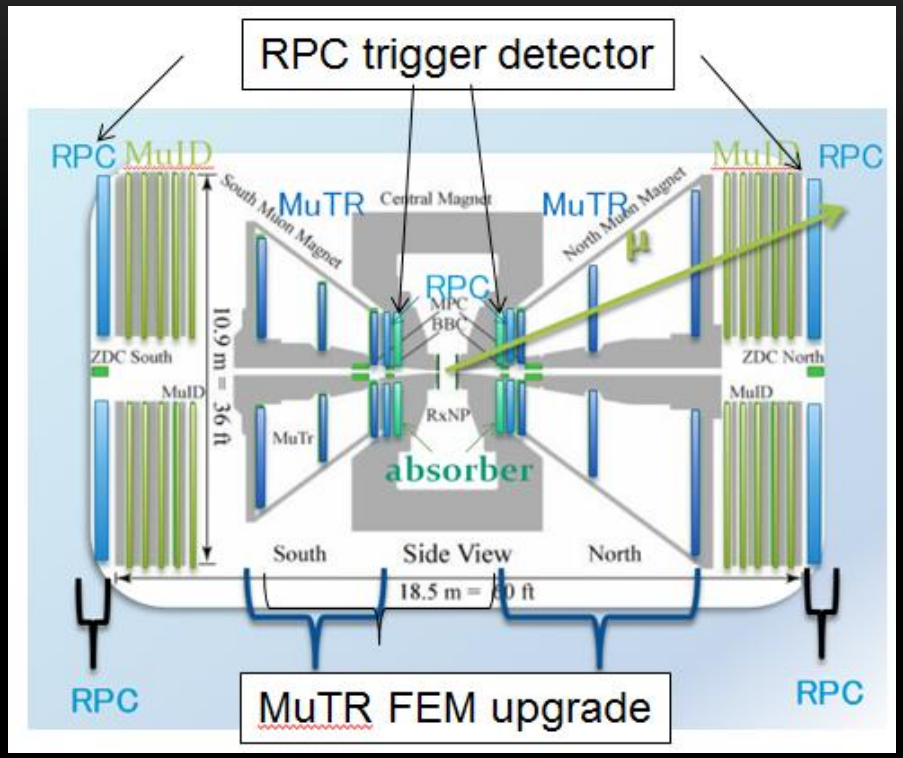
Excess of photons at low (transverse) momentum looks thermal

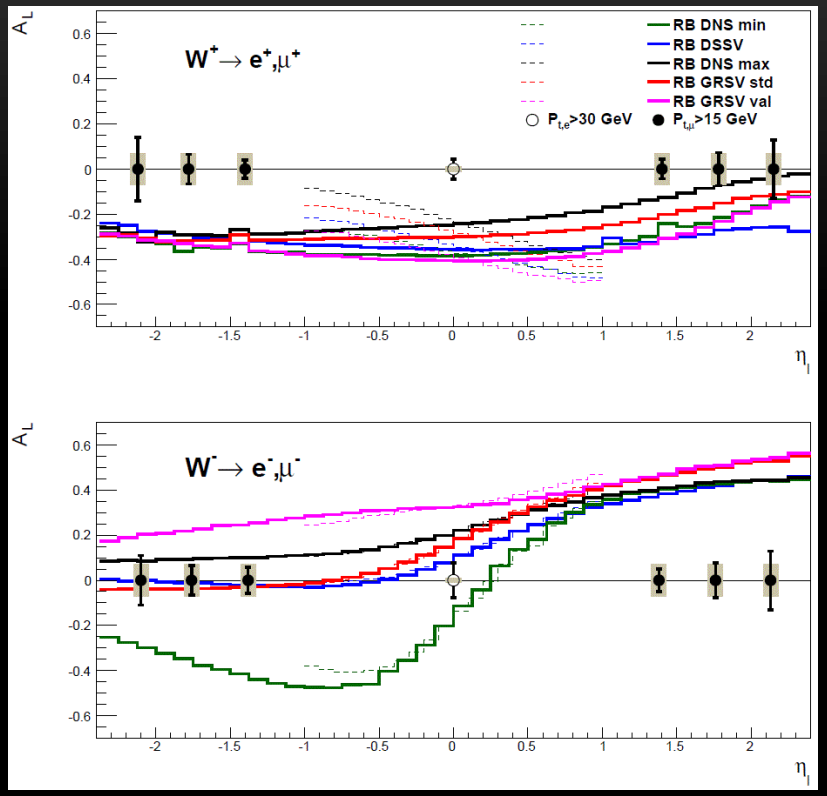
But: photons flow as much as hadrons! Does *not* agree with hydro!

Left: photon excess, ALICE @ LHC Right: photon "flow" - too big!



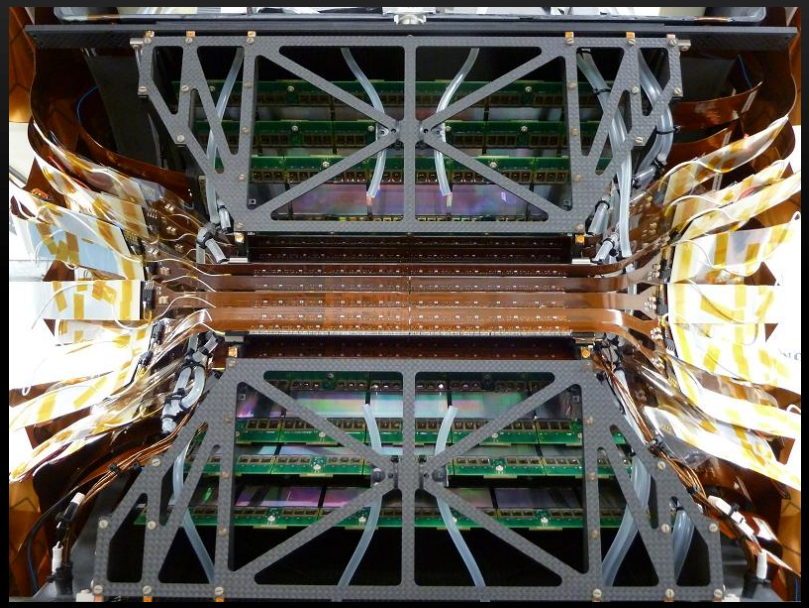
PHENIX UPGRADES: MUON TRIGGER



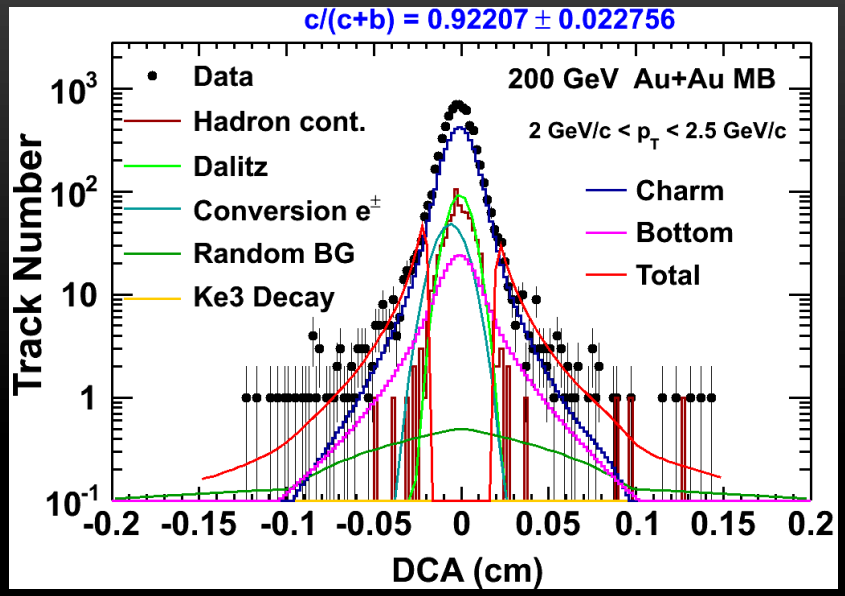


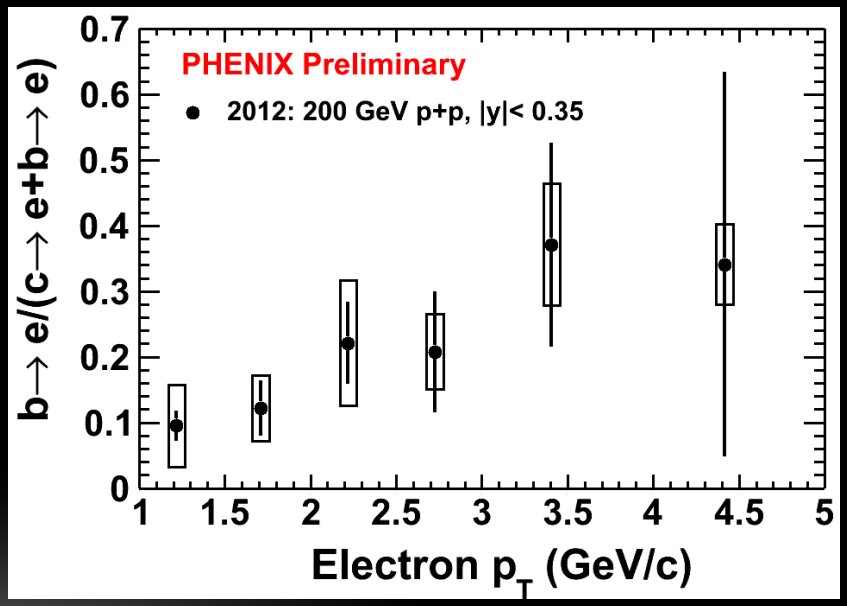
- RIKEN/RBRC has a major role on construction and operation of the μ trigger upgrade
- RUN13 was the main 500 GeV run to measure anti-quark polarization in the proton from the longitudinal single spin asymmetry A_L of W → μ and W→ e
- The analysis of RUN13 W data is going well (→Talk by Ralf Seidl)

PHENIX UPGRADES: VTX

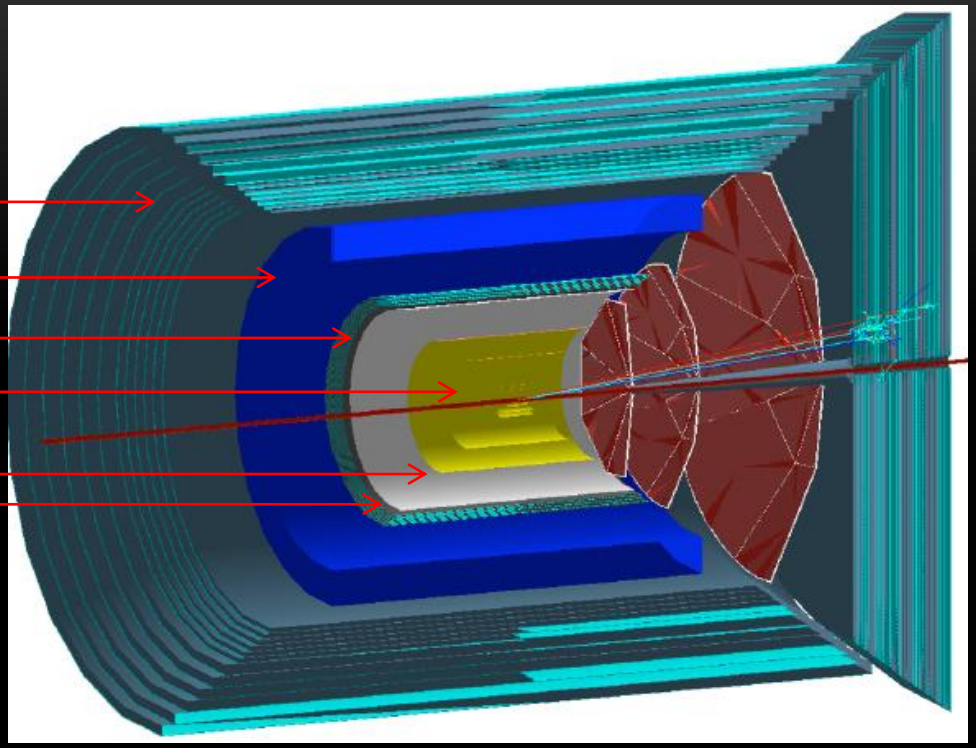


- We built and operated PHENIX VTX detector
- The first results on b/c separation @ QM2012
- Final results from RUN11 Au+Au and RUN12 pp @ QM2014
- More results to come:
  - RUN12 Cu+Au, U+U
  - RUN14 Au+Au (major HF run)
  - RUN15 p+A





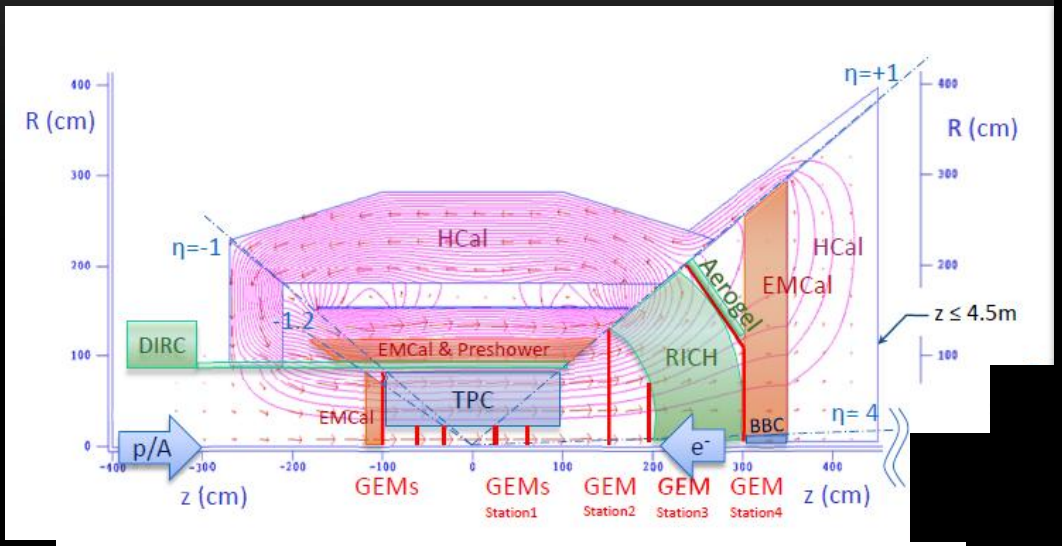
FUTURE: SPHENIX AND FORWARD SPHENIX

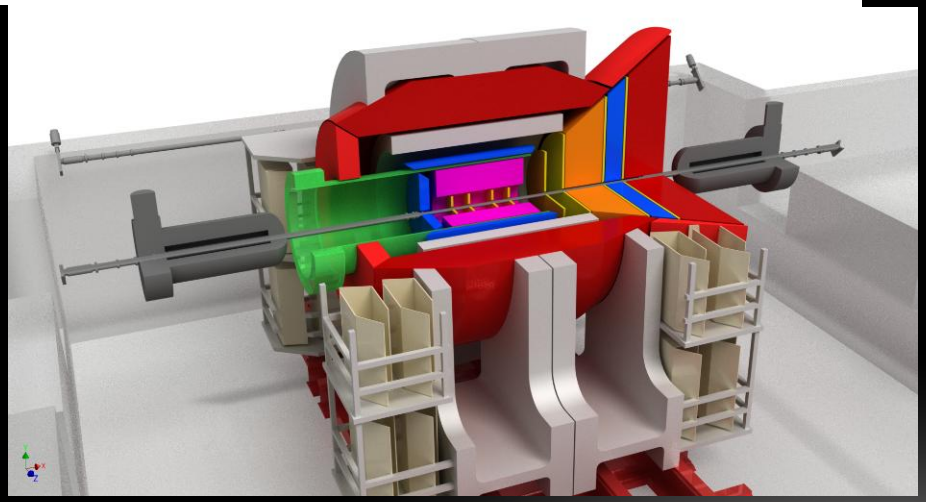


fsPHENIX

- sPHENIX: mid-rapidity upgrade of PHENIX
  - Study QGP by jets, photons, heavy quarks, and upsilons
  - MIE proposal submitted to DOE on Sep30, 2013
  - Compact Hcal and Emcal covering |y|<1. Reuse the Babar solenoid.
  - Central piece of the last stage of RHIC operation before eRHIC
  - Mid-rapidity component of ePHENIX detector of eRHIC
  - RIKEN/BRRC has strong interest on the additional tracking system
- fsPHENIX: upgrade at forward rapidity (→ talk by J. Seele)
  - Spin Physics and small-x physics in pp and pA
  - Forward detector of future ePHENIX

FUTURE: ePHENIX AT eRHIC





- ePHENIX is one of two initial detectors of the first stage eRHIC
  - 10 GeV e x 100 GeV HI
  - 10 GeV e x 250 GeV p
- Physics
  - Spin structure of proton
  - 3D tomography of proton
  - Initial study of the gluon saturation (CGC)
  - Quark propagation in cold nuclear medium
- Evolved from sPHENIX
- LOI of ePHENIX submitted on Sep 30, 2013 with sPHENIX MIE
  - Kieran Boyle and Itaru Nakagawa were members of ePHENIX LOI writing committee

COMPUTING: PHYSICS HIGHLIGHTS

- Physical point (Mpi=135 MeV) simulation using chiral lattice quarks
- Sub-percent accuracy for many fundamental/basic quantities (hadron mass, decay constants, B_K, K_{l3})
- The first signal of muon g-2 light-by-light
- Emerging explanation for $K \rightarrow \pi\pi$ $\Delta I=1/2$ rule
- The first complete K_L-K_S mass difference from 4 point function
- Nucleon physics : form factors, proton decay, Nucleon EDM
- CKM (K & B), PhySyHCAl (Computer Algebra system for perturbation)
- USQCD half rack Blue Gene / Q is installed, total 3.5 racks, 700 Tflops peak at BNL.
- Large production use of new algorithms, All Mode Averaging (AMA) , ~ 10x speedup, in physics measurements



COMPUTING HIGHLIGHTS

- **New Collaborations / Synergies**

  Computational Science Center (HPC code center established) , besides ITD

  Collaboration with KEK for B-physics [Tomomi Ishikawa, Christoph Lehner, Taku Izubuchi]

- **New Staff**

  Ethan Neil (joint fellow with Colorado Univ)

  Chris Kelly (FPR, from Columbia Post Doc)

  Sergey Syritsyn (FPR, from LBL Post Doc)

- Staff Departures

  Christoph Lehner (BNL HET)

  Eigo Shintani (Mainz Post Doc)

  Meifeng Lin (BNL Computational Sci. Ctr.)

- **New Joint Faculty at University of Arizona 2014**

- **Honors , Awards and Press Releases**

  Brian Tiburzi, KITP Scholar, Kavli Institute for Theoretical Physics, UC-Santa Barbara, 2012-2014

  Brian Tiburzi, Alfred P. Sloan Foundation, CUNY Junior Faculty Research Awards in Science & Engineering, 2013-2014

  "Supercomputers Help Solve a 50-Year Homework Assignment" BNL Press-release, September 26, 2013, DOE supercomputing month



Computing History, Performance

QCDSP (Signal Processor)			
1998-2004	1 Rack	50 G flop	
Retired	12 Racks	600 G flop	RBRC
	8 Racks	400 G flop	Columbia
	20 Racks	1 T flop	
QCDOC (On a Chip)			
2005-2011	1 Rack	.833 T flop	
Retired	12 Racks	10 T flop	RBRC
	12 Racks	10 T flop	DOE
		20 T flop	
QCDCQ (Chiral Quarks)			
2012-	1 Rack	200 T flop	BNL
	2 Racks	400 T flop	RBRC
Operational		600 T flop	
January 2013	½ Rack	100 T flop	DOE/USQCD

The Ken Wilson Award for 2012 to RBC Group: "The K → $(\pi\,\pi)_{I=2}$ Decay Amplitude for Lattice QCD"



Cosmology

Since there is activity at BNL and RIKEN in astrophysics & cosmology, we are exploring expanding the RBRC mission

BNL is a long-time member of the LSST collaboration

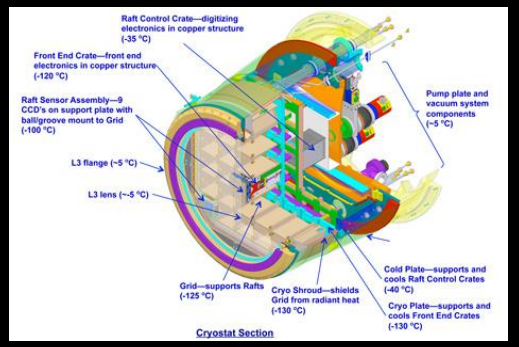
- Responsible for delivering “sensor rafts” for the focal plane detector of the DOE-funded LSST Camera
- Members of Cosmology Group in the Physics Dept. work on DES, BOSS & LSST: interest in Dark Energy

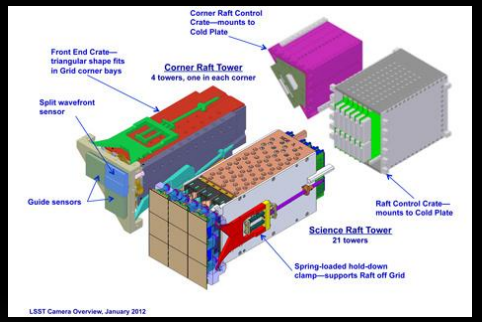
Toru Tamagawa, leader of the Astrophysics Group at RIKEN, is here and will talk tomorrow

RBRC’s role in a RIKEN-BNL collaboration?

- A change in the scope of RBRC’s mission needs approval, starting with the RBRC Management Steering Committee







Recent RBRC Workshops

- Towards a Comprehensive Understanding of Thermal Radiation in Elementary and Heavy-ion Collisions — December 5 – 7, 2012
- The Physics p+A Collisions at RHIC — January 7 – 9, 2013
- Jet Quenching at RHIC vs LHC in Light of Recent d+Au vs. p+Pb Controls — April 15 – 17, 2013
- 2013 National Nuclear Physics Summer School (Provided support to Stony Brook University) — July 15 – 26, 2013



Upcoming RBRC Workshops

- Lattice Meets Experiment 2013:
  Beyond the Standard Model — December 5 – 6, 2013
- The Approach to Equilibrium in
  Strongly Interacting Matter — April 2 – 4, 2014
- Thermal Photons and Dileptons
  in Heavy-Ion Collisions — August 20 – 22, 2014



COMMITTEES

Theory Advisory Committee:

- Larry McLerran
- Anthony Baltz
- Michael Creutz
- Frithjof Karsch
- Dmitri Kharzeev
- Miklos Gyulassy
- Jianwei Qiu

Experimental Advisory Committee:

- Akira Masaike
- Kenichi Imai
- Yousef Makdisi

Lattice Gauge Advisory Committee:

- Michael Creutz
- Sinya Aoki



RBRC Publications

Theory: 90

Experimental: 15

RBRC Seminars

Wednesday – RBRC High Energy Theory

Thursday – RBRC/Lunch

Friday – RBRC Nuclear Theory



Budget

Downward pressure on the RBRC budget (austerity + rate of exchange)

Nishina Center has been taking protecting RBRC but cannot continue to provide full protection

- JFY12: $3000k
- JFY13: $2900k (with the goal of generating a $150k surplus)
- JFY14: TBD but possibly lower

Tunable parameters

- Number of Fellows and post docs
- Number of Workshops
- Size of Administrative Staff



Safety Update

Zero reportable injuries and operational incidents since RBRC's start in 1997

Experimental Group

Round 1

Back to Contents

RBRC Exp. Group: Overview, Detector Upgrade and HI physics

Y. Akiba

RBRC SRC review
2013/10/31

Exp. Group activities

Three major activities

- Spin Physics
  - Study of spin structure of proton using the world only polarized p+p collider
  - Main activity of RBRC/RIKEN
  - RBRC/RIKEN are the leader of Spin Physics at RHIC/PHENIX
- Heavy ion physics at RHIC/PHENIX
  - Study of the properties of the quark gluon plasma formed in heavy ion collisions at RHIC
  - RBRC/RIKEN are focusedon penetrating probes
- PHENIX detector upgrades
  - VTX and Muon trigger upgrade, both completed and we are “reaping harvest”.
  - Working on future upgrades sPHENIX/fsPHENIX/ePHENIX

RBRC Experimental Group

Group Leader



Y. Akiba

Deputy GL



A. Deshpande

University Fellow



S. Bathe

Baruch CCNY



X. Wang

New Mexico State Univ.

Fellow



K. Boyle



J. Seele

RIKEN/RBRC @



R. Seidl



Y. Goto

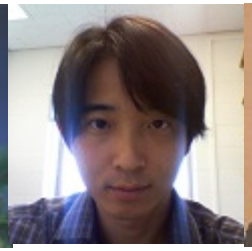


I. Nakagawa

PostDoc



J. Koster



M. Kurosawa



C-H Chen



A. Taketani



T. Hachiya

- Plus Many Students and Visitors
- J. Koster moved to Amazon

Visitors/Collaborators/students

RIKEN/BNL

Takashi Ichihara	Yasushi Watanabe	Atsushi Taketani
Satoru Yokkaichi	Yuji Goto	Itaru Nakagawa
Ralf Seidl	Takashi Hachiya	

Students

Hidemitsu Asano	Ryoji Akimoto	Megumi Sekine
Sanshiro Mizuno	Sangwa Park	Hiroshi Nakagomi
Tomoya Hoshino	Insoek Yoon	TaeBong Moon
Chong Kim	Yasuhiro Fuwa	Shunsuke Ikeda
Masafumi Kumaki	Minjung Kim	

Visiting Scientist

Zheng Li	Kiyoshi Tanida	Akio Ogawa
Naohito Saito		

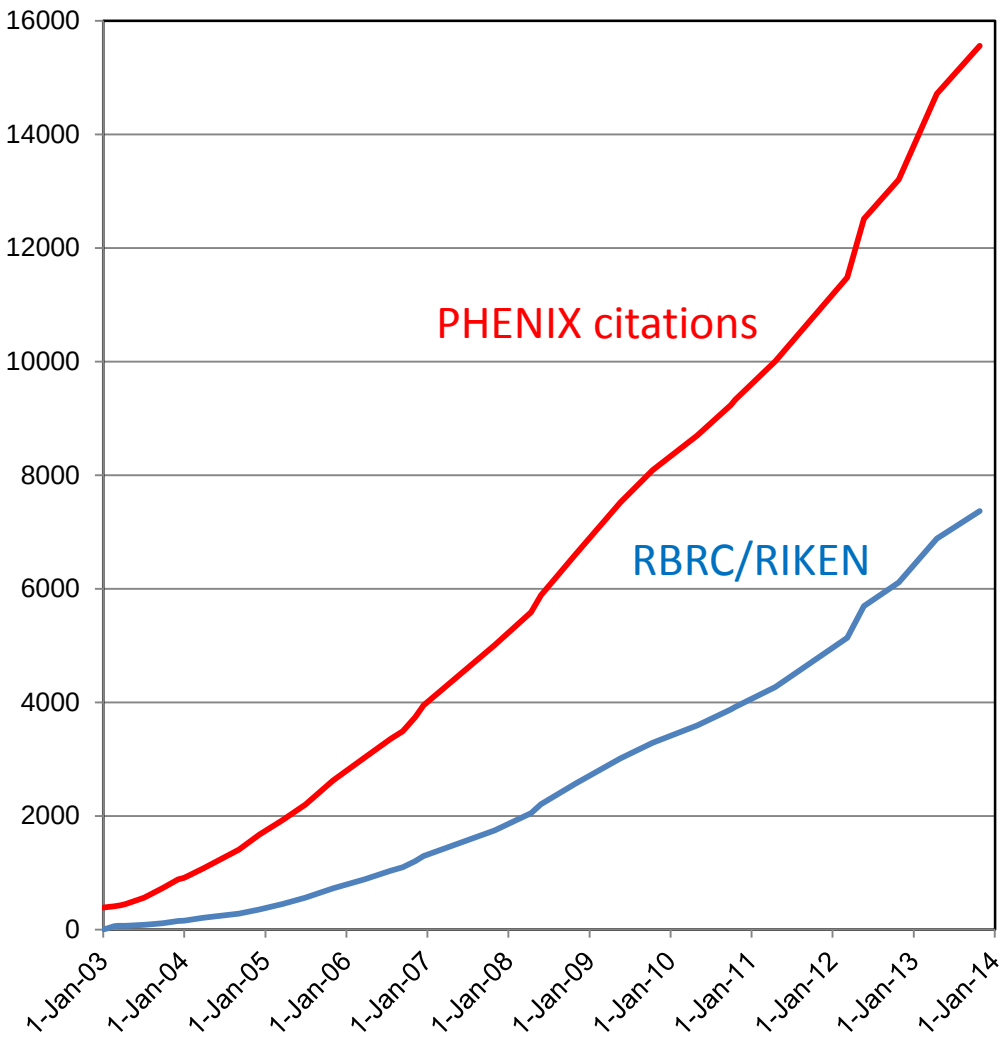
Collaborating Scientist

Masahiro Okamura	Rachid Nouicer	Ady Hershocovitch

PHENIX publications and RBRC

- 126 (52)papers published since 2001
  - Phys. Rev. Lett. 62 (26)
  - Phys. Rev. C 41 (15)
  - Phys. Rev. D 18 (9)
  - Phys. Letter B 4 (1)
  - Nucl. Phys. A 1 (1)
- Total citation: ~16000
  - Topcite 1000+ 1 (1)
  - 500-1000 4 (1)
  - 250-500 10 (3)
  - 100-250 30 (19)
  - 50-100 28 (12)
- 11 (6) papers published since last SRC (Nov 2012)
  - PRL 2 (1)
  - PRC 6 (2)
  - PRD 3 (3)

The number in () is the number of papers whose paper writing committee include RIKEN/RBRC member(s)

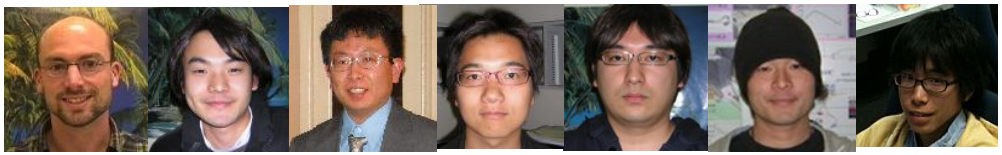


Exp Group Activities

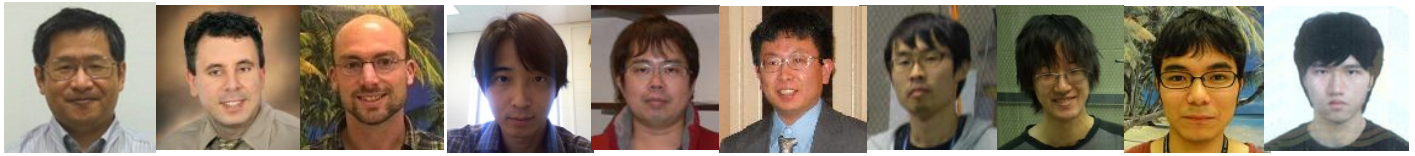
- Heavy Ion Physics at RHIC study of (s)QGP

  RBRC/RIKEN studies sQGP using penetrating probes

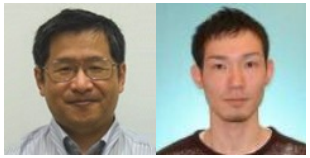
  – High pT, photons



  – Heavy quark

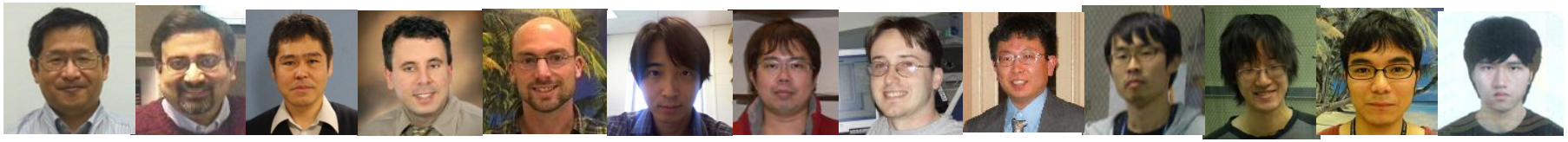


  – Exotics

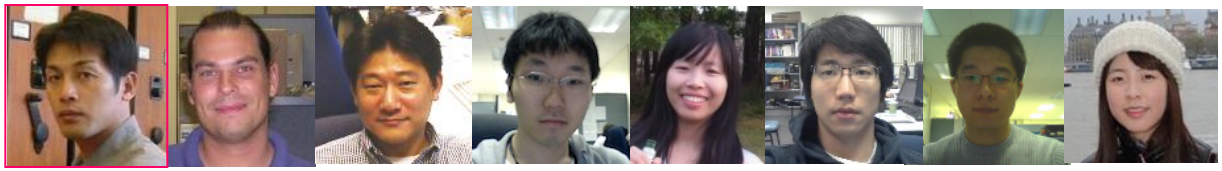


- PHENIX detector (completed)

  – Silicon Vertex Tracker (VTX)



  – Muon Trigger (completed)



+ many more

+ many more

Exp Group Activities on Spin Physics

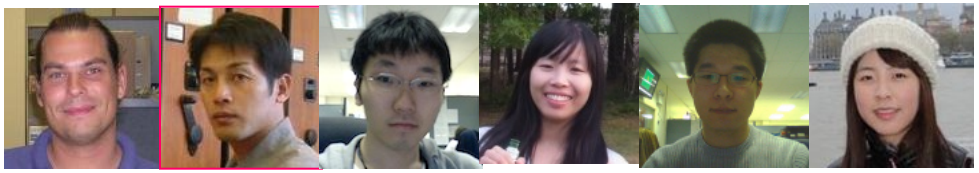
RBRC/RIKEN are leaders of Spin Physics at RHIC/PHENIX

- ΔG measurement

A_{LL} of π^0 , $\pi^{\pm}$, direct γ, jets, charm, etc…



- W → mu analysis



- A_N at RHIC

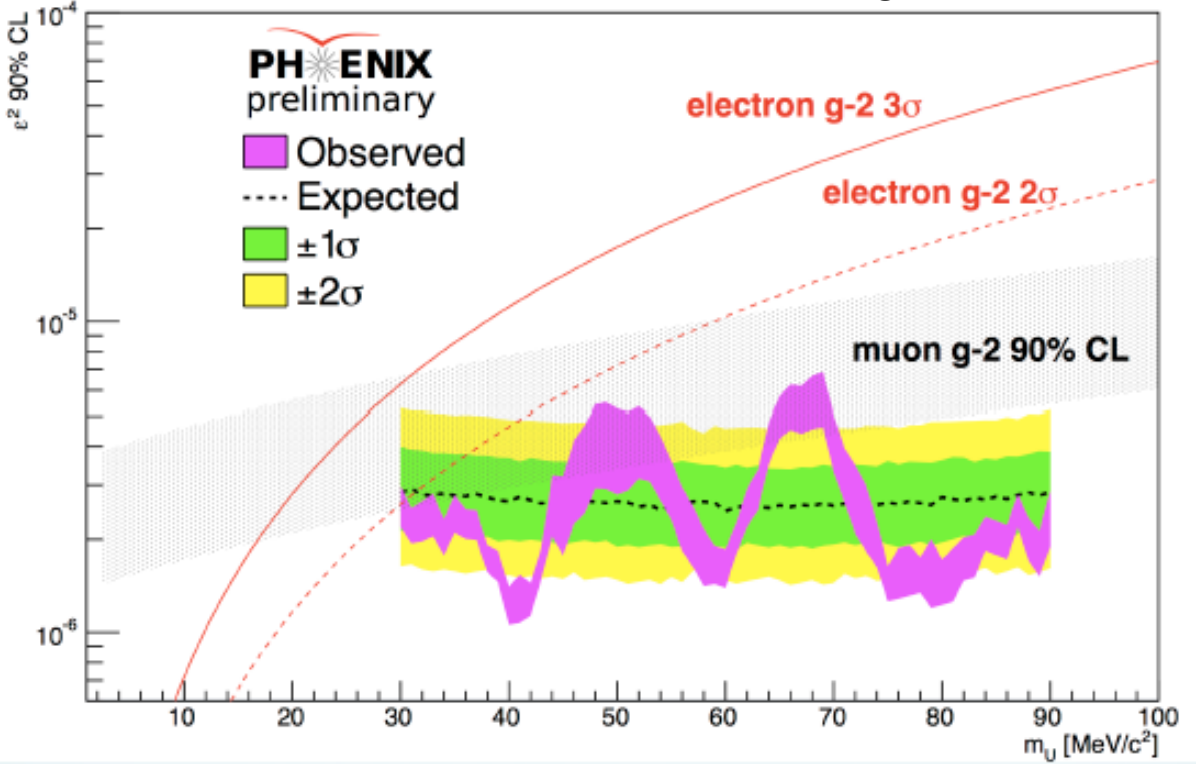


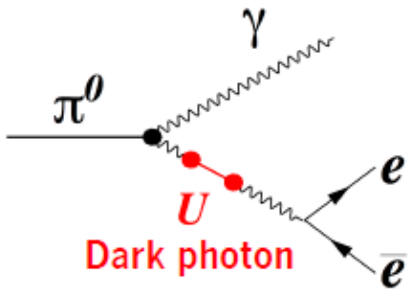
- Local Pol, Rlumi

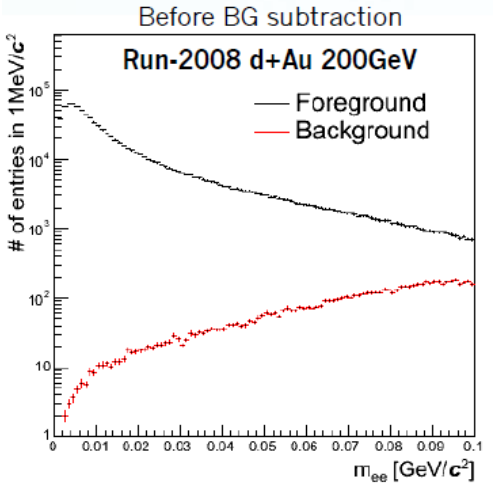


Dark photon search at PHENIX

Y. Yamaguchi and YA

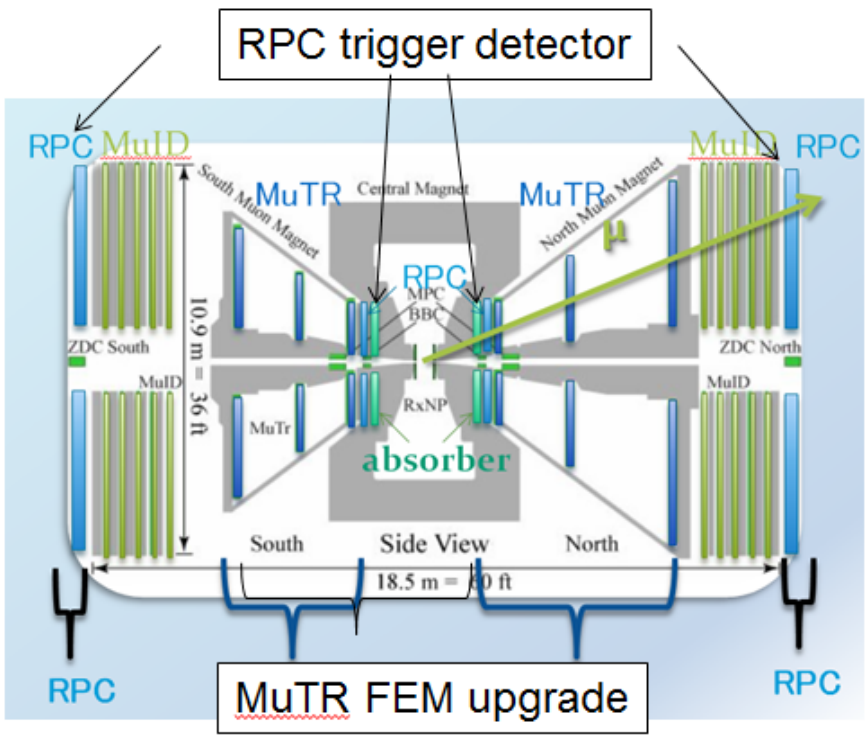


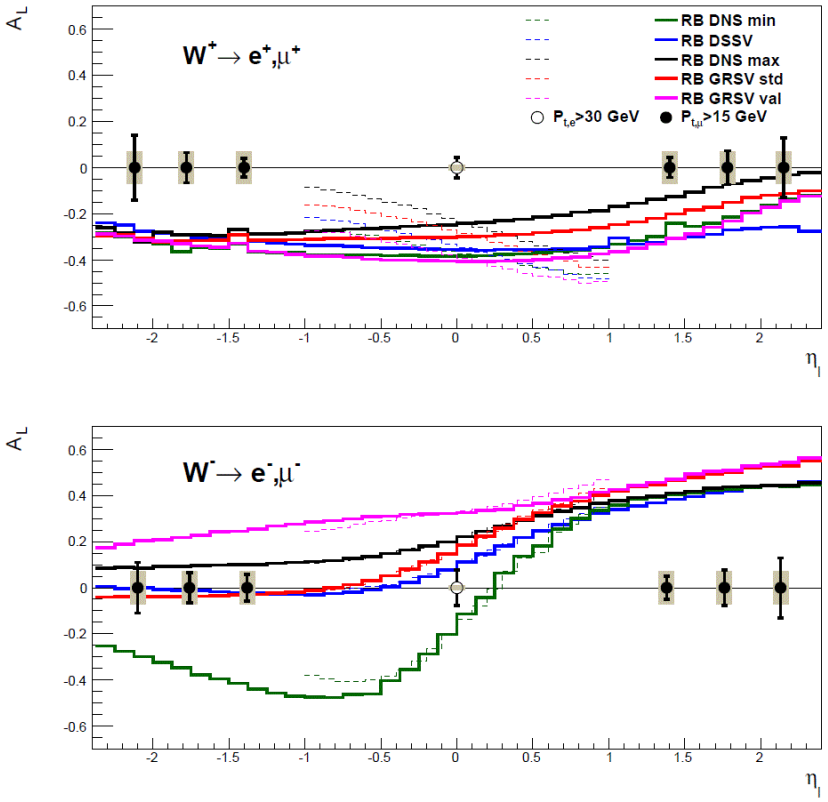




- This result on dark photon search is recently presented at DNP.
  - Dark photon is a hypothetical “heavy photon” that can mix with normal virtual photon, which can show up a sharp peak in e+e- mass spectrum
  - We looked for the signal in large PHENIX data set and set limits. This almost exclude (g-2) prefered band.

Reaping harvest: muon trigger

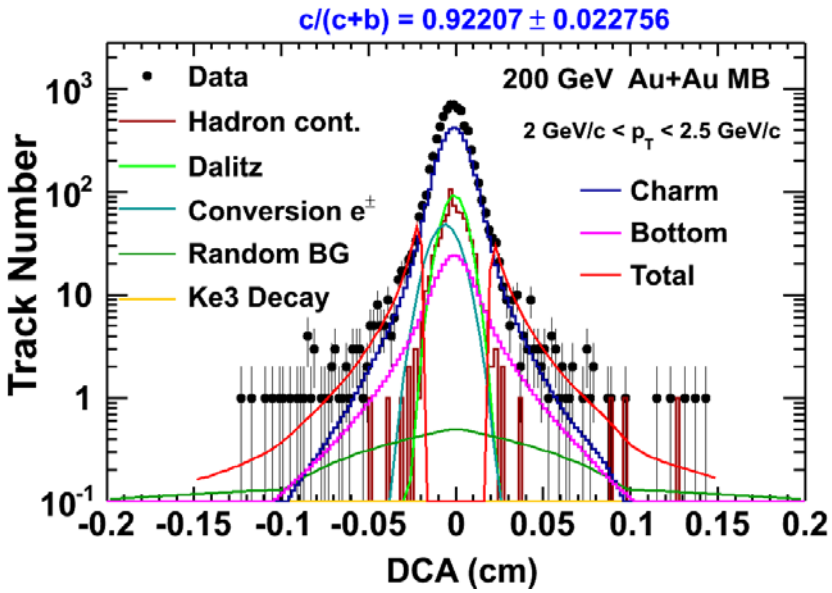




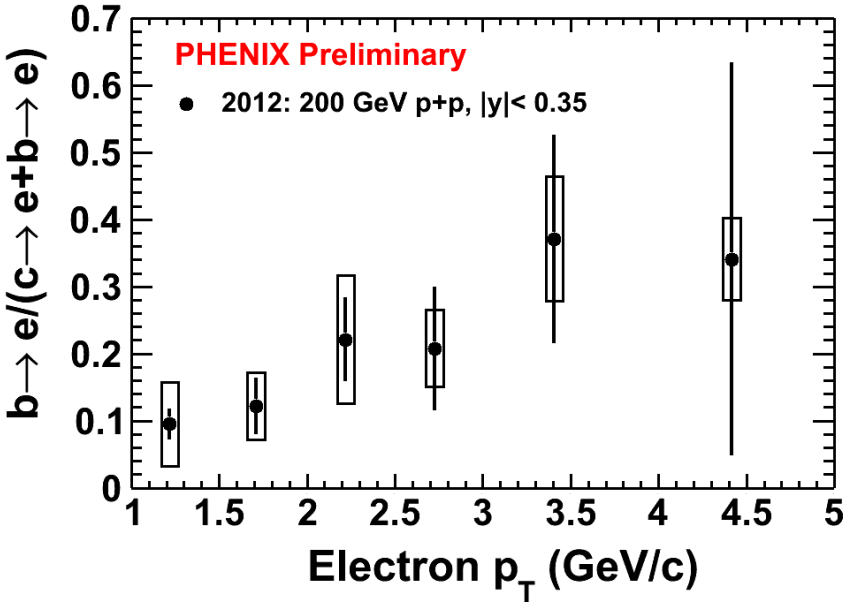
- RIKEN/RBRC has a major role on construction and operation of the muon trigger upgrade
- RUN13 was the main 500 GeV run to measure anti-quark polarization in the proton from the longitudinal single spin asymmetry A_L of W → μ and W→ e
- The analysis of RUN13 W data is going well. We expect the results of the A_L of W→μ soon. (→Talk by Ralf Seidl)

Reaping harvest: VTX

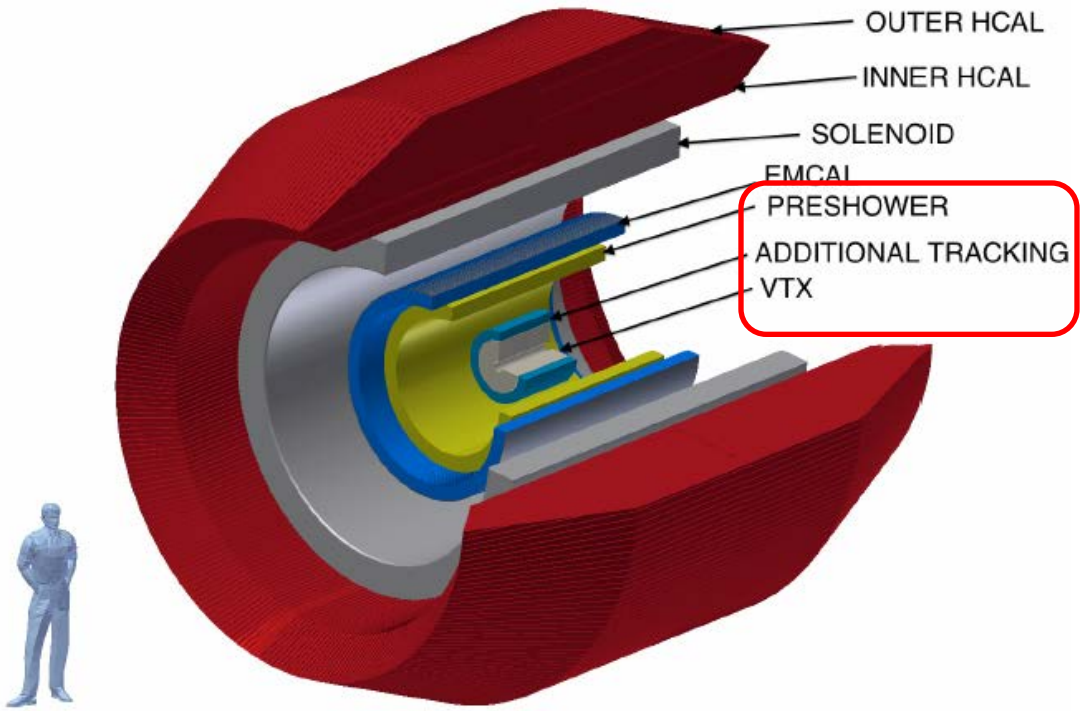




- We build and operated PHENIX VTX detector
- Final results from RUN11 Au+Au and RUN12 pp will be presented in QM2014
- More results to come
  - RUN12 CuAu, U+U
  - RUN14 Au+Au (major HF run)
  - RUN15 p+A
  - RUN16 High statistics AuAu



Future: sPHENIX



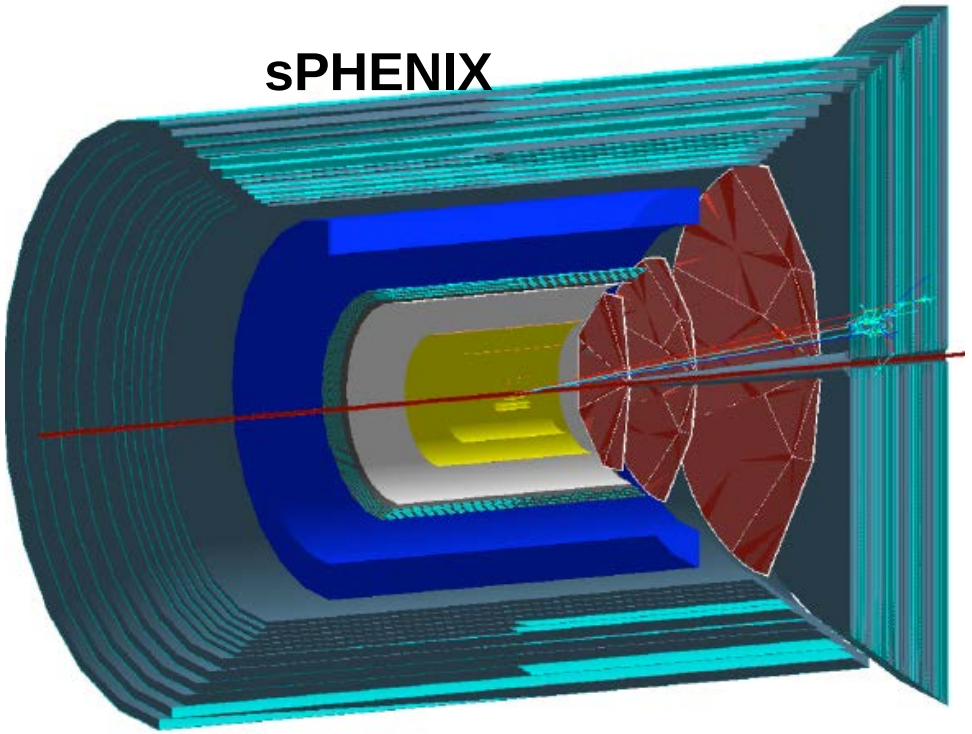
Babar solenoid



Coming to BNL this year

- sPHENIX is a major upgrade of PHENIX detector
  - Study QGP by jets, photons, heavy quarks, and upsilons
  - Compact Hcal and Emcal covering |y|<1.
  - Central piece of the last stage of RHIC operation before eRHIC
  - Recently, we get BaBar solenoid (R=1.4m, B=1.5T) for sPHENIX
  - MIE proposal submitted to DOE on Sep30, 2013. Aiming CD0 in early 2014
  - Engineering run in 2019 and physics in 2021
  - Mid-rapidity component of ePHENIX detector of eRHIC (2025)
  - RIKEN/BRRC has strong interest on the additional tracking system

Future: sPHENiX and forward sPHENIX



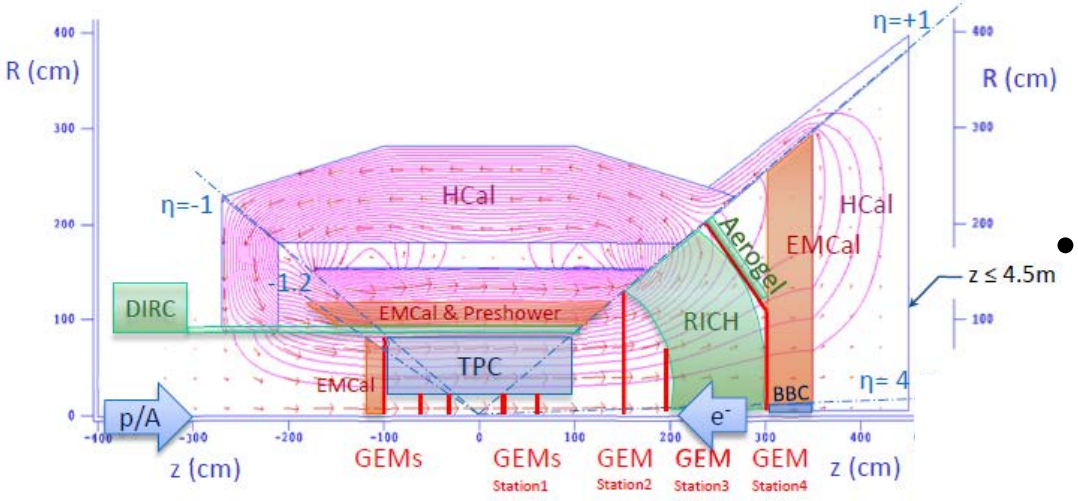
fsPHENIX

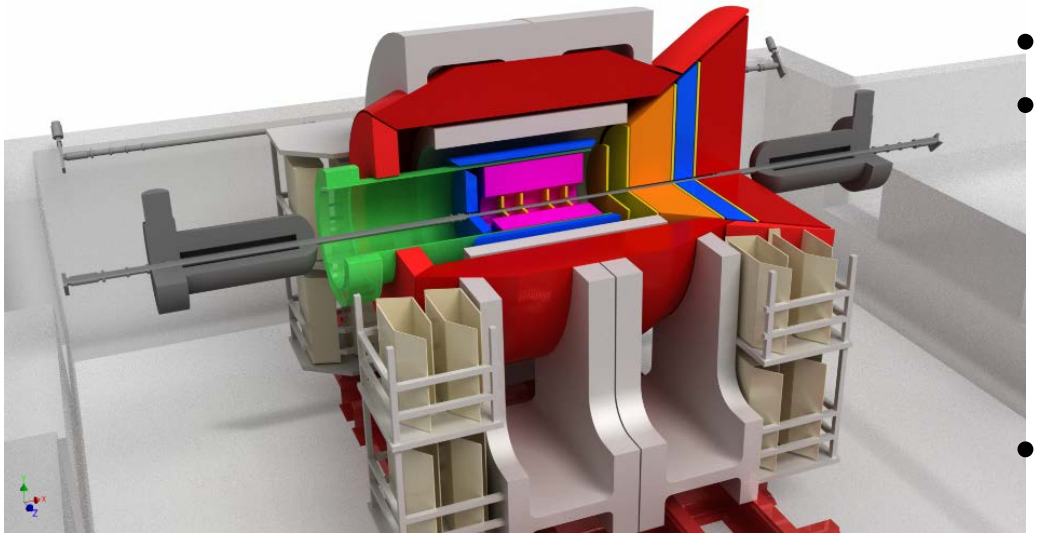
- GEM tracking system
- Forward calorimeter

Detector configuration, cost and schedule is now being discussed.

- fsPHENIX: upgrade at forward rapidity (→ talk by J. Seele)
  - Spin Physics and small-x physics in pp and pA
    - Jet AN, gluon saturation effects
  - Forward detector of future ePHENIX (2025-)
  - Forward physics white paper is due in April 2014
    - Y. Goto, R. Seidl and J. Seele are members of the writing committee
  - Seeking funding outside of DOE
    - recently applied to JSPS grant as a part of 新学術領域 proposal
  - Aiming to implement the detector in the same time scale as sPHENIX and run in 2021-22

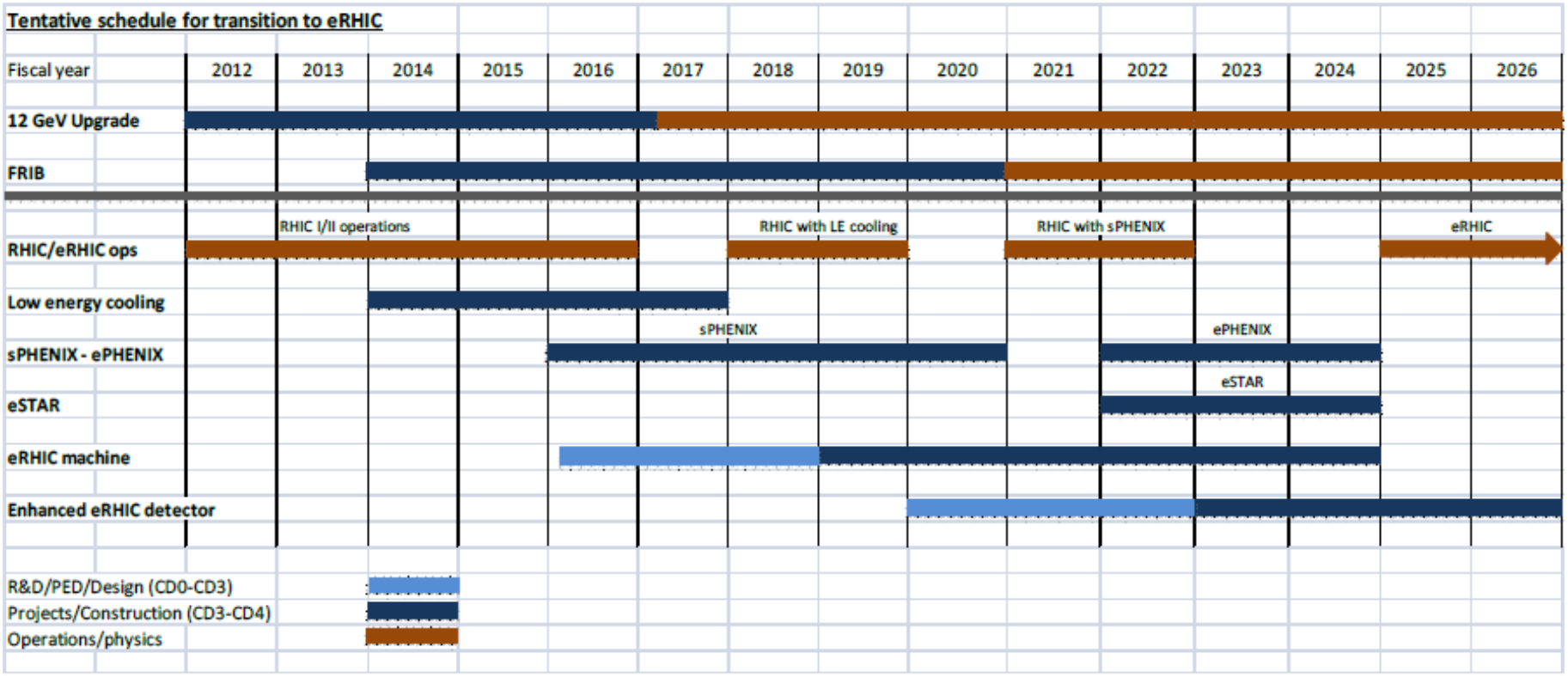
Future: ePHENIX at eRHIC





- ePHENIX is one of two initial detectors of the first stage eRHIC (2025-)
  - 10 GeV e x 100 GeV HI
  - 10 GeV e x 250 GeV p
- Physics
  - Spin structure of proton
  - 3D tomography of proton
  - Initial study of the gluon saturation (CGC)
  - Quark propagation in cold nuclear medium
- Evolved from sPHENIX
- LOI of ePHENIX submitted on Sep 30, 2013 with sPHENIX MIE
  - Kieran Boyle and Itaru Nakagawa were a member of ePHENIX LOI writing committee
- Talk by K. Boyle

RHIC schedule and transition to eRHIC



- sPHENIX
  - CD0 2014
  - Construction 2016-20
  - Engineering run 2019
  - Physics 2021-22
- ePHENIX
  - Construction 2022-24
  - Physics 2025
- eRHIC starts in 2025

Exp Group Presentations

YA	Exp. Group overview
Ralf Seidl	W→ m measurement in PHENIX
John Chen	Studyng the medium properties in dAu via two-particle correlation”
Maki Kurosawa	Operation and current status of Silicon pixel
Abhay Deshpande	Overview of current Spin Physics program and future plans in PHENIX
Xiaorong Wang	Proton spin study with FVTX
Joe Seele	fsPHENIX detector and physics program”
Kieran Boyle	Letter of Intent for ePHENIX

Stefan Bathe	Charged hadron measurements with the PHENIX VTX detector

Summary

- Three pillars of RBRC Experimental Group Activity

  Spin Physics/HI Physics/PHENIX Upgrade

- Spin Physics
  - Main activity of the group
  - RUN13 was the main 510 GeV run → Definitive measurement of anit-quark polarization from W
- Heavy Ion Physics
  - Study of QGP with penetrating probes
  - Important heavy ion results from RBRC
- Two major upgrades, VTX and Muon Triggers, completed. We are reaping harvest of them.
- NEXT: sPHENIX / fsPHENIX → ePHENIX
- RBRC experimental group plays leading roles in Spin Physics, HI physics and PHENIX upgrades

W→μ measurements at

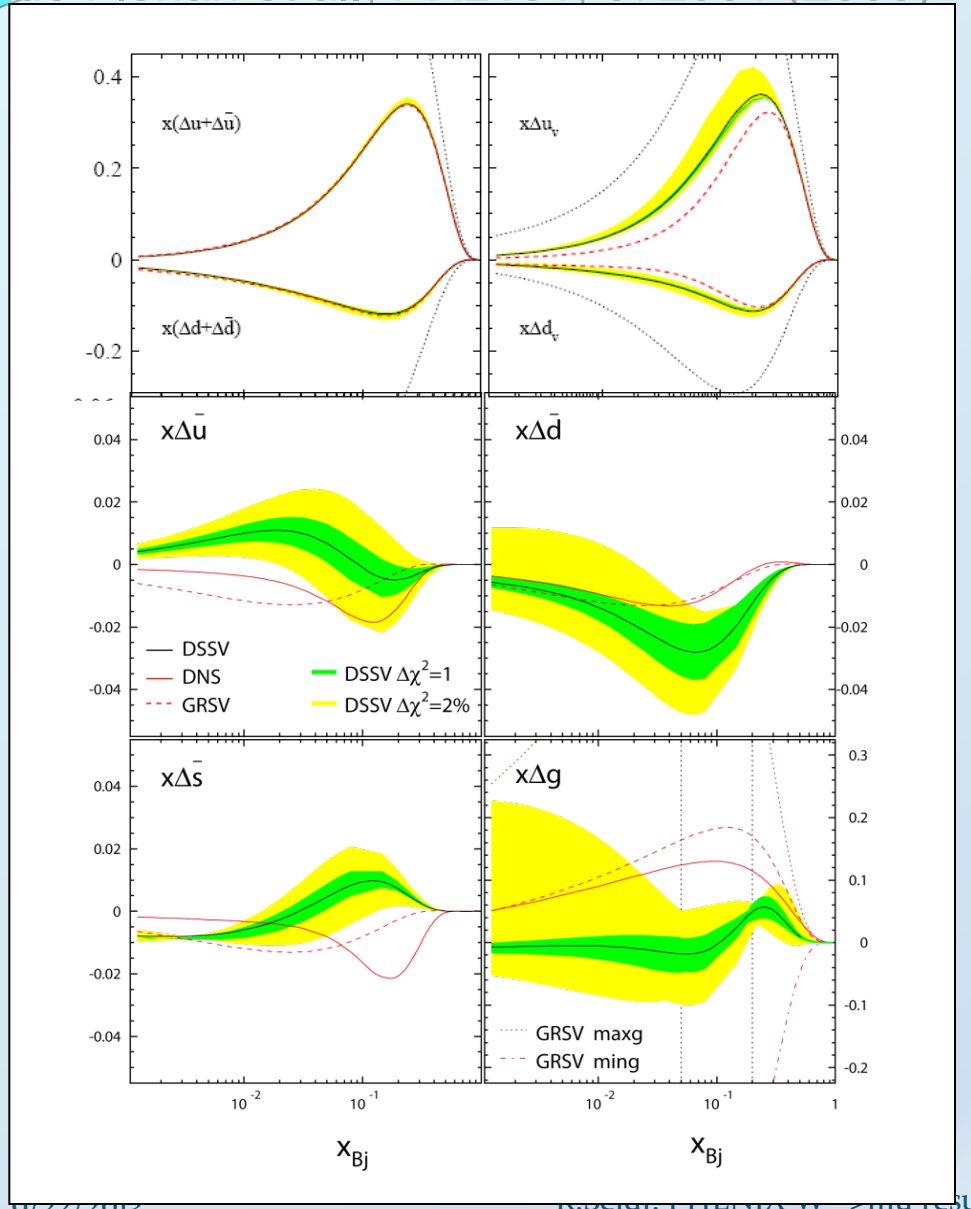


RBRC Science Review,
October 31, 2013

Ralf Seidl
(RIKEN)

Most recent global analysis : DSSV

de Florian et al., PRL101, 072001 (2008)



- NLO analysis
- Inclusion of SIDIS data before COMPASS
- Inclusion of RHIC A_{LL} data(from 200GeV)
- Using most recent NLO fragmentation functions (DSS)
- Large uncertainties still for sea quarks
- Decay data forces Δs to become negative at small x
- RHIC data results in node to Δg

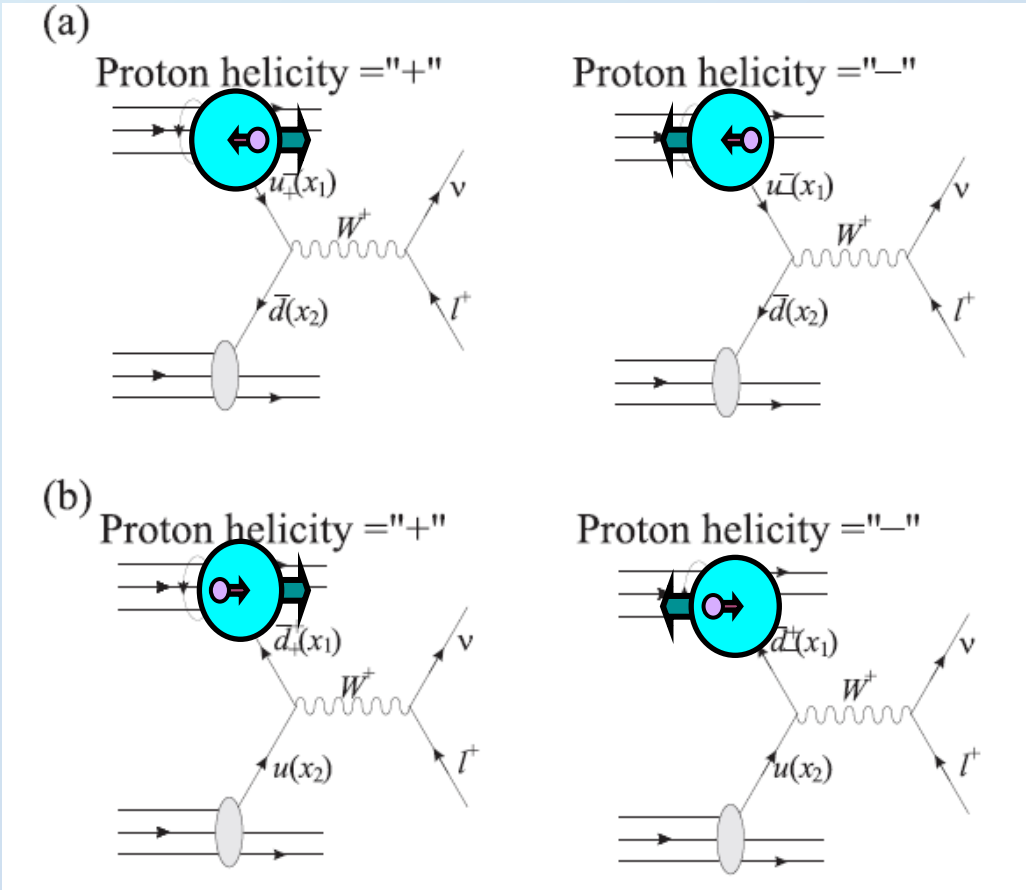
Real W production as access to quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

➔Difference of the cross sections gives quark helicities $\Delta q(x)$

- No Fragmentation function required
- Very high scale defined by W mass



Bourrely , Soffer
Nucl.Phys. B423 (1994) 329-348

Quark and antiquark helicities probed in W production

- Building single spin asymmetries of decay lepton

$$A_L = \frac{1}{P}\frac{\vec{N} - \overleftarrow{N}}{\vec{N} + \overleftarrow{N}}$$

- Positive lepton asymmetries sensitive to $\Delta u(x)$ and $\Delta \bar{d}(x)$

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

- Negativ lepton asymmetries sensitive to $\Delta d(x)$ and $\Delta \bar{u}(x)$

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

Quark and antiquark helicities probed in W production

- Building single spin asymmetries of decay lepton

$$A_L = \frac{1}{P}\frac{\vec{N} - \overleftarrow{N}}{\vec{N} + \overleftarrow{N}}$$

- Positive le
asymmetr
Δu (x) and

$$\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)$$
$$\bar{d}(x_2) - \bar{d}(x_1)u(x_2)$$

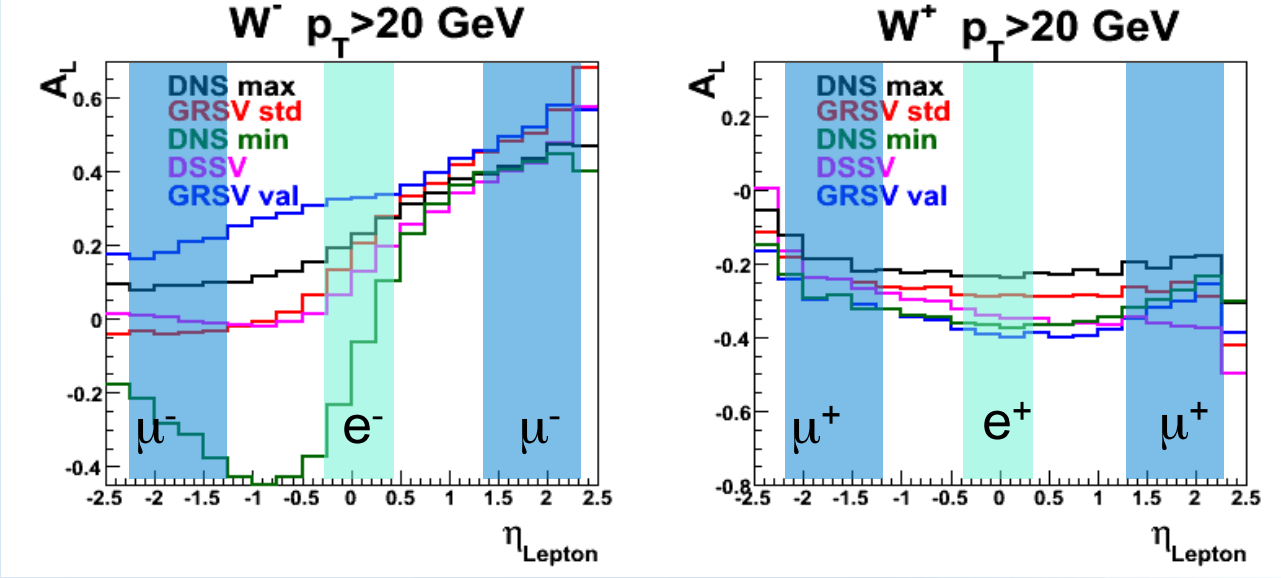
But unfortunately we don't have a 4π detector,
Need to find the Ws inclusively via their decay leptons

- Negativ lepton asymmetries sensitive to Δd (x) and Δ u (x)

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

Sea quark polarization via W production

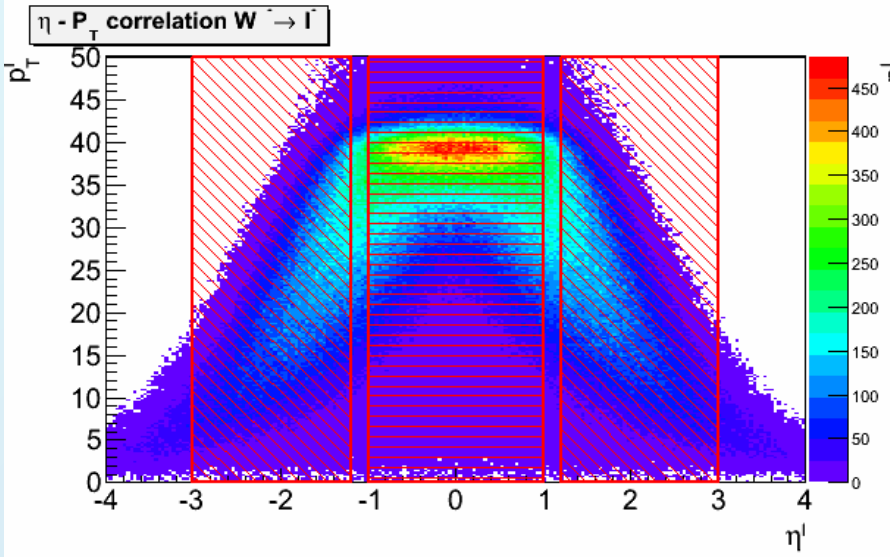
- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics

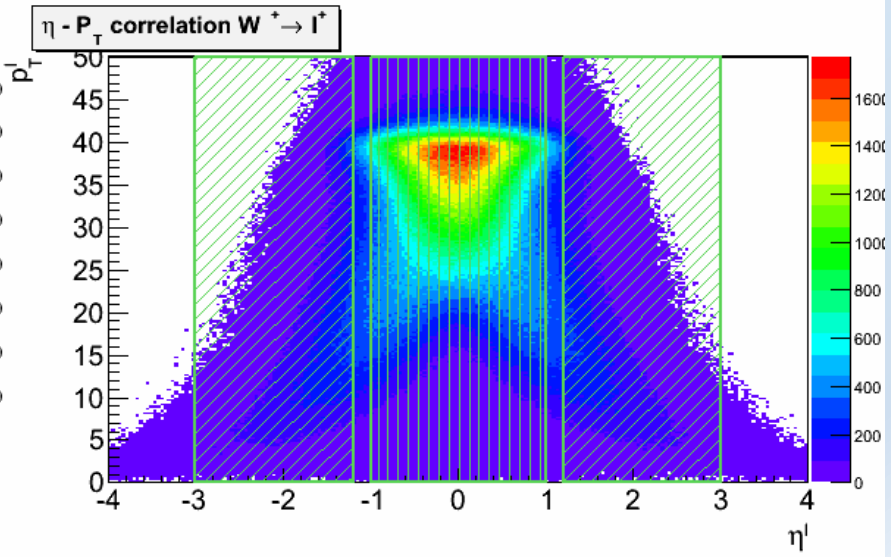


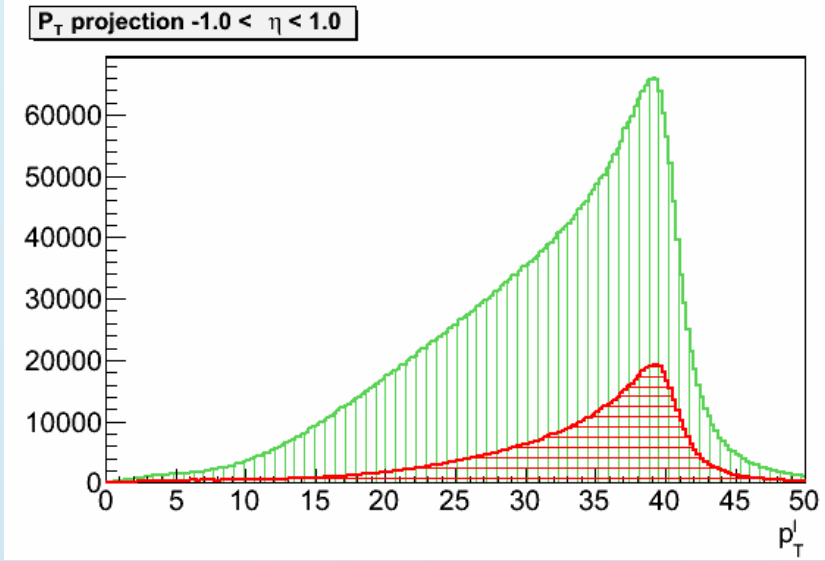
$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

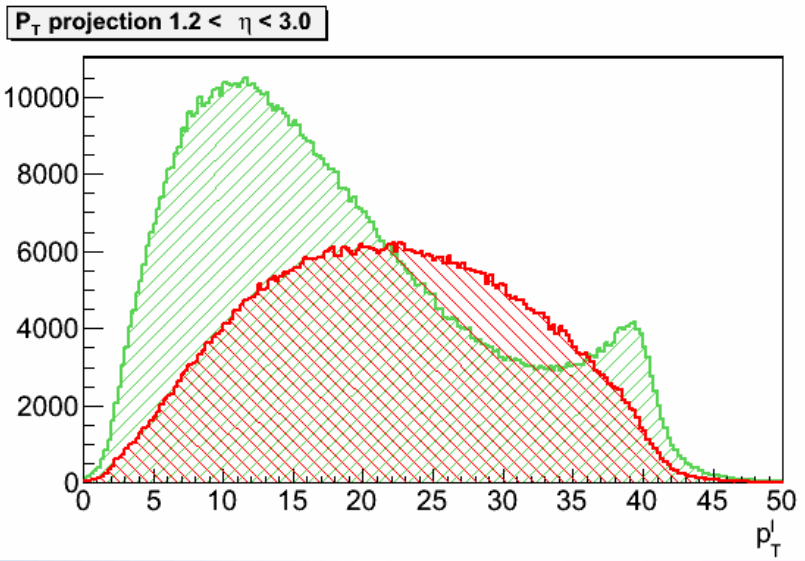
$$A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-\cos\theta)^2}$$

W kinematics







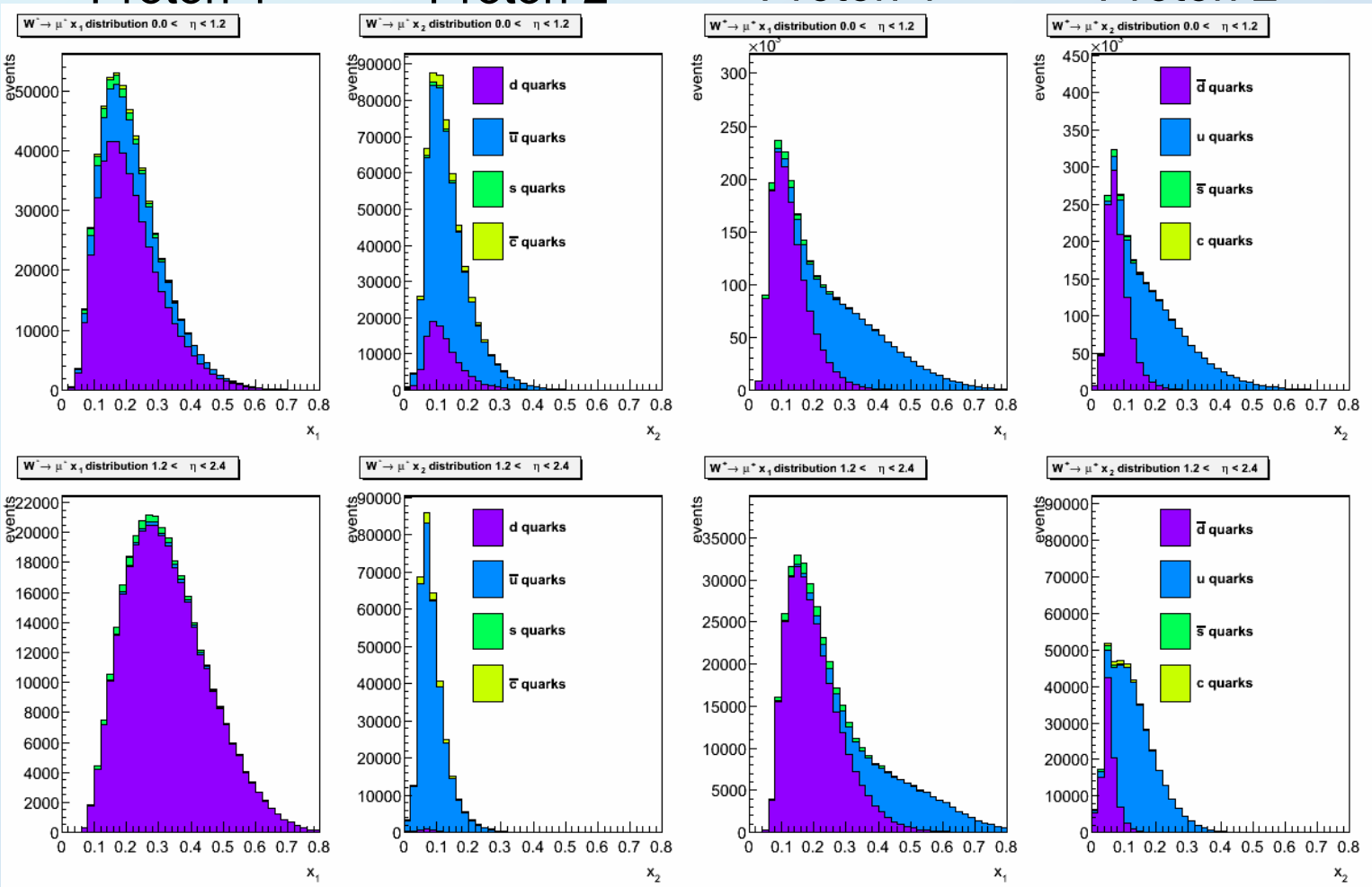


Pythia: quark flavors and x ranges

Proton 1 | Proton 2 | Proton 1 | Proton 2

Central

Forward

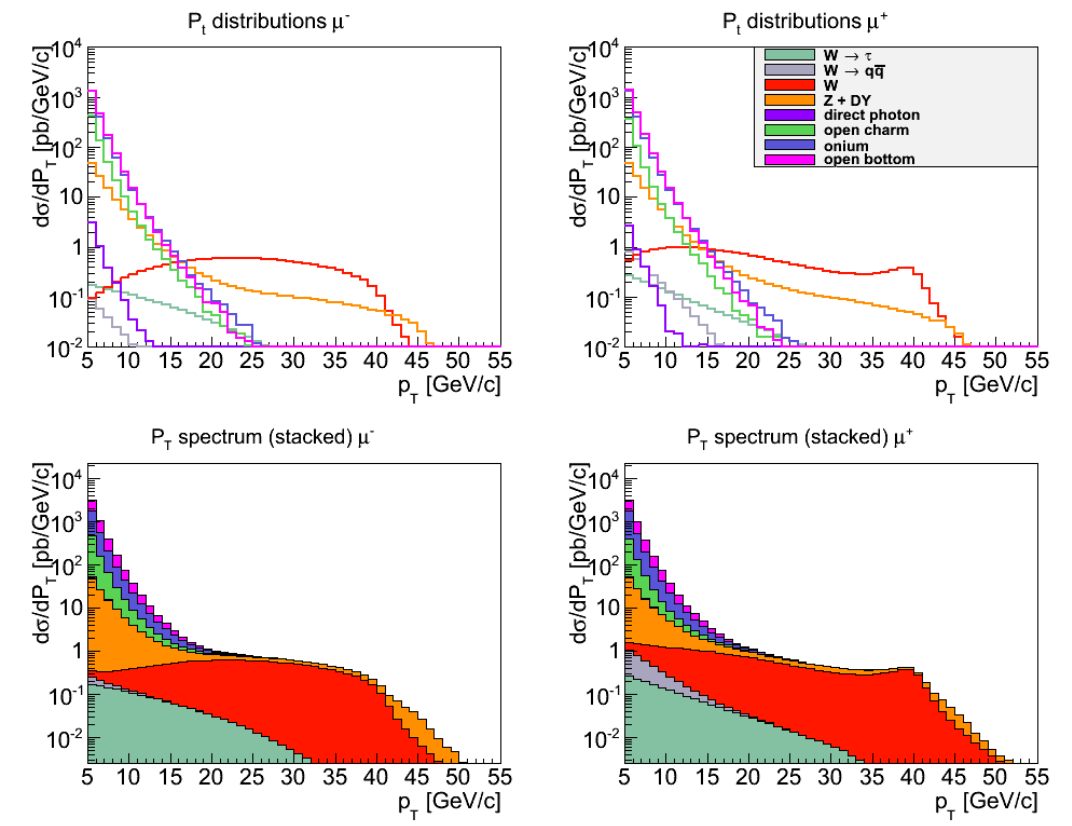


W⁻ →μ case: almost entirely forward d quarks and backwards u

W⁺ →μ case: predominantly forward d quarks and backwards u

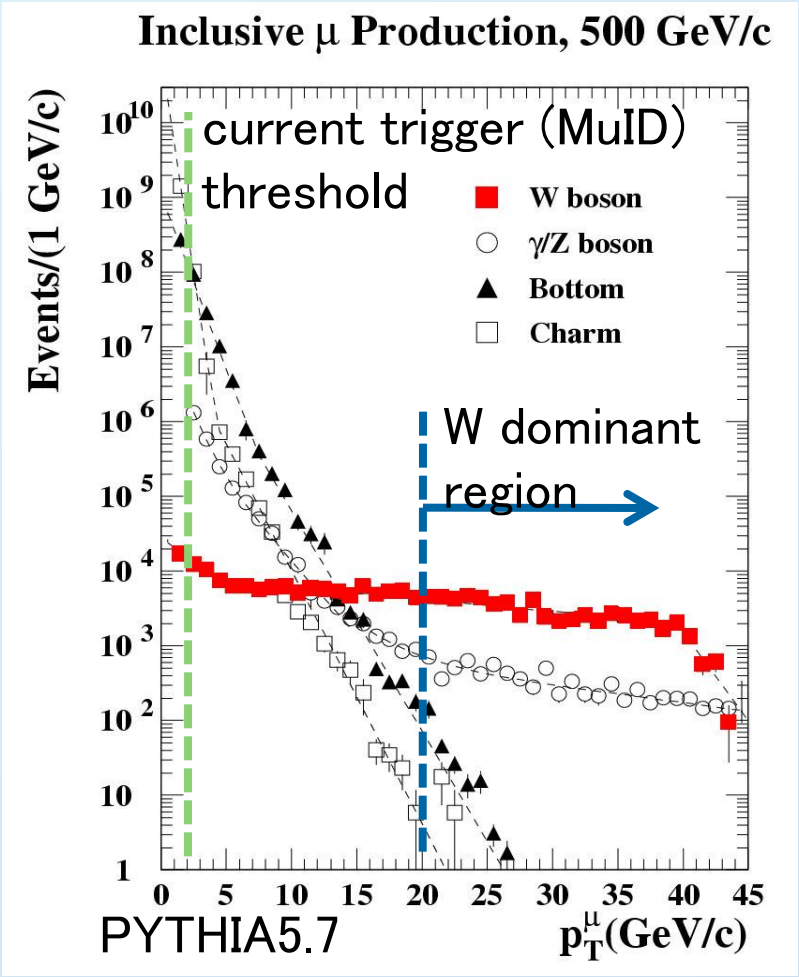
Forward W analysis

- W momentum cannot be ignored
- Jacobian peak only visible for forward moving W^+ decaying at close to 90 degrees
- Need to understand and suppress backgrounds lacking distinct signal signature



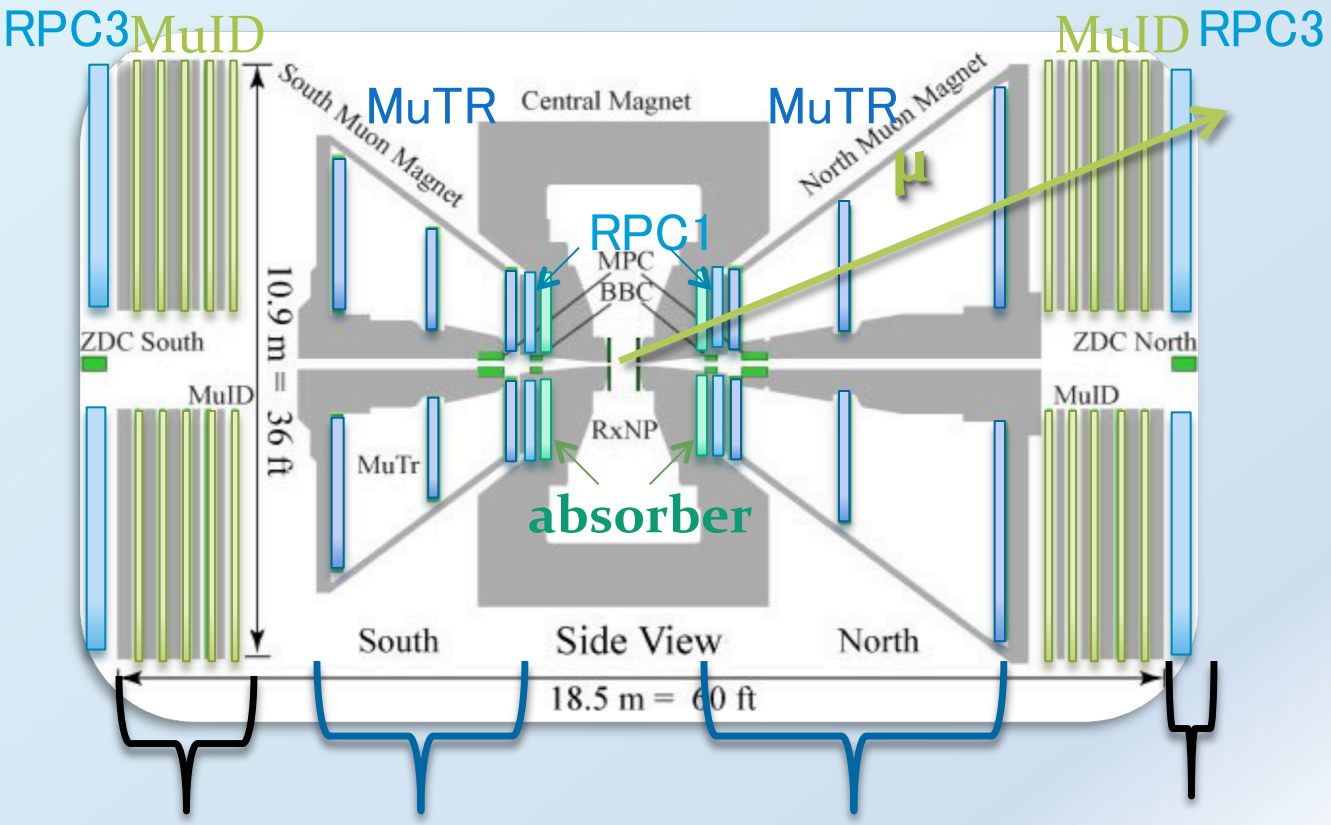
Pythia 6.4, muons in rapidities 1.2 – 2.4

PHENIX Muon trigger upgrade



- σ(tot)=60mb, L=3x10^{32}cm^{-2}s^{-1} (500GeV)
  - collision rate = 18MHz
  - (after luminosity upgrade)
- DAQ rate limit < 2kHz (for muon Arm)
- Therefore, required rejection ratio
  - > 9000
- But, MuID-trigger rejection ratio (500GeV)
  - < 100
- **A higher momentum trigger is needed**

PHENIX Muon Trigger Upgrade detectors



MuID trigger
selecting muon momentum > 2GeV/c

MuTR FEE upgrade
fast selection of high-momentum-tracks

RPC
provide timing information and rough position information

Muon Trigger Upgrade

RPC

RPC project

timing information

rough position information

Station3

MuTr

Station2

sagitta

Station1

B

B

Muon Tracking Chamber

5% of charge

Amplifier Discriminator

Amp

Comp

95% of charge

ADC

digitized hit signal

digitized hit signal

digitized hit signal

MuTRG project

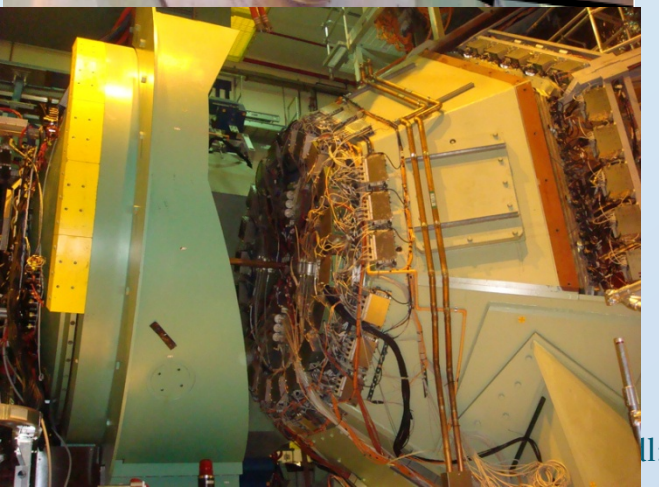
Level-1 trigger board

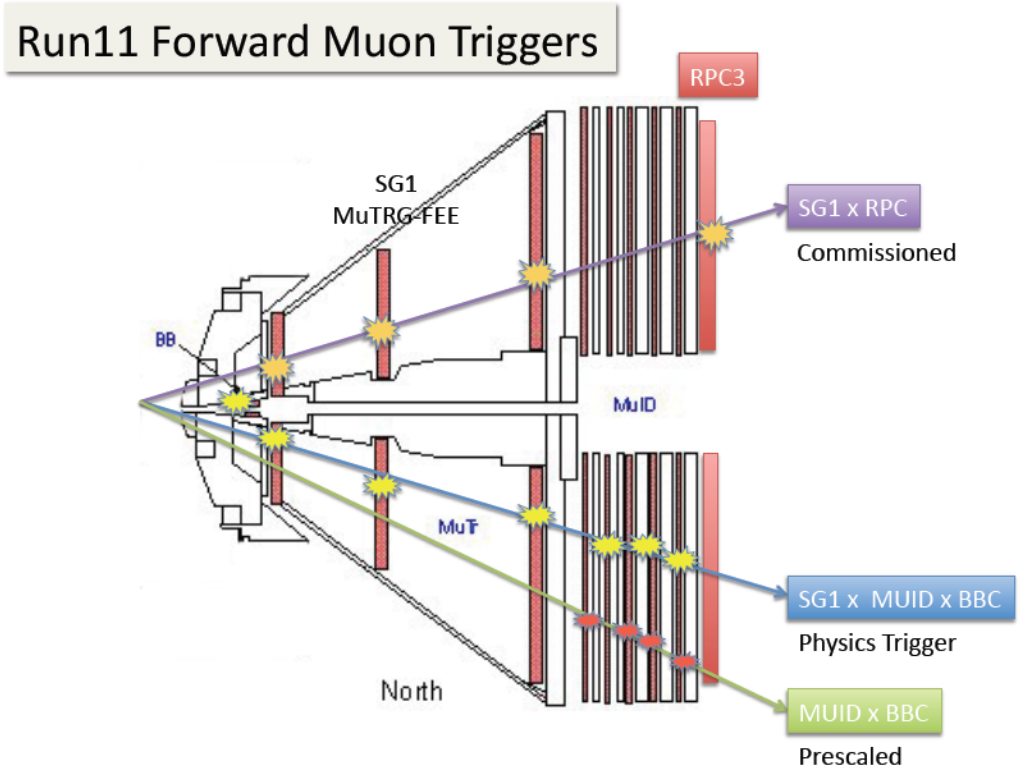
Level-1 trigger

PHENIX Forward W trigger upgrade installation and commissioning





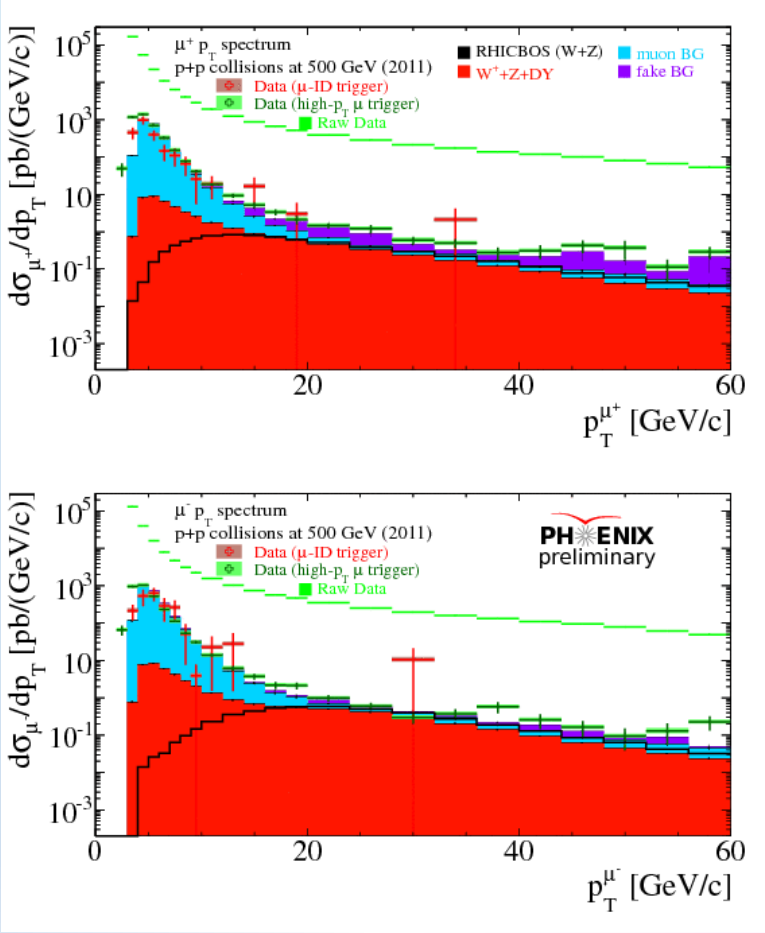




- All systems taking data in Run12
- All systems in triggers in Run13:
  - 3 Rapidity ranges with overlapping RPC1 and 3 acceptances

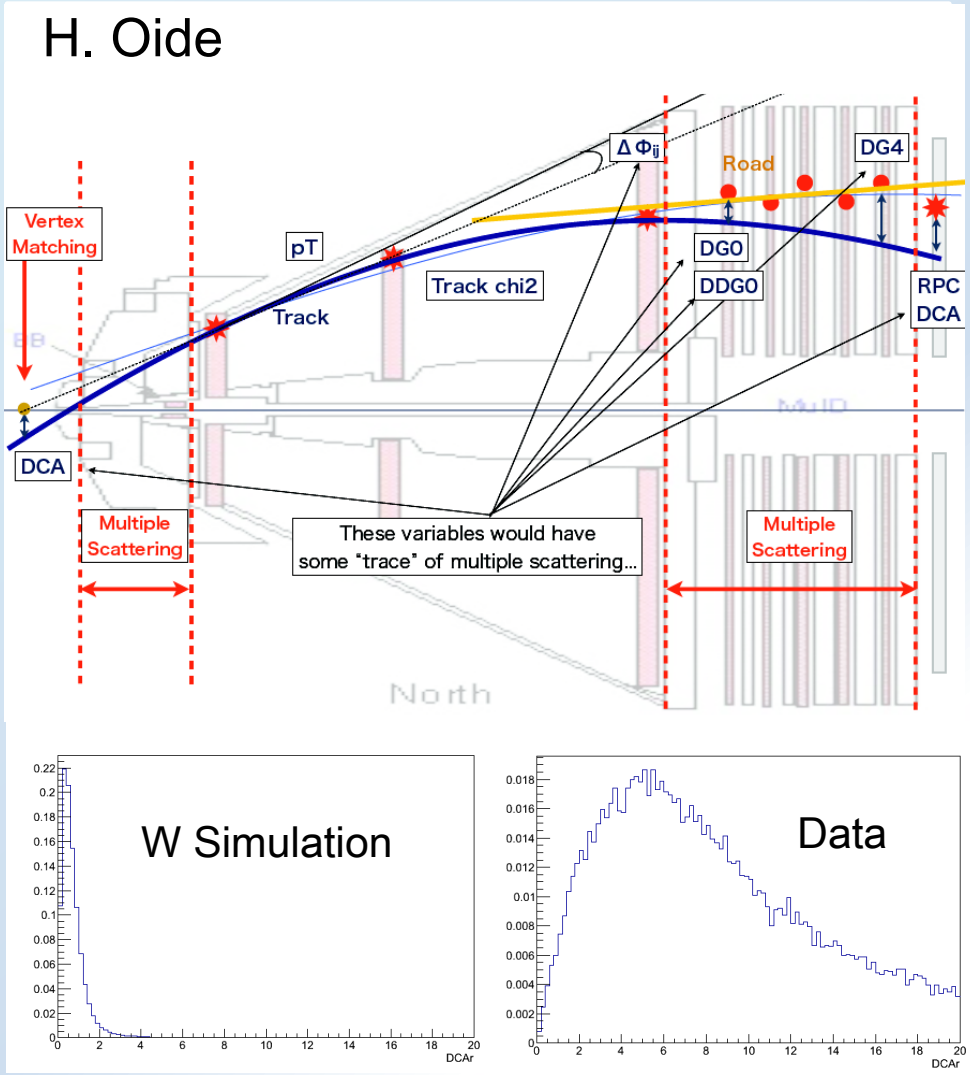
Forward Muon Backgrounds

- Real muons from heavy flavor and DY decays get smeared to higher transverse momenta
- Low energetic hadrons (huge cross section) decay within the muon tracker, mimicking a straight track
- Raw yields 3 orders above signal



Reducing the background components

- Apply sensitivity to multiple scattering to reduce hadronic backgrounds
- Initially (2011) cut based removal of backgrounds
- Improved by using likelihood based pre-selection and unbinned max likelihood fit



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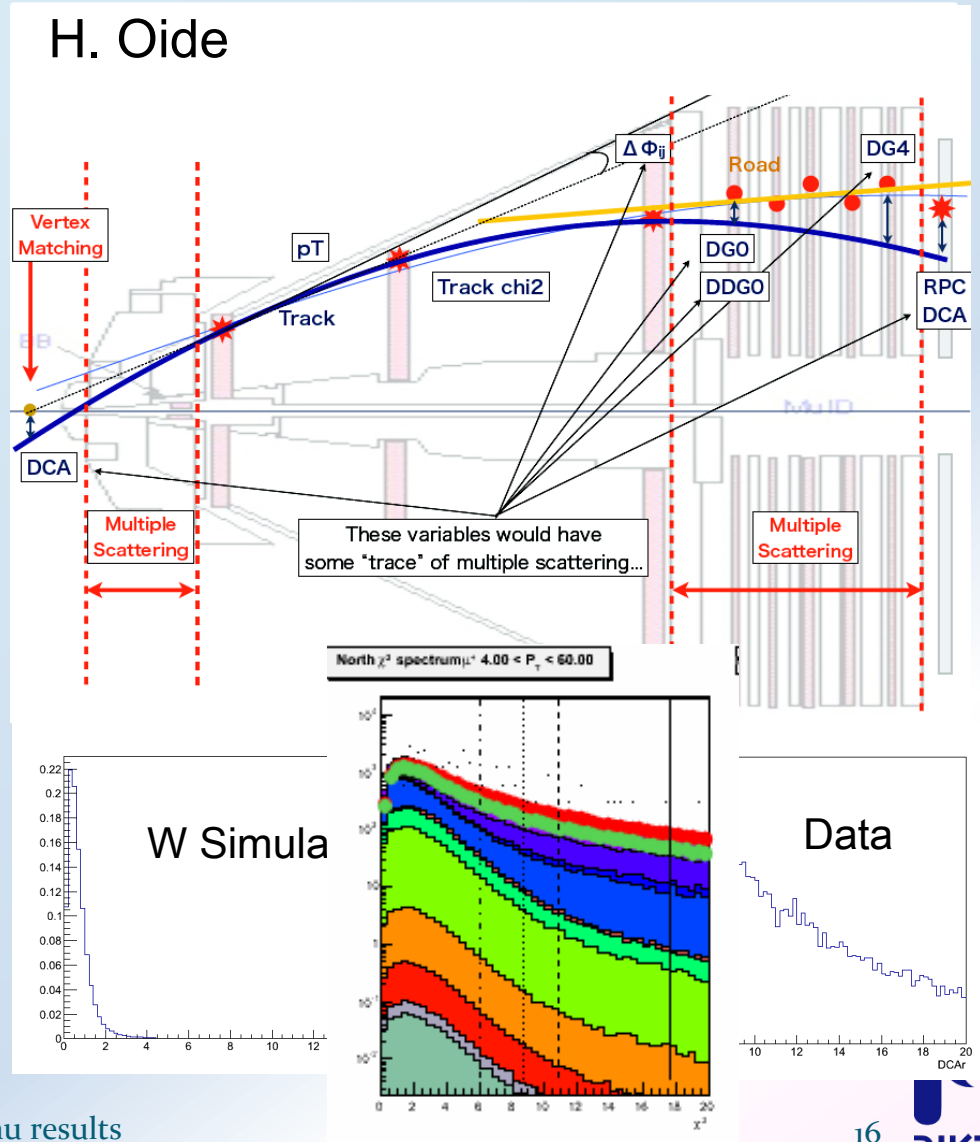
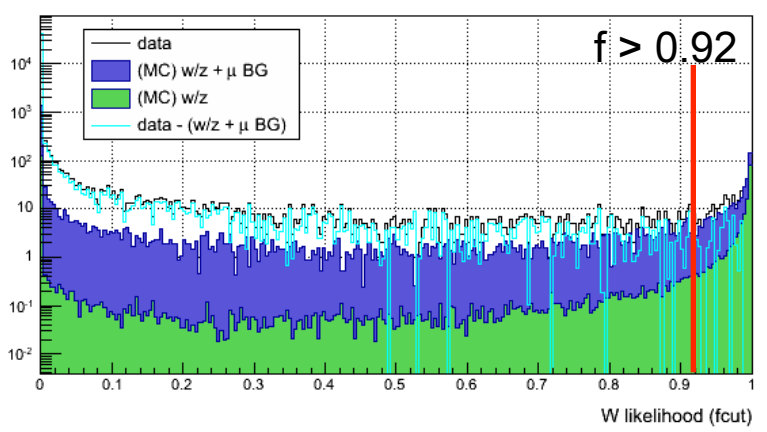
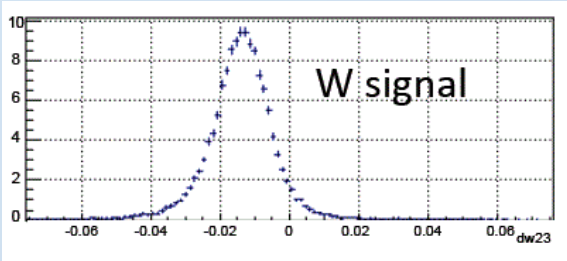


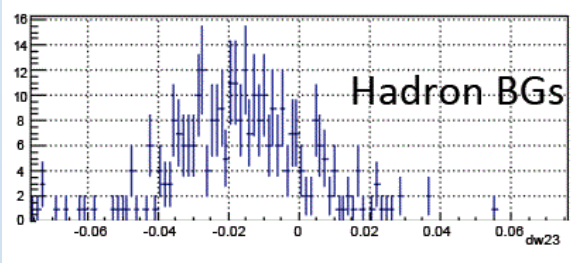
Multivariate analysis

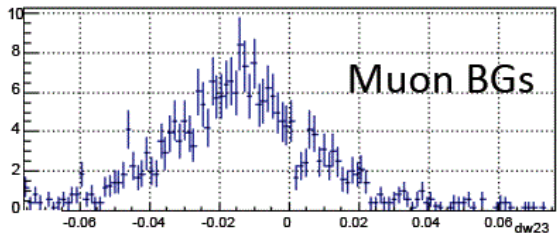


- After preselecting W like events (>0.92) perform unbinned max likelihood fit in independent variables rapidity and effective bending angle



- Define Wness likelihood using 5 kinematic variables based on signal MC and data (= mostly BG)

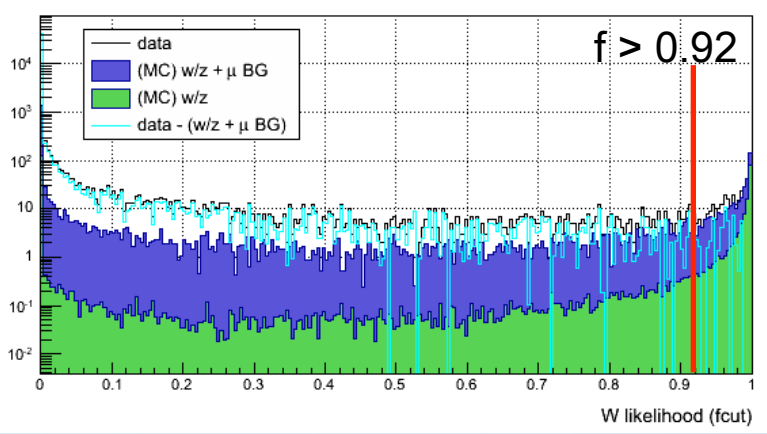




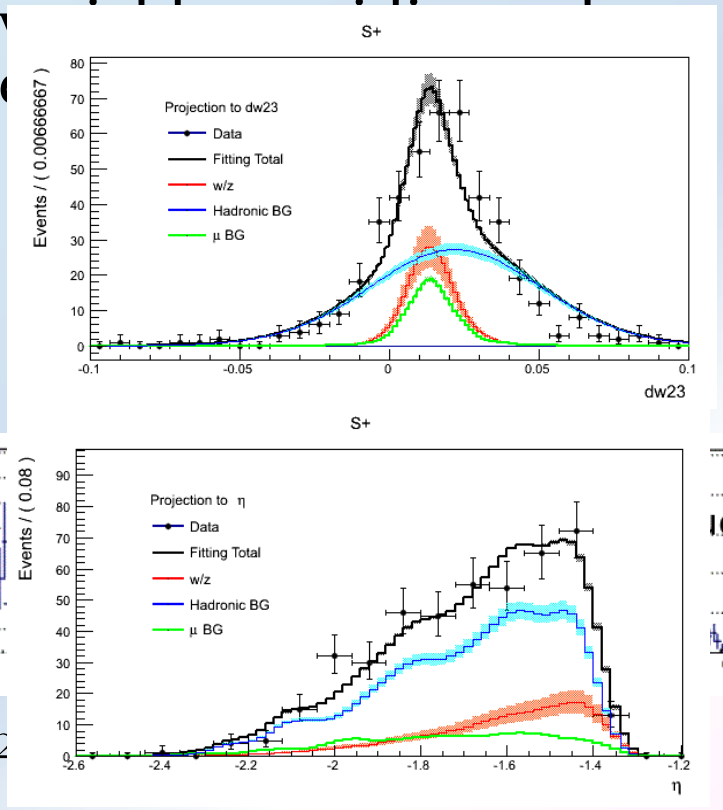
$$Wness = \frac{\lambda_{(SIG)}}{\lambda_{SIG} + \lambda_{BG}}$$

$$\lambda = \left[p(DG0, DDG0), p(DCA_r), p(\chi^2), p(RPC\_DCA)\right]$$

Multivariate analysis



- After preselecting W like events (>0.92) perform unbinned max likelihood fit in independent



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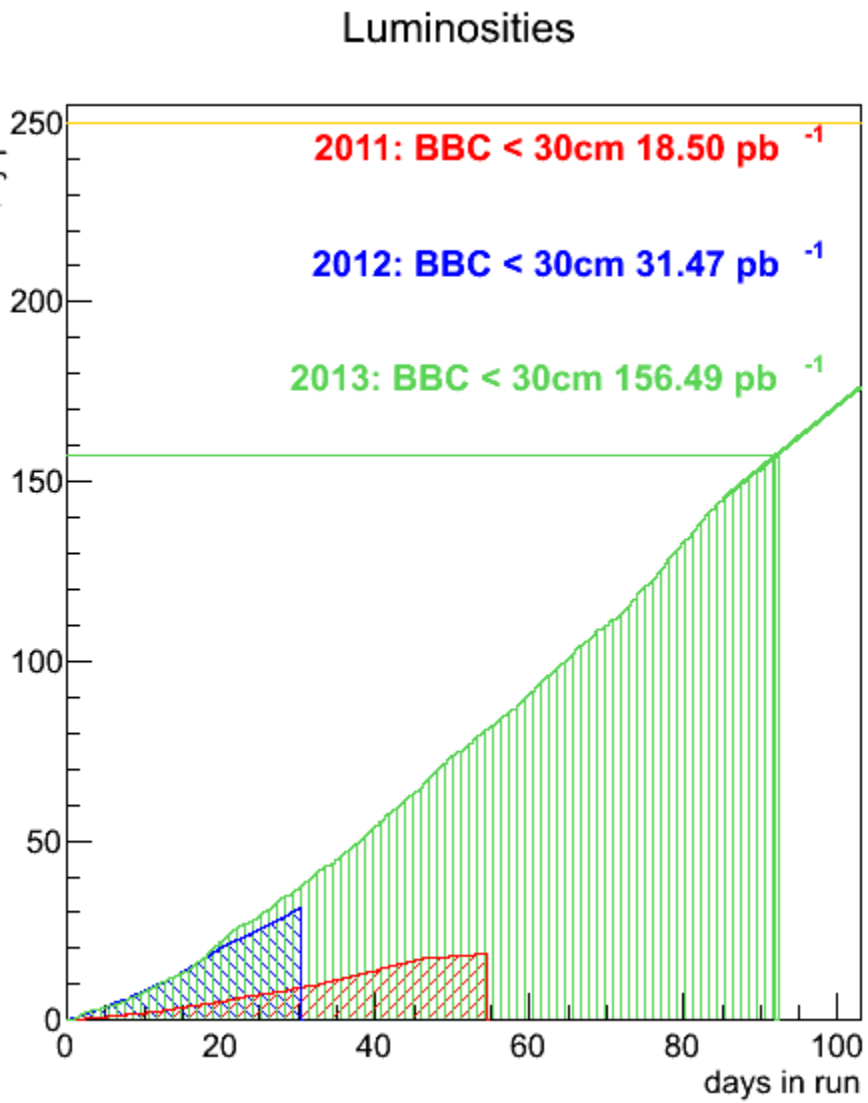
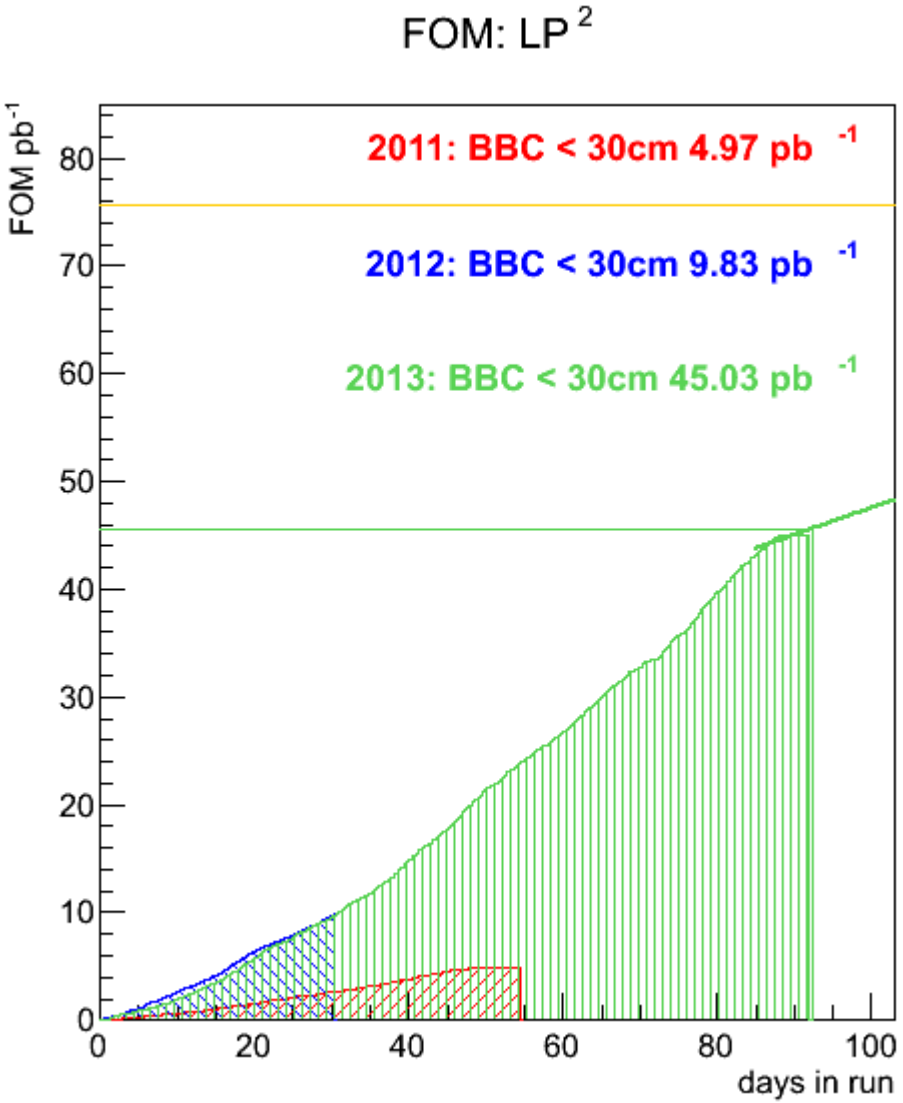
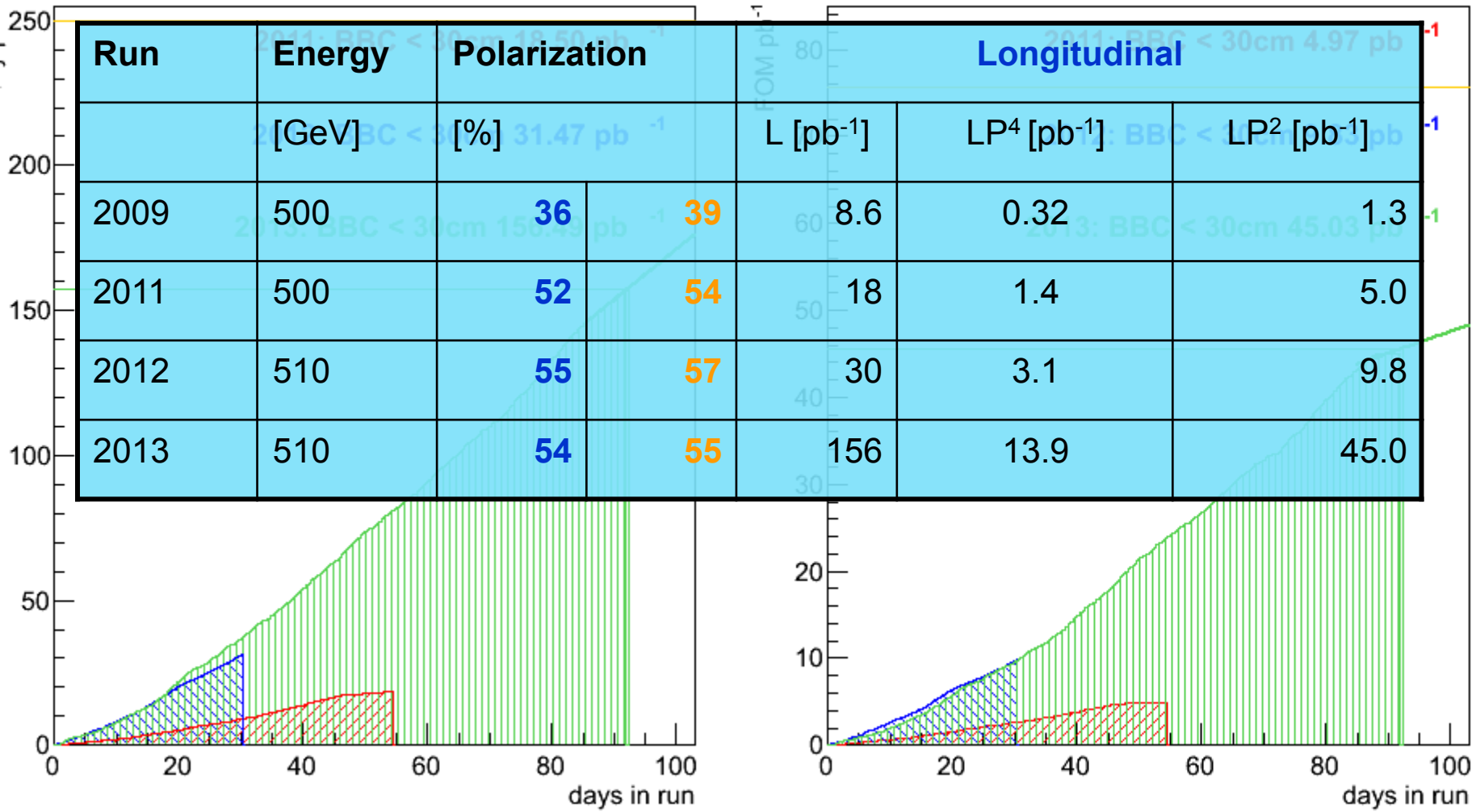
500/510 GeV Data taking periods





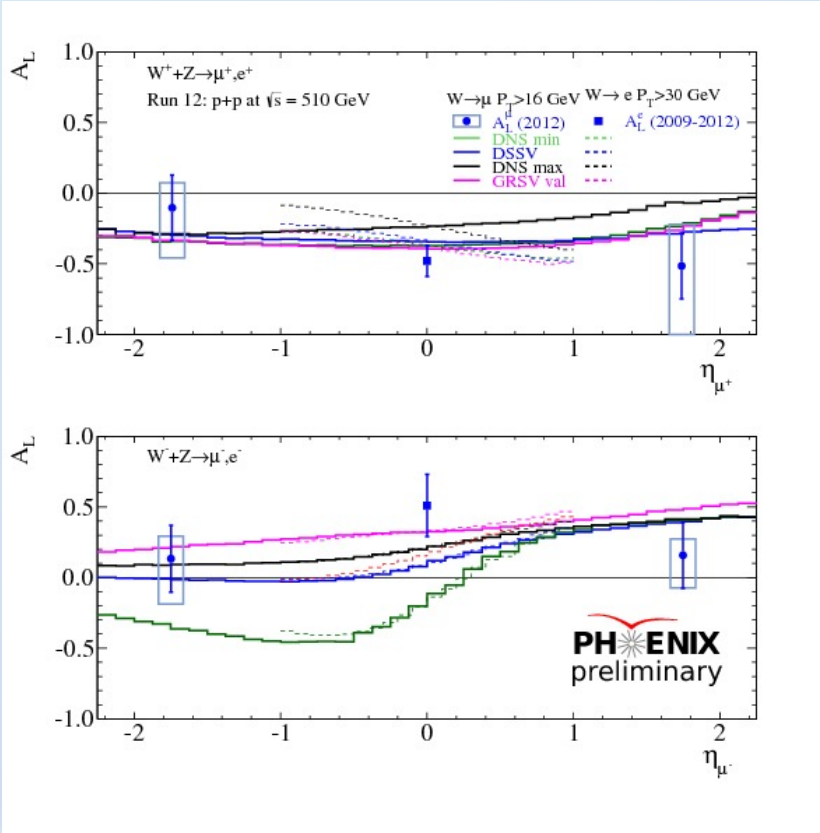
500/510 GeV Data taking periods

Run	Energy	Polarization		Longitudinal		
	[GeV]	[%]		L [pb^{-1}]	LP^4 [pb^{-1}]	LP^2 [pb^{-1}]
2009	500	**36**	**39**	8.6	0.32	1.3
2011	500	**52**	**54**	18	1.4	5.0
2012	510	**55**	**57**	30	3.1	9.8
2013	510	**54**	**55**	156	13.9	45.0



Forward W asymmetries

- After extracting S/BG ratios (in 2012 preliminary data ~0.3) extract asymmetries and correct for BG (BG asymmetries are consistent with zero)
- Inclusion of FVTX information will improve BG rejection (isolation, multiple scattering)
- 2011 and 2012 Analysis will be finalized soon
- 2013 data analysis is ongoing



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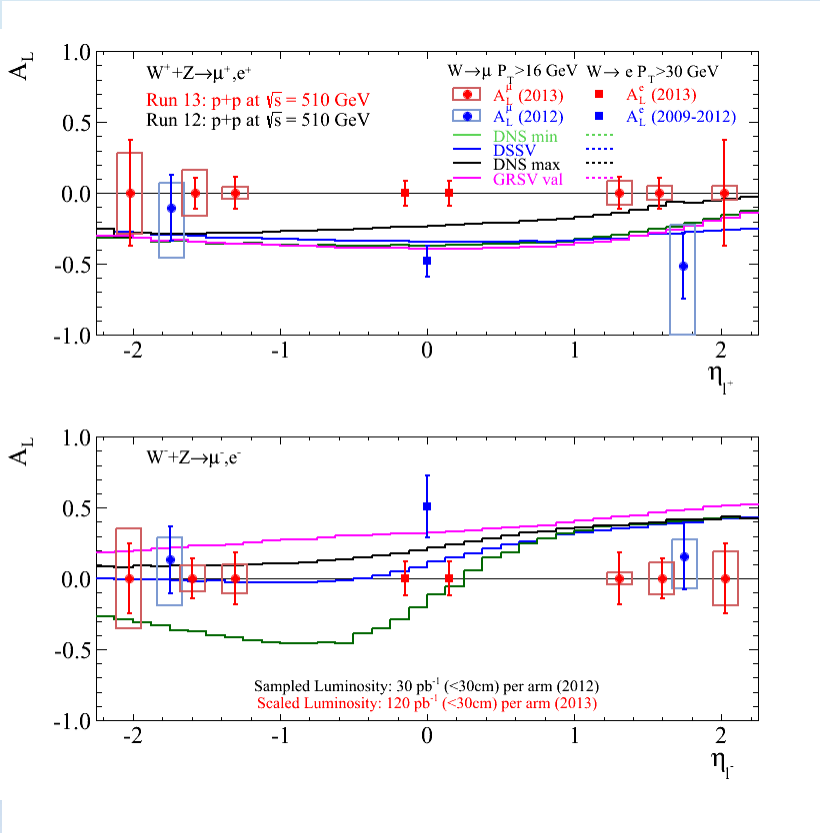
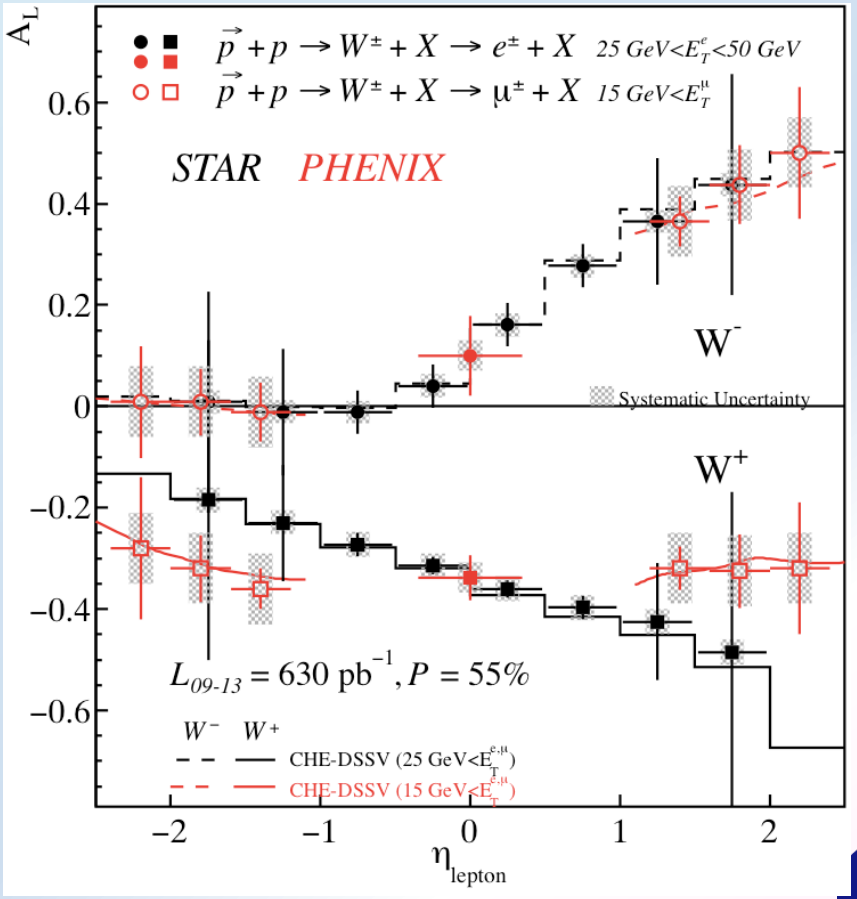


Outlook

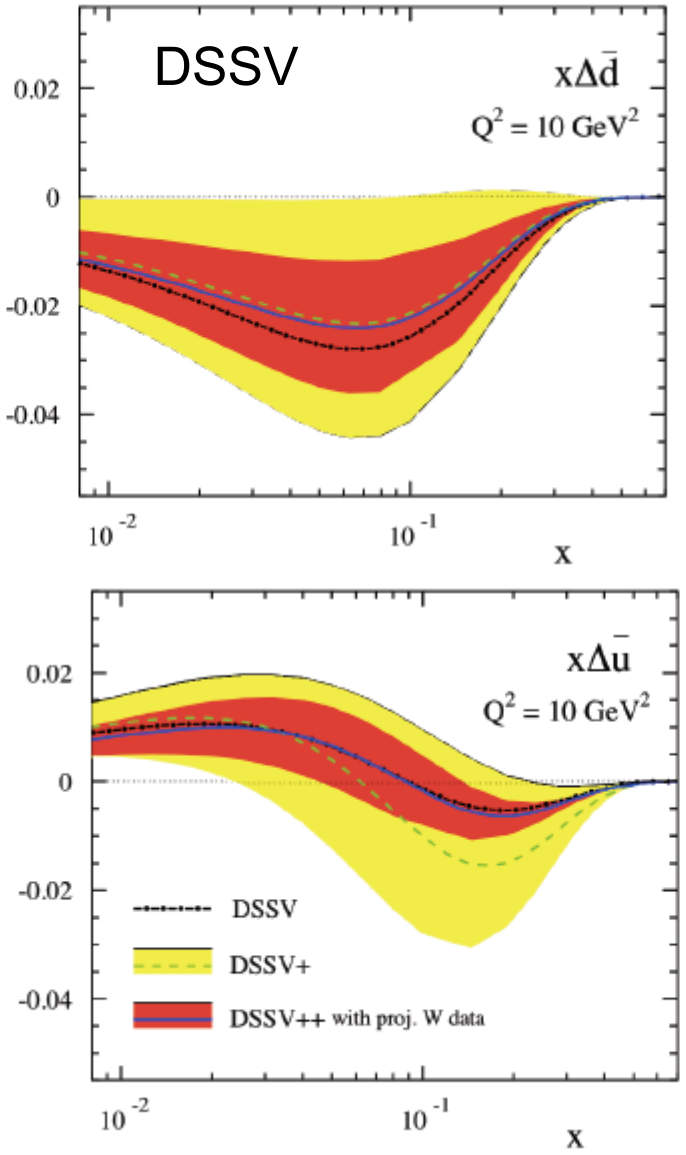
RHIC Spin NSAC write-up:
Aschenauer et. al: arXiv:1304.0079

- Real W boson production as clean access to sea quark helicities
- RHIC has delivered 510 GeV polarized pp collisions from 2009-2013
- Run 13 analysis will significantly improve sea quark helicity knowledge



Expected impact of full data set

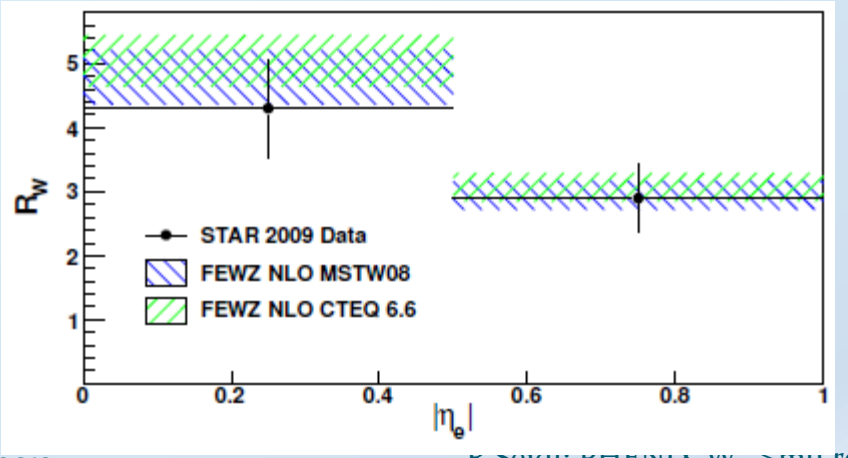
- Substantial uncertainty improvement of the sea quark helicities
- DSSV framework ready to include W asymmtries
- NNPDF in the process of including W asymmetries

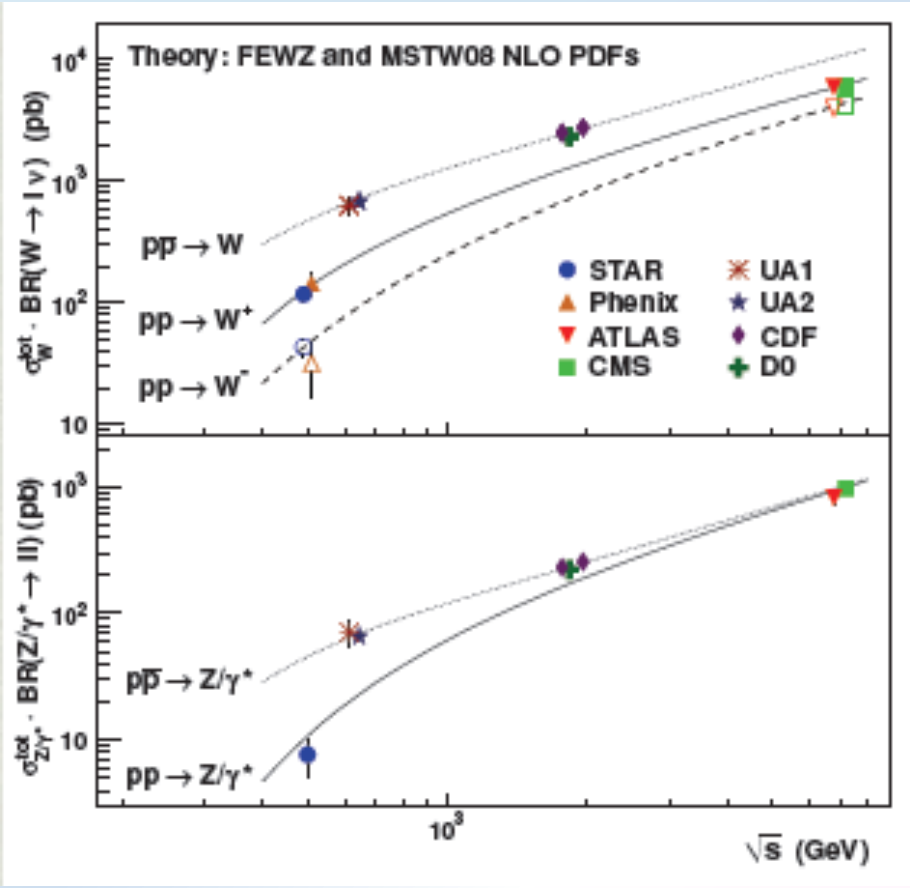


Backup

W Cross sections

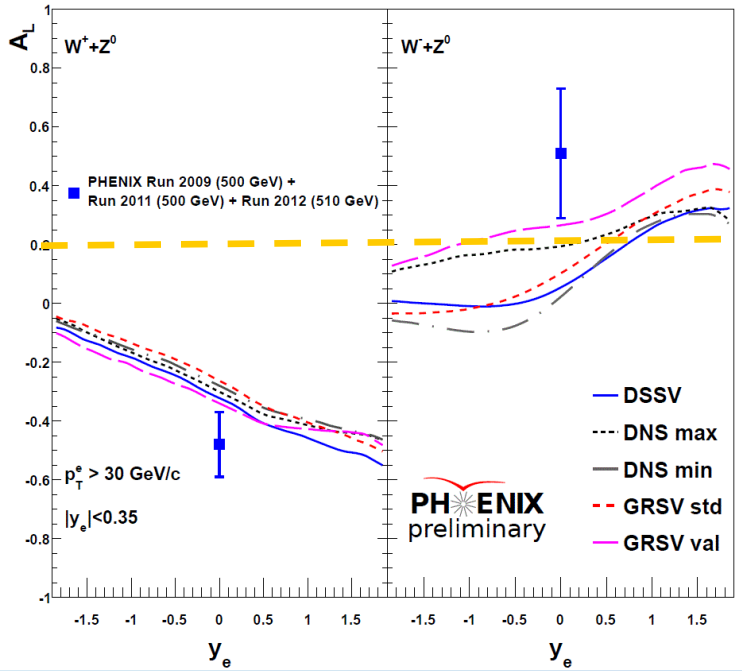
- Correcting acceptance and efficiencies one can obtain the absolute W/Z cross sections:
- Excellent agreement of the scale dependence from RHIC to LHC

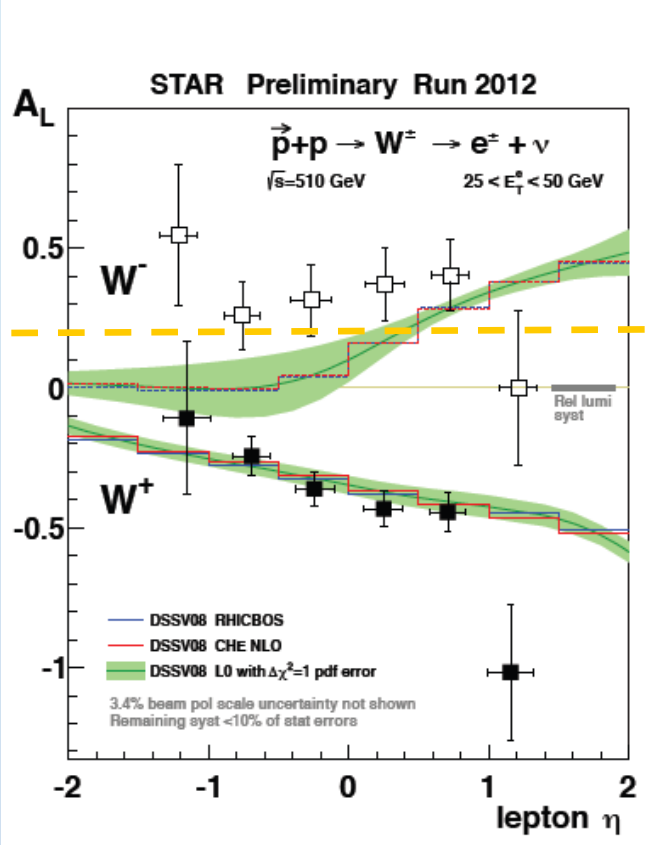




PRL 106:062001(2011)
PRD 85 (2012) 092010

Central W asymmetries





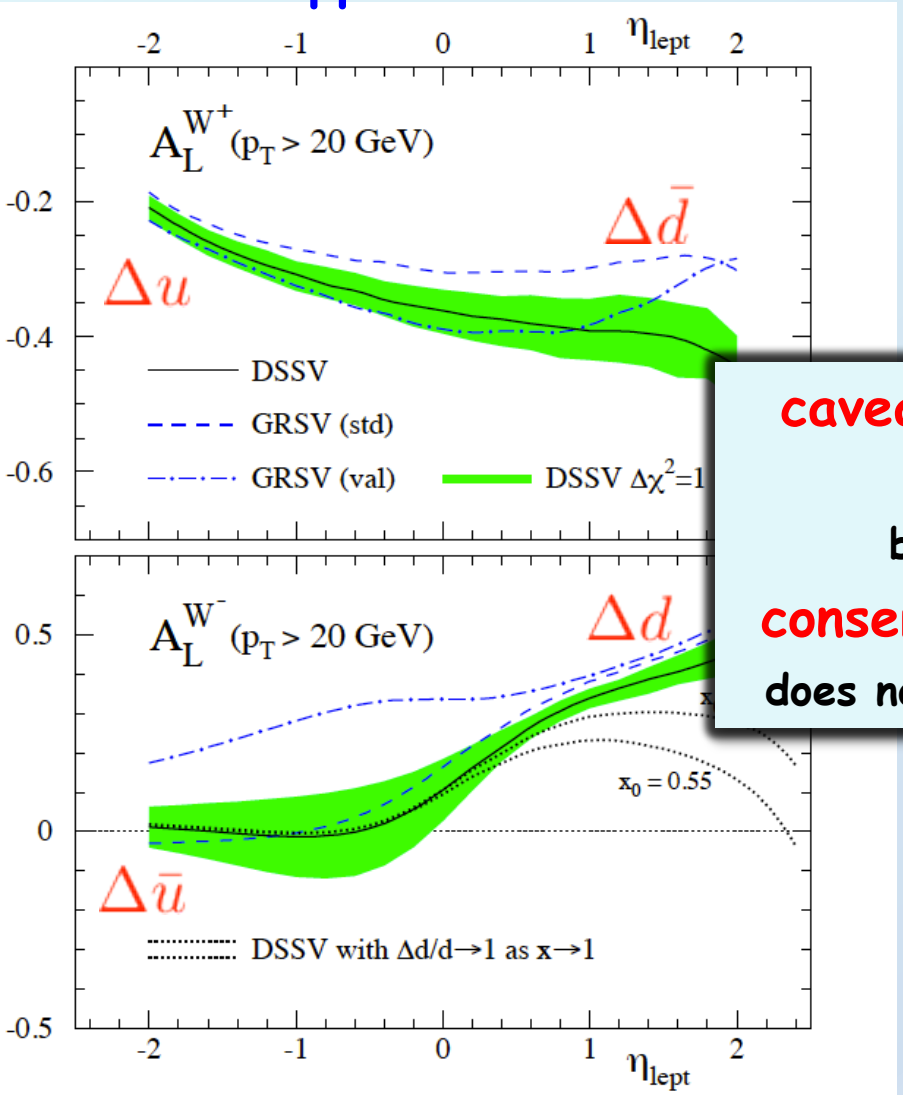
Stevens, arXiv:1302.6639

Indication of $\bar{u}$ quark helicity larger than DSSV, $\bar{d}$ slightly smaller

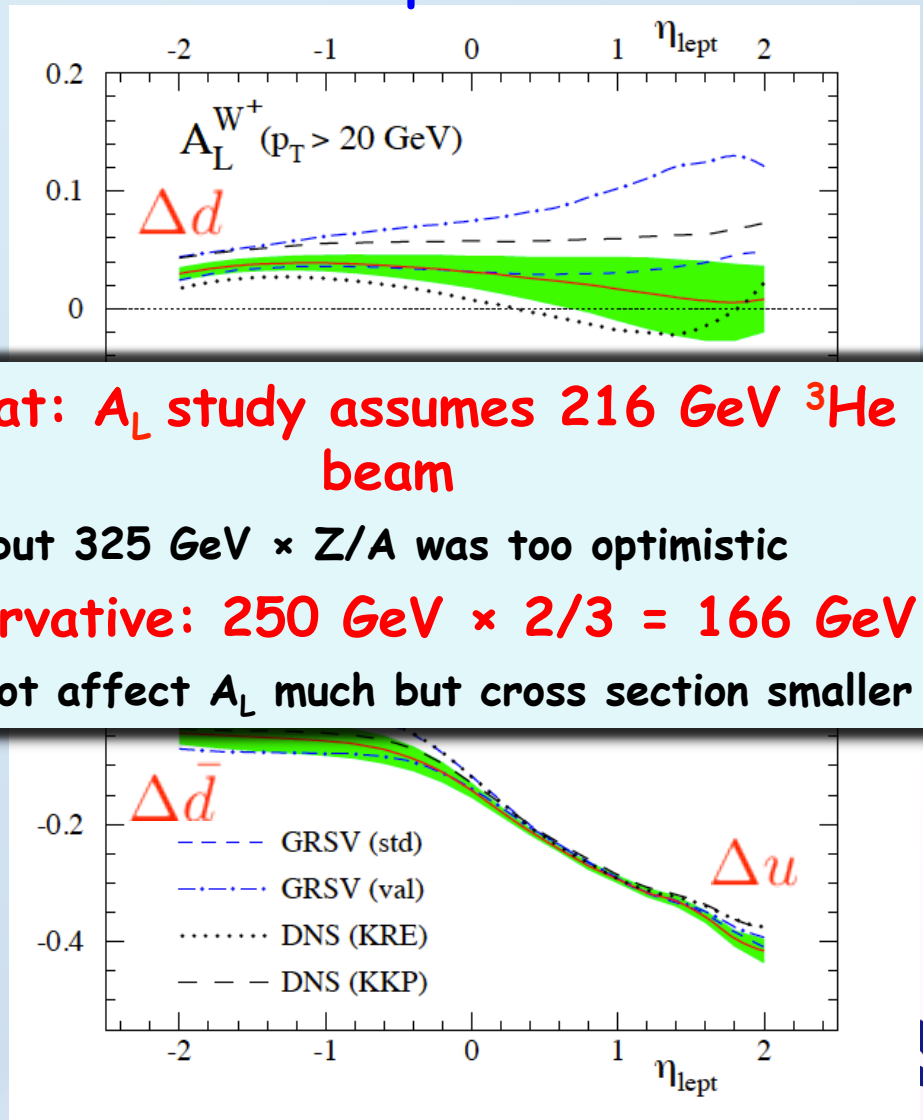
W Outlook ^{3}He p collisions

Marco Stratman (BNL)

pp @ 500 GeV



^{3}He p @ 432 GeV



caveat: A_L study assumes 216 GeV ^{3}He beam

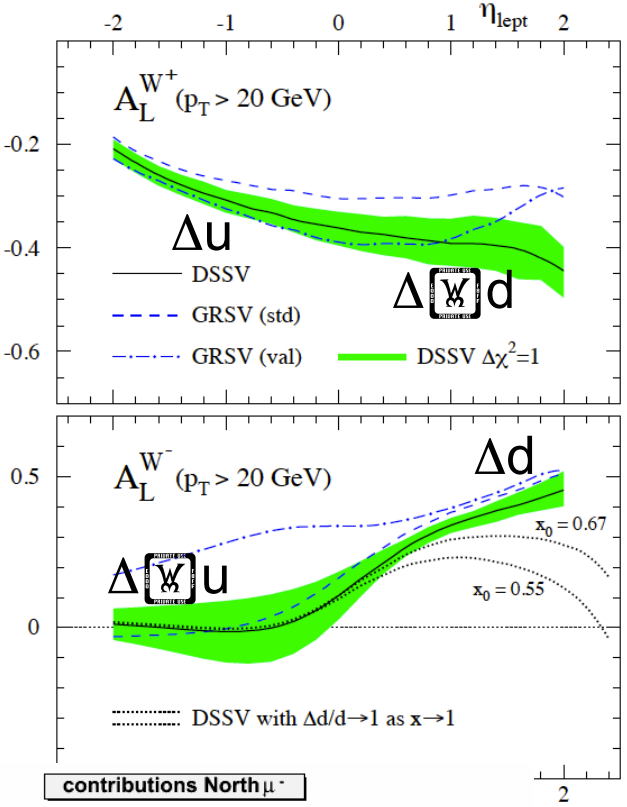
but 325 GeV × Z/A was too optimistic

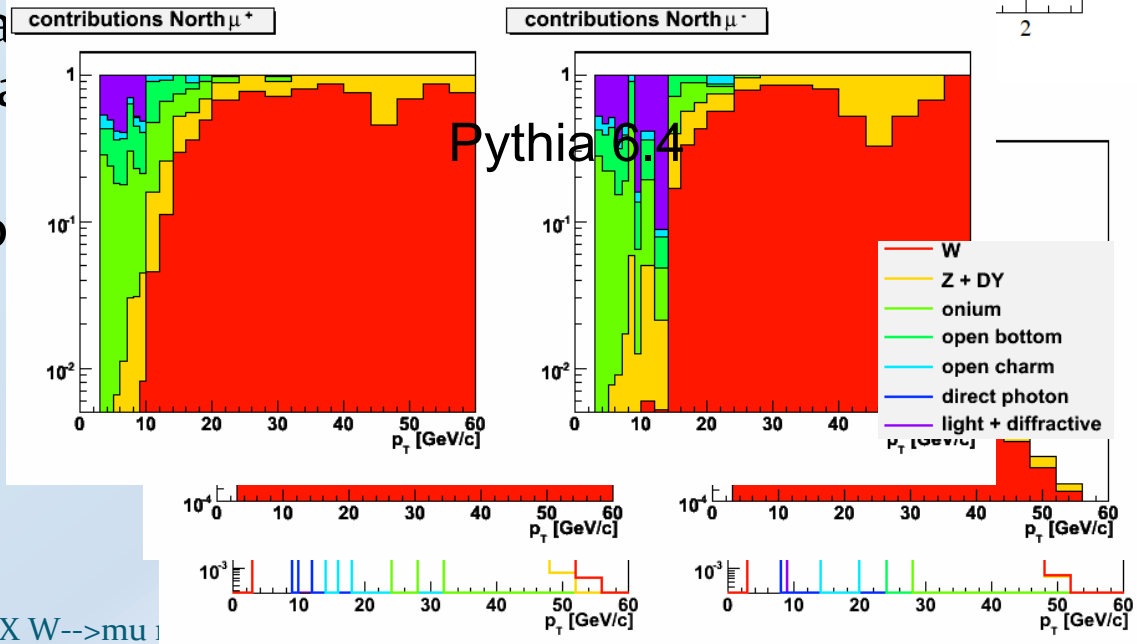
conservative: 250 GeV × 2/3 = 166 GeV

does not affect A_L much but cross section smaller

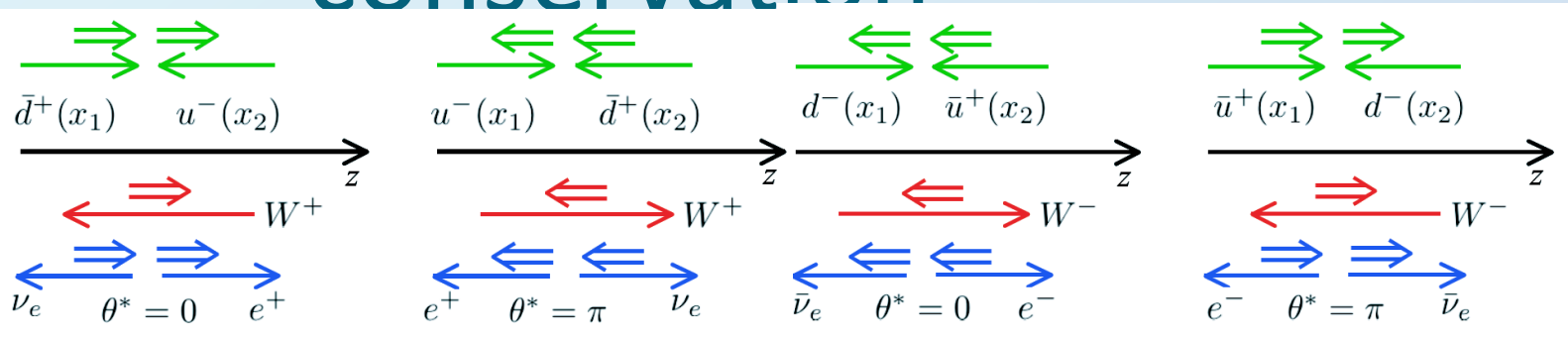
Forward W decays

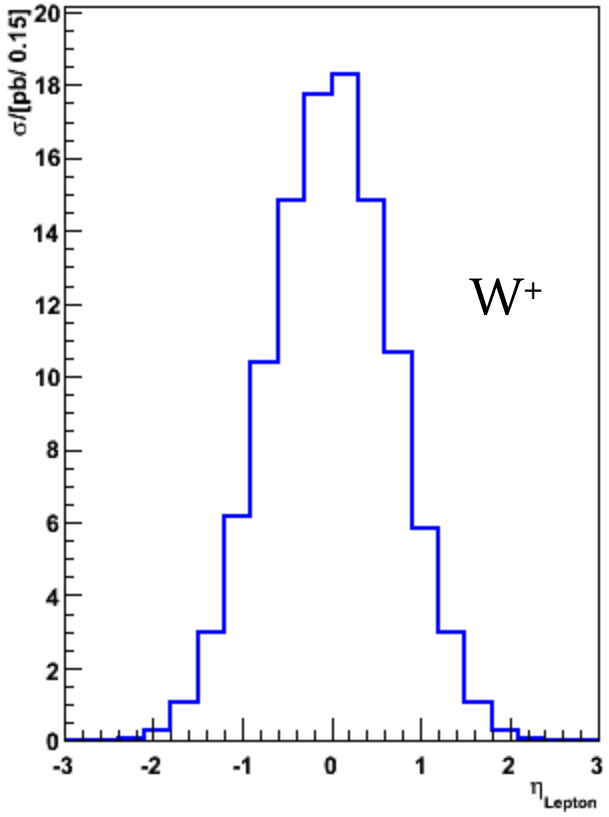
- Forward W decays advantages:
  - largest sensitivity to the anti-u quark polarization
  - some sensitivity to the anti-d quark polariza
    (due to decay kinema
  - With high statistics possibility to test d p
    sign change
- But no Jacobian peak, experimentally more difficult

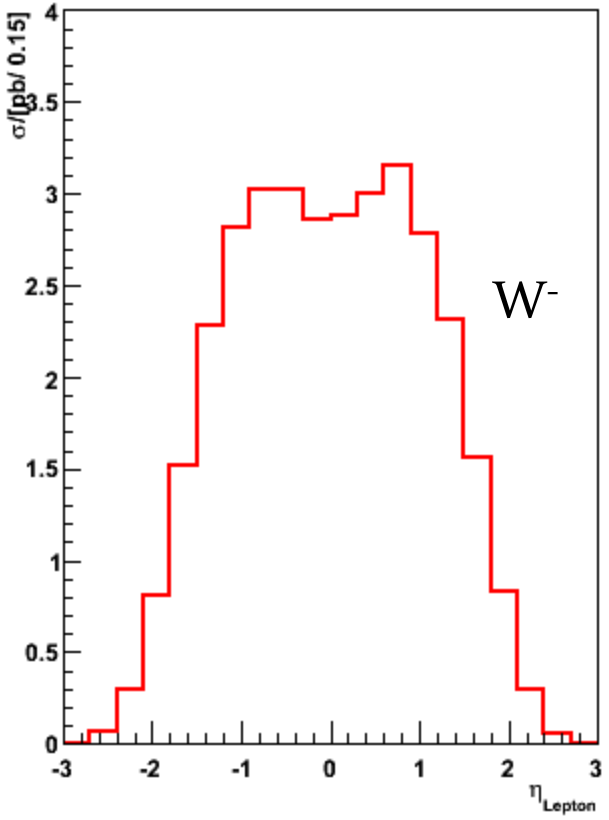




Decay kinematics due to helicity conservation

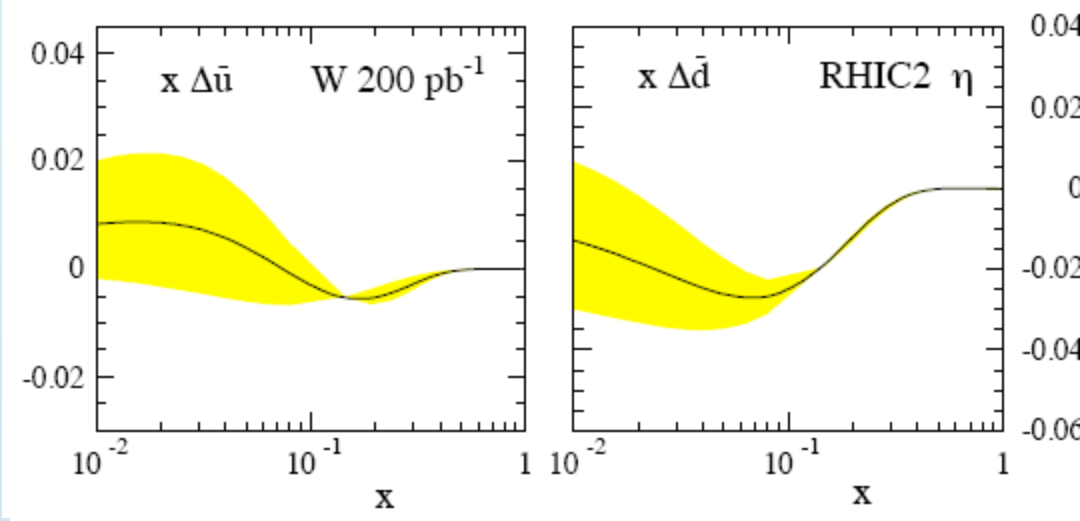






Expected sea quark sensitivities

- Inclusion of W channels into global analysis DSSV prepared
- Expected impact with about 200 pb^{-1} in PHENIX and STAR in $-2 < \eta < 2$ estimated



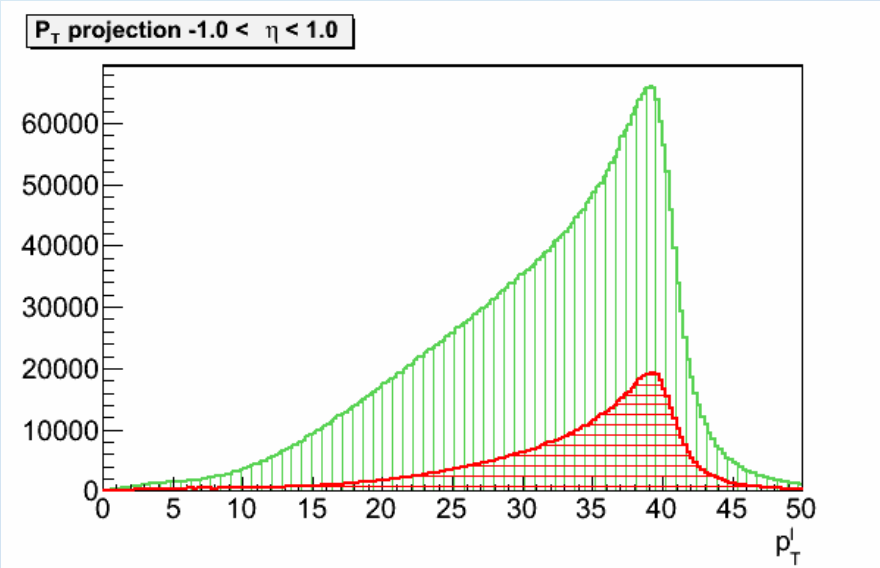
deFlorian, Vogelsang:
Phys.Rev. D81 (2010) 094020

- Reduction of uncertainties in sea quark polarizations of above x~0.1 substantial

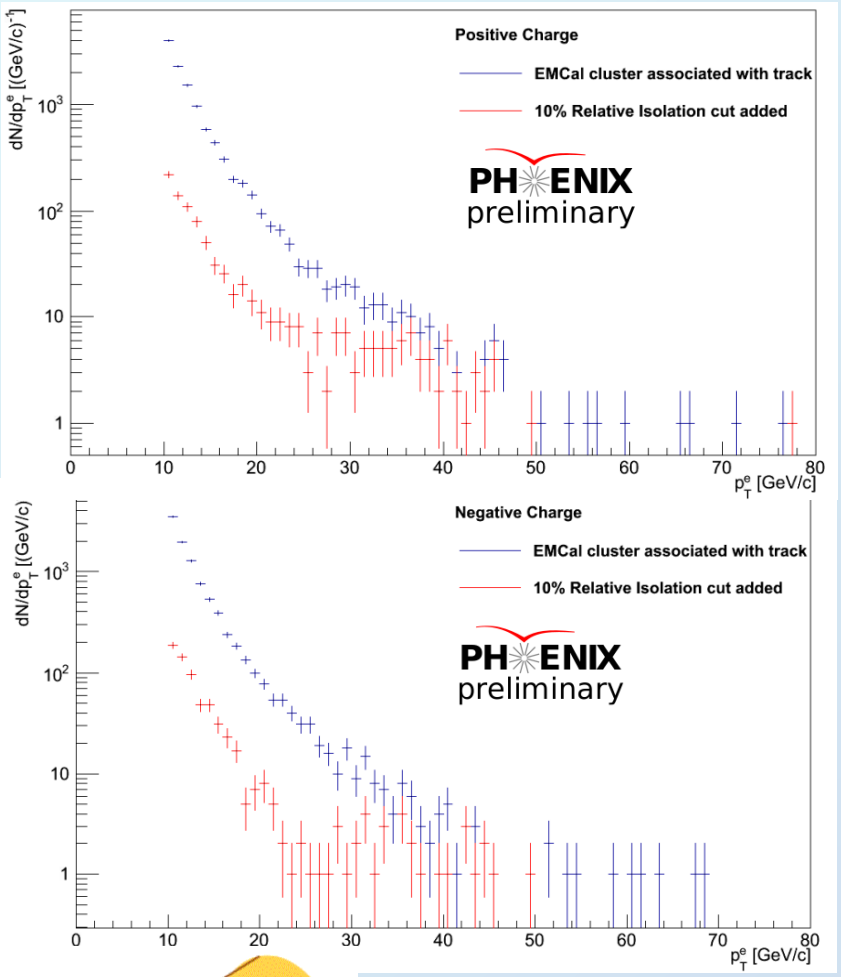
W→e
in central rapidities

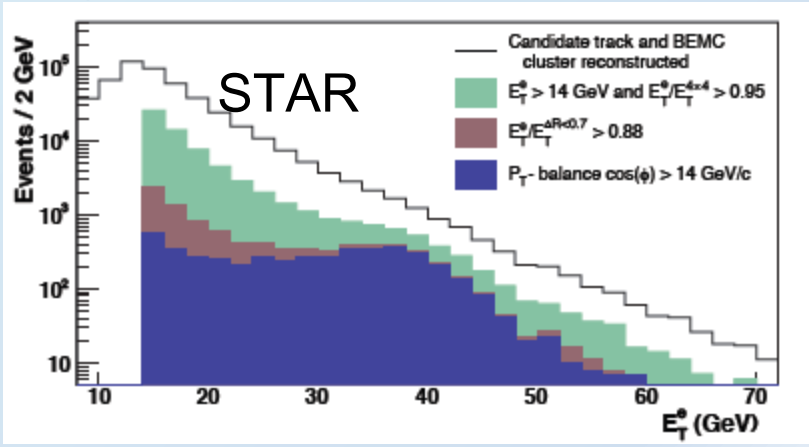
Central W analysis

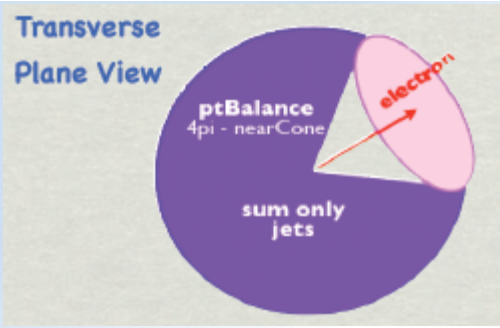
- General Strategy:
  - Find the Jacobian Peak (~0.5 M_W) in Energy or Pt spectrum for electrons
  - Clean up backgrounds by E/P and isolation criteria including away side (neutrino direction) if possible

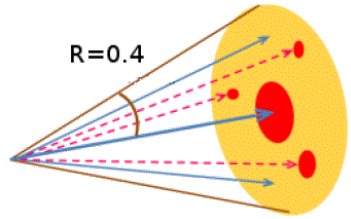


Raw electron yields



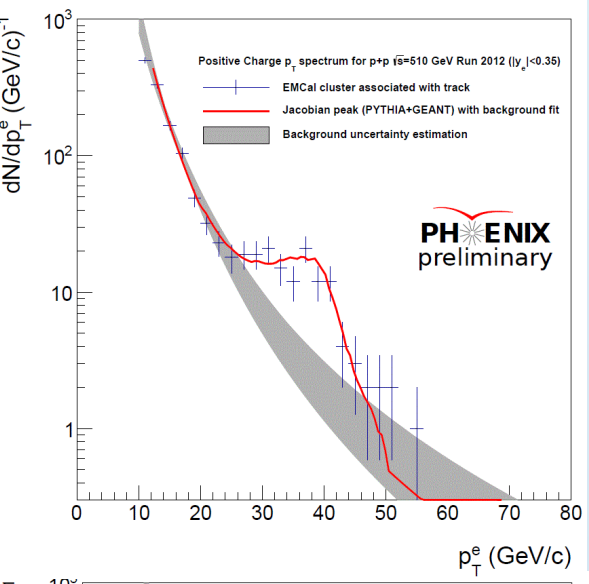


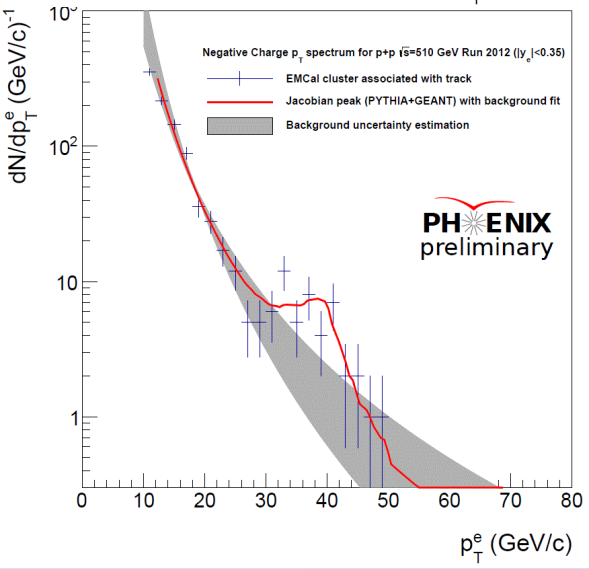


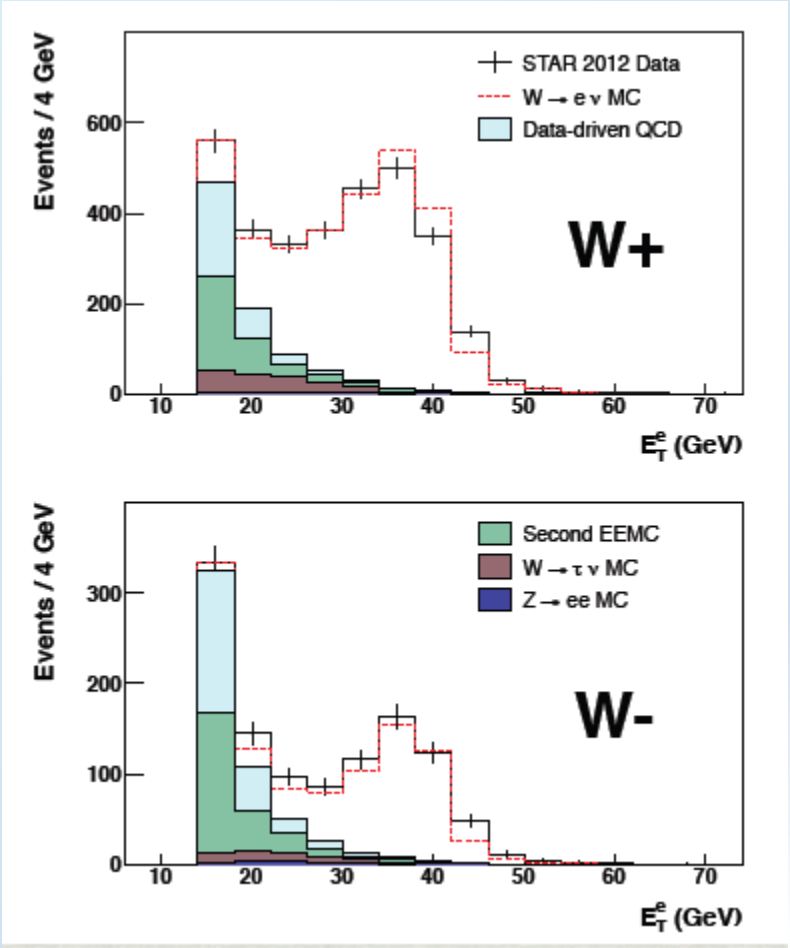


- Raw electron Pt or energy spectra and after successively applying shower shape and isolation selection criteria

Jacobian peaks and background fraction







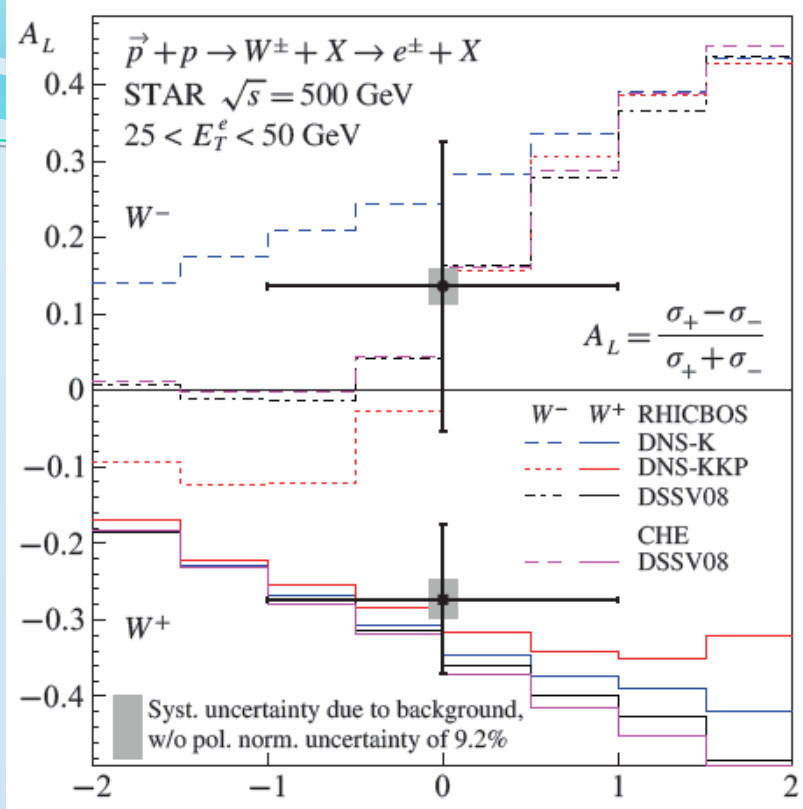
- After all cuts sizeable signals and little background remain

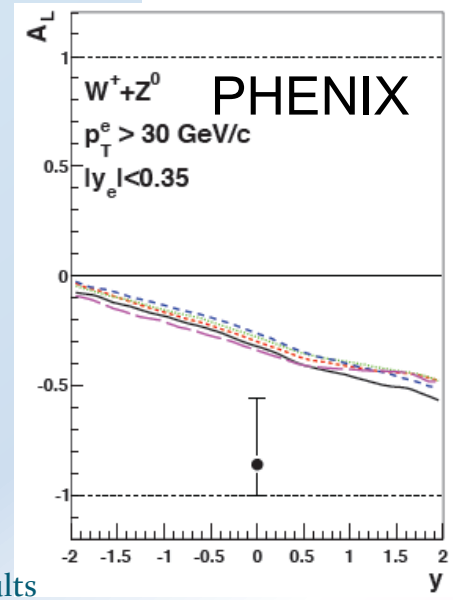
First W results

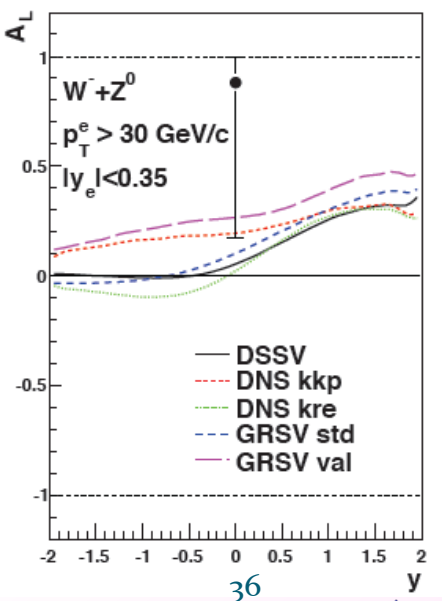
- In 2009: First exploratory RHIC run at 500 GeV
- Both, PHENIX and STAR obtained first central rapidity results,

  PRL 106:062001(2011)

  PRL 106:062002(2011)
- Real W production can be used to access the sea quark polarization!

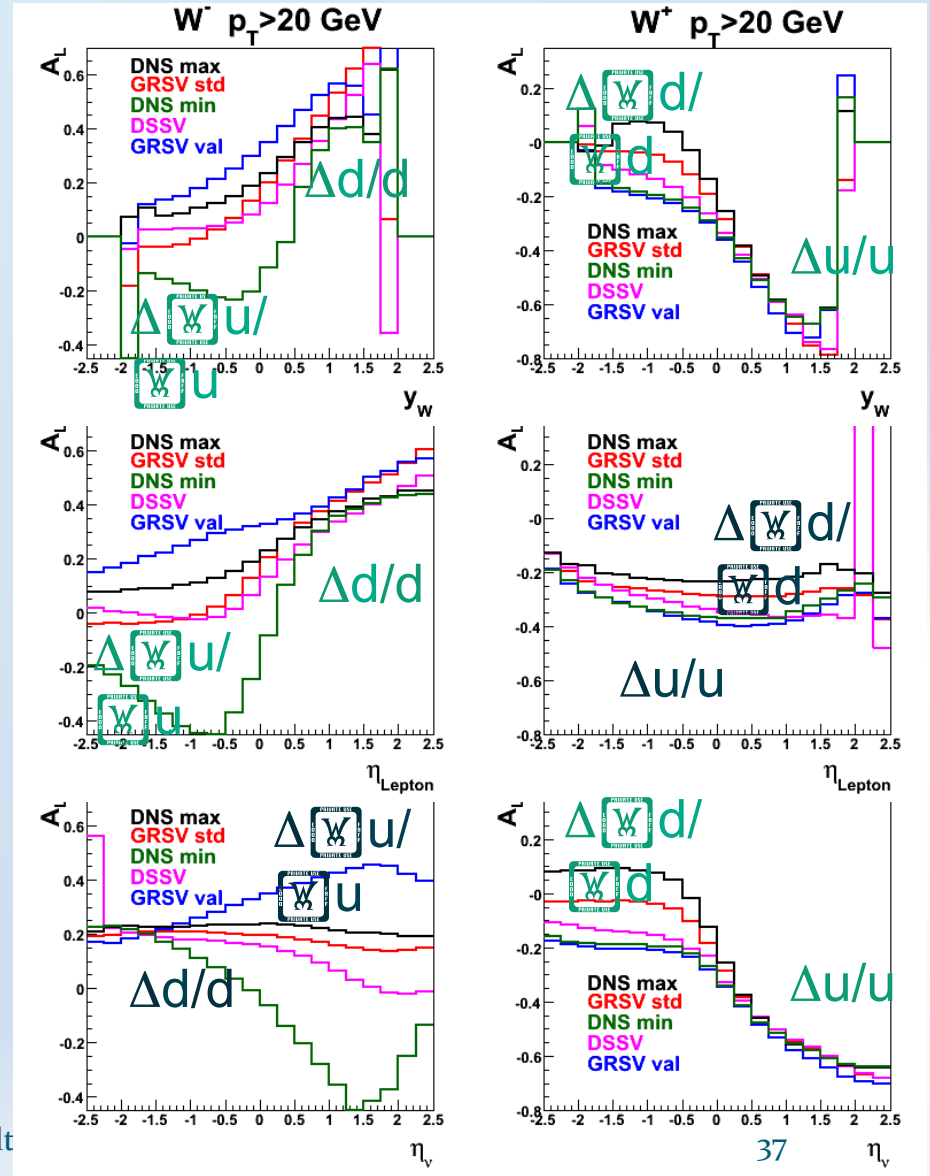






W vs lepton asymmetries

- Clear correlation for W: valence quark polarization→forward sea quark → backward
- However, not for decay muon/electron: enhanced for W^-, mixed for W^+
- reversed effect for neutrino asymmetry
- neutron target reverses that due to isospin asymmetry →run He3 collisions eventully?
- x is not affected by this; still forward is larger x, backward smaller x

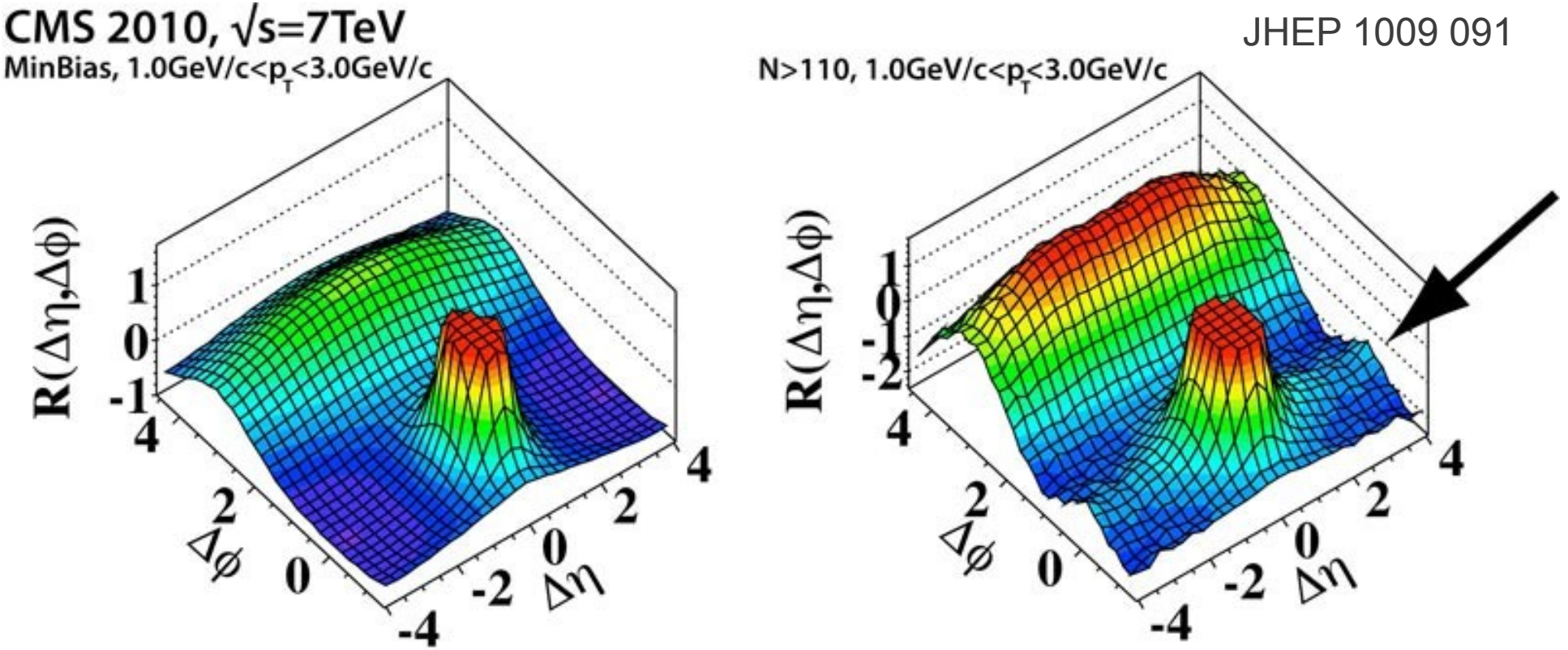


Studying the medium properties in dAu collisions via two-particle correlations

John Chin-Hao Chen

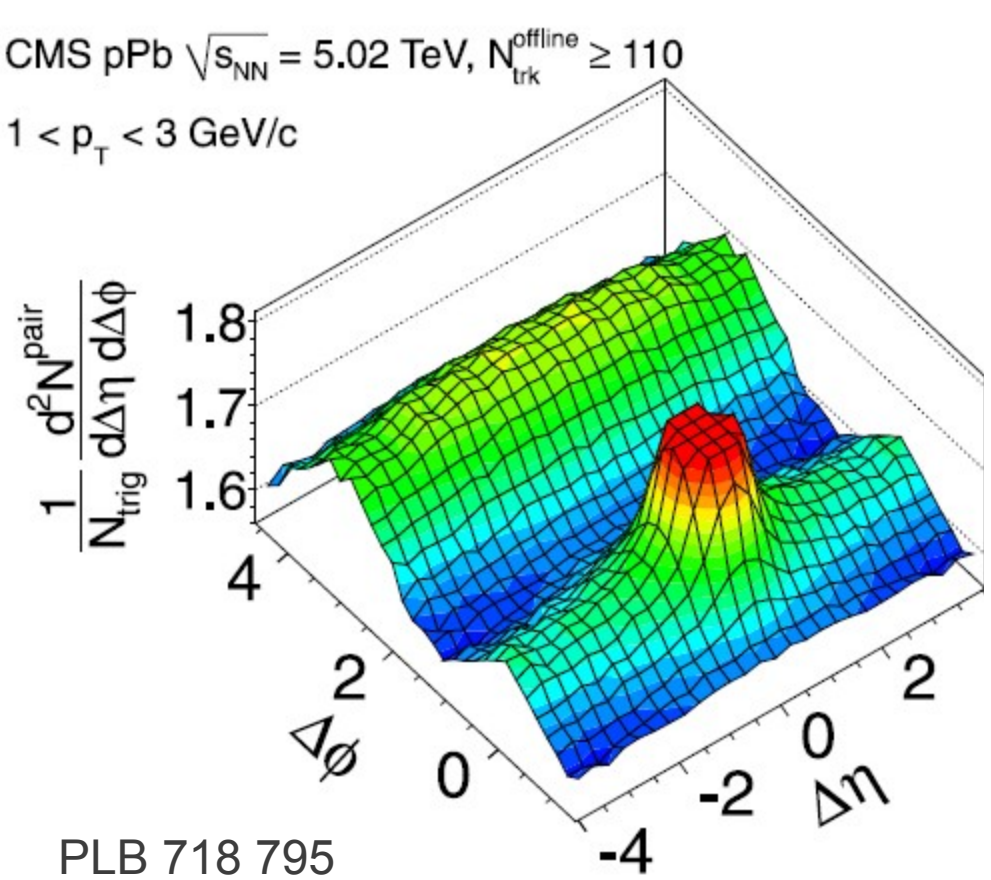
RBRC Scientific Review Meeting
2013/10/31

Surprising long range correlation in LHC

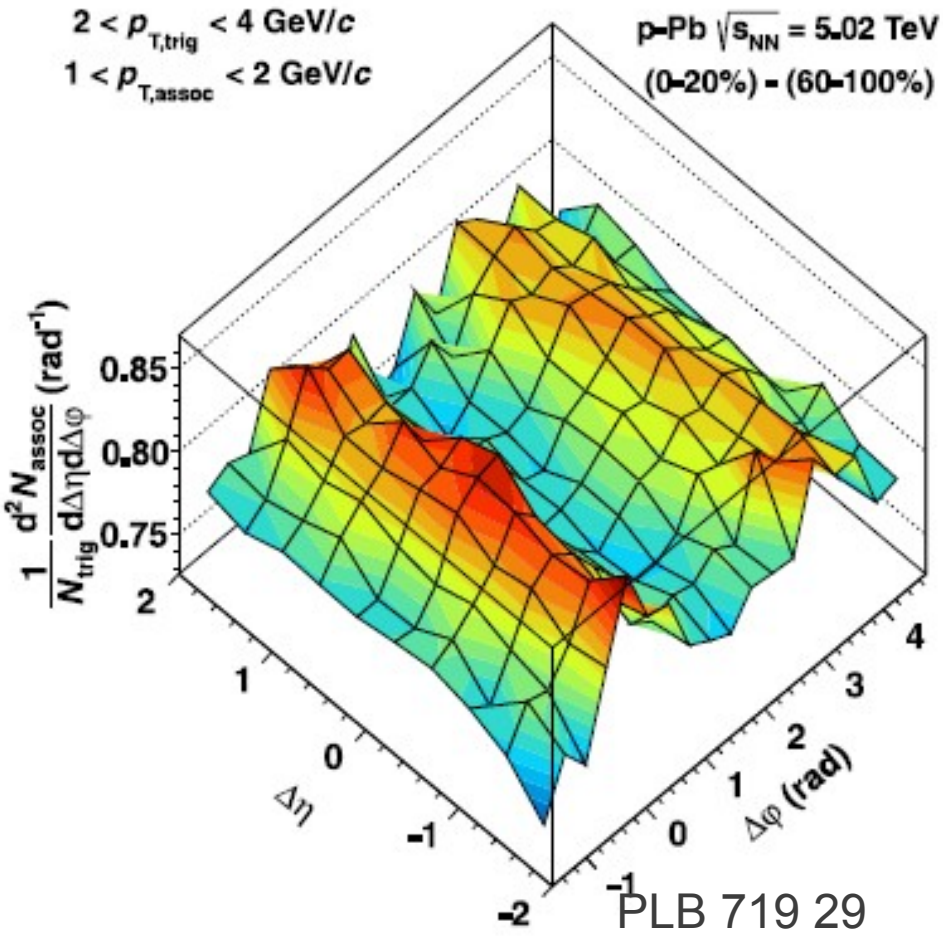


- In MinBias p+p, the correlation has a peak at $\Delta\phi \sim 0$
- A novel long range correlation along $\Delta\eta$ is found in high multiplicity p+p collisions at LHC

Long range correlation in p+Pb!



PLB 718 795



PLB 719 29

- Ridge also appears at high multiplicity p+Pb collisions
- The ridge looks like a v_2 structure

Why so surprising?

- Ridge in heavy ion is thought to be due to the v_3 harmonic coefficient of the collective flow
- p+p and p+Pb are originally thought as a relatively simple system, and no QGP should be formed.
- But in high multiplicity events, the correlation function looks similar to heavy ion case

- Is QGP formed in these small system?
- Can we see similar effect in d+Au at RHIC?

Why d+Au at RHIC is interesting?

- A relatively simple system compare to Au+Au
- A slightly more complicated system than p+Pb
- A much lower energy than LHC (0.2 TeV vs 5.02 TeV)

- Can we see v_2 in d+Au?
- Can we see ridge in d+Au?

Lessons from previous experience

- From the experience of LHC:
  - We need to select high multiplicity events
- From measuring v_2 in Au+Au collisions:
  - The medium in d+Au is thin, the non-flow contribution is strong
  - Need to remove the non-flow contribution as cleanly as possible

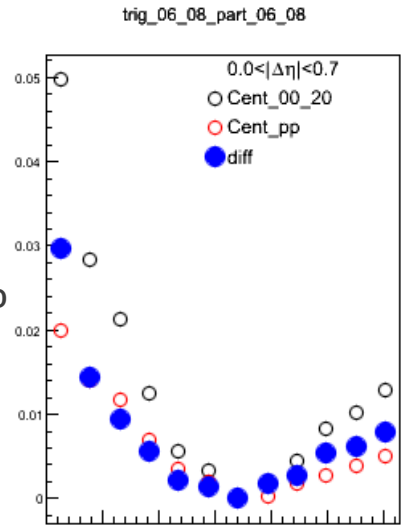
Measuring d+Au v_2 in mid-rapidity

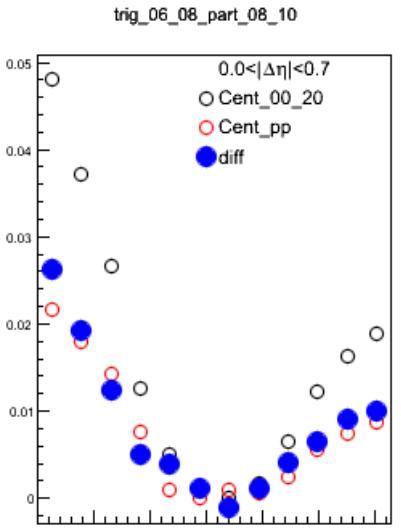
- Use two-particle correlation method
  - Both particles fall in central arm acceptance ($|\eta|<0.35$)
  - Fixed the p_T of the trigger particle, varying the p_T of the partner particle
  - Various $\Delta\eta$ range (0-0.7, 0.3-0.7, 0.5-0.7)
  - Various centralities (0-20, 20-40, 40-60, 60-88%)
- Use p+p collisions as a proxy for non-flow contributions
- After subtracting the non-flow contribution, extract the Fourier coefficients
  $CF(\Delta\phi) = b0(1+\Sigma C_n \cos(n\Delta\phi))$
- By assuming the C_n is factorizable, which is $C_n = v_n^{trig} * v_n^{part}$, we can extract the v_n of a series of partner p_T.

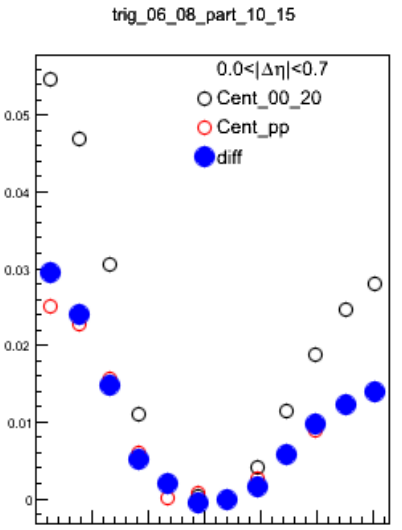
Correlation functions in dAu

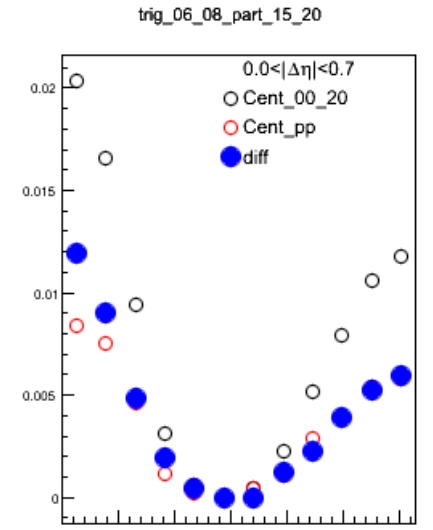
0.6-0.8x0.6-0.8 0.6-0.8x0.8-1.0 0.6-0.8x1.0-1.5 0.6-0.8x1.5-2.0

0-20%

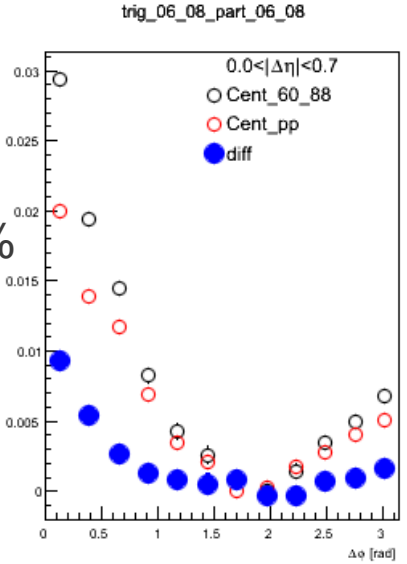


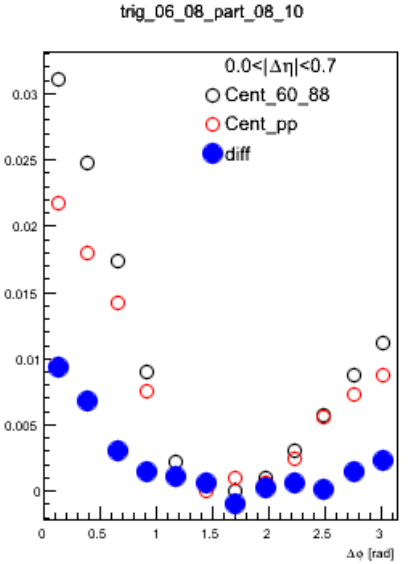


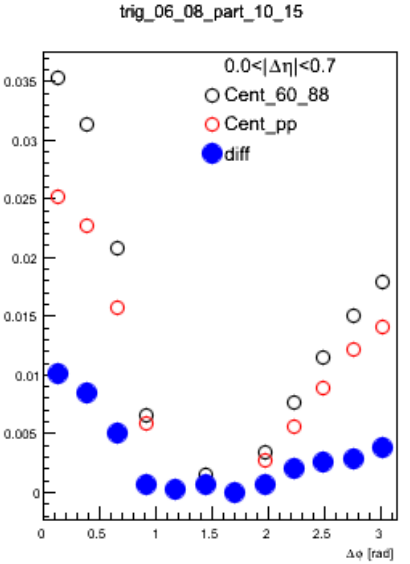


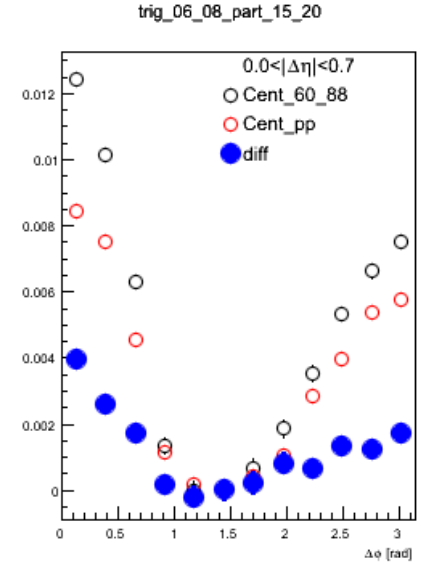


60-88%





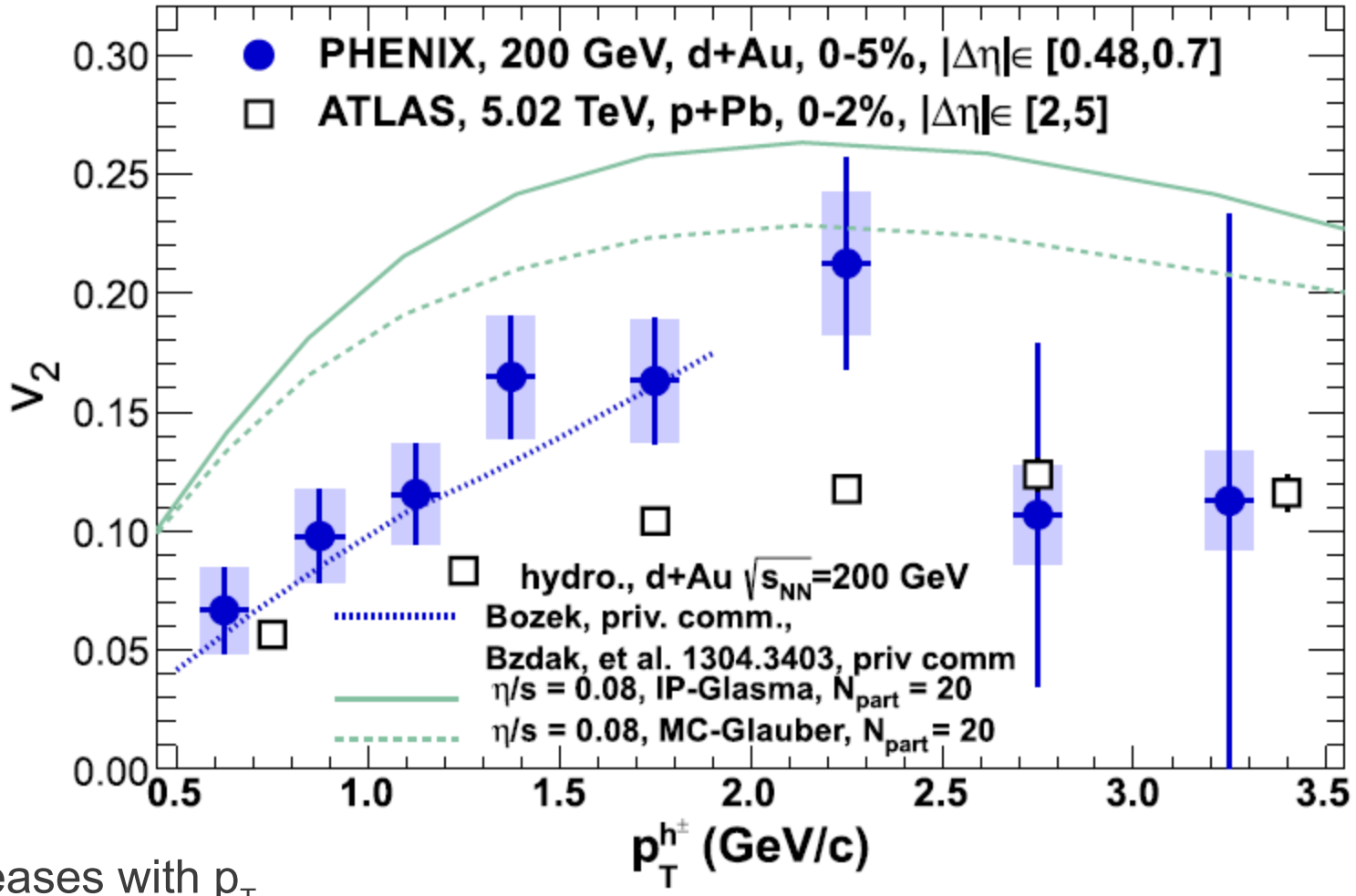




Even in most peripheral d+Au, the shape of the jet function is not the same as p+p

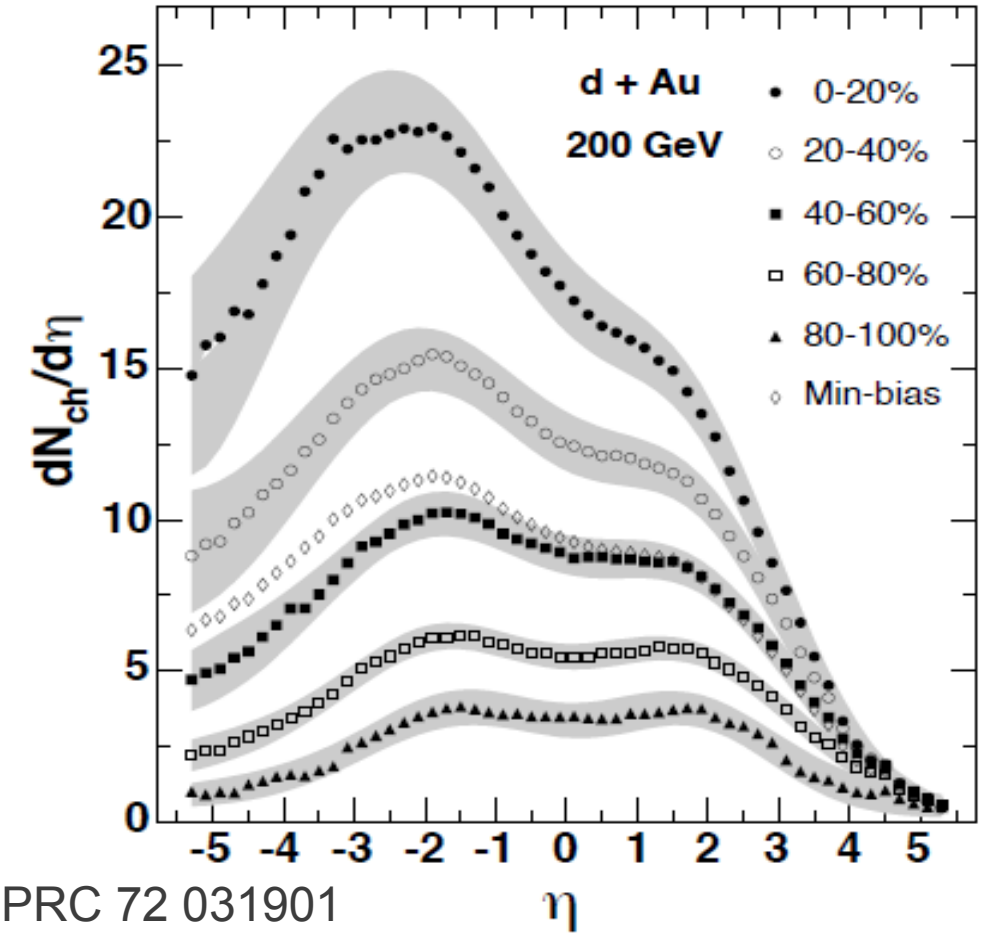
ArXiv:1303.1794
accepted by PRL

v_2 vs p_T



- v_2 increases with p_T
- v_2 in d+Au agrees well with hydro calculations up to 2 GeV
- v_2 in d+Au (@200 GeV) > v_2 in p+Pb (@ 5.02 TeV)

Central-forward (backward) long range correlation



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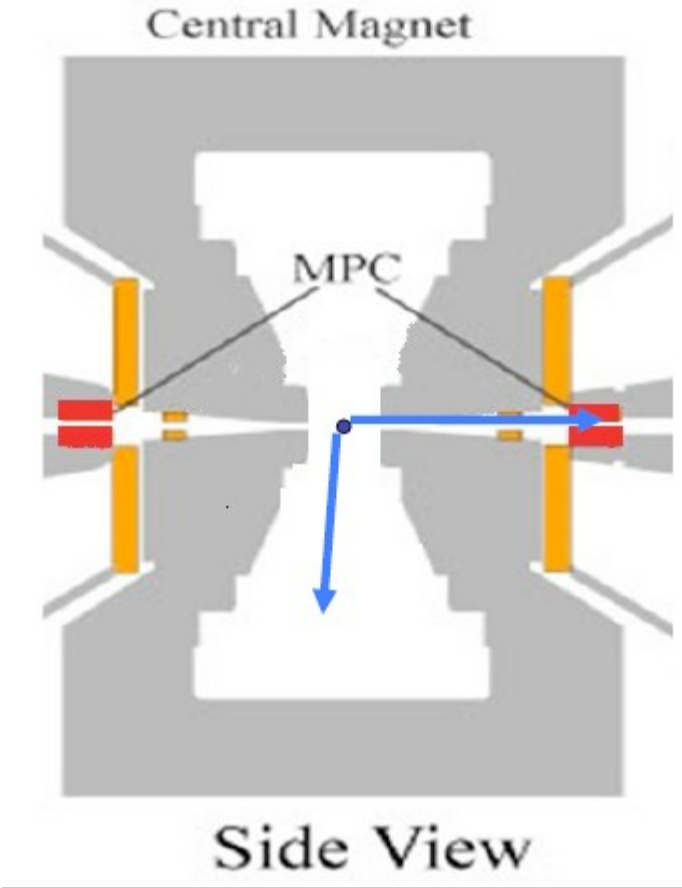
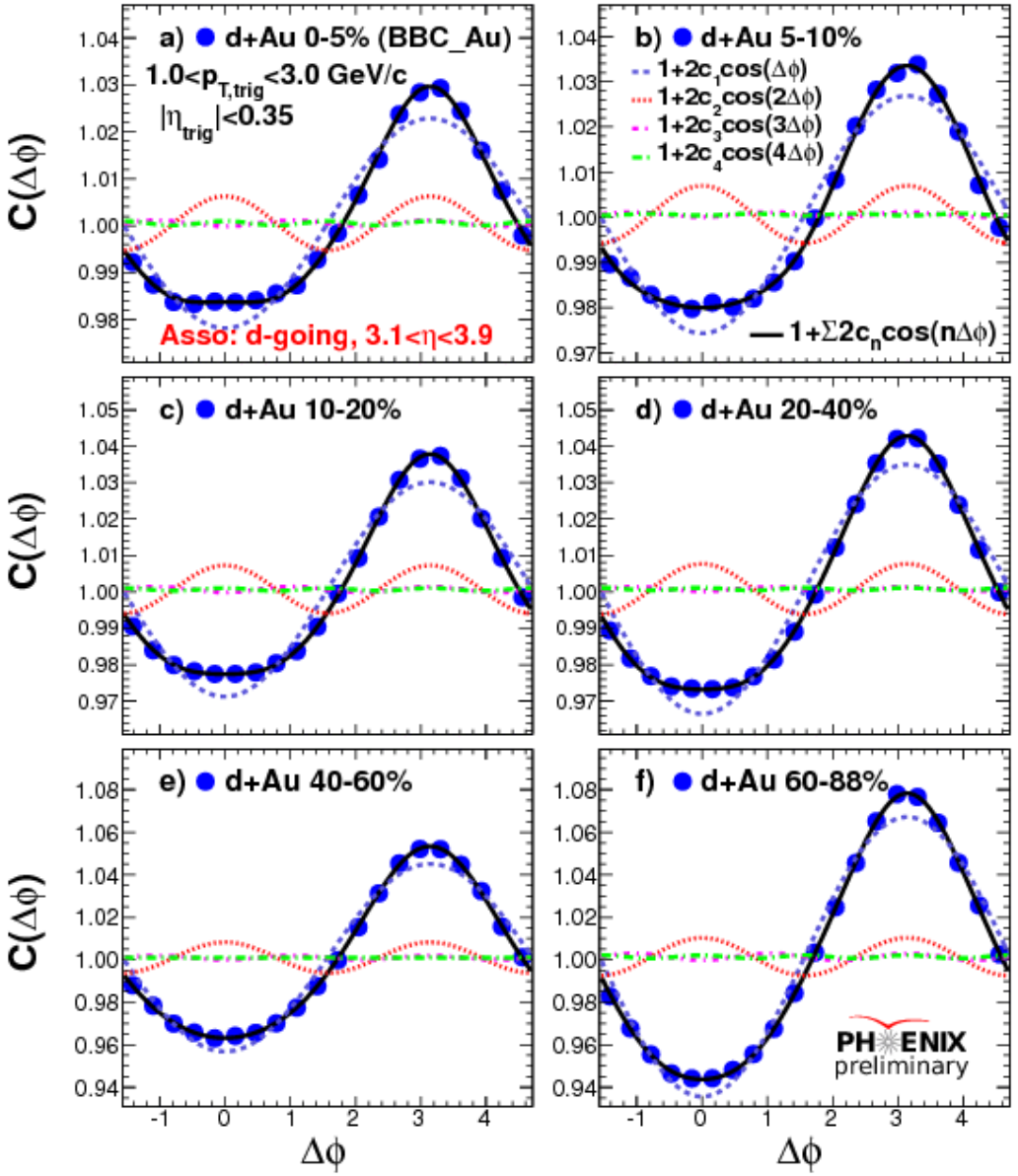


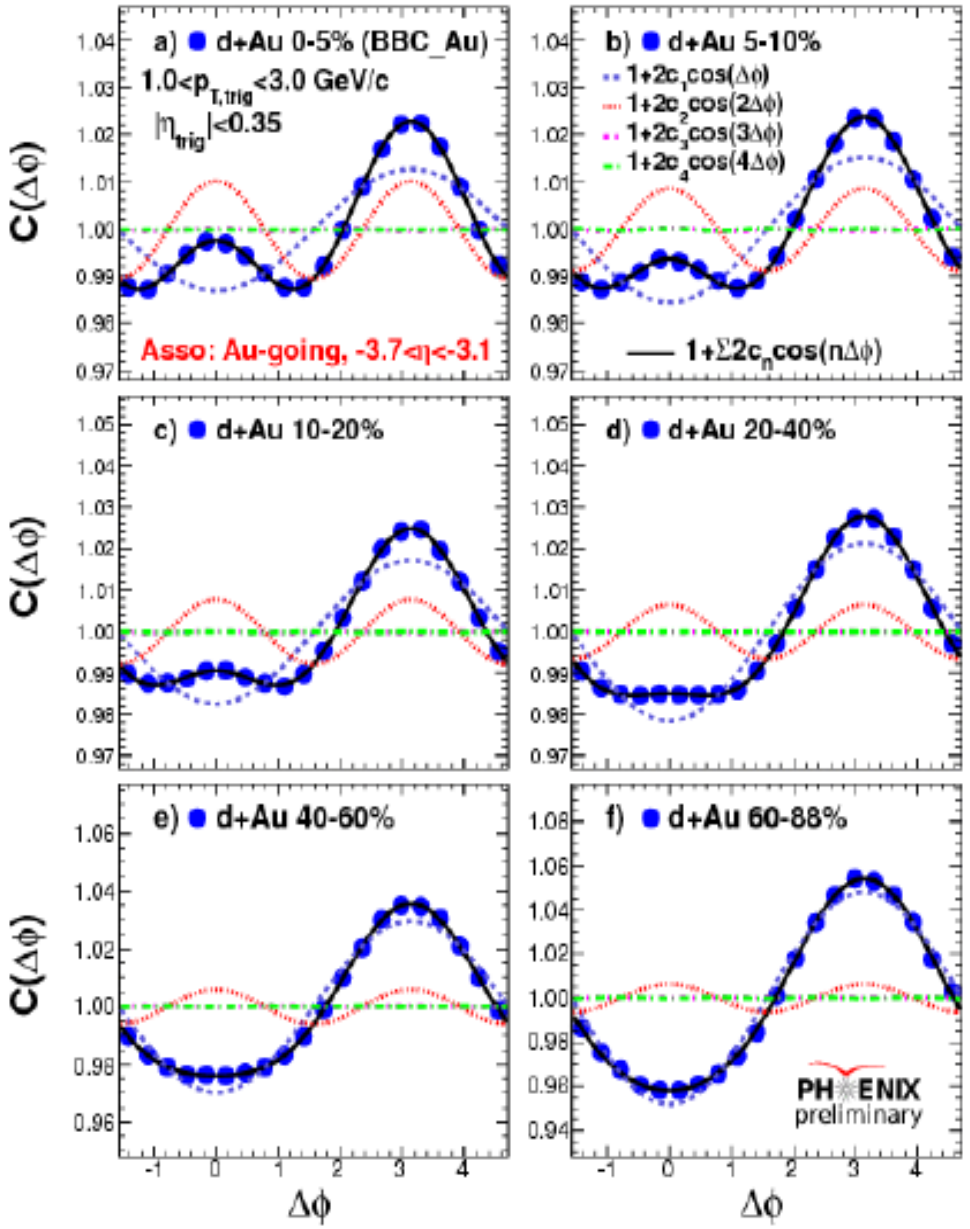
- The multiplicity distributions in d+Au collisions are asymmetric
- Measure the two-particle correlations of one particle at mid-rapidity (with central arm spectrometer, |eta|<0.35) and another particle at forward calorimeter (with Muon Piston Calorimeter, 3.1<|η|<3.9)

Central-forward (d-going side)



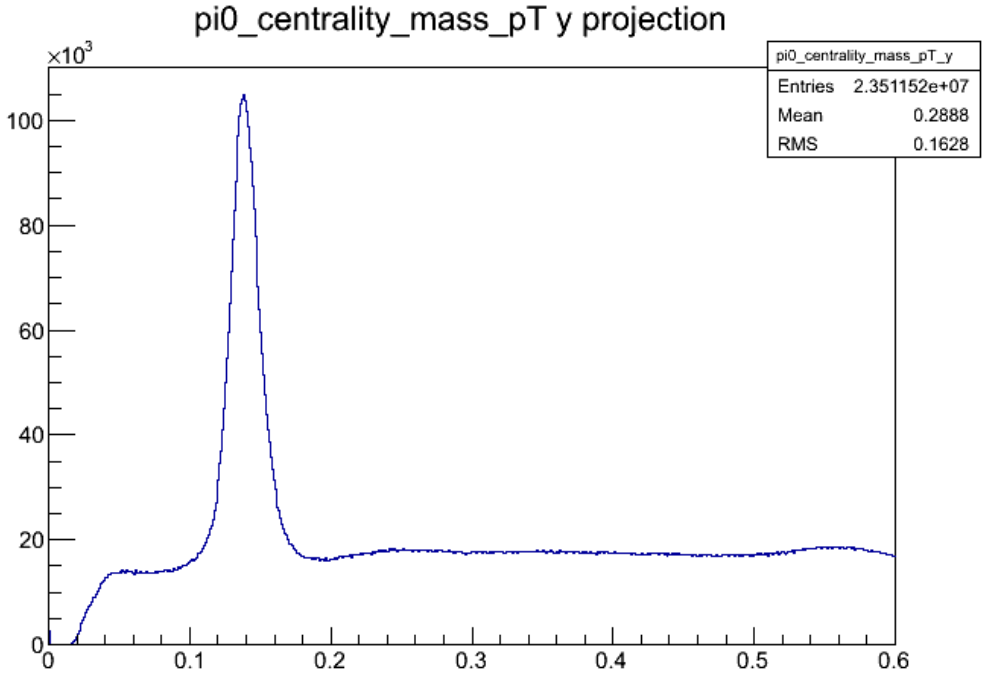
- When correlated with d-going side, there is no local maximum in correlations at $\Delta\phi$ ~0
- The correlation is dominate by c_1 contribution

Central-backward (Au-going side)



- When correlated with Au-going side, there is significant correlations at $\Delta\phi \sim 0$
- The nearside correlation decreases when moving to peripheral d+Au collisions
- c_1 and c_2 are comparable in central d+Au collisions

π^0-MPC correlation



- In order to enhance the p_T reach in mid-rapidity, π^0s are reconstructed in central arm.
- Use ERT triggered data to enhance statistics
- Nice π^0 peak
- Remove the background by sideband subtraction
- Analysis is on going

Summary

- Novel ridge structure in p+p and p+Pb at LHC is surprising and stirs interests in d+Au at RHIC
- Detailed studies of v_2 and ridge in d+Au is in progress
- Differential v_2 of d+Au as a function of centrality and p_T is under study
- The long range correlation to study the ridge in d+Au is pushed to highest possible p_T by triggering on reconstructed π^0.

Operation and Current Status of Silicon Pixel Detector

Maki KUROSAWA



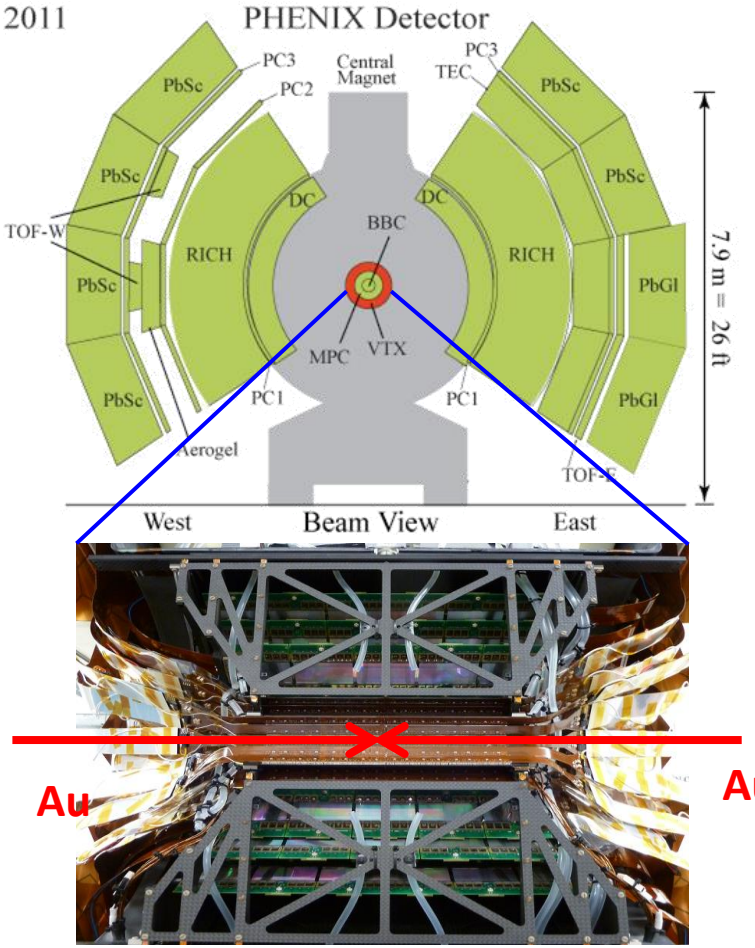
Outline of Talk

1. Introduction
2. Operation Status of VTX at Run13
3. Repair of Pixel Modules
4. Current Status of VTX to Run14
5. Hot Dead Map for VTX
6. Summary

1. Introduction

- **Physics motivation to measure heavy flavor**
  - Initial state of QGP.
  - Detail study of QGP due to large mass.

- **Silicon vertex tracker (VTX) upgrade for PHENIX**
  - Heavy flavor tagging
    - ✓ spatial resolution → σ ~ 77μm
    - ✓ Large acceptance → $|\eta| < 1.2$, $\Delta\phi \sim 2\pi$

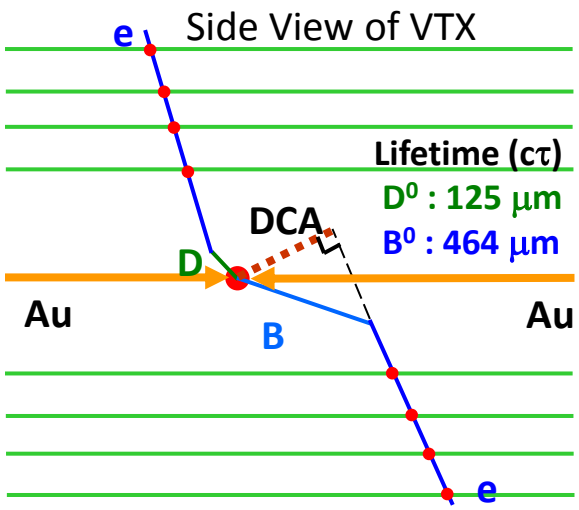


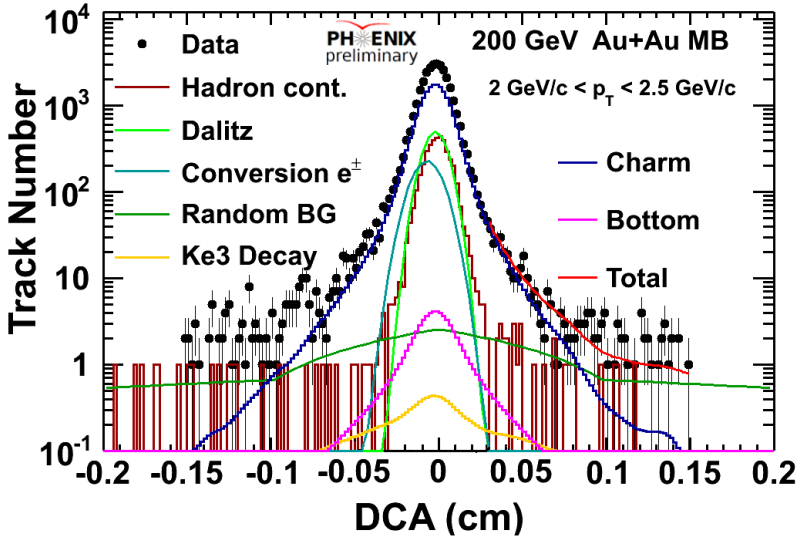
- **Physics observables with VTX**
  - Nuclear modification factor for heavy flavor R_{AA}
  - Azimuthal anisotropy for heavy flavor

Physics Analysis (Run-11 Data)

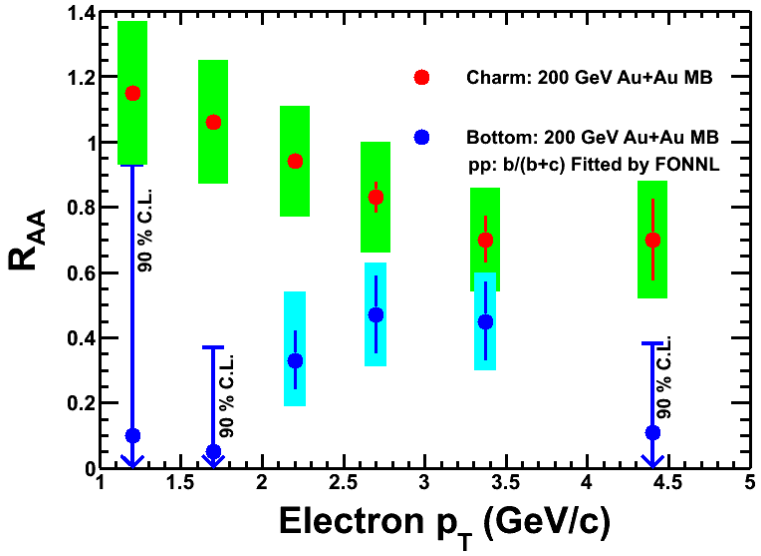
DCA decomposition of charm and bottom

- D and B mesons travel before semi-leptonic decay to electron.

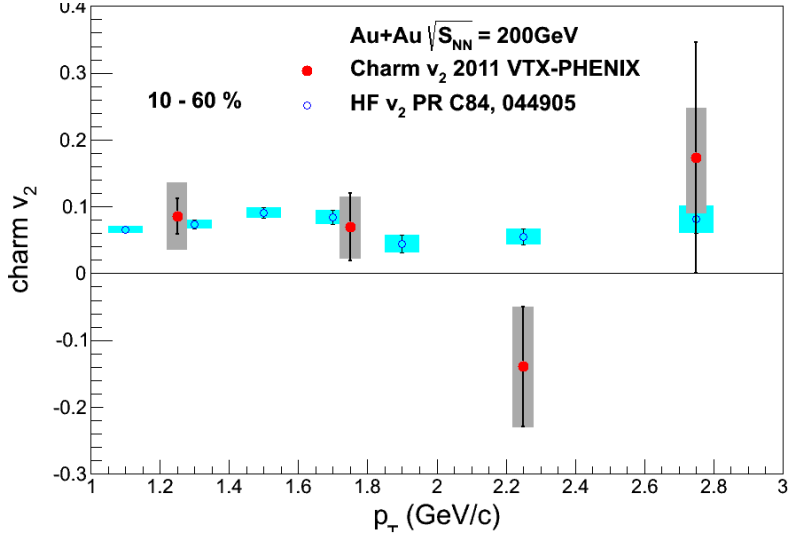




pT dependence of modification factor R_{AA}



pT dependence of v_2 for electron from charm decay



2. Operation Status in Run-12 and Run-13

- In Run-11, two issues for pixel detector were found.
  - **Defects of bump bonds** (All pixel cells of readout chip were bump-bonded to silicon sensor). → Not fixable
  - Some **bonding wires were broken** due to difference of thermal coefficient between encapsulation and readout bus. → Fixable
  - Those issues were happened by **thermal stress** and material type of the encapsulation.

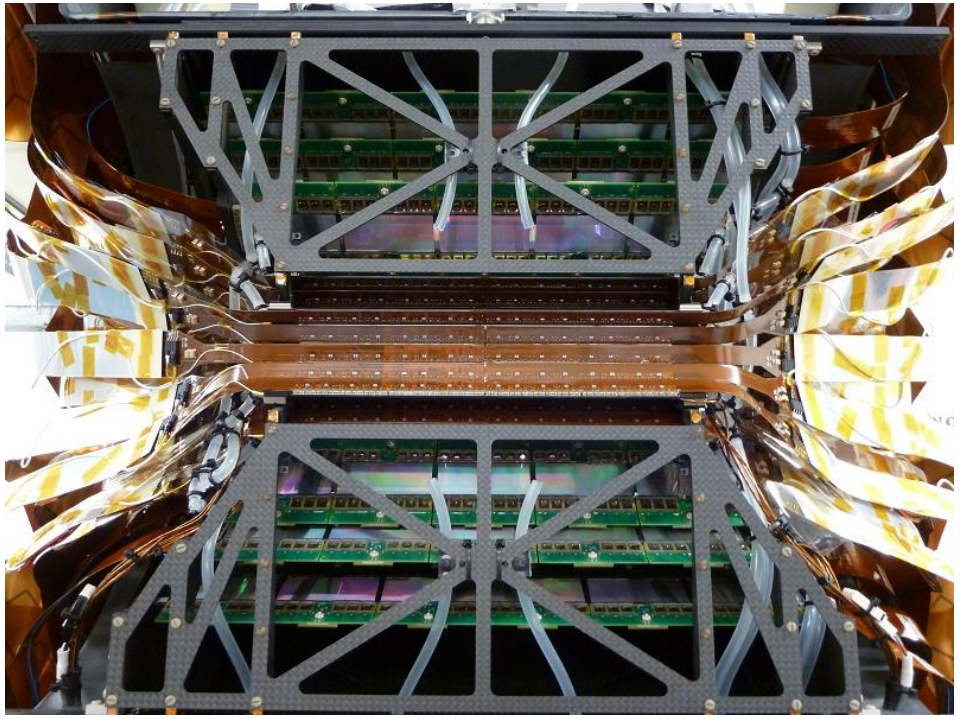
- Solutions
  - Change of operation temperature from 0 to 20 degrees.
  - Use of the different type of encapsulation.

Run	Operation Temp (degree)	Encapsulation (WEST)	Encapsulation (EAST)
Run-11	0	Old	Old
Run-12	20	New (for few modules)	Old
Run-13	20	New	Removed for repair

After changing of operation temperature, no additional dead area was found.

Issues in Run-13

- Only WEST pixel barrel was operated in Run-13.
  - EAST barrel was removed due to the leak issues of strip layers.
  - WEST strip barrel was remained at IR but not operated.



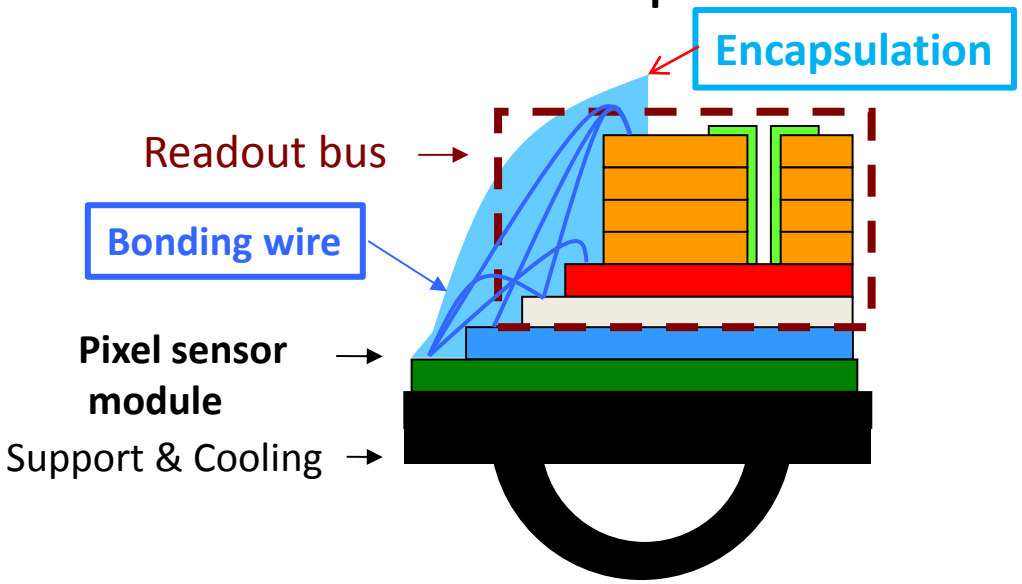
- At this timing, EAST pixel ladders were sent back to assembly company (Hayashi Tokei) to repair them.
  - Several readout chips were not working due to bonding wire issue.
  - **Totally 15 pixel ladders were sent to Hayashi.**

3. Repair of Pixel Ladders

Silicon Pixel Ladder



Cross section of silicon pixel ladder



Repair Process

Remove encapsulation and bonding wires (Hayashi)

↓

wire bond (Hayashi)

↓

Electrical Test (RIKEN)

↓

Encapsulation (Hayashi)

↓

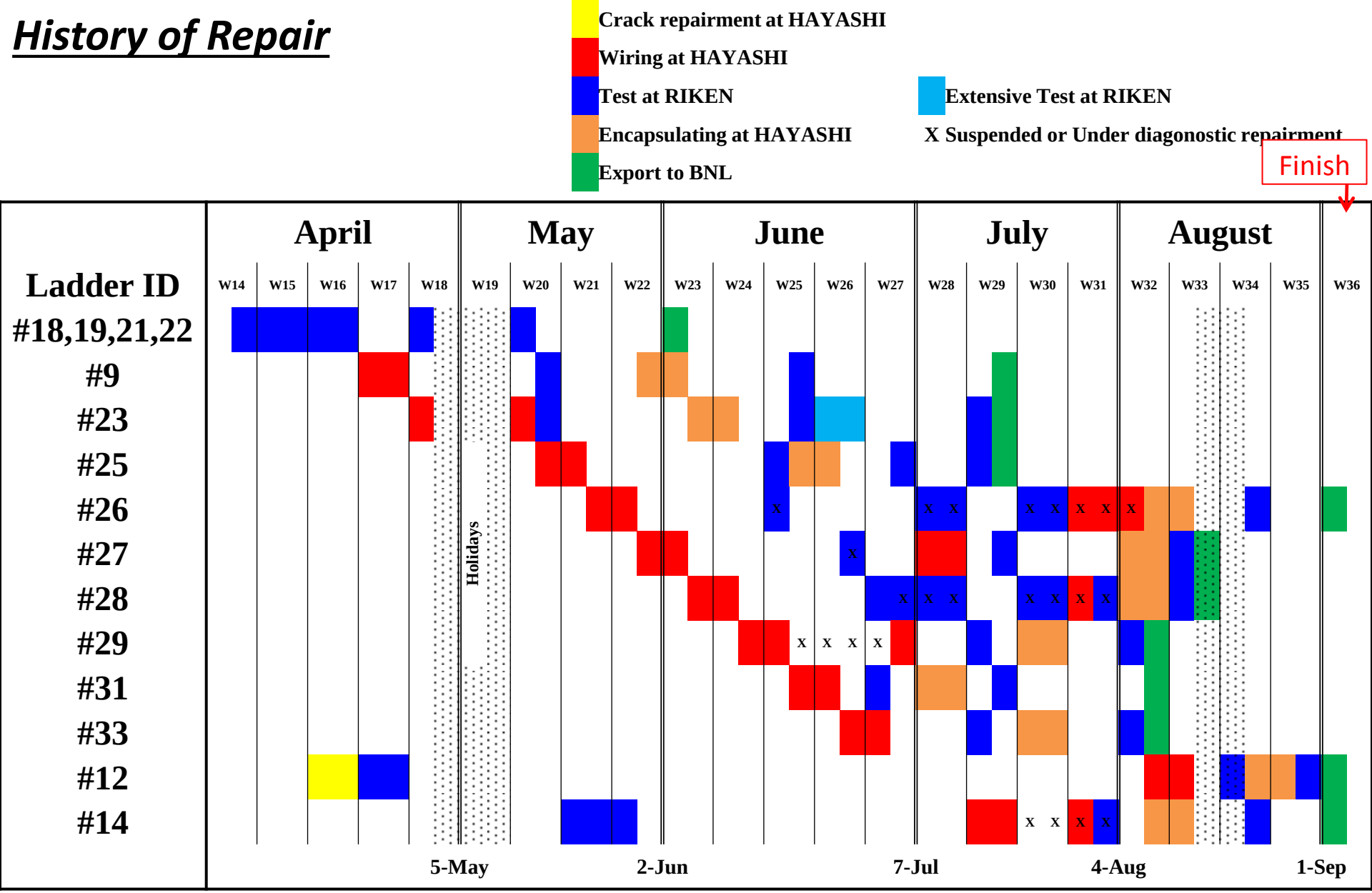
Electrical Test (RIKEN)

↓

Ship to BNL

Issue : Some bonding wires were broken due to difference of thermal coefficient between encapsulation and readout bus.

History of Repair



All 15 ladders had been repaired with the yield of almost 100% during 5 months.

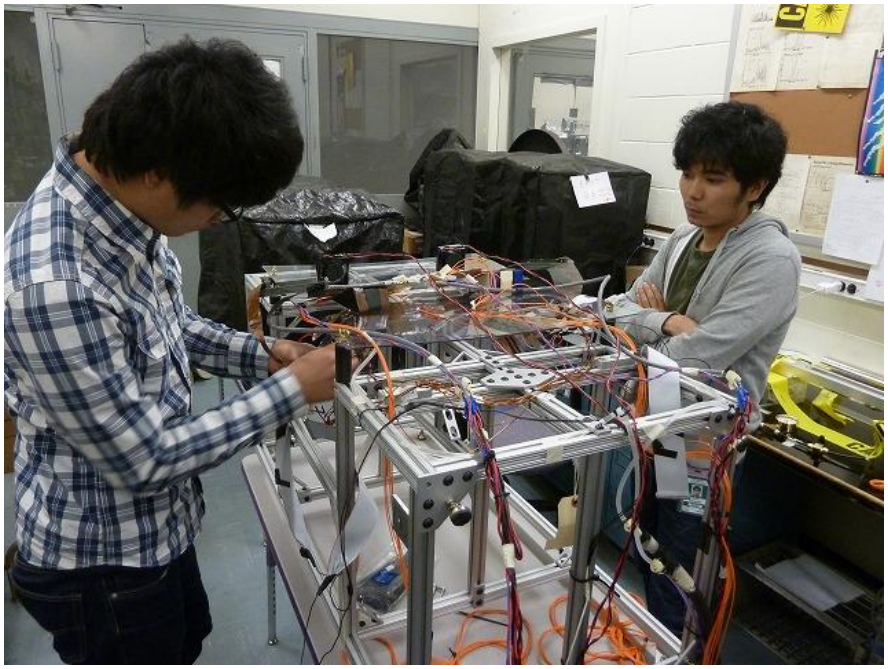
4. Current Status of VTX Assembly

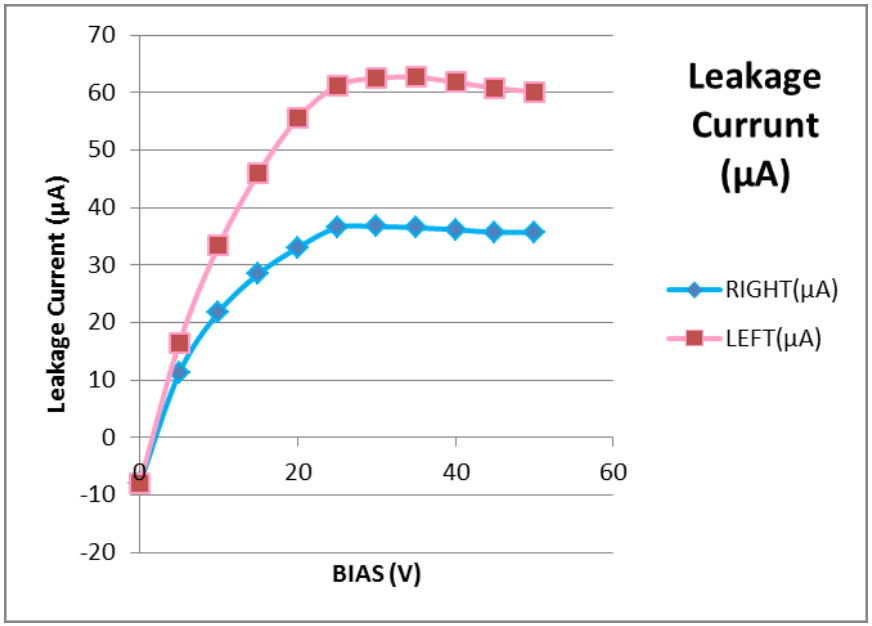
To Do before moving to IR	WEST B0	WEST B1	EAST B0	EAST B1
Mounting ladders on a barrel mount frame	No replacement		Done	Done
⇩ Attaching cooling manifolds	Done	Done	Done	Done
⇩ Pressure test	Done	Done	Done	Done
⇩ Repair leak with glue if it's found	No need	Done	No need	Done
⇩ Electrical test	Done	Done	Done	Done
⇩ Mate both layers	Done	Done	Done	Done
⇩ Mate with Strip barrels				
⇩ Attaching big wheels (SPIROs)				
⇩ Final electrical test				

Electrical Testing

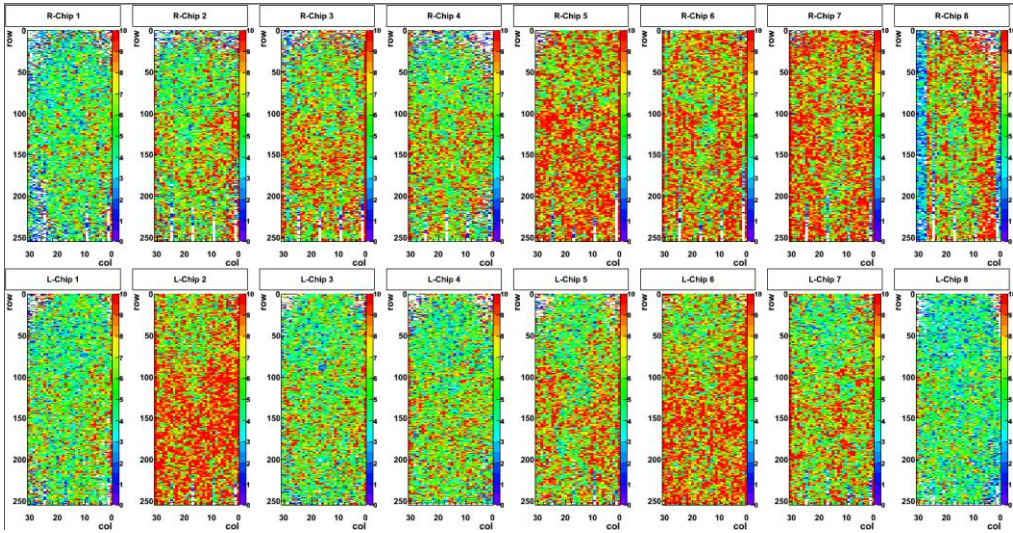
- To confirm if there are any broken channels or not, electrical test had been done for all pixel ladders.

- Test items are current consumption of ladder, bias current of sensors and response from test pulse and noise.



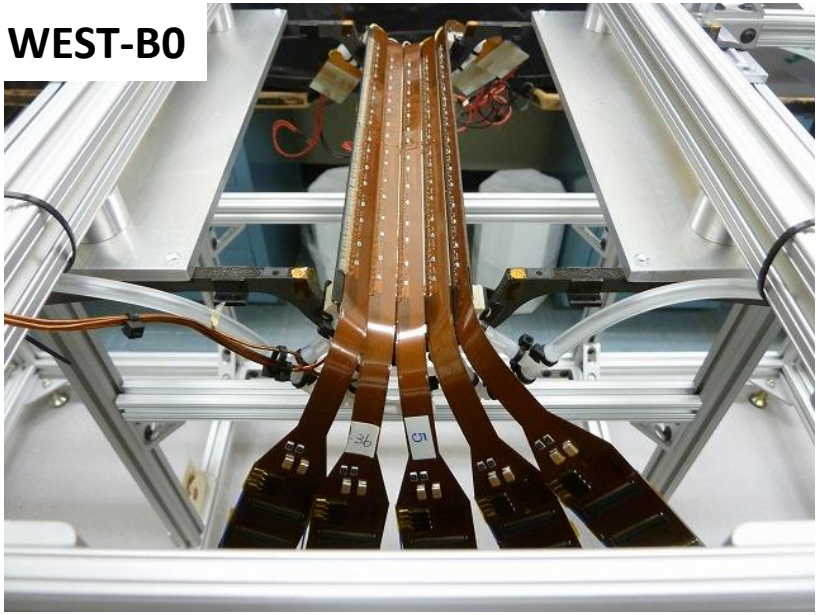


Hit distribution with Sr90

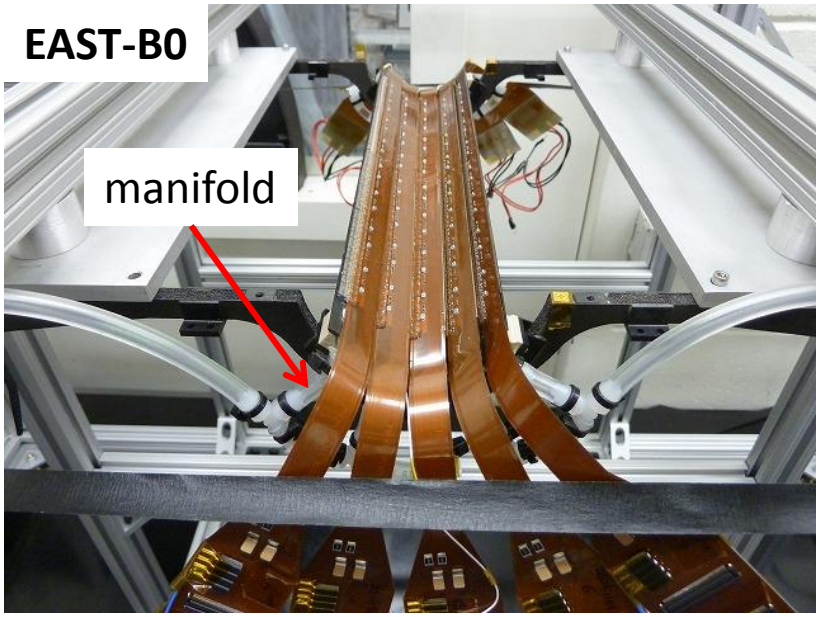


Assembled Layers (Mounting Ladders and Attaching Manifolds)

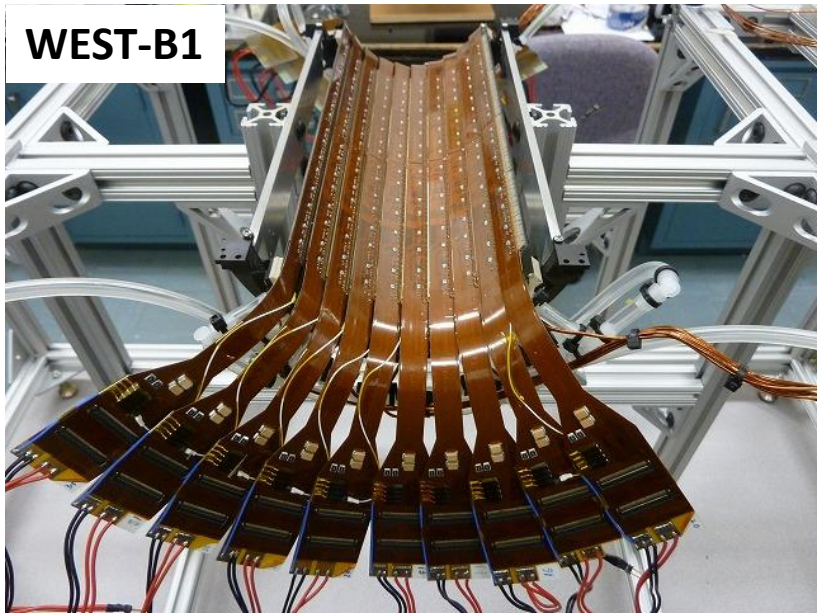
WEST-B0



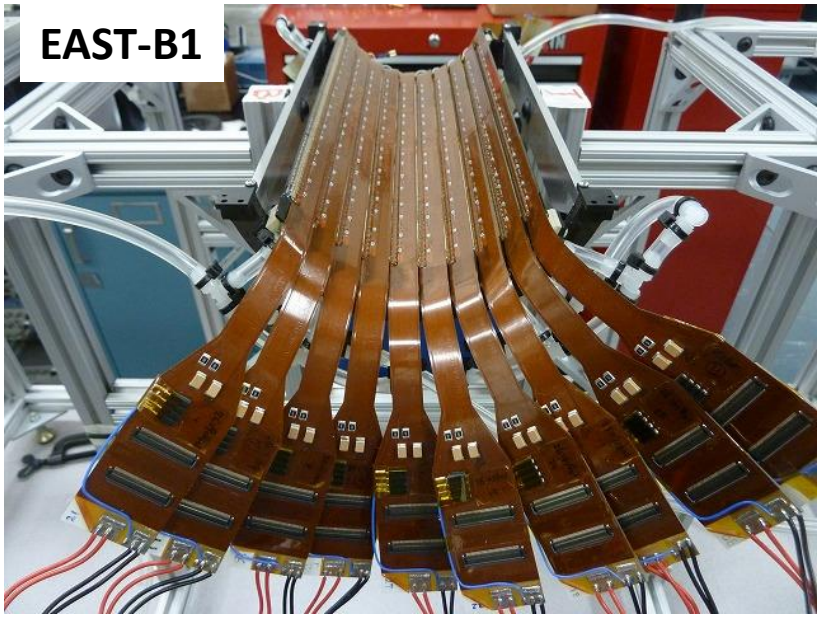
EAST-B0



WEST-B1



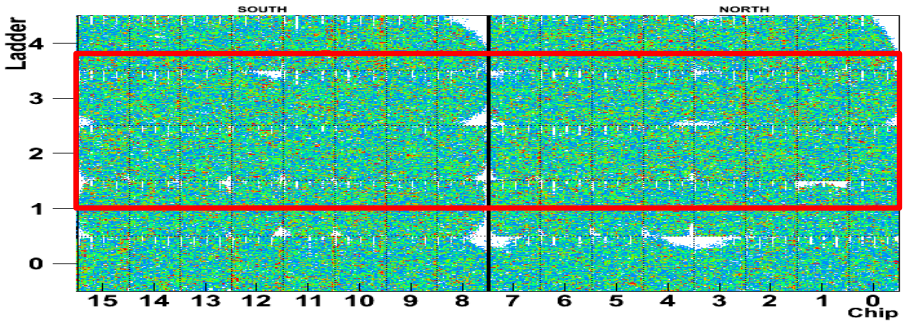
EAST-B1



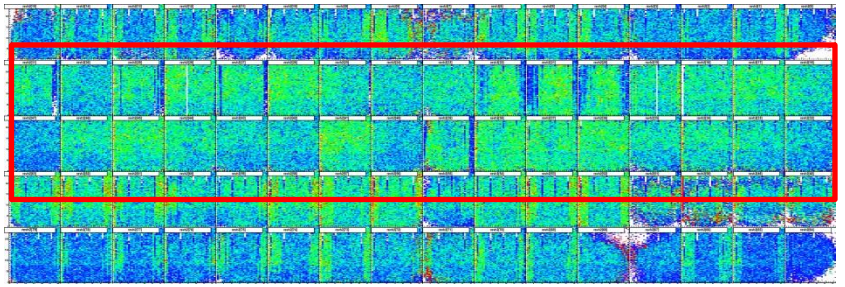
Hit Map for All Pixel Layers

Central Arm Acceptance

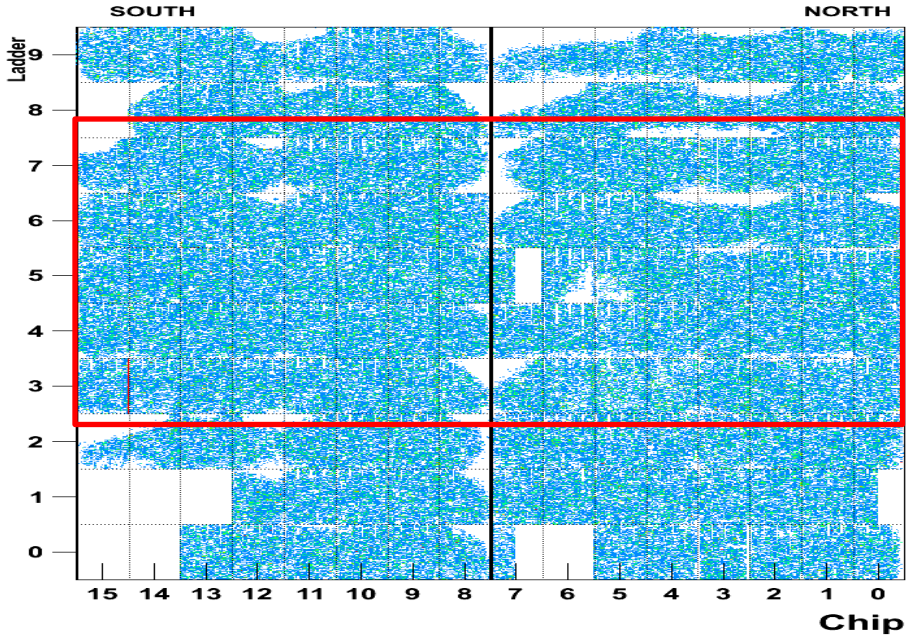
WEST Barrel 0



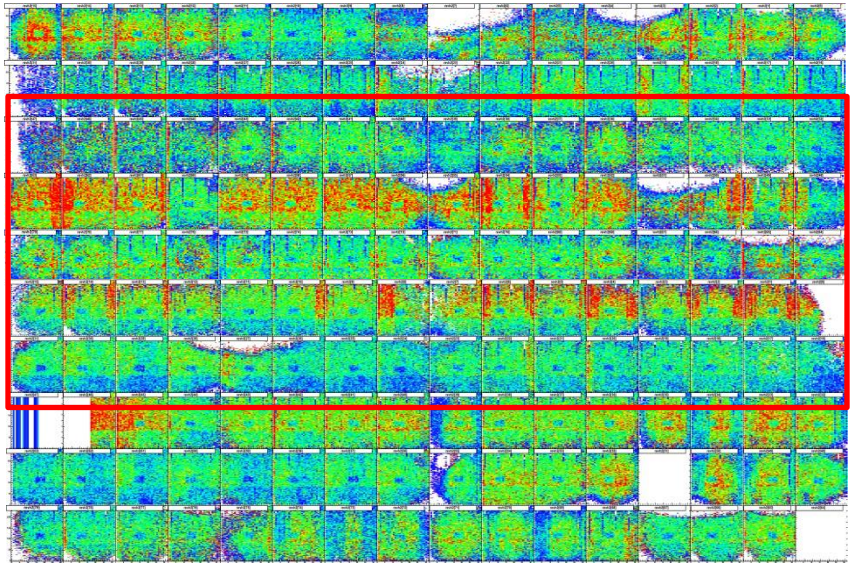
EAST Barrel 0



WEST Barrel 1



EAST Barrel 1



Active area is 90% in Central Arm acceptance.

Current Status of Strip Detectors

- Coolant leak for strip detector has found at the beginning of Run-13.
  - The cause of the leak was due to Galvanic corrosion of Al cooling tube inside staves.

- All staves were replaced with new staves that were using cooling tube of PEEK core.

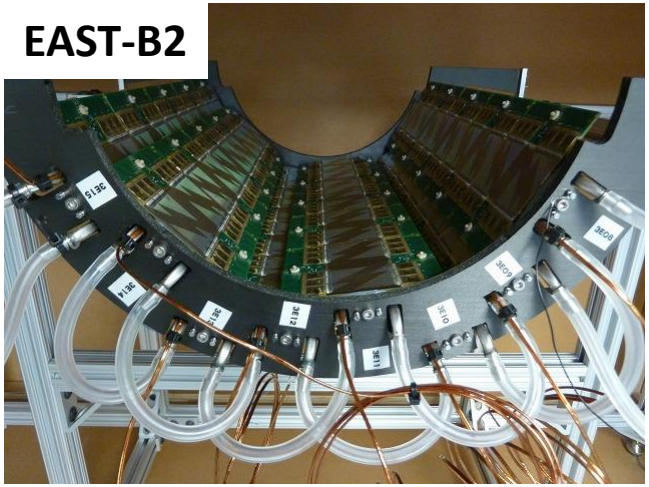
WEST-B2



WEST-B3



EAST-B2



All ladders were fabricated and assembled successfully except for EAST-B3.

6. Summary

- R_{AA} and v_2 for heavy flavor were measured using Run-11 data.
- Repair of pixel ladders were carried out gradually after Run-11.
- Ladders of EAST and WEST detector were successfully repaired with the yield of almost 100% at Hayashi.
- Active area were improved to 90%.
- Assembly of VTX are on-going but almost done.

Spin Physics Overview and Outlook

Status of RHIC:

Polarized p-p collider and the RHIC Spin Results

Future directions:

Forward physics with upgrades of PHENIX with polarized p-p

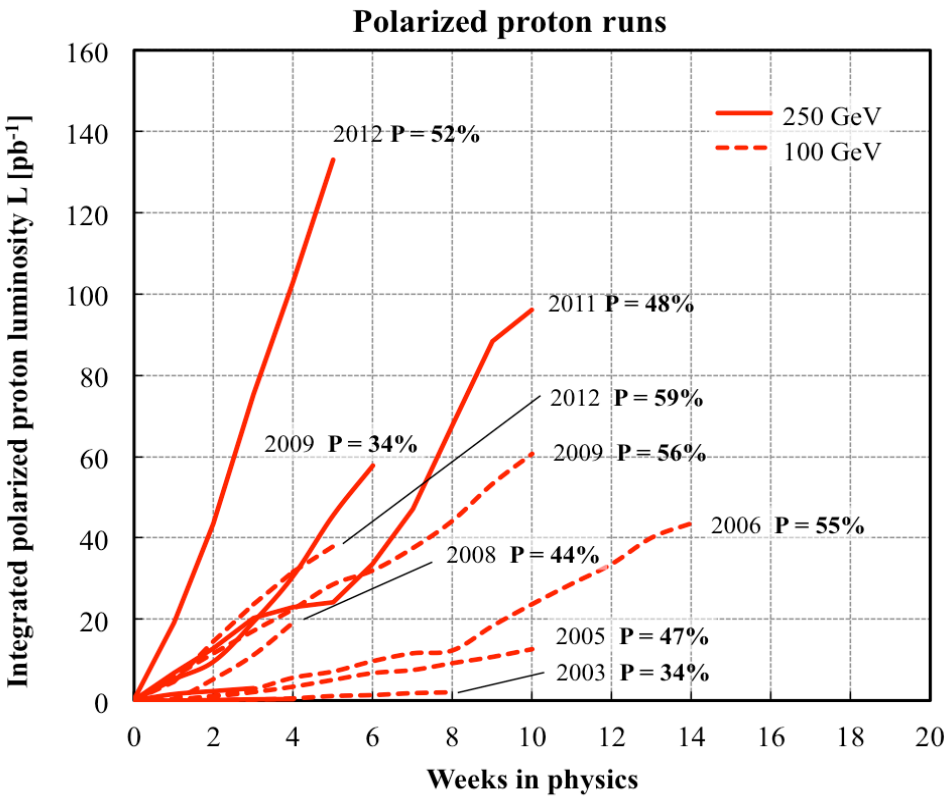
Realization eRHIC: with ePHENIX detector

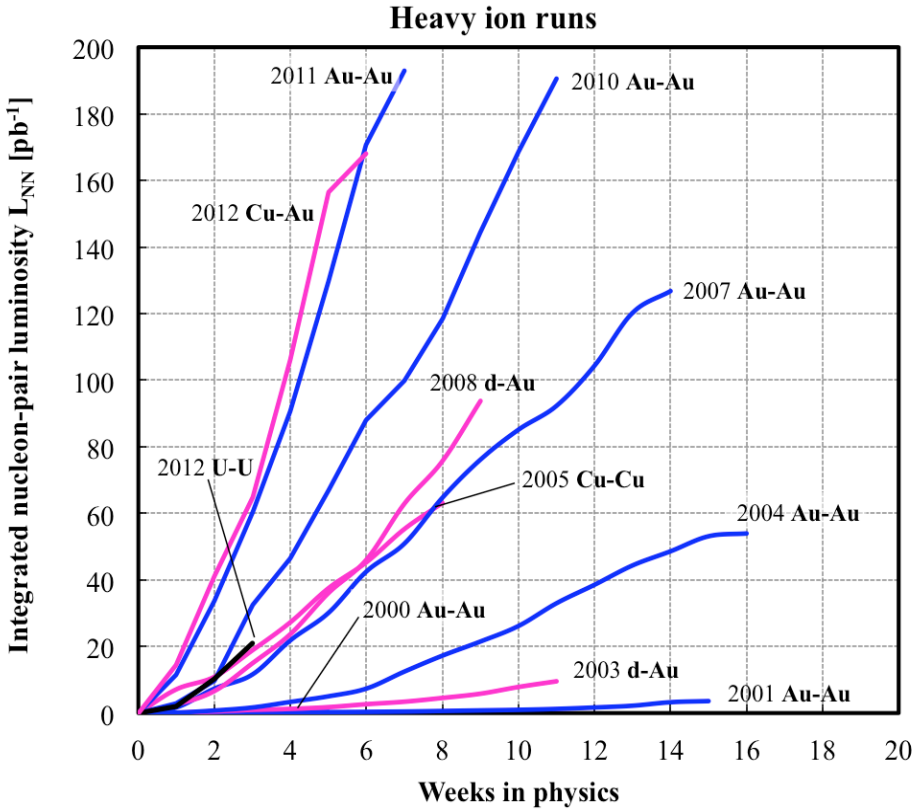
Stony Brook University

Abhay Deshpande

RIKEN BNL Research Center

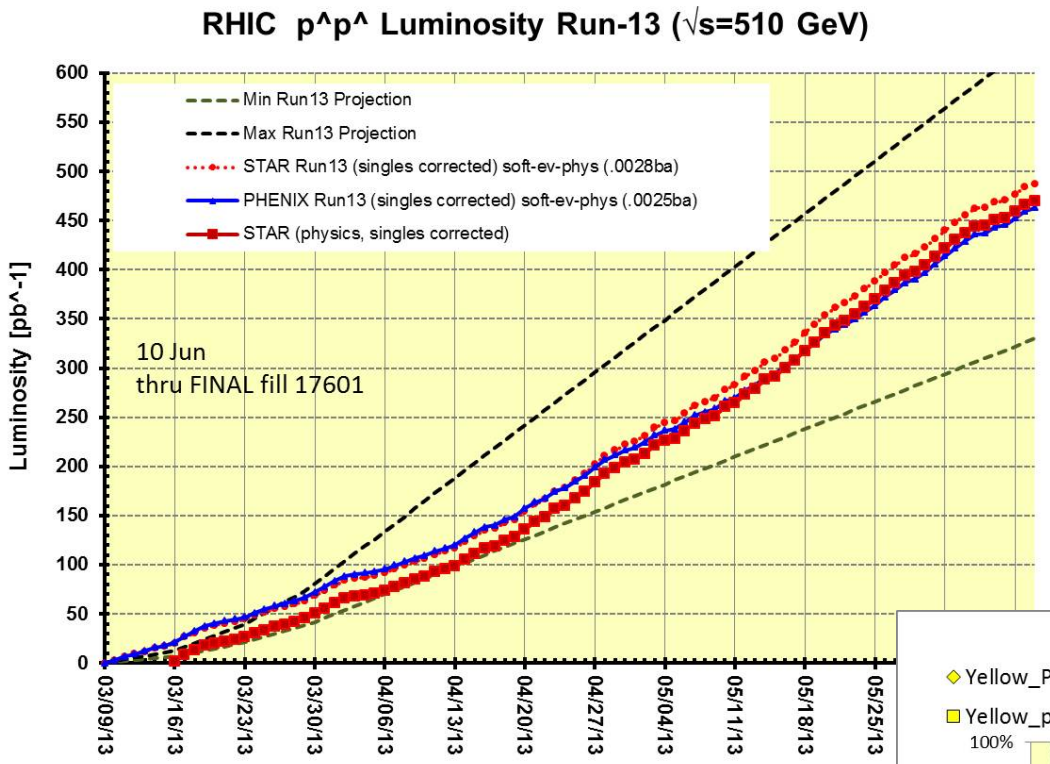
RHIC: The world's most versatile collider!

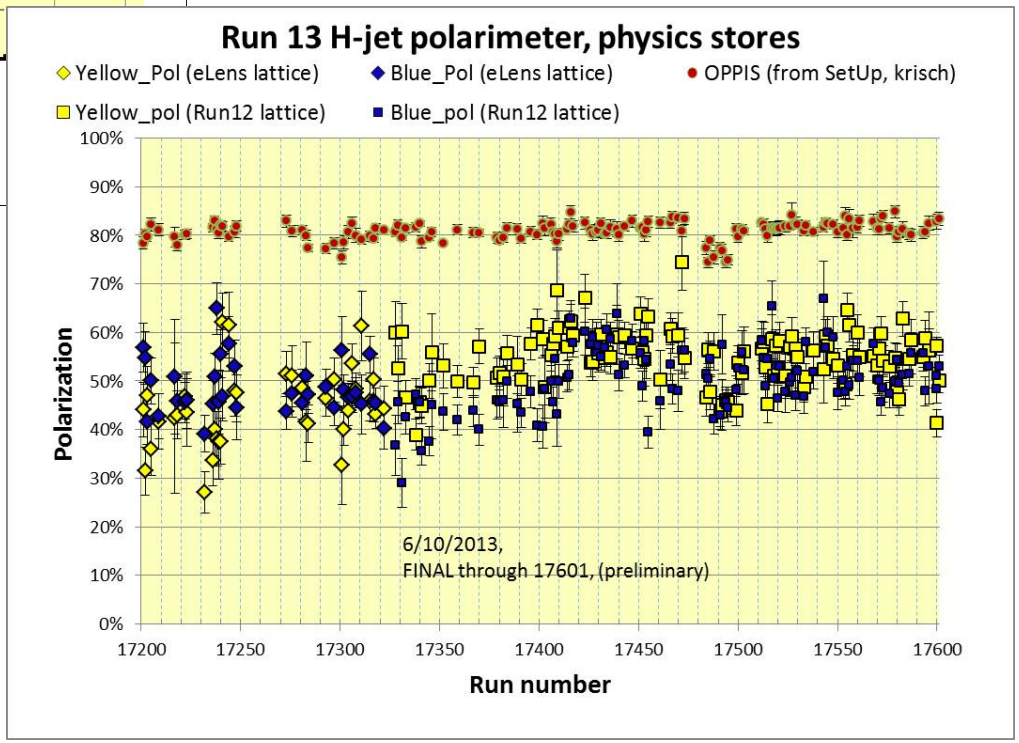




Polarized p-p Run 13

450 pb-1
@ ~52%





Compilation: Phil Pile, BNL CAD

Stony Brook University

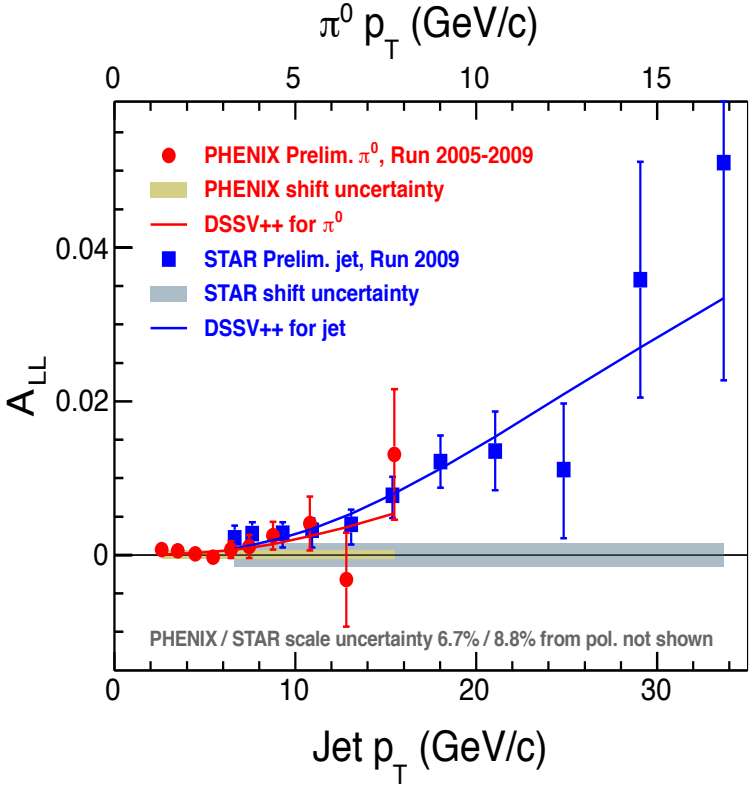
The RHIC Spin Program

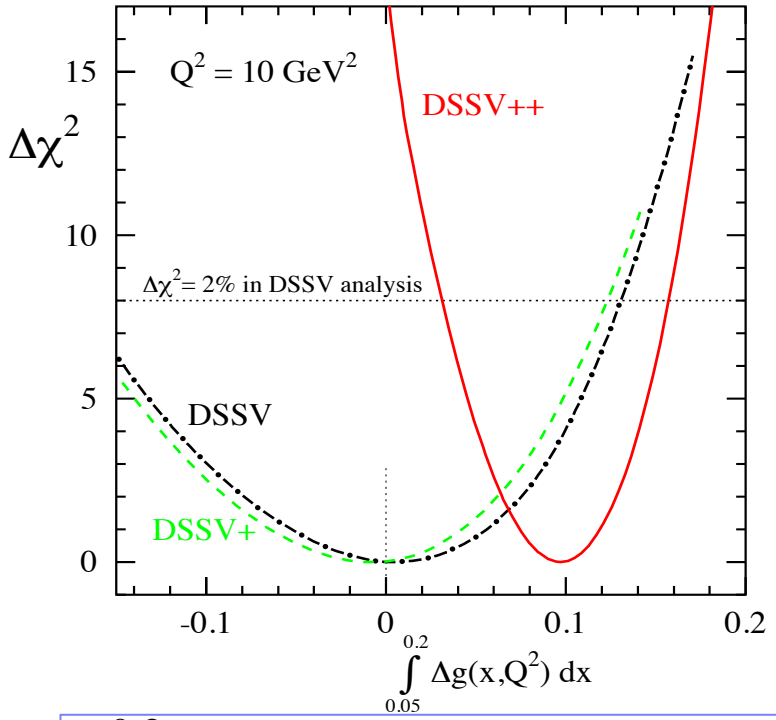
- Direct determination of polarized gluon distribution (ΔG) via multiple probes ($\pi^{0/+/-}$, γ, c-cbar,… production)
  - Double longitudinal helicity asymmetry: A_{LL}
- Direct determination of anti-quark polarization (ΔQbar) using production and parity violating decay of $W^{+/-}$
  - Single longitudinal spin asymmetry: A_L
- Systematic study of transverse spin phenomena
  - Single transverse spin collisions
  - Possible connections to Orbital Angular Momentum (OAM: $\mathbf{L_{Q/G}}$) and other subtle (and not-so-subtle) final state interactions in QCD

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2000	130 GeV Au+Au	Collective flow, jet quenching	Baseline detectors
2001/02	200 GeV Au+Au **200 GeV pol p+p test**	Flow, jet quenching, **p+p baseline**	STAR: SVT, FTPC, pTOF, ... **PHENIX: S Muon Arm**
2003	200 GeV d+Au	Cold nuclear matter comparison	STAR: Partial EMCal PHENIX: N Muon Arm
2004	200 + 62 GeV Au+Au	High statistics Au+Au, J/Ψ melting	STAR: Partial SSD **PHENIX: MuID, EMCal Trig.**
2005	22, 62, 200 GeV Cu+Cu **200 GeV p+p**	System size dependence **Proton spin, p+p baseline**	STAR: Full EMCal PHENIX: Aerogel
2006	**62, 200 GeV pol p+p**	**High statistics p+p reference**	
2007	200 GeV Au+Au p+p/d+Au at 200 GeV	Reaction plane dependence Gluon polarization	PHENIX: TOF, RPD, MPC
2008	200 GeV d+Au **200 GeV pol p+p**	Cold nuclear matter, **proton spin**	STAR: FMS
2009	**200, 500 GeV pol p+p**	**Proton spin, first W measurements**	STAR: DAQ1000 PHENIX: HBD
2010	7.7, 11.5, 39, 62, 200 GeV Au +Au (BES-1)	Search for QCD critical point Low mass dileptons	STAR: TOF complete
2011	**500 GeV pol p+p** 19.6, 27, 200 GeV Au+Au	**Improved W measurement** Critical point search	**PHENIX: VTX, Mu Trig. S**
2012	**200, 500 GeV pol p+p** 193 GeV U+U 200 GeV Cu+Au	**Gluon contribution to proton spin** Initial geometry dependence of flow and fluctuations	STAR: Partial FGT **PHENIX: FVTX, Mu Trig. N**
2013	510 GeV pol p+p	**Anti-Q Polarization: Final W physics run** Asymmetric and other HI collisions	**PHENIX Mu Trig N& S,** STAR Full FGT

RHIC-Spin White Paper, 2012

Status of ΔG with RHIC Data



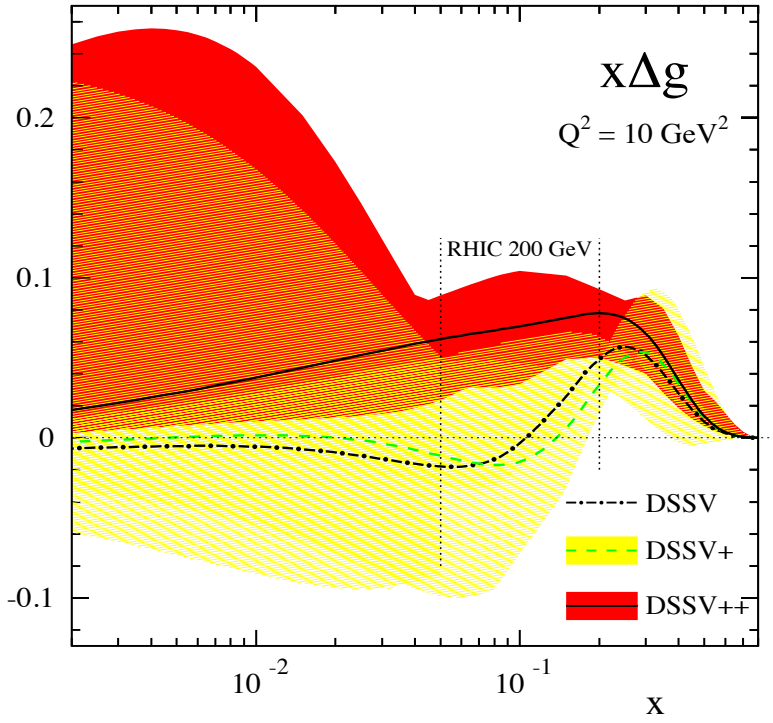


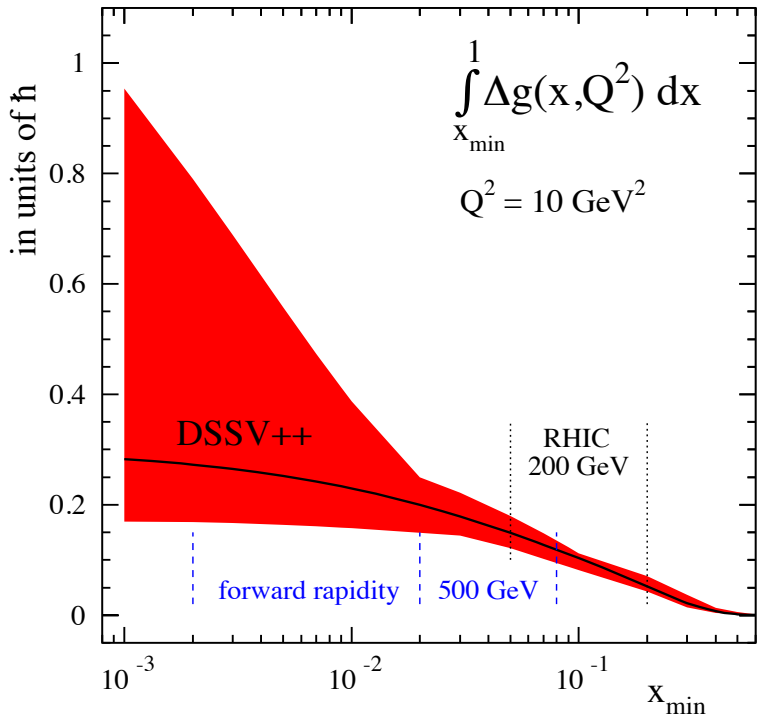
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 GeV^2) dx = 0.10^{+0.06}_{-0.07}$$

Global fit DSSV++
Sassot & Stratmann

PHENIX data: Ph.D. theses
2006 **Kieran Boyle**
2009 Andrew Manion (SBU grad. student) + **KB**
2011-13 500 GeV data sets (?): Low p_T systematics dependent

ΔG Status and future needs…. (low-x)



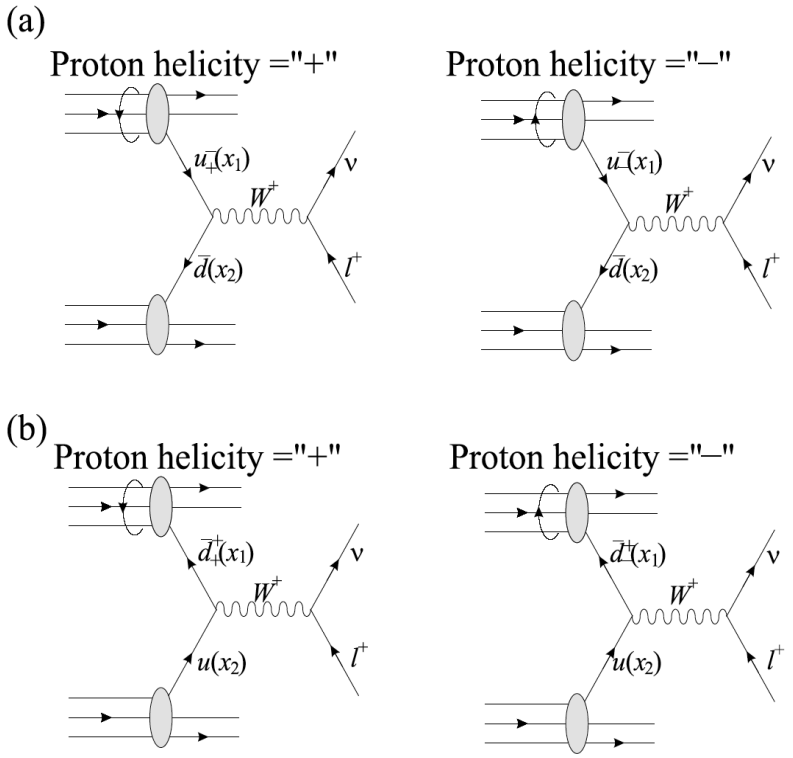


Low x uncertainty reduction requires higher energy & forward rapidity studies

Effort limited by systematic uncertainties in measurements (SRC 2012, K. Boyle)

Electron Ion Collider: eRHIC in the long term future will address this effectively

Anti-Quark Polarization



W production at 500 GeV CM with polarized proton-proton collisions

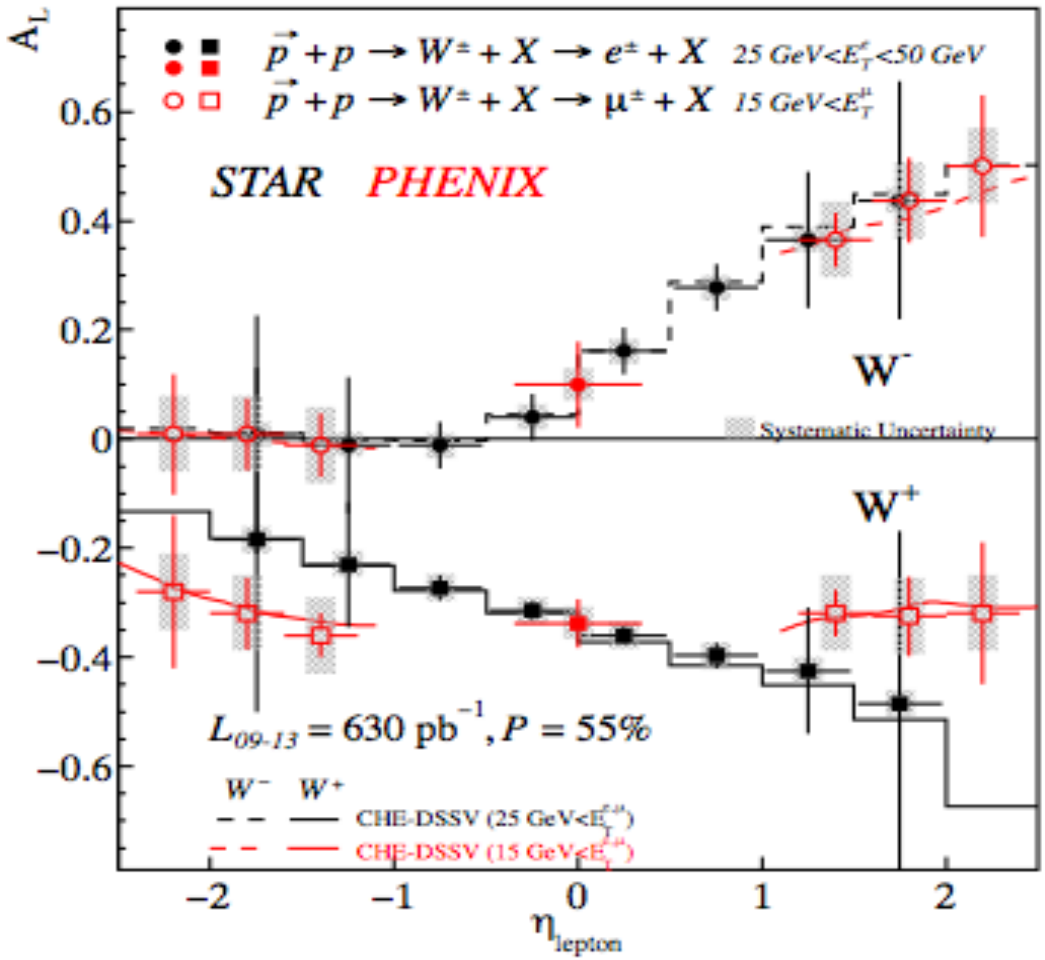
Produced W's decay in to a lepton and a neutrino

High momentum electron (and neutrino) detected (not detected). Experiments need to **trigger** on:

- The charge of the high p_T lepton
- Isolate the lepton from leptons decayed from other mesons
- Background subtraction a challenge

PHENIX Central arm results published last year, with electron in the final state
➔ Ciprian Gal (SBU Grad Student)
Forward MUON arm detector/trigger + use of FVTX upgrade just completed
➔ **Discussed by R. Seidl already this morning (+ X. Wang's talk this session)**

Anticipated uncertainties



Extraction of
Anti-quark polarization
Will need inclusion
In the DSSV++
And such
Globa analyses

DSSV + PHENIX and STAR
Experimental groups
Actively engaged

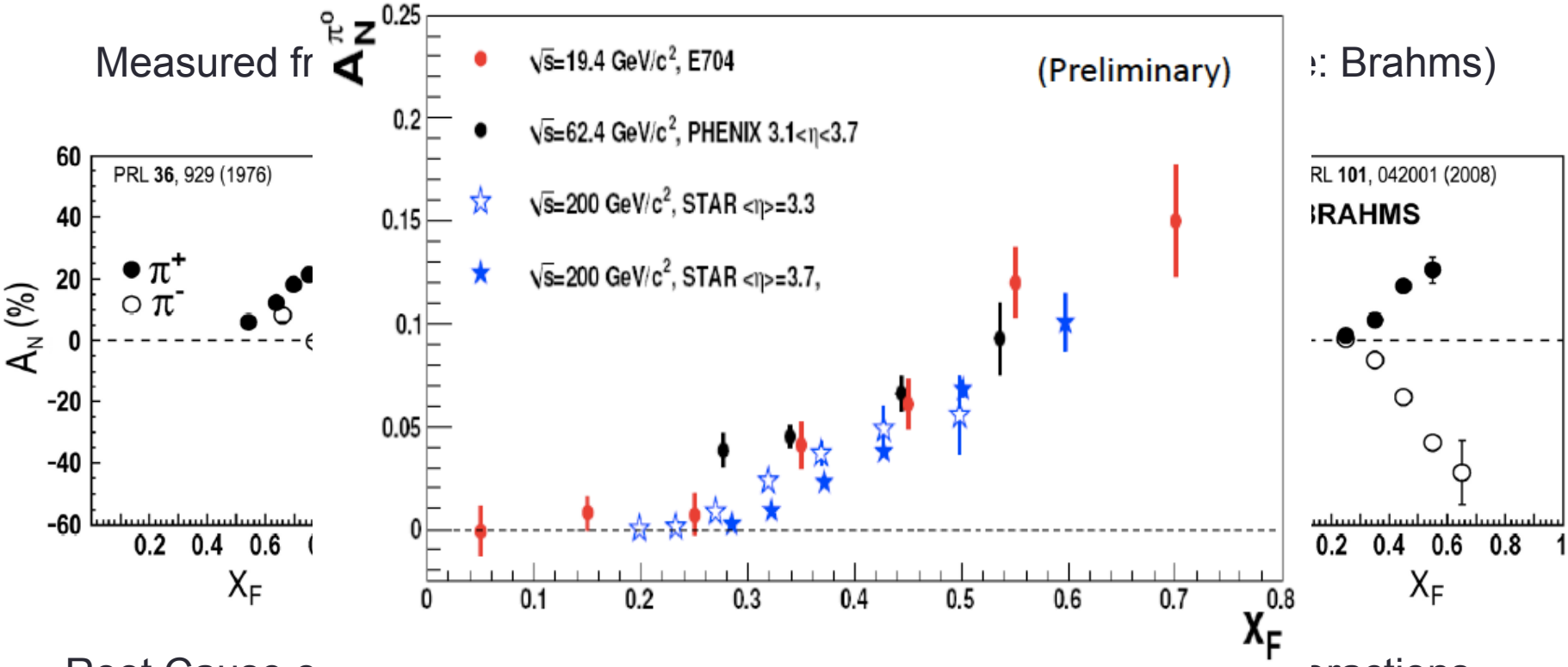
Stay tuned!

Transverse Spin asymmetries:

$$x_F = \frac{2p_l}{\sqrt{s}}$$

PHENIX (**John Koster**) and STAR: At high rapidity

Measured fr : Brahms)



Root Cause of the asymmetries: initial or/and final state partonic interactions

Dedicated effort in the forward direction: current and short term future

➔ **Xiaorang Wang (RBRC-NMSU)** (heavy Q with Forward-VTX)

➔ **Forward physics upgrades of PHENIX: sfPHENIX (Joe Seele, RBRC)**

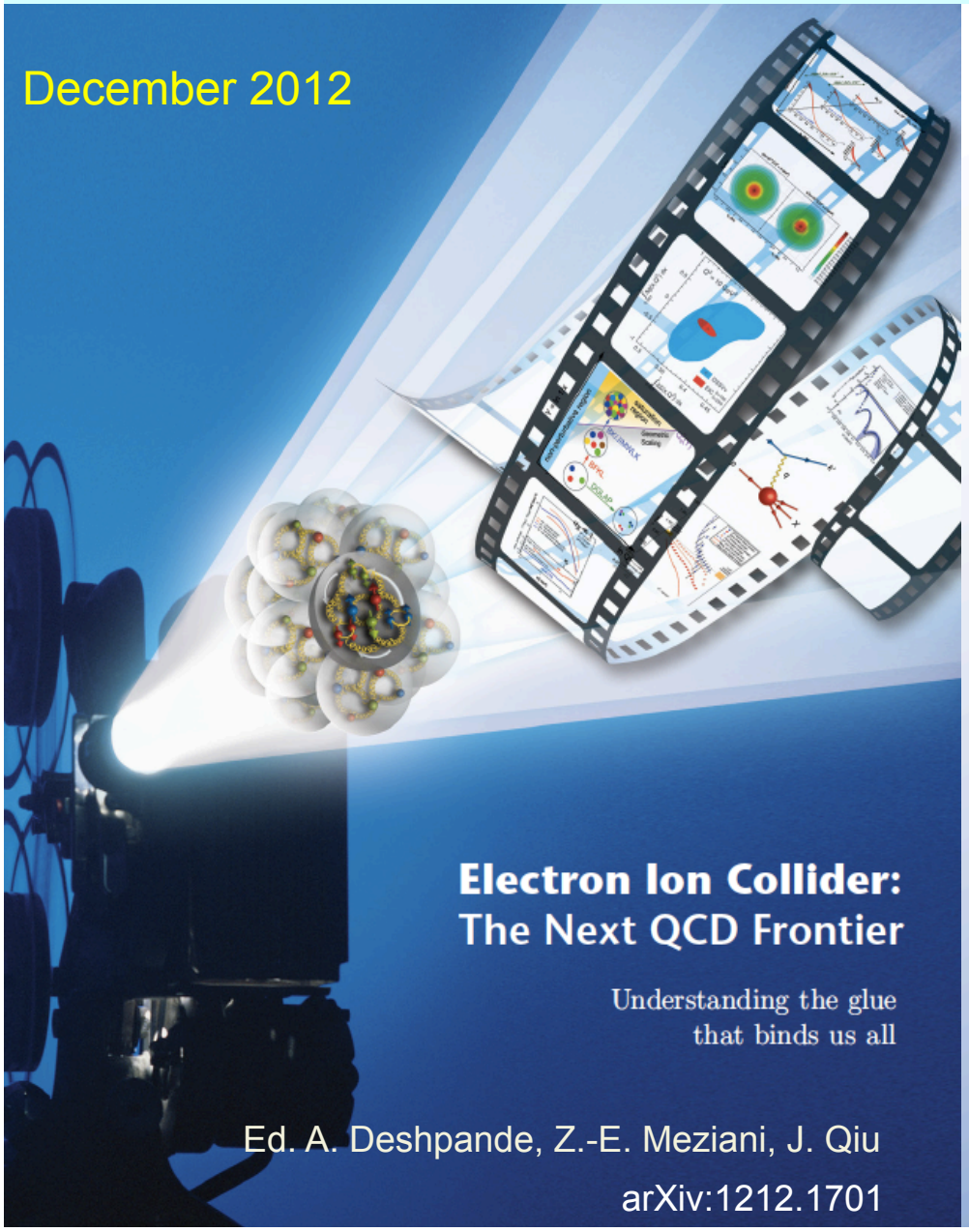
RHIC operations plans future…

B. Mueller

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	**p+p at 200 GeV** **p**+Au, d+Au, **^{3}He**+Au at 200 GeV High statistics Au+Au	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests **Transverse spin physics**	**PHENIX MPC-EX** Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors **p+p**, **p/d+Au** at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX Spin?
2023-24	No Runs		Transition to eRHIC

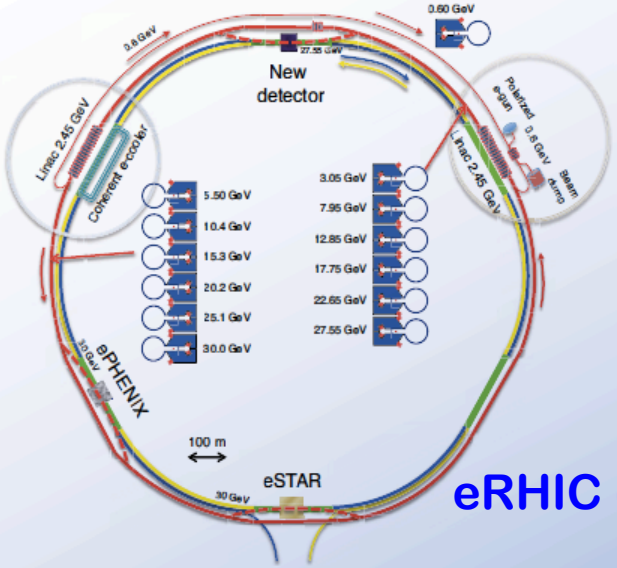
White Paper for the Electron-Ion Collider

December 2012



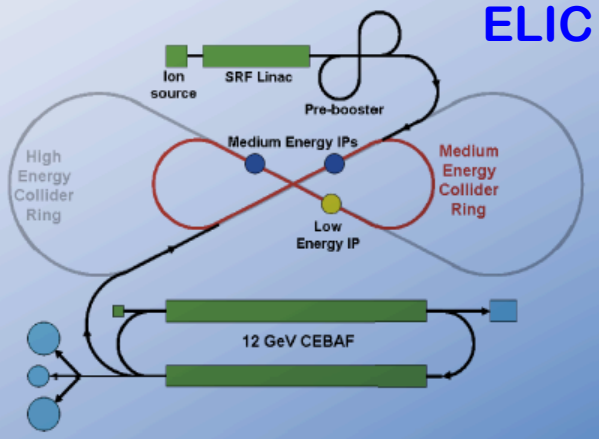
Ed. A. Deshpande, Z.-E. Meziani, J. Qiu

arXiv:1212.1701

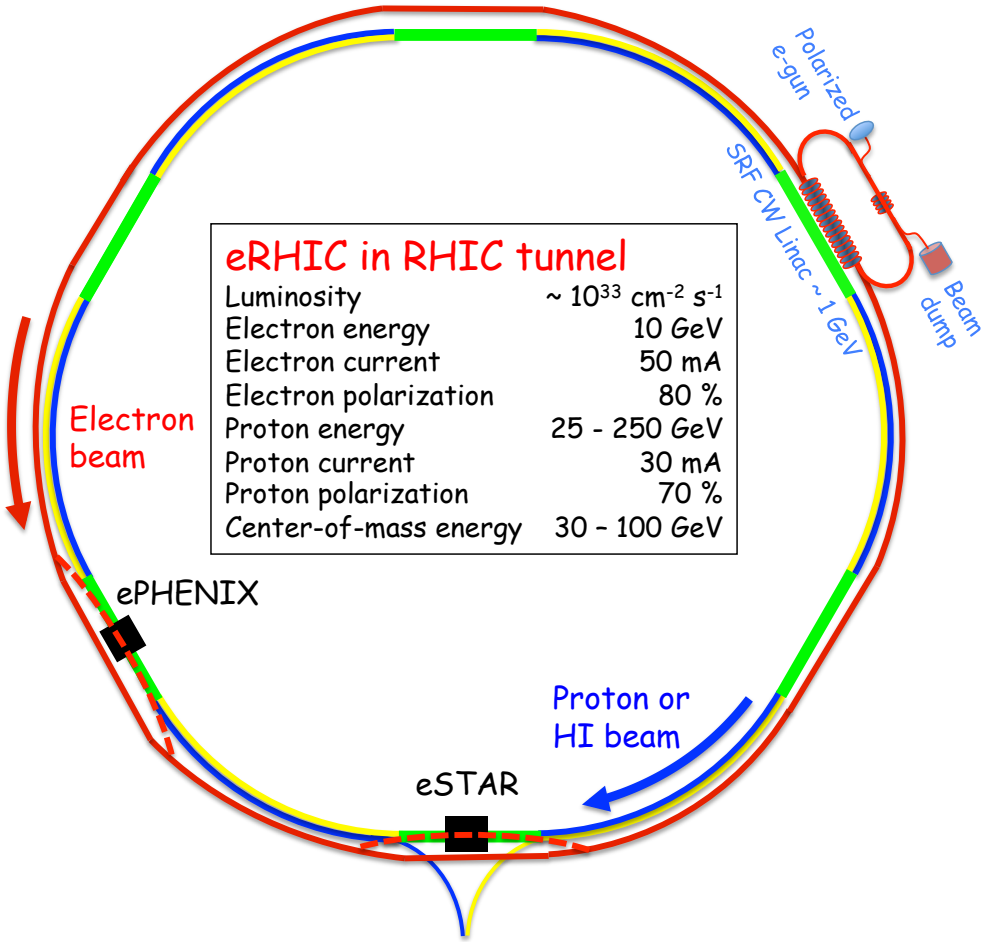


eRHIC (BNL)

ELIC (JLab)



EIC at BNL: eRHIC Stage 1 Configuration

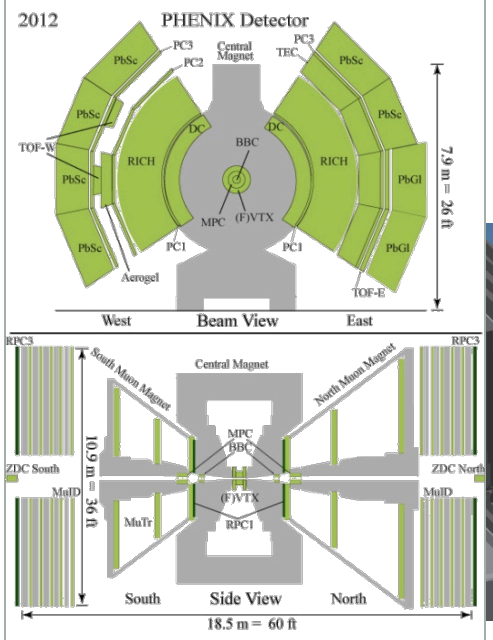


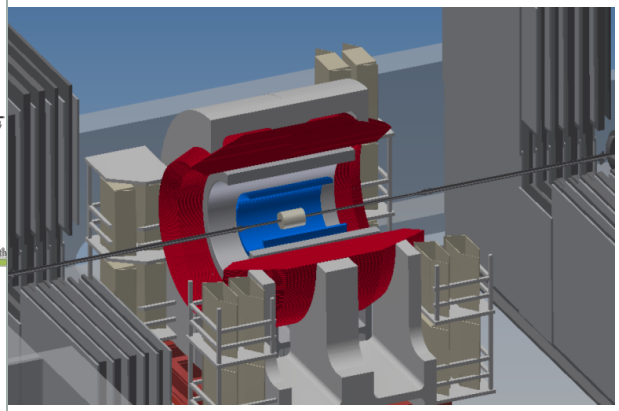
eRHIC in RHIC tunnel

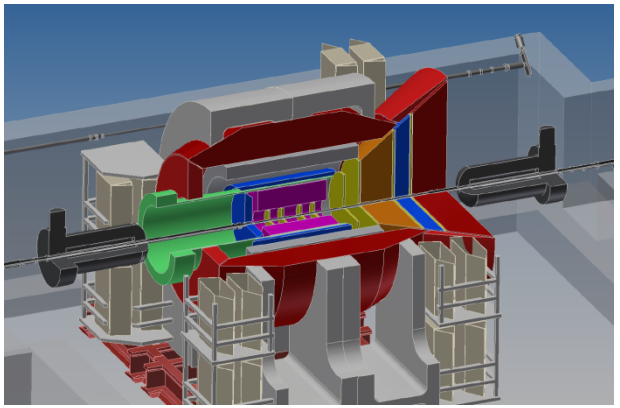
Luminosity	~ 10^{33} cm^{-2} s^{-1}
Electron energy	10 GeV
Electron current	50 mA
Electron polarization	80 %
Proton energy	25 - 250 GeV
Proton current	30 mA
Proton polarization	70 %
Center-of-mass energy	30 – 100 GeV

More in
B. Mueller,
T. Ludlam's
Talks on Friday

PHENIX evolution to ePHENIX

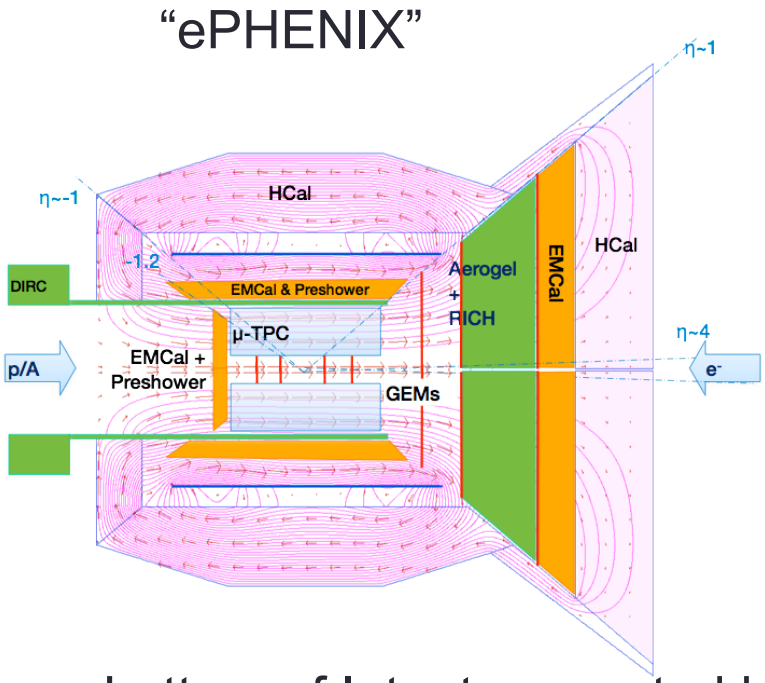
Current PHENIX	sPHENIX	fsPHENIX & ePHENIX
	Central barrel detector Y. Akiba	Talks today: Forward sPHENIX: **J. Seele** ePHENIX: **K. Boyle**

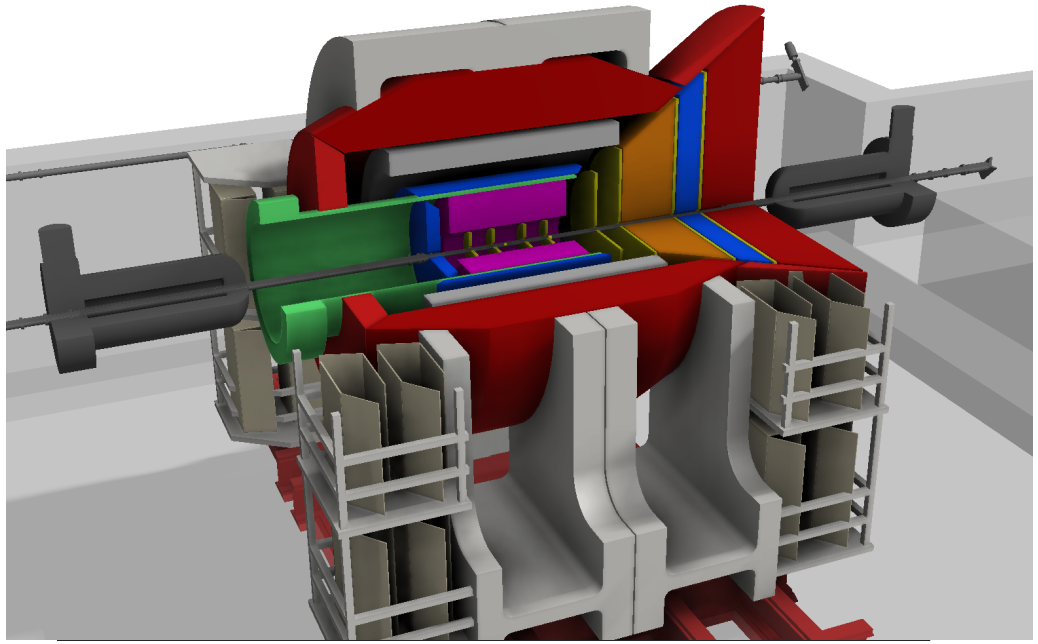




~2000 ~2020 ~2025 Time

eRHIC Stage 1 detectors





- Letters of Intent requested by BNL-ALD from both RHIC collaborations PHENIX → **sPHENIX (Seele, Goto, Seidl)** → **ePHENIX (K. Boyle, A. Deshpande, I. Nakagawa)**
  - Benchmark designs with cost estimates
- Anticipate actual construction of eRHIC detector by new collaboration

Summary:

- Major part of RHIC spin program is now behind us. Great impact so far in ΔG, anticipate the same in near future for anti-quark and transverse spin
- Near future: planning for PHENIX upgrades (sPHENIX and ePHENIX)
- Far future: Electron Ion Collider at BNL: preparation for the NSAC Long Range Plan (anticipated 2014/15)
- **Each of the above stages: RBRC fellows *have played* and *will play* critical and leading roles**

SPIN Measurement with FVTX

Xiaorong Wang

New Mexico State University
Riken BNL Research Center

- Introduction
- FVTX status for run12 and run13
- Spin analysis status with FVTX
- Summary and Outlook

Introduction

- **Physics interest**
  - J/Ψ A_{LL} to probing gluon contribution through heavy flavor channel
  - Study Sivers function and tri-gluon correlation function by measurement of heavy-flavor A_N
  - *W* measurement using FVTX
  - Drell-Yan cross section and A_{LL}
- **NMSU/PHENIX group**
  - Faculties: Steve Pate, Vasili Papavasilliou and Xiaorong Wang
  - Students: Abraham Meles (PhD candidate):

    Run13 W➔μ analysis

    Haiwang Yu (exchange PhD student):

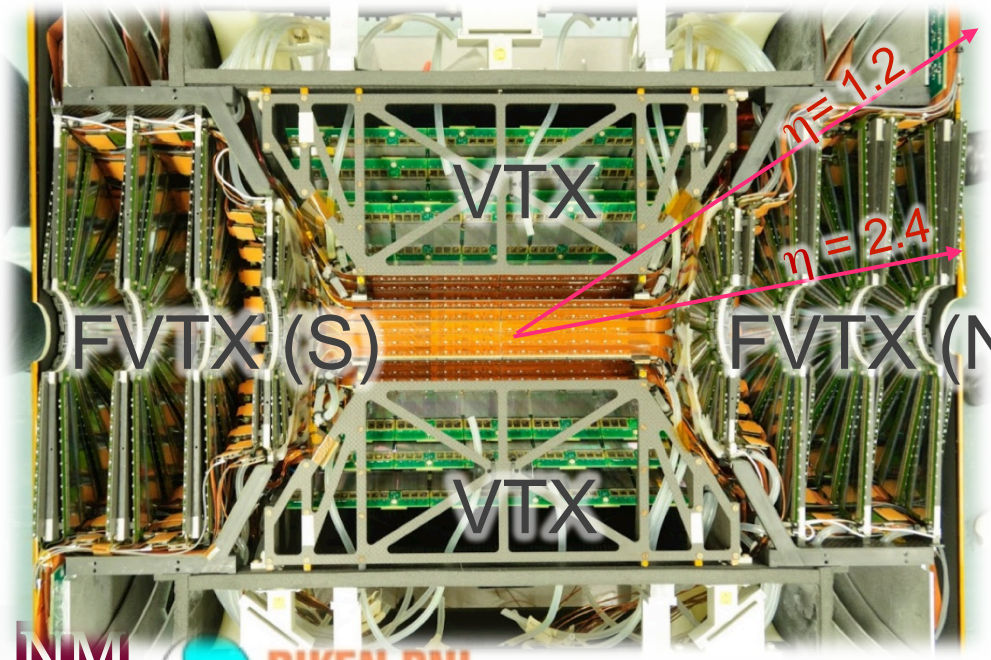
    J/Ψ A_{LL} and DY A_{LL} analysis

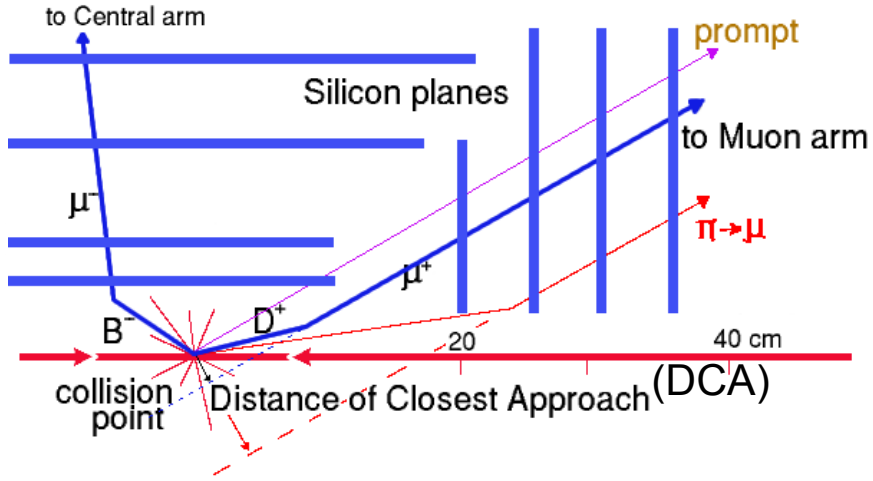
    Darshana Perera: Drell – Yan A_{LL}

    Joengsu Bok: b and c separation
  - Postdoc: Feng Wei

FVTX Improve Forward μ Probes

- FVTX – forward silicon vertex detector with 1M strips along azimuthal direction; 75 μm pitch in r direction, 10 mrad phi direction.
- Differentiate primary vertex / secondary decay using DCA
- Precisely measure di-muon opening angle : J/ψ mass
- Joint tracking with Muon Tracker: suppress decay-in-flight and mis-reconstruction
- Track isolation : suppress hadrons from jet for *W* and DY measurement

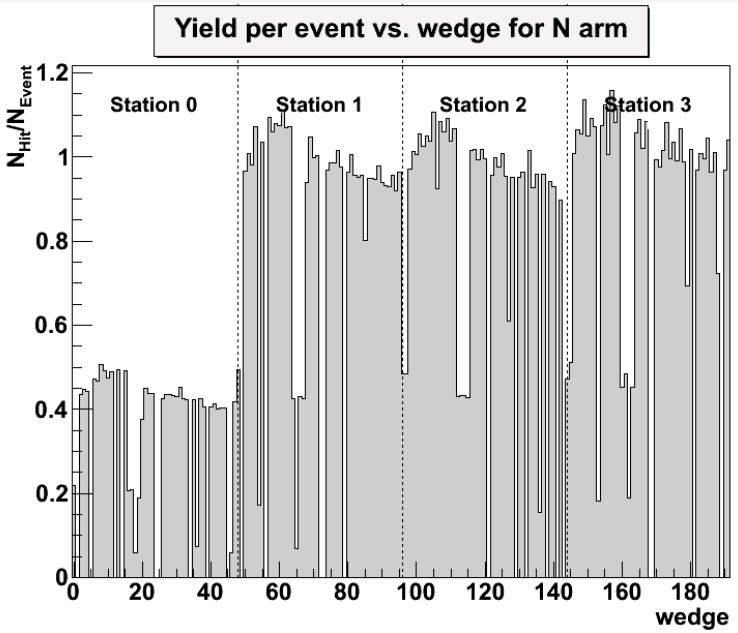




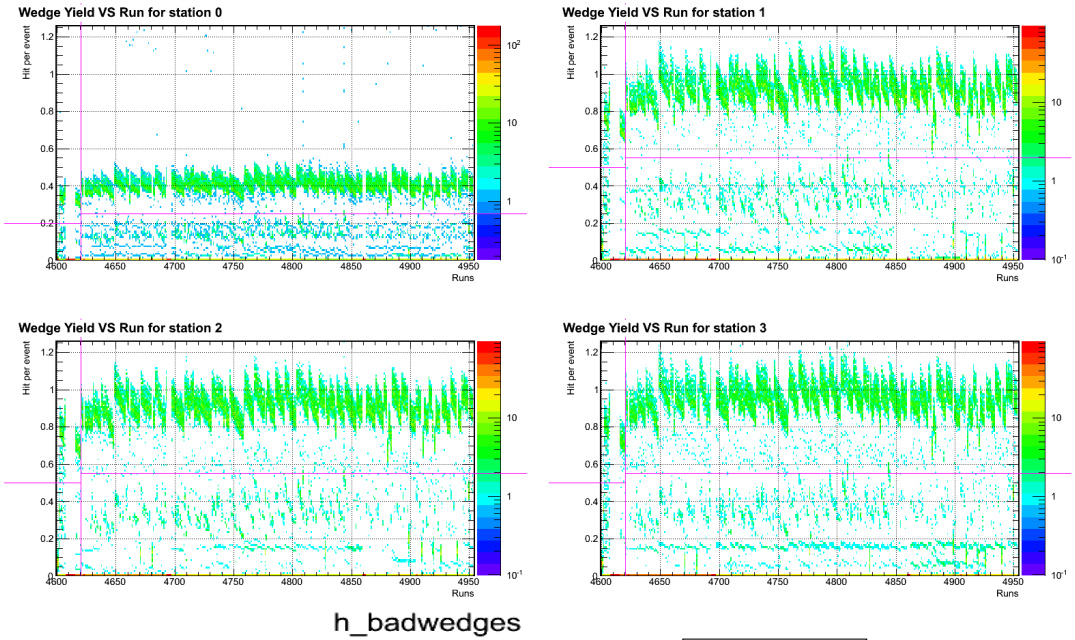
First 500 GeV p + p with FVTX

- **ROC/Wedges QA with online monitor**

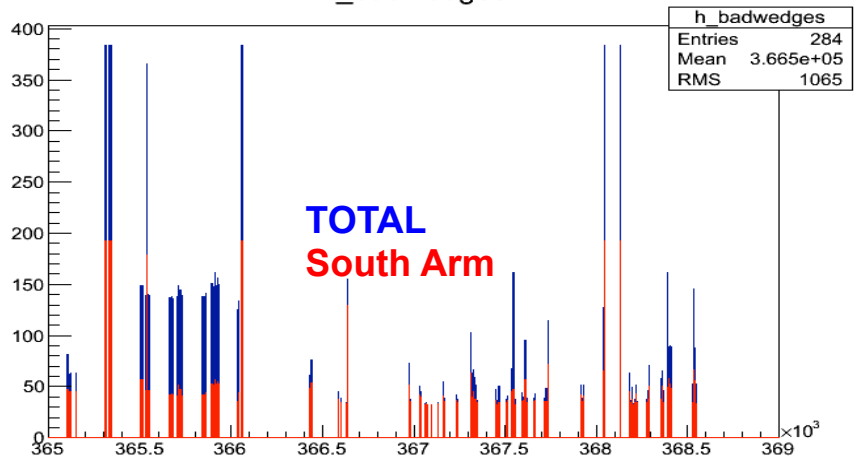
Run 367464



Statistics wedge hit yield over many runs



Dead wedges vs Run number



Successful Run 13 with FVTX

Dead Area

- ROC repair was completed during shutdown
- > 95% live area for Run13
- Small problem during middle of run for a few days, but quickly resolved.

Stability

The major stability issue were Addressed with FPGA code Improvements

Sucessful Run

Overall Run13 was an excellent run for the FVTX and we collected a large set of high-quality data

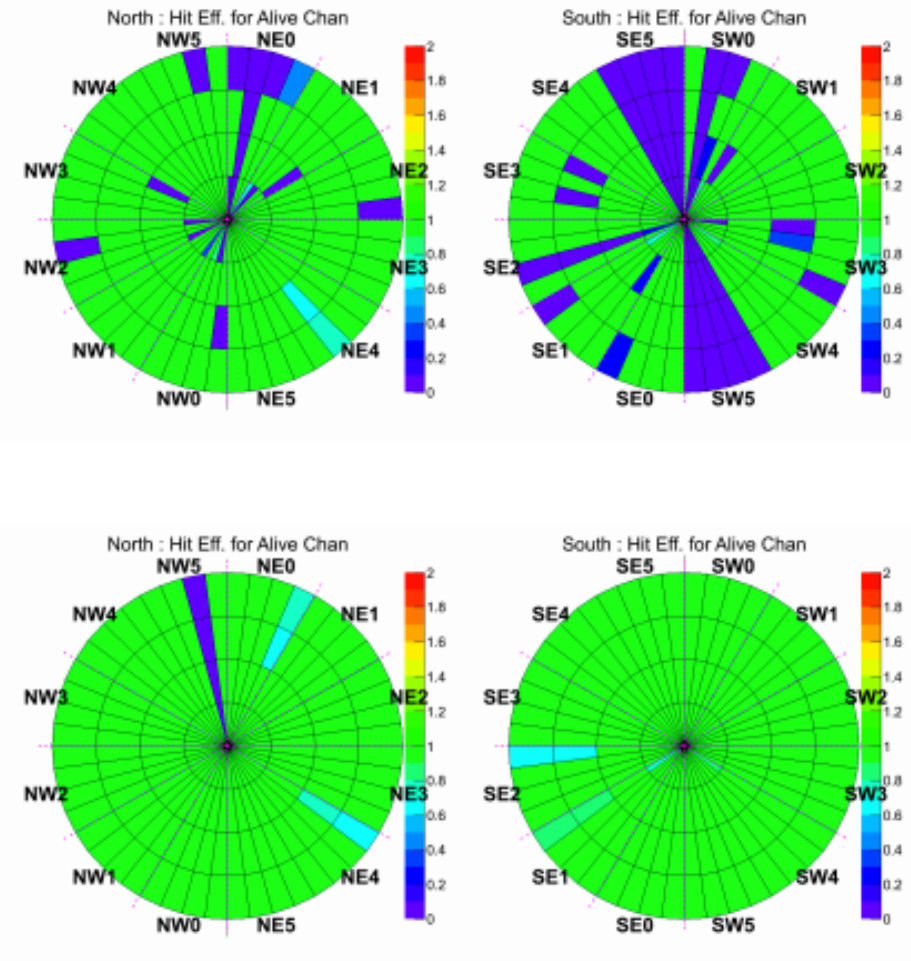
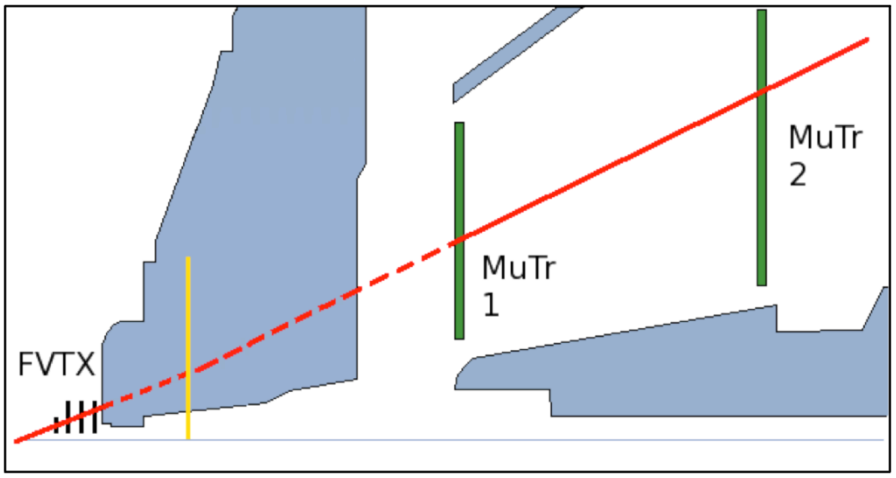
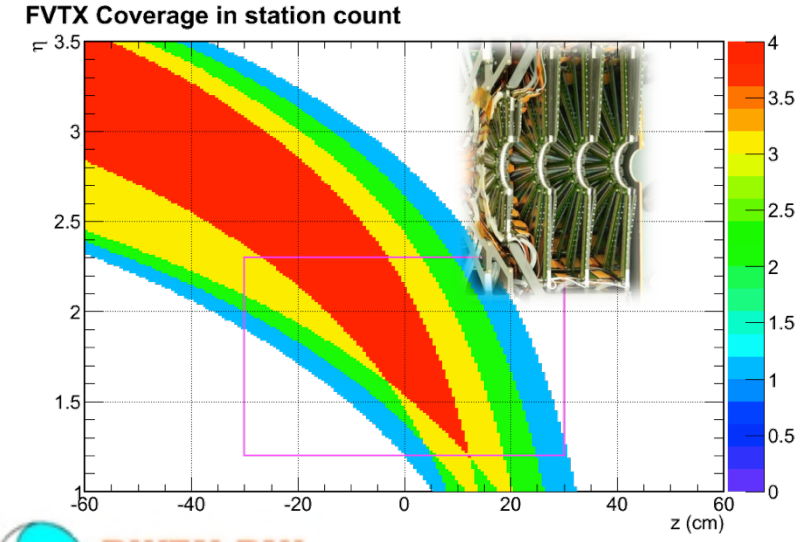


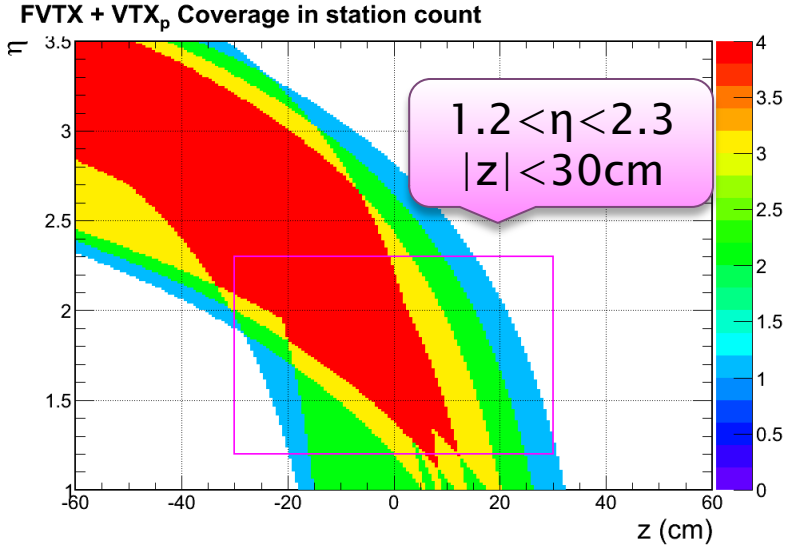
Figure: Live channels: Run12 (top) & Run13 (bottom)

Joint FVTX – MuTr track matching

- FVTX – MuTr track matching can suppress decay-in-flight background
- Tracking acceptance limited by geometric reasons (yellow + red region below),
- <acpt.>~ 17% for Run12
  <acpt.>~ 25% for Run13





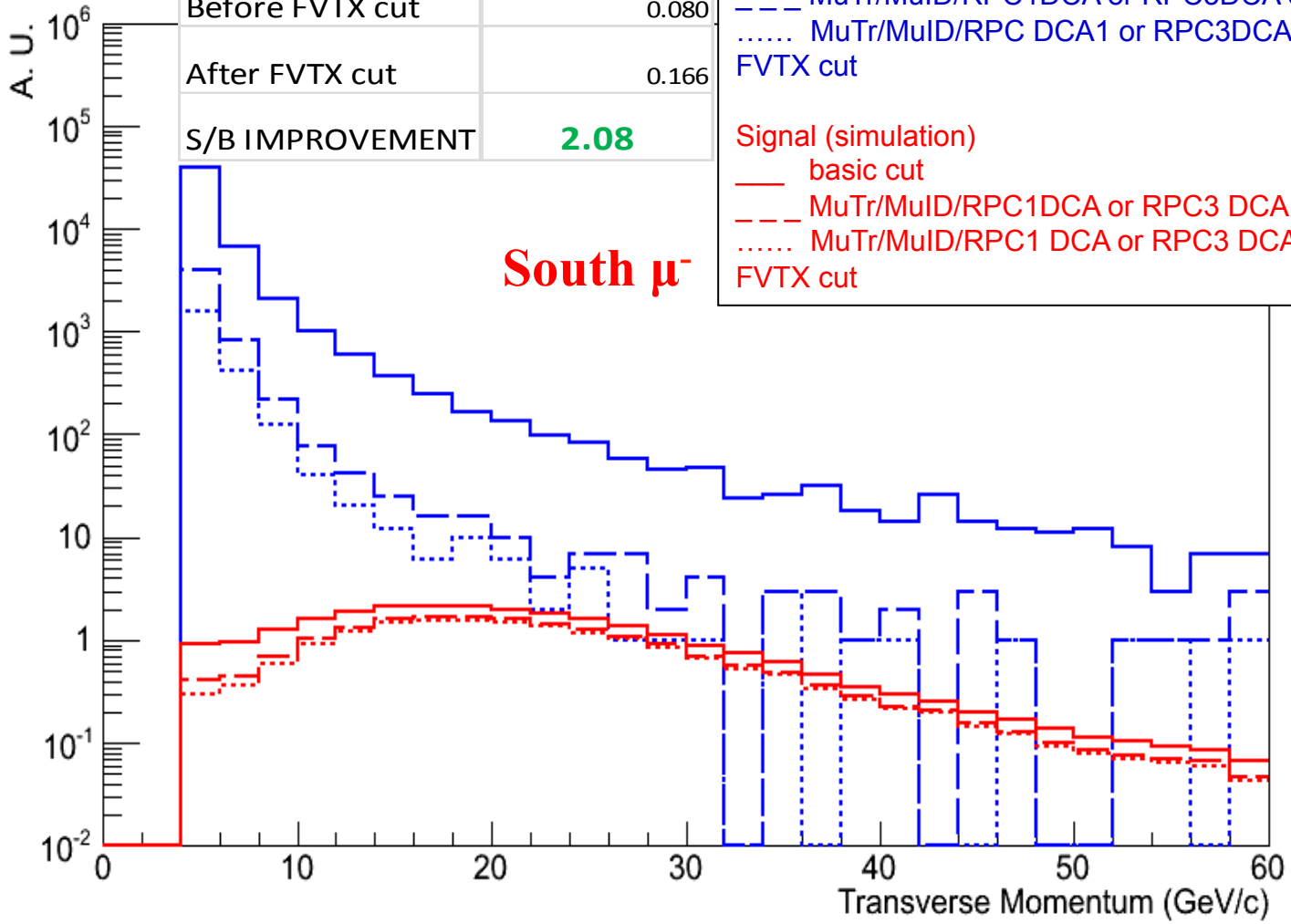


$W \rightarrow \mu$ S/B Improvement with Successive Cut

	S/B=Sig/(Data-Sig)
basic cut	0.007
Before FVTX cut	0.080
After FVTX cut	0.166
S/B IMPROVEMENT	2.08

Background (Run12pp)
___ basic cut
_ _ _ MuTr/MuID/RPC1DCA or RPC3DCA cut
…… MuTr/MuID/RPC DCA1 or RPC3DCA and FVTX cut

Signal (simulation)
___ basic cut
_ _ _ MuTr/MuID/RPC1DCA or RPC3 DCA cut
…… MuTr/MuID/RPC1 DCA or RPC3 DCA and FVTX cut



Abraham Meles

Working on unbined likelyhood method with run 13
W➔μ group

R. Seidl's talk

Isolation Cone Cut

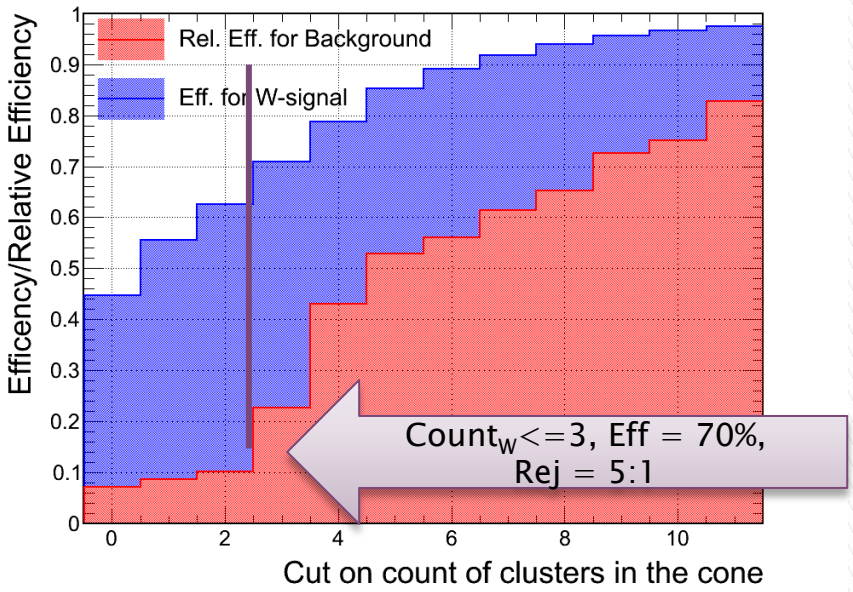


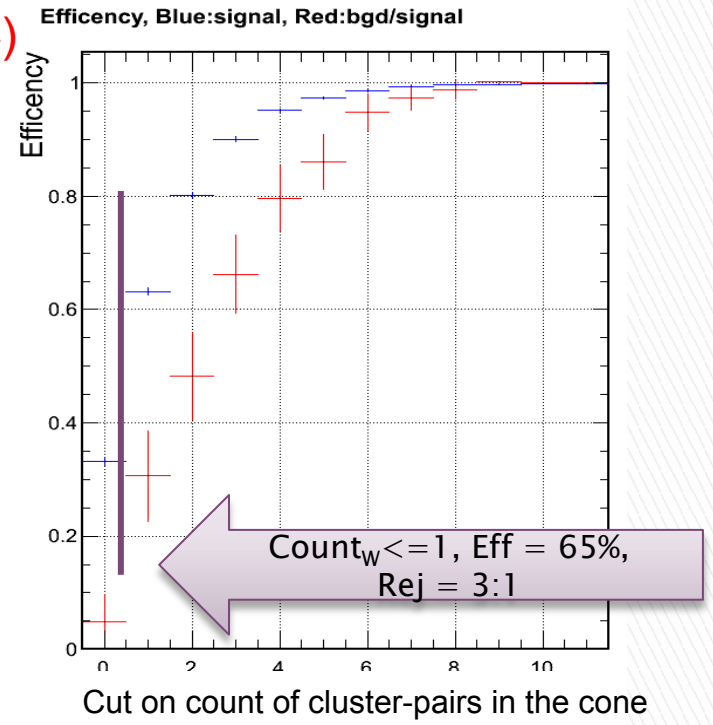
- **For the W/DY signal, the track is usually isolated, but its background events usually come with higher multiplicity**
  - W VS Fake-high P_T background (e.g. hadron from MB jets)
  - DY VS HF background (e.g. bbar and ccbar production)
- **Three ways implemented in the cone isolation study**
  - Tracklet-based – best quality, but lowest stat
  - Cluster-based – highest stat., but vulnerable to background
  - Cluster-pair based – a balance of both

Cone cuts – simulation for |z|<10cm

Evaluated in 510 pp pythia + PISA full event simulation
(no beam and collision background yet)

- Efficiency for W signal
- Relative efficiency for background (Eff_{bgd}/Eff_W)





Cluster based

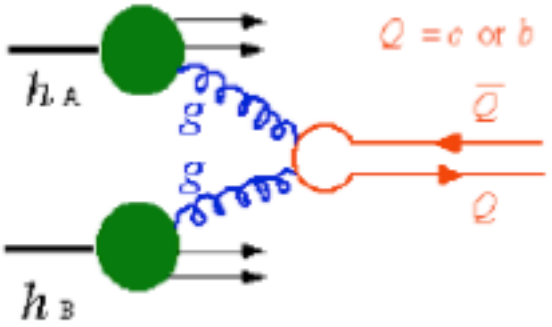
Higher statistics but more vulnerable to beam and collision background

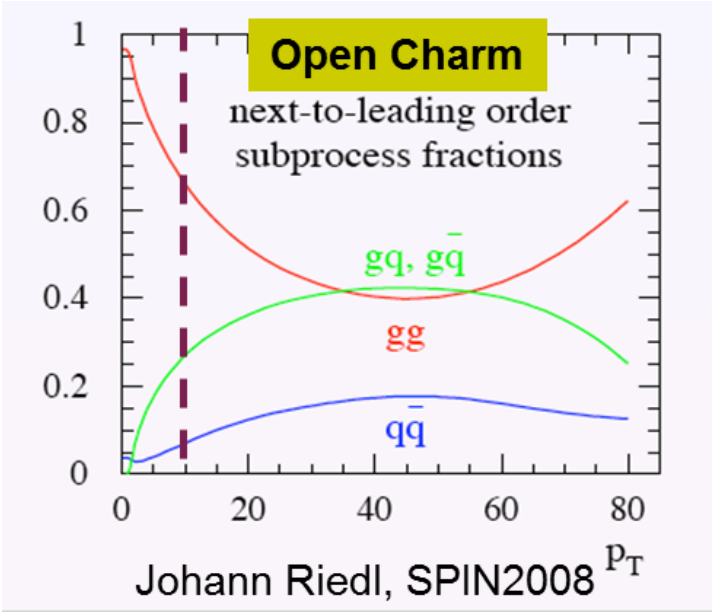
Cluster-pair based

Require at least a pair clusters pointing to the primary vertex, balance of eff. and background

Open Heavy Quark A_N

- **Gluon fusion dominates at NLO**



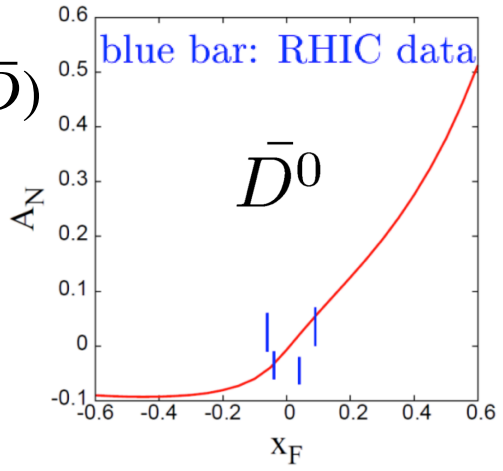


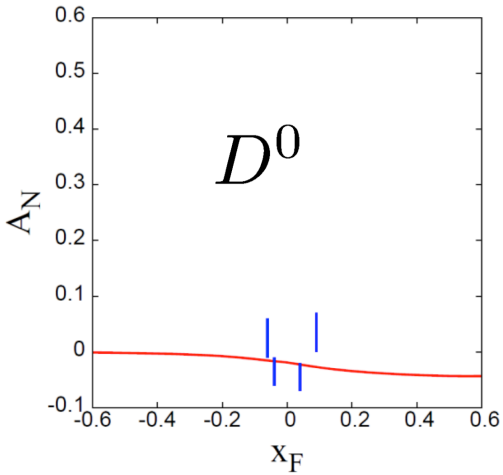
- **Gluon Sivers in TMD framework**
- **Twist-3 Tri-gluon correlation function**

Model 1: $A_N(D) \overset{?}{\neq} A_N(\bar{D})$

$O(x) = 0.004xG(x)$

Koike et al, PRD84, 014026 (2011)
Kang et al, PRD 78, 034005 (2008)

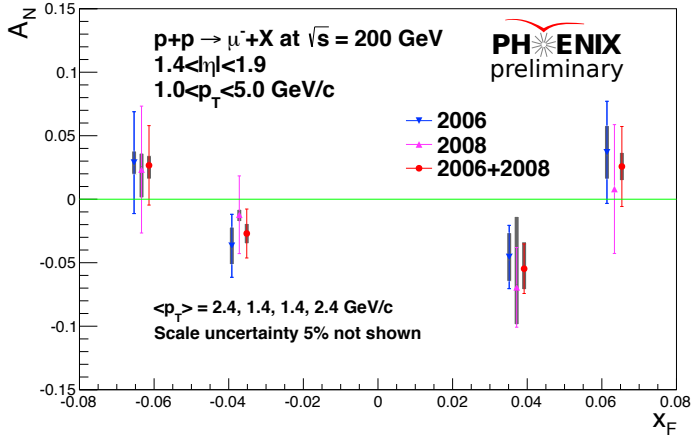


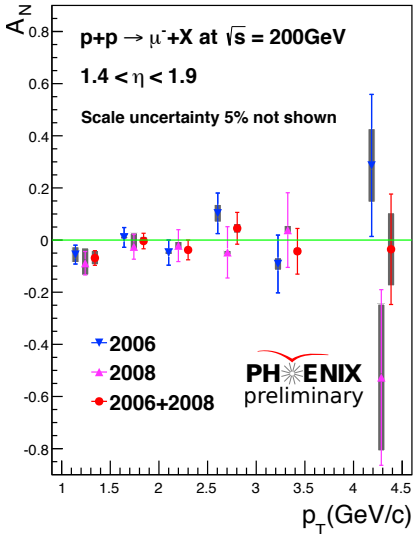


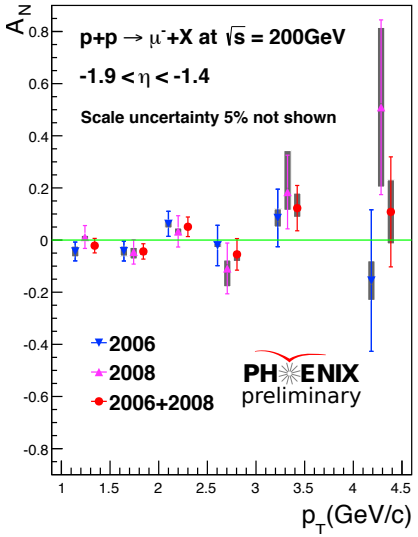
Open Heavy Quark A_N

- **Forward muon arms**
  - Run6 and run8 data $1.2 < |\eta| < 2.4$

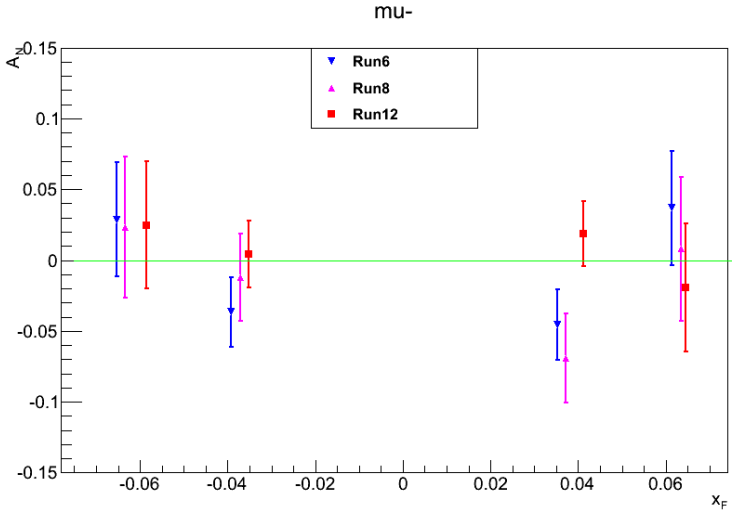
F. Wei, M. Liu, X. Wang







- **Run12: working in progress**
  - Need Cross section measurement from run12 to understand signal / background ratio.
  - need more understanding of Run12 muon triggers.

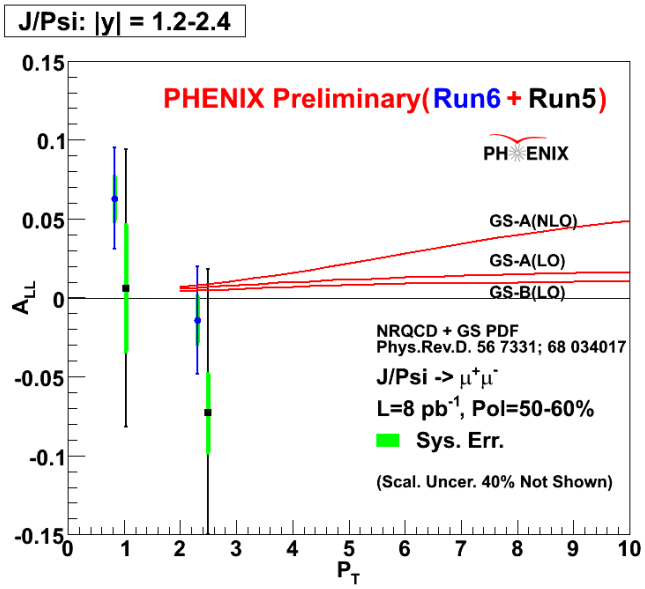


J/Ψ A_{LL} Measurement in p + p 500 GeV

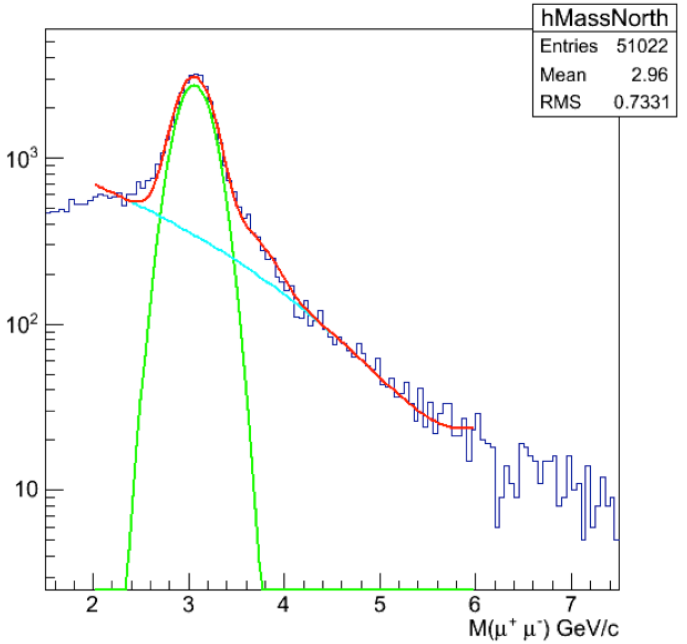
- **Probing gluon contribution with heavy flavor channel**

Run11: 27 pb^{-1}
Run12: 42 pb^{-1}
Run13: 148 pb^{-1}

H. Yu, A Key, J Huang
M. Liu, X. Wang



Di-muon mass, North arm

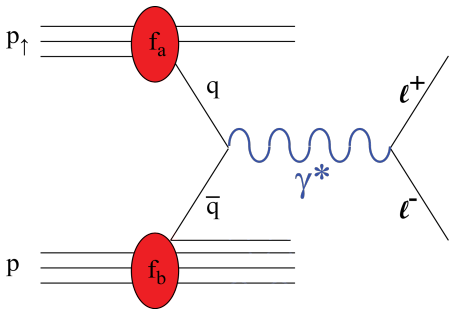


Background Fraction from Run11

pT range	South Arm (r)	North arm (r)
0-6 GeV	0.243	0.233
0-1 GeV	0.295	0.266
1-2 GeV	0.243	0.236
2-3 GeV	0.230	0.200
3-6 GeV	0.202	0.189

Drell-Yan A_{LL} Measurement with FVTX

- Drell-Yan A_{LL} can access $\Delta \bar{u} / \bar{u}$ which gives the anti-quark helicity distributions in the nucleon sea.



$$A_{LL}^{DY} = -\frac{\sum_q e_q^2\{\Delta q(x_1)\Delta\bar{q}(x_2) + \Delta\bar{q}(x_1)\Delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

$$\approx -\frac{\Delta u(x_1)}{u(x_1)} \cdot \frac{\Delta\bar{u}(x_2)}{\bar{u}(x_2)}$$

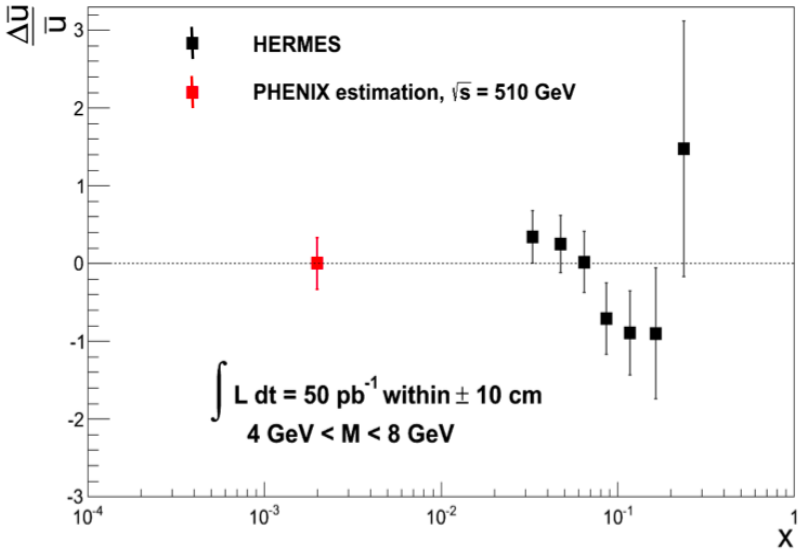
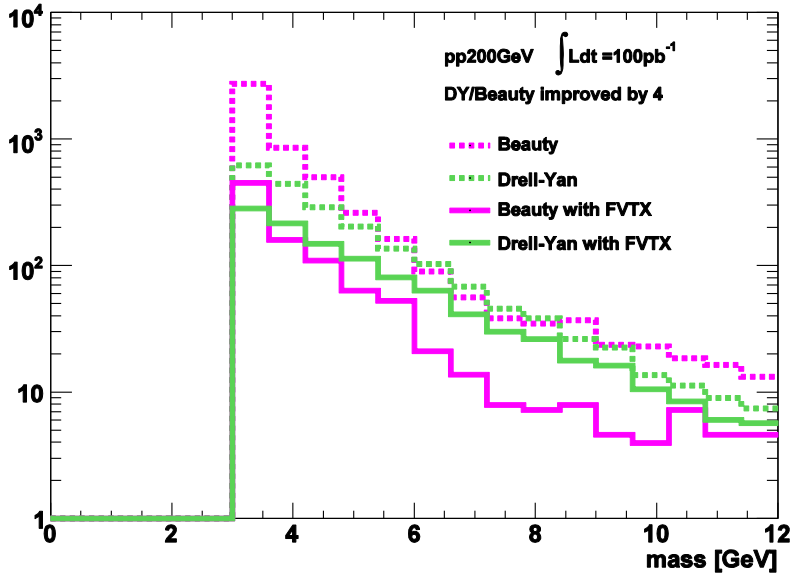
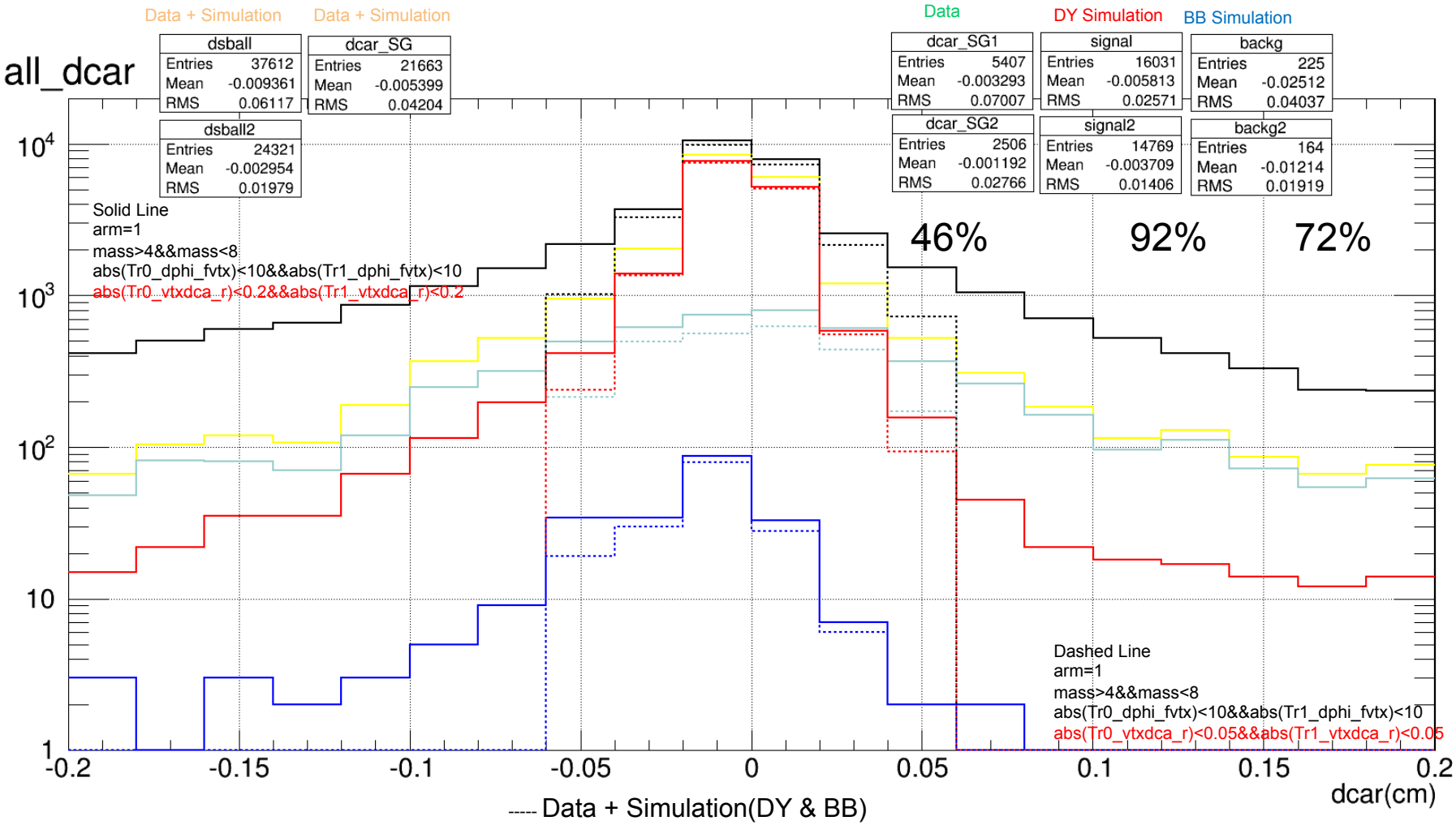


Fig. Δu/u as function of x. PHENIX has <x> ~ 2*10^{-3}

FVTX reject b-bbar background



Run 13 : DCA_R Distribution



---- Data + Simulation(DY & BB)

---- Data After combinatorial background removal + Simulation

---- DY Simulation

---- BB Simulation

---- Data after combinatorial background subtraction

D. Perera

SUMMARY and OUTLOOK

- FVTX has been taking data successfully in run12 and run13.
- FVTX joined run13 $W \rightarrow \mu$ analysis. Cone Isolation and matching variables still need further study.
- Heavy flavor is unique channel to understand gluon Sivers and tri-gluon correlation function. Run12 heavy flavor A_N is working in progress.
- J/Ψ A_{LL} measurement with much better statistics data set is working in progress.
- We also exploring the feasibility to study forward Drell-Yan with FVTX. Drell-Yan A_{LL} with FVTX will allow us access $\Delta\bar{u}/\bar{u}$.
- Interested in involving fsPEHNIX simulation effort.

fsPHENIX Physics Program and Detector

Joe Seele (RBRC)

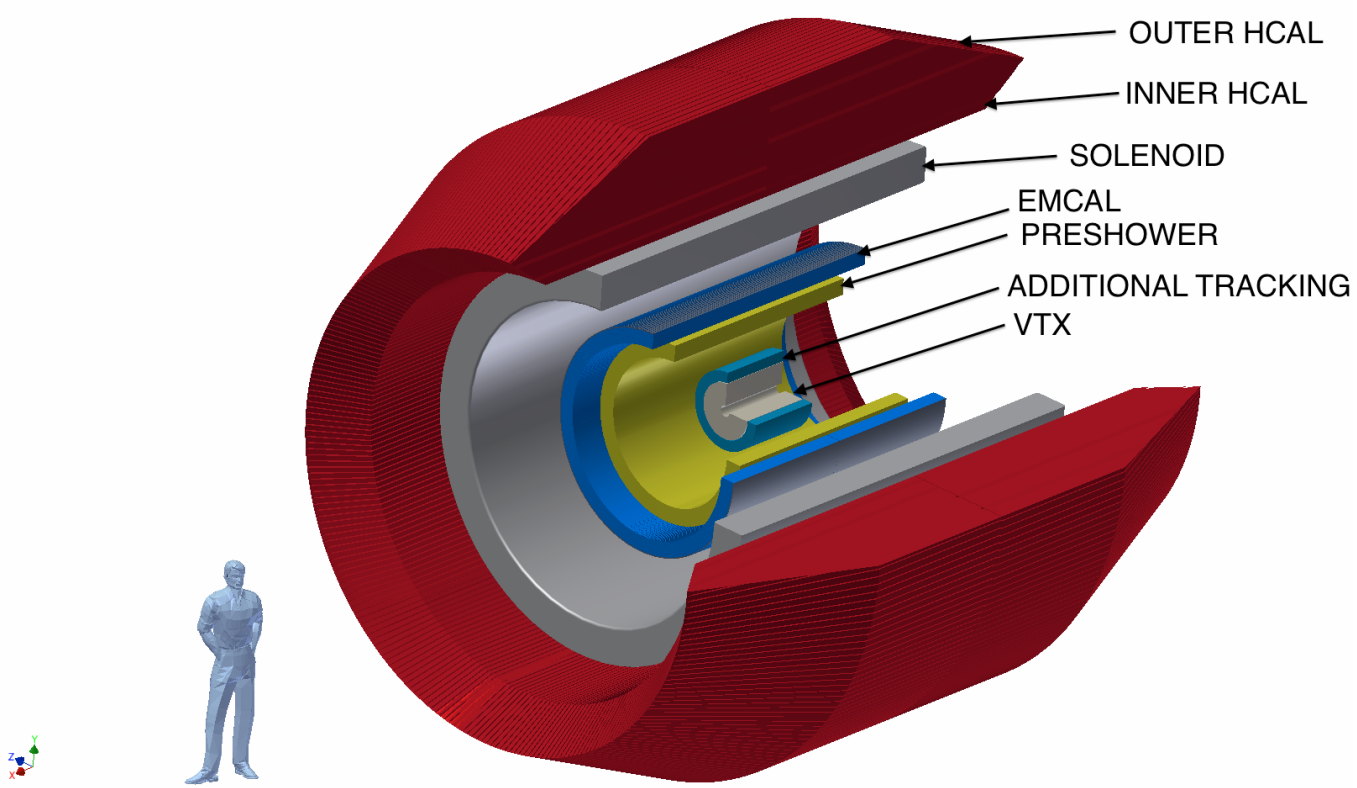
RBRC Scientific Review Committee

10/31/13

Outline

- Physics Program Review
- Design Parameters
- fsPHENIX Detector Overview

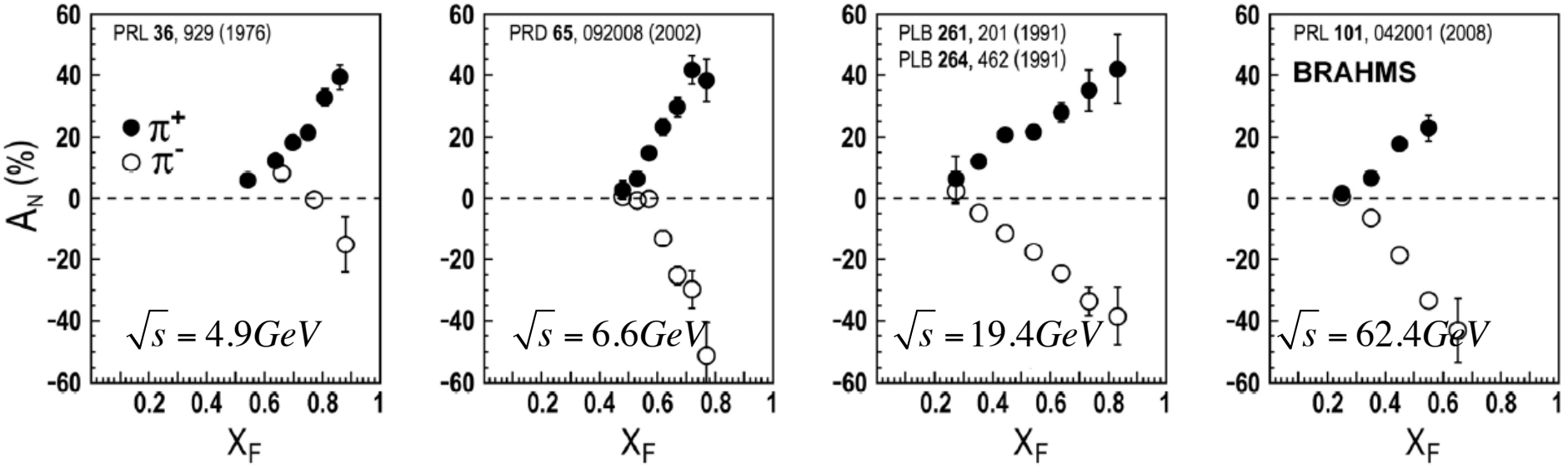
Plugging the hole(s) in sPHENIX



There is a long standing PHENIX tradition that when there is space anywhere in one of our detectors, we plug it by adding new detectors.

Forward Spin Physics - I

Large, forward A_Ns in hadron production in p+p (p+A) have been measured since the mid 70's

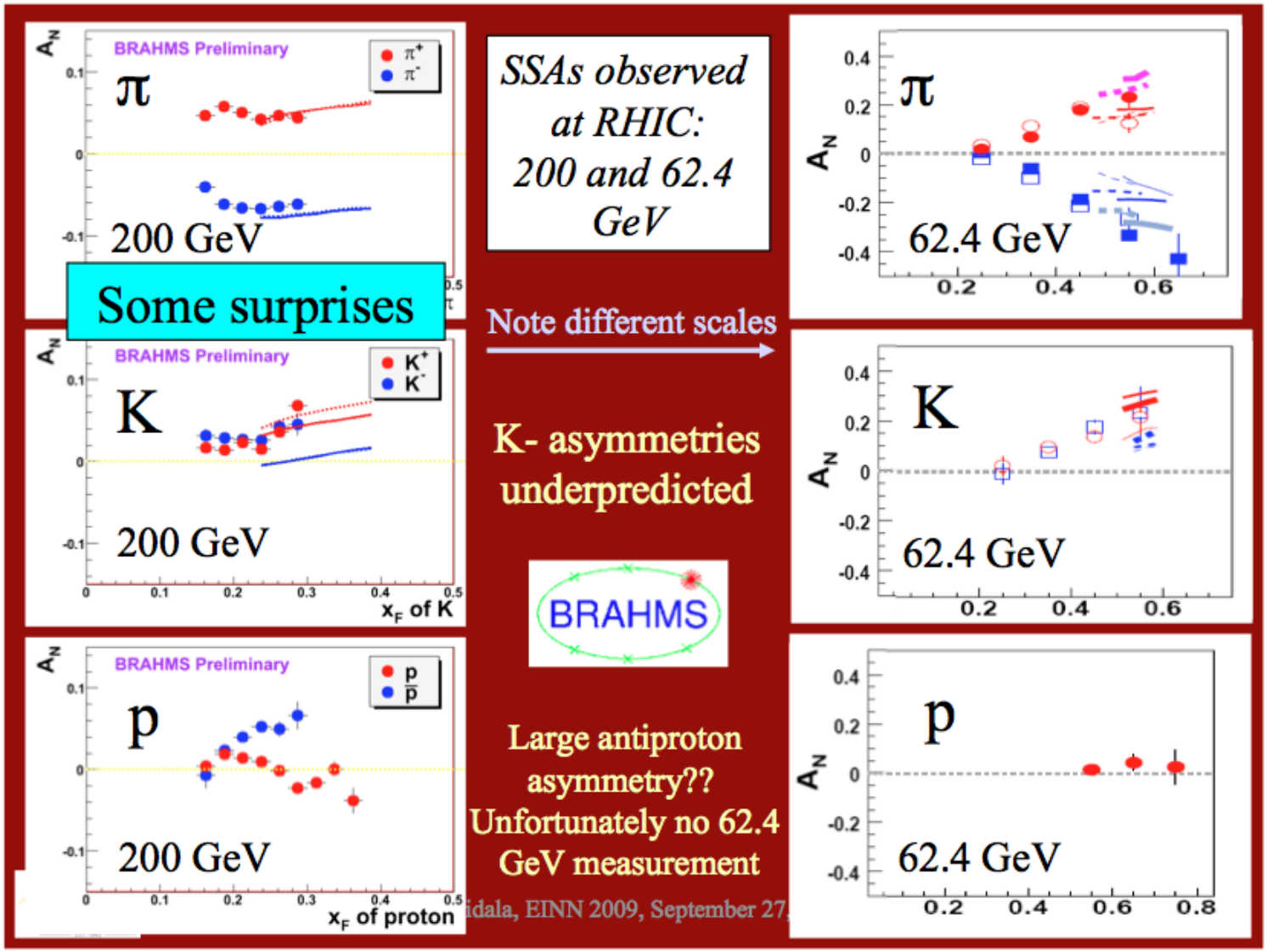


The asymmetries persist from low CM energies to high CM energies. $x_F = \frac{2p_L}{\sqrt{s}}$

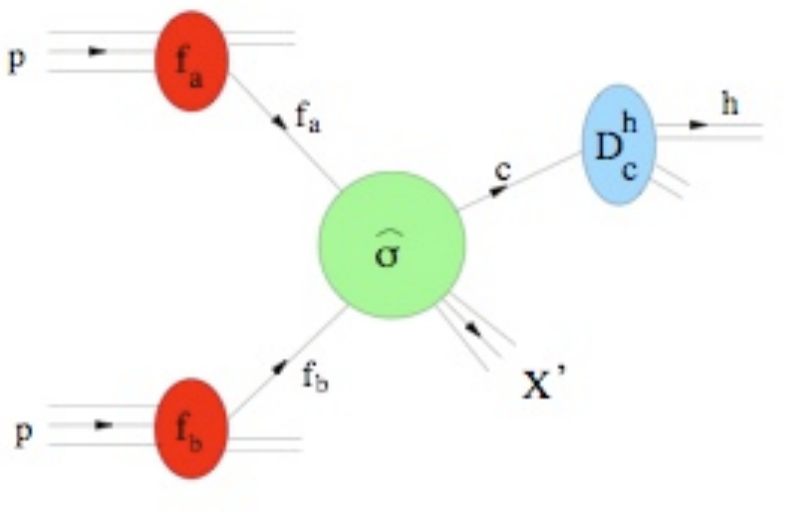
A simple (collinear) pQCD calculation tells us that an A_N can exist, but that it should scale like

$$A_N \approx \frac{m_q \alpha_S}{p_T}$$

Forward Spin Physics - II



Forward Spin Physics - III



Since the mid to late 90's new extended factorization schemes (TMD and Twist-3) have provided a new mechanism to generate single spin asymmetries in these collisions.

1. Initial-state (Sivers-type) spin-momentum correlations – Considers intrinsic transverse momentum in the nucleon and initial-state interactions
2. Final-state (Collins-type) spin-momentum correlations – Considers transverse momentum inside a jet and final-state interactions
3. Other Higher Order Correlations

A_N ~ (Initial State Piece) + (Final State Piece) + (h.o.t.)

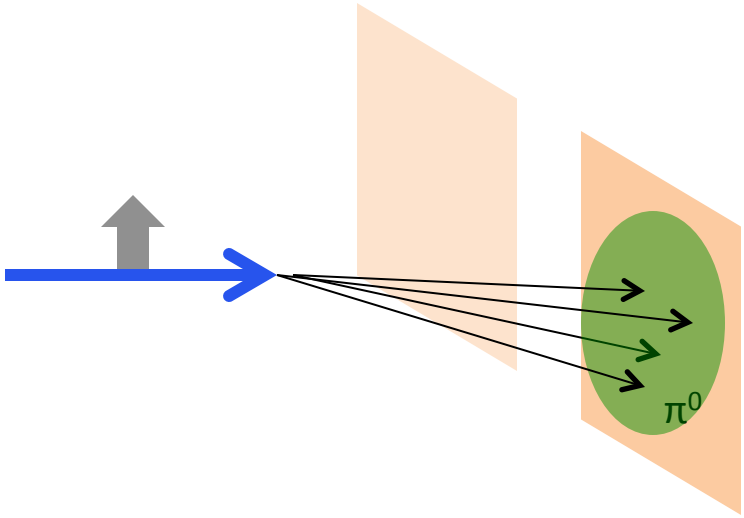
Forward Spin Physics - IV

With a good enough jet detector, we can unambiguously separate these pieces

Initial State Piece

Jets with identified hadrons (measure A_N for jets)

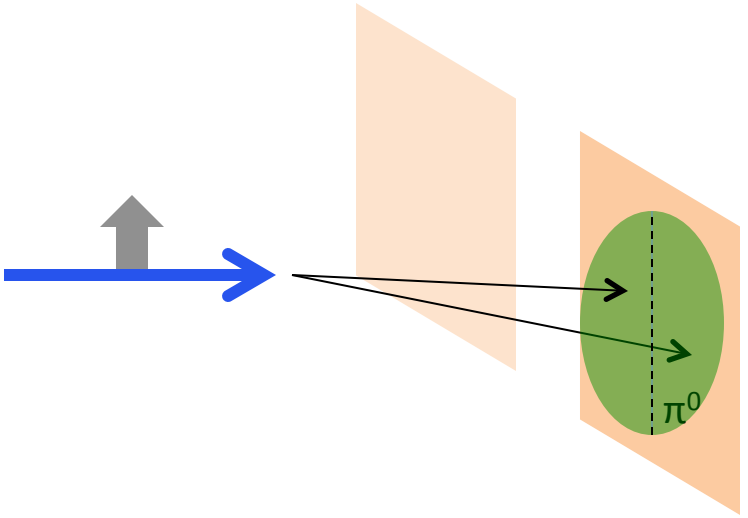
Do jets from certain quarks prefer to go left or right?



Final State Piece

Left-right asymmetry of identified particle inside a jet

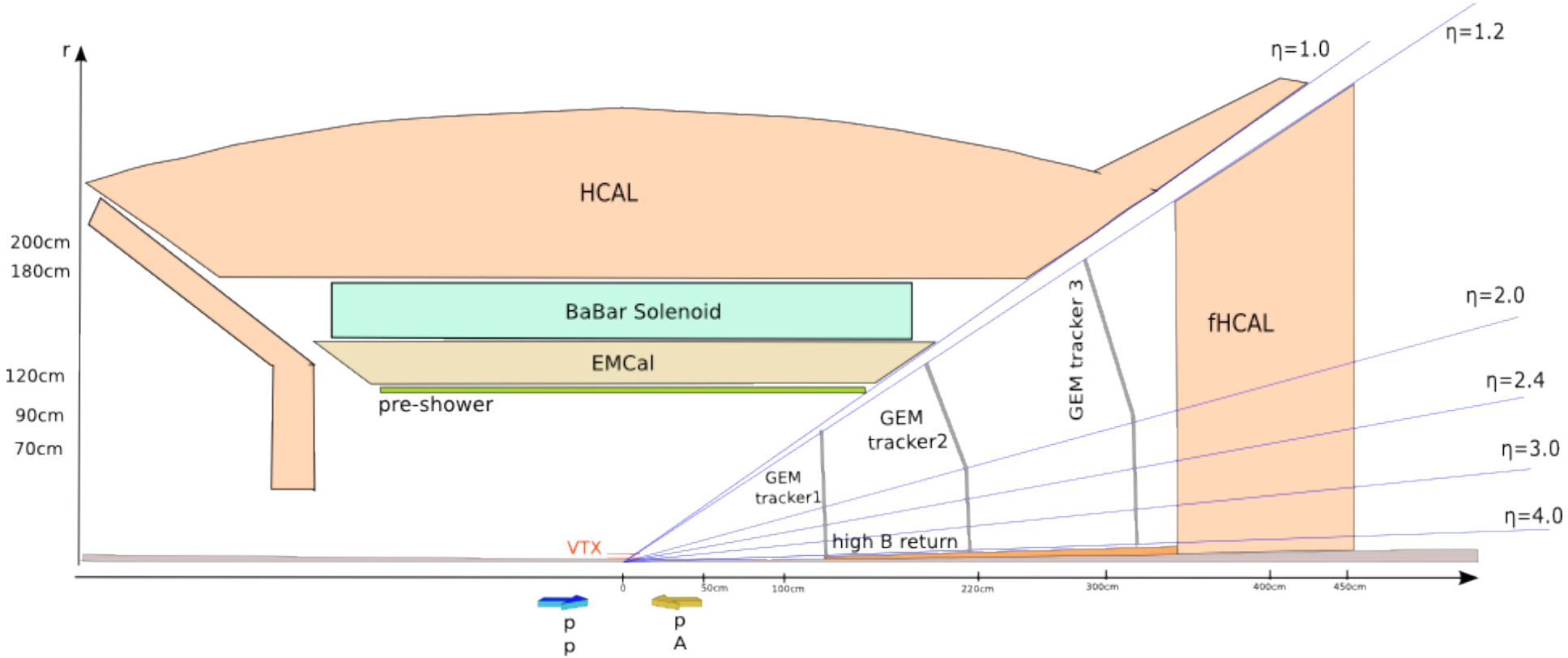
Do certain hadrons fragment from certain quarks to the left or right of the jet axis?



Design Parameters for Hadrons+Jets

- Tracking
  - Reconstruct charge sign to high momentum (dp/p ~ 0.004p for 3-sigma charge sign reco at p~60 GeV)
  - Have enough momentum resolution to use RICH (dp/p ~ 0.004p for reasonable ring separation between species)
- Calorimetry
  - For p+p/p+A , not very constrained
    - For A+A you need fine segmentation, especially at high eta
  - Reasonable energy resolution for jets and EM particles
- Hadron PID
  - Pi/K/p separation above a few GeV and to a high momentum (p~70)

fsPHENIX : A Detector Concept



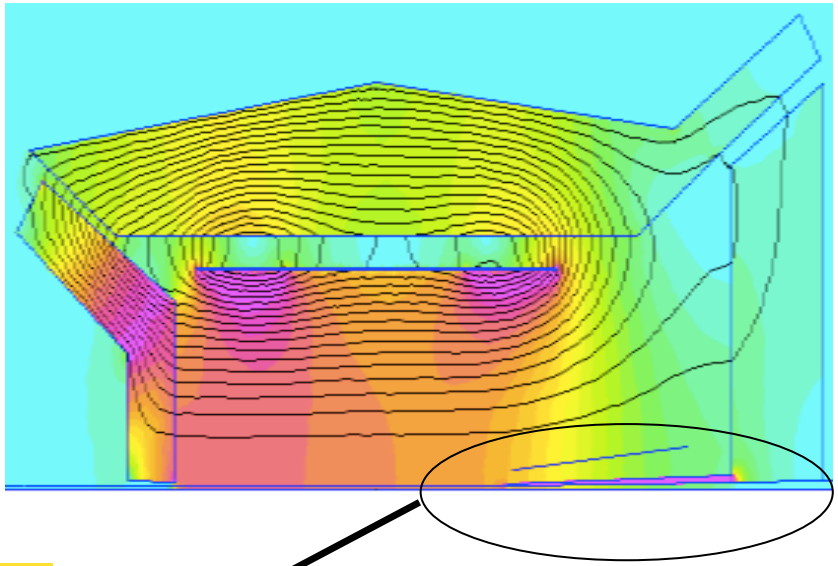
- Designed with modularity in mind (probably only be able to build detector from 2<eta<4)
- Designing all pieces to be part of an ePHENIX detector

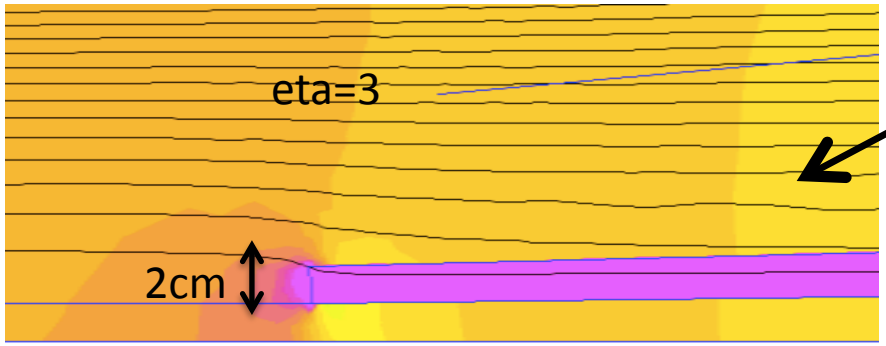
Magnet and Tracking – I

How to shape magnetic field without causing too much stress or background is the most challenging part of the fsPHENIX design

Explored many configurations

- No forward field
- Forward dipole
- Forward toroid
- Needle piston shaper



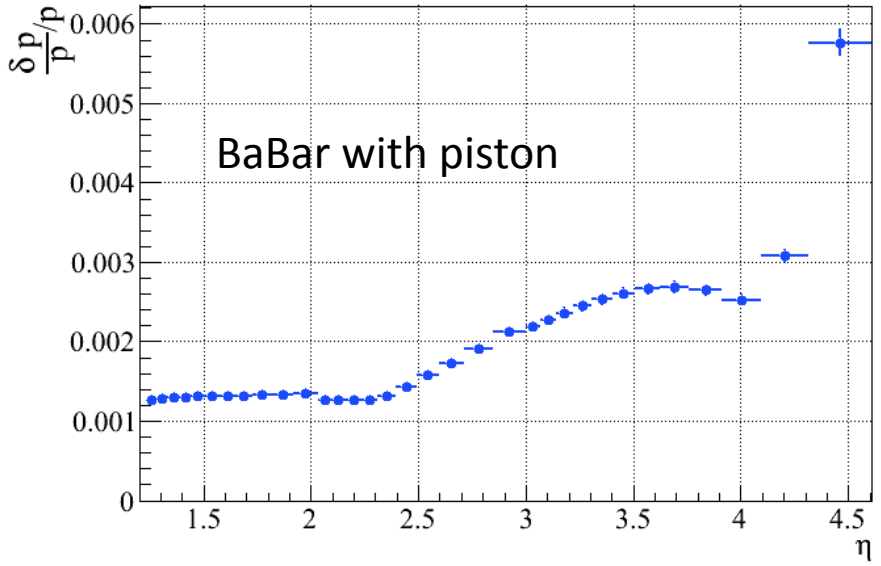


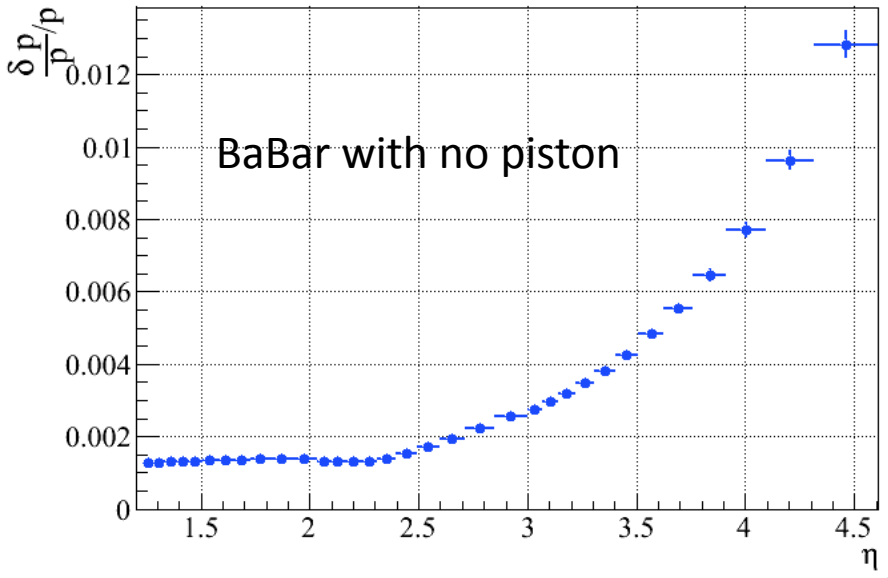
Hiperco-50 (49%Co+49%Fe alloy) passive field shaper provides a boost in the field strength at high eta

Beam pipe radius: (z=0)=2cm; (z=340)=5cm

Magnet and Tracking - II

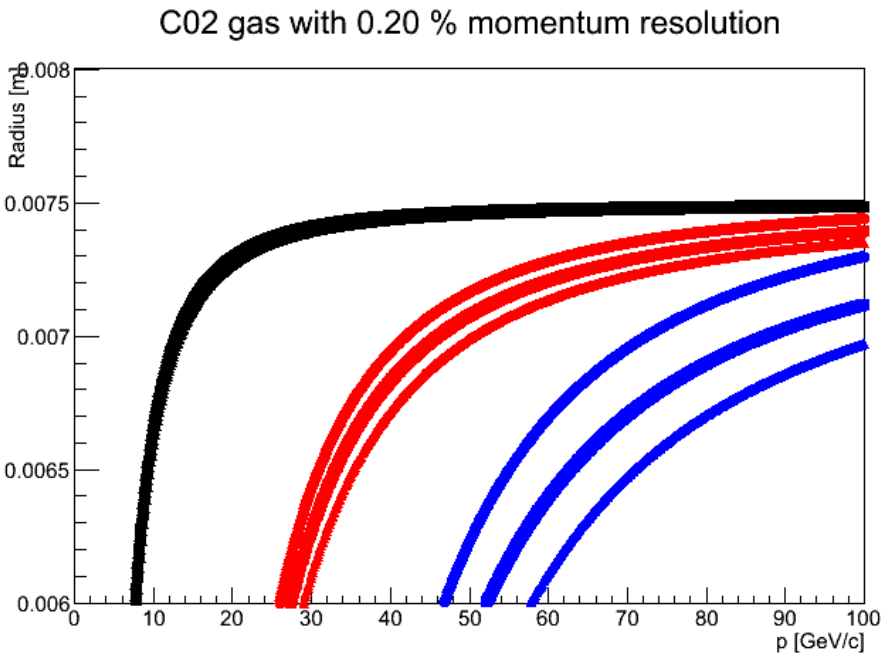
- With the passive field shaper + BaBar magnet we are able to achieve the necessary resolution over a large range in pseudorapidity
- The resolution calculation is only based on sagitta measurement (0.1m*, 1.25m, 3.0m)
- Can get improved resolution with a full tracking+Kalman Filter or Si detector at small angles

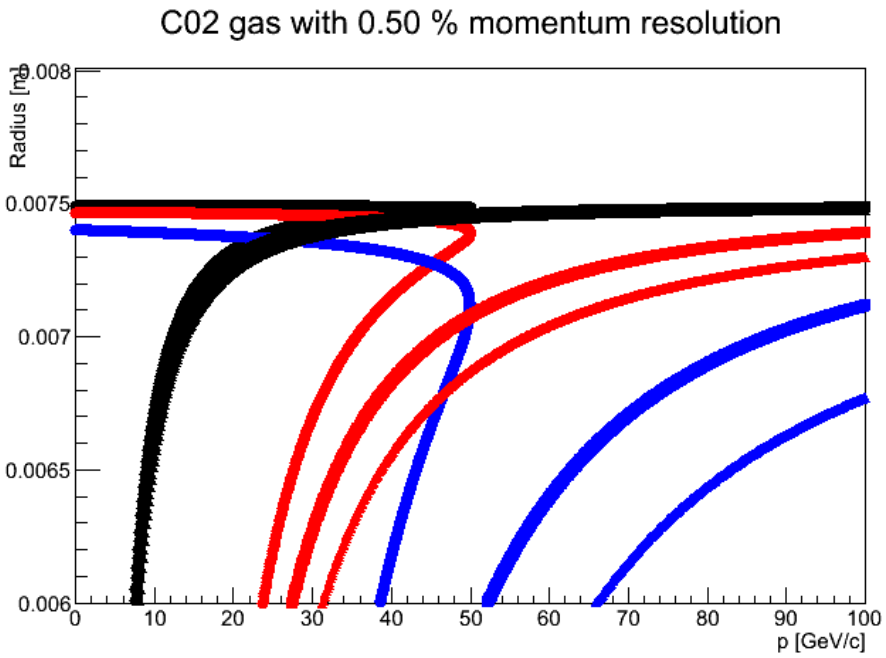




Hadron PID

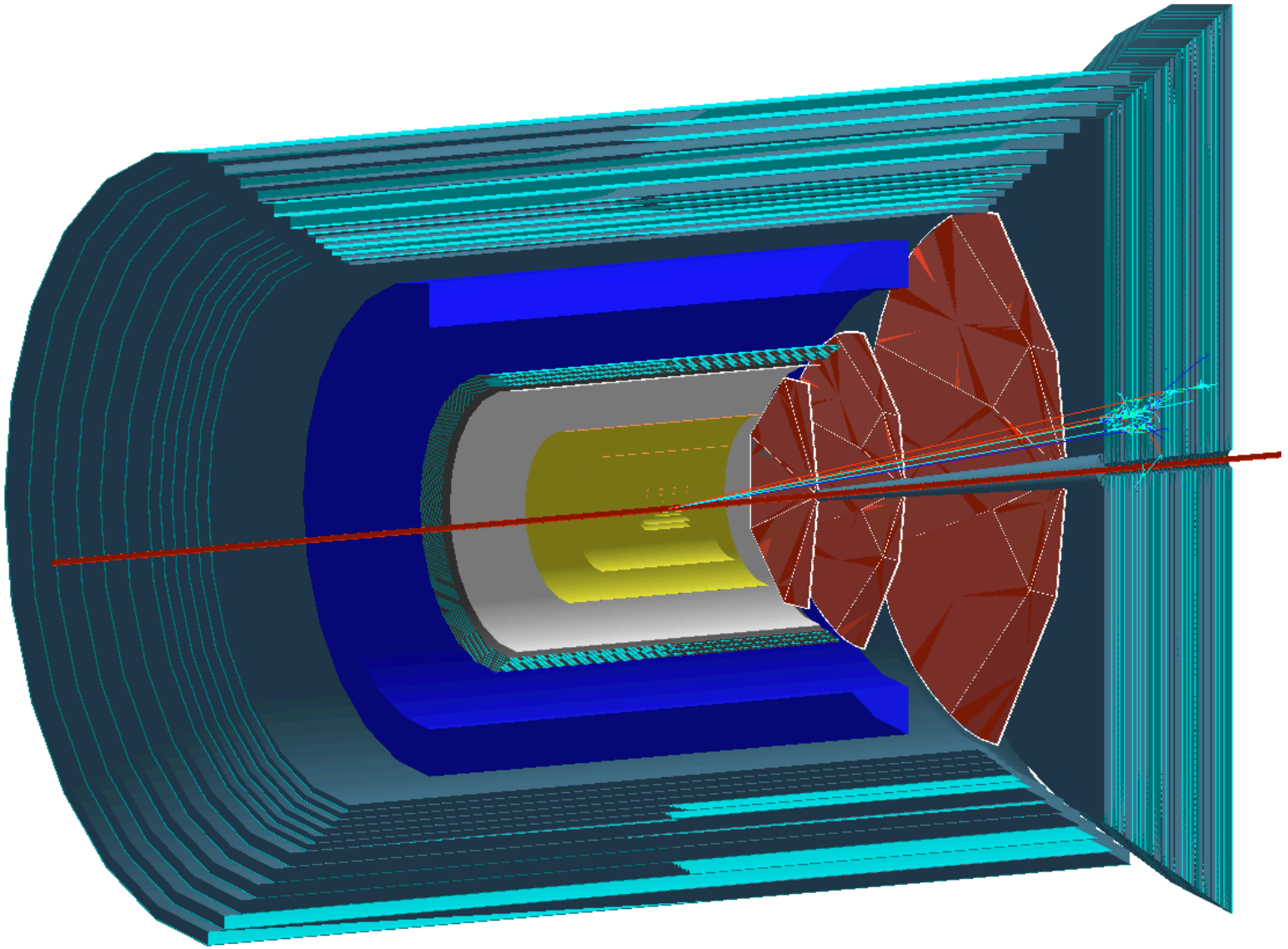
For the hadrons/jets program it is very important (and powerful!) to know the flavor of the hadron.





- 0.2% clearly good for what we need (ignoring detector resolution and other caveats from earlier)
- 0.5% good for much of the physics, but would get everything we'd like

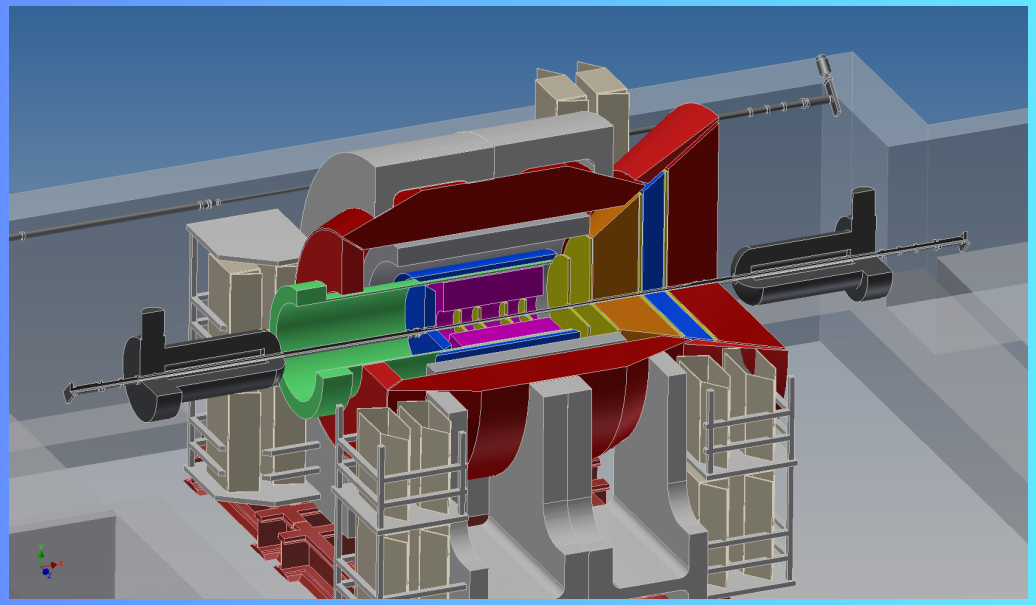
GEANT Simulation of Forward Jet Event



Conclusions

- fsPHENIX will explore a rich area of transverse spin physics (as well as other areas not covered in this presentation, i.e. Drell-Yan, Cold Nuclear Matter)
- The fsPHENIX design is rapidly maturing as the understanding of the physics requirements is maturing
- We have a GEANT simulation up and running and are exploring the parameter space for the detector
- Through a charge from the ALD we expect to have a document outlining the physics and detector potential next spring.

Letter of Intent for



ePHENIX

Kieran Boyle (RIKEN BNL Research Center)

Letter of Intent

- Charge from BNL ALD to PHENIX and STAR to:
  - "Provide specific plans to upgrade/reconfigure the detectors from their present form to first-generation eRHIC detectors"
  - Describe "the physics reach of the upgraded detector"
    - Considering key measurements as described in EIC White Paper (A. Accardi, et al., arXiv:1212.1701)
    - Given expected performance requirements

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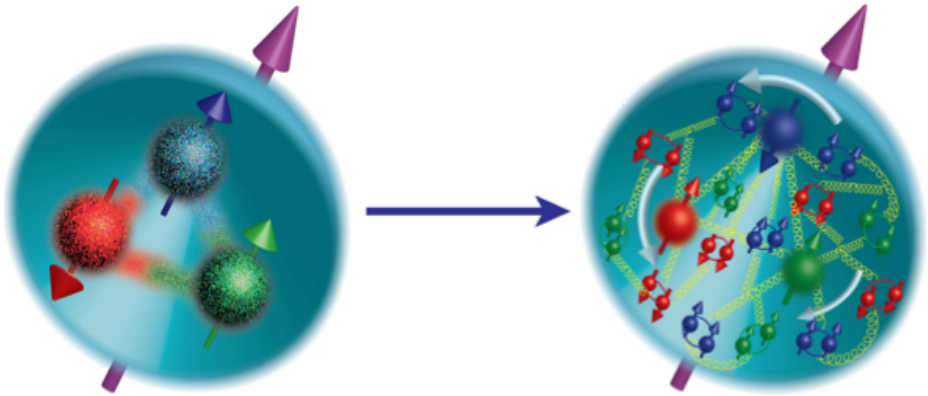
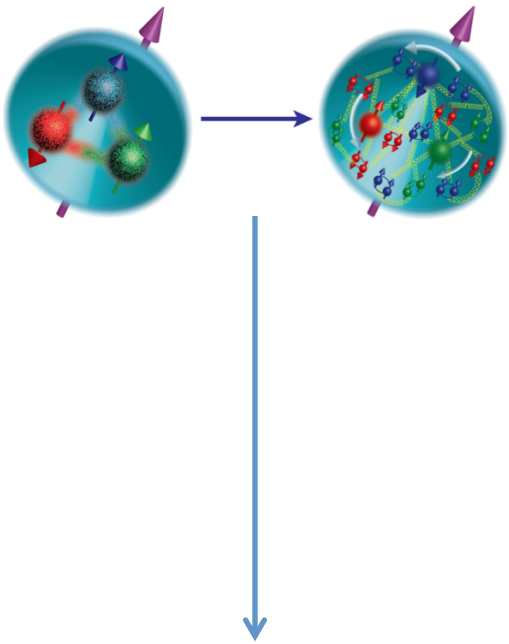
- ePHENIX LOI Writing Committee formed in May
  - Sasha Bazilevsky (co-chair), **KB** (co-chair), **Abhay Deshpande**, Jin Huang, Tom Hemmick, **Itaru Nakagawa**, Craig Woody, John Haggerty, Dave Morrison, Jamie Nagle
- Formally submitted Sept. 27th, 2013.
  - http://www.phenix.bnl.gov/phenix/WWW/publish/dave/PHENIX/ePHENIX_LOI_09272013.pdf

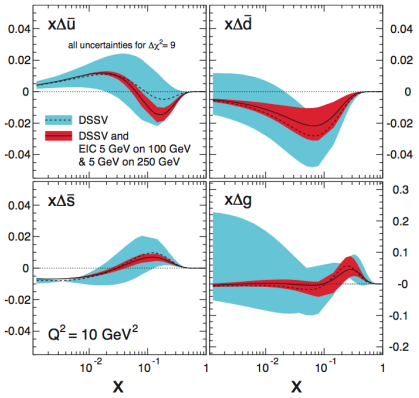


EIC Physics

e+p: Proton Structure



Helicity



A. Accardi, arXiv: 1212.1701

- With eRHIC, significantly improve understanding of proton structure:
  - Helicity Structure
    - Inclusive DIS: $\Delta g(x)$
      - determine gluon spin contribution to proton
    - SIDIS: $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$
      - Test assumptions of large Δs

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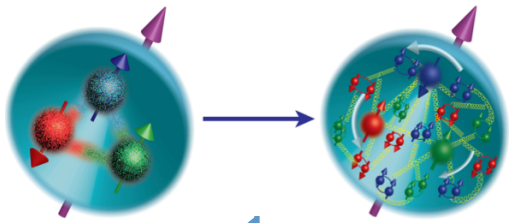
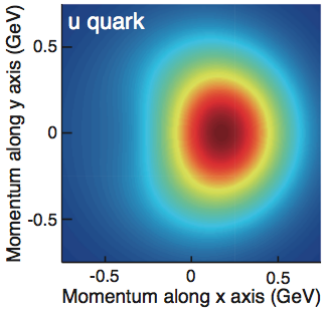
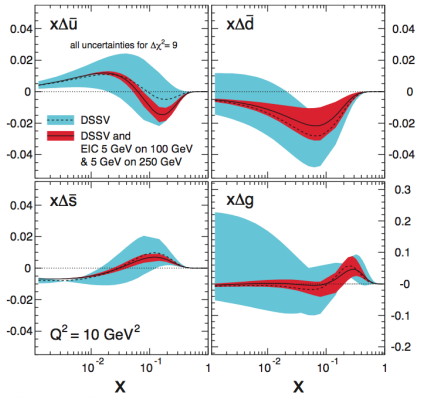


TMDs



Helicity



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  - TMDs
    - SIDIS:
      - Correlations between parton k_T and proton spin
      - Test TMD evolution

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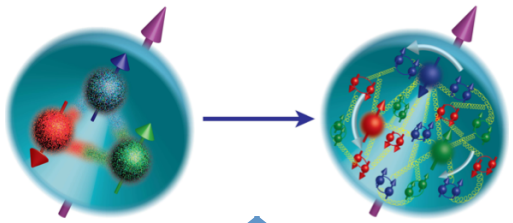

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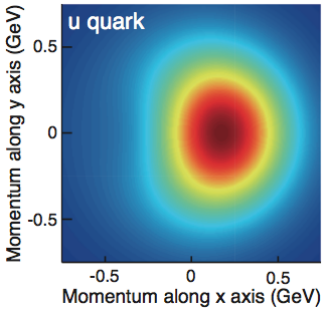
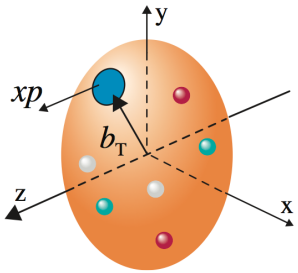
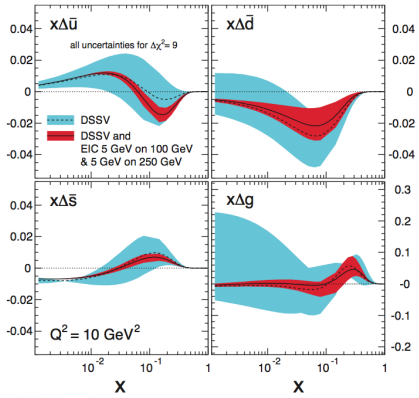


GPDs



Helicity



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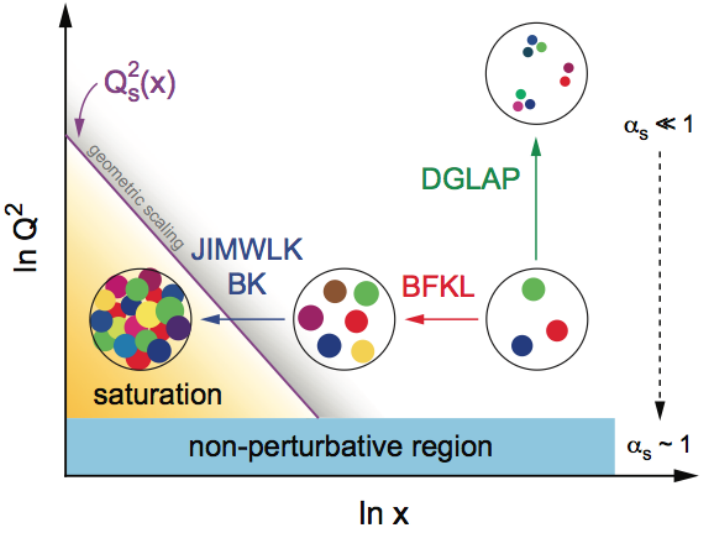
    - SIDIS:
      - Correlations between parton k_T and proton spin
      - Test TMD evolution
  - GPDs:
    - Exclusive DIS: DVCS, J/ψ
      - Image sea quark and gluon distributions in proton
      - Access OAM of partons

e+A

- Gluons at high density
  - Want to understand region where gluon splitting and recombination balance
  - → Saturation
  - e+A collisions allow access to lower x in perturbative regime than previous machines



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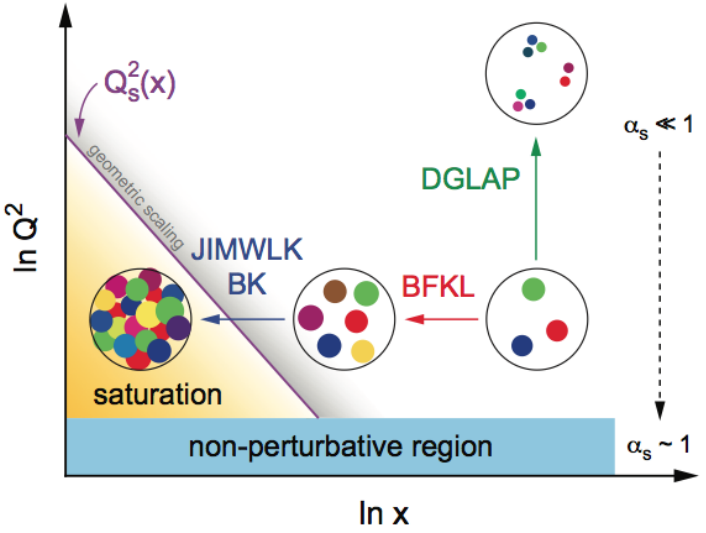
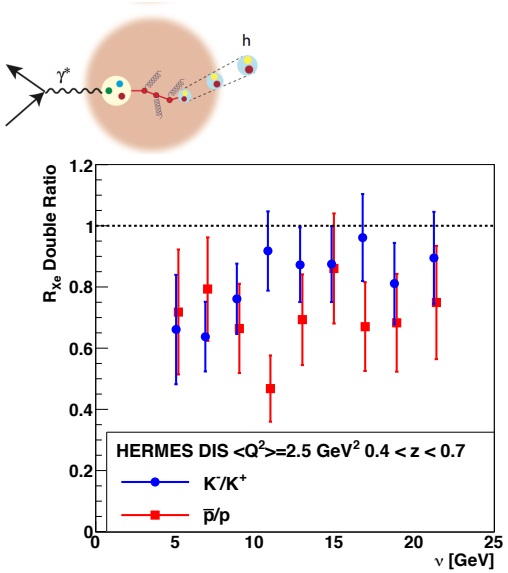
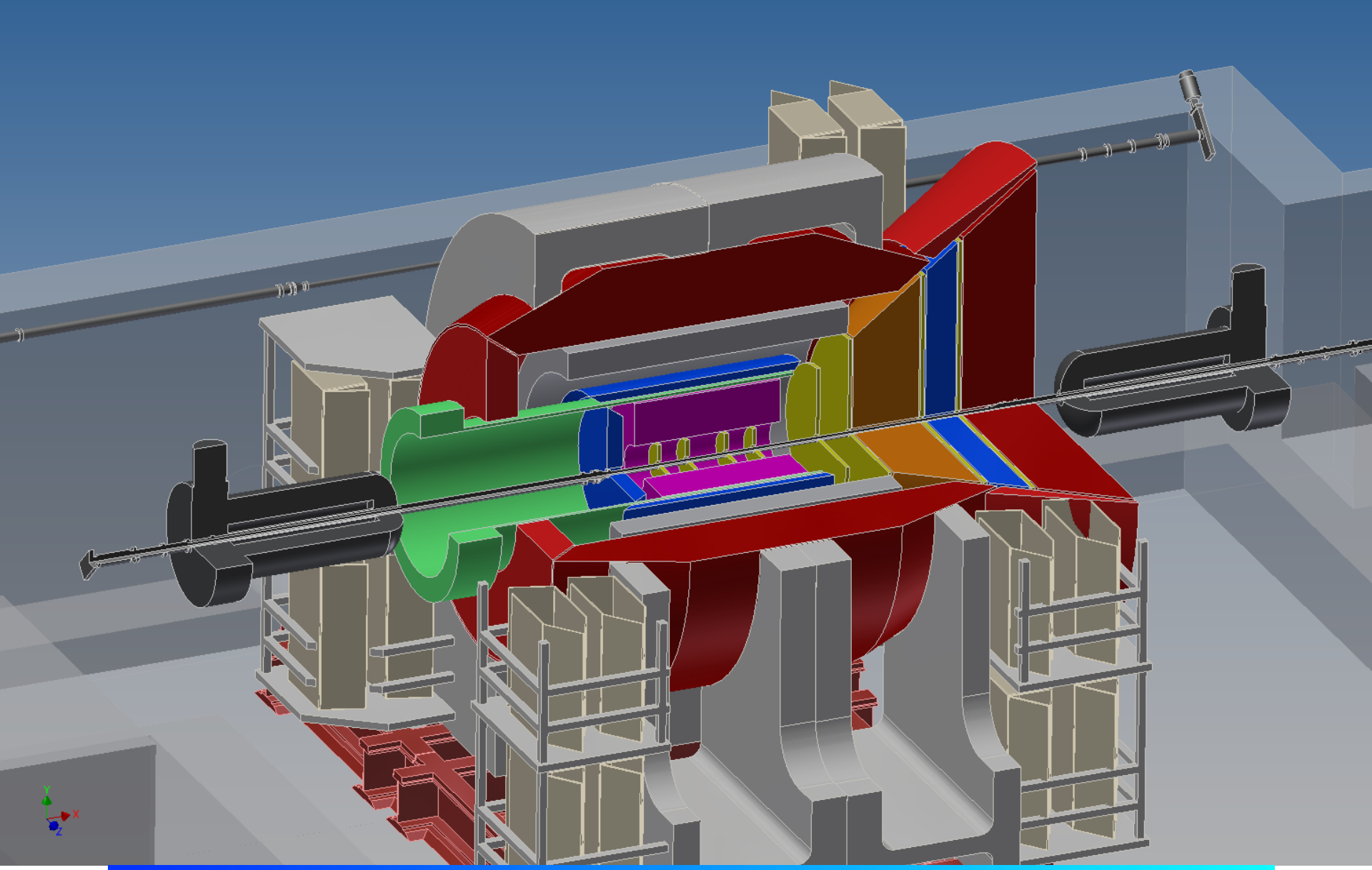


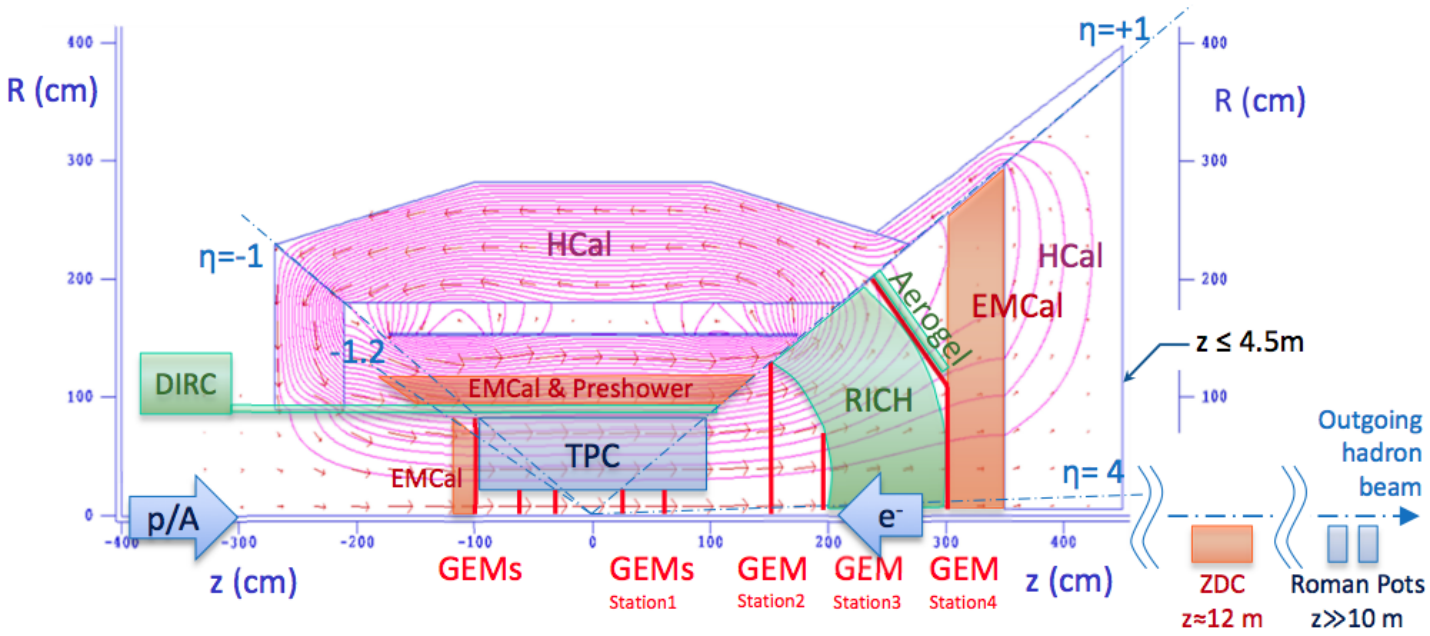


- Hadronization modification in a nuclear medium
  - Variation of ion species
    - "Control" over if hadronization in medium or vaccum
  - R_{Xe}^{K-}/R_{Xe}^{K+} and R_{Xe}^{pbar}/R_{Xe}^{p} show difference from 1
    - What is source?
  - Understanding suppression

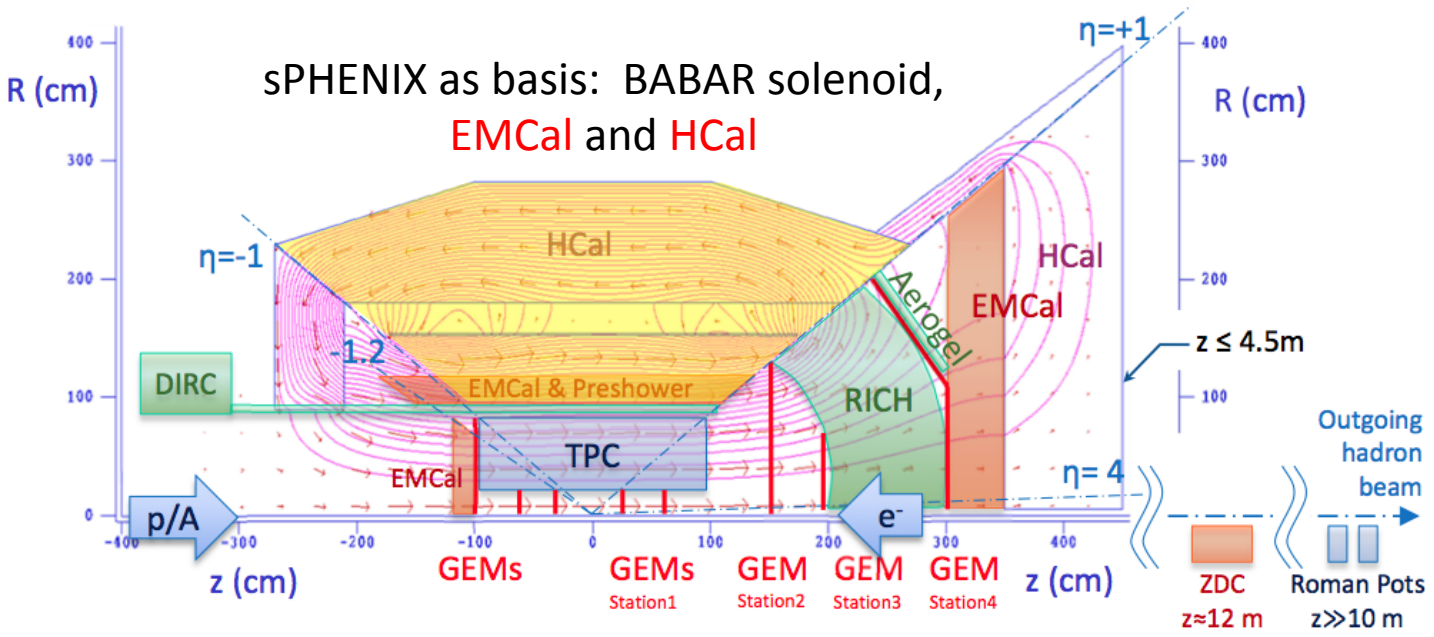


ePHENIX DETECTOR CONCEPT

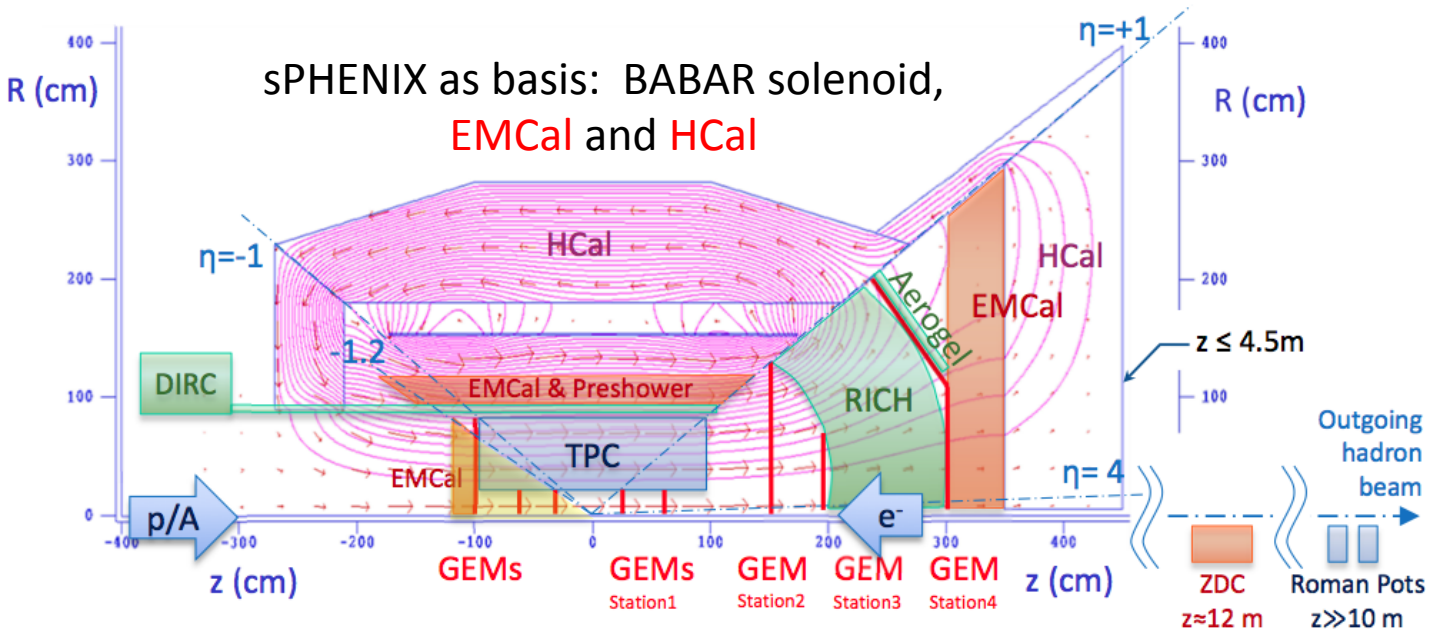
ePHENIX Detector Concept



ePHENIX Detector Concept

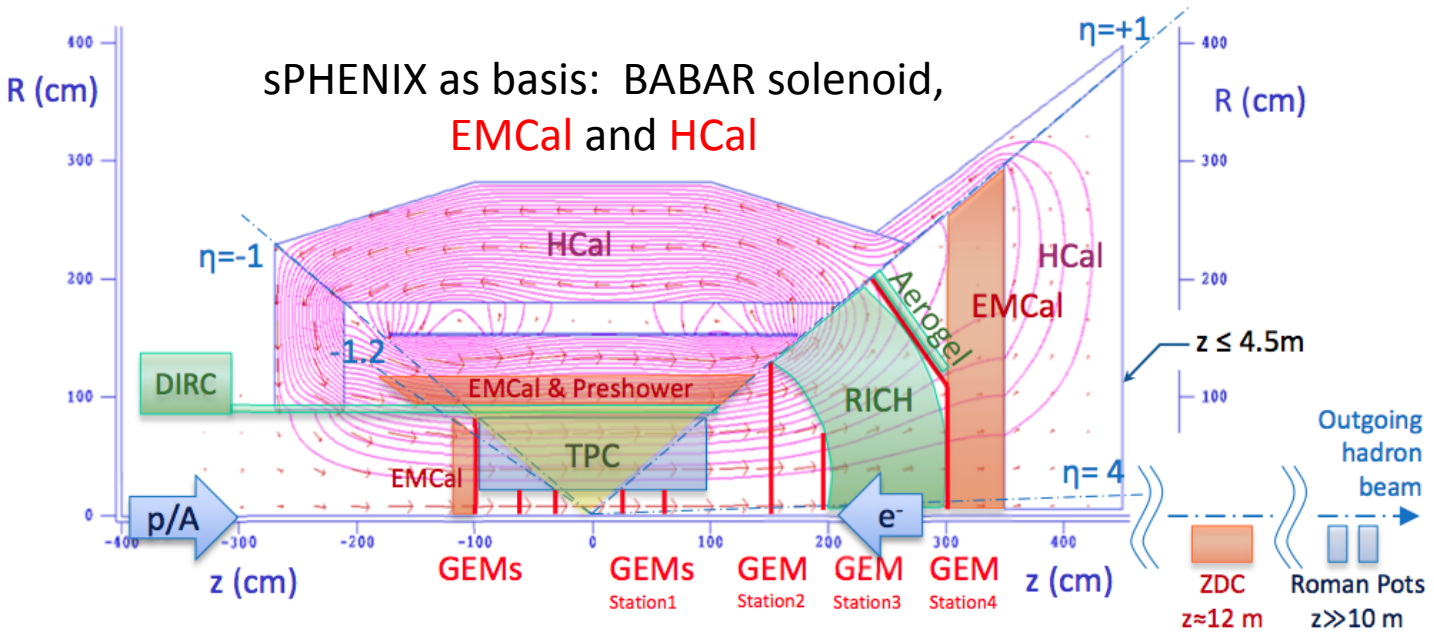


ePHENIX Detector Concept



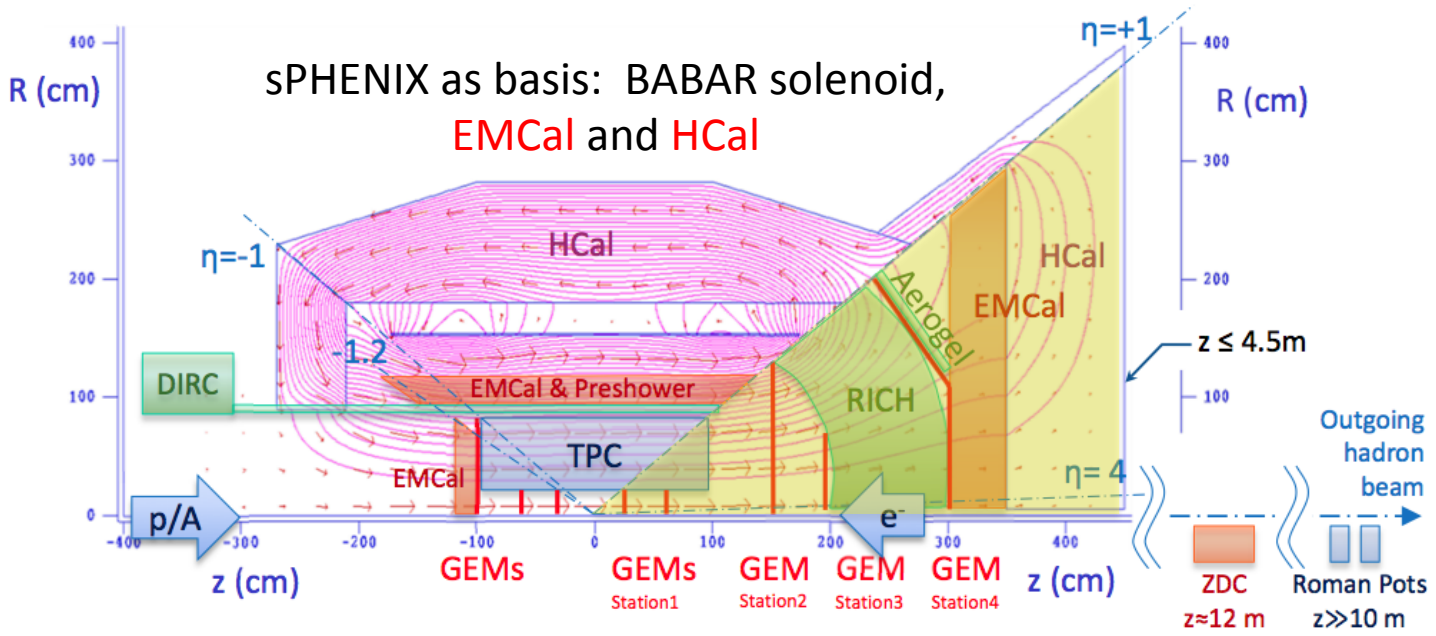
- -4<η<-1 (e-going):
  - Crystal calorimeter with good (1.5%) Energy resolution
  - GEM Trackers

ePHENIX Detector Concept



- -4<η<-1 (e-going):
  - Crystal calorimeter with good (1.5%) Energy resolution
  - GEM Trackers
- -1<η<1:
  - Add Compact-TPC and DIRC

ePHENIX Detector Concept

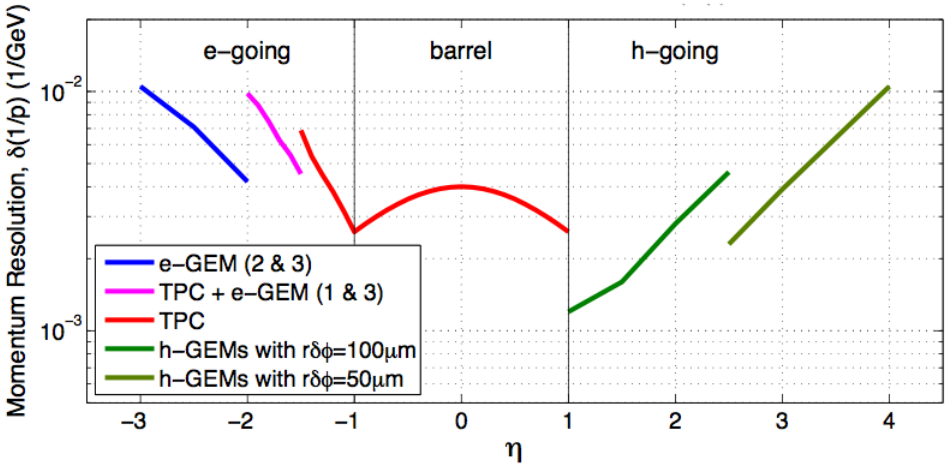


- -4<η<-1 (e-going):
  - Crystal calorimeter with good (1.5%) Energy resolution
  - GEM Trackers
- -1<η<1:
  - Add Compact-TPC and DIRC

- 1<η<4 (h-going):
  - HCal & EMCal (1<η<5)
  - GEM Trackers (+ μ-TPC)
    - PID requires good resolution
  - Aerogel RICH (1<η<2)
  - Gas RICH

BaBar Magnet



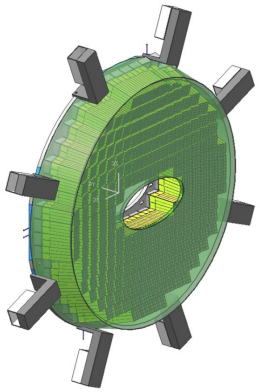


- BaBar magnet:
  - Available after cancellation of SuperB, and BNL has agreement to take possession
  - Large bore 1.5T superconducting solenoid
  - Improved tracking in forward direction due to variation in winding density and larger length
- Good resolution over full tracking acceptance
  - e-going: primarily needed for electron ID (E/p)
  - barrel: low momentum measurements (E<10 GeV)
  - h-going: Needed for PID

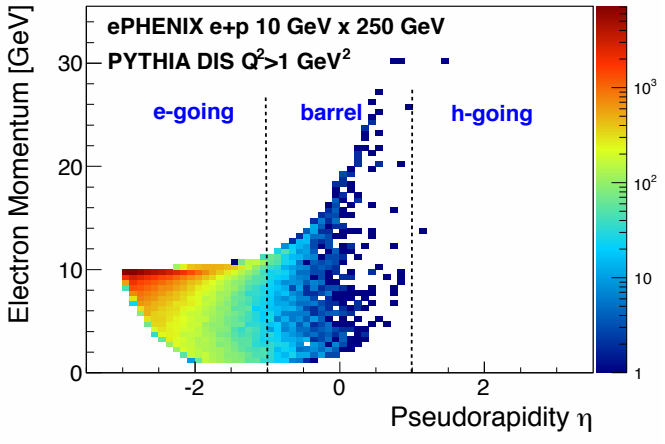
Inclusive Measurements

GOAL: Gluon Helicity, possibly saturation in e+A

Technique: Measure scattered electron

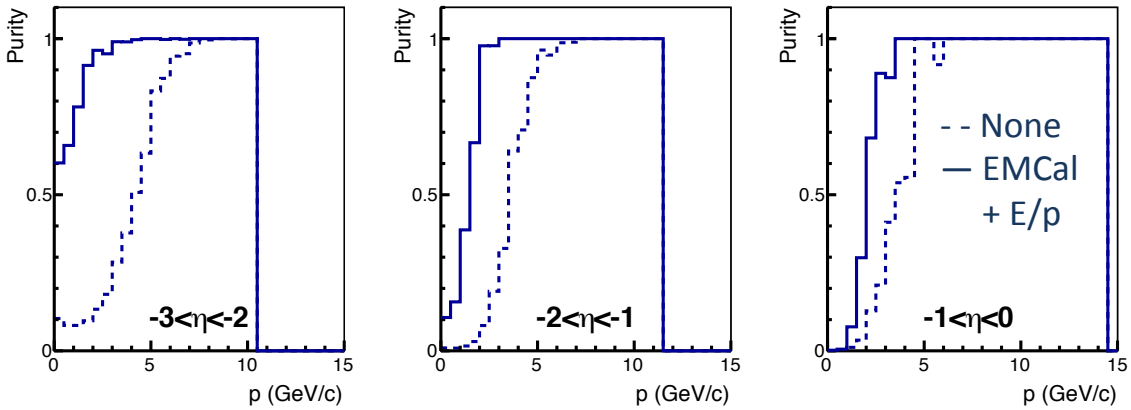


- Endcap Calorimeter:
  - $PbWO_4$ crystal, E_{res} ~ 1.5%/√E
  - Similar to PANDA Endcap design
- Barrel Calorimeter:
  - sPHENIX EMCal, E_{res}~12%/√E

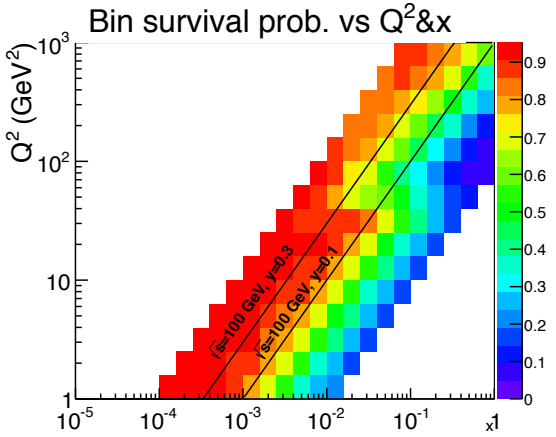


Issues:

Hadronic backgrounds



Kinematic smearing

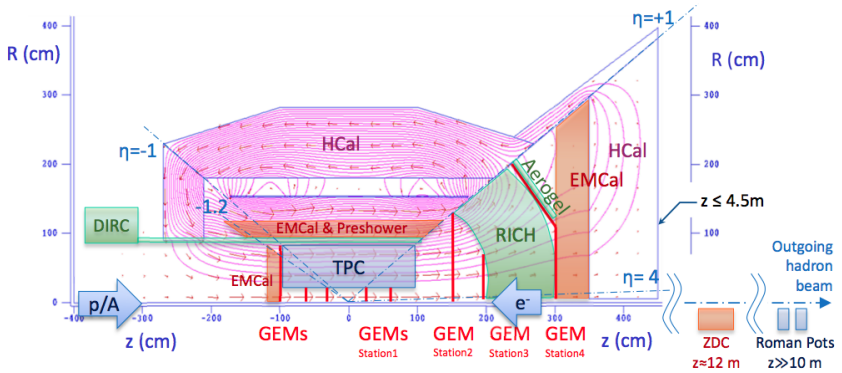


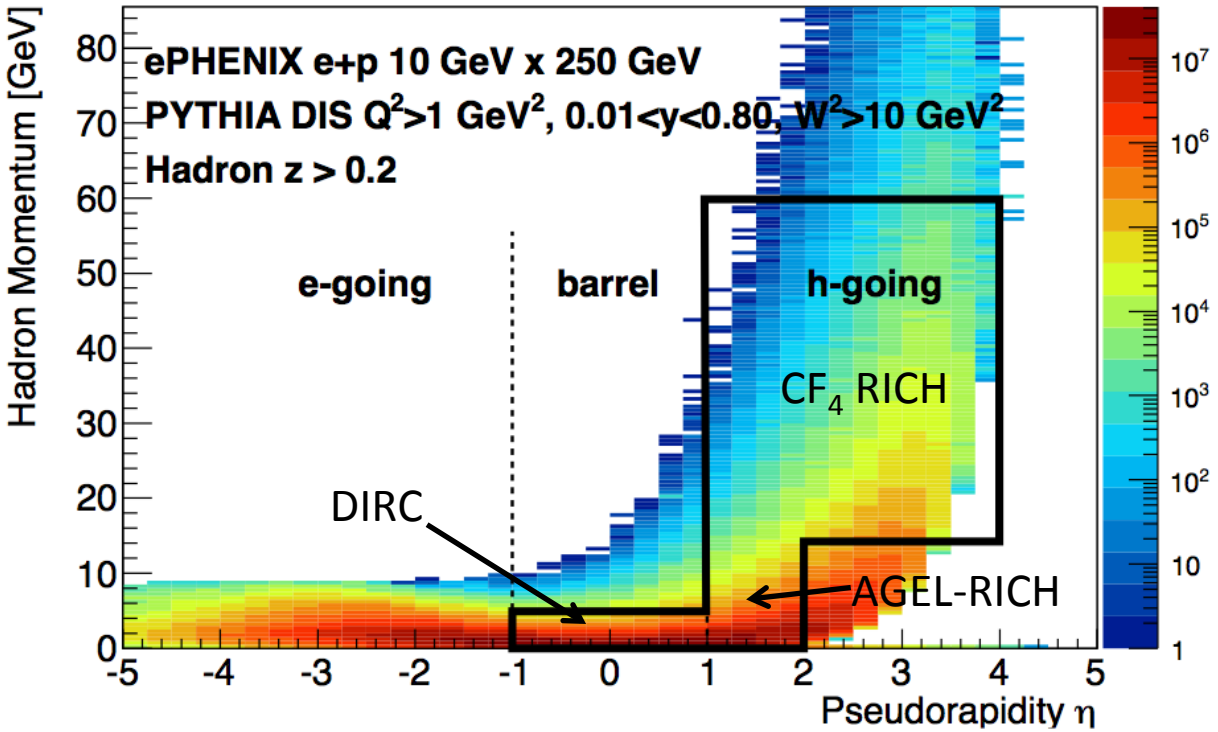
Semi-Inclusive Measurements

GOAL: Quark Helicity, TMDs, Hadronization

Technique: Measure scattered electron & hadron

Detectors: Trackers + Particle ID

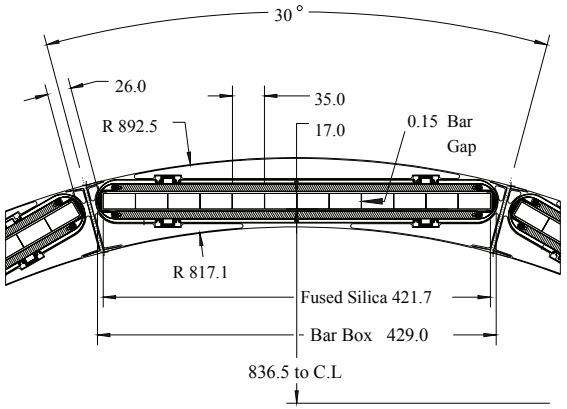




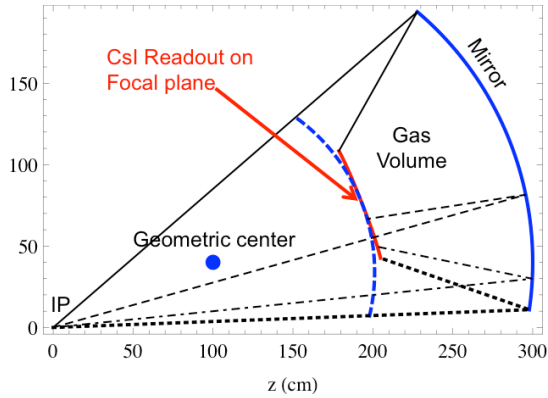
Hadron Particle Identification

- Central PID:
  - TPC at low p
  - DIRC:
    - Cerenkov light internally reflected
    - Based on BaBar DIRC
    - Compact readout similar to FDIRC
  - PID up to 3.5-4 GeV
- Forward PID:
  - Proximity Focused Aerogel RICH:
  - CF_4 gas RICH:
    - Mirror focusing
    - GEM readout in particle path
  - Kaon ID for 4<p<~60 GeV

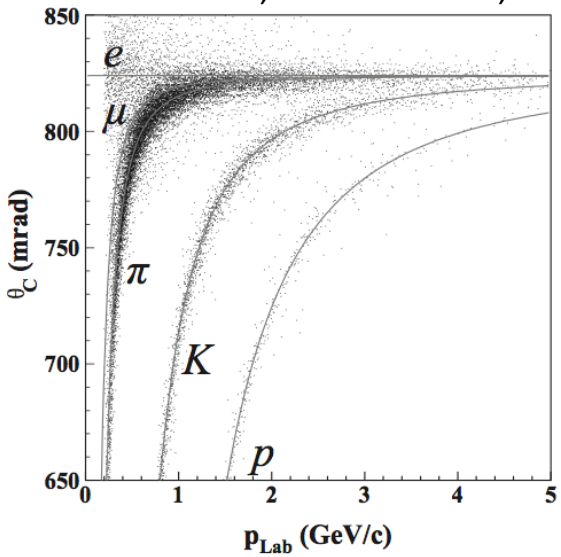
Central

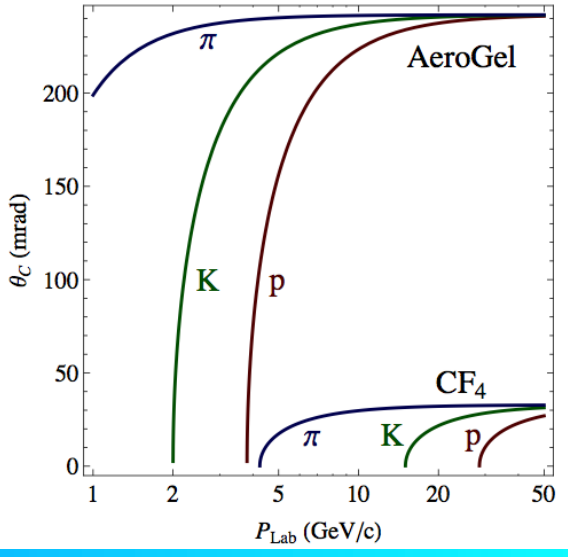


Forward



I. Adam et al. NIM, A538:281–357, 2005





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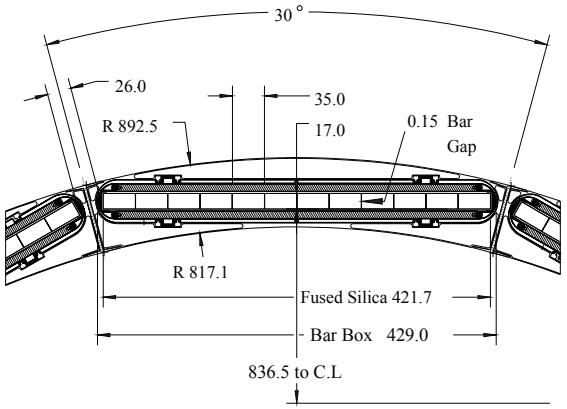

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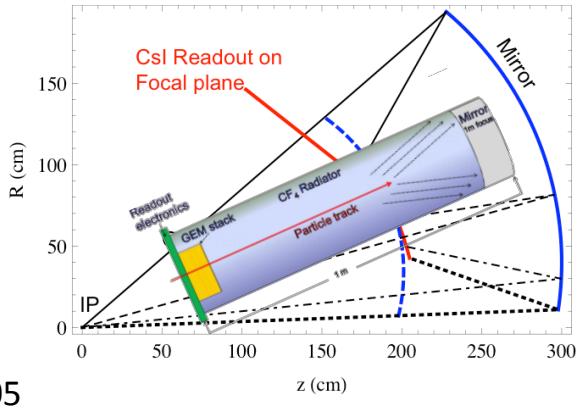

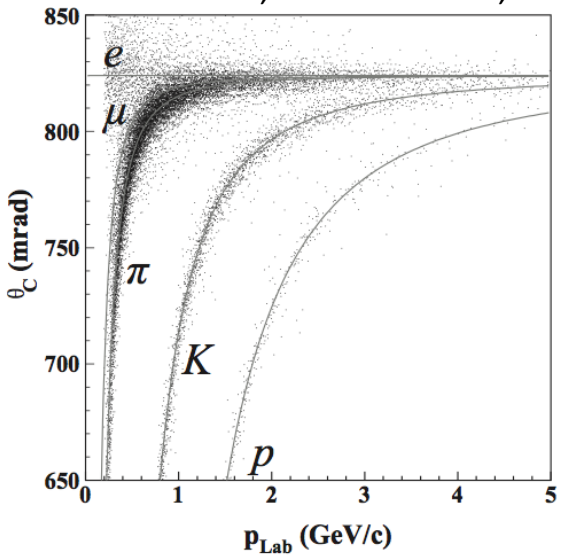

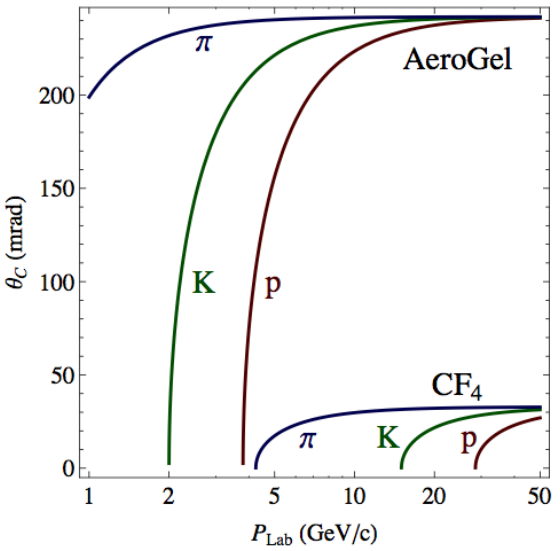

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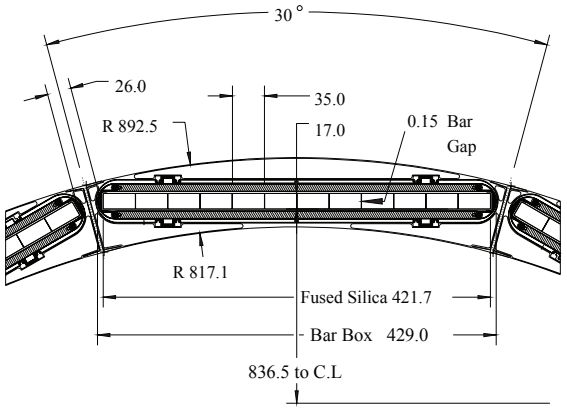

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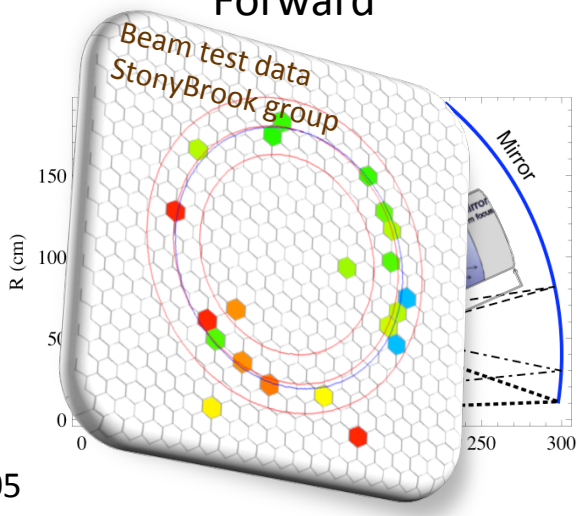
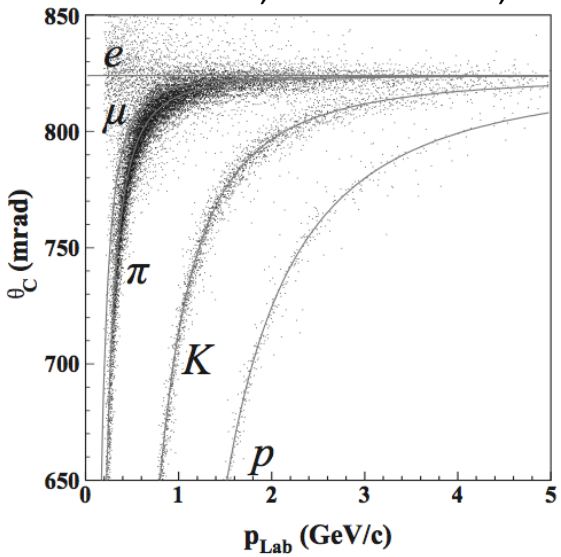
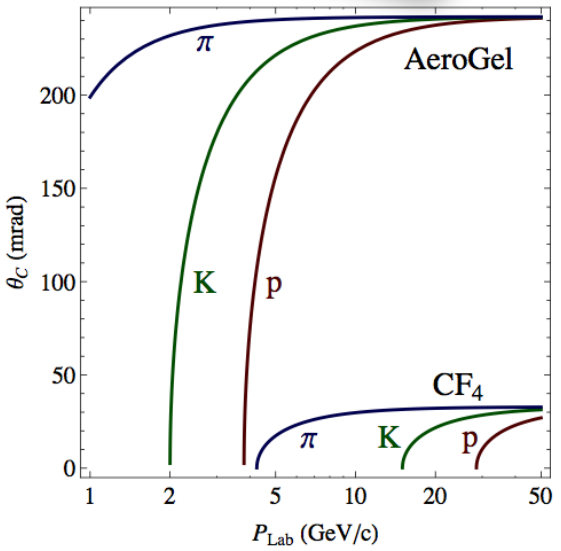
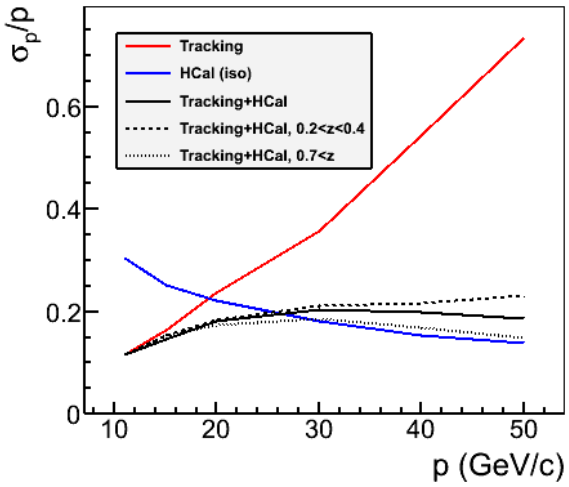


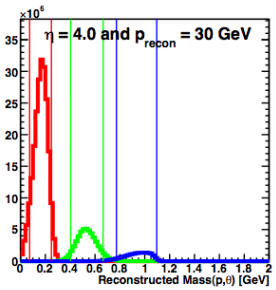


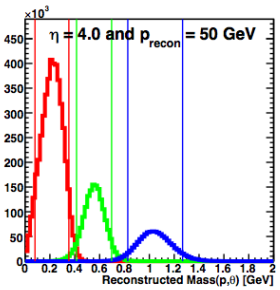


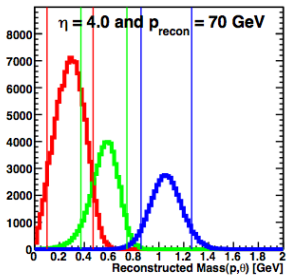
PID at large η

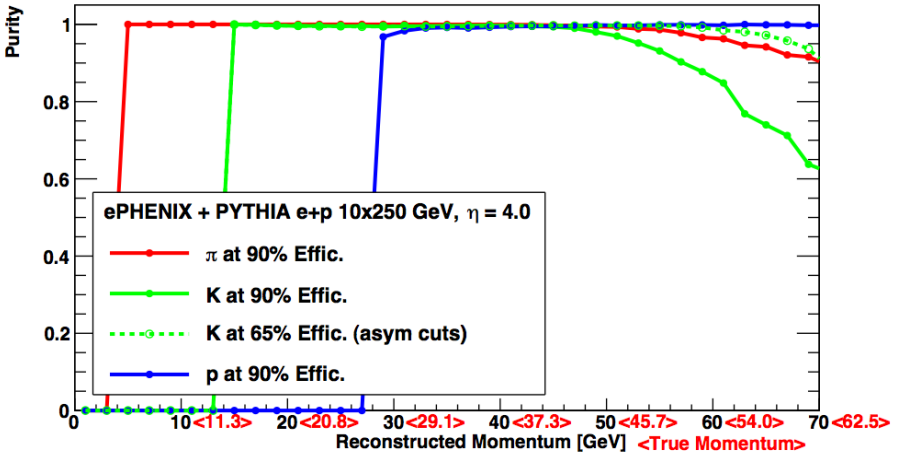
- Difficult to measure accurately at high η (~4)
  - BABAR Fringe field limits p-resolution for high mom.
  - Use HCal to compensate at high mom.
  - Good enough resolution to measure identified kaons up to 60 GeV/c (or more)











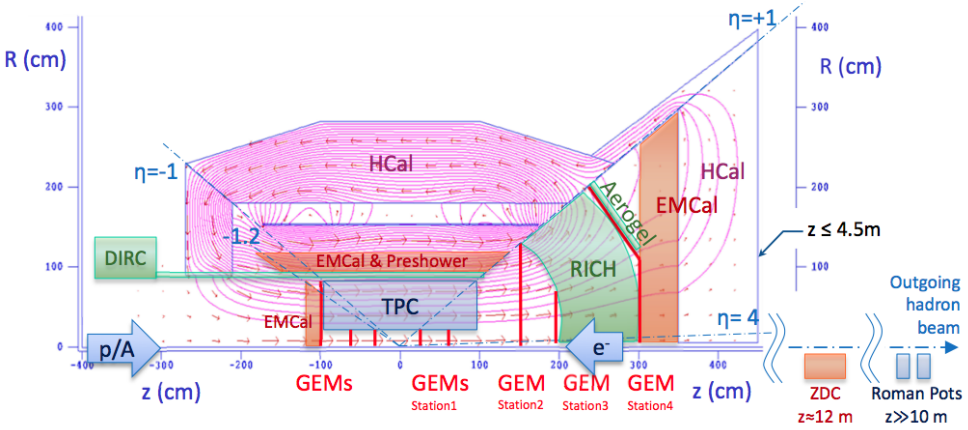
Exclusive Measurements

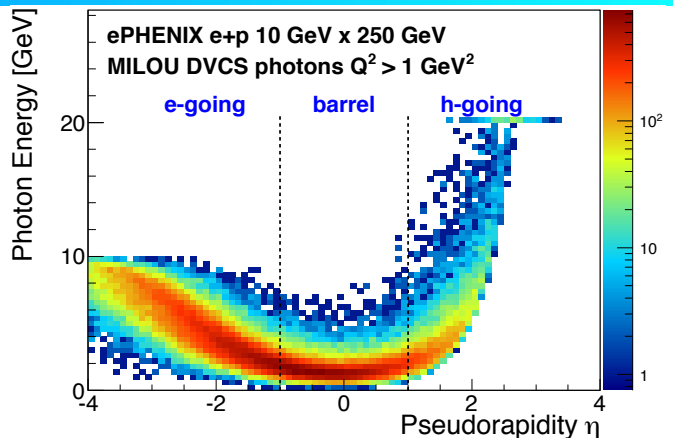
Exclusive Measurements

GOAL: GPDs, proton and nucleon imaging

Technique: Scattered electron, proton, γ or meson

ePHENIX: Wide acceptance for e, γ; Roman Pots





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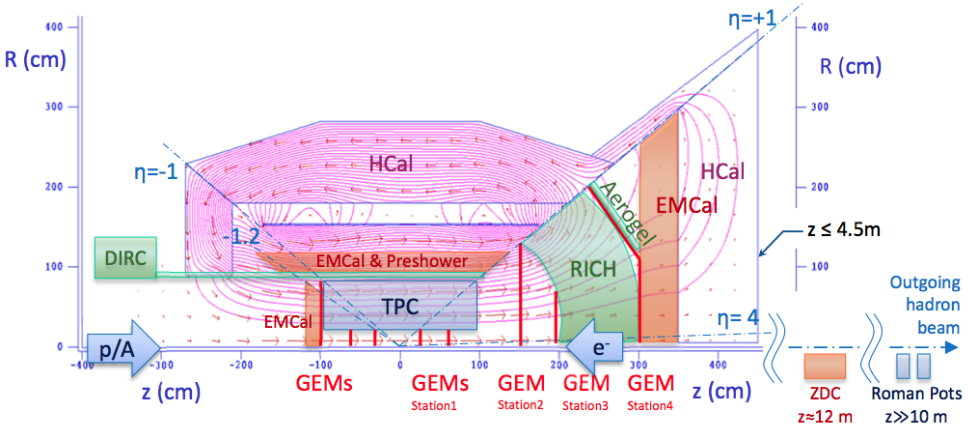
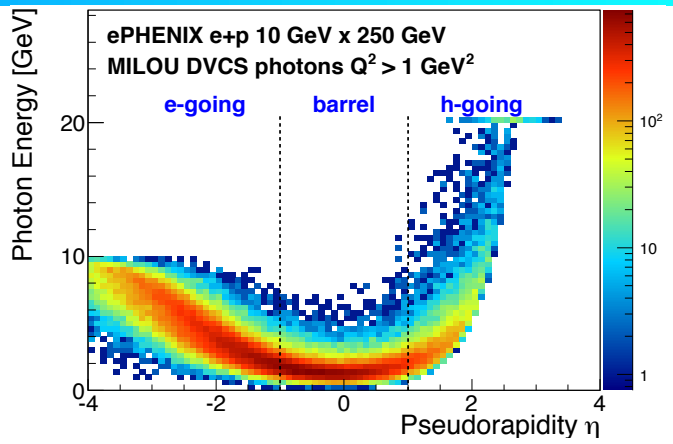
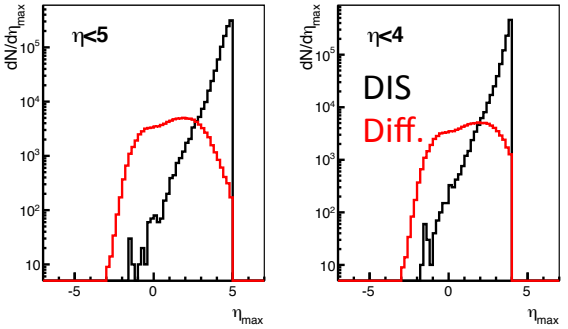






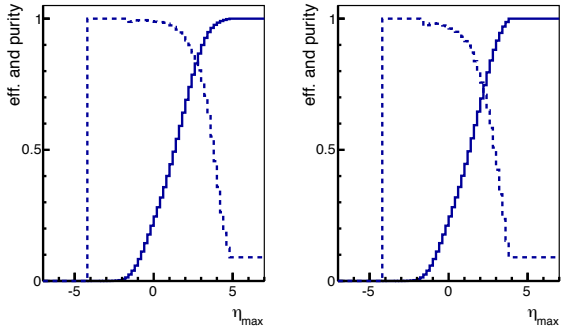
Diffractive Measurements

GOAL: Saturation search

Technique: Scattered electron, rapidity gap

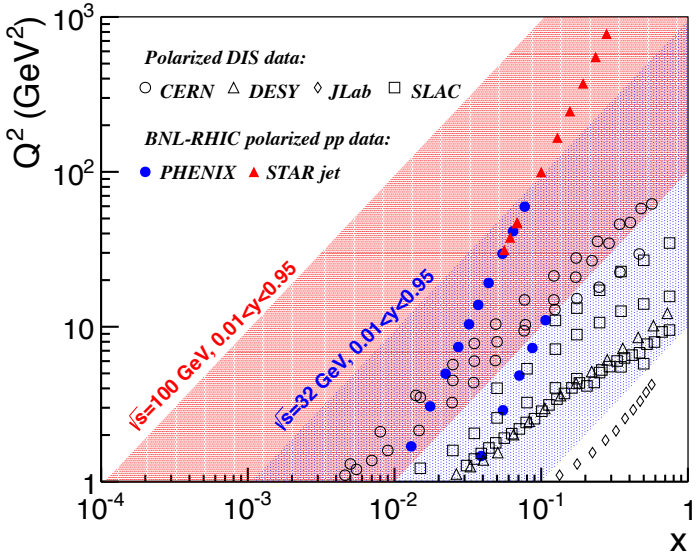
- Measure most forward going particle

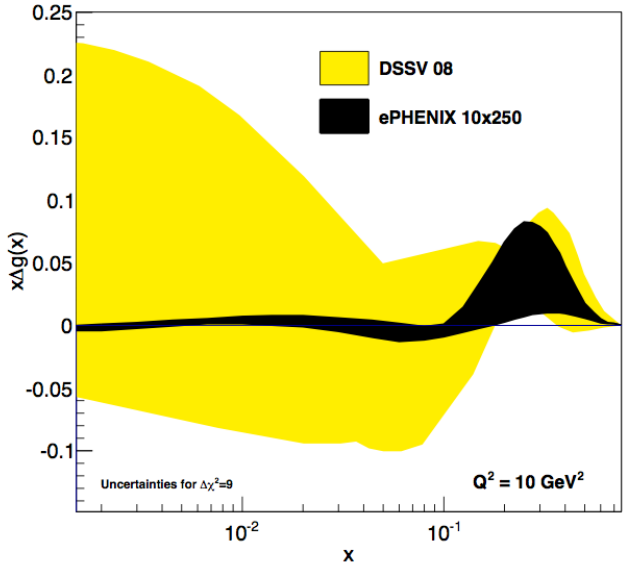
ePHENIX: Wide HCal coverage



Physics Capabilities: e+p

- Wide x,Q^2 reach possible with ePHENIX
  - Significantly extend the kinematic reach of current data
- No significant limitations of ePHENIX capabilities due to acceptance.
  - At low Q^2, limited to y<0.8 if require 99% purity
- Example of physics capabilities: $\Delta g(x)$





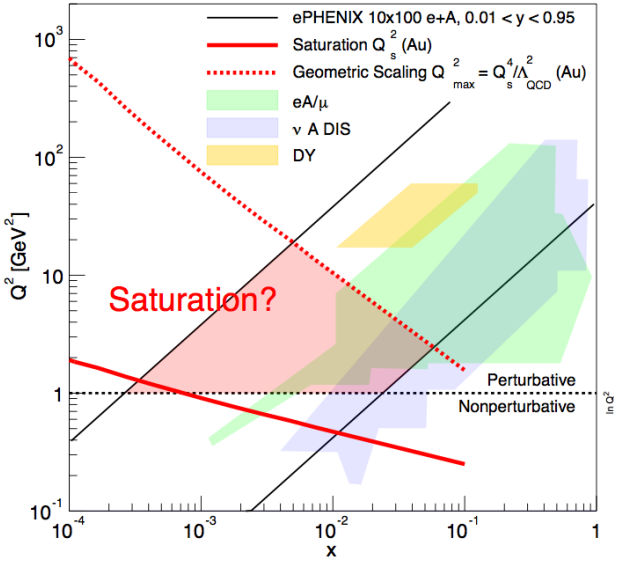
Physics Capabilities: e+A

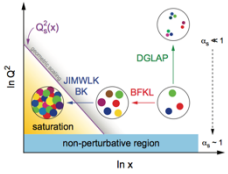
Gluon Saturation

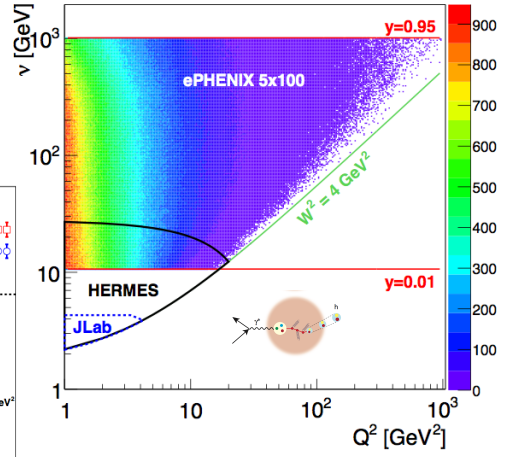
- Can access low x at large Q^2 with ePHENIX
  - Can we be sensitive to saturation effects above saturation scale?
- Also measure via diffraction

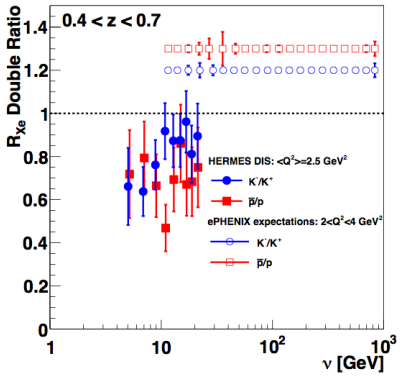
Hadronization

- With collider, large Q^2 and ν coverage
- ePHENIX PID for π, K, p over wide range
- Significantly extend understanding



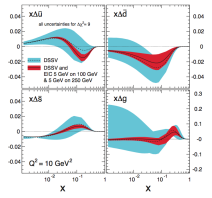


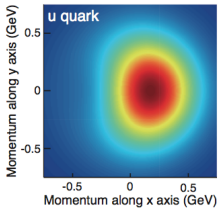


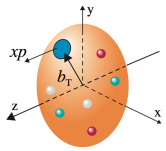


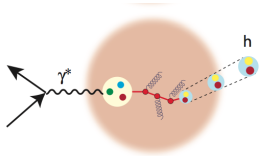
Conclusions

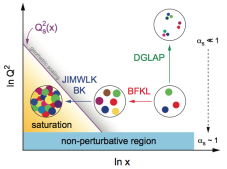
- PHENIX charged to write LOI describing how:
  - PHENIX→sPHENIX→ ePHENIX
- We have designed a world class detector that can do much of the physics available with 5-10 GeV electron beams
  - Cover almost all of the kinematic range available in Inclusive and Semi-Inclusive DIS











- Detector fits in nicely with the evolution of PHENIX
  - sPHENIX barrel with BABAR magnet is good for ePHENIX, and good step along the way
  - fsPHENIX physics requires similar detector in forward arm,
  - sPHENIX and fsPHENIX are a natural bridge between now and eRHIC
- Planning just beginning, lots still to do and new ideas and new collaborators are welcome

Theory Group

Round 1

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Theory at the RBRC: Former fellows & postdoc's

US & Europe

Bass, Duke
Blum, Connecticut
Bodeker, Bielefeld
Fries, Texas A&M
Kharzeev, BNL/SBU
Kusenko, UCLA
Lunardini, Arizona State
Molnar, Purdue
Orginos, William & Mary
Petreczky, BNL
Rischke, Frankfurt
Son, Univ of Chicago
Schaefer, North Carolina
Stephanov, U of Illinois
Tuchin, Iowa
Van Kolck, Paris
Venugopalan, BNL
Yuan, Berkeley

Japan

Iida, Kochi U
Kitazawa, Osaka U
Fujii, U of Tokyo
Itakura, KEK
Nemoto, St. Mariana U
Sasaki, U of Tokyo
Yamada, KEK
Yasui, Tokyo Management
Hirano, U of Tokyo
Fukushima, Keio
Doi, RIKEN
Hidaka, RIKEN
Nara, Akita Int. U
Aoki, Nagoya
Hatta, Kyoto U
Hirono, Sophia U
Fukushima, U of Tokyo
Sasaki, Tohoku U

JSPS Strategic Young Researcher Overseas Visits Program for Accelerating Brain Circulation

Japanese-side chief : T. Hatsuda

- RIKEN Nishina Center : T. Hatsuda, Y. Hidaka
- Univ. Tsukuba : K. Kanaya
- Kyoto Univ. : T. Kunihiro, Y. Hatta









RIKEN+Tsukuba+Kyoto

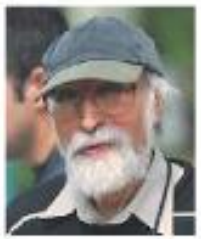


BNL Phys. Dep.

BNL-side chief : R. Venugopalan

- High energy physics GL: A. Soni +
- Lattice gauge theory GL: F. Karsch +
- Nuclear Theory GL: R. Venugopalan +
- RBRC Computational physic GL: T. Izubuchi +
- RBRC theory GL: L. McLerran +





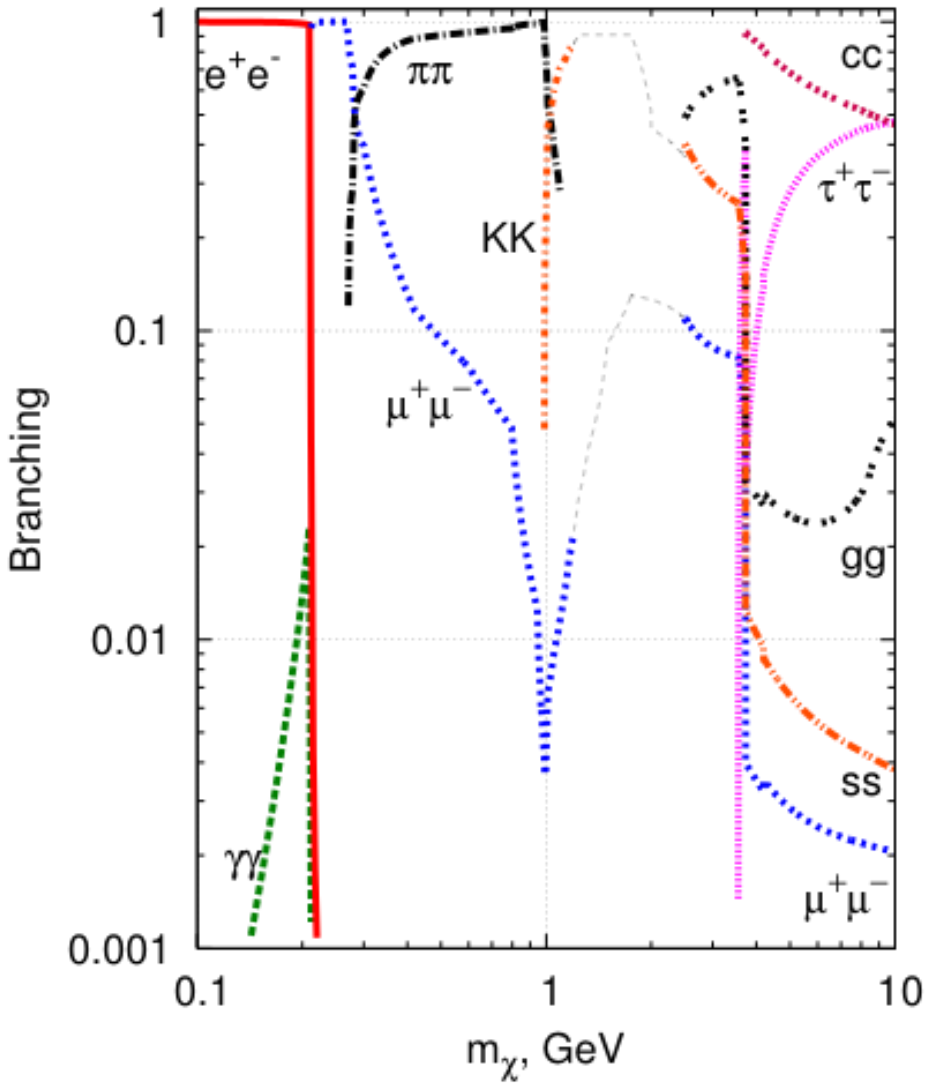




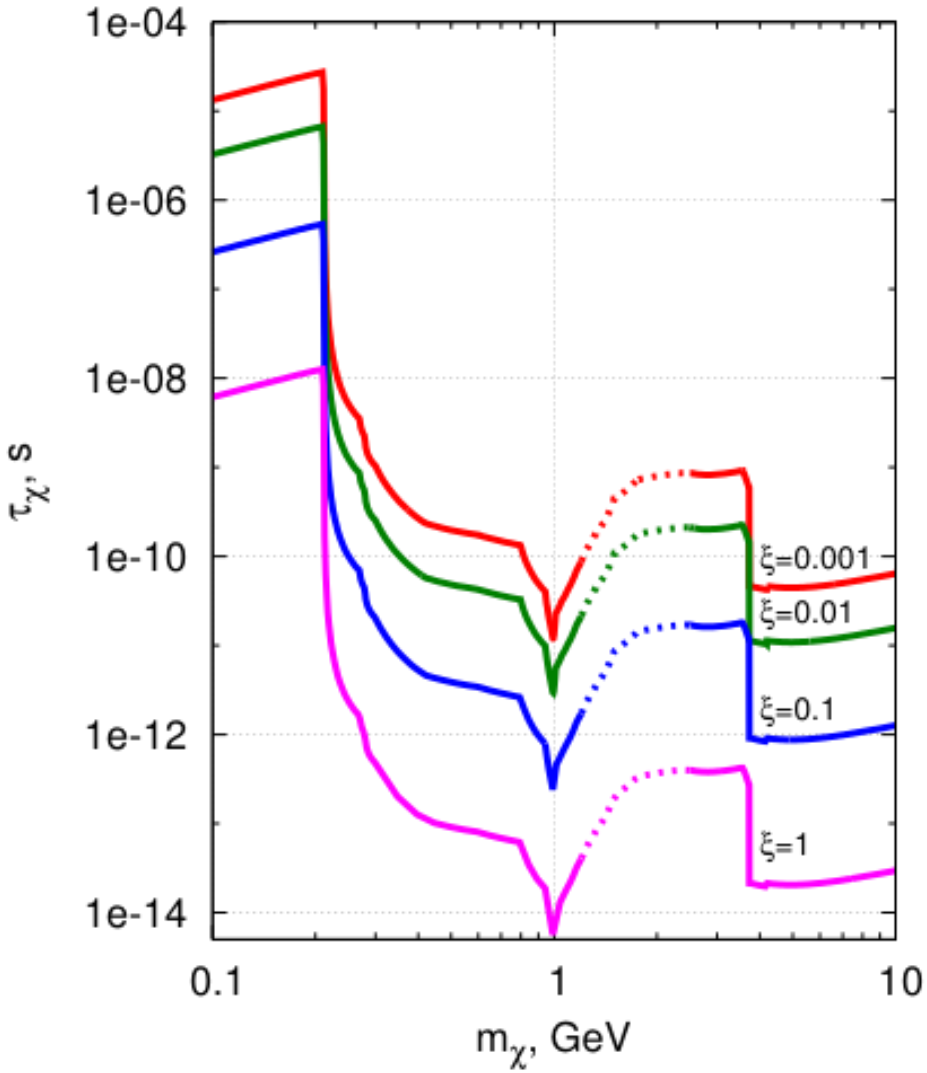

Fedor Bezrukov: inflation with the BEH boson

Inflaton = Standard Model BEH boson with *non*-minimal coupling $\varsigma R \varphi^2$.
Need large $\varsigma \sim 10^4$. Analogous to very small coupling for usual inflaton.
Using data from LHC and WMAP to constrain inflation potential, obtain:

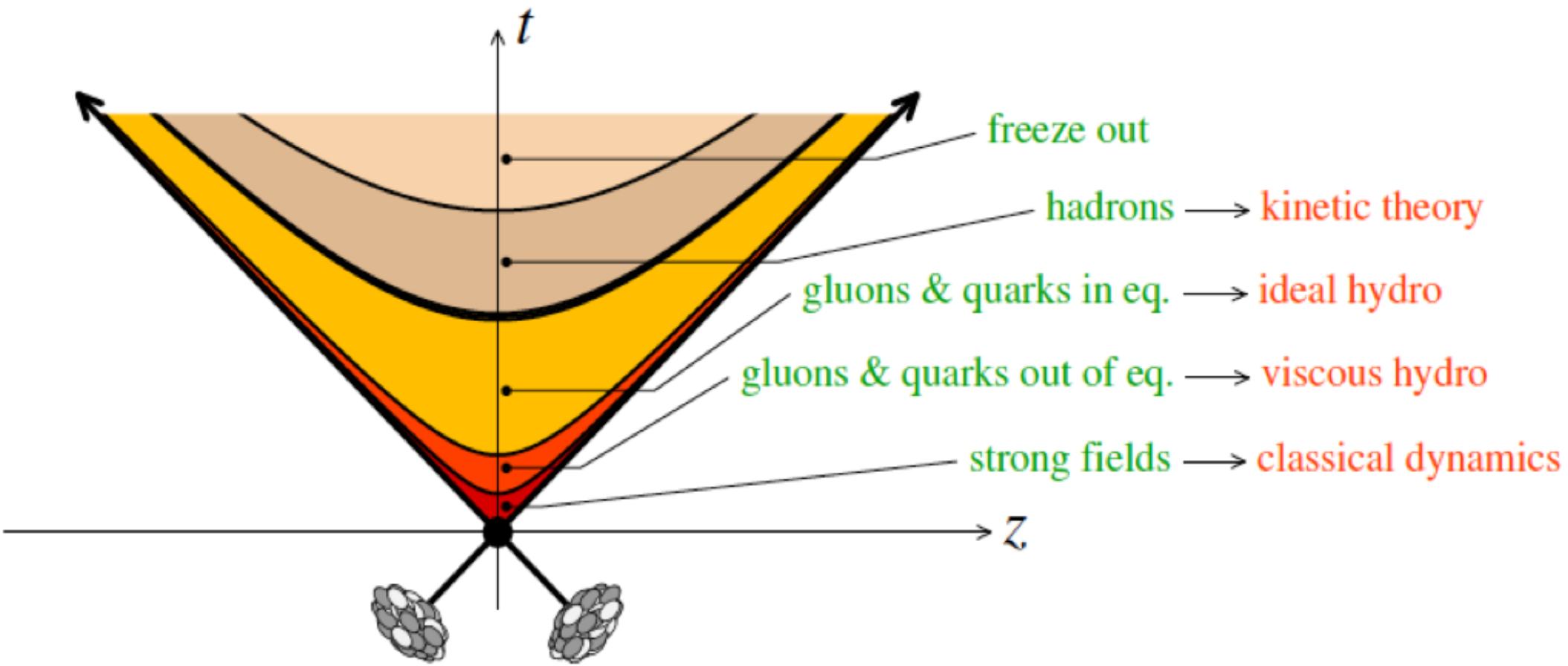
Branching ratios



Lifetime (seconds)



Cartoon of heavy ion collisions



Color Glass Condensate (CGC): high gluon density, dominate at high energy

Glasma: coherent gluons, turbulently evolve into thermal QGP, produce quarks

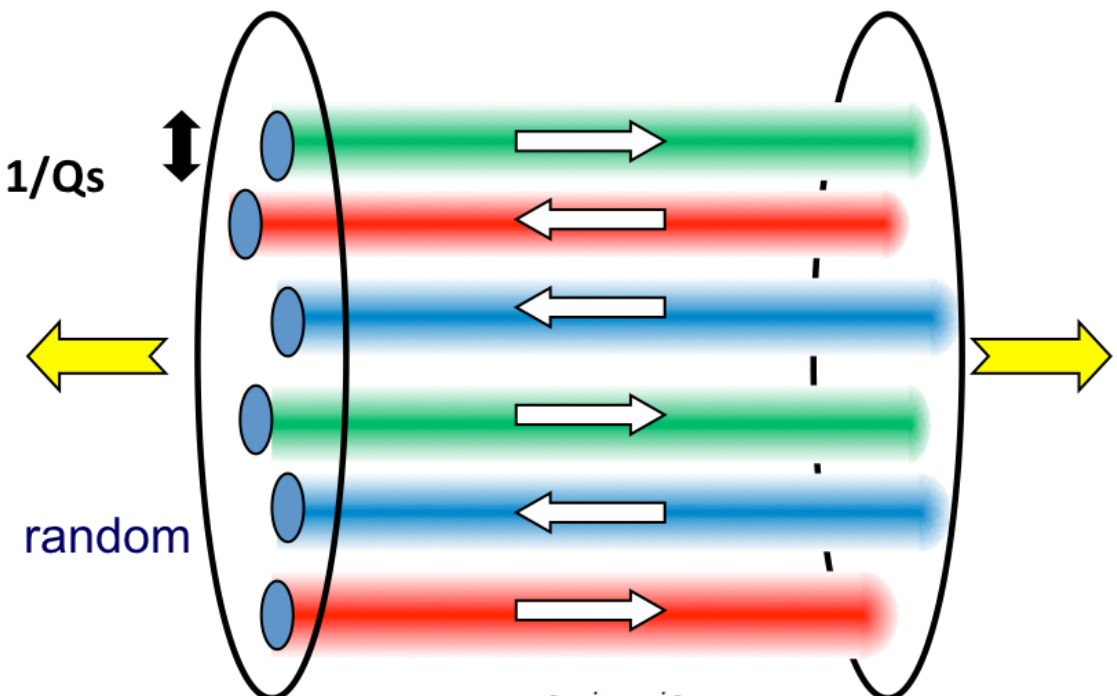
Quark-Gluon Plasma (QGP): thermal, incoherent quarks and gluons

Glasma: getting to the QGP

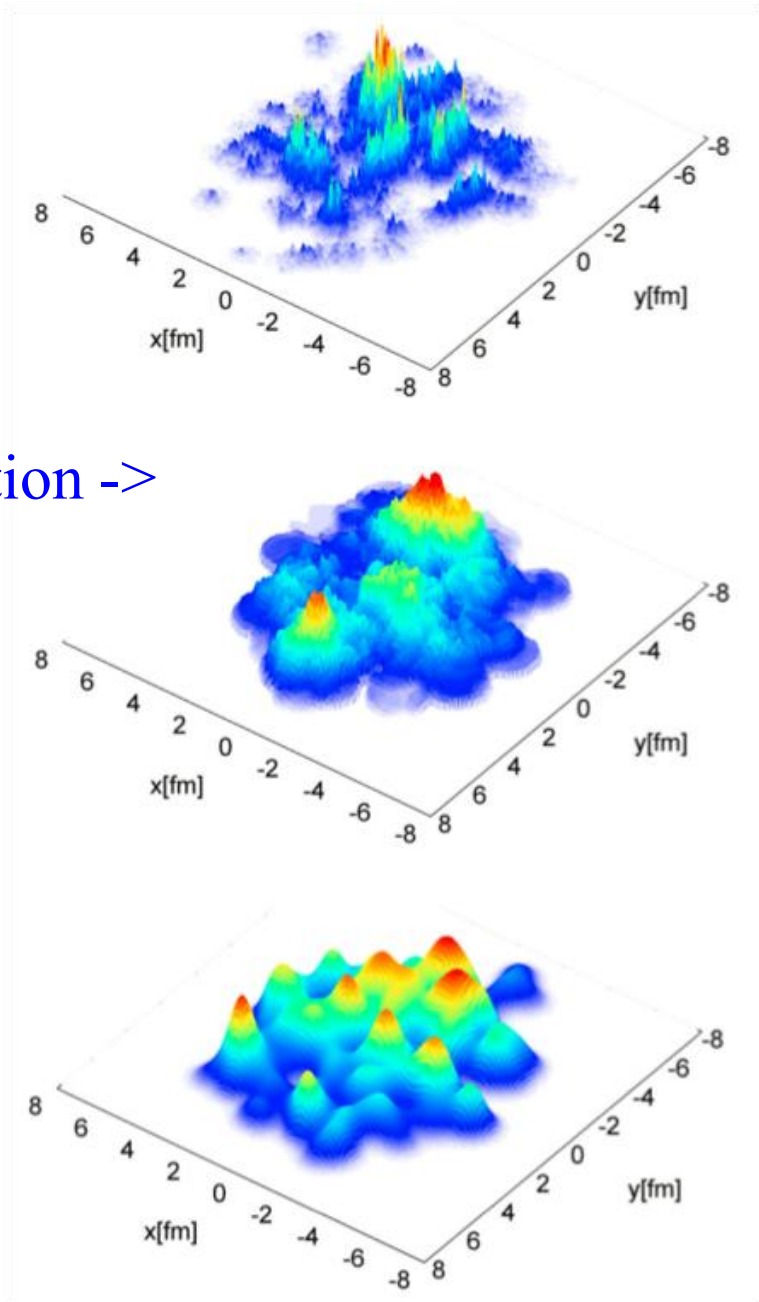
Glasma = coherent colored fields
Stringlike along beam direction
Stochastic transverse to beam

Multiplicity: negative binomial distribution

Right: evolve from lumpy to smooth distribution ->



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$



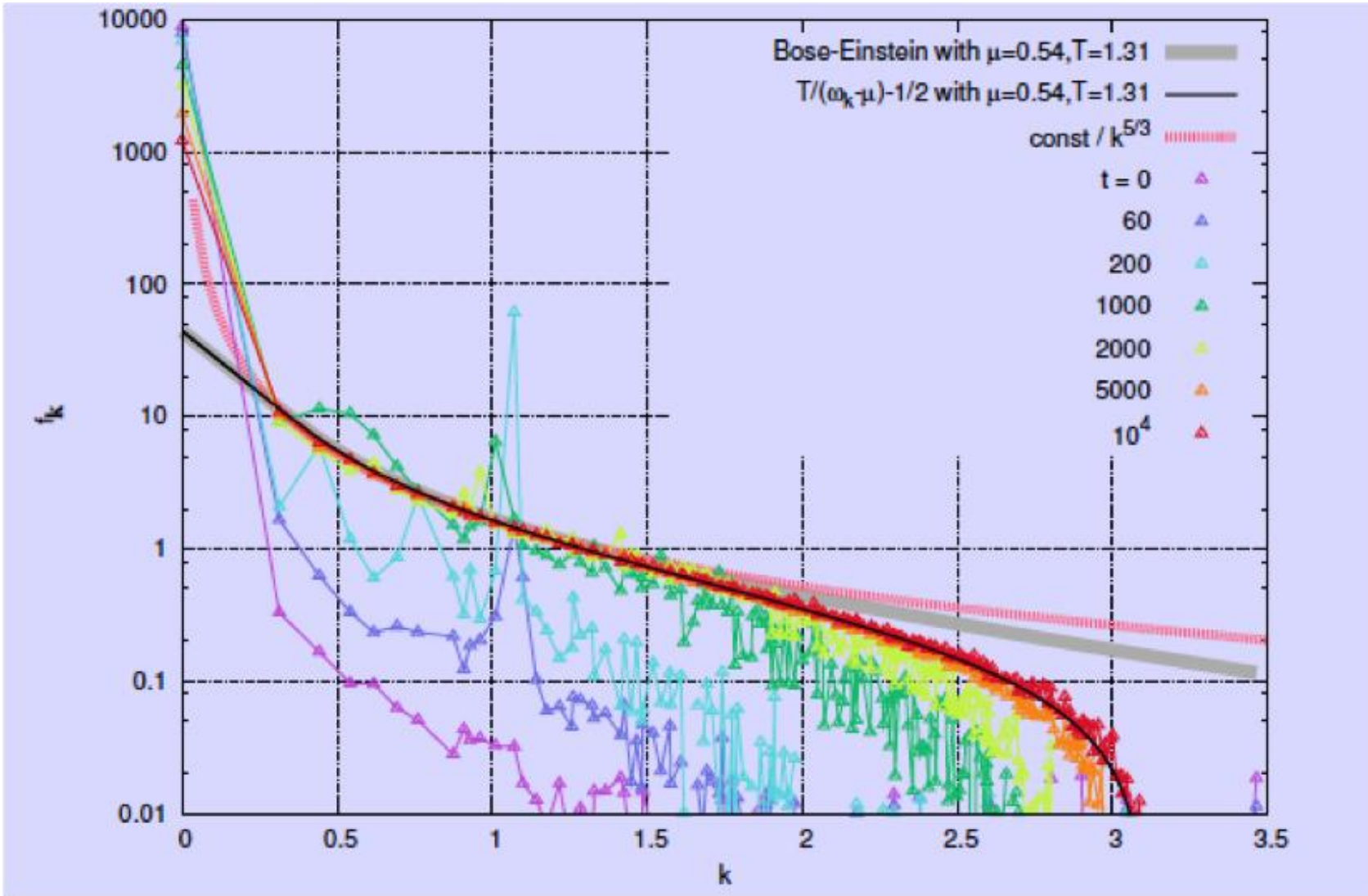
Jinfeng Liao: evolution of glasma

Evolution from Color Glass to QGP: study with classical evolution

Initially, coherent and cutoff scale same, saturation momentum

Thermal distribution: coherent ~ coupling x cutoff scale

Novel physics: Bose-Einstein condensation? Gluon chemical potential?

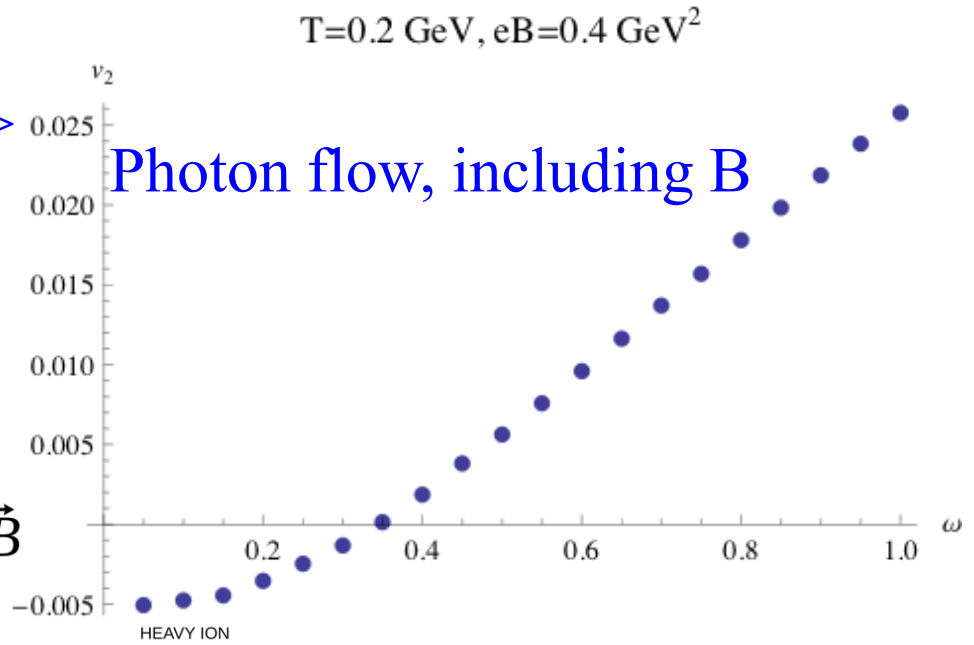


Ho-Ung Yee: Photons & magnetic fields

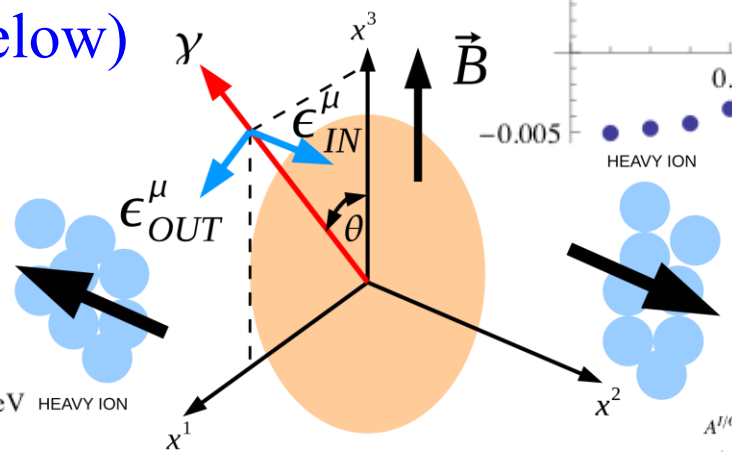
Includes effects of magnetic field B through anomaly terms. Photon flow =>

Also predicts energy dependent effects for ratios of photon polarization:

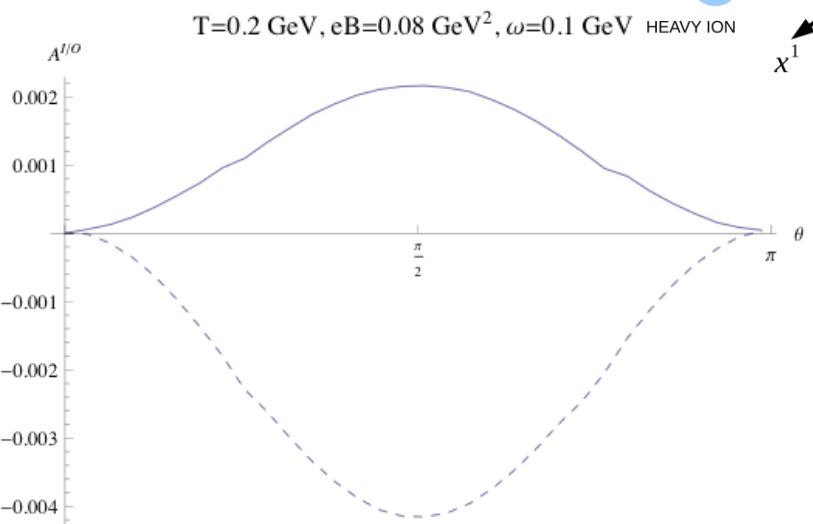
(ignore dotted lines below)



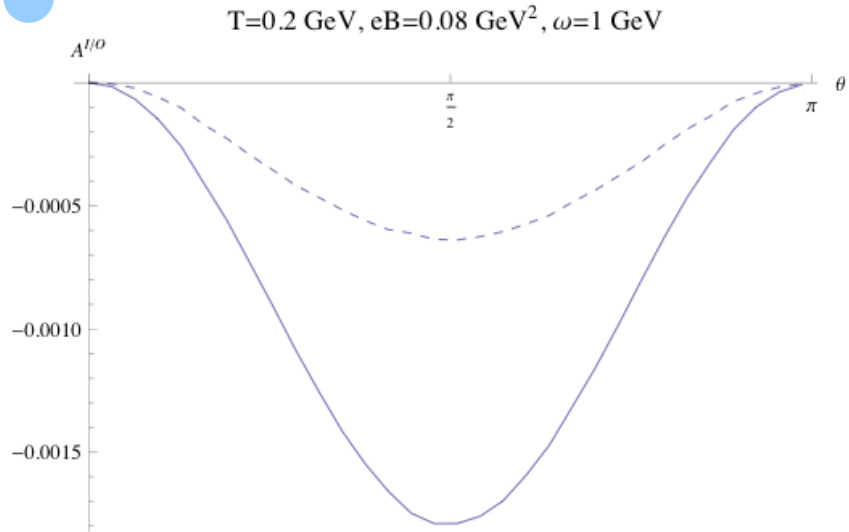
Photon flow, including B



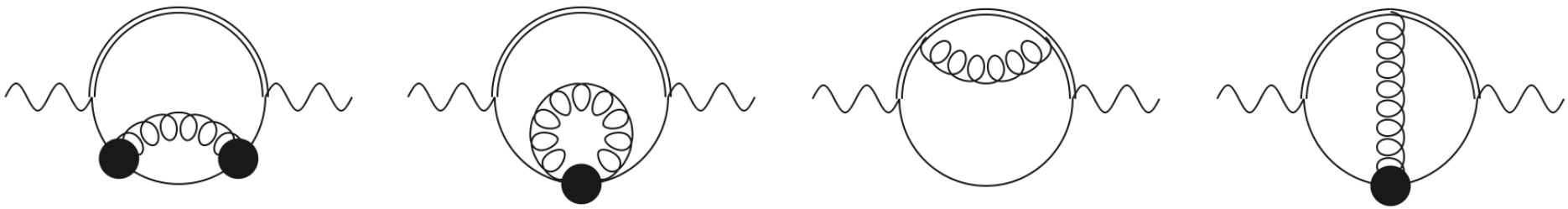
Soft photons



Hard photons



Derek Teaney: production of thermal photons

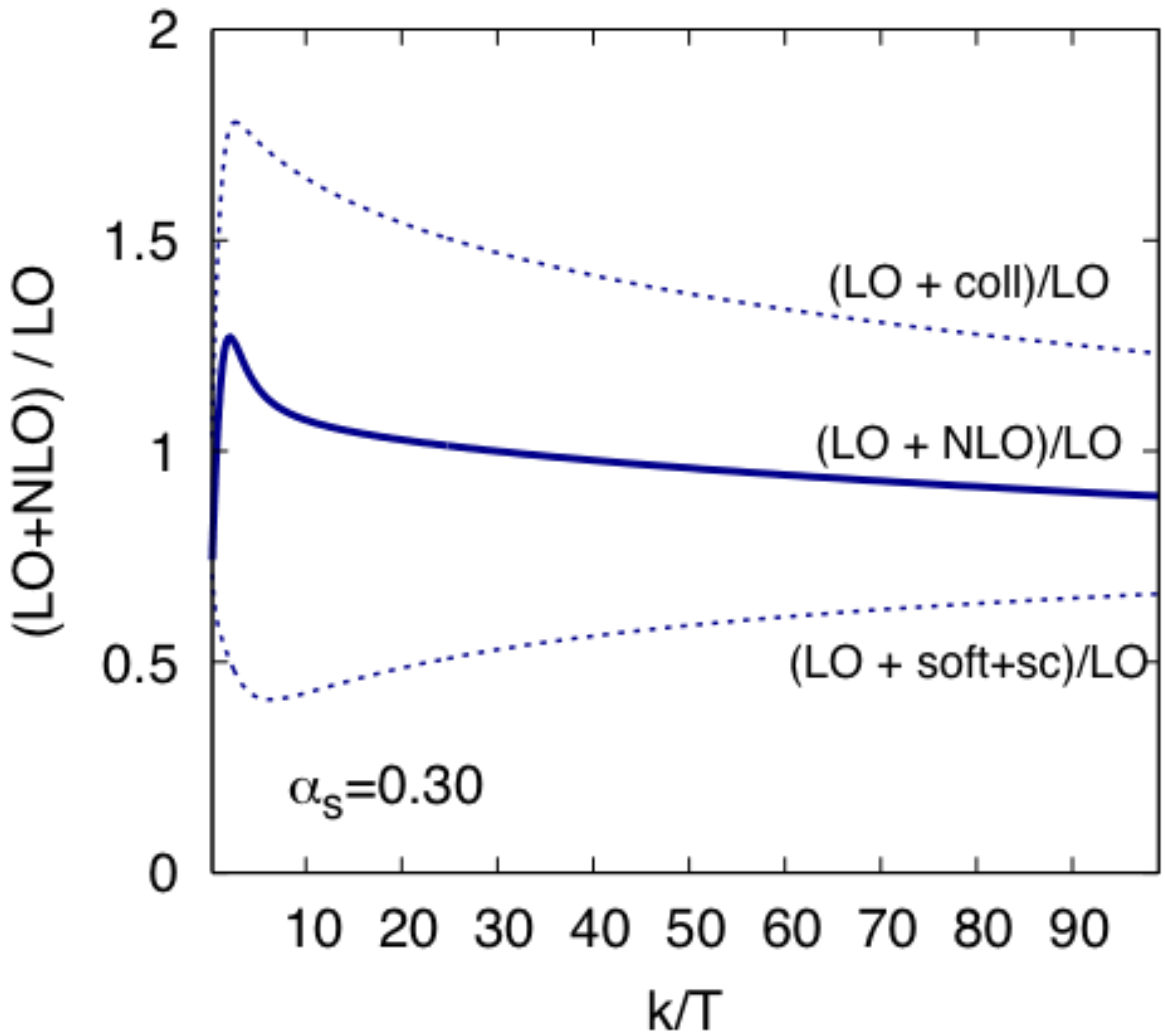


Compute in perturbation theory:
go from Leading Order (LO)
to Next to Leading Order (NLO)
in coupling constant

Heroic computation: many
diagrams, need to resum, etc

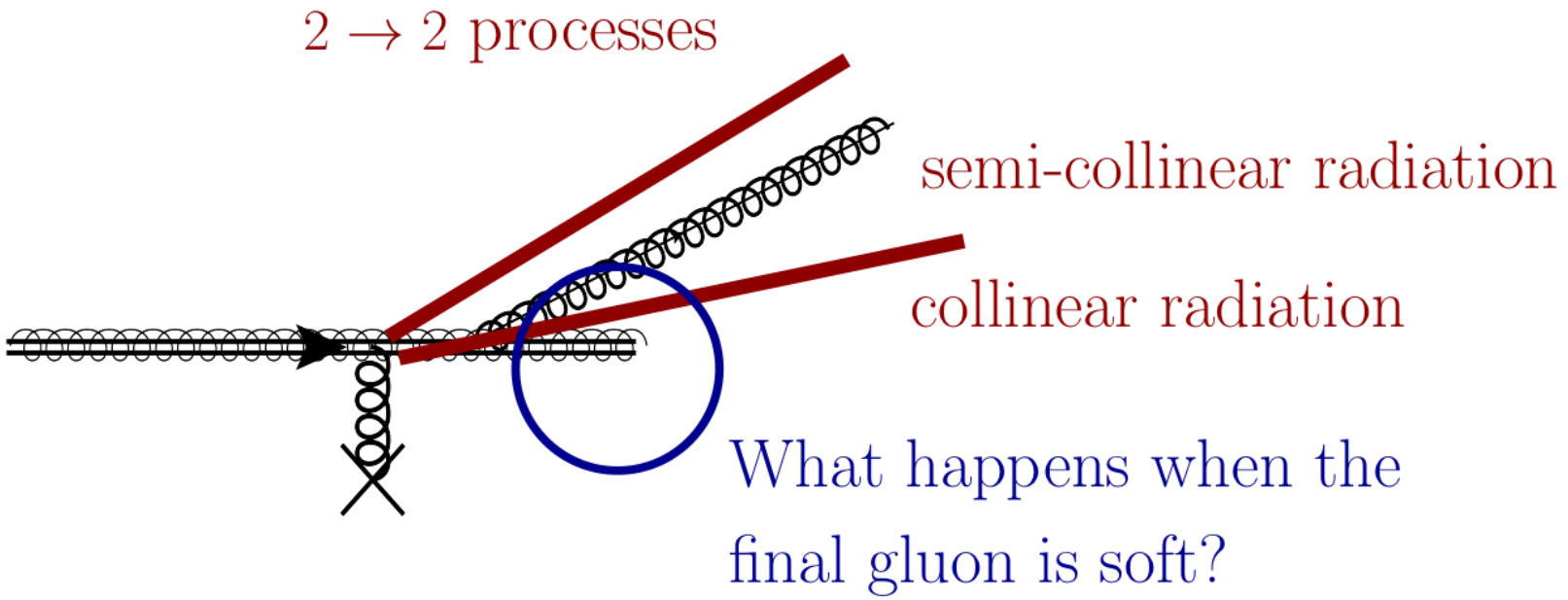
Find: complete results
very insensitive to perturbative
corrections!

Photon puzzle remains



Derek Teaney: perturbative calculation of energy loss at next to leading order

Matching between brem and drag



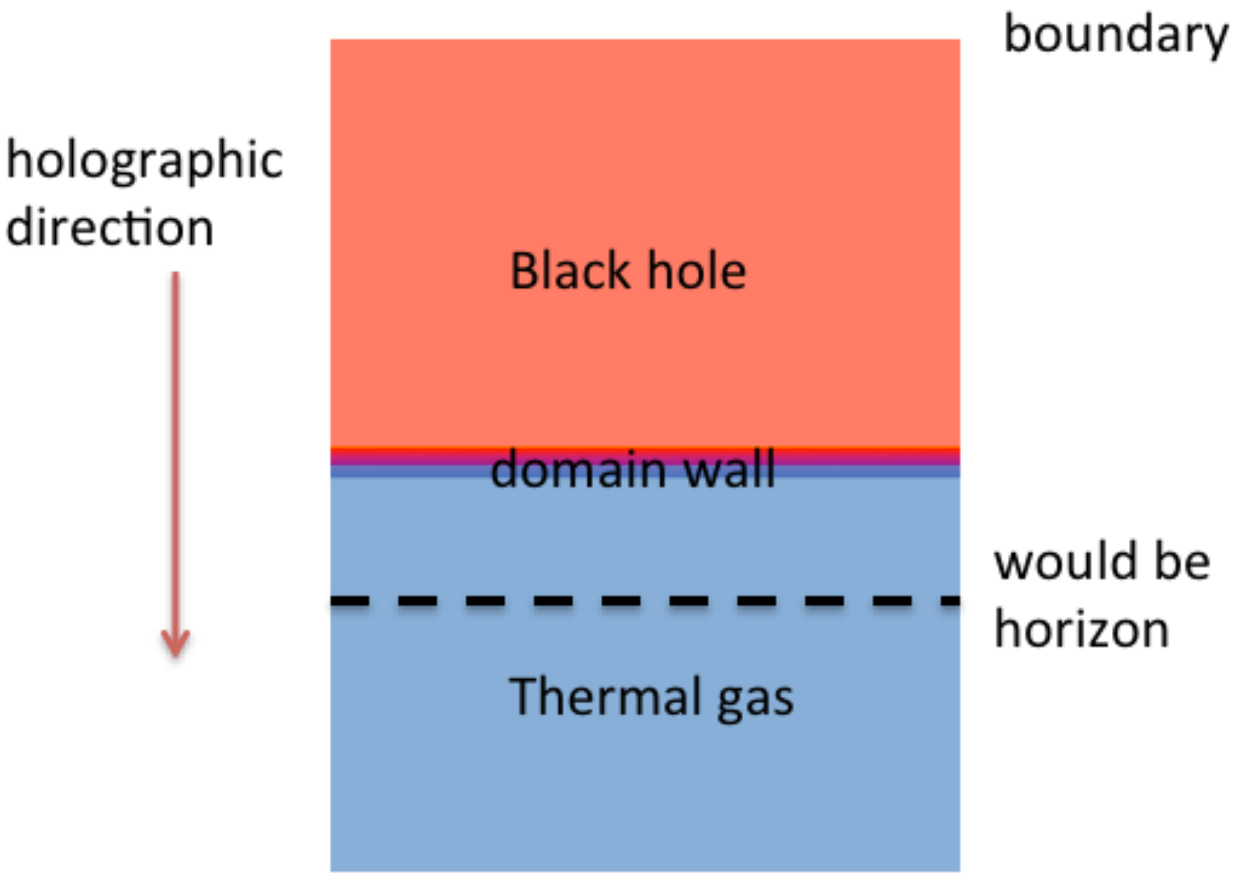
- The semi-collinear emission rate diverges logarithmically when the gluon gets soft

$$\Gamma_{\rm semi-coll} \sim g^2 C_A \overbrace{\frac{\delta m_\infty^2}{4\pi}}^{\sim g^3 T^2} \log\left(\frac{2Tm_D}{\mu}\right)$$

When the gluon becomes soft need to relate radiation and drag.

Shu Lin: instabilities of QCD from holograph

Quantum tunneling via evolution of domain-wall background



domain-wall evolves toward the boundary, shrinking the supercooled QGP phase

Koji Kashiwa: "Hosotani" mechanism in QCD

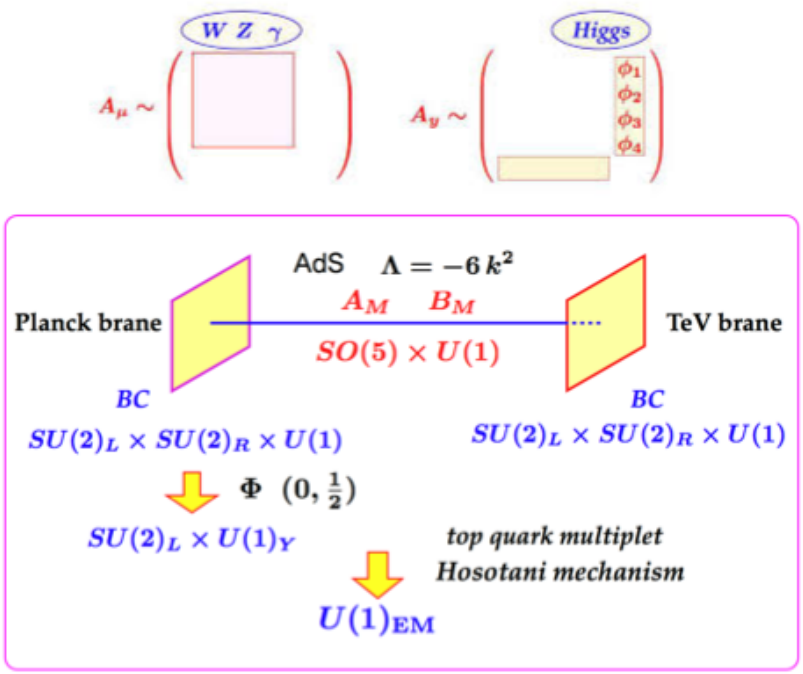
In our world, quarks are fundamental representation.

Dose it means that other representations are meaningless?

These may important in the physics beyond the standard model

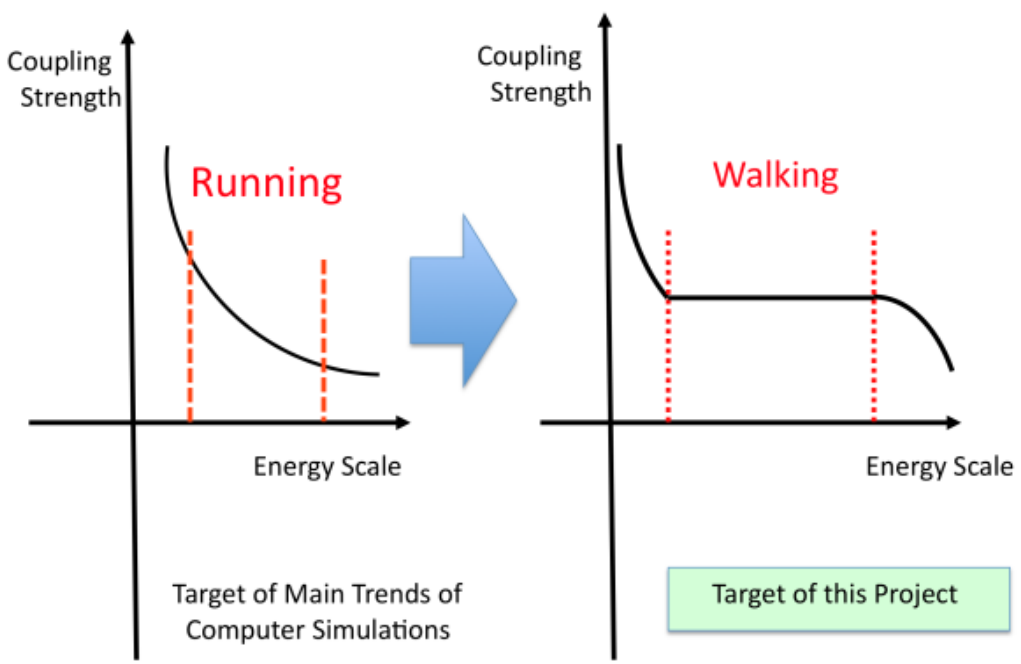
No!!

Hosotani mechanism



From Prof. Hosotani's presentation slides

Walking Technicolor



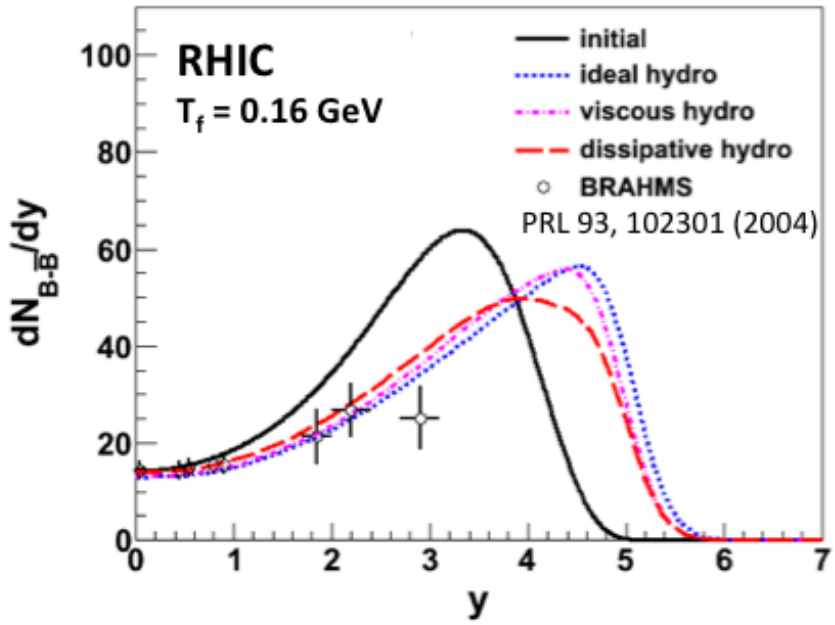
Sextet representation of fermion may play a important role.

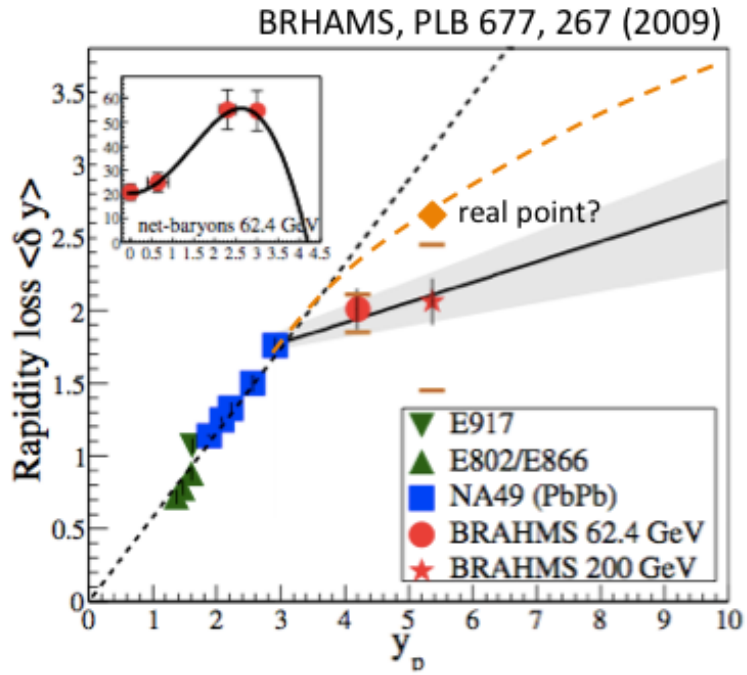
From KMI web page

Akihiko Monnai: hydro in heavy ion collisions

Dissipative hydrodynamics

- Net baryon rapidity distribution at RHIC





- Hydro evolution sends net baryon number to forward rapidity
- Transparency of the collision is effectively enhanced by hydrodynamics

⇨ More kinetic energy is available for QGP production

Adam Bzdak: Wounded Nucleon Model vs Color Glass Condensate

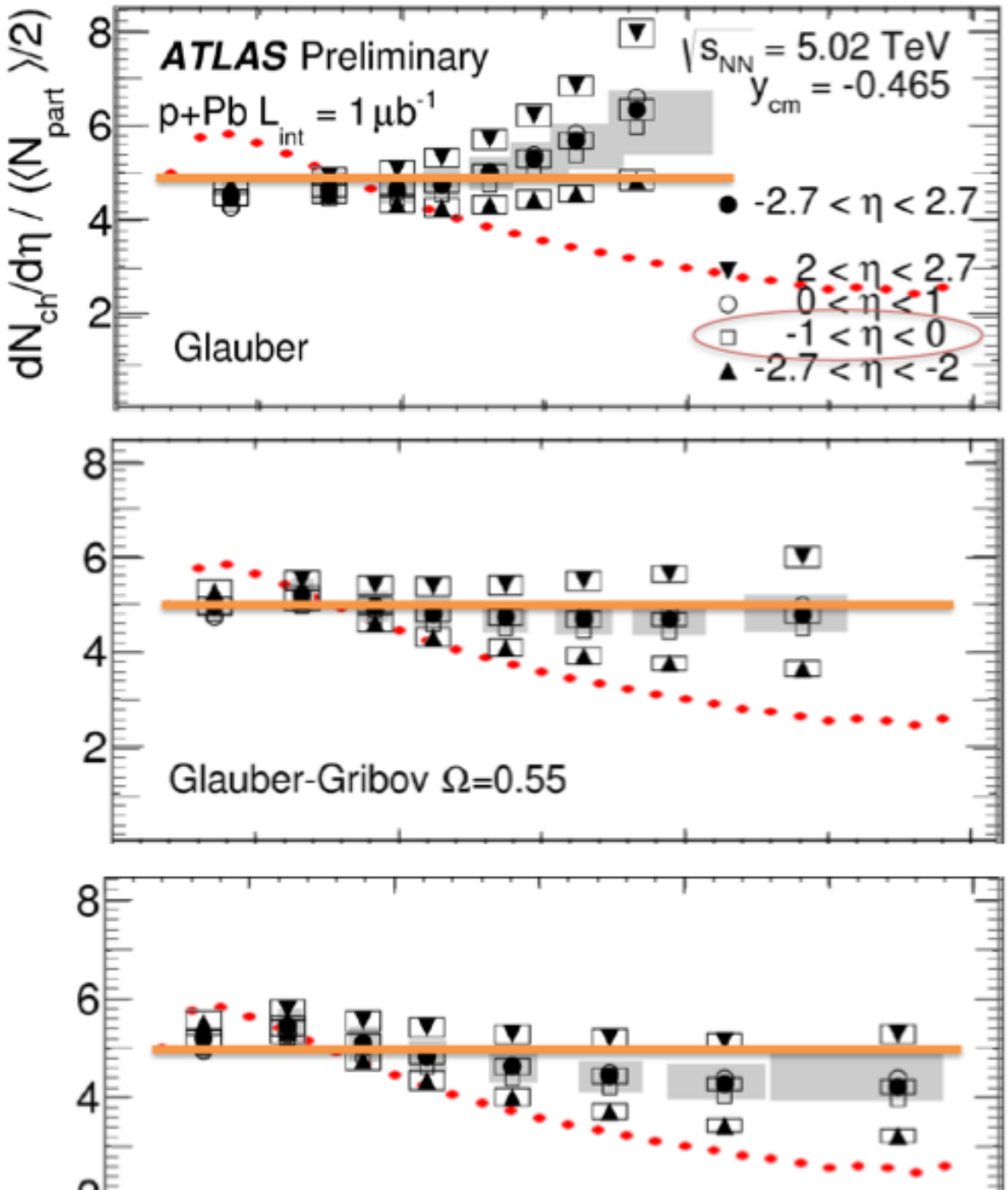
ATLAS preliminary data

WNM

CGC

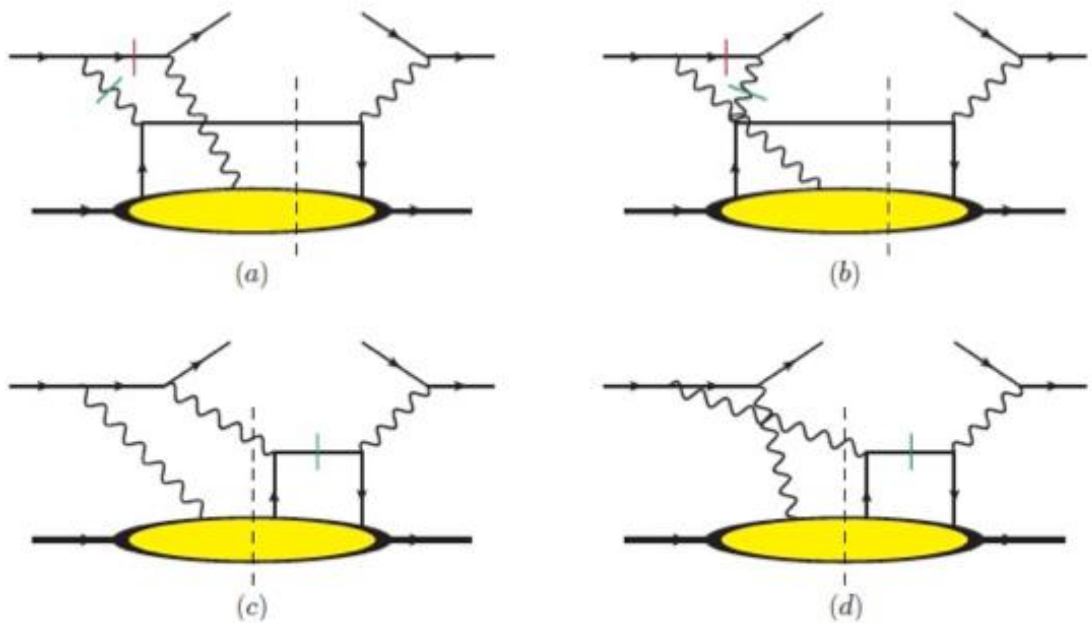
Look at $-1<\eta<0$, the shaded bands

The preliminary data are consistent with the WNM !



Daniel Pitonyak: Single Spin Asymmetries in pp collisions

- SSA in inclusive DIS (Metz, DP, Schaefer, Schlegel, Vogelsang, Zhou, PRD **86** (2012))



$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{8\pi\alpha_{em}^2 x y^2 M}{Q^8} \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\left(2+\frac{\hat{u}}{\hat{t}}\right)\varepsilon^{S_N Pkk'} \sum_q e_q^2 x \tilde{F}_{FT}^{q/N}(x,x)$$

with $\tilde{F}_{FT}(x,x) = F_{FT}(x,x) - x\frac{d}{dx}F_{FT}(x,x)$

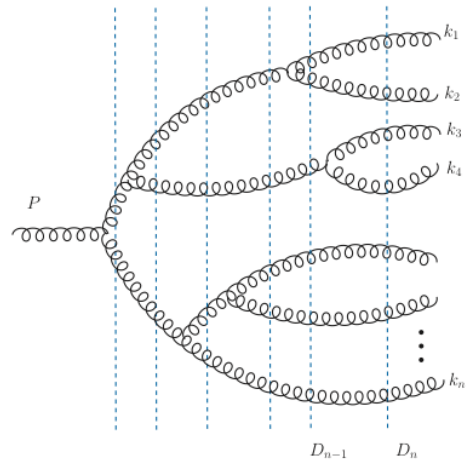
(Work has also been done on both photons coupling to the same quark: Metz, Schlegel, Goeke (2006); Afanasev, Strikman, Weiss (2007); Schlegel (2012))

Anna Stasto: amplitudes at next to next to...leading order

Computation of amplitudes on the light-front

τ

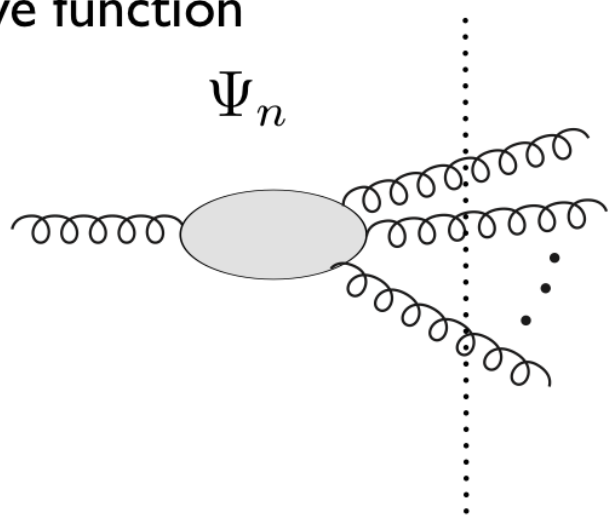
typical graph



$$\sim g^n \frac{\Pi_j V_j}{\Pi_j D_j \;\; \Pi_l k_l^+}$$

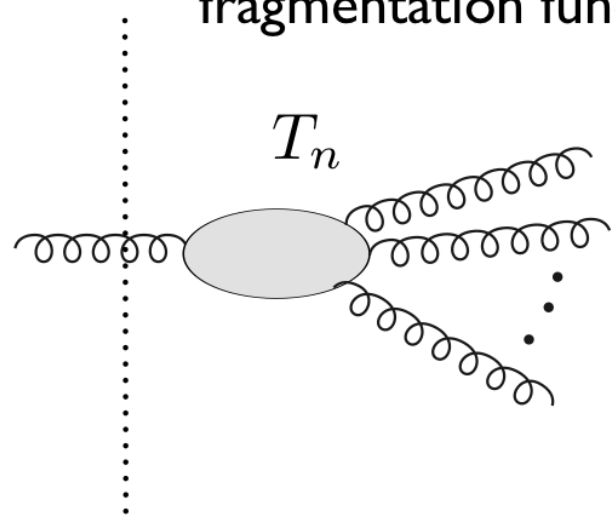
wave function

Ψ_n



fragmentation function

T_n



Energy denominator: either in the last or first state

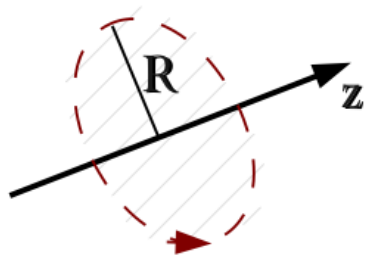
Can use these building blocks for scattering amplitudes

Adrian Dumitru: evolution of the glasma longitudinal initial fields

Analyze classical field configurations at midrapidity: η=0, 2D, SU(2)

what is structure of B_z field ?

magnetic flux loop in x-y plane:

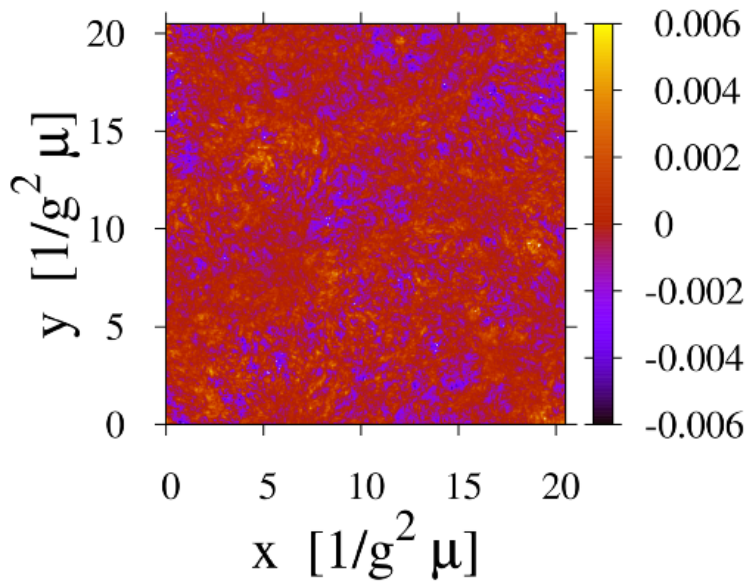


$$M(R) = \mathcal{P}\exp\left(ig\oint dx^i A^i\right)$$

$$W_M(R) = \frac{1}{N_c}\langle \mathrm{tr}\ M(R)\rangle$$

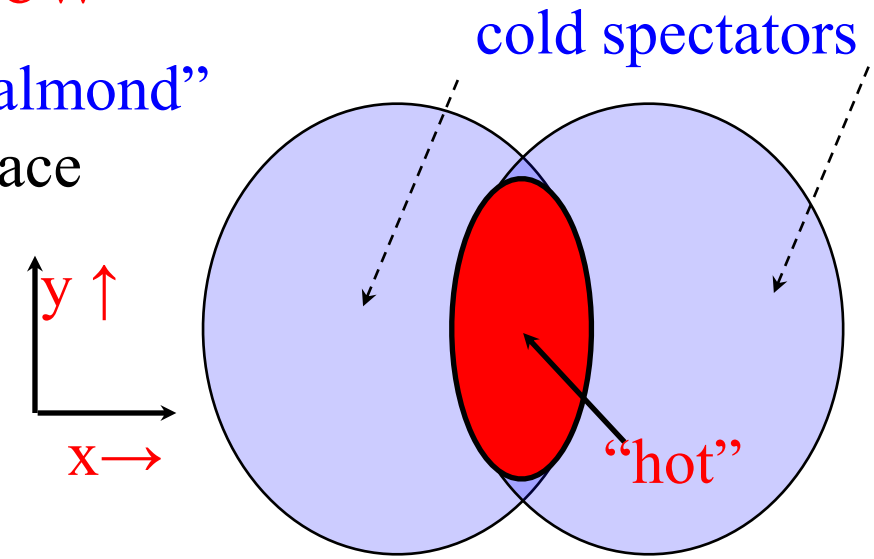
$$W_M^{Z(2)}(R) = \langle \mathrm{sgn\ tr}\ M(R)\rangle$$

actual field configuration B_z



"Elliptic Flow"

For peripheral collisions, overlap region is "almond" in coordinate space, sphere in momentum space



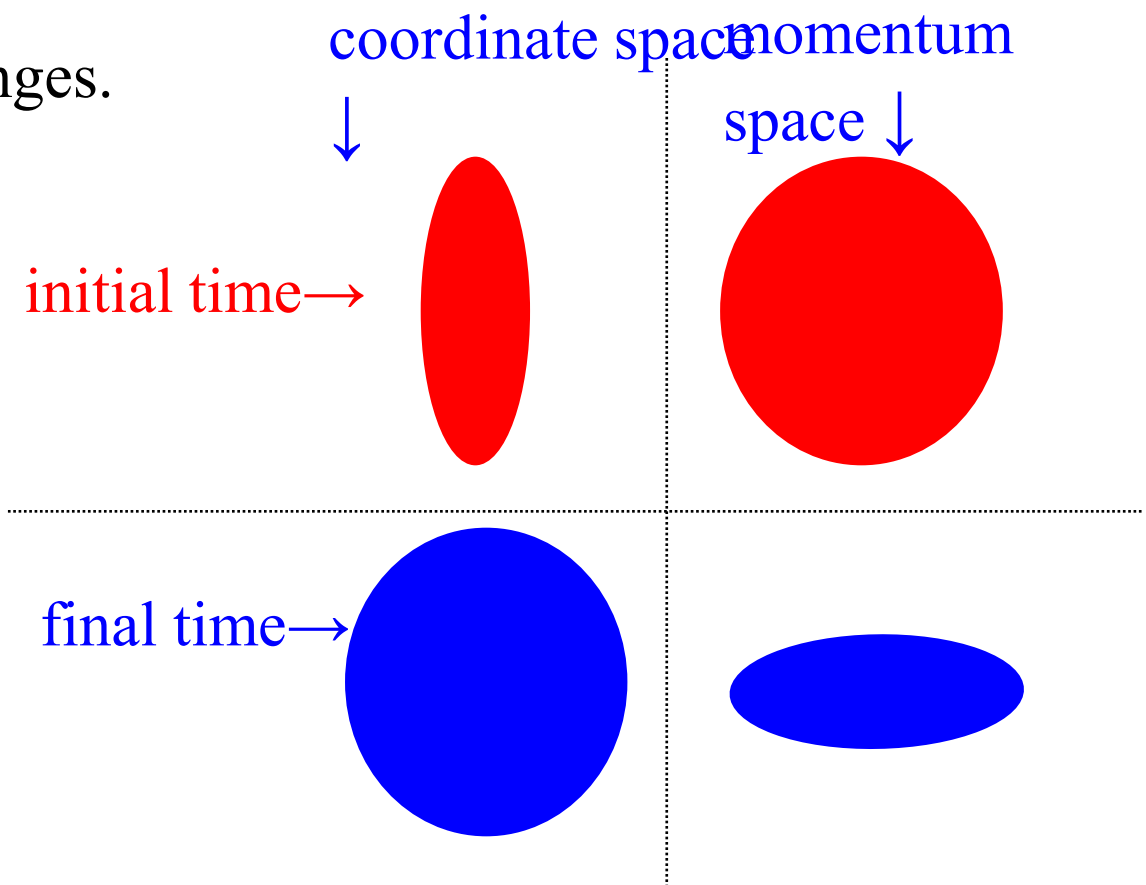
So start with spatial anistropy,

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

If particles free stream, nothing changes.

If collective effects present, end up with sphere in coordinate space, almond in momentum space: "elliptic flow"

$$v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



Light Inflation – Reconciling ϕ^4 Inflation with Planck and Experimental Prospects

F. Bezrukov

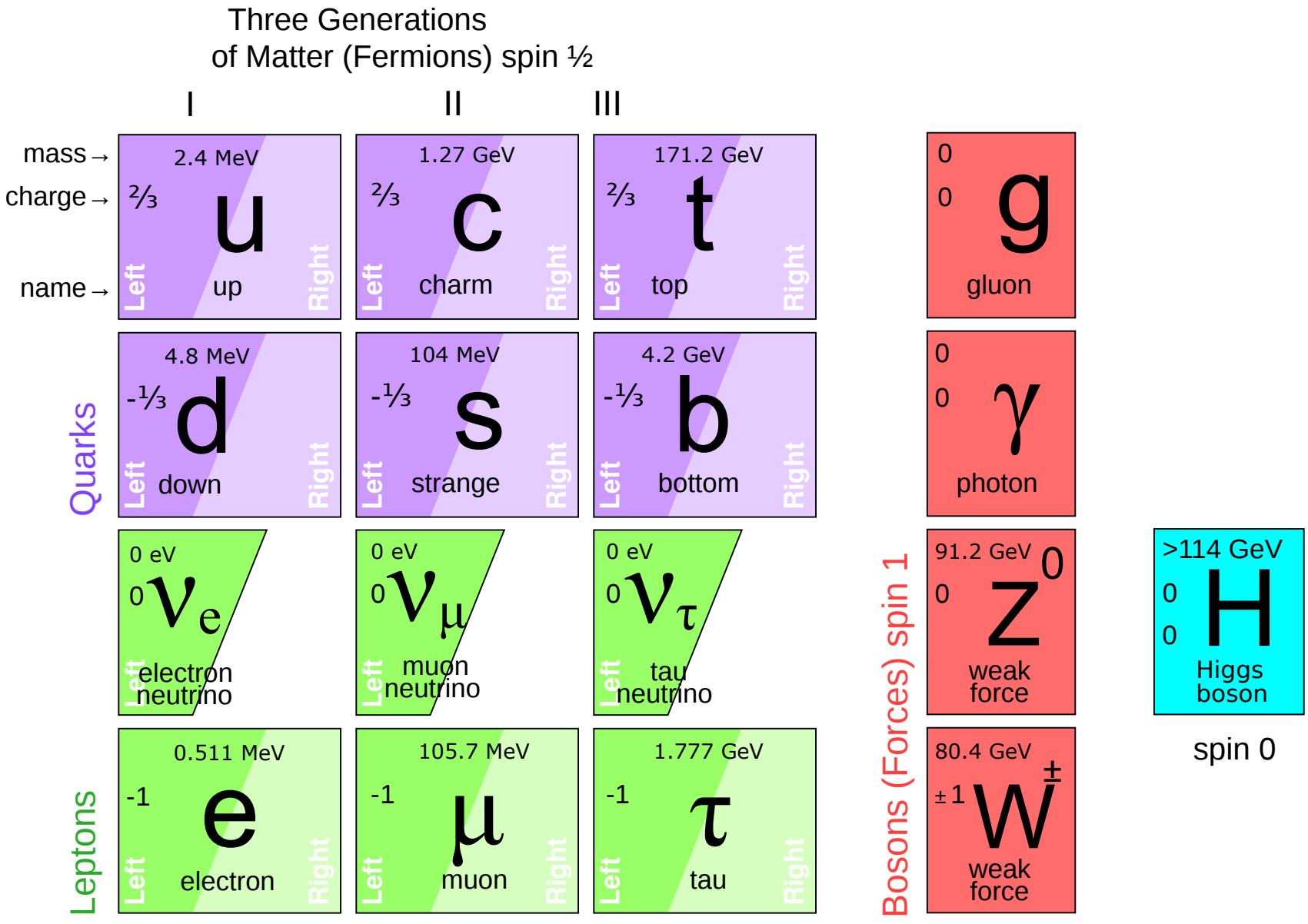
University of Connecticut
&
RIKEN-BNL Research Center
USA

RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Upton, NY
October 30, 2013

Outline

1. Minimally extending the Standard Model
2. ϕ^4 inflation after Planck
   - Minimally coupled inflation
   - Non-minimally coupled inflation
3. Coupling to the SM and cosmological constraints
   - The full model
   - Constraints from reheating and radiative corrections
4. Anything interesting in the laboratory?
   - Direct inflaton search
   - Is the Higgs compatible?

Standard Model of particle physics



Standard Model and nothing else above up to Planck scale?

- No heavy particles/scales
  - no physical high scale quadratic contributions to the Higgs boson mass
  - hierarchy problem is not that scary (however, the gravity should be generous enough not to give quadratically divergent contributions)
  - Processes at the highest energy (inflation) may be directly related to the low energy properties

Standard Model – extended for inflation

Some models that minimally expand the SM and have inflation

- Higgs inflation
  – very direct relation of inflation and SM, some subtleties with the UV properties
- R^2 inflation
  – purely gravitational solution, nothing interesting for the particle physics
- Light inflaton with non-minimal coupling
  – this talk, solution on the particle physics side

Note – the whole Universe evolution should be fully described within the model!

Standard Model – extended for inflation

Some models that minimally expand the SM and have inflation

- Higgs inflation
  – very direct relation of inflation and SM, some subtleties with the UV properties
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- Light inflaton with non-minimal coupling
  – this talk, solution on the particle physics side

Note – the whole Universe evolution should be fully described within the model!

"Standard" chaotic inflation

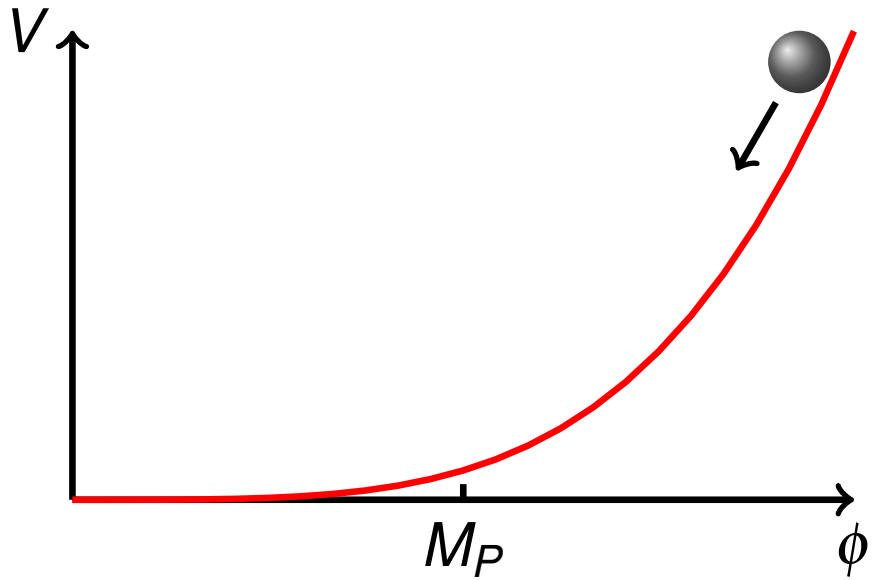
Scalar part of the action

$$S = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R + \frac{\partial_\mu\phi\partial^\mu\phi}{2} - \frac{\beta}{4}\phi^4 \right\}$$

Required to get $\delta T/T \sim 10^{-5}$

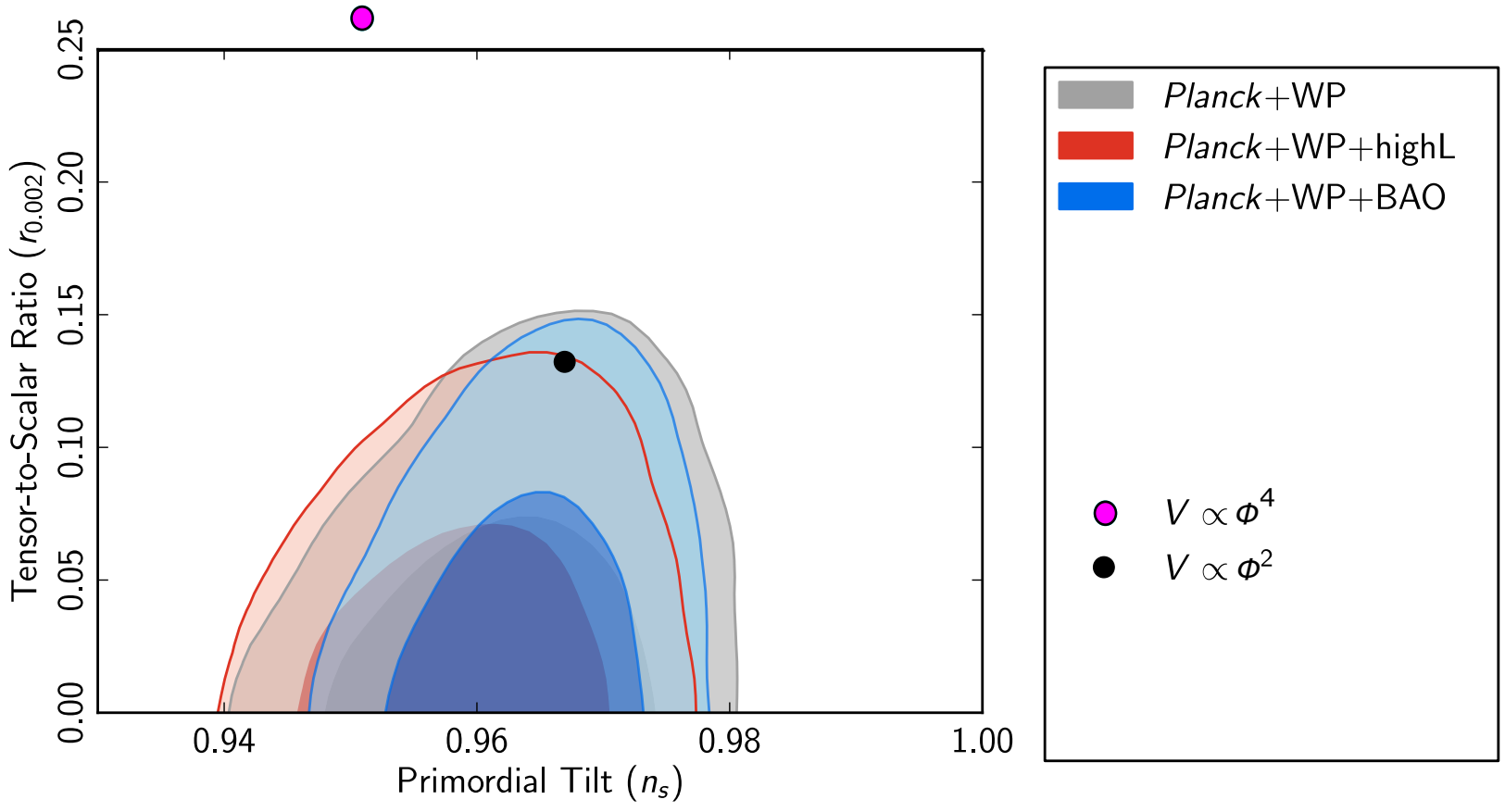
$$\beta \sim 10^{-13}$$

$$m \sim 10^{13}\ \text{GeV}$$



Fields $\gtrsim M_P$, energy $\sim \lambda^{1/4} M_P$.

Planck results disfavor plain ϕ^4



Non-minimal coupling to gravity leads to good inflation

Scalar action with non-minimal coupling

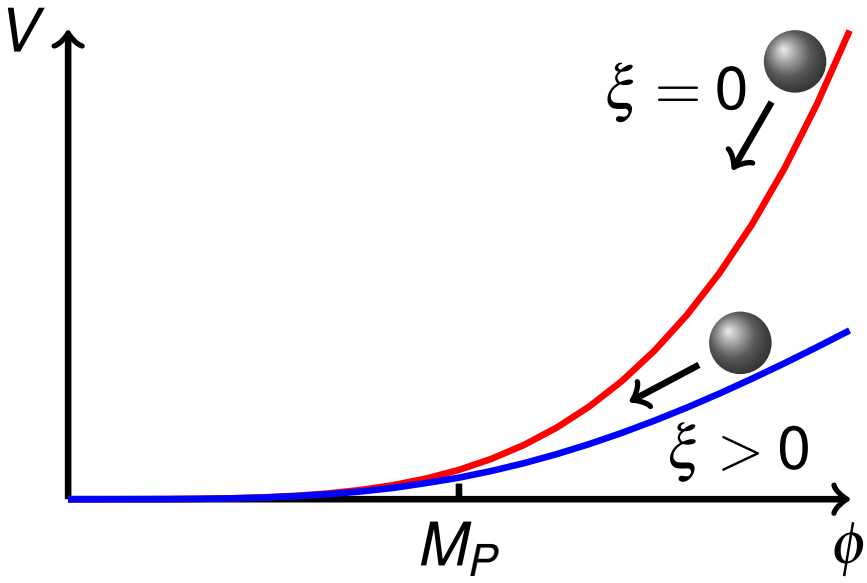
$$S = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi}{2}\phi^2 R + \frac{\partial_\mu\phi\partial^\mu\phi}{2} - \frac{\lambda}{4}\phi^4 \right\}$$

Conformal transformation to the Einstein frame

$$\hat{g}_{\mu\nu} = \sqrt{1+\frac{\xi\phi^2}{M_P^2}}\, g_{\mu\nu},$$

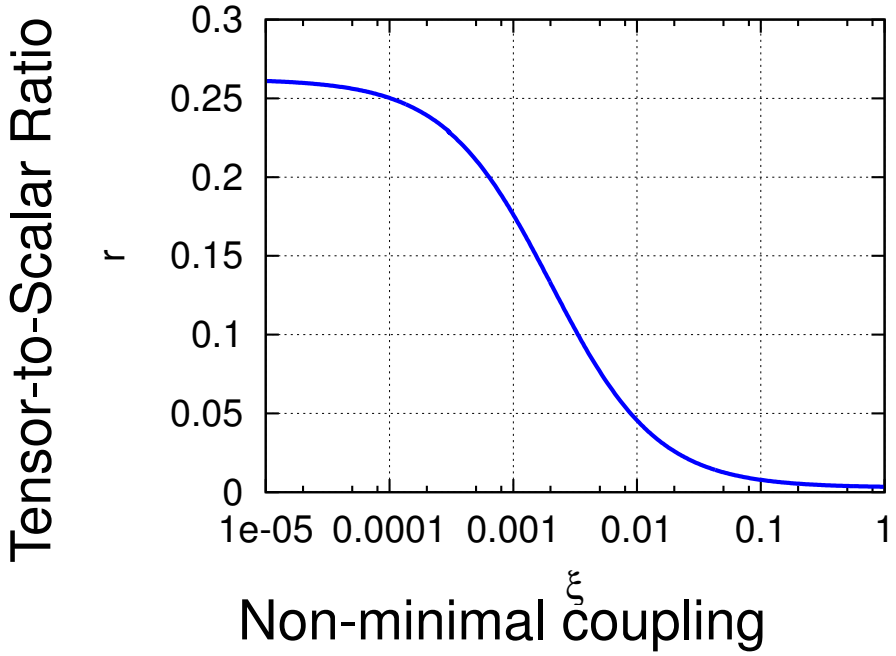
flattens the potential

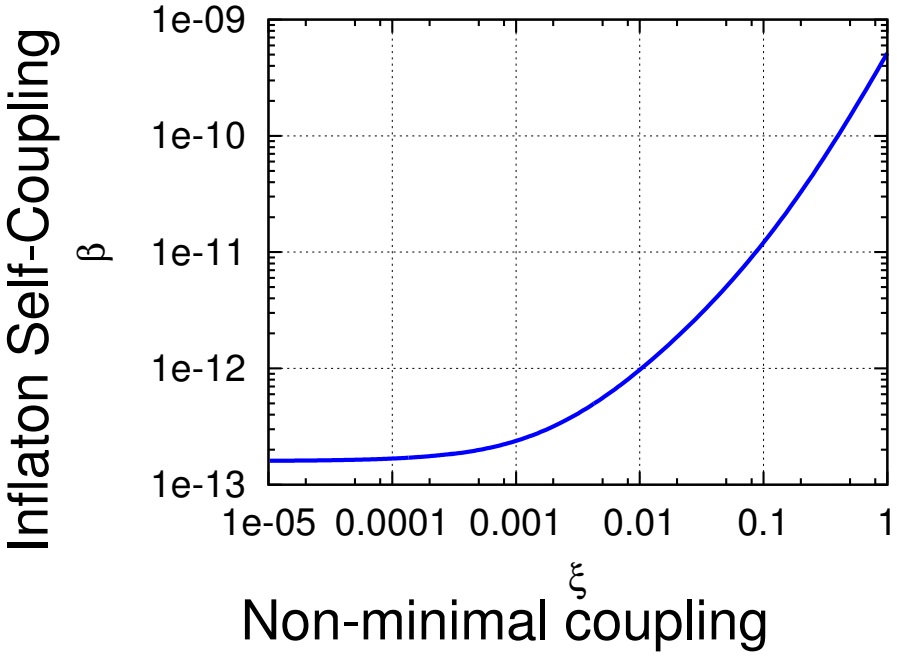
$$V(\phi) \to \hat{V}(\phi) = \frac{V(\phi)}{\left(1+\xi\phi^2/M_P^2\right)^2}$$



(Change of the field $\frac{d\chi}{d\phi} = \sqrt{\frac{1+(\xi+6\xi^2)\phi^2/M_P^2}{(1+\xi\phi^2/M_P^2)^2}}$ is also needed)

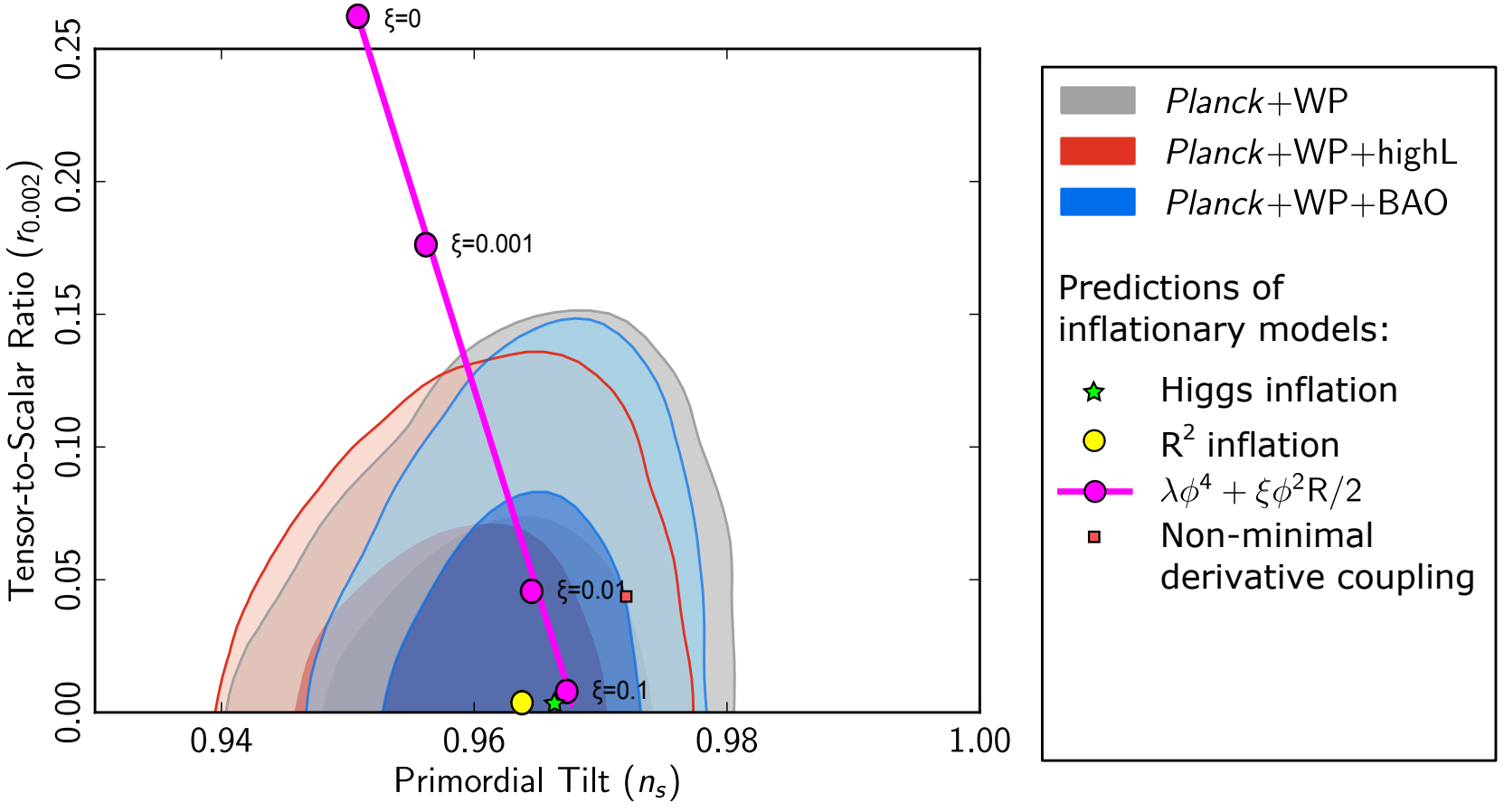
The tensor perturbations are suppressed, inflaton self-coupling β is increased





[Tsujikawa, Gumjudpai'04, FB'08, Okada, Rehman, Shafi'10]

Inflationary predictions are ok for $\xi \gtrsim 0.003$



SM + Light Inflaton coupled in the Higgs sector only

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \alpha H^\dagger H \phi^2 + \frac{\beta}{4}\phi^4 + \frac{\xi\phi^2}{2}R$$

Standard Model | Interaction | Inflationary sector

Inflaton mass depends on interaction strength: $m_\chi = m_h\sqrt{\beta/2\alpha}$

Specifically: the Higgs-inflaton scalar potential is

$$V(H,\phi) = \lambda\left(H^\dagger H - \frac{\alpha}{\lambda}\phi^2\right)^2 + \frac{\beta}{4}\phi^4 - \frac{1}{2}\mu^2\phi^2 + V_0$$

We assumed here, that the scale invariance is broken *in the inflaton sector only*

[Shaposhnikov, Tkachev'06, Anisimov, Bartocci, FB'09, FB, Gorbunov'10,13]

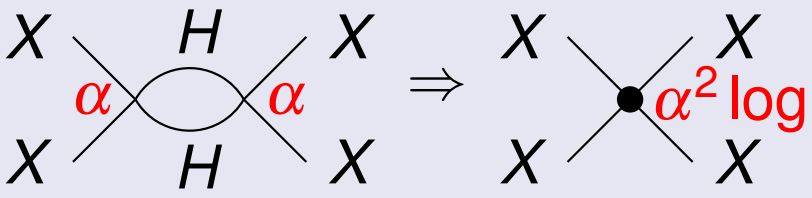
All constants of the model are bound from cosmology

CMB normalization sets $\beta(\xi)$

$$\beta = \frac{3\pi^2 \Delta^2_{\mathscr{R}}}{2} \frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

$\alpha \lesssim \beta^2$ (mass lower bound)

Inflation is not spoiled by the radiative corrections



CMB tensor modes bound ξ

$$r = \frac{16(1+6\xi)}{(N+1)(1+8(N+1)\xi)} \lesssim 0.15$$

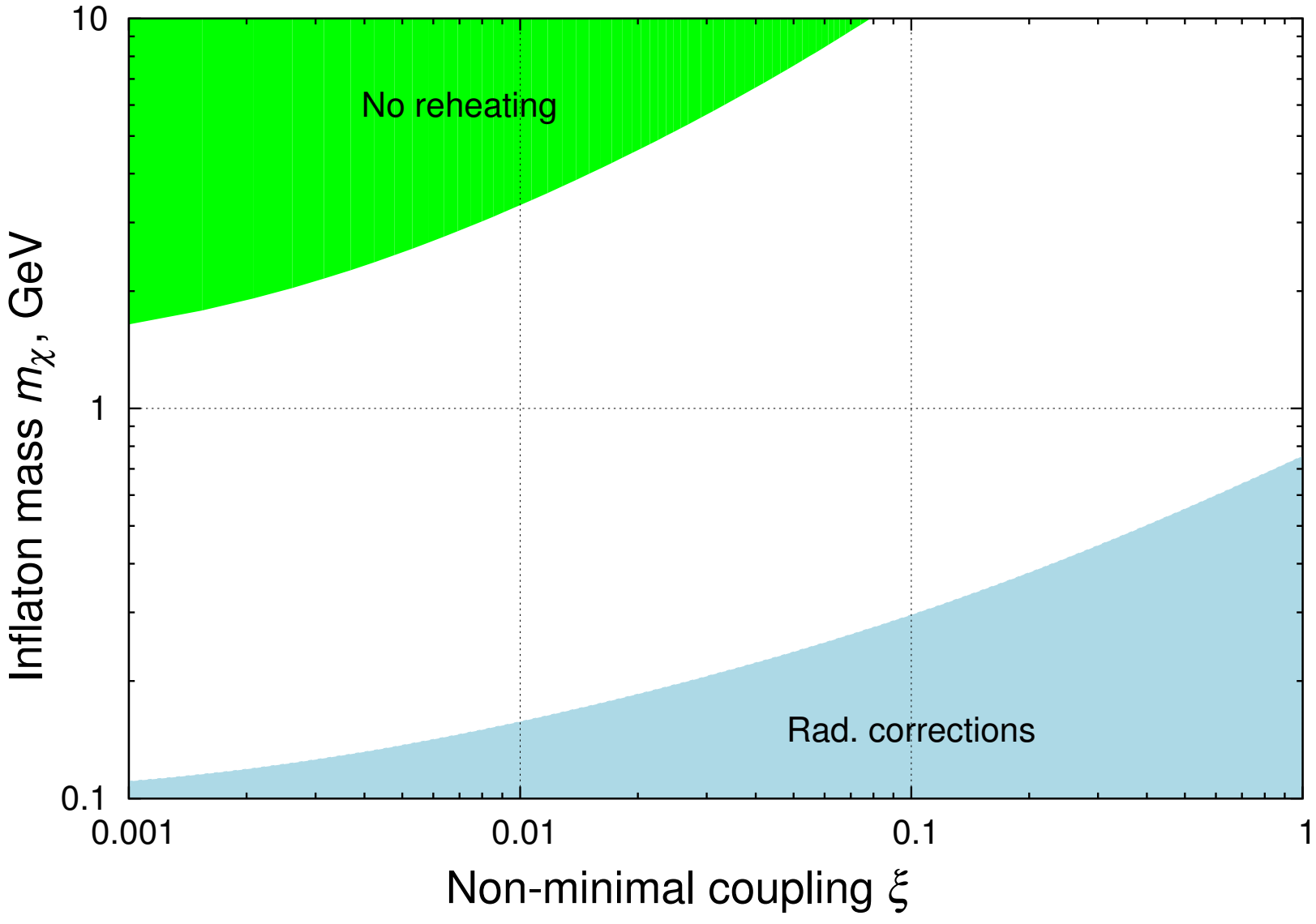
$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

- After inflation: empty & cold
- Needed: hot, $T_r \gtrsim 150$ GeV (to get baryogenesis)

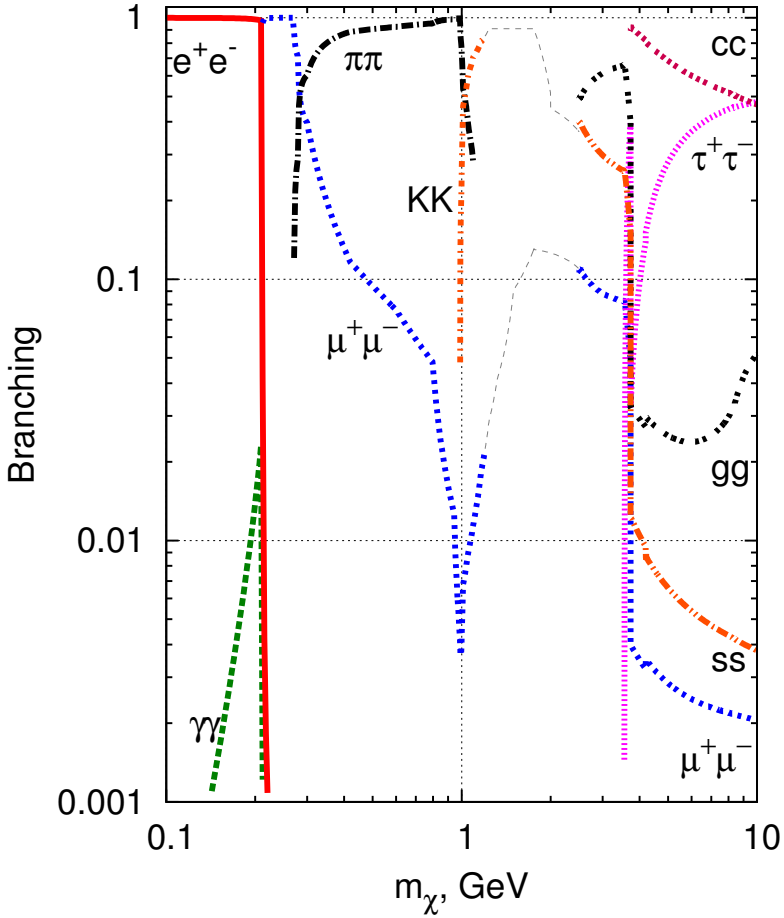
[Anisimov, Bartocci, FB'09]

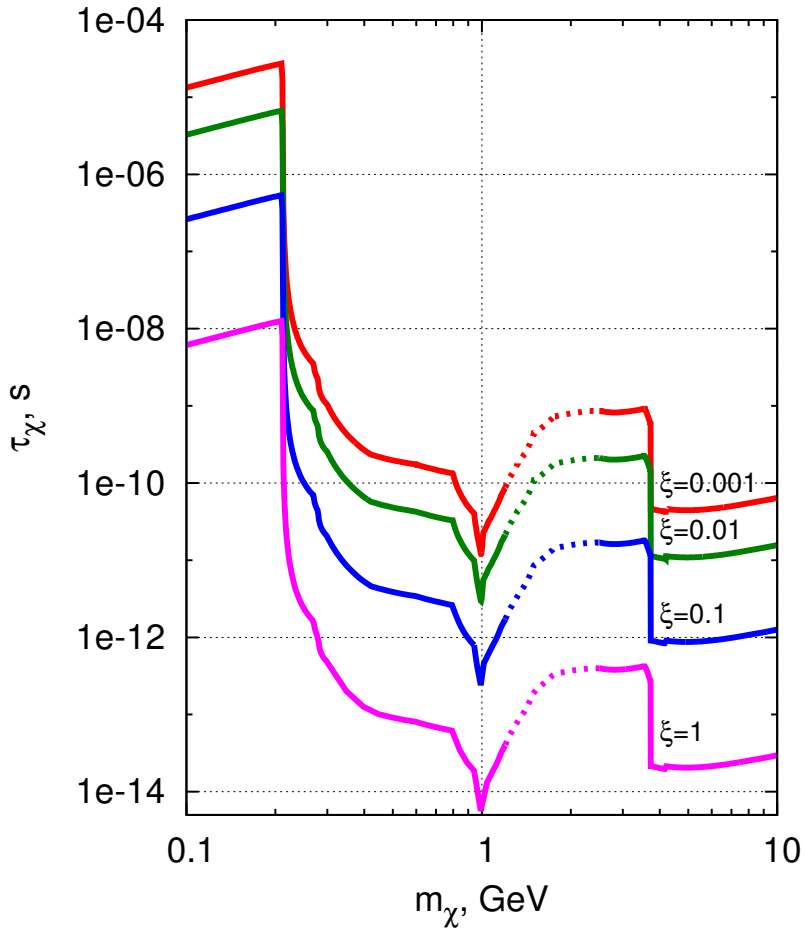
The Inflaton mass is bounded from cosmology



Inflaton decays and lifetime

Coupled to everything proportional particle mass

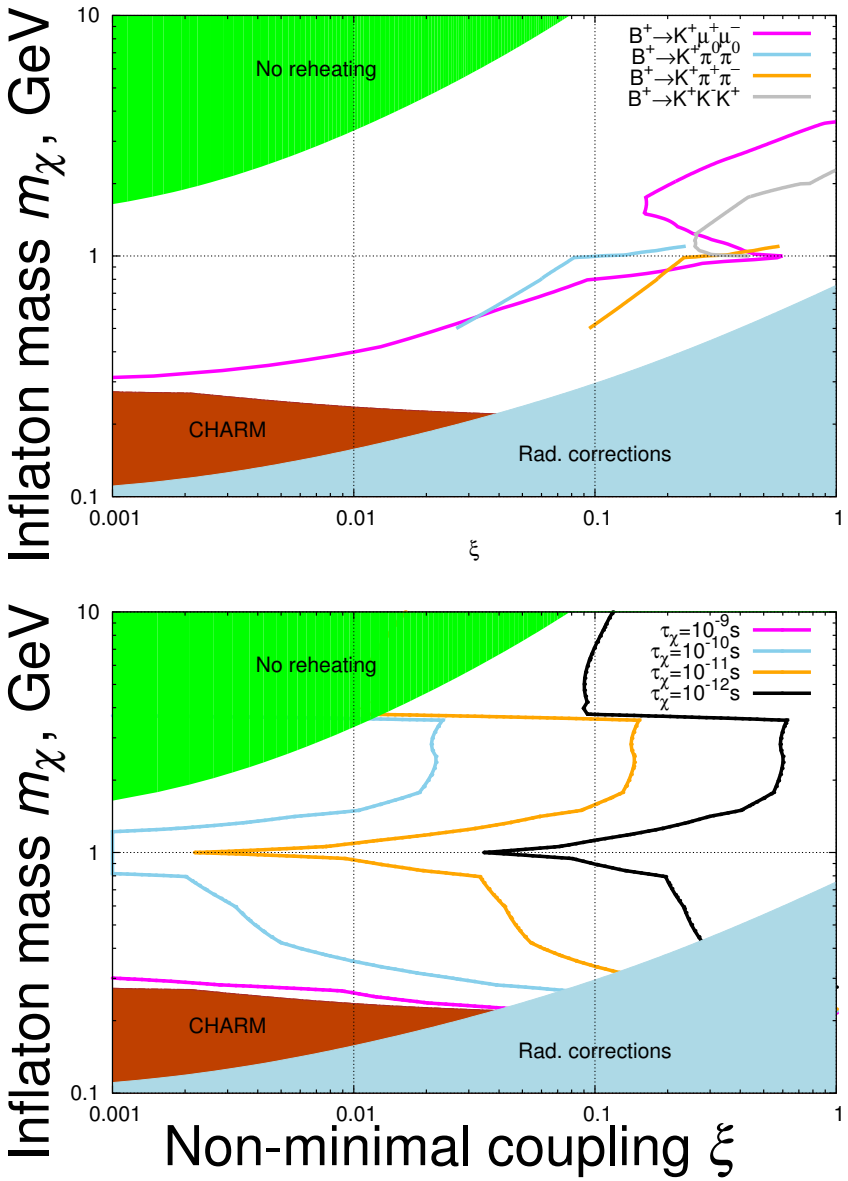




Created in meson decays:

$$\mathrm{Br}(B \to \chi X_s) \simeq 10^{-6} \frac{\beta(\xi)}{1.5\times10^{-13}} \frac{300\ \mathrm{MeV}^2}{m_\chi}$$

Experimental searches are possible



Behaves as light "Higgs" boson, suppresed by $\theta = \sqrt{2\beta}\, v/m_\chi$

- Created in meson decays
- Decays: KK, $\pi\pi$, $\mu\mu$, ee, ...
- Interacts with media: extremely weakly

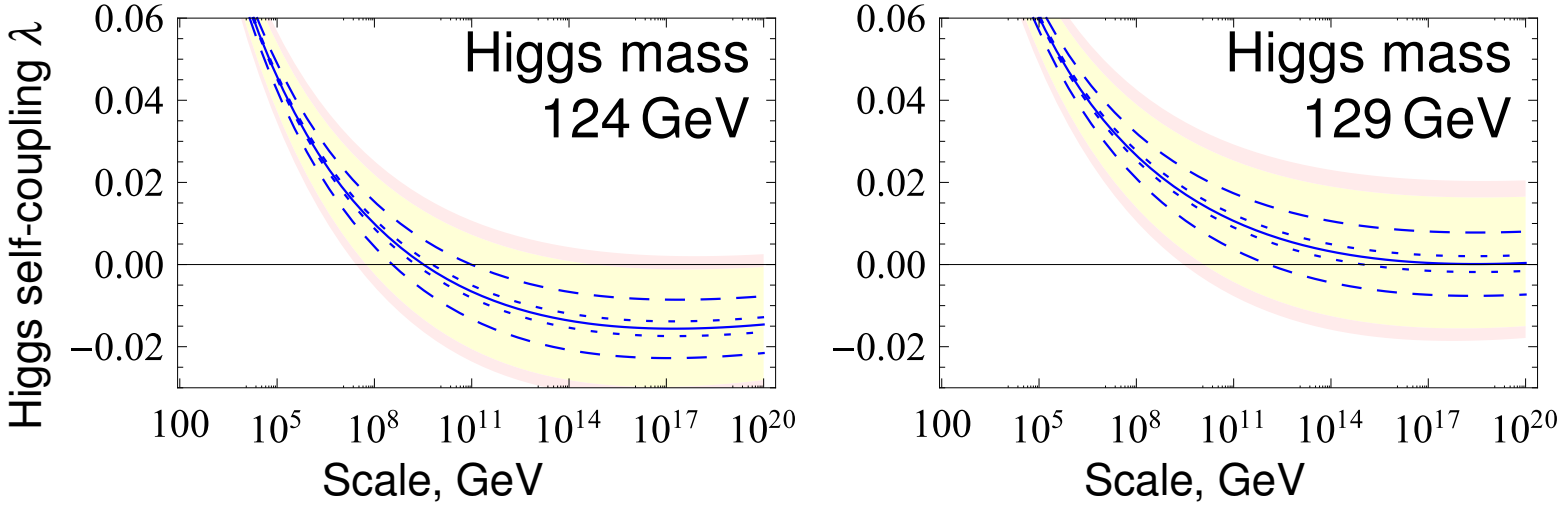
Search (LHCb, Belle)

- Events with offset vertices in B decays
- Peaks in Daltiz plot of three body B decays

Another prediction: The Higgs boson can not be light

Inflation proceeds along $H^\dagger H = \frac{\alpha}{\lambda} X^2$

- The Higgs self-coupling λ: must be positive up to inflationary scales



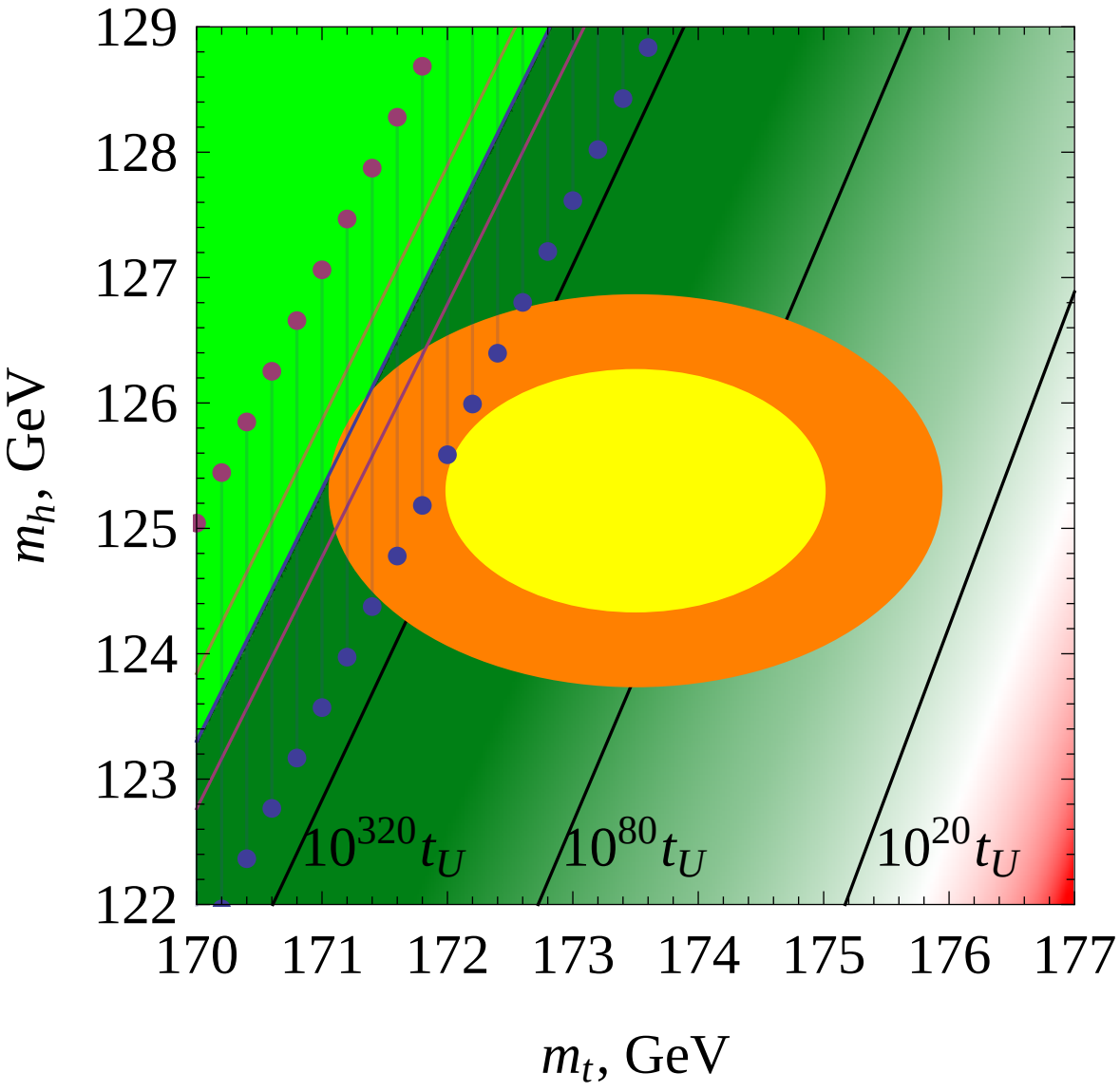
Current experimental value: $m_H = 125.7 \pm 0.4\,\text{GeV}$ (CMS)

Mass for $\lambda(\mu) = \beta_\lambda(\mu) = 0$

$$M_{\text{min}} = \left[129.5 + \frac{M_t - 173.2\text{GeV}}{0.9\text{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right] \text{GeV}$$

[FB, Kalmykov, Kniehl, Shaposhnikov'12, Degrassi et.al'12]

Critical Higgs mass is compatible with M_t and α_s



Vacuum stability

Conclusions 1: Cosmology

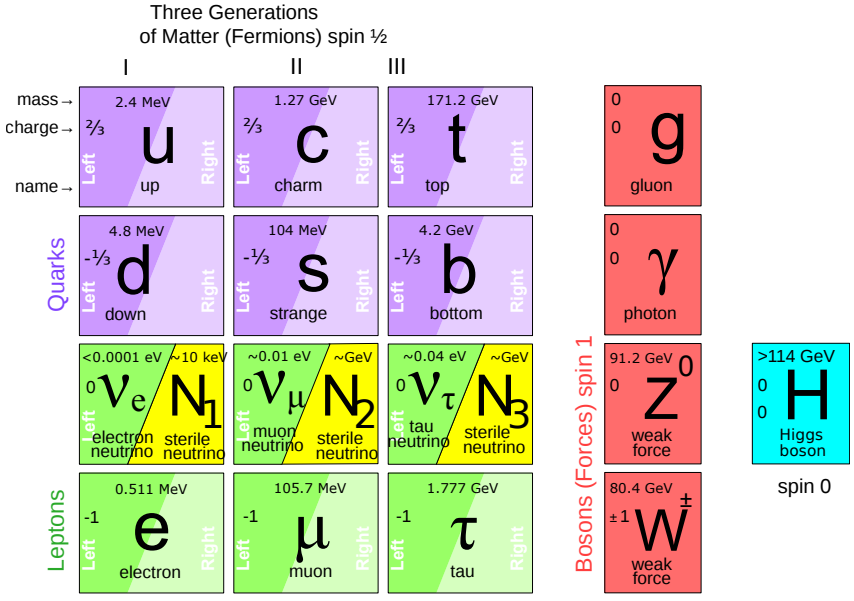
- Single filed quartic inflation with *small* non-minimal coupling is perfectly ok with the current CMB observations

Conclusions 2: Cosmology and Particle Physics

- An example of a model minimally extending SM without any heavy scales: a singlet scalar field with non-minimal coupling
- Cosmological observations constrain the inflaton mass to be light (in GeV range) – interesting for particle physics!
- Further study
  - Detection of tensor modes is especially interesting to constrain the theory
  - The inflaton can be searched in low energy experiments – rare B decays
    - Offset vertices in B decays
    - Peaks in B three body decay Dalitz plot
  - Higgs mass bounds – top quark mass measurement is needed!

Backup slides

Dark matter – add νMSM and stir



Role of sterile neutrinos

N_1 (Warm) Dark Matter, $M_1 \sim 1$–$50\,\mathrm{keV}$

$N_{2,3}$ Baryogenesys, $M_{2,3} \sim \ldots\mathrm{GeV}$

http://arxiv.org/abs/hep-ph/0505013

Dark matter – add νMSM and stir

A νMSM inspired model with inflation χ

$$\mathscr{L} = (\mathscr{L}_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\bar{L}_\alpha N_I \Phi - \frac{f_I}{2}\bar{N}_I^c N_I X + \text{h.c.}) + \frac{1}{2}(\partial_\mu X)^2 - V(\Phi, X)$$

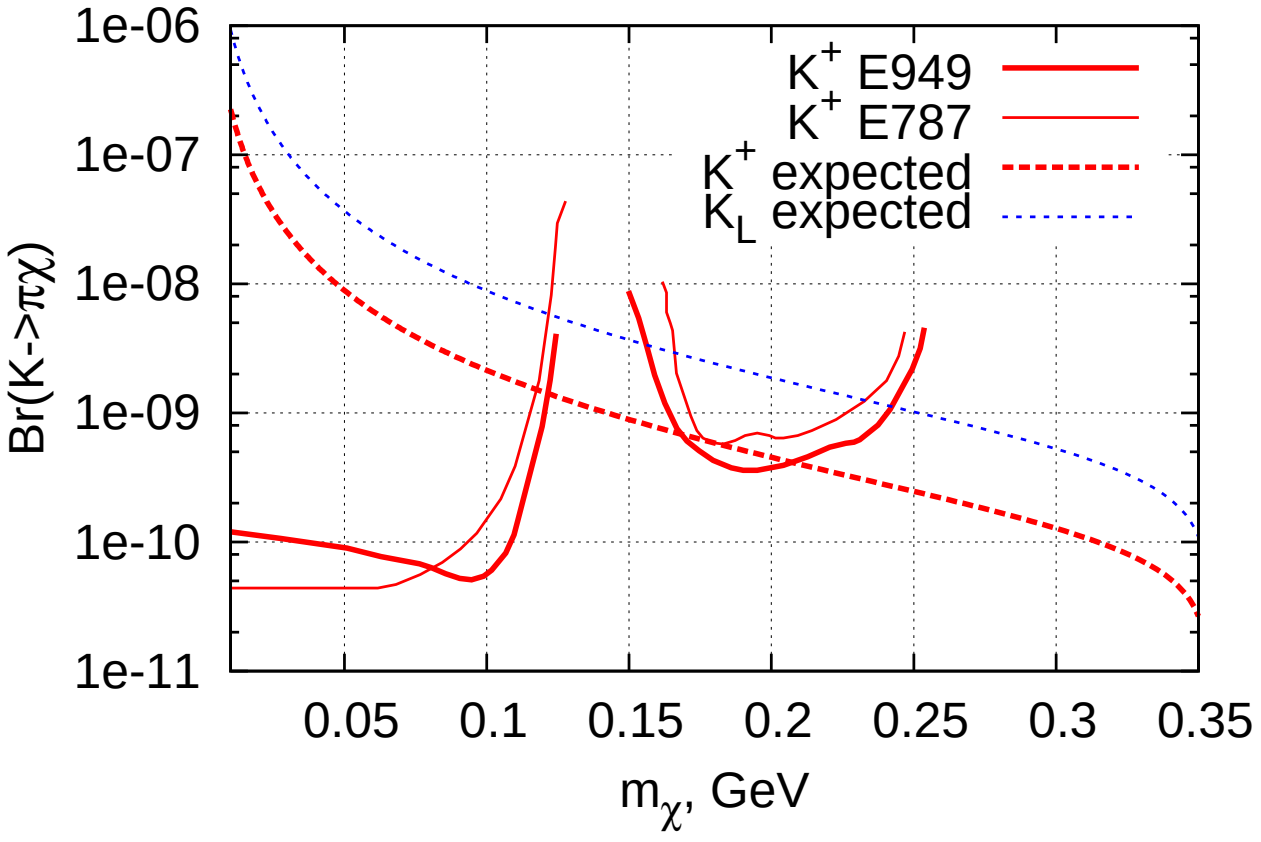
$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5\times 10^{-13}} \cdot \left(\frac{M_1}{10\text{keV}}\right)^3 \cdot \left(\frac{100\text{ MeV}}{m_\chi}\right)^3 ,$$

DM sterile neutrino mass bound

$$M_1 \lesssim 13 \cdot \left(\frac{m_\chi}{300\text{ MeV}}\right)\left(\frac{S}{4}\right)^{1/3} \cdot \left(\frac{0.9}{f(m_\chi)}\right)^{1/3} \text{keV} .$$

[Shaposhnikov, Tkachev'06, FB, Gorbunov'10,13]

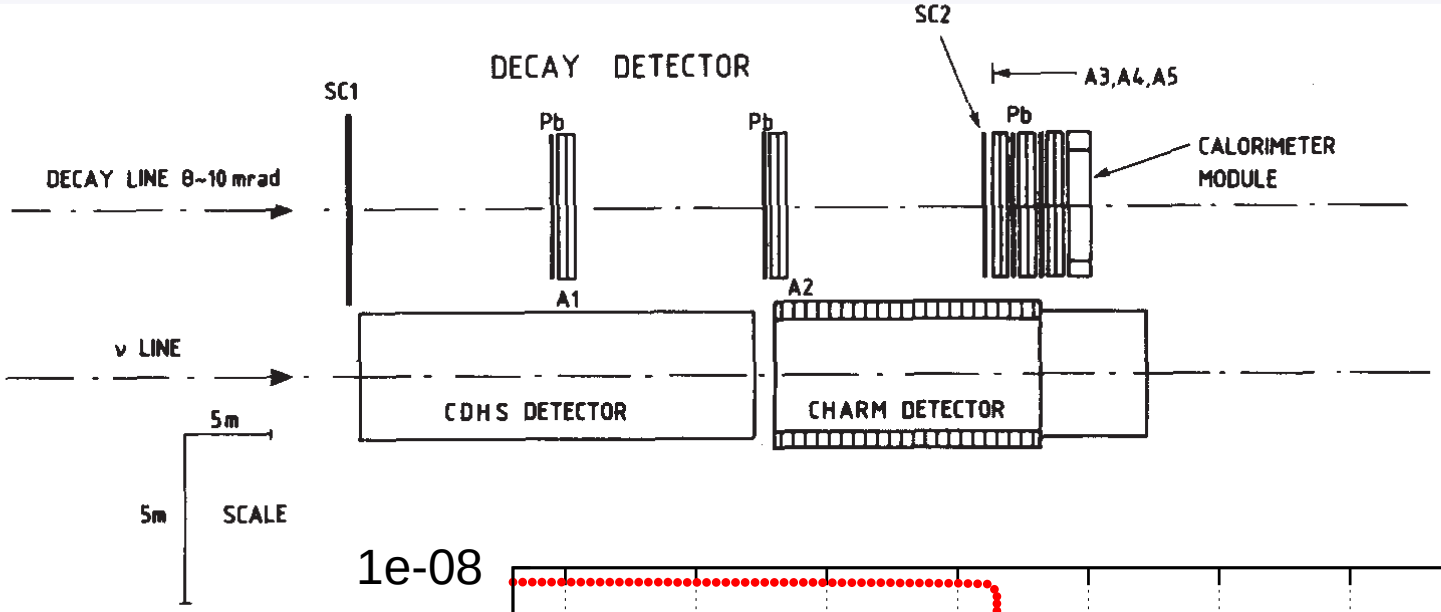
Production: bound from $K^+ \to \pi^+ +$ nothing



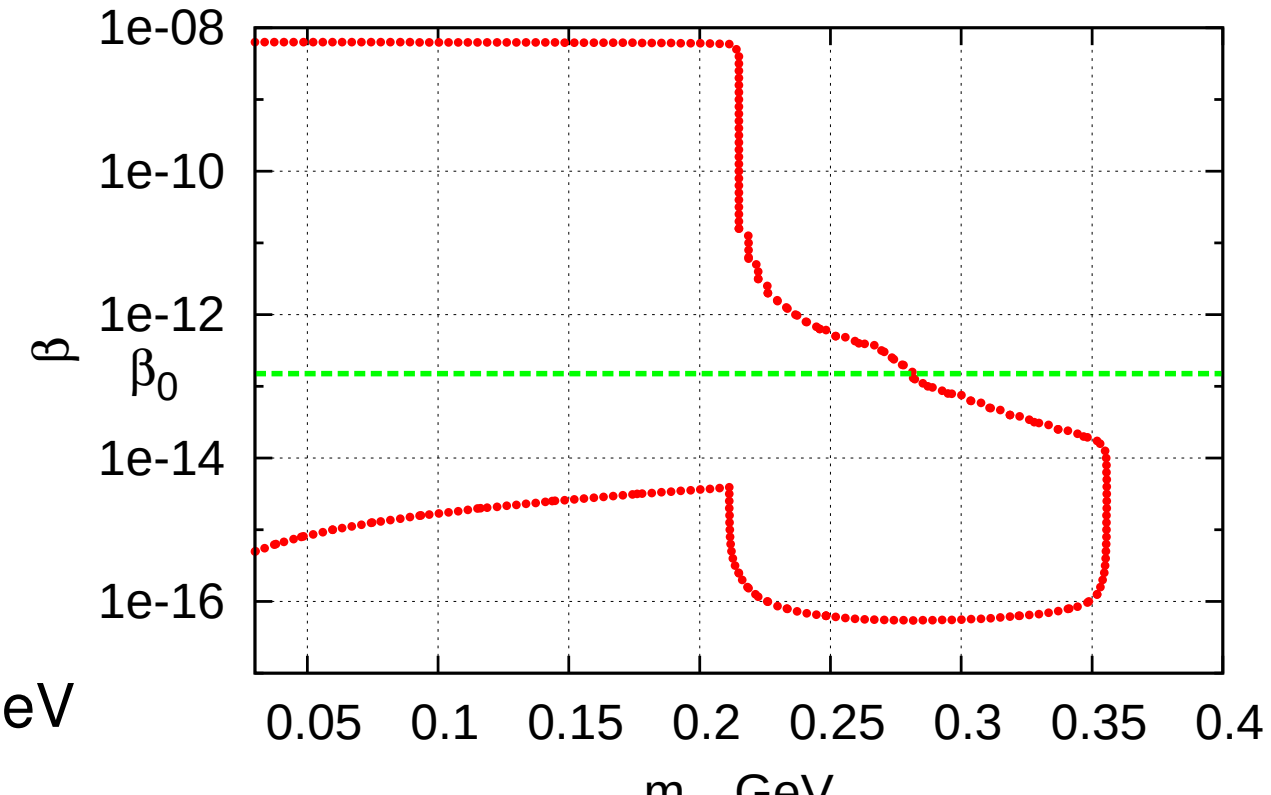
Excluded: $m_\chi \lesssim 120$ MeV

Disfavoured: 170 MeV $\lesssim m_\chi \lesssim 205$ MeV

CHARM – bound



Search for decays of some-thing into $\gamma\gamma$, e^+e^-, $\mu^+\mu^- \Longrightarrow$ $m_\chi < 270$ MeV



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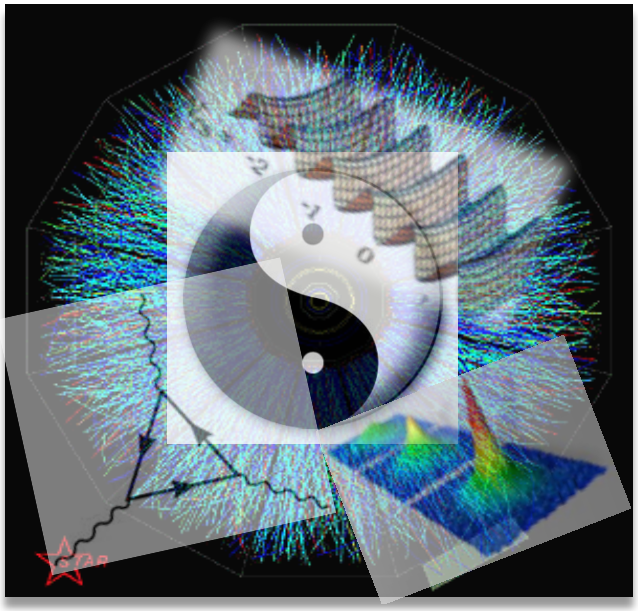
Strongly Interacting Matter In & Out of Equilibrium



Jinfeng Liao

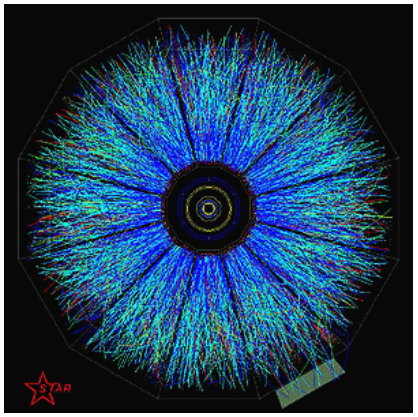
Indiana University, Physics Dept. & CEEM

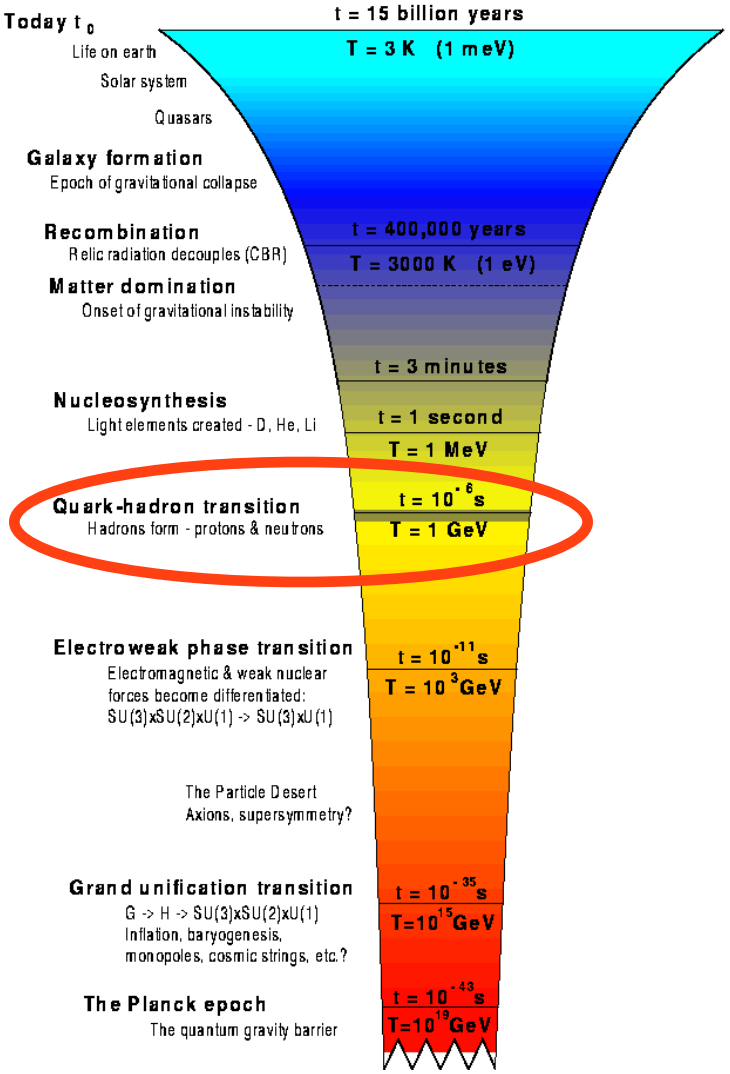
RIKEN BNL Research Center

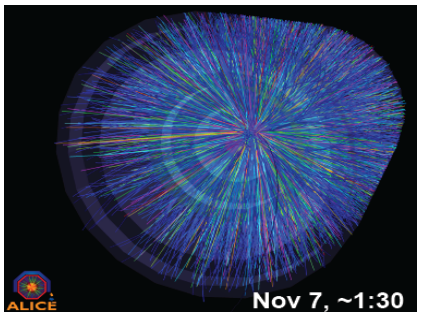
Outline

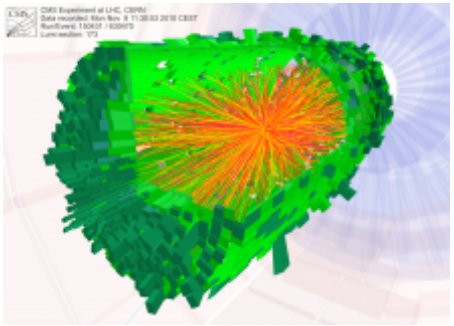
- Introduction: Strongly Interacting Matter
- Thermal QGP as A Topological Matter
- Thermal QGP as A Chiral Matter
- The Overpopulated Pre-Equilibrium Matter
- Summary & Outlook

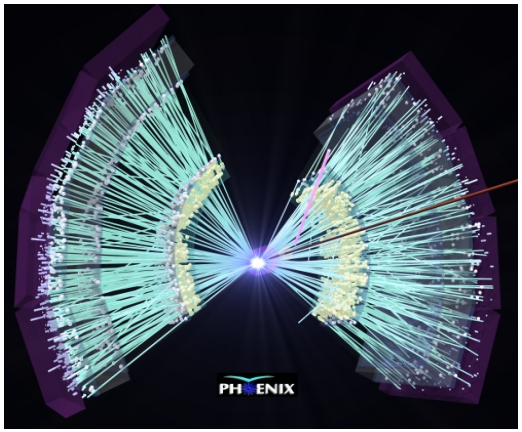
Beautiful "Little Bangs" Delivered

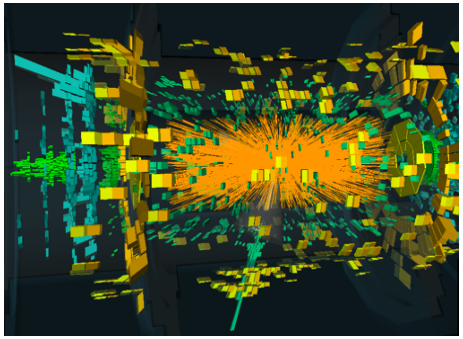






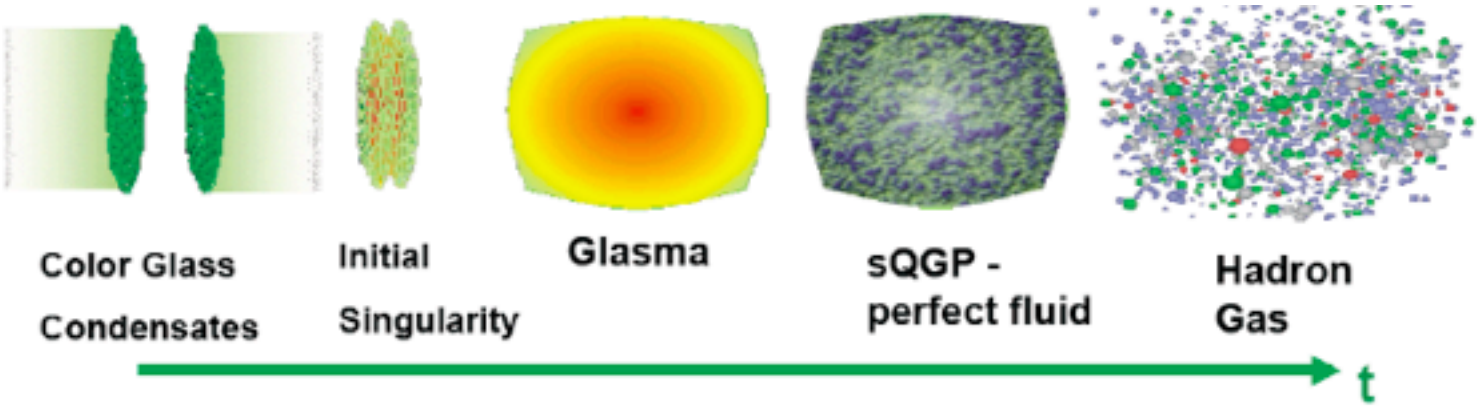


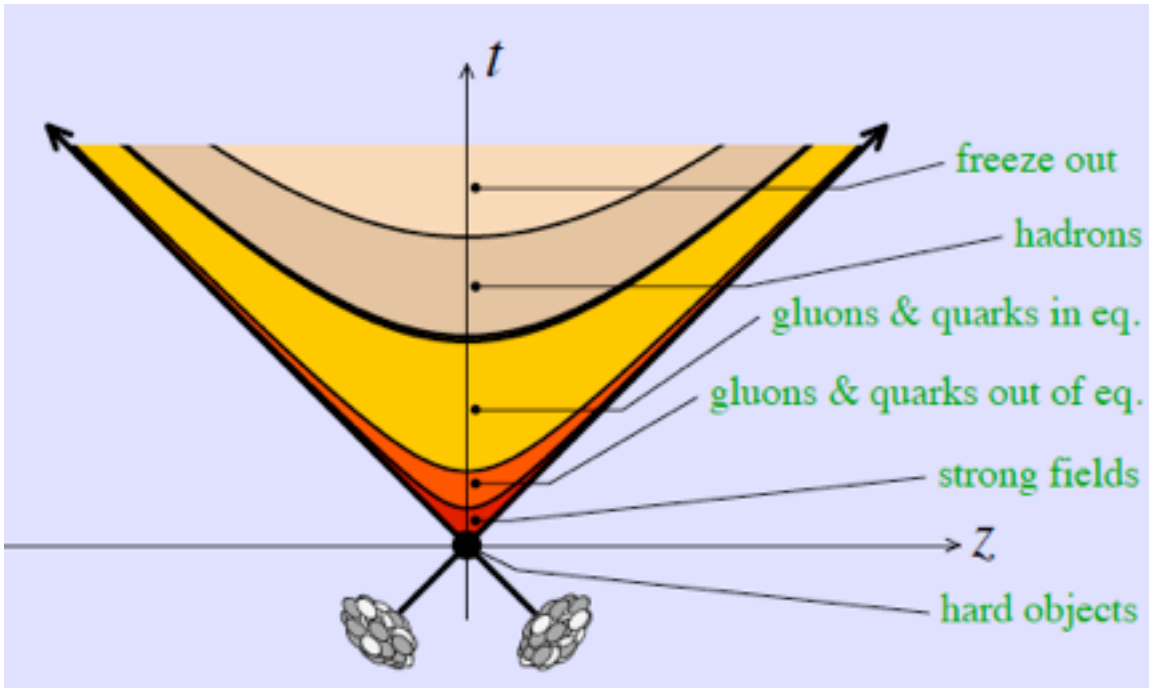




Heavy Ion Collision: the only "Time Machine"
to trace back the matter in early cosmos environment

Different Stages of Heavy Ion Collisions

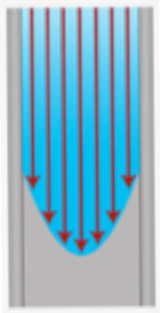




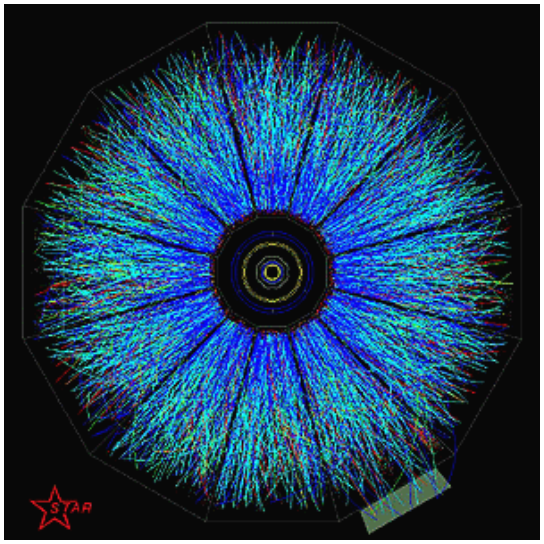
Probing
matter properties:
thermal
&
near thermal
(transport)
&
far-from thermal

The Strongly Interacting Matter

A nearly perfect fluid able to flow through fermi-scale "pipe"



~ *fermi*



A dense partonic matter opaque to high energy color probe



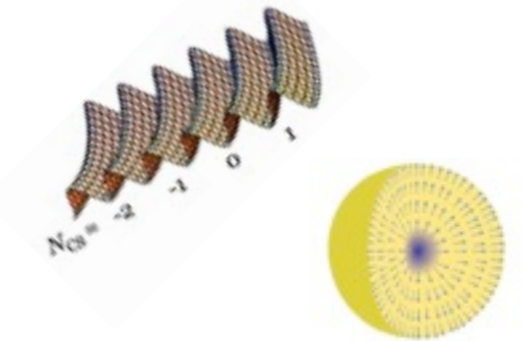
A pre-equilibrium matter that quickly relaxes toward equilibrium like a very stiff spring

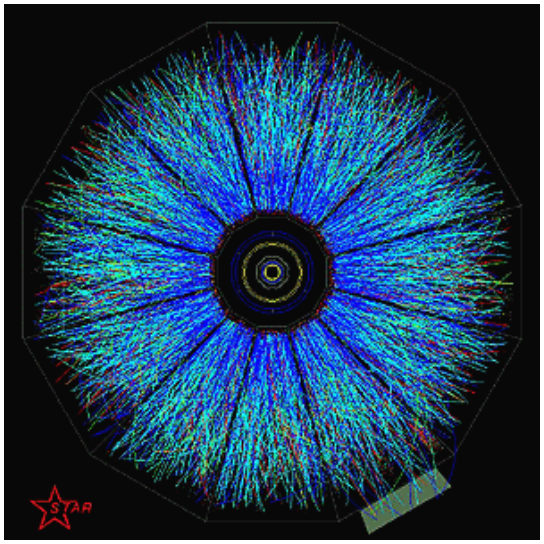


Strongly interacting matter created & measured in heavy ion collisions: a unique laboratory for understanding how QCD operates in Nature.

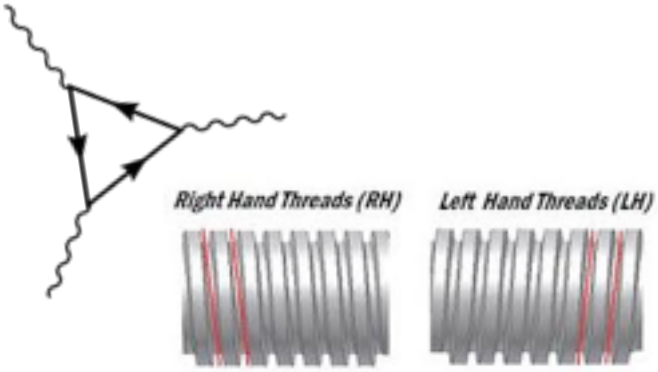
The Strongly Interacting Matter

A Topological Matter

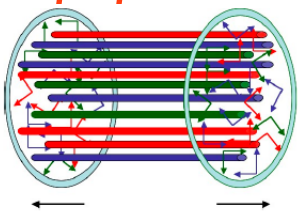


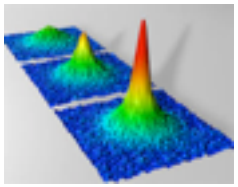


A Chiral Matter



An Overpopulated Pre-Equilibrium Matter



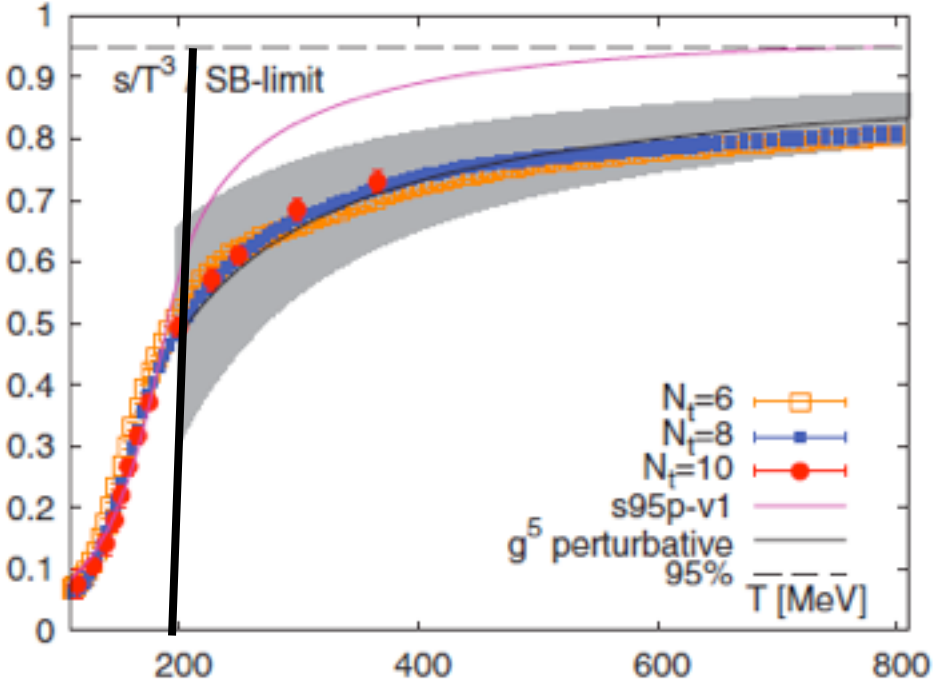


This talk will discuss some of our recent progress in understanding the structure & dynamics of this strongly interacting matter in light of its measured properties.

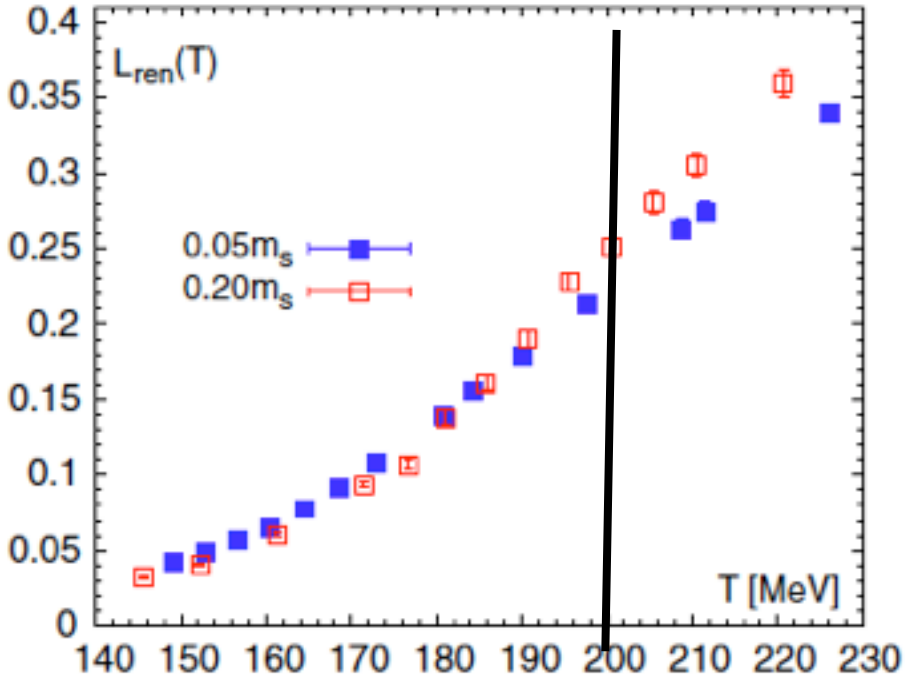
Thermal QGP as A Topological Matter

Liberation of Color?

Degrees of freedom



Degree of color liberation



A region around Tc with liberated degrees of freedom

but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP --- **glue~L^2, quark~L**)

Then what are the "extra" dominant DoF here???

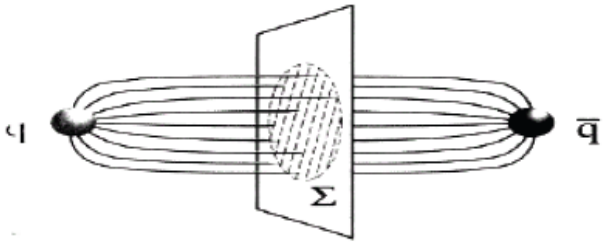
To answer this, we need the topological objects.

Emergent Magnetic Plasma Near Tc

T<< Lambda_QCD | T ~ Lambda_QCD | T>> Lambda_QCD

Vacuum: confined | **Tc** | sQGP | ***wQGP: screening***

T

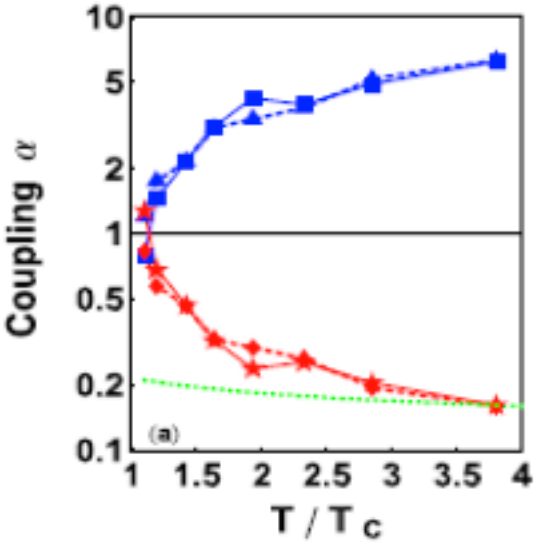


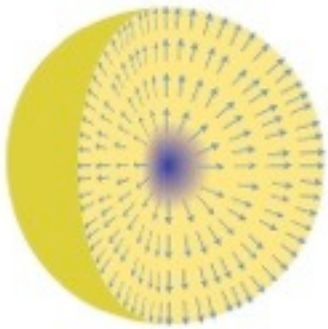
Emergent plasma with E & M charges:
chromo-magnetic monopoles are the "missing DoF"

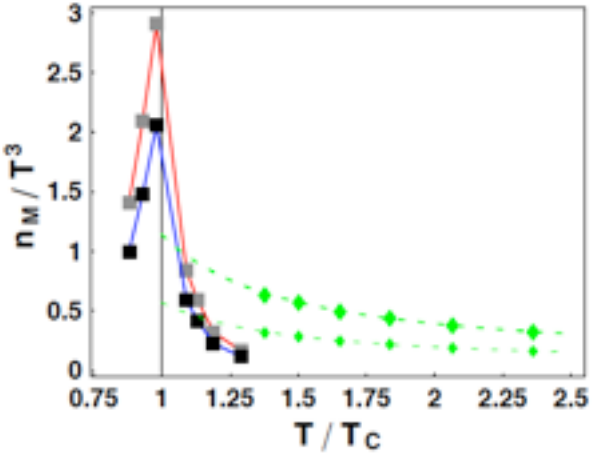
Plasma of E-charges
E-screening: g T
M-screening: g^2 T

Electric Flux Tube:
Magnetic Condensate

$$\alpha_E * \alpha_M = 1.$$





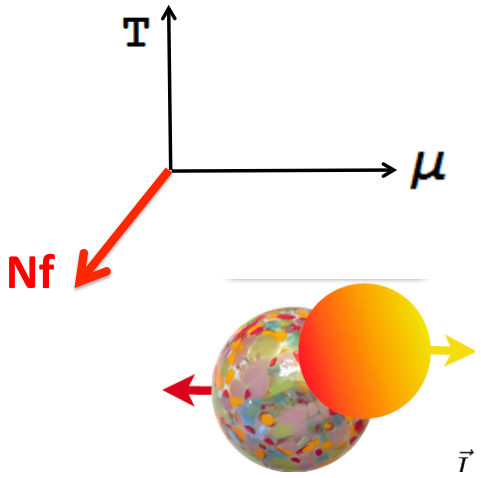


JL & Shuryak:
Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.

Confinement as BEC of Monopoles

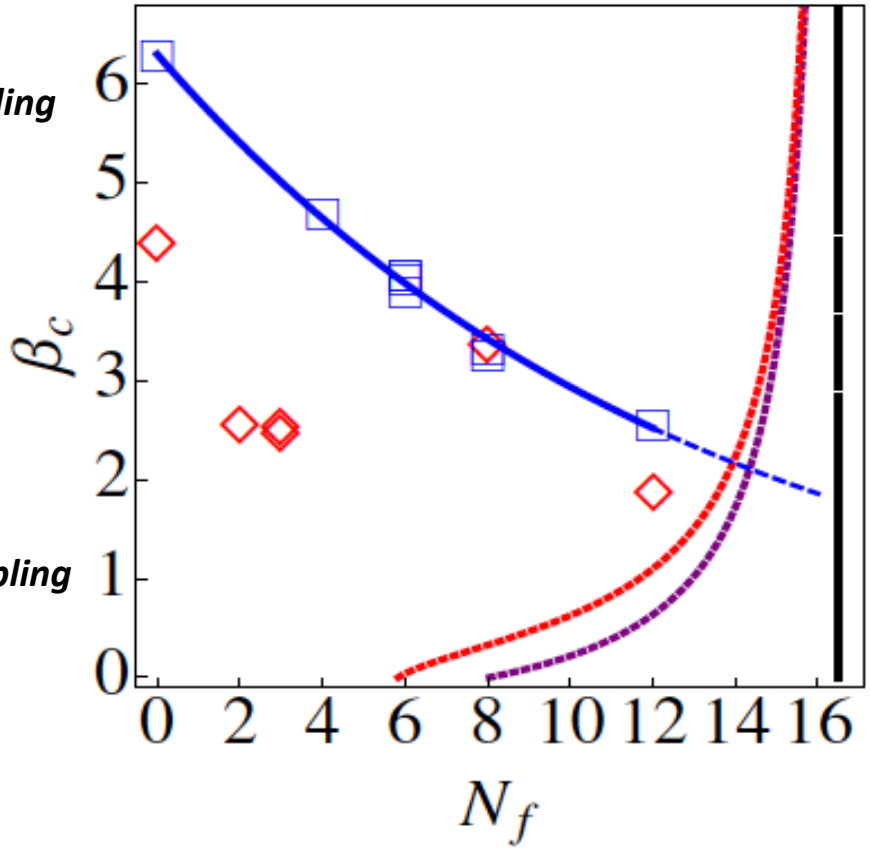
The magnetic scenario helps explain many aspects of near-Tc plasma. Let us here focus on very important issue: confinement transition.

How the confinement transition changes with light flavor number?



Weaker coupling

Stronger coupling

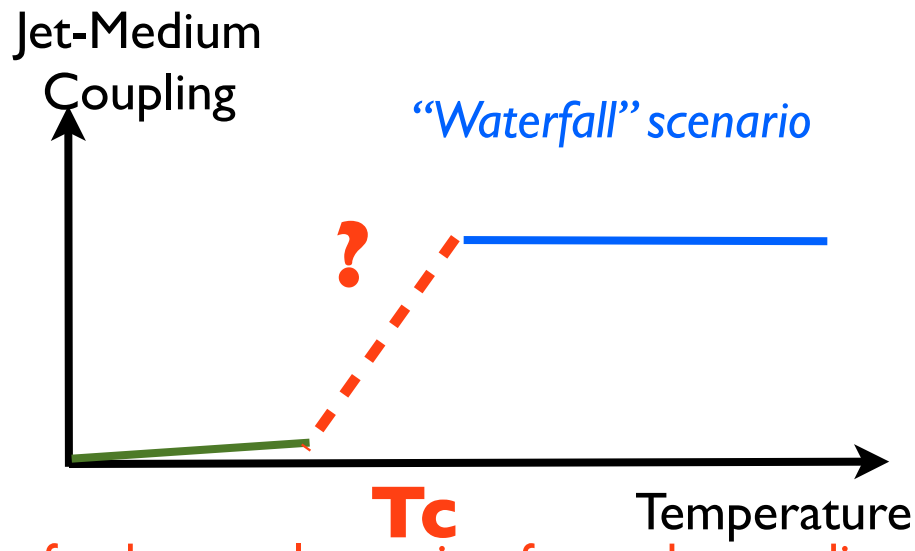


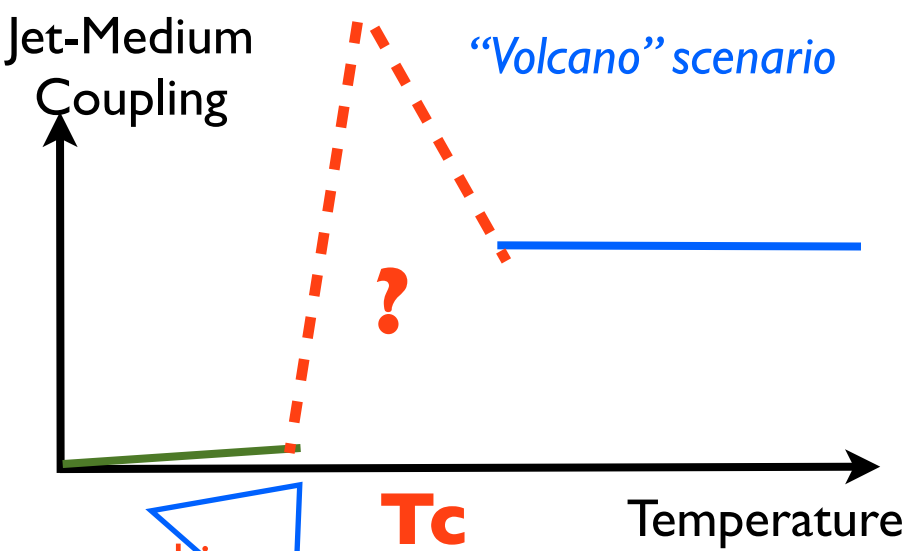
$$\beta_c(N_f) = \beta_0(1+f)^{-8N_f N_M/15}$$

$$f \approx 0.154$$

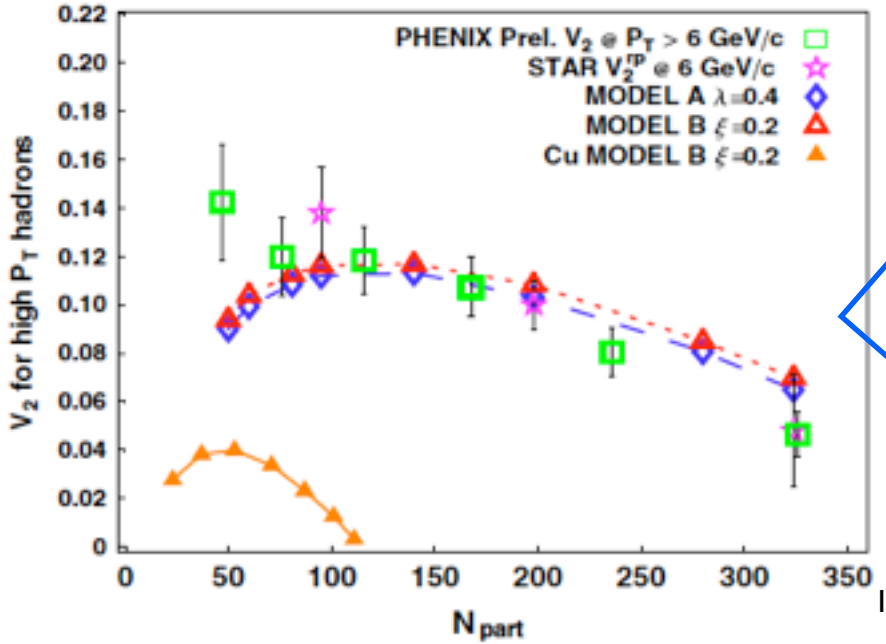
JL & Shuryak, PRL2012

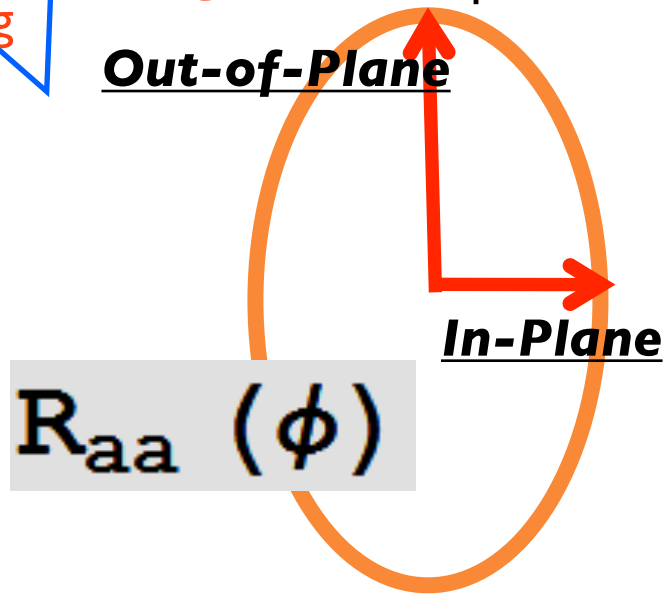
Strong Near-Tc Jet Quenching





a fundamental question for understanding of jet-quenching



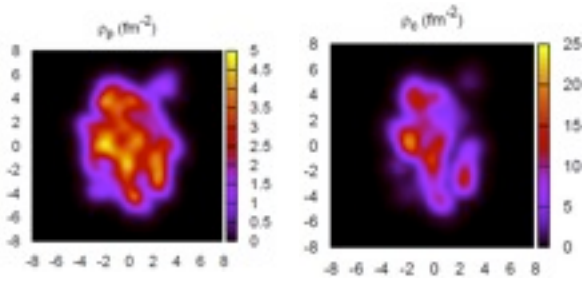


X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245; JL, arXiv:1109.0271; JL & Shuryak, PRL(2009).

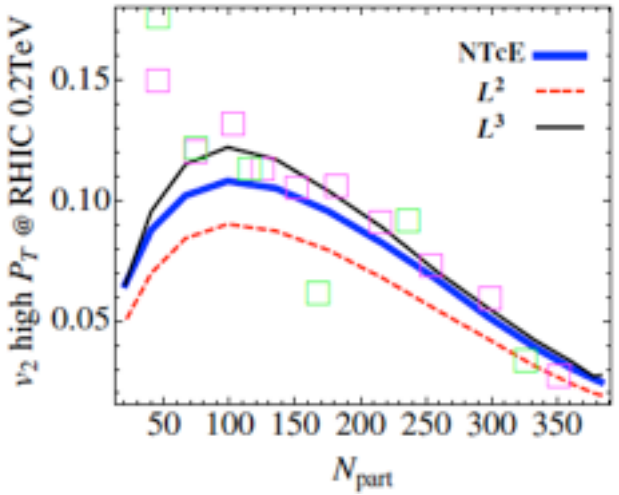
Hard Probe from RHIC to LHC

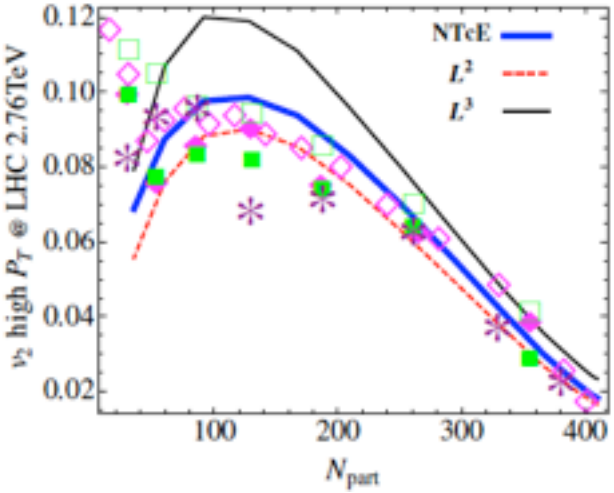
Evidence-1: opaqueness evolution from RHIC to LHC

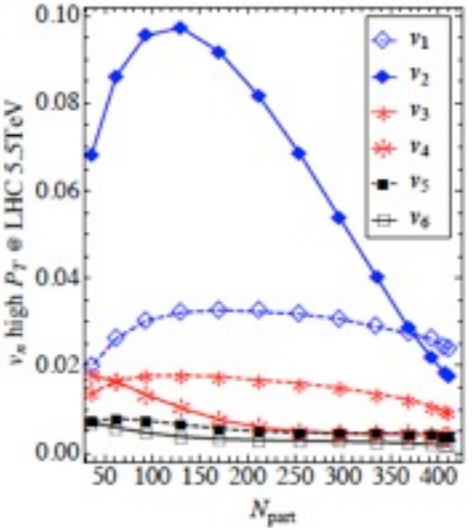
$$< \kappa >_{\mathrm{RHIC}} : < \kappa >_{\mathrm{LHC}} \approx 1 : 0.72$$



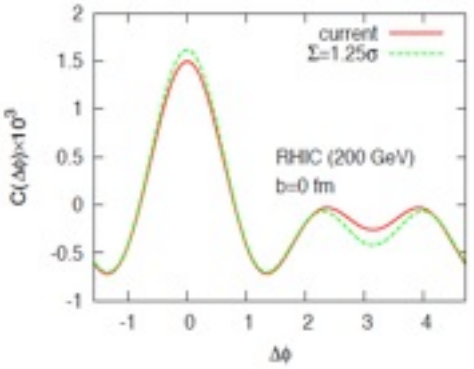
Evidence-2: geo. & fluc. with RHIC + LHC data







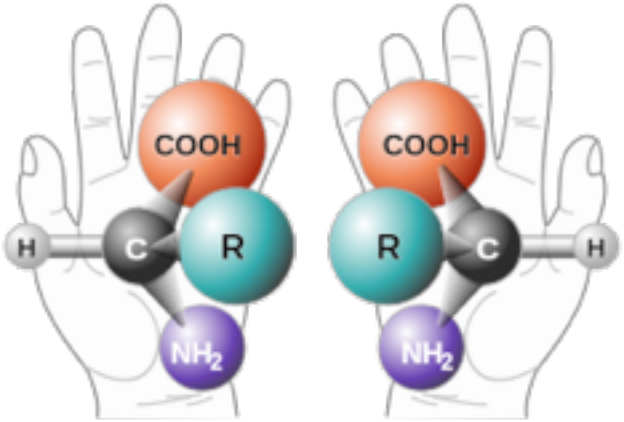
Opaqueness + Responses to Geo. & Fluc. with RHIC+LHC: in favor of strongly enhanced near-Tc jet quenching



X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245(PRC2013)

Thermal QGP as A Chiral Matter

Environmentally "Broken" Symmetry



Our life system is a perfect example of environmental symmetry breaking.

Could a local domain with nonzero macroscopic chirality, that is, a chiral medium, be created in heavy ion collisions?

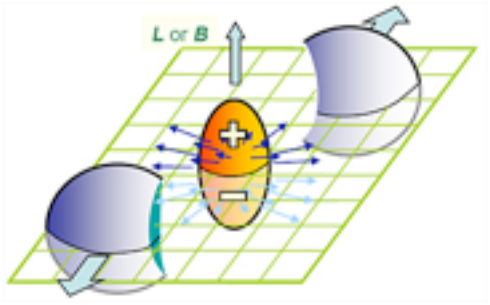
In the local P-Odd QGP domain, there can be anomalous effects that normally could not occur:
e.g. the Chiral Magnetic Effect (CME) ,generation of a vector current through an external Maxwell B field (Kharzeev, et al)

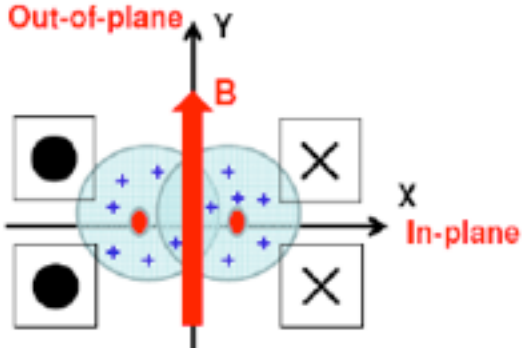
Vector current: P-odd
B field: P-even
It happens only because of the nonzero \mu_A

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

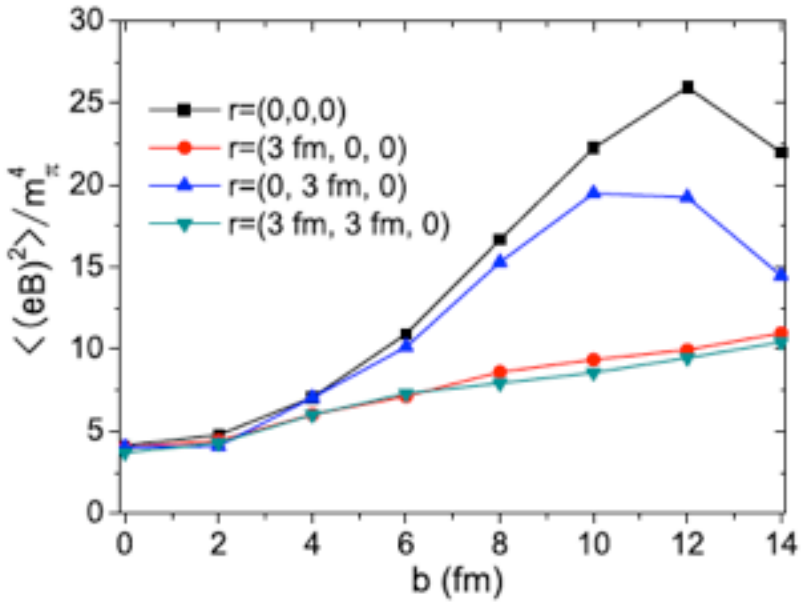
Macroscopic chirality in chiral medium

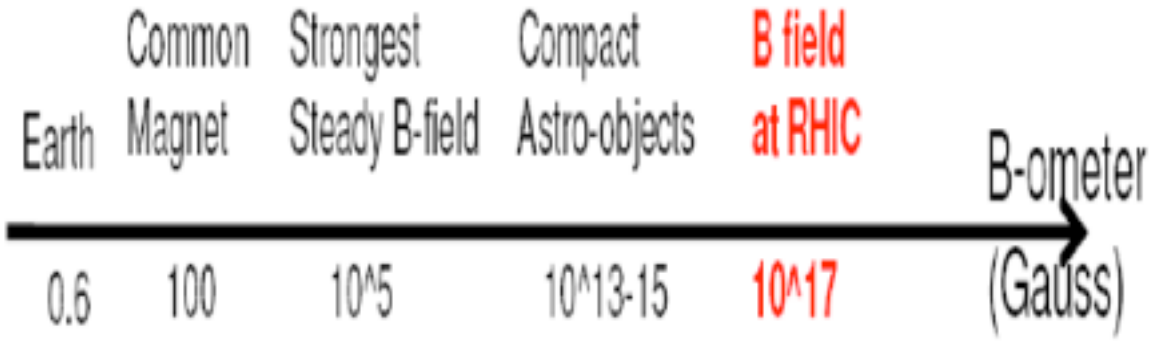
Strong EM Fields in Heavy Ion Collisions





$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$





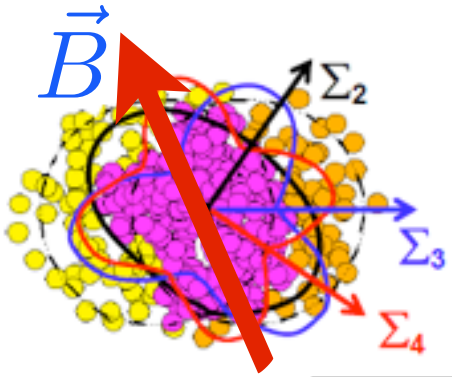
- Strongest B field (and strong E field as well) naturally arises!

[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Tuchin; ...]

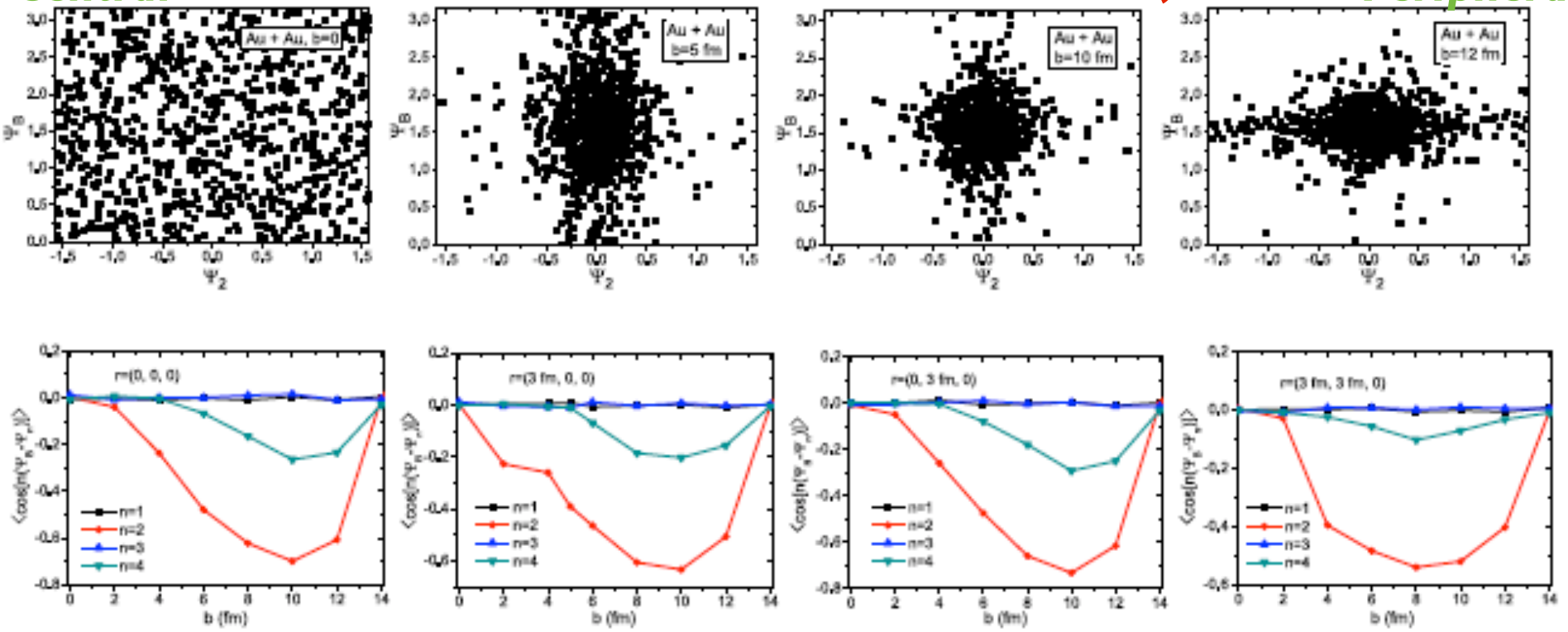
- "Out-of-plane" orientation (approximately)

Azimuthal Fluctuations of B field

Both B field orientation and matter geometry fluctuates from event to event --- we need to know their correlations.



Central **Peripheral**



Bloczynski, Huang, Zhang, JL, arXiv: 1209.6594, Phys. Lett. B

Current Generation in External Fields

Ohm's Law

$$j_V = \sigma E,$$

Chiral Magnetic Effect (CME)

$$j_V = \sigma_5 \mu_A B;$$

Chiral Separation Effect (CSE)

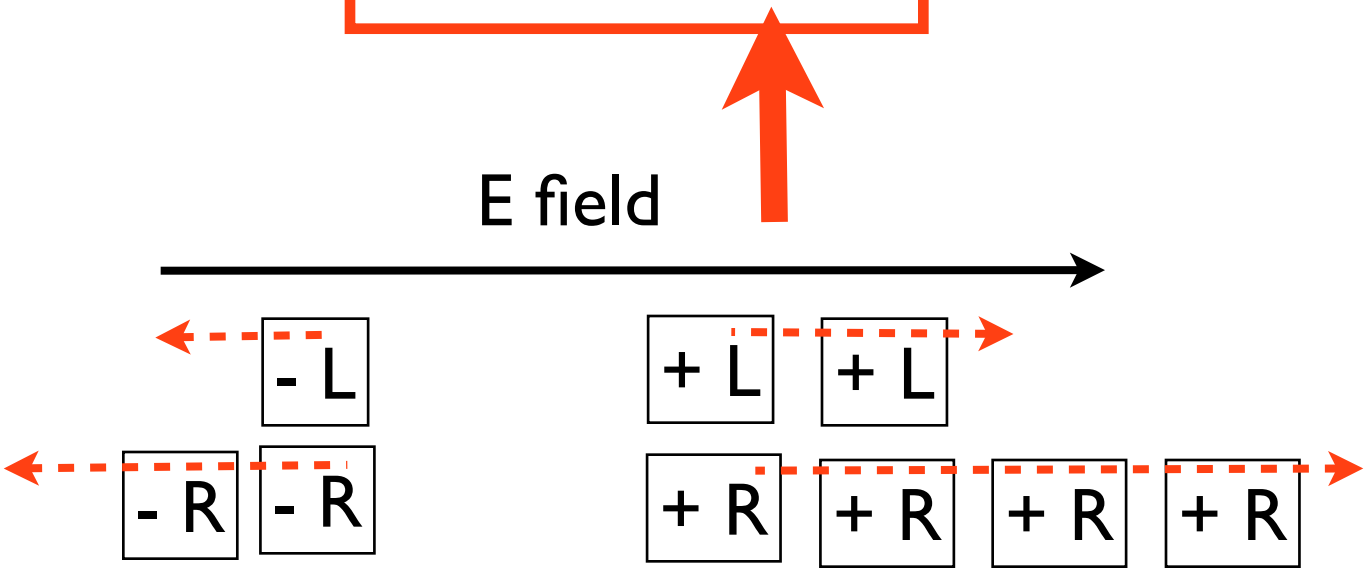
$$j_A = \sigma_5 \mu_V B.$$

	E	B
J_v	YES	YES Mu_A
J_A	???	YES Mu_A

CESE

Chiral Electric Separation Effect (CESE)

$$j_A = \chi_e \mu_V \mu_A E,$$



Imbalance between +/- (nonzero Mu_V)

&

Imbalance between L/R (nonzero Mu_A)

--> Axial current

X.Huang & JL, arXiv:1303.7192, PRL(2013)

Summarizing the Effects together

Ohm, CME, CSE, CESE:

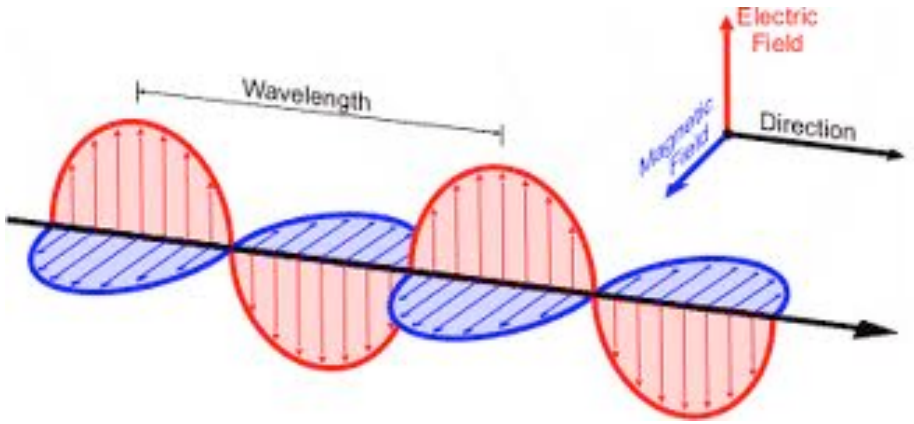
$$\begin{pmatrix} \boldsymbol{j}_V \\ \boldsymbol{j}_A \end{pmatrix} = \begin{pmatrix} \sigma & \sigma_5 \mu_A \\ \chi_e \mu_V \mu_A & \sigma_5 \mu_V \end{pmatrix} \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{B} \end{pmatrix}$$

Linearizing the fluctuations: we can find several collective excitation modes:
Chiral Electric/Magnetic Waves, Vector/Axial Density Waves

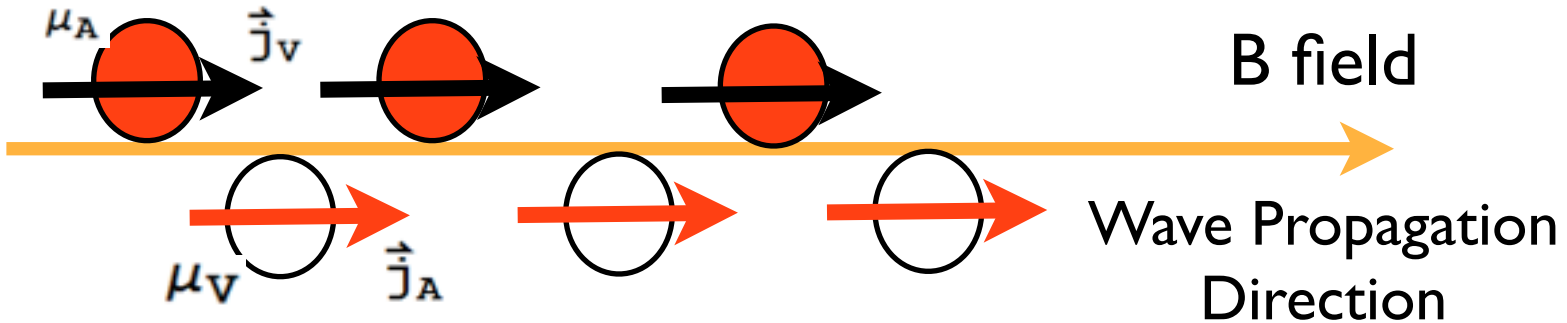
All very nice, but:
can we experimentally observe
one or more of these effects?
--- We discuss one example here, the Chiral Magnetic Wave

The Chiral Magnetic Wave

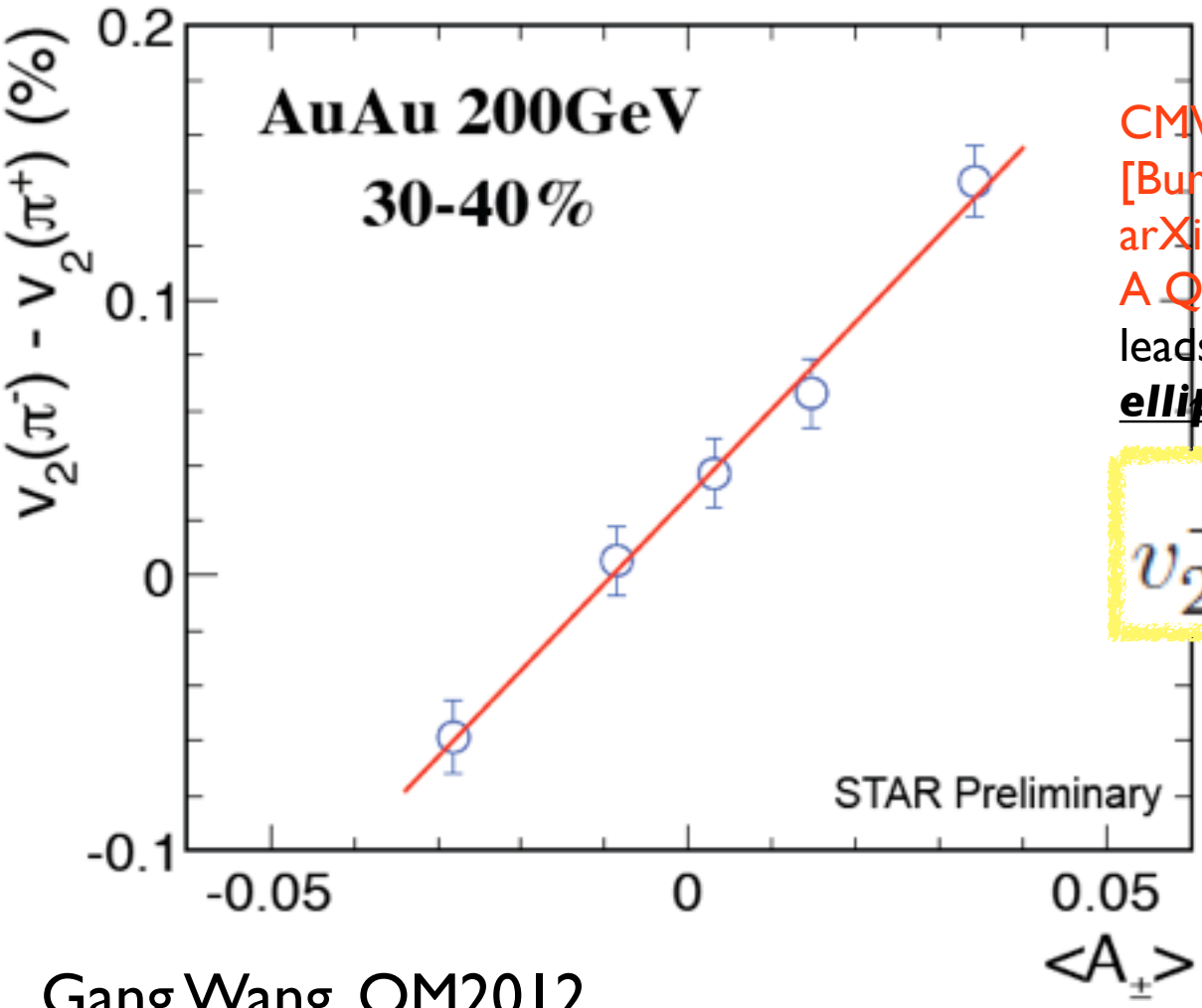
Wave: propagating "oscillations" of two coupled quantities
e.g. sound wave (pressure & density); EM wave (E & B fields)



Chiral Magnetic Wave (CMW):
coupled evolution of Vector & Axial Charge Densities



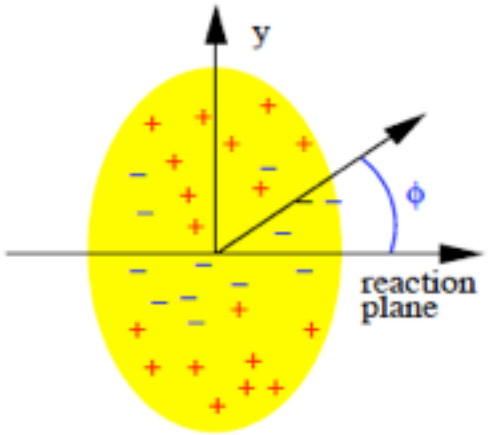
CMW Predictions



Gang Wang, QM2012

CMW Predictions:
[Burnier,Kharzeev,JL,Yee,PRL2011; arXiv:1208.2537]
A Quadrupole of Charge Distribution leads to ***splitting of +/- charge elliptic flow!***

$$v_2^- - v_2^+ = r_e A$$

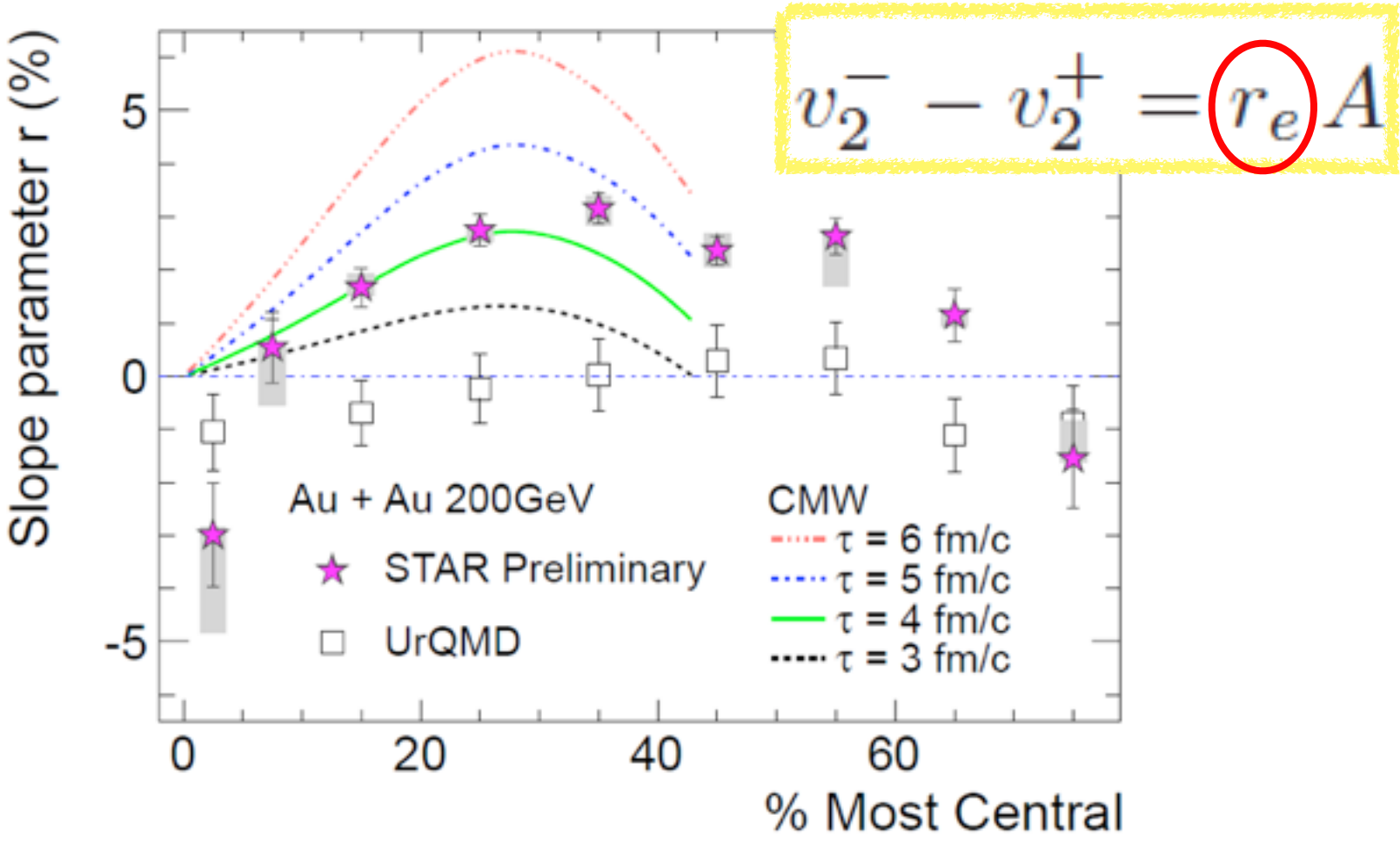


$$A = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$$

Centrality Dependence of Charge Quadrupole

CMW Predictions [Burnier,Kharzeev,JL,Yee,PRL2011; arXiv:1208.2537]

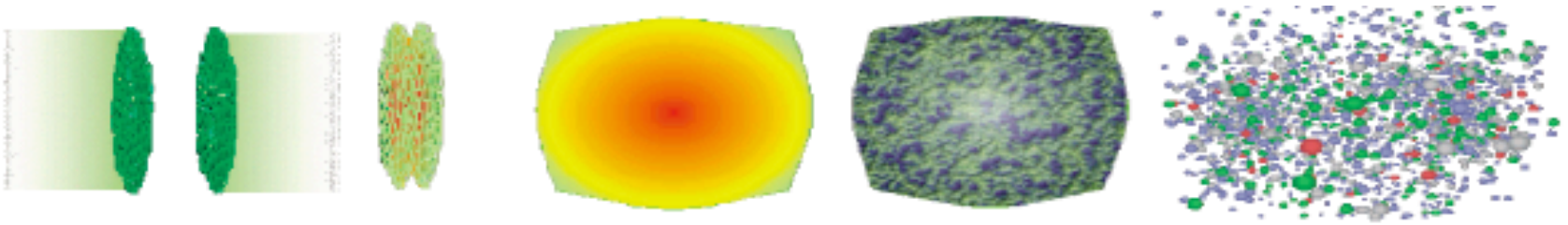
In Agreement with STAR Data [Gang Wang, QM2012]



Gang Wang, QM2012

The Over-Populated Pre-Equilibrium Matter

Thermalization: An Outstanding Puzzle



Color Glass Condensates | Initial Singularity | Glasma | sQGP - perfect fluid | Hadron Gas

t

Strong constraint from the initial condition: **saturation**

$$\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

from classical fields to quantum particles

Pre-Equilibrium Matter (We focus on this!)

Scale in PEM high! Qs~GeV Asyp. Free. Is weak coupling description viable with "fast thermalization"? YES → More is different!

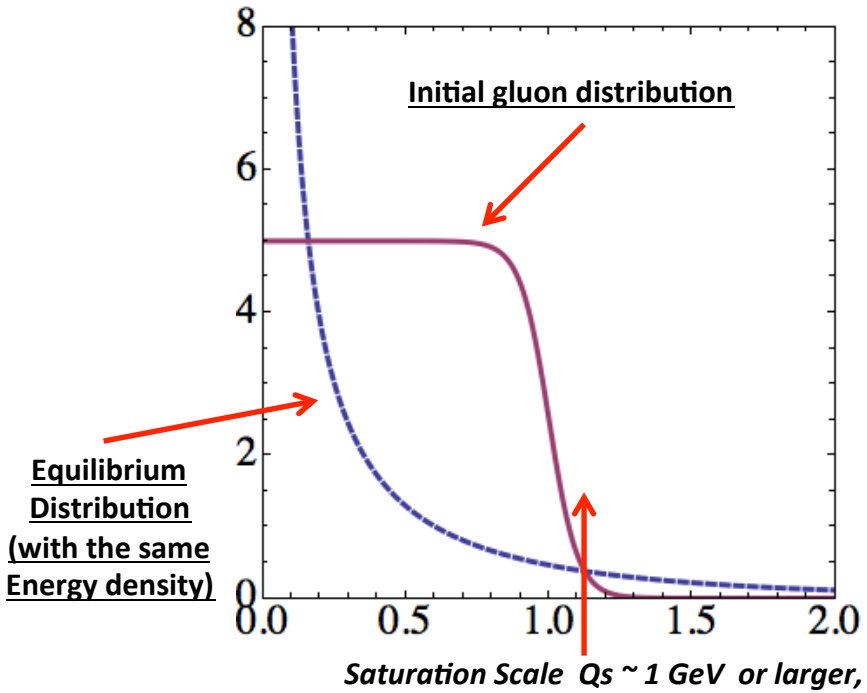
Strong constraint from Hydro modeling and empirical data: **fast "thermalization" ~ fm/c (to the extent of justifying hydro)**

High Overpopulation as a Key

Bose–Einstein condensation and thermalization of the quark–gluon plasma

Jean-Paul Blaizot [a], François Gelis [a], Jinfeng Liao [b,*], Larry McLerran [b,c], Raju Venugopalan [b]

The precursor of a thermal quark-gluon plasma, known as glasma, is born as a gluon matter with **HIGH OVERPOPULATION**:



Very large occupation number $f \sim \frac{1}{\alpha_s}$

Saturation fixes initial scale

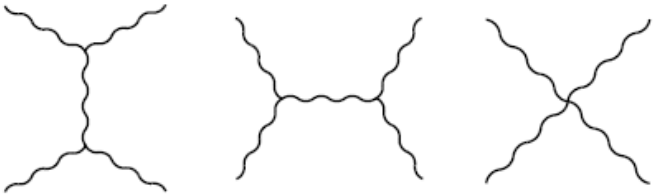
$$\epsilon_0 \sim \frac{Q_s^4}{\alpha_s}$$

$$n_0 \sim \frac{Q_s^3}{\alpha_s}$$

$$\epsilon_0/n_0 \sim Q_s$$

Elastic Collisions at High Occupation

$$\mathcal{D}_t f_1 = \frac{1}{2}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\frac{1}{2E_1} \mid M_{12\to 34} \mid^2$$
$$\times(2\pi)^4\delta(p_1+p_2-p_3-p_4)\{f_3 f_4(1+f_1)(1+f_2) - f_1 f_2(1+f_3)(1+f_4)\}$$



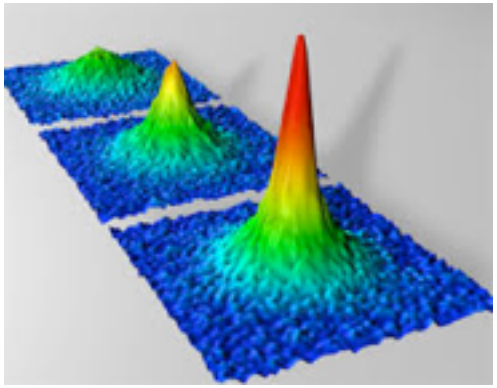
$$f * f * \alpha_s^2 \sim O(1)$$

$$\mid M_{12\to 34} \mid^2 = 72 g^4 \left[3 - \frac{t\,u}{s^2} - \frac{s\,u}{t^2} - \frac{t\,s}{u^2}\right]$$

When f~1/alpha_s, dependence on the coupling drops out!
The quantum nature is important at high occupation.

BEC in The Very Cold





$$f_{\mathrm{eq}}(\boldsymbol{k}) = n_{\mathrm{c}}\delta(\boldsymbol{k}) + \frac{1}{e^{\beta(\omega_k - m_0)} - 1}$$

Ich behaupte, dass in diesem Falle eine mit der Gesamtdichte stets wachsende Zahl von Molekülen in den 1. Quantenzustand (Zustand ohne kinetische Energie) übergeht, während die übrigen Moleküle sich gemäss dem Parameter-Wert $\lambda = 1$ verteilen. Die Behauptung geht also dahin, dass etwas Aehnliches eintritt wie beim isothermen Komprimieren eines Dampfes über das Sättigungs-Volumen. Es tritt eine Scheidung ein; ein Teil "kondensiert", der Rest bleibt ein "gesättigtes ideales Gas." ($A = 0$ $\lambda = 1$).

It took ~70 years to achieve BEC in ultra-cold bose gases.

The key is to achieve **OVERPOPULATION**:

$$n \cdot \epsilon^{-3/4} > \hat{O}(1)\ threshold$$

OVERPOPULATION implies *quantum coherence*:

$$n \cdot \epsilon^{-3/4} \sim (d/\lambda_{dB})^{\alpha} \sim \hat{O}(1)$$

BEC in The Very Hot?!

Our initial gluon system is highly OVERPOPULATED:

$$f(p) = f_0\,\theta(1 - p/Q_s),$$

$$\epsilon_0 = f_0\,\frac{Q_s^4}{8\pi^2}, \qquad n_0 = f_0\,\frac{Q_s^3}{6\pi^2}, \qquad n_0\,\epsilon_0^{-3/4} = f_0^{1/4}\,\frac{2^{5/4}}{3\,\pi^{1/2}},$$

This is to be compared with the thermal BE case:

$$\epsilon_{SB} = (\pi^2/30)\,T^4 \qquad n_{SB} = (\zeta(3)/\pi^2)\,T^3$$

$$n\,\epsilon^{-3/4}|_{SB} = \frac{30^{3/4}\,\zeta(3)}{\pi^{7/2}} \approx 0.28$$

Overpopulation occurs when: $f_0 > f_0^c \approx 0.154$

Identifying f_0 -> 1/alpha_s, even for alpha_s =0.3, the system is highly overpopulated!!

The smaller the alpha_s, the larger overpopulation

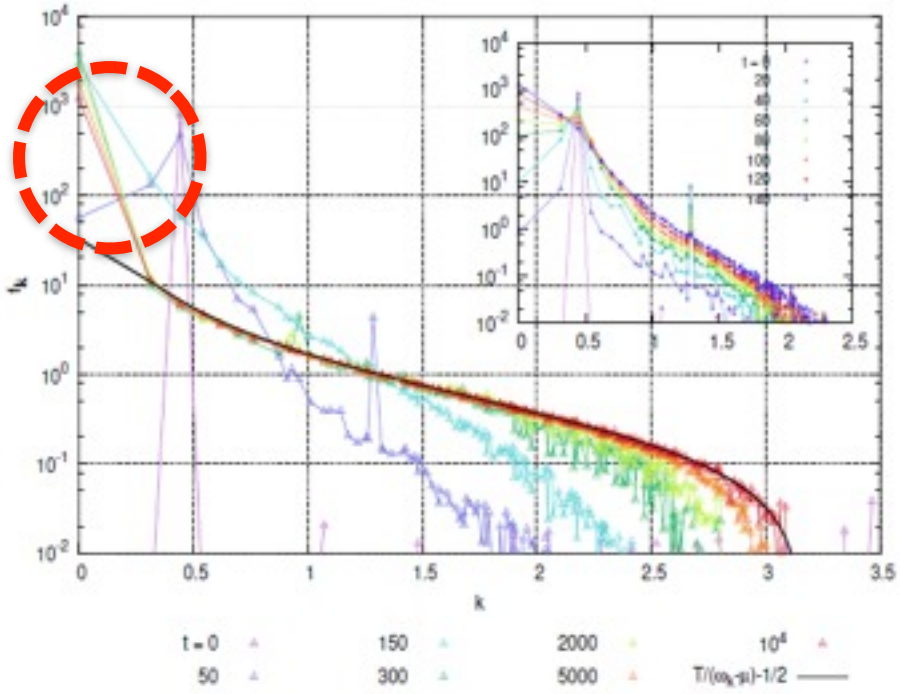
Will the system accommodate the excessive particles by forming a Bose-Einstein Condensate (BEC) ?

Strong Evidence of BEC from Scalar Field Theory Simulations

Bose–Einstein condensation and thermalization of the quark–gluon plasma

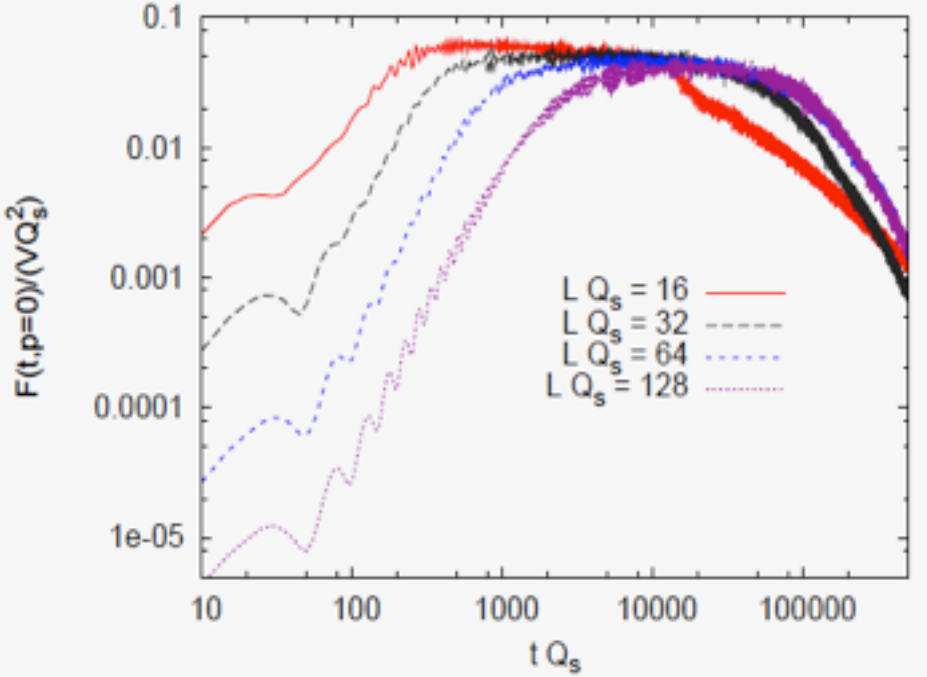
Jean-Paul Blaizot [a], François Gelis [a], Jinfeng Liao [b,*], Larry McLerran [b,c], Raju Venugopalan [b]

Absolutely true for pure elastic scatterings; True, in transient sense, for systems with inelastic processes



From: Epelbaum & Gelis 1107.0668

From: Berges & Sexty 1201.0687



Small Angle Approximation

Kinetic equation under small angle approximation (Blaizot-Liao-McLerran)

$$\mathcal{D}_t f(\vec{p}) = \xi\left(\Lambda_s^2 \Lambda\right) \vec{\nabla} \cdot \left[\vec{\nabla} f(\vec{p}) + \frac{\vec{p}}{p}\left(\frac{\alpha_S}{\Lambda_s}\right) f(\vec{p})[1 + f(\vec{p})]\right]$$

$$\Lambda\left(\frac{\Lambda_s}{\alpha_S}\right)^2 \equiv (2\pi^2) \int \frac{d^3p}{(2\pi)^3} f(\vec{p})\,[1 + f(\vec{p})]$$

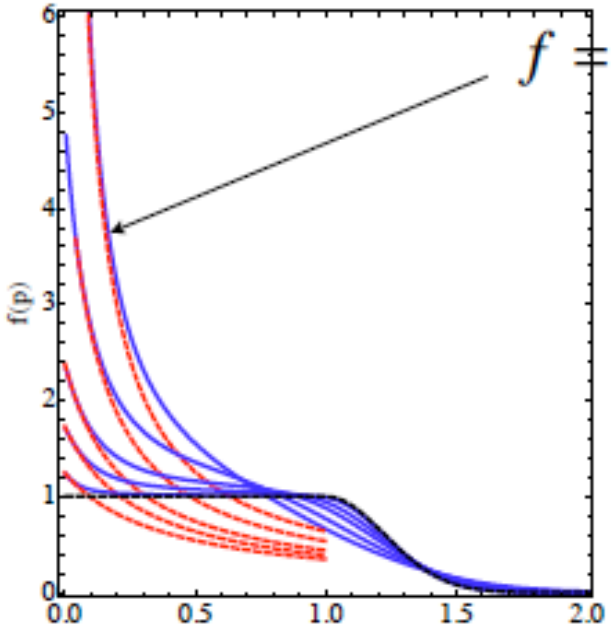
$$\Lambda \frac{\Lambda_s}{\alpha_S} \equiv (2\pi^2)\, 2 \int \frac{d^3p}{(2\pi)^3} \frac{f(\vec{p})}{p}$$

Two important scales:
hard scale Lambda
soft scale Lambda_s

Elastic scattering time scale

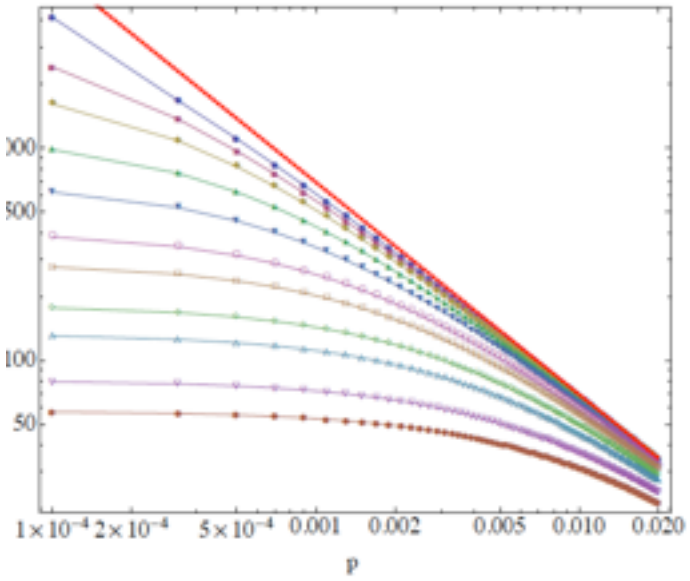
$$t_{scat} \sim \frac{\Lambda}{\Lambda_s^2}$$

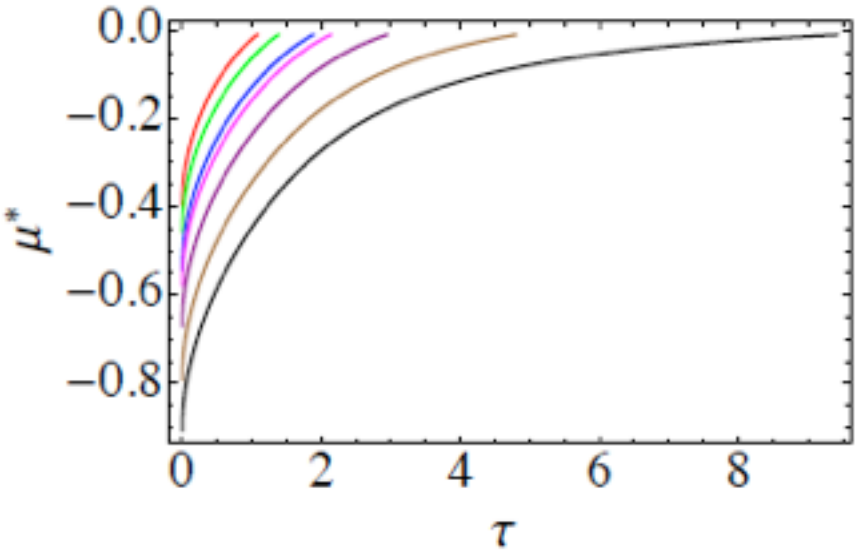
Rapid IR "Local Thermalization" Toward BEC Onset



$$f = \frac{T^*}{p - \mu^*} \qquad (\mu^* < 0)$$

Blaizot, JL, McLerran, arXiv:1305.2119





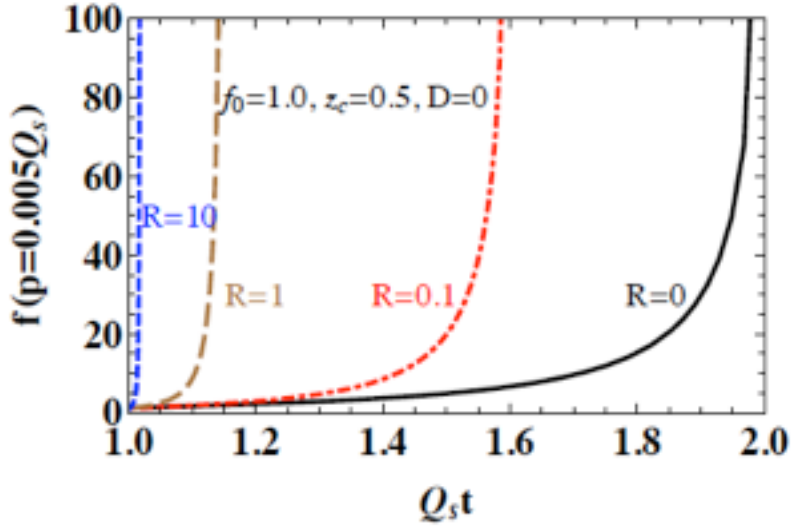
The system develops a critical scaling behavior toward the BEC onset.

$$|\mu^*| = C(\tau_c - \tau)^\eta.$$

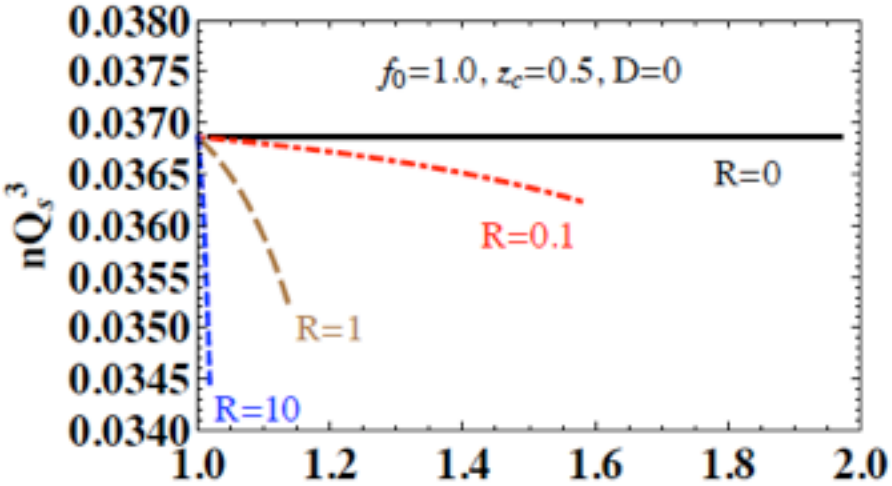
$$\eta \simeq 1$$

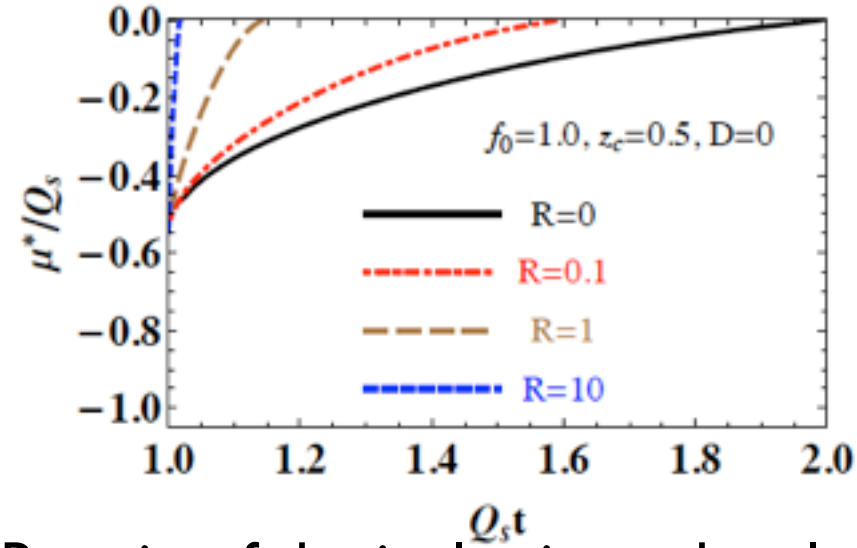
Effects from the Inelastic

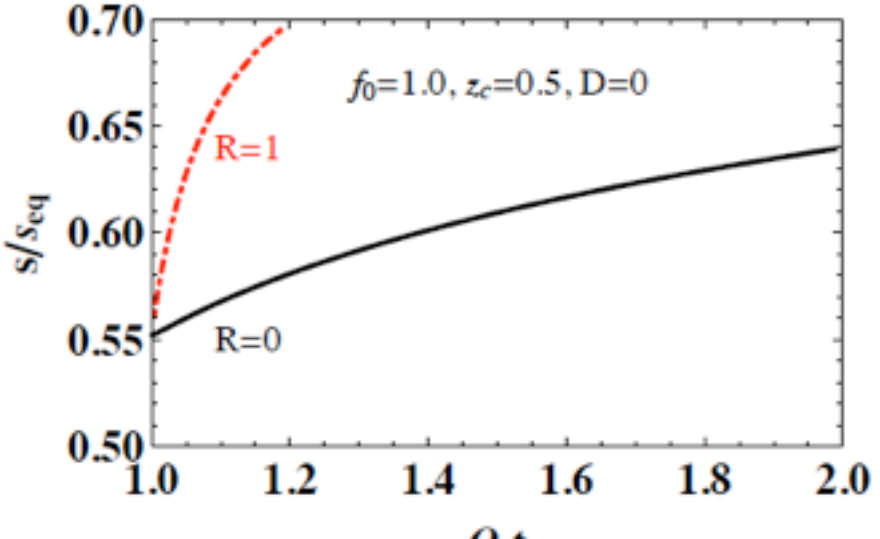
Local effect: enhance IR growth, accelerate the onset



Global effect: reduce number density, enhance entropy growth





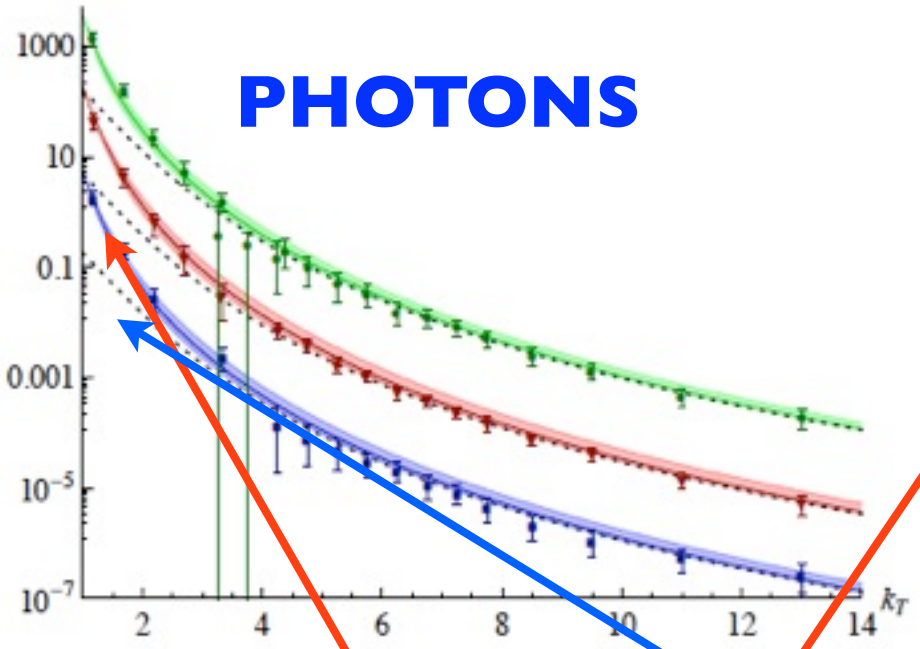


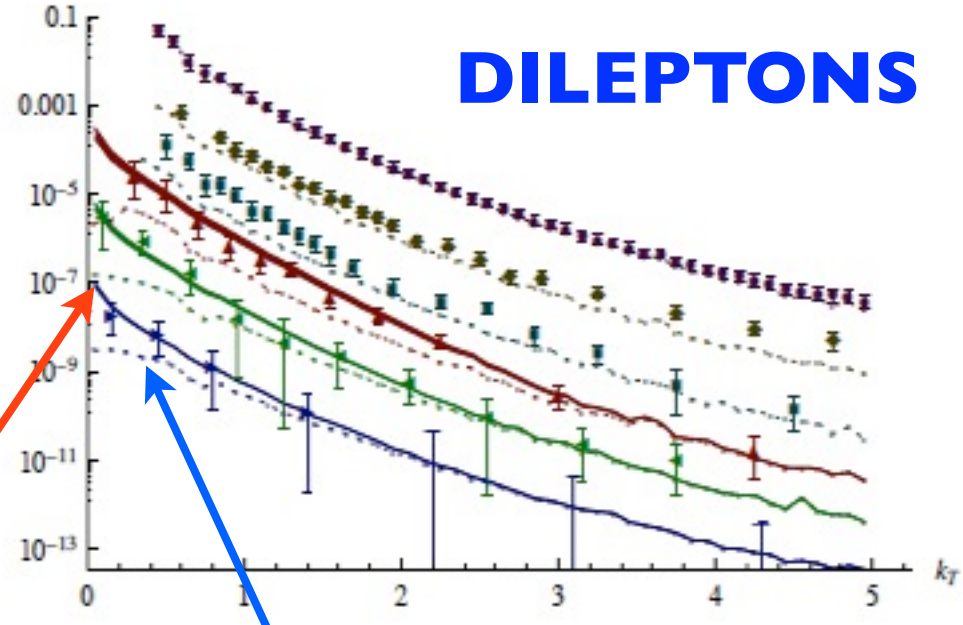
R: ratio of the inelastic to the elastic kernel

Huang & JL, arXiv:1303.7214

Glow of the Pre-Equilibrium Matter

There should be additional EM emission from the pre-equilibrium stage.
We derived formula based on our thermalization scenario and describe interesting aspects of data.





Conventional sources + **our PEM contribution**

Conventional sources total ("cocktail")

Important contributions to EM production from the pre-equilibrium matter !

Chiu, Hemmick, Khachatryan, Leonidov, JL, McLerran, arXiv:1202.3679, NPA

Publication 2011 fall -2013 summer

- **Near-Tc Matter:**

  1206.3989[PRL][with Shuryak];

  1304.7752[JHEP][with Shi]

- **Jet Quenching:**

  1210.1245[PRC], 1208.6361, 1202.1047[PLB] [with Zhang]

- **Anomalous Effects (CME,CMW,CESE,B fields):**

  1303.7192[PRL][with Huang];

  1209.6594[PLB][with Bloczynski,Huang,Zhang];

  1208.2537[with Burnier, Kharzeev, Yee];

  1207.7327[review in Lec.Not.Phys.][with Bzdak,Koch]

- **Pre-Equilibrium Matter(BEC,Inealstic,EM emissions):**

  1305.2119[NPA][with Blaizot,McLerran];

  1303.7214[with Huang];

  1202.3679[NPA][with Chiu,Hemmick,Khachatryan,Leonidov,McLerran]

- **Proceedings:**

  1306.5218[COPD2013]; 1210.6838[QM2012]; 1209.2998[NN2012];

  1209.1052[CIPANP2012]; 1109.0271[PANIC2011]

Workshops Organized

RBRC Workshop Jet Quenching at RHIC vs LHC in Light of Recent dAu vs pPb Controls [co-organized with Gyulassy, Jia] 3 days, 72 registered attendees, 36 talks, http://www.bnl.gov/jqr2013/



RBRC Workshop CPODD2012 [co-organized with Kharzeev, Shuryak, Yee]
3 days, 68 registered attendees, 34 talks, http://www.bnl.gov/pcp2012/



At IU: POETIC2012 [co-organized with Hafidi,Lamont, Londergan,Melnitchouk,Szczepaniak,Venugopalan, Vogelsang,Yuan]
3 days, 65 registered attendees, 32 talks,
http://www.indiana.edu/~ntceic/



Summary

* Thermal QGP near Tc as a **topological matter,** dominated by emergent magnetic monopoles:
  ---- confinement as monopole BEC;
  ---- from RHIC to LHC, getting more viscous and less opaque.

* Chiral-restored QGP as a **chiral matter,** with macroscopic chirality created in local domains on E-by-E basis:
  ---- new anomalous effect Chiral Electric Separation Effect;
  ---- Chiral Magnetic Wave, manifested via pi+/- flow splitting.

* The early time evolution in the **pre-equilibrium matter,** with **overpopulation** playing a key role:
  ---- kinetic evolution & thermalization in overpopulated matter;
  ---- a possible transient Bose-Einstein Condensation.

I gratefully acknowledge the generous and essential support from RBRC!

Triangle Anomaly in Quark-Gluon Plasma

Ho-Ung Yee

University of Illinois at Chicago/ RIKEN-BNL Research Center

RBRC Scientific Review Committee Meeting, Oct 31, 2013

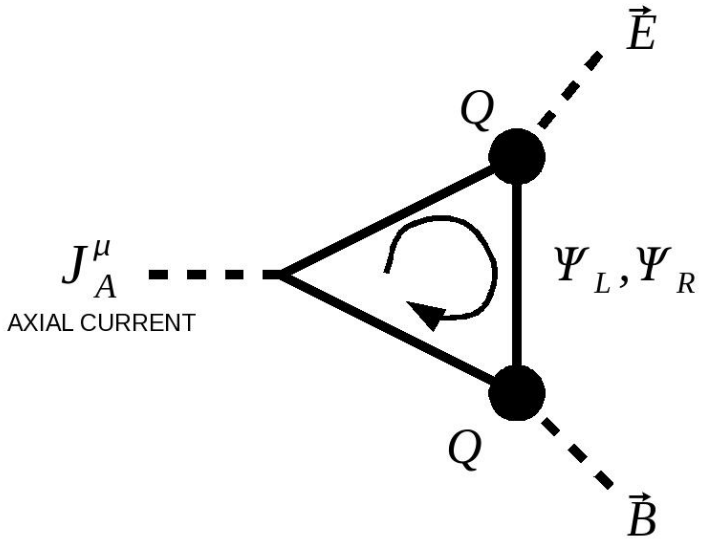
Triangle Anomaly

For a massless Dirac fermion, the $U(1)$ axial symmetry is classically conserved

$$J_V^\mu = \bar{\psi}\gamma^\mu\psi\,, \quad J_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$$

Triangle Anomaly

Quantum mechanically, it is no longer true



$$\partial_\mu J^\mu_A = \frac{N_F}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} = \frac{N_F}{4\pi^2}\vec{E}\cdot\vec{B}$$

Triangle Anomaly in Quark-Gluon Plasma

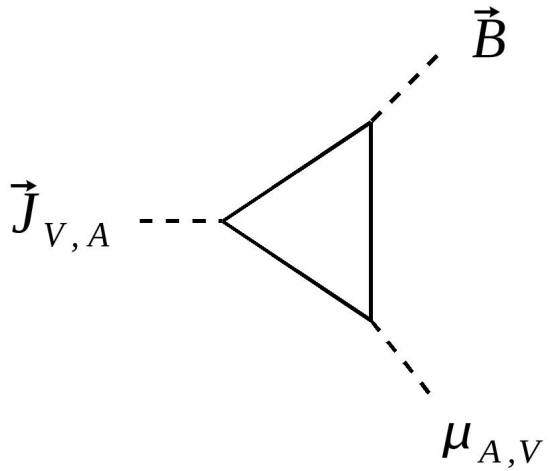
In high temperature QGP phase, the hydrodynamics is based on conservation equations

New hydrodynamic transport phenomena can arise from triangle anomaly

Chiral Magnetic Effect

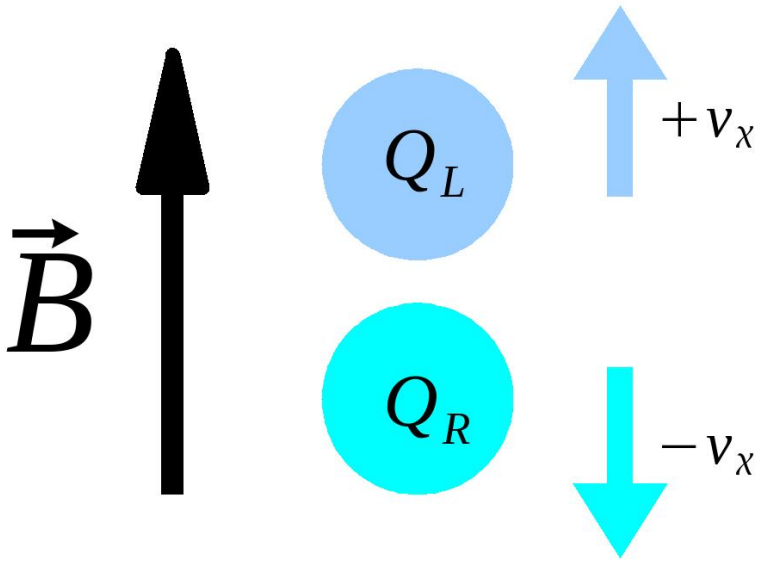
(Kharzeev-McLerran-Warringa, Son-Zhitnitsky)

$$\vec{J}_V = \frac{eN_c}{2\pi^2}\mu_A\vec{B}\,, \quad \vec{J}_A = \frac{eN_c}{2\pi^2}\mu_V\vec{B}$$



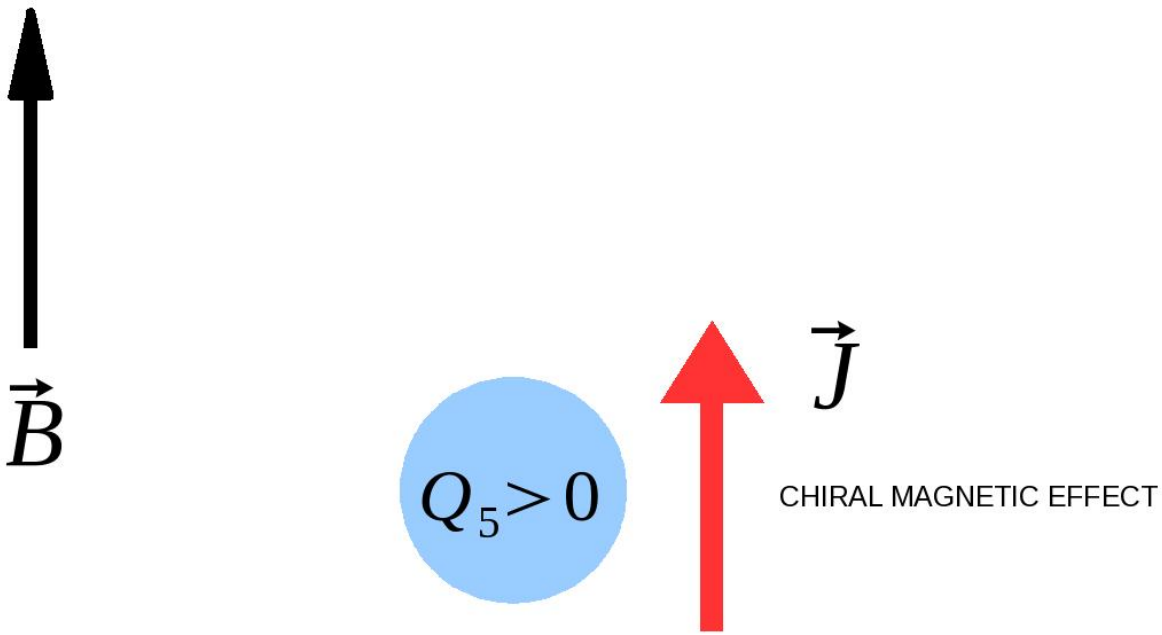
Note the $< AVV >$ structure

Chiral Magnetic Wave (Kharzeev-HUY)



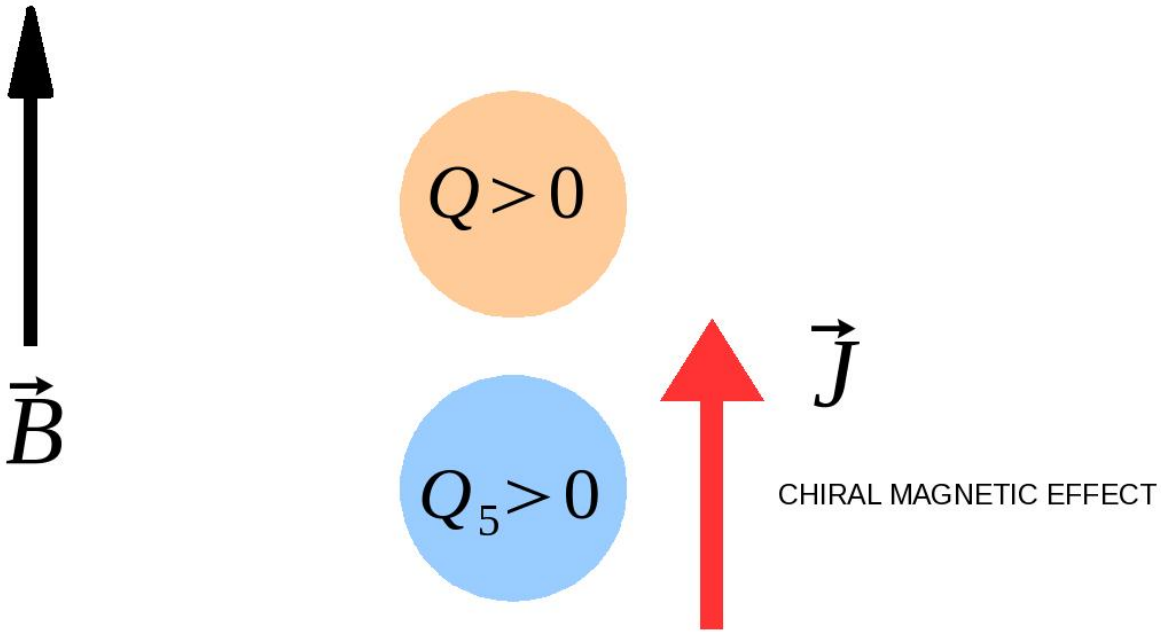
$$\omega = \mp v_\chi k - iD_L k^2 + \cdots \quad , \quad v_\chi = \frac{N_c eB}{4\pi^2}\left(\frac{\partial \mu}{\partial Q}\right)$$

Why do we have waves ?



$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V$$

Why do we have waves ?



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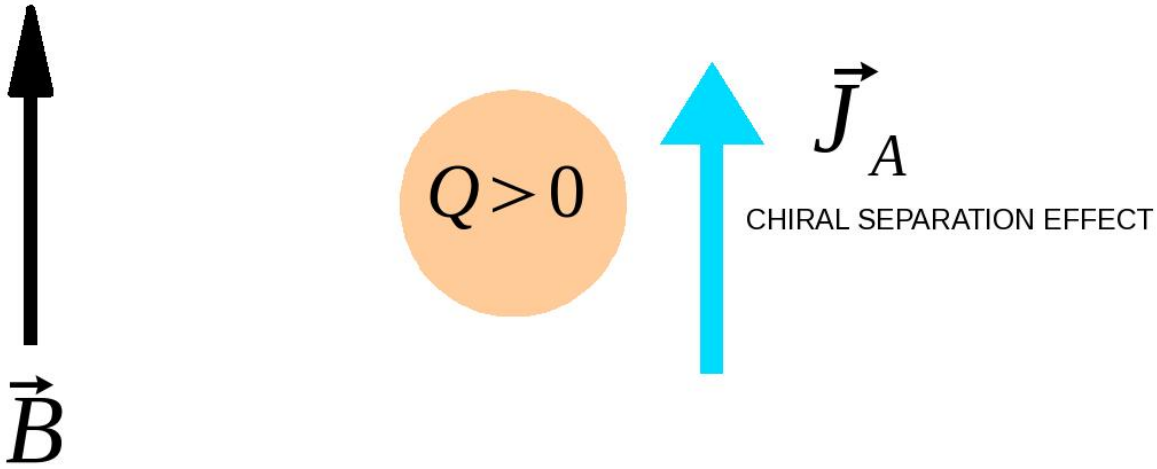
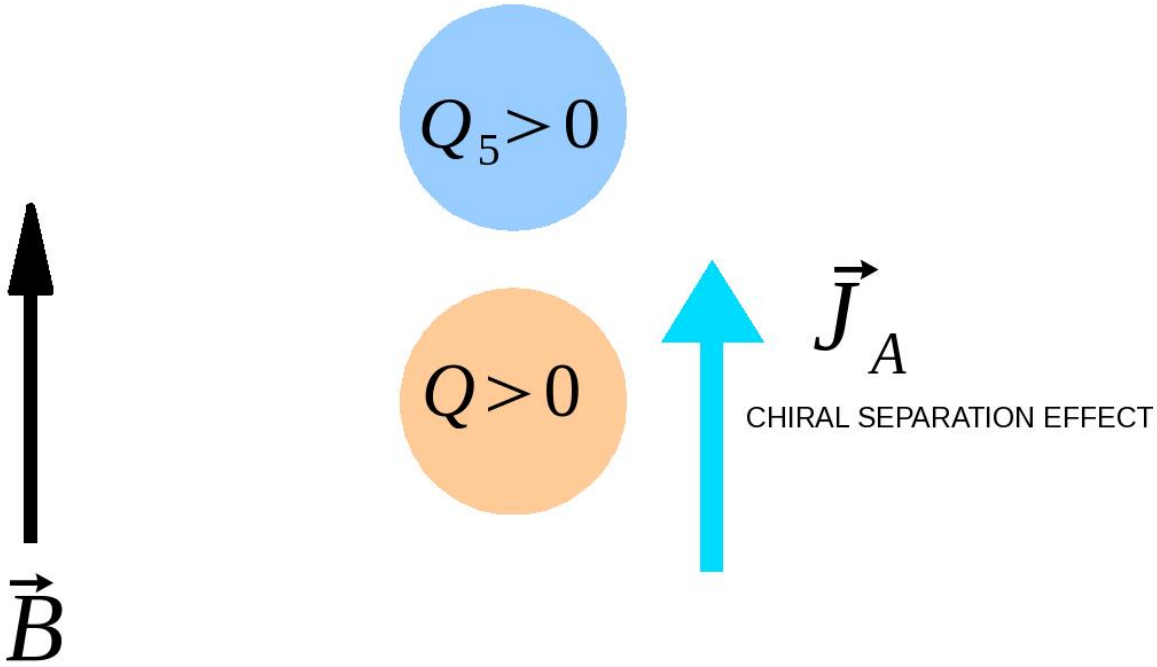


$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2}\mu_V$$

Why do we have waves ?



$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi^2} \mu_A \quad , \quad \vec{J}_A = \frac{N_c e \vec{B}}{2\pi^2} \mu_V$$

Dispersion Relation and Velocity

$$\omega = \mp v_\chi k - iD_L k^2 + \cdots$$

$$v_\chi = \frac{N_c eB\alpha}{2\pi^2} = \frac{N_c eB}{4\pi^2}\left(\frac{\partial \mu_L}{\partial J_L^0}\right) = \frac{N_c eB}{4\pi^2}\left(\frac{\partial \mu_R}{\partial J_R^0}\right)$$

Causality Bound

$$v_\chi = \frac{N_c eB}{4\pi^2}\left(\frac{\partial \mu_L}{\partial J_L^0}\right)$$

looks worrisome in view of causality when $eB \to \infty$

Causality bound on the susceptibility inspired by Chiral Magnetic Wave

$$\chi = \left|\frac{\partial J_L^0}{\partial \mu_L}\right| > \frac{N_c eB}{4\pi^2}$$

An intriguing constraint on the dynamics derived from triangle anomaly

Weak Coupling Test in $eB \to \infty$

- In $eB \to \infty$ limit, the quarks from ψ_L sit on the lowest Landau levels, as the gap between Landau levels is $\Delta = \sqrt{eB} \gg T$. We have an effective 1+1 dimensional reduction
- For a chemical potential μ_L, the 1+1 dimensional free fermion density is simply given by $\frac{\mu_L}{(2\pi)}$. The transverse density of states for the lowest Landau levels is $\frac{N_c eB}{(2\pi)}$. The net 3-dimensional density J_L^0 is then

$$J_L^0 = \frac{\mu_L}{(2\pi)} \times \frac{N_c eB}{(2\pi)} = \frac{N_c eB}{4\pi^2} \mu_L$$

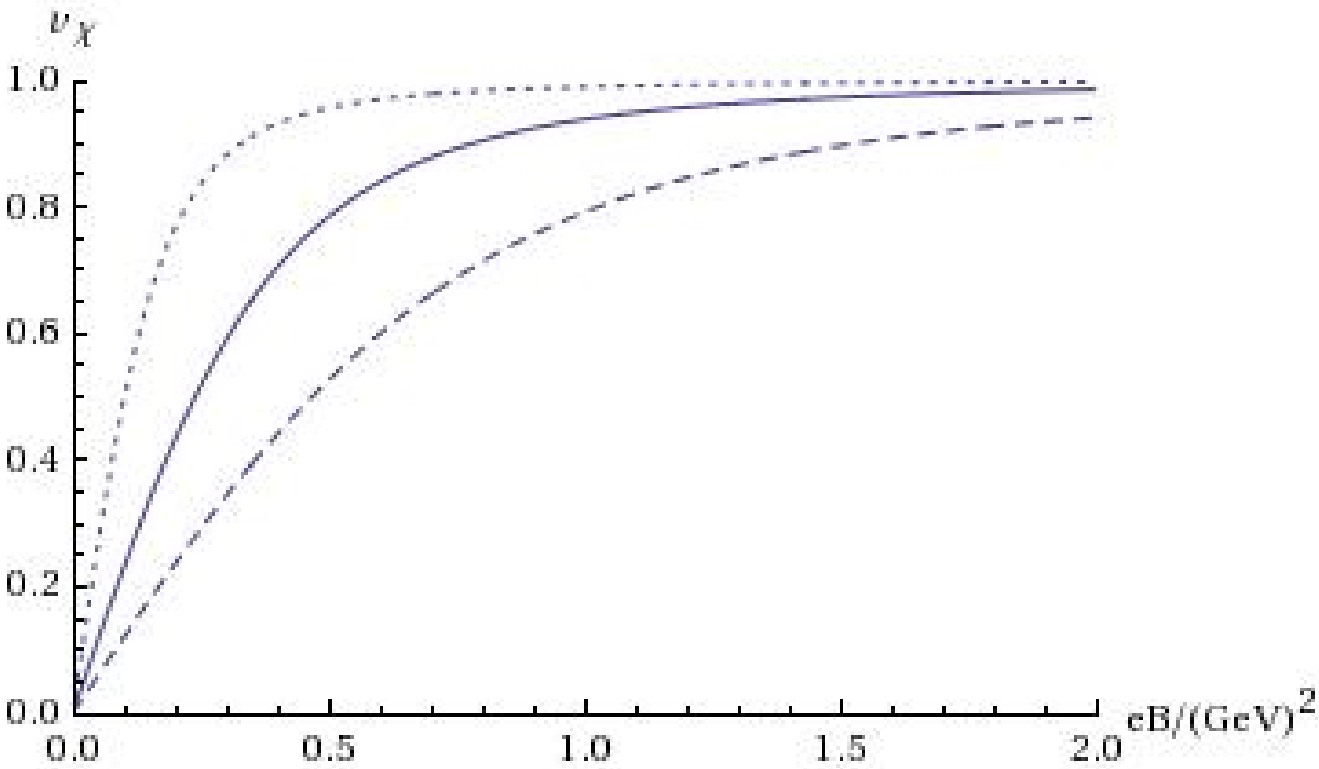
- Therefore in $eB \to \infty$ limit

$$\left(\frac{\partial J_L^0}{\partial \mu_L} \right) = \frac{N_c eB}{4\pi^2}$$

This saturates the causality bound giving

$$v_\chi \to 1$$

Strong Coupling Test in AdS/CFT

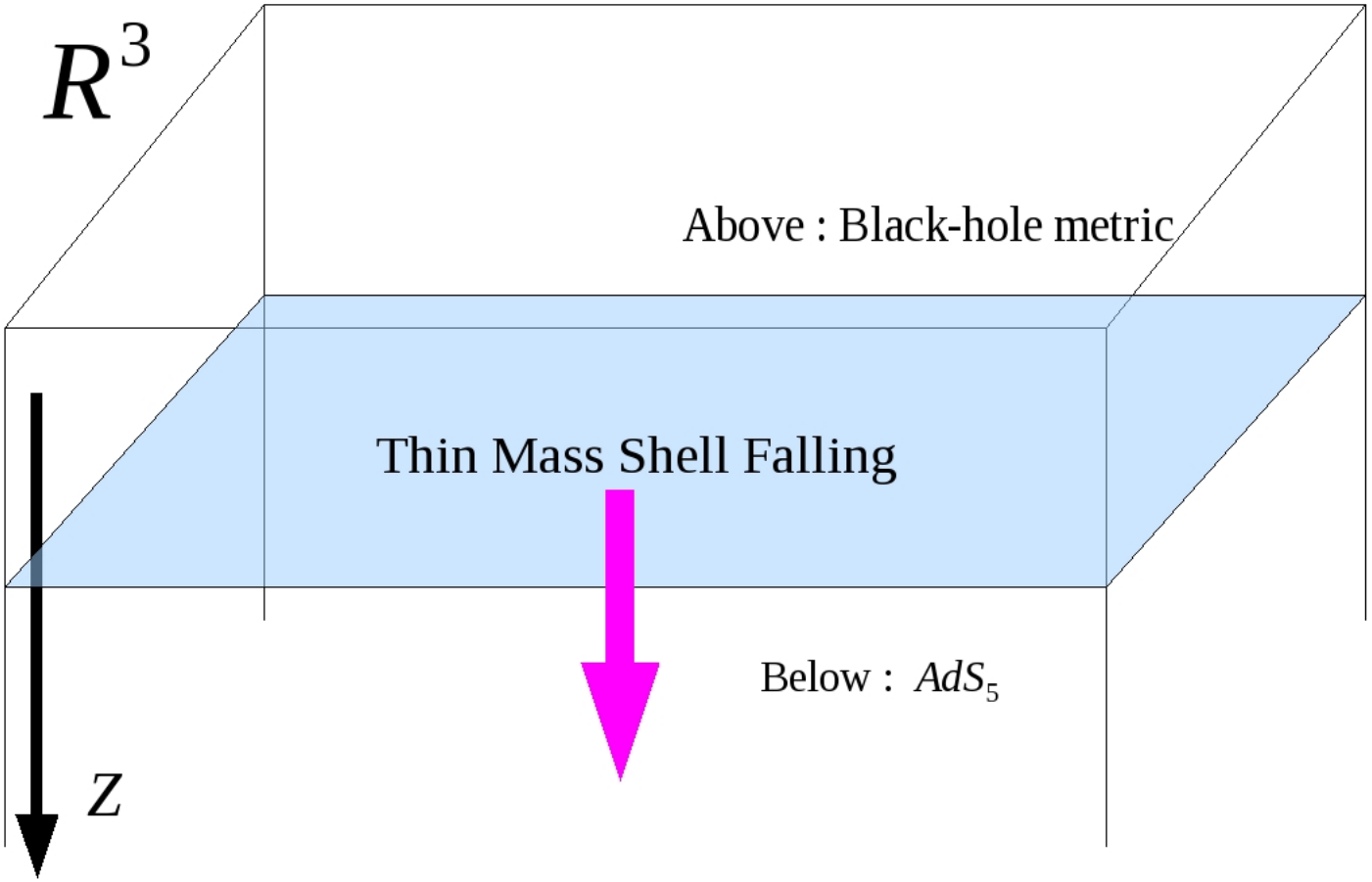


T=150 MeV (dotted), T=200 MeV (plain), T=250 MeV (dashed)

(Sakai-Sugimoto Model)

Out-of-Equilibrium Chiral Magnetic Wave
(Lin-HUY)

(Initial) Thermalization (2) : Falling Mass Shell



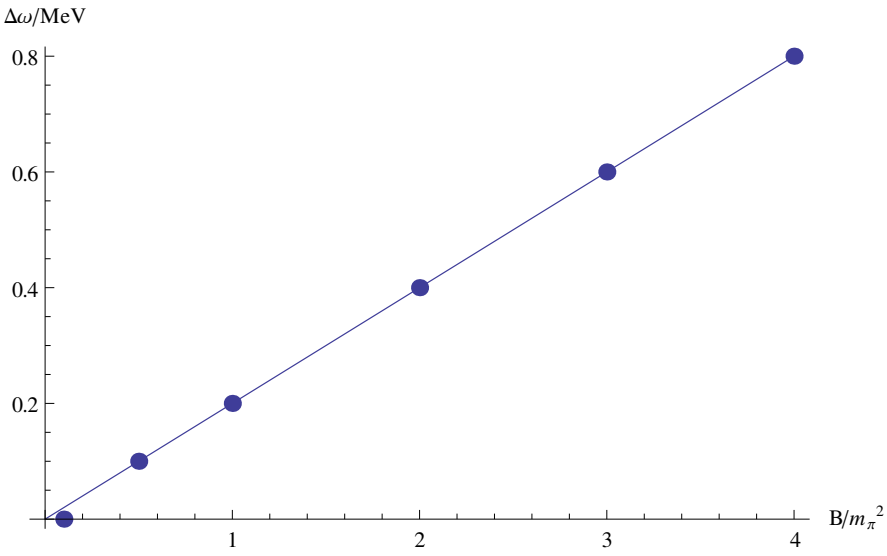
(Lin-Shuryak)

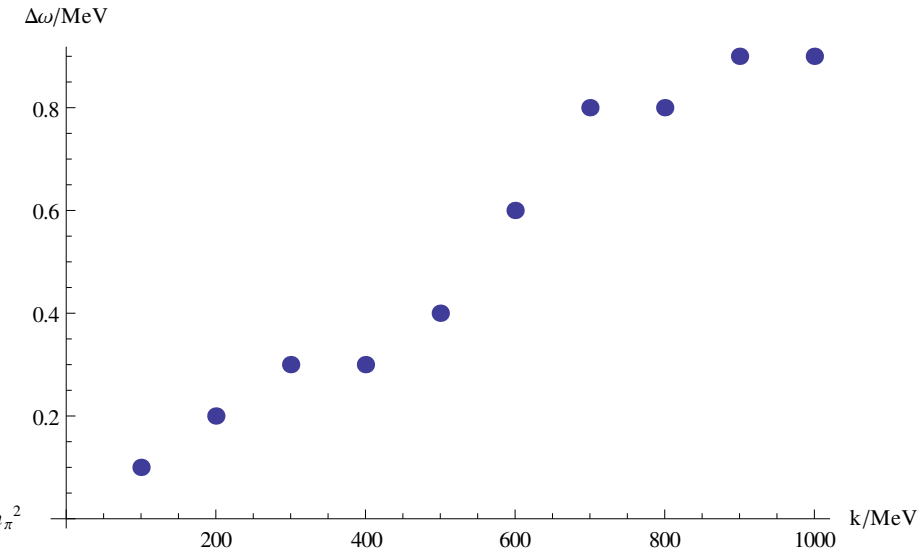
Dispersion Relation

$$\omega = \sqrt{f(z_s)}k + \Delta\omega$$

where z_s is the holographic location of the mass shell and $f(z_s) \to 0$ when $z_s \to z_H$ (horizon)

$\Delta\omega$ features characteristics of Chiral Magnetic Wave





$\Delta\omega$ versus eB (*left*) and $\Delta\omega$ versus k (*right*)

(Recall the Chiral Magnetic Wave dispersion relation $\omega = \frac{N_c eB}{4\pi^2 \chi} k + \cdots$)

A Lesson from This Result

From the dispersion relation

$$\omega = \sqrt{f(z_s)}k + \Delta\omega$$

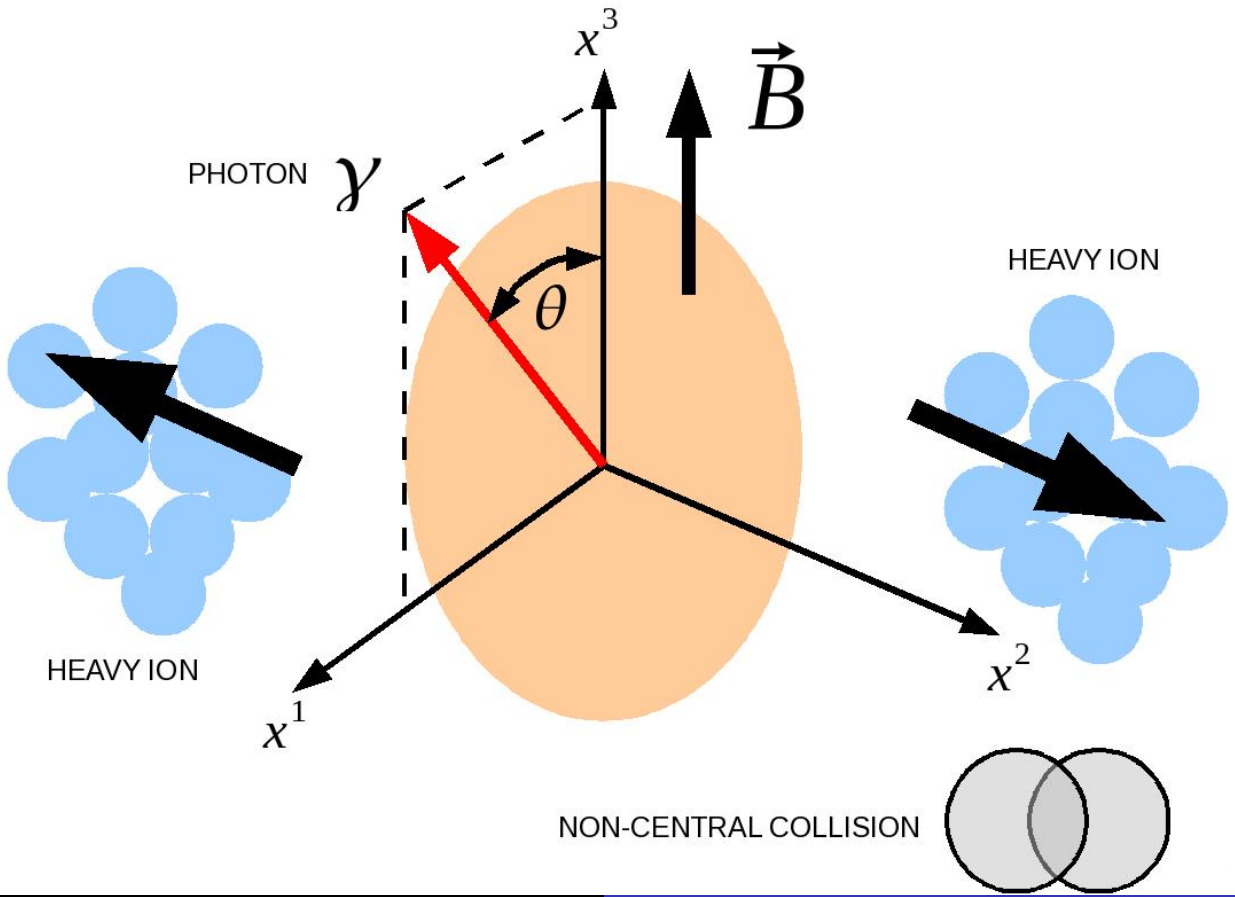
Chiral Magentic Wave velocity is enhanced by $\sqrt{f(z_s)}$ in out-of-equilibrium

$$v_\chi^{\rm OUT} = \sqrt{f(z_s)} + v_\chi^{\rm IN}\,, \quad v_\chi^{\rm IN} \equiv \frac{\partial\Delta\omega}{\partial k}$$

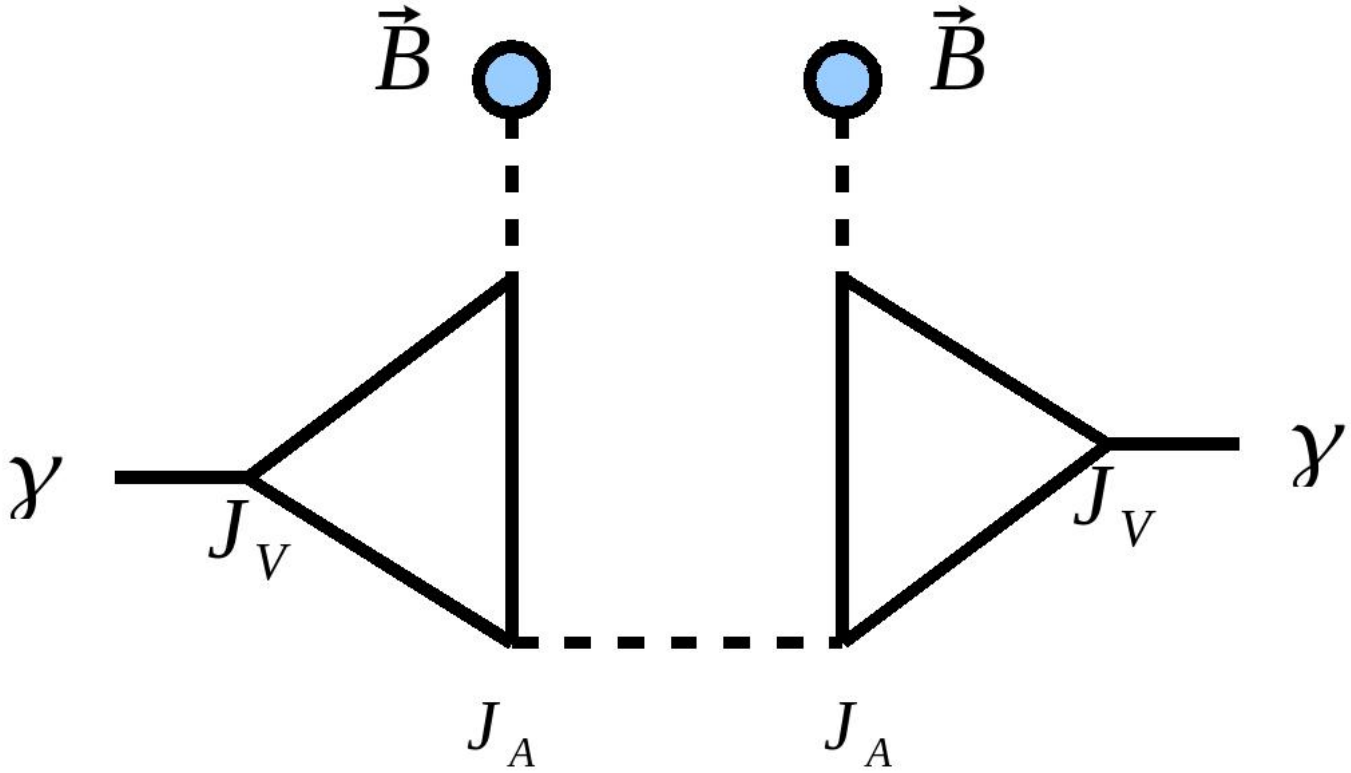
Chiral Magnetic Wave in Photon Emissions (HUY)

Photon emission rate in the presence of magnetic field

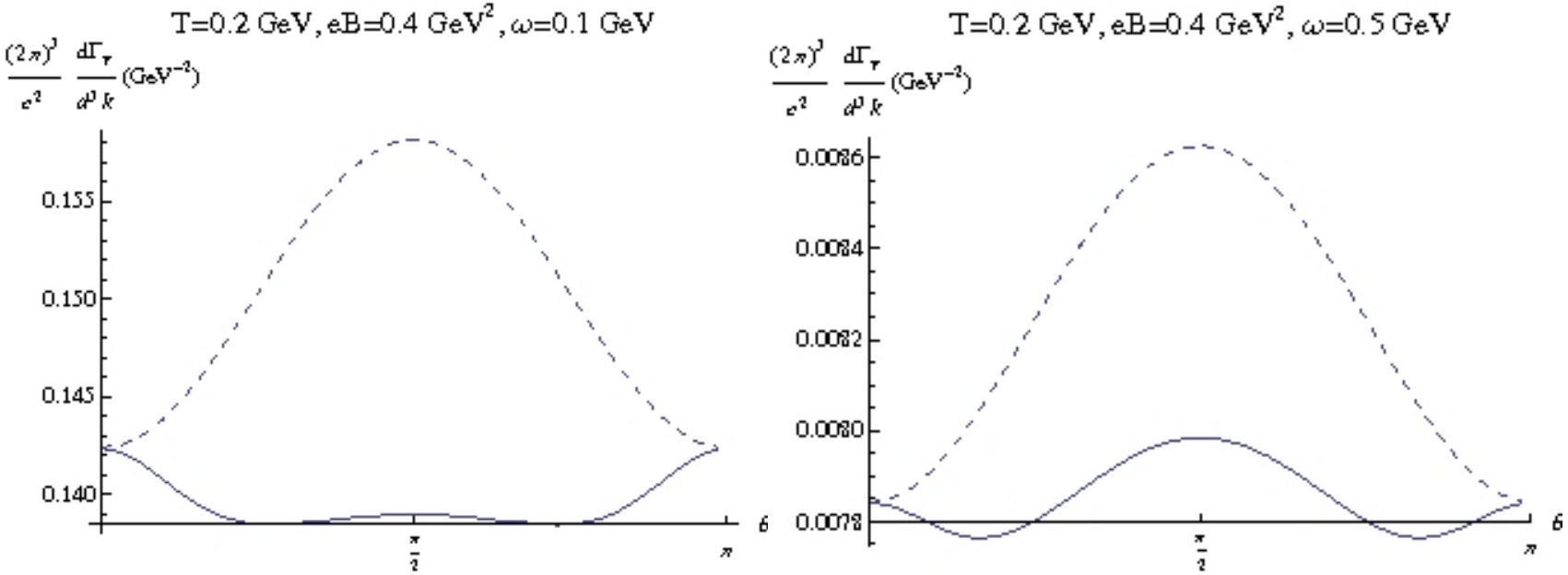
$$\frac{d\Gamma_\gamma}{d^3k}(\epsilon^\mu) = \frac{e^2}{(2\pi)^3}\frac{1}{2\omega}\frac{-2}{e^{\frac{\omega}{T}}-1}\mathrm{Im}\left[\epsilon^\mu\epsilon^{\nu *}G^{\mathrm{RET}}_{\mu\nu}(k)\right]$$



Why Chiral Magnetic Wave in Photon Emission Rates ?



Azimuthal Dependence of Emission Rates

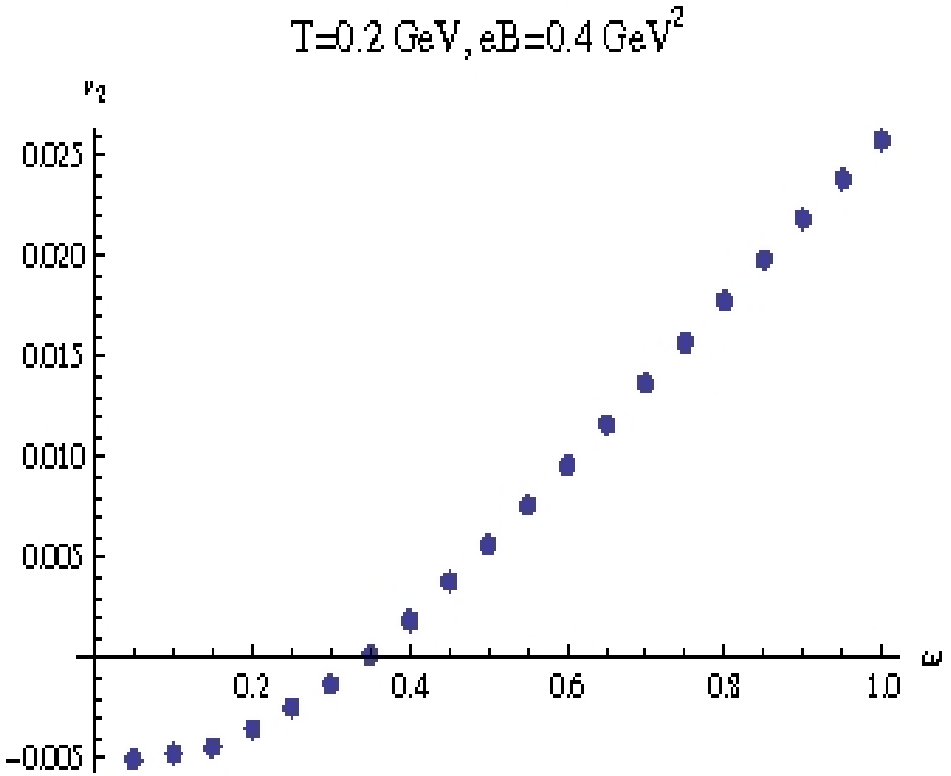


T=200 MeV, eB=0.4 GeV^2, $\omega = 0.1$ and 0.5 GeV

(Sakai-Sugimoto Model)

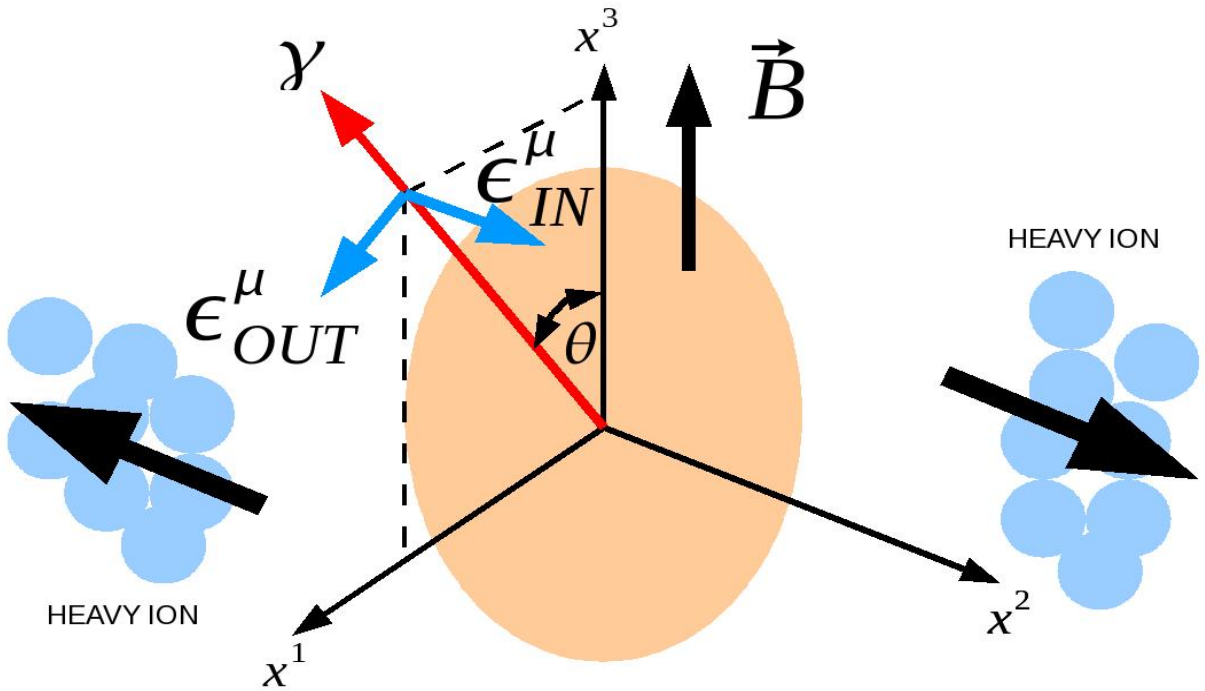
Dashed line : Results without Chiral Magnetic Wave

Non-trivial v_2 Dependence with Energy



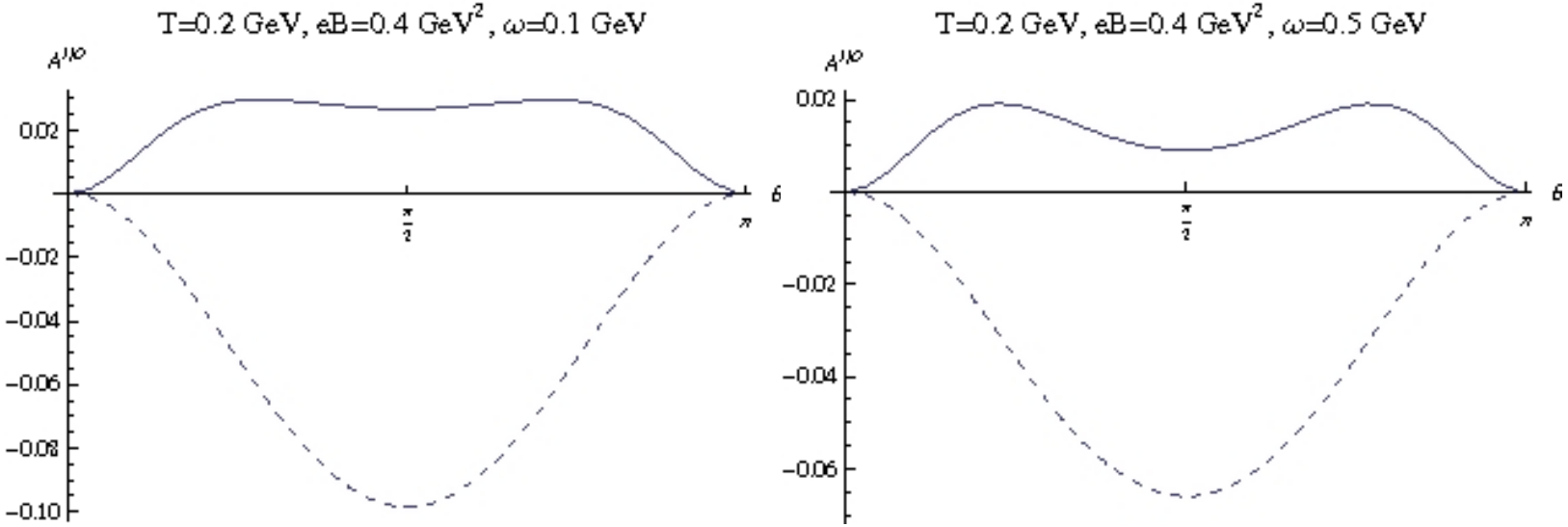
New observable
: In/Out Plane Polarization Asymmetry

$$A^{\mathrm{I/O}} = \frac{\frac{d\Gamma_\gamma}{d^3k}(\epsilon_{\mathrm{IN}}) - \frac{d\Gamma_\gamma}{d^3k}(\epsilon_{\mathrm{OUT}})}{\frac{d\Gamma_\gamma}{d^3k}(\epsilon_{\mathrm{IN}}) + \frac{d\Gamma_\gamma}{d^3k}(\epsilon_{\mathrm{OUT}})}$$



IN- AND OUT-PLANE POLARIZATIONS

Azimuthal Dependence of In/Out Plane Polarization Asymmetry $A^{\mathrm{I/O}}$



T=200 MeV, eB=0.4 GeV^2, $\omega = 0.1$ and 0.5 GeV

Dashed line : Results without Chiral Magnetic Wave

P and CP Odd Photons and Di-leptons
(Mamo-HUY)

Axial Charge is P- and CP-odd

$$\begin{aligned} \psi_L &\rightarrow q_L\,(\text{quark})\,,\ \bar{q}_R\,(\text{anti}-\text{quark}) \\ \psi_R &\rightarrow q_R\,(\text{quark})\,,\ \bar{q}_L\,(\text{anti}-\text{quark}) \end{aligned}$$

$$\begin{aligned} P &: q_L \longleftrightarrow q_R\,,\ \bar{q}_L \longleftrightarrow \bar{q}_R \\ C &: q_L \longleftrightarrow \bar{q}_L\,,\ q_R \longleftrightarrow \bar{q}_R \end{aligned}$$

Axial Charge

$$J^0_A = N(q_L) + N(\bar{q}_L) - N(q_R) - N(\bar{q}_R)$$

P- and CP-odd Observables

- **Using discrete symmetries, P and C**
  No Background Effects Possible
- **Unambiguous signal of axial charge and triangle anomaly**
- **Need to be event-by-event**

Photons

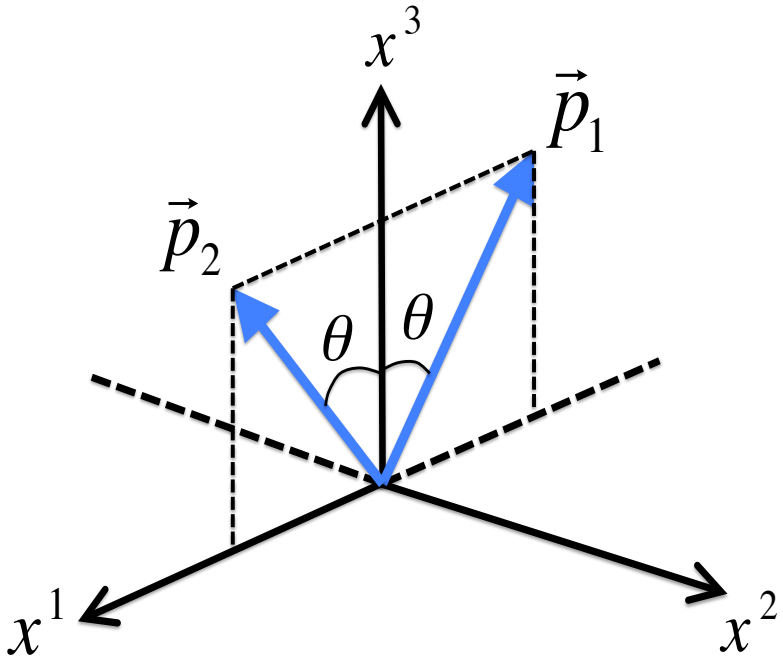
Spin polarization (helicity) is P-odd

$$\epsilon^{\mu}_{\pm} = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)\,, \quad \vec{k} = k\hat{x}^3$$

P- and CP-odd Observable

$$A_{\pm\gamma} \equiv \frac{\frac{d\Gamma}{d^3\vec{k}}(\epsilon_+) - \frac{d\Gamma}{d^3\vec{k}}(\epsilon_-)}{\frac{d\Gamma}{d^3\vec{k}}(\epsilon_+) + \frac{d\Gamma}{d^3\vec{k}}(\epsilon_-)}$$

Di-leptons



$$\Gamma^{s_1,s_2} = \frac{d\Gamma^{s_1,s_2}}{d^3p_1 d^3p_2}$$

where $(s_1, s_2) = (\pm 1/2, \pm 1/2)$ are spin alignments of the di-lepton pair along the momentum direction

$$P \;:\; e_L^- \longleftrightarrow e_R^- \,,\; e_L^+ \longleftrightarrow e_R^+$$
$$C \;:\; e_L^- \longleftrightarrow e_L^+ \,,\; e_R^- \longleftrightarrow e_R^+$$

which gives

$$P \;:\; \Gamma^{+\frac{1}{2},+\frac{1}{2}} \longleftrightarrow \Gamma^{-\frac{1}{2},-\frac{1}{2}} \,,\; \Gamma^{+\frac{1}{2},-\frac{1}{2}} \longleftrightarrow \Gamma^{-\frac{1}{2},+\frac{1}{2}}$$
$$C \;:\; \Gamma^{\pm\frac{1}{2},\pm\frac{1}{2}} \longleftrightarrow \Gamma^{\pm\frac{1}{2},\pm\frac{1}{2}} \,,\; \Gamma^{+\frac{1}{2},-\frac{1}{2}} \longleftrightarrow \Gamma^{-\frac{1}{2},+\frac{1}{2}}$$

P- and CP-odd Observable

$$A_{\pm l\bar{l}} \equiv \frac{\Gamma^{+\frac{1}{2},+\frac{1}{2}} - \Gamma^{-\frac{1}{2},-\frac{1}{2}}}{\Gamma^{+\frac{1}{2},+\frac{1}{2}} + \Gamma^{-\frac{1}{2},-\frac{1}{2}}}$$

It can be shown that

$$A_{\pm\gamma} = \frac{\mathrm{Im}G_+^R - \mathrm{Im}G_-^R}{\mathrm{Im}G_+^R + \mathrm{Im}G_-^R} = \frac{2\,\mathrm{Re}G_{12}^R}{\mathrm{Im}\mathrm{Tr}G^R}\Bigg|_{p^0=|\vec{p}|}$$

$$A_{\pm l\bar{l}} = \left(\frac{2\cos\theta}{1+\cos^2\theta}\right)\cdot\frac{\mathrm{Im}\,G_+^R - \mathrm{Im}\,G_-^R}{\mathrm{Im}\,G_+^R + \mathrm{Im}\,G_-^R}\Bigg|_{p^\mu=p_f^\mu=p_1^\mu+p_2^\mu},$$

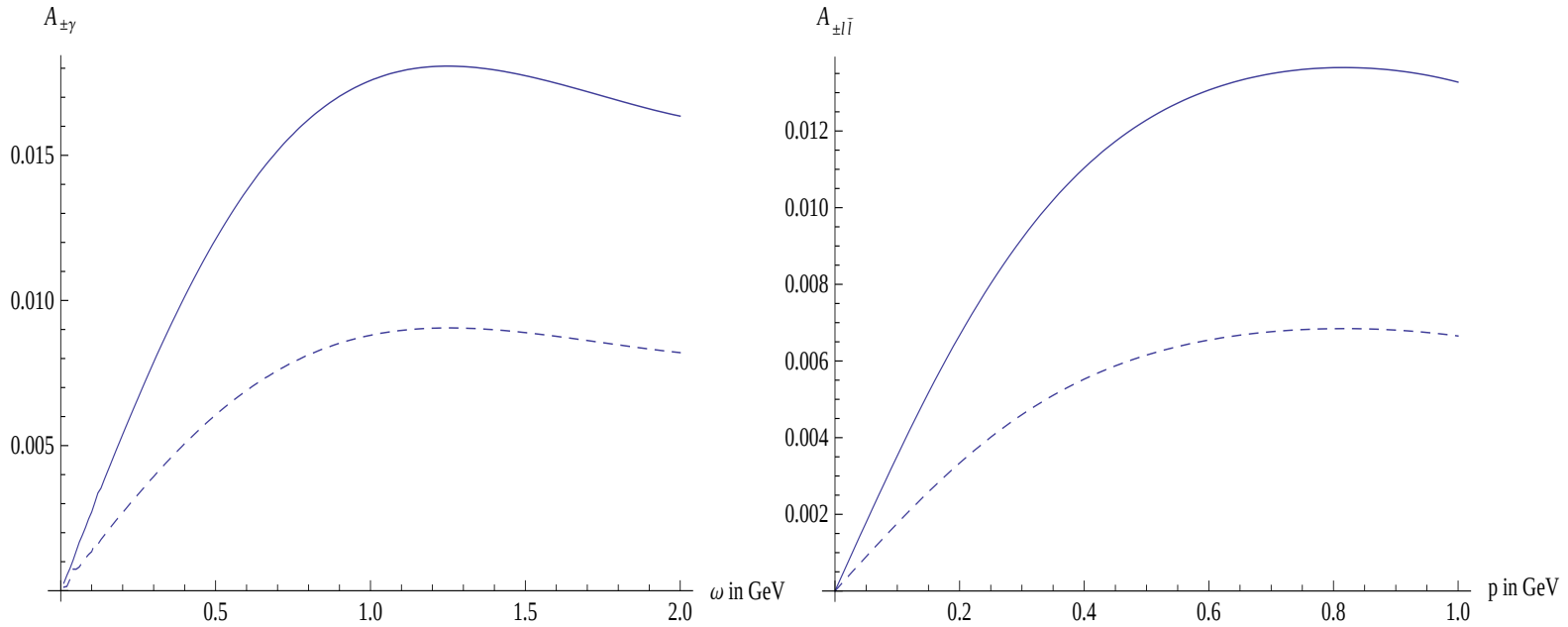
where $G_\pm^R \equiv G_{11}^R \pm iG_{12}^R$

Recall G_{12}^R **comes from the P-odd part**

$$G_{ij}^{R,-} = i\sigma_\chi(k)\epsilon_{ijk}k^k$$

$A_{\pm\gamma}$ **and** $A_{\pm l\bar{l}}$ **measure the imaginary part of chiral magnetic conductivity**

AdS/CFT Model Computation



$T = 300$ **MeV with** $\mu_A = 100$ **MeV (solid) and** $\mu_A = 50$ **MeV (dashed)**
Di-muon pair with $\theta = \frac{\pi}{4}$

The effect is about a percent level

Thank You for Listening

Transport at NLO in Hot QCD

Derek Teaney

Stony Brook University and (former) RBRC Fellow



- Jacopo Ghiglieri, J. Hong, A. Kurkela, G. Moore, DT, JHEP
- Jacopo Ghiglieri, H. Gervais, G. Moore, B. Schenke, DT, in progress

Overview:

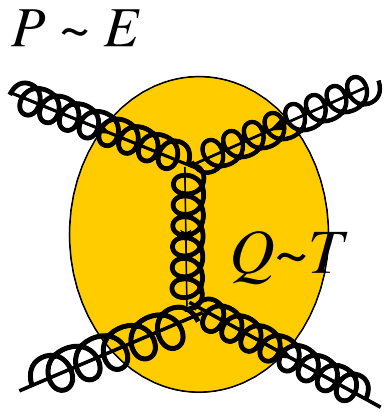
1. Transport in (semi) weakly-coupled plasmas:
   (a) Completed the NLO photon production rate.
   (b) Currently working on energy loss and shear viscosity at NLO (Today's talk.)
2. Hydrodynamics and collective flow in heavy ion collisions:
   (a) Li Yan – PhD 2013. Postdoc at Saclay
   (b) Worked out and non-linear hydrodynamic mode mixing
   (c) Examined the rapidity dependence of hydrodynamic fluctuations with A. Bzdak
      - Future work will combine items (b) and (c).
3. Thermalization of gauge fields in gauge-gravity duality:
   (a) Ongoing work with Paul Chesler at MIT as time allows
   (b) New interest due to the observation of collective flow in small systems, i.e. pA
      - What is the smallest system that can support hydro?

Energy loss and transport in weakly coupled plasmas at NLO

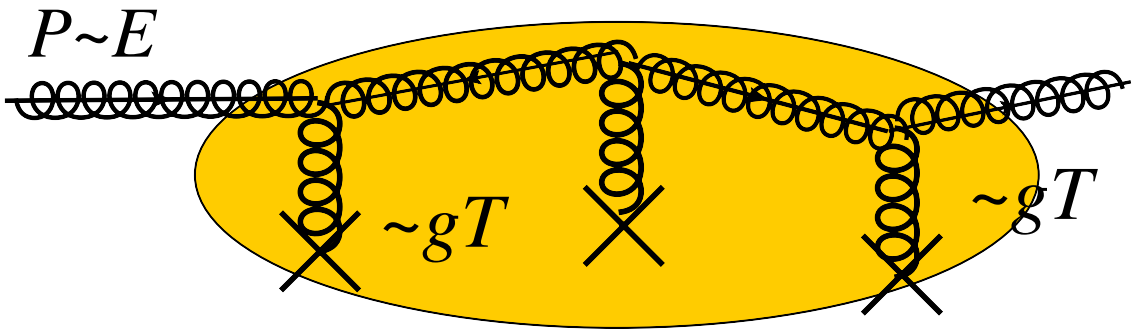
- Philosophy of weakly coupled calculations – there is only one right answer . . .
  1. Collisional vs. radiative loss
  2. Corrections to collinear formalism
  3. Relation between drag (or $\hat{e}$) and radiative loss

Three mechanisms for transport loss at LO

1. Hard Collisions: $2 \leftrightarrow 2$



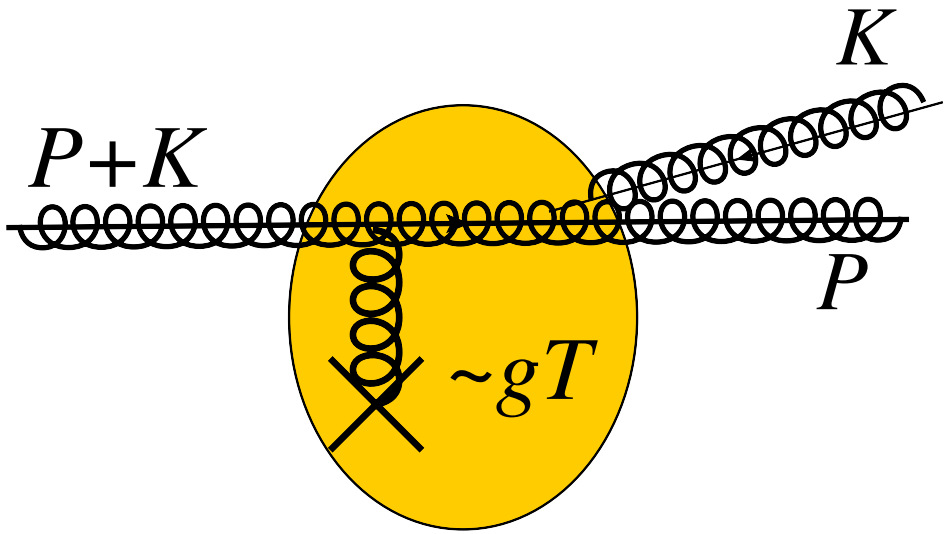
2. Drag: collisions with soft random classical field



$$\frac{dp}{dt} = -\eta(\mu)\hat{\mathbf{v}}$$

3. Brem: $1 \leftrightarrow 2$

- random walk induces collinear bremsstrhalung



- The probability of a transverse kick of momentum $\mathbf{q}_\perp$ from soft fields:

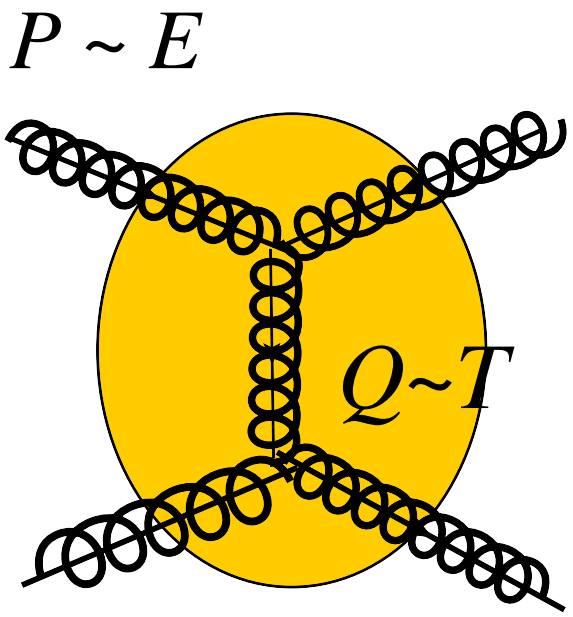
$$C_{LO}[\mathbf{q}_\perp] = \frac{T m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$

NLO involves corrections to these processes and the relation between them.

Same processes determine the shear viscosity of QCD in high temperature plasma!

Three rates for energy loss at leading order:

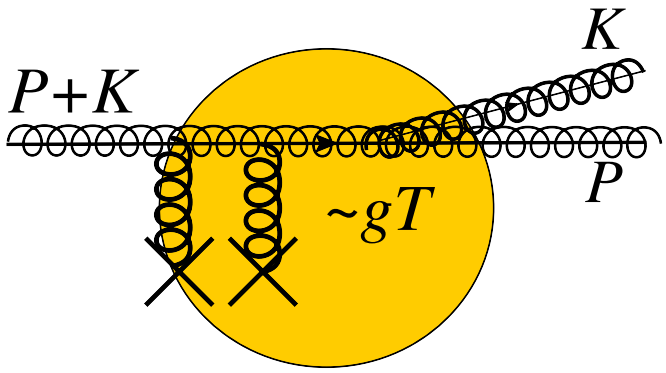
1. Hard Collisions – a $2 \leftrightarrow 2$ processes



$$[\partial_t + v_{\mathbf{k}} \cdot \partial_{\mathbf{x}}]\, f_{\mathbf{k}} = C_{2\leftrightarrow 2}[\mu_\perp]$$

Total $2 \leftrightarrow 2$ scattering rate depends logarithmically on the cutoff

2. Collinear Bremsstrhalung – a $1 \leftrightarrow 2$ processes



$$[\partial_t + v_{\mathbf{k}} \cdot \partial_x] f_{\mathbf{k}} = \underbrace{C_{1\leftrightarrow 2}}$$

LPM + AMY and all that stuff!

The bremsstrhalung rate is proportional to the rate of transverse momentum kicks, $C_{LO}[\mathbf{q}_\perp]$:

$$C_{LO}[q_\perp] = \text{in medium scattering rate with momentum } \mathbf{q}_\perp$$

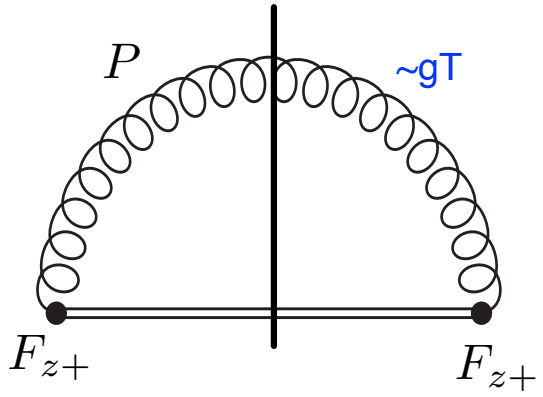
- Need to compute the transverse force-force correlators along the light cone.

$$q_\perp^2 C_{LO}[\mathbf{q}_\perp] = \int \frac{dq_+ dq_0}{(2\pi)^2} \underbrace{\langle F_{i+}(Q) F_{i+} \rangle \, 2\pi\delta(q_+)}$$

evaluate with sum rule at $q_0 = 0$

$$= \frac{T m_D^2}{q_\perp^2 + m_D^2}$$

3. Drag: A longitudinal force-force correlator along the light cone



$$[\partial_t + v_{\mathbf{k}} \cdot \partial_{\mathbf{x}}]\, f_{\mathbf{k}} = \eta(\mu)\mathbf{v} \cdot \frac{\partial f_{\mathbf{k}}}{\partial \mathbf{k}}$$

- Evaluate longitudinal force-force with hard thermal loops + sum-rules

$$\eta(\mu) \propto g^2 C_A \int^{\mu} \frac{d^2\mathbf{p}_T}{(2\pi)^2} \int \frac{dp_+ dp_0}{(2\pi)^4} \underbrace{\langle F_{z+}(P) F_{z+} \rangle\, 2\pi\delta(p_+)}_{\text{evaluate with sum-rule}}$$

$$\propto g^2 C_A \frac{m_\infty^2}{4\pi} \log(\mu^2/m_\infty^2)$$

The $\mu-$dependence of the drag cancels against μ-dependence of the $2 \to 2$ rate

Summary – the full LO Boltzmann equation:

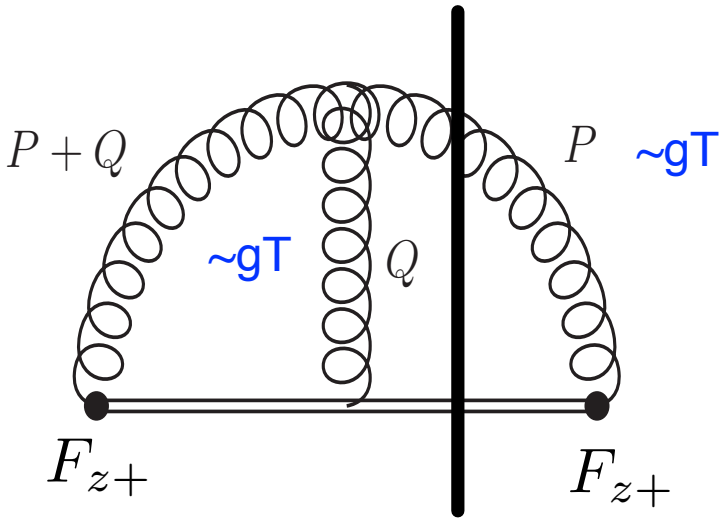
$$[\partial_t + v_{\mathbf{k}} \cdot \partial_{\mathbf{x}}]\, f_{\mathbf{k}} = \eta(\mu)\, \mathbf{v}_{\mathbf{k}} \cdot \frac{\partial f_{\mathbf{k}}}{\partial \mathbf{k}} + C_{2\leftrightarrow 2}[\mu] + C_{1\leftrightarrow 2}$$

The cutoff dependence of the drag cancels against the $2 \to 2$ rate!

$O(g)$ Corrections to Hard Collisions, Drag, Bremm:

1. No corrections to Hard Collisions:

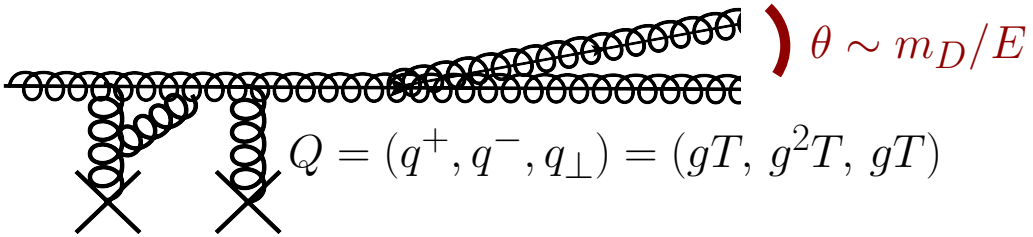
2. Corrections to Drag:



- Nonlinear interactions of soft classical fields changes the force-force correlator
- Doable because of HTL sum rules (light cone causality)

3. Corrections to Bremm:

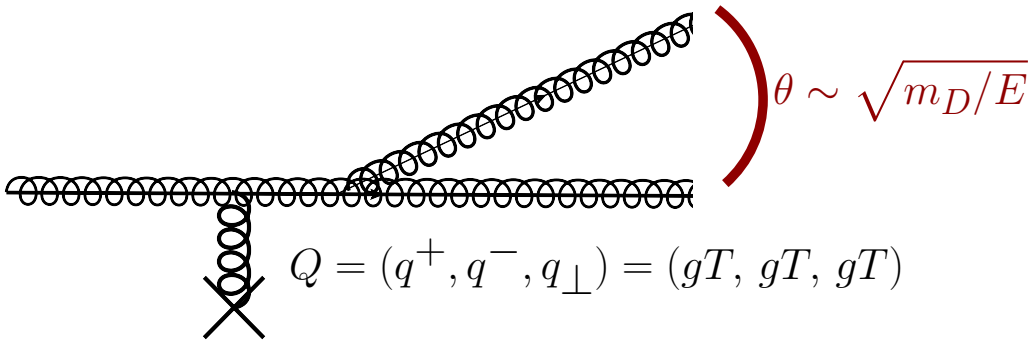
(a) Small angle bremm. Corrections to AMY coll. kernel. (Caron-Huot)



$$C_{LO}[q_\perp] = \frac{Tg^2m_D^2}{q_\perp^2(q_\perp^2 + m_D^2)} \rightarrow \text{A complicated but analytic formula}$$

(b) Large angle brem and collisions with plasmons.

- Include collisions with energy exchange, $q^- \sim gT$.



The large-angle (semi-collinear radiation) interpolates collisional and rad. loss

The NLO Boltzmann equation – a preview:

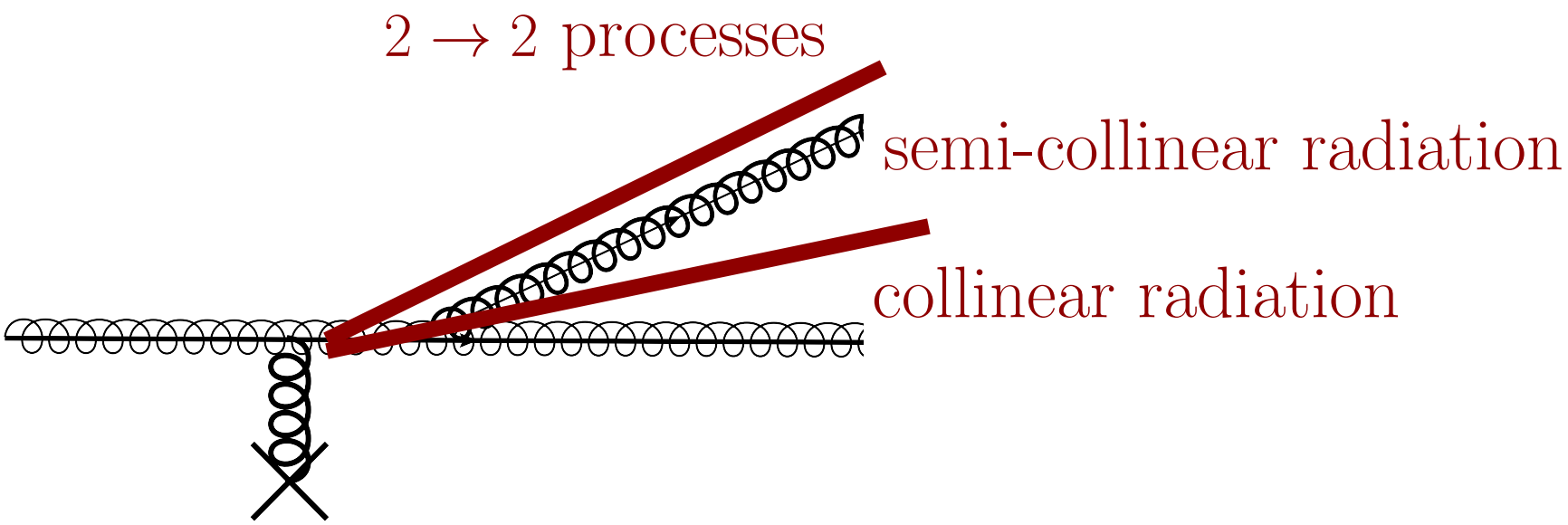
Cutoff dependence cancels

$$[\partial_t + v_{\mathbf{k}} \cdot \partial_{\mathbf{x}}]\, f_{\mathbf{k}} = (\eta(\mu) + \delta\eta(\mu))\ \mathbf{v}_{\mathbf{k}} \cdot \frac{\partial f_{\mathbf{k}}}{\partial \mathbf{k}} + C_{2\leftrightarrow 2}[\mu]$$

$$C_{1\leftrightarrow 2} + \delta C_{1\leftrightarrow 2} + C_{\mathrm{semi-coll}}[\mu]$$

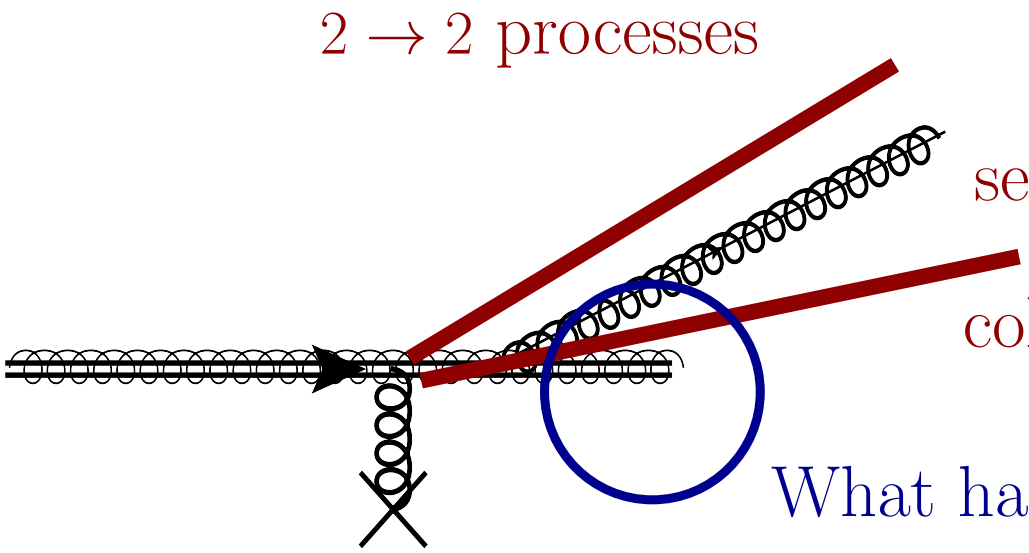
The μ-dependence of the drag at NLO cancels the μ-dependence of semi-collinear radiation

Semi-collinear radiation – a new kinematic window



The semi-collinear regime interpolates between brem and collisions

Matching between brem and drag



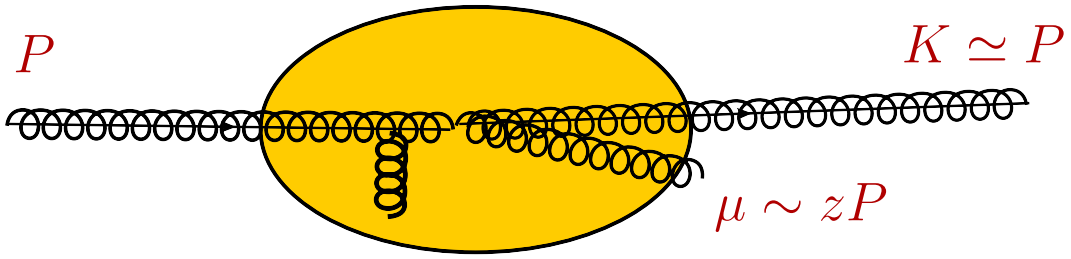
- The semi-collinear emission rate diverges logarithmically when the gluon gets soft

$$\Gamma_{\rm semi-coll} \sim g^2 C_A \quad \overbrace{\frac{\delta m_\infty^2}{4\pi}}^{\sim g^3 T^2} \quad \log\left(\frac{2Tm_D}{\mu}\right)$$

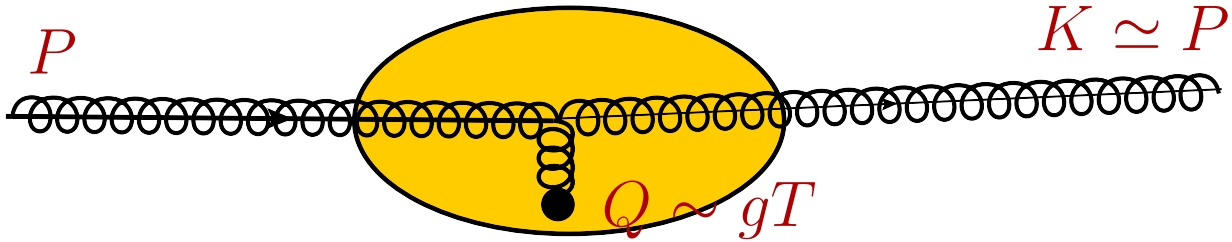
When the gluon becomes soft need to relate radiation and drag.

Matching between semi-collinear brem and drag

- When the final gluon line becomes soft, the brem process:



is not physically distinct from the drag process:

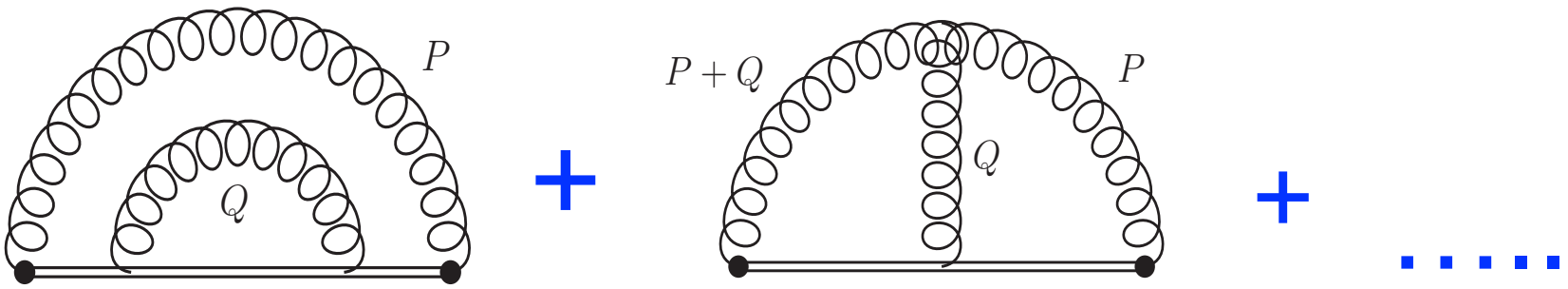


but represents a higher order correction to drag.

Separately both processes depend on the separation scale, $\mu \sim gT$, but . . .

the μ dep. cancels when both rates are included

Computing the NLO drag:



- Evaluate NLO longitudinal force-force with hard thermal loops + sum-rules

$$\eta(\mu) \propto g^2 C_A \int^{\mu} \frac{d^2\mathbf{p}_T}{(2\pi)^2} \frac{m_\infty^2 + \delta m_\infty^2}{p_T^2 + m_\infty^2 + \delta m_\infty^2}$$

$$\propto \text{leading order} + \underbrace{g^2 C_A \frac{\delta m_\infty^2}{4\pi} \left[\log\left(\frac{\mu_\perp^2}{m_\infty^2}\right) - 1\right]}_{\text{NLO correction to drag}}$$

The cutoff dependence of the drag cancels against the semi-collinear emission rate

The NLO Boltzmann equation review:

Cutoff dependence cancels

$$[\partial_t + v_{\mathbf{k}} \cdot \partial_{\mathbf{x}}]\, f_{\mathbf{k}} = (\eta(\mu) + \delta\eta(\mu))\ \mathbf{v}_{\mathbf{k}} \cdot \frac{\partial f_{\mathbf{k}}}{\partial \mathbf{k}} + C_{2\leftrightarrow 2}[\mu]$$

$$C_{1\leftrightarrow 2} + \delta C_{1\leftrightarrow 2} + C_{\mathrm{semi-coll}}[\mu]$$

Now that we have transport equation valid at NLO

Let's use it!

Summary and proposed work for transport at NLO:

1. Compute the photon production rate at NLO. ✓

2. Calculate low-mass dilepton rates beyond LO.

3. The transport equation is being implemented into the MARTINI code for e-loss.

   It sure helps having B. Schenke at BNL!!!

   (a) Understand in detail the transition from radiative to collisional loss.

4. Use the transport eq. to find the NLO shear viscosity and diffusivities of QGP.

Thank you!

Instabilities of QCD near phase transition in holographic models

Shu Lin

RBRC Scientific Review

based on 1309.0789, U. Gursoy, SL and E. Shuryak

Possible realization of supercooled phase in QCD phase transition

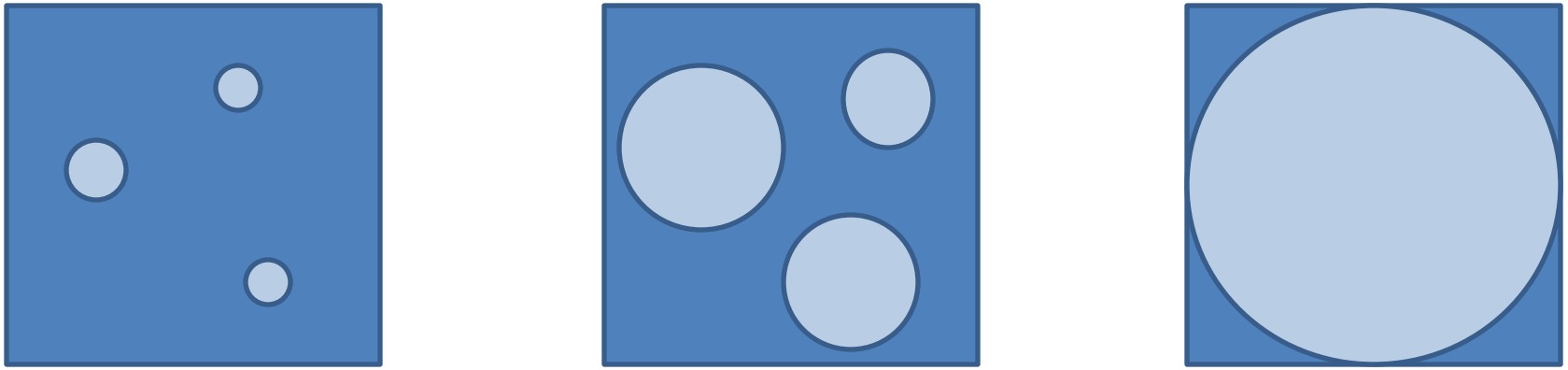
- QCD phase transition is a crossover, but close to first order, like phase transition of water.

QGP fluid: liquid Hadron gas: solid

- Rapid cooling of fireball in HIC might possibly create supercooled QGP at $T<T_c$
- How does supercooled QGP convert to hadronic phase? What instabilities will be triggered in supercooled QGP.

Supercooling in conventional liquid

time

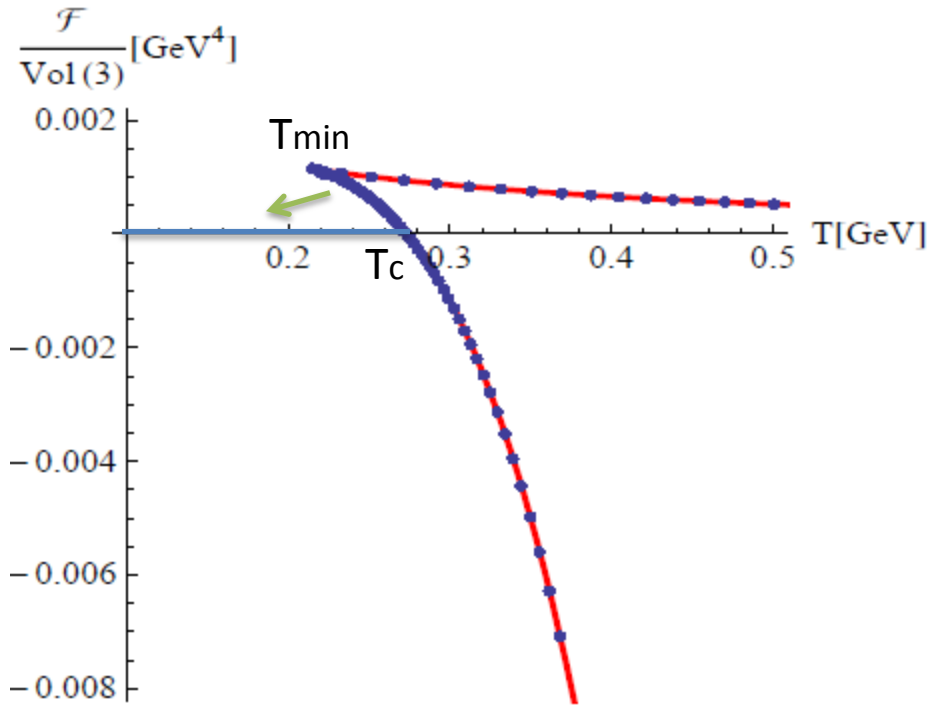


blue: supercooled liquid
white: solid

Supercooled QGP(black hole)?

Improve holographic model

$$S = -\frac{1}{16\pi G_5}\int d^5x\sqrt{G}\left(R - \frac{4}{3}(\partial\phi)^2 - \mathcal{V}(\phi)\right) + \frac{1}{8\pi G_5}\int_\partial d^4x\sqrt{H}K.$$



T_c=273MeV
T_{min}=212MeV

No flavor

Gursoy, Kiritsis et al
Megias et al

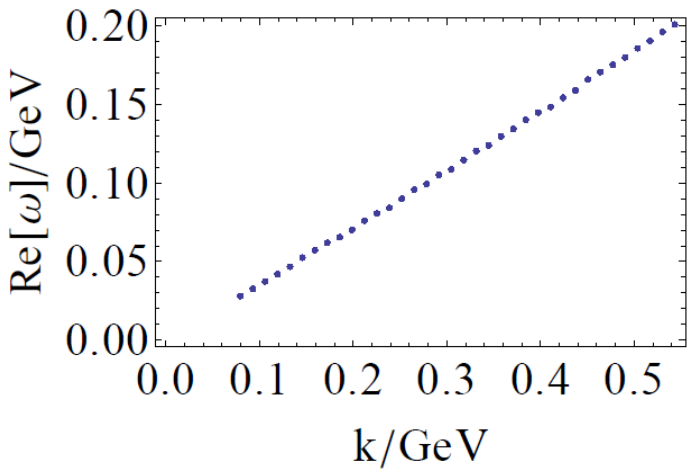
Two types of instabilities to be investigated

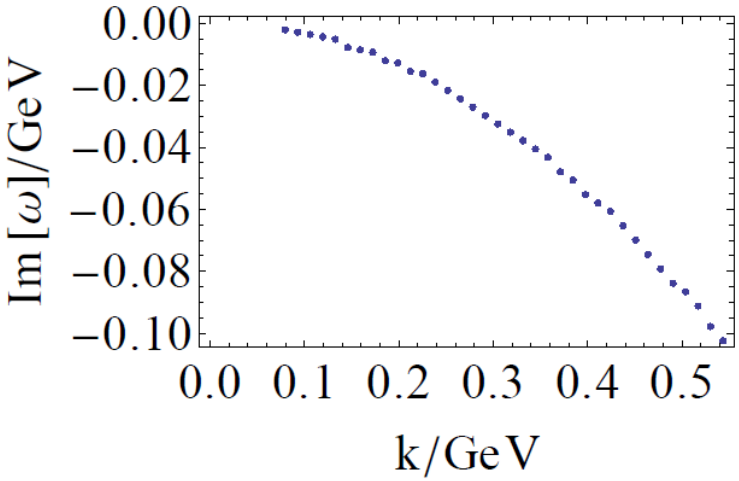
- Classical instability of blackhole: growing sound mode in supercooled QGP fluid?

- Quantum tunneling of blackhole: shrinking of supercooled QGP in a mixture QGP and hadron gas.

Sound mode at finite k at $T<T_c$

T=236MeV

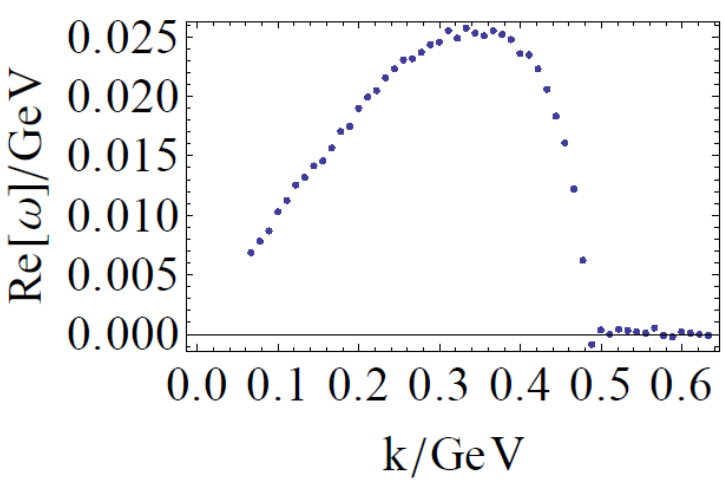


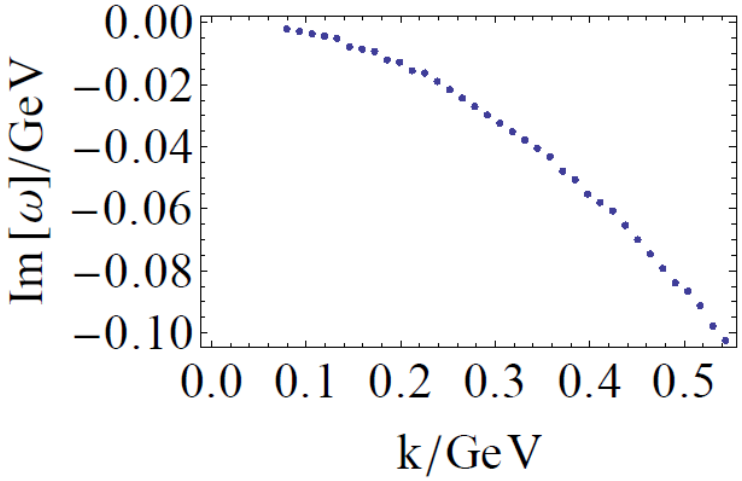


Usual sound mode

Sound mode at finite k at $T=T_{min}$

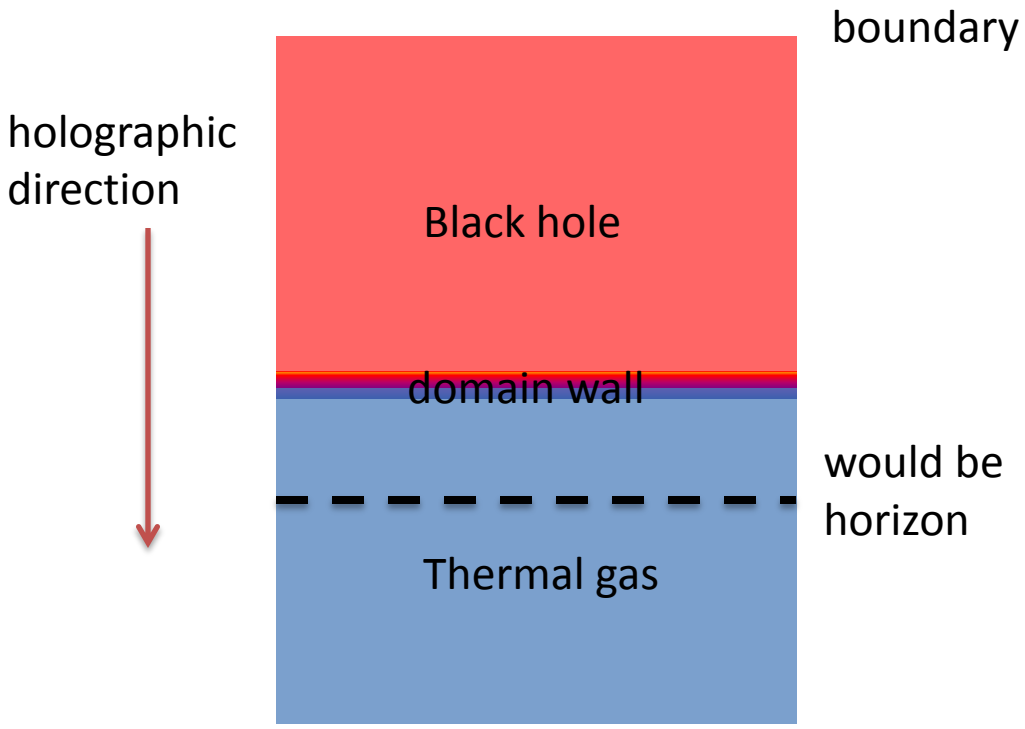
T=212MeV





Stoppage of sound propagation beyond critical k!

Quantum tunneling via evolution of domain-wall background



domain-wall evolves toward the boundary, shrinking the supercooled QGP phase

Effective action for the DW

For infinitesimal domain-wall with trajectory Λ(t)

$$\frac{S}{\beta \mathrm{Vol}} = F - V(\Lambda) + M(\Lambda)\dot{\Lambda}^2 + \frac{\sqrt{P(\Lambda) - Q(\Lambda)\dot{\Lambda}^2}}{P(\Lambda)}$$

free energy

potential

kinetic

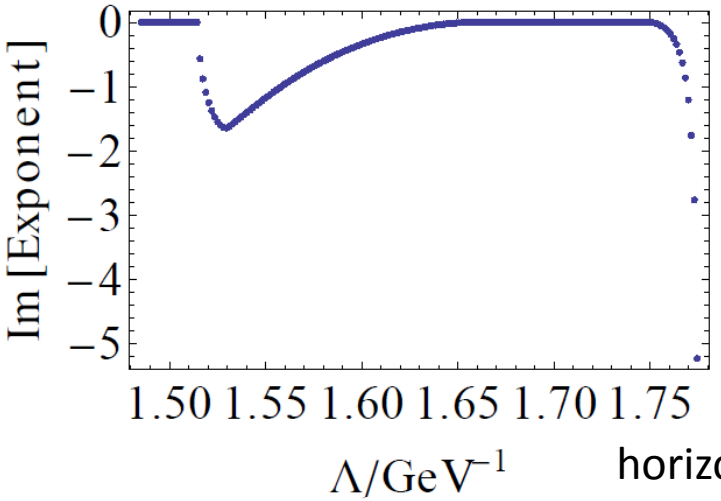
Classical trajectory for positive $\dot{\Lambda}^2$

Quantum tunneling for negative or complex $\dot{\Lambda}^2$

Tunneling probabilities at T<Tc

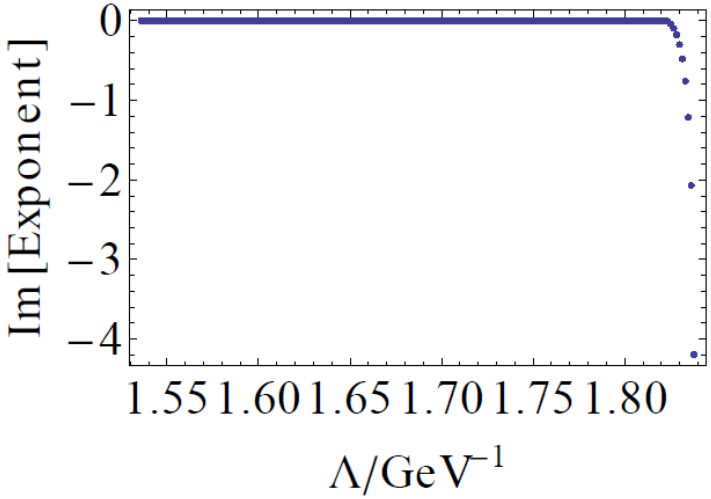
Tunneling probability: $\exp\left(-\int_0^{z_h} d\Lambda d^3x \mathrm{Im}[\mathrm{Exponent}]\right).$

T=236MeV



horizon

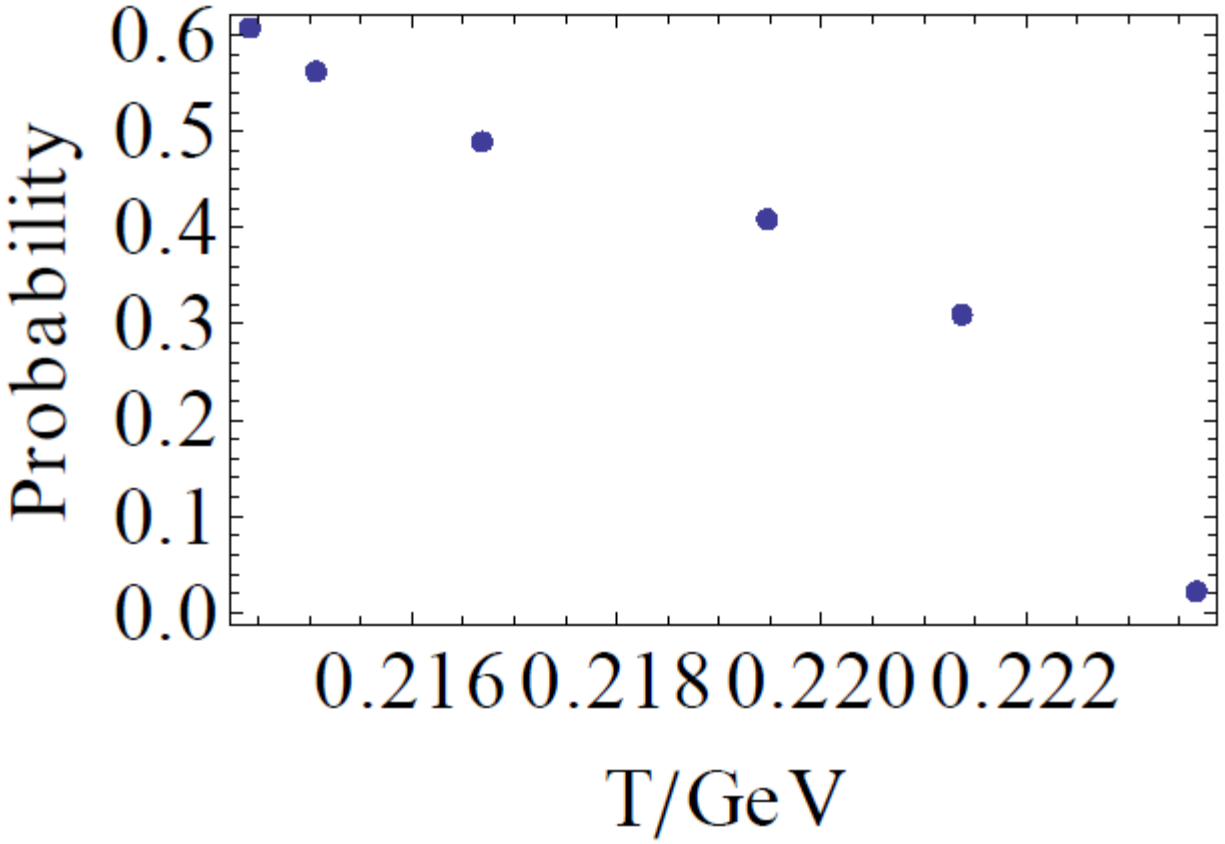
T=212MeV



1: Infinite but integrable barrier at horizon

2: More tunneling windows at higher T

Tunneling probability



For supercooled QGP cluster size ~ 4fm

Summary

- We investigated the evolution of supercooled QGP possibly realized in HIC.
- We found no instability in sound mode, but the stoppage of sound propagation at very low T.
- We constructed a domain-wall background describing the shrinkage of supercooled QGP phase and found its quantum tunneling probabilities to hadronic phase.

Phase structure and Hosotani mechanism in QCD-like gauge theory

Kouji Kashiwa

Introduction

QCD phase diagram at finite chemical potential

Phys. Rev. D87 (2013) 016015

K.K., T. Sasaki, H. Kouno, M. Yahiro

Phys. Rev. D87 (2013) 096009

K.K., R. D. Pisarski

J. Mod. Phys. 4 (2013) 644

T. Hell, **K.K.**, W. Weise

Gauge symmetry breaking in QCD-like gauge theory (Hosotani mechanism)

JHEP 05 (2013) 042

K.K., Tatsuhiro Misumi

Phys. Rev. D 88 (2013) 016002

H. Kouno, T. Misumi, **K.K.**, T. Makiyama, T. Sasaki, M. Yahiro

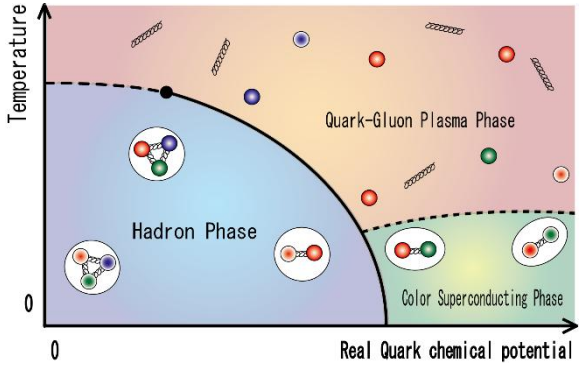
Effect of center domain for Heavy Ion Collision

arXiv:hep-ph/1309.6742 (2013)

K.K., Akihiko Monnai

Introduction

QCD phase diagram at finite chemical potential



Phys. Rev. D87 (2013) 016015

K.K., T. Sasaki, H. Kouno, M. Yahiro

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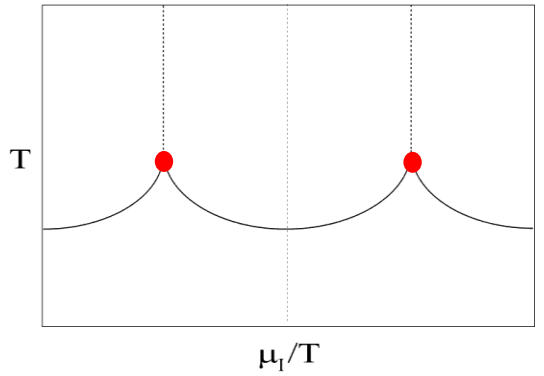
T. Hell, **K.K.**, W. Weise

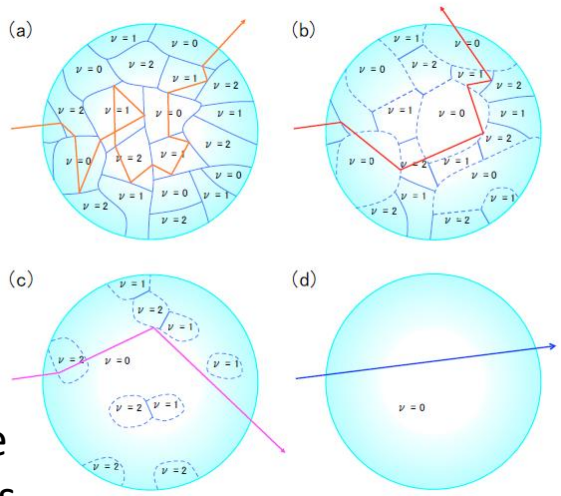


We discussed the QCD phase diagram by using the imaginary chemical potential

How to remove model ambiguities.

Properties of QCD at finite imaginary chemical potential.

Effect of quark contribution for center domain in Heavy Ion Collision



arXiv:hep-ph/1309.6742 (2013)

K.K., Akihiko Monnai

We investigated what happen in heavy ion collision if there is the center domain structure with quark contributions.

Introduction

Gauge symmetry breaking in QCD-like gauge theory (Hosotani mechanism)

JHEP 05 (2013) 042

K.K., Tatsuhiro Misumi

Phys. Rev. D 88 (2013) 016002

H. Kouno, T. Misumi, **K.K.**, T. Makiyama, T. Sasaki, M. Yahiro

If we consider the finite temperature QCD,
the Z_3 symmetry breaking is related with the confinement-deconfinement transition.

In the finite temperature QCD, the boundary condition is strictly determined because of the fermion statistic.

However, such restriction is no longer exist when we consider the compact extra-dimension!

If the compact extra dimension is not simply connected with the system and adjoint fermions exist,
the gauge symmetry breaking expectation value of gauge boson can be formed.

↑ Hosotani mechanism

Adjoint fermion plays a important role!

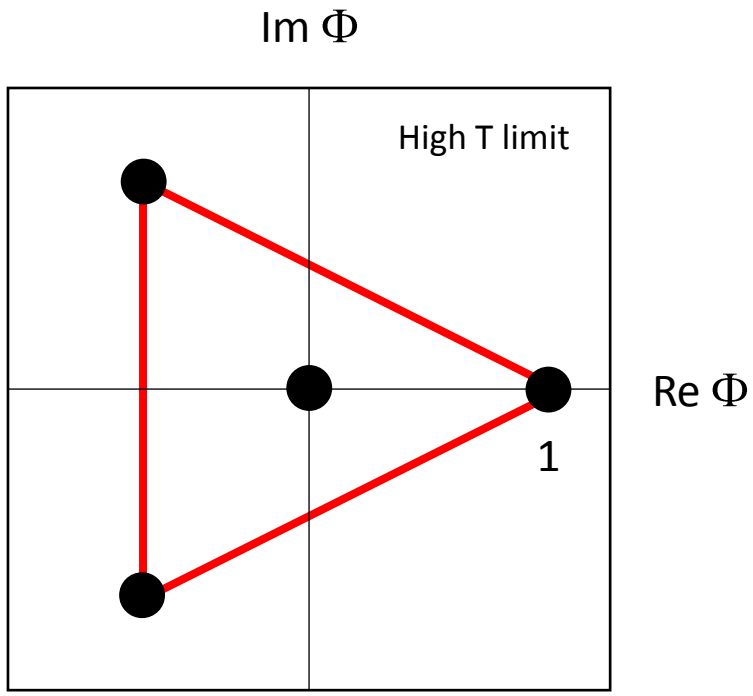
Polyakov-loop and gauge-symmetry breaking

In the paper K.K., T. Misumi, JHEP 05 (2013) 042, we discussed the Hosotani mechanism in 4D.

If we consider the imaginary time direction is the compact dimension,
we can see the spontaneous gauge -symmetry breaking from the Polyakov-loop.

The Polyakov-loop is also the order-parameter of the Z_3 symmetry breaking.

Polyakov-loop



$$W = P\exp\left\{ig\int_C dy A_y\right\} \longrightarrow \mathrm{diag}[e^{2\pi i q_1}, e^{2\pi i q_2}, \cdots, e^{2\pi i q_N}]$$

$$q_i \neq q_j \Rightarrow m_n^2 = \frac{1}{L^2}(n + q_i - q_j)^2$$

(Gauge symmetry breaking is happened)

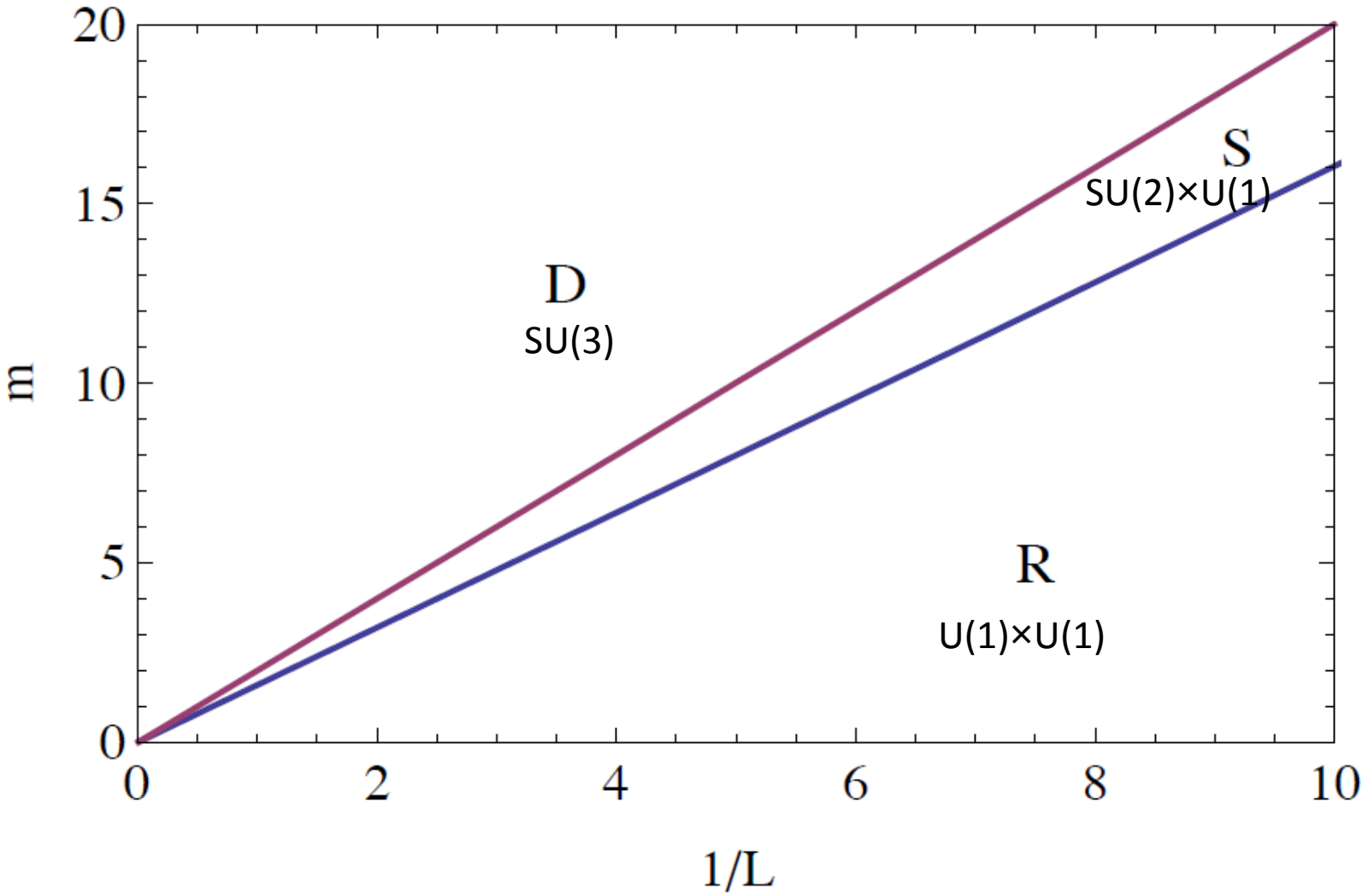
$q_1 = q_2 \neq q_3$: SU(2) ×U(1) , $q_1 \neq q_2 \neq q_3$: U(1) ×U(1)

Phase diagram

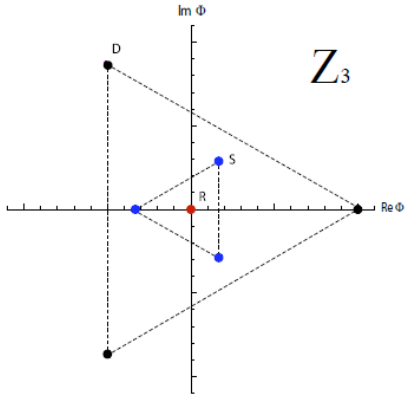
K.K., T. Misumi, JHEP 05 (2013) 042.

Phase Structure

In previous studies for Hosotani mechanism, *fermion mass effects were neglected.*



We use the perturbative one-loop potential.



D : Deconfied phase

S : Split (skewed) phase

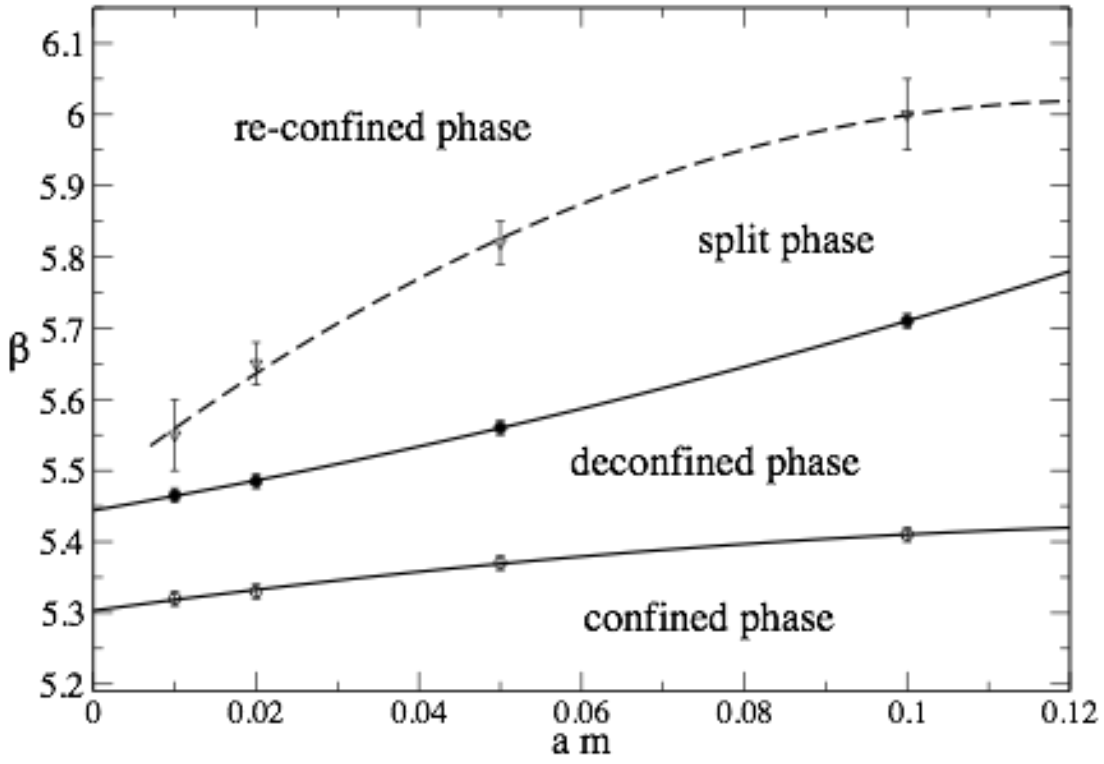
R : Re-confined phase

C : Confined phase

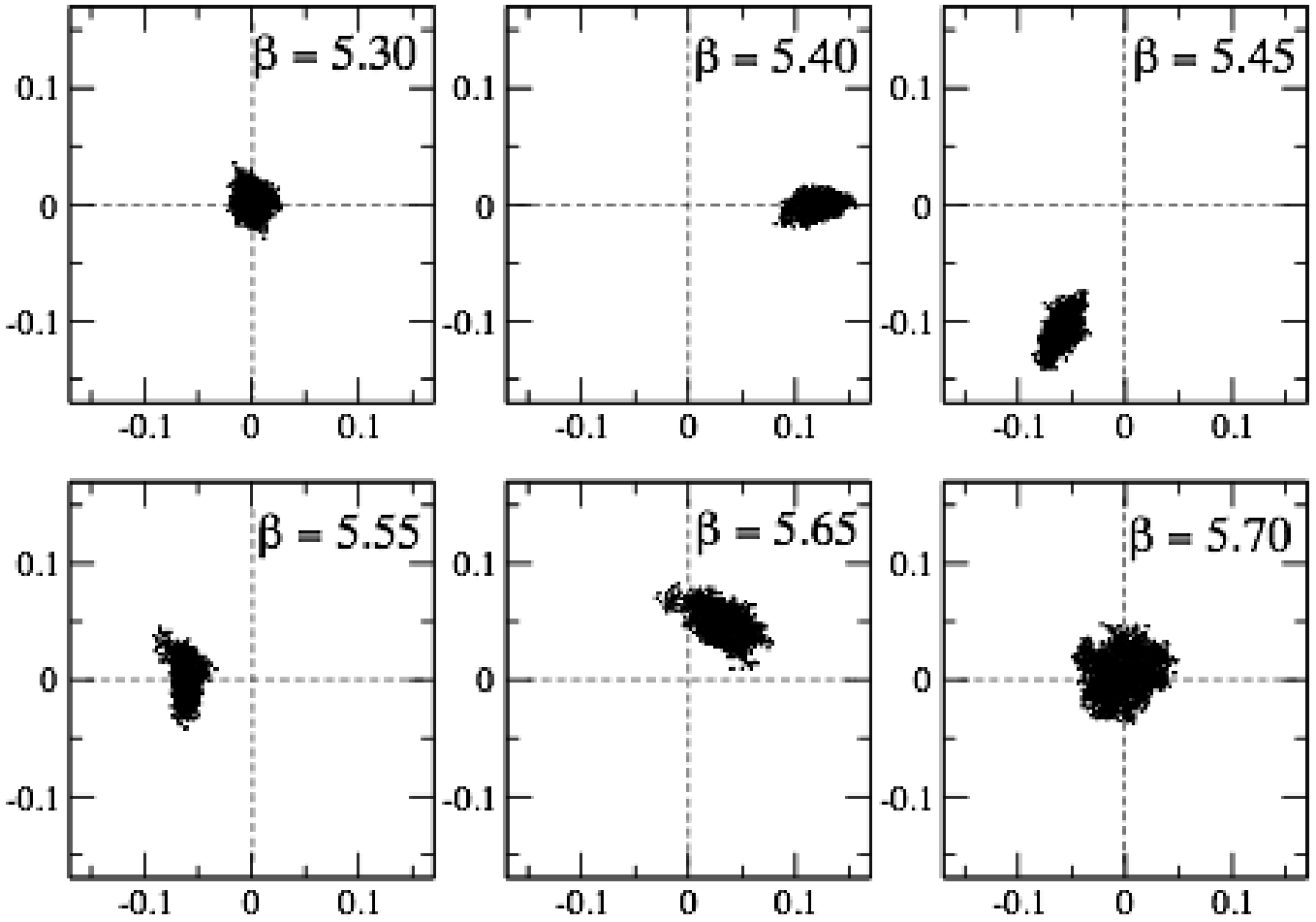
LQCD with adjoint fermion with PBC

Lattice data :
G. Cossu, M. D'Elia, JHEP 07(2009), 048.

Phase Structure



Scatter plot of Polyakov-loop



Lattice setup:

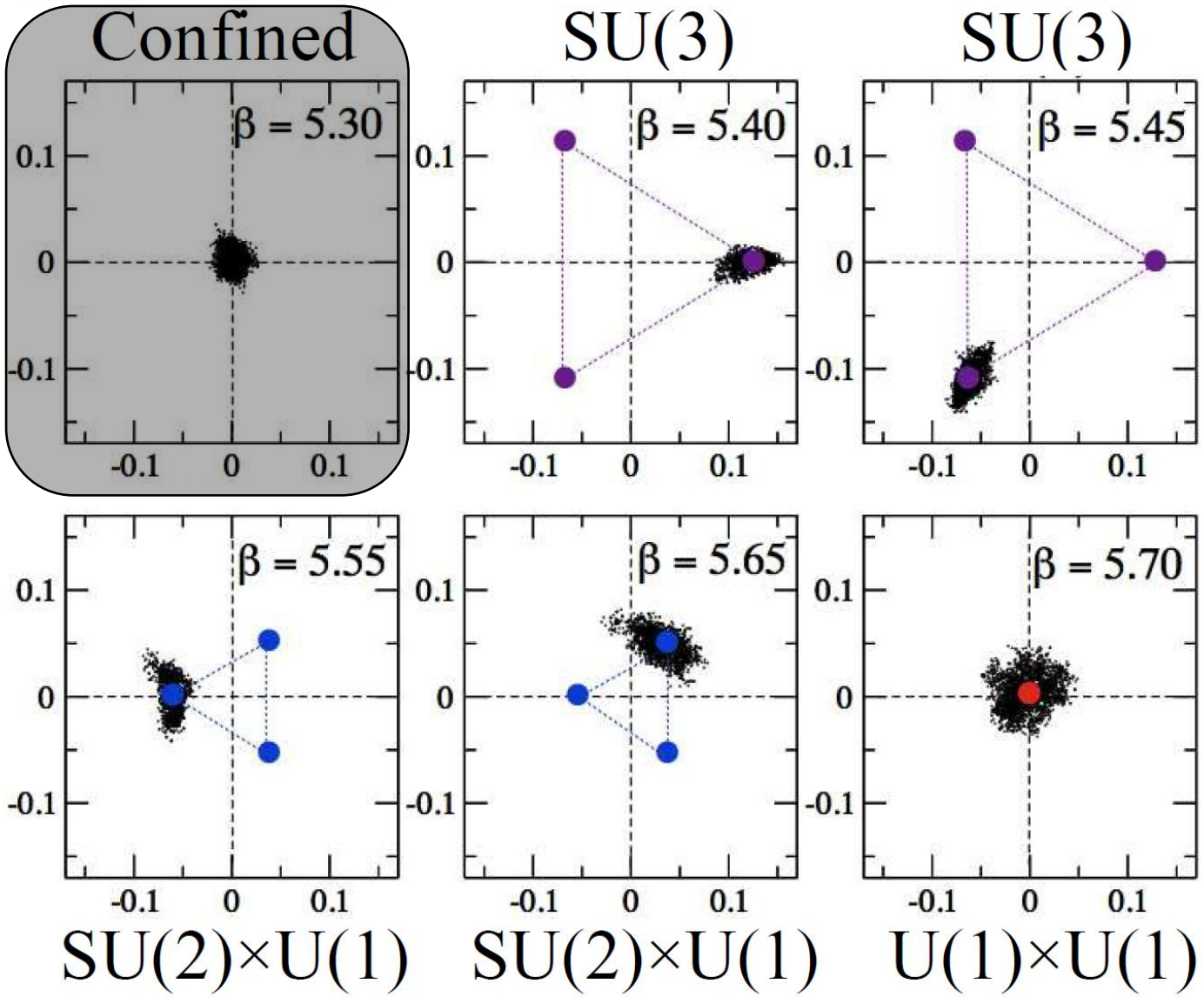
2 flavor, 3 color and adjoint staggered fermion

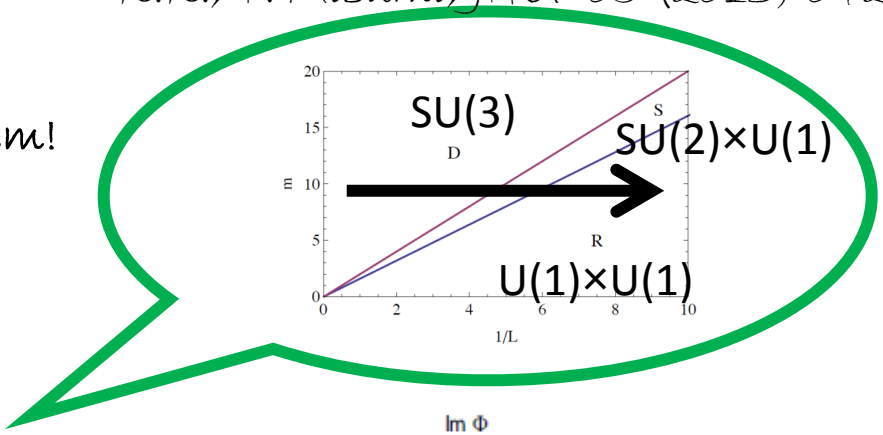
Comparison

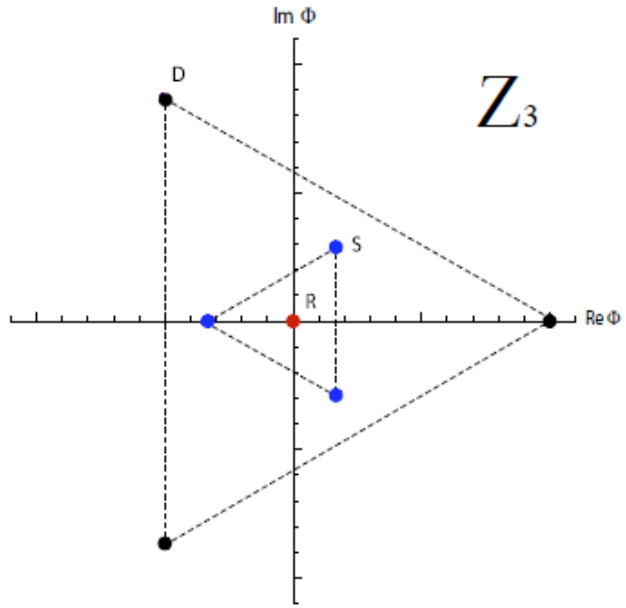
K.K., T. Misumi, JHEP 05 (2013) 042.

Phase Structure

We can understand it from Hosotani mechanism!







Summary

We investigate Hosotani mechanism in 4 dimension.

- Lattice data can be understood from the Hosotani mechanism by considering the fermion mass.

  Fundamental fermion effects are investigated.

  Chiral properties are explored by using the Polyakov-loop extended Nambu—Jona-Lasinio type model.

In Phys. Rev. D 88 (2013) 016002, we show that the gauge-symmetry breaking can be happen
when we consider the fundamental fermions with non-trivial boundary condition.

These studies may be important to the physics beyond the standard model.

Also, the study of the compact dimension can give us the important knowledge for the confinement mechanisms.

↓

How to construct the confinement phase in the effective model and theory?

Fluidity of the quark-gluon plasma in heavy ion collisions

Akihiko Monnai

RIKEN BNL Research Center

Nishina Center for Accelerator-Based Science, RIKEN

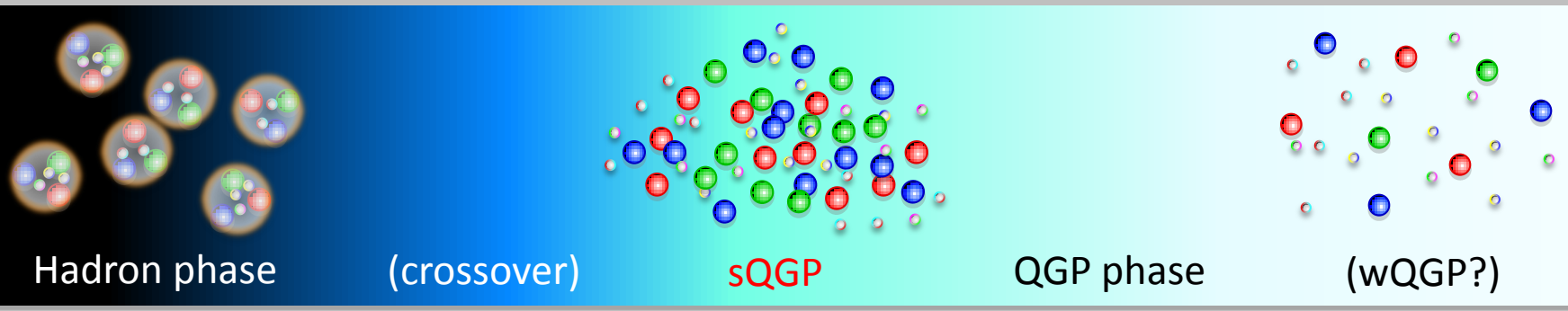
Scientific Review Committee

31st October 2013, Brookhaven National Laboratory, NY

Introduction

- Quark-gluon plasma (QGP): many-body system of deconfined quarks and gluons

Graphics by AM



The QGP is supposed to have filled the early universe;
It can be produced in heavy ion experiments at RHIC & LHC

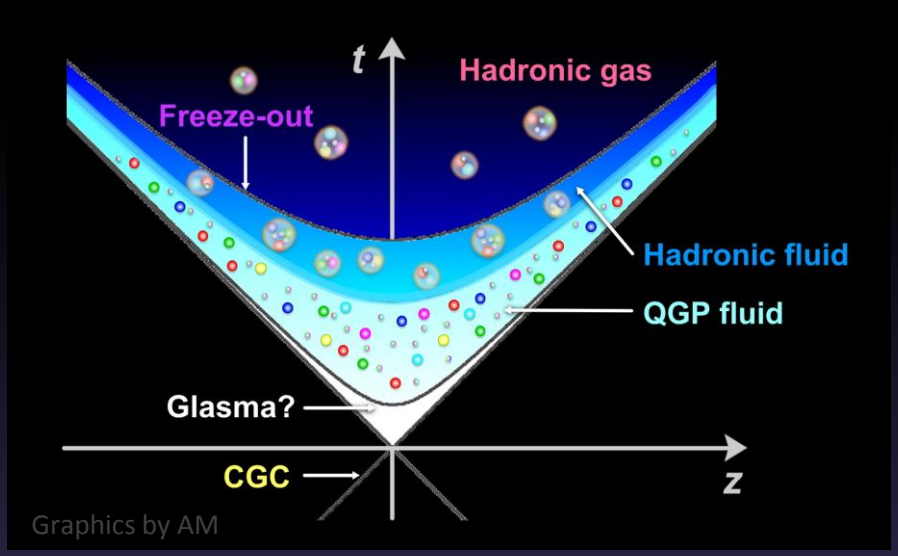
⇨ Heavy ion QGP is characterized with

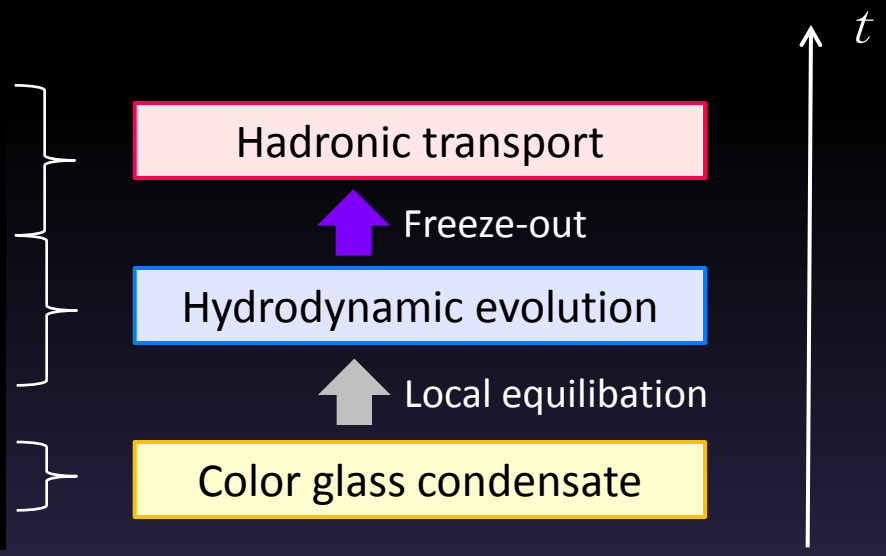
- Near-perfect fluidity
- Large color opacity



Introduction

- "Standard model" of high-energy heavy ion collisions



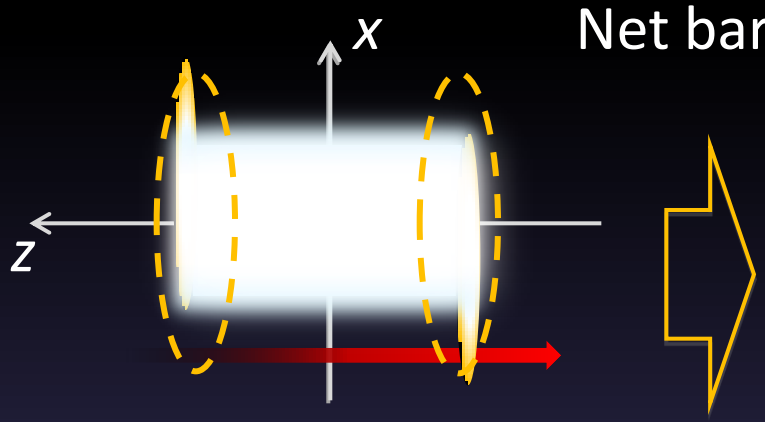


- $\tau < 0$ fm/c: color glass condensate (saturated gluons)
- $\tau \sim$ 0-1 fm/c: glasma? (pre-equilibrated medium)
- $\tau \sim$ 1-10 fm/c: QGP/hadronic fluid (strongly-coupled medium) *How? Why?*
- $\tau > 10$ fm/c: hadronic gas (weakly-coupled medium)

AM, Phys. Rev. C 86, 014908 (2012)

How hydrodynamics works

- Analyses of QGP fluid at finite density with shear viscosity + bulk viscosity + baryon diffusion

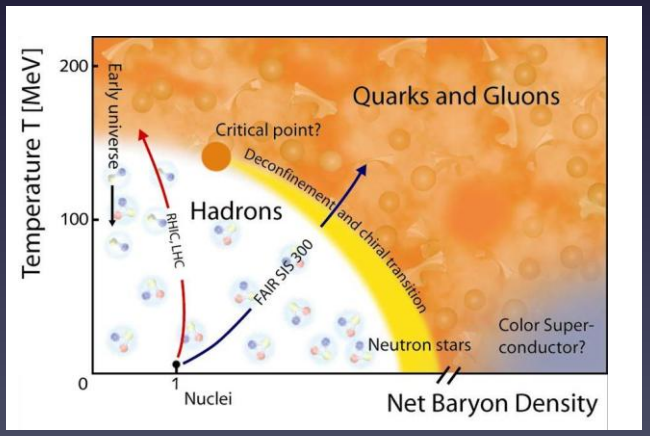


Net baryon distribution can be investigated

(net baryon) = (baryon) - (antibaryon)

- Net baryon number exists only in the colliding nuclei
- It is related to the kinetic energy available for QGP formation

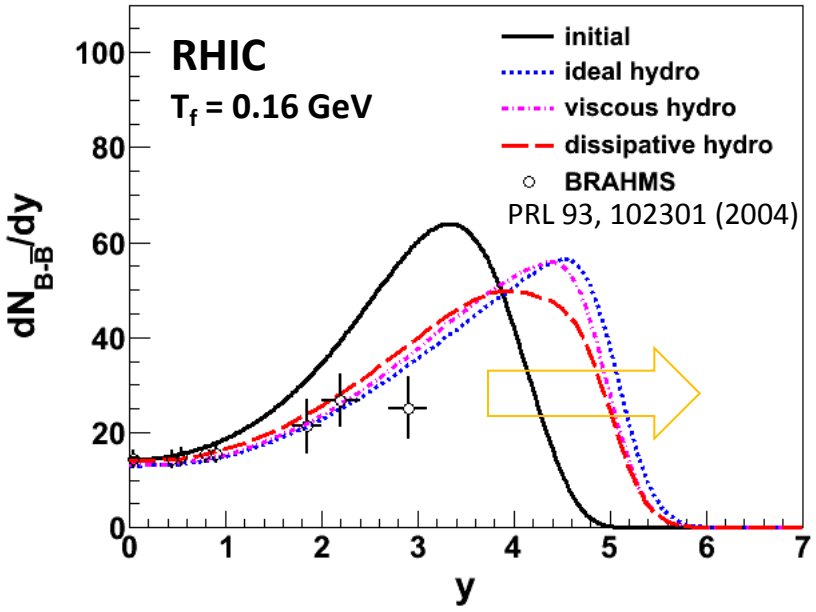
- Future goal: exploration of the QCD phase diagram for critical point (RHIC)
  - Hydrodynamics can be a help as first-principle calculations are difficult at finite baryon density



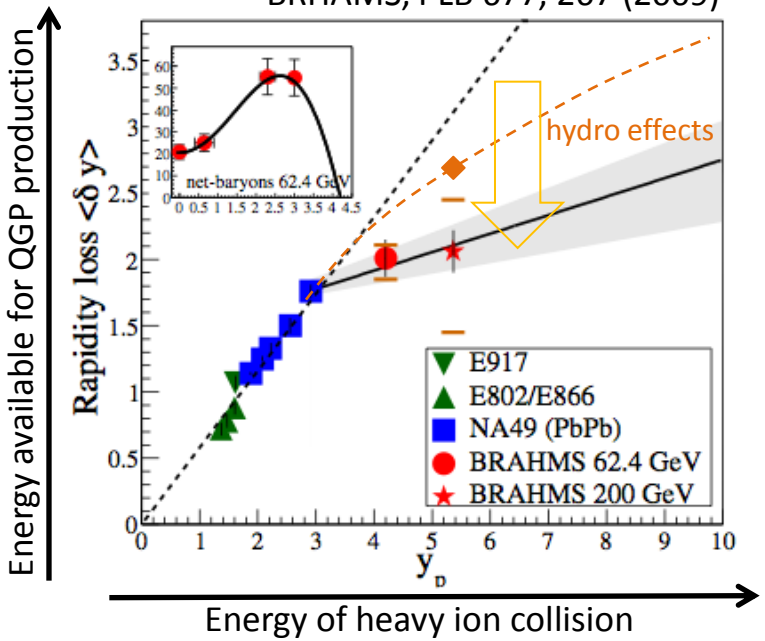
AM, Phys. Rev. C 86, 014908 (2012)

How hydrodynamics works

- Net baryon rapidity distribution at RHIC



BRHAMS, PLB 677, 267 (2009)



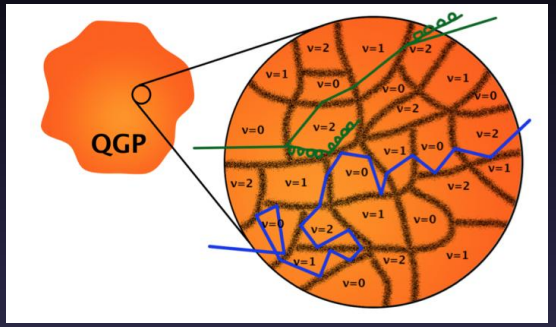
- Hydro evolution sends net baryon number to forward rapidity
- Transparency of the collision is effectively enhanced by hydrodynamics

⇨ More kinetic energy is available for QGP production

K. Kashiwa, AM, arXiv:1309.6742 [hep-ph]

Why hydrodynamics works

- Center domain structure in the QGP Asakawa, Bass and Müller, PRL 110,201301 (2013)
  - One knows *how*, but not *why* hydrodynamics work so well
  - Z_3 (center) symmetry in pure gauge system
    - ⇨ Due to a symmetry in QCD, three different states may be allowed in the QGP phase
    - ⇨ Center domain structure can develop because CGC and glasma imply the typical size of correlation is ~1/Qs
    - ⇨ Mean free path is characterized by the size of domain; small viscosity and large opacity can be explained

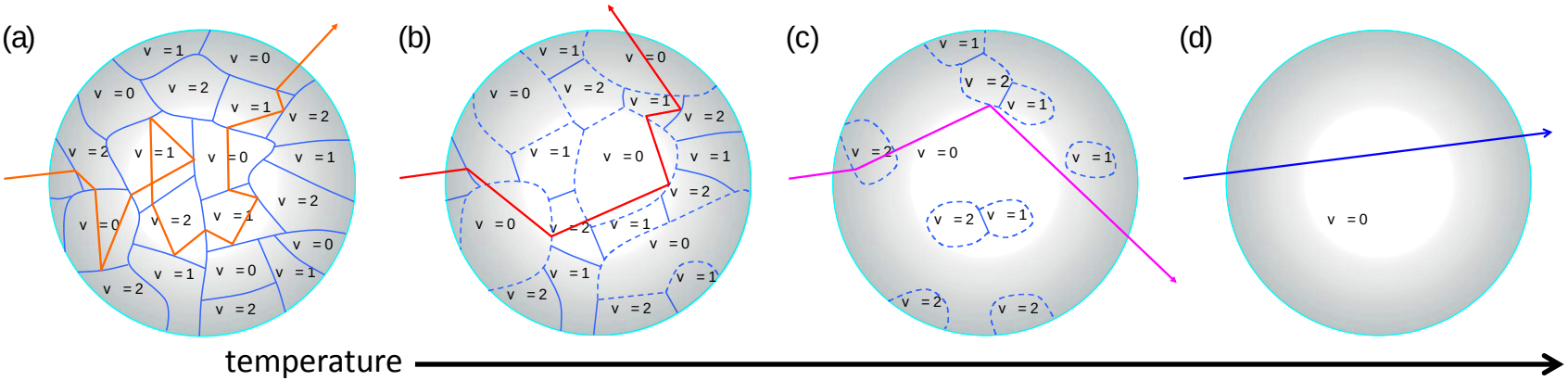


  - Motivation: how does it approach perturbative QCD picture at high temperatures?

K. Kashiwa, AM, arXiv:1309.6742 [hep-ph]

Why hydrodynamics works

- Quark contribution



- (b) Stable domains expand (v=0) and metastable ones (v=1,2) shrink due to existence of quarks ⇨ Mean free path is longer, increasing viscosity
- (c) Percolation of stable domains occurs
- (d) Metastable states completely vanish above a critical temperature T_{cri} - large viscosity and transparency will be observed

⇨ A smooth bridge from strongly-coupled QGP (hydrodynamics) to weakly-coupled QGP (pQCD)

Summary and outlook

- Dissipative hydrodynamic model at finite baryon density
  - Baryon stopping is effectively reduced by hydrodynamic flow
    - ⇨ Energy available for QGP production could be larger
  - Net baryon distribution is sensitive to baryon diffusion
  - Future prospects: three dimensional analyses and more realistic transport coefficients for quantitative discussion, etc.
- Center domain structure with quark contribution
  - It provides a bridge from hydrodynamics to pQCD
  - A topological critical temperature may be present in high temperature region
  - Future prospects: analyses on system size dependence, boundary effects, etc.

Comments on particle production in pp and pA collisions

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RIKEN BNL Research Center

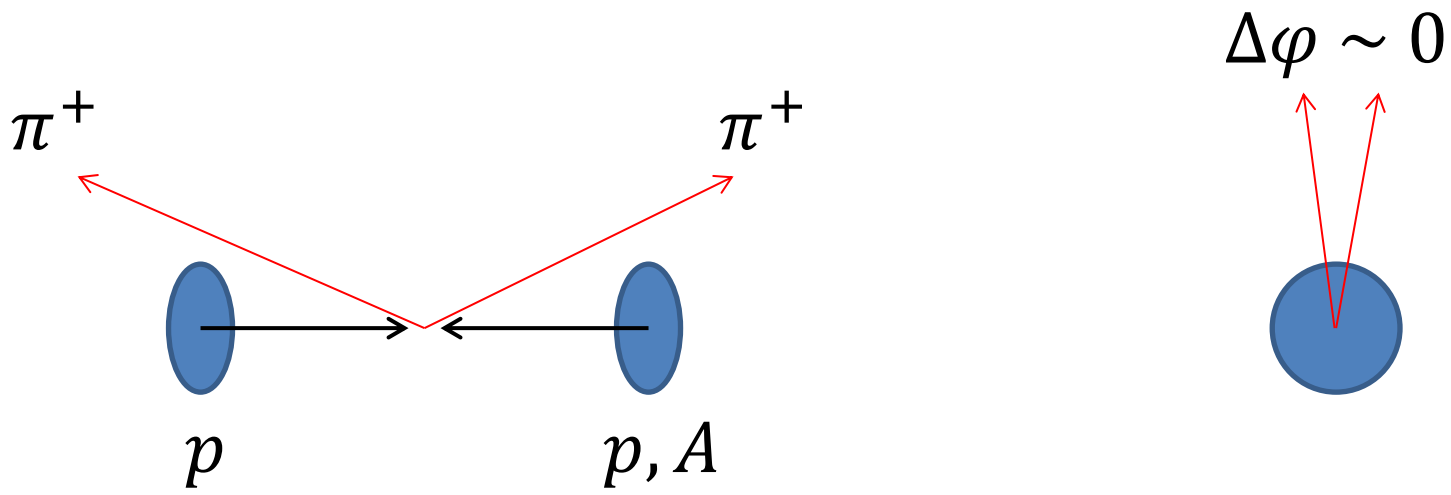
Brookhaven National Laboratory

Introduction
Hydrodynamics
Color Glass Condensate (CGC)
CGC vs. hydrodynamics
Conclusions

Discovery at the LHC

Proton-proton collisions at $\sqrt{s} = 7000$ GeV

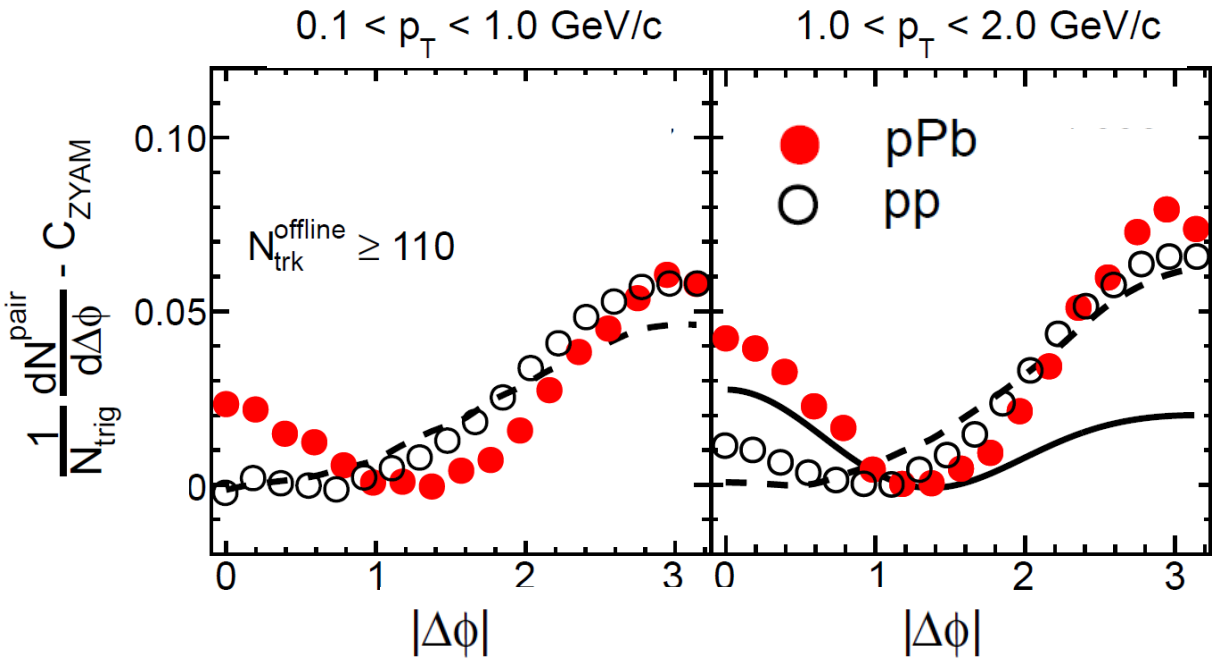
Proton-lead collisions at $\sqrt{s} = 5020$ GeV



Particles with large rapidity separation prefer similar azimuthal angles (collimation)!

Back-to-back contribution also present (obvious)

Experimental data (sample)

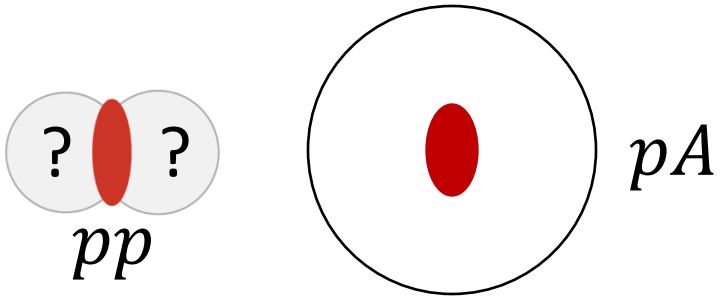


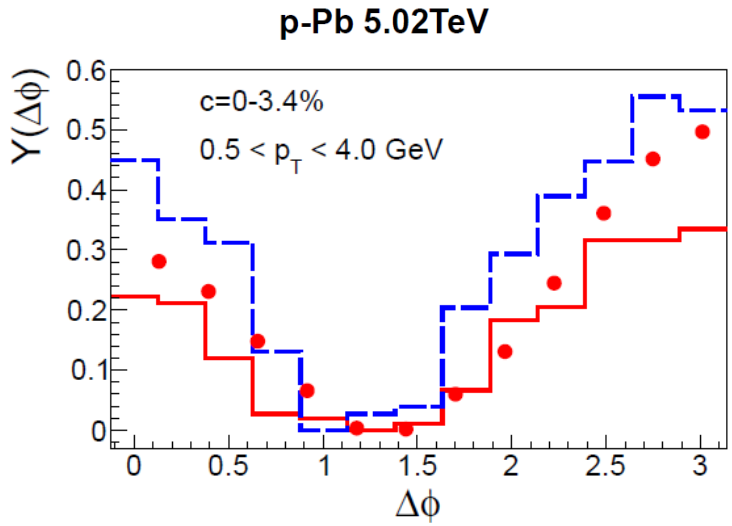
The effect is larger in p+Pb than p+p collisions (at the same multiplicity)

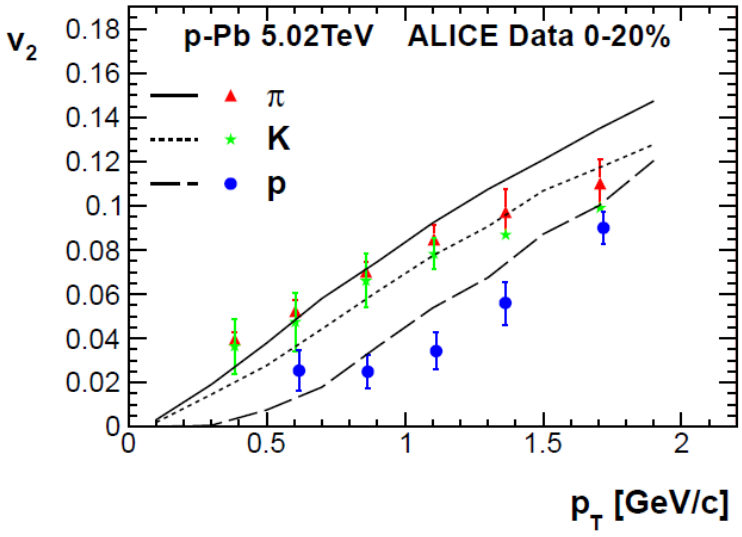
The more particles the stronger the effect

CMS Coll., JHEP 1009 (2010) 091; Phys. Lett. B718 (2013) 795
ALICE Coll., Phys. Lett. B719 (2013) 29
ATLAS Coll., Phys. Rev. Lett. 110, 182302 (2013)
PHENIX Coll., arXiv:1303.1794 [nucl-ex], d+Au at 200 GeV

Perhaps we can apply hydrodynamics to high-multiplicity pp and pA collisions. The interaction region is small but can be also asymmetric.





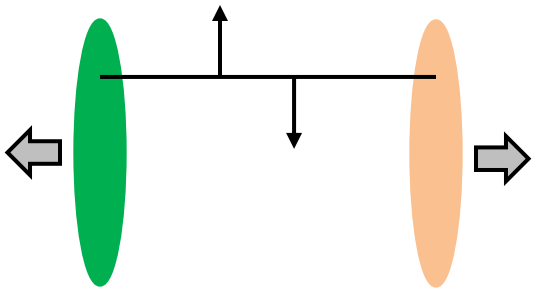


Hydro can <u>fit</u> the data for p+Pb quite well, p+p still to be checked

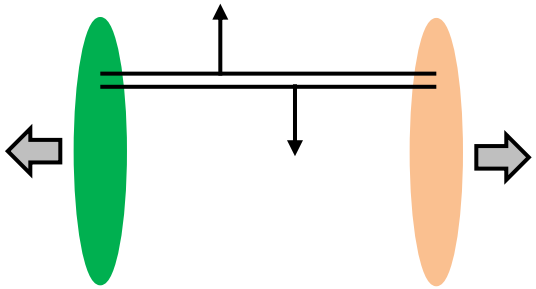
P.Bozek, PRC 85 (2012) 014911; P.Bozek, W.Broniowski, PRC 88 (2013) 014903
P.Bozek, W.Broniowski, G.Torrieri, arXiv:1307.5060 [nucl-th]
AB, B.Schenke, P.Tribedy, R.Venugopalan, PRC 87 (2013) 064906
G.Qin, B.Müller, arXiv:1306.3439 [nucl-th]

Color Glass Condensate

Relevant diagrams:

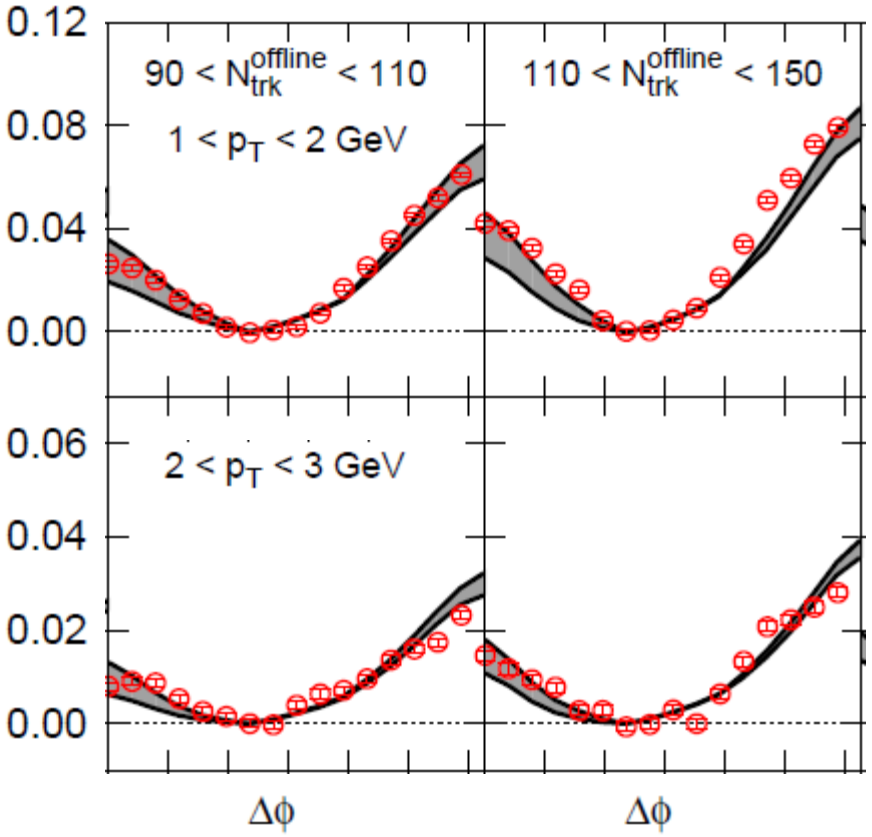


two back-to-back jets



collimation “diagram”

CGC results (sample)



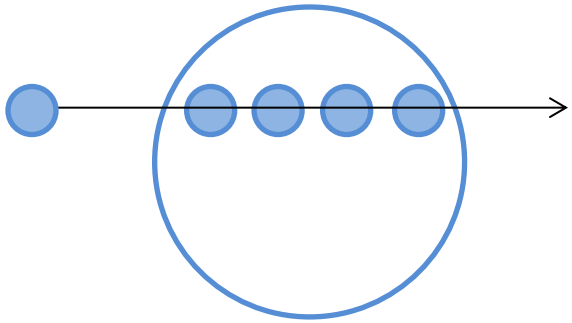
K.Dusling, R.Venugopalan, PRD 87 (2013) 094034; PRL 108 (2012) 262001

Wounded Nucleon Model (WNM)

A.Bialas, M.Bleszynski, W.Czyz,
Nucl. Phys. B 111, 461 (1976)

Number of "sources" scaling

At $y = 0$ or for the total number of particles:



$N_{part} = 4 + 1$

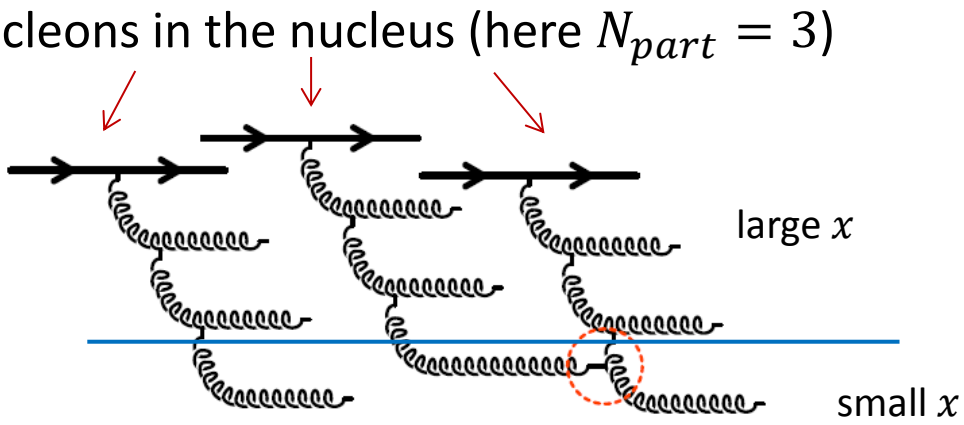
$N_{coll} = 4$

$$\langle N_{pA} \rangle = \frac{\langle N_{pp} \rangle}{2} N_{part}$$

Not clear how to understand this in QCD

The model works very well in the non-perturbative region for 200 GeV d+Au collisions at RHIC (and for smaller energies in various p+X collisions). To be checked at LHC.

CGC in general gives something different



Number of large-x partons is proportional to N_{part}

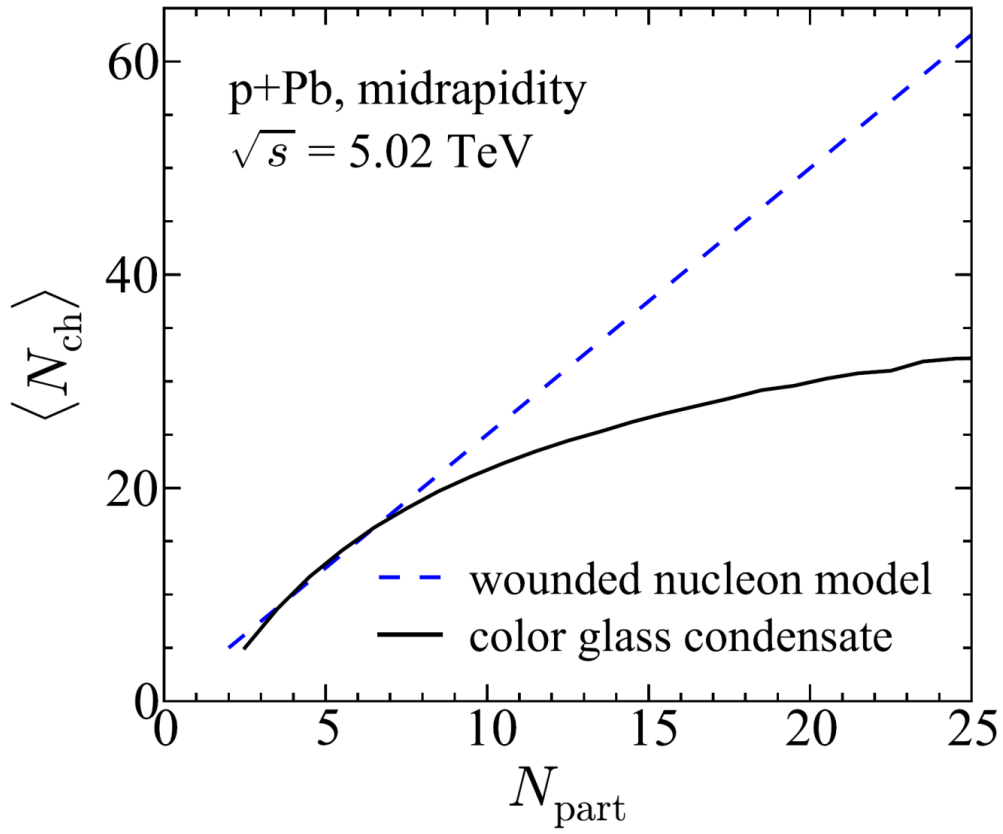
Number of low-x gluons (saturation) do not scale with N_{part} since we are in the nonlinear regime

$$\langle N_{pA} \rangle \sim \ln(N_{part})$$

CGC: $\langle N_{pA} \rangle \sim \ln(N_{part})$ checked in rcBK, IP-Glasma, KLN

WNM: $\langle N_{pA} \rangle \sim N_{part}$

rapidity = 0



AB, V.Skokov, Phys. Rev. Lett. 111 (2013) 182301

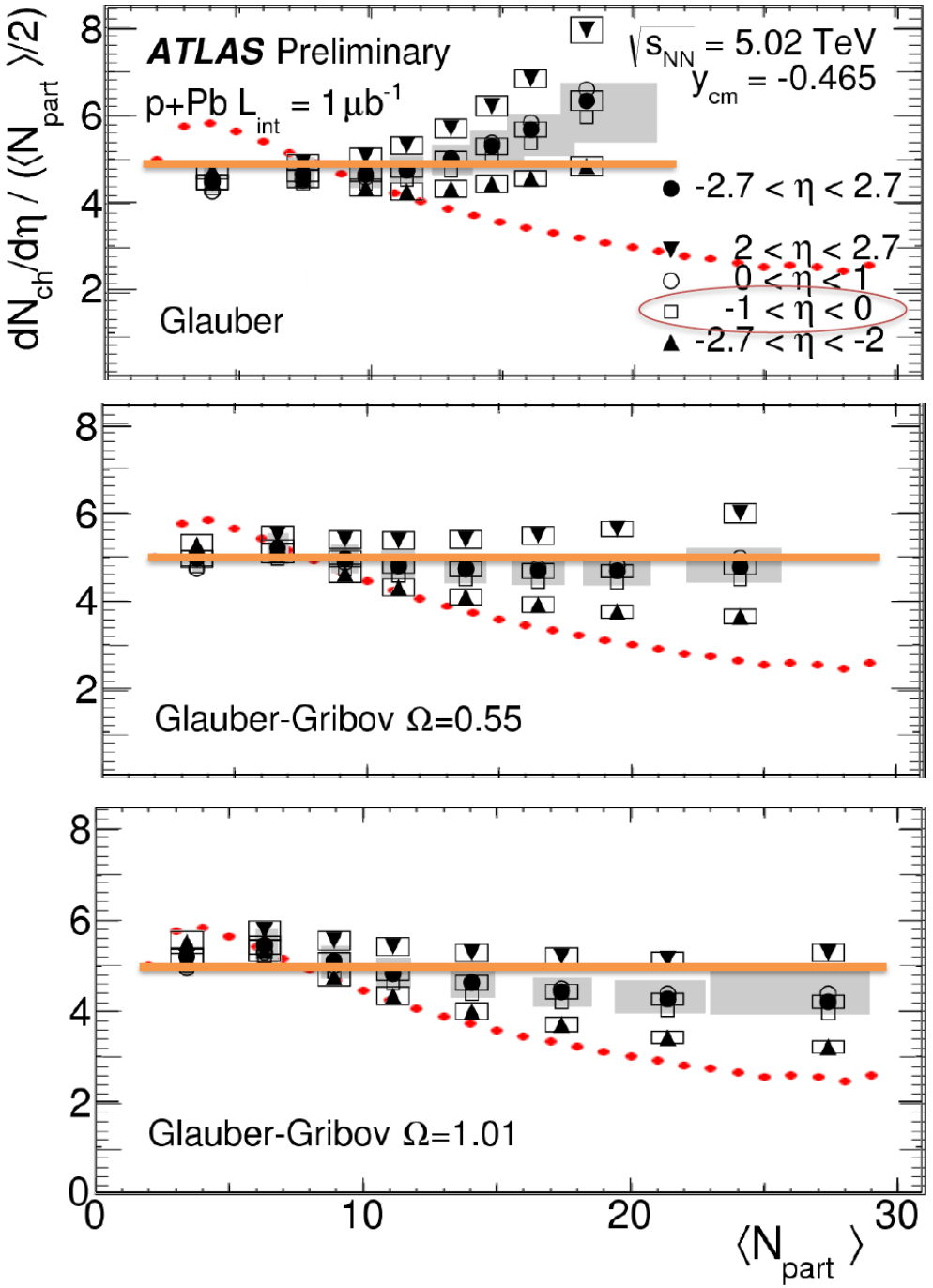
ATLAS preliminary data

WNM

CGC

Look at $-1 < \eta < 0$, the shaded bands

Preliminary data consistent with the WNM !

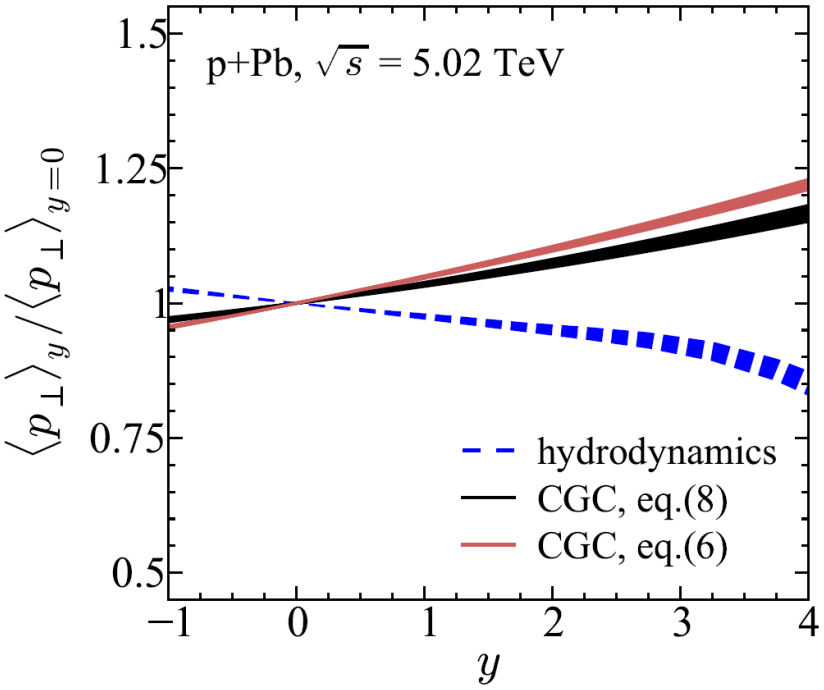


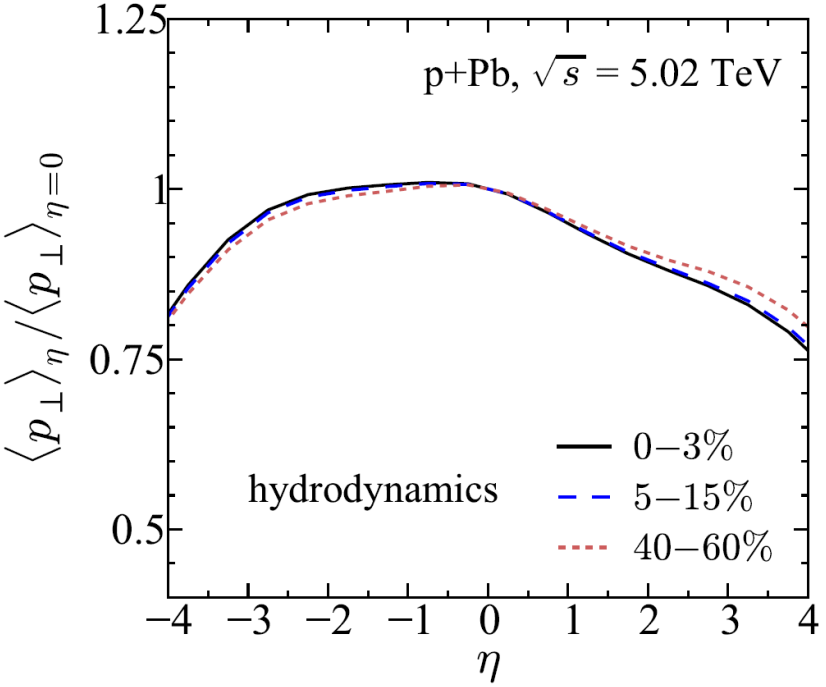
E.Shulga (ATLAS Coll.), talk at IS2013

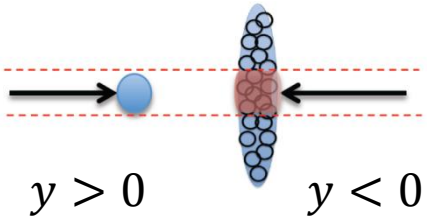
CGC vs. hydro

$\langle p_T \rangle$ versus η on proton side can help to distinguish

proton side, $y > 0$







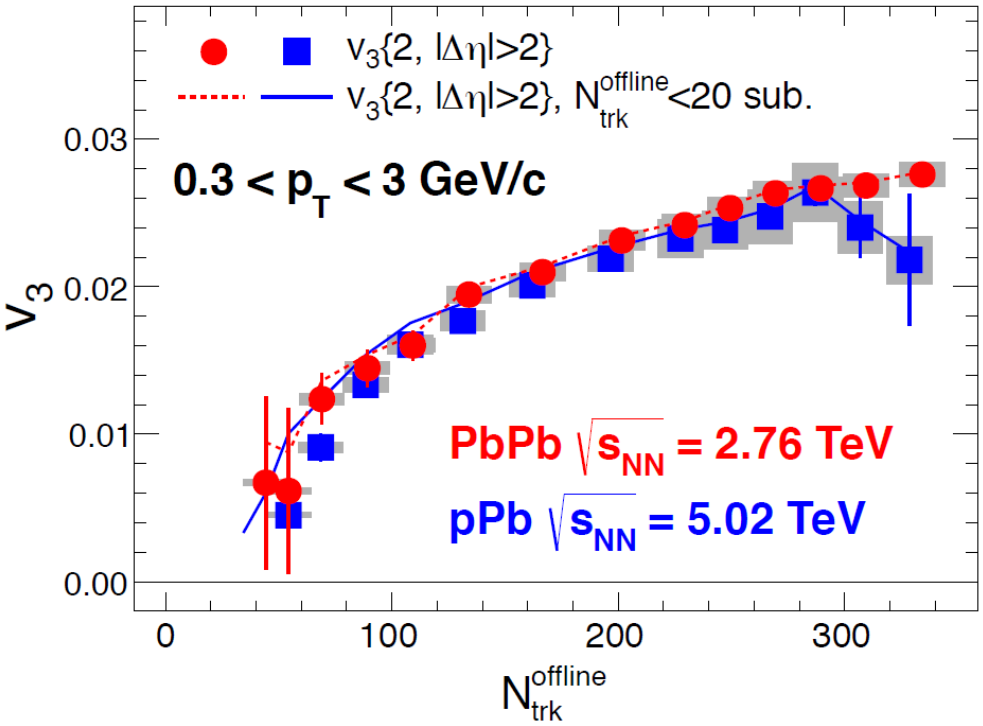
P.Bozek, AB, V.Skokov, arXiv:1309.7358 [hep-ph]

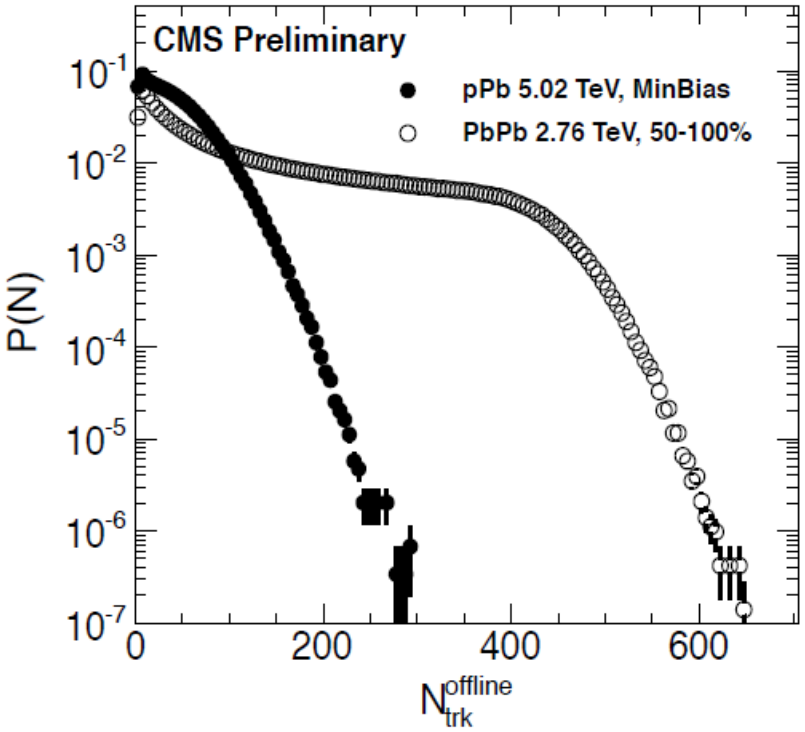
Conclusions

- surprising long-range (in rapidity) azimuthal collimation in p+p, p+Pb, d+Au collisions
- the more particles the stronger the effect
- hydrodynamics explains the data
- CGC explains the data
- the preliminary ATLAS data support the wounded nucleon model, what about CGC?
- CGC vs. hydro: $\langle p_T \rangle$ as a function of η can help

Backup slides

v_3 in p+Pb and Pb+Pb

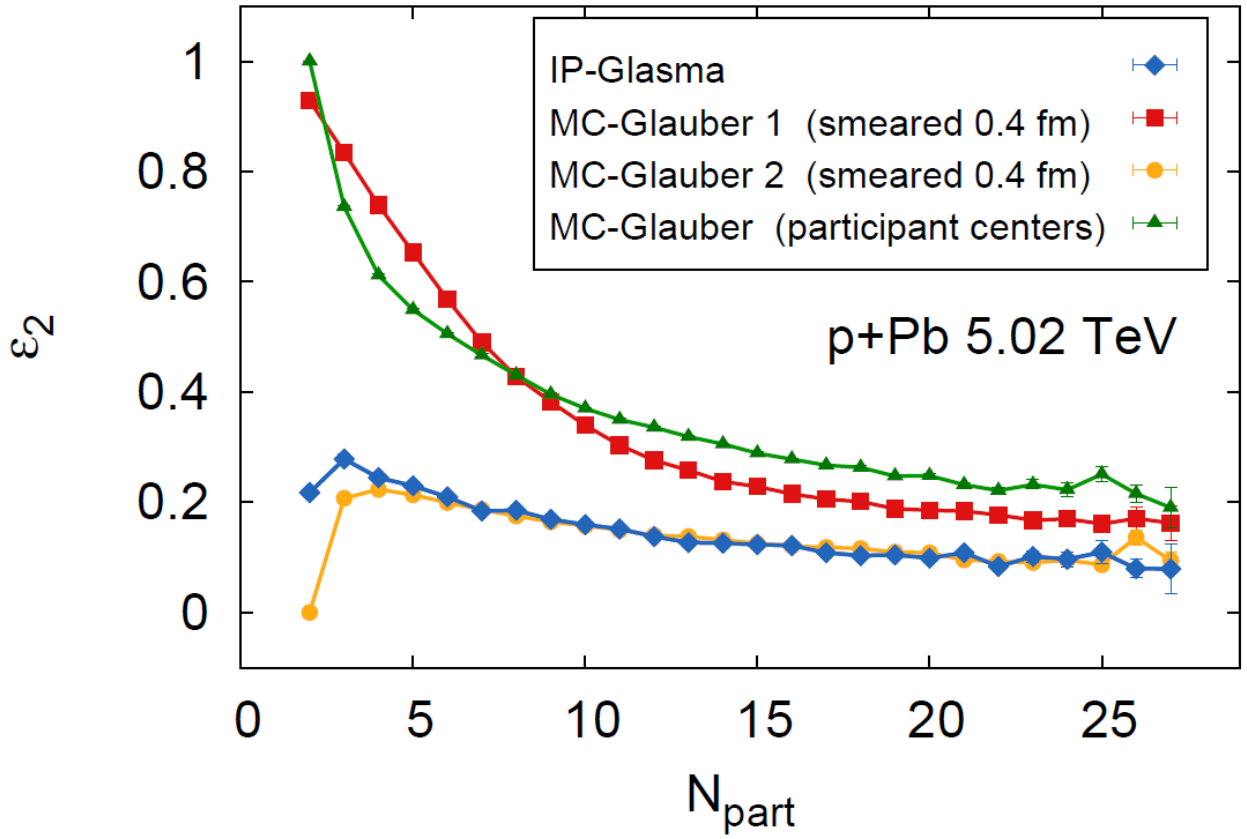




$\mathrm{N_{trk}}$ in $|\eta| < 2.4, p_T > 0.4$ GeV

Coincidence?

No control over initial conditions in p+A

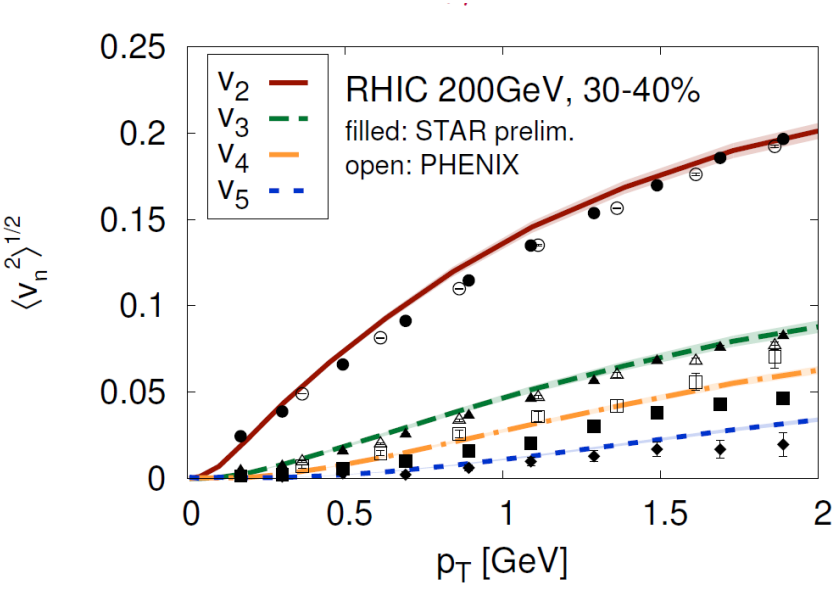


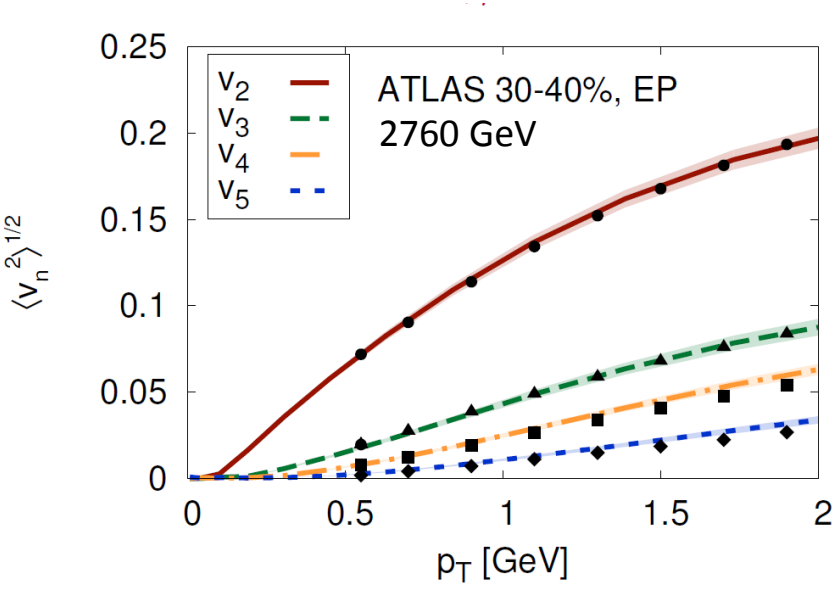
AB, B.Schenke, P.Tribedy, R.Venugopalan, PRC 87 (2013) 064906

Similar correlations are present in AA collisions

$$C_2(\Delta\varphi) \sim \sum_n \langle {v_n}^2 \rangle \cos(n\Delta\varphi)$$

At RHIC (Au+Au) and the LHC (Pb+Pb) hydro is very successful

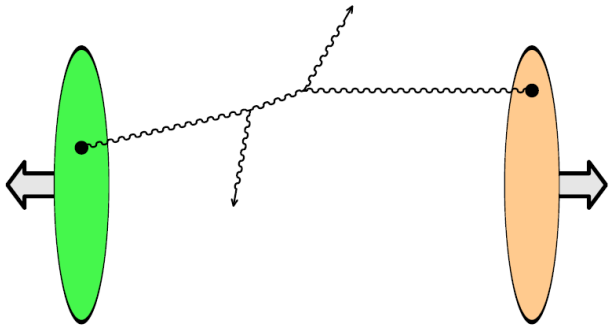




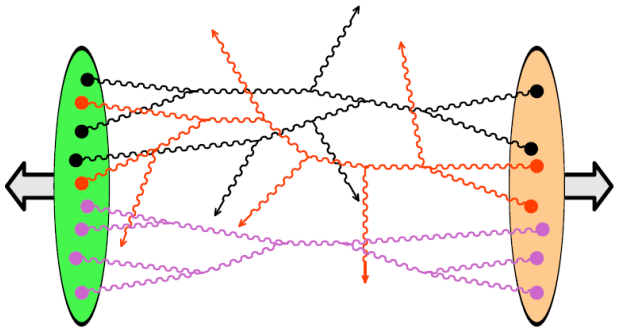
We need a non-zero viscosity,
$\eta/s \sim 0.1 - 0.2$

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan,
Phys.Rev.Lett. 110 (2013) 012302

CGC, multi-parton interactions are important



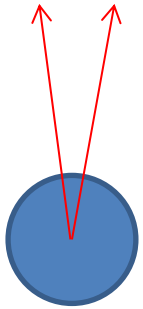
dilute system,
Feynman diagrams



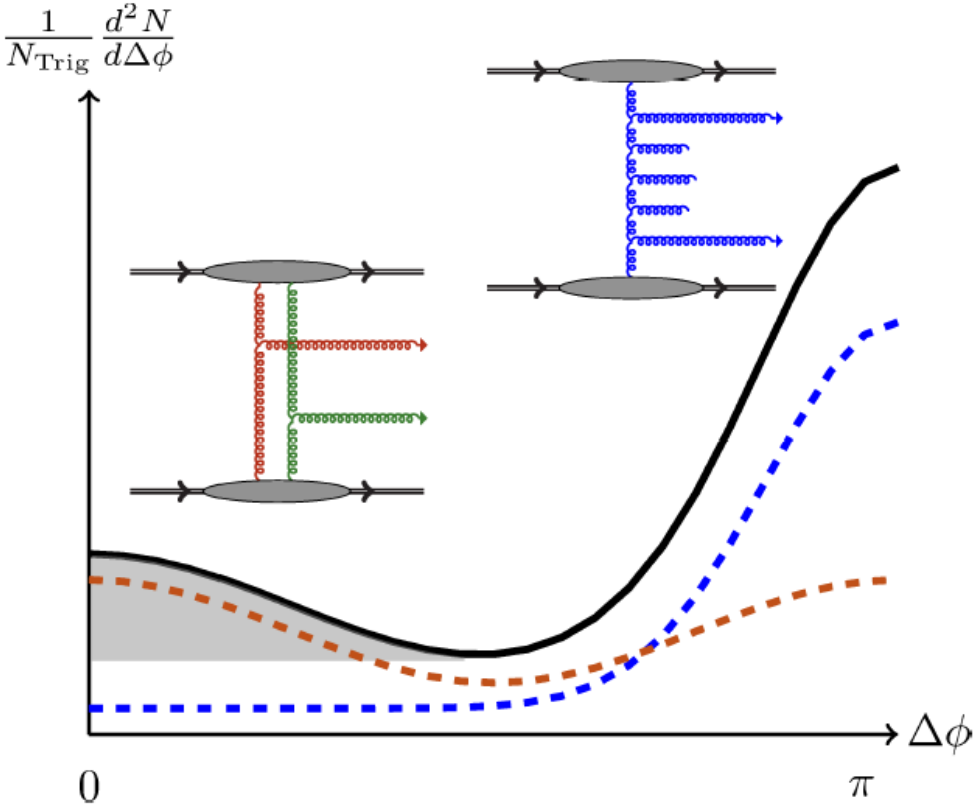
dense system,
multi-parton interactions

Multi-parton interactions lead to azimuthal collimation!

$$\Delta\varphi \sim 0$$



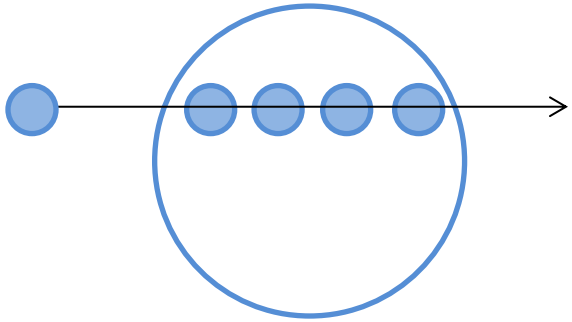
CGC calculation



- CGC can fit the data for p+p and p+A
- it is the initial state effect
- difficulty to obtain positive $\cos(3\Delta\varphi)$ (under investigation)

p+A collisions

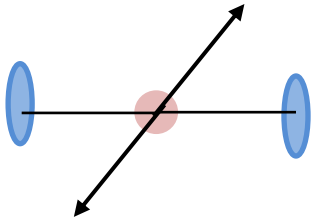
Number of collisions scaling:



$N_{coll} = 4$

$$\langle N_{pA} \rangle = \frac{\langle N_{pp} \rangle}{1} N_{coll}$$

Easy to understand in pQCD



pp

It works very well for <u>high</u> p_t particles, but not for low p_t

Transverse single-spin asymmetries and the "sign mismatch" crisis

Daniel Pitonyak

RIKEN BNL Research Center
Brookhaven National Lab, Upton, NY

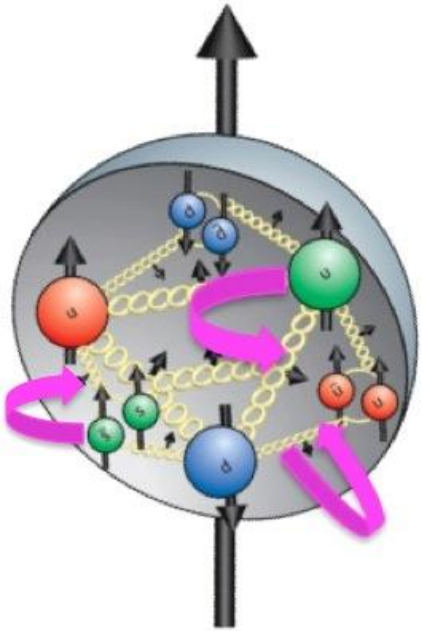
RBRC Scientific Review
October 31, 2013

Outline

- Introduction
- Single-spin asymmetries (SSAs)
  - SSAs in proton-proton collisions
  - SSAs in semi-inclusive deep-inelastic scattering (SIDIS)
  - The “sign mismatch” crisis and possible resolutions
- Summary and outlook

Introduction

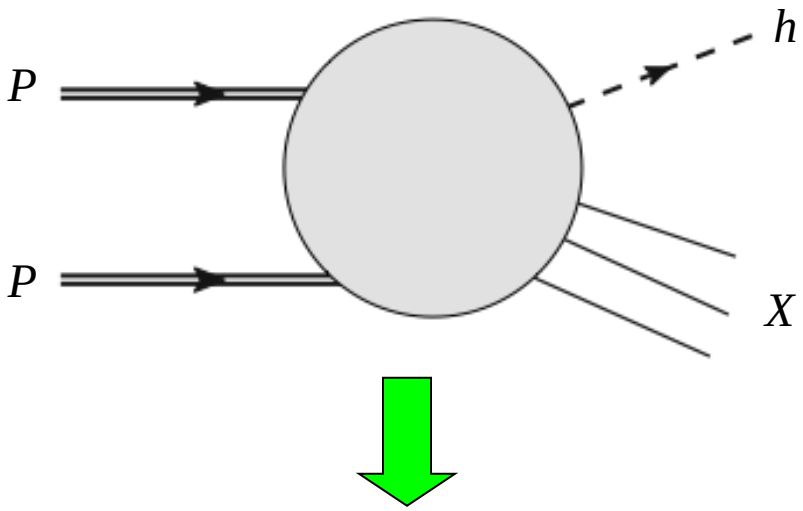
➢ Motivation for studying spin asymmetries



- Rich internal (spin) structure of hadrons
  - ➡ Study correlations between hadron spin and parton spins and orbital motion
- Extract PDFs and FFs through experiment
- Explore pQCD (collinear factorization, TMD factorization, resummation, etc.)

What do these observables tell us about perturbative and non-perturbative QCD dynamics?

- Basics of inelastic collisions



Fragmentation function (FF)

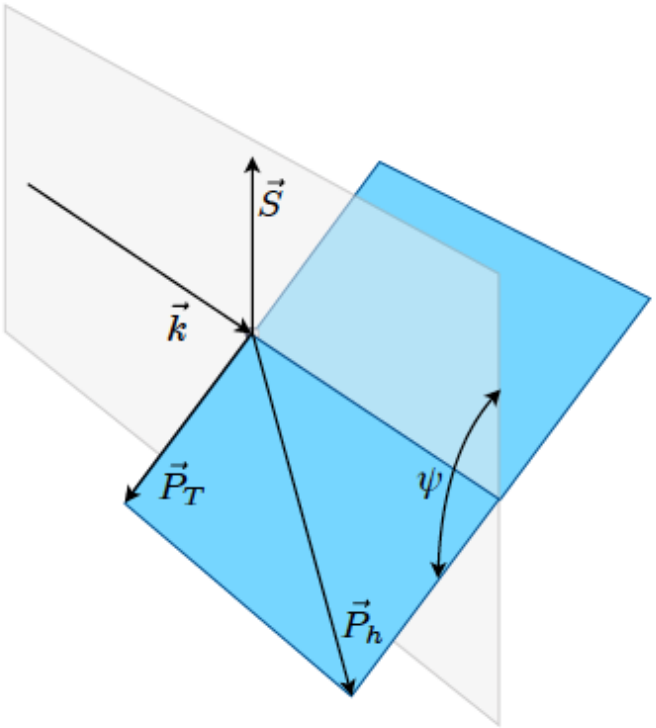
…rbative = expand in α_s (valid because of …ptotic freedom: $\alpha_s(Q) \rightarrow 0$ as $Q \rightarrow \infty$)

…ative = expansion in the strong coupling …T valid: extract from experiment, a model or in lattice QCD

Single-Spin Asymmetries (SSAs)

- SSAs in proton-proton collisons

$$A_N = \frac{d\sigma(\uparrow_y) - d\sigma(\downarrow_y)}{d\sigma(\uparrow_y) + d\sigma(\downarrow_y)}$$



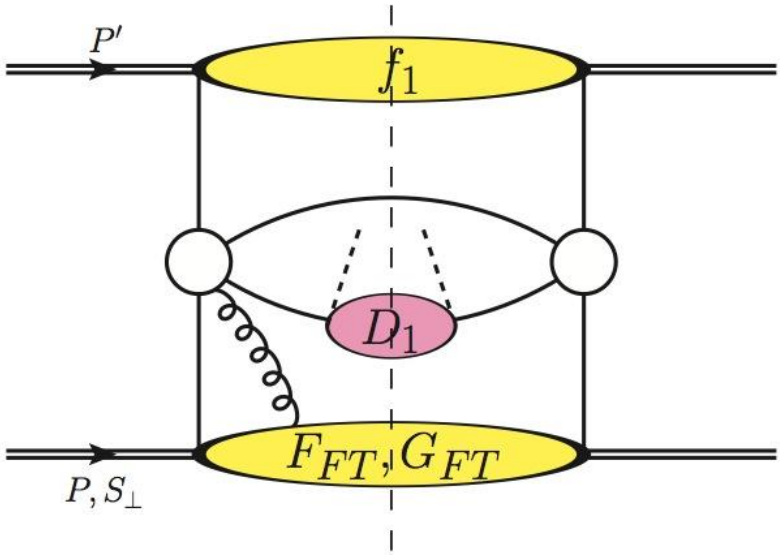
(Figure from Airapetian, et al. (2013))

$$d\sigma = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}$$

Collinear twist-3 approach

(Efremov and Teryaev (1982, 1985))

$P_{hT} >> \Lambda_{QCD}$



- T-odd effect ➡ need to generate an imaginary part ➡ soft-gluon pole (SGP) or soft-fermion pole (SFP) ➡ internal particle goes on-shell

- SGP term (Qiu and Sterman (1999), Kouvaris, et al. (2006)):

$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to h}(z) \int_{x'_{\min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z}\phi_{b/B}(x')$$
$$\times \sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{\ell s_T n\bar{n}}}{z\hat{u}}\right)\frac{1}{x}\left[T_{a,F}(x,x) - x\left(\frac{d}{dx}T_{a,F}(x,x)\right)\right] H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

Qiu-Sterman function

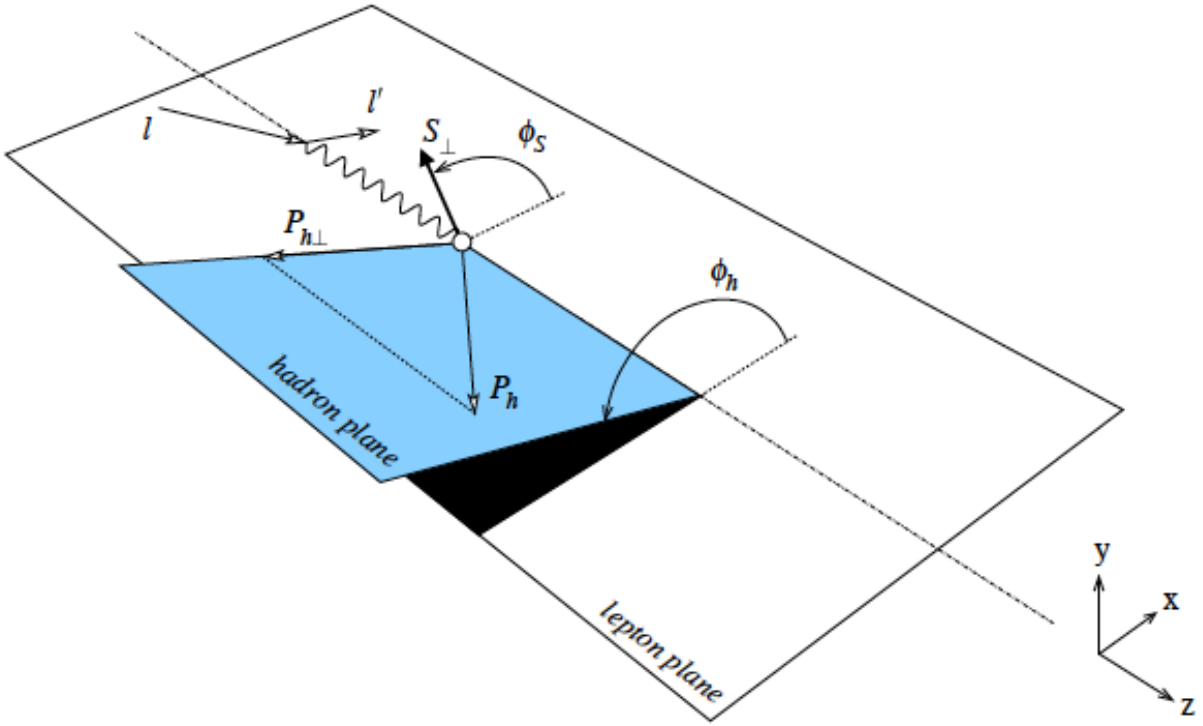
- SFP term (Koike and Tomita (2009)):

$$E_h \frac{d^3\Delta\sigma^{\rm SFP}}{dP_h^3} = \frac{\alpha_s^2}{S}\frac{M_N\pi}{2}\epsilon^{pnP_hS_\perp}\int_{z_{min}}^1 \frac{dz}{z^3}\int_{x'_{min}}^1 \frac{dx'}{x'}\int \frac{dx}{x}\frac{1}{x'S+T/z}\delta\left(x - \frac{-x'U/z}{x'S+T/z}\right)$$
$$\times\Bigg[\sum_{a,b,c}\left(G_F^a(0,x)+\widetilde{G}_F^a(0,x)\right)\left\{q^b(x')\left(D^c(z)\hat{\sigma}_{ab\to c}+D^{\bar{c}}(z)\hat{\sigma}_{ab\to\bar{c}}\right)\right.$$
$$\left.+q^{\bar{b}}(x')\left(D^c(z)\hat{\sigma}_{a\bar{b}\to c}+D^{\bar{c}}(z)\hat{\sigma}_{a\bar{b}\to\bar{c}}\right)\right\}$$
$$+\sum_{a,b}\left(G_F^a(0,x)+\widetilde{G}_F^a(0,x)\right)\left(q^b(x')D^g(z)\hat{\sigma}_{ab\to g}+q^{\bar{b}}(x')D^g(z)\hat{\sigma}_{a\bar{b}\to g}\right)$$
$$+\sum_{a,c}\left(G_F^a(0,x)+\widetilde{G}_F^a(0,x)\right)G(x')\left(D^c(z)\hat{\sigma}_{ag\to c}+D^{\bar{c}}(z)\hat{\sigma}_{ag\to\bar{c}}\right)$$
$$+\sum_{a}\left(G_F^a(0,x)+\widetilde{G}_F^a(0,x)\right)G(x')D^g(z)\hat{\sigma}_{ag\to g}\Bigg]$$

$$T_F \sim G_F \sim F_{FT}$$
$$\tilde{T}_F \sim \tilde{G}_F \sim G_{FT}$$

- SSAs in semi-inclusive deep-inelastic scattering (SIDIS)

$$A_{UT}^{sin(\phi_h-\phi_s)} = \frac{\int d\phi_h d\phi_S \, \sin(\phi_h - \phi_S)\, d\sigma}{\int d\phi_h d\phi_S \, d\sigma}$$



(Figure from Bacchetta, et al. (2007))

Sivers function

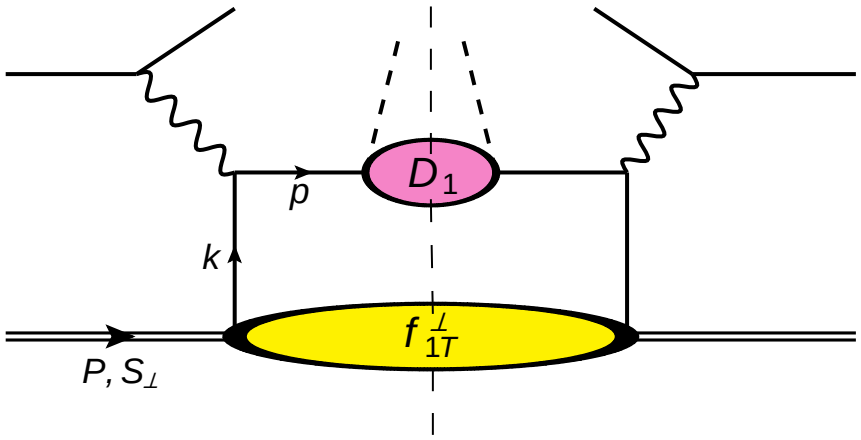
$$A_{UT}^{sin(\phi_h-\phi_s)} = \frac{w(k_\perp)\, f_{1T}^{\perp,q}(x,\vec{k}_\perp) \otimes D_1^{h/q}(z,\vec{p}_\perp)}{f_1^q(x,\vec{k}_\perp) \otimes D_1^{h/q}(z,\vec{p}_\perp)}$$

Sivers asymmetry

TMD approach

(Sivers (1990, 1991), Collins (1993))

$Q >> P_{hT} \geq \Lambda_{QCD}$



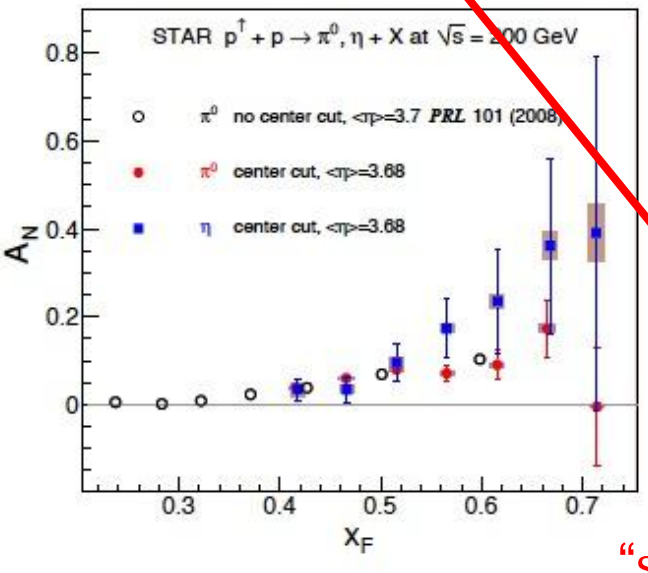
- T-odd effect ➡ imaginary phase is generated by “Wilson line”
  ➡ multiple re-interactions of the quark with the target remnants

➢ "Sign mismatch" crisis and possible resolutions

$p^{\uparrow} p \to h\, X$

Kouvaris, et al. (2006)
KQVY input

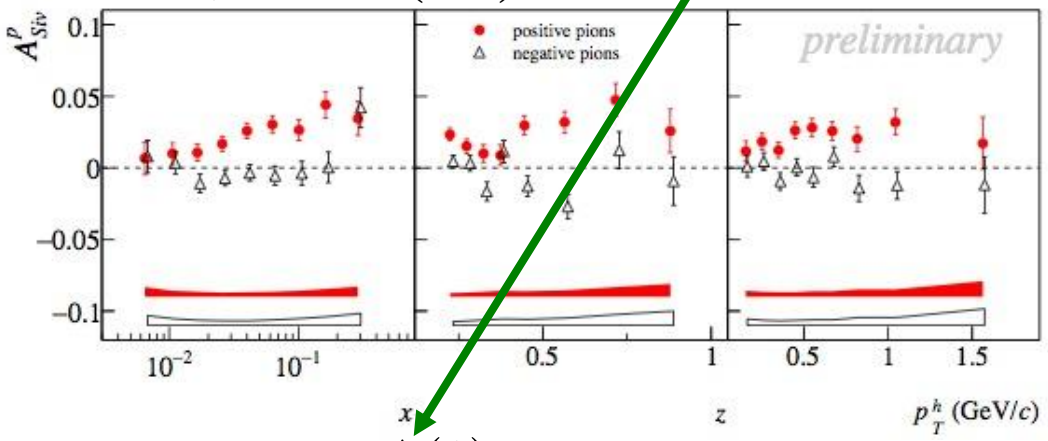
RHIC, STAR (2012)



$\ell N^{\uparrow} \to \ell' h\, X$

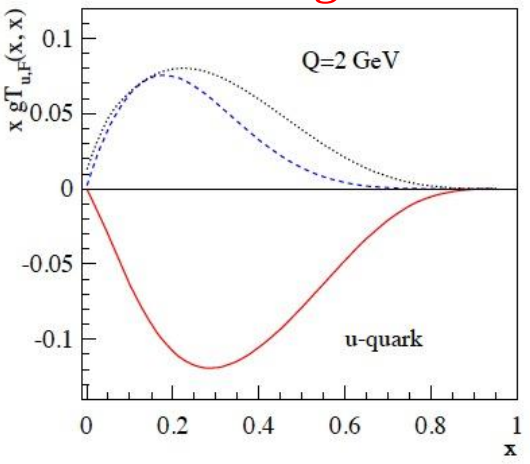
Anselmino, et al. (2008)
Sivers input

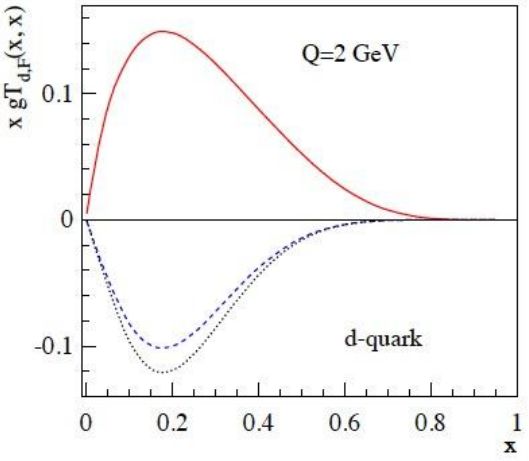
CERN, COMPASS (2013)



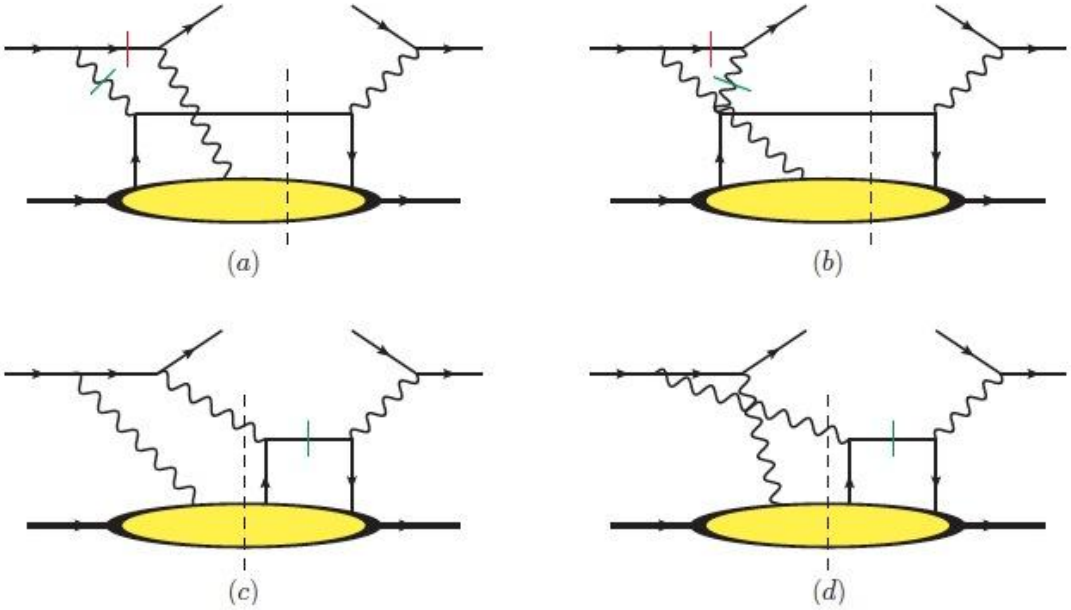
$$\pi\, F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$$

"sign mismatch" (Kang, et al. (2011))





- SSA in inclusive DIS (Metz, DP, Schaefer, Schlegel, Vogelsang, Zhou, PRD **86** (2012))

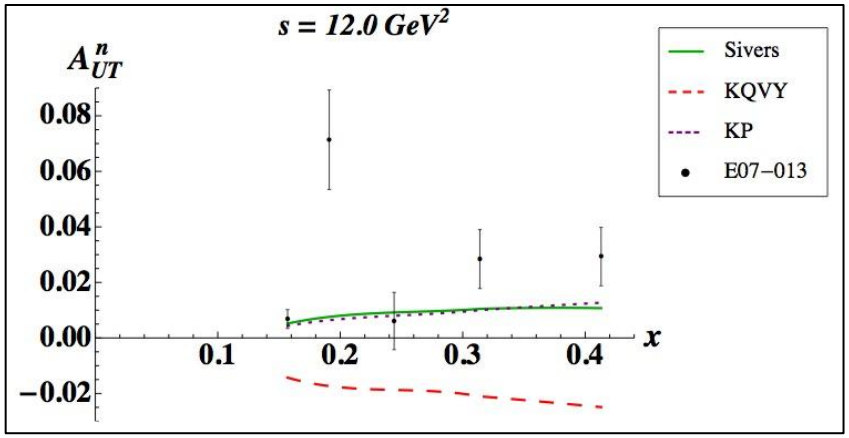


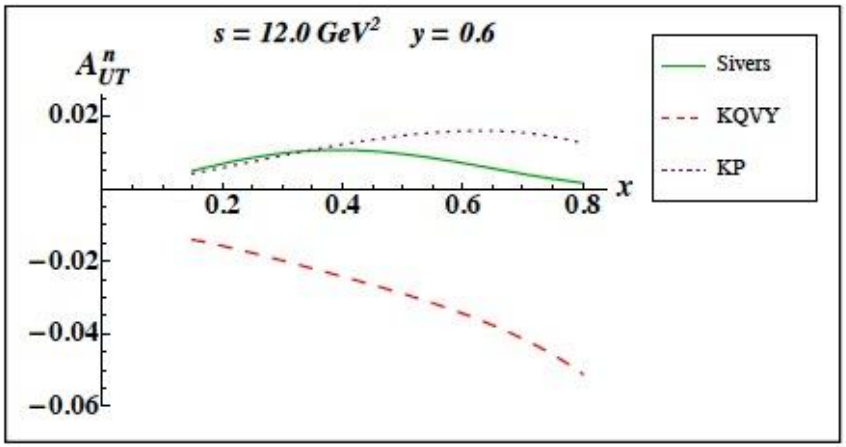
$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{8\pi\alpha_{em}^2 xy^2 M}{Q^8} \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\left(2+\frac{\hat{u}}{\hat{t}}\right)\varepsilon^{S_N Pkk'} \sum_q e_q^2 x\tilde{F}_{FT}^{q/N}(x,x)$$

$$\text{with} \quad \tilde{F}_{FT}(x,x) = F_{FT}(x,x) - x\frac{d}{dx}F_{FT}(x,x)$$

(Work has also been done on both photons coupling to the same quark: Metz, Schlegel, Goeke (2006); Afanasev, Strikman, Weiss (2007); Schlegel (2012))

- Neutron SSA:





Sivers input agrees reasonably well with the preliminary JLab data

➡ Node in k_T for the Sivers function can be ruled out/Also node in x is disfavored from proton data from HERMES (see also Kang and Prokudin (2012))

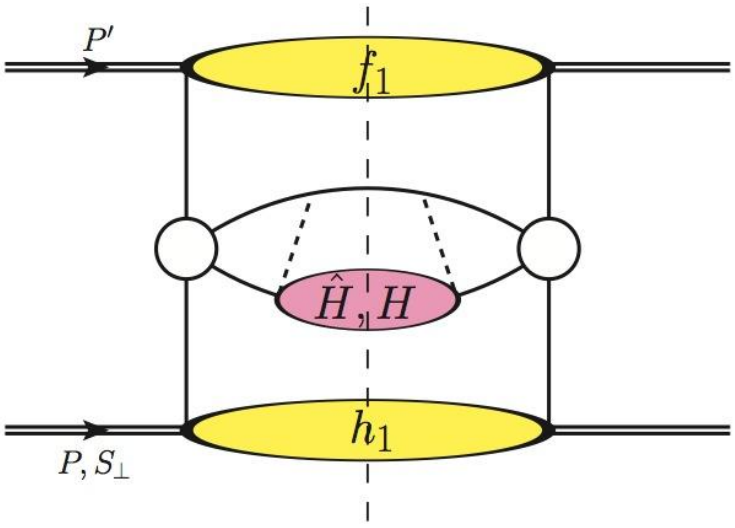
➡ FIRST INDICATION that the Sivers effect is intimately connected to the re-scattering of the active parton with the target remnants (PROCESS DEPENDENT)

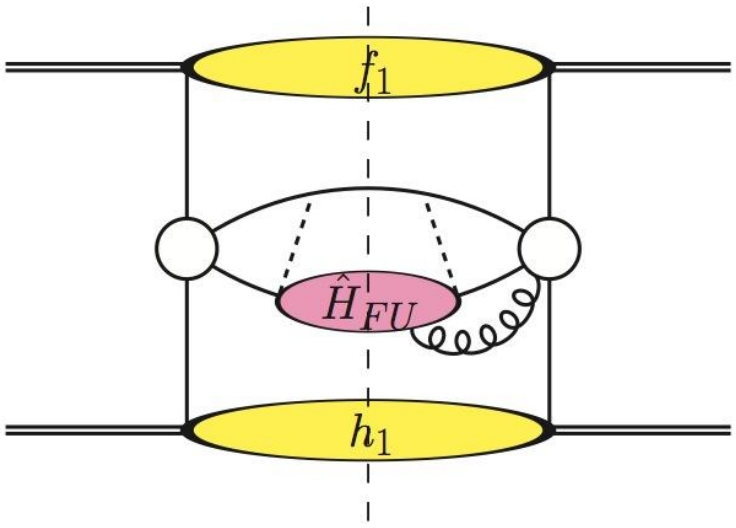
KQVY input gives the wrong sign ➡ SGP contribution on the side of the transversely polarized incoming proton cannot be the main cause of the large SSAs seen in pion production (i.e., T_F (x,x) term)

$$d\sigma = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)}$$
$$+ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)}$$
$$+ \tilde{H}' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}$$

→ Negligible (Kanazawa and Koike (2000))

- Collinear twist-3 fragmentation term:
  - Could at the very least give a contribution comparable to SGP term (Kang, Yuan, Zhou (2010); Kang and Yuan (2011); Anselmino, et al. (2012))
  - Calculation of *qq* and *qgq* correlator terms (Metz and DP, PLB **723** (2013))





$$\frac{P_h^0 d\sigma_{pol}}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\,\epsilon_{\perp\mu\nu}\,S_\perp^\mu P_{h\perp}^\nu \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \frac{1}{-x\hat{u} - x'\hat{t}}$$

$$\times\ \frac{1}{x}\,h_1^a(x)\,f_1^b(x') \left\{ \left(\hat{H}^{C/c}(z) - z\frac{d\hat{H}^{C/c}(z)}{dz} \right) S_{\hat{H}}^i + \frac{1}{z}\,H^{C/c}(z)\,S_H^i \right.$$

$$\left. + 2z^2 \int \frac{dz_1}{z_1^2}\,PV \frac{1}{\frac{1}{z} - \frac{1}{z_1}}\,\hat{H}_{FU}^{C/c,\Im}(z, z_1)\,\frac{1}{\xi}\,S_{\hat{H}_{FU}}^i \right\}$$

First time we have a complete pQCD result for this term

"Derivative term" has been calculated previously (Kang, Yuan, Zhou (2010))

Derivative and non-derivative piece combine into a "compact" form as on the distribution side

Important to determine the impact of *qgq* fragmentation correlator terms

Cannot rule out SFPs (Koike and Tomita (2009); Kanazawa and Koike (2010)) or tri-gluon correlators (see, e.g., Koike and Yoshida (2011, 2012)) on the distribution side, but they are unlikely to resolve the "sign mismatch" issue

Summary and outlook

- "Sign mismatch" ➡ still do not fully understand the mechanism behind the large transverse SSAs seen in hadron production from *pp* collisions
- Global analysis involving several reactions will be needed in order to extract the collinear twist-3 distribution and fragmentation functions in $p^{\uparrow}p \to hX$

  ➡ Measurement of $p^{\uparrow}p \to jet\,X$ by the AnDY Collaboration (Bland, et al. (2013))

  ➡ Measurements of Drell-Yan in $p^{\uparrow}p$ and $p^{\uparrow}p \to \gamma\,X$ at RHIC (also DY experiment planned at COMPASS for $\pi p^{\uparrow}$)

  ➡ Large $P_{h\perp}$ measurement of Sivers and Collins asymmetries in SIDIS should also be possible at JLab12, COMPASS, or a future EIC

  ➡ HERMES (Airapetian, et al. (2013)) has recently published data on $ep^{\uparrow} \to hX$:

  "simple" process that allows one to explore the collinear twist-3 framework (Gamberg, Kang, Metz, DP, Prokudin, work in progress)

Computing Group

Round 1

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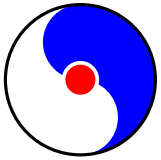
Computing Group Overview

Taku Izubuchi



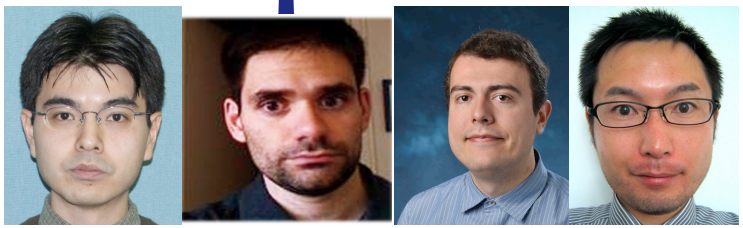
RIKEN BNL
Research Center

BROOKHAVEN
NATIONAL LABORATORY

RIKEN

RBRC Scientific Review Committee Meeting, BNL, Oct 31, 2013

Computing Group



- Group Leader : Taku Izubuchi (BNL)
- University Fellows :
  Brian Tiburzi (CCNY) Ethan Neil (Colorado)
- Fellow : Tomomi Ishikawa
- PostDocs : Christopher Kelly
  (Foreign PostDoc, FPR)
  Sergey Syritsyn (FPR)



(past PDs) Christoph Lehner (FPR) → BNL staff member
Eigo Shintani (in-house PD) → Mainz PD
(T. Misumi → Univ. Keio faculty)

- Visiting Scientists/Students :

Michael Abramczyk (Connecticut)
Yasumichi Aoki (Nagoya)
Thomas Blum (Connecticut)
Chulwoo Jung (BNL)
Hyung-Jin Kim (BNL, SciDAC)
Meifeng Lin (Argonne→BNL CSC)
Robert Mawhinney (Columbia)
Shigemi Ohta (KEK)

RBC/UKQCD Collaborations 2013

- BNL HEP Theory
  Chulwoo Jung, Taku Izubuchi, Taichi Kawanai, Hyung-Jin Kim, Christoph Lehner, Amarjit Soni
- RIKEN-BNL Research Center
  Tomomi Ishikawa, Taku Izubuchi
  Christopher Kelly (Eigo Shintani),
  Sergey Syritsyn Shigemi Ohta
- Columbia University
  Ziyuan Bai, Norman Christ, Xu Feng,
  Luchang Jin, Jasper Lin, Robert Mawhinney,
  Greg McGlynn, David Murphy,
  Hantao Yin, Jianglei Yu, Daiqian Zhang
- University of Connecticut
  Tom Blum
  Michael Abramczyk
- Boston University
  Oliver Witzel
- BNL Computational Science Center
  Meifeng Lin

17 current students,
~30 PhD theses since 2005

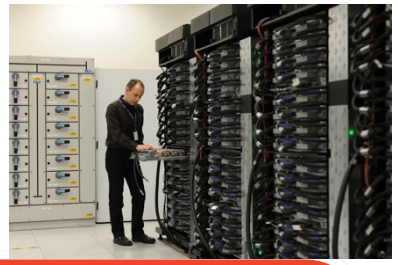
- + UKQCD Collaboration (2005-)
  - Univ. of Edinburgh
    4 faculty, 1 PostDocs, 1+3 students
  - Univ. of Southampton
    3 faculty, 3 Postdoc, 4 students
- + JLQCD (2012- , collaborating for physics measurement methods)
  - KEK, Osaka Univ
- + LHPC (2013-, collaboration for Nucleon structure) MIT, New Mexico, William&Mary,





RIKEN RICC ('09) ~ 110 Tflops peak

BG/Q('12) @Edinburgh, KEK~ 2 x 1.2 Pflops peak

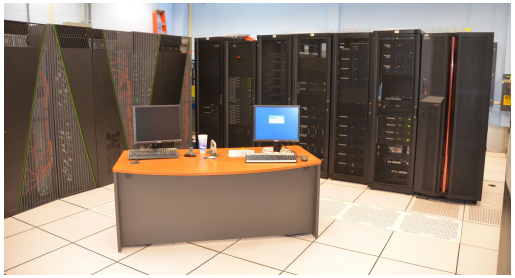


RBRC Computing

RIKEN/ Nishina

BNL HEP/NP/LGT

US Universities (Columbia Connecticut CCNY, Colorado, Arizona)

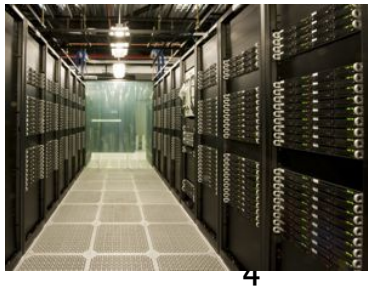


QCDCQ('12) ~ 700Tflops peak

RIKEN-BNL Research Center

UKQCD (Edinburgh Southampton) JLQCD (KEK)

FNAL/Jlab ~ 160 Tflops peak



BNL CSC (HPC Code Center) / ITD

USQCD



ANL Mira ('12) ~10 Pflops peak

Physics highlights 2013

- Physical point (Mpi=135 MeV) simulation using chiral lattice quarks
- Sub-percent accuracy for many fundamental/basic quantities (hadron mass, decay constants, B_K, K_{l3}) [R. Mawhinney's talk]
- The first signal of muon g-2 light-by-light [T. Blum's talk]
- $K \to \pi\pi$ I=2 & 0, Emerging explanation for $\Delta I=1/2$ rule
  [R. Mawhinney, C. Kelly's talks]
- The first complete K_L-K_S mass difference from 4 point function
  [N. Christ's talk]
- CKM Heavy Flavor physics [T. Ishikawa's talk]
  PhySyHCAl
  (Computer Algebra system for perturbation by C. Lehner)

- Nucleon physics :
  Electromagnetic properties [B. Tiburzi's talk]
  Form factors & structure functions [S. Syritsyn's talk]
  Electric Dipole Moments [This talk]
- Beyond the Standard Model [E. Neil's talk]

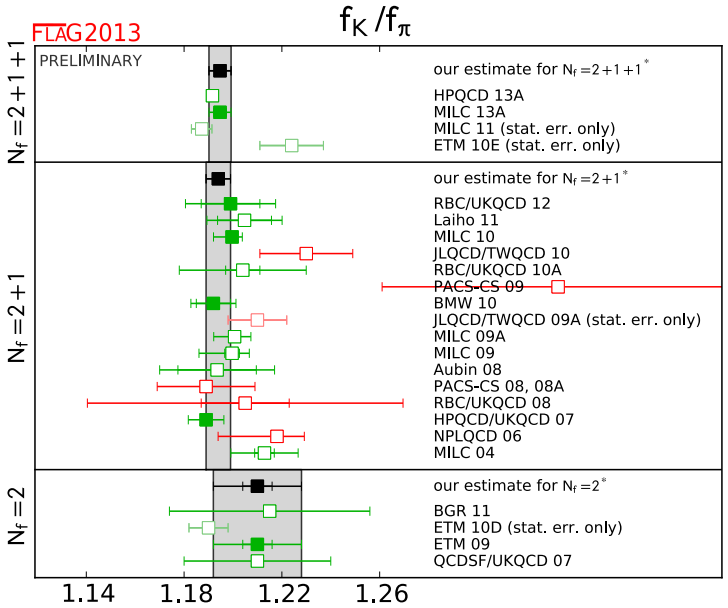
- USQCD half rack Blue Gene / Q is installed,
  total 3.5 racks, 700 Tflops peak at BNL.
- Large production use of new algorithms,
  All Mode Averaging (AMA) , ~ 10x speedup, or more, in physics measurements

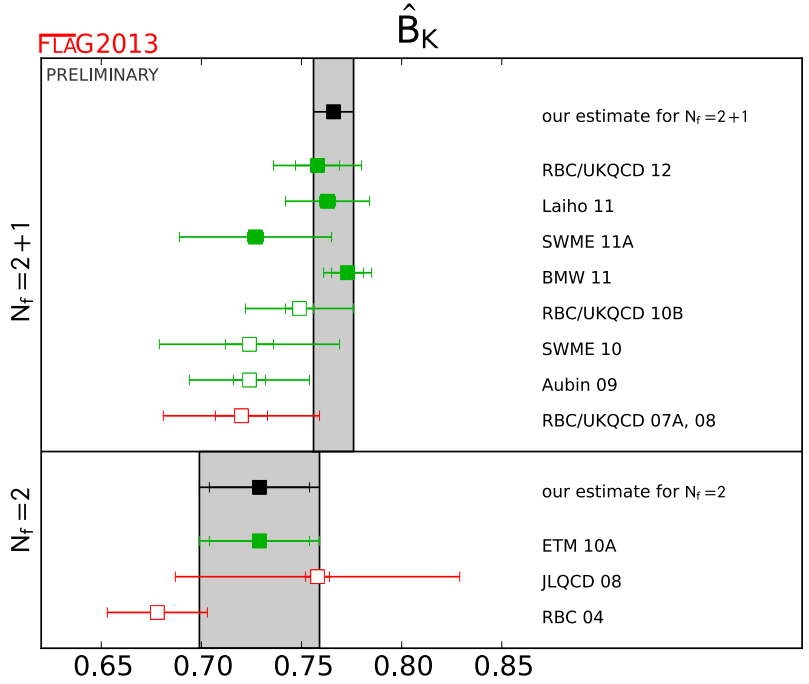
Sub-percent accuracy on Physical point [R. Mawhinney's talk]

- now adding on-physical point (M_π=135 MeV), a^{-1} = 1.7 and 2.4 GeV, V~(5.5 fm)^3 !

$$f_\pi/f_K = 1.199(12)(14) \quad [\text{RBC/UKQCD 12}]$$
$$\Longrightarrow 1.195(5)(?) \quad \text{Preliminary } [\text{RBC/UKQCD 13}]$$

$$N_f = 2+1 : \hat{B}_K = 0.766(10) \quad [\text{FLAG13}]$$
$$\Longrightarrow 0.754(4) \quad \text{Preliminary } [\text{RBC/UKQCD 13}]$$





$(g\text{-}2)_\mu$ [T.Blum's talk]

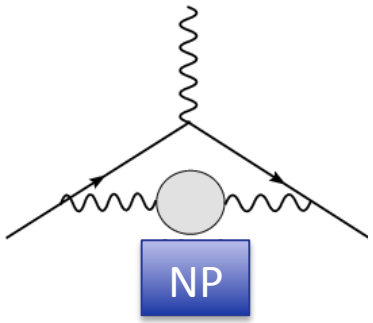
$$a_e^{\mathrm{EXP}} = (11\ 596\ 521.807\ 6 \pm 0.0027) \times 10^{-10}$$
$$a_\mu^{\mathrm{EXP}} = (11\ 659\ 208.9 \pm 6.3) \times 10^{-10}$$

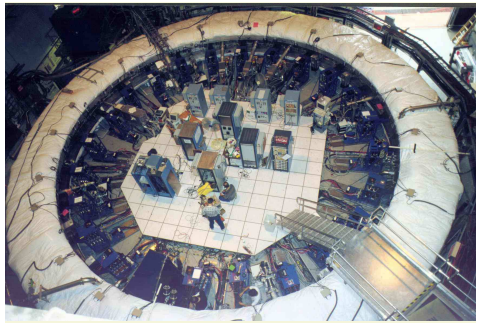
$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10} \quad [3.3\sigma]$$

$$(a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (25.0 \pm 8.6) \cdot 10^{-10} \quad [2.9\sigma]$$

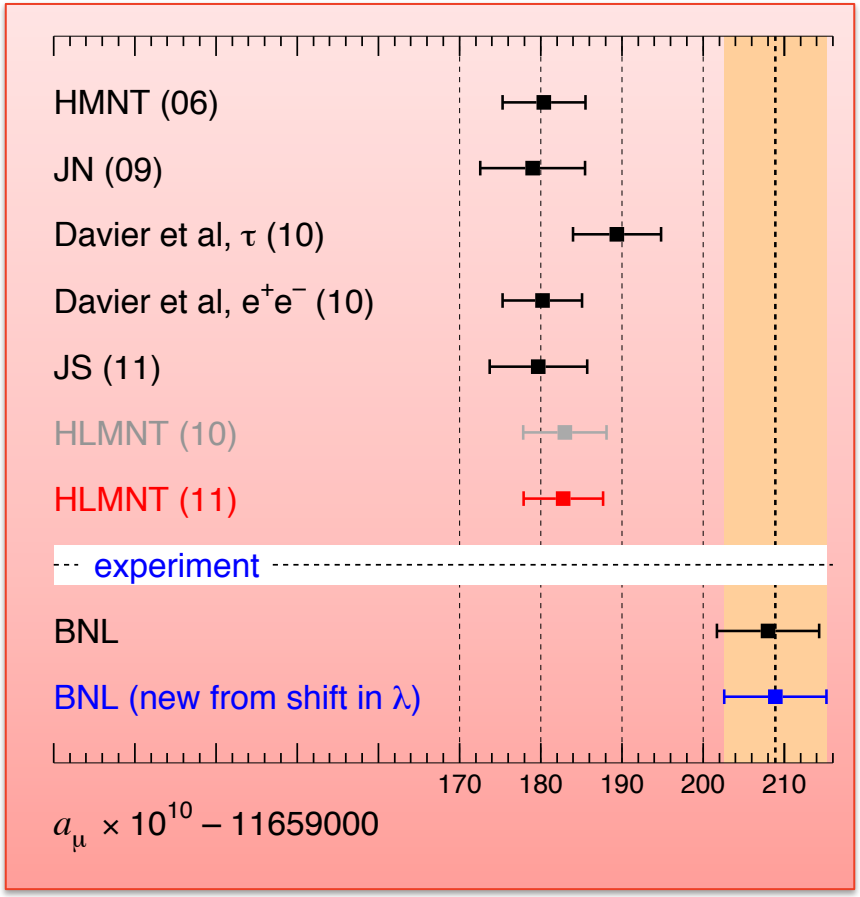
- ~ 3 σ discrepancy
- Hadronic uncertainties ?

  New Physics ?



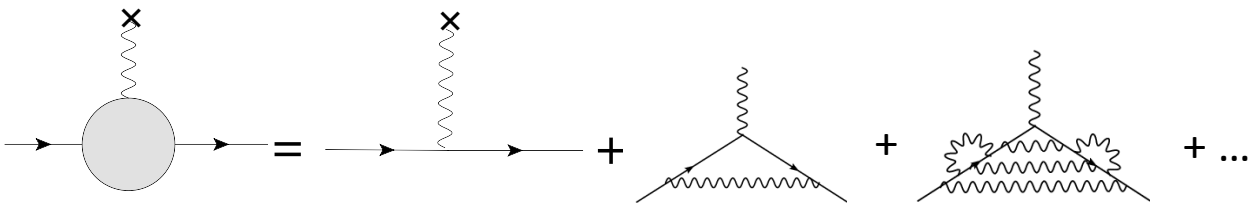


[K. Hagiwara et al., J. Phys. G 38, 085003 (2011)]

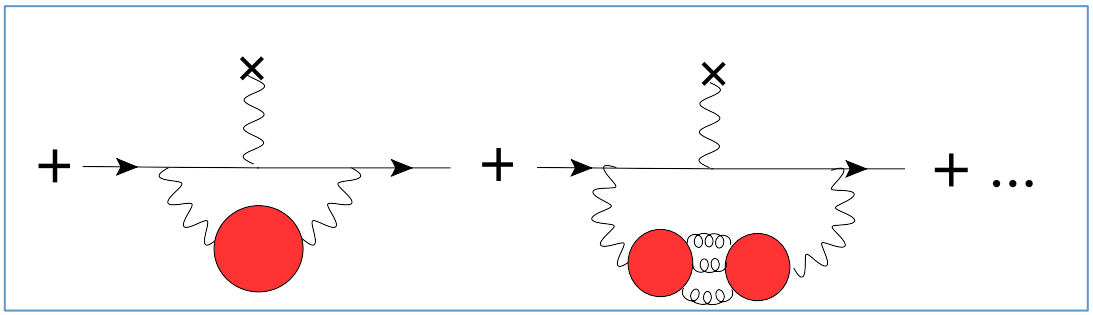


Hadronic contributions for $(g-2)_\mu$

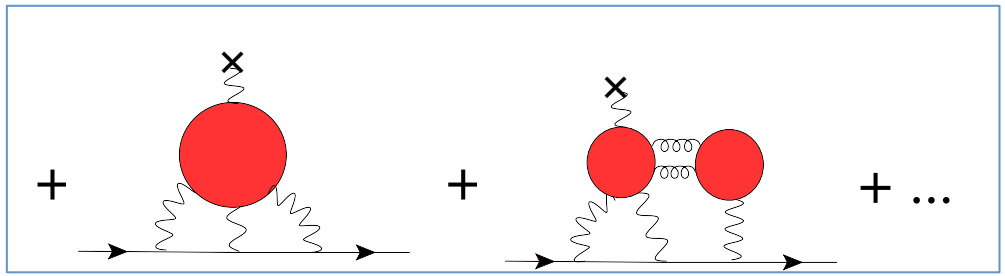
- SM Theories



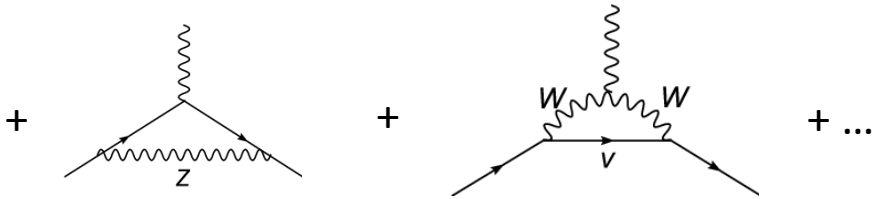
QED (5-loop)
Aoyama et al.
PRL109,111808 (2012)



Hadronic vacuum polarization (HVP)



Hadronic light-by-light (Hlbl)

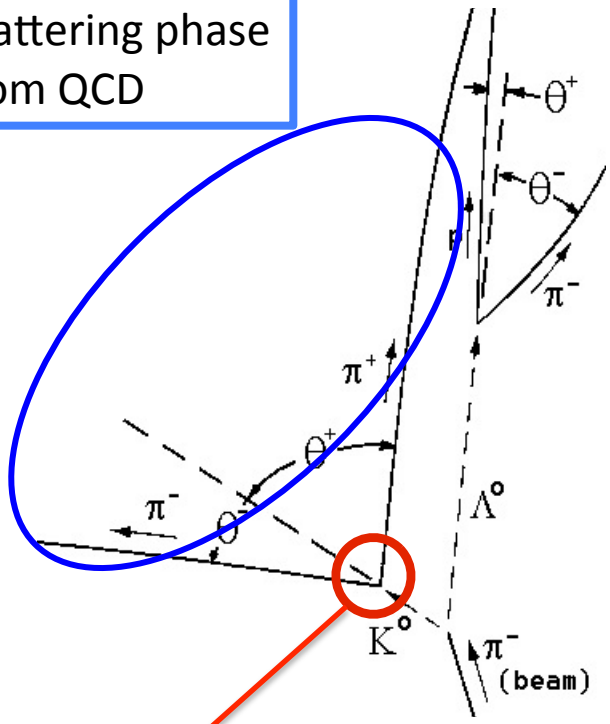


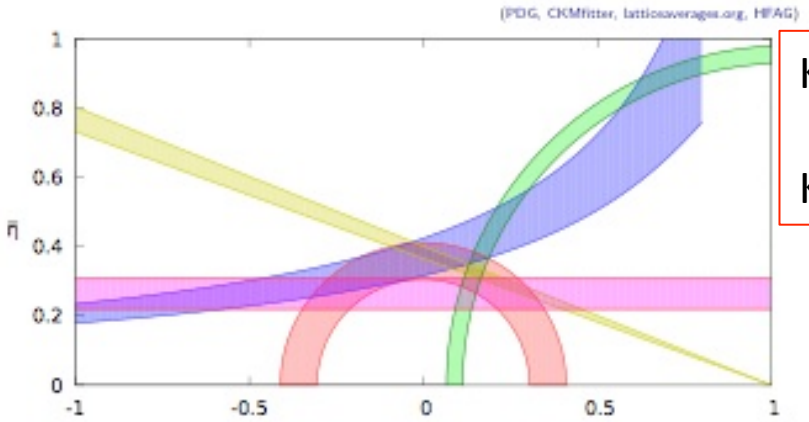
Electroweak (EW)
Knecht et al 02
Czarnecki et al. 02

K → π π decay amplitude
[RBC/UKQCD]

- 50 years awaited theoretical calculation
  [1964 Cronin-Fitch, Nobelprize
  1999 NA48@CERN, KTeV@FNAL]
- Provide a new constraint on CKM Unitarity

π π final state scattering phase from QCD

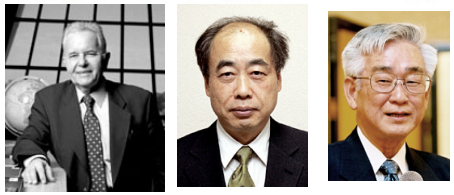




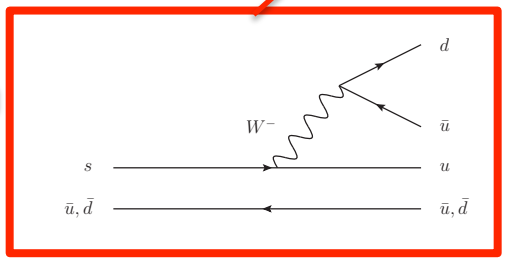
$K_L \rightarrow \pi\pi\pi$ (CP even)

$K_S \rightarrow \pi\pi$ (CP odd)

Δ I = ½ rule
ε' / ε

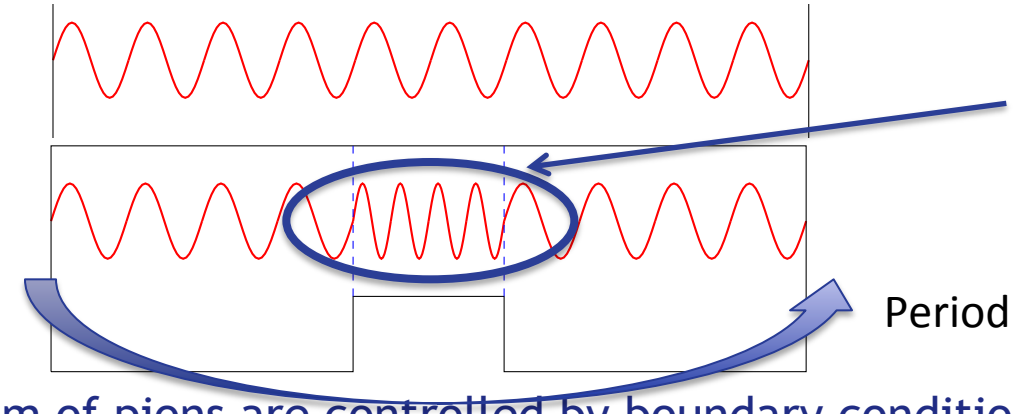


Electro-Weak (CKM) phase
Vus V*ud, Vts V*td

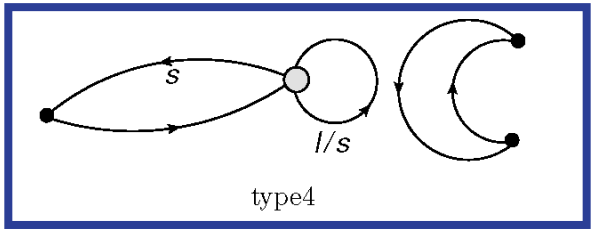


$K \to \pi\pi$ decay on lattice
[C. Kelly's talk]

- Relates energy on finite volume $E_{\pi\pi}(V)$ to phase shift δ to obtain complex Amp($K \to \pi\pi$) = $|A_I| e^{i\delta_I}$ (Luscher, Lellouch-Luscher)



- Momentum of pions are controlled by boundary condition
  → anti-periodic b.c for down quark in I=2, or G-parity b.c. for I=0
- Mixing and Renormalization of operator is done using non-perturbative renormalization (NPR)
- Chiral Symmetry is curtail
- I=2 channel is under control, I=0 is still a challenge due to disconnected diagrams.



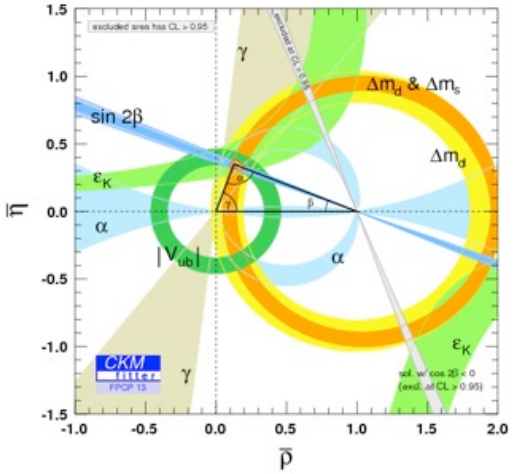
CKM and heavy flavor
[T. Ishikawa's talk]

- Gold-plated "lattice" process

$\mathbf{V_{ud}}$ $\pi \to l\nu$	$\mathbf{V_{us}}$ $K \to l\nu$ $K \to \pi l\nu$	$\mathbf{V_{ub}}$ $B \to \pi l\nu$
$\mathbf{V_{cd}}$ $D \to l\nu$ $D \to \pi l\nu$	$\mathbf{V_{cs}}$ $D_s \to l\nu$ $D \to Kl\nu$	$\mathbf{V_{cb}}$ $B \to Dl\nu$ $B \to D^* l\nu$
$\mathbf{V_{td}}$ $B_d \leftrightarrow \bar{B}_d$	$\mathbf{V_{ts}}$ $B_s \leftrightarrow \bar{B}_s$	$\mathbf{V_{tb}}$

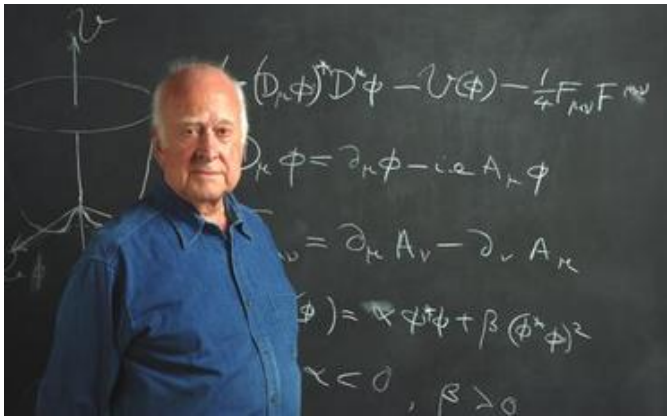
- 1 hadron in the initial state, 0 or 1 hadron in the final state
- stable hadrons (or narrow, far from threshold)
- controlled chiral extrapolation

- Constraints to the CKM unitary triangle
  - overconstrain ⟶ unveiling NP
  - b quark is suitable for studies of the limits of the SM and in searches in BSM.
    (sufficiently heavy to have a huge number of decay modes, sufficiently light to produce many)

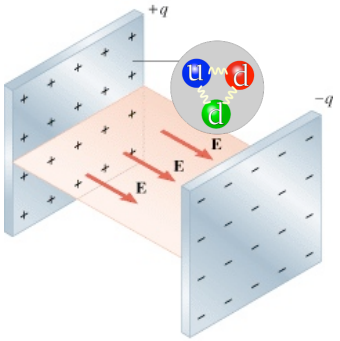


Future directions

- Particle : Beyond the Standard Model on Lattice
  [E. Neil's talk]
  Composite Higgs & Composite Dark matter



- Nuclear :
  Electromagnetic properties
  [B. Tiburzi's talk]



Brian Tiburzi,

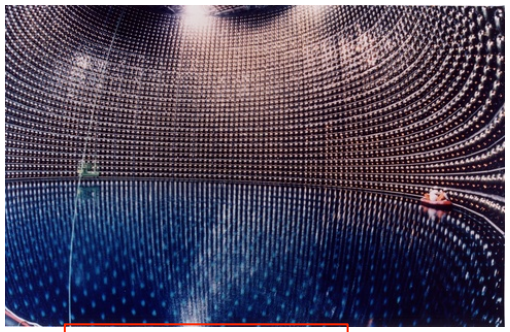
KITP Scholar, Kalvi Institute for Theoretical Physics, UC-Santa Barbara (2012-2014)

Alfred P. Sloan Foundation, CUNY Junior Faculty Research Awards in Science and Engineering (2013-2014)

Nucleon calculations for High Energy Physics

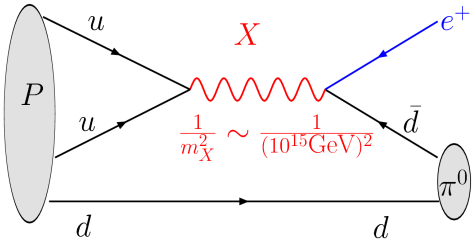
- Proton Decay Matrix Elements
  [Y. Aoki, E. Shintani, A. Soni arXiv:1304.7424]
  taking all uncertainties into account
  ~ 30% error (w/o AMA)
- Strangeness contents in Nucleons for Direct Dirk Matter search
  [C. Jung]

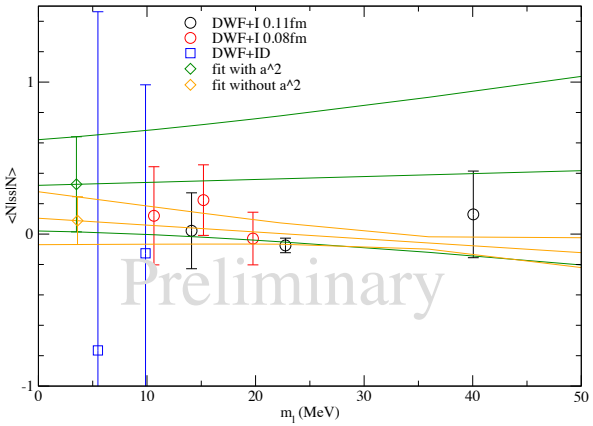
$$\langle N|\bar{s}s|N\rangle$$

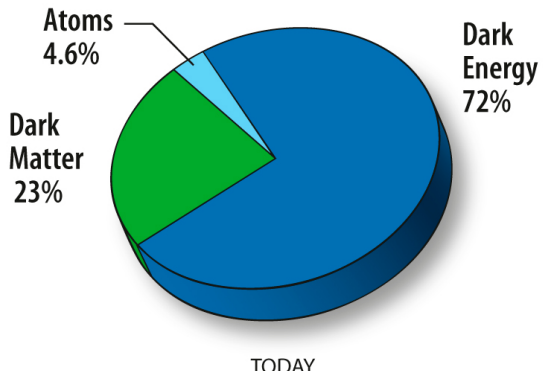


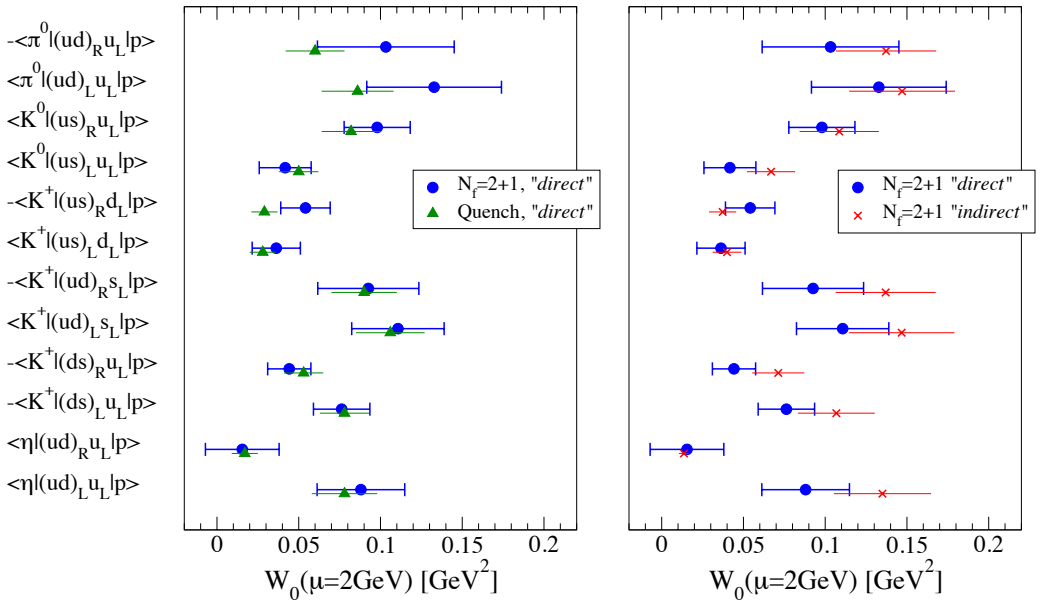
Kamiokande

$$\Gamma_P \propto \left| \overline{v_e^c} \langle \pi | (ud)_{R/L} u_L | P \rangle \right|^2$$









[Blum, TI, Shintani arXiv:1208.4349, arXiv:1212.5542]

All Mode Averaging (AMA)

Original

unbiased
imporved

$$\mathcal{O} = \mathcal{O}^{(\mathrm{appx})} + \mathcal{O}^{(\mathrm{rest})}$$

Lattice Symmetry

$$\mathcal{O}^{(\mathrm{imp})} = \frac{1}{N_G} \sum_{g \in G} \mathcal{O}^{(\mathrm{appx}),g} + \mathcal{O}^{(\mathrm{rest})}$$

Cheap : frequently measured, N_G times

Expensive : infrequently measured

- $O^{(\mathrm{imp})}$ has smaller error
- $O^{(\mathrm{appx})}$ is a cheap approximation

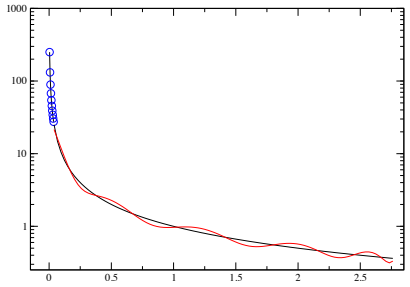
  e.g. a polynomial approximation of quark propagator (sloppy CG)
- N_G suppresses the bulk part of noise cheaply
- One could also use non-covariant approximations using random choice to measure $O^{(\mathrm{rest})}$

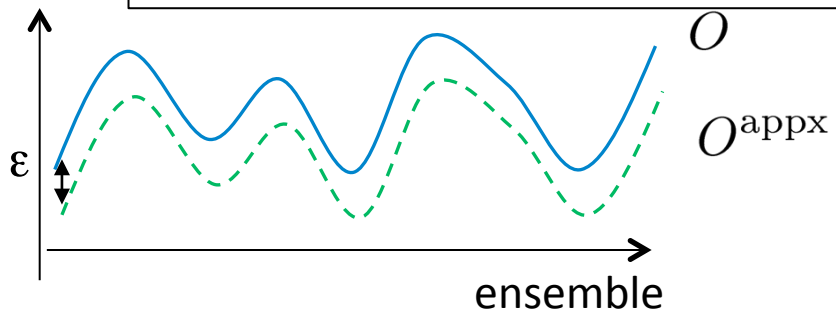
$$\mathcal{O}^{(\mathrm{appx})} = \mathcal{O}[S_l],$$

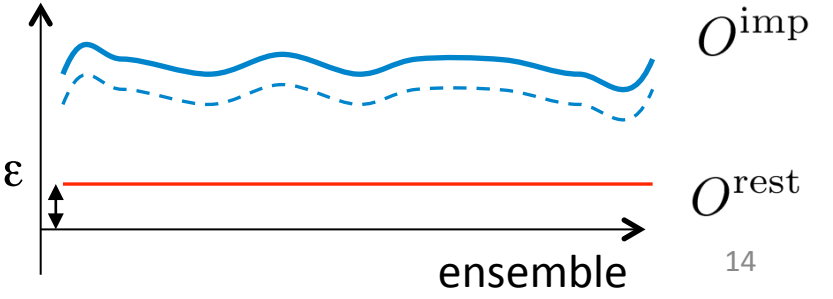
$$S_l = \sum_\lambda v_\lambda f(\lambda) v_\lambda^\dagger,$$

$$f(\lambda) = \begin{cases} \frac{1}{\lambda}, & |\lambda| < \lambda_{\mathrm{cut}} \\ P_n(\lambda) & |\lambda| > \lambda_{\mathrm{cut}} \end{cases}$$

$$P_n(\lambda) \approx \frac{1}{\lambda}$$





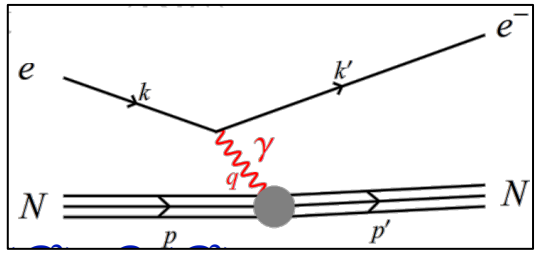


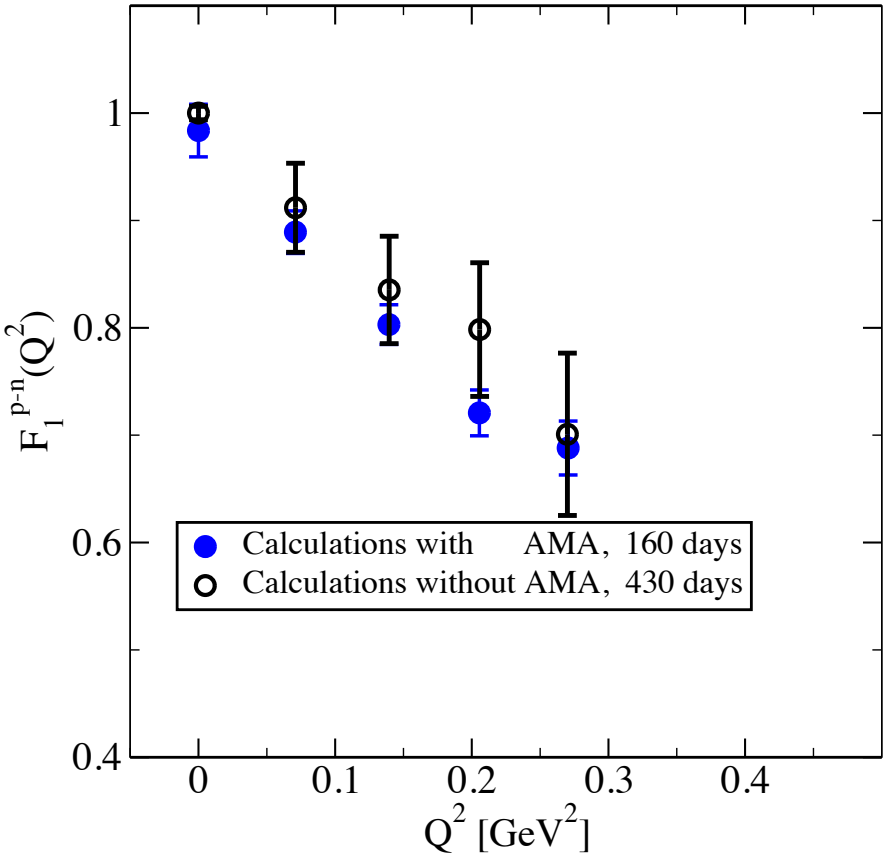
AMA at work

- Target : $V=32^3 \times 64 = (4.6\text{fm})^3 \times 9.6\text{fm}$, Ls=32 Shamir-DWF, $a^{-1}=1.37$ GeV, Mpi = 170 MeV
- Use Ls=16 Mobius as the approximation
  [Brower, Neff, Orginos, arXiv:1206.5214]

- quark propagator cost on SandyBridge 1024 cores (XSEDE gordon@SDSC)
  - non-deflated CG, r(stop)=1e-8 : ~9,800 iteration, 5.7 hours / prop
  - Implicitly restarting Lanczos of Chebyshev polynomials of even-odd prec operator for 1000 eigenvectors
    [Neff et al. PRD64, 114509 (2001)] : 12 hours
  - deflated CG with 1000 eigenvectors : ~700 iteration, 20 min /prop
  - deflation+sloppy CG, r(stop)=5e-3 : ~125 iteration, 3.2 min /prop
- Multiplicative Cost reduction for General hadrons could combine with {EigCG | AMG} and Distillation:
  x1.2 (Mobius) x 14 (deflation) x 7 (sloppy CG) ~ x 110

Nucleon calculation
[M. Lin]





- $F_1(Q^2)$: tsep = 9 a ~ 1.3 fm

  1 forward + 2 (up and down) seq-props, contraction cost is ~15% of sloppy propagator

- Error bar
  x 2 - 2.7 ~ sqrt(4400/600)
- Total cost reduction upto
  (430 / 160) * (4400/600)
  ~ x19.7

- Note this is still sub-optimal, 4 exact source and without deflation. (would be x30 for 2 exact sources)

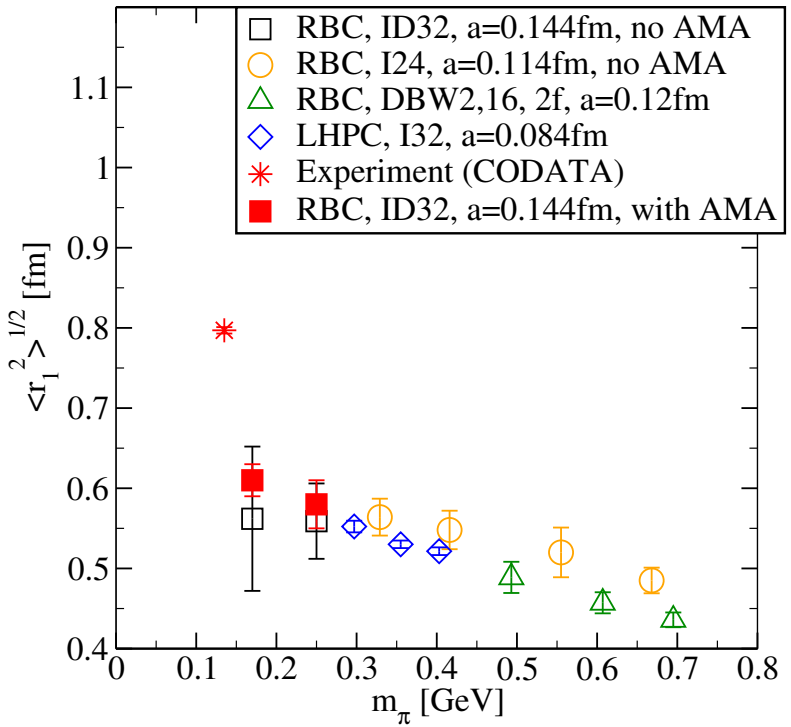
- non-deflated CG, 150 config x 4 sources = 600 measurements :
  5.7 * 3 * 4 * 150 config = 10K hours, 430 days

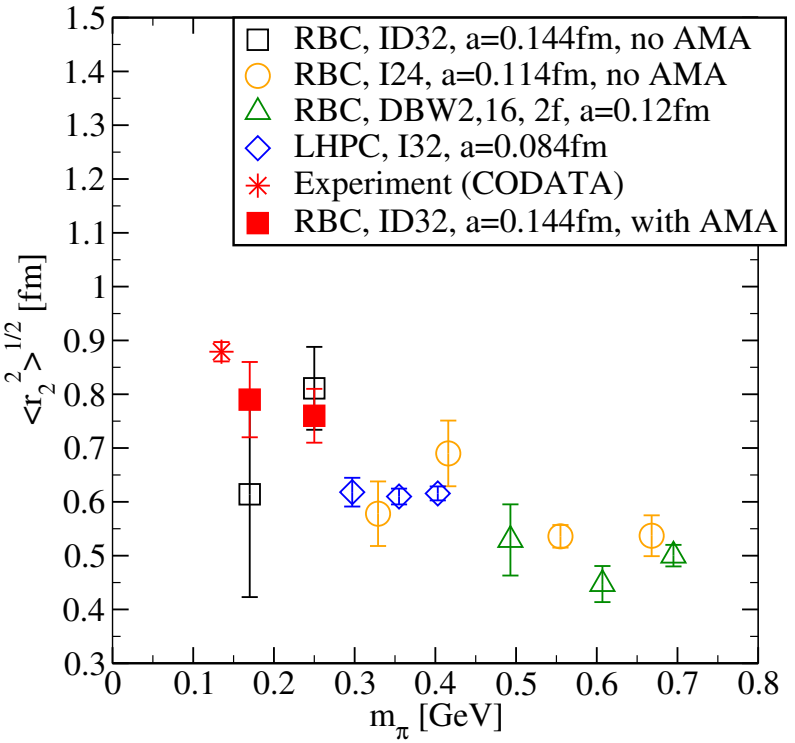
- AMA : 39 config, 4 exact solves / config (perhaps overkill) , N_G=112 sloppy solves
  => 39 x 112 = 4400 AMA measurements :
  (5.7 * 3 * 4 + 12 + 0.06 * 3 * 112) * 39 config = 3.9 K hours, 160 days
  4-exact (68%) + Lanczos (12%) + sloppy CG (20%)

Dirac and Pauli radii [Meifeng Lin]

Preliminary

- Statistical error is much reduced by AMA
- r2 at Mpi=170MeV is closest result (~8 % stat err)!
  r1 still undershoots (~ 4% stat err) [S. Syritsyn's talk]
- Anomalous magnetic moment κ = F2(0) = 3.2 (3) at M(pi)=170 MeV
  experiment : κ (exp) = 3.71





Axial Charge gA [S. Ohta]

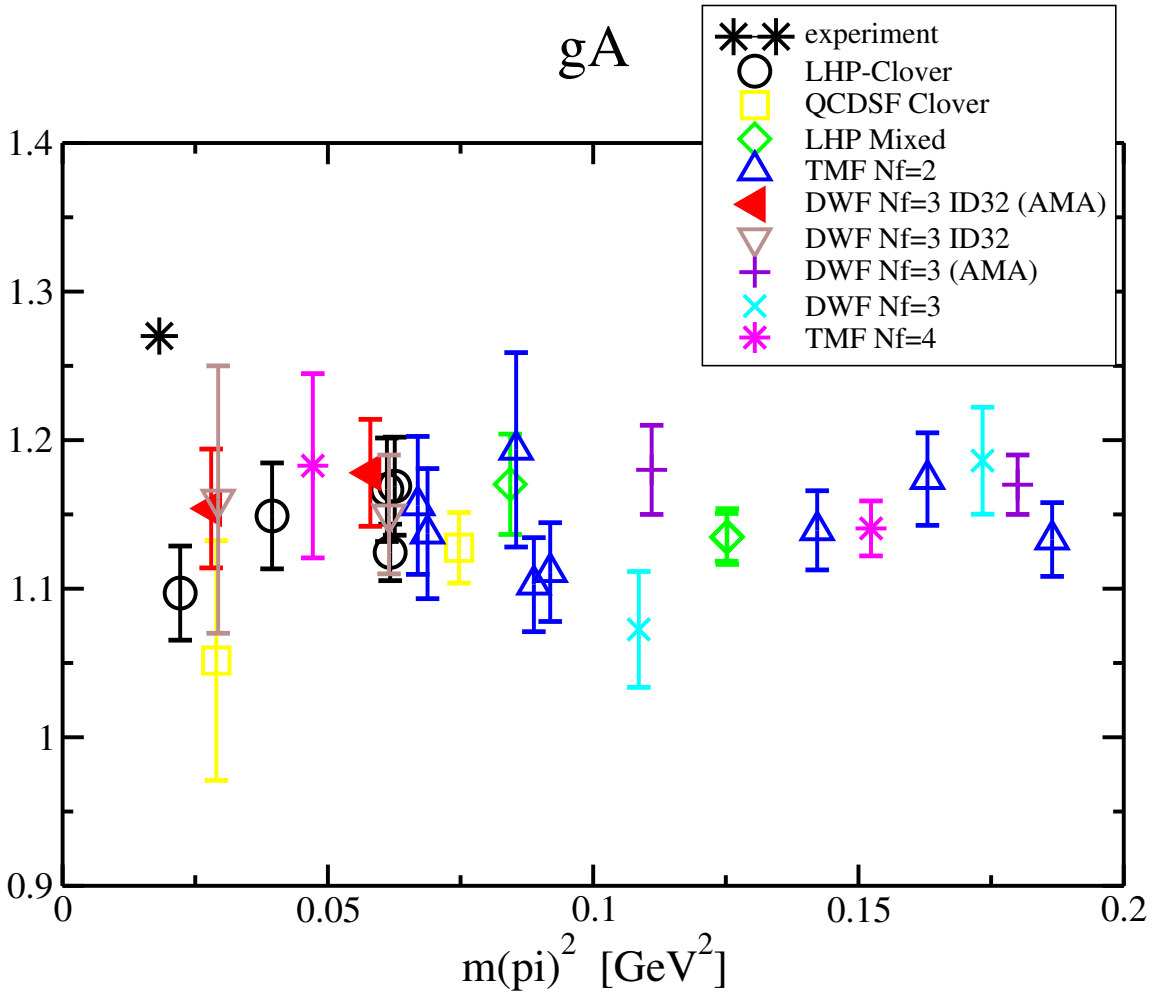
Preliminary

$$\langle p|A_\mu^+|n\rangle = \overline{u}_p \left[\gamma_\mu\gamma_5 G_A(q^2) + q_\mu\gamma_5 \frac{G_P(q^2)}{2M_N}\right] u_n$$

- ~ 10%, 3 σ deficit

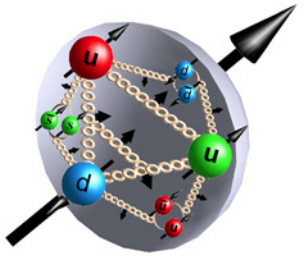
- excited state (v)
- statistics (v)
- Discretization (v)

- Finite Volume ?



Computing Group
New Collaboration

- RHIC-Spin & eRHIC Physics
- Future BNL or Jlab experiments
- Structure and Spin of Nucleon
- LHP Collaboration



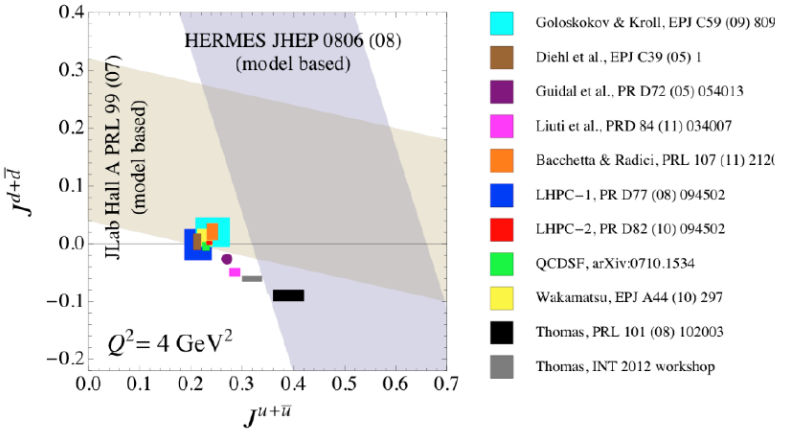
J. Negele, A. Pochinsky, S. Meinel (MIT)

K. Orginos (W&M), A. Walker-Loud (LBL)

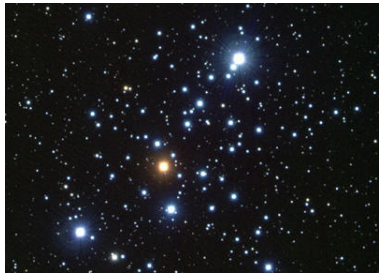
M. Engelhardt (NMSU)

Sergey Seryzin (RBRC)

- On-physics point DWF
- Clean operator mixing
- AMA to reduce statistics



Nucleon Electric Dipole Moments [E. Shintani, T. Blum]

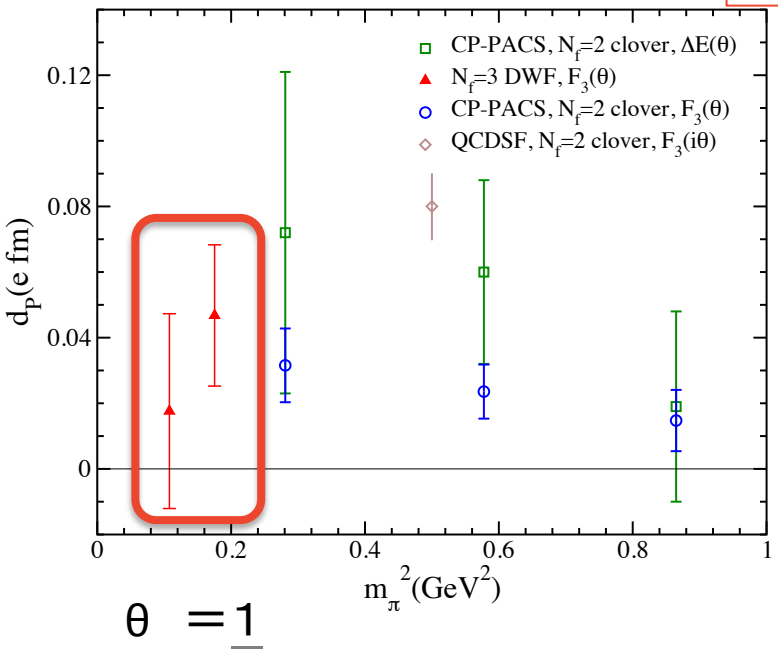


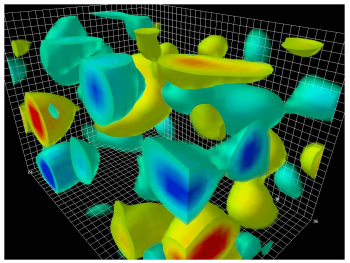
- Sakharov's condition for matter rich Universe
  A nonzero EDM is a signature of
  P and T (CP through CPT) violation
- Chiral Symmetry of Lattice quark is known to be crucial

since the first calculation [S. Aoki et al, PRL65 (1900)]

PRELIMINARY

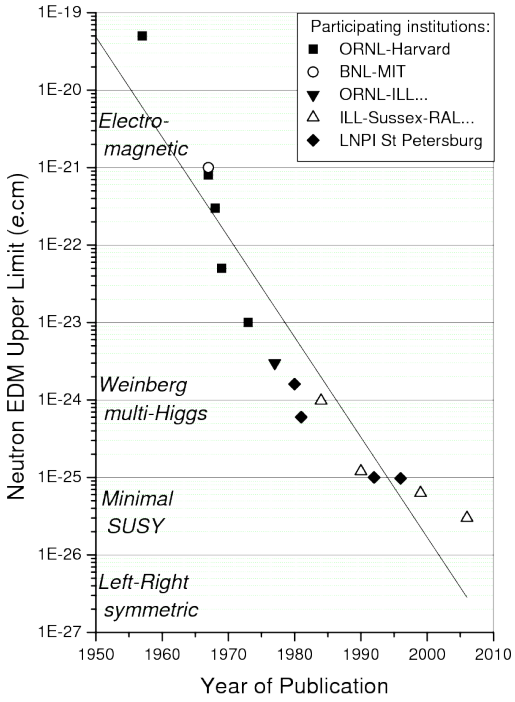
$$S_\theta = i\frac{\theta}{32\pi^2}\int d^4x\ \mathrm{tr}[\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}G^{\mu\nu}] = i\theta\ Q_{\mathrm{top}}$$





$$\langle N(p')|V_\mu^{\mathrm{EM}}(q)|N(p)\rangle = F_1(q^2)\gamma_\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N} + F_3(q^2)\frac{\sigma^{\mu\nu}q^\nu\gamma^5}{2m_N}$$

$$d_N = \lim_{Q^2\to 0} F_3(Q^2)/2m_N$$



exp: ΔH ~ 10^{-6} Hz ~ 10^{-21} eV
→ |d| < ΔH/E ~ 10^{-25} e cm

if theo: d ~ 10^{-2} x 1 MeV / Λ^2_{CP}
→ Λ_{CP} >~ O(1) TeV

2013 Plenary/invited talks

- Sergey Syritsyn, "Hadron Structure Review" (Lattice 2013)
- Chulwoo Jung, "Progress in Algorithms and Numerical Techniques" (Lattice 2013)

- Norman Christ, "Nonleptonic Kaon Decays from Lattice QCD" (Kaon13)
- Robert Mawhinney, "KAON 2013: A View of Kaons from the Lattice" (Kaon13)

- Taku Izubuchi, "Nucleon Structure by Lattice QCD" (PHENIX Workshop 2013)

- Yasumichi Aoki, "Proton Decay Matrix Elements from Lattice QCD", (Trento ECT* Workshop on Nucleon Matrix Elements for New-Physics Searches 13)
- Tom Blum, "The muon anomalous magnetic moment" and "Lattice calculation of nucleon electric dipole moments", (Trento ECT* Workshop on Nucleon Matrix Elements for New-Physics Searches 13)
- Tom Blum, "Computing K to pi pi decays with lattice QCD", (APS13)
- Norman Christ, "QCD at One PFLOPS " (IWCSE13)
- Taku Izubuchi, "Lattice QCD and the HEP Intensity Frontier" (ORNL, Lattice QCD Computational Science Workshop)
- Taku Izubuchi, "Lattice-QCD Calculations for EDMs", (FNAL EDMs13)
- Hyung-Jin Kim, "GPU and Lattice", (RIKEN/Wako AICS GPU meeting)
- Meifeng Lin, "The search for the conformal window on the lattice", (Workshop on "Phase Structure of Gauge Theories", National Chiao-Tung University, Hsinchu, Taiwan. 2013)
- Ethan Neil, "Lattice field theory: QCD and beyond" (APS four corners section 2013)
- Eigo Shintani, "Neutron and proton EDMs from the Lattice", (Mainz ITP Workshop on Low-Energy Precision Physics)
- Eigo Shintani, "Application of GPU computation toward particle physics",(RIKEN symposium, Jun 23, 2013, RIKEN, Japan).
- Eigo Shintani, "Nucleon EDM & Decay from the Lattice ", (Brookhaven forum 2013)
- Eigo Shintani, "Nucleon EDM in lattice QCD", (CP VIOLATION 2013 India)
- Brian Tiburzi, "Towards Exploring Fundamental Symmetries with Lattice QCD," (INT-13-2b)
- Brian Tiburzi, "Looking Under the Femtoscope: A Focus on Strong Interactions," (Colloquium, William & Marry

2013 Committees and Community services

- Lattice 2014 in NY !
- Norman Christ, Robert Mawhinney, Shigemi Ohta, Lattice 2013 IAC
- Norman Christ, USQCD Executive Committee
- Taku Izubuchi, USQCD Scientific Program Committee
- Chulwoo Jung, Robert Mawhinney, USQCD Software Committee
- Yasumichi Aoki, FLAG heavy quark WG, Tom Blum, FLAG quark mass WG
- Tom Blum, Robert Mawhinney, XSEDE Resources Allocation Committee
- Tom Blum, Convener for Lattice QCD, Computing Frontier, Snowmass 2013
- Tom Blum, Ethan Neil, two whitepapers for the Snowmass 2013
- Ethan Neil, Christoph Lehner, Taku Izubuchi,
  USQCD/RBRC Workshop for Lattice Meets Experiments 2013 (Dec 2013)

Computing Group Overview

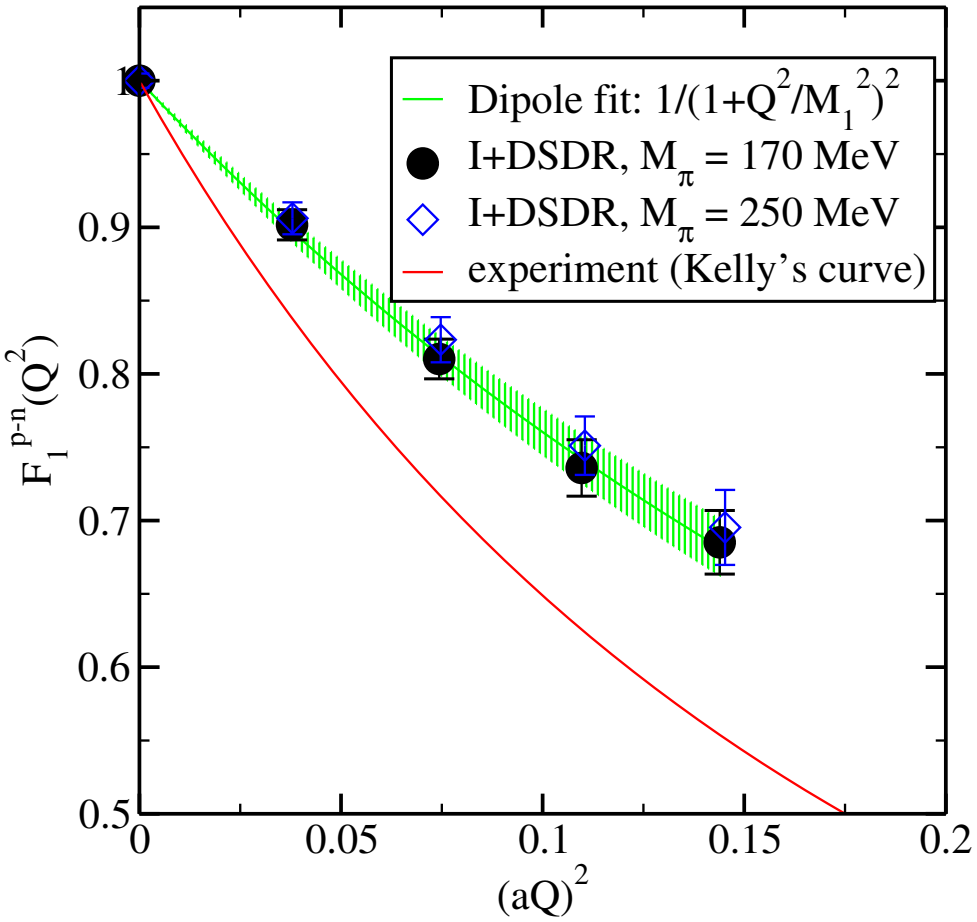
- RBRC's Computing group's mission:
  Non-Perturbative studies of Strong Interactions
  - Domain wall QCD for particle/nulcear physics,
    now on-physical point (Mπ=135 MeV), a^{-1} = 1.7 , 2.4 GeV, V=(5.5 fm)^3
  - Expand in Nuclear Physics & Beyond Standard Model
- Synergies with BNL, RIKEN, U.S. & U.K. Universities
  - 3 BNL Theory groups , RIKEN Nishina Center
  - Columbia, Connecticut, Edinburgh, Southampton
  - Tenure track fellows from CCNY, Colorado, (Arizona)
- Young talents in lattice theories
  - Wide spectrum of interesting and challenging physics
  - Opportunities to interact many scientists, collaborators
  - Software and hardware, both in-house and leadership class

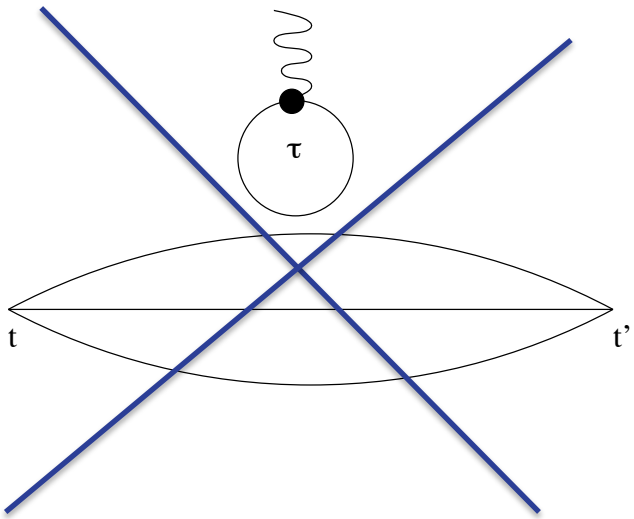
BACKUP SLIDES

Isovector $F_1(Q^2)$ [Meifeng Lin]

Preliminary

- Mild quark mass dependence
- Dipole fit, Dirac radius from slope at Q2 = 0



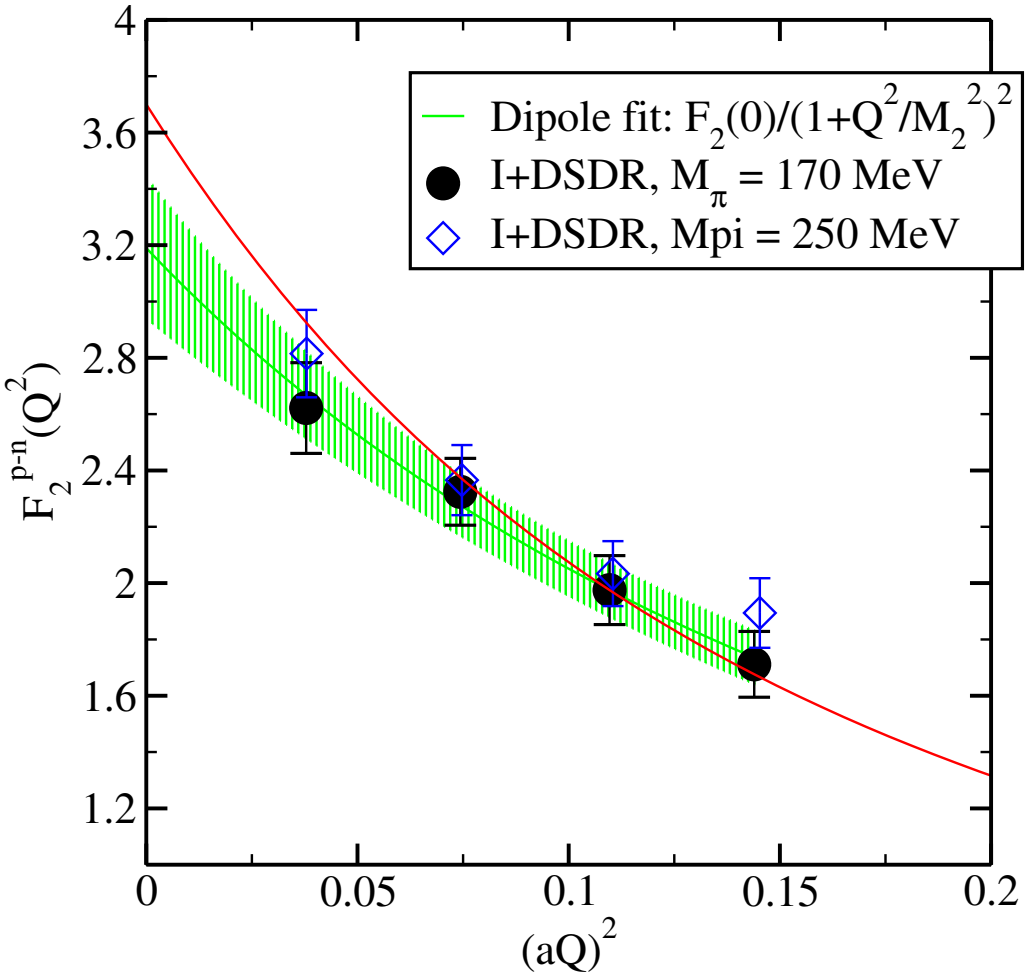


[Iso scalar needs
disconnected diagram]

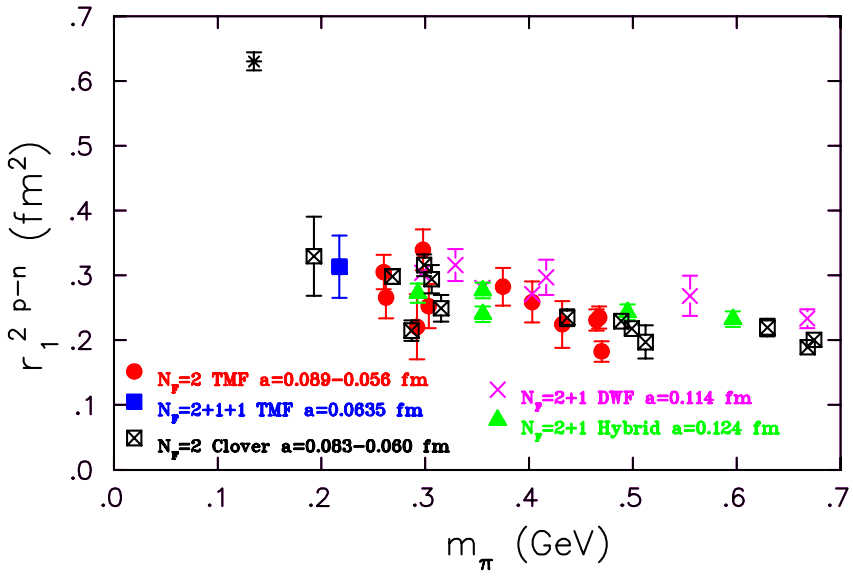
Isovector $F_2(Q^2)$ [Meifeng Lin]

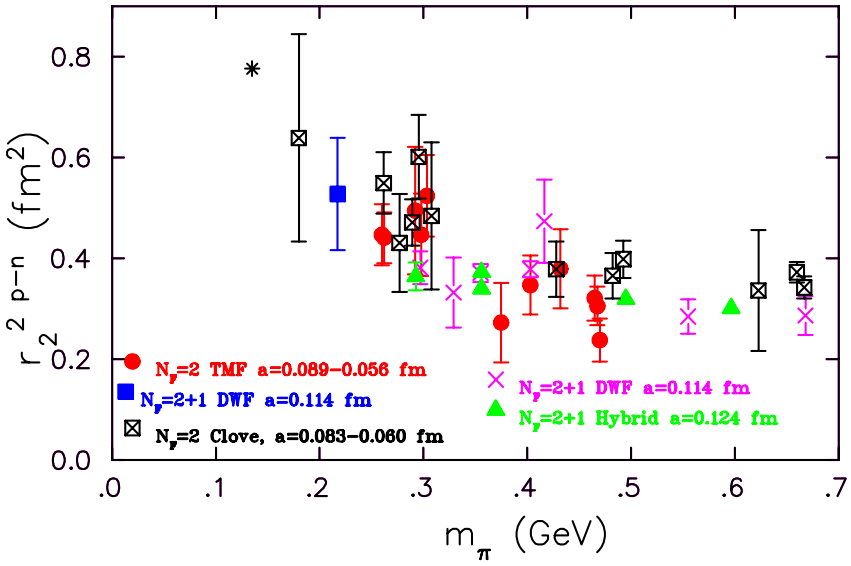
Preliminary

- Mild quark mass dependence
- Much smaller statistical error with AMA



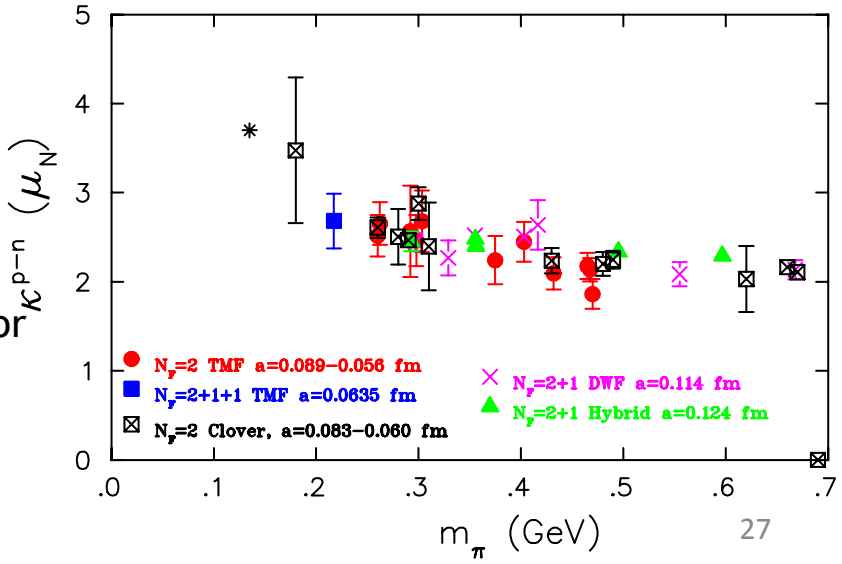
Radii, κ results by others





Compilation Alexandrou et al. arXiv:1303.6818

- Isovector (no disconnected quark diagrams)
- Dirac radius, r1, undershoots
- r2 also except the lightest results with 30% error
- still large extraction in quark mass
- Finite Volume Effects / Discretization Error



Kaon Program

RBRC Scientific Review Committee Meeting
Brookhaven National Laboratory
October 31, 2013

Robert Mawhinney
Columbia University

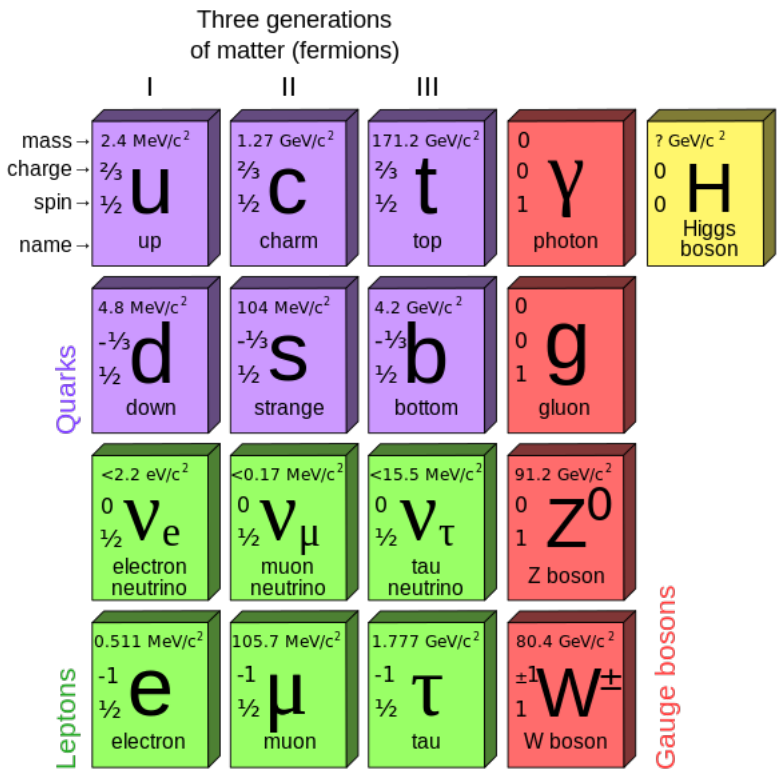
RIKEN BNL Columbia (RBC) members

Ziyuan Bai
Thomas Blum
Norman Christ
Xu Feng
Tomomi Ishikawa
Taku Izubuchi
Luchang Jin
Chulwoo Jung
Taichi Kawanai
Chris Kelly
Hyung-Jin Kim
Christoph Lehner
Jasper Lin
Meifeng Lin
Robert Mawhinney
Greg McGlynn
David Murphy
Shigemi Ohta
Eigo Shintani
Amarjit Soni
Oliver Witzel
Hantao Yin
Jianglei Yu
Daiqian Zhang

UKQCD members

Rudy Arthur
Peter Boyle
Hei-Man Choi
Luigi Del Debbio
Shane Drury
Jonathan Flynn
Julien Frison
Nicolas Garron
Jamie Hudspith
Tadeusz Janowski
Andreas Juettner
Richard Kenway
Andrew Lytle
Marina Marinkovic
Enrico Rinaldi
Brian Pendleton
Antonin Portelli
Chris Sachrajda
Ben Samways
Karthee Sivalingam
Matthew Spraggs
Tobi Tsang

Known Elementary Particles



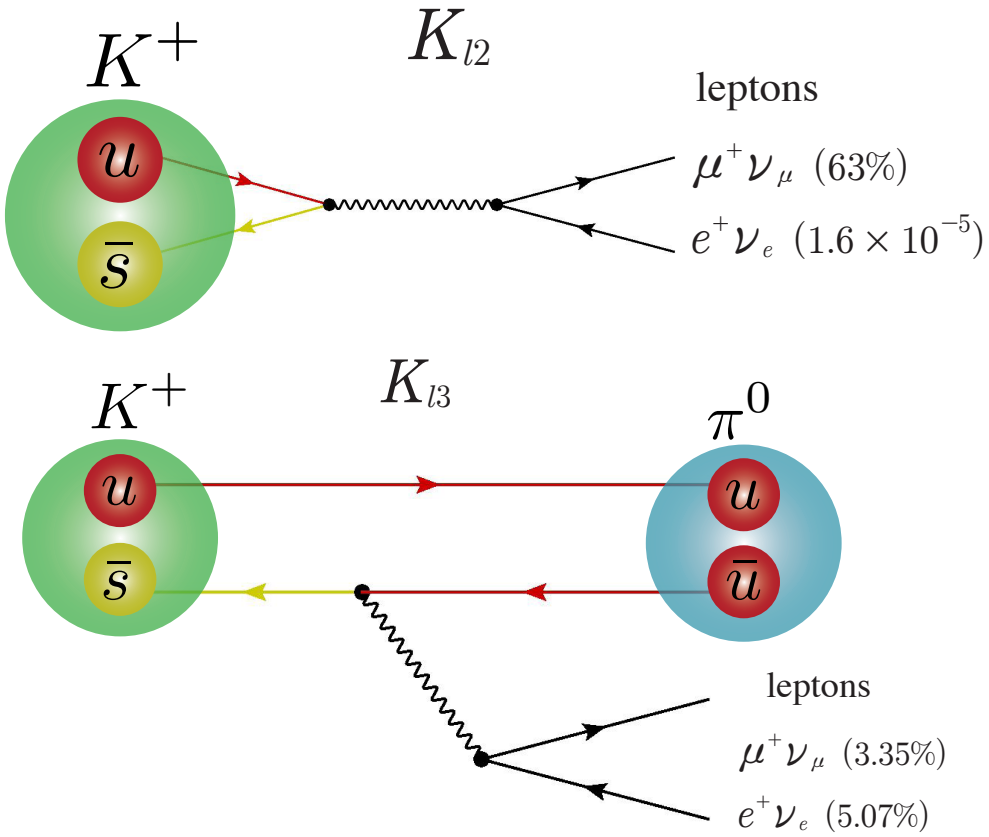
Standard Model quark decays involve elements of a 3 by 3 unitary matrix, the CKM matrix, described by 4 parameters

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

QCD + Electroweak

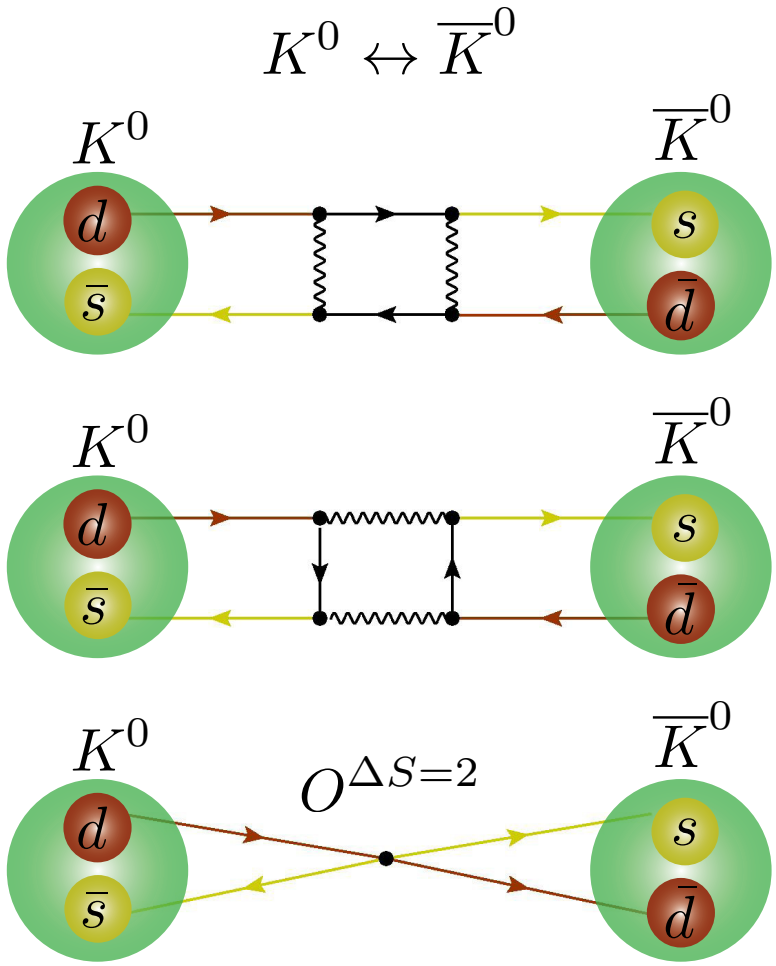
Decays of quarks via weak interactions predicted by Standard Model.

Experiments measure decays of hadrons



For K_{l3} we have: $\Gamma_{K\to\pi l\nu} = C_K^2 \dfrac{G_F^2 m_K^5}{192\pi^3} I\, S_{EW}[1 + 2\Delta_{SU(2)} + 2\Delta_{EM}] |V_{us}|^2 |f_+(0)|^2$

Direct CP Violation Measured in 1964



$$\varepsilon = \frac{e^{i\pi/4}}{\sqrt{2}\,\Delta M_K}\left(\mathrm{Im}(M_{12}) + 2\frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}\,\mathrm{Re}(M_{12})\right) = \kappa_\varepsilon\,\frac{e^{i\phi_\varepsilon}}{\sqrt{2}}\left[\frac{\mathrm{Im}(M_{12}^{O^{\Delta S=2}})}{\Delta m_K}\right]$$

$$\varepsilon_K = \kappa_\varepsilon\, C_\varepsilon\, \hat{B}_K\, \mathrm{Im}(\lambda_t)\,\{\mathrm{Re}(\lambda_c)[\eta_1\, S_0(x_c) - \eta_3\, S_0(x_c,x_t)] - \mathrm{Re}(\lambda_t)\,\eta_2\, S_0(x_t)\}\, e^{i\pi/4}$$

Generic Process	Examples	Experiment	LQCD calculates
$Kl2$	$K^+ \to \mu^+ \nu_\mu$ $K^+ \to e^+ \nu_e$	f_K	f_K (also f_π)
$Kl3$	$K^+ \to \pi^0 l^+ \nu_l$ $K^0 \to \pi^- l^+ \nu_l$	$\lvert V_{us} f^+(0)\rvert^2$	$f^+(0)$
$Kl4$	$K \to \pi\,\pi\, l\, \bar{\nu}_l$		??
$K \to \pi\pi$ (CP conserving)	$K^0 \to \pi^+\ \pi^-$ $K^+ \to \pi^+\ \pi^0$	$\lvert A_0\rvert$ $\lvert A_2\rvert$	$\lvert A_0\rvert$ $\lvert A_2\rvert$ ($\mathrm{SM}_{\mathrm{cpc}}$ inputs)
Δm_K (CP conserving)	$K^0 \leftrightarrow \pi\,\pi \leftrightarrow \overline{K}^0$ (LD) $K^0 \leftrightarrow O_{\Delta S=2} \leftrightarrow \overline{K}^0$ (SD)	Δm_K	Δm_K ($\mathrm{SM}_{\mathrm{cpc}}$ inputs)
$K^0 \to \pi\ \pi$ (indirect CP violation)	$K_L \to \pi\,\pi$ $\left(K^0 \leftrightarrow \overline{K}^0\right) \to \pi\,\pi$ independent of $\pi\,\pi$ isospin	$\epsilon = \dfrac{\hat{B}_K F_K^2\,\mathrm{SM}}{\Delta m_K}$	$B_K, \dfrac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}$
$K^0 \to \pi\ \pi$ (direct CP violation)	$K_L \to \pi\,\pi$ depends on $\pi\,\pi$ isospin	$\mathrm{Re}(\epsilon'/\epsilon)$ $= f(A_0, A_2, \mathrm{SM})$	A_0 A_2 ($\mathrm{SM}_{\mathrm{cpc}}$ inputs)
$K \to \pi ll$	$K_L \to \pi^0 l^+ l^-$ $K_S \to \pi^0 l^+ l^-$		??

$\mathrm{SM}_{\mathrm{cpc}}$ = Standard Model CP-conserving parameters

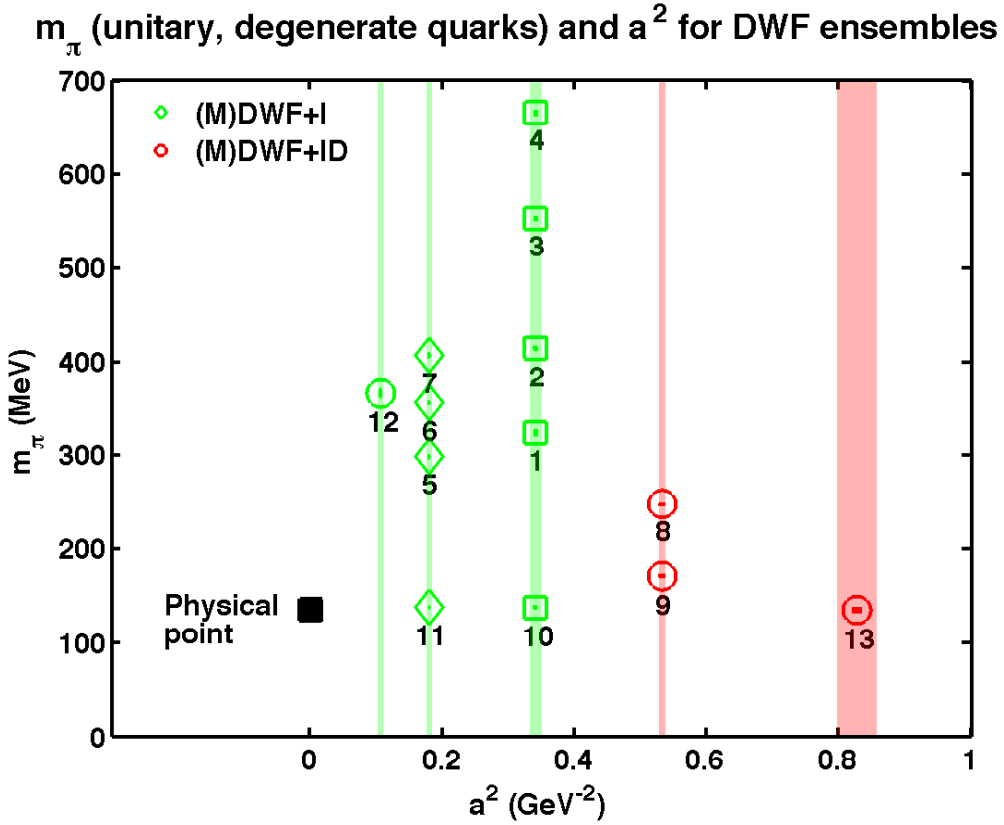
Major Development: Physical Quark Mass DWF Ensembles

RBC, UKQCD and HotQCD

Ens.	Action (G+F)	$1/a$ (GeV)	Lattice volume	m_l	m_s	$m_{\rm res}$ (in lattice units)	m_π (MeV)	Size (fm)
1	DWF+I	1.75(3)	$24^3\times64\times16$	0.005	0.04	0.00308	330	2.7
2	DWF+I	1.75(3)	$24^3\times64\times16$	0.01	0.04	0.00308	420	2.7
3	DWF+I	1.75(3)	$24^3\times64\times16$	0.02	0.04	0.00308	560	2.7
4	DWF+I	1.75(3)	$24^3\times64\times16$	0.03	0.04	0.00308	670	2.7
5	DWF+I	2.31(4)	$32^3\times64\times16$	0.004	0.03	0.000664	310	2.6
6	DWF+I	2.31(4)	$32^3\times64\times16$	0.006	0.03	0.000664	370	2.6
7	DWF+I	2.31(4)	$32^3\times64\times16$	0.008	0.03	0.000664	420	2.6
8	DWF+ID	1.37(1)	$32^3\times64\times32$	0.0042	0.046	0.00184	250	4.5
9	DWF+ID	1.37(1)	$32^3\times64\times32$	0.001	0.046	0.00184	180	4.5
10	MDWF+I	1.75(3)	$48^3\times96\times24$	0.00078	0.0362	0.000614	138	5.5
11	MDWF+I	2.31(4)	$64^3\times128\times12$	0.000678	0.02661	0.000314	139	5.5
12	DWF+I	3.06(6)	$32^3\times64\times12$	0.0047	0.0186	0.00060	380	2.0
13	MDWF+ID	1.12(4)	$32^3\times64\times24$	0.00022	0.05960	0.0021	135	5.8

Table 1: Dynamical 2+1 flavor domain wall fermion ensembles produced (1-9) and being produced (10-13) by the RBC and UKQCD collaborations (10-12) and the RBC and HotQCD collaborations (13). The gauge and fermion (G+F) action abbreviations are: DWF = domain wall fermions, MDWF = Mobius domain wall fermions, I = Iwasaki gauge action, ID = Iwasaki plus Dislocation Suppressing Determinant Ratio (DSDR) gauge action. The total light quark mass (in lattice units) is $m_l + m_{\rm res}$ and the total strange quark mass is similarly $m_s + m_{\rm res}$.

Major Development: Physical Quark Mass DWF Ensembles

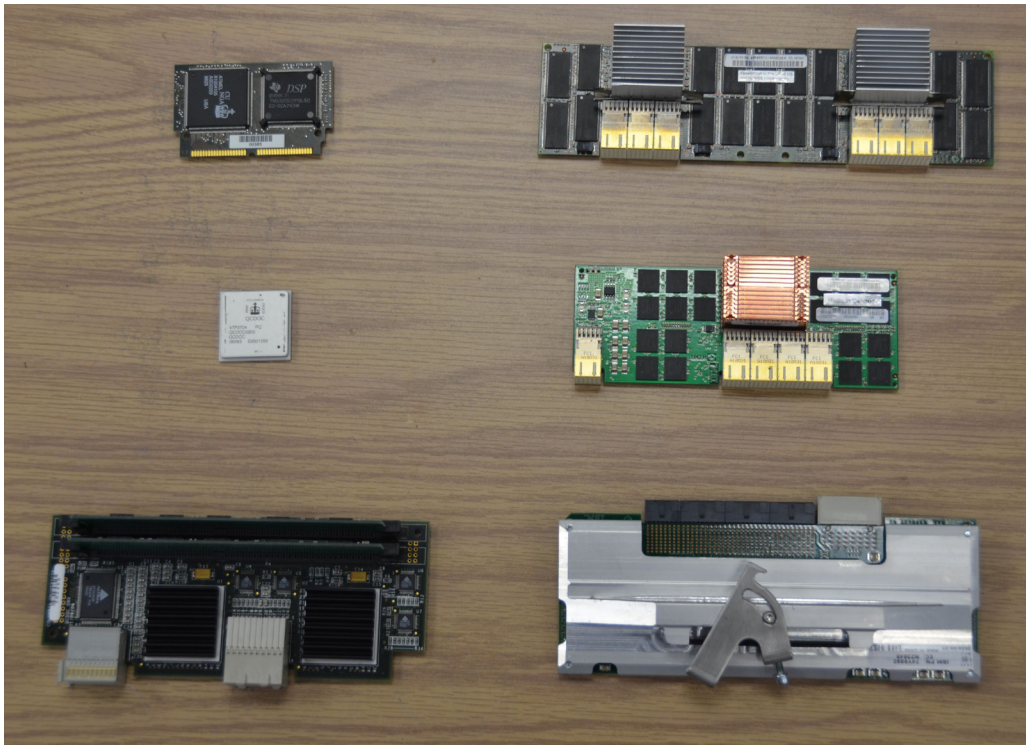


Ens.	Action (G+F)	$1/a$ (GeV)	Lattice volume	m_l (in lattice units)	m_s (in lattice units)	$m_{\rm res}$ (in lattice units)	m_π (MeV)	Size (fm)
10	MDWF+I	1.75(3)	$48^3\times 96\times 24$	0.00078	0.0362	0.000614	138	5.5
11	MDWF+I	2.31(4)	$64^3\times 128\times 12$	0.000678	0.02661	0.000314	139	5.5

Using force gradient integrator of Clark and Kennedy, as implemented by Hantao Yin.
Gave 2 speed-up over Omelyan at 1/a = 2.31 GeV and m_π = 220 MeV on 48^3.
Expect even larger speed-up here, but too expensive to run Omelyan to measure effect.

Computers

Columbia/RBRC
QCDSP 1998-2005
0.050 GFlops/node



IBM BGL 2005-2013
2.8 GFlops/node

IBM BGP 2007-
13.6 GFlops/node

Columbia/RBRC
and UKQCD
QCDOC 2005-2011
0.8 GFlops/node

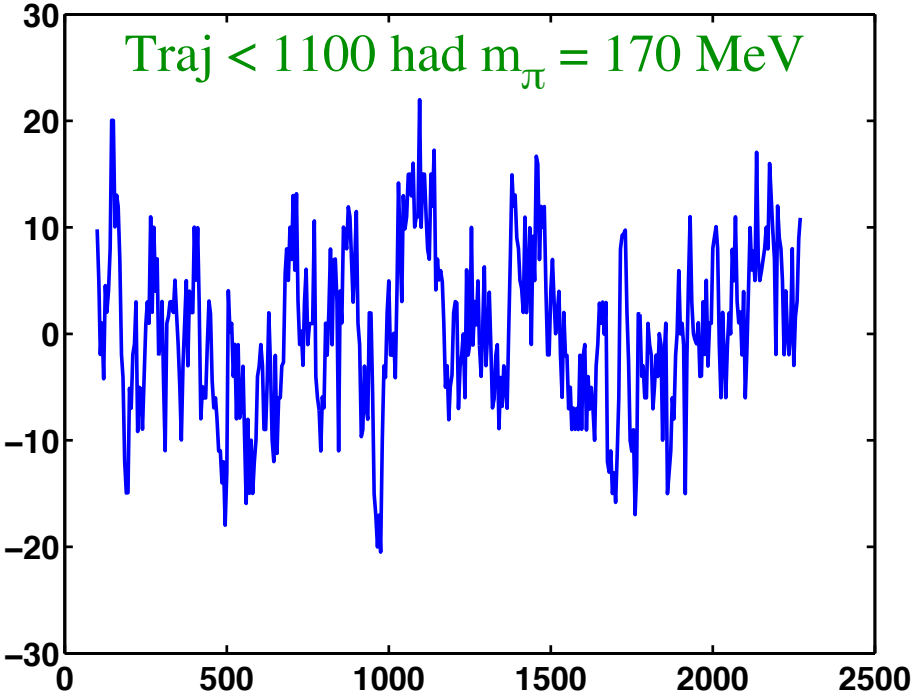
IBM BGQ 2012-
200 GFlops/node

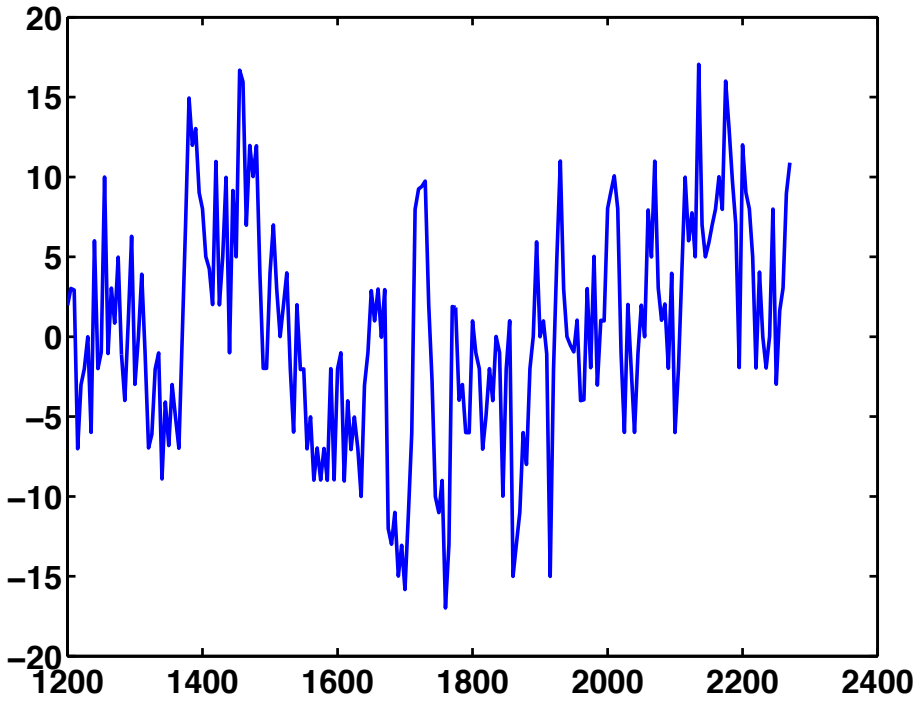
~ 4,000 speed-up per node over 15 years, ~ 700 speed-up in Flops/$ w/o inflation.

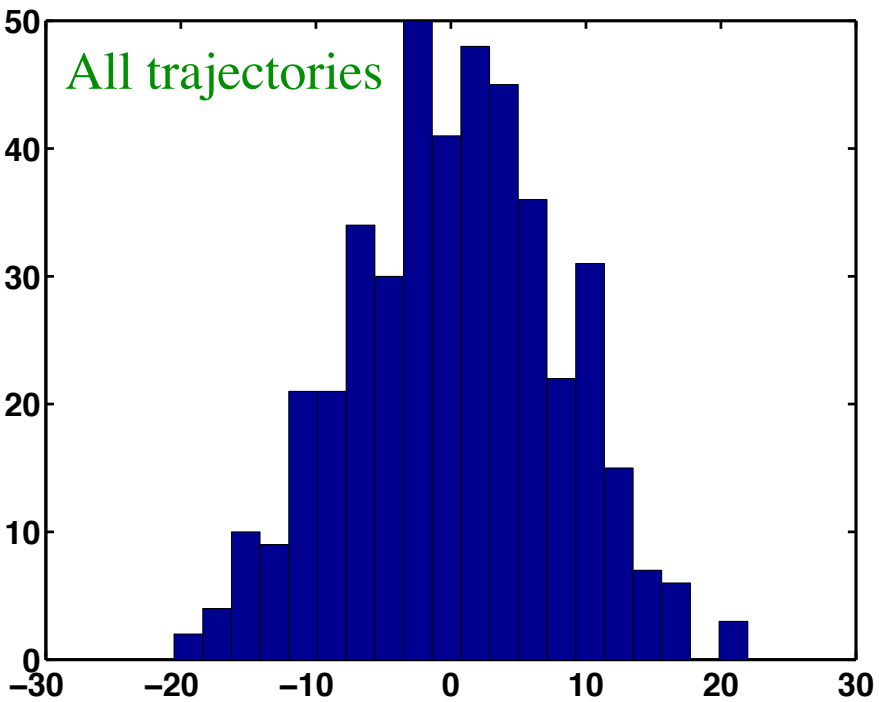
RBC/UKQCD have production jobs on the Argonne ALCF BGQ that sustain 1 PFlops on 32 racks = 32k nodes = 0.5 M cores.

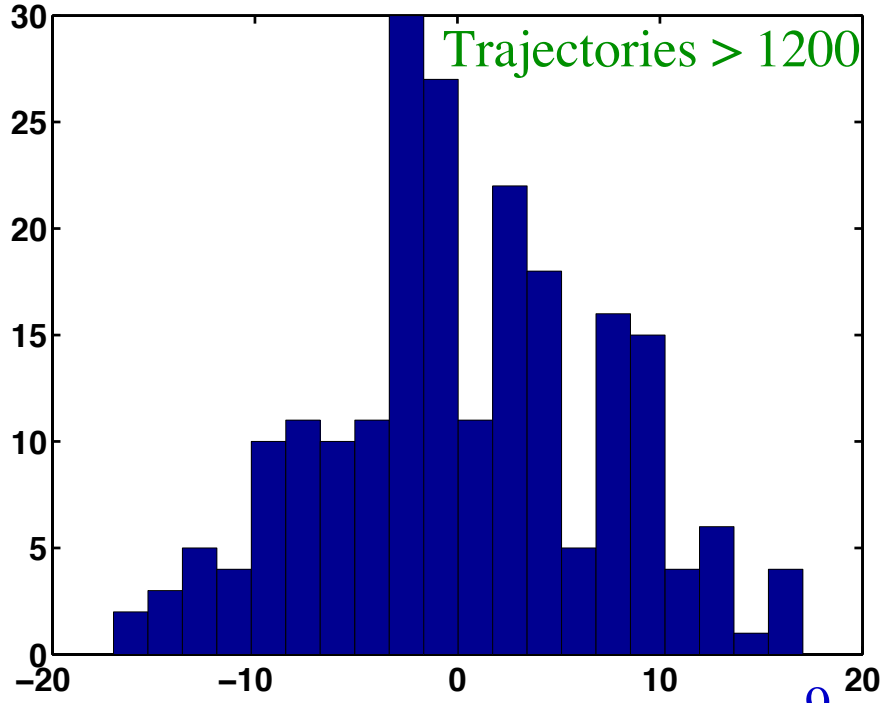
The BNL DD2 BGQ is working very reliably - ran 5.5 day measurement jobs all spring
The 2 DD1 racks reliability has improved this year, but not as good as DD2.
We have purchased (BNL funds) and are using a 1 PByte disk system.
IBM has given us an extensive set of retired DD1 parts to use.

Topology on 64^3 Ensemble

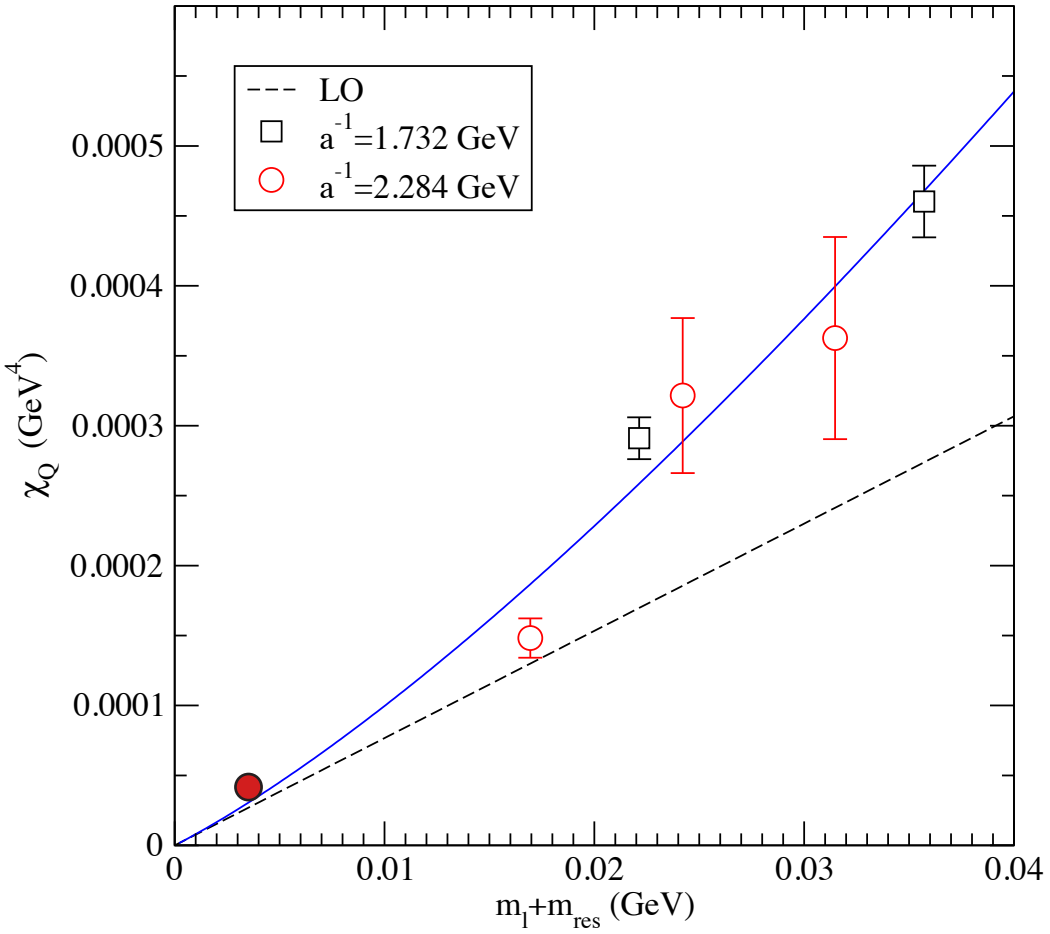








Chiral Susceptibility



No attempt at an error yet, but the preliminary result is encouraging.

RBC/UKQCD 2+1 flavor MDWF ensembles

Using Mobius DWF (MDWF) with the Iwasaki gauge action

Very close to physical parameters:

	Physical value	48^3	48^3 deviation	64^3	64^3 deviation
m_π / m_K	0.2723	0.2797(7)	2.7%	0.2739(12)	0.6%
m_π / m_Ω	0.0807	0.0828(5)	2.5%	0.0821(5)	1.7%
m_K / m_Ω	0.2964	0.2959(18)	-0.2%	0.2997(14)	1.1%

Previous simulations and chiral extrapolations used to choose input parameters

Measurement Techniques

Are using a combination of new techniques to speed up calculations by 10x

EigCG and All Mode Averaging used together

Measurement package developed by Hantao Yin (former student)

Runs on up to 500,000 cores of BGQ at Argonne!

	48^3	64^3
Light modes calculated	600 (7.3 TBytes)	1500 (29 TBytes)
Light quark EigCG setup	29.5	79
Exact light solves (10^{-8})	18.7	12
Inexact light solves (10^{-4})	64	45
Exact strange solves (10^{-8})	8	17
Contractions	3	17
Total BGQ rack-hours	124	170
Time and # of BGQ racks	124 hours on 1 rack	5.3 hours on 32 racks

Times in BGQ rack-hours

Solver sustains 1 PFlops

RBC/UKQCD 2+1 flavor Ensembles

Ensembles used by RBC and UKQCD Collaborations for kaon and pion physics

The new ensembles this year are the 140 MeV ensembles, with the large volumes

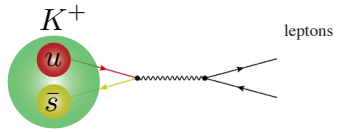
Ensemble Name	a (fm)	Volumes	Unitary m_π (MeV)
1/a= 1.37 GeV	0.146	$(4.7\ \text{fm})^3$	170, 250
1/a = 1.71 GeV	0.117	$(2.8\ \text{fm})^3\ (5.6\ \text{fm})^3$	140, 320, 410
1/a = 2.36 GeV	0.0847	$(2.7\ \text{fm})^3\ (5.4\ \text{fm})^3$	140, 295, 350, 400
1/a = 3.07 GeV	0.0651	$(2.1\ \text{fm})^3$	360

Preliminary global fit to m_π, m_k, m_Ω, f_π, f_K, using m_π, m_k, m_Ω to set (β, m_l, m_s)

$f_\pi = 130.3 \pm 1.7_{\text{stat}}$ MeV (Preliminary)

$f_K = 155.7 \pm 1.8_{\text{stat}}$ MeV (Preliminary)

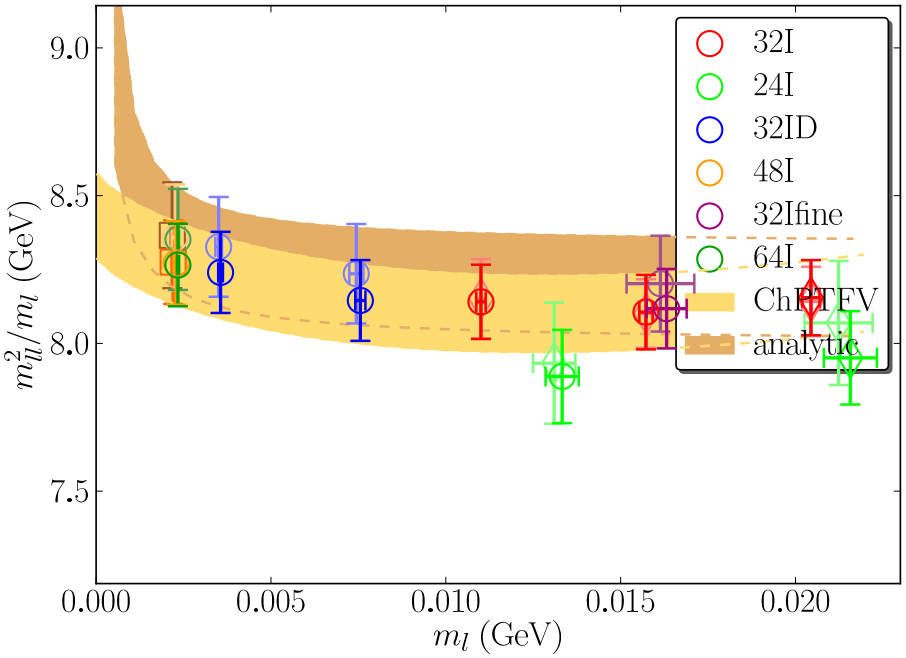
$f_\pi / f_K = 1.195 \pm 0.005_{\text{stat}}$ (Preliminary)

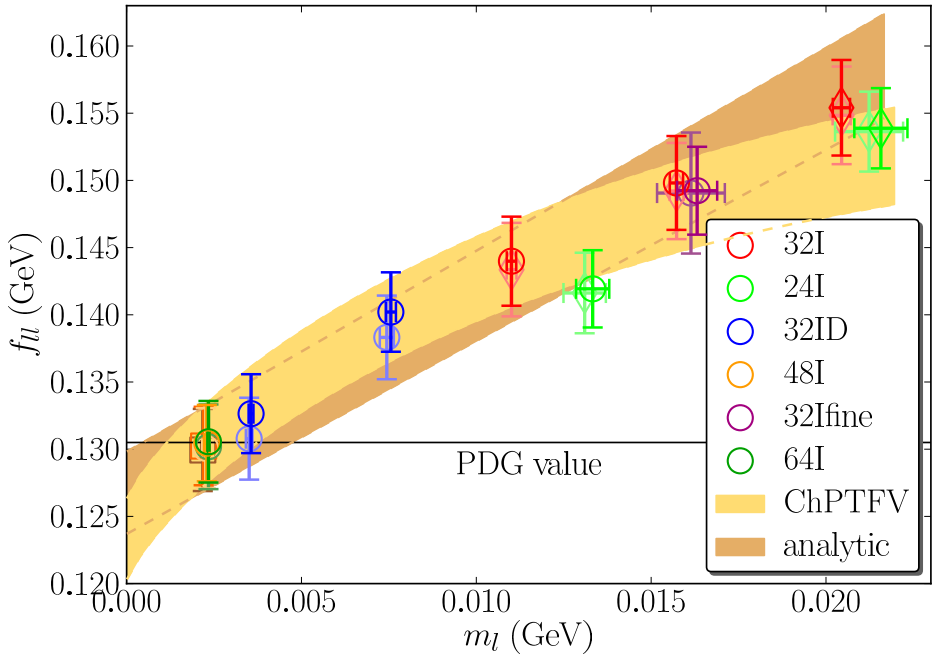


48^3: $Z_V = 0.7088(15)$, $Z_A = 0.71198(16)$, agree to 0.5%, so good chiral symmetry.

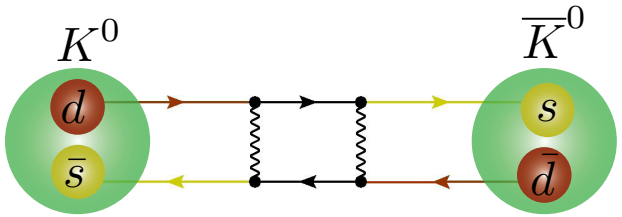
Preliminary Global Fit

New 48^3 and 64^3 data very close to physical point.





B_K



RBC/UKQCD value from PRD 84 (2011) 014503

$$B_K(\overline{\mathrm{MS}}, 3\,\mathrm{GeV}) = 0.529 \pm 0.005_{\mathrm{stat}} \pm 0.015_{\mathrm{chiral}} \pm 0.002_{\mathrm{finite\ V}} \pm 0.011_{\mathrm{pert}}$$

RBC/UKQCD value from PRD 87 (2013) 094514

$$B_K(\overline{\mathrm{MS}}, 3\,\mathrm{GeV}) = 0.535 \pm 0.008_{\mathrm{stat}} \pm 0.007_{\mathrm{chiral}} \pm 0.003_{\mathrm{finite\ V}} \pm 0.011_{\mathrm{pert}}$$

Using results from our 2 new, physical quark mass lattices gives

$$B_K(\overline{\mathrm{MS}}, 3\,\mathrm{GeV}) = 0.533 \pm 0.003_{\mathrm{stat}} \pm 0.000_{\mathrm{chiral}} \pm 0.002_{\mathrm{finite\ V}} \pm 0.011_{\mathrm{pert}}$$ (Preliminary)

$$\hat{B}_K = 0.754 \pm 0.004_{\mathrm{stat}} \pm 0.0015_{\mathrm{sys}}$$ (Preliminary)

Marked reduction in the statistical error and essentially no chiral extrapolation error.

Can reduce perturbative error through non-perturbative step scaling on the lattice, so that perturbative matching can be done at higher scales.

$$\varepsilon_K = \kappa_\varepsilon\, C_\varepsilon\, \hat{B}_K\, \mathrm{Im}(\lambda_t) \{\mathrm{Re}(\lambda_c)[\eta_1\, S_0(x_c) - \eta_3\, S_0(x_c, x_t)] - \mathrm{Re}(\lambda_t)\, \eta_2\, S_0(x_t)\}\, e^{i\pi/4}$$

B_K

$$\varepsilon = \frac{e^{i\pi/4}}{\sqrt{2}\,\Delta M_K}\left(\mathrm{Im}(M_{12}) + 2\,\frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}\,\mathrm{Re}(M_{12})\right) = \kappa_\varepsilon\,\frac{e^{i\phi_\varepsilon}}{\sqrt{2}}\left[\frac{\mathrm{Im}(M_{12}^{O^{\Delta S=2}})}{\Delta m_K}\right]$$

$-1.61\,(28) \times 10^{-4}$
RBC 2011

$C_\varepsilon = \dfrac{G_F^2\, F_K^2\, m_K\, M_W^2}{6\sqrt{2}\,\pi^2\,\Delta M_K}$

$\lambda_t = V_{ts}^*\, V_{td}$

Overall $|V_{cb}|^4$

$$\varepsilon_K = \kappa_\varepsilon\, C_\varepsilon\, \hat{B}_K\, \mathrm{Im}(\lambda_t)\,\{\mathrm{Re}(\lambda_c)[\eta_1\, S_0(x_c) - \eta_3\, S_0(x_c, x_t)] - \mathrm{Re}(\lambda_t)\,\eta_2\, S_0(x_t)\}\, e^{i\pi/4}$$

0.94 0.02
Buras,Guadagnoli, Isidori

$(\varkappa_\varepsilon)_{abs} = 0.924 \pm 0.006$
RBC 2011

$\eta_3^{NLO} \equiv \eta_{ct}^{NLO} \equiv 0.457 \pm 0.073$
$\eta_3^{NNLO} \equiv \eta_{ct}^{NNLO} \equiv 0.496 \pm 0.047$

Brod and Gorbahn, PRD 82 094026 (2010)
3% overall change in ε_K

Reminders about K_{l3}

Kl3 decays: $\Gamma_{K\to\pi l\nu} = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} I\, S_{EW}[1 + 2\Delta_{SU(2)} + 2\Delta_{EM}] |V_{us}|^2 |f_+(0)|^2$

Define form factors: $\langle \pi(p')|V_\mu|K(p)\rangle = (p_\mu + p'_\mu) f_+(q^2) + (p_\mu + p'_\mu) f_-(q^2)$

$$f_0(q^2) = f_+(q^2) + \frac{q^2}{m_K^2 - m_\pi^2} f_-(q^2)$$

Ratio method gives: $$\frac{\langle \pi|\bar{s}\gamma_0 u|K\rangle\langle K|\bar{u}\gamma_0 s|K\rangle}{\langle K|\bar{s}\gamma_0 s|K\rangle\langle \pi|\bar{u}\gamma_0 u|\pi\rangle} = |f_0(q^2_{\max})|^2 \frac{(M_K + M_\pi)^2}{4M_K M_\pi}$$

Traditional method: measure $|f_0(q_{\max})|^2$ and then try to measure slope and other discrete q values to get to $q^2 = 0$

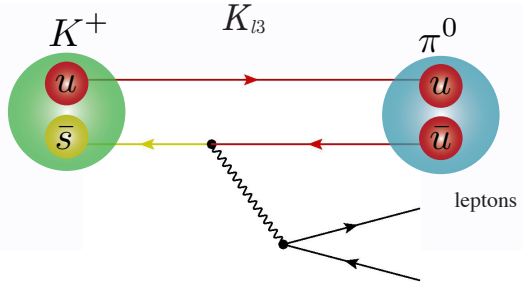
Recent improvement by RBC-UKQCD Collaborations, Eur. Phys. J. C69 (2010) 159

* Use twisted b.c. to allow a continuous set of $\vec{p}$ values, with $0 \lesssim q^2 \leqq q^2_{\max}$ (Boyle, et. al. JHEP 0705 (2007) 016)

* Measure $\langle \pi(p')|V_\mu|K(p)\rangle$ and extract $f_+(q^2)$ from momentum dependence

FNAL/MILC: use Ward-Takahashi identity to give: $f_0(q^2) = \frac{(m_s - m_l)}{(m_K^2 - m_\pi^2)} \langle \pi|S|K\rangle$

$K \to \pi$ semi-leptonic form factor (RBC+UKQCD Collaborations)

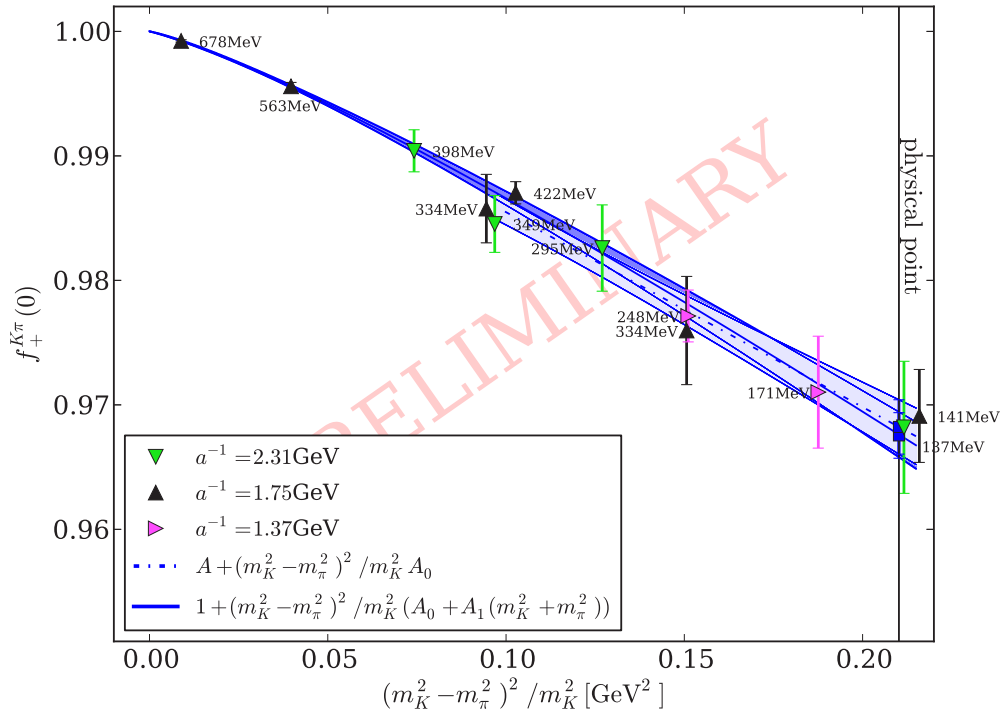


Phys.Rev.Lett. 100 (2008) 141601, Eur.Phys.J. C69 (2010) 159-167, arXiv:1305.7217
Talks by B. Mawhinney (Thursday, 8C, 17:30) and A. Jüttner (Thursday, 7C, 14:20)

- $\langle \pi | V | K \rangle \to f_+^{K\pi}(q^2 = 0)$
- part. twisted boundary conditions
- $N_f = 2 + 1$ domain wall fermions
- a^2-scaling study (0.09fm-0.14fm) $\to$ tiny cut-off effects
- physical point simulation

  m_π: 171–670MeV $\to$ arXiv:1305.7217
  137–670MeV $\to$ PRELIMINARY

  - polynomial ansatz describes data over entire mass range
  - phys. point data eliminates large systematic due to χ extrapolation



$$f_+^{K\pi}(0) = 0.9670(20)\binom{+0}{-42}_{m_q}(7)_{\text{FSE}}(17)_a$$

$$|V_{us}| = 0.2237\,(7)\,\binom{+10}{-0}_{m_q}(2)_{\text{FSE}}(4)_a$$

$\to \approx 0$ with phys. point data

precision $\lesssim 0.3\%$ feasible!

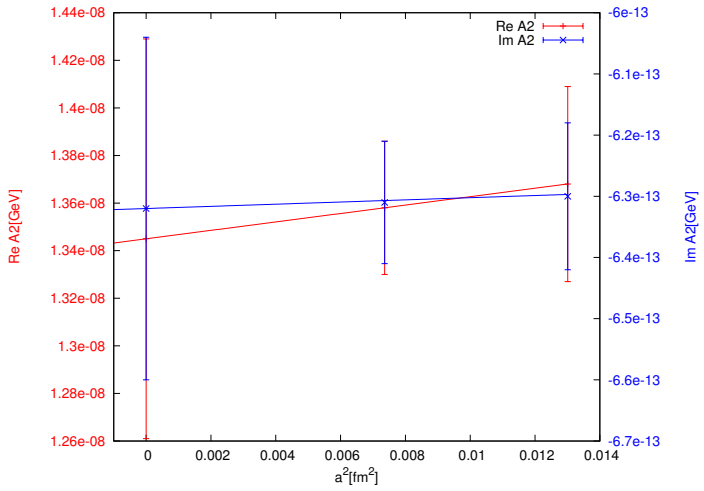
RBC/UKQCD K -> ππ, I = 2 Amplitudes

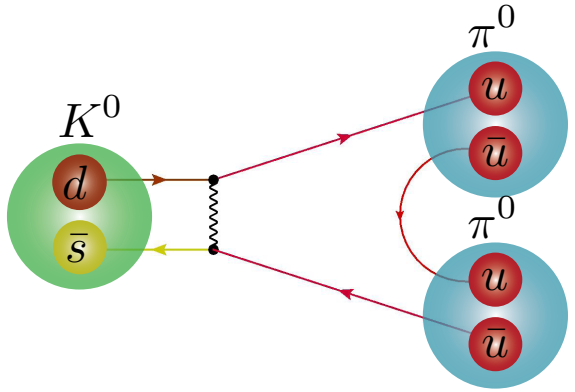
Previous published result (PRL 108 (2012) 141601 and PRD 86 (2012) 074513):

$$\mathrm{Re}\, A_2 = (1.381 \pm 0.046_{\mathrm{stat}} \pm 0.135_{\mathrm{sys\ no}\ a^2} \pm 0.207_{a^2}) \times 10^{-8}\ \mathrm{GeV}$$
$$\mathrm{Im}\, A_2 = -(6.54 \pm 0.46_{\mathrm{stat}} \pm 0.72_{\mathrm{sys\ no}\ a^2} \pm 0.98_{a^2}) \times 10^{-13}\ \mathrm{GeV}$$

Systematic error dominated by a^2 error estimate for the single DSDR ensemble.

Now have 2 lattice spacings from new ensembles with the Iwasaki gauge action, allowing a continuum limit extrapolation





$$\mathrm{Re}\, A_2 = (1.345 \pm 0.084_{\mathrm{stat}} \pm 0.135_{\mathrm{sys\ no}\ a^2} \pm 0.0_{a^2}) \times 10^{-8}\ \mathrm{GeV}$$
$$\mathrm{Im}\, A_2 = -(6.32 \pm 0.28_{\mathrm{stat}} \pm 0.72_{\mathrm{sys\ no}\ a^2} \pm 0.0_{a^2}) \times 10^{-13}\ \mathrm{GeV}$$

(Preliminary)

Markedly reduced statistical errors for Im A_2

Other systematic errors will be revisited and likely will be reduced.

2+1+1 Flavor Simulations

Errors in range of 0.3 - 1% possible for many quantities in isopsin symmetric QCD without electromagnetic effects.

Matching of matrix elements to continuum perturbation theory (needed to use continuum Wilson coefficients) more reliable at higher scales.

Dynamical charm quark required to reach these scales, say 3 to 5 GeV.

Want correct running between O(500) GeV (scale of kaon matrix elements) and 3-5 GeV, where matching will be done.

Also want GIM mechanism active for observables.

Need dynamical charm quark ensembles at weak couplings.

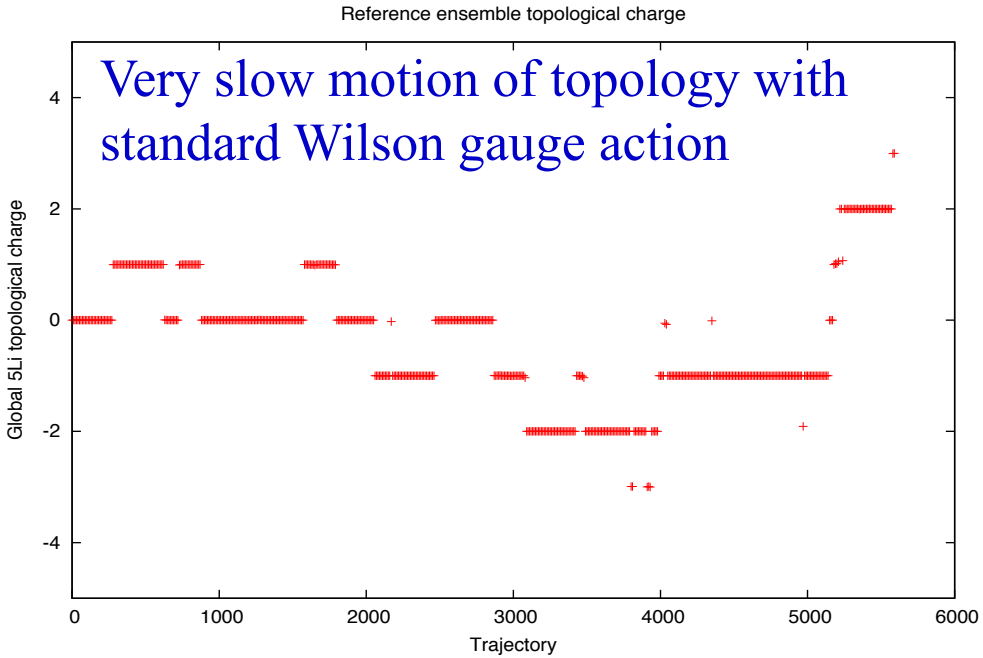
Problem: known algorithms lose ergodicity at weak coupling. In particular, global topology become frozen.

With Greg McGlynn, working on solutions to this problem

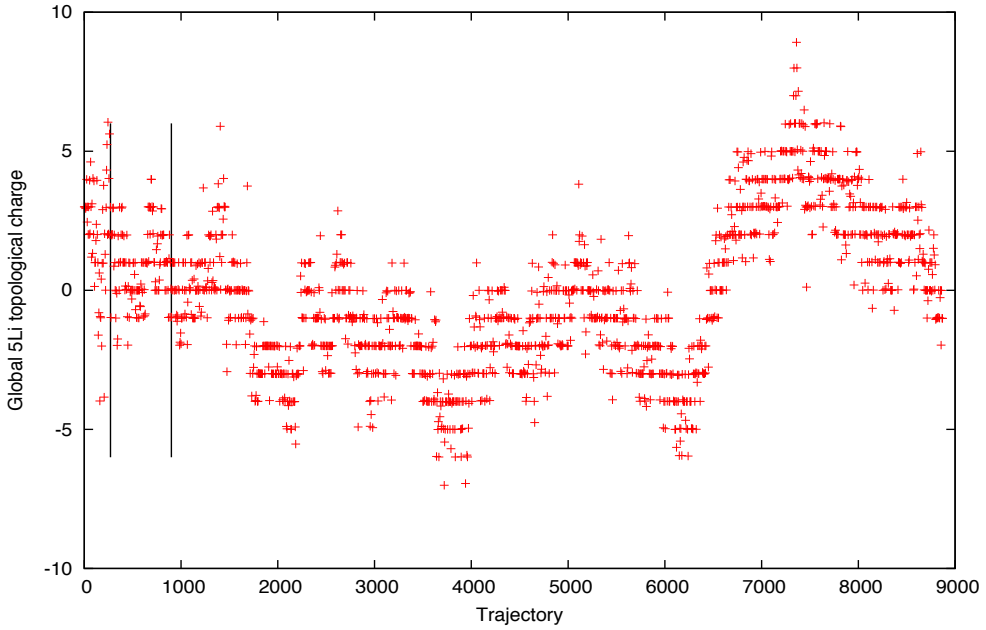
Adding term to the action, that is unimportant in the continuum limit, to enhance gauge field configurations which change topology.

DED = dislocation enhancing determinant

2+1+1 Flavor Simulations: Quenched, 1/a = 4 GeV



Marked improvement with DED term added, but current run not symmetric about Q = 0, indicating more statistics needed (longer run).



Conclusions

2+1 flavor QCD physical quark mass simulations on large $(5.5\ \text{fm})^3$ volumes yielding precise results.

Our measurement code produces a given statistical error 10x faster than before, largely due to algorithmic developments (EigCG and AMA).

Through our work on the BGQ, our access to early hardware at IBM and RBRC/BNL, a strong software team, we have been able to take advantage of early user time on the BGQ at ANL. We are 1-2 years ahead of schedule on these calculations.

The RBRC computing environment has been vital to this success. Our evolution code to generate lattices and our measurement package for kaon physics was developed and heavily tested on the RBRC and BNL BGQ.

We are preparing for 2+1+1 flavor calculations as our next major project.

The calculations reported here have been done on BGQ computers of ANL, LLNL, the University of Edinburgh, BNL and the RBRC.

Lattice calculation of the hadronic contributions to the muon anomalous magnetic moment

Tom Blum (UConn / RIKEN BNL Research Center)

RBRC Review, October 31, 2013

Collaborators

Work on g-2 done in collaboration with

HVP	HLbL
Christopher Aubin (Fordham U)	Saumitra Chowdhury (UConn)
Maarten Golterman (SFSU)	Masahi Hayakawa (Nagoya)
Santiago Peris (SFSU/Barcelona)	Taku Izubuchi (BNL/RBRC)
	Eigo Shintani (RBRC)
RBC/UKQCD	Norikazu Yamada (KEK)

New work with RBC/UKQCD collaboration

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a_μ(HLbL) Summary/Outlook

The magnetic moment of the muon

Interaction of particle with static magnetic field

$$V(\vec{x}) \quad = \quad -\vec{\mu} \cdot \vec{B}_{\text{ext}}$$

The magnetic moment $\vec{\mu}$ is proportional to its spin ($c = \hbar = 1$)

$$\vec{\mu} \quad = \quad g \left(\frac{e}{2m} \right) \vec{S}$$

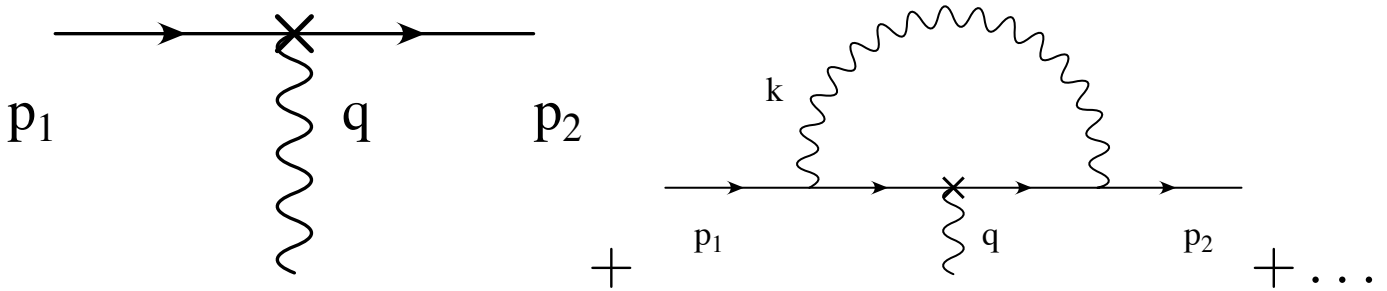
The Landé g-factor is predicted from the free Dirac eq. to be

$$g \quad = \quad 2$$

for elementary fermions

The magnetic moment of the muon

In interacting quantum (field) theory g gets corrections



$$\gamma^\mu \quad \rightarrow \quad \Gamma^\mu(q) = \left(\gamma^\mu F_1(q^2) + \frac{i\,\sigma^{\mu\nu}\,q_\nu}{2m} F_2(q^2) \right)$$

which results from Lorentz and gauge invariance when the muon is on-mass-shell.

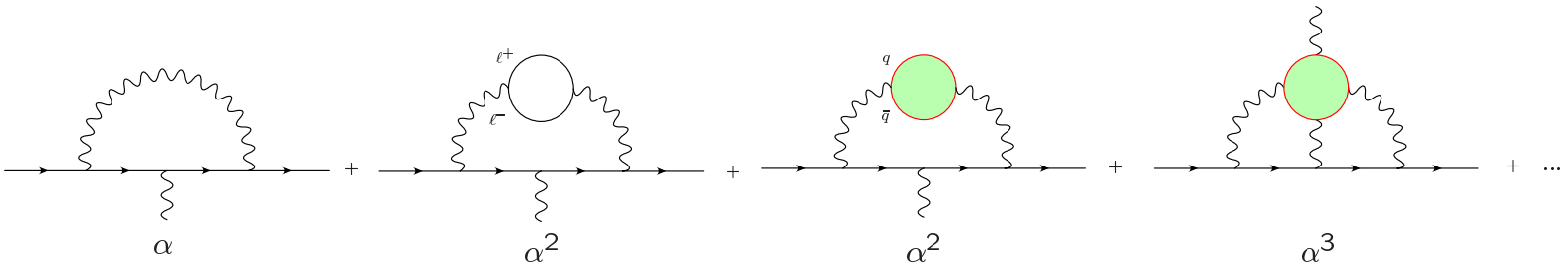
$$F_2(0) \quad = \quad \frac{g-2}{2} \equiv a_\mu \qquad (F_1(0) = 1)$$

(the anomalous magnetic moment, or anomaly)

The magnetic moment of the muon

Compute these corrections order-by-order in perturbation theory by expanding $\Gamma^\mu(q^2)$ in QED coupling constant

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137} + \dots$$

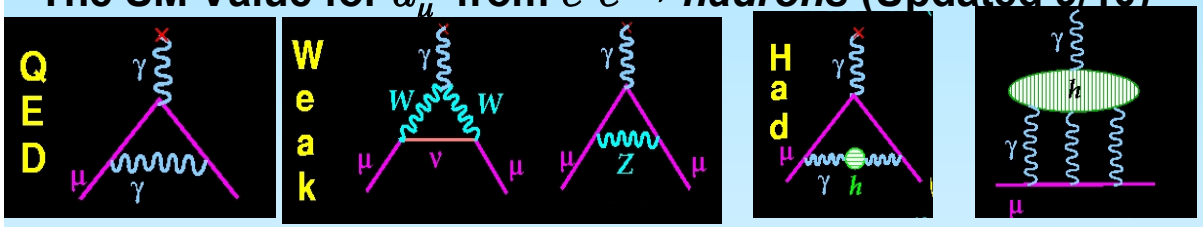


Corrections begin at $\mathcal{O}(\alpha)$; Schwinger term $= \frac{\alpha}{2\pi} = 0.0011614\dots$

hadronic contributions $\sim 6 \times 10^{-5}$ times smaller (leading error).

Value in the standard model

The SM Value for a_μ from $e^+e^- \to$ *hadrons* (Updated 9/10)



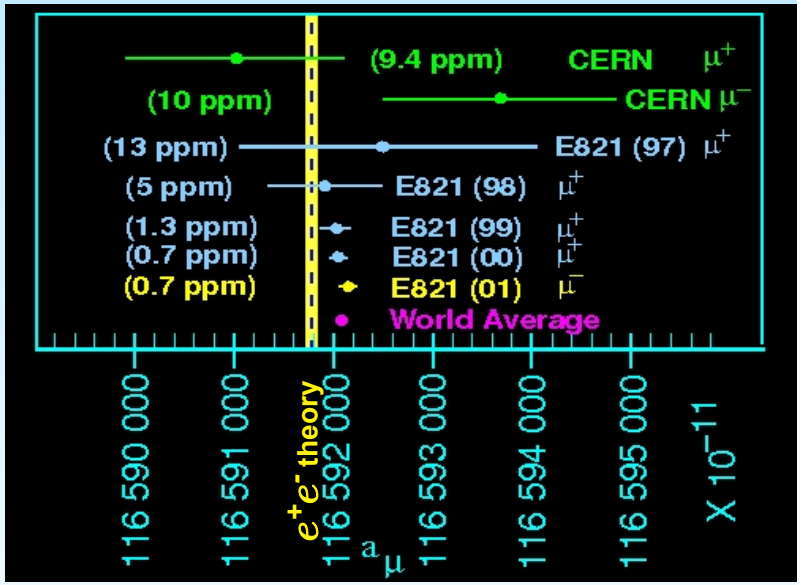
CONTRIBUTION	RESULT $(\times 10^{-11})$ UNITS
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 914 \pm 42_{\rm exp} \pm 14_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-98 \pm 1_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 793 \pm 51$

A. Höcker Tau 2010, U. Manchester September 2010

- new: QED thru $O(\alpha^5)$ [Aoyama, *et al.*, 2012]

Experimental value (dominated by BNL E821)

E821 achieved ± 0.54 ppm. The e^+e^- based theory is at the ~0.4 ppm level. Difference is ~3.6 σ



$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\,\text{ppm})$$
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11}$$

Theory: arXiv:1010.4180v1 [hep-ph] Davier, Hoecker, Malaescu, and Zhang, Tau2010

BOSTON UNIVERSITY

Lee Roberts - INT Workshop on HLBL 28 February 2011

New experiments + new theory

- Fermilab E989, $\sim$ 5 years away, 0.14 ppm
- J-PARC E34 ? (recently, lower priority than $\mu \to e$)
- a_μ(Expt)-a_μ(SM) $= 287(63)(51)$ ($\times 10^{-11}$), or $\sim 3.6\sigma$ (or 2.9)
- If both central values stay the same,
  - E989 ($\sim 4\times$ smaller error) $\to\sim 5\sigma$
  - E989+new HLBL theory (models+lattice, 10%) $\to\sim 6\sigma$
  - E989+new HLBL +new HVP (50% reduction) $\to\sim 8\sigma$
- Big discrepancy! (New Physics $\sim 2\times$ Electroweak)
- Lattice calculations crucial
- a_μ good for constraining and explaining BSM physics

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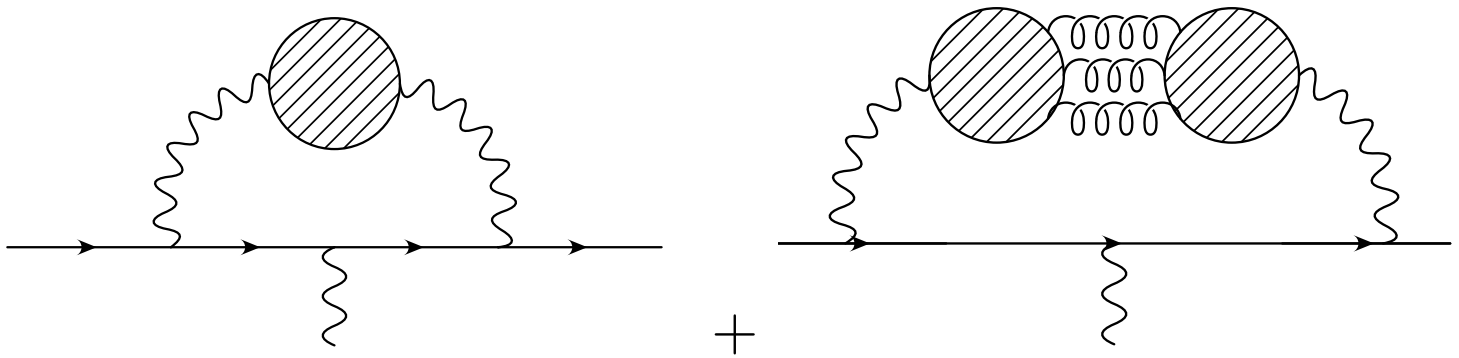
Hadronic vacuum polarization (HVP)



The blobs, which represent all possible intermediate hadronic states, are not calculable in perturbation theory, but can be calculated from

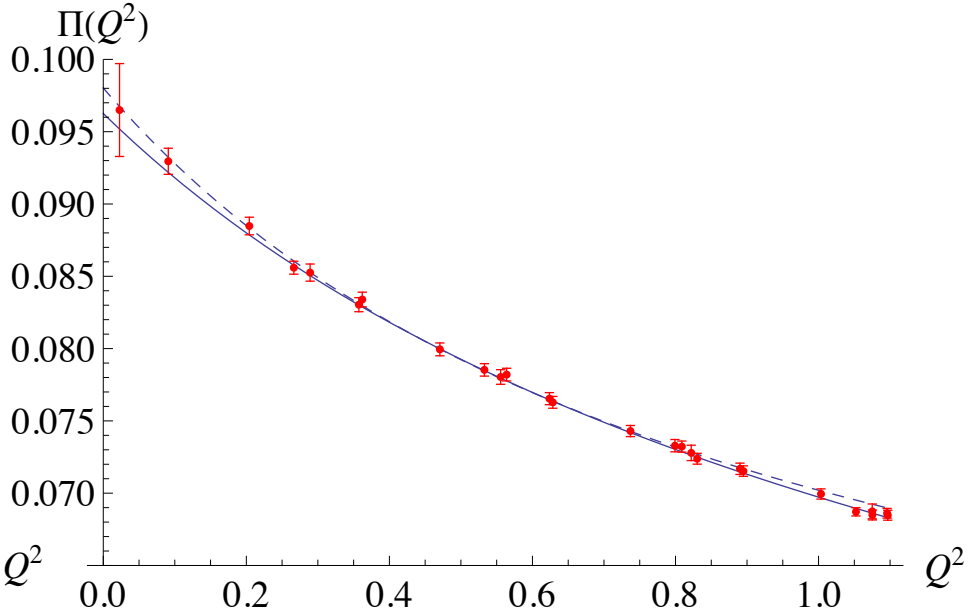
- dispersion relation + experimental cross-section for $e^+e^-(\text{and } \tau) \to \text{hadrons}$ $a_\mu^{\text{had}(2)} = \frac{1}{4\pi^2}\int_{4m_\pi^2}^{\infty} \text{d}s\, K(s)\sigma_{\text{total}}(s)$
- first principles using lattice QCD, $a_\mu^{(2)\text{had}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2\, f(Q^2)\,\Pi(Q^2)$ [Lautrup and de Rafael 1969, Blum 2002]

a_μ(HVP), lattice reg.

a_μ	N_f	errors	action	group
713(15)	2+1	stat.	Asqtad	Aubin, Blum (2006)
748(21)	2+1	stat.	Asqtad	Aubin, Blum (2006)
641(33)(32)	2+1	stat., sys.	DWF	UKQCD (2011)
572(16)	2	stat.	TM	ETMC (2011)
618(64)	2+1[1]	stat., sys.	Wilson	Mainz (2011)

[1] strange quark is quenched

HVP: Pade approximants [talk by M. Golterman (ABGP)]

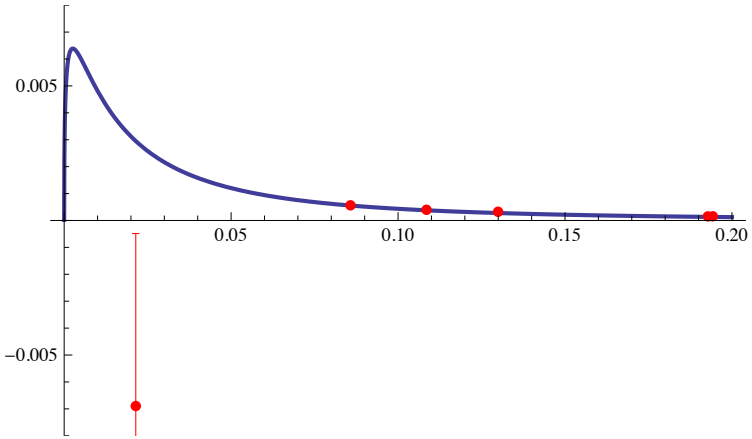


[1,1] corr. (solid) and VMD uncorr. (dashed)

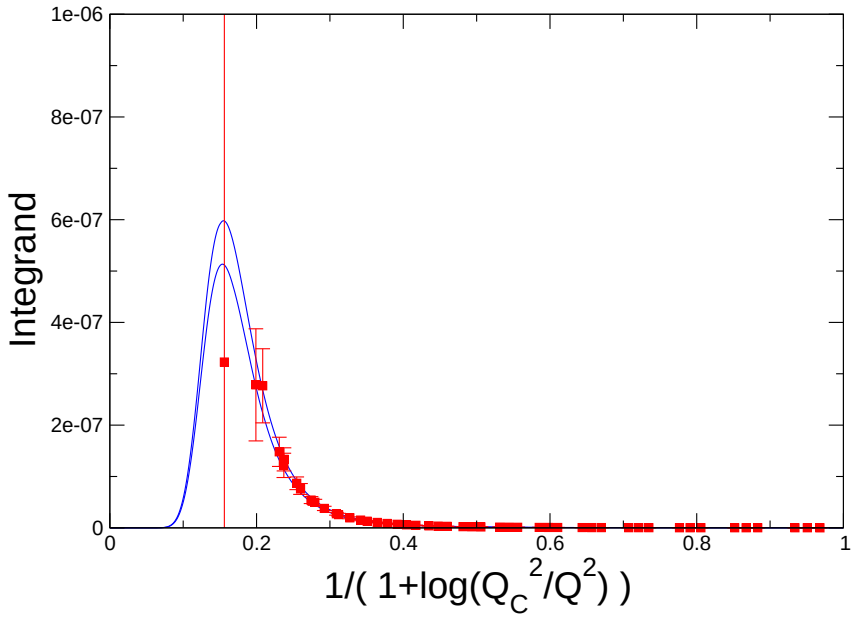
- Pade: model independent. Stieltjes function constrains Pade approximants
- Pade: 350(8)
- VMD: 413(8)
- 17% diff.
- both good fits
- tendency to undershoot low Q^2 points

$a = 0.06$ fm, $m_\pi \approx 400$ MeV, MILC Asqtad ensemble

a_μ(HVP) integrand: low momentum region



Integrand of $a_\mu^{\rm HLO}/(4\alpha^2)$ compared with data
(MILC, $a = 0.06$ fm , $m_\pi = 220$ MeV)



⇒ need more data at low Q^2 with smaller errors! In progress...

Talk by M. Golterman [Aubin, *et al.*, arXive:1205:3695] UKQCD [arXive:1107.1497]

a_μ(HVP) low momentum region: twisted b.c.'s

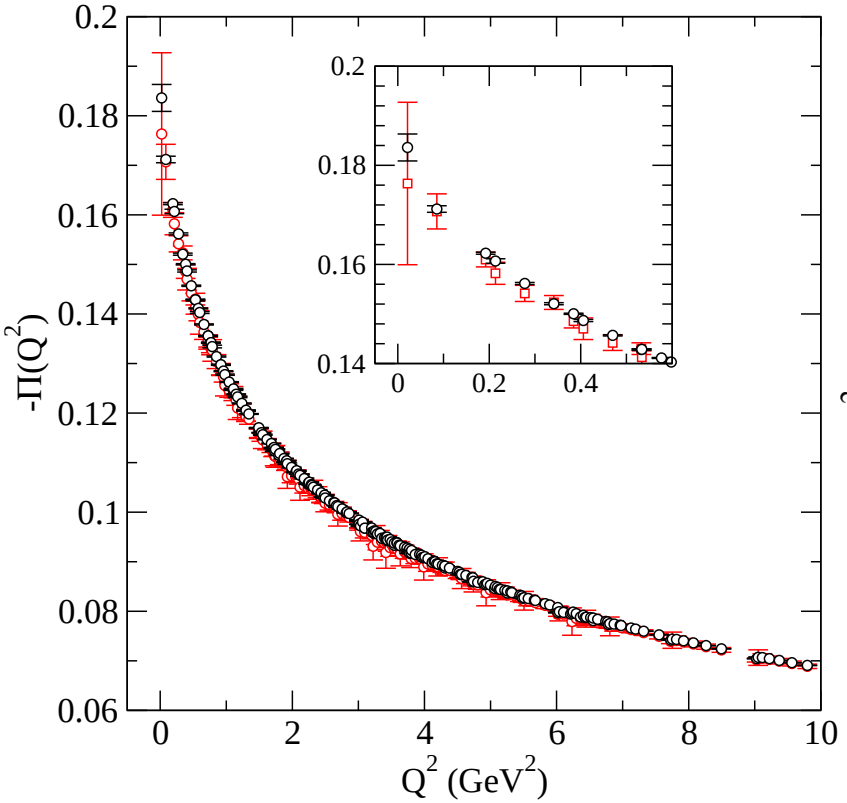
[See talk by Aubin, Lattice 2013, *et al.*, arXiv:1307.4701]

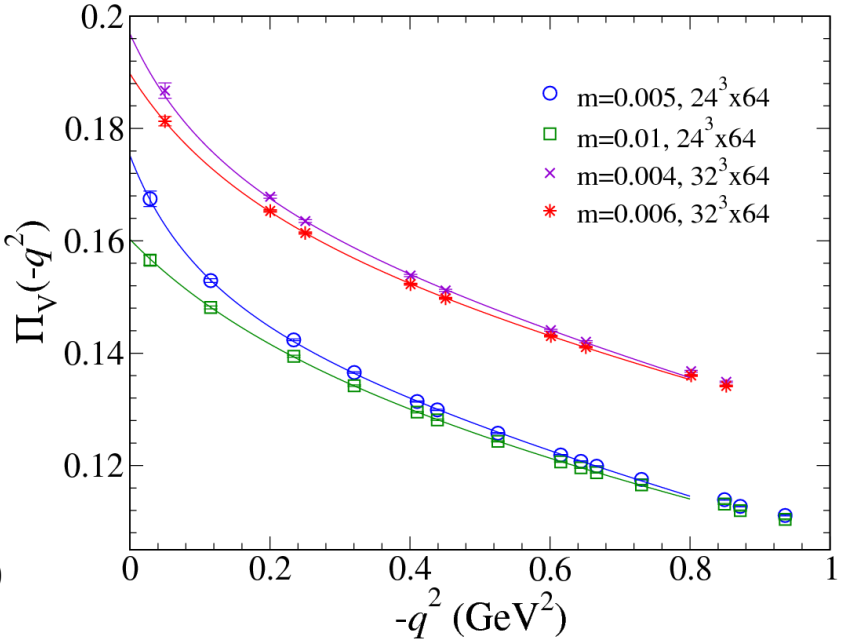
- Twisted b.c. $q_t(x) = \exp -i\theta_\mu q_t(x + L_\mu)$

$$p_\mu = \frac{2\pi n_\mu + \theta_\mu}{L_\mu} , \qquad n_\mu \in \{0, 1, \ldots, L_\mu - 1\} .$$

- Breaks isospin symmetry!
- WTI no=longer satisfied, $\Pi_{\mu\nu}$ is not transverse; $\Pi_{\nu\nu}$ is quadratically divergent
- Contact term $\sim \theta/a^2 L$ can be subtracted exactly
- Twisting increases statistical errors
- Is twisting worth it?

a_μ(HVP) Reducing statistical errors





Use AMA, 1400 LM / 704 sources, $48^3 \times 144$ (MILC), 20 configs, 2.6-20 $\times$ error reduction for same cost!. RBC/UKQCD preliminary DWF results also show large error reduction (see Shintani, Lattice 2013).

[AMA method: arXiv:1208.4349]

a_μ(HVP) Summary

Controlling errors at the 1% level

- Q^2 dependence
  - AMA
  - Twisted BC's or large box
  - Pade approximants for model independent fits
  - or avoid fit, analytically continue (DESY+KEK, Mainz)
- physical quark masses / large boxes
- disconnected diagrams / isospin breaking
- charm contribution

Will give confidence that dispersive calculation is right

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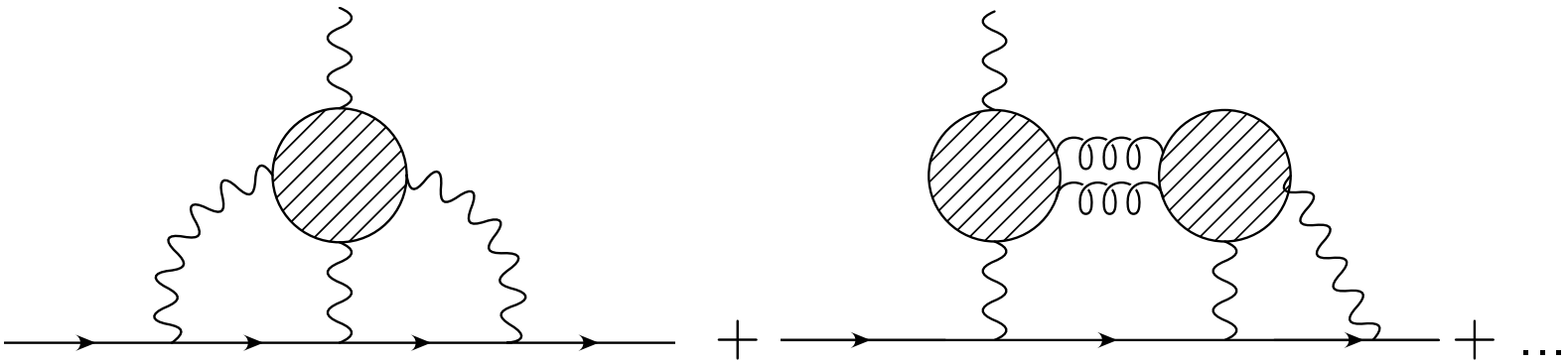
HLbL



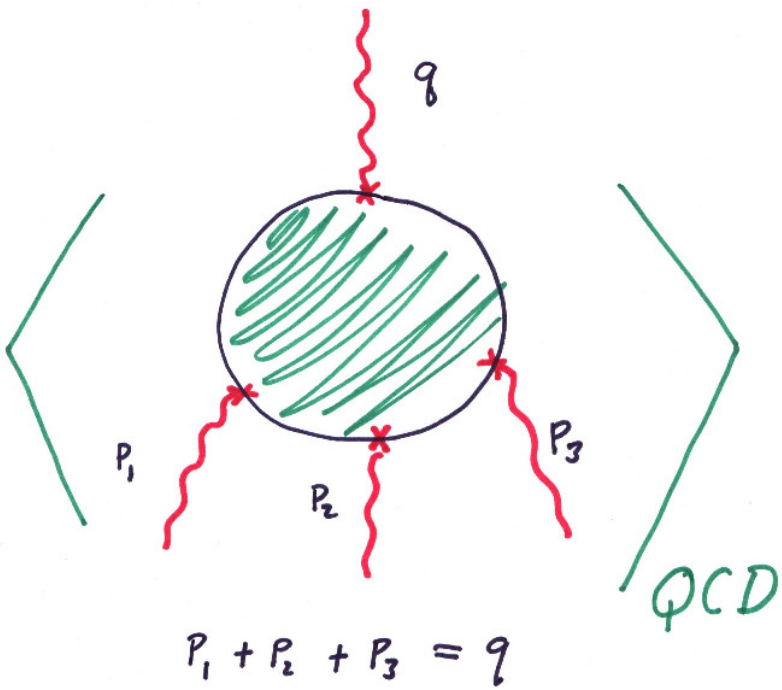
Blobs: all possible hadronic states

Model estimates put this $\mathcal{O}(\alpha^3)$ contribution at about $(10-12)\times 10^{-10}$ with a 25-40% uncertainty

No dispersion relation *a'la* vacuum polarization

Lattice regulator: model independent, approximations systematically improvable

Lattice QCD: conventional approach



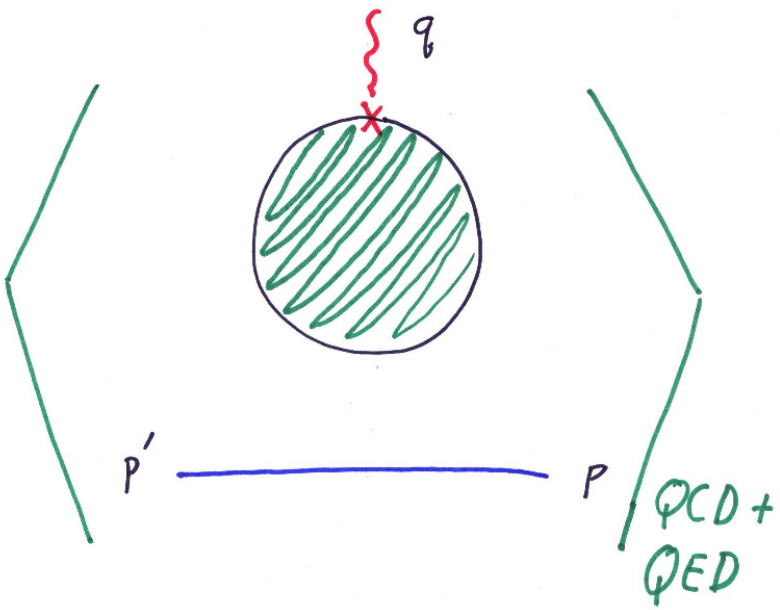
Correlation of 4 EM currents $\Pi^{\mu\nu\rho\sigma}(q, p_1, p_2)$

Two independent momenta +external mom q

Compute for all possible values of p_1 and p_2, (O(V^2)) four index tensor (32 Lorentz structures for g-2!)

several q,(extrap $q \rightarrow 0$), fit, plug into perturbative QED two-loop integrals

New approach (QCD+QED on the lattice)



Average over combined gluon *and* photon gauge configurations

Quarks coupled to gluons and photons

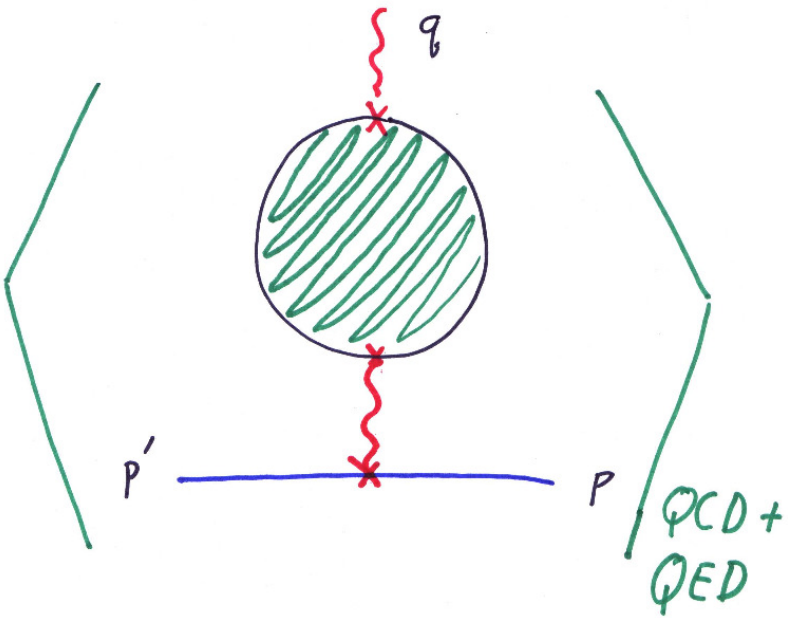
muon coupled to photons

[Hayakawa, *et al.* hep-lat/0509016;

Chowdhury *et al.* (2008);

Chowdhury Ph. D. thesis (2009)]

New approach (QCD+QED on the lattice)



Attach one photon by hand (see why in a minute)

Correlation of hadronic loop and muon line

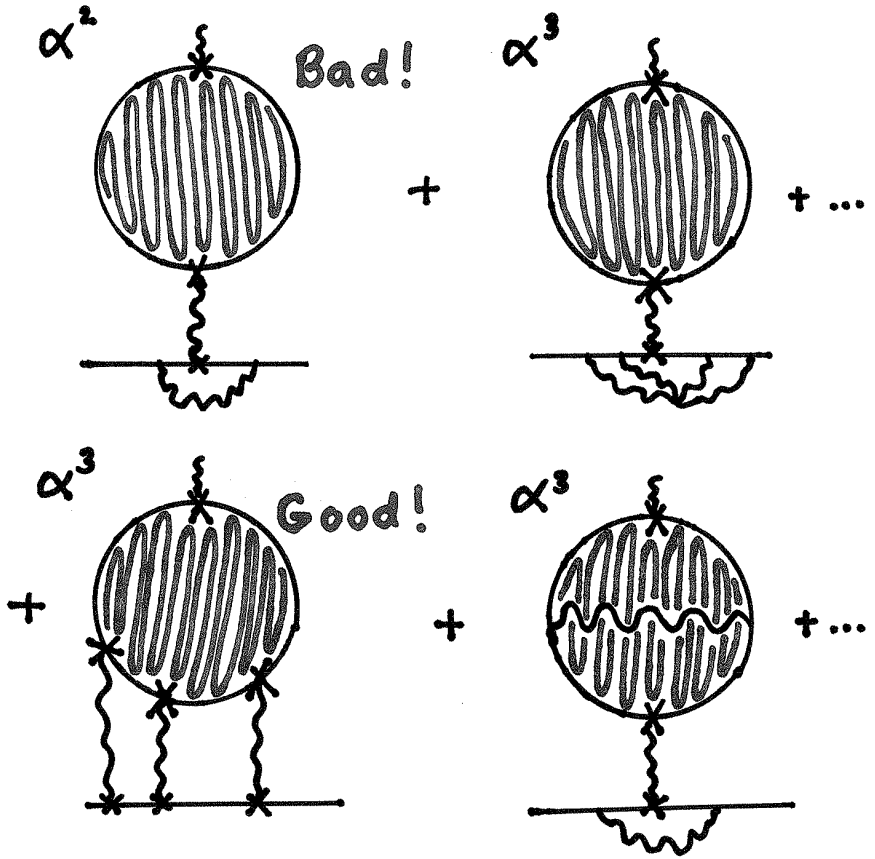
[Hayakawa, *et al.* hep-lat/0509016;

Chowdhury *et al.* (2008);

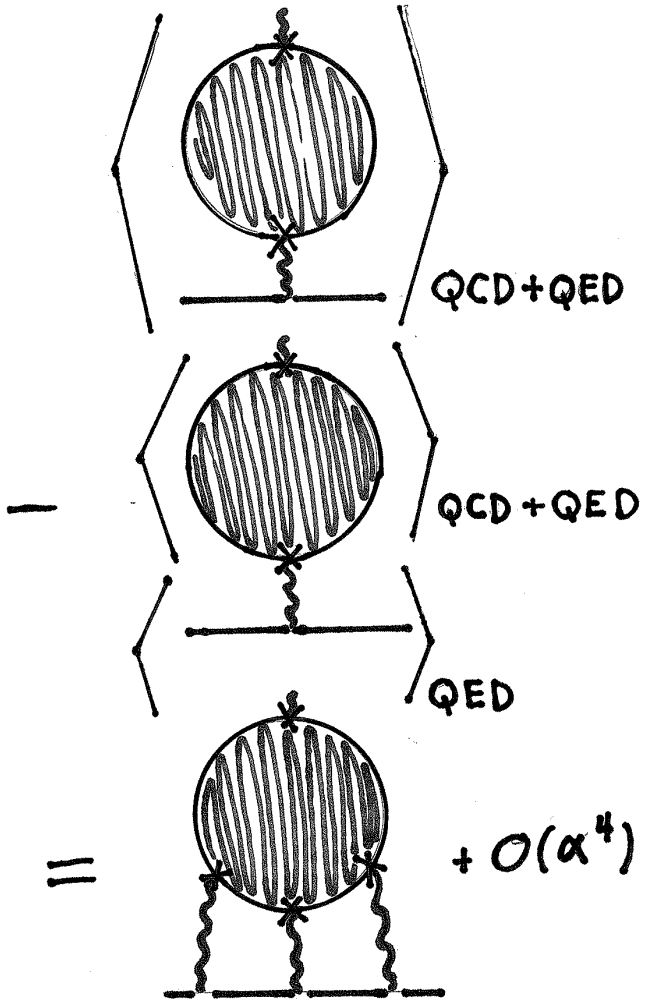
Chowdhury Ph. D. thesis (2009)]

New approach: Formally expand in α

The leading and next-to-leading contributions in α to magnetic part of correlation function come from



New approach: Subtraction of lowest order piece

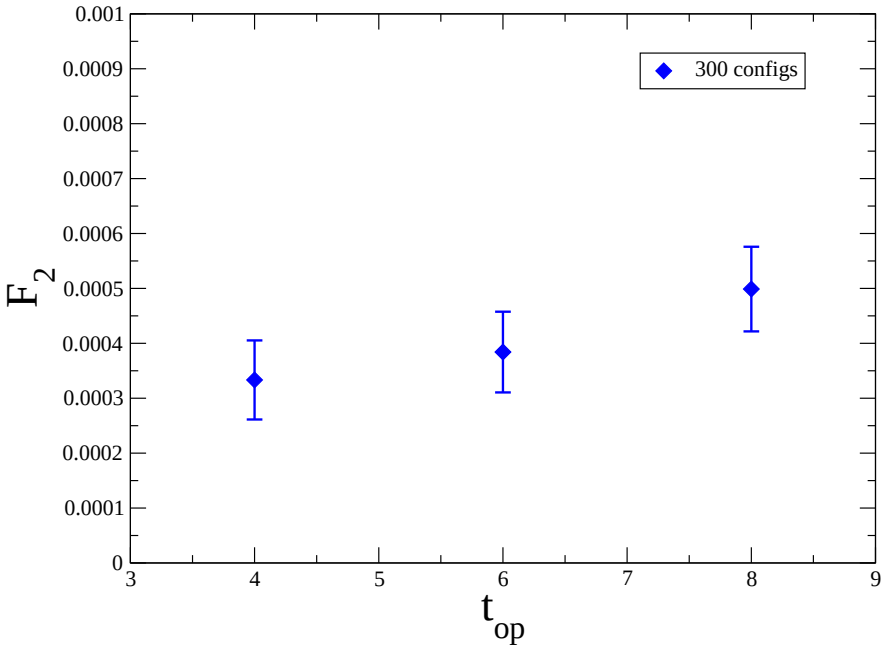


Subtraction term is product of separate averages of the loop and line

Gauge configurations identical in both, so two are highly correlated

In PT, correlation function and subtraction have same contributions except the light-by-light term which is absent in the subtraction

F_2 ($m_\mu/m_e = 40$, QED only) (Chowdhury Ph. D. thesis, UConn, 2009)



$F_2 = (3.96 \pm 0.70) \times 10^{-4}$

- $e = 1$
- $16^3 \times 32$ lattice size
- lowest non-zero momentum only
- **stat error only**

- Expected size of enhancement (compared to $m_\mu/m_e = 1$)
- Continuum PT result: $\approx 10(\alpha/\pi)^3 = 1.63 \times 10^{-4}$ ($e = 1$)
- roughly consistent with PT result, large finite volume effect

F_2, $m_\mu/m_e = 40$, finite volume study (QED only)

- Repeat calculation with 24^3 lattice volume
- Bigger box $F_2 = (1.19 \pm 0.32) \times 10^{-4}$
- Small box $F_2 = (3.96 \pm 0.70) \times 10^{-4}$
- finite volume effects manageable
- Continuum PT result: $\approx 10(\alpha/\pi)^3 = 1.63 \times 10^{-4}$ $(e = 1)$
- Roughly consistent with PT result

a_μ(HLbL) in 2+1f QCD+QED (PRELIMINARY)

- Same as before, but with $U = U(1) \times SU(3)$ [Duncan, *et al.*]
- QCD in the loop only (same in subtraction)
- QED in both loop and line
- 2+1 flavors (u, d, s) of DWF (RBC/UKQCD)
- $a = 0.114$ fm, $16^3 \times 32\,(\times 16)$, $a^{-1} = 1.73$ GeV
- $m_q \approx 0.013$, $m_\pi \approx 420$ MeV
- $m_\mu \approx 692$ MeV ($m_\mu^{\rm phys} = 105.658367(4)$ MeV)
- 100 configurations (one QED conf. for each QCD conf.)
- $(N_s/4)^3 = 64$ (loop) propagator calculations/configuration

$a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

- $a_\mu(\mathrm{HLbL}) = (-15.7 \pm 2.3) \times 10^{-5}$ (lowest non-zero mom, $e = 1$)
- Magnitude 5-10 times bigger, sign opposite from models
- HLBL amplitude depends strongly on m_μ (m_μ^2 in models)
- Non-leading terms in models can give large, negative values
- Check subtraction is working by varying $e = 0.84, 1.19$
  - HLbL amplitude ($\sim e^4$) changes by ~ 0.5 and 2 ✓
  - while unsubtracted amplitude stays the same ✓

$a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

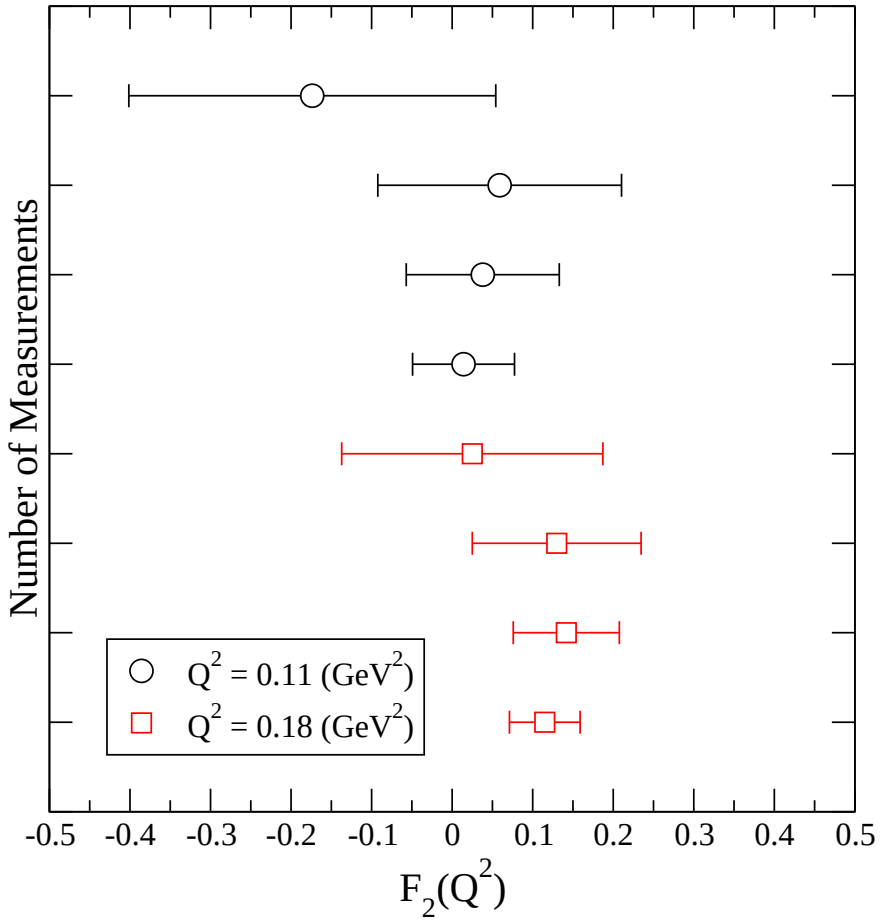
- Easy to lower muon mass (muon line is cheap)
- Try $m_\mu \approx 190$ MeV
- $a_\mu(\mathrm{HLbL}) = (-2.2 \pm 0.8) \times 10^{-5}$ (lowest non-zero mom, $e = 1$). Right direction...

$a_\mu(\mathrm{HLbL})$ in 2+1 flavor lattice QCD+QED

- Try larger lattice size, 24^3 $((2.7\ \mathrm{fm})^3)$
- Pion mass is smaller too, $m_\pi = 329$ MeV
- Same muon mass (190 MeV)
- $0.11 \lesssim Q^2 \lesssim 0.31\ \mathrm{GeV}^2$
- Use All Mode Averaging (AMA)
  - 6^3 (5^3) point sources/configuration $= 216$ (125)
  - AMA approximation: "sloppy CG", $r_{\mathrm{stop}} = 10^{-4}$

a_μ(HLbL) in 2+1f lattice QCD+QED (PRELIMINARY)

Stable as measurements increase (20 $\rightarrow$ 40 $\rightarrow$ 80 $\rightarrow$ 160 configs)



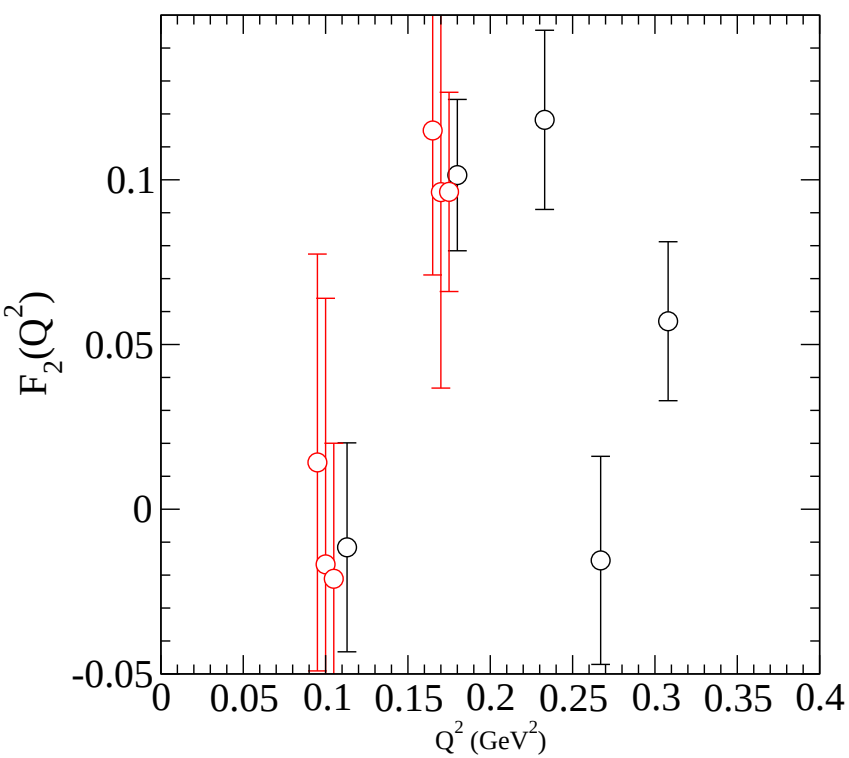
24^3 lattice size

$Q^2 = 0.11$ and 0.18 GeV^2

$m_\pi \approx 329$ MeV

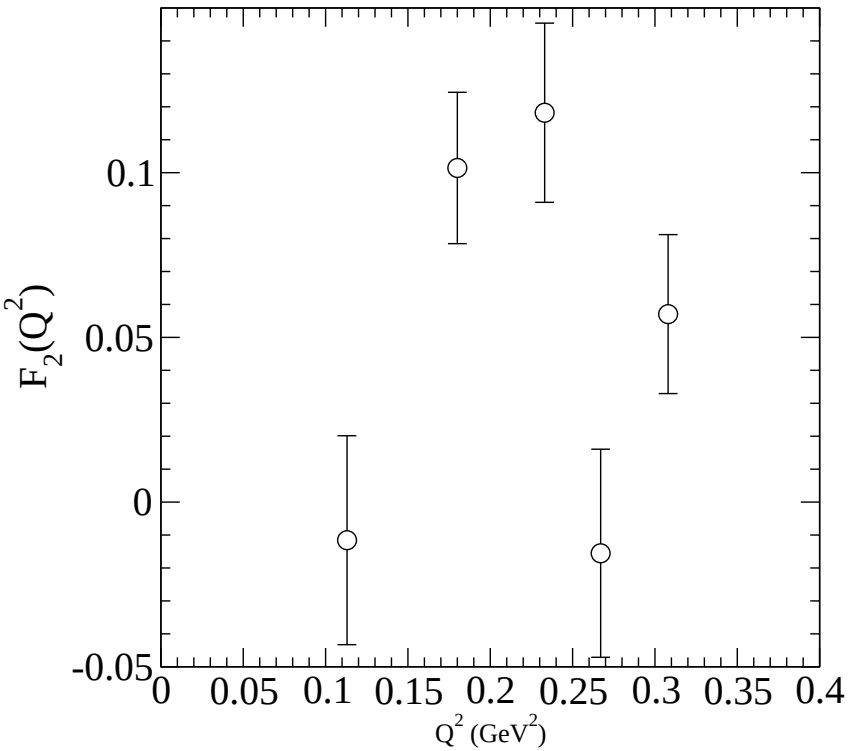
$m_\mu \approx 190$ MeV

a_μ(HLbL) in 2+1f lattice QCD+QED (PRELIMINARY)



- 157+190+375=722 configs, lowest 2 momenta
- 375 configs, highest 3 momenta
- Two points zero within large errors for momenta in 1 direction
- Statistics? 6, 24, 24, 6, 48 mom. combinations for Q^2 = 1, 2, 3, 4, 5
- Different directions correlated, cancelations

a_μ(HLbL) in 2+1f lattice QCD+QED (PRELIMINARY)



- Weighted average
- full jackknife will be done

$a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

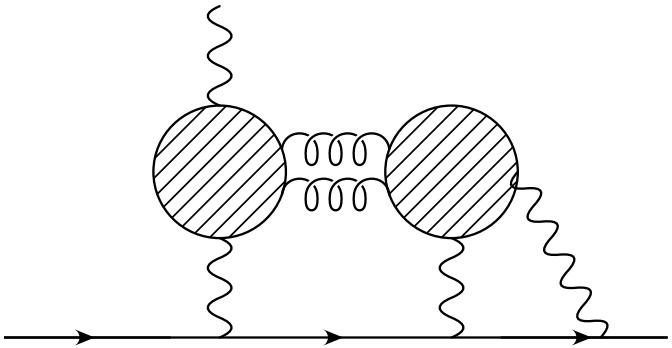
Signal may be emerging in the model ballpark:

- $F_2(0.23\ \mathrm{GeV}^2) = (0.118 \pm 0.027) \times \left(\frac{\alpha}{\pi}\right)^3$
- $F_2(0.18\ \mathrm{GeV}^2) = (0.101 \pm 0.023) \times \left(\frac{\alpha}{\pi}\right)^3$
- $F_2(0.11\ \mathrm{GeV}^2) = (-0.012 \pm 0.031) \times \left(\frac{\alpha}{\pi}\right)^3$
- $a_\mu(\mathrm{HLbL/model}) = (0.084 \pm 0.020) \times \left(\frac{\alpha}{\pi}\right)^3$

Lattice size 24^3, $m_\pi = 329$ MeV, $m_\mu \approx 190$ MeV

model value/error is "Glasgow Consensus" (arXiv:0901.0306 [hep-ph])

a_μ(HLbL) "Disconnected" diagrams (quark loops connected by gluons)

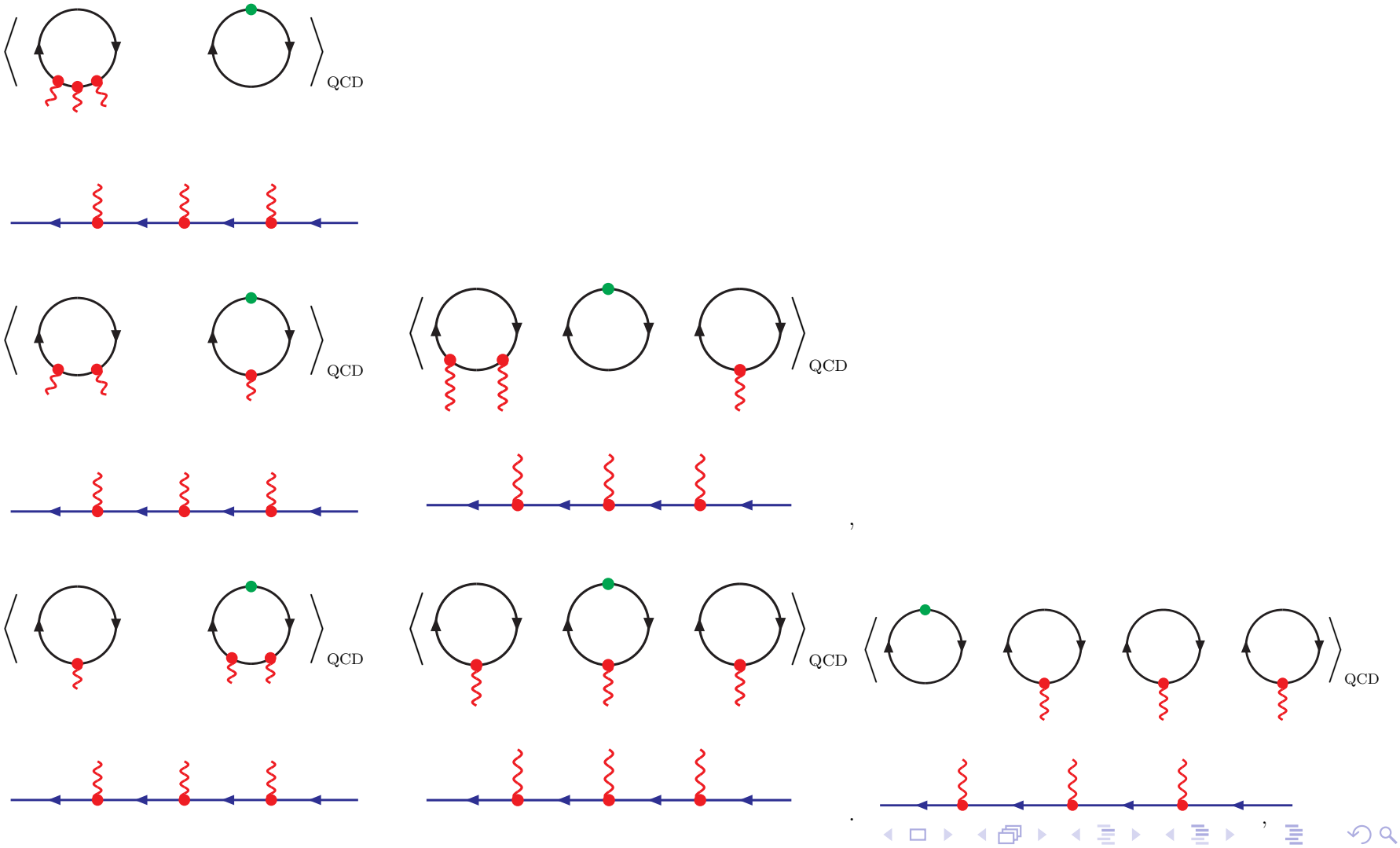


not calculated yet (not suppressed)

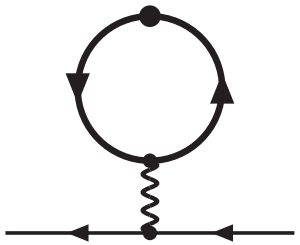
Several possibilities,

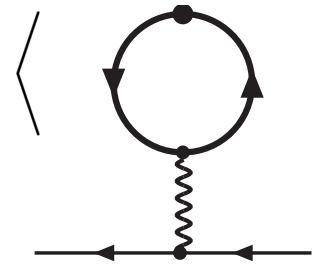
1. Use multiple valence quark loops (qQED)
2. Re-weight in α (T. Ishikawa) or dynamical QED in HMC, and use same non-perturbative method as for quenched QED
3. "$\not{A}$ SeqSrc" (see Izubuchi's talk) (no subtraction)

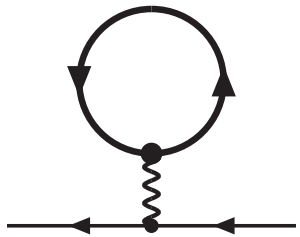
a_μ(HLbL) Disconnected quark loop diagrams

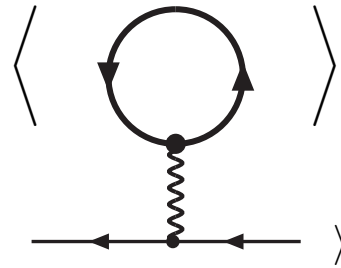


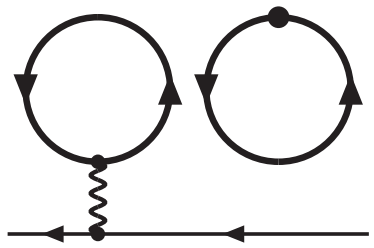
a_μ(HLbL) Disconnected quark loop diagrams in our non-perturbative method

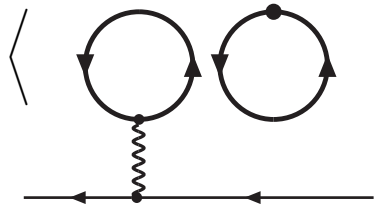
$\mathcal{M}_C = \left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$,

$\mathcal{S}_C =$ $\left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$ $\left\langle \right.$ $\left. \right\rangle_{\text{f-QED}}$.

$\mathcal{M}_{C'} = \left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$,

$\mathcal{S}_{C'} =$ $\left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$ $\left\langle \right.$ $\left. \right\rangle_{\text{f-QED}}$.

$\mathcal{M}_D = \left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$

$\mathcal{S}_D =$ $\left\langle \right.$  $\left. \right\rangle_{\text{QCD+f-QED}}$ $\left\langle \right.$ $\left. \right\rangle_{\text{f-QED}}$.

a_μ(HLbL) Disconnected quark loop diagrams in our non-perturbative method

Diagrams in non-perturbative method have various "multiplicities"

	$\mathcal{M}_C + \mathcal{M}_{C'}$	$\mathcal{M}_D$
LBL(4)	3	0
LBL(1,3)	0	3
LBL(2,2)	1	2
LBL(3,1)	2	1
LBL(1,1,2)	0	3
LBL(2,1,1)	1	2
LBL(1,1,1,1)	0	3

But, physical linear combination,
$\mathcal{M}_C + \mathcal{M}_{C'} + \mathcal{M}_D$
has overall factor of 3

$a_\mu(\mathrm{HLbL})$ more systematic errors

Need to address

- Finite volume
- $q^2 \to 0$ exptrap
- $m_q \to m_{q,\,\mathrm{phys}}$
- $m_\mu \to m_{\mu,\,\mathrm{phys}}$
- excited states/"around the world" effects
- $a \to 0$
- QED renormalization
- ...

Outline

Introduction

The hadronic vacuum polarization (HVP) contribution (O(α^2))

The hadronic light-by-light (HLbL) contribution (O(α^3))

a_μ(HLbL) Summary/Outlook

a_μ(HLbL) Summary/Outlook

- Demanding, but straightforward calculation
- Early HLbL lattice calculation encouraging
- Optimistic lattice+models+expt can reach 10% goal (INT WS on HLbL, Feb. 2011)
- White papers, prospects for lattice QCD:
  - USQCD white-paper (http://www.usqcd.org/collaboration.html)
  - Fundamental physics at the Intensity Frontier white-paper (arXiv:1205.2671 [hep-ex])
  - Project X Physics Study 2012 (arXiv:1306.5009)
- Expected precision
  - E989: 0.14 PPM (factor of 3-4 better than E821)
  - SM theory, HVP: 0.3% (factor of 2)
  - SM theory, HLbL 10% or better (?)
  - Same central values, a_μ discrepancy $\rightarrow$ 5-8 σ

Acknowledgments

- This research is supported in part by the US DOE
- Computational resources provided by the RIKEN BNL Research Center and USQCD Collaboration
- Lattice computations done on
  - QCDOC at BNL
  - Ds cluster at FNAL
  - q-series clusters at JLab

Experimental Group

Round 2

Back to Contents

Charged hadron measurement with the PHENIX VTX detector

RBRC Scientific Review 2013

Stefan Bathe

Baruch COLLEGE CUNY

RIKEN BNL Research Center

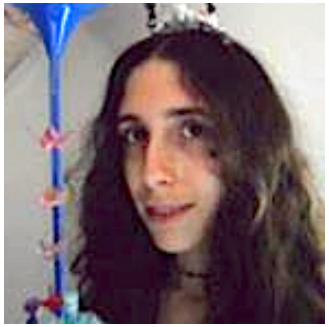
Experimental Baruch-CUNY Group

- PI Stefan Bathe
  - Assoc. Prof. (tenure track), RBRC Faculty Fellow
  - At Baruch since 2010

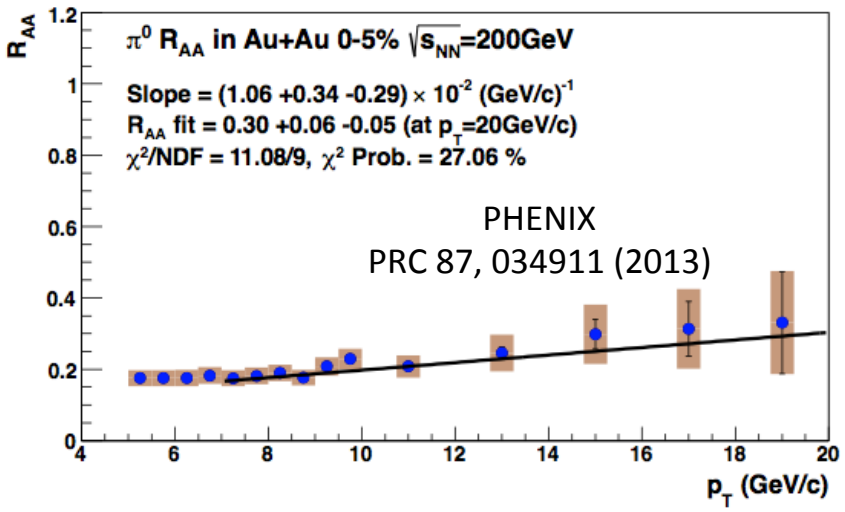




- GS Jason Bryslawskyj
  - Joined group Fall 2010
  - Undergraduate MIT
- GS Zachary Rowan
  - Joined group Fall 2012
  - Undergraduate SUNY Binghampton
- GS Kate Burleson-Lesser
  - Joined group Fall 2013
  - Undergraduate SUNY Albany



High p_T charged hadrons



- Single hadron R_{AA} still provides strongest constraints on energy loss mechanisms (T. Renk, Nucl.Phys.A904-905 2013 (2013) 725c)
- Currently best measurement at RHIC comes from neutral pions
- Charged hadrons have completely independent systematics and thus provide additional constraint

High-p_T Charged Hadron Analysis

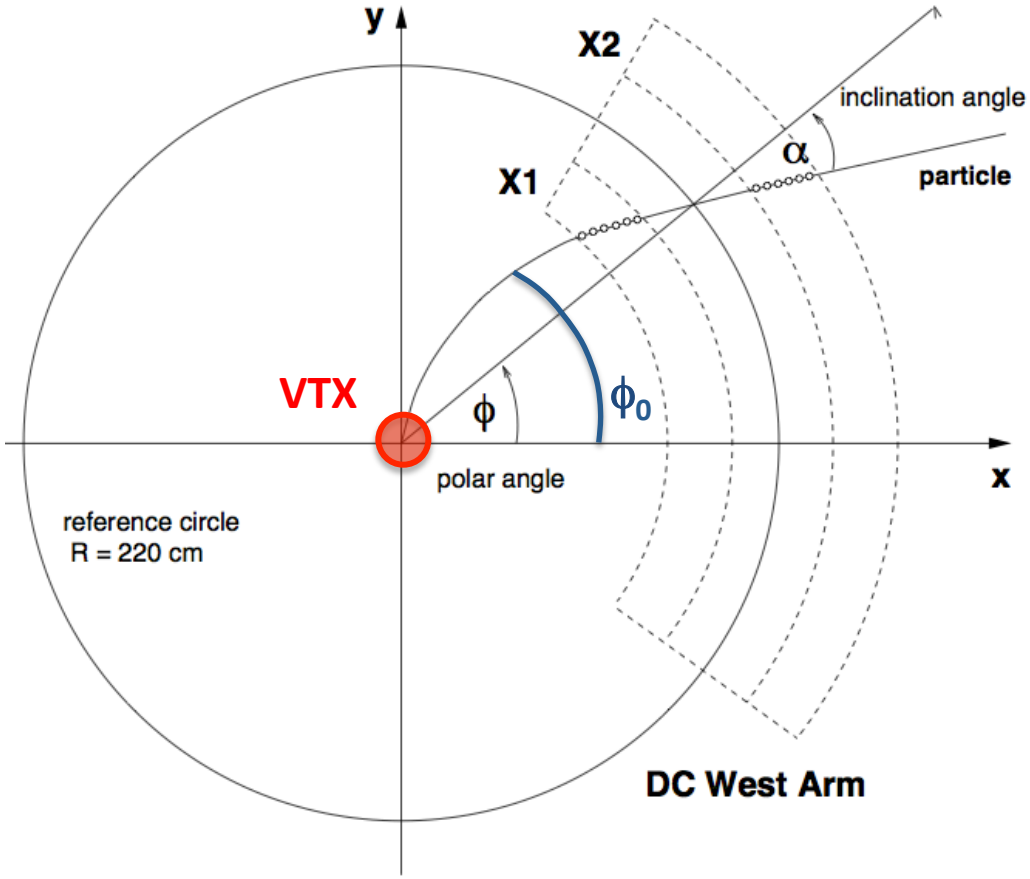
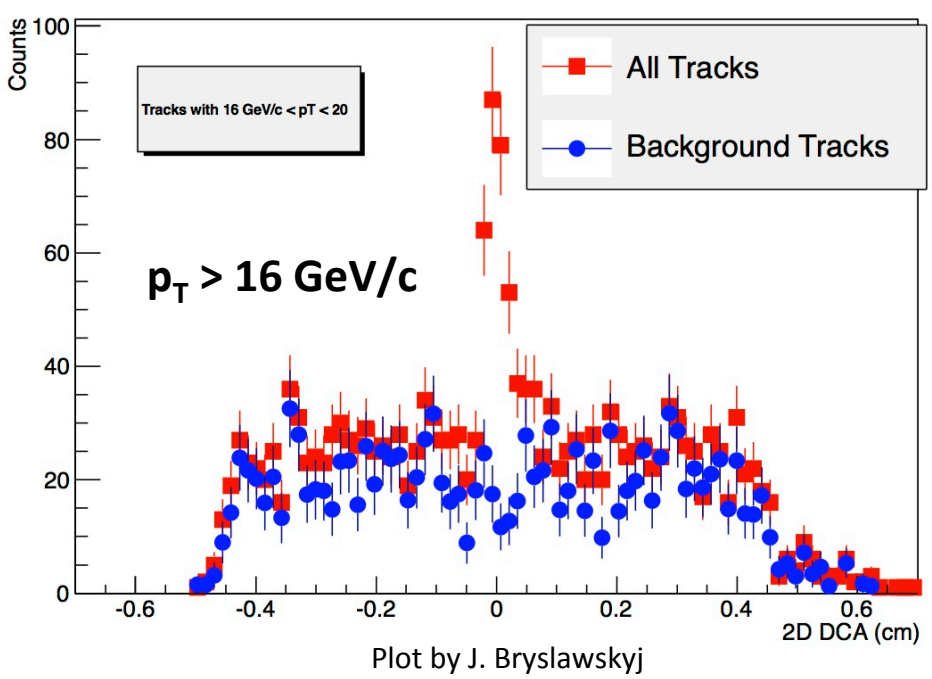


Figure adapted from J. Jia's thesis

- Problem in old PHENIX
  - No magnetic field in DC
  - Conversions, weak decays can mimic high p_T particle
  - Charged hadron measurement limited to $p_T < 10$ GeV/c
- Solution
  - VTX confirms primary vertex origin of particle
  - Conversions, weak decays rejected
  - VTX improves momentum resolution

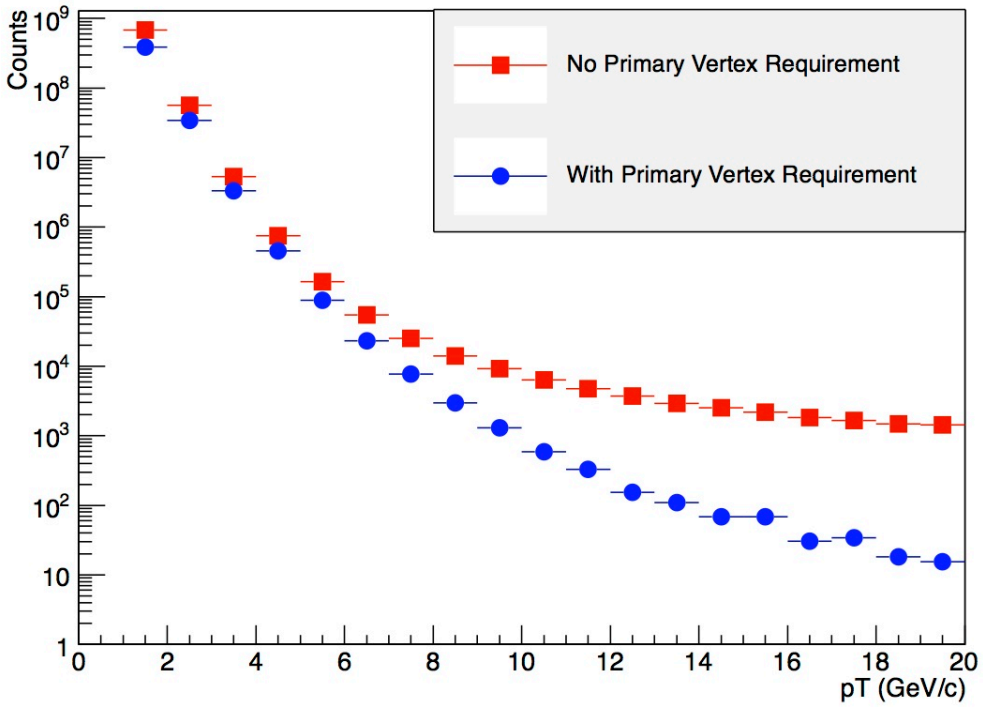
DCA distribution



Plot by J. Bryslawskyj

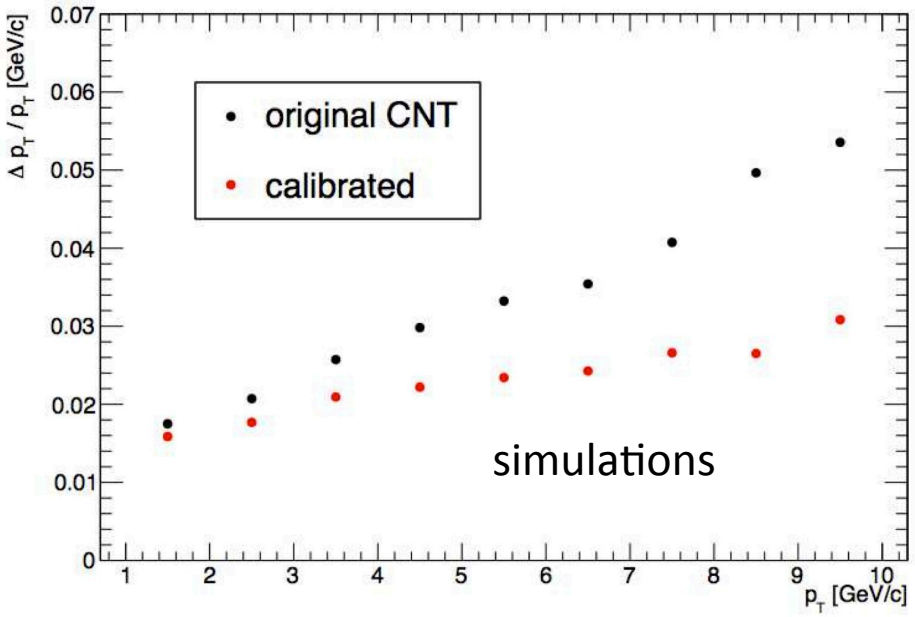
- DCA: Distance of Closest Approach of track projection to primary vertex
- Genuine charged hadrons have DCA = 0 (within detector resolution)
- Background tracks have any DCA
- Confirmed to work to at least 20 GeV/c

p_T distribution



- Without primary vertex requirement spectrum of charged hadron candidates dominated by background for $p_T > 6$ GeV/c
  - Becomes un-physically flat
- With primary vertex requirement spectrum continues to fall to at least 20 GeV/c
- Ultimately limited only by statistics (which will come)

Momentum resolution

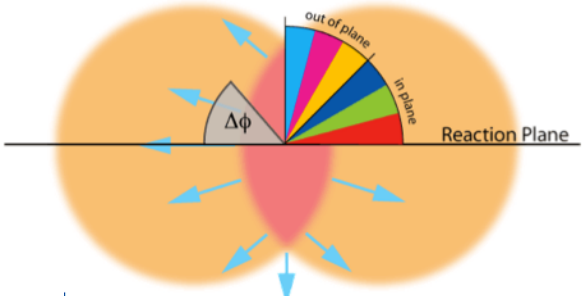


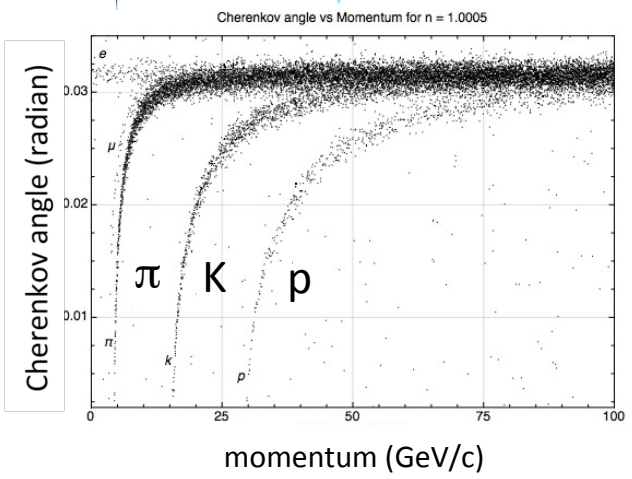
Plot by A. Dion

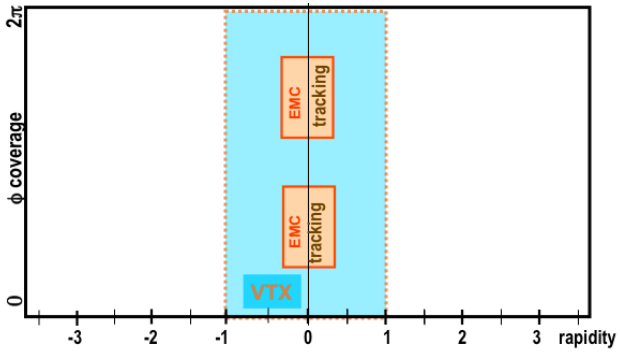
- Azimuthal angle measurement of VTX improves momentum resolution by at least factor 2 compared to angle measurement from DC alone

Outlook

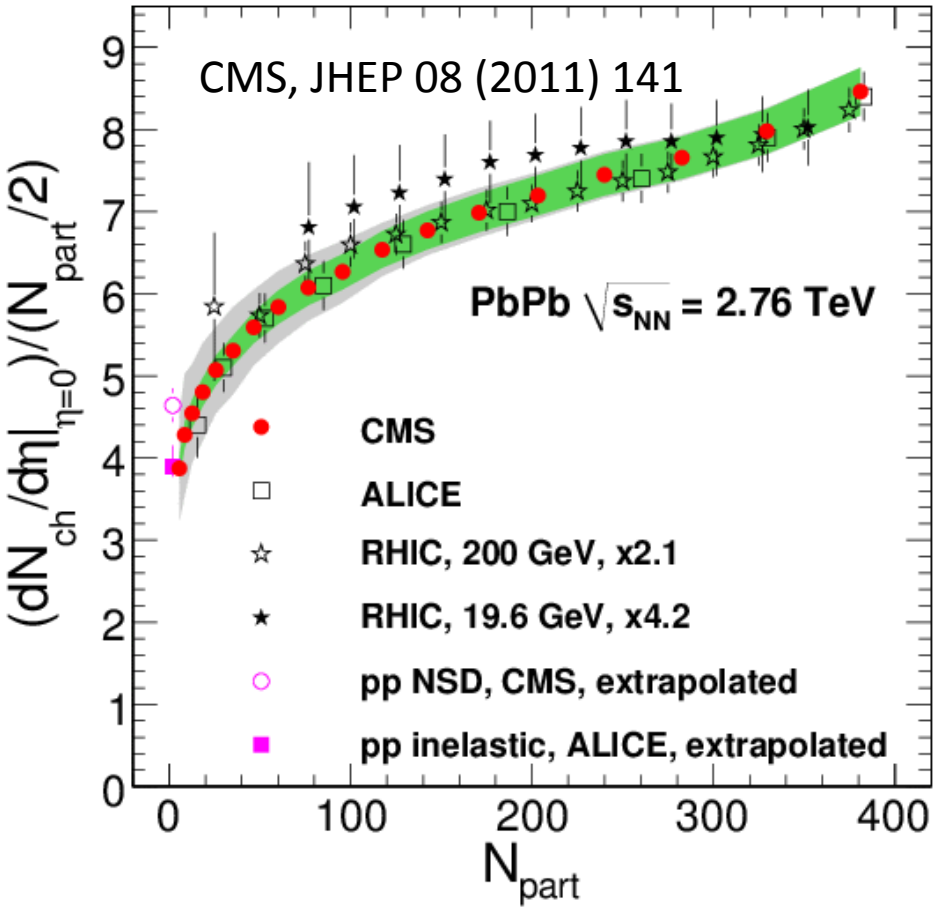
- Path length dependence via RxNP dependence
- Identify p, K, p with RICH
- γ-h with large VTX acceptance





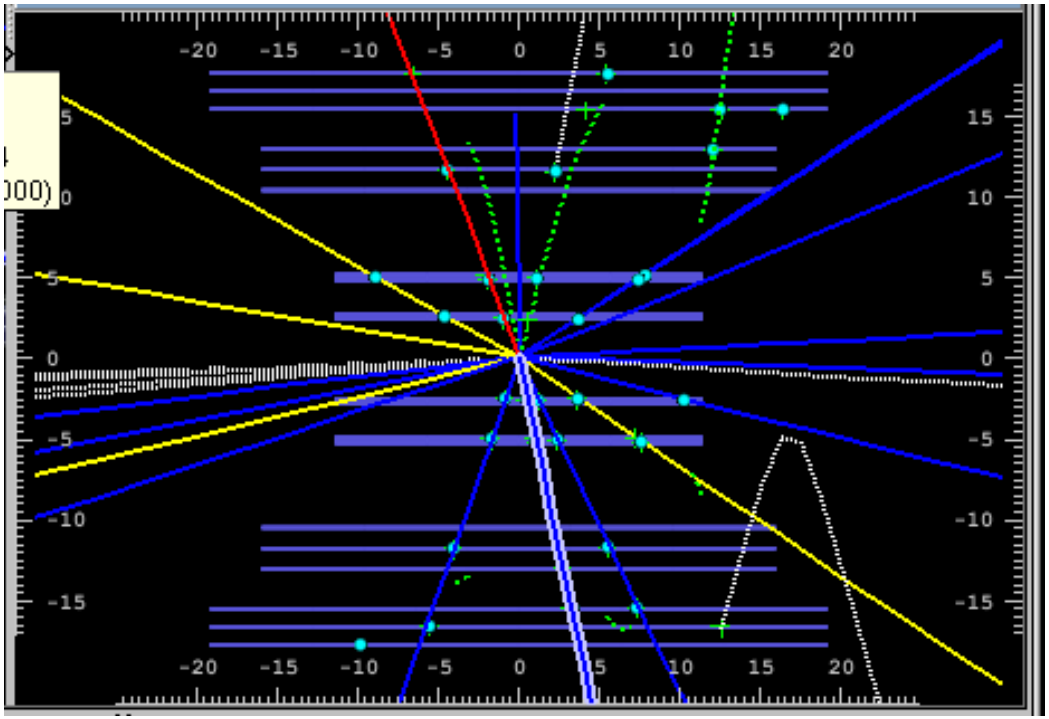


Multiplicity Measurement



- In light of recent discussion on collective effects in p(d)+A and p+p
  - Prudent to revisit and understand all aspects of peripheral A+A
  - In particular peripheral $dN_{ch}/d\eta$ not carefully mapped out at RHIC

Multiplicity Measurement with VTX



- Pixel layers
  - Low occupancy
    - 0.1 % in central Au+Au
  - Large acceptance
    - Almost 2 π in azimuth
    - $|\eta| < 1.4$ nominal
    - $|\eta| < 2.5$ for $|z| < 20$ cm
  - High sensitivity

- Plan to measure multiplicity from tracklets in field off data

Astrophysics/Theory Group

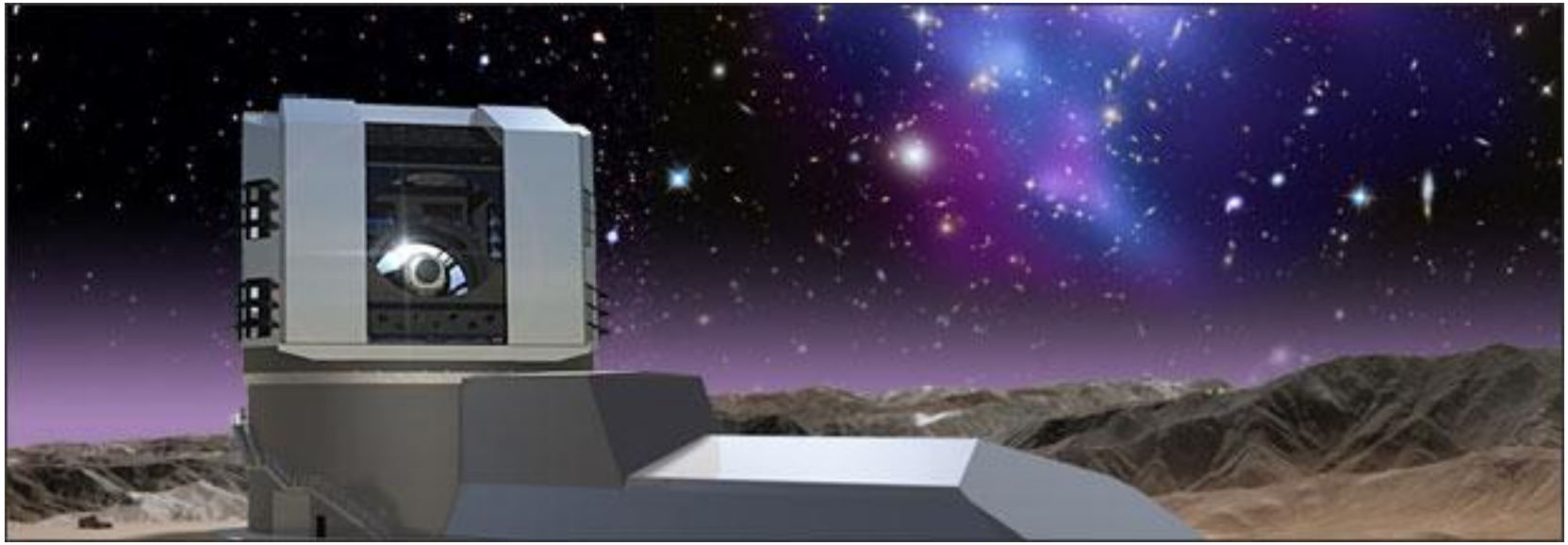
Round 2

Back to Contents

Astrophysics/Cosmology and RBRC

High Energy Astrophysics Laboratory
RIKEN Nishina Center

Toru Tamagawa



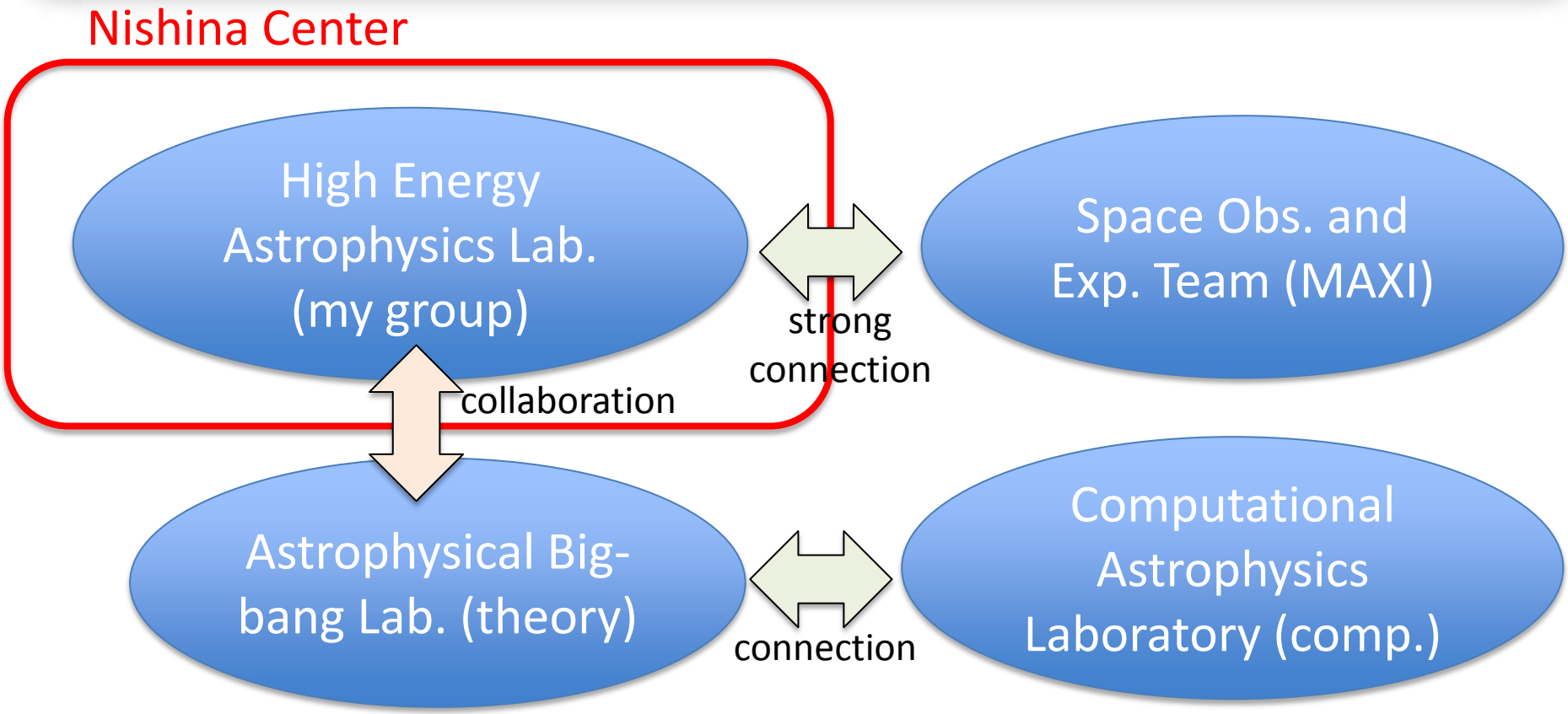
Executive summary

- I intend to join Large Synoptic Survey Telescope (LSST) via RBRC. (BNL is one of the core institute of LSST.)
- The LSST survey opens a new window in both Cosmology and Astrophysics. Since LSST is not a fully-international project, Joining via BNL is the best path.
- I will send postdoc(s) to RBRC. He/she contributes to LSST at BNL. Near future we may provide some devices (such as optical filters if possible).
- I will give an overview of astrophysics/cosmology and RBRC.

CONTENTS

- Astrophysics research at RIKEN
- Large Synoptic Survey Telescope (LSST)
- Time Domain Astrophysics and LSST
- Contribution to LSST at RBRC

1.1 Astrophysics Labs at RIKEN



- Two groups for experiment in astrophysics
- Two groups for theory in astrophysics
- No cosmology group

1.2 High Energy Astrophysics Lab.

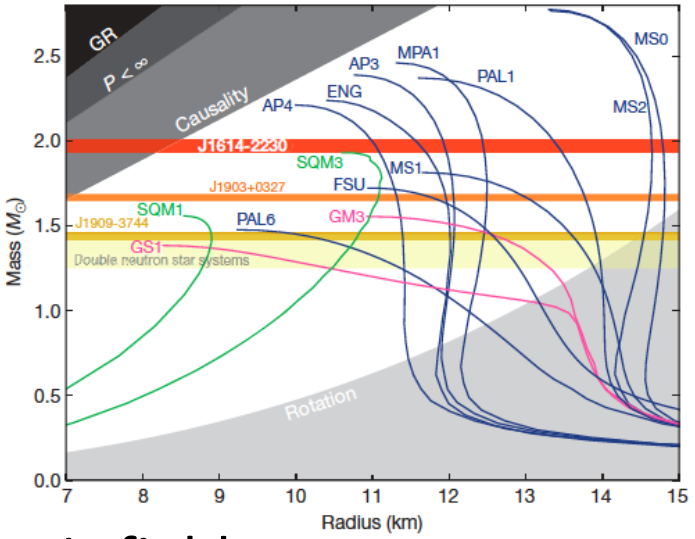
Research interests of my group: We are covering all the high energy phenomena in the universe. In particular,

- Nucleosynthesis in stars/supernovae

  low abundant elements, r-process elements, explosion mechanism of supernovae etc.

- Interior of Neutron stars

  Equation of state of neutron star matter.



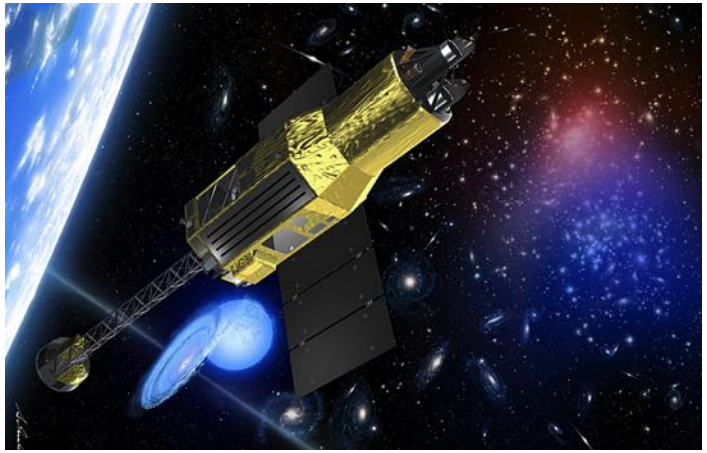
- Physics in strong gravitational and magnetic field

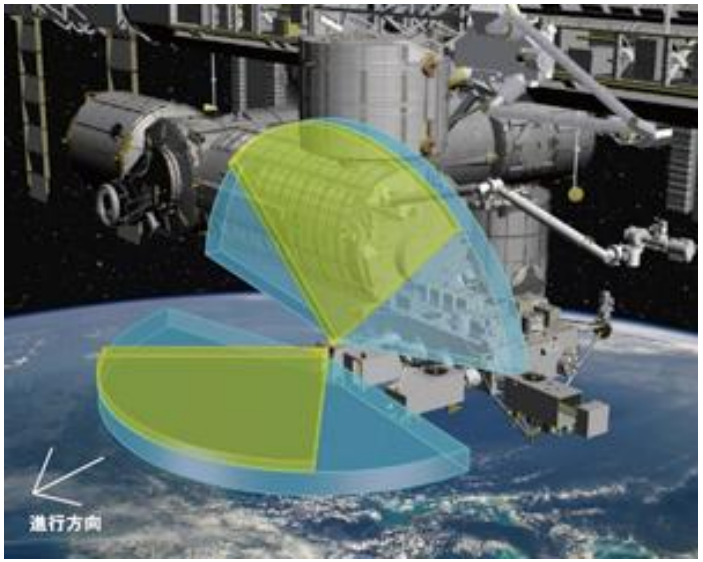
  Time-space structure around blackholes,

  tests of QED effects near magnetars in the magnetic field of 10^{15} gauss.

1.3 Projects of HEA Lab.

- ASTRO-H (JAXA) for high resolution spectroscopy dE=6eV@6keV, under construction, launch in 2015--
- GEMS (NASA/RIKEN/JAXA) for world's first deep X-ray polarimetry, project pending, launch in 2019 or later
- MAXI (RIKEN/JAXA) and Swift (NASA) for monitoring X-ray/gamma-ray sky in operation



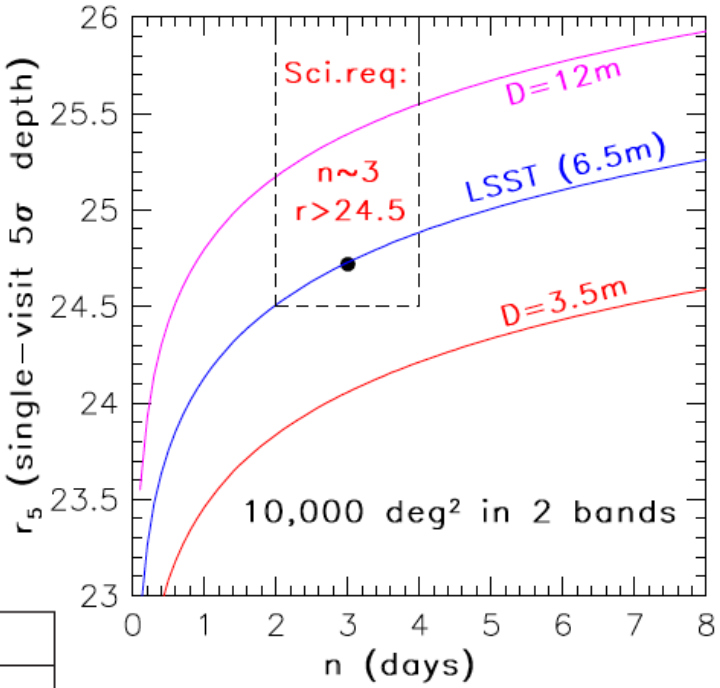


We are searching the next project we can contribute (2020-)

2.1 What is LSST?

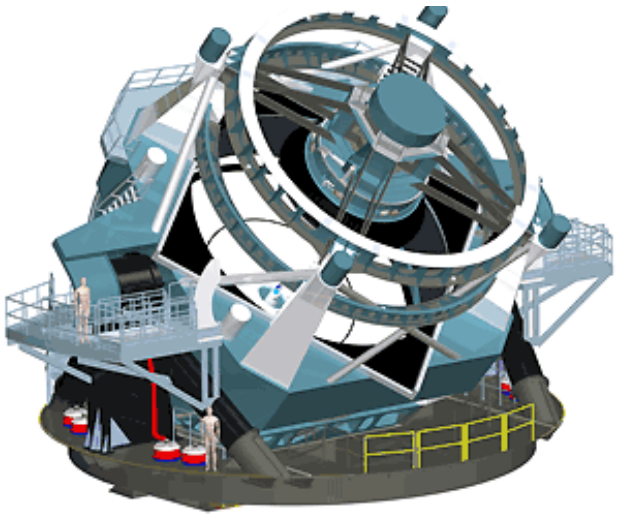
- Large Synoptic Survey Telescope
  WIDE, FAST, and DEEP
- Main Science Themes

✓ Probing Dark Energy and Dark Matter
✓ Taking an Inventory of the Solar System
✓ Exploring the Transient Optical Sky
✓ Mapping the Milky Way



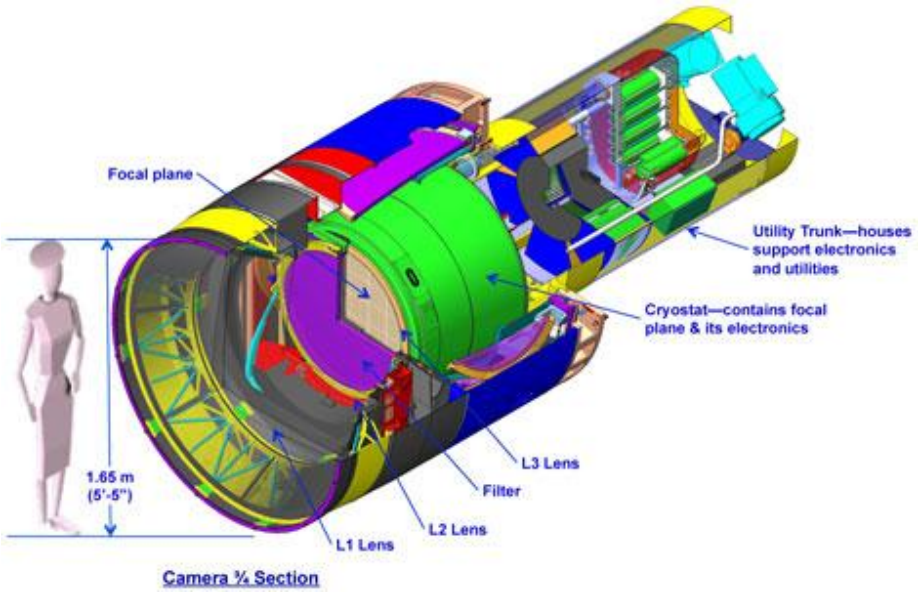
Quantity	Baseline Design Specification
Optical Config.	3-mirror modified Paul-Baker
Mount Config.	Alt-azimuth
Final f-ratio, aperture	f/1.234, 8.4 m
Field of view, étendue	9.6 deg^2, 319 m^{2}deg^2
Plate Scale	50.9 μm/arcsec (0.2" pix)
Pixel count	3.2 Gigapix
Wavelength Coverage	320 – 1050 nm, *ugrizy*
Single visit depths^a (5σ)	23.9, 25.0, 24.7, 24.0, 23.3, 22.1
Mean number of visits	56, 80, 184, 184, 160, 160
Final (coadded) depths^a	26.1, 27.4, 27.5, 26.8, 26.1, 24.9

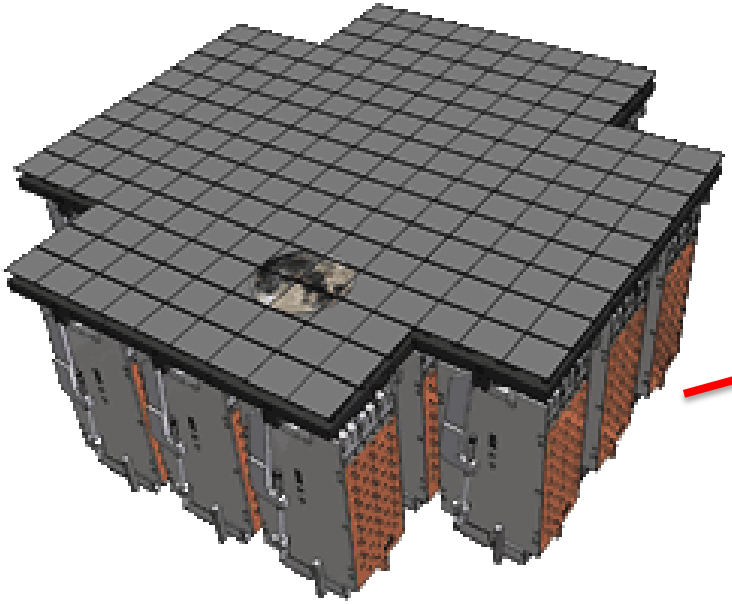
(LSST document, v2)

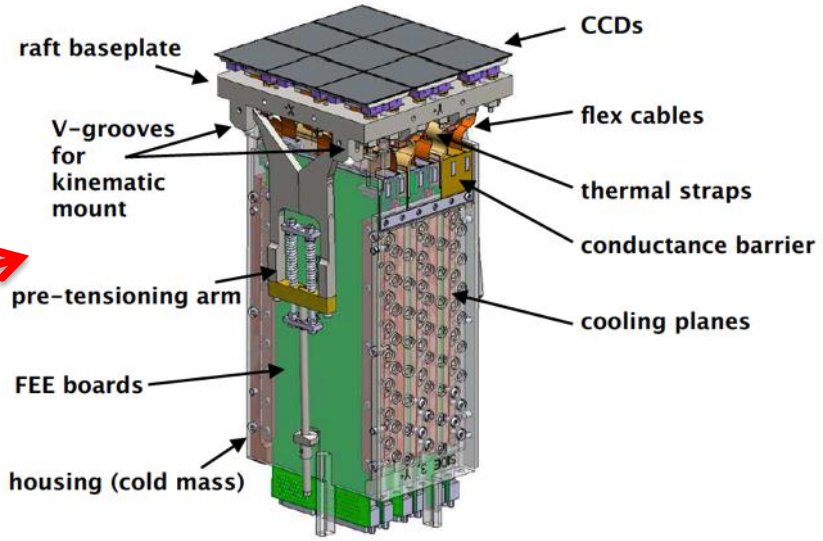


2.2 Contribution of BNL to LSST

BNL is leading the development of a multi-gigapixel focal plane detector for LSST.



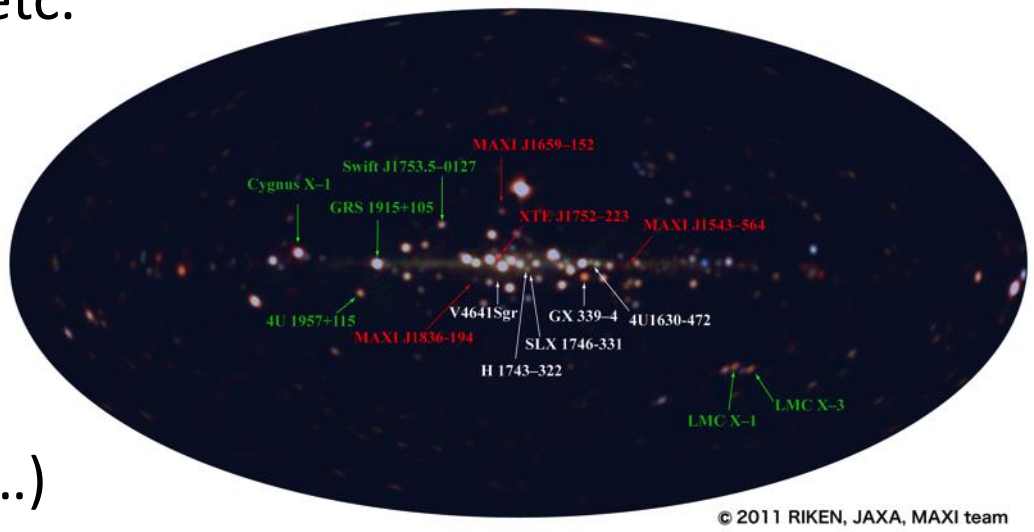




5.1 Time Domain Astrophysics

- Science
  - ✓ Gamma-ray bursts
  - ✓ Supernova explosions
  - ✓ EM counterpart of GW
  - ✓ NS/BH binary system etc.
- Projects
  - ✓ MAXI (RIKEN)
  - ✓ Swift (NASA)
  - ✓ Fermi (US-Japan-Itary…)
  - ✓ NICER / LOFT

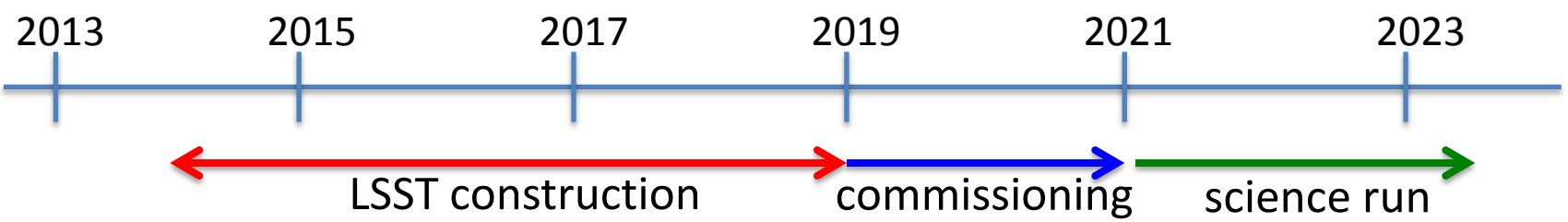
LSST provides a lot of transient trigger. Only a few % of them will be followed-up. Very clever ideas are needed to select targets and for good science outcomes.

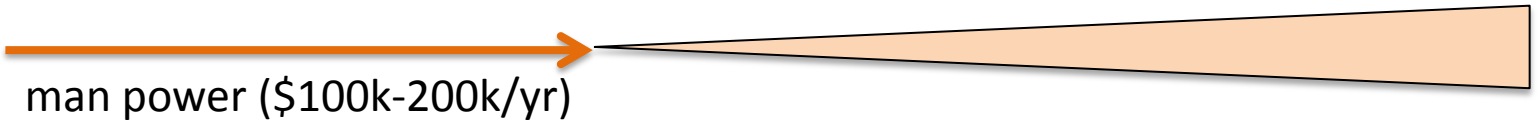


6.1 Contribution to LSST at RBRC

- I will send postdocs to RBRC for contributing to the construction of the camera. Mass production will start soon.
- I want to provide some hardware to keep our presence in the project. (e.g. we can provide optical filters to the camera. ~$1M in total, Asahi Spectra Co.Ltd.)
- We should keep a good relation to Japanese optical/infrared community and Subaru/HSC members for future contribution.

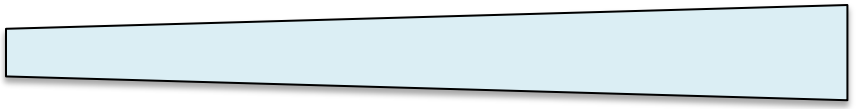
6.2 Timeline





RIKEN's contribution





Covered by
* RIKEN internal fund
* KAKENHI
* RBRC or Nishina?

Need strong support of Japanese optical/infrared community. (cf. TMT)

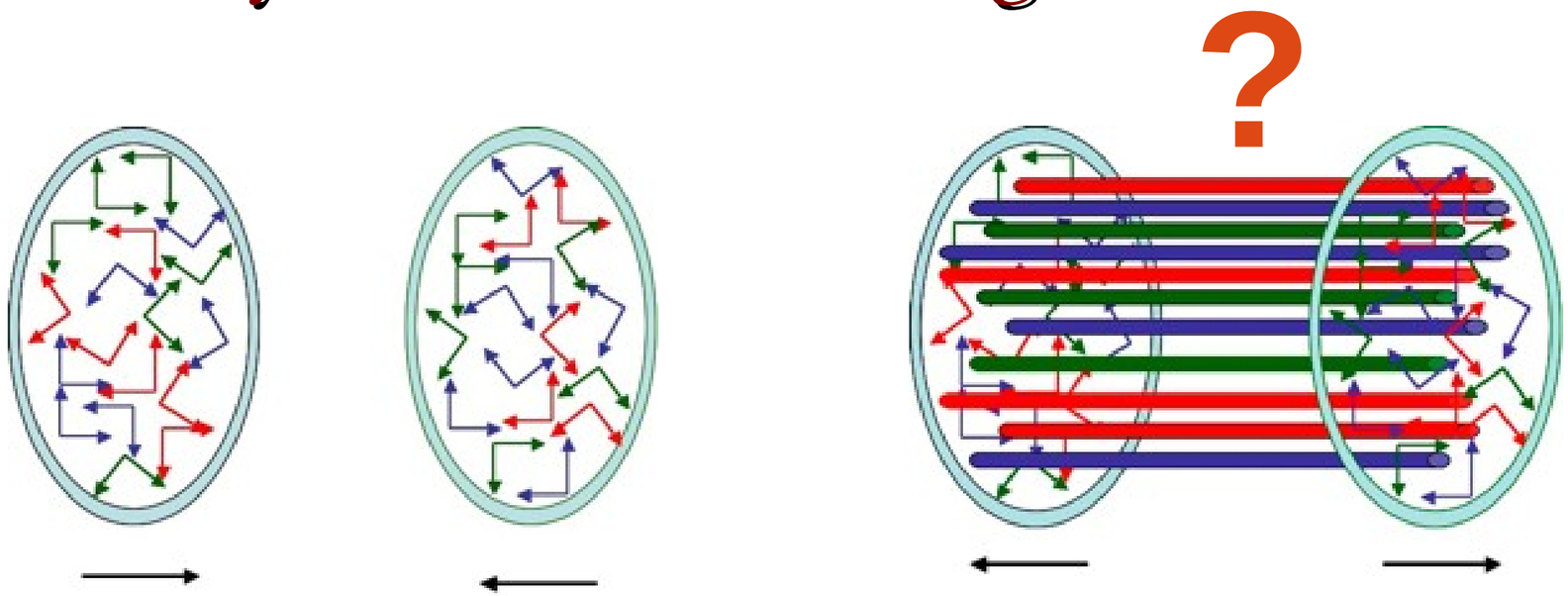
Spatial Wilson loops in heavy-ion collisions

Adrian Dumitru
Baruch College (CUNY)

Talk based on:

A.D., Y. Nara, E. Petreska, arXiv:1302.2064
A.D., H. Fujii, Y. Nara, arXiv:1305.2780

Heavy-ion collision: long. initial fields



before collision

right after impact

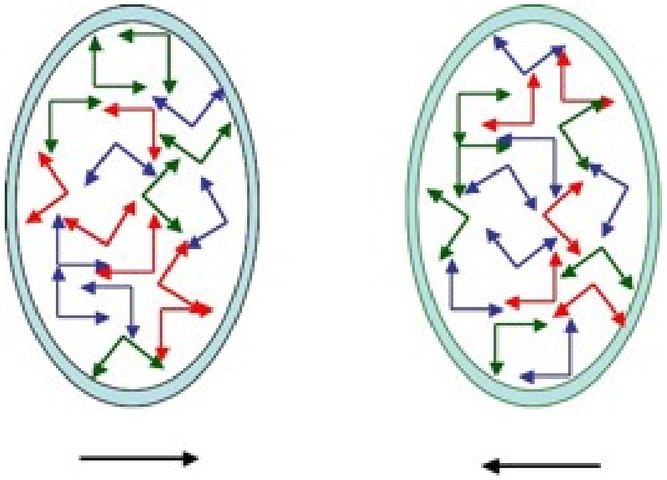
$$\partial^i \alpha^i = g\ \rho$$

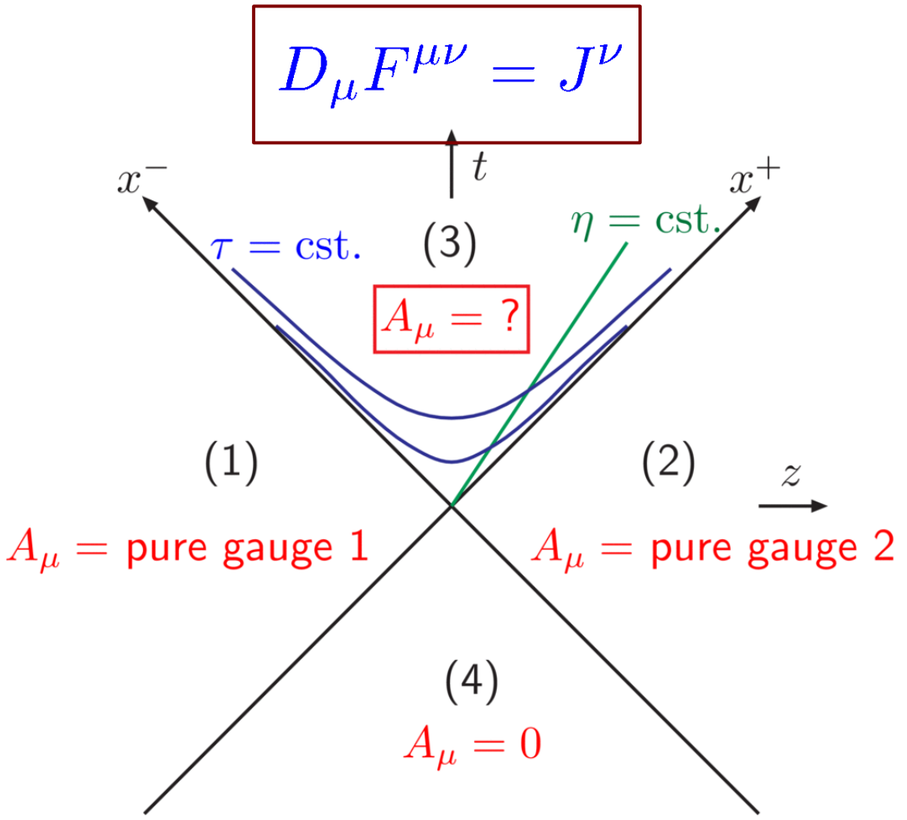
$$E^z = ig\left[\alpha_1^i, \alpha_2^i\right] \quad , \quad B^z = ig\epsilon^{ij}\left[\alpha_1^i, \alpha_2^j\right]$$

$$\nabla \cdot \mathbf{B} = ig\left[A^i, B^i\right]$$

Kharzeev, Krasnitz, Venugopalan: PLB 2002
R. Fries, J. Kapusta, Y. Li: nucl-th/0604054
Lappi + McLerran NPA 2006

Heavy-ion collisions





before collision

$$\alpha_m^i = \frac{i}{g} U_m \partial^i U_m^\dagger \qquad SU(N) \text{ 2D pure gauge}$$

$$\partial^i \alpha_m^i = g\rho_m \qquad (m = 1, 2 \;\; \text{Proj/Targ})$$

$$A^i = \alpha_1^i + \alpha_2^i \qquad (\tau = +0)$$

gauge : $x^+ A^- + x^- A^+ = 0$

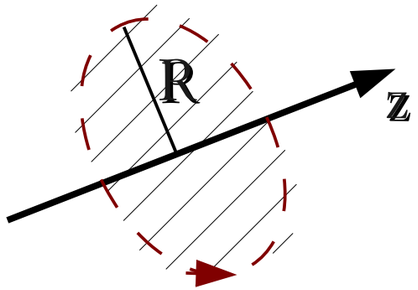
avg configurations: $S_{\text{MV}} = \int d^2x_\perp \frac{1}{2\mu^2} \rho^a \rho^a$

- ρ random from point to point
- NOT so for A^i !

Analyze classical field configurations at midrapidity: η=0, 2D, SU(2)

what is structure of B_z field ?

magnetic flux loop in x-y plane:

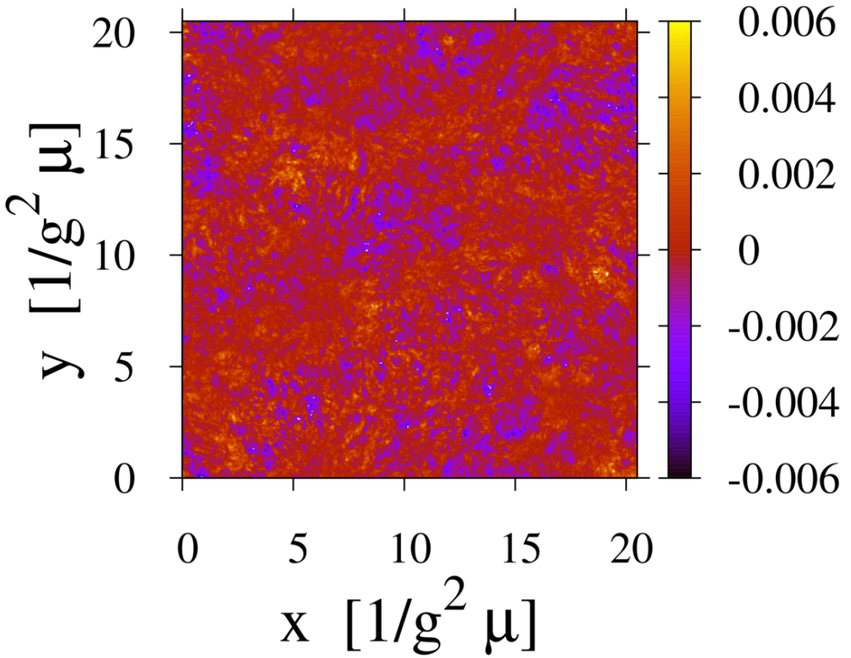


$$M(R) = \mathcal{P}\exp\left(ig\oint dx^i A^i\right)$$

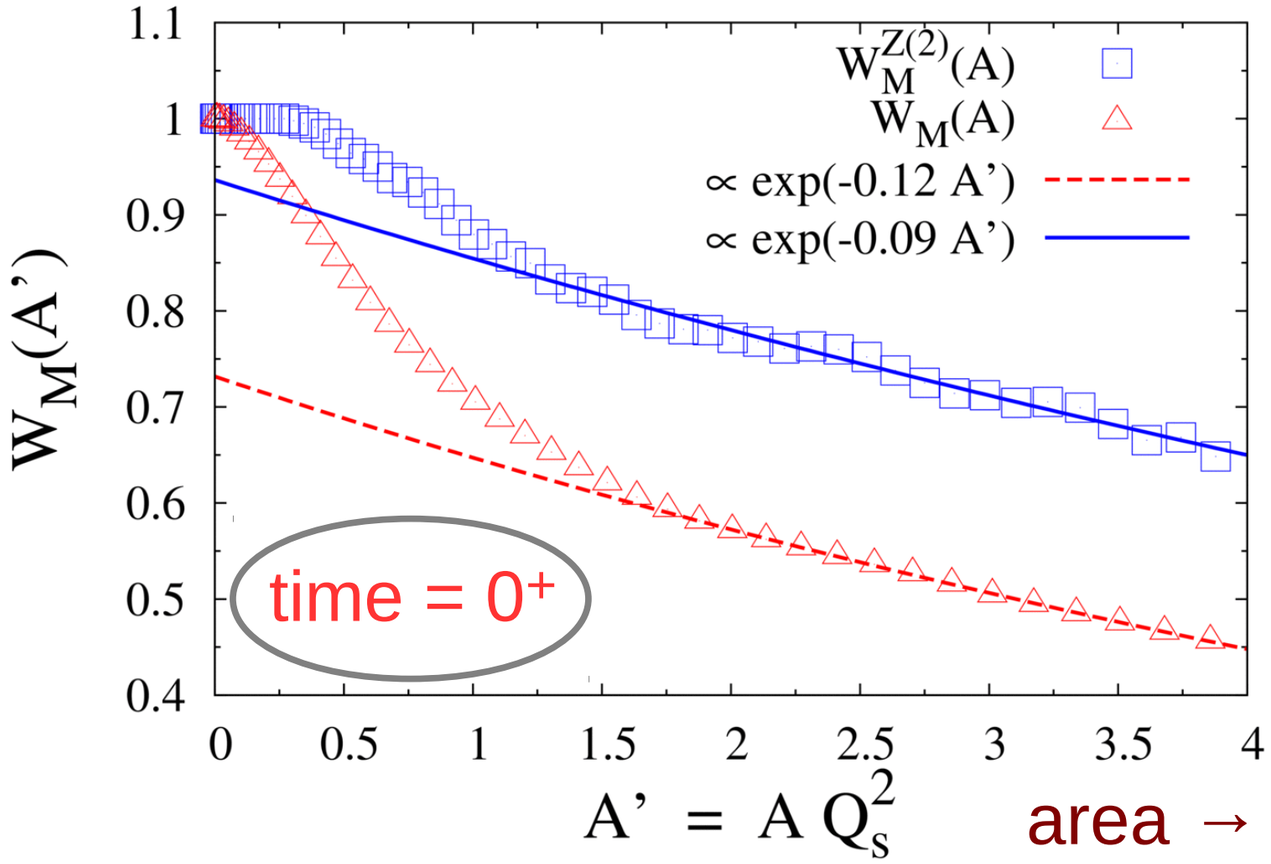
$$W_M(R) = \frac{1}{N_c}\langle \mathrm{tr}\ M(R)\rangle$$

$$W_M^{Z(2)}(R) = \langle \mathrm{sgn\ tr}\ M(R)\rangle$$

actual field configuration B_z^3



SU(2) solution :

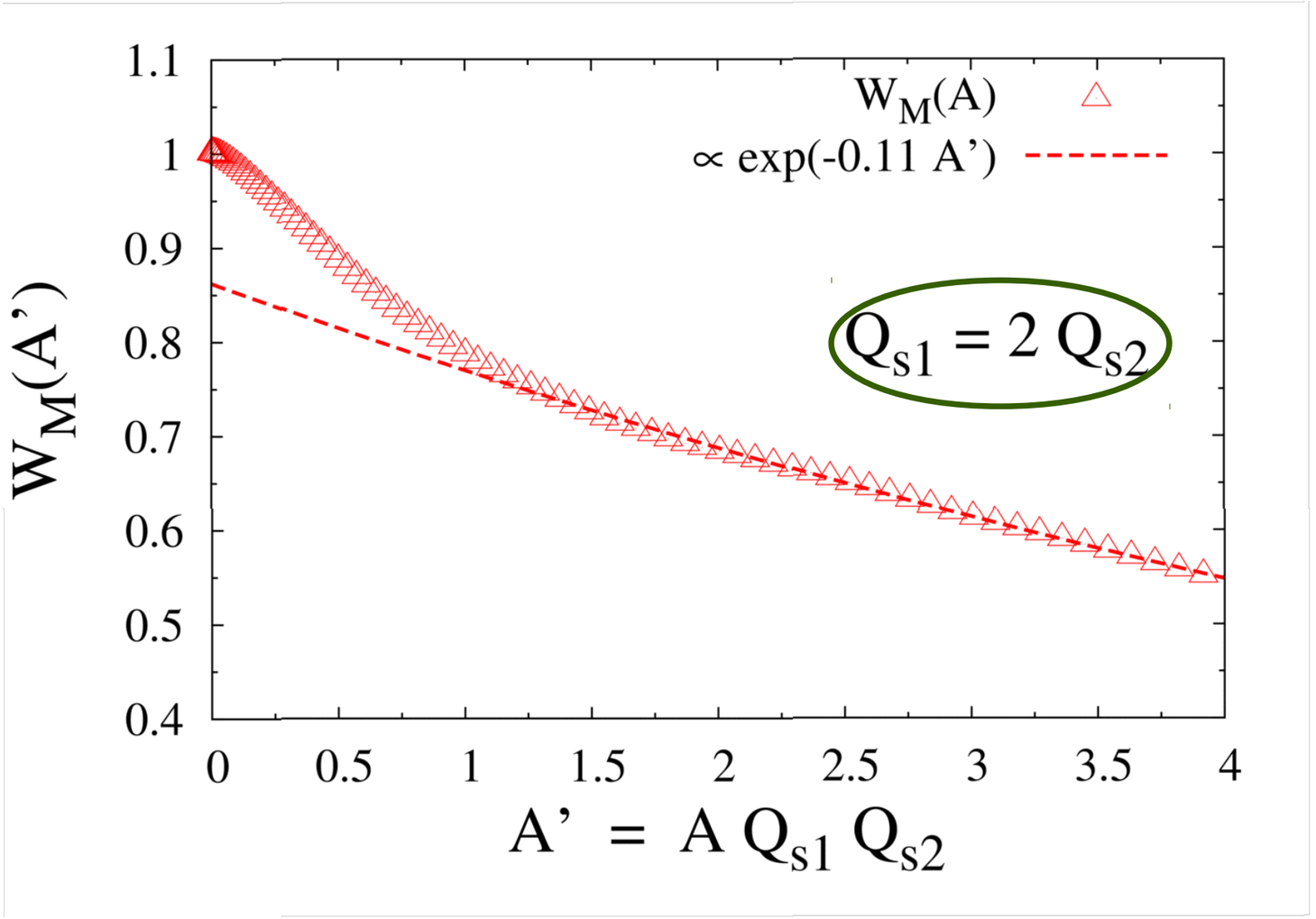


- evidence for domain structure
- area law for loops with area A ≥ 1.5 – 2
- $\sigma_M \sim 0.12\ Q_s^2$; thermal SU(N): $\sigma_M \sim g_{3D}^2 \sim (g^2 T)^2$
- small loops ∉ Z(2) but roughly ok for large ones!
- structure of B_z ~ uncorrelated vortices ?!
- $R_{vtx} \sim 1/Q_s$ from onset of area law

random uncorrelated vortex fluctuations:

density ≈ 1 / 20 Q_s^2

lattice solution for ***asymmetric*** collision



- ~ same string tension $\sigma_M = 0.11\ Q_{s1}\ Q_{s2}$

Magnetic screening !

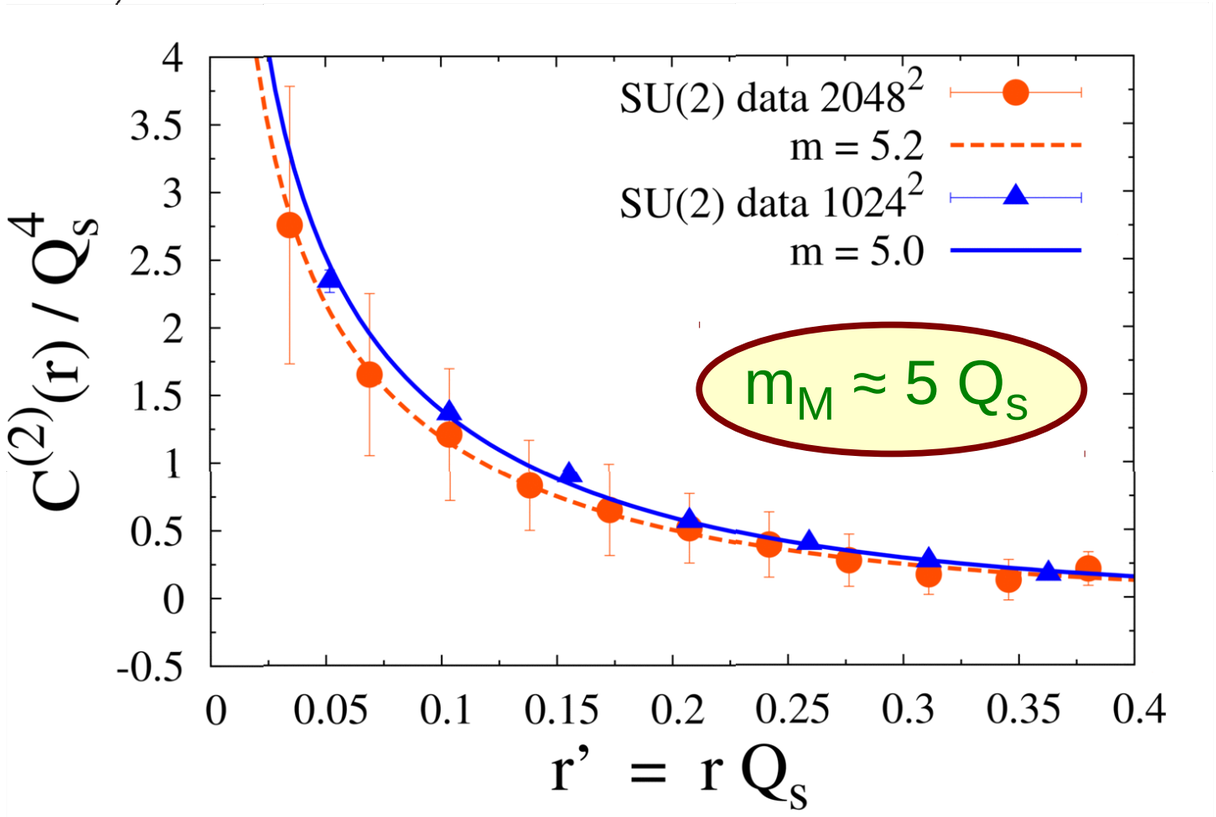
$$C^{(2)}(r) = \langle \mathrm{tr}\, G(\mathbf{0})\, G(\mathbf{x}) \rangle$$

$$G(\mathbf{x}) = g\, U(\mathbf{0} \to \mathbf{x})\, F_{xy}(\mathbf{x})\, U(\mathbf{x} \to \mathbf{0})$$

expectation: (d=2)
$$\int d^d p\, \frac{e^{ipx}}{p^2 + m^2} \sim \frac{1}{r^{(d-1)/2}}\, \exp(-m\, r)$$

Note:

- gauge links: interactions of external legs with produced gluons $A^i = \alpha_1{}^i + \alpha_2{}^i$



Perturbative analytical calculation :

it usually goes like this :

$$\nabla^2 \Phi = g \rho$$
$$\alpha^i = -\partial^i \Phi$$

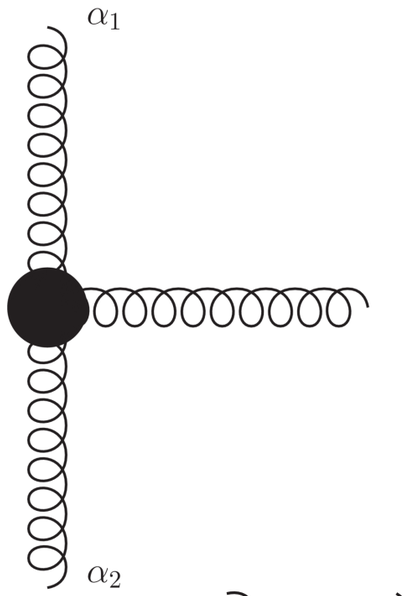
but : $\oint dx^i \, \partial^i \Phi = 0$

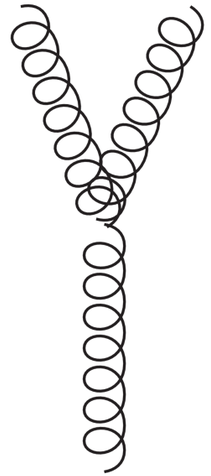
so we need :

$$\alpha^i = -\partial^i \Phi + \frac{ig}{2} \left(\delta^{ij} - \partial^i \frac{1}{\nabla^2} \partial^j \right) \left[\Phi, \partial^j \Phi \right]$$

result : $W_M(A) = 1 - \#A^2 Q_s^8 \frac{1}{\Lambda^4}$

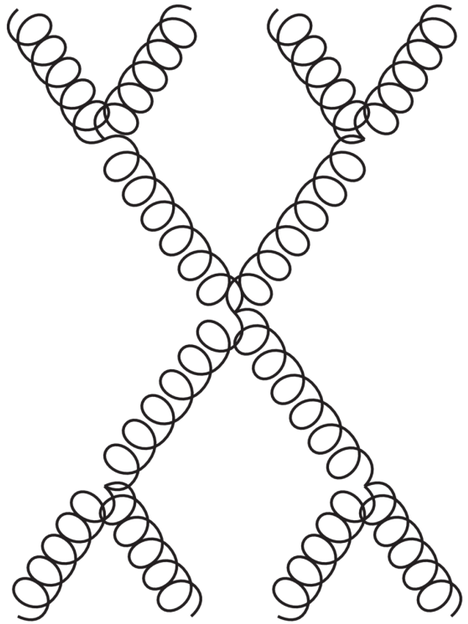
(E. Petreska, in preparation)



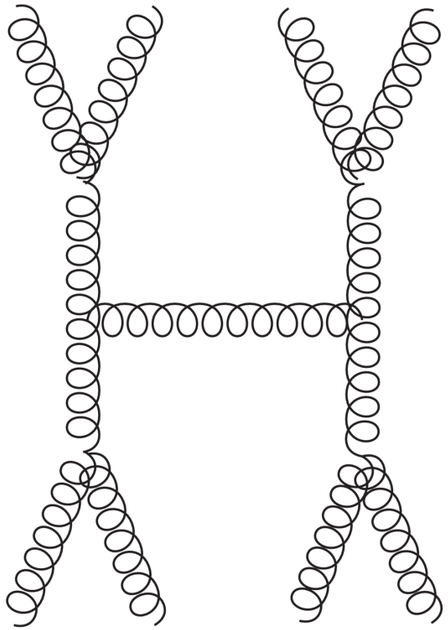


Careful though: quantum diagrams may dominate at this order, for small loops ($A\, Q_s^2 \ll 1$) !

classical diagram:



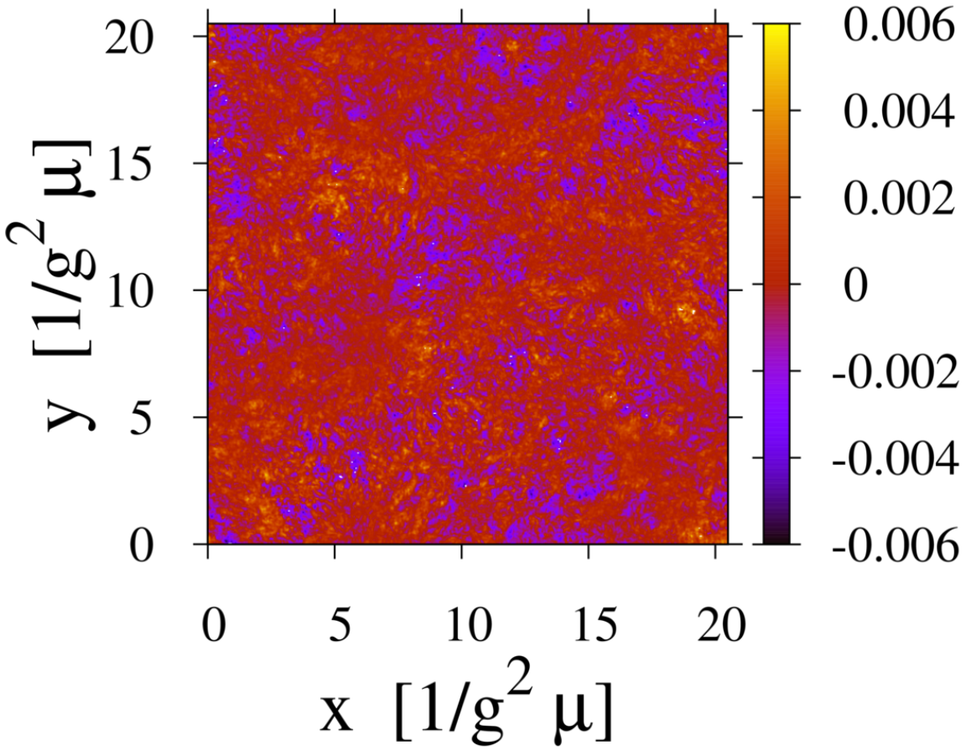
quantum diagram:



Summary

(structure of long. fields in initial stage)

B_z



- "Clumping" of magnetic field / domains
- area law: $W_M(A) \sim \exp(-\sigma_M A)$ for loop radius $R \sim 1/Q_s$
- $\sigma_M \cong 0.1\, Q_{s1}\, Q_{s2}$
- Z(2) projected loop gives similar σ_M
- magnetic screening at scale $m_M \cong 5\, Q_s$

Thank you RIKEN / RBRC !

Scattering amplitudes and recursion relations on the light front

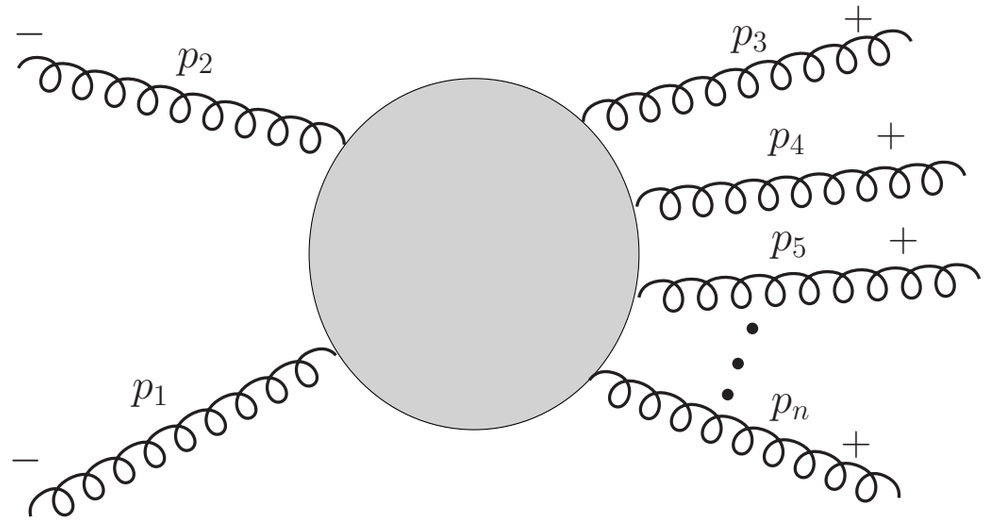
Anna Stasto

RBRC Review Meeting, November 1st, 2013

Introduction

Helicity amplitudes in QCD

Scattering 2 to n:



Enormous progress in computational techniques in recent decades

Introduction

Helicity amplitudes in QCD

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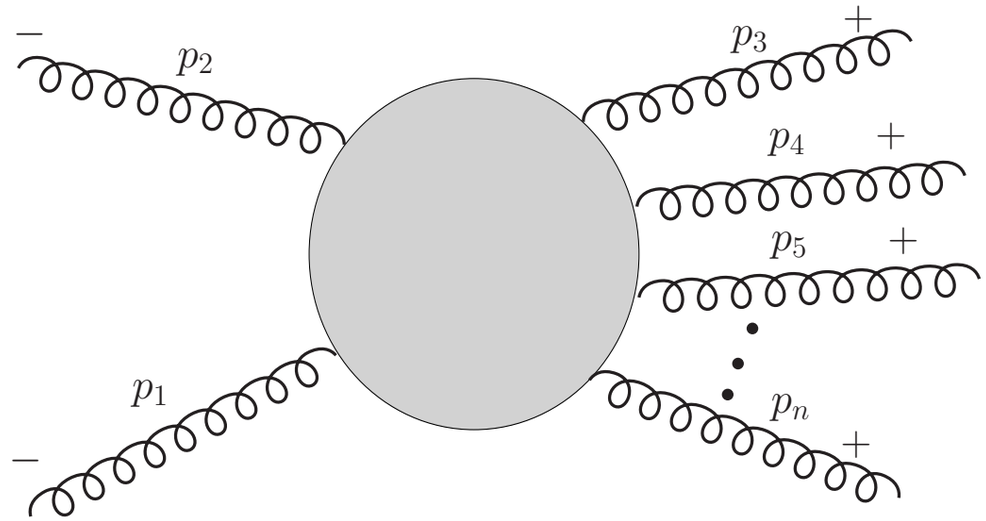

Enormous progress in computational techniques in recent decades

Goals:

Compute amplitudes within framework of light -front perturbation theory.

Construct recursive relations on the light-front.

Obtain insight into patterns and general structure of amplitudes from the light-front theory perspective.

Introduction

Helicity amplitudes in QCD

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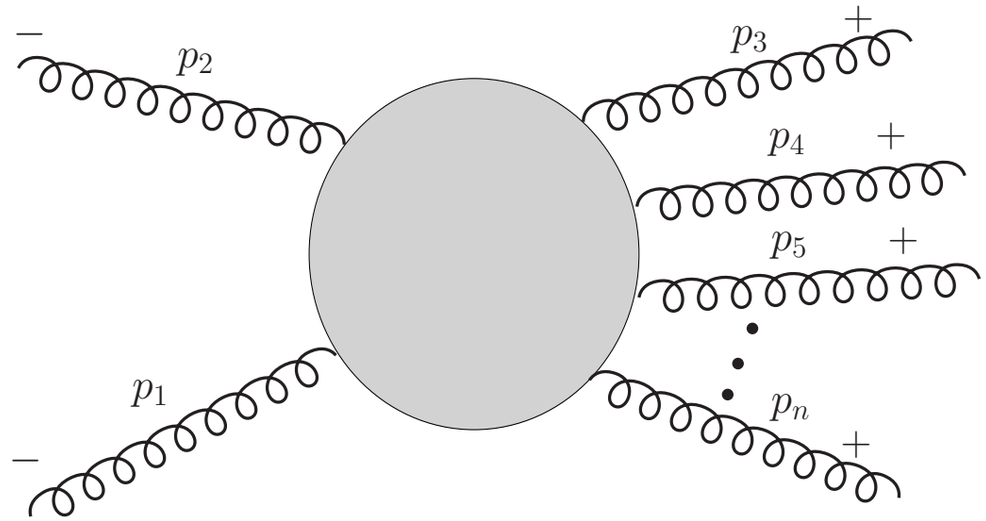

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Compute amplitudes within framework of light -front perturbation theory.

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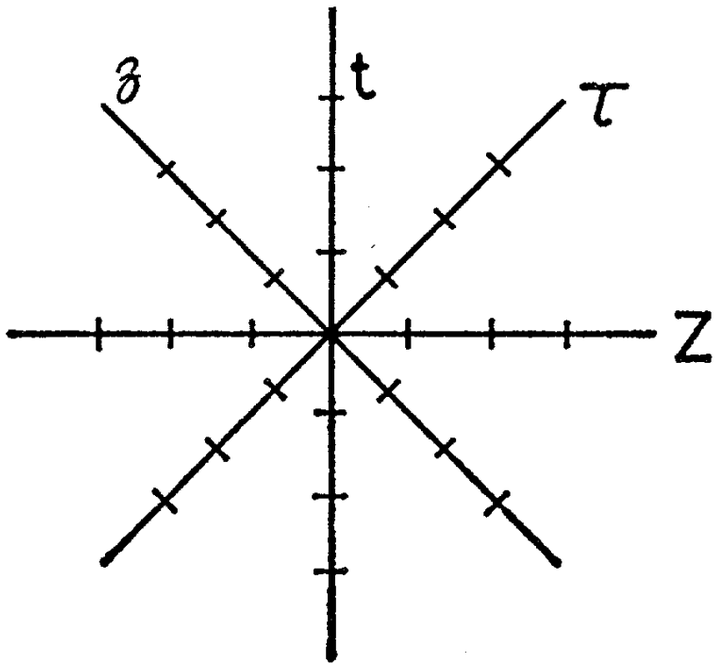
Work in collaboration with C.Cruz-Santiago arXiv:1301.3075, arXiv:1308.1062

Light-front formalism

Dirac



Kogut,Soper

Infinite momentum frame: a limit of a Lorentz frame moving in the -z direction with a (nearly) the speed of light.

Susskind

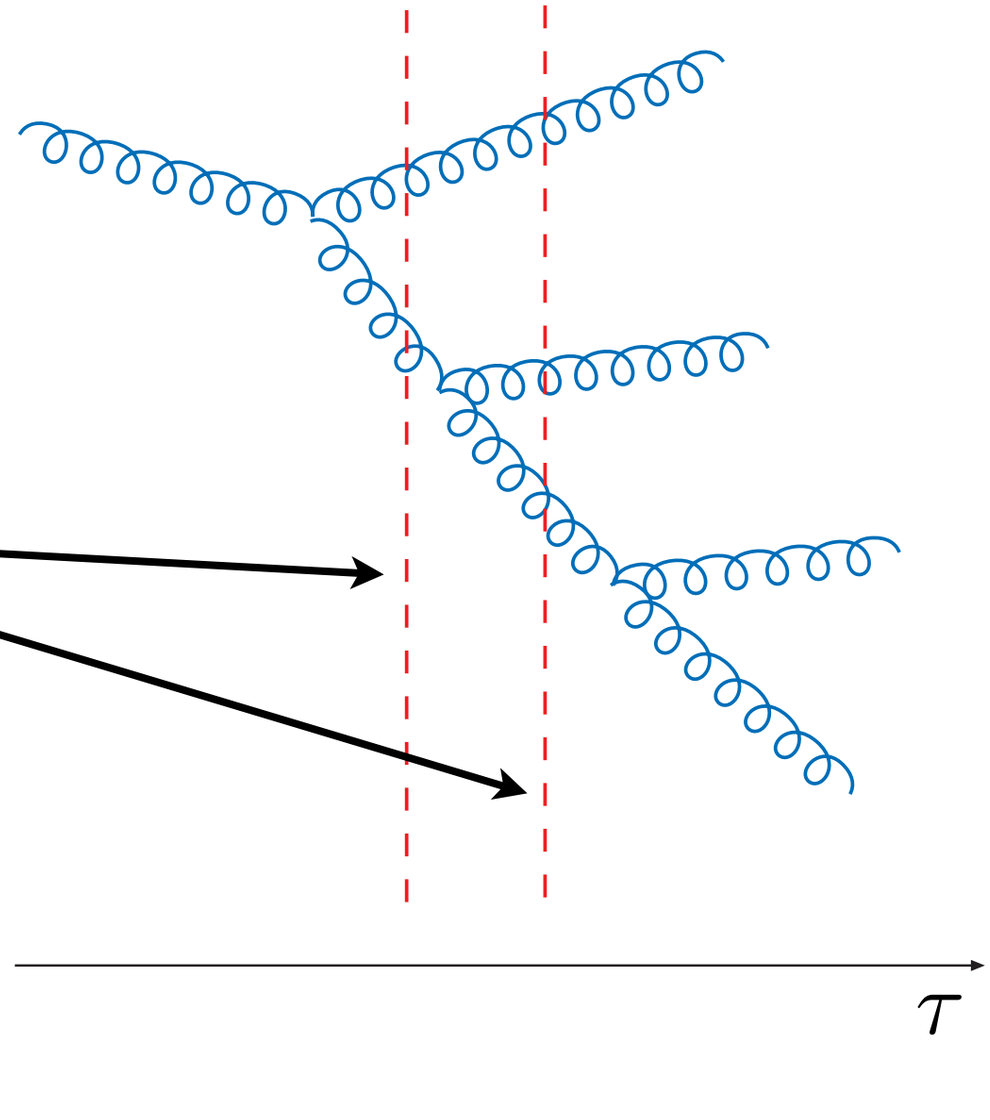
Isomorphism with the Galilean dynamics in 2 dimensions:

P^- ⟶ Hamiltonian

P^+ ⟶ Mass

P_T ⟶ 2-dim. momentum

Non-covariant (light-front) time ordered diagram



Energy denominators

Difference of light - cone energies:

$$D_n = P^- - \sum_i k_i^-$$

Initial state

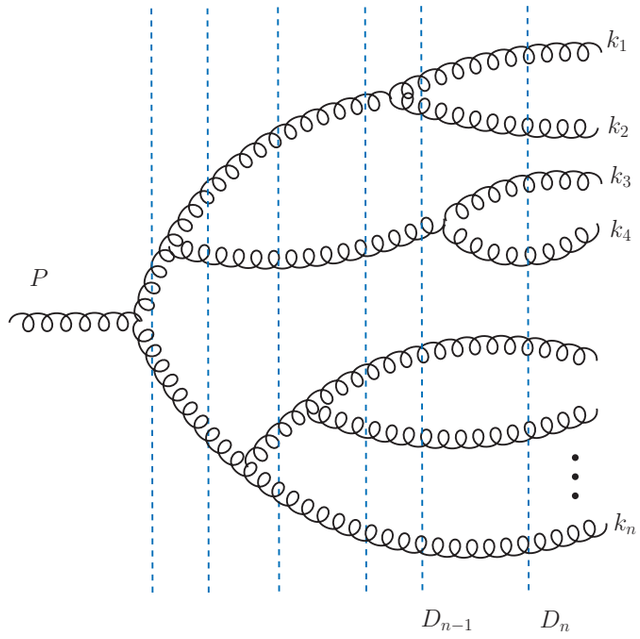
Intermediate states

Particles are on-shell but conservation of 3 momentum components in the intermediate states

Computation of amplitudes on the light-front

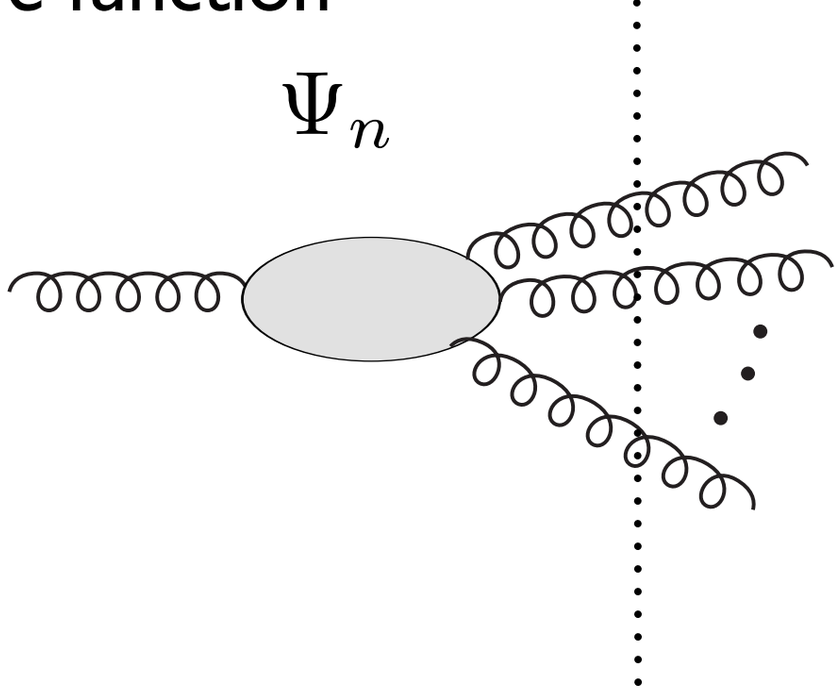
τ

typical graph

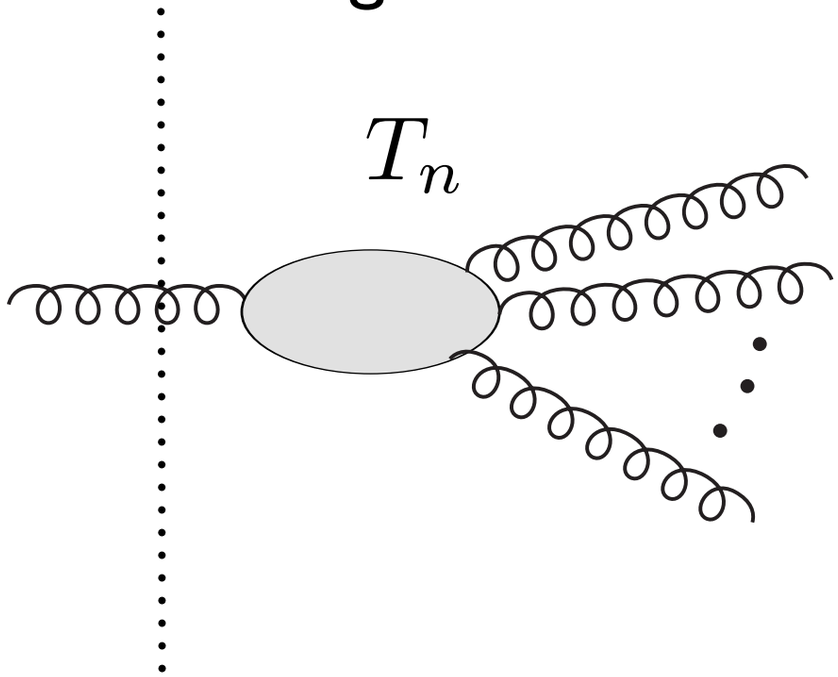


$$\sim g^n \frac{\Pi_j V_j}{\Pi_j D_j \;\; \Pi_l k_l^+}$$

wave function



fragmentation function



Energy denominator: either in the last or first state

Can use these building blocks for scattering amplitudes

Recurrence relations between wave functions

$$\Psi_{n+1}(k_0, k_1, \ldots, k_n) = \frac{g}{\sqrt{\xi_{01}}} \frac{\underline{\epsilon}^{(-)} \underline{v}_{01}}{D_n + \xi_{01}\, \underline{v}_{01}^2} \Psi_n(k_{01}, k_2, \ldots, k_n)$$

z_i fraction of longitudinal momentum of i'th particle

$\underline{k}_i$ transverse momentum of the i'th particle

Recurrence relations between wave functions

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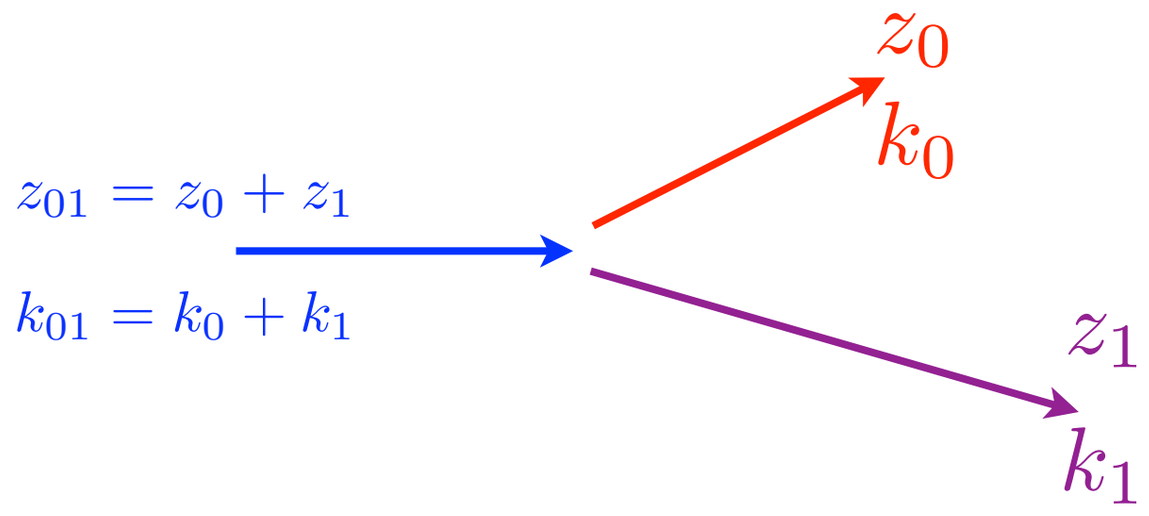

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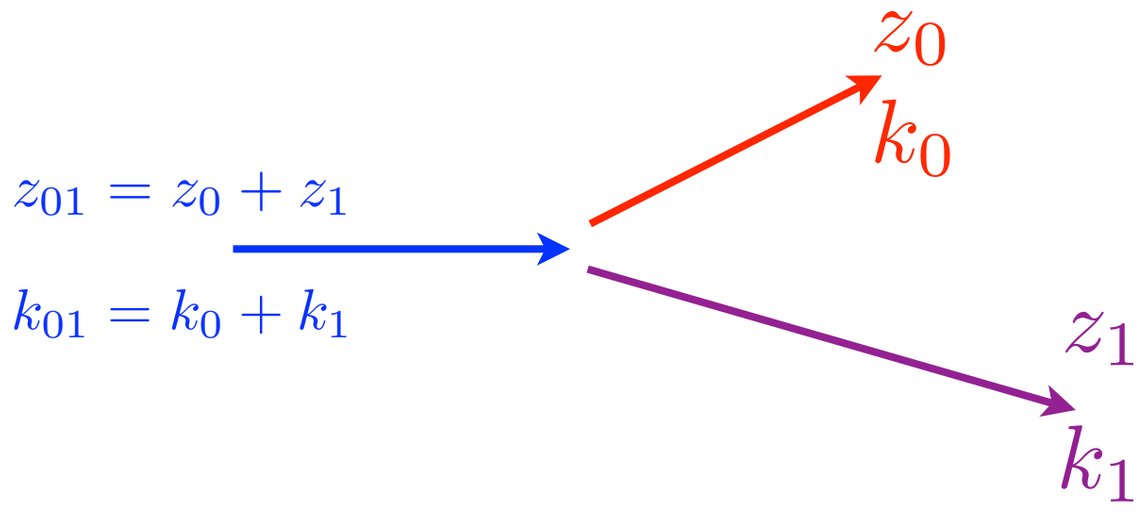

reduced mass:

$$\xi_{01} = \frac{z_0 z_1}{z_0 + z_1}$$

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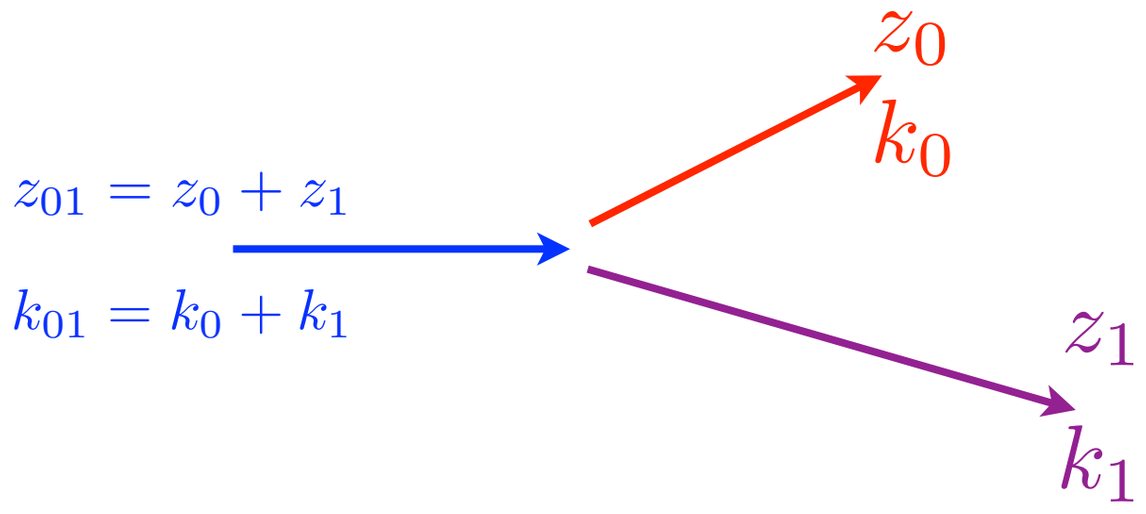

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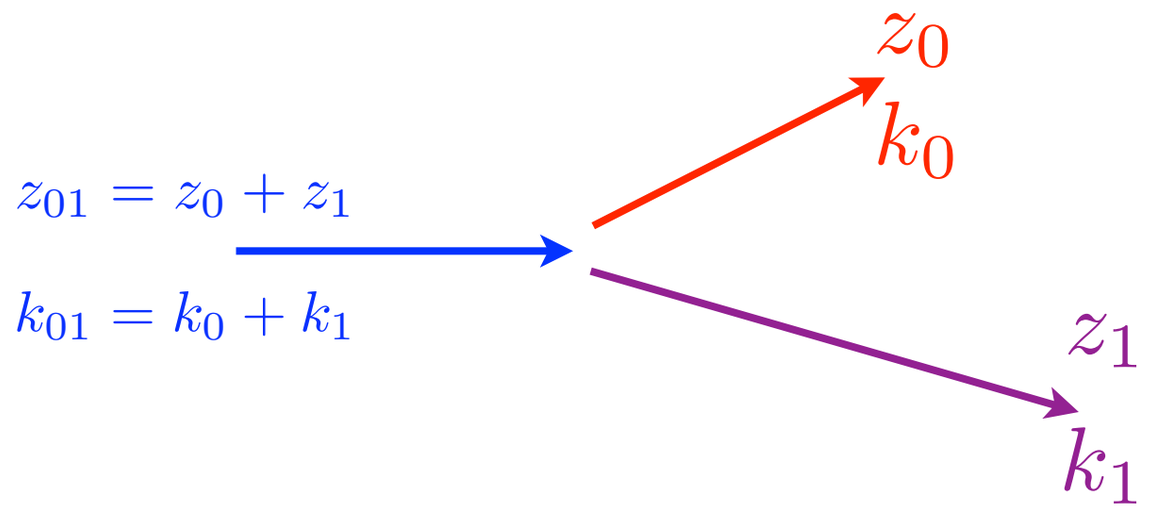

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Isomorphism with non-relativistic dynamics apparent in the variables.

Light cone wave function

Case of the on-shell incoming gluon.

Can resum the wave function completely.

$$-D_{n+1}\,\Psi_{n+1}(1,2,\ldots,n+1) \;=\; g\sum_{i=1}^{n}\frac{v^*_{(i,i+1)}}{\sqrt{\xi_{(i,i+1)}}}\Psi_n(1,2,\ldots,(i\,i+1),\ldots,n+1) \qquad n\longrightarrow n+1$$

$$-D_n\Psi_n(1,2,\ldots,n) \;=\; g\sum_{k=1}^{n-1}\frac{v^*_{(k,k+1)}}{\sqrt{\xi_{(k,k+1)}}}\Psi_{n-1}(1,2,\ldots,(k\,k+1),\ldots,n) \qquad n-1\longrightarrow n$$

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...

Tree-level gluon wave function with exact kinematics

$$\Psi_n(1,2,\ldots,n) \;=\; (-1)^{n-1}g^{n-1}\,\Delta^{(n)}\,\frac{1}{\sqrt{z_1z_2\cdots z_n}}\,\frac{1}{\xi_{(12\ldots n-1)n}\,\xi_{(12\ldots n-2)(n-1\,n)}\,\cdots\,\xi_{1(2\ldots n)}}$$

$$\times\,\frac{1}{v_{(12\ldots n-1)n}\,v_{(12\ldots n-2)(n-1\,n)}\,\cdots\,v_{1(2\ldots n)}}\,.$$

$$v_{(i_1i_2\ldots i_p)(j_1j_2\ldots j_q)} = \frac{k_{i_1}+k_{i_2}+\ldots+k_{i_p}}{z_{i_1}+z_{i_2}+\ldots+z_{i_p}} - \frac{k_{j_1}+k_{j_2}+\ldots+k_{j_q}}{z_{j_1}+z_{j_2}+\ldots+z_{j_q}},$$

$$\xi_{(i_1i_2\ldots i_p)(j_1j_2\ldots j_q)} = \frac{(z_{i_1}+z_{i_2}+\ldots+z_{i_p})(z_{j_1}+z_{j_2}+\ldots+z_{j_q})}{z_{i_1}+z_{i_2}+\ldots+z_{i_p}+z_{j_1}+z_{j_2}+\ldots+z_{j_q}}\,,$$

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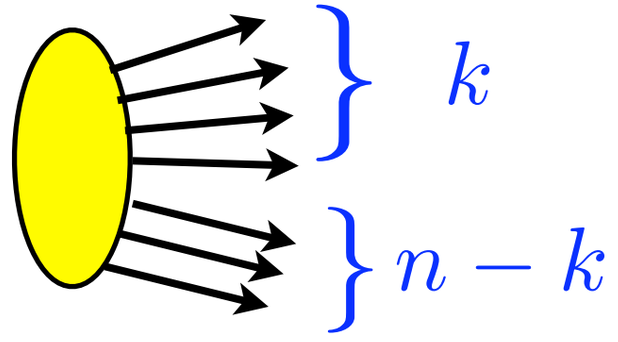
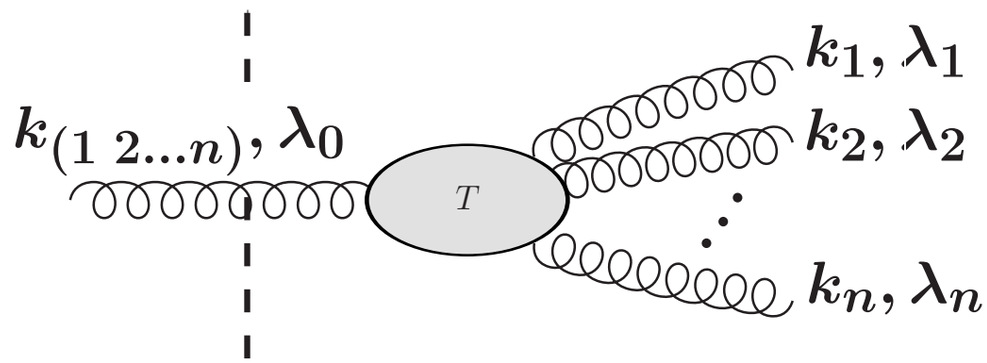


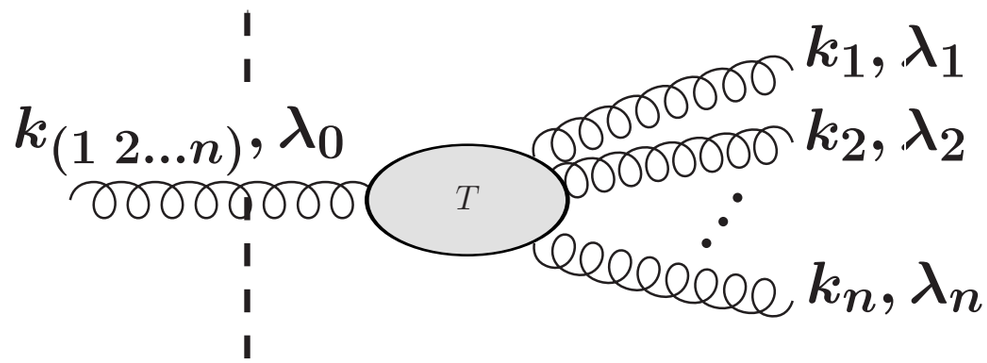
Fragmentation functions



For special case of : $(+ \to + + \cdots +)$ transition

$$T_n[(12\ldots n)^+ \to 1^+, 2^+, \ldots, n^+] = (-ig)^{n-1} \left(\frac{z_{1\ldots n}}{z_1 \ldots z_n}\right)^{3/2} \frac{1}{v_{n\,n-1} v_{n-1\,n-2} \ldots v_{21}}$$

Fragmentation functions



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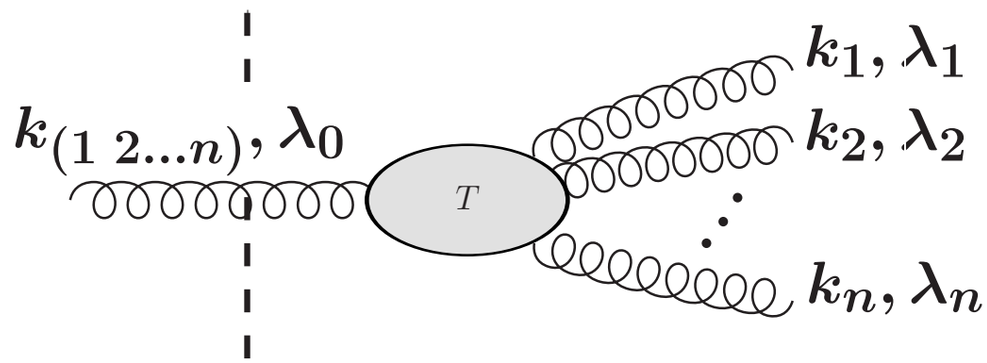
From this (off- shell) object one can obtain on-shell amplitude

Fragmentation functions



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From this (off- shell) object one can obtain on-shell amplitude

$$T_n \to \mathcal{A}_{2\to n}$$

$k_1 \to -k_1 \qquad \lambda_1 \to -\lambda_1$

and remove the first energy denominator

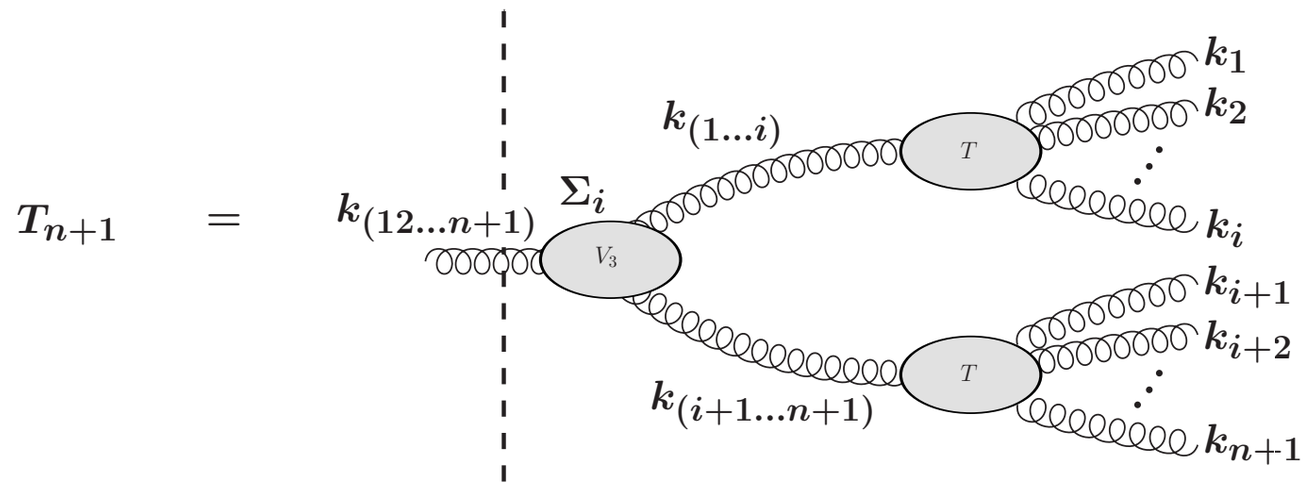
$$\mathcal{A} \sim T_n D_n$$

$D_n \to 0 \qquad \mathcal{A}(+- \to + + \cdots +) = 0$

as a result of energy conservation

Fragmentation functions

Factorization property (see also cluster expansion Brodsky et al)



for the special case of only '+' helicities:

$$T_{n+1}[(12\ldots n+1)\to 1,2,\ldots,n+1] \;=\; -\frac{2ig}{D_{n+1}}\;\sum_{i=1}^{n}\left\{\frac{v^*_{(1\ldots i)(i+1\ldots n+1)}}{\sqrt{\xi_{(1\ldots i)(i+1\ldots n+1)}}}\right.$$
$$\left.\times\, T_i[(1\ldots i)\to 1,\ldots,i\,]\;T_{n+1-i}[(i+1\ldots n+1)\to i+1,\ldots,n+1]\right\}$$

Special case of light-front Berends-Giele recursion relation

Relation to Parke-Taylor amplitudes

$$\mathcal{M}_n = \sum_{\{1,\ldots,n\}} \mathrm{tr}(t^{a_1} t^{a_2} \ldots t^{a_n})\, m(p_1,\epsilon_1;p_2,\epsilon_2;\ldots;p_n,\epsilon_n)\ ,$$

Color part

Kinematical part

Relation to Parke-Taylor amplitudes

$$\mathcal{M}_n = \sum_{\{1,\ldots,n\}} \mathrm{tr}(t^{a_1} t^{a_2} \ldots t^{a_n})\, m(p_1,\epsilon_1;p_2,\epsilon_2;\ldots;p_n,\epsilon_n)\ ,$$

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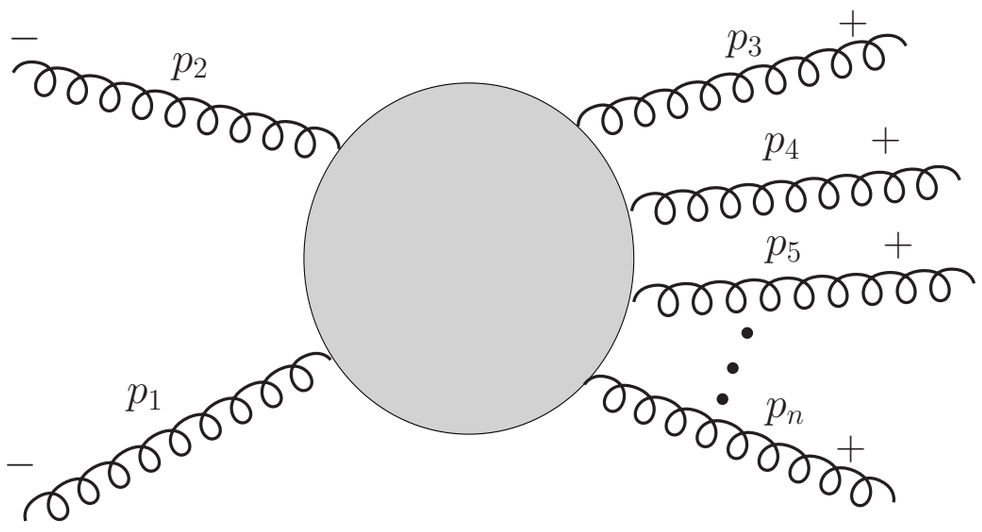
Maximally Helicity Violating amplitude for gluons: 2 to n

Here: all gluons are outgoing



$$\langle ij \rangle = \sqrt{z_i z_j}\ \underline{\epsilon}^{(+)} \cdot \left(\frac{\underline{k}_i}{z_i} - \frac{\underline{k}_j}{z_j} \right)$$

$$\langle\, ij \,\rangle = \sqrt{z_i z_j}\ \underline{\epsilon}^{(+)} \cdot \underline{v}_{ij},$$

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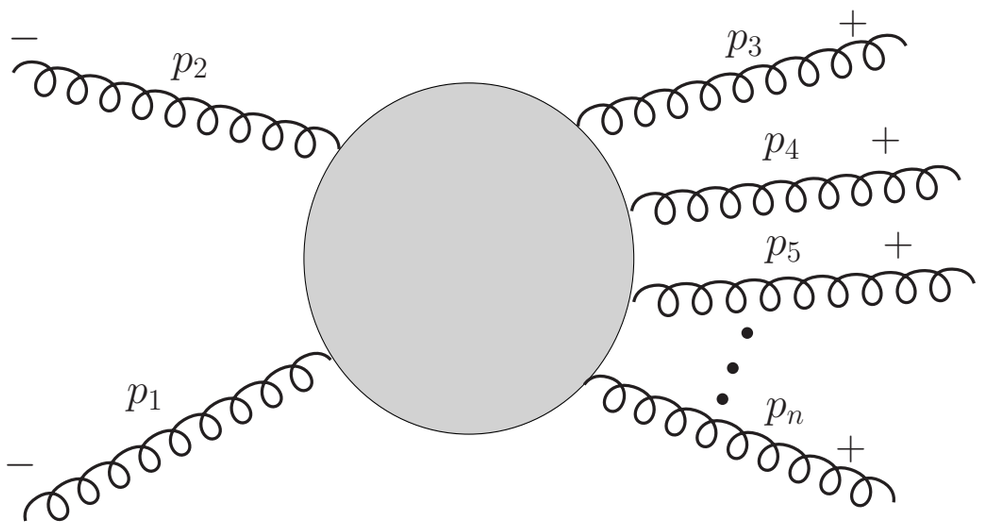

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Tree level, Parke-Taylor formula

$$m(1^-,2^-,3^+,\ldots,n^+) \;=\; i g^{n-2}\, \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle \ldots \langle n{-}2\; n{-}1\rangle\langle n{-}1\; n\rangle\langle n1\rangle}\ ,$$

Light-front to MHV dictionary...

$$|i\pm\rangle \;=\; \psi_\pm(k_i) \;=\; \frac{1}{2}(1\pm\gamma_5)\psi(k_i) \;\;, \quad \langle\pm i| \;=\; \overline{\psi_\pm(k_i)}\,,$$

$$\langle i|j\rangle = \langle i-|j+\rangle\,, \quad [ij] = \langle i+|j-\rangle$$

spinor products

$$\langle ij\rangle = \sqrt{z_i z_j}\;\underline{\epsilon}^{(+)}\cdot\left(\frac{\underline{k}_i}{z_i}-\frac{\underline{k}_j}{z_j}\right) \qquad [ij] = \sqrt{z_i z_j}\;\underline{\epsilon}^{(-)}\cdot\left(\frac{\underline{k}_i}{z_i}-\frac{\underline{k}_j}{z_j}\right)$$

$$\langle\, ij\,\rangle = \sqrt{z_i z_j}\;\underline{\epsilon}^{(+)}\cdot\underline{v}_{ij}\,,$$

$$[\, ij\,] = \sqrt{z_i z_j}\;\underline{\epsilon}^{(-)}\cdot\underline{v}_{ij}\,,$$

More general recursion

MHV amplitude $(- - + \cdots +)$ (here all particles outgoing)

T_n $(+ \to - + \cdots +)$ (1st is incoming particle)

$$T_n[(12\ldots n)^+ \to 1^-, 2^+, \ldots, n^+] = \frac{1}{\sqrt{z_{1\ldots n} z_1 \cdots z_n}} \frac{i}{D_n} \overline{M}_{1\to n}$$

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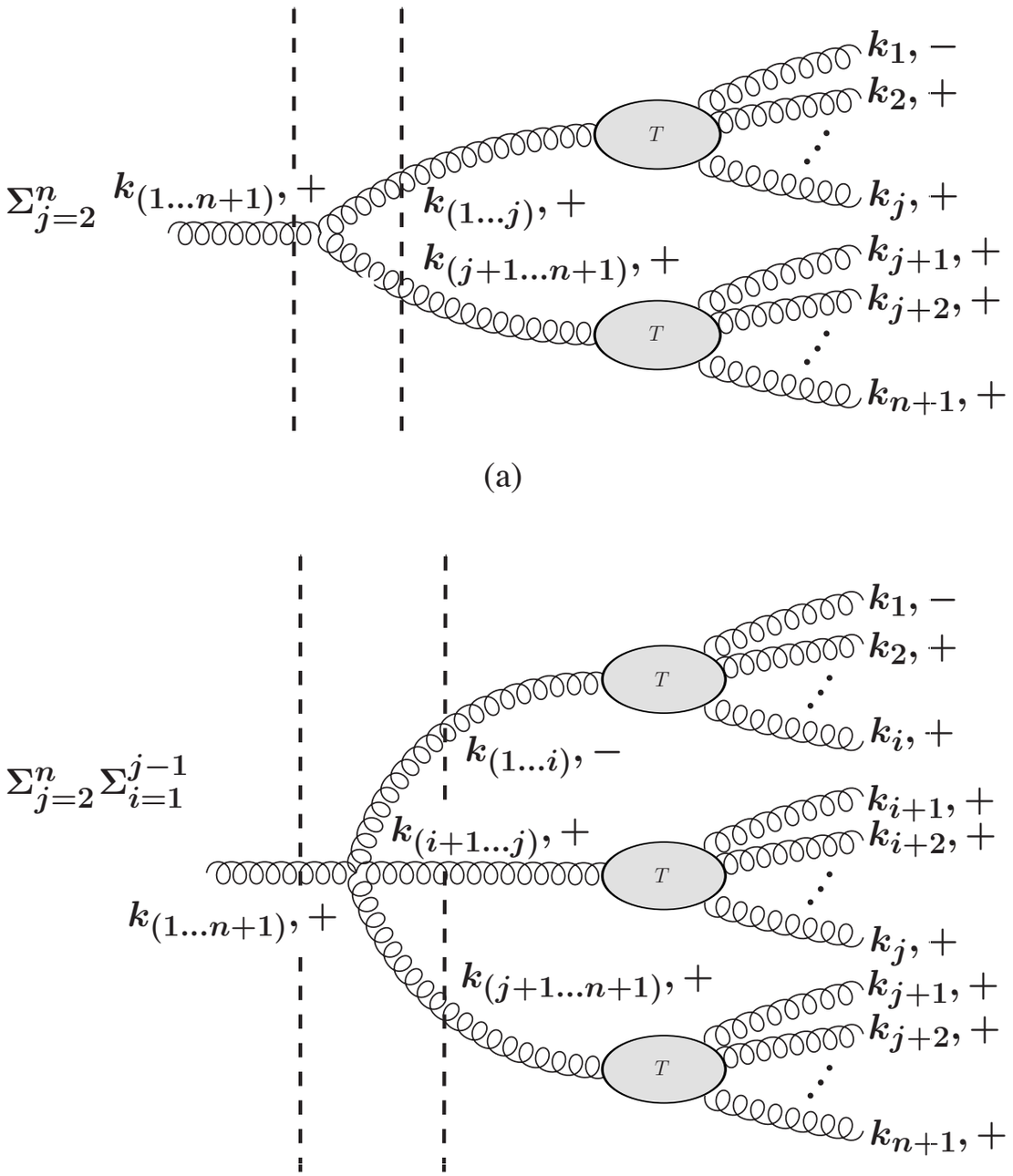
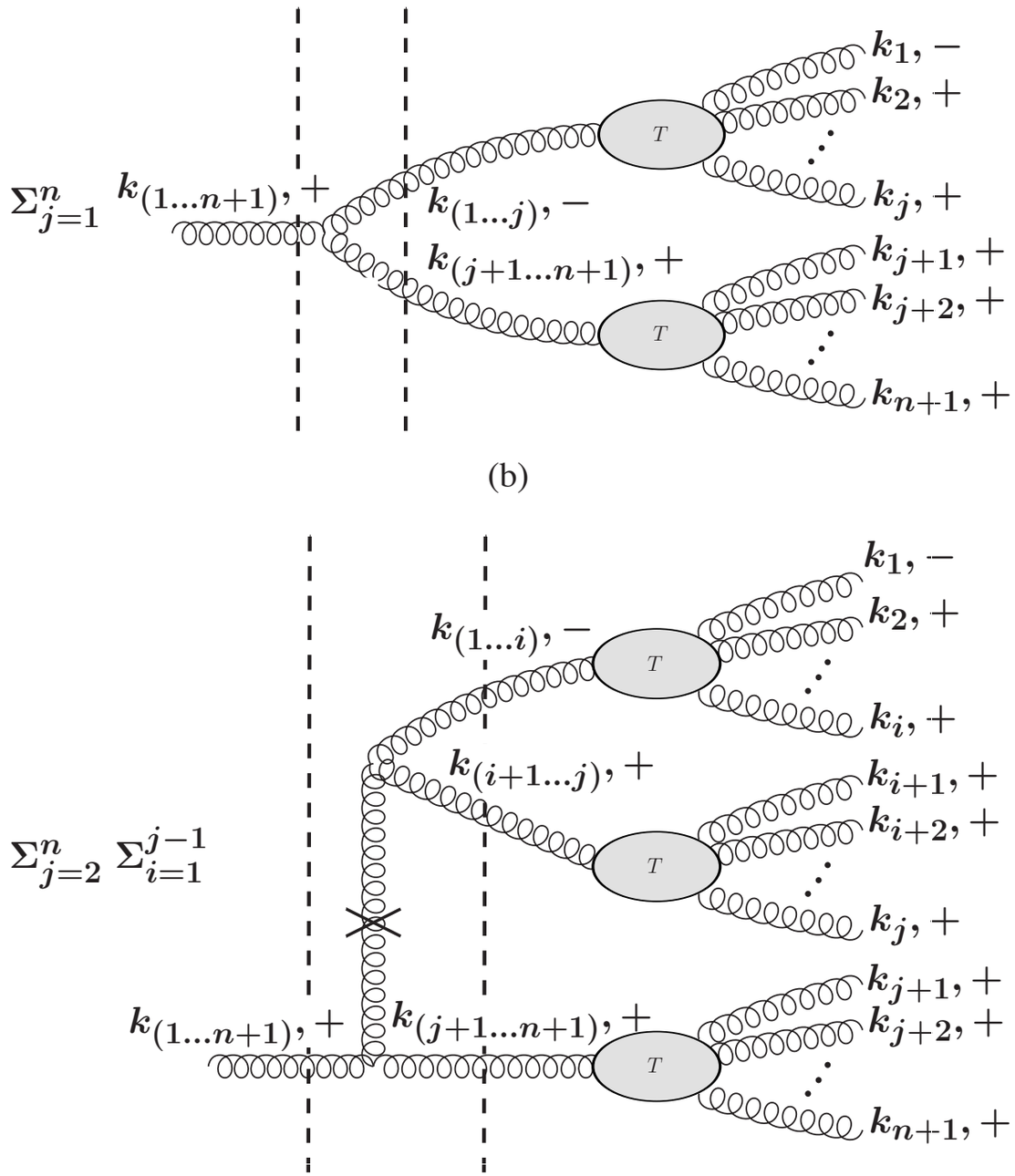
$$\begin{aligned}
\overline{M}_{1\to n+1} = & \sum_{j=2}^{n} V_+ \sqrt{\frac{z_1 z_2 \cdots z_{n+1}}{z_{1\ldots j} z_{j+1\ldots n+1}}}\; T_j[(1\ldots j)^+ \to 1^-, 2^+, \ldots, j^+]\; T_{n+1-j}[(j+1\ldots n+1)^+ \to (j+1)^+, \ldots, (n+1)^+] \\
& + \sum_{j=1}^{n} V_- \sqrt{\frac{z_1 z_2 \cdots z_{n+1}}{z_{1\ldots j} z_{j+1\ldots n+1}}}\; T_j[(1\ldots j)^- \to 1^-, 2^+, \ldots, j^+]\; T_{n+1-j}[(j+1\ldots n+1)^+ \to (j+1)^+, \ldots, (n+1)^+] \\
& + \sum_{j=2}^{n} \sum_{i=1}^{j-1} (V_4 + V_{\rm Coul}) \sqrt{\frac{z_1 z_2 \cdots z_{n+1}}{z_{1\ldots i} z_{i+1\ldots j} z_{j+1\ldots n+1}}} T_i[(1\ldots i)^- \to 1^-, 2^+, \ldots, i^+] \\
& \qquad \times\; T_{j-i}[(i+1\ldots j)^+ \to (i+1)^+, \ldots, j^+]\; T_{n+1-j}[(j+1\ldots n+1)^+ \to (j+1)^+, \ldots, (n+1)^+]\,.
\end{aligned}$$

light-front analog of Berends-Giele recursion relation

Diagrammatic recursion



(a)



(b)

(c)

(d)

All MHV on the light front

Lowest order amplitudes:

$$\overline{M}_{1\to 2} = 2i^2 g^1 M_{1\to 2}, \qquad \overline{M}_{1\to 3} = 2i^3 g^2 \left\{ M_{1\to 3} - \frac{D_3}{D_2}\frac{z_{123}}{z_{12}}\frac{1}{z_3}\frac{M_{1\to 2}}{v_{3(123)}} \right\},$$

$$\overline{M}_{1\to 4} = 2i^4 g^3 \left\{ M_{1\to 4} - \frac{D_4}{D_3}\frac{z_{1234}^2}{z_{123}z_{1234}}\frac{1}{z_4}\frac{1}{v_{4(1234)}} M_{1\to 3} - \frac{D_4}{D_2}\frac{z_{1234}^2}{z_{12}z_{123}}\frac{1}{z_3 z_4}\frac{1}{v_{34}}\frac{M_{1\to 2}}{v_{3(123)}} \right\}$$

off-shell

on-shell

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off-shell

on-shell

Solution by induction:

$$\overline{M}_{1\to n} = 2i^n g^{n-1} \left\{ M_{1\to n} - z_{1\dots n}^2 D_n \sum_{i=2}^{n-1} \frac{1}{z_{1\dots i} z_{1\dots i+1}} \frac{1}{z_{i+1}\cdots z_n} \frac{1}{v_{i+1\ i+2}\cdots v_{n-1\ n}} \frac{M_{1\to i}}{v_{i+1(1\dots i+1)} D_i} \right\}$$

$$M_{1\to n} \equiv \frac{z_{1\dots n}\ z_1}{z_2 z_3 \cdots z_n} \frac{v_{(1\dots n)1}^3}{v_{12} v_{23}\cdots v_{n-1\ n} v_{n(1\dots n)}}$$

$$\overline{M}_{1\to n} \xrightarrow{D_n \to 0} 2i^n g^{n-1} M_{1\to n}$$

$$ig^{n-2} \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\dots\langle n-2\ n-1\rangle\langle n-1\ n\rangle\langle n1\rangle}$$

Summary and next steps

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- All MHV tree level amplitudes computed on the light front.

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Summary and next steps

- All MHV tree level amplitudes computed on the light front.
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- Can the last recursion (i.e. between off-shell and on-shell amplitudes) be used for higher order computation?

Computing Group

Round 2

Back to Contents

Exploring Electromagnetic Properties on the Lattice

Brian Tiburzi

1 November 2013









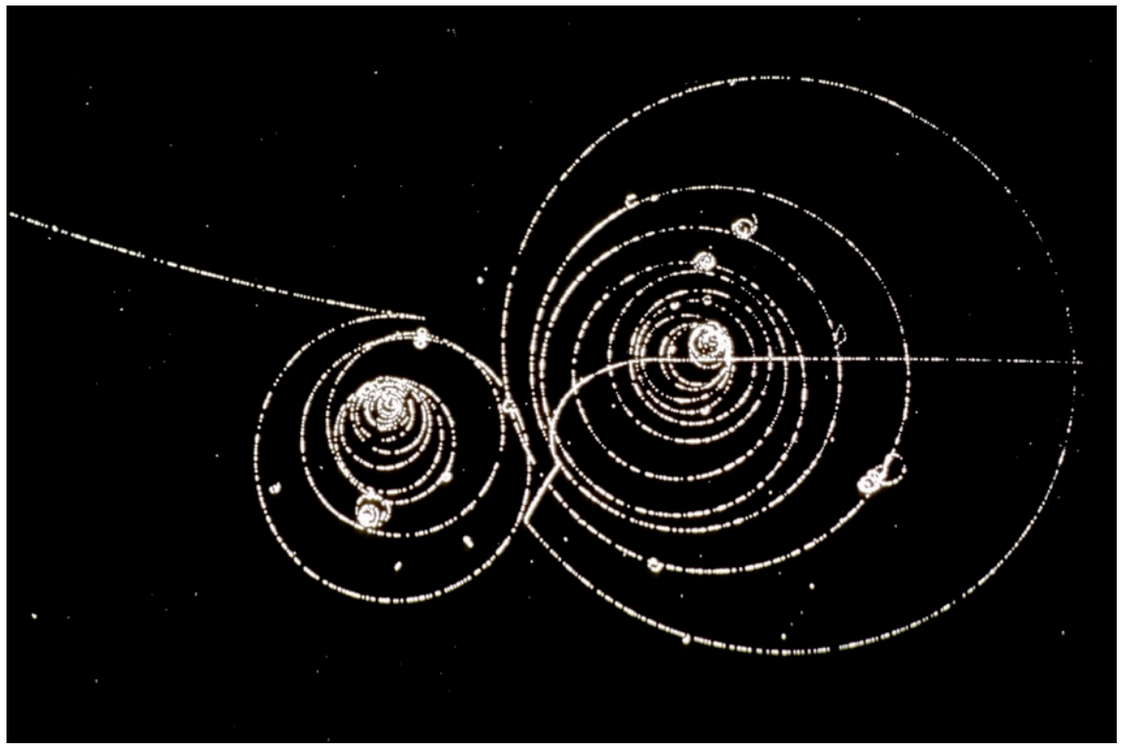


Exploring Electromagnetic Properties on the Lattice

- **Goal:**
  Determine hadron properties from *Lattice QCD*

- Hadrons: pion, nucleon, light nuclei

- Properties: electromagnetic to start



Ambitious electromagnetic observables to compute

Electric & Magnetic polarizabilities of pion

- *ChPT* vs. Experiment: 2.5σ discrepancy

  [Large cast of characters...]

- Will *COMPASS* resolve? JLAB expt. approved...
- Contribution to hadronic light-by-light (constraint in π loop models)

  [Engel, Patel, Ramsey-Musolf PRD (2012) & 1309.2225]

Magnetic polarizability of nucleon

- Experiment: 50% - 100% uncertainty
- *ChPT* in single and few nucleon systems

  [Large cast of characters...]

- Dominant error in determining nucleon EM mass splitting

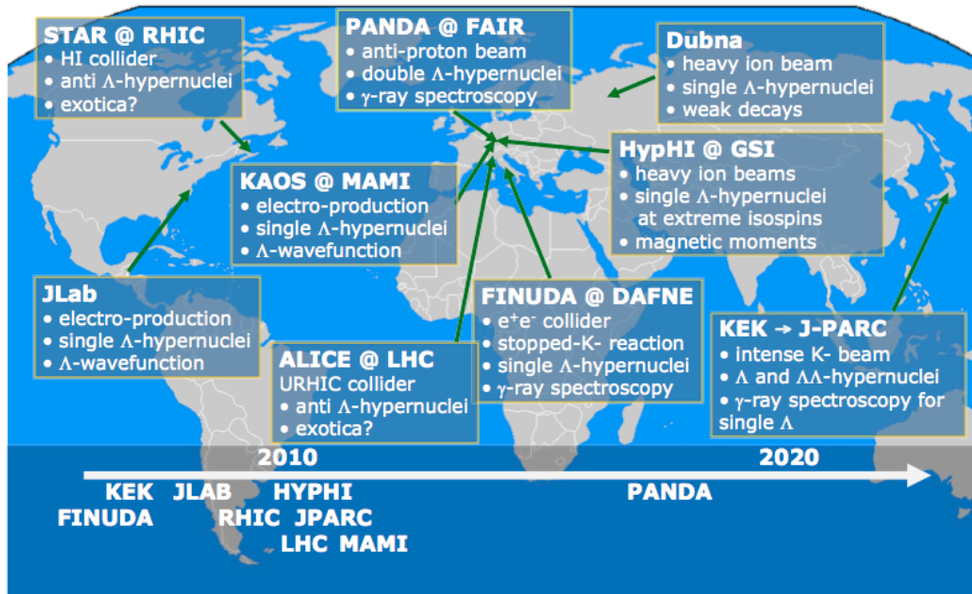
  [Walker-Loud, Carlson, Miller PRL (2012)]

- Help constrain proton structure corrections to *μ-H*

  [Hill, Paz PRL (2011)]

Moments and polarizabilities of light nuclei

- Little known about moments of Λ hypernuclei $^{5}_{\Lambda}\mathrm{He}$ $^{7}_{\Lambda}\mathrm{He}$



Exploring Electromagnetic Properties on the Lattice

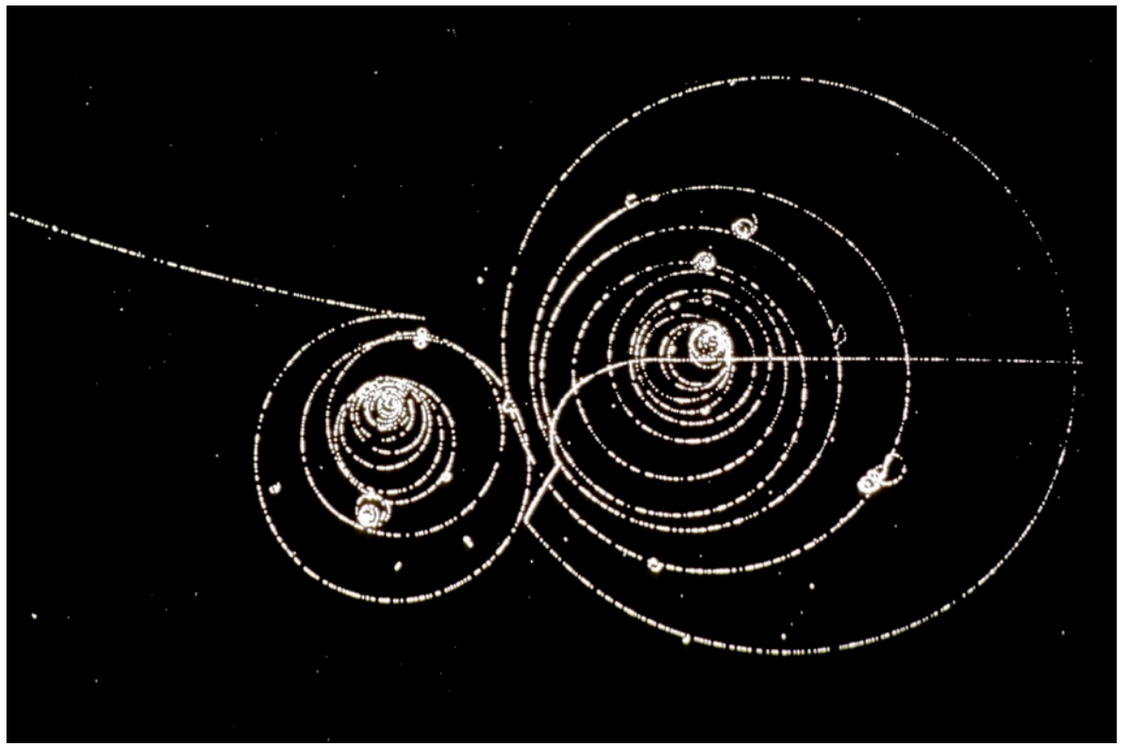
- **Prior work:**

Electric polarizabilities of pseudoscalars

[Detmold, Tiburzi, Walker-Loud PRD (2009)]

Nucleon magnetic moments and electric polarizabilities

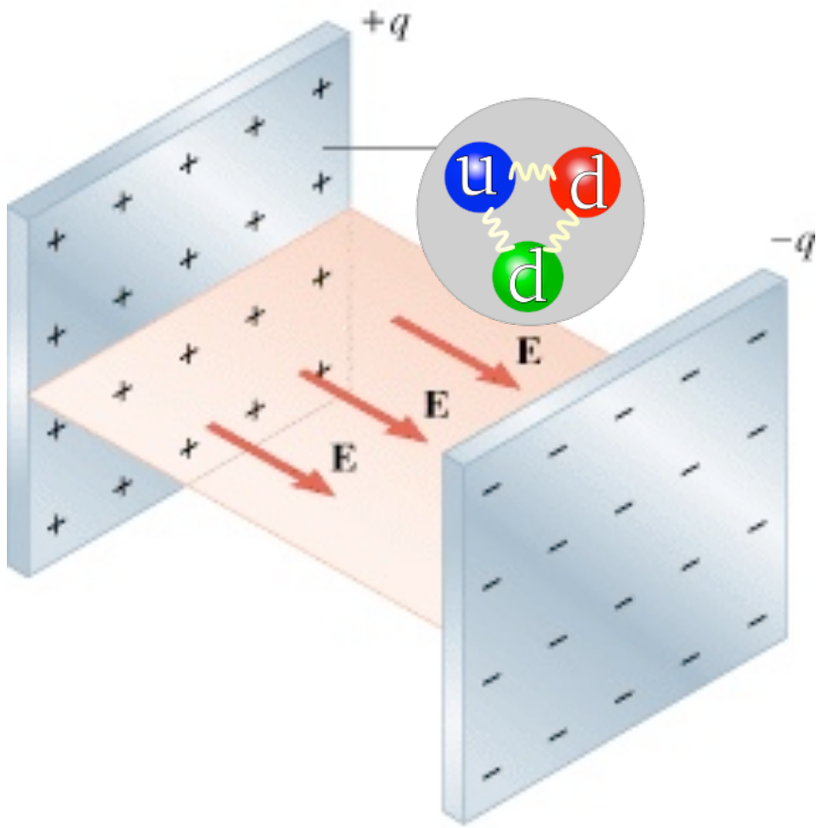
[Detmold, Tiburzi, Walker-Loud PRD (2010)]



Lattice QCD in External Fields

Couple classical electromagnetic fields to quarks and then study hadron spectroscopy

$$D_\mu = \partial_\mu + ig\,G_\mu + iqA_\mu$$



‘t Hooft quantization $\quad q\,\mathcal{E} = \dfrac{2\pi n}{\beta L}$

Gauge links

$$U_\mu(x) = e^{igG_\mu(x)} \in SU(3)$$

$$U^{\text{e.m.}}_\mu(x) = e^{iqA_\mu(x)} \in U(1)$$

Strong magnetic field studies on thermodynamic lattices

[Chernodub, et al.]

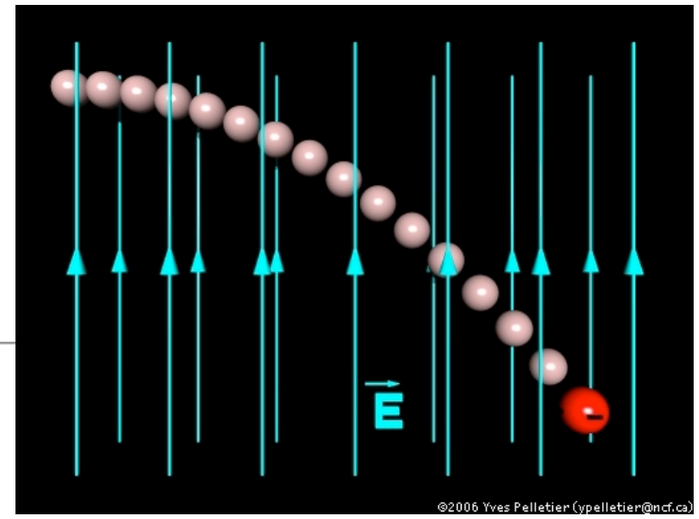
[D’Elia, Mukherjee, et al.]

[BM&W collaboration]

Exploratory *weak* electric field studies: U(1) field couples only to valence quarks

[Detmold, Tiburzi, Walker-Loud]

Lattice QCD in Electric Fields



Method basics are basic

- Measure hadronic correlation functions in classical electromagnetic fields
- Study field strength dependence to determine parameters in effective action

E.g. *charged* pion in electric field

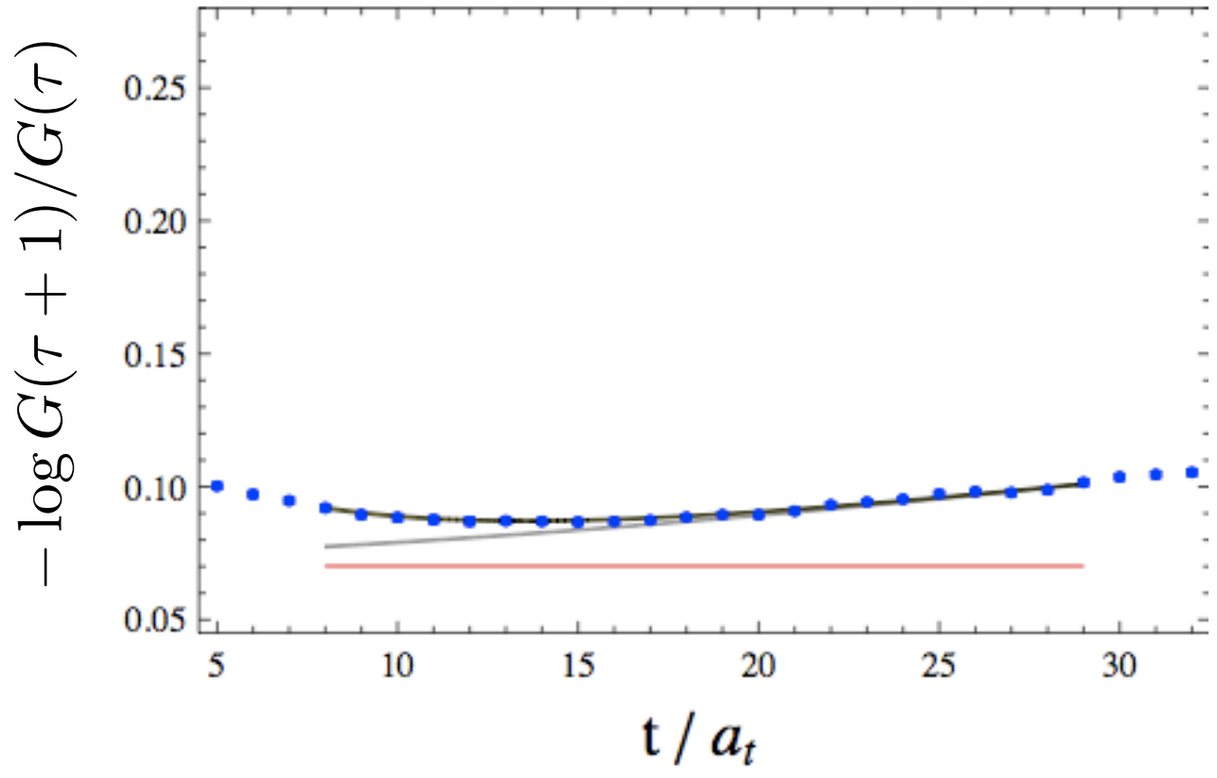
$$A_\mu = -\mathcal{E} x_4 \delta_{\mu 3}$$

[Detmold, Tiburzi, Walker-Loud PRD (2009)]

Anisotropic clover lattices (HadSpec)

$20^3 \times 128$ $\qquad$ $m_\pi = 390\,\mathtt{MeV}$

$$E = m_\pi + \frac{1}{2}\alpha_E \mathcal{E}^2 + \ldots$$



$$G(\tau) = \langle \tau | \frac{1}{2\mathcal{H} + E^2} | 0 \rangle = \frac{1}{2} \int_0^\infty ds\, e^{-\frac{1}{2} s E^2} \langle \tau | e^{-s\mathcal{H}} | 0 \rangle$$

[Schwinger PR (1951)]

[Tiburzi NuPhA (2008)]

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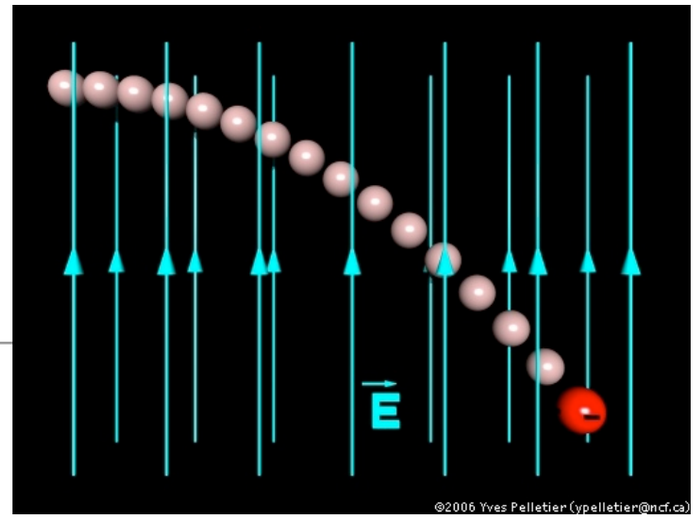

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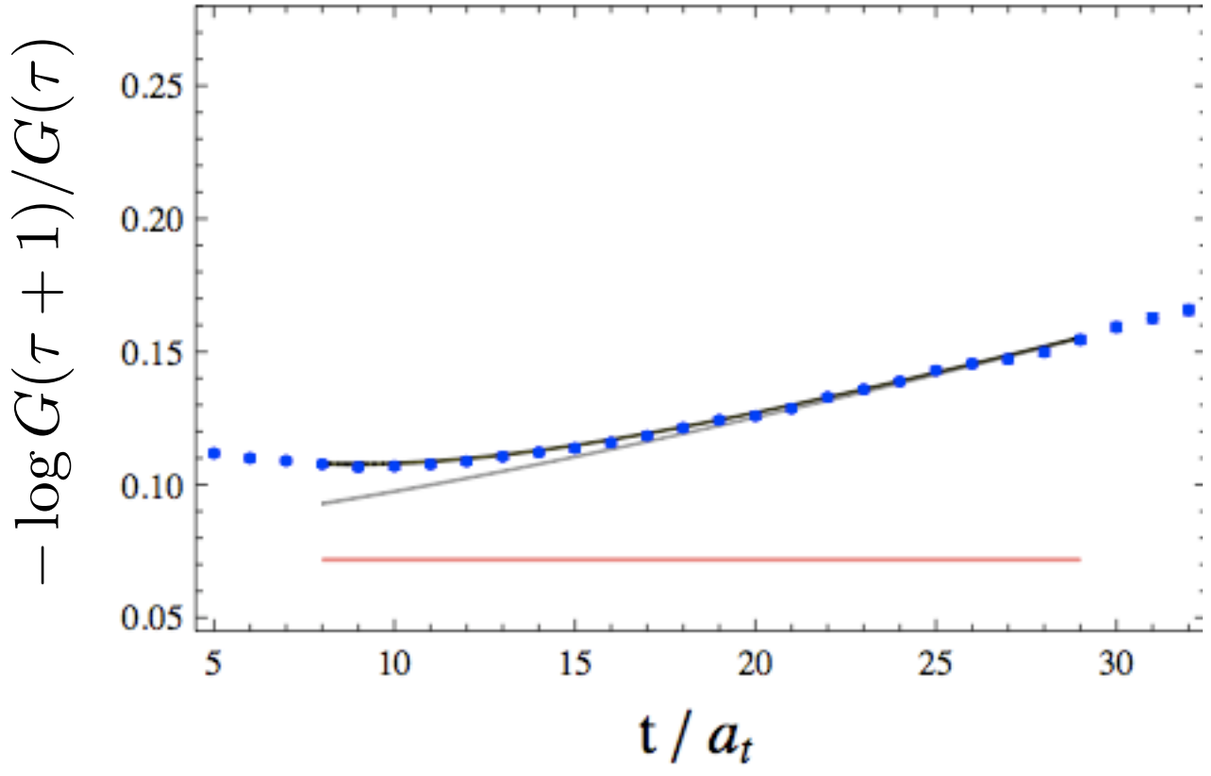

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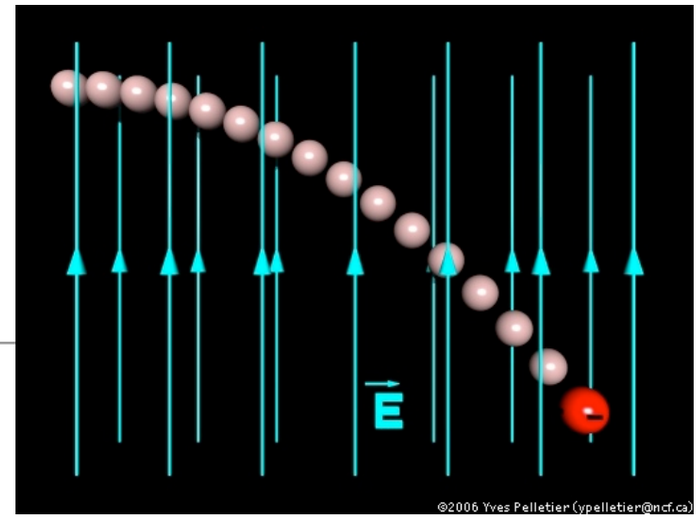

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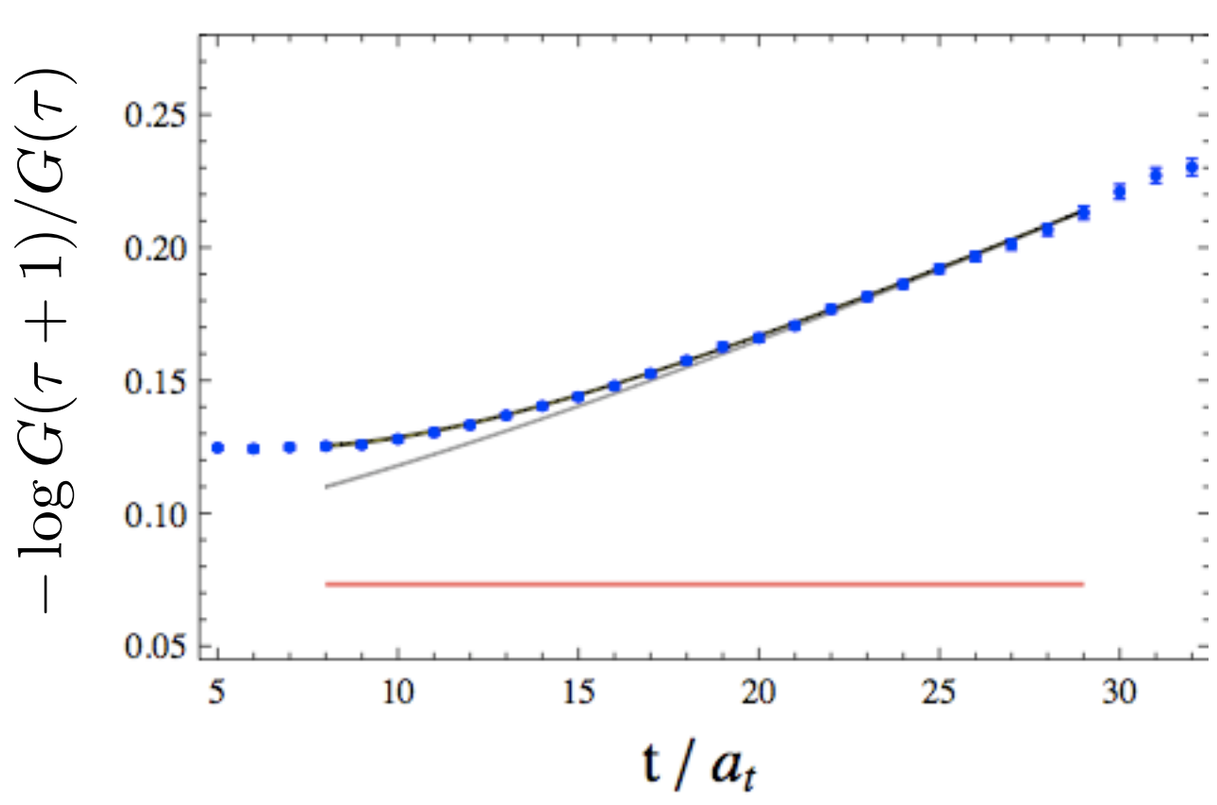

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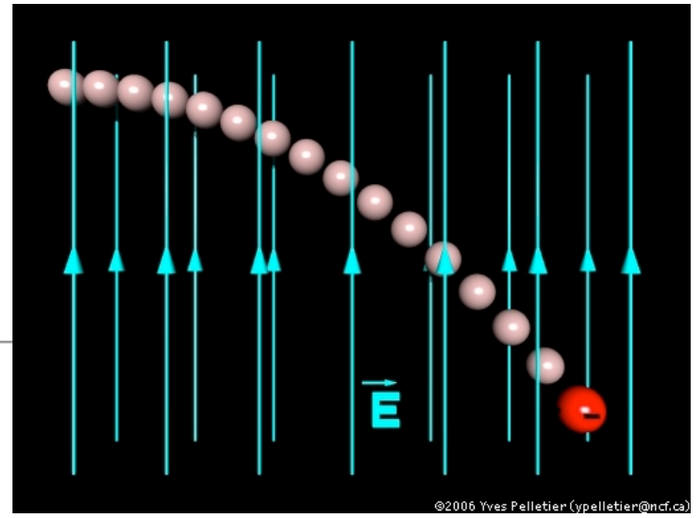

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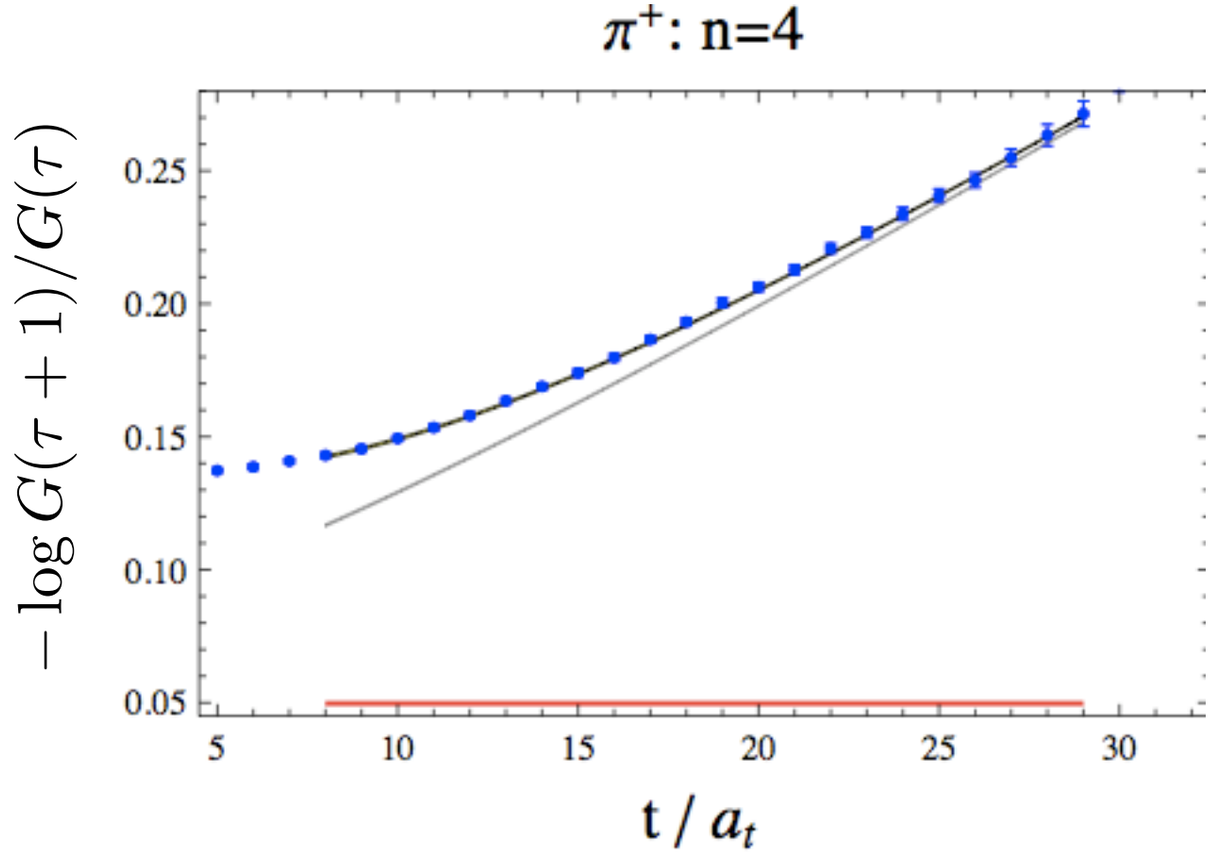

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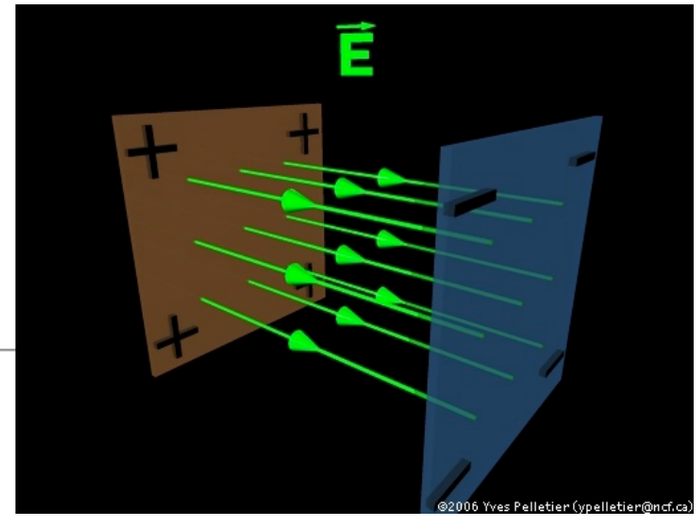

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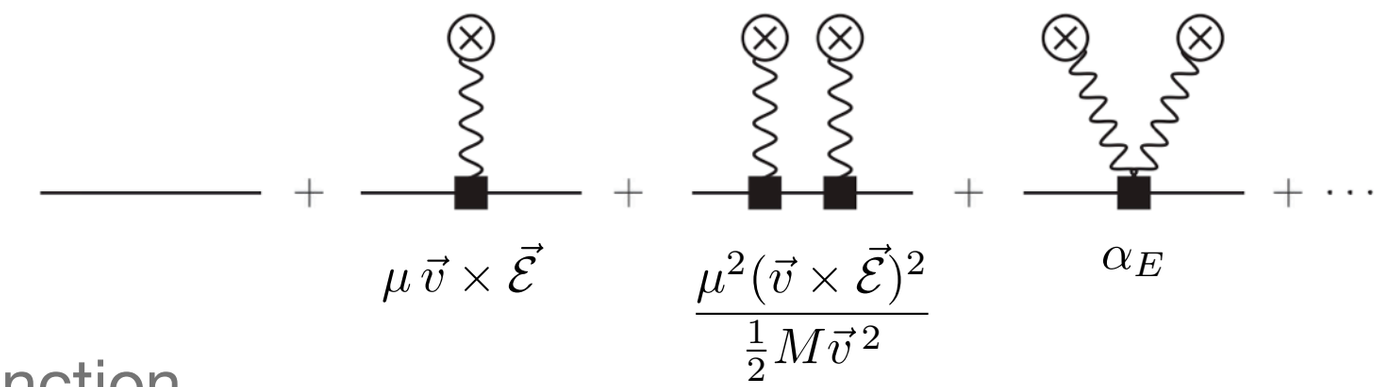
E.g. neutron in electric field [Detmold, Tiburzi, Walker-Loud PRD (2010)]

Effective action $\mathcal{L} = N^\dagger \left[\gamma_\mu \partial_\mu + E - \frac{\mu}{4M_N} \sigma_{\mu\nu} F_{\mu\nu} \right] N$

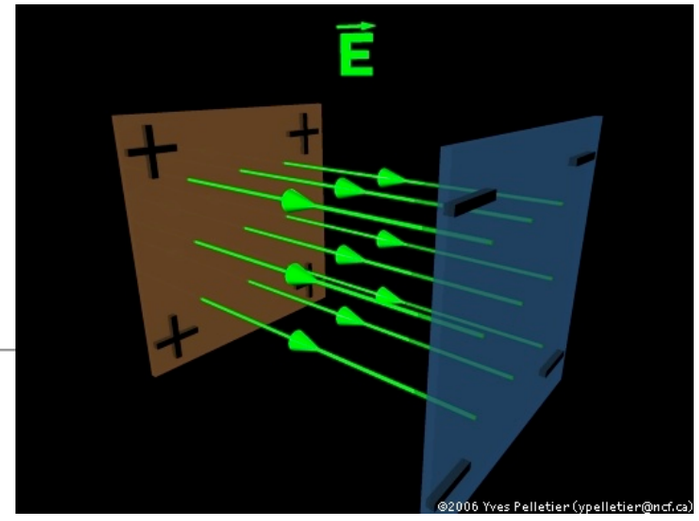
$G(\tau) = \sum_{\vec{x}} \langle \chi(\vec{x}, \tau) \chi^\dagger(\vec{0}, 0) \rangle$



Spin-averaged correlation function

$$G(\tau) = Z e^{-E_{\text{eff}}\,\tau} \qquad E_{\text{eff}} = M + \frac{1}{2}\mathcal{E}^2 \left(\alpha_E - \frac{\mu^2}{4M^3} \right) + \ldots$$

Lattice QCD in External Fields



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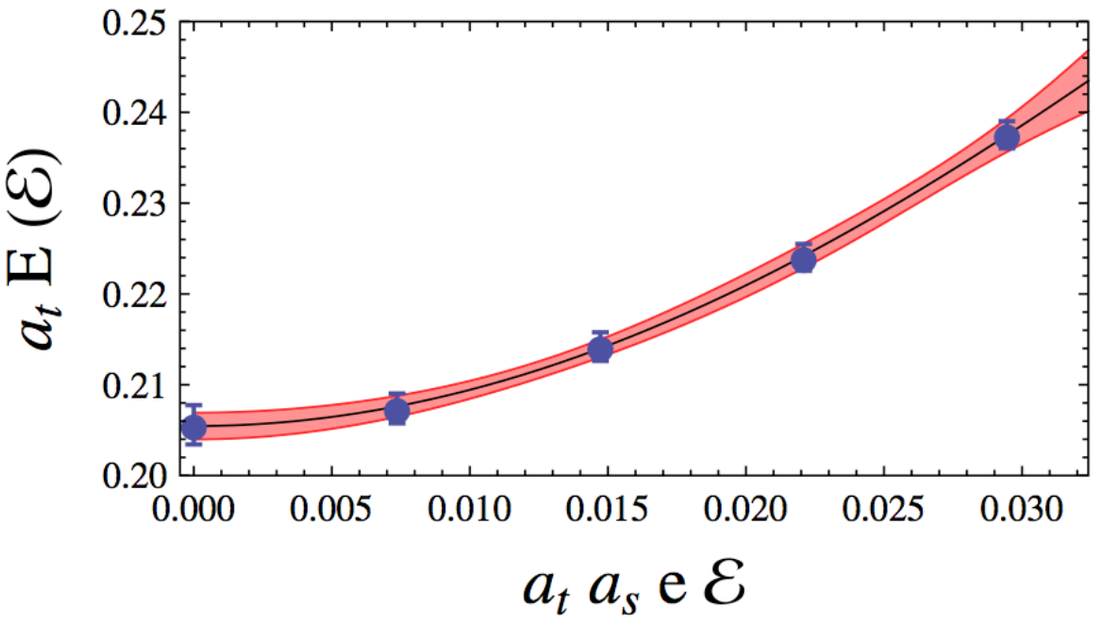


$$\mathrm{Tr}[\mathcal{P}_{\pm}G(\tau)] = Z\left(1 \pm \frac{\mu\mathcal{E}}{2M_N^2}\right)\exp(-\tau E_{\mathrm{eff}})$$

Simultaneous fit to "*boost-projected*" correlators

$$\mu_n = -1.6(1)\,[\mu_N]$$
$$(\mu_n)_{\mathrm{exp}} = -1.9\,[\mu_N]$$

$$\alpha_E^n = 3(1)\times 10^{-4}\,\mathtt{fm}^3$$
$$(\alpha_E^n)_{\mathrm{exp}} = 11(2)\times 10^{-4}\,\mathtt{fm}^3$$

Our results have known sources of systematic error

$E = M + \frac{1}{2}\mathcal{E}^2\alpha_E + \ldots$ Not E_{eff} which includes *Born term*

proton results too...

Exploring Electromagnetic Properties on the Lattice

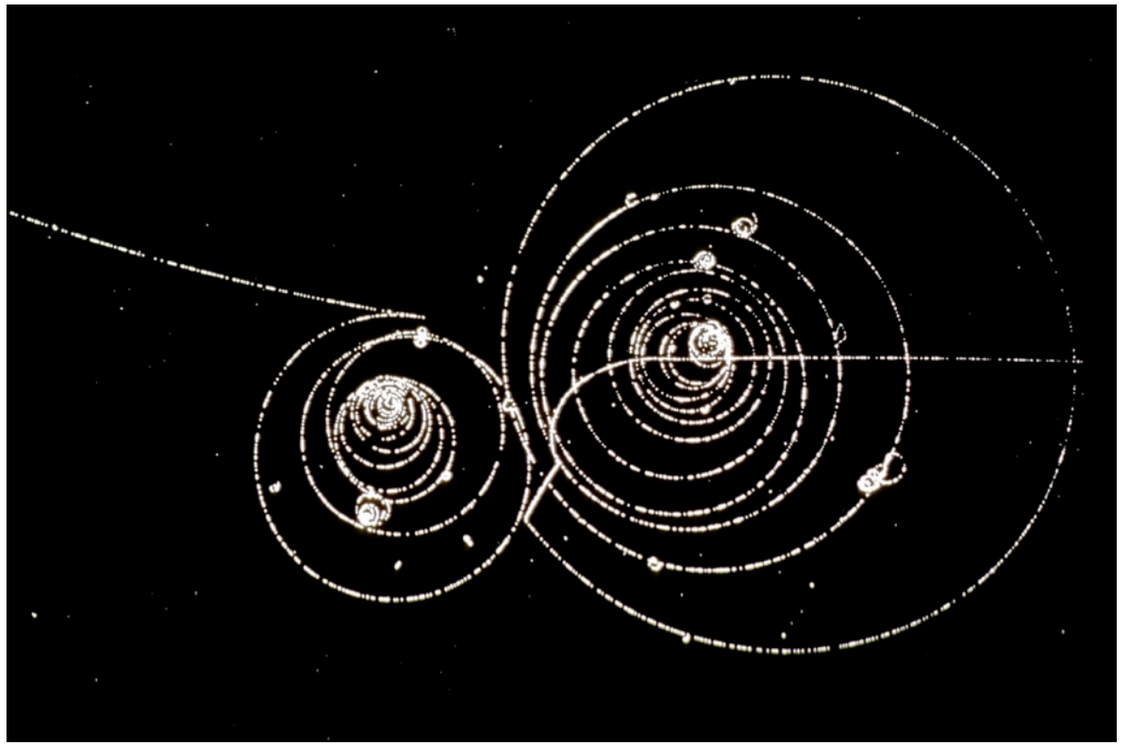
- **Recent work:**

Treating Landau levels

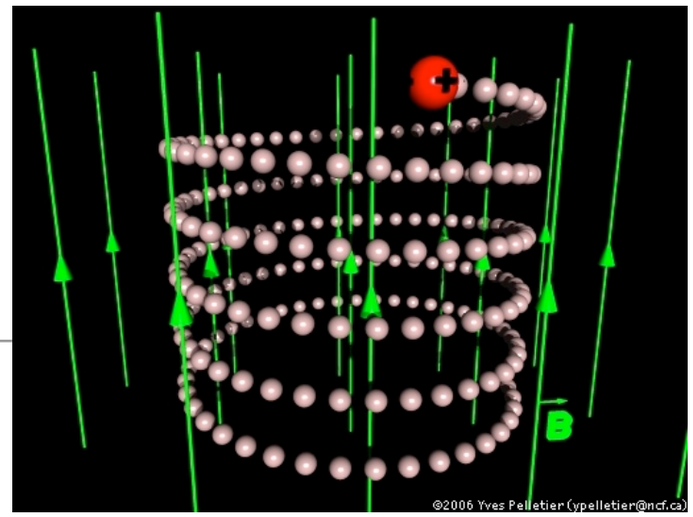
[Tiburzi & Vayl PRD (2013)]

Critique of Dirichlet boundary

[Tiburzi PRD (2013)]



Lattice QCD in Magnetic Fields



Method basics are basic

- Measure hadronic correlation functions in classical electromagnetic fields
- Study field strength dependence to determine parameters in effective action

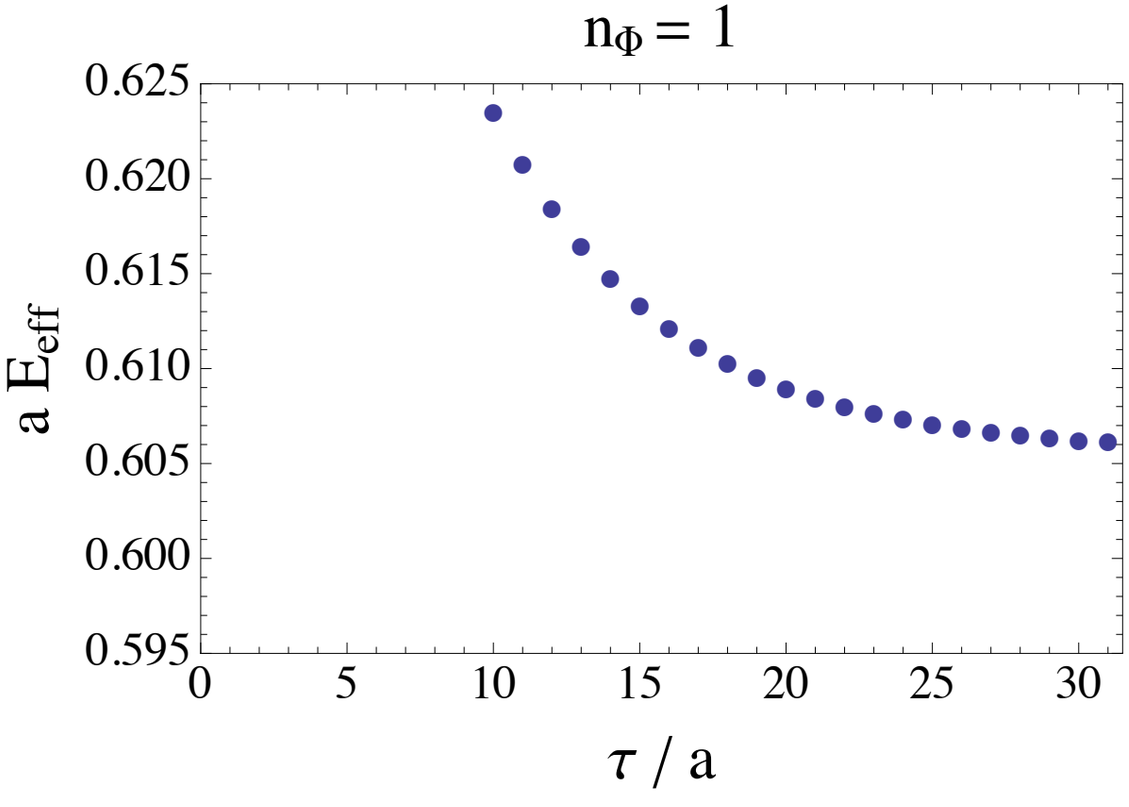
E.g. *charged* scalar in magnetic field

$$A_\mu = -Bx_2\delta_{\mu 1}$$

Synthetic data for heavy scalar “nucleon”

$32^3 \times 64$

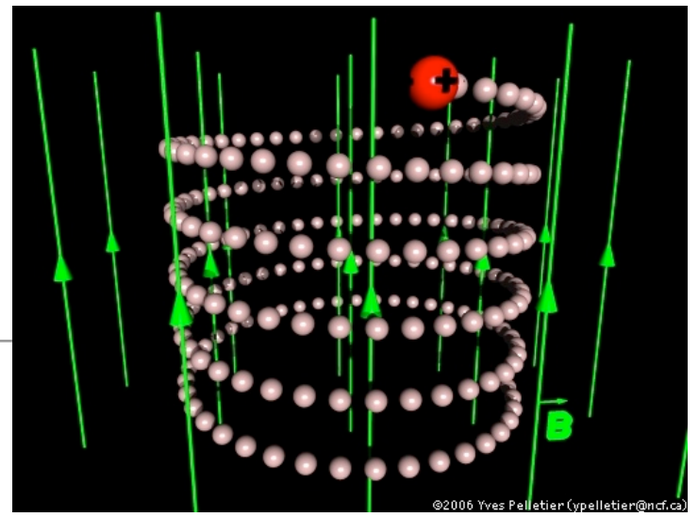
$$G(\tau) = \sum_{\vec{x}} \langle \chi(\vec{x},\tau)\chi^\dagger(\vec{0},0)\rangle$$



Need to measure small energy shifts

[Tiburzi & Vayl PRD (2013)]

Lattice QCD in Magnetic Fields



Method basics are basic

- Measure hadronic correlation functions in classical electromagnetic fields
- Study field strength dependence to determine parameters in effective action

E.g. *charged* scalar in magnetic field

$$A_\mu = -Bx_2\delta_{\mu 1}$$

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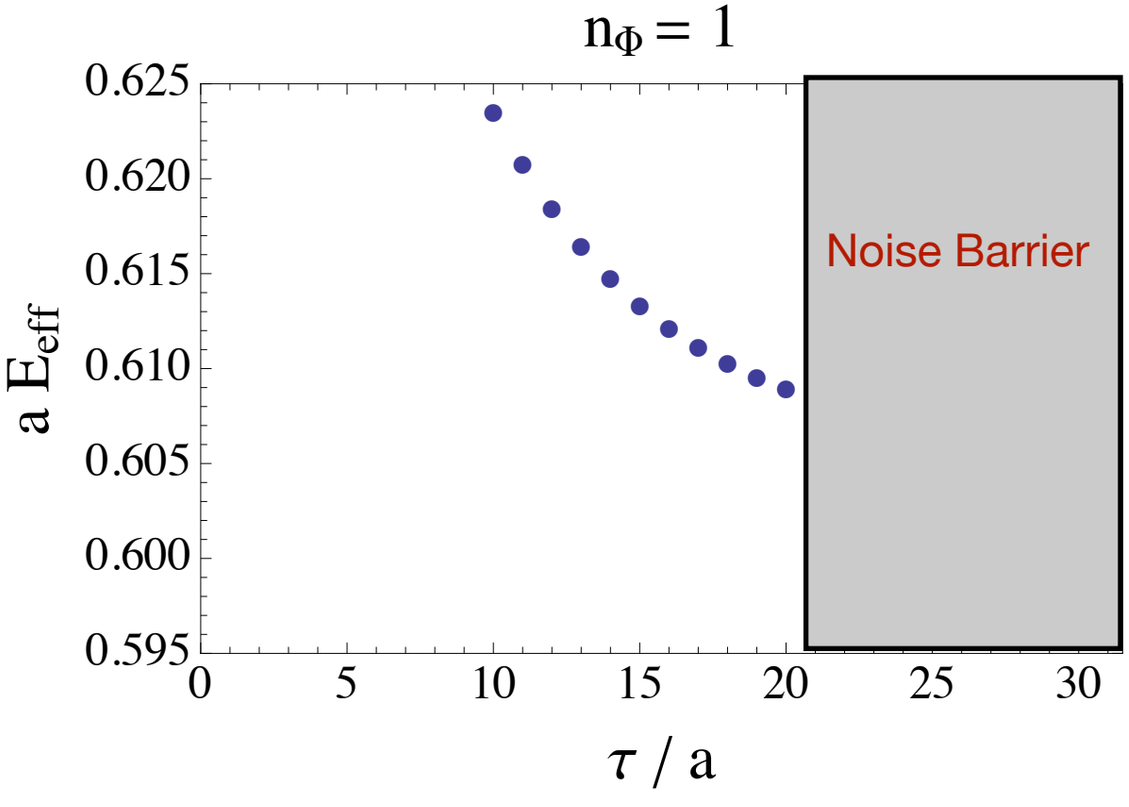
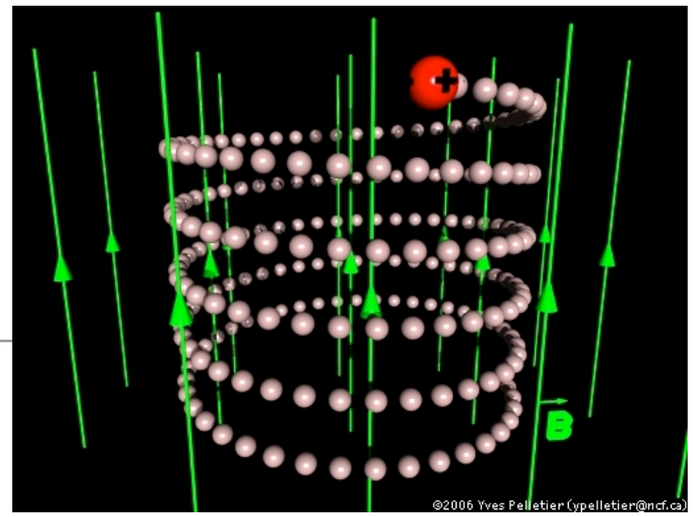


Need to measure small energy shifts

This model does not have hadronic excited states

[Tiburzi & Vayl PRD (2013)]

Lattice QCD in Magnetic Fields



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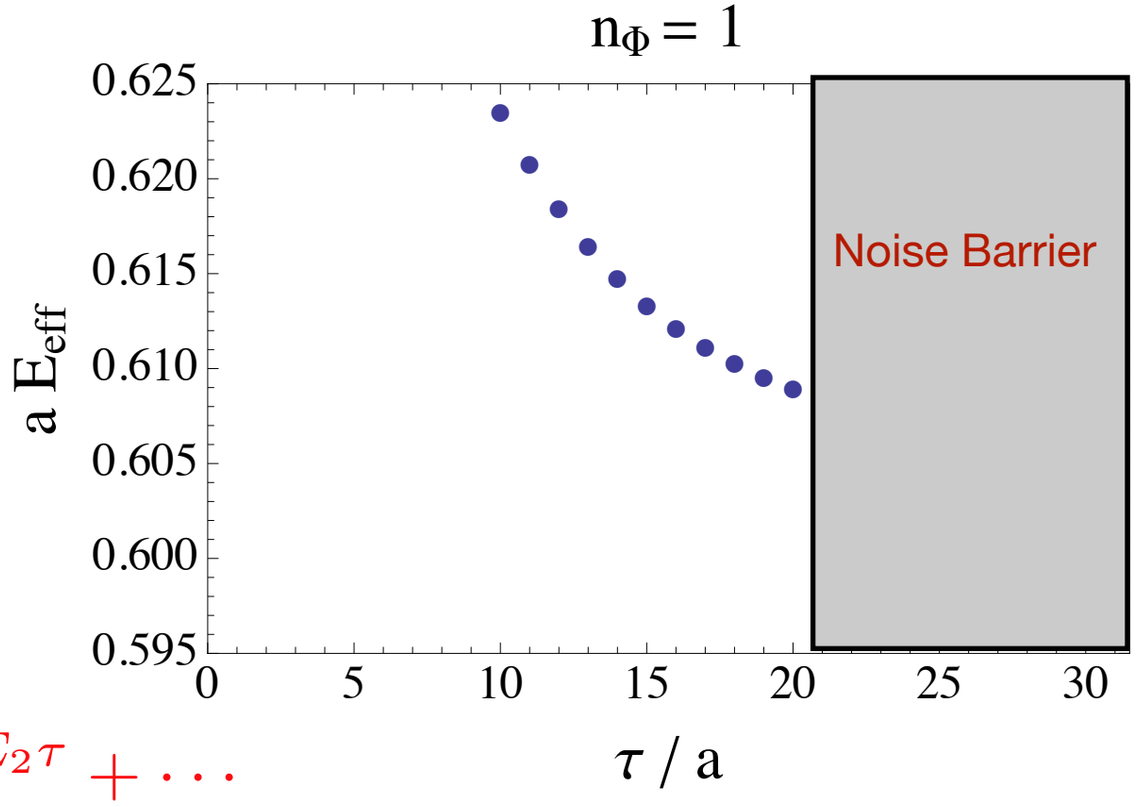
$$G(\tau) = \sum_{\vec{x}} \langle \chi(\vec{x},\tau)\chi^\dagger(\vec{0},0)\rangle$$

$$= Z_0 e^{-E_0\tau} + Z_1 e^{-E_1\tau} + Z_2 e^{-E_2\tau} + \cdots$$

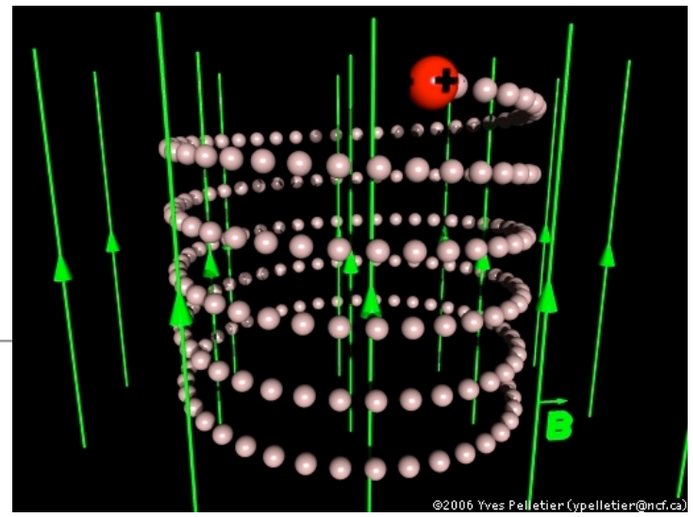


This model does not have hadronic excited states

... but there are Landau levels

[Tiburzi & Vayl PRD (2013)]

Lattice QCD in Magnetic Fields



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- Study field strength dependence to determine parameters in effective action

E.g. *charged* scalar in magnetic field

$$A_\mu = -Bx_2\delta_{\mu 1}$$

Synthetic data for heavy scalar “nucleon”

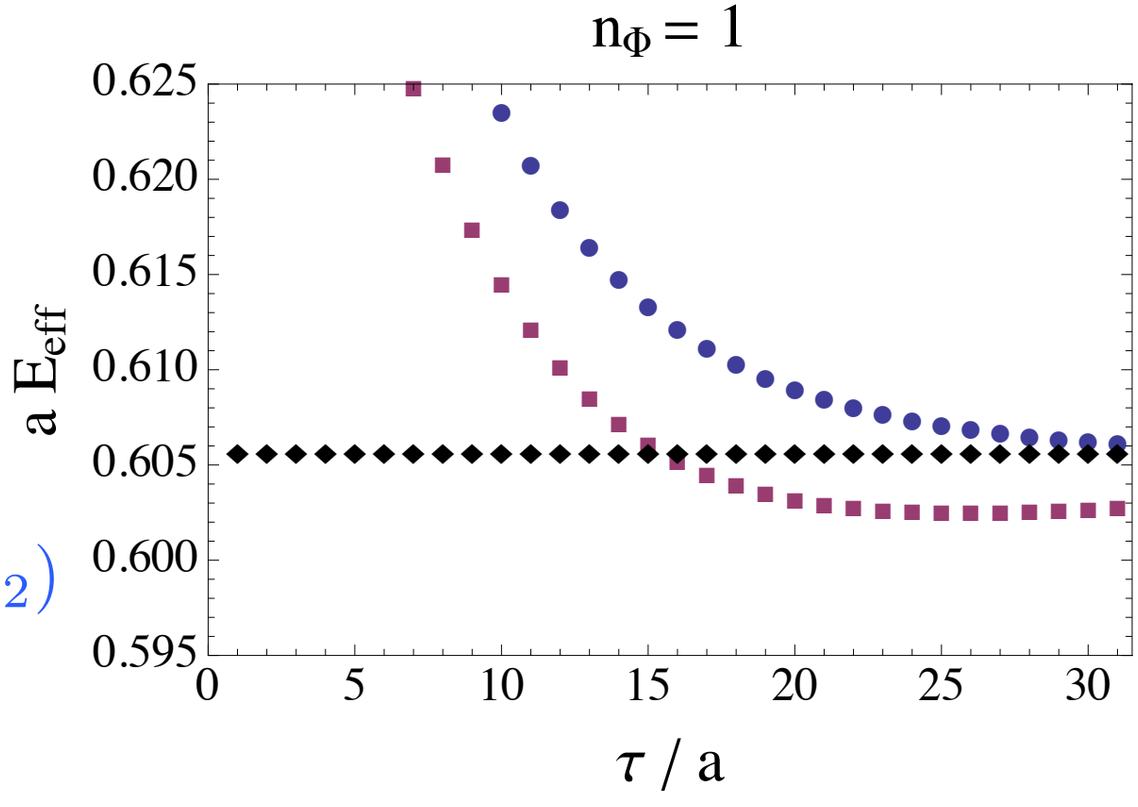
$32^3 \times 64$

$$G(\tau) = \sum_{\vec{x}} \langle \chi(\vec{x},\tau)\chi^\dagger(\vec{0},0)\rangle \times \psi^*_{n=0}(x_2)$$

$$= e^{-E_0\tau}$$

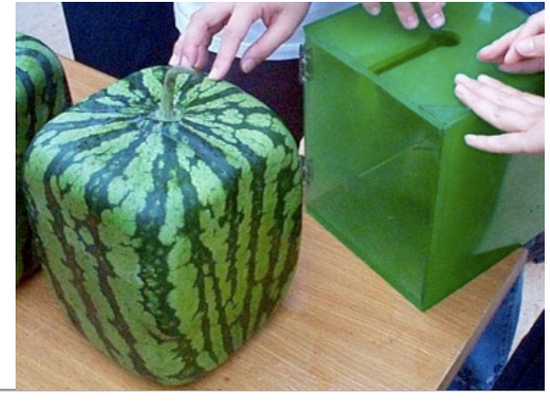
... but there are Landau levels

[Tiburzi & Vayl PRD (2013)]

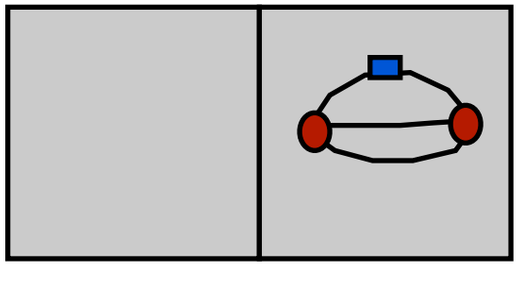


- Magnetic periodic images needed

Dirichlet Boundary Conditions



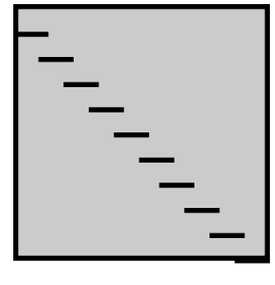
- Frustrate spontaneous chiral symmetry breaking $\langle\overline{\psi}\psi\rangle\Big|_{\text{boundary}} = 0$



1). Chopping lattices in time

2). External field calculations (competitors!)

3). Lattice QCD in rotating frames



4). Schrödinger functional **SFBC**s

Sigma Model with **DBC**s

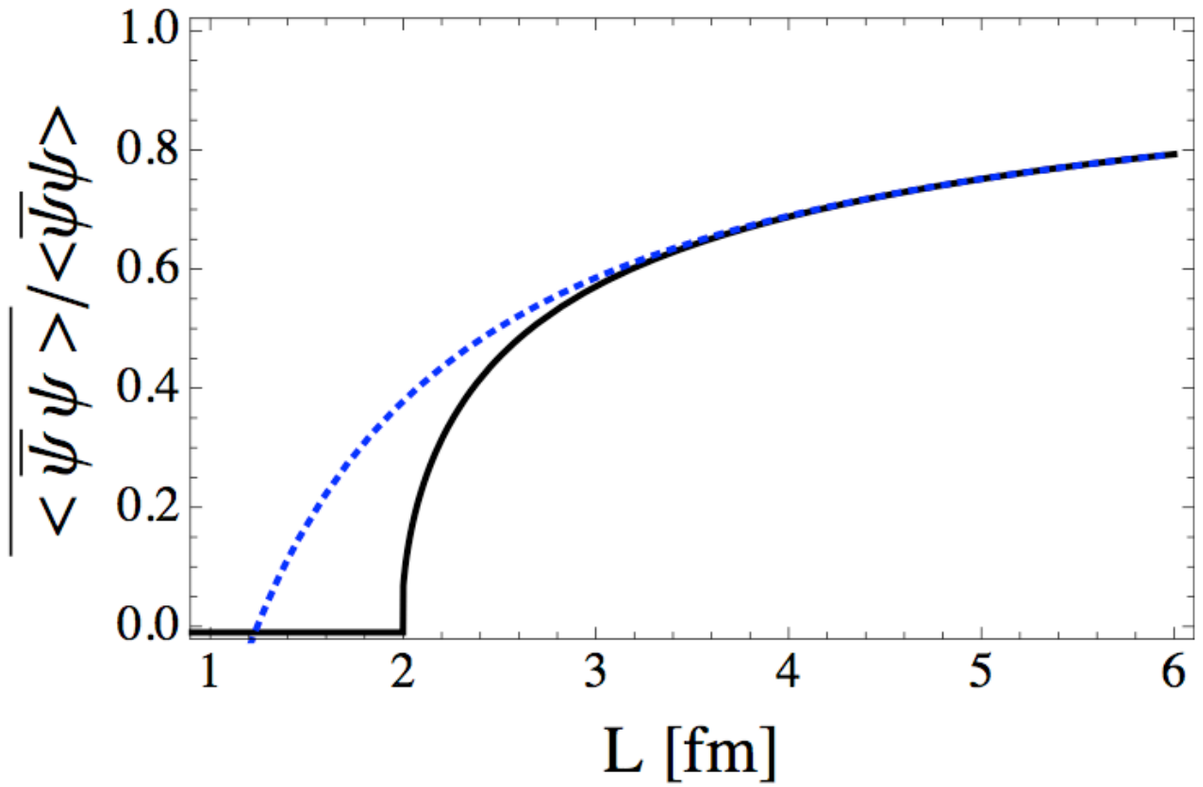
Asymptotics

$$\overline{\langle\overline{\psi}\psi\rangle}/\langle\overline{\psi}\psi\rangle = 1 - \frac{4\log 2}{m_\sigma L}$$

Model Dependent

IR physics from pions cannot describe!

Mechanism of ChSB important

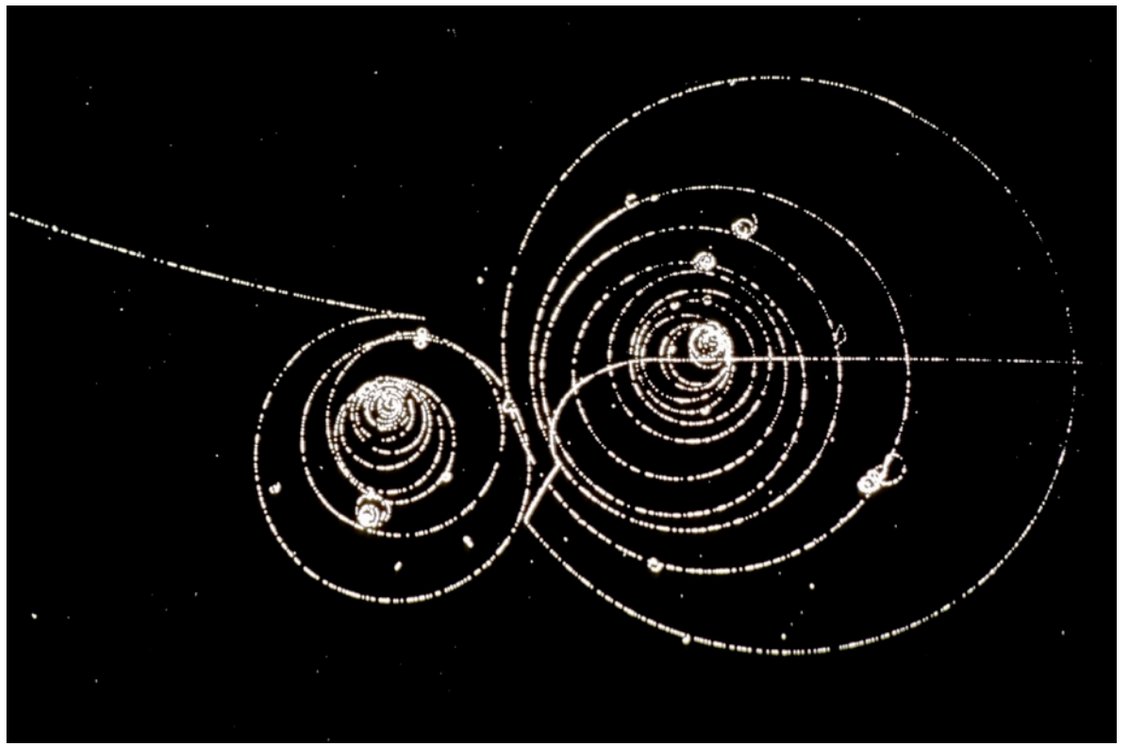


Exploring Electromagnetic Properties on the Lattice

- **In progress**

NRQED Matching
[Lee & Tiburzi]

Volume and pion mass dependence
[Detmold,Tiburzi, Walker-Loud]



- **Outlook**

Computation of polarizabilities challenging
Many things to explore (e.g. magnetic case, gauge field reweighting, B>1)

Confinement and Chiral Symmetry Breaking

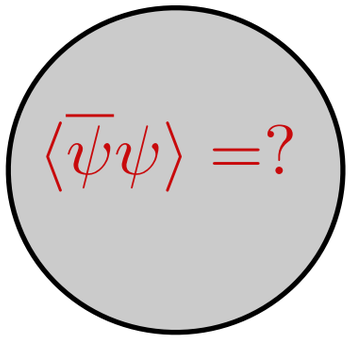
[BACKUP]

- Rephrase as: can *ChSB* be confined to a sphere? $\langle\overline{\psi}\psi(R)\rangle = 0$

  Enforcing “bag-model” confinement [Chodos, Jaffe, Johnson, Thorne, Weisskopf]

- In sigma model answer appears to be *NO...* for *any R*!

$$S[\Sigma_0] = \frac{1}{\frac{4}{3}\pi R^3}\int_V \left[\frac{1}{2}\vec{\nabla}\Sigma_0\cdot\vec{\nabla}\Sigma_0 + \Lambda(\Sigma_0^2 - v^2)^2\right]$$



spherical symmetry

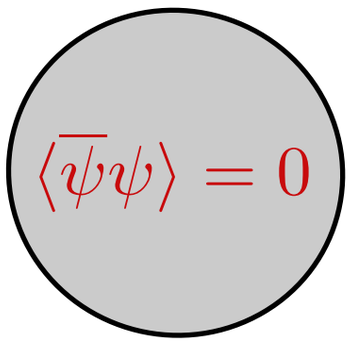
$t \sim r, \quad x \sim r\Sigma_0$ $\qquad \ddot{x} = \frac{x}{2}\left(\frac{x^2}{t^2} - 1\right)$

Numerically appears only trivial solution

Analytical proof...

- Model points to impossibility of confining the condensate

- Reimagine: spherical droplet of *symmetric* matter?



$\langle\overline{\psi}\psi\rangle = ?$

Only oscillatory solution for condensate asymptotically

Quark mass effects? Not likely...

New theories, new physics, and lattice simulations

Ethan T. Neil

RBRC Scientific Review Meeting

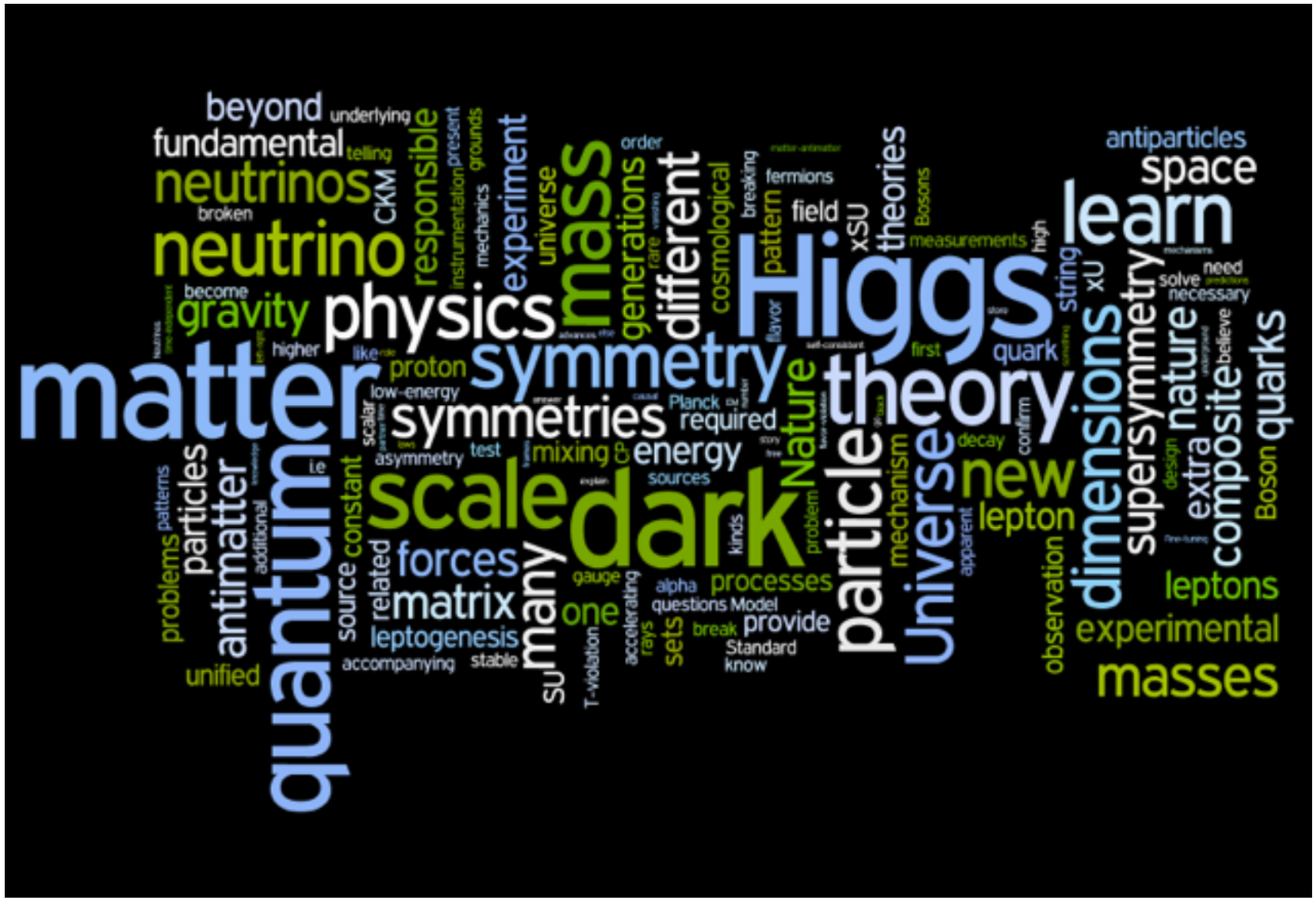
October 31, 2013





Overview

- Many puzzles in particle physics today!
- Theorists come up with new models to explain some of these mysteries, and study experimental signatures.
- Things become hard when coupling is strong! Intersections with QCD important. Properties of new strongly-coupled theories murky.



(from “Big Questions”, Snowmass 2013)

Lattice is an important precision tool to separate QCD and new physics, and a “numerical laboratory” to expand our knowledge of new theories!

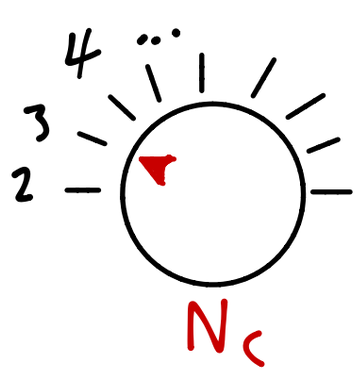
New strongly-coupled theories, new physics

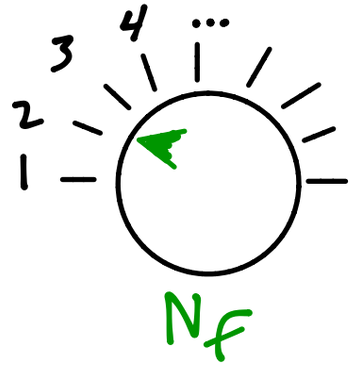
- Physics of QCD is very rich - many composite states with complex interactions, from a handful of parameters
- Not only that, specific phenomena in QCD have obvious applications to other problems!

spontaneous χSB	⟷	Higgs mechanism
neutral bound states	⟷	dark matter

- QCD is just one example in a huge space of strongly-coupled gauge theories… what changes if we play with the dials?

$$\mathcal{L} = -\frac{1}{4g^2}\sum_{a=1}^{N_c^2-1} F^a_{\mu\nu} F^{\mu\nu,a} + \sum_{i=1}^{N_f} i\bar{\psi}_i \gamma^\mu D_\mu \psi_i$$





Exploring the Space

- A subset of strongly-coupled theories containing QCD: SU(N_c) gauge symmetry, N_f light "quarks".

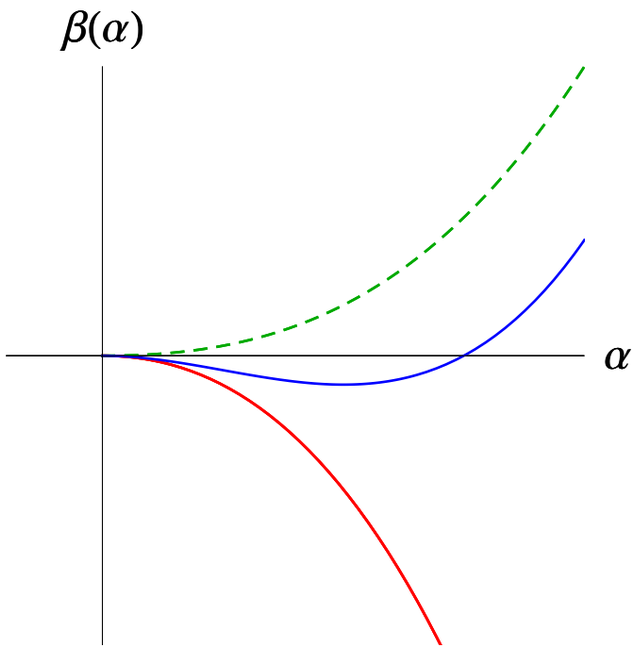
  (QCD: N_c=3, N_f=2,3,4)

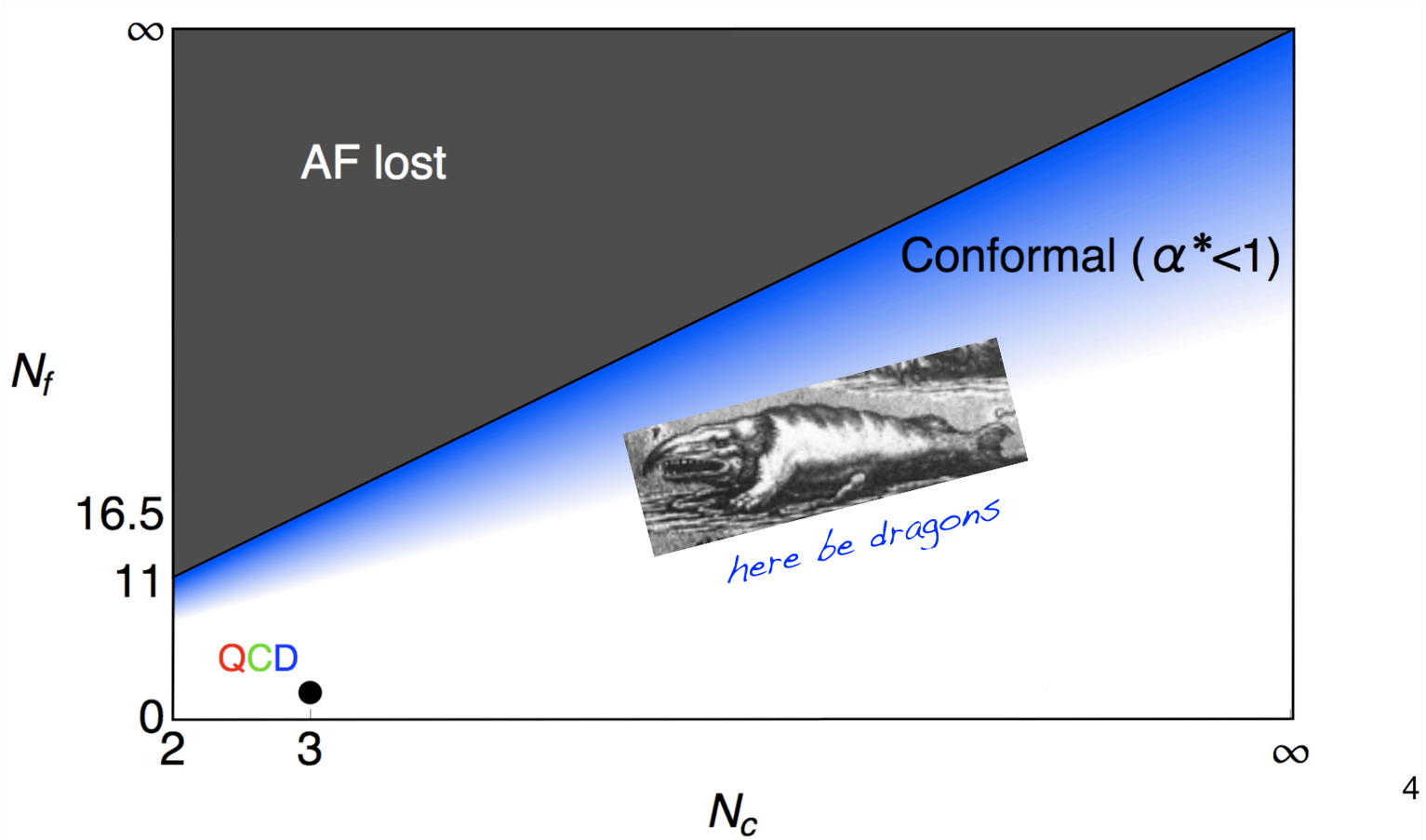
- Strongly-coupled fixed point near the transition - *lattice*!

$$\beta(\alpha) \equiv \frac{\partial \alpha}{\partial(\log \mu^2)} = -\beta_0 \alpha^2 - \beta_1 \alpha^3 - \ldots$$

$$\beta_0 = \frac{1}{4\pi}\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right)$$

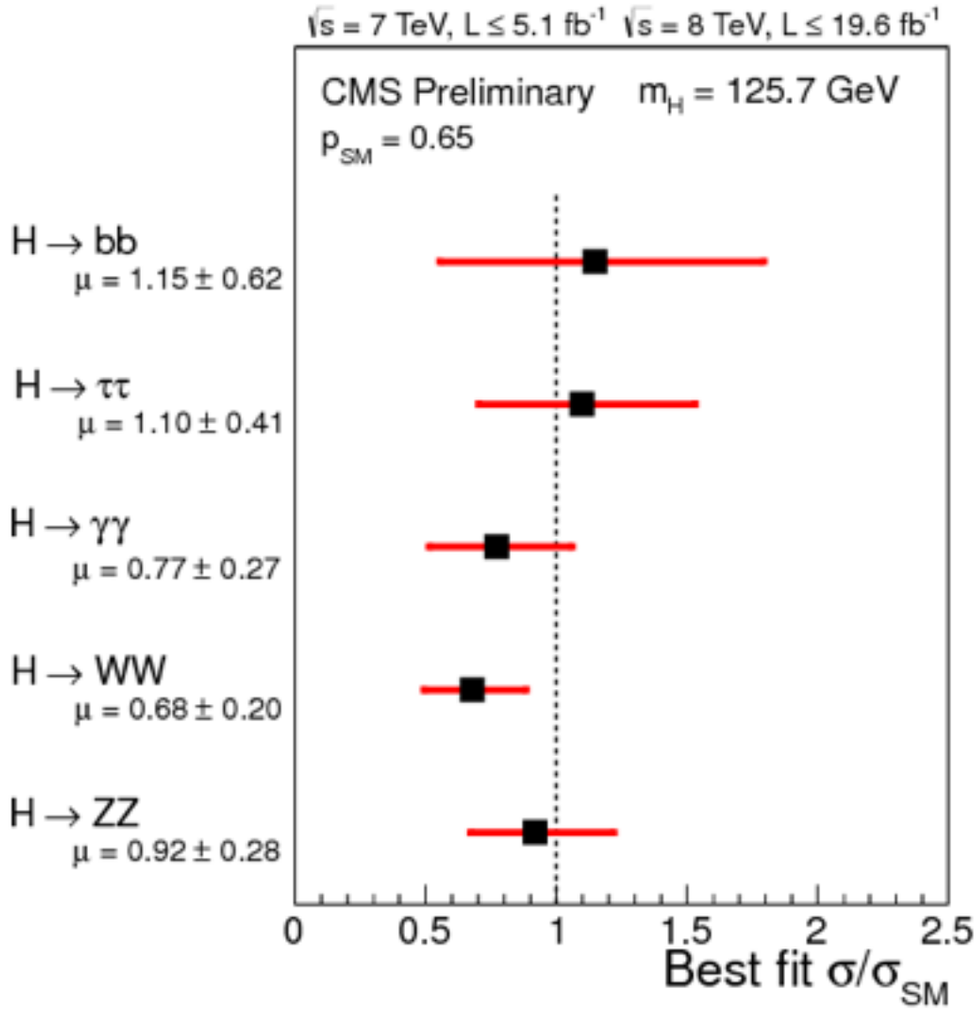
$$\beta_1 = \frac{1}{16\pi^2}\left(\frac{34}{3}N_c^2 - \left[\frac{13}{3}N_c - \frac{1}{N_c}\right]N_f\right)$$





Composite Higgs

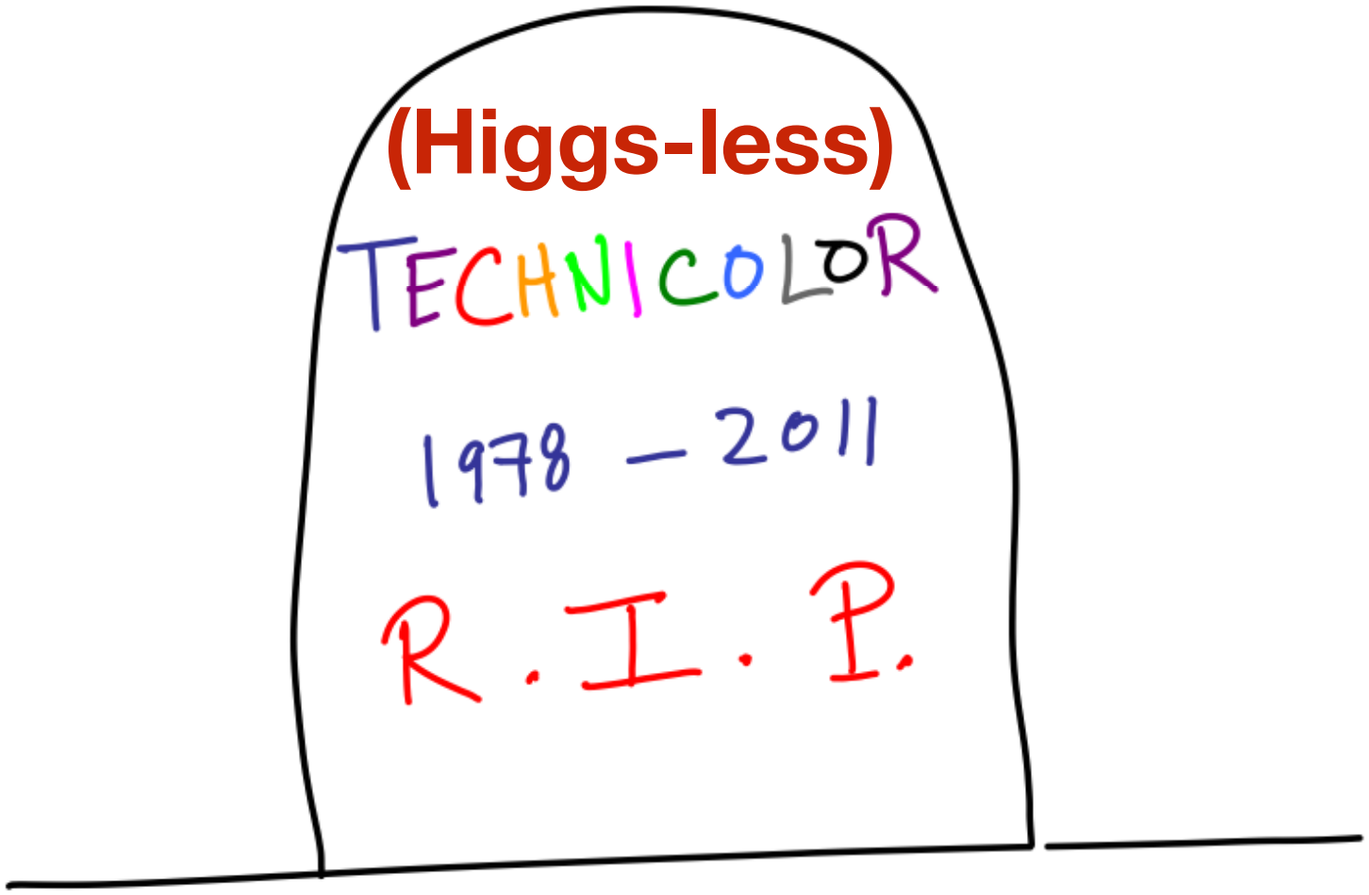
Composite Higgs, briefly



- We have a Higgs, thanks to the LHC!
- We don't have anything else yet…which means we still have a naturalness (fine-tuning) problem
- If Higgs is a composite bound state, we fix the problem; loop effects cut off at compositeness scale

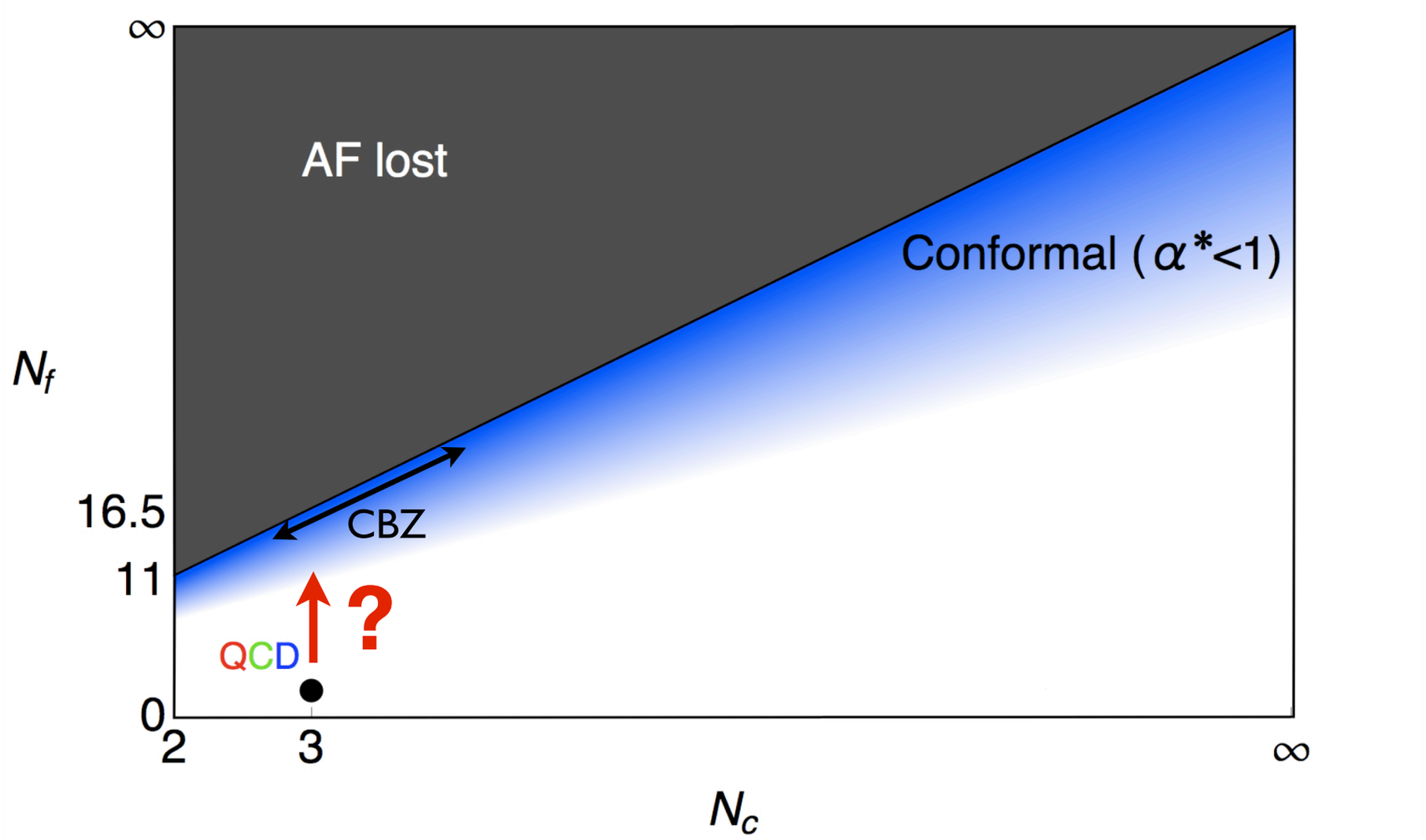
Arkani-Hamed '12

TRIUMPH OF WEAK COUPLING



Composite Higgs/dynamical EW symmetry breaking is no more dead than TeV-scale SUSY…but the "obvious" variants of both theories are certainly buried by the LHC first run.

Towards the conformal window



- What effect does approaching the transition have on the spectrum? Other phenomenology?
- As part of my work with **L**attice **S**trong **D**ynamics (**LSD**) collaboration, investigate trends moving away from “QCD”. So far, compare N_f=2 to N_f=6. Nf=8 next!

Lattice **S**trong **D**ynamics Collaboration

James Osborn

Rich Brower
Michael Cheng
Claudio Rebbi
Oliver Witzel
Evan Weinberg

Ethan Neil

Ethan Neil
Sergey Syritsyn

Meifeng Lin

Chris Schroeder
Pavlos Vranas
Enrico Rinaldi

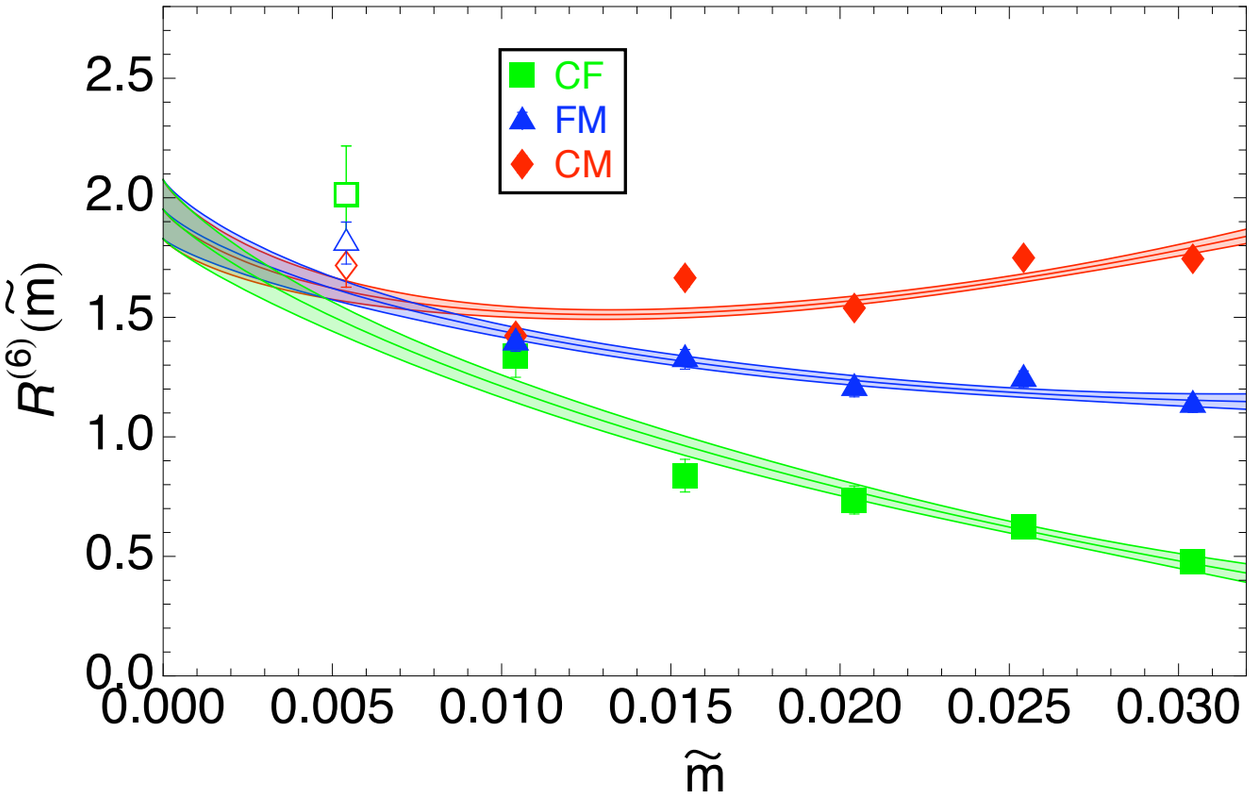
Joe Kiskis

David Schaich

Tom Appelquist
George Fleming
Gennady Voronov

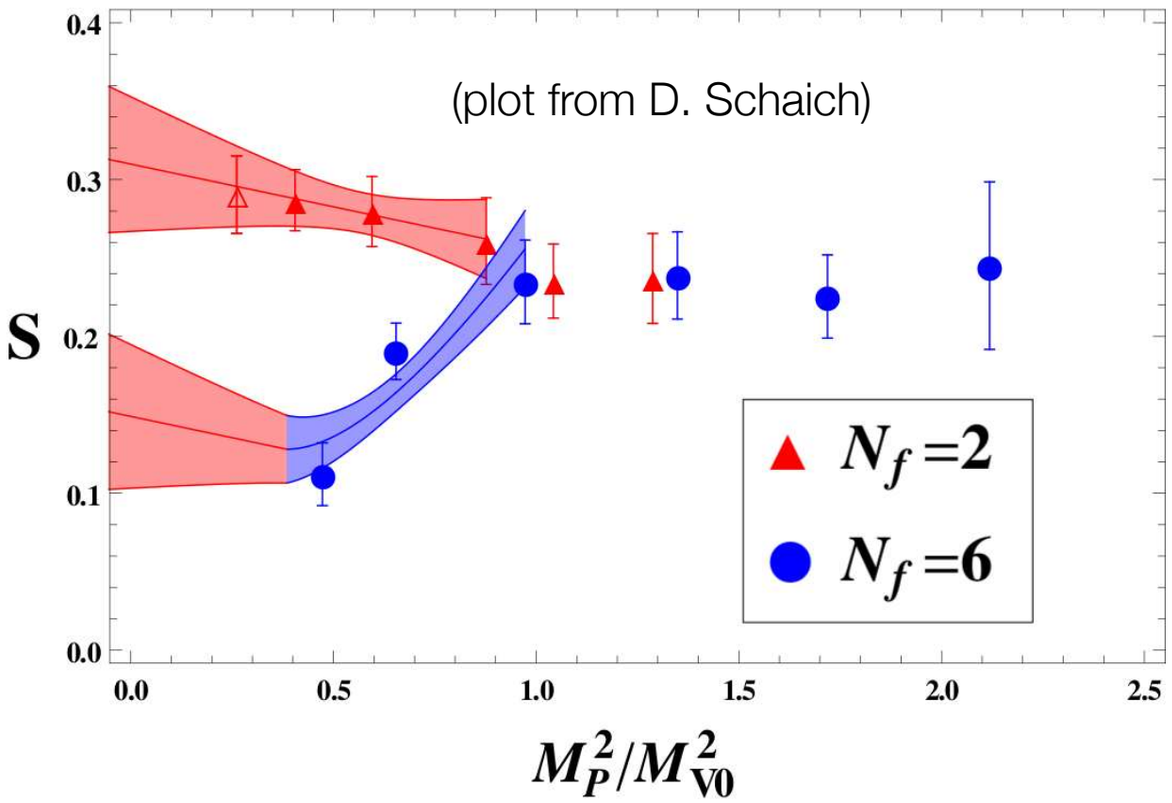
Mike Buchoff

Phenomenology near the conformal window



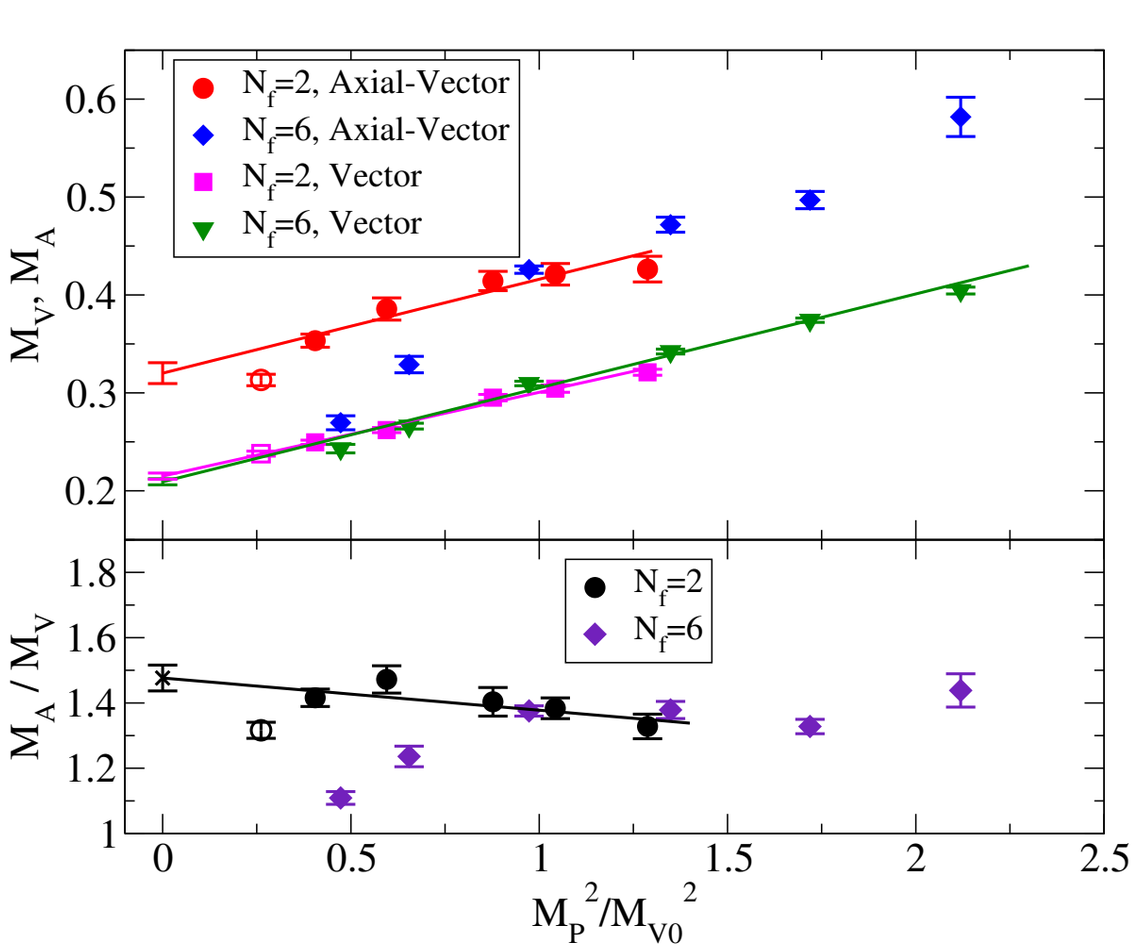
Chiral condensate (fermion mass)

S-parameter

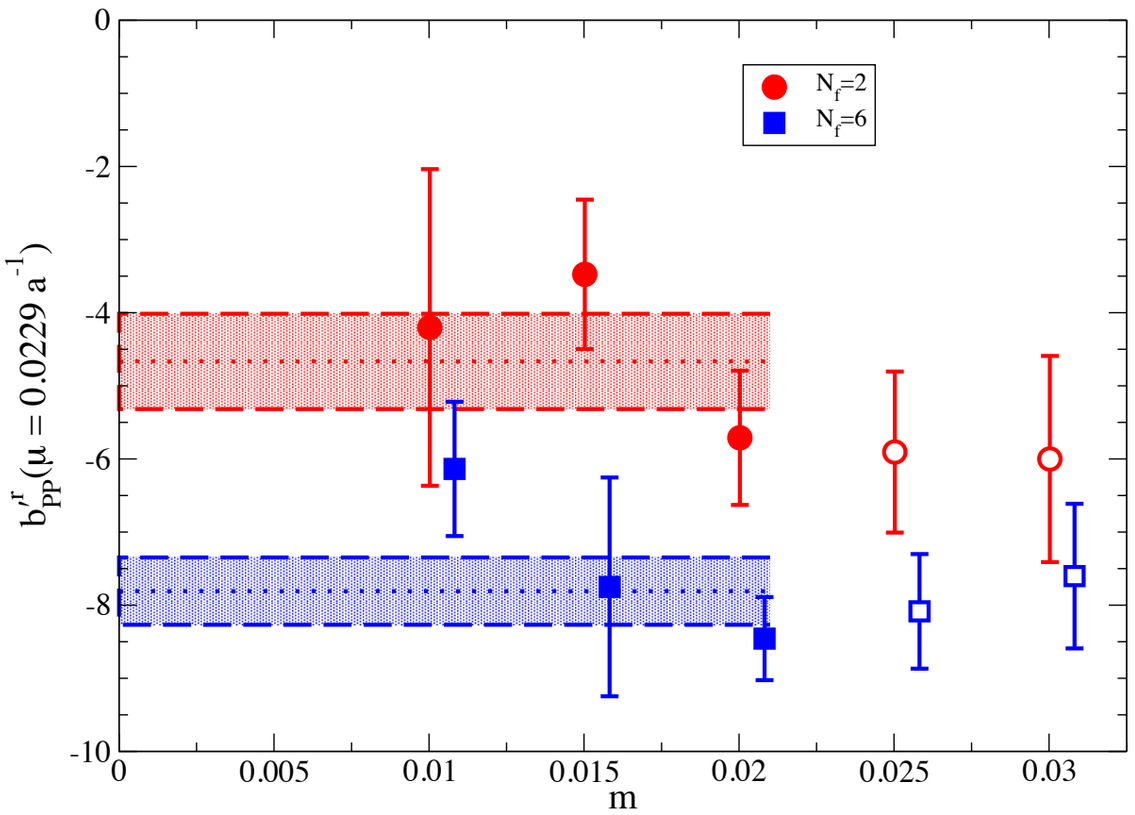


Phenomenology near the conformal window

Spectrum and “parity doubling”



W-W scattering length



Composite dark matter

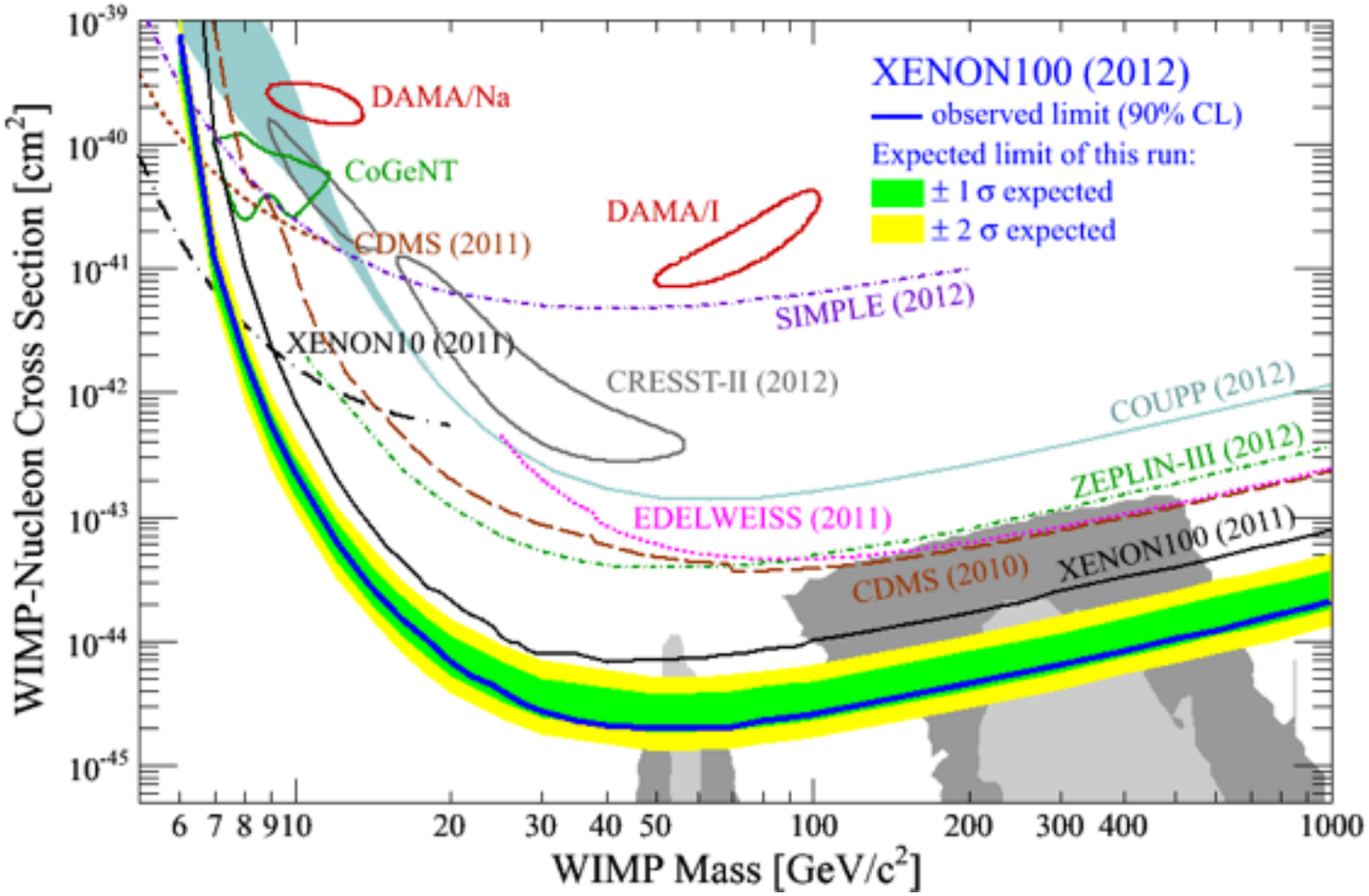
Composite Dark Matter

- Composite dark matter: stable, **neutral** bound state of **charged** components

- Charged states can freely interact when deconfined in the early universe

- Origin of mass scale independent of EW symmetry breaking/Higgs

- Can naturally arise as part of more complete strongly-coupled models (technicolor/ composite Higgs) - but appealing on its own



Basic setup

- QCD-like model: SU(3) gauge group with N_f=2 or 6 light* fermions.

$(i = 1 \ldots N_f/2)$	$SU(3)_D$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q_u^i	3	1	1	$+2/3$
Q_d^i	3	1	1	-1/3

*The opposite limit (heavy fermions) is interesting too! - see 0909.2034

- Not a model of EWSB, but a simple stand-in (and a valid DM model itself.)

- Our goal is extraction of EM form factors, to be obtained by directly measuring overlap of baryon matrix elements with EM currents:

$$\langle N(p')|\overline{\psi}\gamma^\mu\psi|N(p)\rangle$$

"quark" spinor

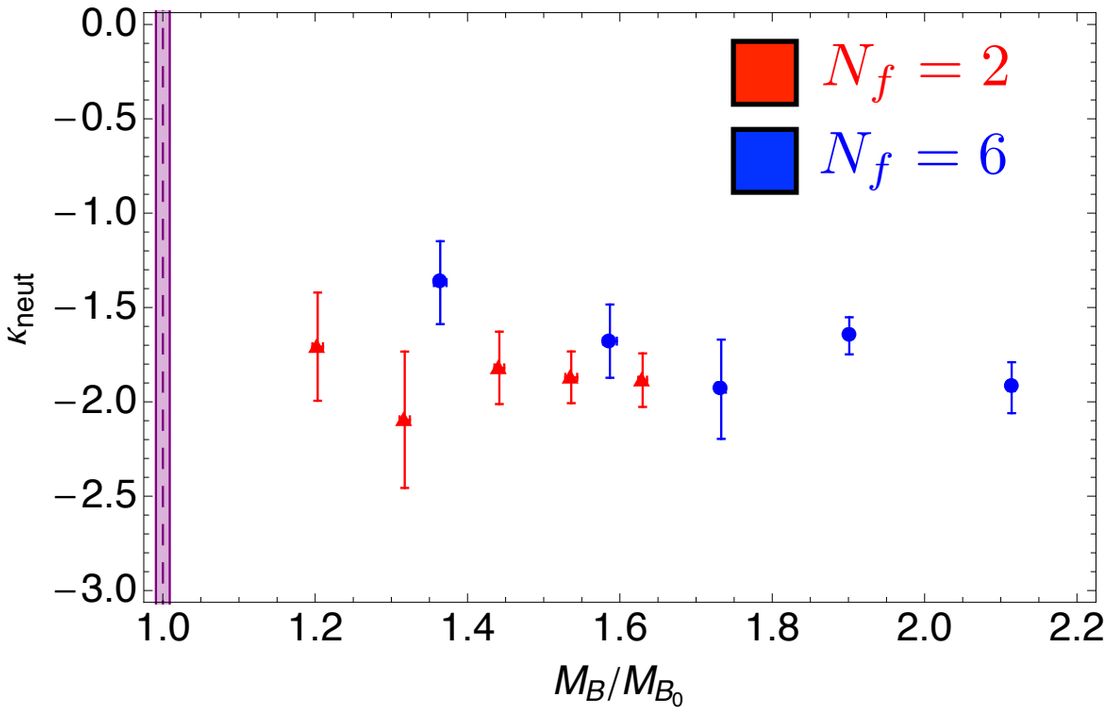
"neutron" spinor

$$= \overline{U}(p')\left[F_1^\psi(Q^2)\gamma^\mu + F_2^\psi(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_B}\right]U(p)$$

$$[Q^2 = (p-p')^2]$$

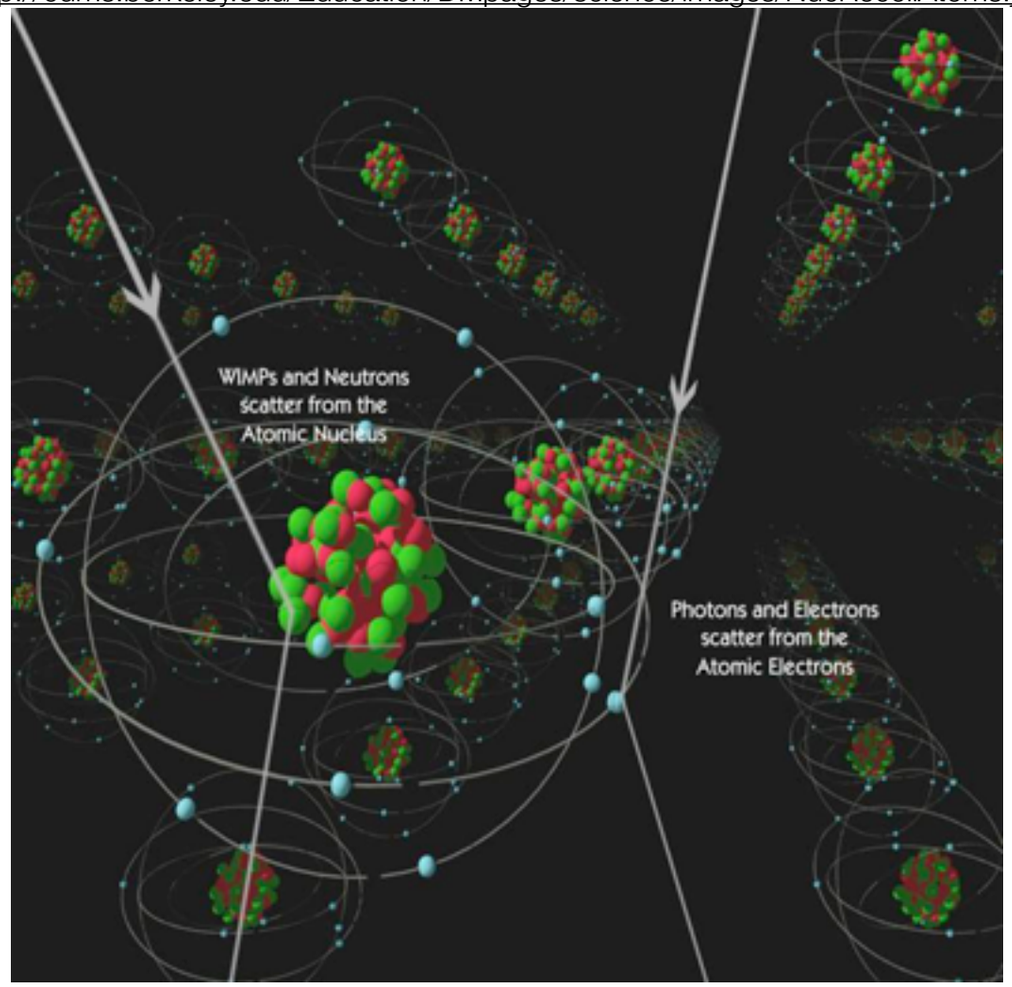
Dark matter detection: EM form factors

(T. Appelquist, EN, et al., LSD collaboration)



- Electromagnetic form factors of “neutron” (defined right, shown above) crucial for DM direct detection.
- Simulation results show little to no trend of reduction from N_f=2 to N_f=6!

http://cdms.berkeley.edu/Education/DMpages/science/images/NucRecoilAtoms.jpg



$$\langle N(p')|\bar{q}\gamma^\mu q|N(p)\rangle$$

$$= \bar{u}_{p'}\left[F_1^q(Q^2)\gamma^\mu + F_2^q(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_B}\right]u_p$$

(M. Buckley and EN, Phys. Rev. D87, 043510 (2013)

Another construction: thermal composite DM

$$\mathcal{L} = \bar{Q}_i(i\not{D} + m_i)Q_i$$

	$SU(2)_E$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Q_u	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$+1/2$	$+1/2$
Q_d	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	$+1/2$

- Canonical example: two flavors of $SU(2)_E$ "ectocolor", charged under fundamental **2**=$\bar{\mathbf{2}}$. With m_i=0, field redef. lets us rewrite as big four-component Weyl spinor:

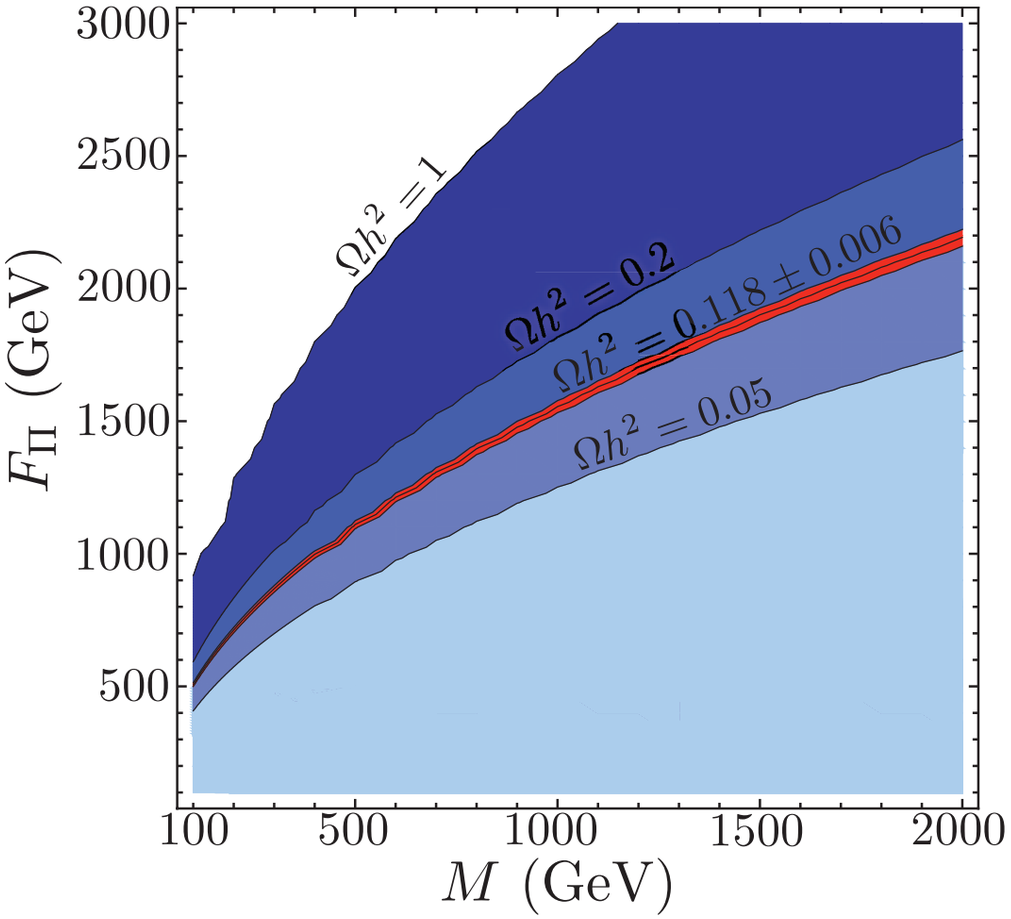
$$\begin{cases} \psi_{i,L} & \equiv -i\bar{Q}_{i,R}\sigma_2\tau_2 \\ \bar{\psi}_{i,L} & \equiv i\sigma_2\tau_2 Q_{i,R} \end{cases} \longrightarrow \mathcal{L} \propto \left(\bar{Q}_{i,L}, \bar{\psi}_{i,L}\right) \bar{\sigma} \cdot D \begin{pmatrix} Q_{i,L} \\ \psi_{i,L} \end{pmatrix}$$

- Manifest SU(4) global symmetry. **2** is pseudoreal, so pattern SU(4)->Sp(4) yields five PNGBs:

$$\Pi^+ = Q_u\bar{Q}_d, \Pi^- = Q_d\bar{Q}_u, \Pi^0 = (Q_u\bar{Q}_u - Q_d\bar{Q}_d)$$
$$N = Q_uQ_d, \bar{N} = \bar{Q}_u\bar{Q}_d$$

- Charged pions carry $U(1)_Y$, ectonucleons are EM neutral but carry net $U(1)_X$, preventing decay. Set m_u=m_d=m_q<<Λ, so we can work in χPT.

Thermal history: relic density



- For lightest masses, **M**<<**F**; around 2 TeV we have **M**~**F**, which is about right for QCD. Expect good convergence of χPT over the whole range.

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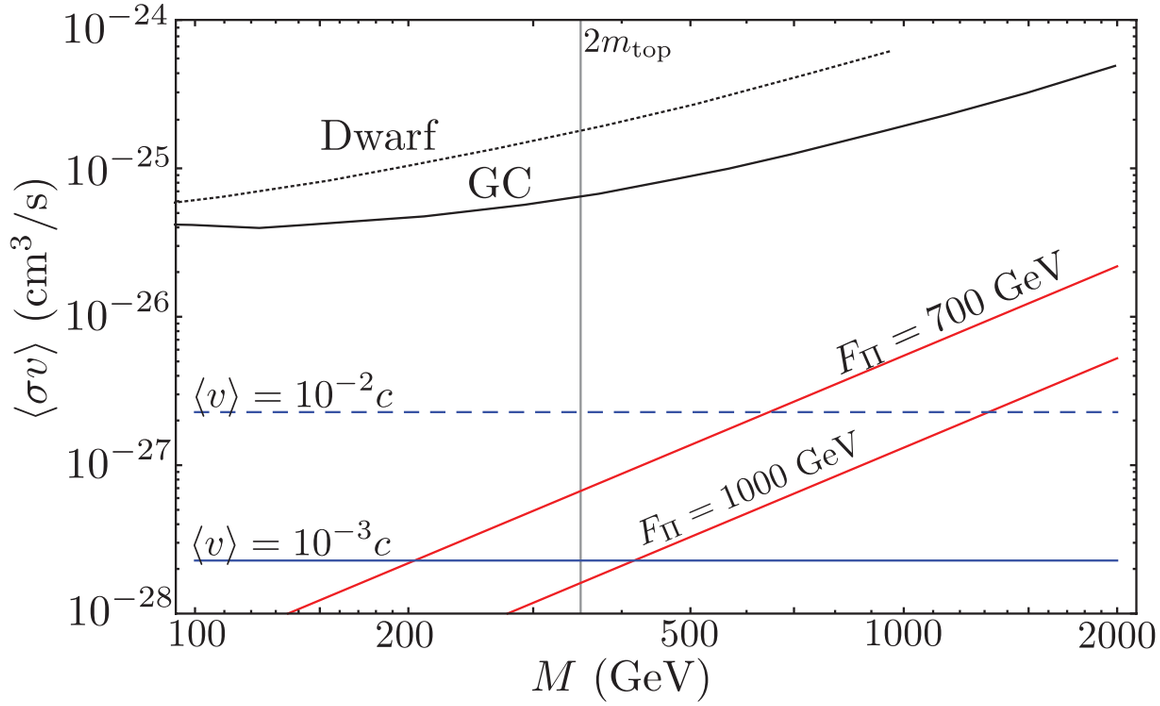


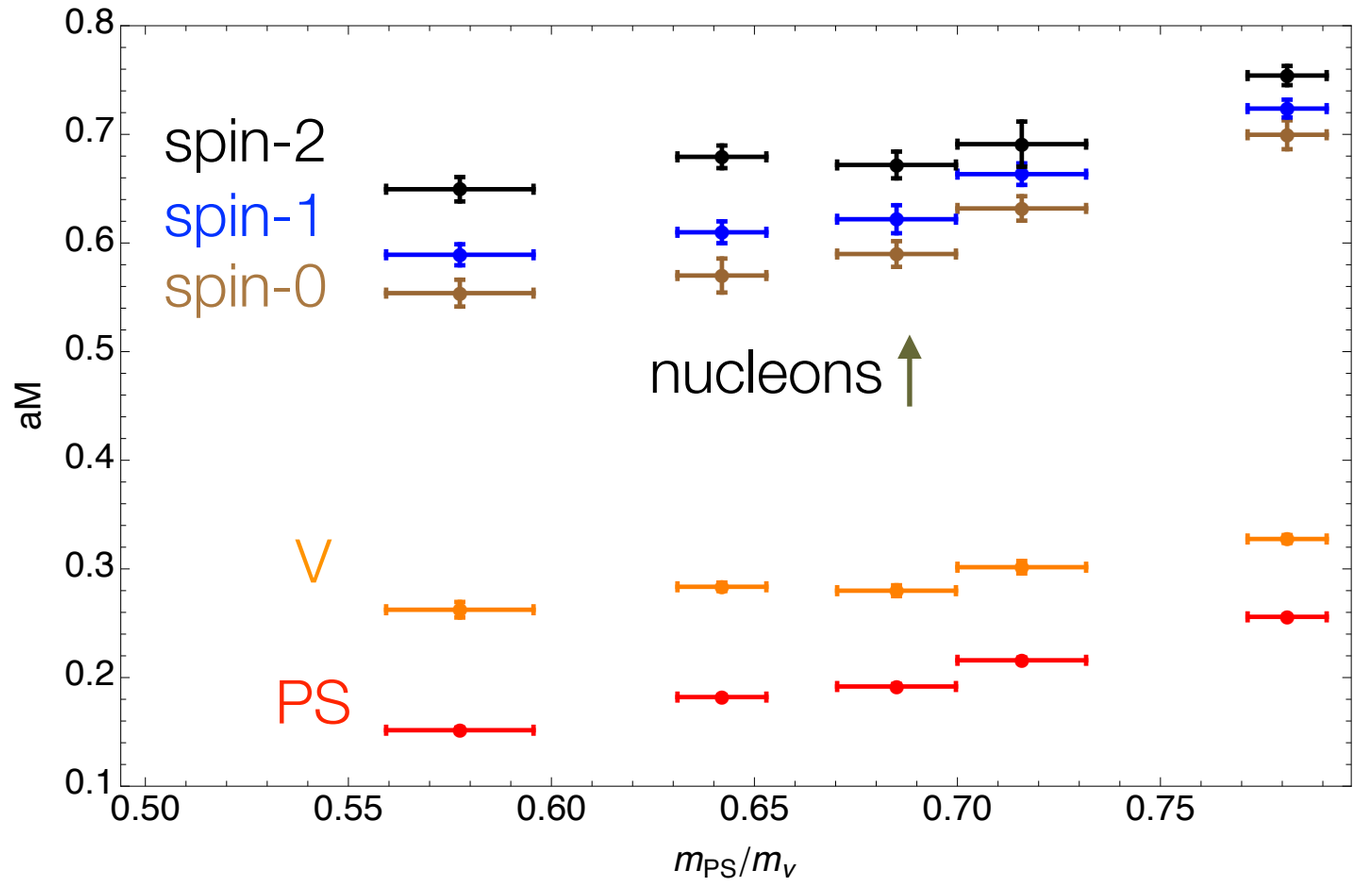
From three to four

- In progress: study of **four-color** composite DM: bosonic baryons!

- Work w. G. Kribs (Oregon) and M. Buchoff (Washington) on model setup. Minimal construction to allow couplings to all EW + Higgs without running into precision bounds

- First LSD spectrum paper forthcoming - calculation of form factors next

Field	$\mathrm{SU}(4)_D$	$(\mathrm{SU}(2)_L, \mathrm{SU}\ (2)_R \times \mathrm{U}(1)_{Y'}$	
		Model 1	Model 2
F_1	$\mathbf{4}$	$(\mathbf{2},\mathbf{1})_0$	$(\mathbf{2},\mathbf{1})_{+1/2}$
F_2	$\bar{\mathbf{4}}$	$(\bar{\mathbf{2}},\mathbf{1})_0$	$(\bar{\mathbf{2}},\mathbf{1})_{-1/2}$
F_3	$\mathbf{4}$	$(\mathbf{1},\mathbf{2})_0$	$(\mathbf{1},\mathbf{2})_{+1/2}$
F_4	$\bar{\mathbf{4}}$	$(\mathbf{1},\bar{\mathbf{2}})_0$	$(\mathbf{1},\bar{\mathbf{2}})_{-1/2}$



Future directions

- Extension of phenomenology work in SU(3) gauge theory with large N_f. PNGB form factors, N_f=8, light scalar?

- Application of SU(2) enhanced symmetry to composite Higgs models - Higgs as a PNGB. Inclusion of dynamical top-quark effects in simulation?

- Calculation of “pion” form factors in SU(2) gauge theory - application to both PNGB Higgs and thermal composite dark matter

- Other applications of novel gauge theories: work on SU(4) with anti-symmetric rep. fermions at finite chemical potential in progress (with DeGrand, Liu, Svetitsky, Shamir); large-Nc relation to QCD

USQCD

US Lattice Quantum Chromodynamics

Lattice Meets Experiment 2013: Beyond the Standard Model

Topic areas:

- proton decay
- $n\bar{n}$ oscillation
- anomalous EDMs
- supersymmetry
- composite Higgs
- composite dark matter
- many-fermion theories

Organizing committee:

- G. Fleming (Yale)
- C. Lehner (BNL)
- E. Neil (Boulder/RBRC)
- T. Izubuchi (BNL/RBRC)

BROOKHAVEN NATIONAL LABORATORY

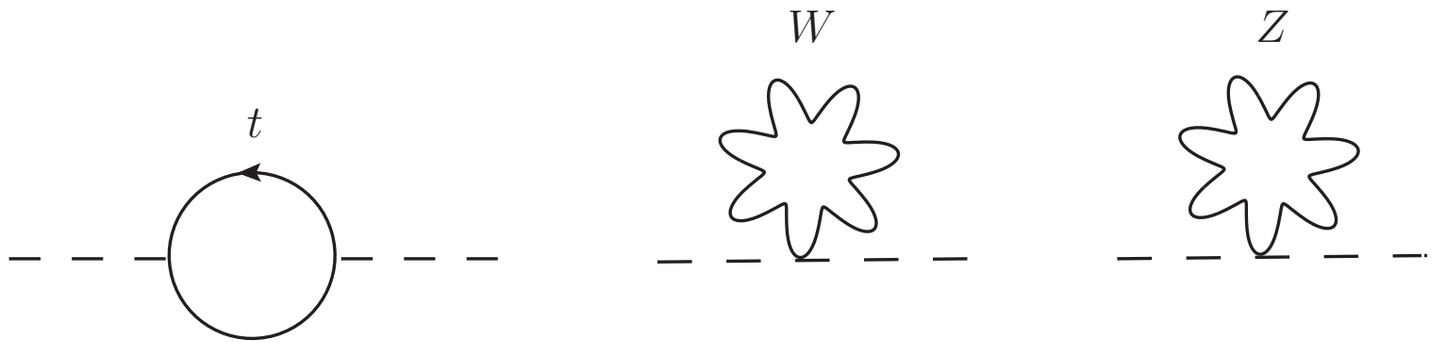
5-6 December, 2013

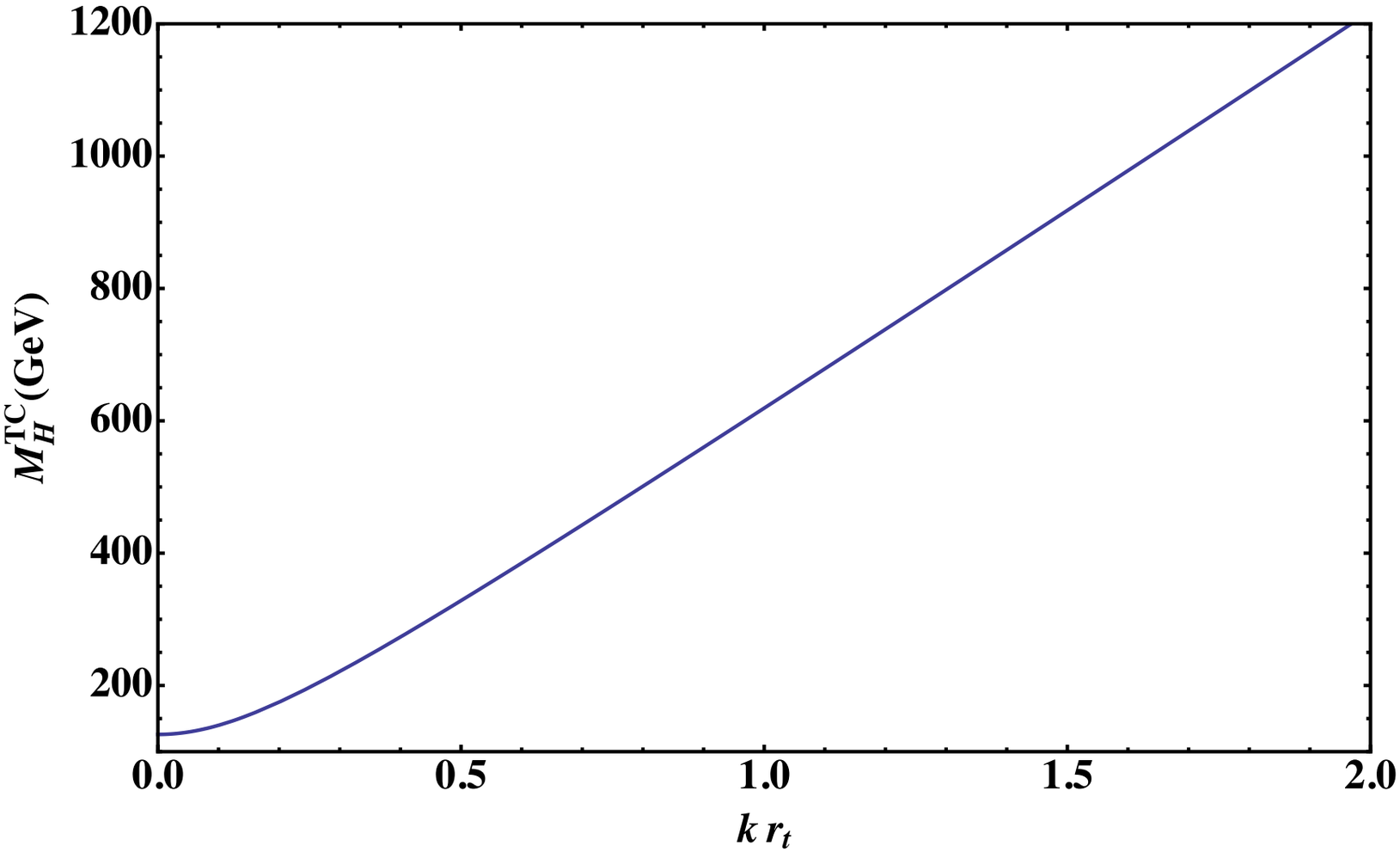
Backup slides

The unbearable lightness of Higgs

- Higgs state from strong theory clearly needs to be “light and narrow”.

- EW loop effects (esp. top) and kinematics are important! Even QCD sigma can be reasonable…





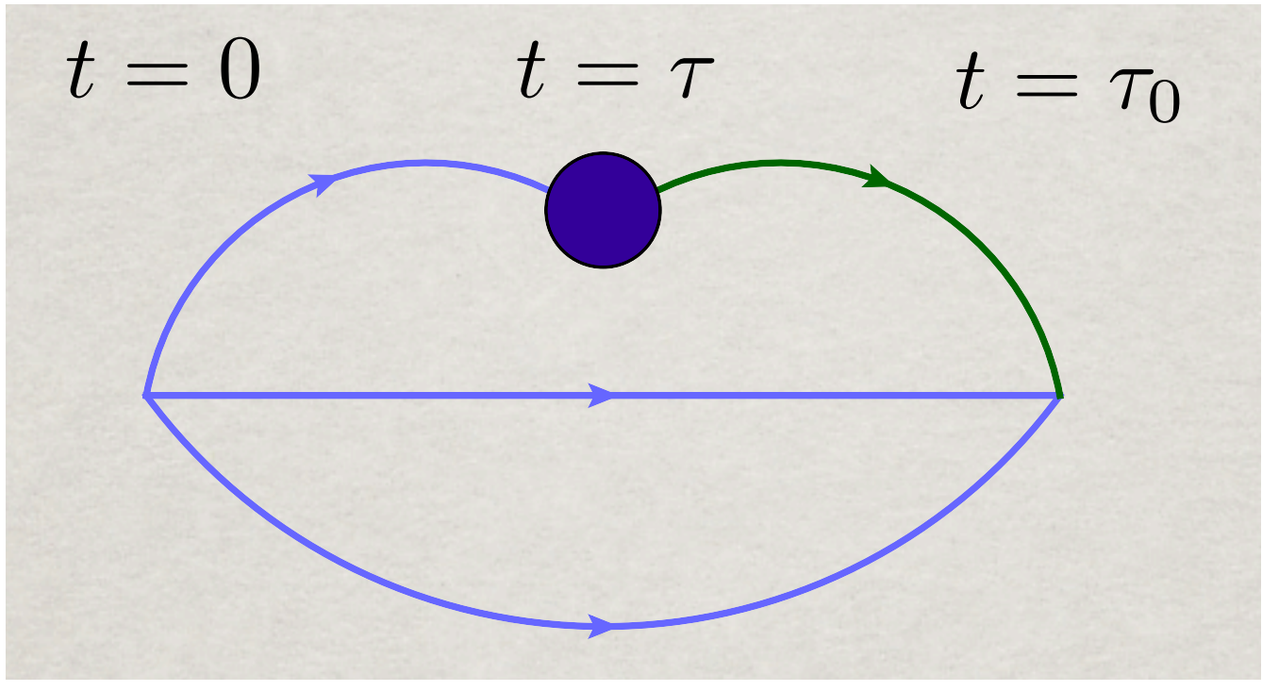
(from Foadi, Frandsen, Sannino, arXiv:1211.1083)

Constructing the form factors

- Calculation of three-point function: nucleon source/ sink with EM current insertion.

$$C_{NN}(\tau, \mathbf{p}) = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}} \langle N(\mathbf{x}, \tau) \bar{N}(0) \rangle$$

$$C_{N\mathcal{O}N}(\tau, T, \mathbf{p}, \mathbf{p}') = \sum_{\mathbf{x},\mathbf{y}} e^{-i\mathbf{p}'\cdot\mathbf{x} + i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{y}} \times \langle N(\mathbf{x}, T) \mathcal{O}(\mathbf{y}, \tau) \bar{N}(0) \rangle$$



(caveat: no quark-disconnected diagrams!)

- Combine with two-point function in appropriate ratio in order to get the desired matrix element from large Euclidean time behavior:

$$R_{\mathcal{O}}(\tau, T, \mathbf{p}, \mathbf{p}') = \frac{C_{N\mathcal{O}N}(\tau, T, \mathbf{p}, \mathbf{p}')}{\sqrt{C_{NN}(T, \mathbf{p}) C_{NN}(T, \mathbf{p}')}} \times \sqrt{\frac{C_{NN}(T-\tau, \mathbf{p}) C_{NN}(\tau, \mathbf{p}')}{C_{NN}(T-\tau, \mathbf{p}') C_{NN}(\tau, \mathbf{p})}} \longrightarrow \boxed{\langle N(\mathbf{p}') | \mathcal{O} | N(\mathbf{p}) \rangle} + \mathcal{O}(e^{-\Delta\tau}) + \mathcal{O}(e^{-\Delta(T-\tau)}) + \mathcal{O}(e^{-\Delta T})$$

B Physics on the Lattice

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RBRC Scientific Review Committee Meeting
2013/10/31-11/01, RBRC, USA

CKM matrix and B Physics

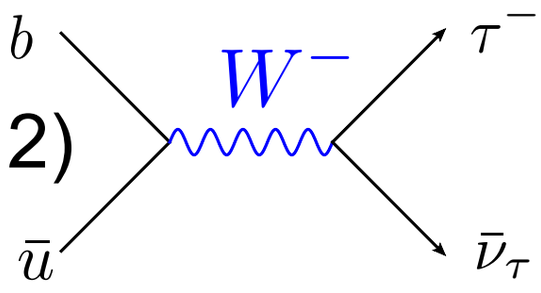
The CKM matrix

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\underbrace{\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix}}_{\text{weak eigenstates}} = V_{CKM} \underbrace{\begin{bmatrix} d \\ s \\ b \end{bmatrix}}_{\text{mass eigenstates}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Lattice QCD for nonperturbative QCD effects

e.g. $B \longrightarrow \tau\nu$



- Branching ratio: EXP $(1.65 \pm 0.34) \times 10^{-4}$ (PDG'12)

$$Br(B \to \tau\nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

$Br(B \to \tau\nu)$: experiment; f_B^2: lattice QCD

- Knowing f_B and experimental value $Br(B \to \tau\nu)_{\text{exp}}$, we can obtain CKM matrix element V_{ub} .

CKM matrix and B Physics

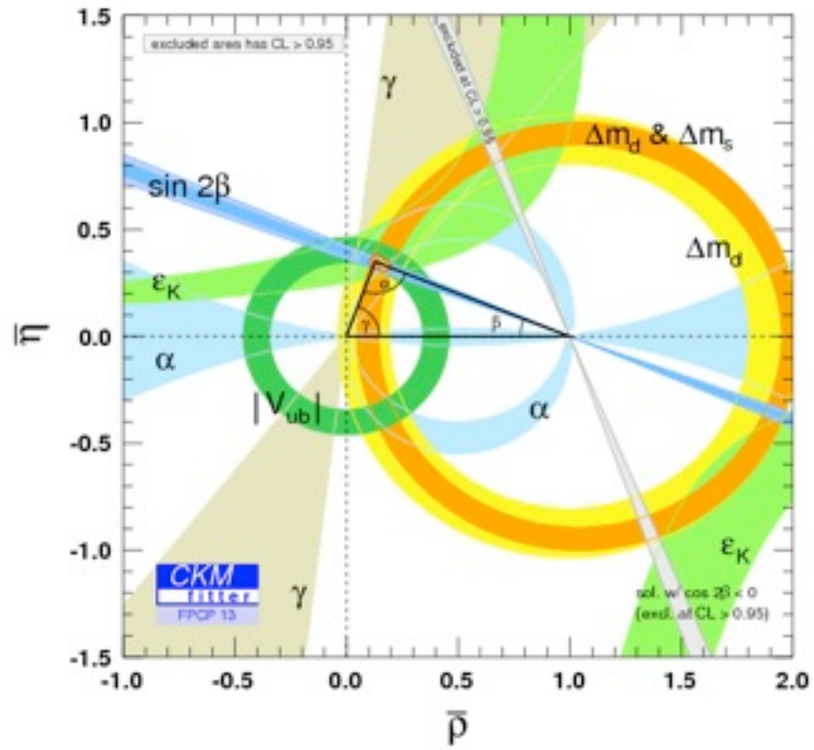
- Gold-plated "lattice" process

$\mathbf{V_{ud}}$ $\pi \to l\nu$	$\mathbf{V_{us}}$ $K \to l\nu$ $K \to \pi l\nu$	$\mathbf{V_{ub}}$ $B \to \pi l\nu$
$\mathbf{V_{cd}}$ $D \to l\nu$ $D \to \pi l\nu$	$\mathbf{V_{cs}}$ $D_s \to l\nu$ $D \to K l\nu$	$\mathbf{V_{cb}}$ $B \to D l\nu$ $B \to D^* l\nu$
$\mathbf{V_{td}}$ $B_d \leftrightarrow \bar{B}_d$	$\mathbf{V_{ts}}$ $B_s \leftrightarrow \bar{B}_s$	$\mathbf{V_{tb}}$

- 1 hadron in the initial state, 0 or 1 hadron in the final state
- stable hadrons (or narrow, far from threshold)
- controlled chiral extrapolation

- Constraints to the CKM unitary triangle

- overconstrain ⟶ unveiling NP
- b quark is suitable for studies of the limits of the SM and in searches in BSM.
(sufficiently heavy to have a huge number of decay modes, sufficiently light to be produced a lot)



RBC/UKQCD activity on B Physics

Heavy Quark Effective Theory (HQET)

- Based on heavy quark expansion
- Lowest order of the expansion is static approximation.

~10% uncertainty

- By including $O(1/m_b)$ the uncertainty is reduced to ~1% level.
- Old fashioned, but clean.
- can be used for interpolation between lower mass region and static point.

Relativistic Heavy Quark (RHQ)

- $O((m_Q a)^n)(^\forall n)$ error is removed by tuning action parameters in mass dependent way.
- applies for all quark mass region from light to heavy.
- has a smooth continuum limit.

RBC/UKQCD B Physics papers (Static)

- V. Gadiyak and O. Loktik, *Lattice calculation of SU(3) flavor breaking ratios in* $B^0 - \bar{B}^0$ *mixing*, Phys. Rev. D 72 (2005) 114504 [hep-lat/0509075].
- O. Loktik and T. Izubuchi, *Perturbative renormalization for static and domain-wall bilinears and four-fermion operators with improved gauge actions*, Phys. Rev. D 75 (2007) 034504 [hep-lat/0612022].
- C. Albertus, Y. Aoki, P. A. Boyle, N. H. Christ, T. T. Dumitrescu, J. M. Flynn, T. I, T. Izubuchi, O. Loktik, C. T. Sachrajda, A. Soni, R. S. Van de Water, J. Wennekers and O. Witzel, *Neutral B-meson mixing from unquenched lattice QCD with domain-wall light quarks and static b-quarks*, Phys. Rev. D 82 (2010) 014505 [arXiv: 1001.2023 [hep-lat]].
- T. I, Y. Aoki, J. M. Flynn, T. Izubuchib, and O. Loktik, *One-loop operator matching in the static heavy and domain-wall light quark system with O(a) improvement*, JHEP 05 (2011) 040 [arXiv: 1101.1072 [hep-lat]].

RBC/UKQCD B Physics papers (RHQ)

- H.-W. Lin and N. Christ, *Non-perturbatively Determined Relativistic Heavy Quark Action,* Phys. Rev. D 76 (2007) 074506 [hep-lat/0608005].
- N. Christ, M. Li and H.-W. Lin, *Relativistic Heavy Quark Effective Action,* Phys. Rev. D 76 (2007) 074505 [hep-lat/0608006].
- Y. Aoki, N. H. Christ, J. M. Flynn, T. Izubuchi, C. Lehner, M. Li, H. Peng, A. Soni, R. S. Van de Water, and O. Witzel, *Nonperturbative tuning of an improved relativistic heavy-quark action with application to bottom spectroscopy*, Phys. Rev. D 86 (2012) 116003 [arXiv:1206.2554 [hep-lat]].

Talks at LATTICE 2013 @ Mainz

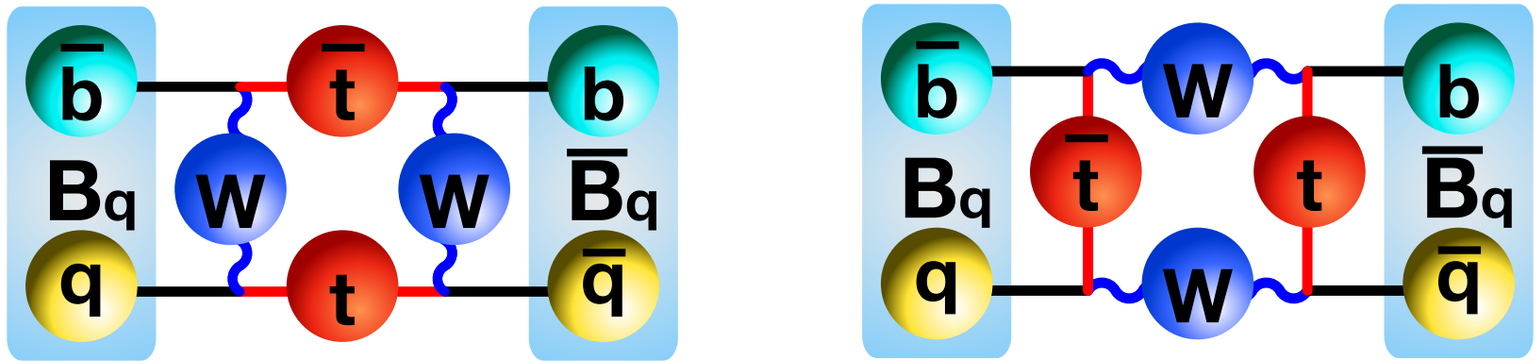


- "*The form factor for B to π semileptonic decay from 2+1 flavors of domain-wall fermions*", T. Kawanai (BNL/RIKEN) [RHQ]
- *"A new computer algebra system for (lattice) perturbation theory and the RBC/UKQCD heavy quark program"*, C. Lehner (BNL) [RHQ]
- *"The $B^* B\pi$ coupling with relativistic heavy quarks"*, B. Samways (University of Southampton) [RHQ]
- "*Chiral and continuum extrapolation of B-meson decay constants computed using domain-wall light quarks and nonperturbatively tuned relativistic b-quarks"*, O. Witzel (Boston University) [RHQ]
- "*Neutral B meson mixing with static heavy and domain-wall light quarks"*, T. I (RBRC) [Static]

$B^0 - \bar{B}^0$ mixing using static approx

[Y. Aoki, T. I, T. Izubuchi, C. Lehner, A. Soni]

- $B^0 - \bar{B}^0$ mixing



$q = \{d, s\}$

- Neutral mesons are not eigenstates of the weak interactions.
- NP comes through loop diagrams.
- Mass difference between physical eigenstates:

$$\Delta m_q = \frac{G_F^2 m_W^2}{16\pi^2 m_{B_q}} |V_{tq}^* V_{tb}|^2 S_0 \left(\frac{m_t^2}{m_W^2}\right) \eta_B \mathcal{M}_{B_q}$$

$\longrightarrow$ constraints to V_{td}, V_{ts}

- $\Delta B = 2$ mixing matrix elements (non-perturbative hadronic)

$$\mathcal{M}_{B_q} = \langle \overline{B}_q^0 | [\bar{b}\gamma_\mu P_L q][\bar{b}\gamma_\mu P_L q] | B_q^0 \rangle = \frac{8}{3} m_{B_q}^2 f_{B_q}^2 B_{B_q}$$

$B^0 - \bar{B}^0$ mixing using static approx

- SU(3) breaking ratio ξ

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B_s}}{m_{B_d}}} \qquad \xi = \frac{m_{B_d}}{m_{B_s}}\sqrt{\frac{\mathcal{M}_{B_s}}{\mathcal{M}_{B_d}}}$$

  - The most attractive quantity in the mixing phenomena
  - Many of the uncertainties cancel in the ratio.
  - In the simulation, fluctuations are largely canceled in the ratio.

- Ratio quantities (ξ , f_{B_s}/f_{B_d}) in the static limit
  - Error coming from the static approximation is reduced to:

$$O\left(\frac{m_s - m_d}{\Lambda_{\rm QCD}} \times \frac{\Lambda_{\rm QCD}}{m_b}\right) \sim 2\%$$

Lattice setup

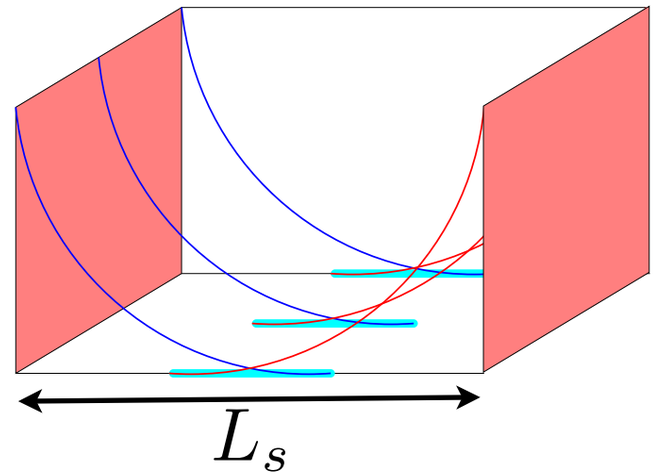
- Standard static action with link smearing

$$S_{\rm stat} = \sum_{\vec{x},t} \overline{\Psi}_h(\vec{x},t) \left[\Psi_h(\vec{x},t) - U_0^\dagger(\vec{x},t-a)\Psi_h(\vec{x},t-a) \right]$$

  - Reduced 1/a power divergence by link smearing

HYP1, HYP2

- Domain-wall light quark action
  - 5 dimensional formulation
  - controllable approximated chiral symmetry



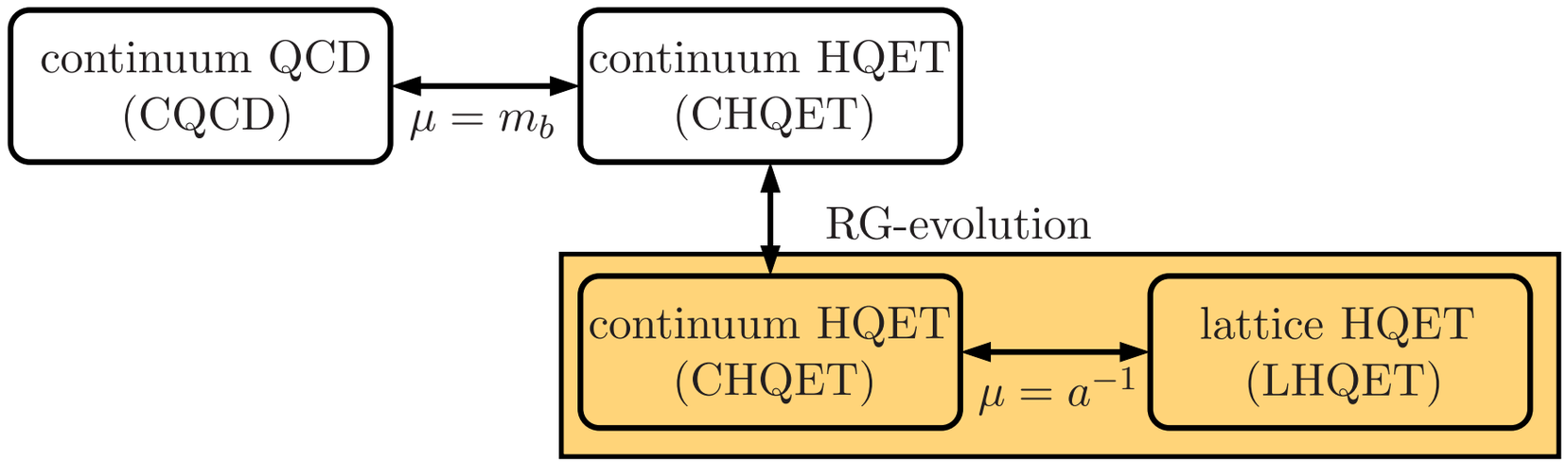
- RBC/UKQCD ensemble [Phys. Rev. D 83, 074508 (2011)]

action	$1/a$ [GeV]	lattice	size [fm]	m_π [MeV]
DWF + IW	1.73	$24^3 \times 64 \times 16$	2.8	$320 - 420$
DWF + IW	2.28	$32^3 \times 64 \times 16$	2.8	$290 - 400$

Matching

Operator matching

- Matching to continuum QCD (Static)



Static with link smearing + DWF

1-loop PT, O(a) error is taken into account.

[T.I, Y. Aoki, J. M. Flynn, T. Izubuchi, O. Loktik (2011)]

- Automated lattice PT could reduce the burden.

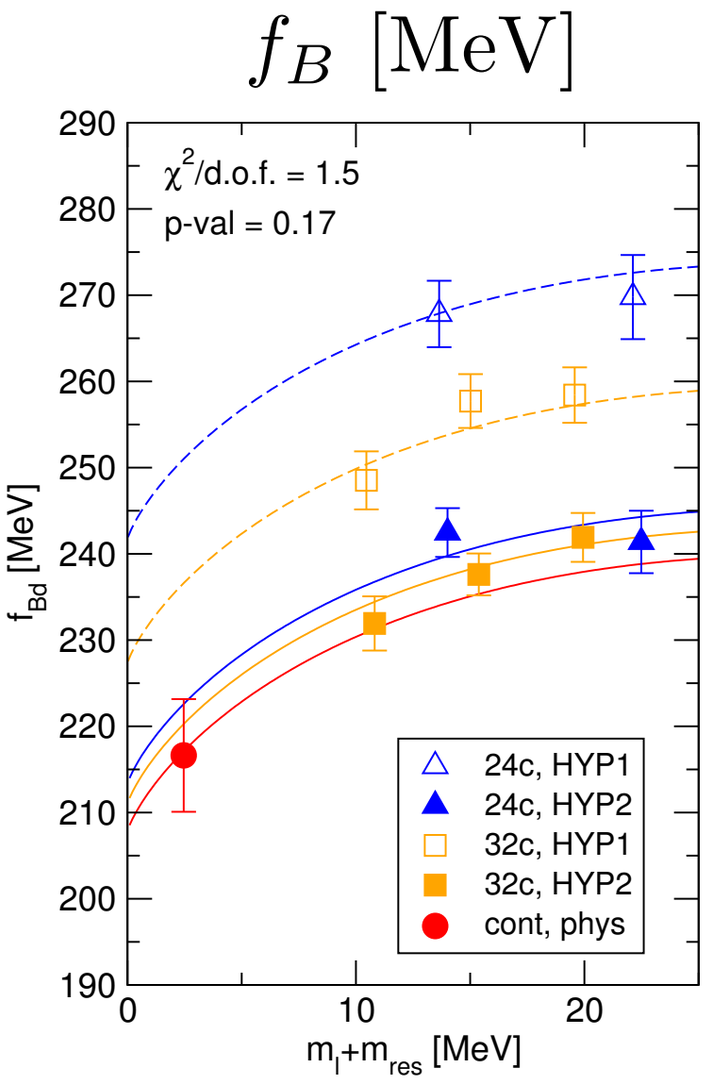
A Physics System based on Hierarchical Computer Algebra

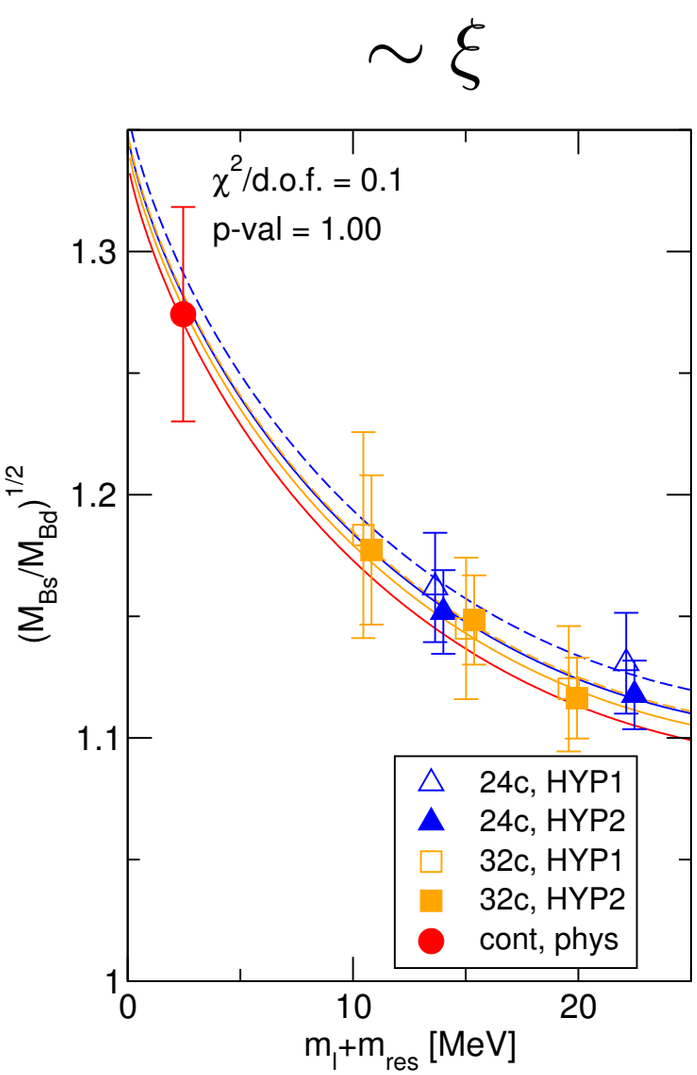
PhySyHCAl [C. Lehner (2013)]

- applied to RHQ tuning and operator matching

Chiral and continuum extrapolation

- NLO SU(2) HMChPT fit





- Chiral and continuum extrapolation are taken simultaneously.
- 2 kinds of link smearing (HYP1 and HYP2) are used in the fit.
- Linear fit function hypothesis is not excluded. (uncertainty)

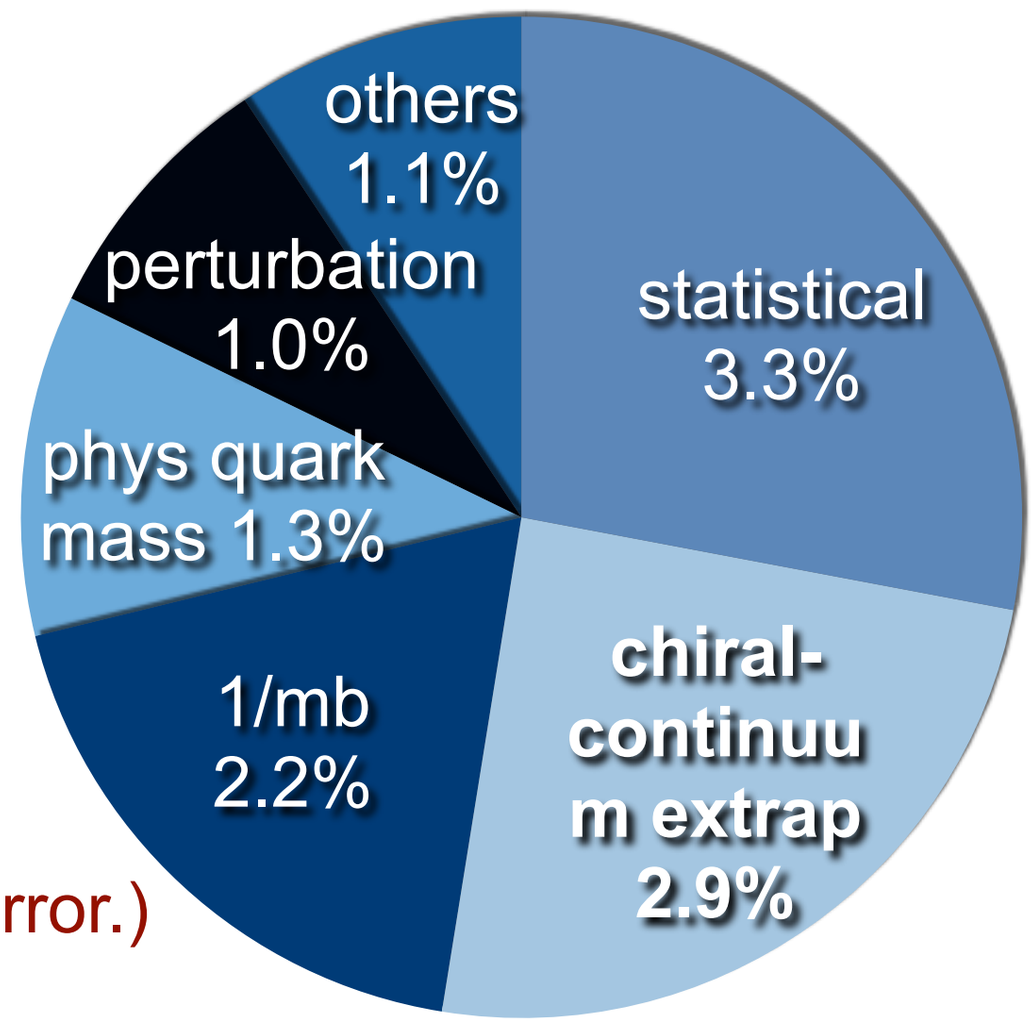
Static results

- Preliminary results [LATTICE 2013]

	not incl 1/mb uncertainty	incl 1/mb uncertainty
f_{B_d} [MeV] =	222(17),	222(31),
f_{B_s} [MeV] =	265(19),	265(37),
f_{B_s}/f_{B_d} =	1.192(43),	1.192(51),
$\mathcal{M}_{B_d}$ [(GeV)^4] =	2.79(44),	2.79(56),
$\mathcal{M}_{B_s}$ [(GeV)^4] =	4.34(46),	4.34(69),
$\sqrt{\mathcal{M}_{B_s}/\mathcal{M}_{B_d}}$ =	1.238(59),	1.238(66),
$\hat{B}_{B_d}$ =	1.15(13),	1.15(19),
$\hat{B}_{B_s}$ =	1.22(10),	1.22(18),
B_{B_s}/B_{B_d} =	1.047(65),	1.047(80),
ξ =	1.218(58),	1.218(65).

(Systematic errors are included in the error.)

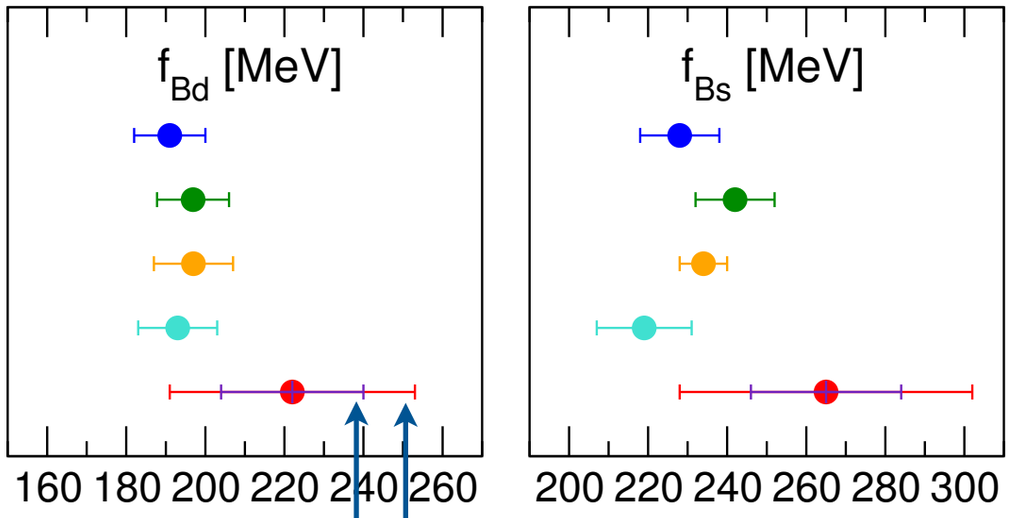
Error budget on ξ (total 5.3% error)



Reducing statistical and chiral/continuum extrapolation errors important.

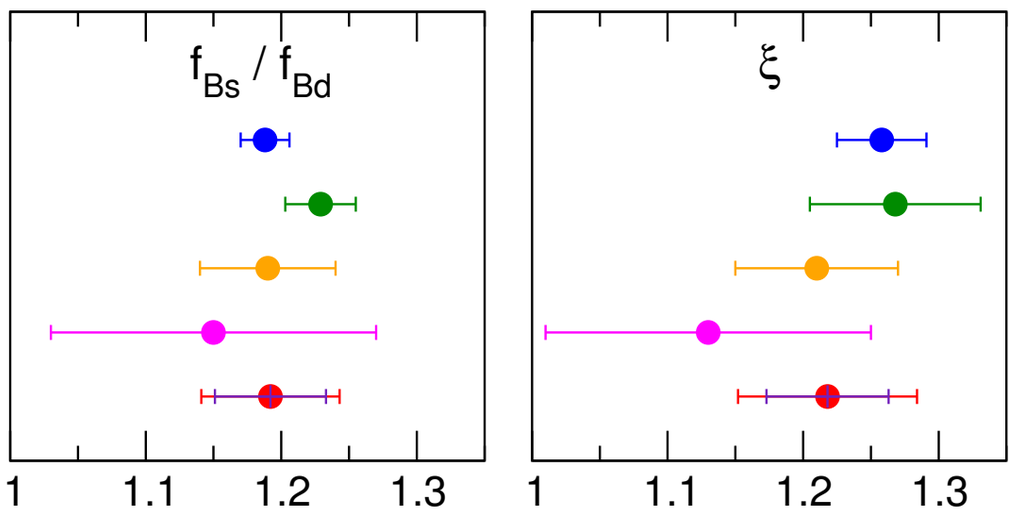
Static results

- Comparison



HPQCD '12 (NRQCD)
FNAL/MILC '11 (Fermilab)
ETM '12 (Ratio method, Nf=2)
ALPHA '12 (HQET, Nf=2)
This work (Static)

1/mb uncertainty is included in the error.



HPQCD '12 '09 (NRQCD)
FNAL/MILC '11 '12 (Fermilab)
ETM '12 (Ratio method, Nf=2)
RBC/UKQCD '10 (Static)
This work (Static)

1/mb uncertainty is not included in the error.

Decay constants have ~10% deviation from other works.
Ratio quantities do not have such a significant deviation.

Prospects

Improvements for next

- All-Mode-Averaging (AMA) [T. Blum, T. Izubuchi, E. Shintani (2012)]

  improved operator using lattice symmetry ⟶ good statistics

- Almost physical pion ensemble (Mobius domain-wall (RBC/UKQCD))

action	$1/a$ [Gev]	lattice	size [fm]	m_π [MeV]
MDWF + IW	1.75	$48^3 \times 96 \times 24$	5.5	138
MDWF + IW	2.31	$64^3 \times 128 \times 12$	5.5	139

- Non-perturbative renormalization working with JLQCD (KEK)

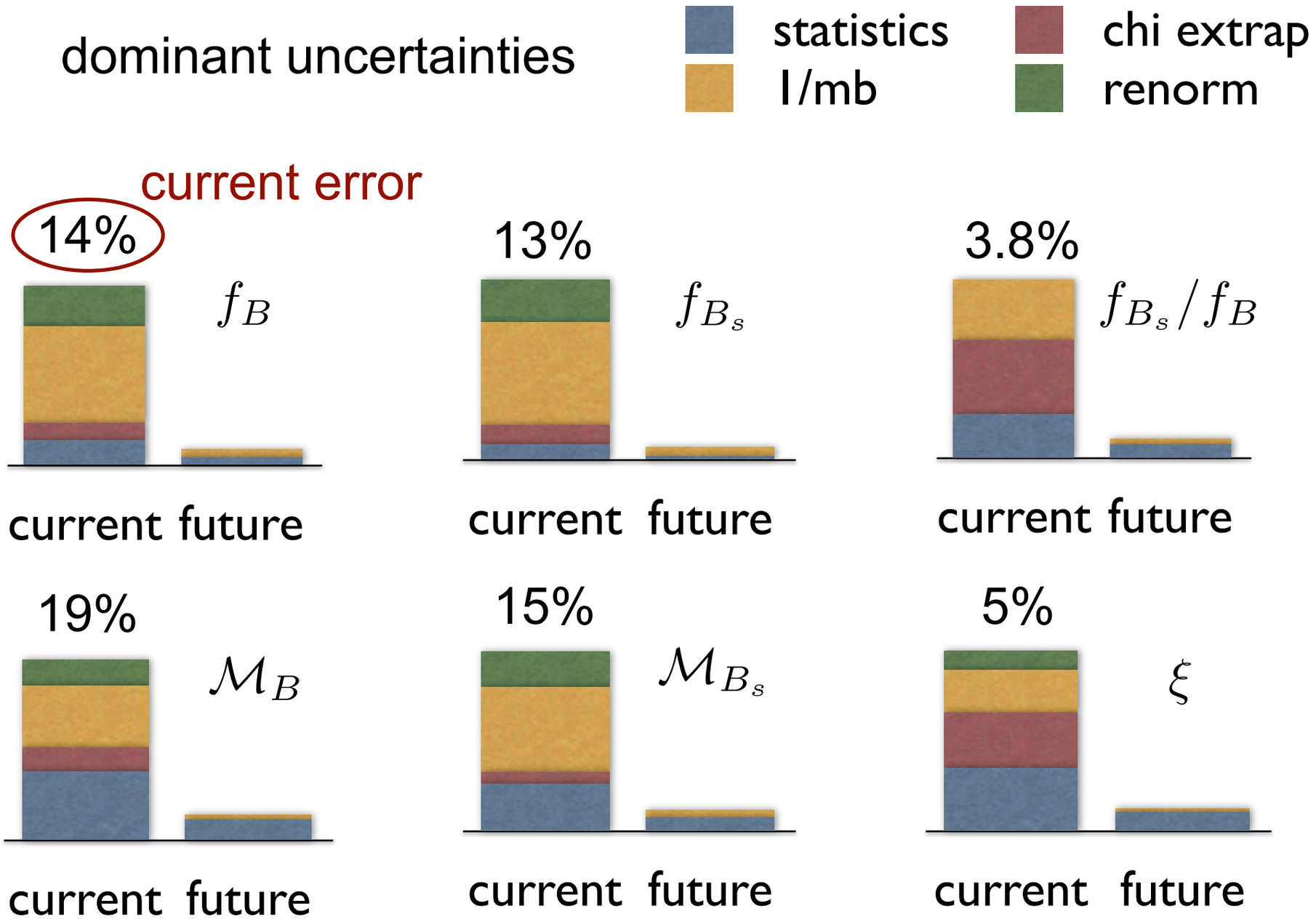
  $1/a$ power divergence needs to introduce additional renormalization condition than usual one, but possible.

- Including $1/m_b$ correction

  It requires NPR. Uncertainty is reduced down to ~1%.

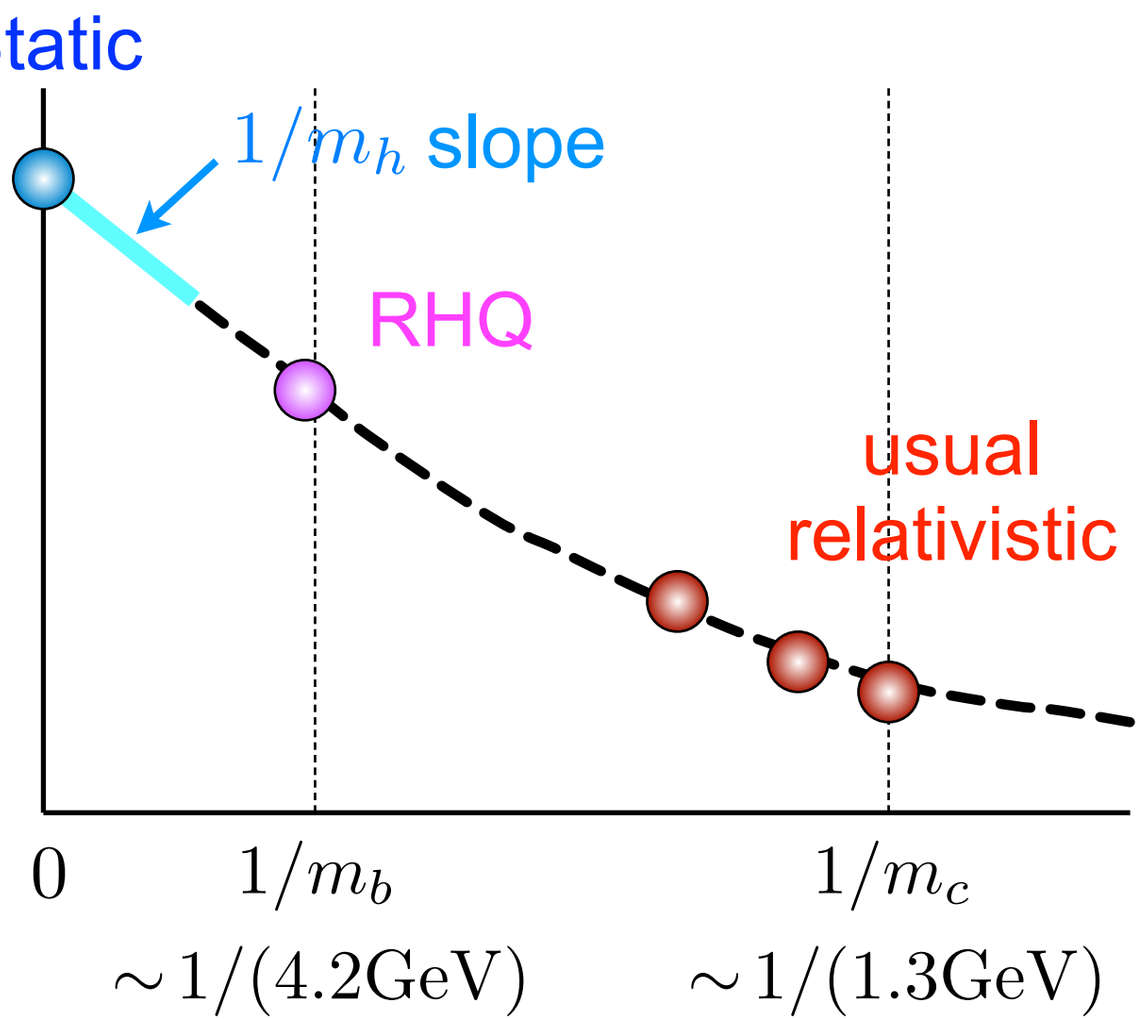
Prospects

- Impacts of the improvements



Prospects

- Everything would be consistent.



- Static + 1/mb correction (slope)
- Interpolation between static and charm quark region
- HQET and RHQ would give consistent results.

Summary

- RBC/UKQCD activity on B Physics: HQET(Static) & RHQ
- RHQ: Calculations on B meson decay constants, $B \to \pi \ell \nu$ process, $B^* B \pi$ coupling are on-going or have been almost finished.
- Static: B meson decay constants and neutral B meson mixing matrix elements obtained using static approximation. Almost finished up.
- AMA technique are now being used to substantially reduce statistical errors.
- Simulations at physical pion mass point are being prepared.
- Non-perturbative renormalization is planned.
- Considering to include 1/mb correction and make interpolation between static and charm quark mass region.
- 2 approaches (HQET & RHQ) would be mutually beneficial.

Standard Model Direct CP-violation in $K \to \pi\pi$ Decays from First Principles using Lattice QCD

Christopher Kelly

RBRC Review 2013



RIKEN BNL
Research Center

BROOKHAVEN
NATIONAL LABORATORY

A Little About Myself

- Undergrad: **University of Oxford, UK (02-06)**

- PhD: **University of Edinburgh, UK (06-10)**
  - Supervisor: Peter Boyle

- Postdoc: **Columbia University, USA (10-Aug 13)**
  - Supervisor: Norman Christ

- RIKEN FPR: **BNL (Sept 13 - ...)**
  - Supervisor: Taku Izubuchi

$\mathbf{K \to \pi\pi}$ Decays

- Direct CP-violation first observed in $K \to \pi\pi$ decays.
- Two types of decay:

$$\begin{aligned} \Delta I = 3/2 \ : \quad & K^+ \to (\pi^+\pi^0)_{I=2} && \text{with amplitude } A_2 \\ \Delta I = 1/2 \ : \quad & K^0 \to (\pi^+\pi^-)_{I=0} \\ & K^0 \to (\pi^0\pi^0)_{I=0} && \text{with amplitude } A_0 \end{aligned}$$

- Direct CP-violation: $\epsilon' = \dfrac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}}\left(\dfrac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \dfrac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right)$

  where $\omega = \mathrm{Re}A_2/\mathrm{Re}A_0$

  and δ_I are strong scattering phase shifts.
- ϵ' is highly sensitive to BSM sources of CPV.
- Strong interactions very important – origin ([arXiv:1212.1474]) of the so-called $\Delta I = 1/2$ rule: preference to decay to $I = 0$ final state.

Physical kinematics

- Desire physical kinematics in the decay: $E_{\pi\pi} = m_K$
- $m_\pi = 135\ \mathrm{MeV}$ and $m_K = 500\ \mathrm{MeV}$: need moving pions
- However ground state comprises stationary pions.
- Could attempt to tune L such that first excited state energy matches kaon mass.
- Multi-exponential fits are required to extract excited state, thus result will be very noisy.
- Especially when there are disconnected diagrams (I=0), it is highly unlikely that a decent signal could be extracted.

Workaround for $\Delta I = 3/2$ calculation

- Circumvent problem by imposing antiperiodic BCs on d-quark propagator. Changes finite-volume momentum discretization:

$$p = \frac{2\pi n}{L} \rightarrow \frac{(2n+1)\pi}{L}$$

- π^+/π^- become antiperiodic: $\bar{d}(x+L)u(x+L) = -\bar{d}(x)u(x)$ and hence have minimum momentum of π/L .
- Unfortunately neutral pion remains periodic (0 momentum ground state) and we need $\pi^+\pi^0$ final state. However...
- Wigner-Eckart theorem:

$$\langle (\pi^+\pi^0)_{I=2} | Q^{\Delta I_z = 1/2} | K^+ \rangle = \frac{\sqrt{3}}{2} \langle (\pi^+\pi^+)_{I=2} | Q^{\Delta I_z = 3/2} | K^+ \rangle$$

- APBCs on d-quark break isospin symmetry allowing mixing between isospin states: however this is prevented by charge conservation as $\pi^+\pi^+$ is the only charge-2 state with the remaining q-numbers.

The $\Delta I = 1/2$ case

- Must measure $K^0 \to \pi^+\pi^-$ and $K^0 \to \pi^0\pi^0$
- Wigner-Eckart trick cannot be used for $I = 0$ final state
- If we stay with APBC on d-quarks, isospin-breaking would allow mixing between $I = 0$ and $I = 2$ final states.
- No way to avoid requirement of moving π^0 .
- Would like BCs that commute with isospin and produce moving π^0 as well as π^+ and π^-.
- G-parity boundary conditions satisfy these criteria.

G-Parity Boundary Conditions

- G-parity is a charge conjugation followed by a 180 degree isospin rotation about the y-axis:

$$\hat{G} = \hat{C}e^{i\pi\hat{I}_y} \quad : \qquad \hat{G}|\pi^{\pm}\rangle = -|\pi^{\pm}\rangle$$
$$\hat{G}|\pi^{0}\rangle = -|\pi^{0}\rangle$$

Kim, arXiv:hep-lat/0311003 (2003)

Wiese, Nucl.Phys.B375, (1992)

- With G-parity BCs pions are all antiperiodic: $p_{\min} = \pi/L$
- G-parity commutes with isospin.
- At the quark level: $\hat{G}\begin{pmatrix} u \\ d \end{pmatrix} = \begin{pmatrix} -C\bar{d}^T \\ C\bar{u}^T \end{pmatrix}$ where $C = \gamma^2\gamma^4$. in our conventions
- In practise take $\psi^0 = d,\ \psi^1 = C\bar{u}^T$ such that BCs transform to

$$\psi^0(x + 2L) = \psi^1(x + L) = -\psi^0(x)$$

- Requires extensive code modifications to treat two flavours that mix at the boundary.

Gauge Field Boundary Conditions

- Dirac operator for ψ^1 field involves conjugate links U^*.
- As this field transitions to the regular d-field at the boundary, the links must also transition from U to U^*, i.e. links obey complex conjugate BCs (equiv to charge conjugation BCs).
- Boundary link gauge transformation is unusual:

$$U_\mu(L-1) \to V^\dagger(L-1)U_\mu(L-1)V^*(0)$$

- Necessitates generation of new ensemble of gauge links satisfying these BCs.

  (Note: for other choices of BC, e.g. APBC, new ensembles would still need to be generated, but due to presence of disconnected diagrams)

Unusual Contractions

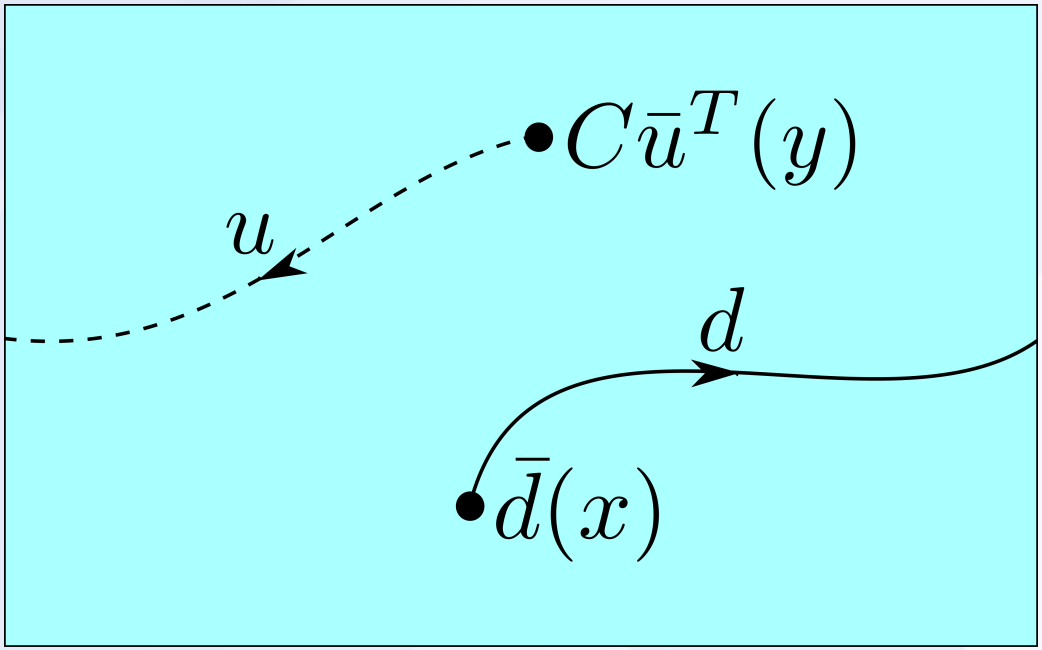
- Flavor mixing at boundary allows contraction of up and down fields:

$$\mathcal{G}^{(2,1)}_{y,x} = C\bar{u}^T_y d_x \,,$$
$$\mathcal{G}^{(1,2)}_{x,y} = -d_x u^T_y C^T$$

- Interpret as boundary creating/destroying flavor (violating baryon number)
- More Wick contractions to evaluate.
- Some states mix at the boundary, e.g.

$$uud \leftrightarrow \bar{d}\bar{d}\bar{u}$$

hence the proton is not an eigenstate.



Kaons

- $K \to \pi\pi$ calculation needs stationary K^0.
- Need an eigenstate that is periodic under translations by L.
- $K^0 = \bar{s}d$ is not a G-parity eigenstate: $\bar{s}d \leftrightarrow \bar{s}\bar{u}$
- Introduce 'strange isospin' : s-quark in doublet $\begin{pmatrix} s' \\ s \end{pmatrix}$
- Can now form an eigenstate:

$$\tilde{K}_0 = \frac{1}{\sqrt{2}}(\bar{s}d + \bar{u}s') = \frac{1}{\sqrt{2}}(K_0 + K_0')$$

  with e-val +1 (periodic).

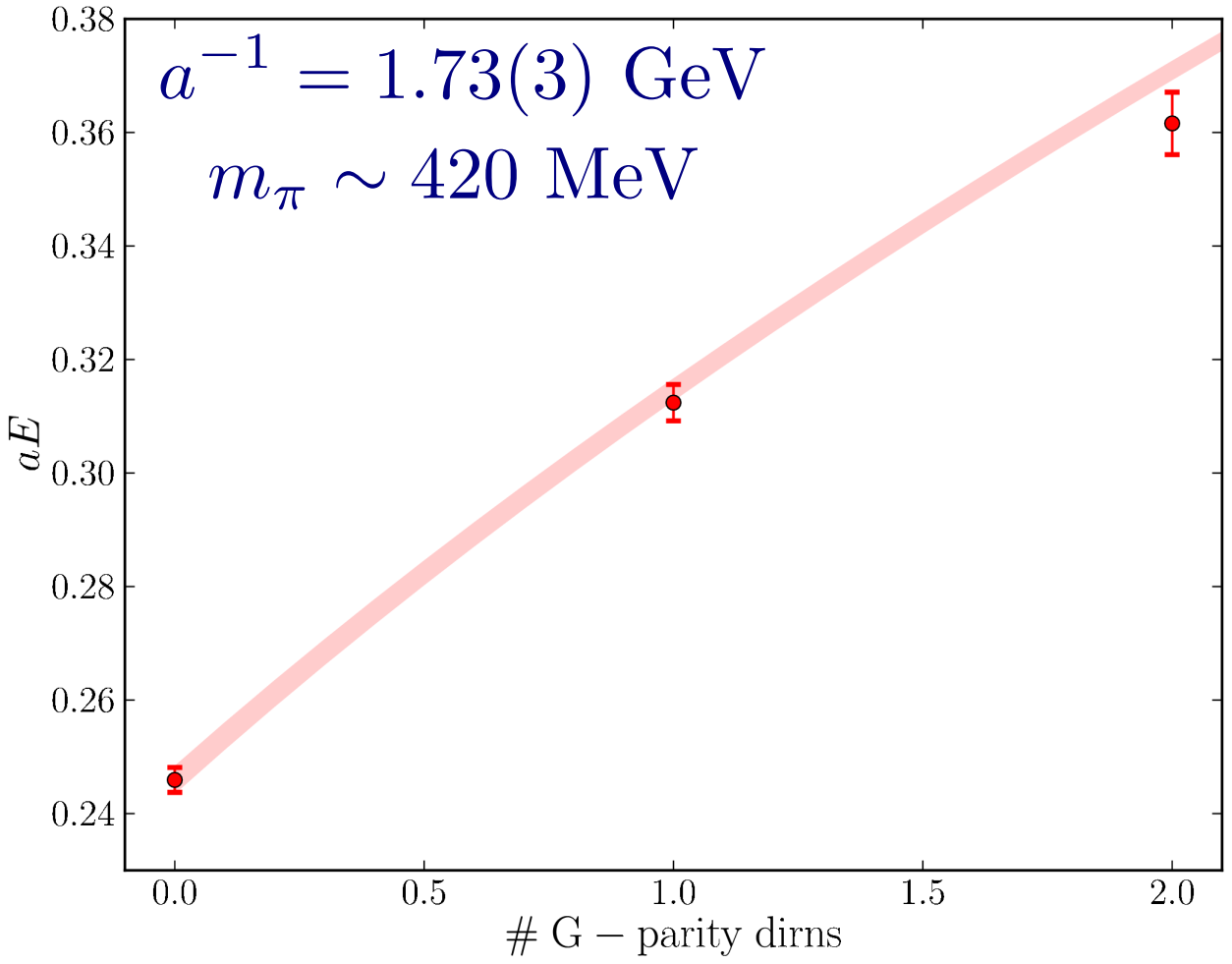
- Unphysical partner K_0' mixes with physical state K_0. For a physical operator, e.g. $A_\mu = \bar{s}\gamma^5\gamma^\mu d$, K_0' only contributes after propagating through the boundary: suppressed like $e^{-m_K L}$, a sub-% effect.
- Up to these effects, only change is a normalization factor.

Locality

- Theory has one too many flavors. Must take square-root of s'/s determinant in evolution to revert to 3 flavors. Determinant becomes non-local.
- Non-locality is however only a boundary effect that vanishes as $L \to \infty$. With sufficiently large volumes the effect should be benign.
- Estimate size of effect : Staggered ChPT?

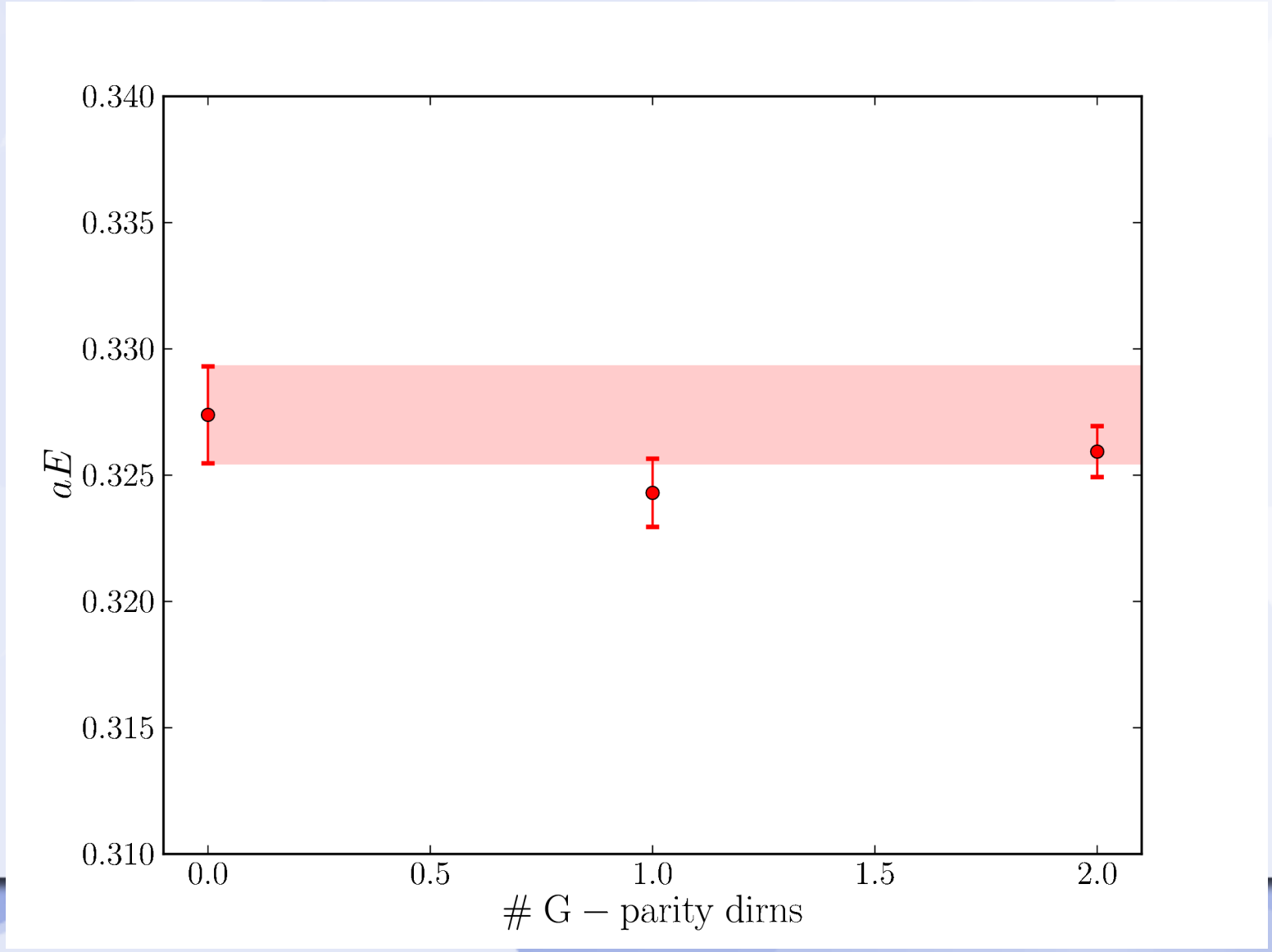
Results: Pion Dispersion Relation

- Generated $16^3 \times 32$ fully dynamical test ensembles with G-parity BCs in 0,1,2 directions.



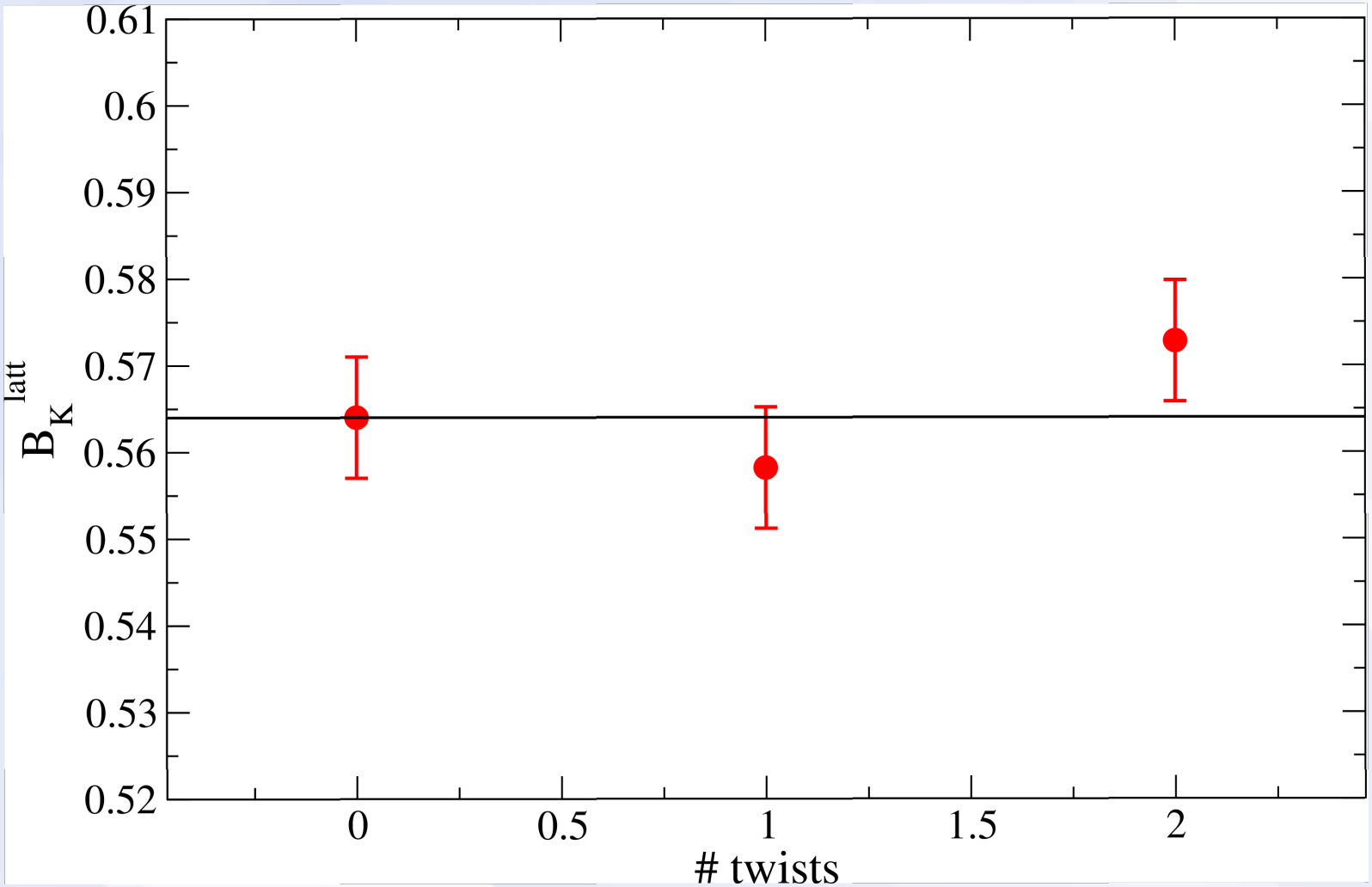
Results: Kaon Dispersion Relation

- Stationary kaon states demonstrated:



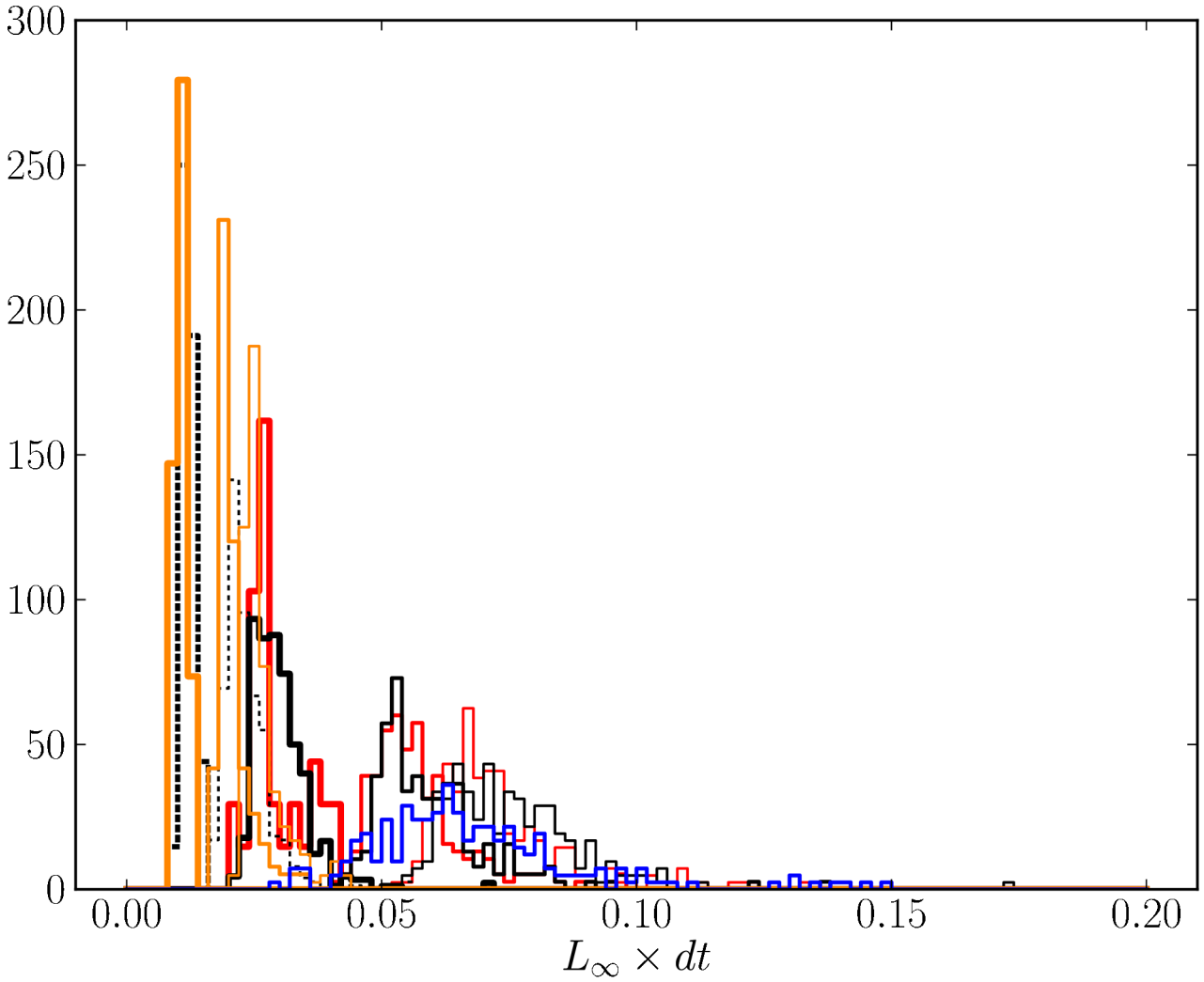
Results: B_K

- $\bar{K}^0 \leftrightarrow K^0$ mixing amplitude shown to be independent as expected. Similar 4-quark operators to $K \to \pi\pi$ calculation.



Ensemble for $K \to (\pi\pi)_{I=0}$ calculation

- Evolution code (CPS+BFM) for Mobius DW and Iwasaki+DSDR gauge action with G-parity BCs is now complete.
- Currently generating $32^3 \times 64 \times 16$ ensemble USQCD BGQ half-rack at BNL.
- Parameters are the same as the ensemble used for the $\Delta I = 3/2$ calculation: $\beta = 1.75$ $(a^{-1} = 1.37(1)\ \mathrm{GeV})$ and $m_\pi = 143(1)\ \mathrm{MeV}$ (PQ) , $171(1)\ \mathrm{MeV}$ (unitary)
- Mobius parameters tuned to match to regular DWF, allows factor of 2 reduction in Ls for same physics.
- Dirac matrix is intrinsically 2-flavor, hence $\det(M^\dagger M)$ contains 4 flavors: must use RHMC even for light quarks. Larger computational overheads make it more difficult to tune evolution.

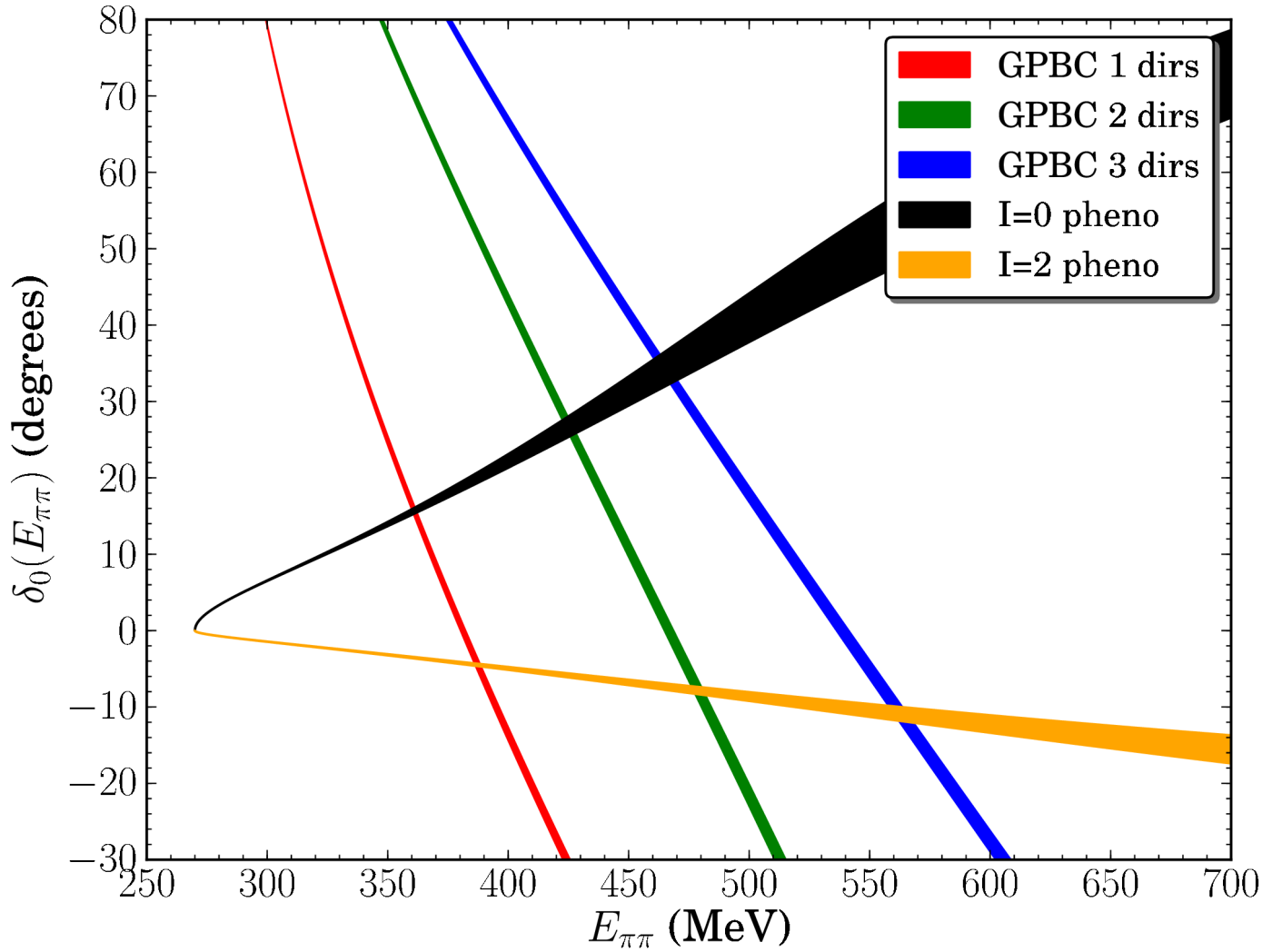

300
250
200
150
100
50
0
0.00
0.05
0.10
0.15
0.20
$L_\infty \times dt$

Status and Outlook

- Substantial progress has been made in the march towards calculating the $\Delta I = 1/2$ amplitude.
- Further investigation of systematic errors associated with G-parity technique is required. However all tests to date have not indicated any sicknesses with the approach.
- D.Zhang (CU) and I are currently developing G-parity contraction code using A2A propagators.
- G-parity techniques may be useful for controlling errors in other frontier calculations performed by RBC & UKQCD, e.g. $K_L - K_S$ mass difference.

$\Delta I = 3/2$

Extra Slides


GPBC 1 dirs
GPBC 2 dirs
GPBC 3 dirs
I=0 pheno
I=2 pheno
$\delta_0(E_{\pi\pi})$ (degrees)
$E_{\pi\pi}$ (MeV)
80
70
60
50
40
30
20
10
0
−10
−20
−30
250
300
350
400
450
500
550
600
650
700

RBC & UKQCD 2+1f T=0 Simulations

- Multiple lattices:

Lattice Size	Action	β	a^{-1} (GeV)	m_π Range (MeV)
$32^3 \times 64 \times 16$	DWF+Iwasaki	2.25	2.31	
$24^3 \times 64 \times 16$	DWF+Iwasaki	2.13	1.75	
$32^3 \times 64 \times 32$	DWF+IDSDR	1.75	1.37	
$64^3 \times 128 \times 16$	Mobius+Iwasaki	2.25	2.31	
$48^3 \times 96 \times 16$	Mobius+Iwasaki	2.13	1.75	

Simultaneous Chiral/Continuum Fits - I

- Measured quantities: $m_\pi,\ f_\pi,\ m_K,\ f_K,\ m_\Omega,\ B_K$ etc
- Symanzik theory (DWF - good chiral symmetry):

$$Y(\{m\}, a) = f^Y_{\text{contnm}}(\{m\}) + C^Y_a a^2 + \mathcal{O}(ma^2, a^4, ...)$$

- Fits to data: can use ChPT or general analytic function to describe continuum mass dependence.
- Mass dependence and scale dependence are separable – can do combined fit to all ensembles.
- ChPT contains parameters shared between different quantities (B, f, etc) – benefit from simultaneously fitting multiple quantities.

Simultaneous Chiral/Continuum Fits - II

- Choose a 'scaling trajectory' through parameter space along which we approach continuum.
- Each lattice has 2 unknown masses ($am_{u/d}$, am_s) and 1 unknown scale (a) that must be tuned to match the real world.
- Can choose any set of convenient quantities. We use m_π/m_Ω , m_K/m_Ω and m_Ω
- For these quantities the coeff. is de

Exploration of Nucleon Structure on a Lattice: Progress and Challenges

Sergey Syritsyn

RBRC Review
Oct 30 - Nov 1, 2013

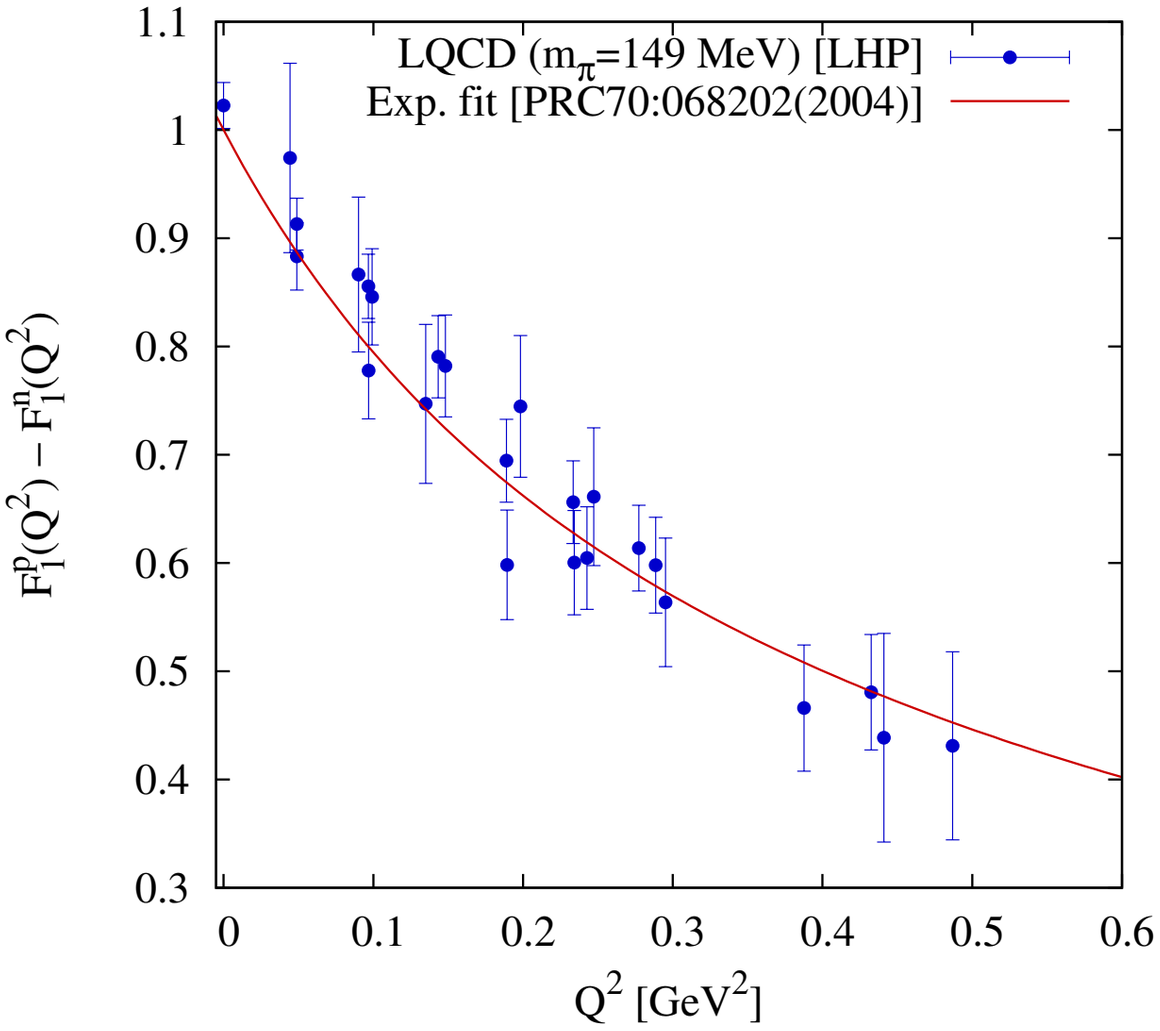
Nucleon Structure: Lattice Perspective

- Vector Form Factors
  - *magnetic moment*
  - *charge & magnetization radii*
- Axial Form Factors
  - *axial charge & radius*
  - *pseudoscalar coupling*
  - *pion pole dominance*
- Decomposition of the Proton Spin
  - *contributions of light quark spin and orbital motion to the proton spin*
- Parton Distributions on a Lattice
  - *moments of parton distributions*
  - *generalized form factors*
  - *direct calculation of PDFs and TMDs on the lattice*

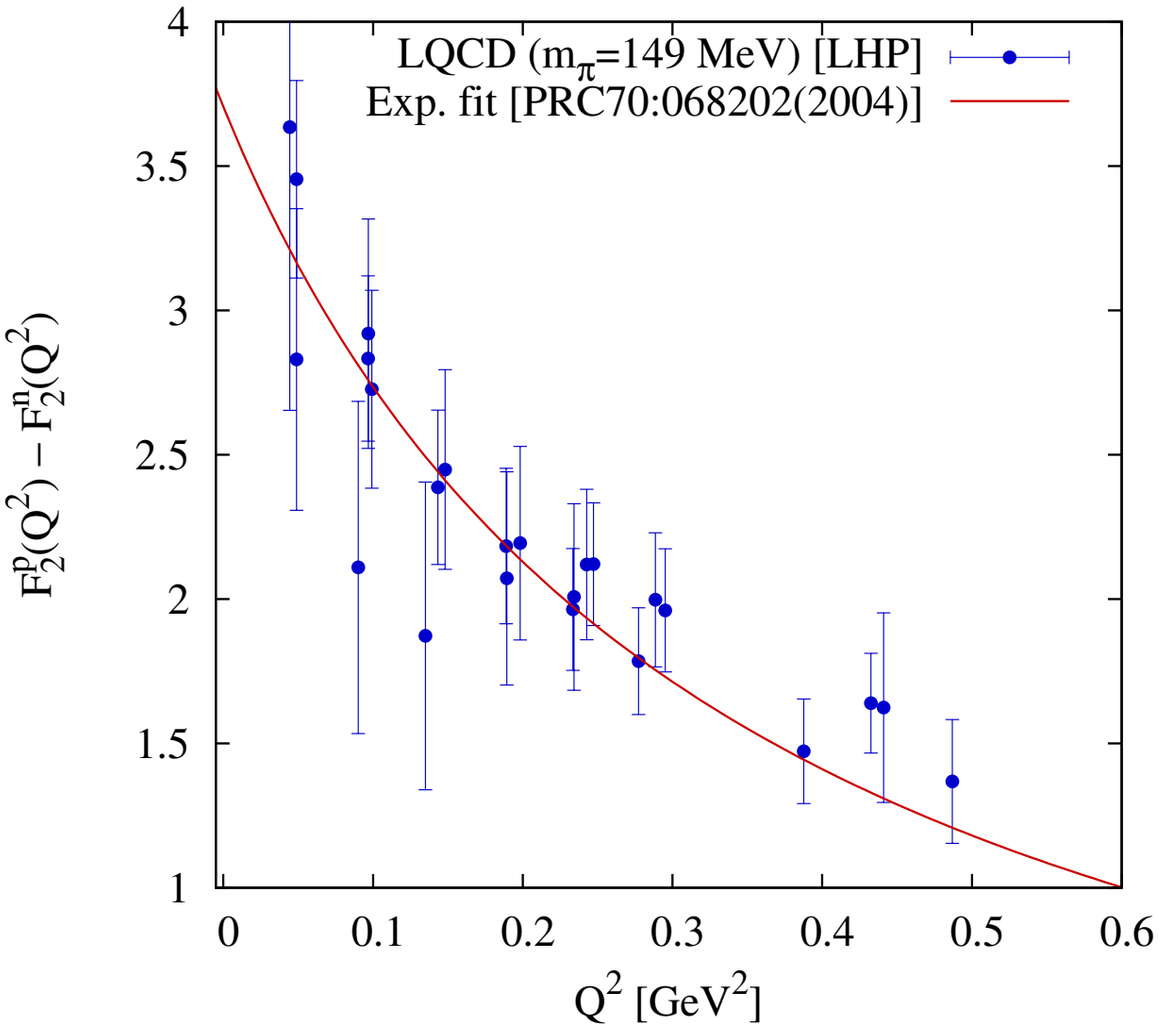
Vector Form Factors

$$\langle P+q|\,\bar{q}\gamma^{\mu}q\,|P\rangle \;=\; \bar{U}_{P+q}\Big[\,F_1(Q^2)\,\gamma^{\mu} + F_2\,(Q^2)\,\frac{i\sigma^{\mu\nu}q_{\nu}}{2M_N}\Big]U_P$$

Dirac Form Factor

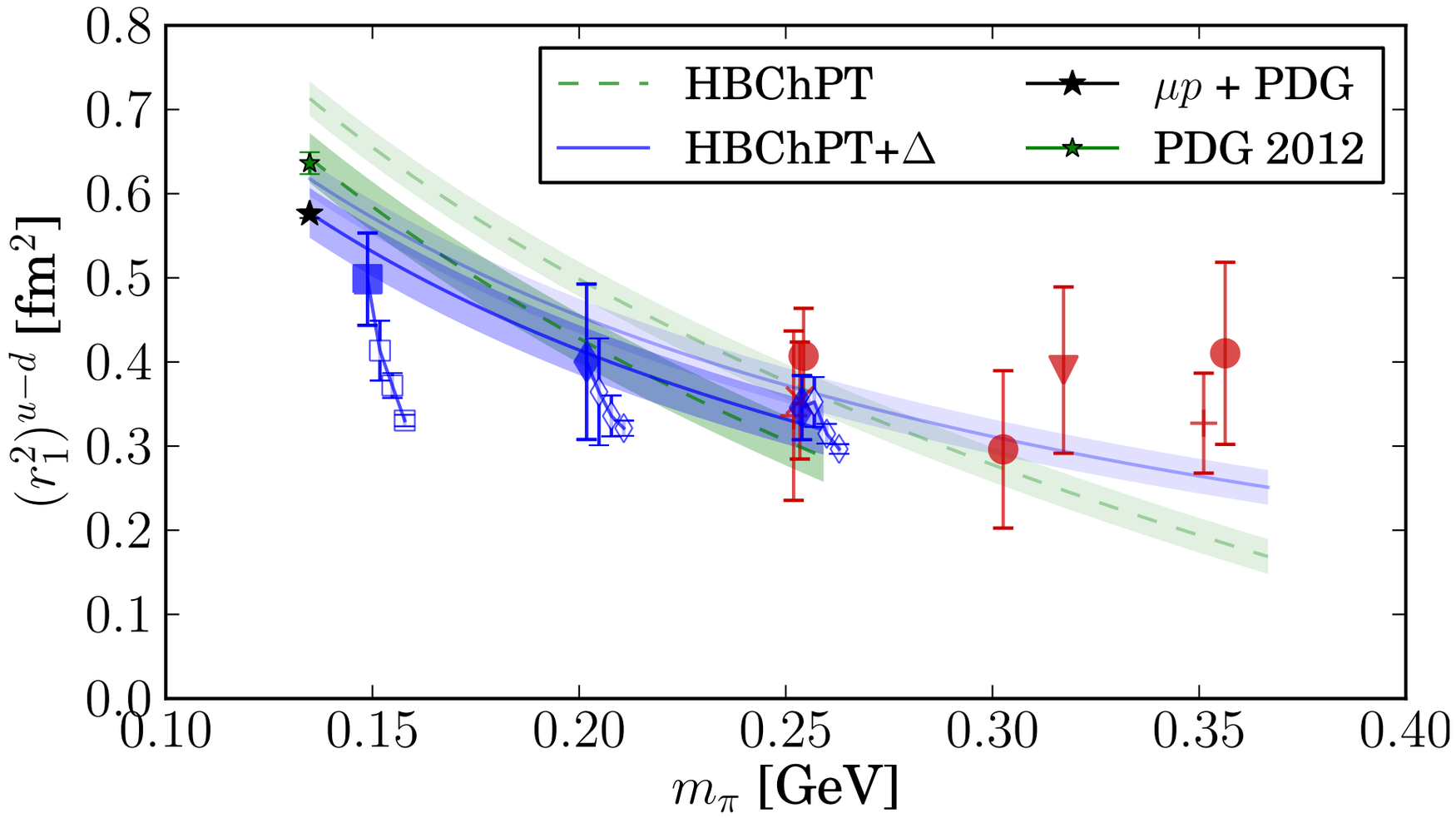


Pauli Form Factor



[Lattice Hadron Physics collaboration (SNS et al), in preparation]

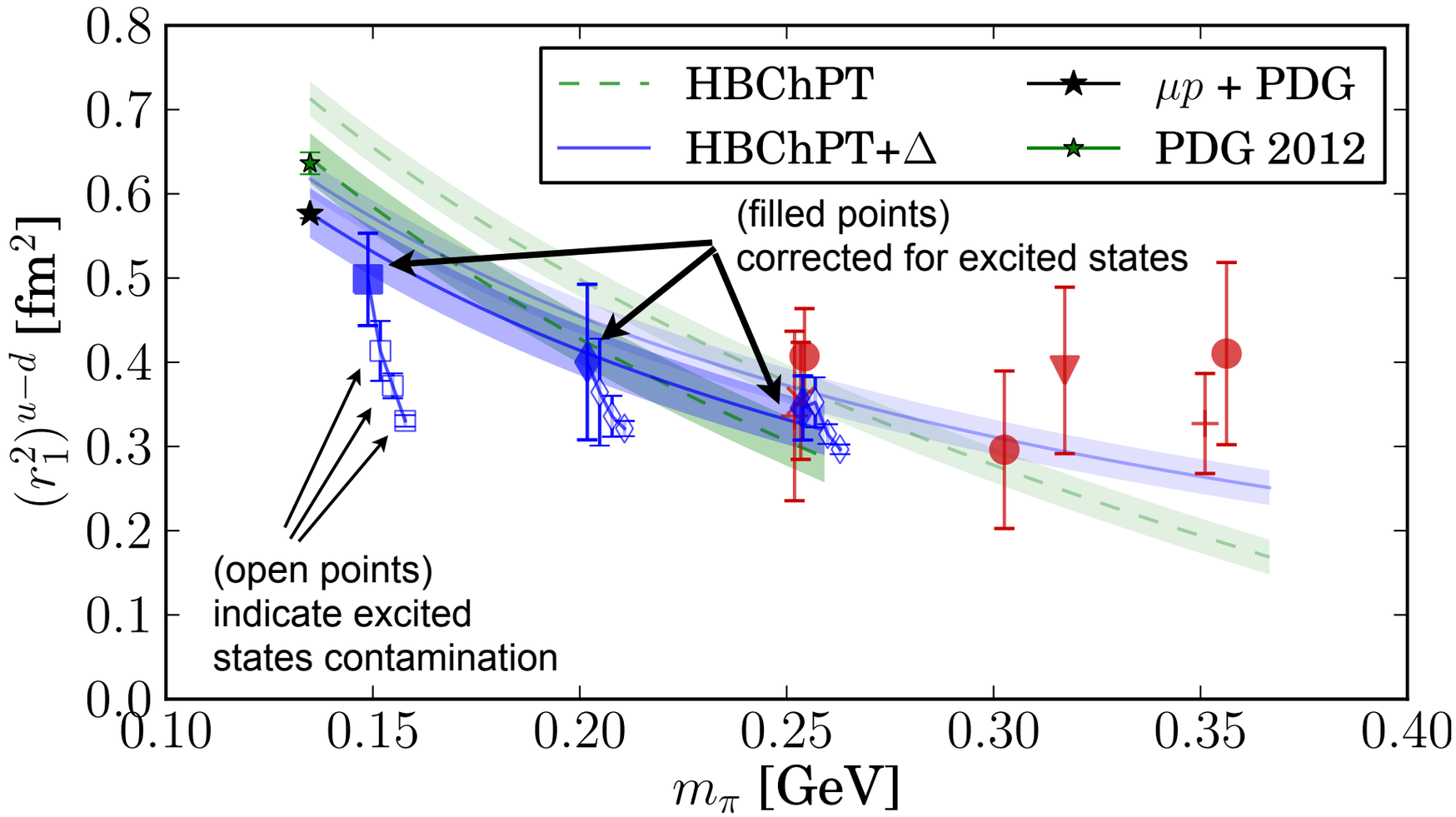
Isovector Dirac Radius



$$F_1^{u-d}(Q^2) \approx 1 - \frac{1}{6}Q^2\langle r_1^2\rangle^{u-d} + \mathcal{O}(Q^4)$$

[Lattice Hadron Physics collaboration (SNS et al), arXiv:1209.1687]

Isovector Dirac Radius



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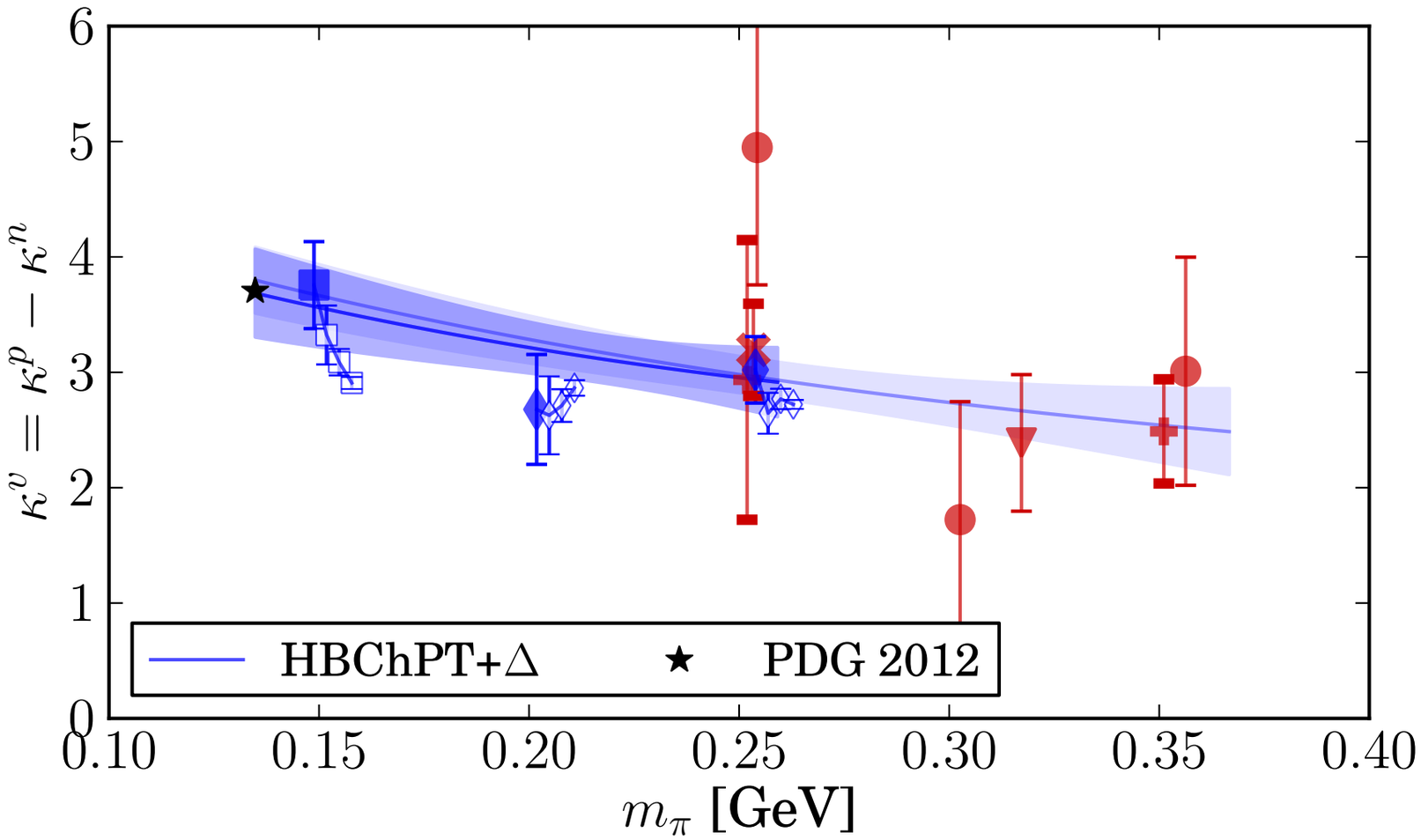
[Lattice Hadron Physics collaboration (SNS et al), arXiv:1209.1687]

Isovector Anomalous Magnetic Moment



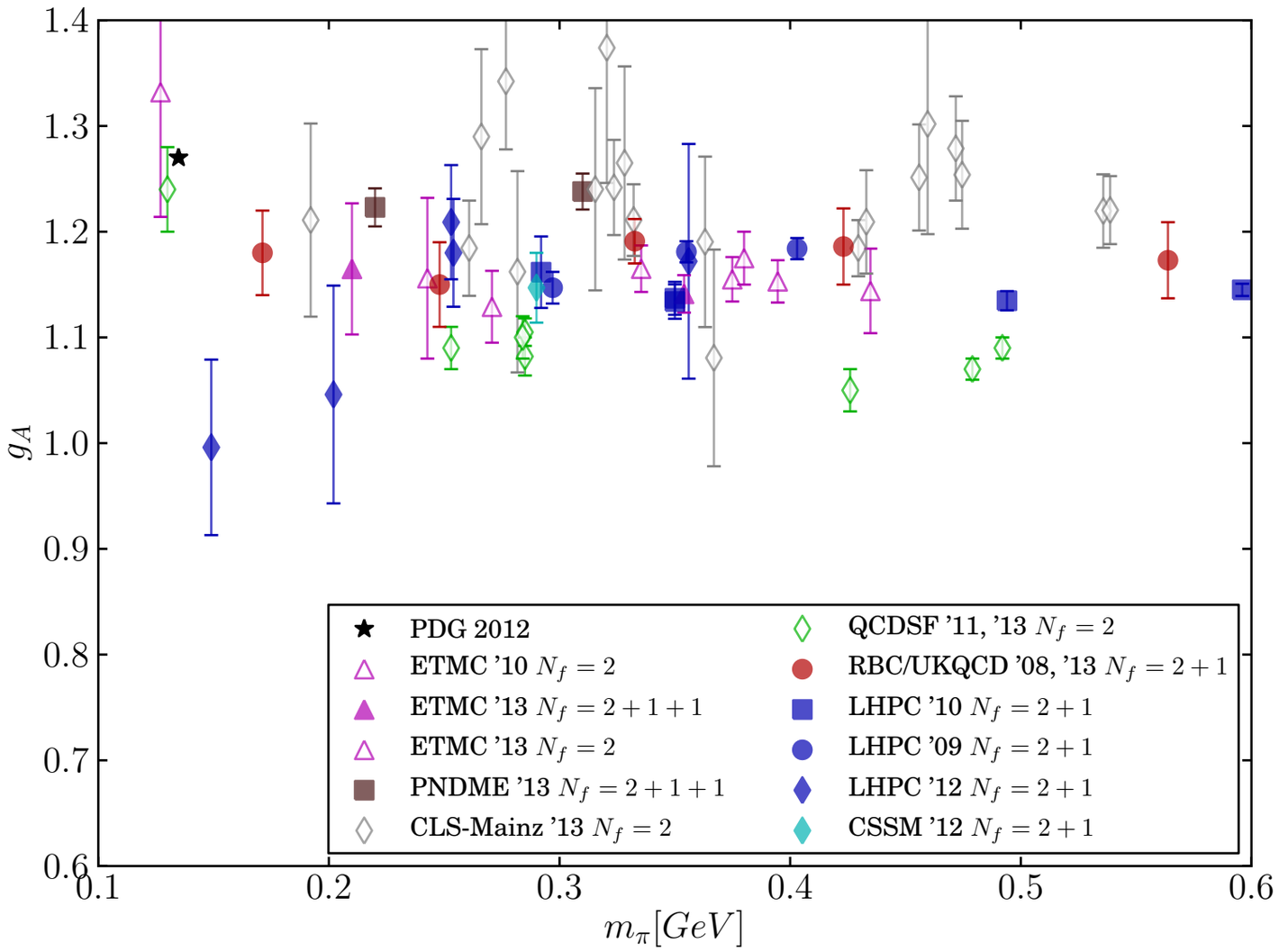
$$\kappa^{u-d} = F_2^{u-d}(Q^2 = 0)$$

[Lattice Hadron Physics collaboration (SNS et al), arXiv:1209.1687]

Nucleon Axial Charge

$$\langle N(p)|\bar{q}\gamma^\mu\gamma^5 q|N(p)\rangle = g_A\,\bar{u}_p\gamma^\mu\gamma^5 u_p\,,$$

Experiment (W.A.) [PDG'12] $\quad g_A^{\rm ave} = 1.2701(25)$



Most calculations underestimate g_A by 10-15%

[SNS, Lattice 2013 plenary talk]

Nucleon Axial Charge

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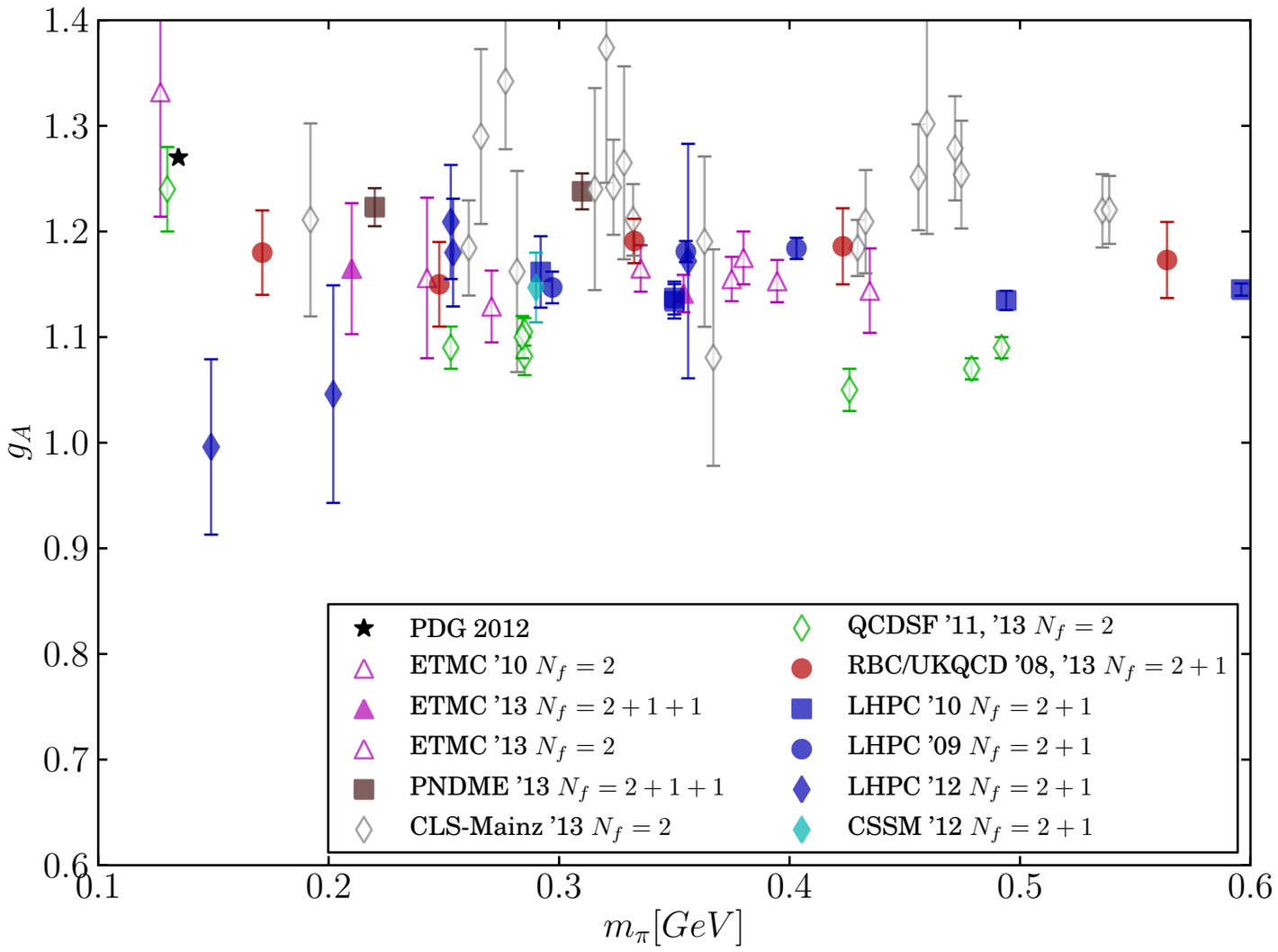

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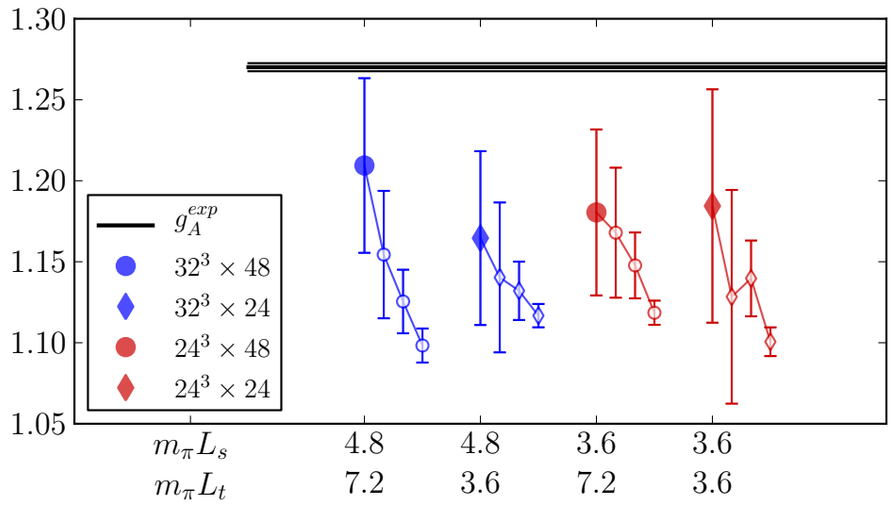
[SNS, Lattice 2013 plenary talk]



Finite size effects?

$$g_A(L_s, L_t) = g_A^\infty + Be^{-m_\pi L_s} + Ce^{-m_\pi L_t}$$
$$\vdots$$

At $m_\pi \approx 250$ MeV

$$g_A^{(m_\pi L_s = 4)} - g_A^\infty = -0.009(54)$$
$$g_A^{(m_\pi L_t = 4)} - g_A^\infty = -0.016(39)$$

[SNS et al, in preparation]

Origin of the Nucleon Spin

Proton spin puzzle:

1989 EMC experiment finds $\Delta\Sigma = \sum_q (\Delta q + \Delta\bar{q}) = 0.2 \ldots 0.3$

Spin sum rule:

$$J_{\rm glue} + \sum_q J_q = \frac{1}{2}\,,$$

$$J_q = \frac{1}{2}\Delta\Sigma_q + L_q$$

Quark Spin:

$$\langle N(p)|\bar{q}\gamma^\mu\gamma^5 q|N(p)\rangle = (\Delta\Sigma_q)\left[\bar{u}_p\gamma^\mu\gamma^5 u_p\right]$$

Angular momentum (J_q):

$$J_{q,glue} = \frac{1}{2}\Big[A_{20}^{q,glue}(0) + B_{20}^{q,glue}(0)\Big]$$

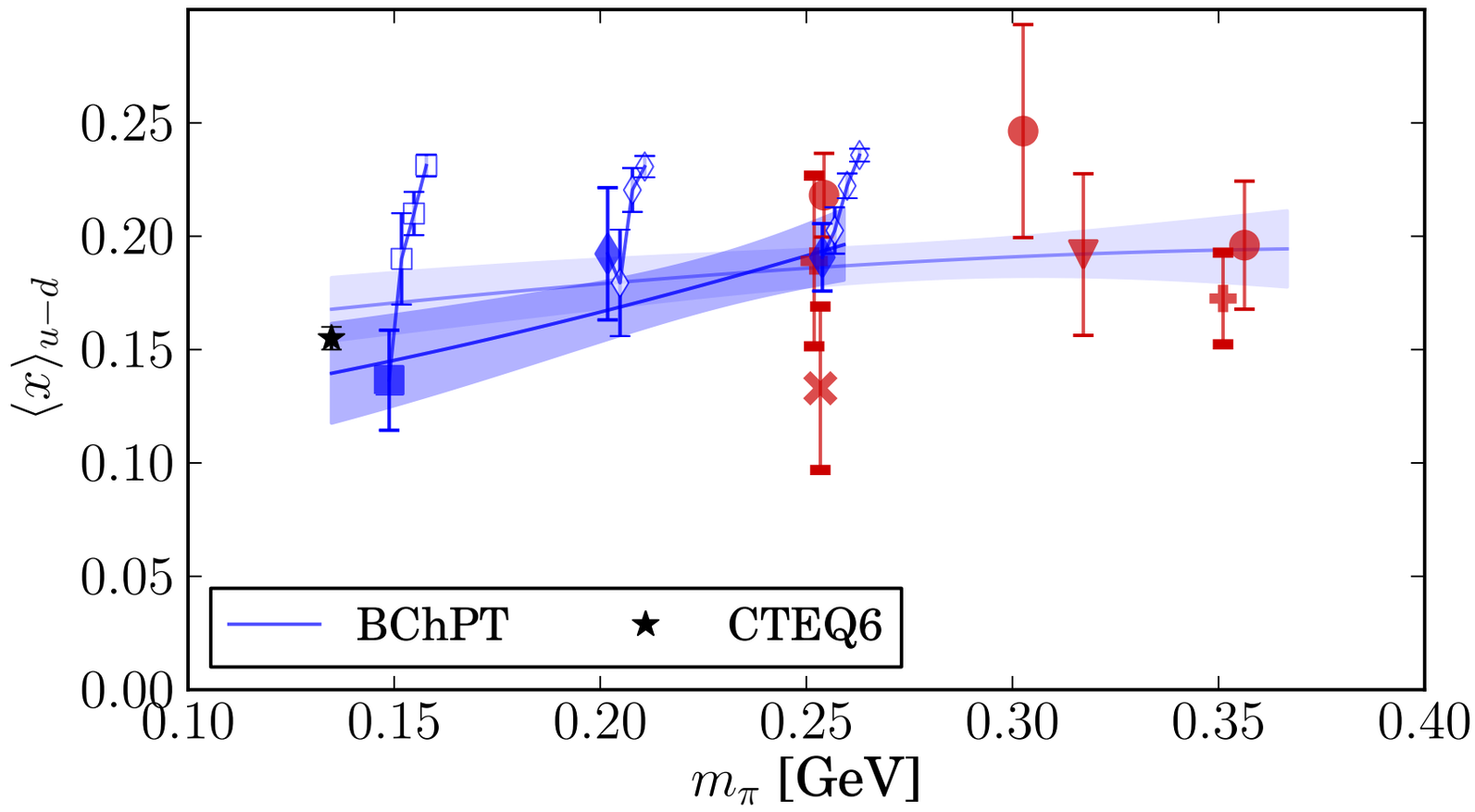
where A_{20} , B_{20} are E.-M. tensor form factors:

$$\langle N(p+q)|\, T_{\mu\nu}^{q,glue}\, |N(p)\rangle \to \Big\{A_{20},\, B_{20},\, C_{20}\Big\}(Q^2)$$

$$T^q_{\mu\nu} = \bar{q}\,\gamma_{\{\mu}\overleftrightarrow{D}_{\nu\}}\,q$$

$$T^{\rm glue}_{\mu\nu} = G^a_{\mu\lambda}G^a_{\nu\lambda} - \frac{1}{4}\delta_{\mu\nu}(G_{\mu\nu})^2$$

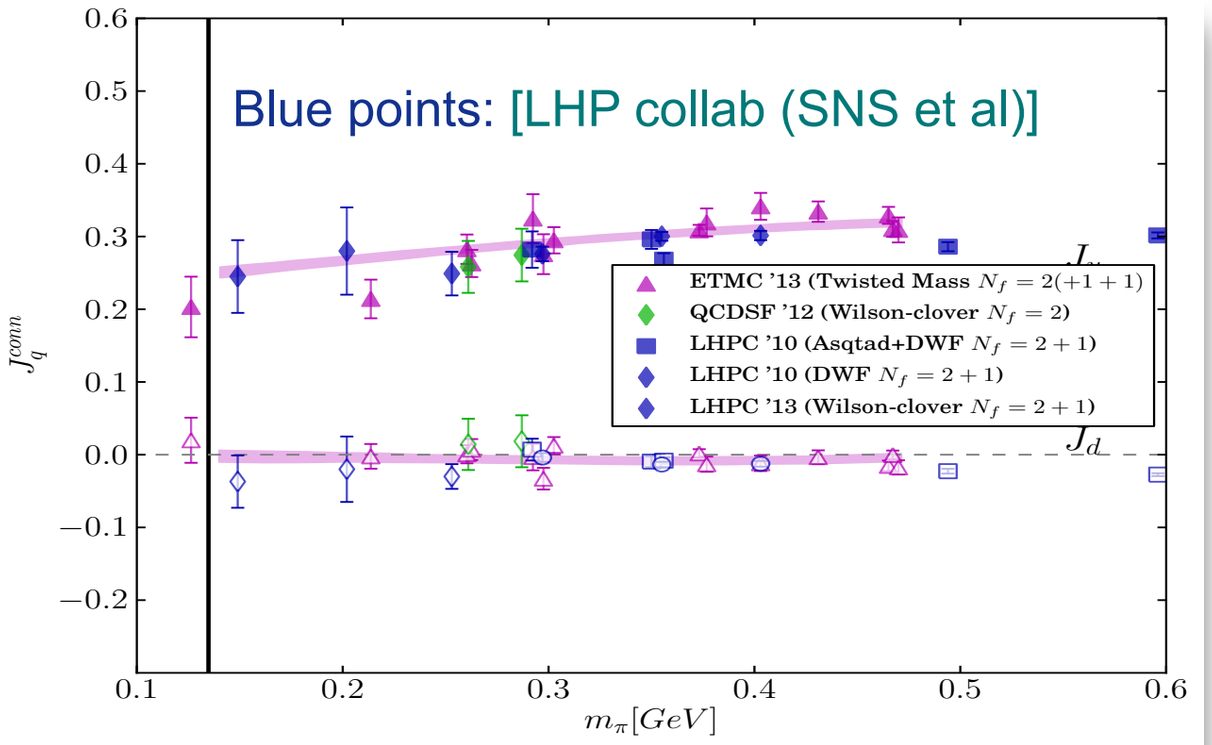
Isovector Quark Momentum Fraction



$$\langle x \rangle_{u-d} = \int dx\, x\, (u + \bar{u} - d - \bar{d})$$

[Lattice Hadron Physics collaboration (SNS et al), arXiv:1209.1687]

Quark Angular Momentum and Spin (Connected)

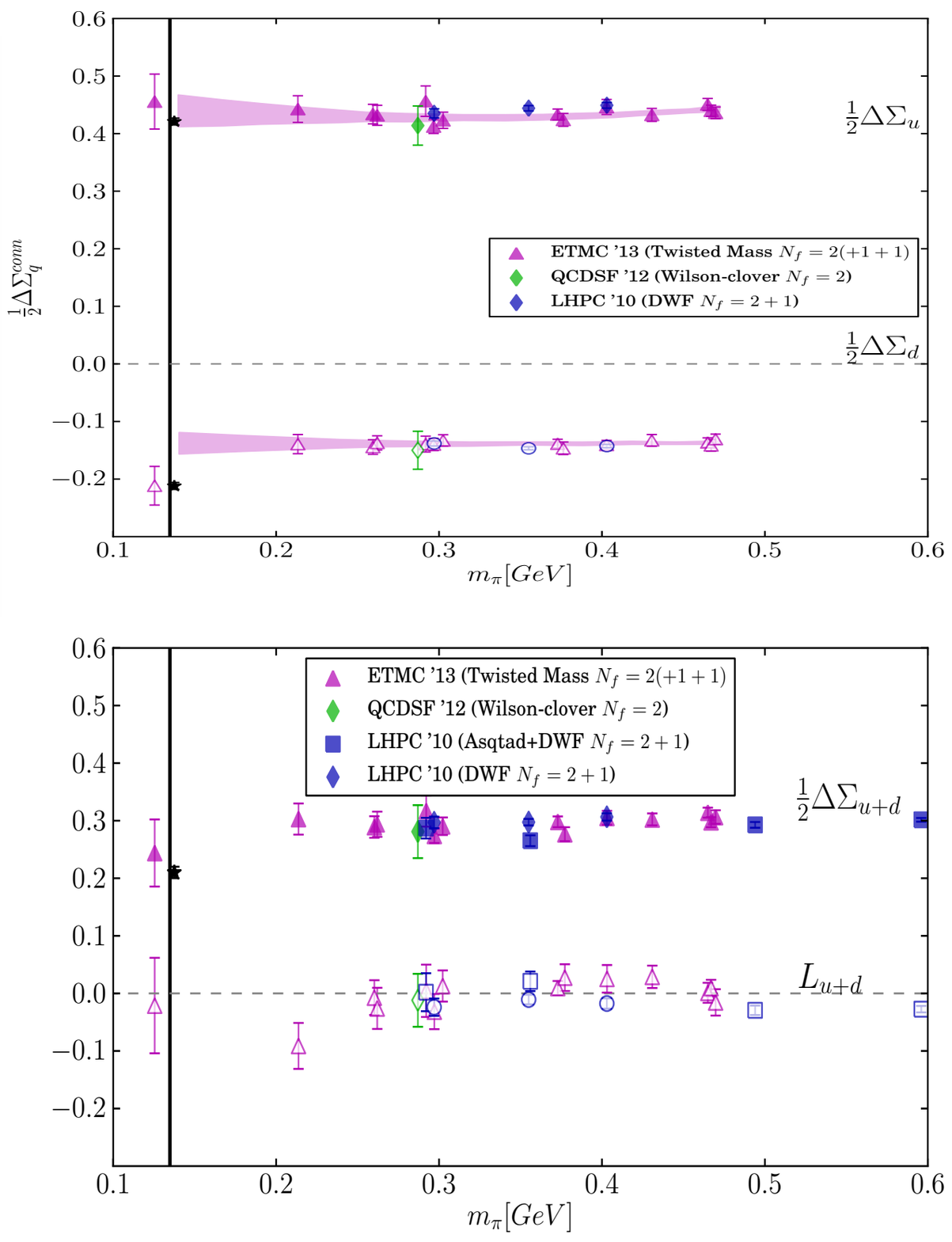


$$J_u \approx 40 - 50\% \quad *$$

$$|J_d| \lesssim 10\% \quad *$$

$$|L_{u+d}| \ll \frac{1}{2}\Delta\Sigma_{u+d} \quad *$$

(*) not including disconnected diagrams!



Summary & Outlook

Summary

★ Calculations of nucleon structure on a lattice with realistic light quarks are underway

★ Some agreement is reassuring;
yet, (much) more work is required to properly control all systematic effects

★ Isolating ground nucleon state becomes difficult at the physical point

Outlook

★ Current project : QCD with chiral quarks at the physical point

★ Speed-up a number of methods
eigenvalue deflation
improved stochastic estimators (all-mode-averaging)
“distillation” of nucleon interpolating operators

BNL Future Plan

Back to Contents

BNL Future Plans

From RHIC to eRHIC

Berndt Mueller

RBRC SRC Meeting

BNL

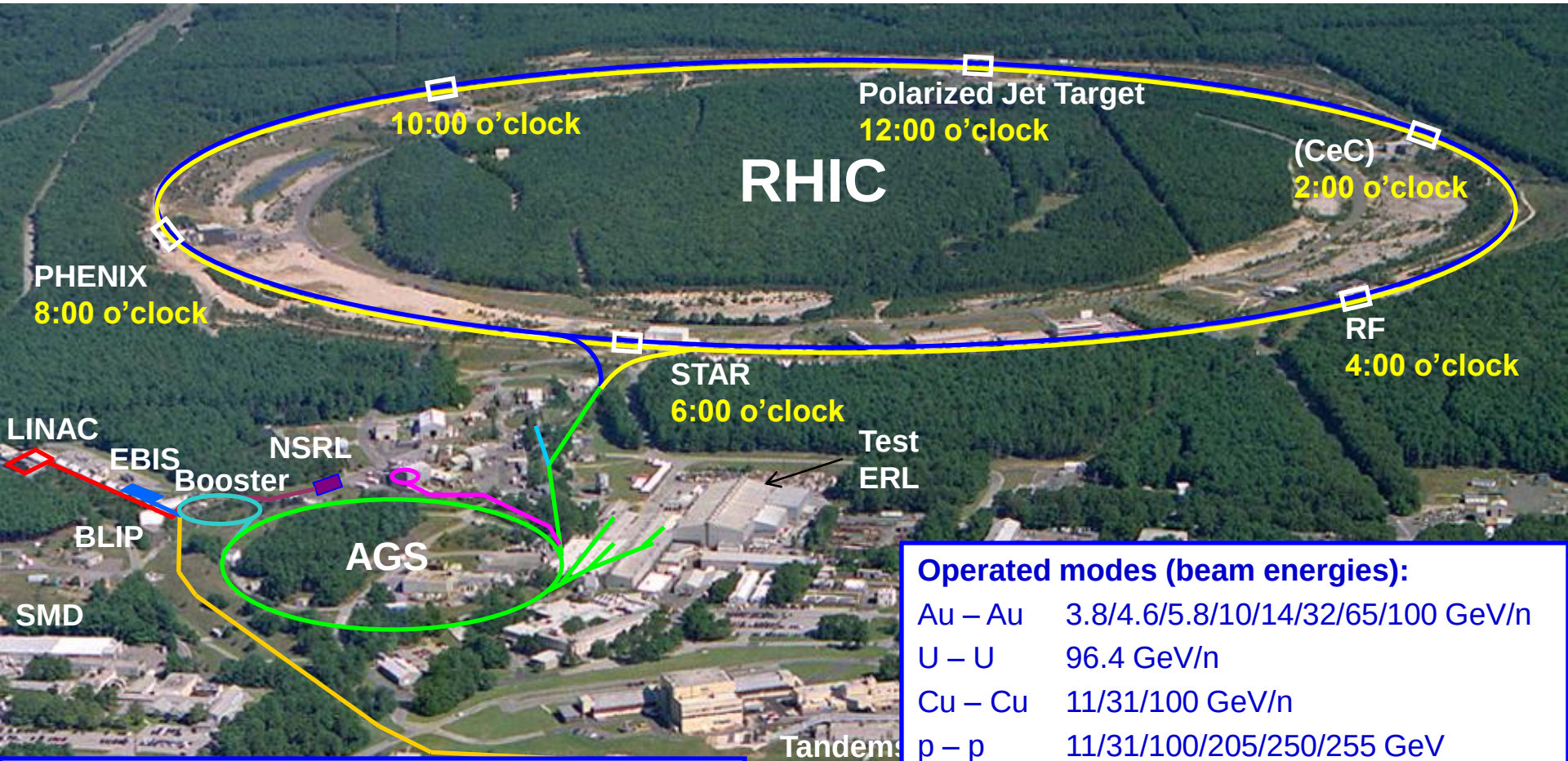
Oct 30 – Nov 1, 2013

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science U.S. DEPARTMENT OF ENERGY

RHIC – Hadron & Nucleus Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p – p (255 GeV)	210×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	490×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

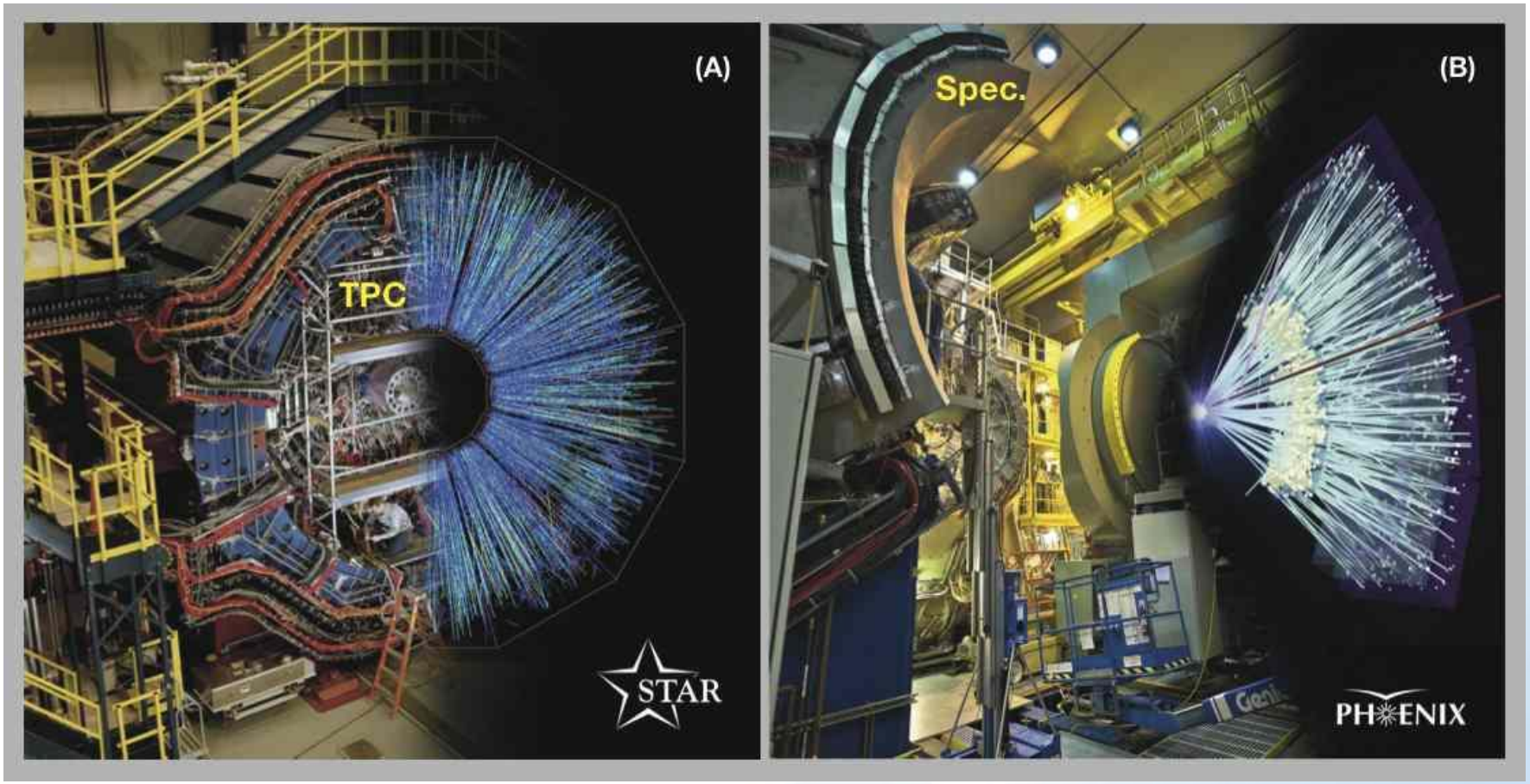
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p – p	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

Planned or possible future modes:

Au – Au	2.5 GeV/n
p – Au*	100 GeV/n
p – ^{3}He*	166 GeV/n

(*asymmetric rigidity)

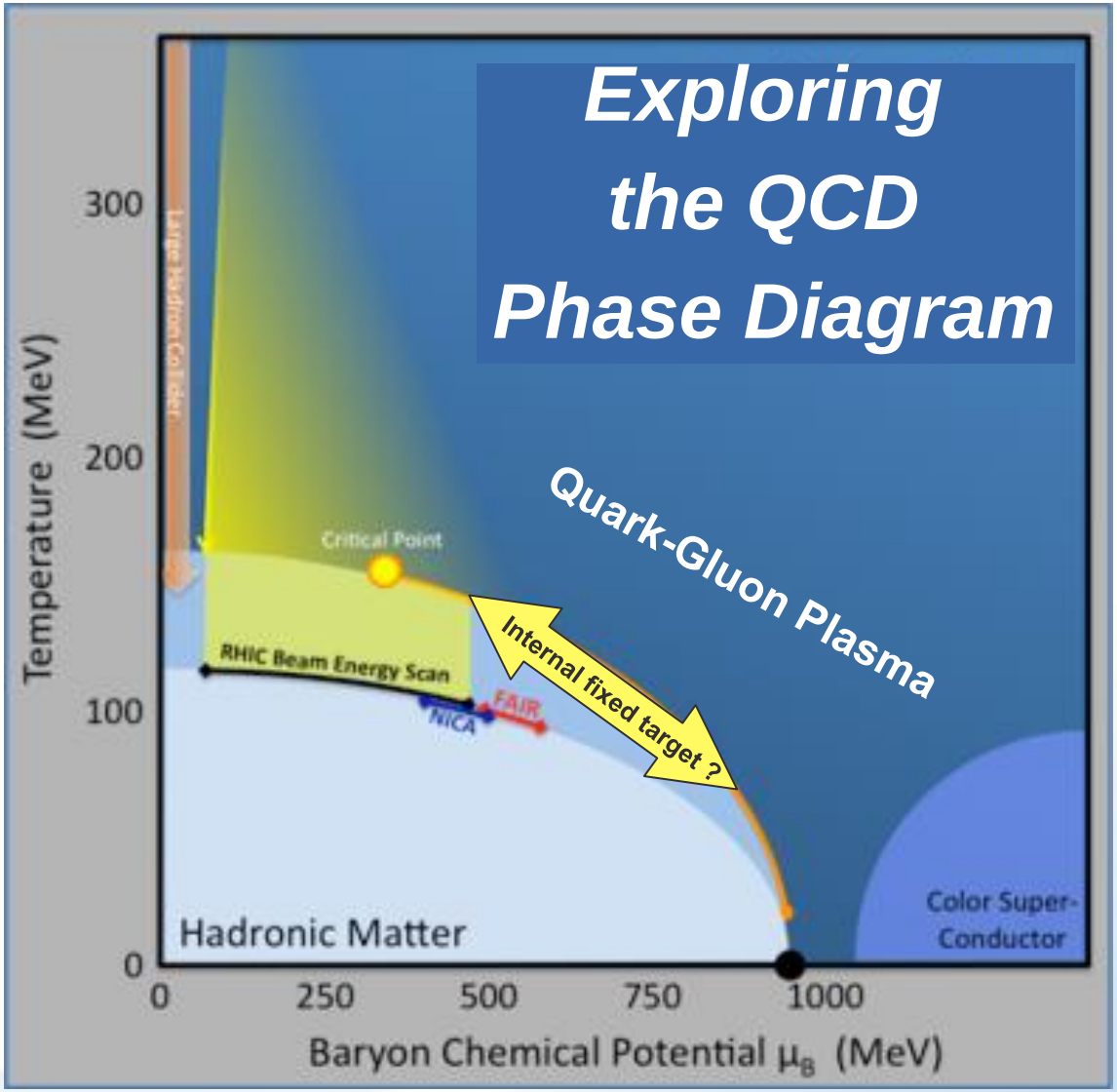
Detector Collaborations



559 collaborators from 12 countries

550 collaborators from 15 countries

RHIC's Mission



RHIC's Main Discoveries

- Hot nuclear matter produced in collisions at RHIC is a liquid quark-gluon plasma. The plasma is made up of individually flowing quarks, not quarks bound into baryons and mesons.
- The QGP is a strongly coupled "perfect" liquid (η/s near the quantum limit); RHIC's QGP is more "perfect" than that produced at LHC.
- Quarks moving through the QGP lose energy rapidly, causing jets to be strongly "quenched".
- Heavy quark bound states (J/ψ, Υ) "melt" in the QGP due to color screening and ionization. RHIC and LHC data together indicate that heavy quarks can recombine when the QGP hadronizes.

- Approx. 20% of the proton spin may be carried by gluons.

The “Missing” Proton Spin

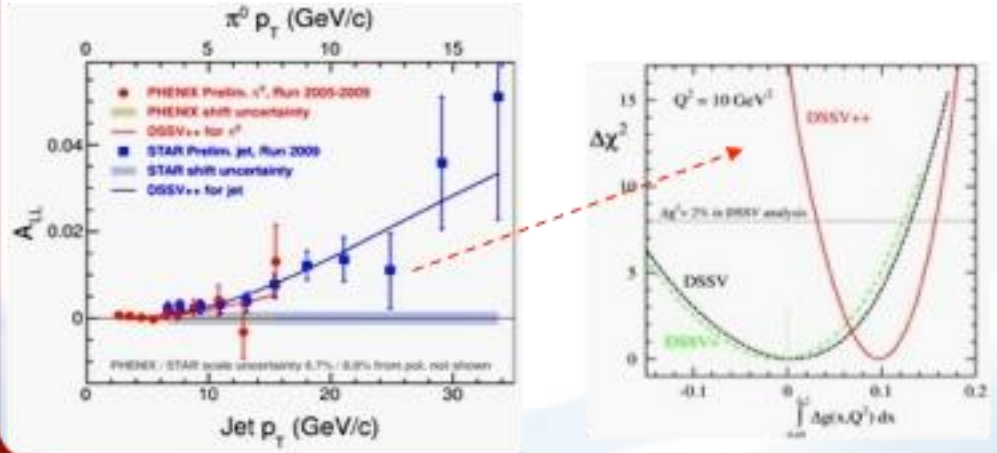
The spin of atoms resides in electrons and nuclei, not in the electric field. Is this different for protons?

Indications from Run-12 are that 20% of proton spin resides in the gluon field.

Run-13 will yield precision results on gluon and quark sea contributions.



$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\text{GeV}^2)\, dx = 0.10^{+0.06}_{-0.07}$$



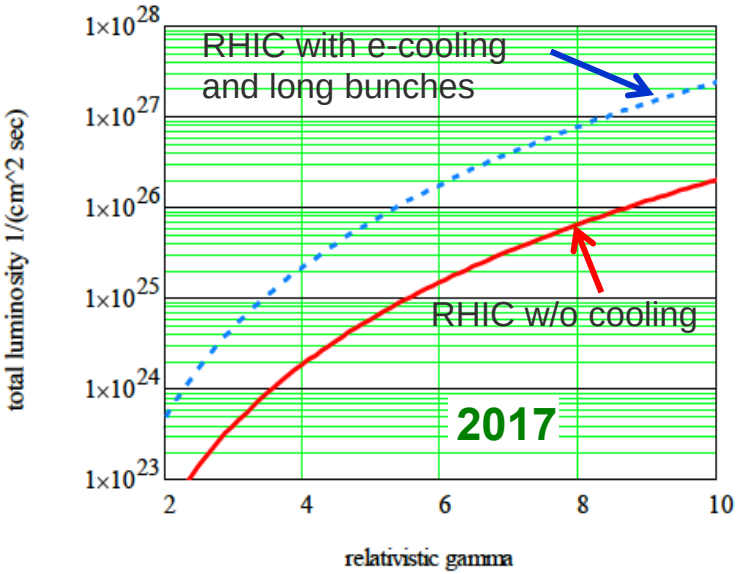
Precursor of the physics that can be done with much higher precision at an electron-ion collider (EIC) which will measure not just the total contribution of gluons to the spin, but provide complete images of the gluon distribution

Planned Upgrades

Machine upgrade:

Bunched beam electron cooling for low-E beams

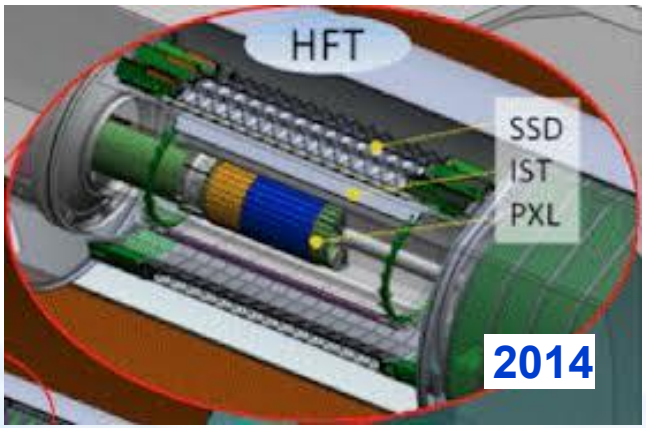
~10x luminosity



Detector upgrades:

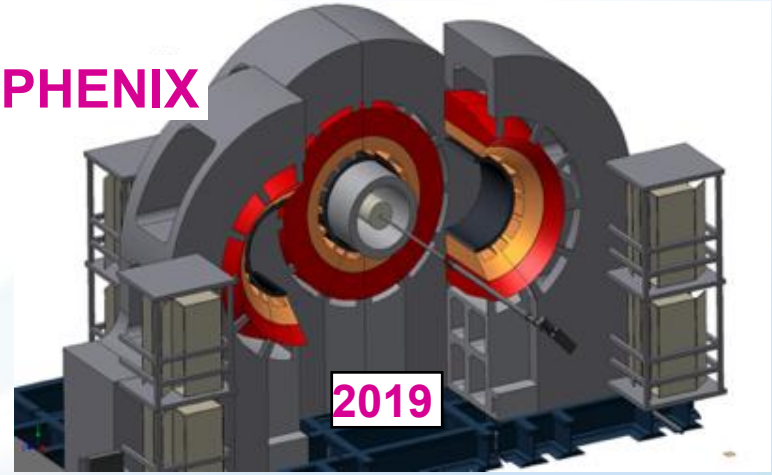
- **STAR HFT**
- **PHENIX MPC-EX**
- **STAR TPC pad rows**

- **sPHENIX: BaBar solenoid, EMCAL+HCAL for jet reconstruction @ RHIC**



STAR Heavy Flavor Tracker

sPHENIX

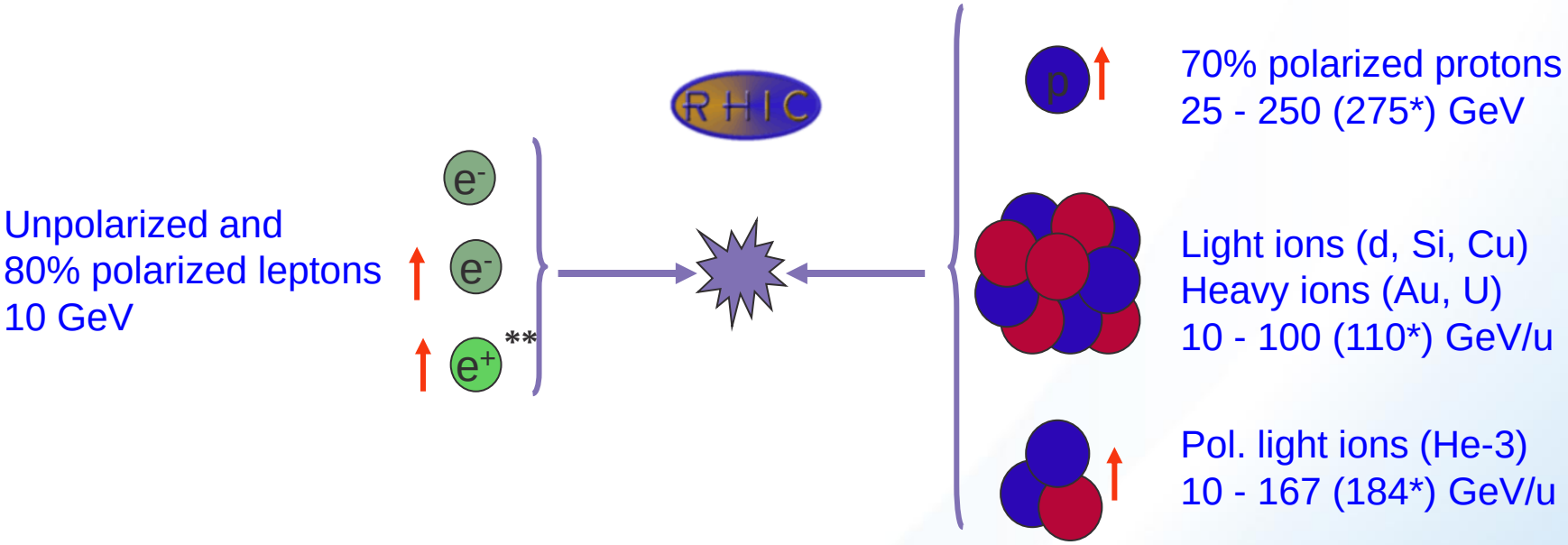


Run Schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

eRHIC: QCD Facility at BNL

Add an electron accelerator to the existing $2B RHIC, using existing RHIC tunnel, cryo facility, and detector halls.



Center-of-mass energy range: 30 - 100 GeV (ep)
Any polarization direction in lepton-hadron collisions

* It is possible to increase RHIC ring energy by 10%
** Positron-ion collider possible at lower luminosity with extra ring

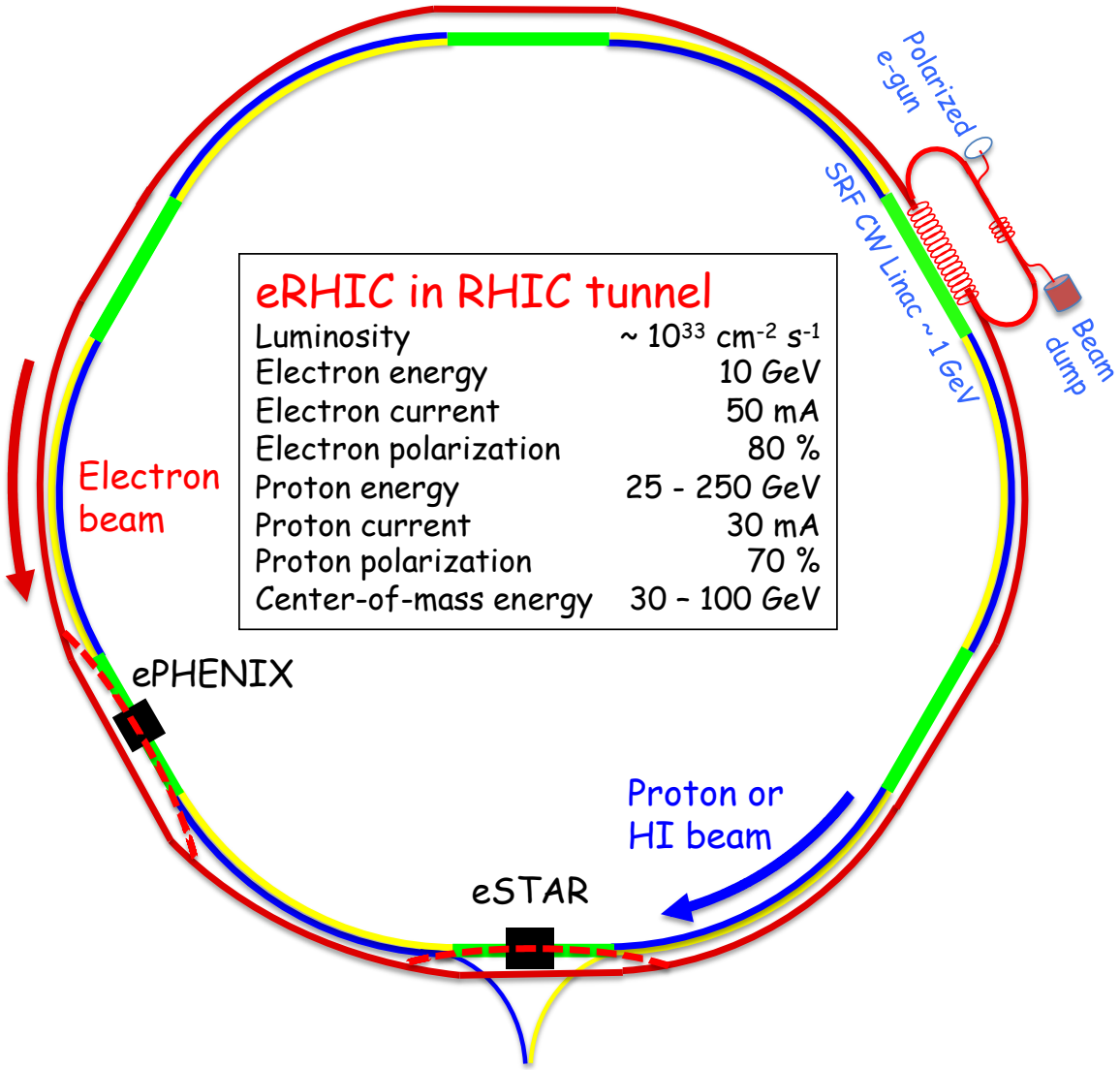
Goals

- Enable execution of a compelling subset of the EIC science program outlined in the EIC White Paper
- Create an affordable version of the EIC, i.e. cost in the range $500-600M.
- Reuse as much as possible of the $2B infrastructure in place at RHIC.
- Create a flexible QCD research facility serving a large user community.
- Create a facility that is upgradable to higher energy and luminosity.

Performance goals

- Highly polarized (> 70%) electron, proton and He-3 beams
- Ion beams from proton to the heaviest nuclei (uranium)
- Center of mass energy range: ~ 30 – 100 GeV
- Non-zero crossing angle to minimize synchrotron radiation background
- Possibility to have multiple interaction regions
- High luminosity: 10^{33} cm^{-2} s^{-1}
- Future upgrade to CM energy of ~150 GeV and luminosity of 10^{34} cm^{-2} s^{-1} possible

Basic eRHIC configuration



eRHIC in RHIC tunnel	
Luminosity	~ 10^{33} cm^{-2} s^{-1}
Electron energy	10 GeV
Electron current	50 mA
Electron polarization	80 %
Proton energy	25 - 250 GeV
Proton current	30 mA
Proton polarization	70 %
Center-of-mass energy	30 – 100 GeV

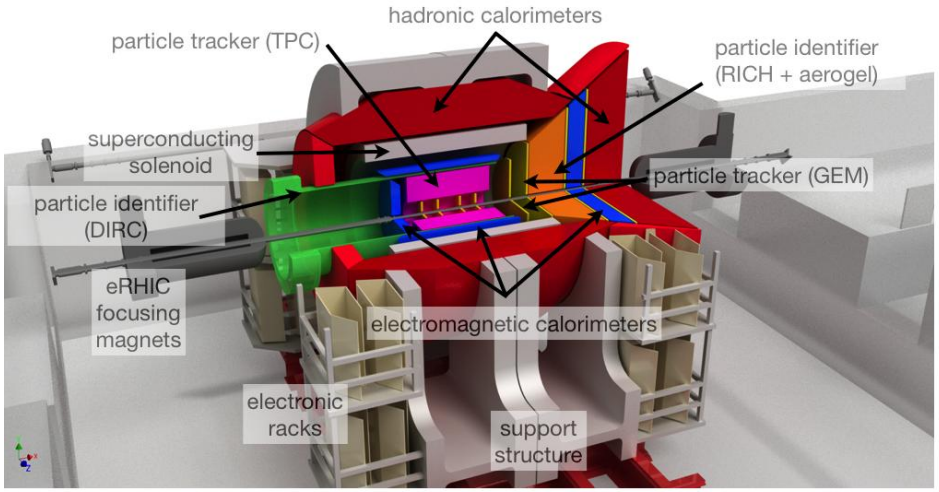
eRHIC Cost Optimization

- Bottom-up cost estimation for eRHIC first stage (5 GeV e-beam) has been done during 2012 (full TPC in FY12$ including ~ 33% average contingency, not including detector):
  - Cost optimization for layout with 4 local recirculation passes for low energy and 2 re-circulating passes in RHIC tunnel: ~ $550M TPC

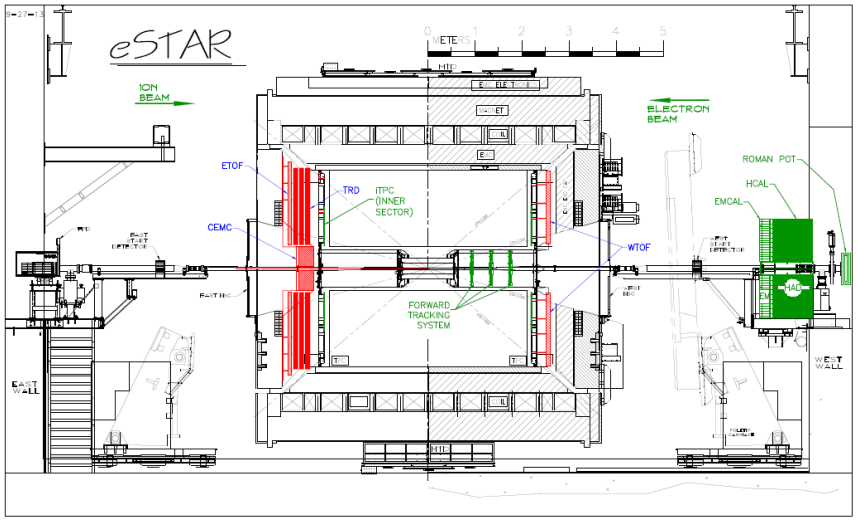
- Further value engineering is in progress, which could reduce the cost and/or increase performance:
  - FFAG design of recirculation passes (large momentum acceptance arcs), possibly with permanent magnets, could replace multiple passes with single pass.
  - Goal is to reach 10 GeV electron energy for similar cost.

eRHIC detectors

“ePHENIX”

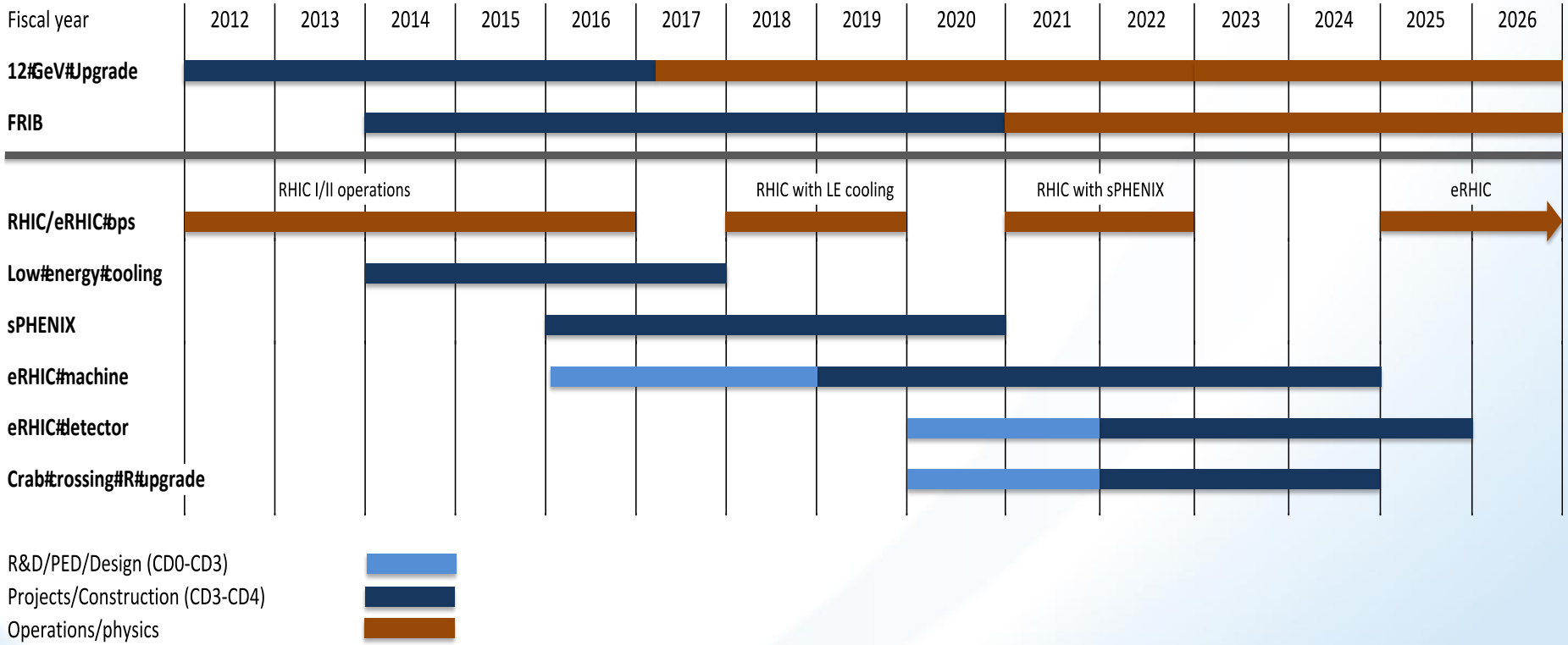


“eSTAR”



- Letters of Intent from both RHIC collaborations have produced benchmark designs with cost estimates.
- Invitation to develop similar LoI document for a “from scratch” EIC detector has been issued to the EIC Task Force @ BNL.
- eRHIC detectors will be designed and built by new collaborations!

Notional eRHIC schedule



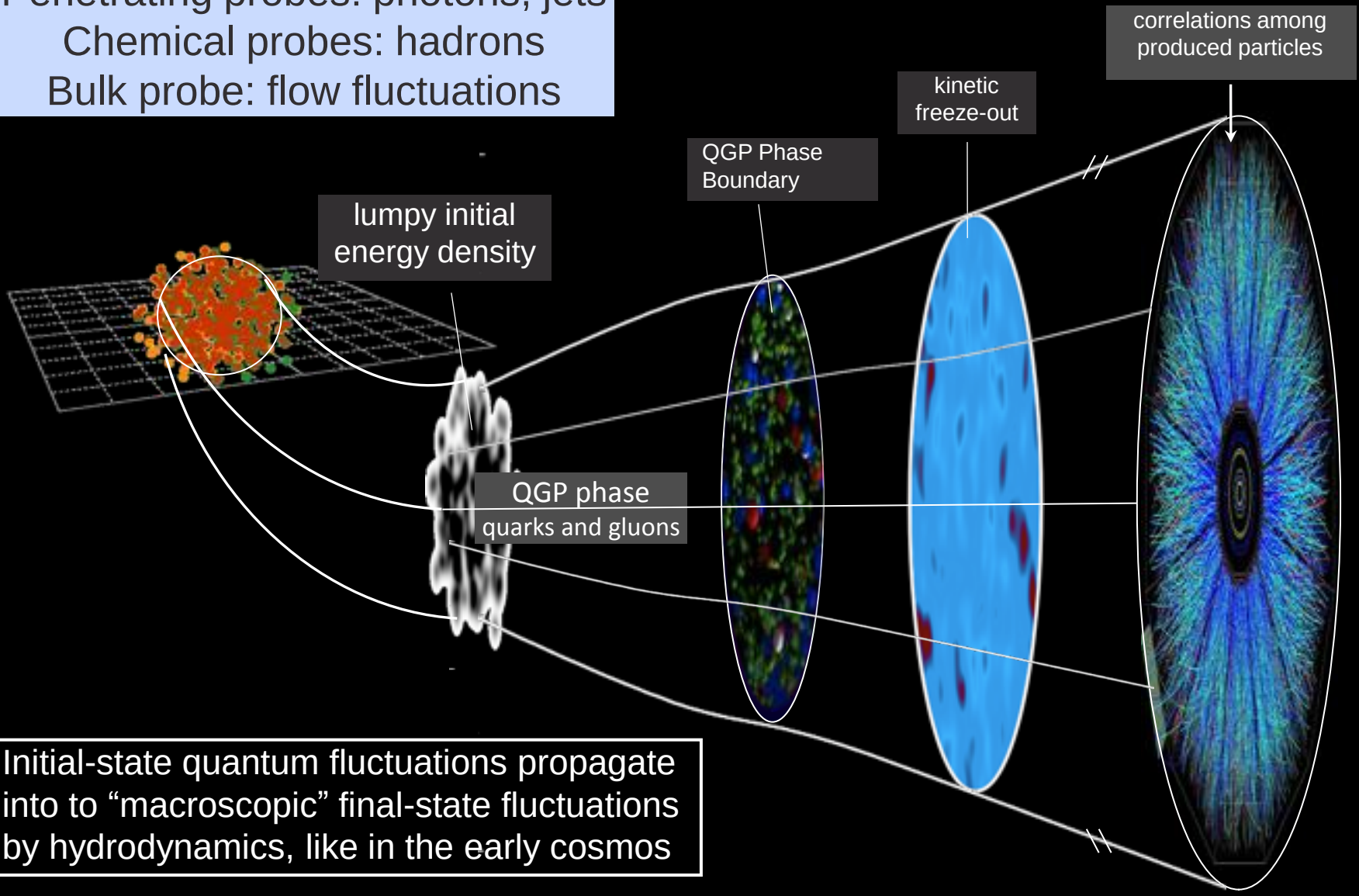
Summary

- ERL+ring design of eRHIC reaches high luminosity (initially 10^{33} cm^{-2} s^{-1} upgradable to 10^{34} cm^{-2} s^{-1}) over wide CM energy range
- Uses existing RHIC facility for heavy ion and polarized proton beam and existing RHIC tunnel and cryo-facility for e-beam.
- eRHIC (5 GeV e-beam with 10^{32} - 10^{33} cm^{-2} s^{-1} luminosity using existing technology) has preliminary cost estimate of ~ $550M
- R&D under way to achieve cost effective option of 10 GeV e-beam (FFAG arcs)
- LoI's from RHIC collaborations provide benchmarks for eRHIC detector design

Back-up Slides

RHIC Scientists' Tools

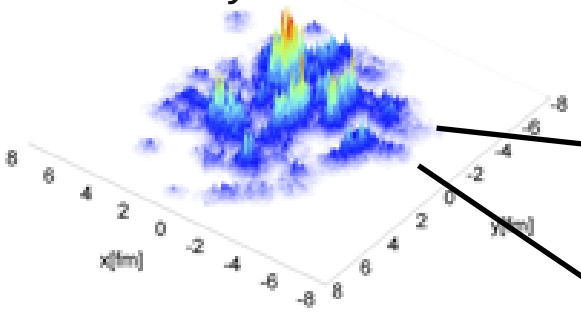
"Little Bang"
Penetrating probes: photons, jets
Chemical probes: hadrons
Bulk probe: flow fluctuations

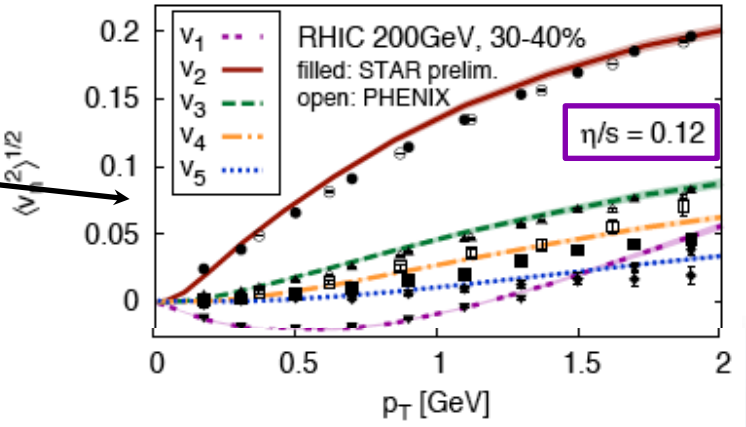


Initial-state quantum fluctuations propagate into to "macroscopic" final-state fluctuations by hydrodynamics, like in the early cosmos

QCD Matter at RHIC is most "perfect"

Initial density distribution

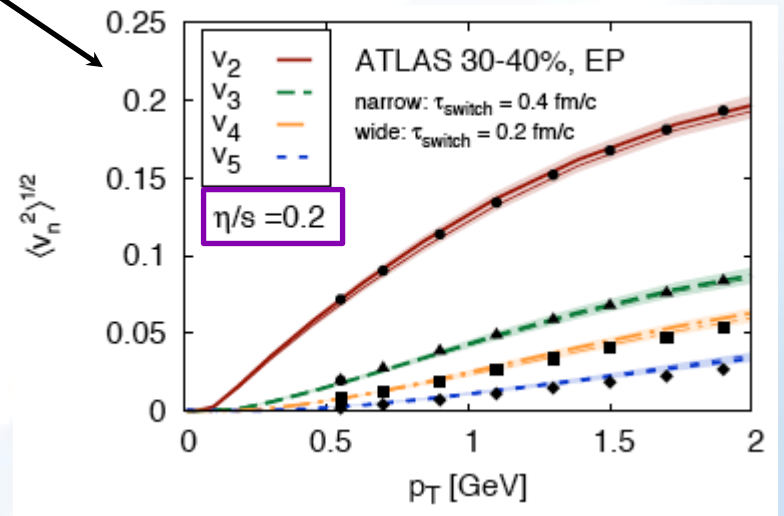




RHIC

Quantum limit: $\eta/s = 0.08$.

$(\eta/s)_{RHIC} \approx 0.6\ (\eta/s)_{LHC}$



LHC

A study of the opacity of the matter to energetic quarks (jets) confirms this conclusion:

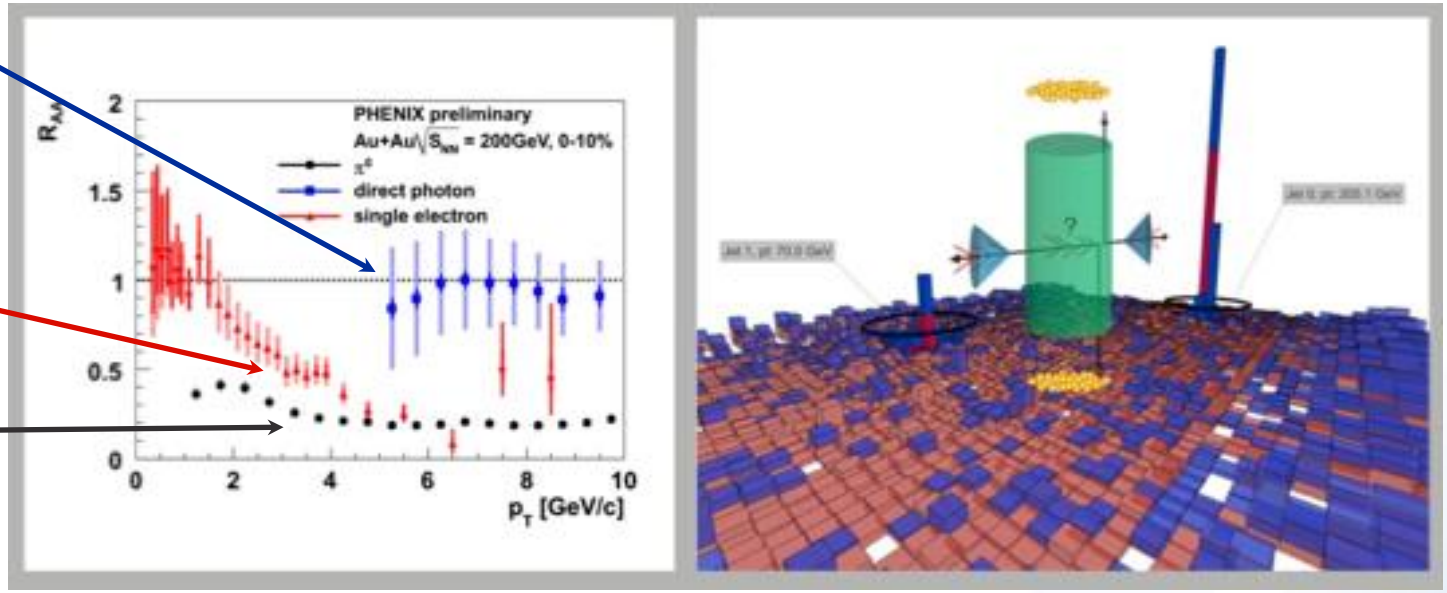
QCD matter at RHIC is less transparent by the same factor 0.6.

Jet quenching = parton energy loss

Photons don't lose energy

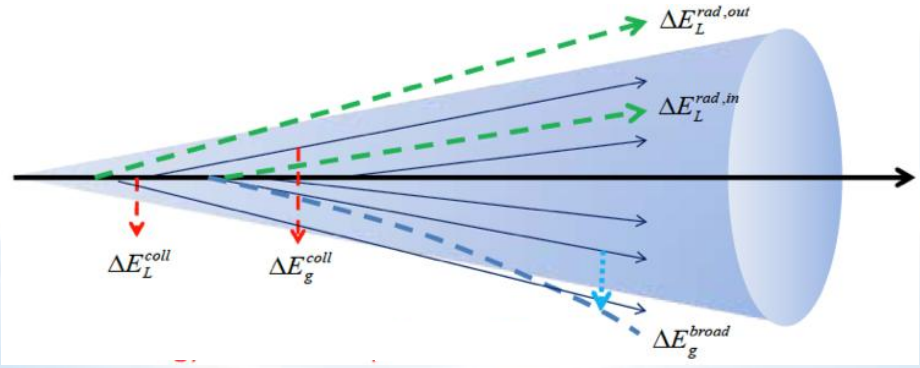
Heavy quarks

Light quarks



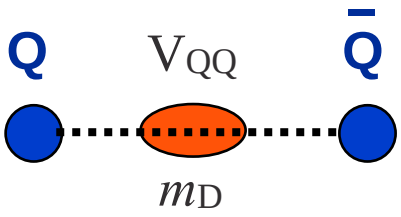
Jet quenching @ RHIC

Jet quenching @ LHC

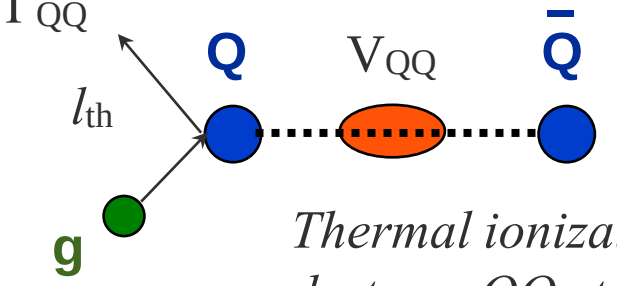


Energy is lost by the leading parton in interactions with the hot matter, scattered out of the jet cone and absorbed

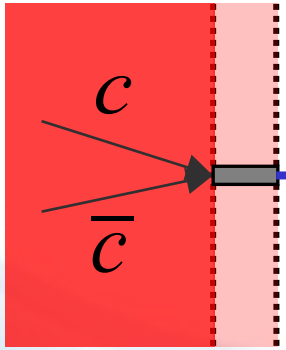
J/ψ suppression



Color screening causes "melting"

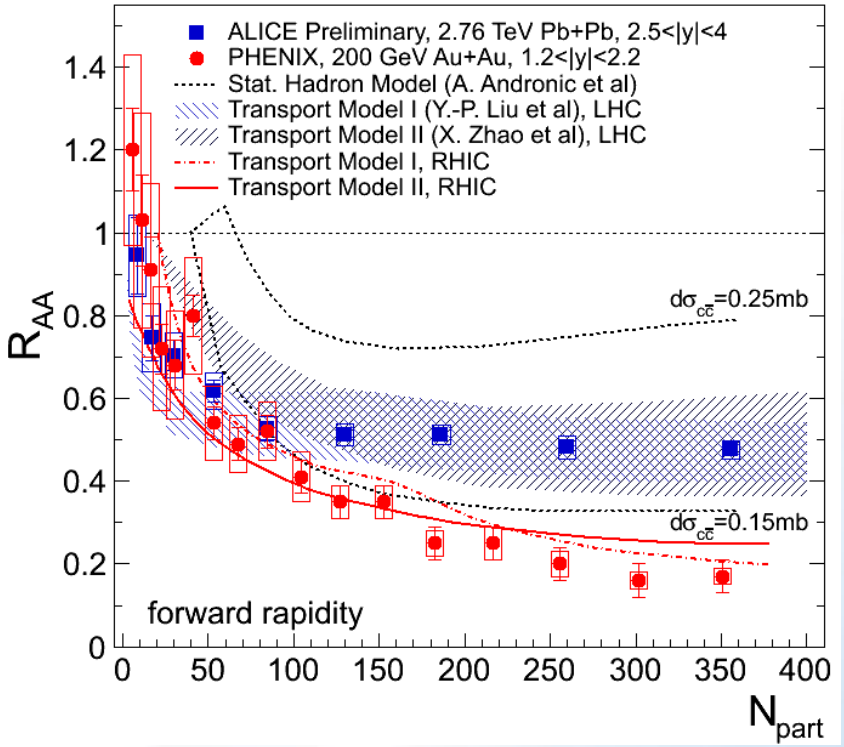


Thermal ionization destroys QQ states



Recombination at hadronization

J/Ψ



Less J/ψ suppression at LHC than at RHIC, at mid-rapidity and mid-forward rapidities:
c-cbar recombination explains data.

Main design elements

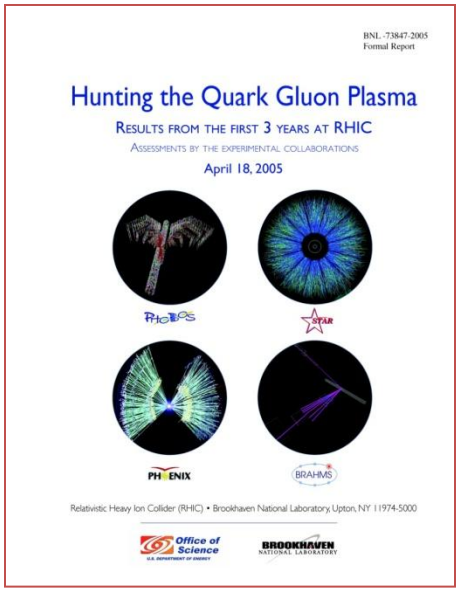
- Single collision pass for electrons allows for large collision disruption of electron bunches, giving high luminosity and full electron polarization transparency
- Small electron beam size allows for small magnets with gaps of 8 mm (and 13 mm at the two lowest energy orbits)
- Linac-ring collider uniquely allows energy change of colliding hadrons from 25 GeV to 250 GeV
- Using recent advances in super-conducting quadrupole technology allows design IR with $\beta^* = 5$ cm
- Crab-crossing with large crossing angle following success at KEK-B
- Need 50 mA of polarized electron beam current for high luminosity
- Strong cooling of hadron beam (÷10 emittance) in both longitudinal and transverse directions using coherent electron cooling
- Up to 3 detector regions

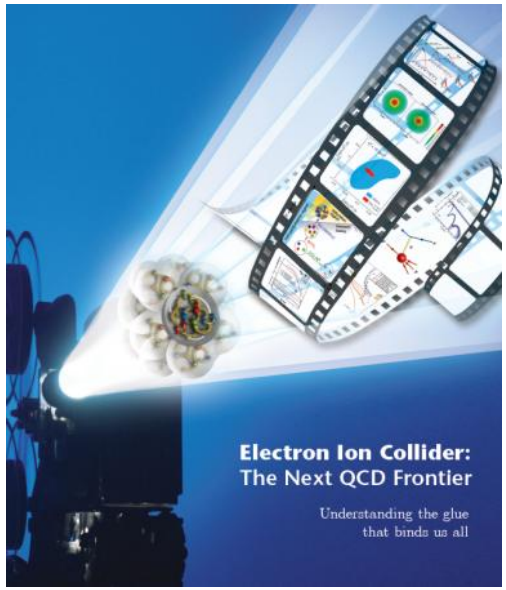
Evolving Detectors for RHIC and eRHIC

T. Ludlam

RBRC Scientific Review

November 1, 2013



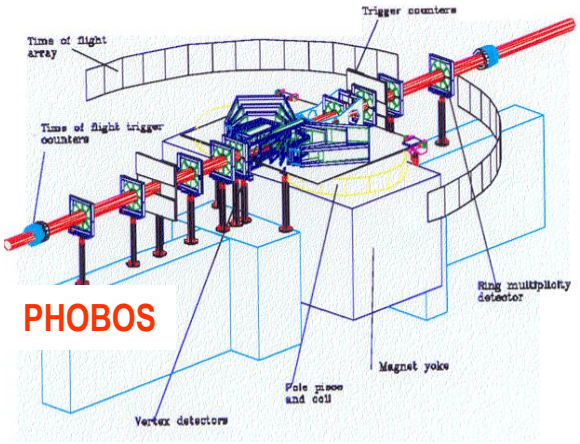


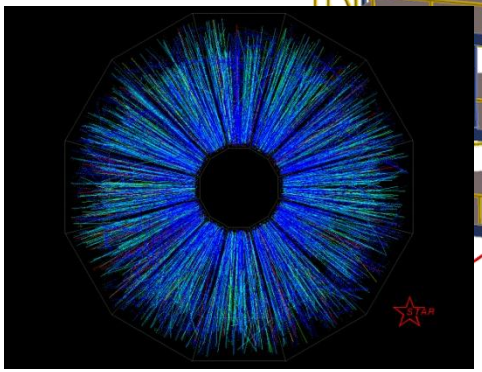
Office of Science
U.S. DEPARTMENT OF ENERGY

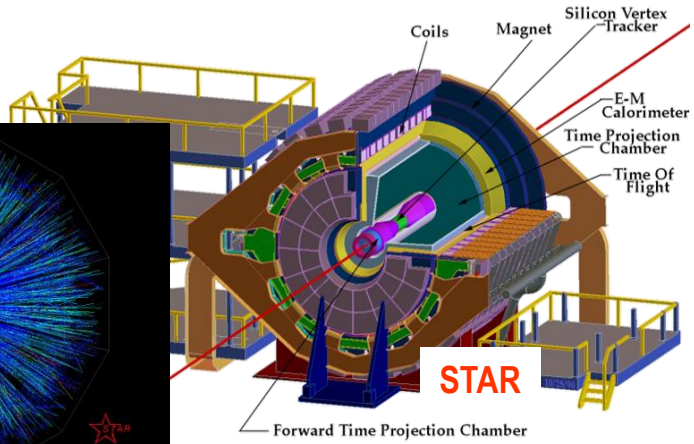
BROOKHAVEN NATIONAL LABORATORY

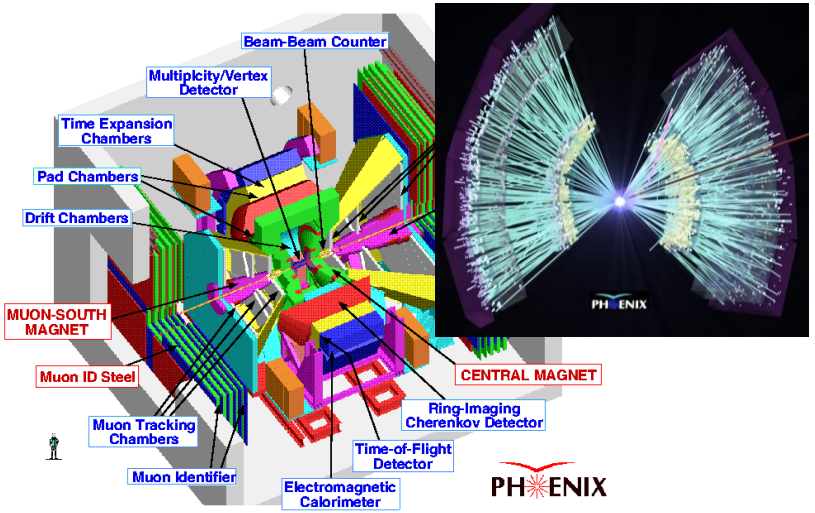
In the Beginning: First operation in 2000

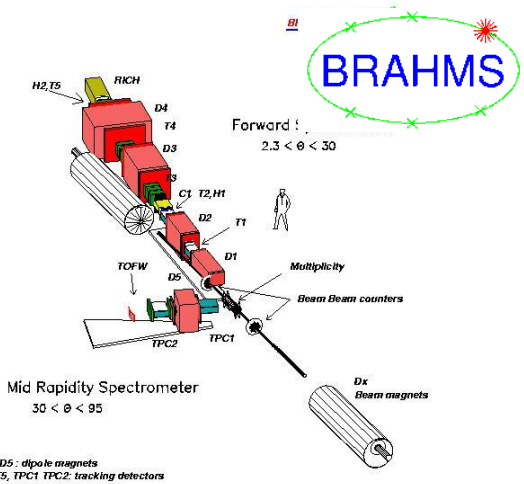
RHIC experiments focused on global features in the central region, with c. 1990 technology





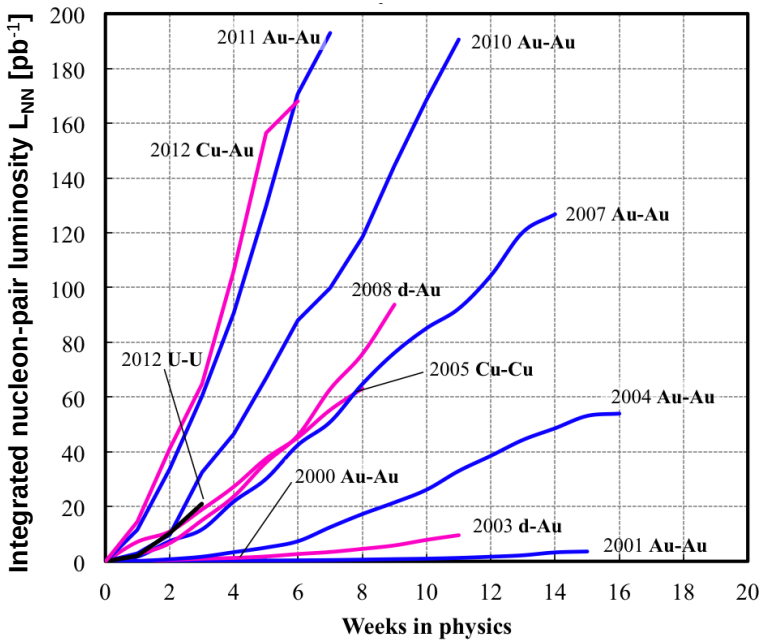






Discoveries Drive Continuous Improvement of Machine and Detectors

Evolution of Luminosity Delivered by RHIC



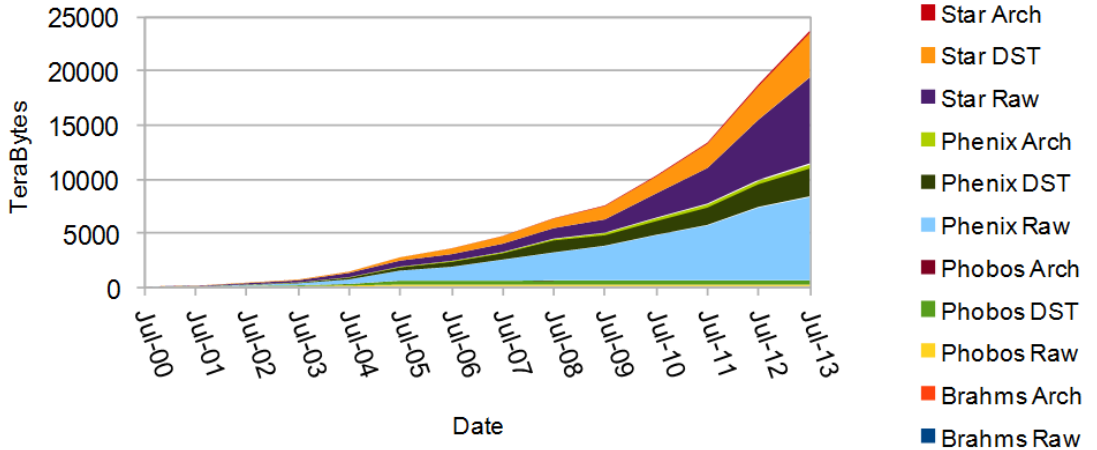
New Physics Probes:

- Heavy Flavor
- W± production
- Jet reconstruction
- Multiparticle correlations
- Precision spin measurement

Expanded Detector Requirements:

- Enhanced rate capability
- Intelligent front-end trigger capability
- Larger phase space coverage
- Charged and neutral particle ID
- Precision vertex tracking

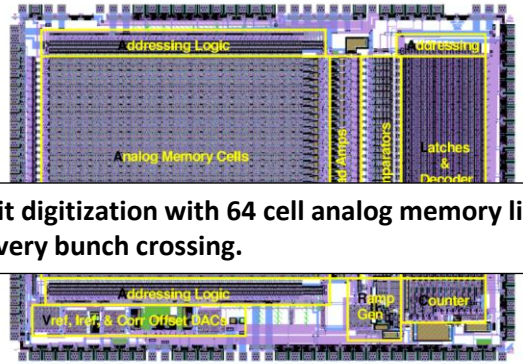
Evolution of Data Volume archived on Tape



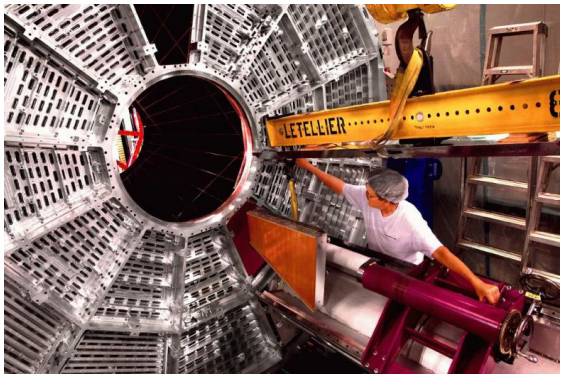
Evolving Technology Makes RHIC Physics Possible

Electronics and Computing:

PHENIX was among the pioneers in using custom integrated circuits (ASICs) for readout and trigger with high channel-count detectors.
Initial PHENIX construction had 8 ASIC applications.



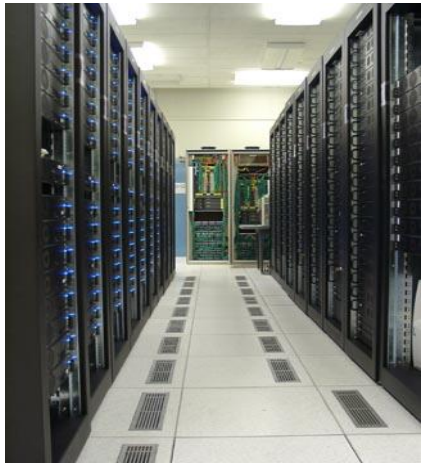
12-bit digitization with 64 cell analog memory live on every bunch crossing.



STAR 2009 TPC electronics upgrade: DAQ1000 (135,000 channels)
Utilized ASIC chips developed at CERN for ALICE for signal processing, digitizing, event buffering.

Increased event rate limit from few Hz to 1 KHz with 1% dead time. Transformed STAR to a high-rate detector for physics in the era of RHIC-II luminosity.

RHIC Computing Facility: Scalable architecture based on arrays of commodity components keeps pace with Moore's law through annual "refresh" of equipment at modest cost. CPU and storage capacity have kept pace with increasing data volume.

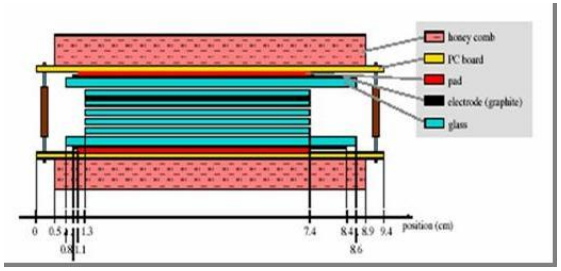


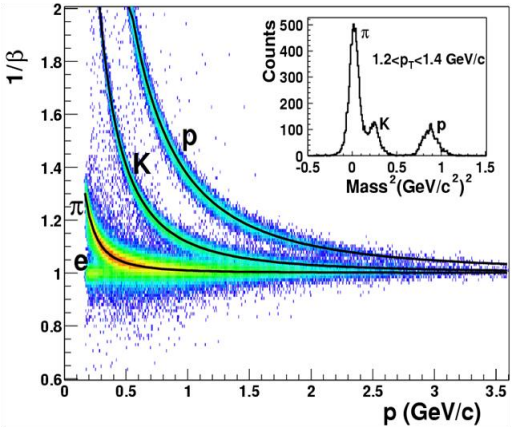
New Detector Technologies Increase the Physics Reach

STAR MRPC Time-of-Flight:

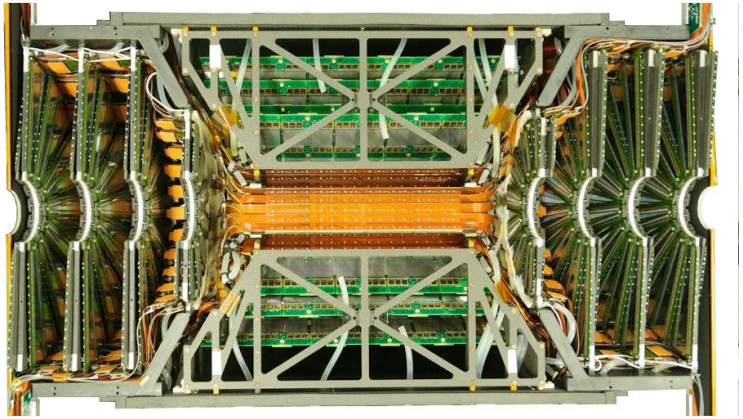
A breakthrough that has allowed fine-grain tiling of the full TPC barrel with 23,000 channels of TOF readout and timing resolution of 80 ps.

Multi-gap Resistive Plate Chamber



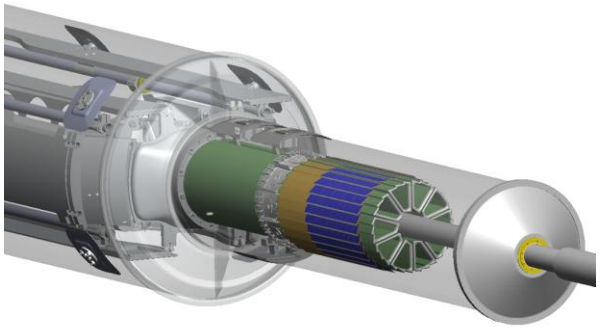


Precision Silicon Vertex Tracking



PHENIX Barrel and Forward Si Trackers

Barrel: 4×10^6 pixels, 50 x 425 μm^2; 4×10^5 strips
Forward: 5.3×10^5 mini-strips in each of 2 arms



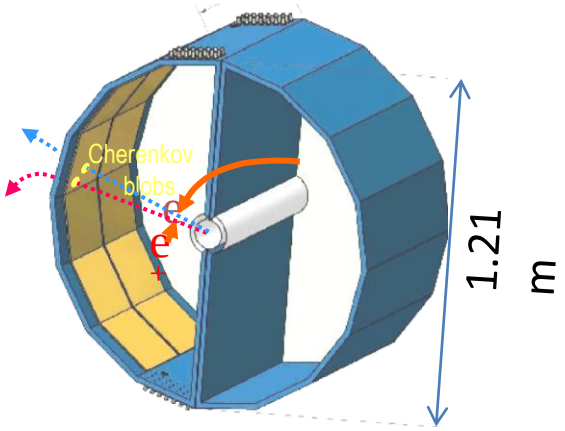
STAR Heavy Flavor Tracker

Innermost Pixel Layers use 400 Monolithic Active Pixel Sensors (MAPS): 3.6×10^8 pixels, 20.7 μm/pixel

First large-scale use of MAPS technology

Compact Micro-Pattern Detectors: Present at RHIC… Promise for eRHIC

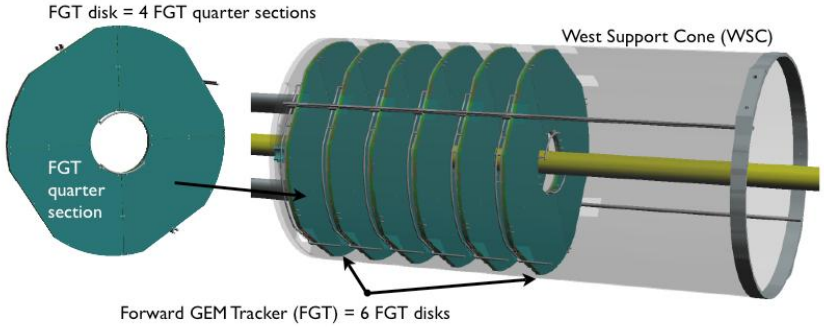
GEM-Based Detectors



PHENIX Hadron Blind Detector

Windowless, proximity focused Cherenkov detector.
Triple GEM readout planes with CsI photocathode.

Data taken in Run 10. Removed to make way for Si Trackers.



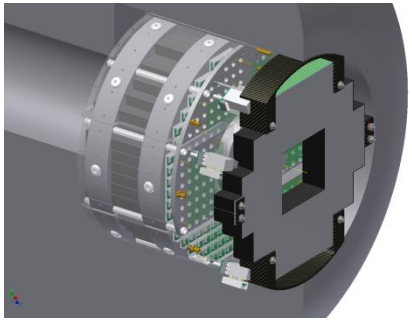
STAR Forward GEM Tracker

Six disks of triple-GEM detectors with pad readout.
Particle tracking inside TPC inner radius.

Compact Calorimetry

PHENIX MPC-EX: Si-W preshower detector

4.6 X_0 Deep; 1.8x15 mm^2 minipads
Distinguish π^0/γ to 80 GeV



Post-2006 Detector Upgrades: STAR

Costs shown are U.S. DOE funds

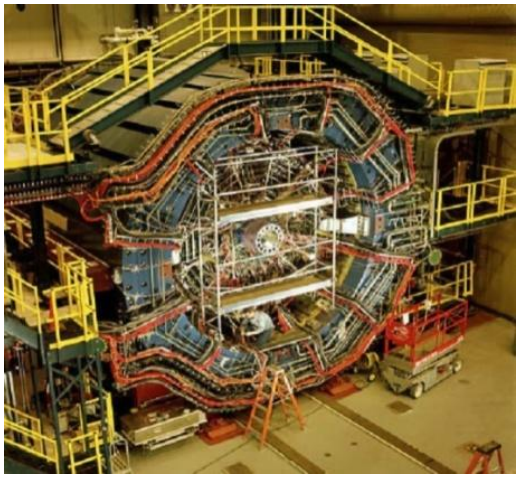
	First Physics Operations
Time of Flight (TOF) $4.8M U.S./China collaboration	2010
DAQ 1000 $1.8M	2009
Forward Meson Spectr. (FMS) $0.8M	2008
Forward Gem Tracker (FGT) $2M	2013
Muon Telescope Det. (MTD) $1.7M U.S./China collaboration	2014
Heavy Flavor Tracker (HFT) $16.4M	2014

Complete; Operating for physics

Partially installed; Engineering runs

Completing construction

These upgrades have brought STAR from a low-rate tracking detector as originally designed to a high-rate detector with large-solid-angle capability for strange, charm and bottom particle detection, as well as forward-angle detection of hadrons and $W^{\pm}$ decays, at full RHIC-II luminosity.



Post-2006 Detector Upgrades: PHENIX

Costs shown are U.S. funds

	First Physics Operations
Hadron Blind Detector $1.2M	2010
Si Vertex Tracker (VTX) $4.7M U.S./Japan collaboration	2011
Forward Vertex Tracker (FVTX) $4.9M	2012
Muon Trigger $4.3M U.S. (NSF)/Japan collaboration	2012
MPC-EX $0.9M	2015

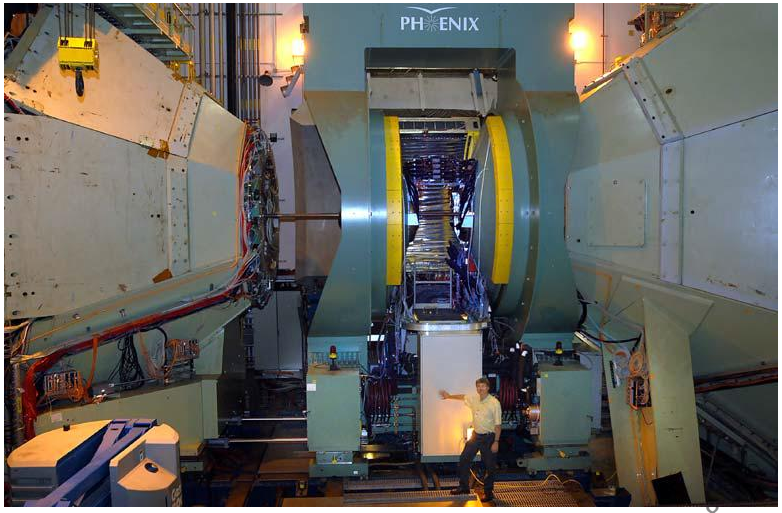
Physics run complete

Complete; Operating for physics

Under construction

These upgrades give PHENIX :

- **A unique look at background-suppressed low-mass e-pairs.**
- **The capability to exploit RHIC-II luminosities with the measurement of identified heavy flavor production in HI collisions, flavor-identified sea-quark contribution to the proton spin via $W^{\pm}$ decay in 500 GeV p-p collisions, and identified forward photons in p-p and d/p-Au collisions.**



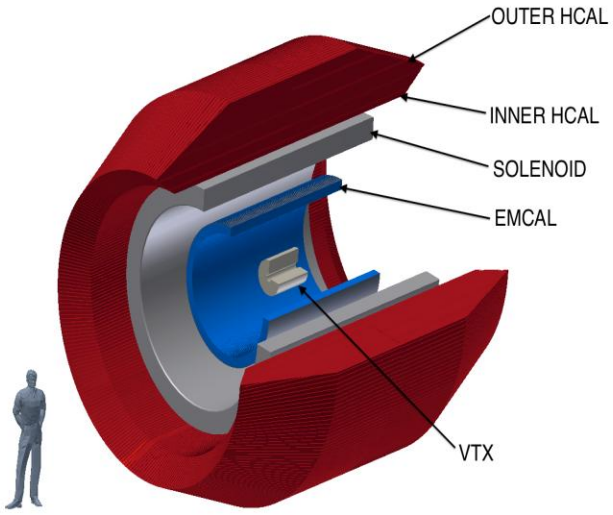
Future PHENIX: sPHENIX

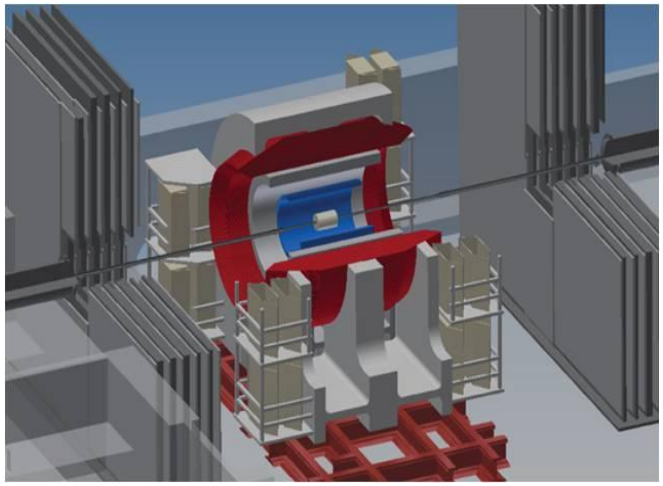
Convert the central region of PHENIX to an open geometry detector with a 1.5 T superconducting solenoid and large acceptance EM and hadronic calorimetry.



Definitive QGP measurements with jet and heavy quark (Upsilon)observables at RHIC-II luminosity.

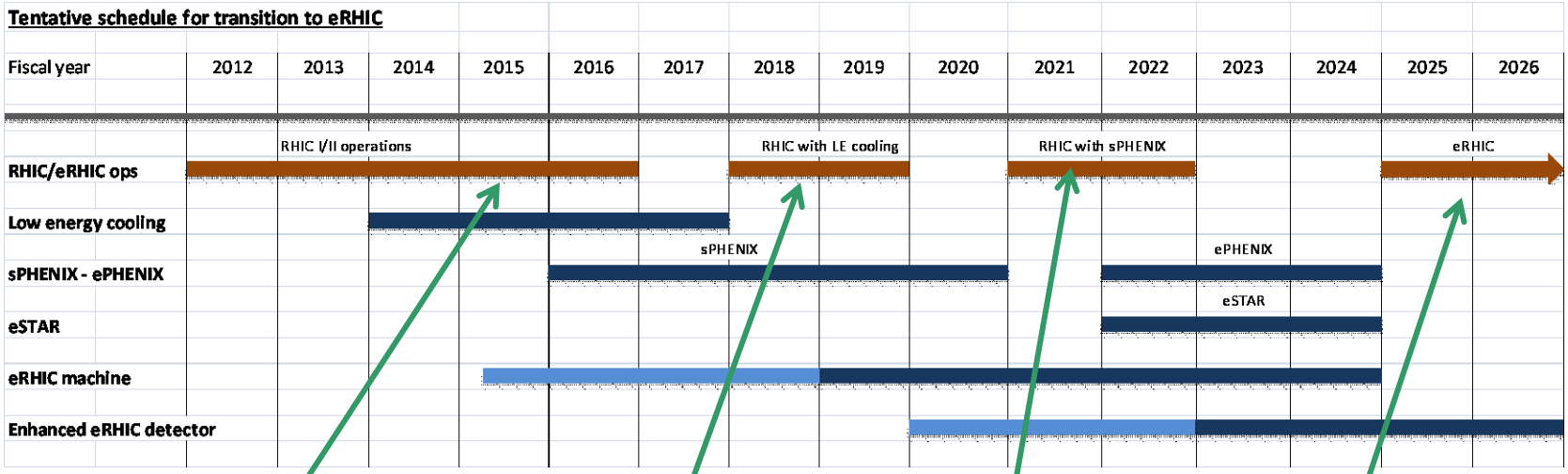
An excellent basis for an eRHIC detector.





sPHENIX is a proposed $34M project, to become operational in 2021.
Additional tracking and a pre-shower detector, essential for Upsilon measurements, is being pursued through proposals to Japanese funding agencies.

Concept for a transition from RHIC to eRHIC



QGP and transverse spin studies with current upgrades: Heavy Flavor probes.

Beam Energy Scan with e-cooling of low energy ion beams.

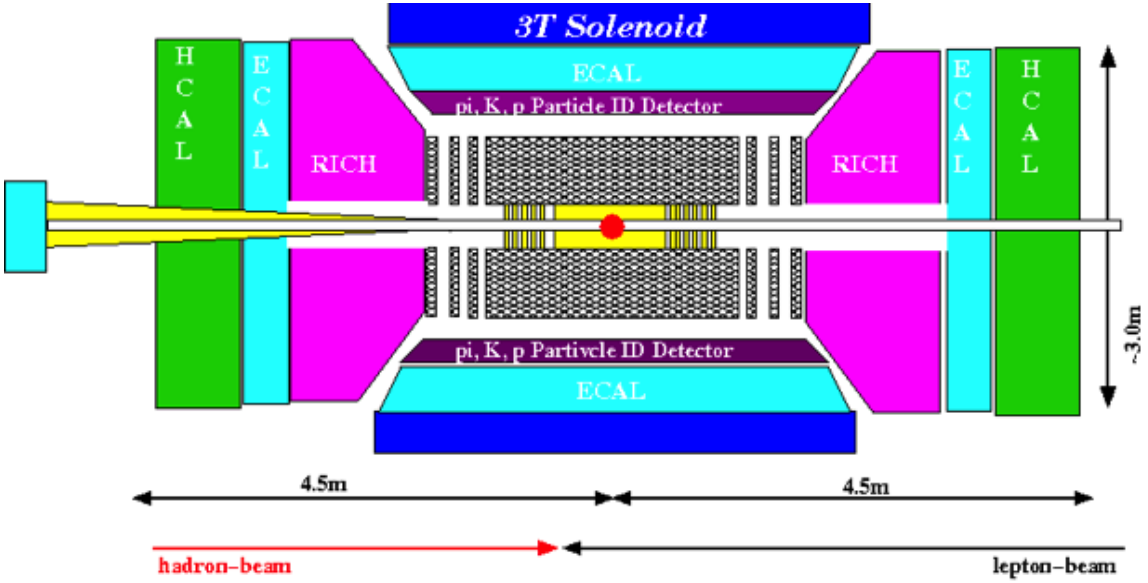
Jet probes of parton transport and energy loss; quarkonia probes of color screening

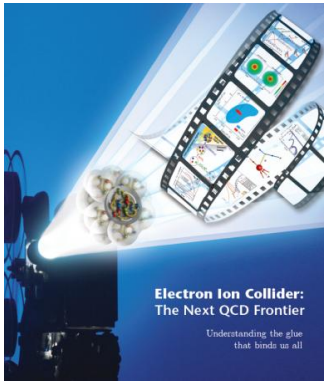
First eRHIC experiments

Shut-down years for RHIC operations will allow substantial resources to be re-directed to eRHIC construction.

Planning for eRHIC Experiments

Conceptual Detector Layout: from EIC White Paper



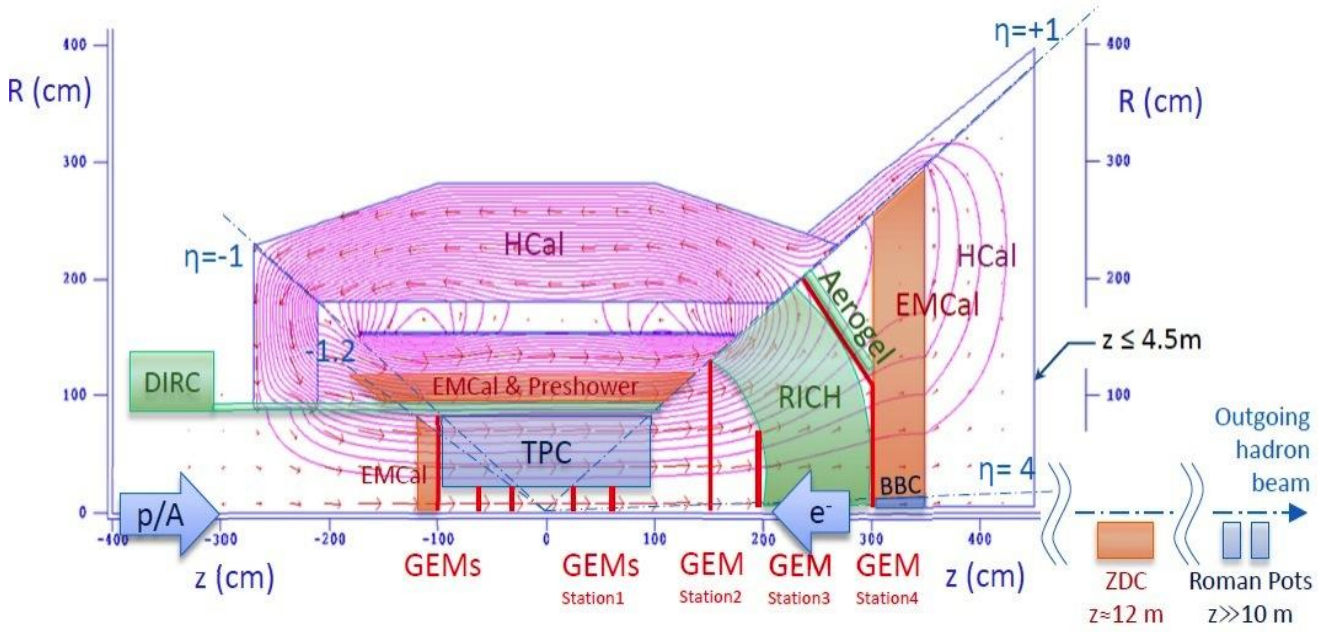


Requirements for specific "Golden Measurements":

- High acceptance: $-5 < \eta < 5$ central detector
- Good PID (π, K, p, and lepton) and vertex resolution
- Tracking: compact TPC, Si devices, GEM
- Low material density: minimize mult. scattering, bremsstrahlung
- Very forward electron and proton/neutron detection: Roman pots, ZDC

Letters of Intent: ePHENIX and eSTAR
Upgrading RHIC detectors for eRHIC Physics

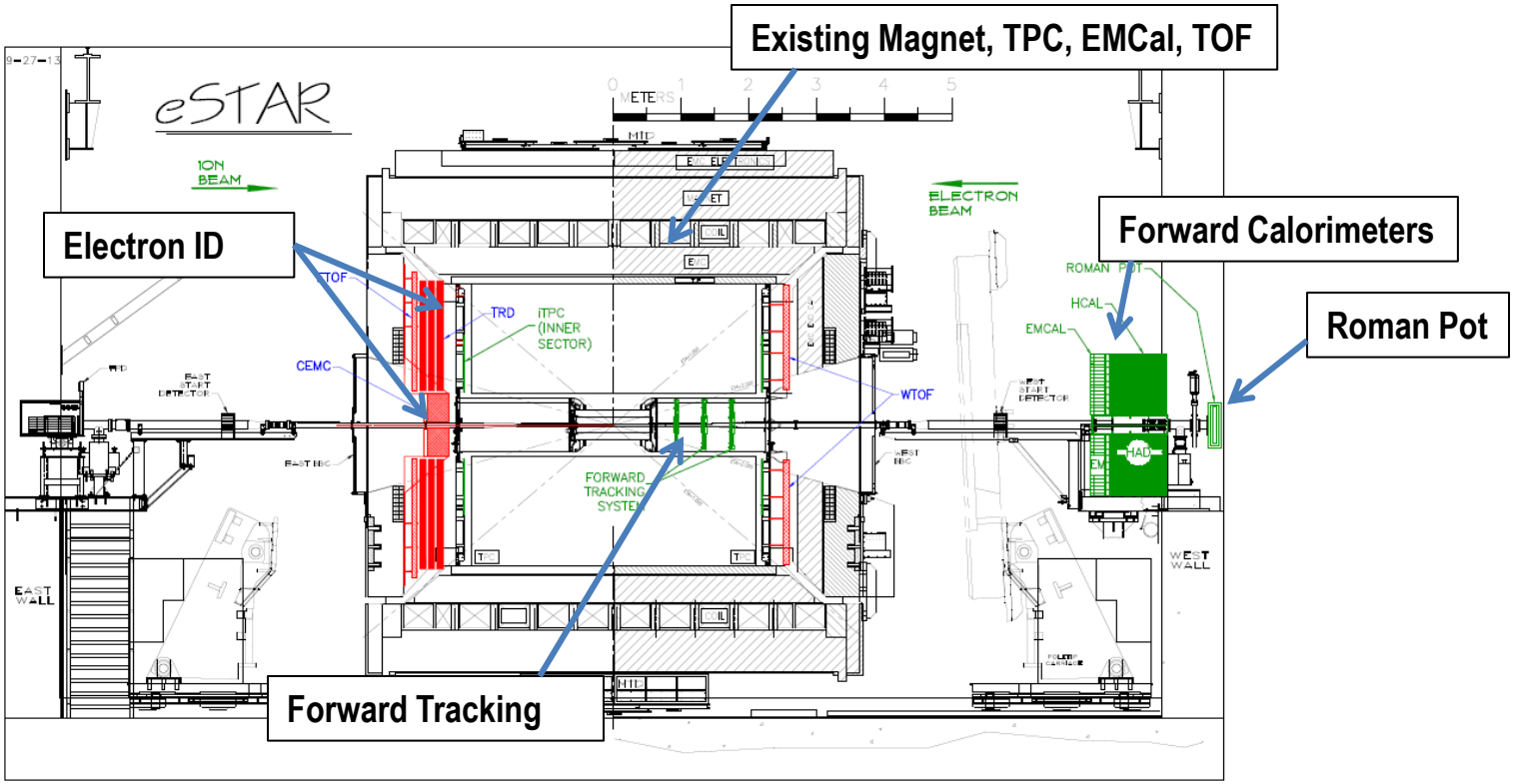
Concerted effort by the existing collaborations to address the scientific opportunities and the technical and demographic implications of transition to eRHIC.



Cross section through the top half of the ePHENIX detector concept, based on sPHENIX.

Note: The beam crossing rate for eRHIC is the same as for RHIC, allowing for continued use of existing readout electronics.

eSTAR Detector Concept



- The ePHENIX and eSTAR Letters of Intent indicate a healthy level of engagement of the RHIC community.
- A successful transition from RHIC to eRHIC needs the engagement and participation of the larger NP QCD community. eRHIC detectors will be designed and built by new collaborations.
- The actual implementation of an experimental program will depend on funding, and will be carried out through a proposal driven process.

Summary

- The scientific productivity of the RHIC program is driven by continuous upgrades of the detectors, as well as the machine.

- The international RHIC community has been in the forefront of detector development and is preparing for the coming decade with state-of-the-art instrumentation.

- The RHIC community is becoming deeply engaged in the eRHIC effort.

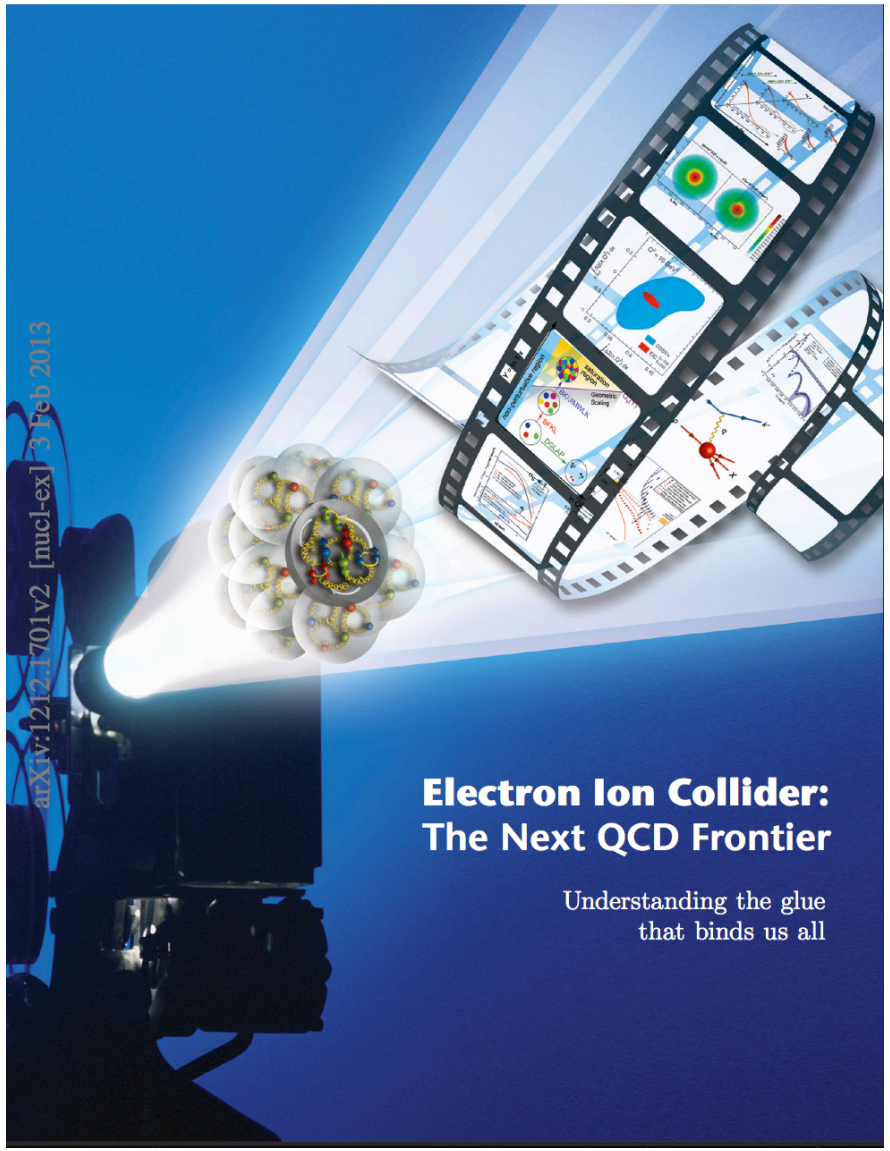
- International partnerships have been and will continue to be key to the success of the experimental program.

Why EIC is Interesting

Yuri Kovchegov
The Ohio State University

Electron-Ion Collider (EIC) White Paper

- EIC WP was finished in late 2012
- A several-year effort by a 19-member committee + 58 co-authors
- arXiv:1212.1701 [nucl-ex]
- EIC can be realized as eRHIC (BNL) or as ELIC (JLab)



EIC Physics Topics

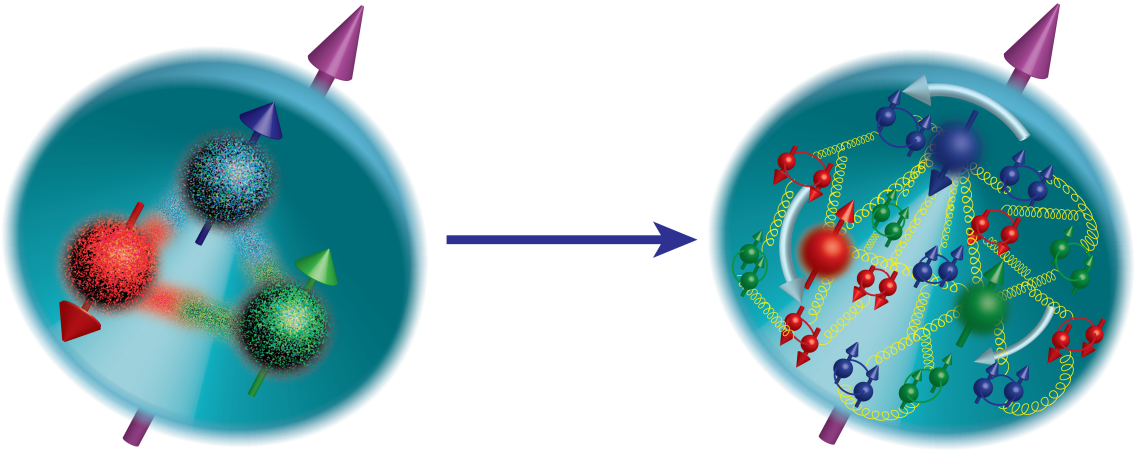
- Spin and Nucleon Structure
  - Spin of a nucleon
  - Transverse momentum distributions (TMDs)
  - Spatial imaging of quarks and gluons
- QCD Physics in a Nucleus
  - High gluon densities and saturation
  - Quarks and Gluons in the Nucleus
  - Connections to p+A, A+A, and cosmic ray physics

Big Questions

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- Where does the saturation of gluon densities set it?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Spin and Nucleon Structure

Proton Spin



Our understanding of nucleon spin structure has evolved:

- In the 1980's the proton spin was thought of as a sum of constituent quark spins (left panel)

- Currently we believe that the proton spin is a sum of the spins of valence and sea quarks and of gluons, along with the orbital angular momenta of quarks and gluons (right panel)

Proton Spin Puzzle

- Helicity sum rule: $$\frac{1}{2} = S_q + L_q + S_g + L_g$$

  with the net quark and gluon spin

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\,\Delta\Sigma(x,Q^2) \qquad S_g(Q^2) = \int_0^1 dx\,\Delta G(x,Q^2)$$

- The helicity parton distributions are

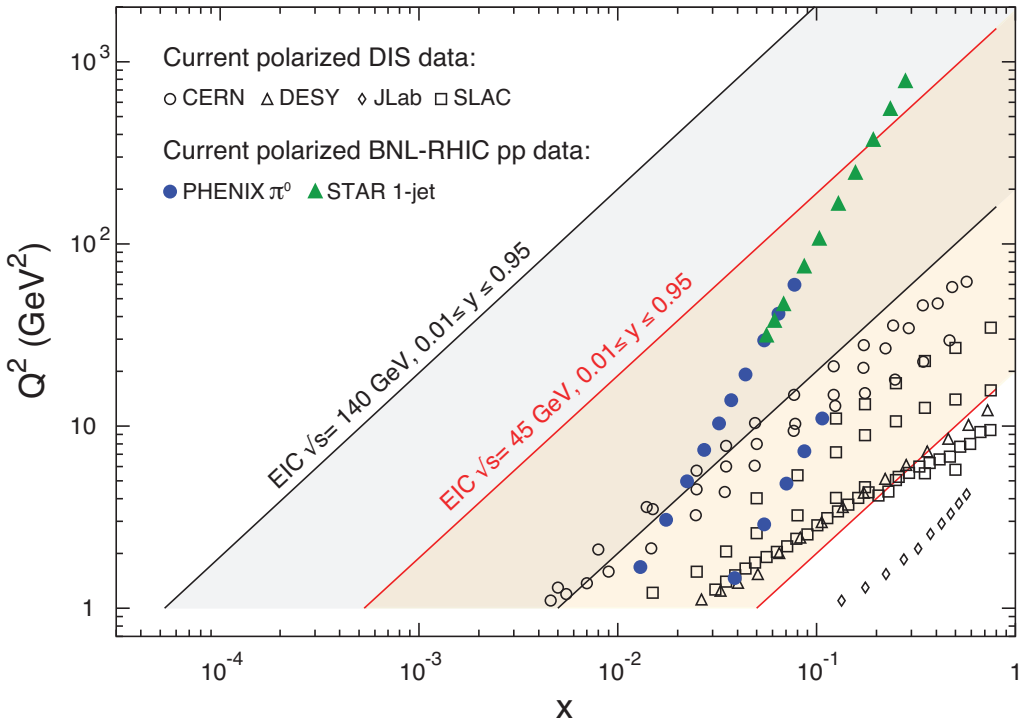
$$\Delta f(x,Q^2) \equiv f^+(x,Q^2) - f^-(x,Q^2)$$

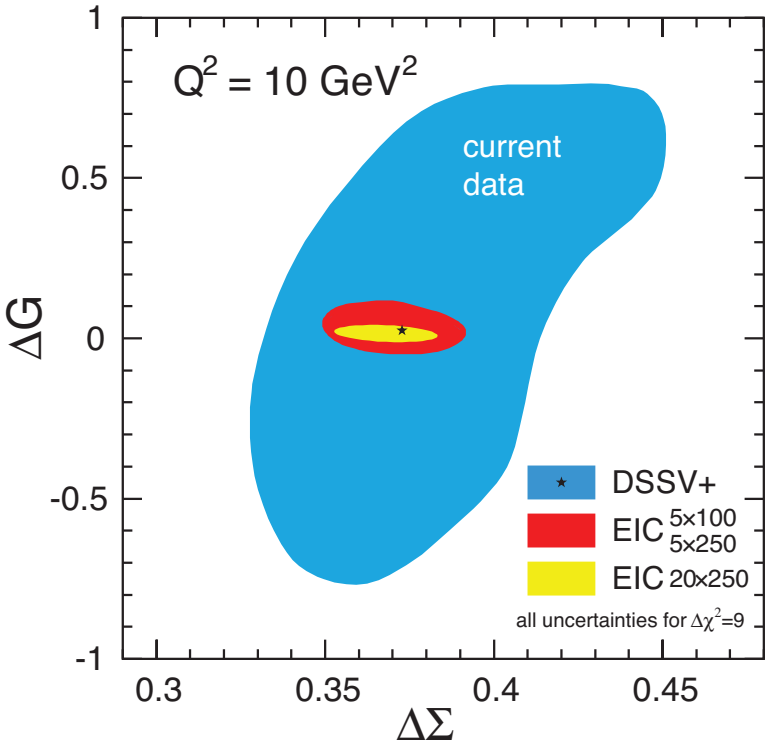
  with the net quark helicity distribution

$$\Delta\Sigma \equiv \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

EIC & Spin Puzzle

- Parton helicity distributions are sensitive to low-x physics.
- EIC would have an unprecedented low-x reach for a spin DIS experiment, allowing to pinpoint the values of quark and gluon contributions to proton's spin:

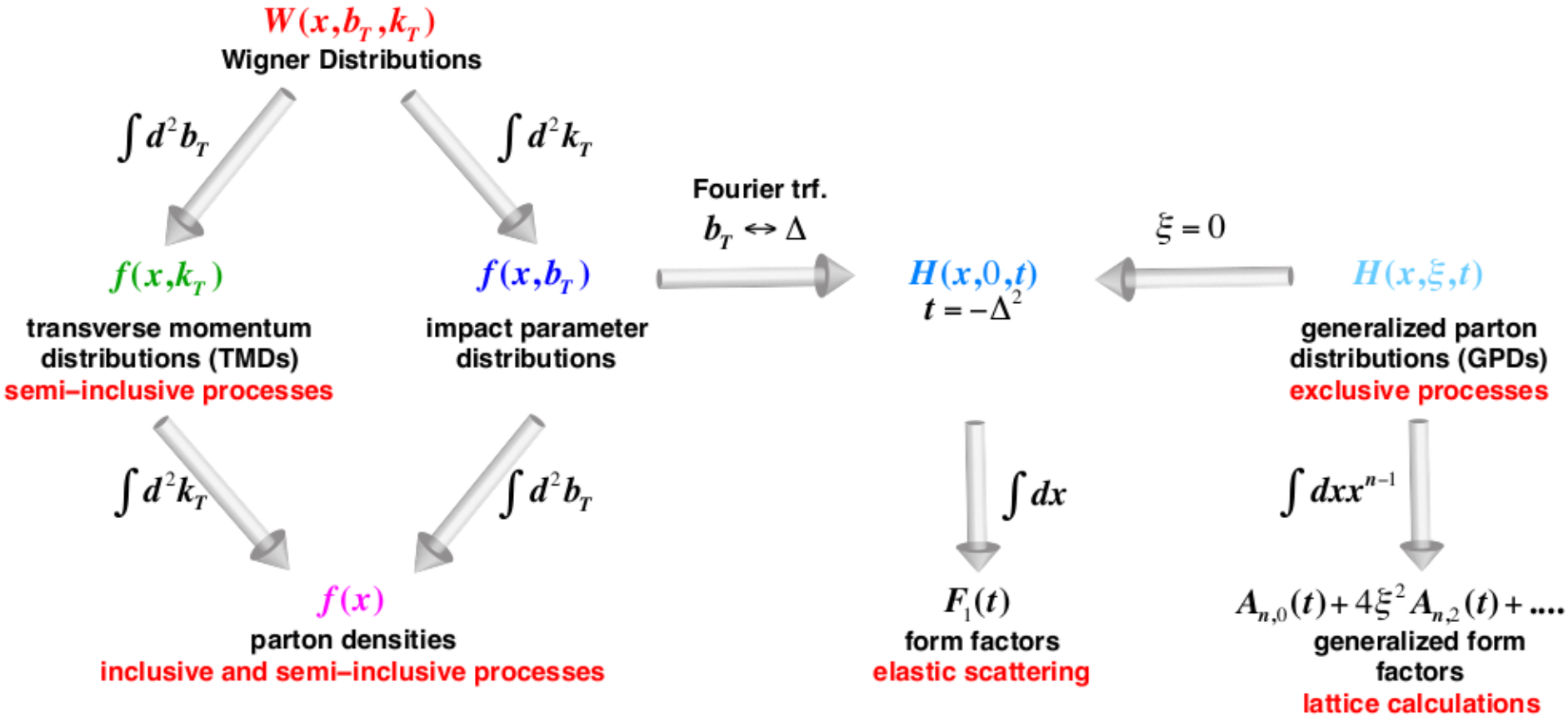




- ΔG and ΔΣ are integrated over x in the 0.001 < x < 1 interval.

Transverse Momentum Distributions (TMDs)

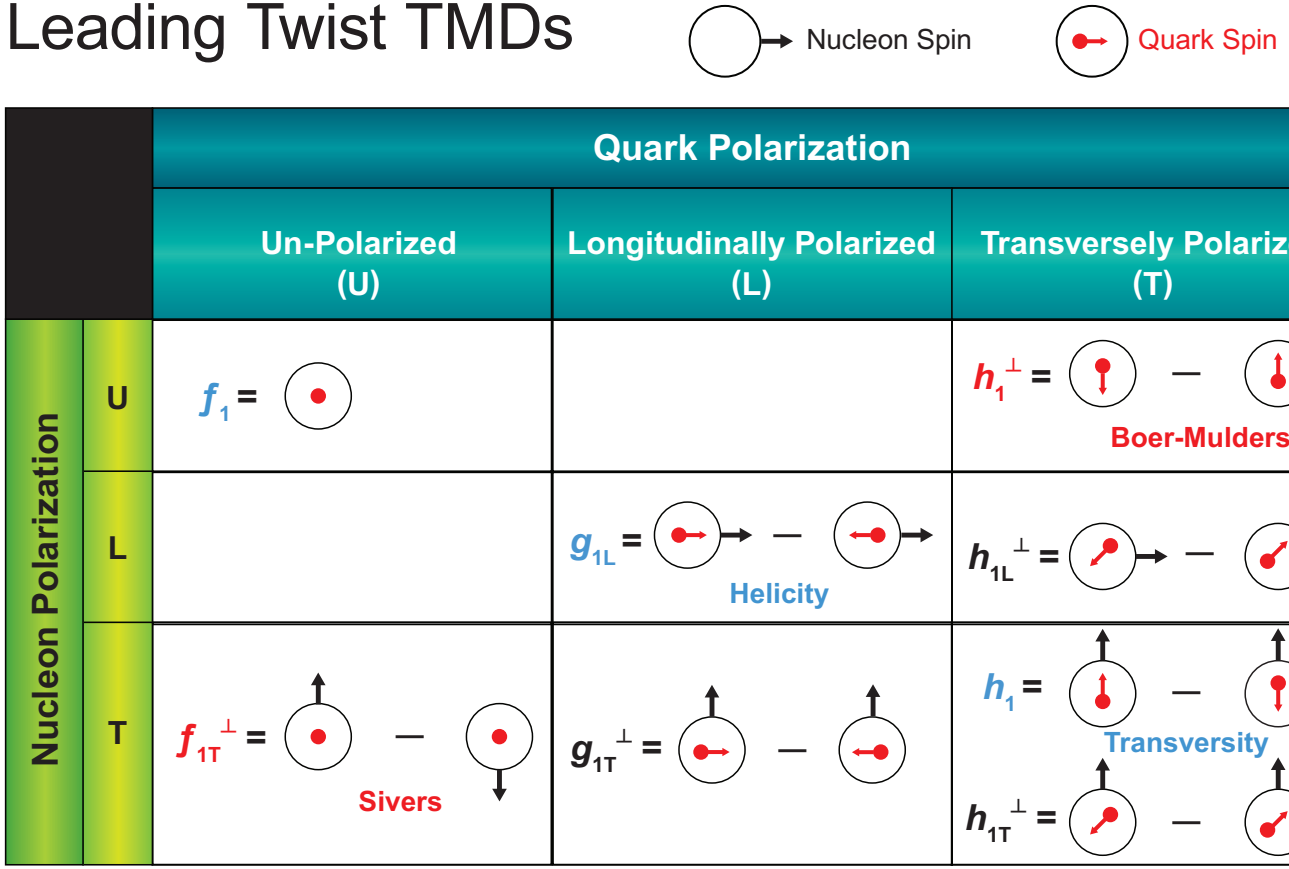
- PDFs are insufficient to study the proton structure. Ideally one would like to know the transverse momentum and position distribution of the quarks and gluons in the proton. The tool of choice is the (quark or gluon) Wigner distribution along with associated distribution functions:



TMDs at EIC

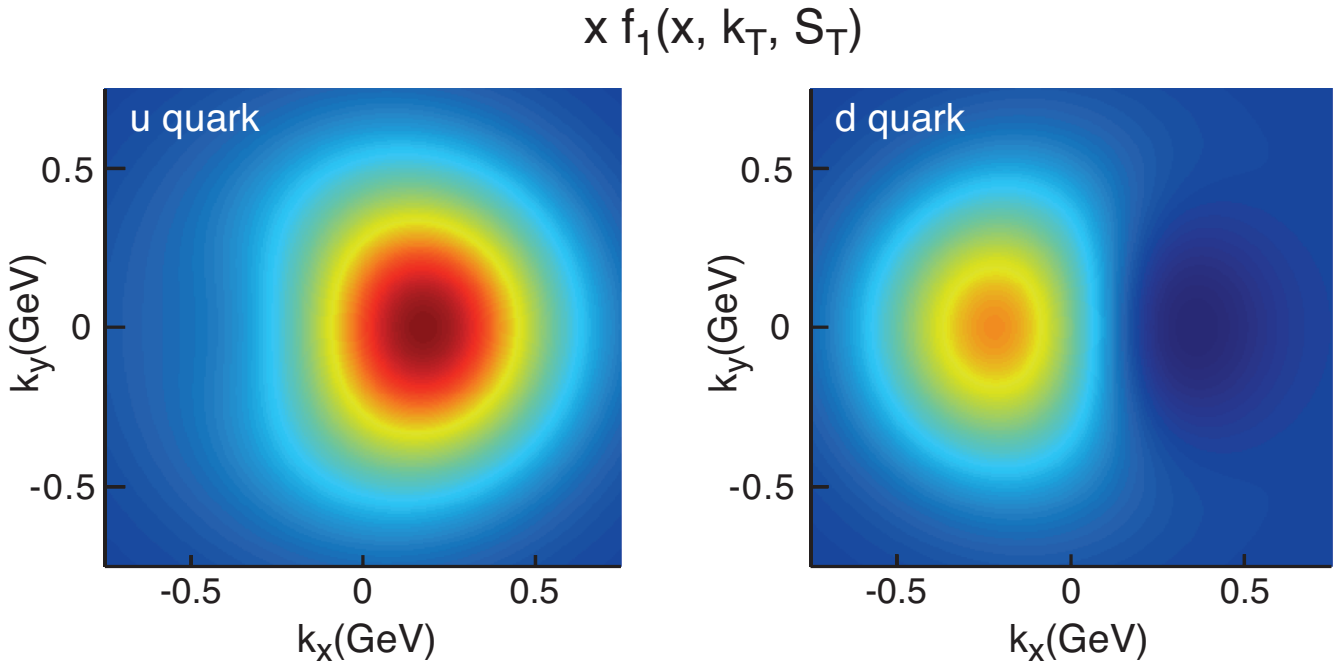
- EIC would allow to measure gluon and anti-quark TMDs for the first time ever, giving an unprecedented insight into proton structure.
- By studying TMDs at EIC we could better understand the proton's 3D structure, orbital motion of the partons, and spin-orbit correlations.

Leading Twist TMDs



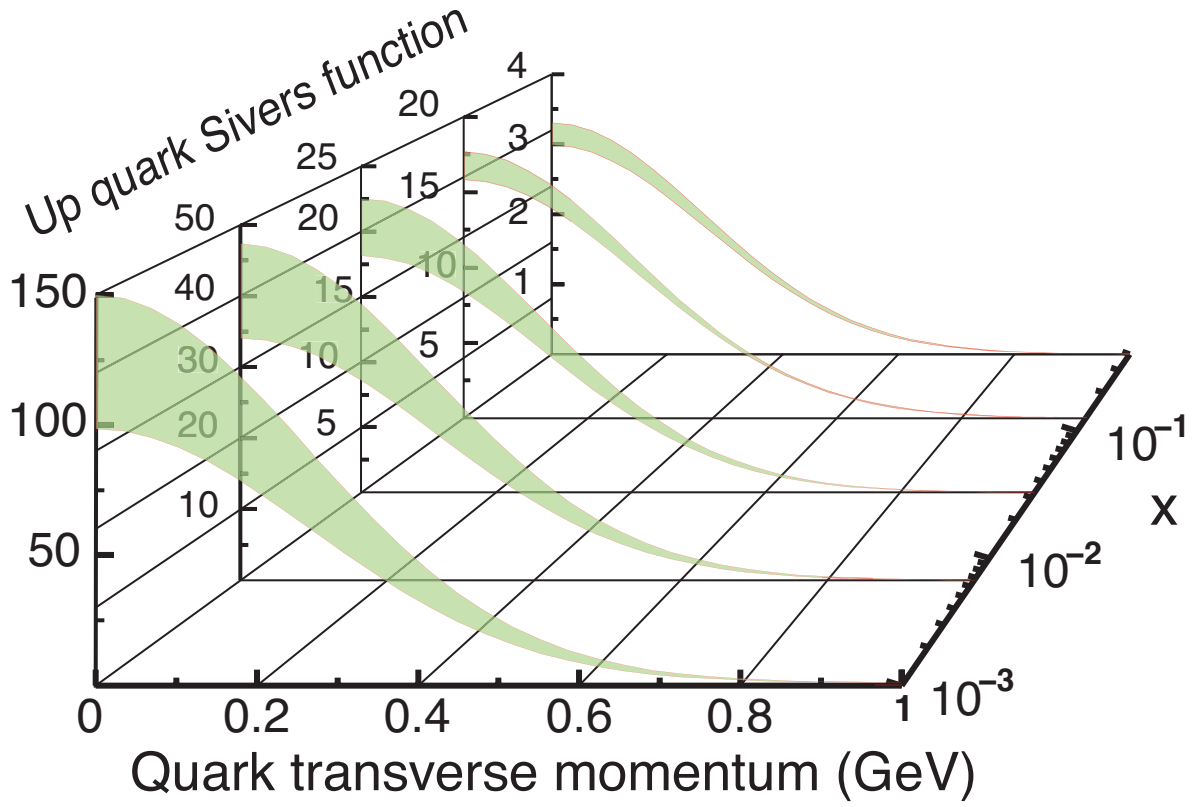
TMD measurements at EIC

- TMD measurement could give us the transverse momentum distribution of partons, as shown below for u- and d-quark TMDs in a transversely polarized proton (along the y-axis):



TMD measurements at EIC

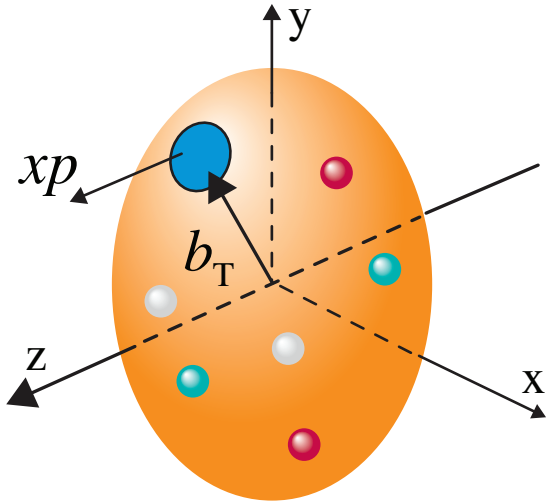
- Another TMD, known as the Sivers function (responsible for the single transverse spin asymmetry), can also be measured down to very low-x:



Spatial Imaging of Quarks and Gluons

- Spatial imaging is complimentary to TMDs.

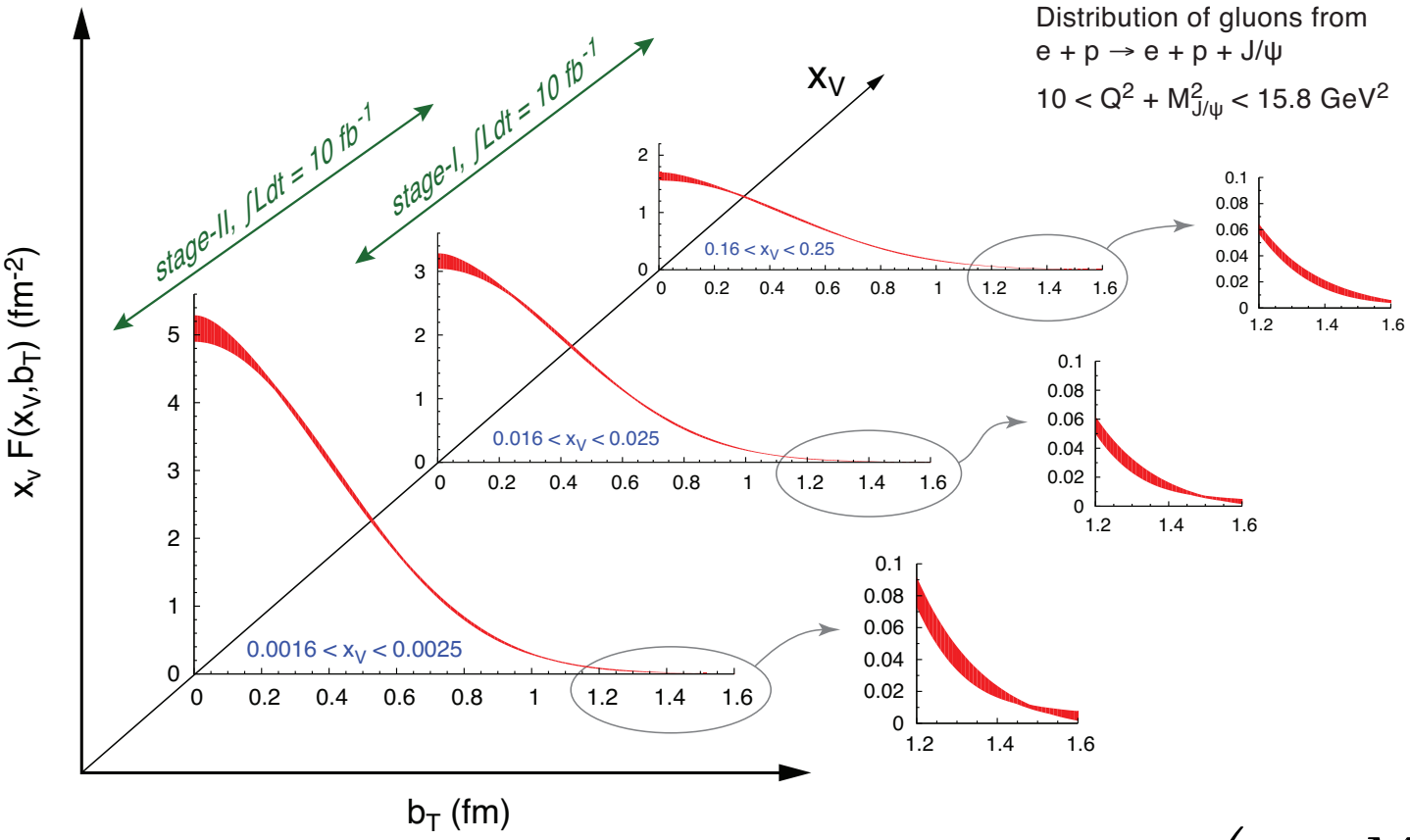
- It is accomplished by measuring generalized parton distributions (GPDs) H(x,ξ,t) and E(x,ξ, t).



- GPDs contain detailed information about spin-orbit correlations and the angular momentum carried by the partons.

GPD Measurements at EIC

- GPDs can be measured at EIC in exclusive vector meson production

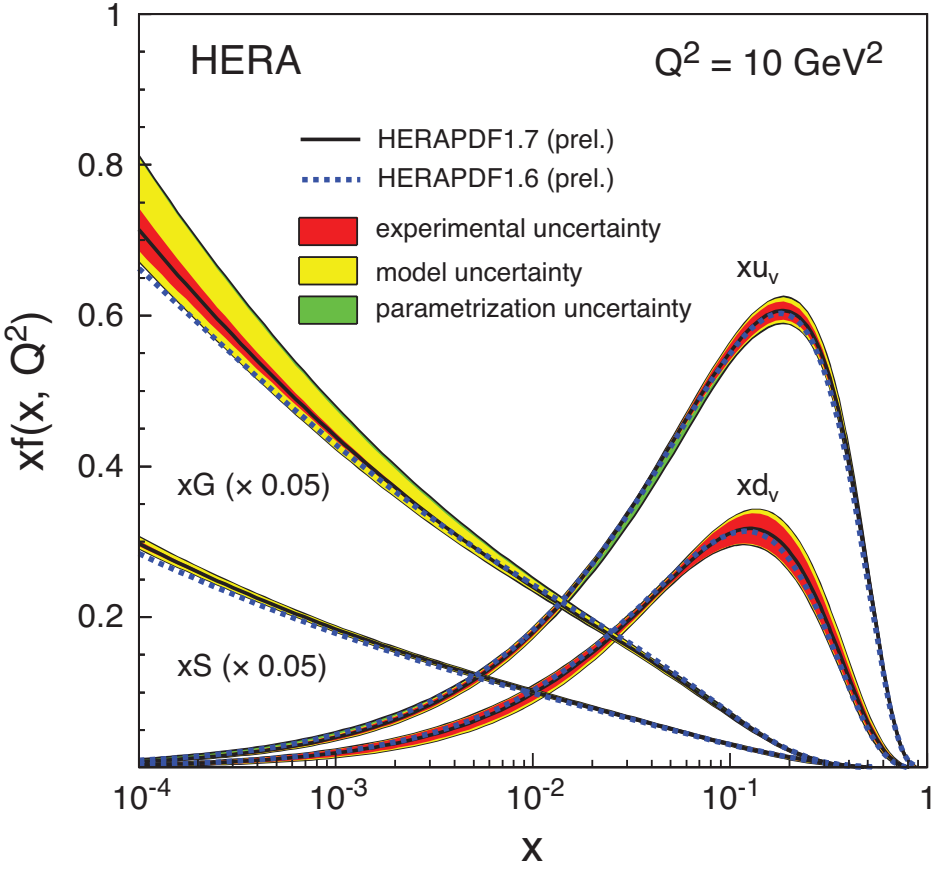


$$x_v = x\left(1 + \frac{M^2_{J/\psi}}{Q^2}\right)$$

QCD Physics in a Nucleus

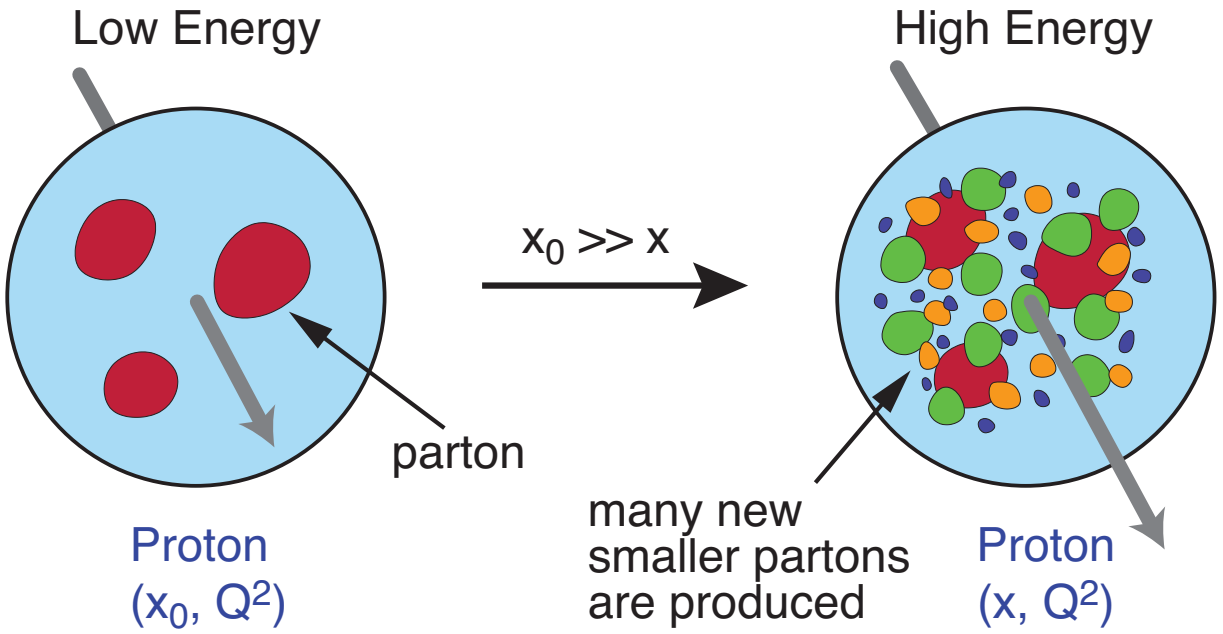
Gluons at Small-x

- There is a large number of small-x gluons (and quarks) in a proton:



High Density of Gluons

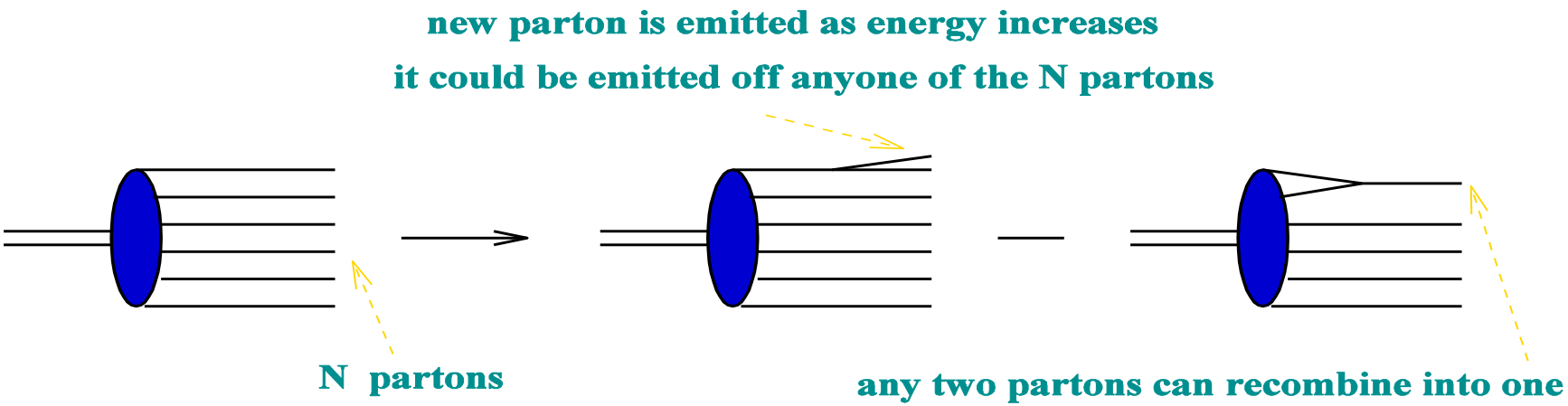
- High number of gluons populates the transverse extend of the proton or nucleus, leading to a very dense saturated wave function known as the Color Glass Condensate (CGC):



"Color Glass Condensate"

Nonlinear Equation

At very high energy parton recombination becomes important. Partons not only split into more partons, but also recombine. Recombination reduces the number of partons in the wave function.



$$\frac{\partial}{\partial Y} N(x,k_T^2) = \alpha_s K_{BFKL} \otimes N(x,k_T^2) - \alpha_s [N(x,k_T^2)]^2$$

Number of parton pairs ~ N^2

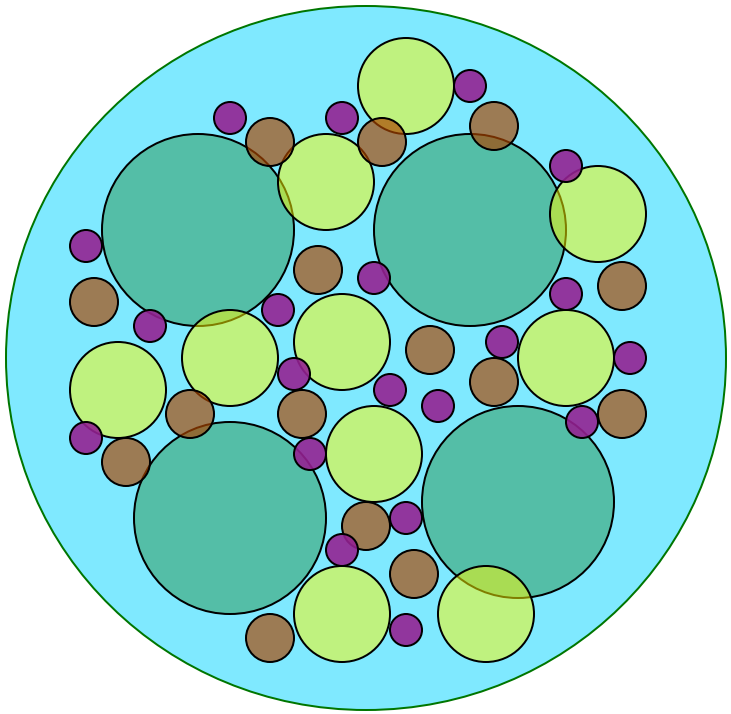
I. Balitsky ' 96 (effective Lagrangian)
Yu. K. ' 99 (large N_c QCD)
JIMWLK '98-'01 (beyond large-N_c)

Nonlinear Evolution at Work

✓ First partons are produced overlapping each other, all of them about the same size.

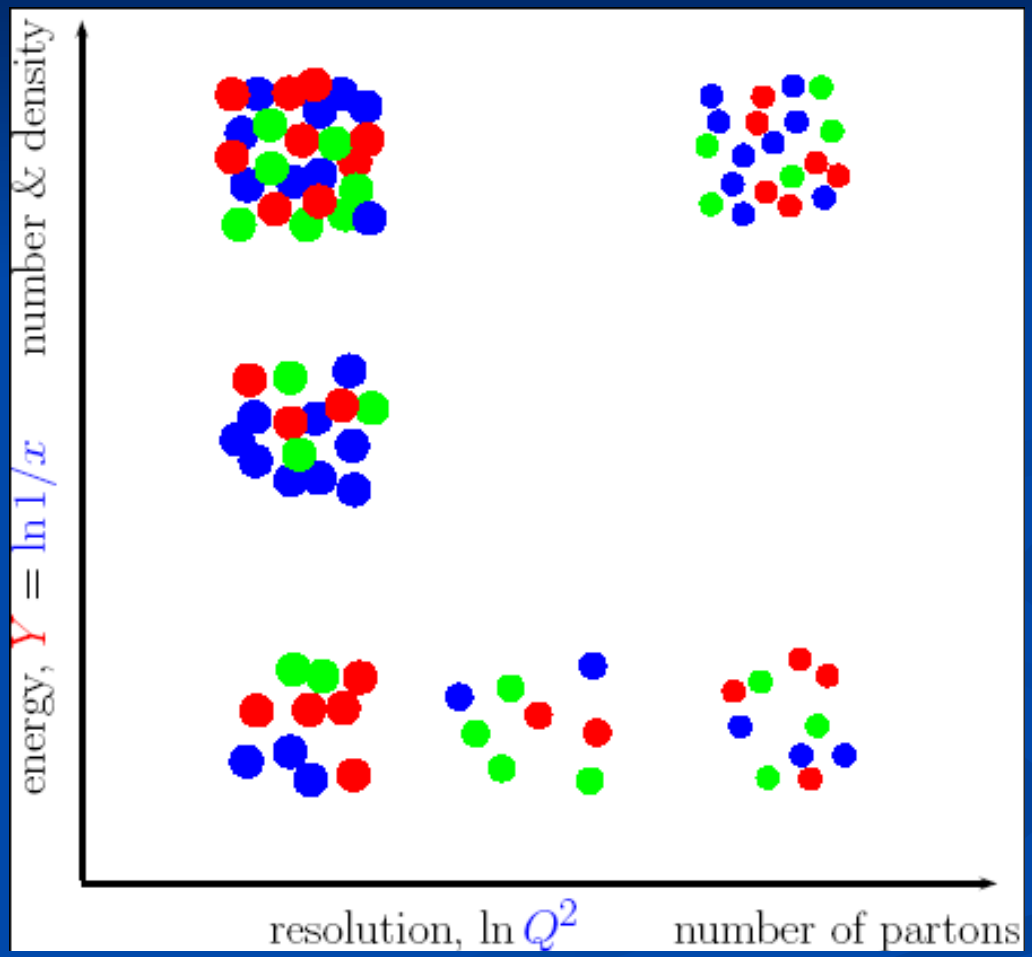
✓ When some critical density is reached no more partons of given size can fit in the wave function. The proton starts producing smaller partons to fit them in.

Proton



Color Glass Condensate

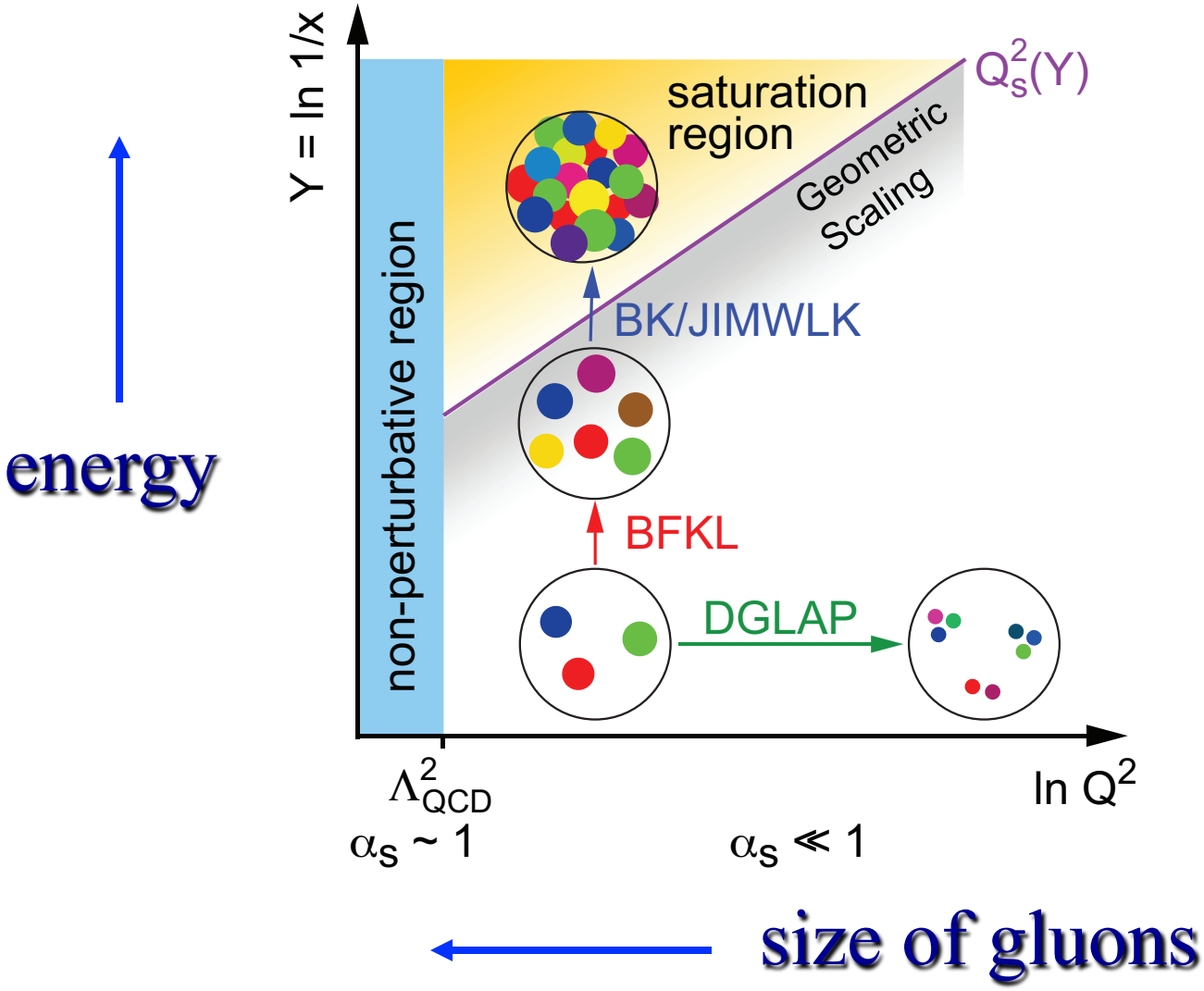
Map of High Energy QCD



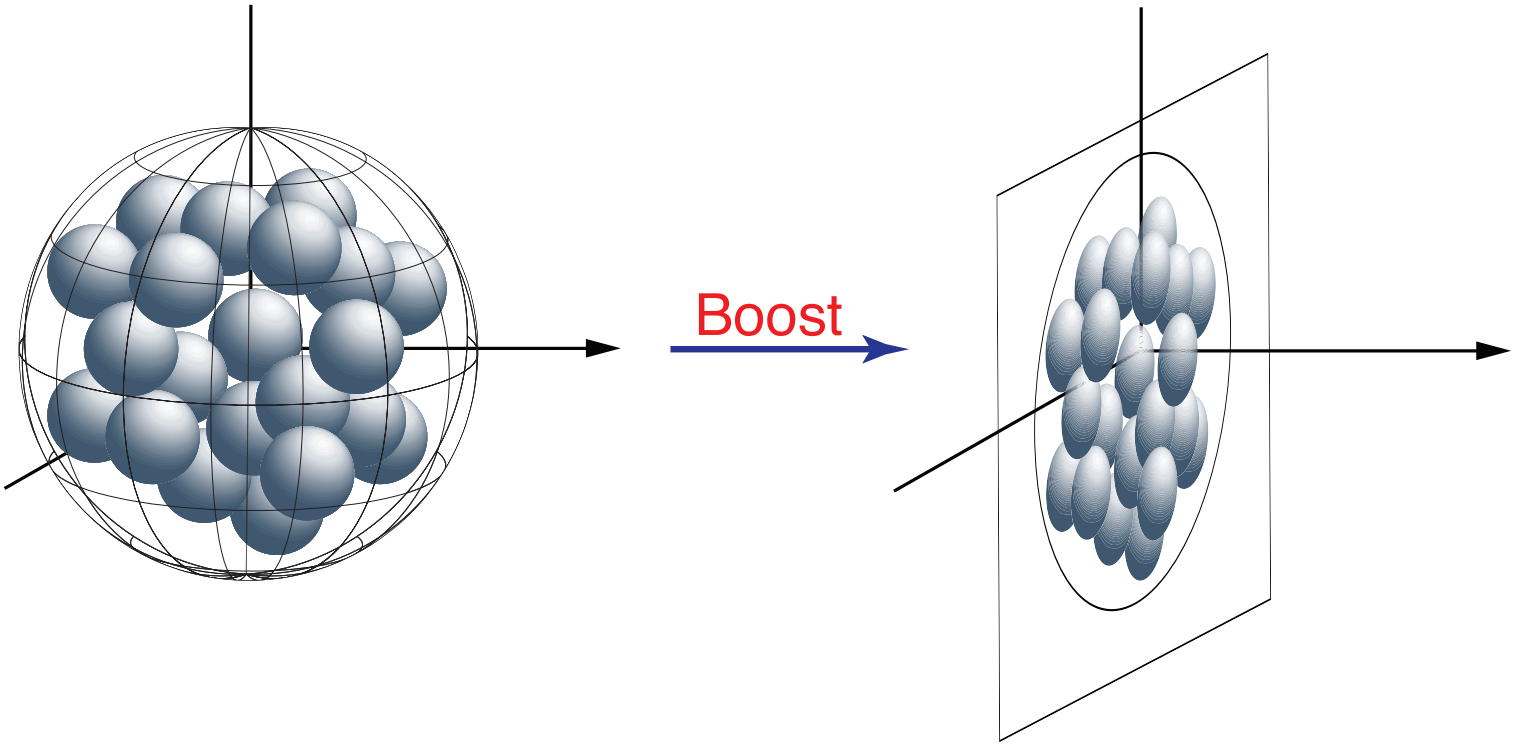
energy

size of gluons

Map of High Energy QCD



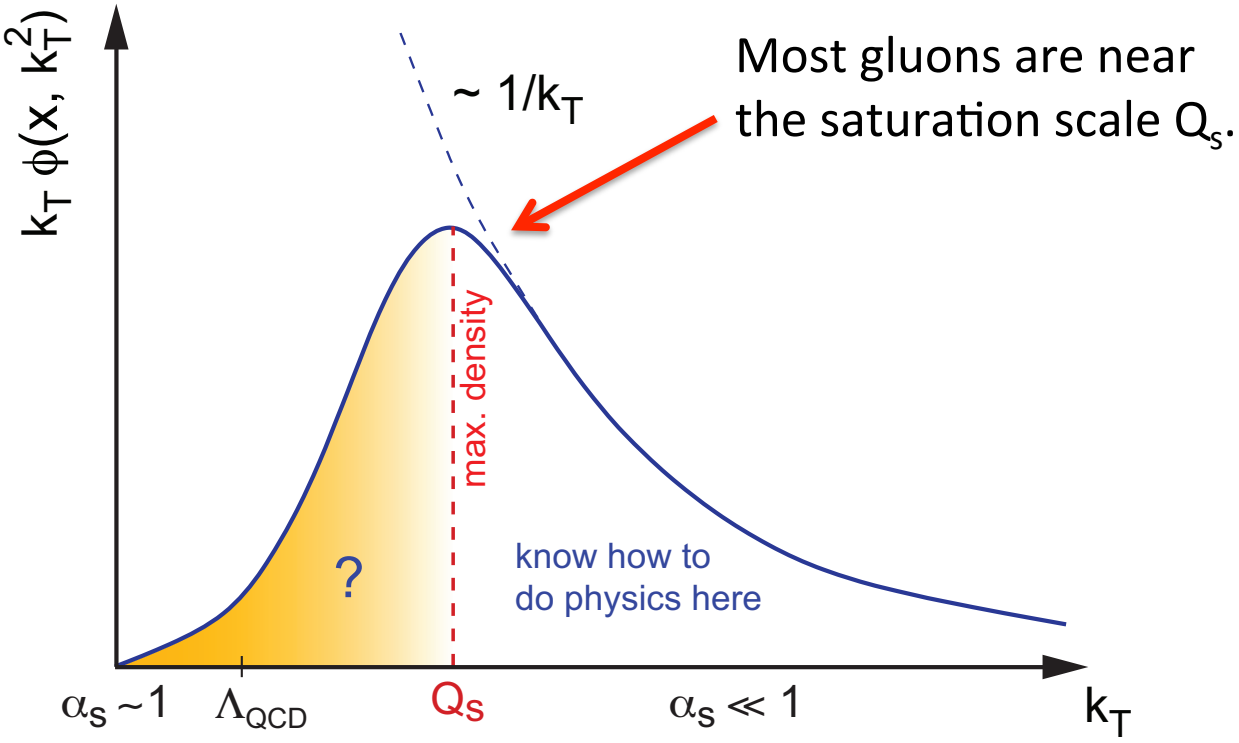
McLerran-Venugopalan Model



- Large parton density gives a large momentum scale Q_s (the saturation scale): Q_s^2 ~ # partons per unit transverse area.
- For $Q_s >> \Lambda_{QCD}$, get a theory at weak coupling $\alpha_s(Q_s^2) \ll 1$

Typical gluon "size"

Number of gluons (gluon TMD)
times the phase space



Gluon "size" = 1/transverse momentum
= $1/Q_s$

momentum transverse
to the beam

High Energy QCD: saturation physics

- The nonlinear BK/JIMWLK equations and the MV model lead to a large internal momentum scale Q_S which grows with both energy s and nuclear atomic number A

$$Q_S^2 \sim A^{1/3}\ s^{\lambda}$$

such that

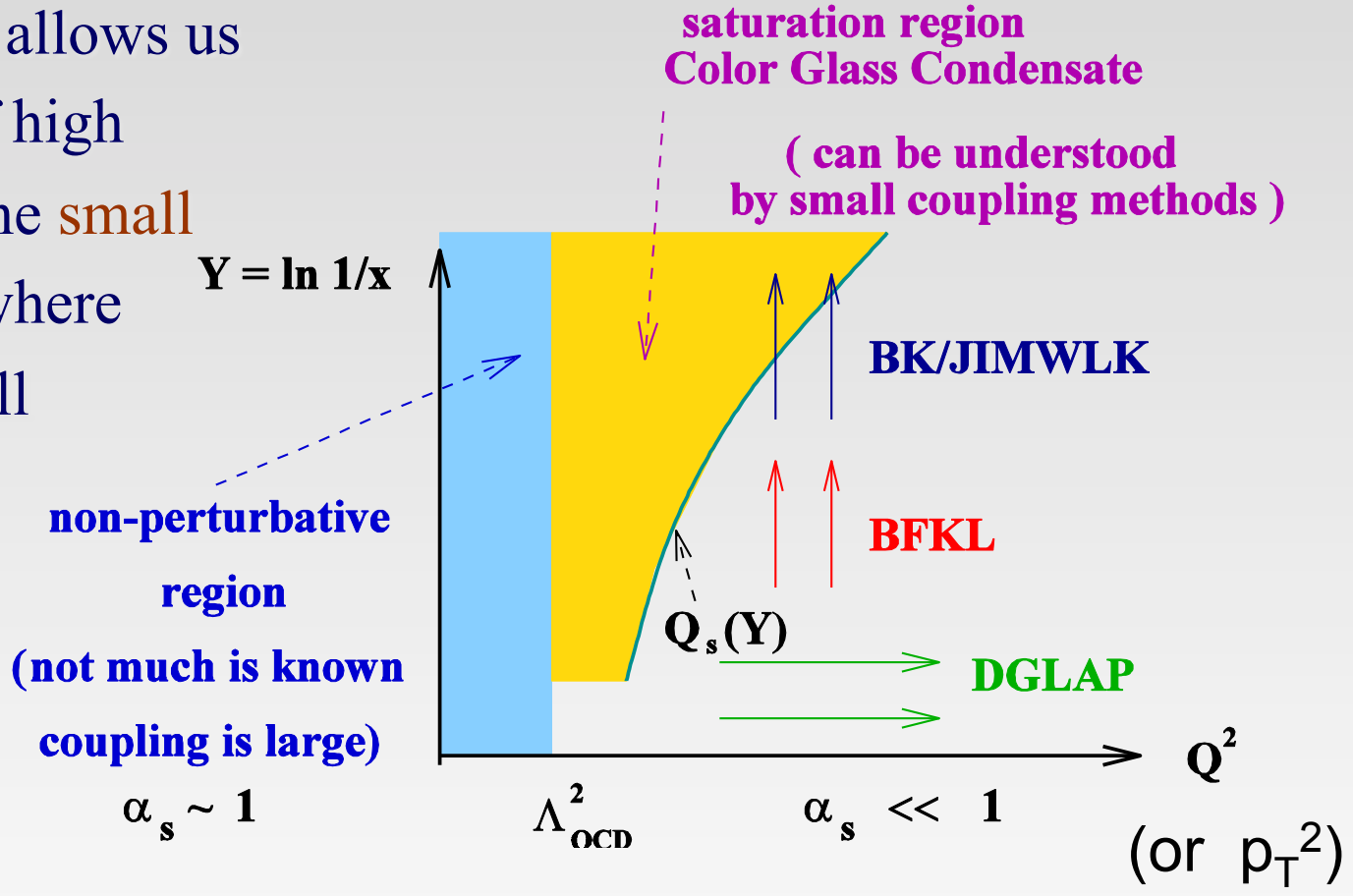
$$\alpha_S = \alpha_S\left(Q_S\right) << 1$$

and we can calculate total cross sections, particle multiplicities, etc, from first principles.

- Bottom line: everything is weakly-coupled, Feynman diagrams work! But: the system is dense and physics is nonlinear!

Map of High Energy QCD

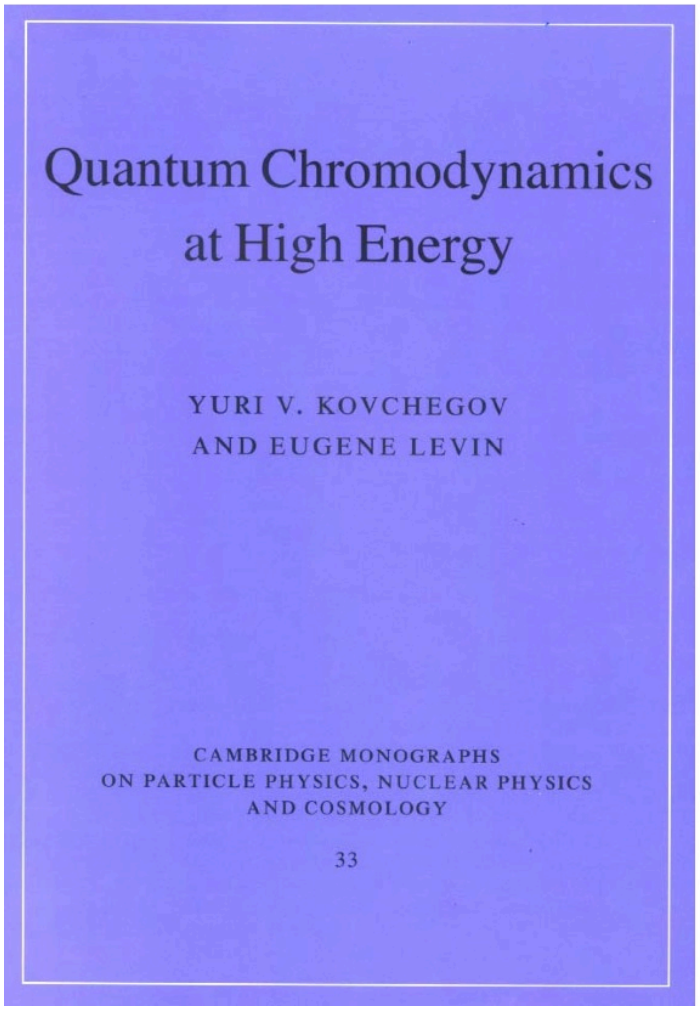
Saturation physics allows us to study regions of high parton density in the small coupling regime, where calculations are still under control!



Transition to saturation region is characterized by the saturation scale

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

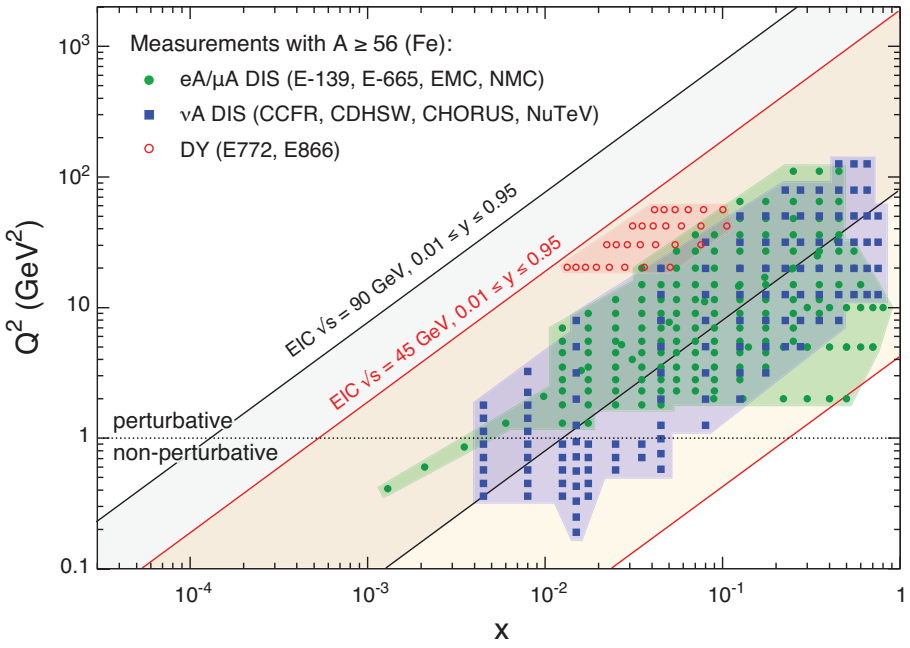
A reference

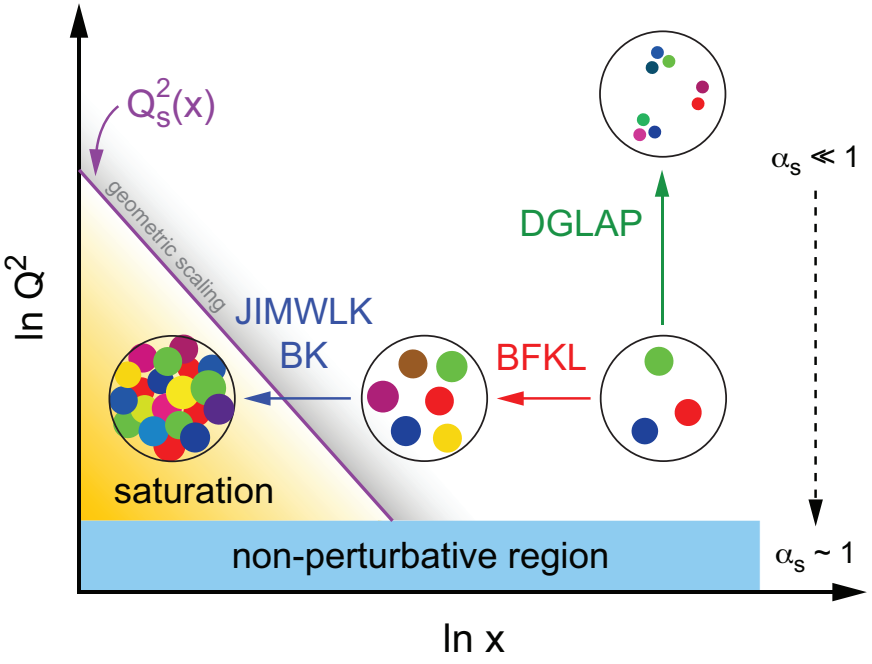


Published in September 2012
by Cambridge U Press

Can Saturation be Discovered at EIC?

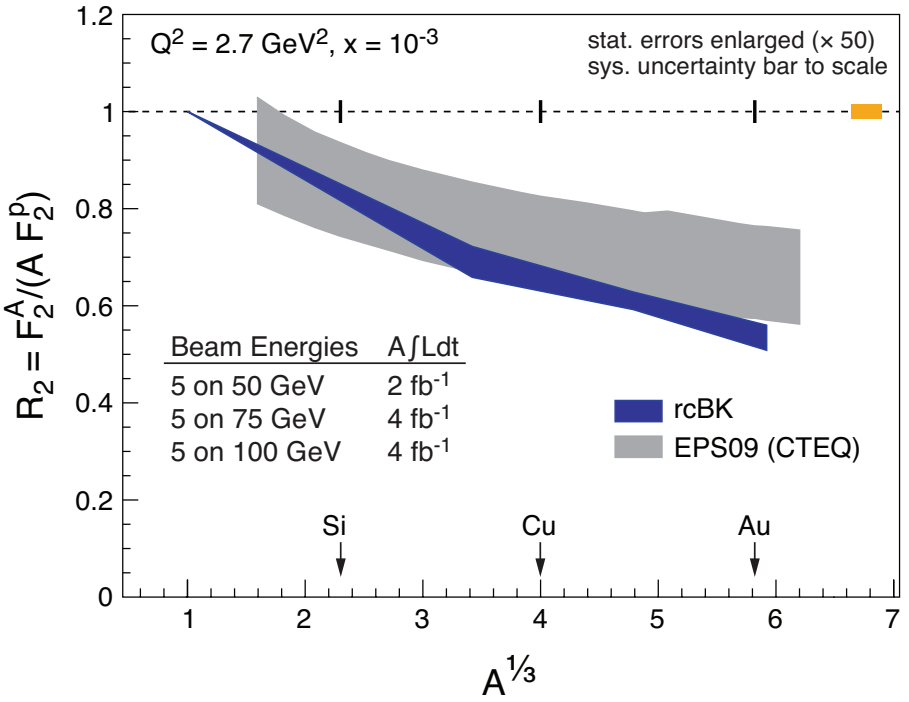
EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties:

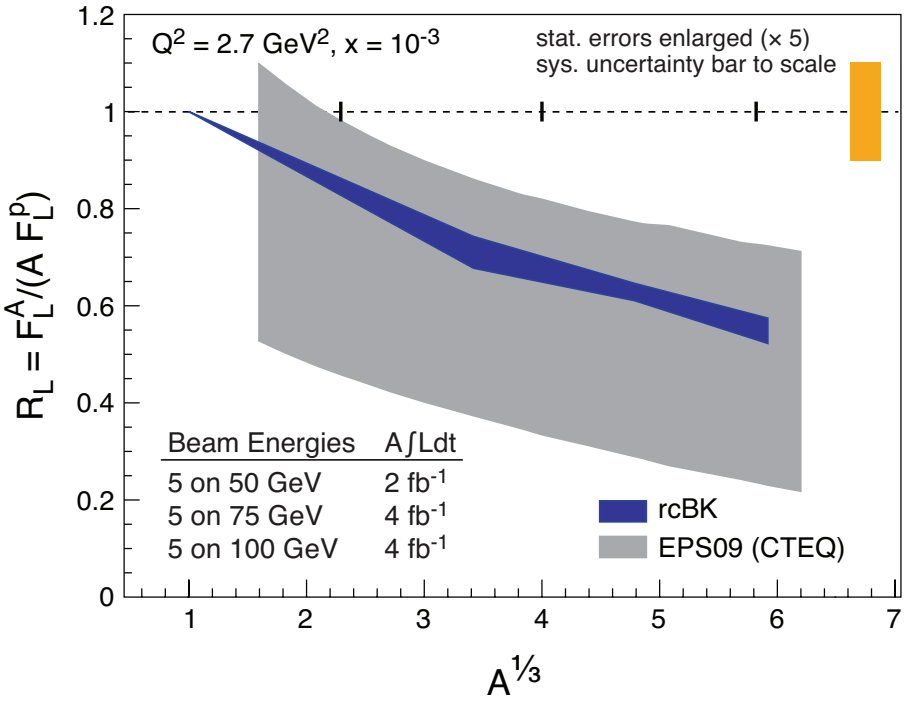




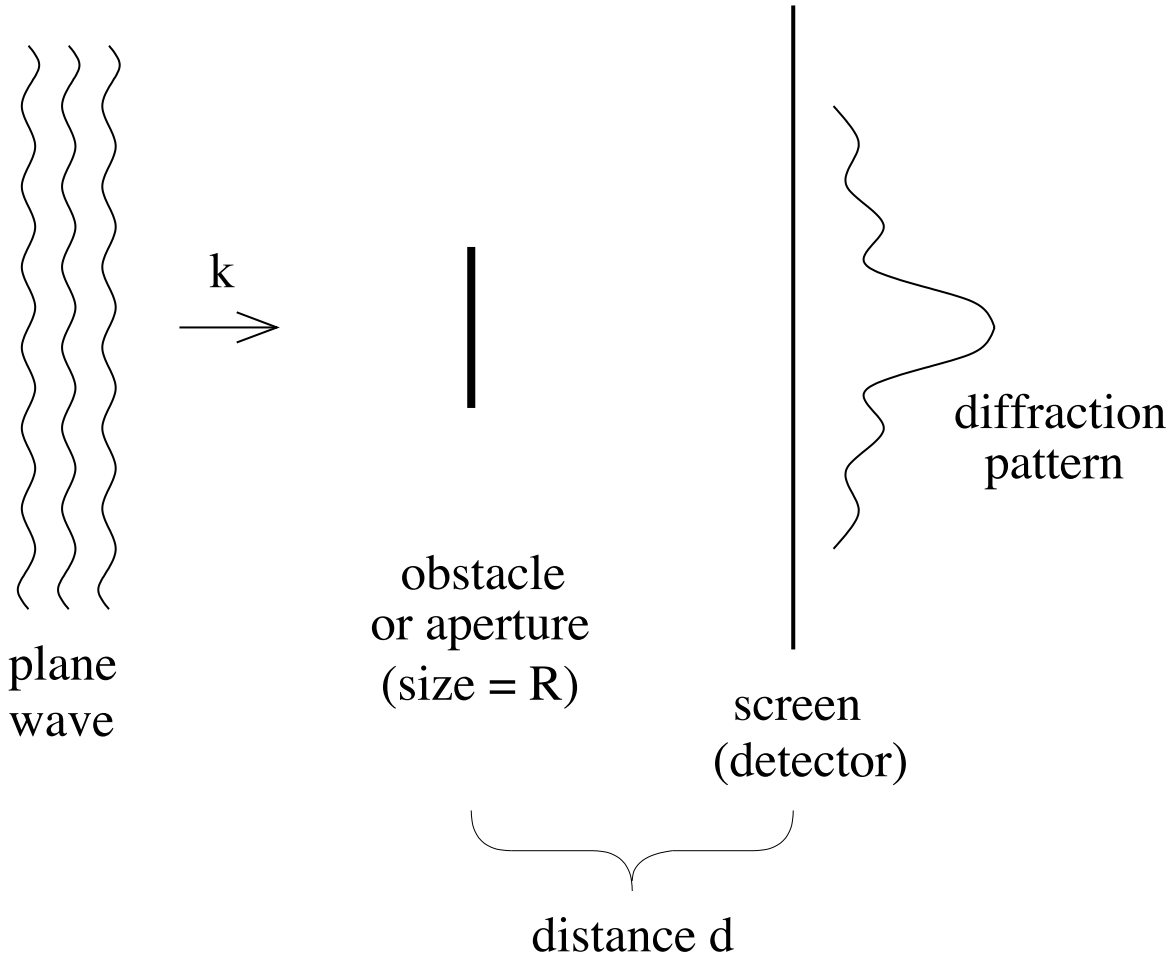
Saturation Measurements at EIC

- Unlike DGLAP evolution, saturation physics predicts the x-dependence of structure functions with BK/JIMWLK equations, though the difference with models for DGLAP initial conditions is modest



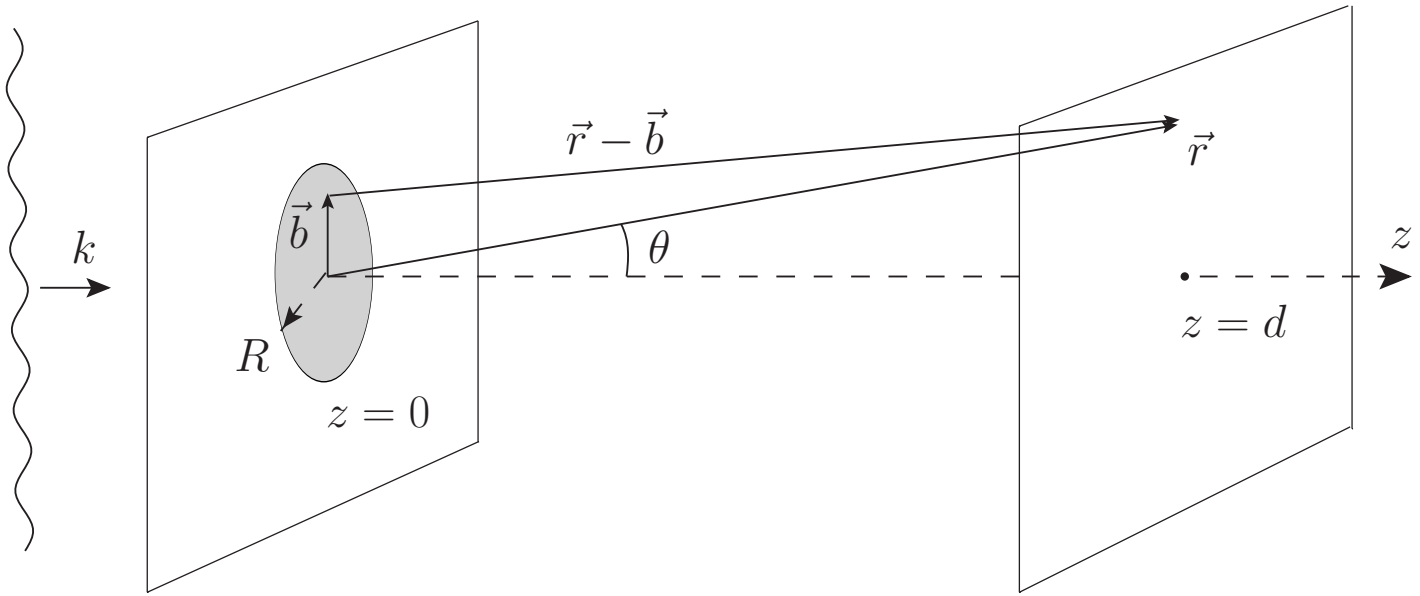


Diffraction in optics



Diffraction pattern contains information about the size R of the obstacle and about the optical “blackness” of the obstacle.

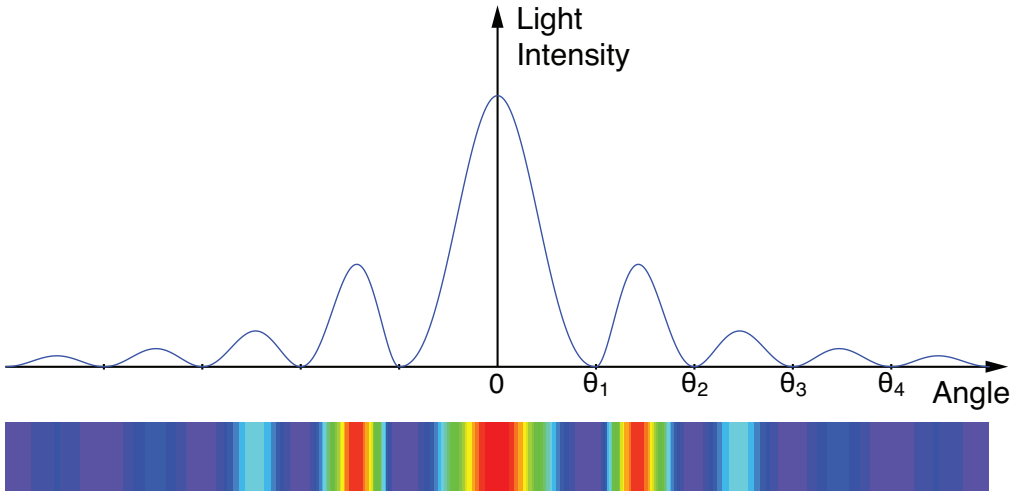
Diffraction in optics and QCD

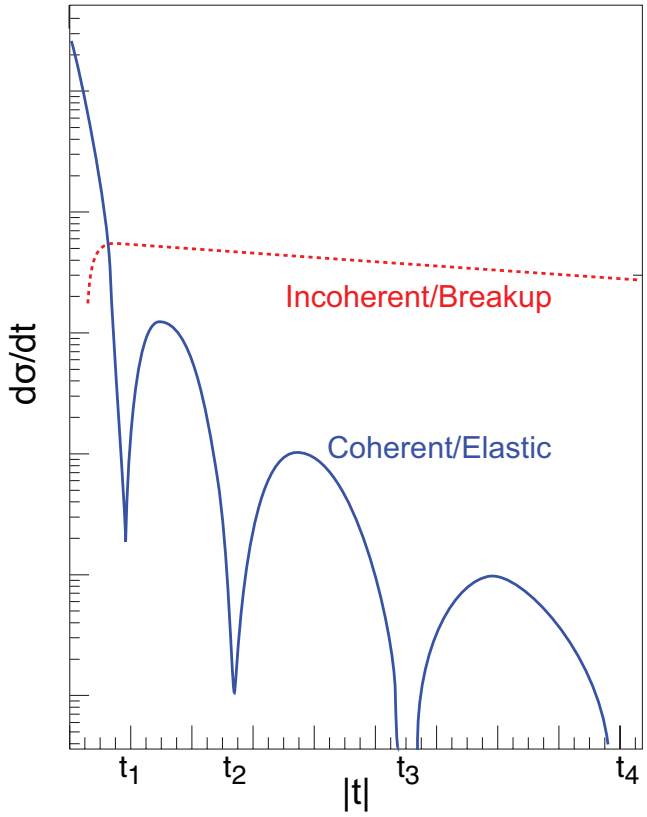


- In optics, diffraction pattern is studied as a function of the angle θ.
- In high energy scattering the diffractive cross sections are plotted as a function of the Mandelstam variable $t = k \sin \theta$.

Optical Analogy

Diffraction in high energy scattering is not very different from diffraction in optics: both have diffractive maxima and minima:

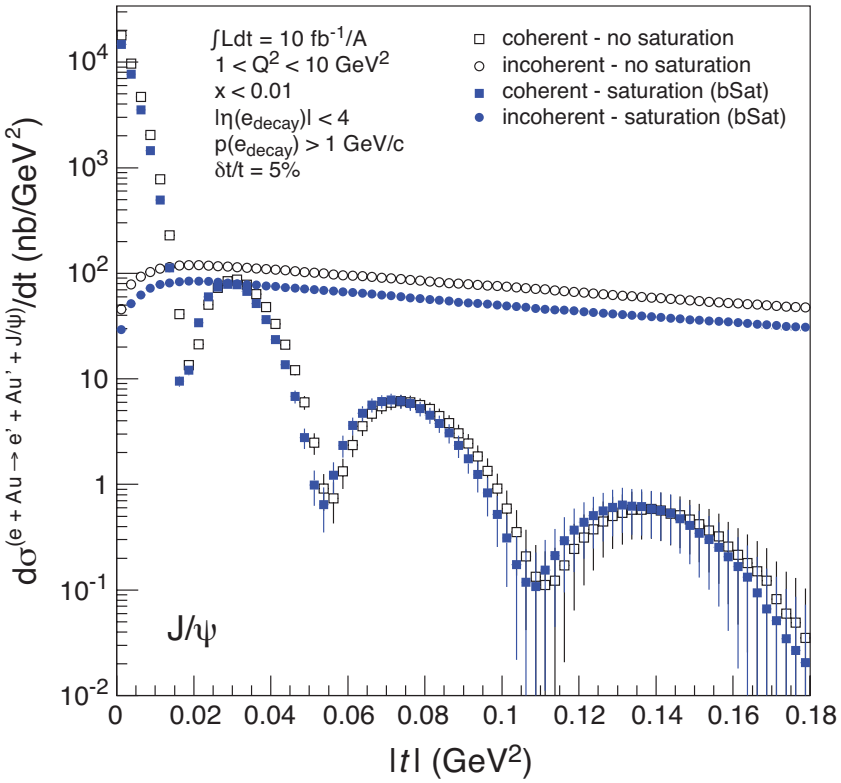


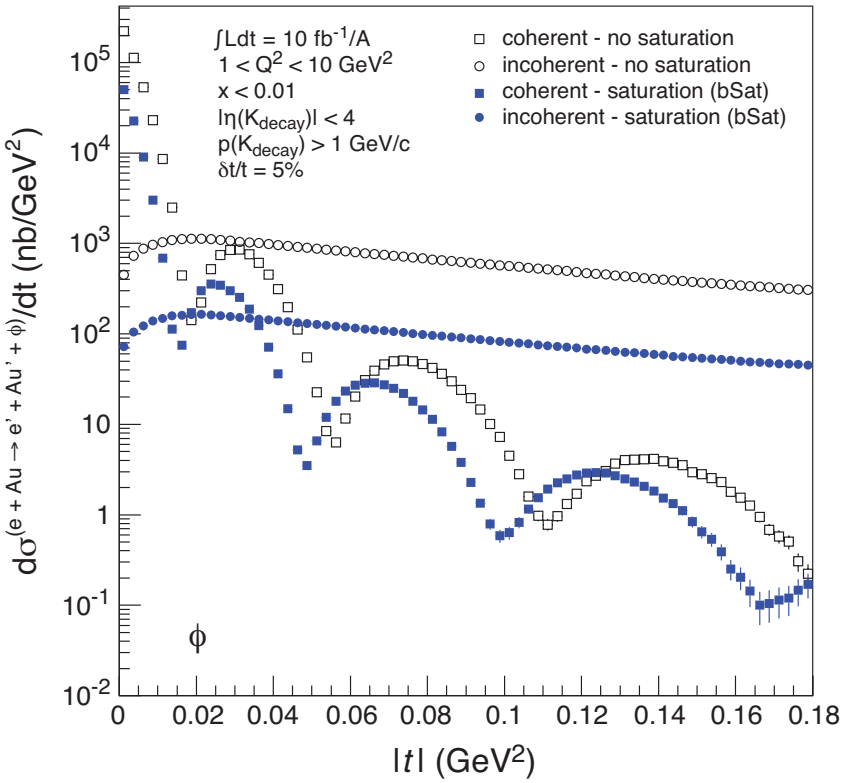


Coherent: target stays intact;

Incoherent: target nucleus breaks up, but nucleons are intact.

Exclusive VM Production as a Probe of Saturation





Plots by T. Toll and T. Ullrich using the Sartre even generator (b-Sat (=GBW+b-dep+DGLAP) + WS + MC).

- J/psi is smaller, less sensitive to saturation effects
- Phi meson is larger, more sensitive to saturation effects
- EIC stage-II measurement (most likely)

Diffraction on a black disk

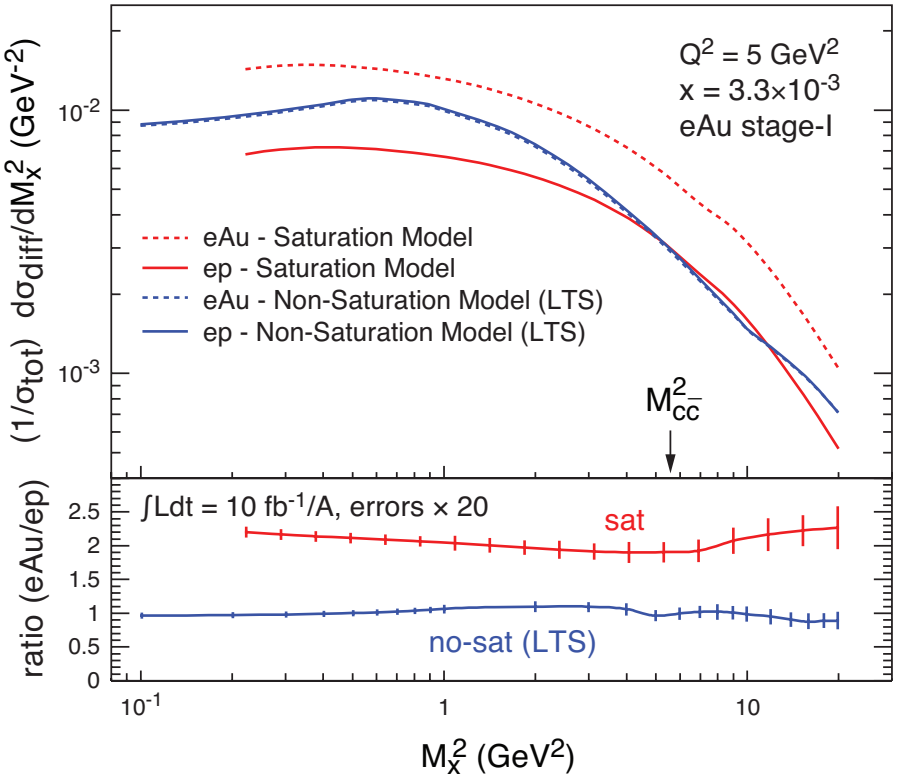
- For low Q^2 (large dipole sizes) the black disk limit is reached with N=1
- Diffraction (elastic scattering) becomes a half of the total cross section

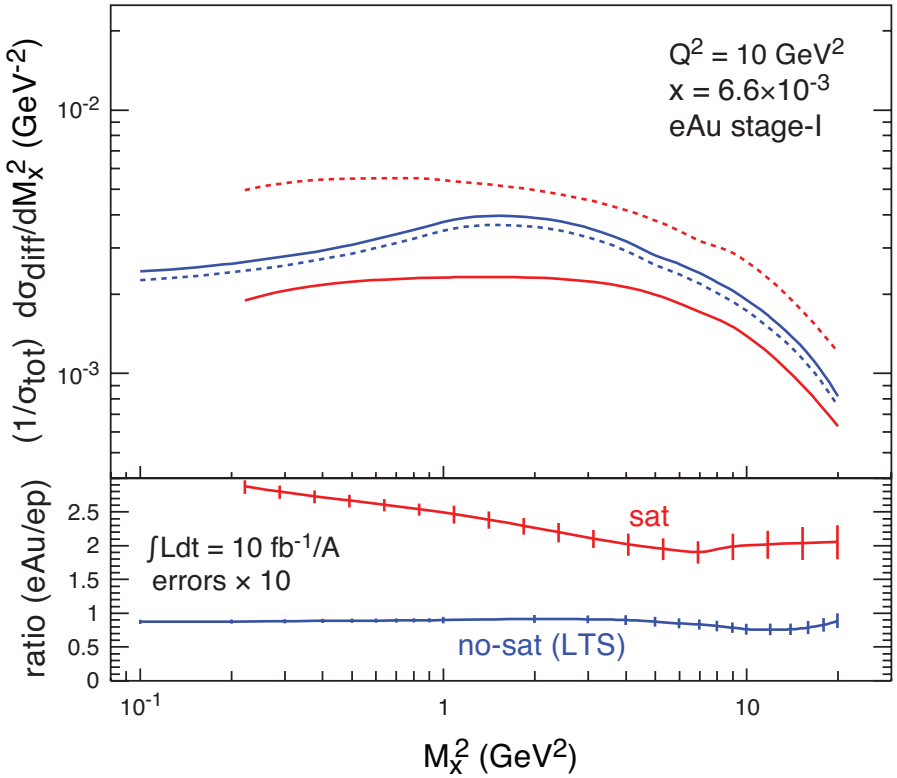
$$\frac{\sigma_{el}^{q\bar{q}A}}{\sigma_{tot}^{q\bar{q}A}} = \frac{\int d^2b\, N^2}{2\int d^2b\, N} \longrightarrow \frac{1}{2}$$

- Large fraction of diffractive events in DIS is a signature of reaching the black disk limit!

Diffractive over total cross sections

- Here's an EIC stage-I measurement which may distinguish saturation from non-saturation approaches:

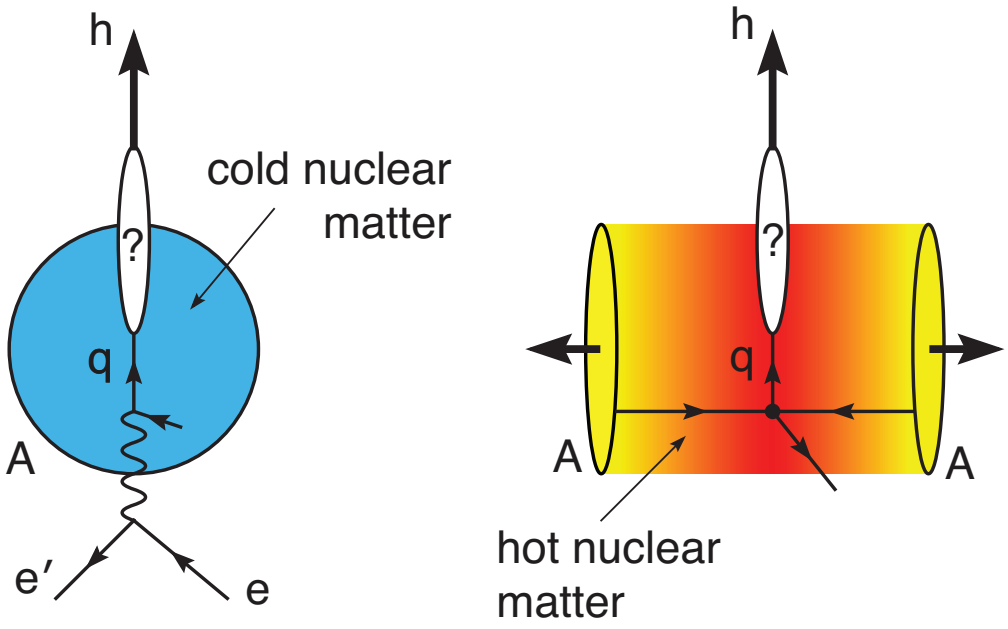




sat = Kowalski et al '08, plots generated by Marquet
no-sat = Leading Twist Shadowing (LTS), Frankfurt, Guzey, Strikman '04, plots by Guzey

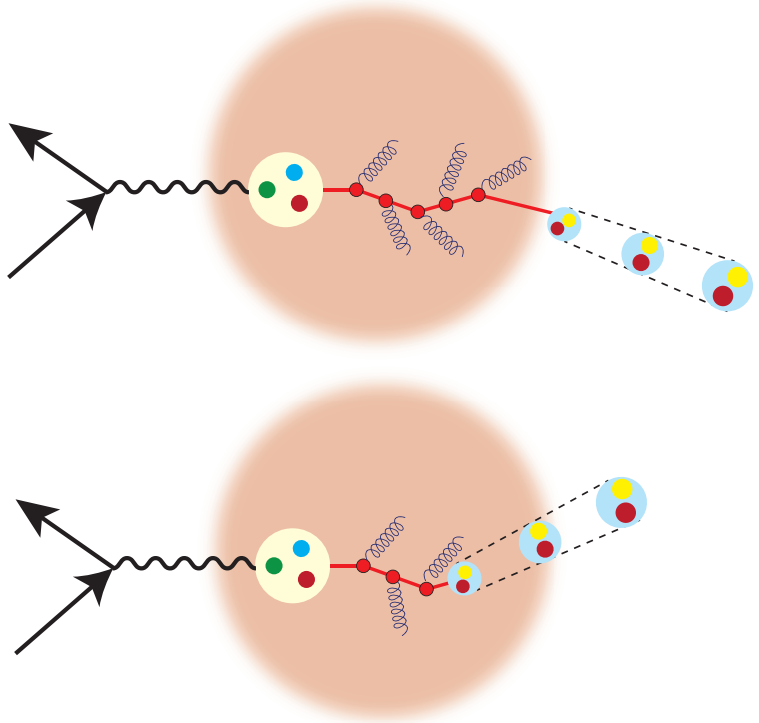
Energy Loss in Cold Nuclear Matter

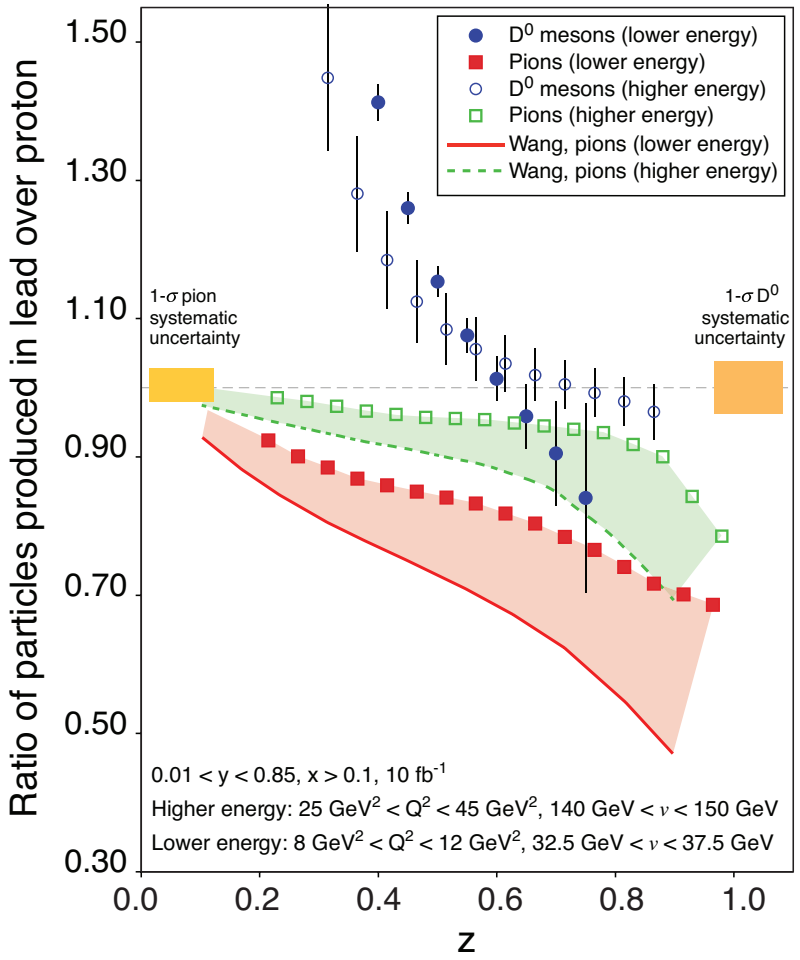
- EIC would be able to measure the energy loss of quarks in a cold nuclear matter, complementing the RHIC and LHC measurements of energy loss in hot QCD plasma:



Energy Loss in Cold Nuclear Matter

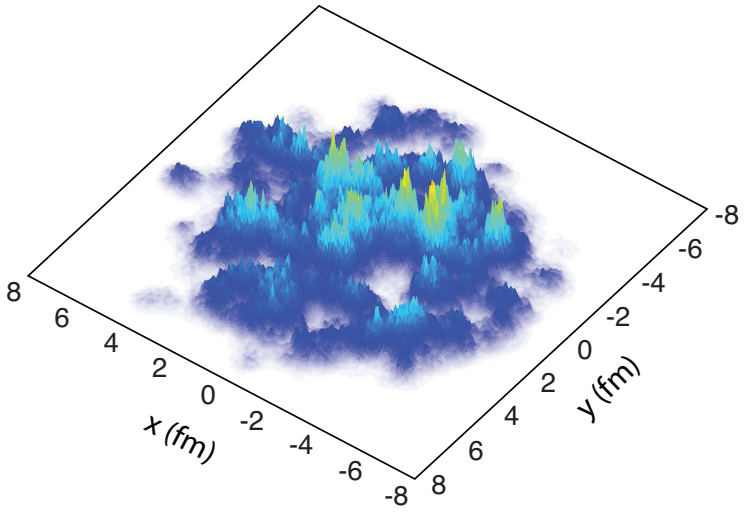
- By studying quark propagation in cold nuclear matter we can learn important information about hadronization and may even measure qhat in the cold nuclear medium:

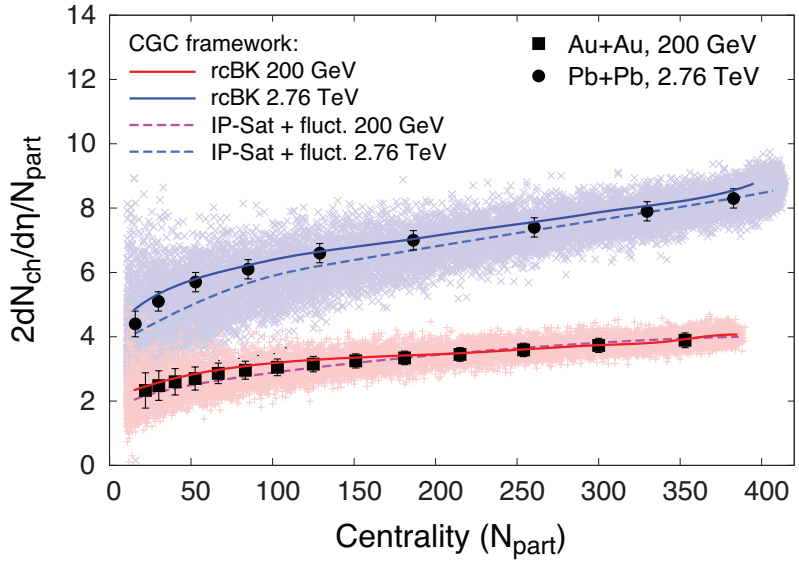




Connections to Heavy Ion Physics

- CGC Physics also plays important role in the early-time dynamics of heavy ion collisions
- By exploring it at EIC we would get a better handle on formation of QGP and on fluctuations



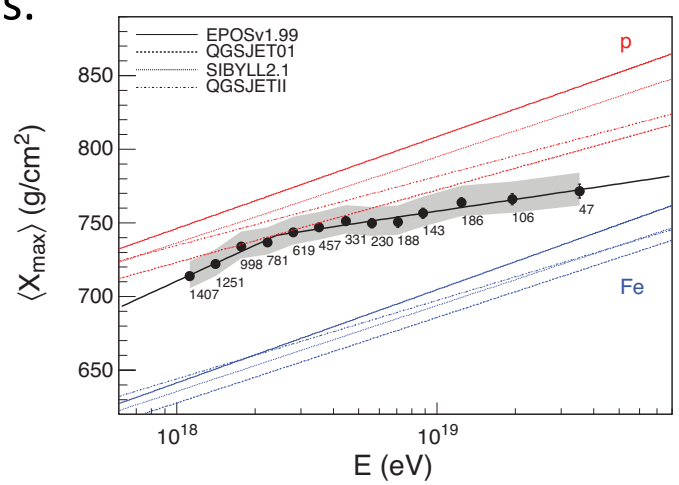


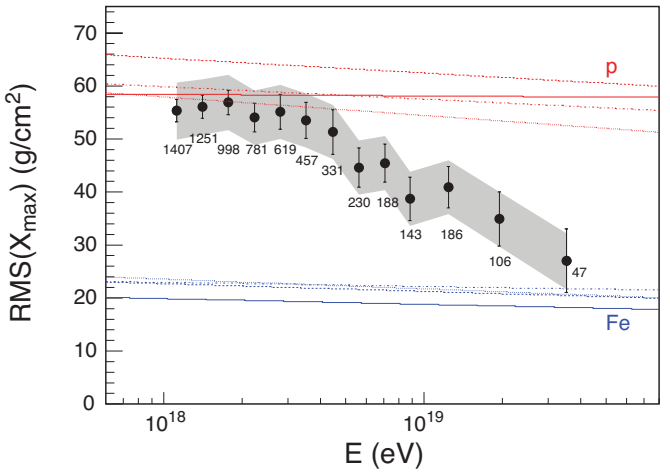
Connections to Cosmic Rays

- There is a known problem in Auger data indicating that cosmic rays behave like protons at lower energies and like nuclei at higher energies, according to the existing QCD Monte-Carlos.

- It could be that the problem is with our understanding of QCD at this super-high energies.

- Perhaps saturation physics, with input from EIC, could help improve our understanding of the Auger data.





Conclusions

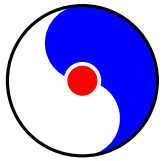
- EIC would allow us to address the spin puzzle and map out the nucleon at an unprecedented level of precision.

- EIC may complete the discovery of saturation/CGC physics and study its properties.

- Both achievements would significantly improve our understanding of QCD in nucleons and nuclei.

Summary of Future Prospects Computing Group

Taku Izubuchi



RIKEN BNL
Research Center

BROOKHAVEN
NATIONAL LABORATORY

RIKEN

RBRC Scientific Review Committee Meeting, BNL, Nov 1, 2013

Gathering Top Notch Lattice physicists from world

- Past records (Computing-related only):

Y.Aoki (Nagoya),T.Blum (Connecticut), T.Doi (RIKEN), M.Kitazawa (Osaka), C.Lehner (BNL), T.Misumi (Keio), Y.Nemoto (Marrianna), J.Noaki (KEK), S.Sasaki(Tohoku), E.Shintani(Mainz), P.Petreczky (BNL), K.Orginos (William&Mary), M.Wingate (Cambridge), T.Wettig (Regensburg), N.Yamada (KEK), T.Yamazaki (Nagoya)

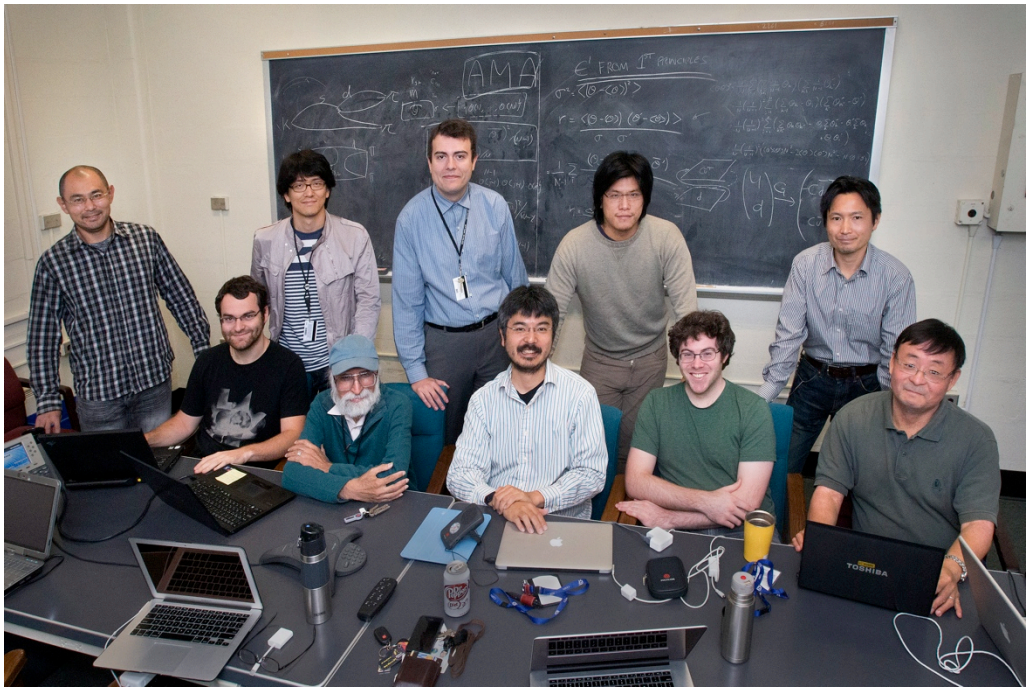
1 PD + 4 Fellow(5yrs) + 11 Permanent/Tenured

- Current Member

1 GL, 2+1 University Fellows,
1 In-house Fellow, 2 PD (FPR),
+ Visiting scientists







Exciting Subjects
- Flavor, CKM physics -

- $\Delta I=1/2$ $K \rightarrow \pi\pi$, $\varepsilon' / \varepsilon$
  [C. Kelly's & N. Christ's talks]
- Sub-percent accuracy for basic quantities,
  quark masses π, K leptonic decays (f_π, f_K), B_K,
  $K \rightarrow \pi l \nu$ decay (K_{l3}) [R. Mawhinney's talk]
- Including iso-spin breakings (m_{up}-m_{down} , QED effects)
  [T. Ishikawa et al 2012, T. Blum et al 2010]
- B and D meson physics using both RHQ and Static actions (for now) [T. Ishikawa's talk]
  [collaboration with KEK]

Exciting Subjects
- Flavor Neutral sector -

- Muon g-2 hadronic contributions
  for the new experiments at FNAL (and J-PARC)
  (HVP & Light-by-light) [T. Blum's talk]
- Electric Dipole Moment & matter rich universe
  [E. Shintani, et al 2013]
  - θ angle
  - quark's (Chromo) EDM
    [LANL/RBC Collaboration starting]

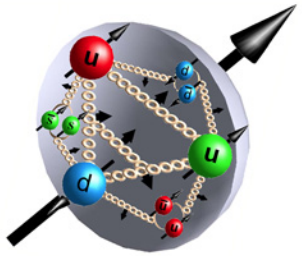
  CP-violating πNN coupling

Exciting Subjects
- BSM & Nuclear Physics -

- BSM & Dark Matter [E.Neil's talk]
  [E. Neil, S. Syritsyn LSD Collaboration]
  (USQCD, RBRC workshop LME13)
  Proton Decay [E. Shintani et al 2013]

- Nuclear Physics
  [B. Tiburzi's & S. Syritsyn's talks]
  - Electromagnetic Properties
  - Form factors, Structure Functions [LHP/RBC Collaboration]

  RHIC Spin & EIC (eRHIC) physics
  [T. Blum, C. Jung, M. Lin, S. Ohta, S. Syritsyn, B. Tiburzi, T. Ishikawa, S. Yoshida, …]



Exciting Subjects
- Formalism, Algorithm & Software –

- The physical mass simulation possible by Error/Cost reduction techniques (Hasenbush method, AMA, A2A) & hardware (BG/Q) and software, 1-2 years ahead of schedule !

- Next break-through awaited for the finer lattice spacing (e.g. $a^{-1} \sim 5$ GeV) [R. Mawhinney's talk] , which will enable
  - D & B physics without relying on effective theories, Nf=2+1+1
  - Direct computation of Parton distribution function (not moments) [e.g. proposal by X. Ji 2013]

RBRC In-house Computing resources



2k node RBRC BGQ, 400 TFlops, 2012-
1k node BNL BGQ, 200 TFlops, 2012-



3k nodes RBRC/BNL BGQ, 600 TFlops, 2012
0.5 k nodes USQCD BGQ, 100 TFlops, 2013-2

- Rapid R&D of idea
- Try & error algorithms
- Optimize code on fully controlled **in-house machine**

- attract top-notch scientists
- define computing group



48 k node ALCF Mira, 10 PFlops



88 k node , AICS Kei, 11 PFlops

Extends / propagates to leadership computers
Kei, ANL, ONL

many breakthroughs in science & computing

Future plan : Center of Excellence for young lattice physicists

- Excellent members & Collaborations
  - Joint tenure track position with Univ. Arizona (2014-)
- Excellent Subjects
  from the standard model, nuclear physics, to BSM
- Computer resources to support activities
- In-house computers, essential to explore new ideas quickly and defines the computing group
  → 3 PFLOPS peak accelerator base (~ X 5 QCDCQ) in 2015/16 by RIKEN, BNL and USQCD(DOE)
- Synergies with BNL Computational Science Center (CSC) HPC Code Center, and BNL IT-Division (ITD)

Lattice 2014 in NYC!



[poster & logo are tentative, subject to change]

Future RBRC Computing and Lattice QCD

RBRC Review

November 1, 2013

Norman H. Christ

Outline

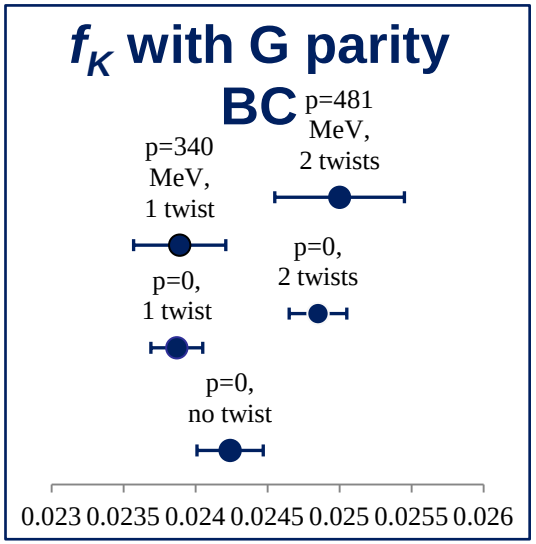
- RBRC Lattice QCD: Now
  - Computing resources
  - Lattice QCD at one Petaflops
- Next physics opportunities
- Computing challenges

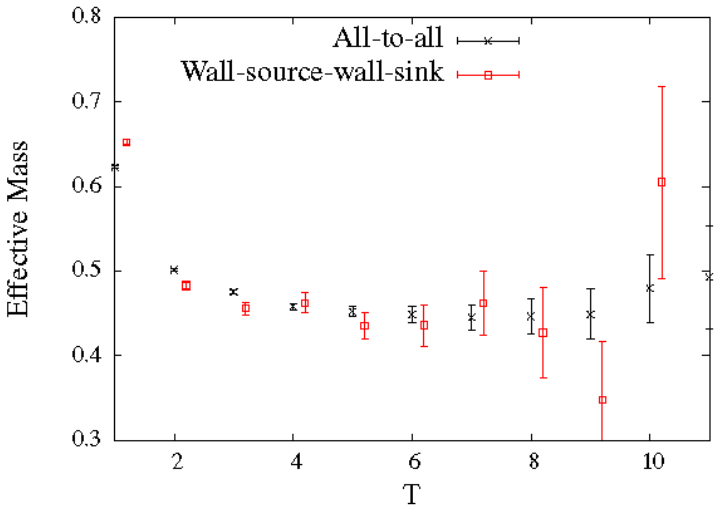
Present RBRC Computing

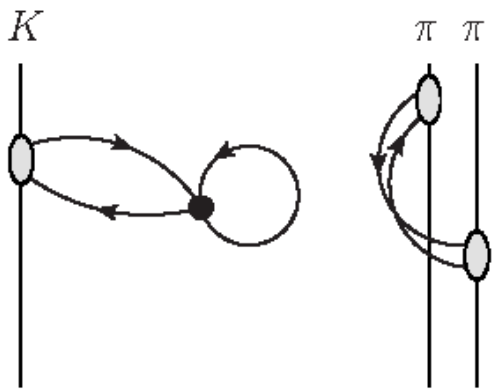
- QCDCQ (QCD with Chiral Quarks) at RBRC/Brookhaven (5/2012)
  - 2 DD1 racks (RBRC), 1 DD2 rack (BNL)
  - 600 Tflops peak/200 Tflops sustained.
  - Platform for much exploratory physics
  - Critical for developing algorithms and code for Edinburgh, ANL and LLNL
- BG/Q at ANL (12/2012) and LLNL (6/2012)
- BG/Q at Edinburgh, 6 racks (5/2012)
- ~500 M core hours at the RBRC/BNL increased > 4x by ANL/LLNL/Edinburgh

RBRC Lattice QCD Examples

- Work with m_π = 135 MeV, requires AMA and >1 Pflops sustained at ANL.
- $K \rightarrow \pi\pi$, $\Delta I = ½$: compute ε'
  - 32^3 x 64, 189 trajectories G-parity BC (Chris Kelly)
  - All-to-all propagators: 5x improvement (Daiqian Zhang)

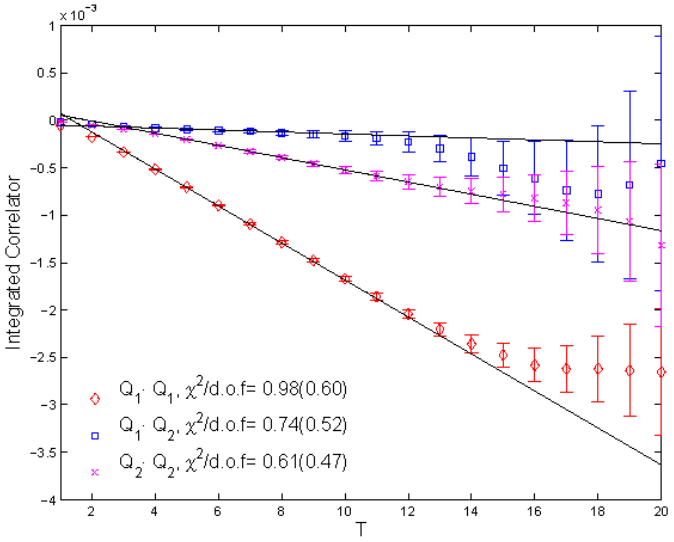






RBRC Lattice QCD Examples

- $M_{K_L} - M_{K_S}$ -- now all diagrams (Jianglei Yu)
  - Control charm loops
  - Needed for $K \rightarrow \pi\pi$, $\Delta I = ½$
  - Great fundamental importance – sensitive to 1000 TeV physics!
  - Not yet realistic parameters



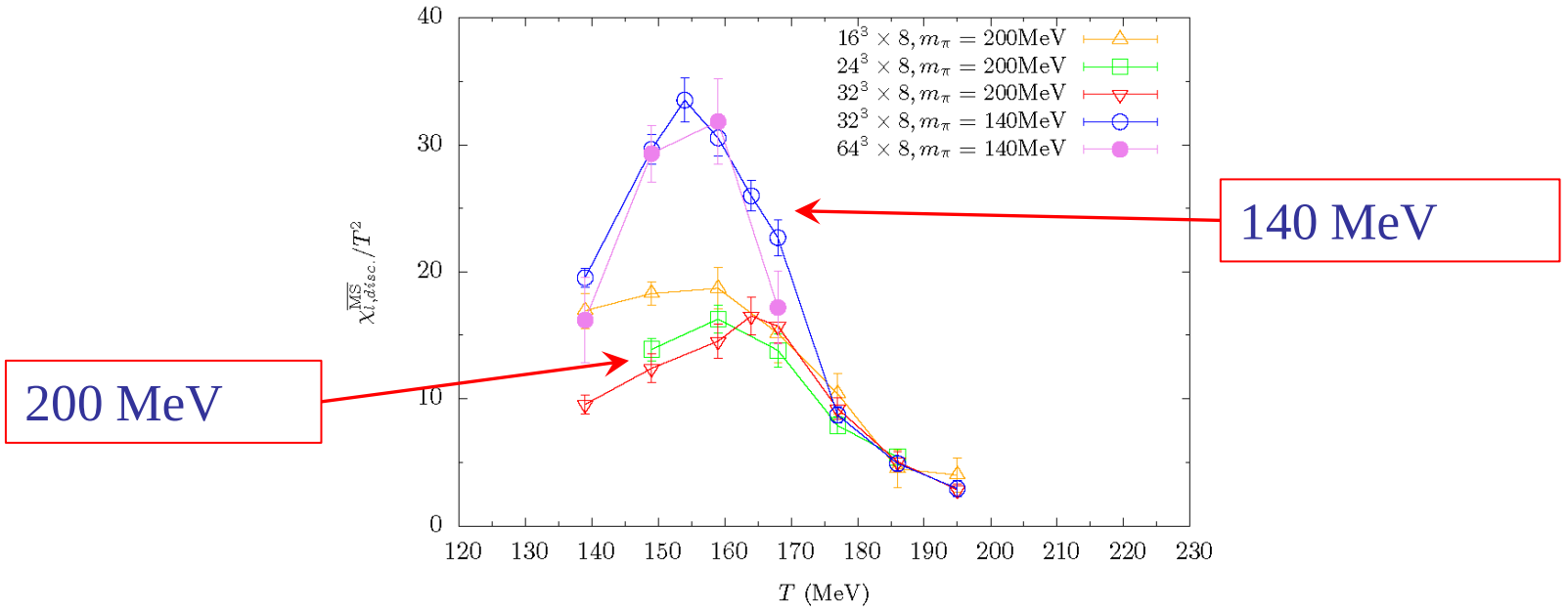
x 10^{-12} MeV

Diagrams	$Q_1 \cdot Q_1$	$Q_1 \cdot Q_2$	$Q_2 \cdot Q_2$	ΔM_K
Type 1,2	1.485(80)	1.567(38)	3.678(56)	6.730(96)
All	0.754(42)	-0.16(15)	2.70(18)	3.30(34)

$\Delta M_K^{\text{expt}} = 3.483(6)\ 10^{-12}$ MeV

RBRC Lattice QCD Examples

- The QCD phase transition at m_π = 135 MeV
  - 32^3 x 8 and 64^3 x 8 volumes
  - Cross-over behavior at T ≈ 155 MeV
  - Large chiral susceptibility peak
  - First calculation with chiral quarks!



Next Physics Opportunities

- $K \rightarrow \pi\pi$, $\Delta I = ½$ and $\boldsymbol{\varepsilon'}$
  - Complete 32^3 x 64 pilot calculation (2014)
  - Evaluate continuum limit (2015-2016)
  - Understand effects of charm:
    - Is $\boldsymbol{\Lambda_{QCD} << m_c}$?
    - Can charm be integrated out using QCD perturbation theory?
- Compute $M_{K_L} - M_{K_S}$
  - Use m_π = 135 MeV
  - Achieve $m_c << 1/a$
- Generate 80^3 x 160, $1/a$=3 GeV ensembles, with larger values of $1/a$ to follow.

Next Physics Opportunities

- Many other very exciting goals:
  - Include E&M and $m_u \neq m_d$
  - f_π, f_K, $Kl3$ at ≈ 0.1% precision
  - Light-by-light contribution to g_μ-2
  - *B* and *D* mesons using the RHQ method and finer ensembles.
- **Taku will summarize**

RBRC Computing

- Opportunities for large increases in performance.
  - Chip feature size has dropped 2x since BG/Q (implies 4x transistor count).
  - Network speeds and densities also increasing but less rapidly.
- Impressive floating point accelerators:
  - NVIDIA K40 4 Tflops GPU (SP)
  - Intel Phi with 60 *X*86 cores, 1.2 Tflops
- Engineering development costs also growing.

Commercial super-computer co-design

- Partnership with IBM very successful.
- Close relationship with IBM continues.
- However, after recent changes we do not have a current joint project with IBM.
- Systems based on future generations of Intel Xeon Phi chip offer high performance and possible new collaborations are being explored.
- Likely 4-5 year time scale for commercial collaboration (IBM or others).

Near Term Project – 2015/16

- Exploit next generation of Intel Xeon Phi accelerators. Single node:
  - ***Knight's landing*** 14 nm, 3 Tflops/DP peak
  - Sustain 1 Tflops in mixed precision?
  - 16^4 local volume, ≥ 8 Gbytes memory.
  - Current algorithms require ~125 Gbyte/sec network BW: 4x larger than future 32 lane PCIe gen4!
  - Better algorithm needed: domain decomposition?
  - For $4K/node: 25x BG/Q performance at 4x BG/Q cost
  - Can node+communication cost be kept to $4K/node?
  - Will a ~1K-node machine be sufficiently reliable?

Future Proposal

- Assemble 1K-node machine
  - $4 M cost
  - RIKEN, BNL and USQCD funding
  - 1 Pflops sustained
- Collaborate with Edinburgh (software, perhaps hardware)
- Work with Brookhaven's Computational Science Center (CSC) and USQCD.
- Prepare for large Xeon Phi-based DOE machines.

Summary

- Physics opportunities of lattice QCD are now spectacular.
- It is not easy to improve upon QCDCQ!
- Possible 1 Pflops machine (3 Pflops peak) assembled from commercial accelerators – 2015/2016
- Collaboration with Intel, Cray or IBM also being explored.

Report of the RBRC Scientific Review Committee
Brookhaven National Laboratory
October 30 - November 1, 2013

I. Introduction

The RBRC Scientific Review Committee met last on November 6-8, 2012. This report discusses the important developments over the past year.

The Scientific Review Committee consists of Sinya Aoki, Peter Braun-Munzinger, Kenichi Imai, Tetsuo Matsui, Richard Milner (Chair), Alfred Mueller, Charles Prescott, and Akira Ukawa. The committee membership is listed in an appendix to this report, with members' addresses and affiliations.

At the beginning of the meeting, in executive session, the committee was pleased to hear the opening remarks given by Dr. Hideto En'yo, Director of the RIKEN Nishina Center for Accelerator-Based Science, who traveled to Brookhaven specifically for the purpose of attending this review. Dr. En'yo gave an overview of the RIKEN review system and schedule, terms of reference, and outlook. The RBRC MOU runs through JFY2017. Within this MOU period, it is expected that the primary goals of the present RHIC will be accomplished. It is anticipated that new projects, e.g. sPHENIX, ePHENIX, and eRHIC, will emerge by 2017 and the MOU for the period of JFY2018 and beyond will be based on these new projects.

The committee would like to express deep appreciation to Dr. Nick Samios for his outstanding leadership of RBRC in the decade 2003-2013. This period was one of enormous productivity for RHIC. RBRC played an essential role in this great scientific success story. Dr. Samios assumed the Director's position in 2003 following the retirement of T. D. Lee from that position. He undertook the challenges of that role with enthusiasm. With wisdom, hard work, and good humor, he guided the program for the next 10 years. He leaves behind a healthy and dynamic organization with a promising future.

The committee also wishes to acknowledge the contributions of Dr. Satoshi Ozaki, who has served as Principal Advisor to Dr. Samios during this period. Dr. Ozaki was a principal contributor in the establishing of RHIC and served on the RBRC Management Steering Committee since the beginning in 1997. He continues to serve today as Sr. Scientist Emeritus. Our appreciation goes to both for their outstanding contributions.

In this report we review the current program and recent achievements.

II. Overview of the current program

Dr. Sam Aronson, the RBRC Director, presented an overview of RBRC personnel as well as recent achievements in the scientific program and the performance of the RHIC accelerator. The committee is pleased with the smooth leadership transition to the third RBRC Director. The committee is impressed that distinguished, former BNL Directors are willing to assume the leadership of RBRC. In addition, the committee feels that the appointment of a Deputy Director R. Pisarksi and an Administrator is a wise move.

At the beginning of his presentation, Dr. Aronson discussed the management of RBRC and the role RBRC plays in the career development of scientists and scientific leadership. There have been expressions of interest from several universities in Fellow Positions. He reported that Dr. Y. Akiba remains Experimental group leader with Dr. A. Deshpande, his deputy, and Dr. L. McLerran remains Theory group leader with R. Pisarski, his deputy. Dr. T. Izubuchi continues in the position of Computing Group Leader.

Dr. Aronson reported on experience in Run-13 and plans for Run-14. In Run-13, polarized protons were collided at center-of-mass energy of 510 GeV with record peak beam polarization (55-60%) and record peak luminosity (2.1×10^{32} cm^{-2} s^{-1}). In addition in Run-13, the new Optically Pumped Polarized Ion Source (OPPIS) was successfully commissioned providing improved polarization and intensity. In the past year, there were engineering tests of RHIC electron lenses. These will be commissioned in Run-14. Further, a new 56 MHz storage cavity for shorter vertex length will be installed for commissioning during Run-14.

Dr. Aronson described significant R&D efforts on the future eRHIC accelerator in three principal areas: high current (50 mA) polarized electron gun; multi-pass high average current energy-recovering linac; and coherent electron cooling of the hadron beam. In the initial configuration, eRHIC would have a 10 GeV electron beam and provide a luminosity of 10^{33} cm^{-2} s^{-1} in collision with the RHIC beam. PHENIX detector based upgrades for RHIC and eRHIC were described.

Discussing the impressive progress in Lattice QCD calculations he pointed out that

QCD Chiral Quarks was brought into operations at 600 TFlops in 2012. This was increased by another 100 TFlops early in 2013.

Dr. Aronson described significant interest in expanding the RBRC mission to include a focus on the search for Dark Energy based on the LSST experiment, where BNL is a long-time member of the collaboration.

Dr. Aronson reported on downward pressure on the RBRC budget. He has a number of degrees of freedom to manipulate to maintain the health of the collaboration. Finally, Dr. Aronson pointed out that RBRC has had a perfect safety record over its 15-year lifetime.

III. Scientific Progress

A. Experimental Program

RBRC Experimental Group leader Yasuyuki Akiba described the three main activities of the group: spin physics, heavy ion physics, and PHENIX detector upgrades. He reported that the rate of publications continues to be healthy, with RBRC members playing a strong role in about half. He reported on a search for a dark photon using π^0 decays in PHENIX. The VTX and muon trigger upgrades are yielding data. He described the efforts of his group on future detector upgrades, including sPHENIX, fsPHENIX, and ePHENIX.

Ralf Seidl (RIKEN/RBRC) reported on the W➔μ measurements at PHENIX. This is motivated by the desire to determine the sea quark helicities in an unambiguous way. The muon trigger upgrade has substantially enhanced the quality of the measurement. The recent Run-13 has greatly increased the data set. Reducing background is challenging and is a major aspect of the analysis.

John Chen (RBRC post-doc) reported on a study of the medium properties in deuteron-gold collisions via two-particle correlations. High multiplicity events at the LHC are yielding unexpected structures, surprisingly even in pA collisions. This has motivated a search for similar phenomena in d-Au collisions at RHIC. The focus is on the anisotropies in the flow.

Maki Kurosawa (RBRC post-doc) reported on the operational performance and current status of the silicon pixel detector. In particular, these are required for studies of heavy flavor. In Run-13, the EAST barrel was removed due to leak issues. The pixel ladders were sent back to the assembly company in Japan for repair. The WEST barrel was not removed but was not operated. All fifteen ladders were repaired and have been returned to BNL. They are undergoing pressure and electrical testing in advance of installation.

Abhay Deshpande (Deputy Experimental Group Leader) opened the second session chaired by Anne Sickles with an overview of spin physics and future directions. He described the very successful polarized p-p run in March-May 2013. Integrated luminosity was greatly improved from previous runs, and polarization was also significantly improved. Early predictions from the accelerator division projected an integrated luminosity from 300 to 600 pb^{-1}. Both PHENIX and STAR accumulated 450 pb^{-1} for this run. The hydrogen jet polarimeter provided real-time measurements of both beam polarizations, showing values between ~45 to ~60 %; average value over the run was 52%.

The PHENIX spin program advanced significantly with this accumulation of highly polarized p-p collisions. Three main objectives in PHENIX with these data are: (1) ΔG (gluon polarization) through direct photons, π^0s, and c-c-bar production; (2) anti-quark polarization through forward and backward W production with subsequent decay to muons ; and (3) study of the transverse spin asymmetries for hadrons, i.e. large asymmetries at high p_t for transversely polarized protons.

The transverse spin phenomena remain mostly unexplained. Initial and final state interactions are usually invoked, but precise dynamic predictions remain elusive. Run-13 (510 GeV p-p) is the last scheduled polarized p-p running. For W production, analysis of the earlier runs (in 2009 and 2011) is complete. The data are somewhat limited, and the Run-13 data will significantly augment these measurements. Projections of the anti-quark polarization determination by PHENIX and STAR looks very promising.

The ΔG determinations from 2009 and 2011 runs have been published. The 2013 running will significantly augment these data as well. Both PHENIX and STAR show rising A_{LL} for jets at high p_t (up to 30 GeV/c). The best fits to these data (DSSV+) shows $\Delta G = 0.10\ ^{+.06}_{-.07}$ for the x-range 0.05 to 0.2. The interpretation is that gluons, like quarks contribute approximately 20% of the proton spin. The remaining spin is presumed to lie with the anti-quarks (yet to be determined) and with orbital motion of

the constituents (also yet to be determined). Also it should be noted that low x remains an unmeasured region. Measurements at forward rapidity are needed, requiring higher energy and forward instrumentation in the detectors. This need will be addressed by eRHIC.

The anti-quark issues and transverse spin issues were described by Dr. Deshpande in some detail. With the muon and vertex (and FVTX) tracking now working well, Run-13 data should significantly determine these contributions to the proton spin. (Separate talks by R. Seidl and X. Wang went into the details of muon tracking and FVTX tracking.)

Transverse spin is interesting to the spin program because it may address the orbital motion issues. The large asymmetry A_n for hadrons (π^{+-}, π^0 , etc.) has been around for decades since high p_t measurements using polarized targets existed. However, the dynamics leading to these large A_n values is still not well understood. Initial and final state interactions are most commonly invoked. Measurements in the forward regions by sPHENIX and a possible forward upgrade, (fsPHENIX) are motivated by the continuing proton spin "crisis", which these data could help resolve.

Dr. Deshpande went on to discuss the future running plans and detector upgrade plans. Accelerator upgrades include electron lenses and e-cooling. (stochastic cooling has already been a dramatic success for RHIC). Upgraded detectors STAR, and sPHENIX, could be ready by 2018-2019. The tentative long range planning shows no running in 2017 and 2020 to allow for these upgrades. Also transition to eRHIC was shown as occurring in 2023-2024. Dr. Deshpande concluded his presentation with a brief description of what the detectors would look like for eRHIC.

Xiaorang Wang (University Fellow with RBRC/New Mexico State Univ.) discussed the physics goals that use the FVTX vertex tracker. Displaced vertices (tracks that originate away from the event origin) indicate Charm or Bottom quark production. Through the displacement of vertices, J/ψ mesons can be selected, and the associated A_{LL} probes gluons in the interaction through the production mechanism. The group working with Dr. Wang are working with the muon tracking group, and combining FVTX tracking with muon tracking, W bosons can be better identified and tracked.

The FVTX consists of 10^6 strips, 75 mm pitch in radius and 10 mrad strips in φ. The unique tracking of the FVTX also allows for identification of di-muon events, and serves to reduce backgrounds of all tracks through reduction of the combinatorial confusion.

Early runs for commissioning FVTX, in Run-12, showed inefficiencies in some sectors, and those were repaired. For Run-13, the overall tracking efficiency exceeded 95%. Rapidity coverage, when combined with muon tracking was $1.2 < \eta < 2.3$ (or about 25% of the acceptance). Software improvements have been underway and continue. (see R. Seidl's talk)

Gluon fusion is expected to dominate in heavy quark production. Plans to study heavy quarks through the A_N asymmetry serve as a test of the Sivers mechanism. In the di-muon channel, a significant J/Psi signal exists, and this will be a clean signal for testing hadron dynamics with the A_N asymmetry. Below the J/ψ signal, di-muon events come from the Drell-Yan process that probes the Δu-bar/u-bar content of the proton spin through the A_{LL} asymmetry. These analyses are planned.

Joseph Seele (RBRC Fellow) presented an overview of the proposed fsPHENIX physics program and detector. sPHENIX takes advantage of the BABAR solenoidal magnet which PHENIX has inherited. The concept for sPHENIX using the magnet leads to a conventional solenoidal field surrounded by up-to-date systems for tracking and particle ID. Since forward angles are not covered in the initial phase of sPHENIX, Dr. Seele presented a concept for filling the forward directions of the acceptance.

The physics goals are motivated by the large A_N asymmetries that have been observed at high x_f for hadrons since the 1970's in pp and pA interactions. Perturbative QCD has no ability to explain these observations quantitatively. Today initial state (Sivers-type) and final state (Collins-type) interactions are invoked as a possible explanation, along with other ideas. Data related to these effects are needed.

A forward detector for jets is proposed, to investigate the dynamics at high energies. The instrumentation planned at fsPHENIX in the forward direction should measure momentum to $\delta p/p < .004p$, have hadron and EM calorimetry, and hadron particle ID to separate p/K/p. The coverage in rapidity should be $2 < \eta < 4$.

An important constraint on this (or any) design is compatibility with a future ePHENIX detector. Dr. Seele presented some magnetic field profiles and detector component concepts that satisfy these requirements. GEANT simulations are underway, and a document is planned to be ready sometime next year.

Kieran Boyle (RBRC Fellow) discussed a letter of intent (LOI) with the charge to "upgrade/configure detectors from their present form to first generation eRHIC detectors" and "to describe the physics reach of the upgraded detector". The LOI Committee consists of RBRC members Dr. Boyle, Dr. Deshpande, Dr. Nakagawa, and

other PHENIX collaborators. They completed the study and the LOI document was submitted recently, in September 2013.

The physics goals are both an extension and expansion of the current spin physics program at PHENIX as well as the study of the partonic structure of nuclei with high energy electron beams. These include helicity structure of the proton ($\Delta g(x)$ extended to low x, for example) and Δu, Δd, Δs and sea quark distributions to low x. Semi-inclusive processes will also be studied. In e+A collisions, ePHENIX will want to investigate gluon splitting and recombination and saturation effects at low x. Variation of the species A will allow control of hadronization and suppression effects.

eRHIC is based on the BABAR solenoidal magnet, EM and pre-shower detectors in the central region ($-1<\eta<1$), hadron calorimetry ($-1.2<\eta<1$), a BABAR-style DIRC for the central region, a compact TPC for tracking in the central region, and forward detectors for hadrons ($1<\eta<4$) with particle ID, EM and hadron calorimetry. An endcap crystal calorimeter for scattered electrons ($-4<\eta<-1$) would have excellent energy resolution (1.5 % $\delta E/E$). For tracking of forward and backward going particles, planes of GEM detectors would be placed along the beamline around the interaction point.

In the forward region, hadron particle ID would be achieved with an aerogel ring imaging Cerenkov counter (RICH), followed by a gas RICH. Kaon ID would be possible over a large range of momenta ($4<p<60$ GeV/c).

In summary, ePHENIX would be capable of greatly extending the x and Q^2 reach of many processes. $\Delta g(x)$ reach would extend well below x = .01. Hadron studies would be extended beyond $Q^2 \approx 100$ GeV^2/c^2 with $\sqrt{} > 10^3$ GeV, and saturation studies for $x < 10^{-3}$.

The Letter of Intent is now available at:

http://www.phenix.bnl.gov/phenix/WWW/publish/dave/PHENIX/ePHENIX_LOI_09272013.pdf

Stefan Bathe (RBRC/Baruch College University Fellow) presented the future plans for the VTX silicon detector. The status of the VTX upgrade was presented separately in the talk by M. Kurosawa. The detector was initially tested with Run-11. Inefficiencies were observed during that run, and sectors of the VTX detector were subsequently re-worked to improve efficiencies and coverage.

Prior to the VTX, tracking in the central region with the drift chamber has been limited by the weak magnetic field in the drift chamber region. Extending the tracking down to the event origins serves to improve tracking efficiencies and eliminate confusion, while improving the momentum resolution. Momentum resolution of 3% at $p_t = 10$

GeV/c was shown. Dr. Bathe also showed clear improvement in the track reconstruction and reduction of backgrounds. Vertex reconstruction is good and tracks up to $p_t \sim 20$ GeV/c can be usefully reconstructed.
Multiplicity spectra, properly normalized, were shown for PHENIX in agreement with those from Alice and CMS in Pb-Pb collisions. The outlook for PHENIX with the VTX is to revisit the Au-Au and p-A measurements in the future. The analysis reported by Dr. Bathe is in its initial stage, and no actual transverse momentum spectra were reported. The committee looks forward to seeing charged particle spectra and R_{AA} distributions as soon as available.

B. Theory Program

We reemphasize the conclusion from our last review that the collection of theorists at the RBRC along with neighboring theorists in the BNL Nuclear and High Energy theory groups constitute the strongest theory effort in the world focused on QCD and related topics. Indeed, a recent DOE evaluation of all nuclear physics groups in universities and laboratories in the US put the BNL Nuclear Theory group among the top five of all the theory groups. We note with pleasure that Adrian Dumitru and Derek Teaney have recently been promoted to tenure at Baruch and Stony Brook. Anna Stasto is now up for tenure at Penn State and we expect her promotion to occur in the present academic year. The remaining Theory Fellows form a diverse and vigorous set of talented young theorists whose work will be described below. There are currently a large number of postdocs associated with nuclear theory at BNL. The activity of the young theorists seems well directed and topical. We see the mentoring of young theorists by Larry McLerran and the other theorists at BNL as dynamic and effective. Many of the postdocs are in active collaboration with senior theorists. There are also good collaborations among the postdocs. All in all the theory effort is very successful and we look forward to new Fellows coming on board to replace those departing into tenure positions. This year Rob Pisarski gave a nice overview of the work currently being done by RBRC postdocs and Fellows. A brief description of that work follows.

Fedor Bezrukov described an interesting picture reconciling phi-fourth inflation with recent Planck data which rules out a scalar field coupled to gravity in a minimal way. The idea is to add a, non-minimal, phi-squared times curvature term to the action which flattens the inflationary potential in agreement with Planck data. The scalar particle must be in the GeV mass range thus opening the possibility of a new observable

scalar particle in addition to particles already present in the standard model.

Adam Bzdak described work aimed at understanding particle correlations as a function of rapidity in high multiplicity proton-proton and proton-nucleus collisions at RHIC and the LHC. Azimuthal correlations of particles over long rapidity intervals (ridge effect) can be explained in terms of hydrodynamics as well as in the color glass condensate picture. He makes an interesting suggestion to look at transverse momentum of produced particles as a function of rapidity to distinguish between hydrodynamics and the CGC.

Adrian Dumitru described a consequence of the strong longitudinal color electric and magnetic fields suggested to appear in the initial stage of the high energy nucleus-nucleus collision in the framework of the color glass condensate model for nuclear wave functions. The random magnetic field configuration generates non-vanishing spatial Wilson loops with an area law which resembles the origin of string tension for usual temporal Wilson loops. He argued that these random magnetic fields generate magnetic screening in the formative quark-gluon plasma.

Kouji Kashiwa described an understanding of the QCD phase structure found in lattice simulations in terms of the Hosotani mechanism of gauge symmetry breaking. The new element in the present studies is the inclusion of quark mass effects which make agreement with lattice studies of the Polyakov-loop possible.

Jinfeng Liao described the strongly coupled quark-gluon plasma created by ultra-relativistic nucleus-nucleus collision as a topological matter with color magnetic monopoles carrying degrees of freedom responsible for the onset of confinement and for observed strong jet quenching. He also discussed the quark-gluon plasma as a chiral matter with novel chiral magnetic waves propagating, which he argued can explain the asymmetry observed in the elliptic flow parameter for charged pions. He also described an interesting possibility of formation of a Bose-Einstein condensate of gluons in the expansion dominated by two-body scattering that preserves the number of gluon excitations.

Shu Lin described work focused on understanding whether a supercooled phase of the QCD plasma could exist. In the AdS analogy the question concerns that of an unstable black hole and how long it can live. No instabilities were found in the sound mode, but simply a lack of propagation at low temperature. Quantum tunneling probabilities to the hadronic phase were calculated for sample temperatures.

Akihito Monnai described his full three-dimensional hydrodynamic calculations with dissipative effects for strongly interacting matter with finite net baryon density. He showed that the baryon number deposited at the edges of the central rapidity region

will be pushed back to the fragmentation regions carried by the collective flow of matter in the longitudinal direction. The effect of baryon number diffusion appeared small in his calculation using the value of the thermal conductivity suggested by the AdS/CFT method for strongly coupled gauge theories.

Daniel Pitonyak described the sign mismatch crisis in single-spin asymmetries observed in the polarized proton-proton collisions and in semi-inclusive deep inelastic lepton scattering off polarized proton and discussed a possible resolution of the problem within the scheme of the collinear twist-3 parton distribution function and fragmentation function. He emphasized the need of global analyses for different reactions in polarized pp collisions and deep inelastic lepton scatterings to fully resolve the crisis.

Anna Stasto described a program of calculating scattering amplitudes, involving an arbitrary number of external gluons, using light front perturbation theory. So far the Parke-Taylor amplitudes, having maximum helicity violation (MHV), have been recovered using the light front technique. Also a light front analog of the Berands-Giele recursion relations has been obtained. The light front procedure covers both wave functions and fragmentation functions. The next goal is to obtain the Britto-Cachazo-Feng-Witten recursion relation and then to see it the light front formalism is convenient for adapting these results to carry out loop computions.

Derek Teaney described his extensive program for describing the dynamics of the quark-gluon plasma focusing on his recent work on the next leading order (NLO) calculations of the gluon scattering and emission by Bremsstrahlung in the gluon transport equation for a weakly coupled quark-gluon plasma. He computed the two body collisions, drag forces by soft random background field, and inelastic collisions due to collinear Bremsstrahlung in the NLO approximation to be used for viscosities and thermal conductivity of the weakly coupled quark-gluon plasma.

Ho-Ung Yee described work on analyzing effects of the triangle anomaly in the quark-gluon plasma. One interesting phenomenon is the presence of chiral magnetic waves in the plasma. A curious result is that a causality requirement on the propagation of chiral magnetic waves appears to put a bound on the susceptibility of the plasma. Chiral magnetic waves might be visible in the polarization asymmetry in photon emission from the quark gluon plasma.

C. Lattice QCD computing program

Overview

Taku Izubuchi, as the group leader of the computing group, reviewed the organization of the group and RBRC computing facilities as well as the physics highlights in 2013. In addition to himself, the RBRC computing group now consists of three fellows, two postdoctoral fellows, six visiting scientists and two students. The group has been engaged in a close collaboration with physicists at Columbia University, University of Connecticut, Boston University, and BNL (high energy theory and computational science center) since 1998 as the RBC collaboration, and with the UKQCD Collaboration in Great Britain since 2005. It has also started a somewhat loose collaboration with the JLQCD collaborations in Japan on measurement methods since 2012. Quite recently, in addition, a new collaboration with the LHP collaboration has been started on nucleon structure. The RBC collaborations have worked well in fostering young talent, producing 30 PhD theses since 2005, and currently having 17 PhD students. The computing resources of the group consist of the QCDCQ at RBRC, ANL Mira(BlueGene/Q) at Argonne National Laboratory, BlueGene/Qs operated at Edinburgh and KEK through the collaborations, and some clusters at RIKEN RICC and FNAL/Jlab. The scientific activities of the group continue to attract world attention as evidenced by 5 plenary talks presented and 15 invited talks by the group members in 2013. They have also played active roles in the lattice QCD community, serving on various committees and organizing workshops and meetings.

Physics highlights were briefly introduced by Izubuchi, and were followed in detail by individual presentations. Izubuchi emphasized that a new generation of lattice QCD simulations has now produced several important results: (i) lattice QCD simulations at the physical pion mass of 139 MeV using chiral lattice quarks have been performed at 2 lattice cutoffs (1/a=1.7 and 2.3 GeV) on a large volume of $(5.5\ \mathrm{fm})^3$, (ii) sub-percent accuracy can be achieved for many fundamental/basic quantities such as hadron masses, decay constants, B_K and K_{l3} form factors, (iii) the first signal of muon g-2 light-by-light contribution is obtained (iv) kaon decay to two pions is investigated for both I=0 and 2 channels, indicating the $\Delta I=1/2$ rule, (v) the first complete $K_L - K_S$ mass difference is extracted from 4-point functions, (vi) many other varieties of physical observables are examined, and (vii) those developments are made possible through new and existing computing resources as well as new computational algorithms. In particular, the All Mode Averaging (AMA) developed at RBC, achieves more than a factor of 10 times

speedup for physics measurements.

Individual presentations

Robert Mawhinney presented the status of kaon physics program. Employing gauge ensembles generated at the physical pion mass of 139 MeV and two lattice cutoffs (1/a=1.7 and 2.3 GeV), a very precise value of neutral kaon mixing parameter, B_K , was reported. A preliminary value in the continuum limit of the MS-bar scheme, B_K (3 GeV) = $0.533(3)_{stat}$ $(0)_{chiral}(2)_{finitV}(11)_{pert}$, which is converted to the renormalization group invariant value, B_K^{inv} = $0.754(4)_{stat}(15)_{stat}$, has a much reduced statistical error and essentially no chiral extrapolation error, as compared with the result in the last year, B_K (3 GeV) = $0.535(8)_{stat}(7)_{chiral}(3)_{finitV}(11)_{pert}$. The largest source of systematic errors is the one associated with the perturbative matching at low energy scale, which can be reduced through non-perturbative step scaling on the lattice, so that the perturbative matching can be done at higher scales. Using the same gauge ensembles at the physical pion mass, K_{l3} form factors were calculated. Although the final analysis is still under way, the large systematic uncertainty due to the chiral extrapolation of the previous result, f_+ (0) = $0.9670(20)_{stat}(+0/-42)_{chiral}(7)_{finitV}(17)_{cont}$, for the $K \Rightarrow \pi$ form factor, will be almost entirely eliminated, leading to a determination of V_{us} within 0.3% uncertainty. Calculating the two-pion decay amplitude of the K-meson, thereby verifying the Standard Model understanding of CP violation, has been one of long-term goals of lattice QCD. In 2012, the first ever calculation of the I=2 decay amplitude treating the two pion final state directly and with physical kinematics was reported by the RBC collaboration:

Re A_2 = $1.381(46)_{stat}(135)_{sys}(207)_{cont}$ $x10^{-8}$ GeV, Im A_2 = $-6.54(46)_{stat}(72)_{sys}(98)_{cont}$ $x10^{-13}$ GeV . This year, a preliminary result after taking the continuum extrapolation is presented as Re A_2 = $1.345(84)_{stat}(135)_{sys}(0)_{cont}$ $x10^{-8}$ GeV, Im A_2 = $-6.32(28)_{stat}(72)_{sys}(0)_{cont}$ $x10^{-13}$ GeV, where the statistical error, which includes the one associated with continuum extrapolation, is much reduced for Im A_2 . He finally reported 2+1+1 flavor simulations as one of future projects in kaon physics.

Tom Blum reported lattice calculation of the hadronic contributions to the muon anomalous magnetic moment, a_{mu} =(g-2)/2. He first discussed the status of lattice calculations for the hadronic vacuum polarization (HVP) contribution. Since the statistical error associated with the lattice results for the HVP is still much larger than model estimations, his group employed a new error reduction technique, AMA, developed at RBRC, to achieve 2.6-20 times error reduction for the same cost as with

the previous calculation. Results with improved precision are expected soon. The hadronic light-by-light (HLbL) contribution is much more difficult to evaluate than HVP. He and his collaborators have worked on this problem for many years. In his talk, he reported that a non-zero signal was obtained for the first time in 2+1 flavor QCD with domain wall fermion at a=0.11 fm on 16^3 x 32 (x16) lattice with 420 MeV pion and 690 MeV muon masses. A very preliminary result gives a_{mu}(HLbL)=-15.7(2.3)x10^{-5} at the lowest non-zero momentum and the electric charge e=1, which is 5-10 time larger and opposite in sign from model estimates. At the lighter muon mass of 190 MeV, they obtain a_{mu}(HLbL)=-2.2(0.8)x10^{-5} . They are currently repeating the calculation on larger volumes and the results are expected in near future.

Brian Tiburzi described his work to employ lattice methods to explore electromagnetic properties of hadrons. He has already investigated the electromagnetic properties of charged pion and neutron. He reported results on the magnetic moment and polarizability of neutron, μ_n = -1.6(1) [μ_N] and α_E^n = 3(1) x 10^{-4} fm^3 , respectively, while their experimental values are μ_n = -1.9 [μ_N] and α_E^n = 11(2) x 10^{-4} fm^3 . Recently, he considered a charged scalar field in magnetic field to investigate Landau levels in lattice QCD. He also discussed via the sigma model analysis that the Dirichlet boundary condition is incompatible with the chiral symmetry breaking.

Ethan T. Neil reported results of lattice simulations to explore the technicolor theory as a candidate of beyond-standard-model theories. In particular, as a member of Lattice Strong Dynamics (LSD) collaboration, he discussed a property of SU(3) color gauge theories with many (N_f) flavors, by comparing theories with N_f =2 and N_f=6. He found that the S-parameter in N_f =6 is smaller than that in N_f =2, suggesting that the S-parameter in N_f =6 might be consistent with the experimental constraint, and that masses of vector and axial-vector mesons become almost equal toward the chiral limit, indicating that the chiral symmetry might be restored. He will extend this phenomenological investigation to the N_f =8 case, to find a good candidate for the technicolor theory. He also presented his research on composite dark matters.

Tomomi Ishikawa, after briefly summarizing RBRC activities of B physics on the lattice, reported his results of B meson decay constants and mixing parameters using the static quark action. Employing 2+1 DWF QCD ensembles generated by RBC/UKQCD collaboration at two lattice cutoffs (1/a=1.7 and 2.3 GeV) with several pion masses ranging between 290 and 420 MeV, he took both chiral and continuum limits

simultaneously and obtained, for example, B meson decay constant, f_B = 222(31) MeV, and the ratio of B-meson mixing amplitudes, ξ= 1.218(65). For the decay constant $1/m_b$ correction gives a large error of O(10%), while 3.3% statistical error, 2.9 % chiral-continuum extrapolation error, and 2.2 % $1/m_b$ correction appear for ξ, whose total error is 5.3%. He finally discussed future prospects of this research such as error reduction by AMA, removal of chiral extrapolation by physical point ensembles, non-perturbative renormalization and inclusion of $1/m_b$ correction.

Christopher Kelly reported his ambitious project, the direct lattice calculation of the I=0 two pion decay amplitude of the kaon, which is important to explain the ΔI=1/2 rule and the direct CP violation in the standard model. To overcome technical difficulties in the direct calculation of I=2 decay amplitude, RBC/UKQCD collaborations introduced a special boundary condition, called G-parity boundary condition, whose properties was reported in his talk. As an exploratory study, he generated a gauge ensemble with G-parity boundary condition at 1/a=1.7 GeV on 16^3 x 32 lattice with 420 MeV pion mass, and demonstrated the correct dispersion relation of pion and expected stabilities of kaon mass and B_K. Currently, an ensemble with G-parity on larger volume, 32^3 x 64, is being generated.

Sergey Syritsyn described exploration of nucleon structure on a lattice. He presented results on vector form factors of nucleon, showing that both isovector Dirac radius and anomalous magnetic moment agree with experimental values at the physical pion mass by the extrapolation through the heavy baryon chiral perturbation theory (HBChPT) if contaminations from excited states are carefully removed. A similar tendency was reported for the nucleon axial charge, where other lattice calculations tended to undershoot the experimental value. He also calculated the isovector quark moment fraction, which agrees with the experimental value, and quark spin and angular momentum inside nucleon to understand the origin of the nucleon spin, known as the proton spin puzzle.

Future of computing at RBRC

Norman Christ discussed the future of computing at RBRC. The partnership with IBM has been very successful, leading to the development of QCDOC and QCDCQ as the in-house computer and at the same time providing the gateway to large DOE machines. While the possibility of commercial collaborations with IBM, Intel and others are being explored, the likely time scale for realization will be 4-5 years.

For the near future time frame of 2015/16, he suggested that exploiting the next generation of Intel Xeon Phi accelerator presents an attractive possibility. He proposed to assemble a system with 1,000 nodes with 1 Pflops sustained performance as a RIKEN, BNL and USQCD joint effort. Collaboration with Edinburgh was envisaged, and work with Brookhaven's Computational Science Center (CSC) and USQCD would play an important role.

Taku Izubuchi followed up by presenting his vision on the future of the RBRC computing group as center of excellence for young lattice physicists. Building upon the excellent track record, he is confident that the group will continue to attract excellent members and collaborators, working on excellent subjects spanning the Standard Model, nuclear physics, and Beyond Standard Model. He emphasized the essential need of in-house computers for exploring new ideas quickly, and hence of securing the follow-up to QCDCQ system in the 2015/16 time frame.

Assessment of computing at RBRC

Achievements in this year by the computing group at RBRC are well balanced between mainstream calculations of lattice QCD such as physical point simulations, with which very precise values of hadron masses, decay constants, B_K and K_{l3} form factors, can be obtained, and more difficult and challenging calculations such as muon g-2 light-by-light contribution, kaon decay to two pions for both I=0 and 2 channels, and the $K_L - K_S$ mass difference. This is the strongest and unique point of the RBRC lattice group, which now becomes one of the excellent research groups of lattice QCD in the world, as a part of the RBC collaboration. For example, All Mode Averaging (AMA), developed mainly at the RBRC, brings great computational benefits not only internally to the RBC collaboration but also to worldwide lattice QCD research groups. In addition, there appears several different projects at RBRC such as nucleon physics and the beyond standard model physics, which add new features to this group.

Basically the RBRC group should follow the current research projects and styles, in order to continue producing excellent results. The Review Committee, however, would like to suggest that the RBRC computing group could enlarge research areas including finite temperature and density QCD as well as hadron interactions, taking advantages of the RBRC/BNL, which has strong theory/lattice groups and RHIC experimental groups. We believe that these enlargements make the RBRC computing group a unique and irreplaceable group in the world.

D. Astrophysics

Dr. Toru Tamagawa from the High Energy Astrophysics Laboratory of the RIKEN Nishina Center gave an overview of astrophysics research at RIKEN and presented the case for his participation in the Large Synoptic Survey Telescope (LSST). Among the science themes of LSST are the study of the origins of Dark Energy and Dark Matter and the exploration of the transient optical sky. BNL is one of the core institutes in LSST and is leading the development of a multi-gigapixel focal plane detector for the telescope. Dr. Tamagawa proposes to send post-docs to RBRC to contribute to the construction of the camera. In addition, his group can provide optical filters for the camera.

The committee finds the physics motivation for the proposed broadening of scope of the RBRC mission to be compelling. The proposed initiative leverages the RBRC relationship. The committee advises that care should be taken in initiating this new effort that the existing hadronic physics program, the essential basis of RBRC, is not negatively affected in any way.

IV. Future perspective

Brookhaven ALD Berndt Mueller reported on the future plan for RHIC and eRHIC. After summarizing the RHIC collider performance, in terms of luminosity achieved and versatility of operation, he reported on the status of the detector collaborations (PHENIX and STAR) and described the main discoveries made at RHIC. In addition to establishing the 'perfect liquid' scenario and 'jet quenching' they include, together with measurements at the LHC, that heavy quarks recombine when the QGP hadronizes, indicating deconfinement before hadronization. In addition, the experiments with polarized p-p collisions have now established that approximately 20% of the proton spin resides in gluons.

Important for the program are the machine and detector upgrades planned for the next 5 years. They include on the accelerator side bunched electron cooling to increase the luminosity by at least an order of magnitude at low energy (down to 2.5 GeV/nucleon beam energy) as well as the STAR HFT (Heavy Flavor Tracker) and the PHENIX MPC-EX (Muon Piston Calorimeter EXtension). With these upgrades the physics possibilities with the already successful RHIC Beam Energy Scan can be very significantly improved, promising a strong statement on the (non-)existence of a critical

point in the QCD phase diagram in the energy range between $\sqrt{s}$ = 5 GeV and 200 GeV. With the new vertex detectors and calorimeters STAR and PHENIX have now much improved capabilities for heavy flavor and photon measurements which should also lead to major new physics results between 2014 and 2018-2019.

An important change planned for PHENIX is the transition, in 2019 and 2020, to a new, calorimetry based experiment (sPHENIX) with a new magnet (the BABAR solenoid). This is a major and ambitious change, practically a new experiment, with the main aim to provide new insights into the microscopic origin of jet quenching and color screening for different quarkonia. In the version presented to the committee sPHENIX has no charged particle tracking in addition to that of the existing VTX detector. This is an issue that may be revisited, especially in view of the plans of a transition to eRHIC described below.

Concerning the strategy for the transition to eRHIC as a major new QCD Facility at BNL, the ALD outlined in a concise way its goals: create an affordable (< 600 M$) version of an electron-ion collider (EIC) based on the re-use of much of the RHIC infra-structure. The eRHIC program should be focused on the science program outlined in the EIC white paper and be upgradable to higher energy and luminosity.
In its basic configurations it will be an Energy-Recovery Linac + Ring design that uses the existing polarized proton and heavy ion beams and RHIC tunnels as well as cryo-facility. In this fashion it is clear that the transition from RHIC to eRHIC also marks the end of RHIC as a heavy ion collider. This is considered as an important step to establish a new facility (eRHIC) and is strongly supported by the committee. Concerning detectors for eRHIC two interaction regions are part of the project. These could be suitably modified/upgraded versions of the STAR and sPHENIX detectors and LoI's from both collaborations provide benchmarks for this, including cost estimates. In addition, the EIC task force at BNL is invited to provide a similar LoI for an entirely new EIC detector. In either case the eRHIC detector(s) will be designed and built by new collaborations.

Overall, this looks like a coherent and convincing case and BNL management together with the eRHIC community needs to make this strongly at the next NSAC Long Range Plan.

Dr. Thomas Ludlam gave a comprehensive overview of the future detector upgrades in the scenario where RHIC ceases operation around 2020 and eRHIC starts operation around 2025.

Dr. Yuri Kovchegov presented the science case for EIC based on the study of nucleon structure and of QCD physics in a nucleus. He posed three big questions: How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? Where does the saturation of gluon densities set it? How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? He concluded that EIC would allow us to address the spin puzzle and map out the nucleon at an unprecedented level of precision. EIC may complete the discovery of saturation/CGC physics and study its properties. Both achievements would significantly improve our understanding of QCD in nucleons and nuclei.

Dr. Taku Izubuchi and Dr. Norman Christ presented their perspective on the future of lattice QCD. They are seriously considering a 1Pflops machine assembled from commercial accelerators on the timescale of 2015/2016. X. Ji has proposed direct computation of parton distributions.

IV. Overall evaluation of the program and recommendations

- In general, the committee is very positively impressed. The RBRC enterprise is healthy and strong.
- RBRC remains a unique, highly successful model for international scientific collaboration. The growing, worldwide network of RBRC faculty at research universities and laboratories is very impressive.
- The young people in RBRC are a dynamic, enthusiastic, and effective group.
- RBRC workshops continue to play a major role in the evolution of the RHIC scientific community.
- It is important that the PHENIX collaboration produce spin results competitive with those from STAR in a timely way. RBRC can play a key role in this effort.
- We commend RBRC leadership for maintaining a constant staffing level in a constrained fiscal climate.
- In terms of RHIC operations, the RHIC II era has been realized and is in a productive phase.
- Further, the recent RHIC-spin running has yielded a substantial amount of new data so that the total integrated luminosity of 630 pb^{-1} (at average polarization of 50%) has been reached in running from 2009 through 2013.
- The Laboratory has developed a sound plan for the future based on the electron-ion collider eRHIC starting operation in the mid-2020s. eRHIC would provide dramatic new capabilities to explore proton spin and nuclei in the region dominated by gluons and sea quarks.
- A crucial next step on the realization path for the electron-ion collider is to receive a green light from the US nuclear physics community at the next long range planning exercise. The committee commends BNL management for coherently working with Jefferson Lab to develop and articulate the strongest science case for the next QCD machine in the U.S.

Appendix

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Li Keran **Nuclei as heavy as bulls** ©CCASTA
Through collision
Generate new states of matter.
T.D. Lee

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