BNL-99621-2013

RIKEN/RBRC Workshop

Scientific Review Committee Meeting

November 6-8, 2012

Proceedings of RIKEN BNL Research Center Workshop

Volume 112

RBRC

RIKEN BNL Research Center

DISCLAIMER

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002, 2007 and again in 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.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has over 95 graduates (Fellows and Post-docs) of which approximately 40 theorists and 20 experimenters 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. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are over one hundred proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. QCDOC was decommissioned in May 2012. The next generation computer in this sequence, QCDCQ (600 Teraflops), is currently operational and is expected to produce many more interesting discoveries in the future.

N. P. Samios, Director
November 2012

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

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RBRC Scientific Review Committee Meeting

November 6 - 8, 2012

Brookhaven National Laboratory, Upton, NY 11973

The twelfth evaluation of the RIKEN BNL Research Center (RBRC) took place on November 6 – 8, 2012 at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC), present at the meeting, were: Prof. Wit Busza, Prof. Miklos Gyulassy, Prof. Kenichi Imai, 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.

N. P. Samios

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RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510, Room 2-160
November 6, 7, & 8, 2012
Agenda

Committee Members

Busza, Wit	busza@mit.edu
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Imai, Kenichi	ken1.imai@gmail.com
Milner, Richard	milner@mit.edu (RBRC SRC Chair)
Mueller, Alfred	amh@phys.columbia.edu
Prescott, Charles Young	prescott@slac.stanford.edu
Ukawa, Akira	ukawa@ccs.tsukuba.ac.jp

Tuesday, November 6, 2012

6:30 PM Executive Dinner (Chachama Grill, Patchogue)

Wednesday, November 7, 2012 – Room 2-160, Building 510

8:00 AM to 9:00 AM *SRC Executive Session and Continental Breakfast*

8:00 AM	Welcome	Samuel Aronson
8:10 AM	RIKEN Overview	Hideto En'yo
8:25 AM	RBRC Overview	Nicholas Samios
8:40 AM	SRC Executive Session	

Open Session – Hamilton Seminar Room, Building 555

9:00 AM to 10:15 AM EXPERIMENTAL GROUP PRESENTATIONS – Abhay Deshpande, CHAIR

9:00 AM	*RBRC Exp. Group: Overview, Detector Upgrade and HI physics*	Yasuyuki Akiba
9:15 AM	*Probing Hot and Dense Matter with Charm and Bottom Measurements with PHENIX VTX Tracker*	Rachid Nouicer
9:30 AM	*Flow measurement of charged hadrons and heavy flavor electrons with PHENIX VTX tracker*	Maki Kurosawa
9:45 AM	*Measuring the charged hadrons and heavy flavor electrons with VTX*	Chin-Hao Chen
10:00 AM	*High p_T hadrons with the PHENIX VTX detector*	Stefan Bathe

10:15 AM to 10:45 AM COFFEE BREAK

10:45 AM to 12:30 PM EXPERIMENTAL GROUP PRESENTATION – Yasuyuki Akiba, CHAIR

10:45 AM	*Experimental Group Overview*	Abhay Deshpande
11:00 AM	*Reducing systematic uncertainties: Understanding false asymmetries from beam dynamics at PHENIX*	Kieran Boyle

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11:15 AM *The sPHENIX Forward Upgrade*
Joseph Seele
11:30 AM *SPIN measurement with FVTX*
Xiaorong Wang
11:45 AM *Run12 Spin PHENIX Report*
John Koster
12:00 PM *Sea Quark Polarization Measurement in Forward Rapidity via W-Boson Production*
Itaru Nakagawa
12:15 PM *Inclusive cross section and single transverse-spin asymmetry of very forward neutron production*
Yuji Goto

12:30 PM to 1:30 PM *SRC Executive Session - Working Lunch (Room 2-160, Building 510)*

1:30 PM to 3:10 PM THEORY GROUP PRESENTATION – Robert Pisarski, CHAIR

1:30 PM *Theory Group Overview*
Larry McLerran
1:50 PM *CGC predictions for LHC energies*
Adrian Dumitru
2:10 PM *Particle correlations in hadron-nucleus collisions as a signature of high parton density*
Anna Stasto
2:30 PM *Electromagnetic and Heavy Flavor Probes of Quark Gluon Plasma*
Rainer Fries
2:50 PM *Overview of Current Research*
Derek Teaney

3:10 PM to 3:50 PM Coffee Break

3:50 PM to 5:00 PM THEORY GROUP PRESENTATIONS – Robert Pisarski, CHAIR

3:50 PM *The Ubiquitous Chiral Magnetic Waves*
Ho-Ung Yee
4:10 PM *The Higgs boson mass – its meaning for the Standard Model*
Fedor Bezrukov
4:30 PM *Baryon number conservation and limited acceptance vs. cumulants of net proton distribution*
Adam Bzdak
4:40 PM *Evolution of singularities in thermalization of strongly coupled gauge theory*
Shu Lin
4:50PM *Columbia plot and QCD thermodynamics in effective model*
Koji Kashiwa

7:00 PM Reception and Dinner (Three Village Inn, Stony Brook)

Thursday, November 8, 2012 – Room 2-160, Building 510

8:00 AM to 8:45 AM *SRC Executive Session and Continental Breakfast*

Open Session – Hamilton Seminar Room, Building 555

8:45 AM *Strongly Interacting Matter in Heavy Ion Collisions*
Jinfeng Liao

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9:00 AM to 11:00 AM	COMPUTING GROUP PRESENTATIONS – Taku Izubuchi, CHAIR	
9:00 AM	*Computing Group Overview*	Taku Izubuchi
9:25 AM	*The two-pion decay and mixing of neutral K mesons*	Norman Christ
9:45 AM	*RBRC/BNL BGQ Computers and LQCD Simulations*	Robert Mawhinney
10:00 AM	*Electroweak Properties of the Nucleon from Lattice QCD*	Brian Tiburzi
10:15 AM	*Exploring Full QED Effects through Reweighting*	Tomomi Ishikawa
10:30 AM	*Nucleon Electric Dipole Moment in Nf=2+1 Lattice QCD*	Eigo Shintani
10:45 AM	*Precise constraints on CP violation from lattice QCD*	Christoph Lehner

11:00 AM to 11:45 AM	Thomas Roser Presentation *RHIC, the next decade, and eRHIC*
11:45 AM to 12:30 PM	Interviews (Room 2-160 and Room 2-95)
12:30 PM to 1:30 PM	*SRC Executive Session - Working Lunch*
1:30 PM to 3:00 PM	Interviews (Room 2-160 and Orange Room, 510 Lobby)
3:00 PM to 4:15 PM	*SRC Executive Session with Coffee Break*
4:15 PM to 5:00 PM	Closeout/Adjourn

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RBRC Scientific Review Committee Membership 2012

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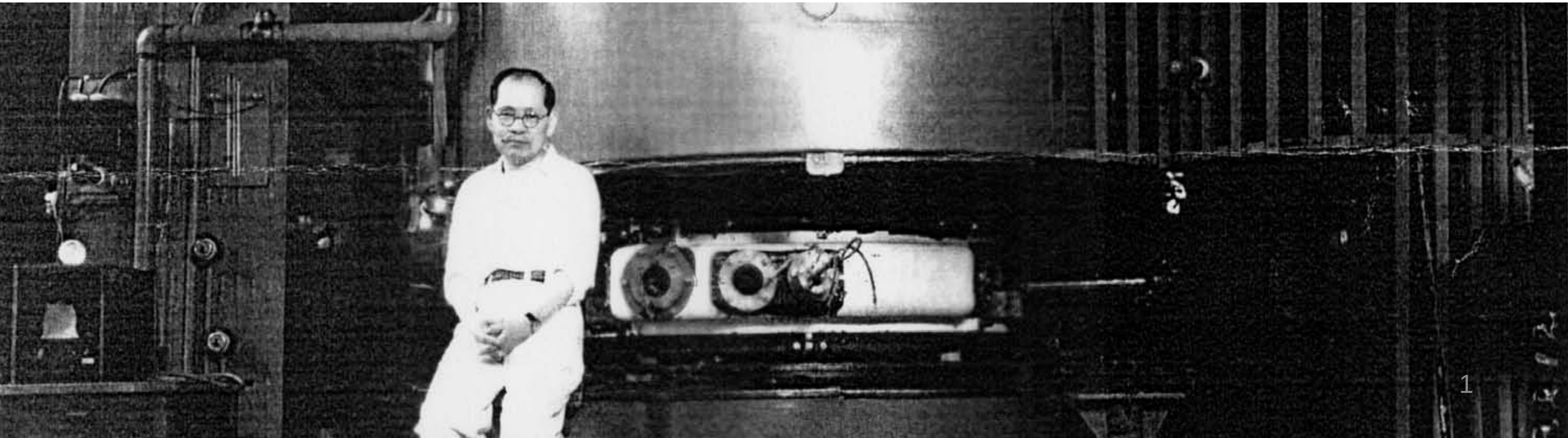
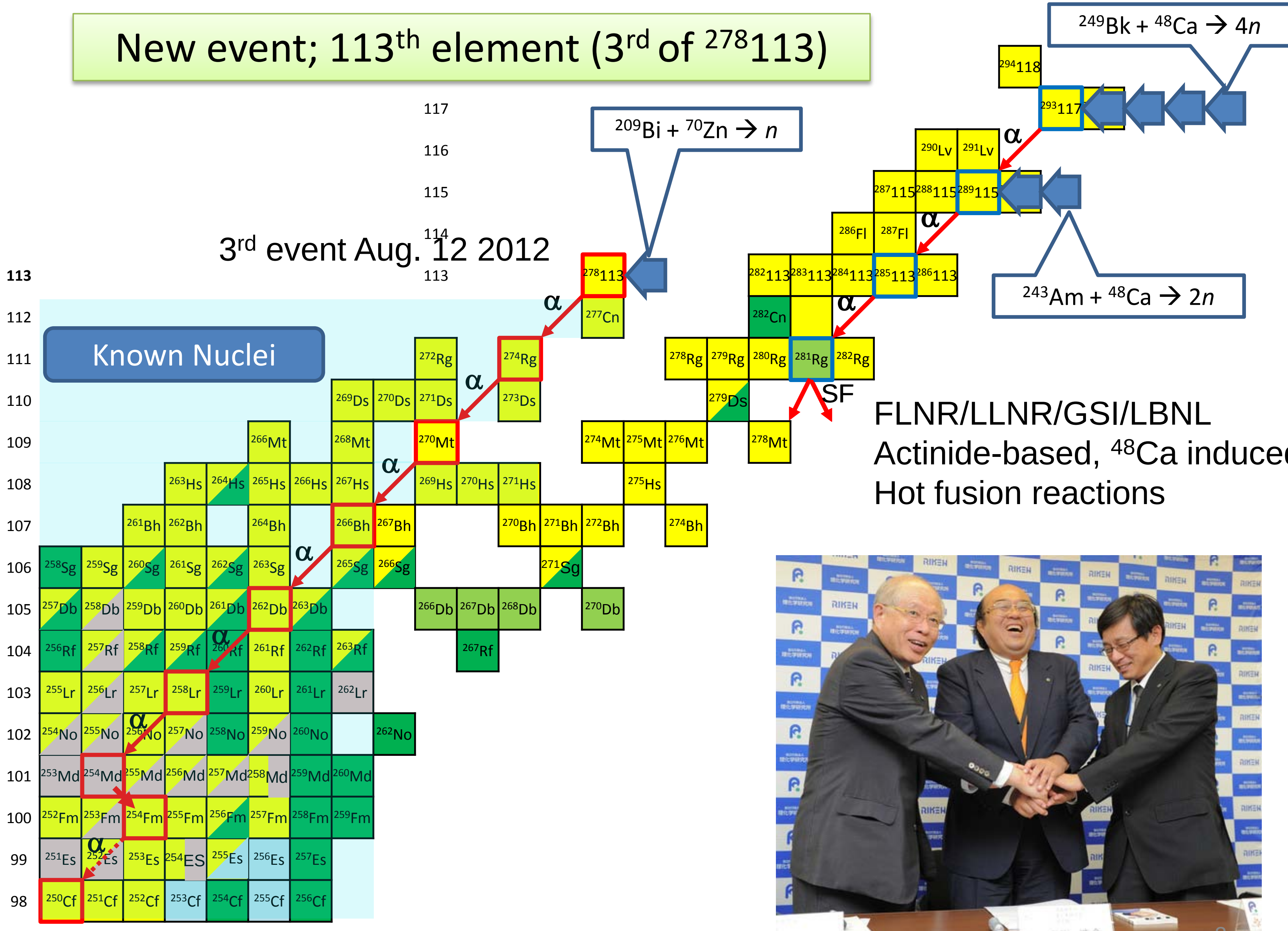
RIKEN OVERVIEW

November 7^{th} 2012
RBRC - SRC
Hideto En'yo
RIKEN Nishina Center

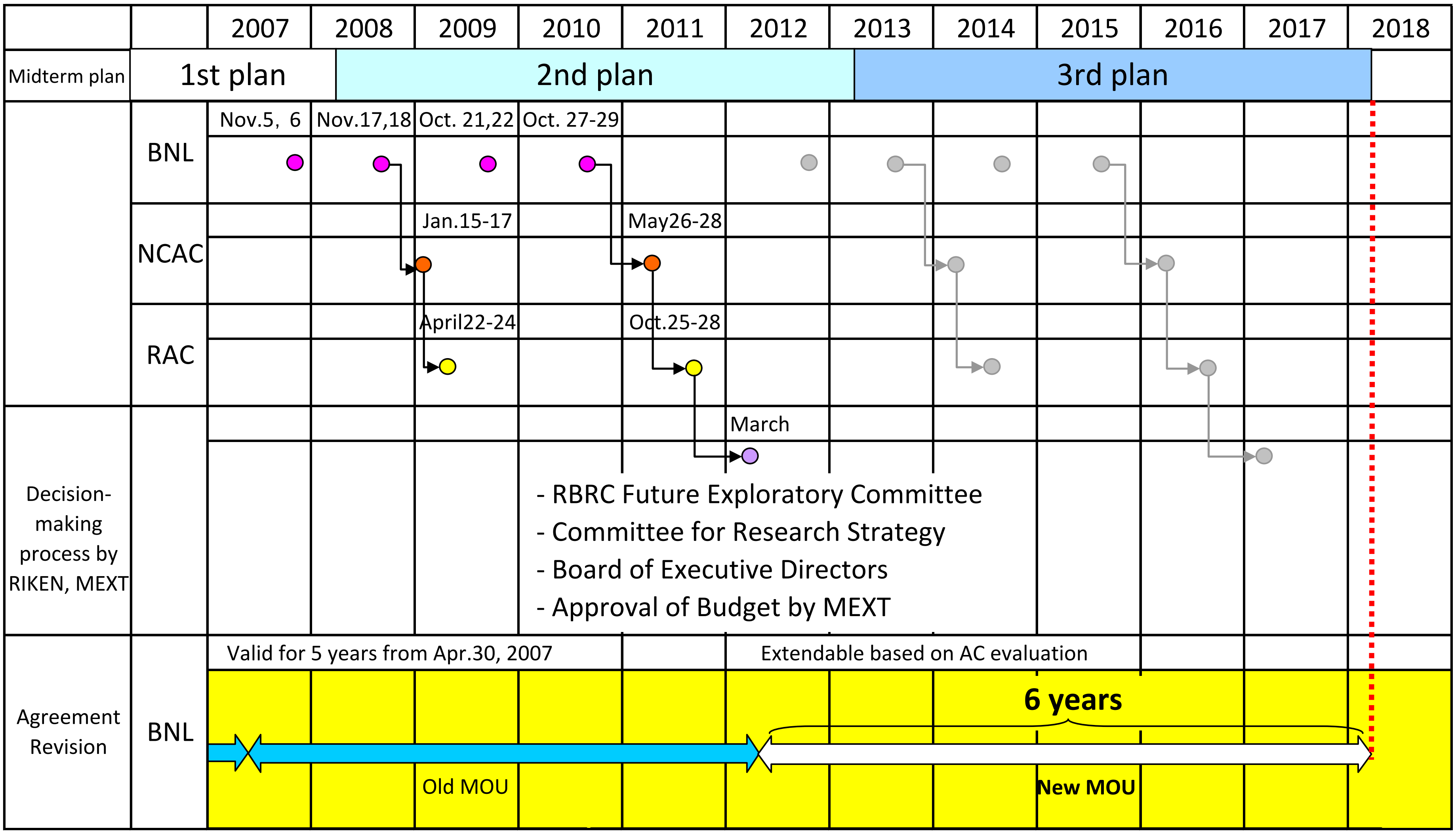


New event; 113th element (3rd of ^{278}113)



FLNR/LLNR/GSI/LBNL
Actinide-based, ^{48}Ca induced
Hot fusion reactions

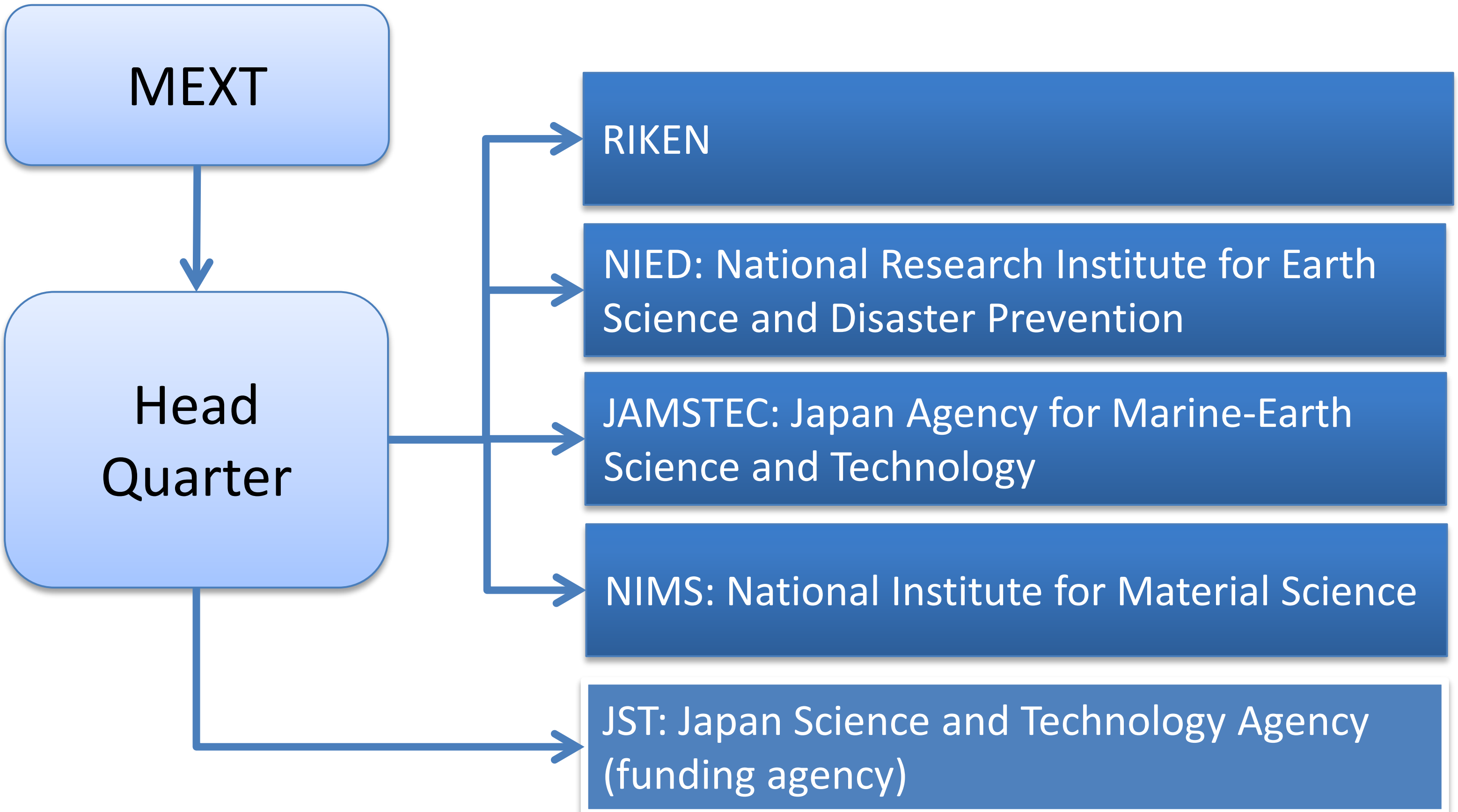
Schedule of BNL-SRC, RNC-AC, and revision of the agreement with BNL



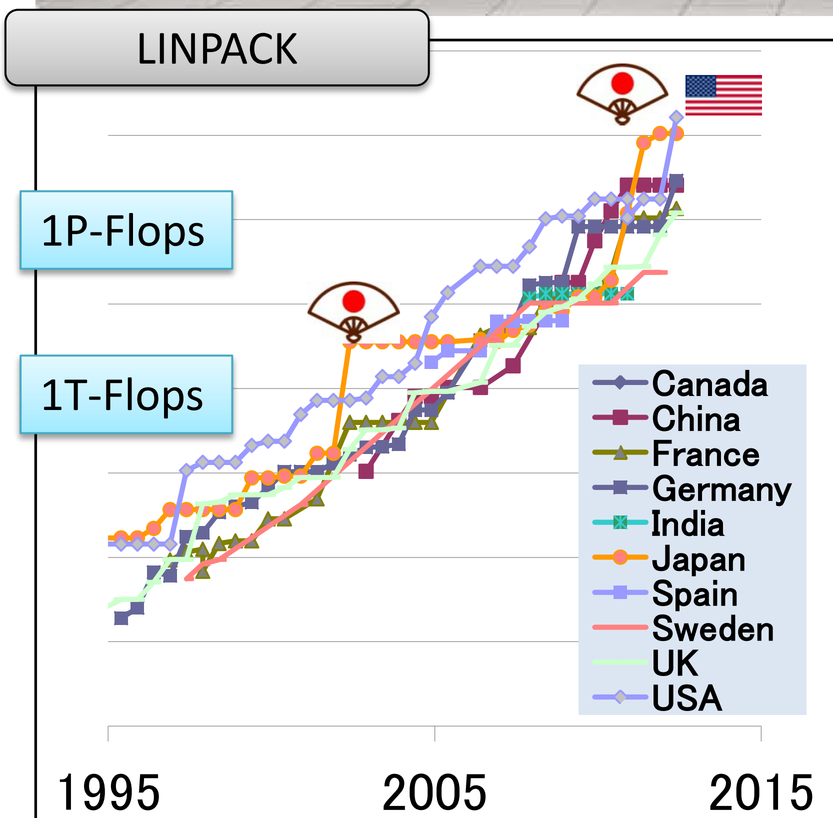
*Extendable based on AC evaluation and Decision Making Process by RIKEN

Unification of 5 Independent Administrative Institutions

To be effective from JFY2014

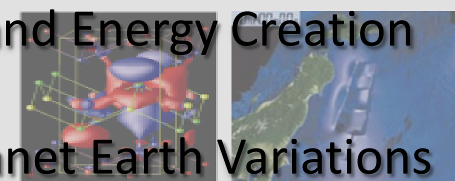


K-computer (RIKEN, Kobe) Operational



Strategic Programs for Innovative Research (Governmental initiative, 5M$/year/field)

Field 1: Predictable life science, healthcare and drug discovery foundation



Field 2: New Materials and Energy Creation

Field 3: Projection of Planet Earth Variations for Mitigating Natural Disasters

Field 4: Next-generation manufacturing technology

Field 5: The origin of matter and the universe

Strategic Programs for Innovative Research

Field 5:
The origin of matter and the universe

Shinya Aoki

Director

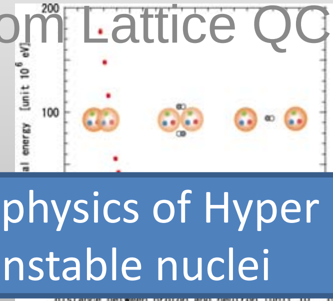
To apply, theorists have to declare 5-year deliverables for 5M$/year/field.

K computer costed 1200M$

Lattice QCD

NN, YN, 3body force

From Lattice QCD



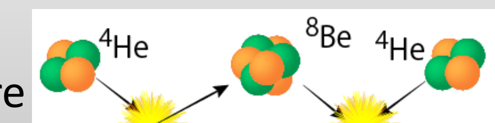
Unification of physics of Hyper nuclei and unstable nuclei

Yoshinobu Kuramashi

Tetsuo Hatsuda

Nuclear Structure

Hoyle state reproduction with Monte Carlo shell model



Bridge over cluster model-ers and shell model-ers

Takaharu Otsuka

Early Star Formation

Junichiro Makino

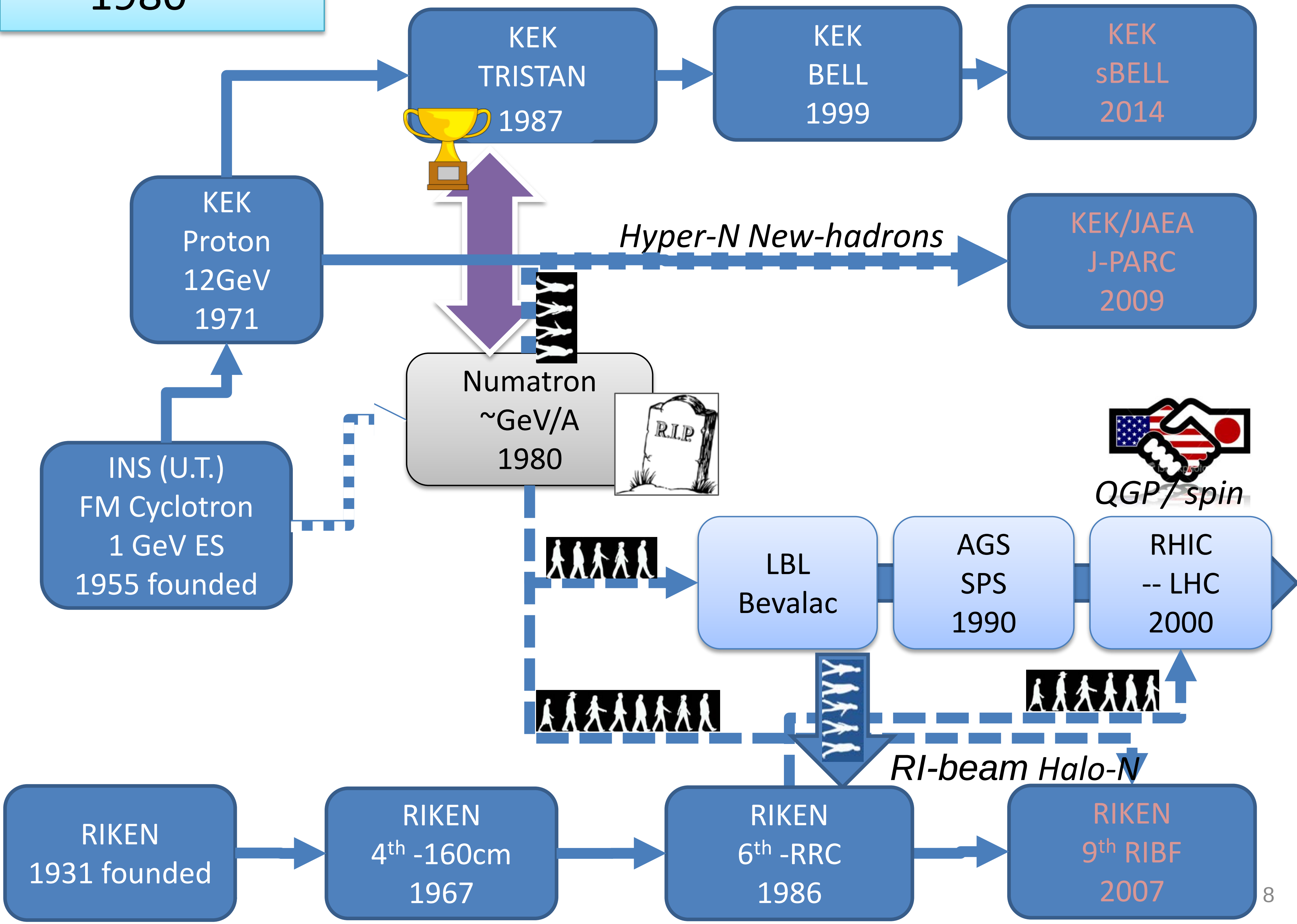
Supernova Explosion

Dai Shibata

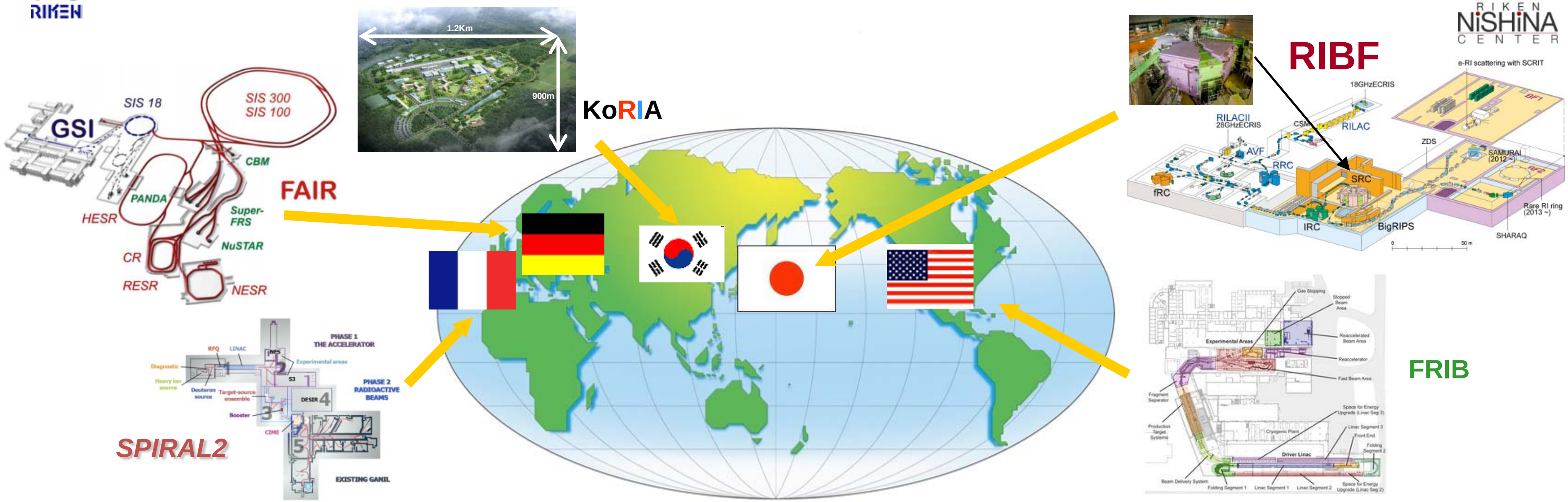
RIBF-FRIB-RHIC
from RIKEN's view point

(pickup from my DNP talk)

1980~~


KEK
TRISTAN
1987
KEK
BELL
1999
KEK
sBELL
2014
KEK
Proton
12GeV
1971
Hyper-N New-hadrons
KEK/JAEA
J-PARC
2009
Numatron
~GeV/A
1980
R.I.P
INS (U.T.)
FM Cyclotron
1 GeV ES
1955 founded
QGP/spin
LBL
Bevalac
AGS
SPS
1990
RHIC
-- LHC
2000
RI-beam Halo-N
RIKEN
1931 founded
RIKEN
4th -160cm
1967
RIKEN
6th -RRC
1986
RIKEN
9th RIBF
2007

Road Map of Nishina Center and International Competition

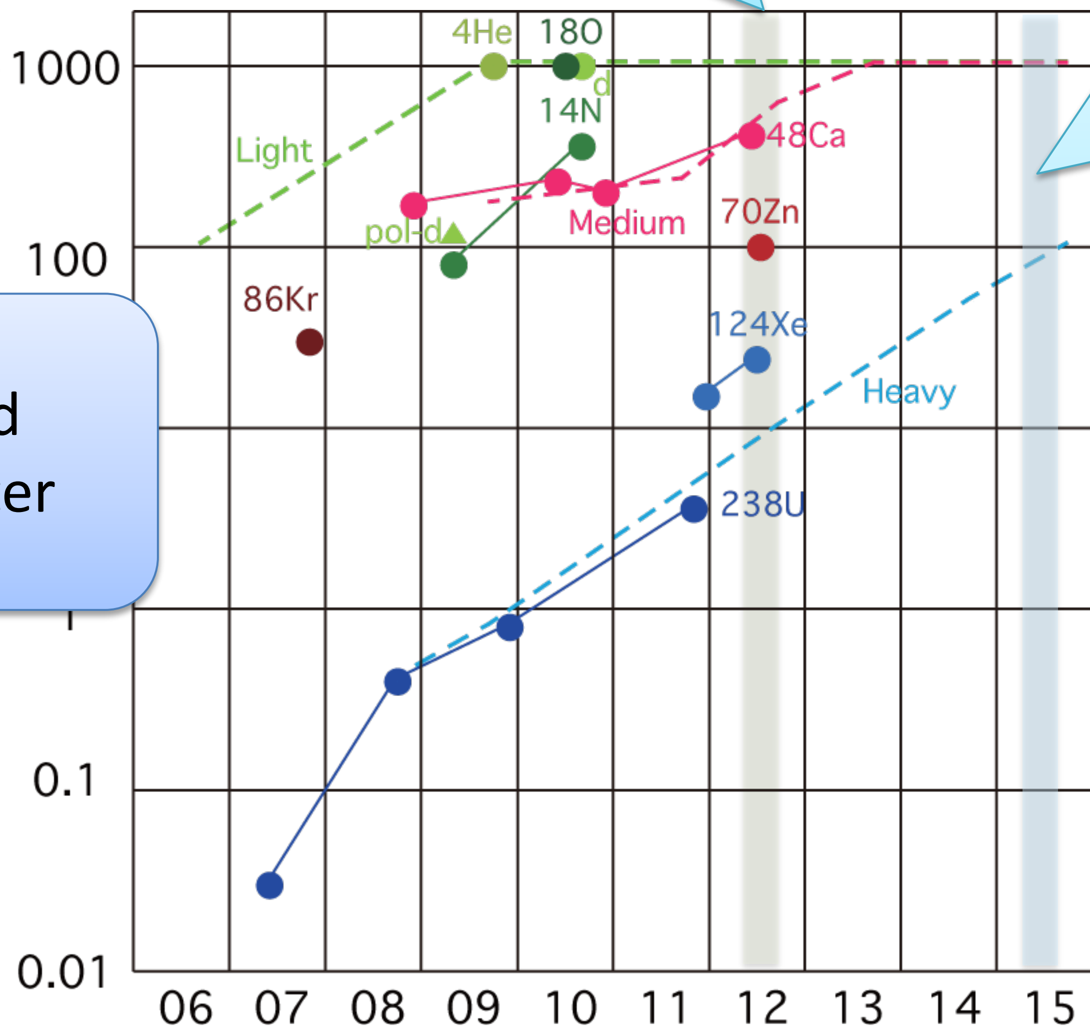


Japanese Era	H19	H20	H21	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31
CE	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
		Second Mid Term					Third Mid Term					Fourth	
Japan	**Start Exp**					**Completion of construction** RIBF has superiority				**Need new project to compete with the world**			
Germany	**Start Const.**				FAIR@GSI				**Start Exp**		**Completion of construction**		
USA							**Start Const.**			FRIB@MSU			**Start Exp**
France		**Start Const.**		SPIRAL2@GANIL				**Start Exp**			**RI beam Available?**		
Korea						**Start Const.**			RISP(KoRIA)		**Start Exp.**		

RIBF operation
Achieved Intensities and Projections

Current facility design value (approved Limit)

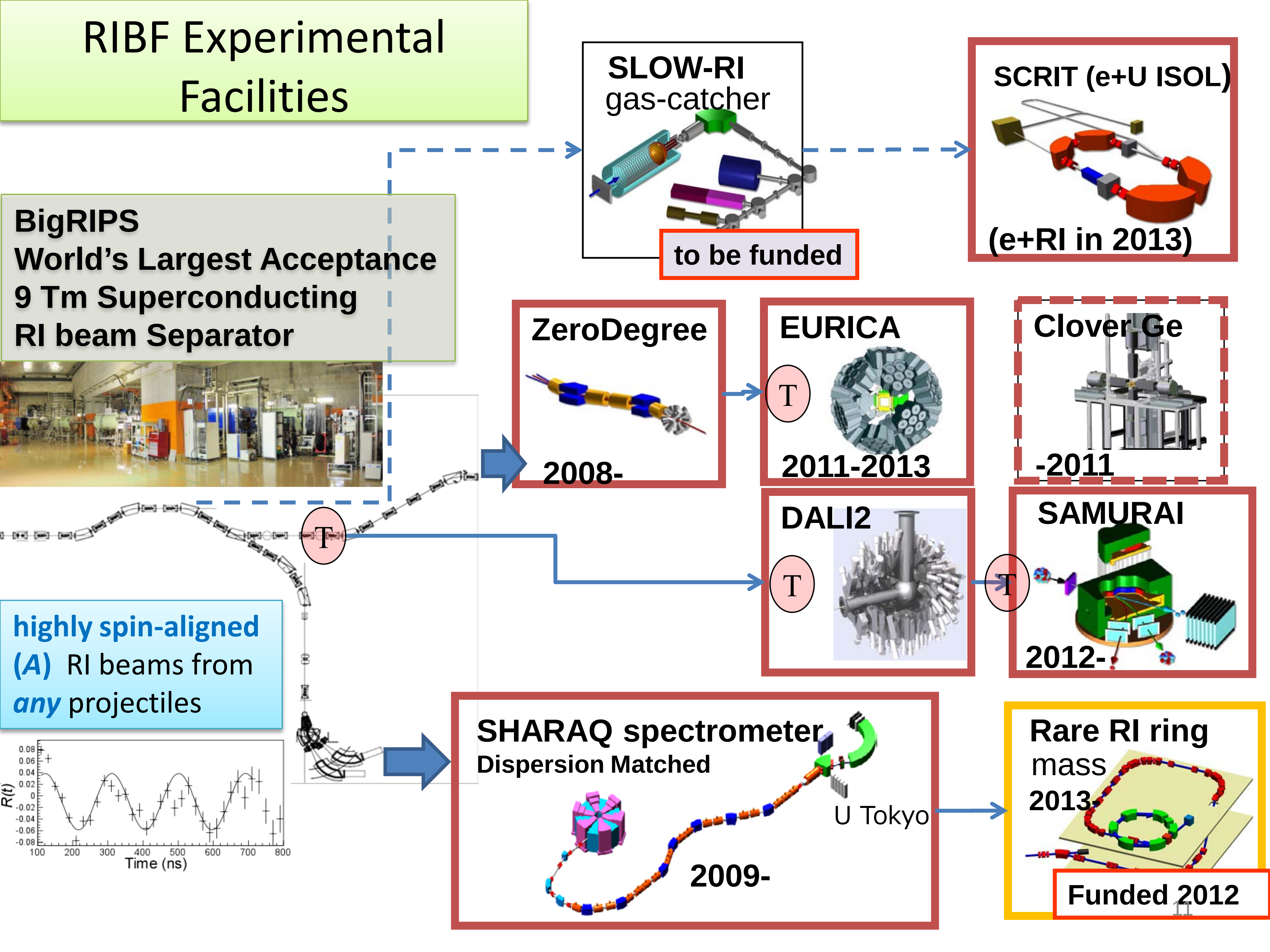
Present



Japanese Fiscal Year

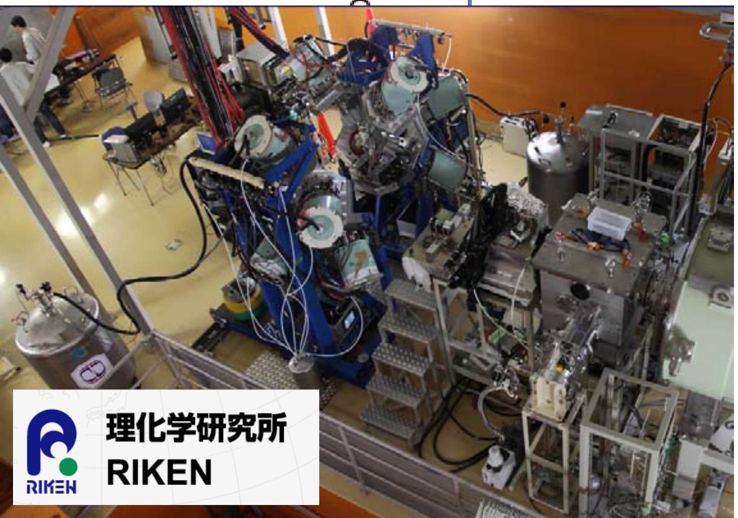
Head Quarter

1000pnA
for Light and Medium Nuclei
100pnA
for Heavy Nuclei
By 2015

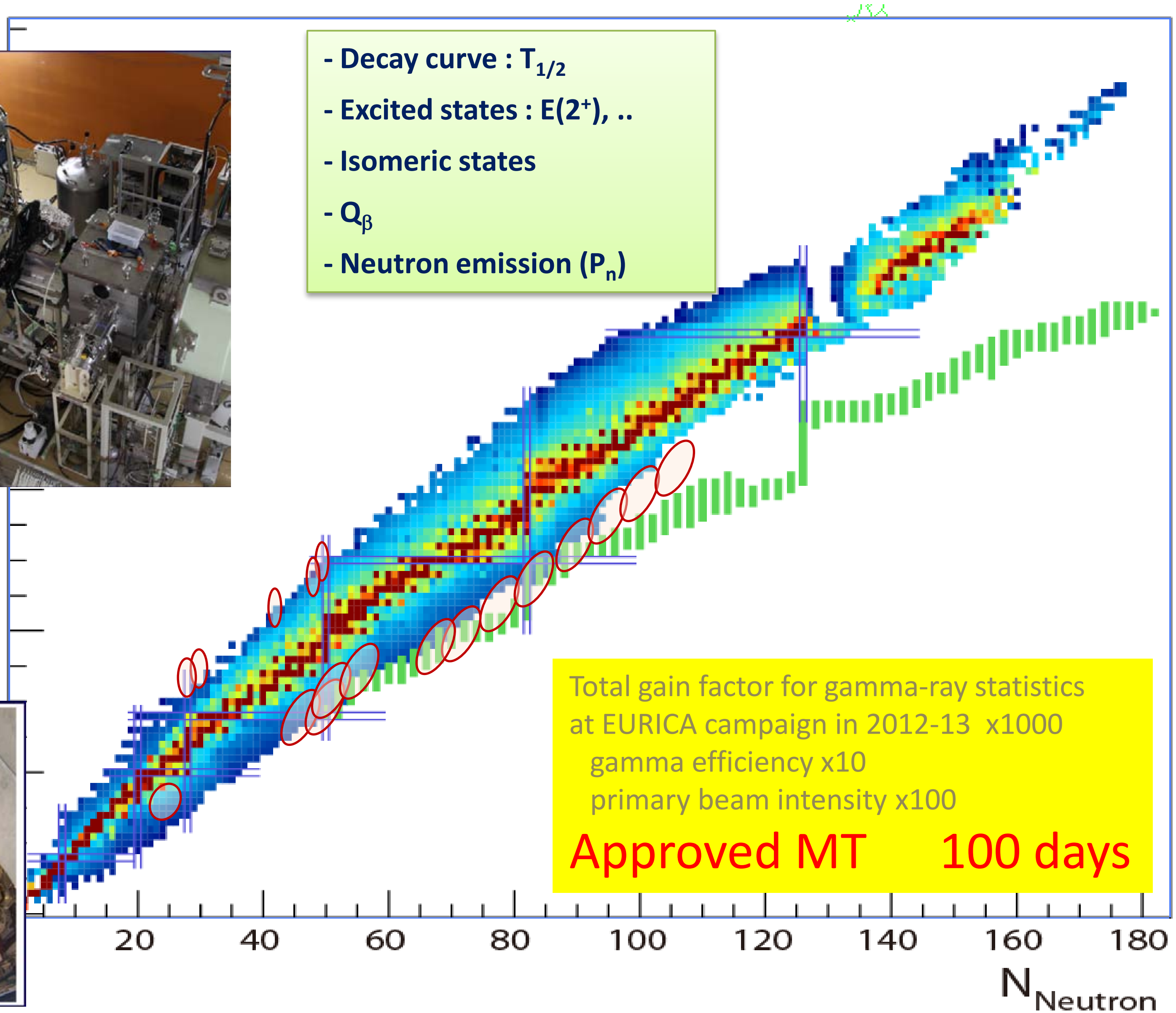

RIBF Experimental Facilities
SLOW-RI
gas-catcher
to be funded
SCRIT (e+U ISOL)
(e+RI in 2013)
BigRIPS
World's Largest Acceptance
9 Tm Superconducting
RI beam Separator
ZeroDegree
2008-
EURICA
2011-2013
Clover Ge
-2011
DALI2
SAMURAI
2012-
T
T
T
T
highly spin-aligned
(A) RI beams from
any projectiles
R(t)
Time (ns)
SHARAQ spectrometer
Dispersion Matched
U Tokyo
2009-
Rare RI ring
mass
2013-
Funded 2012
11

EURICA Project at RIBF

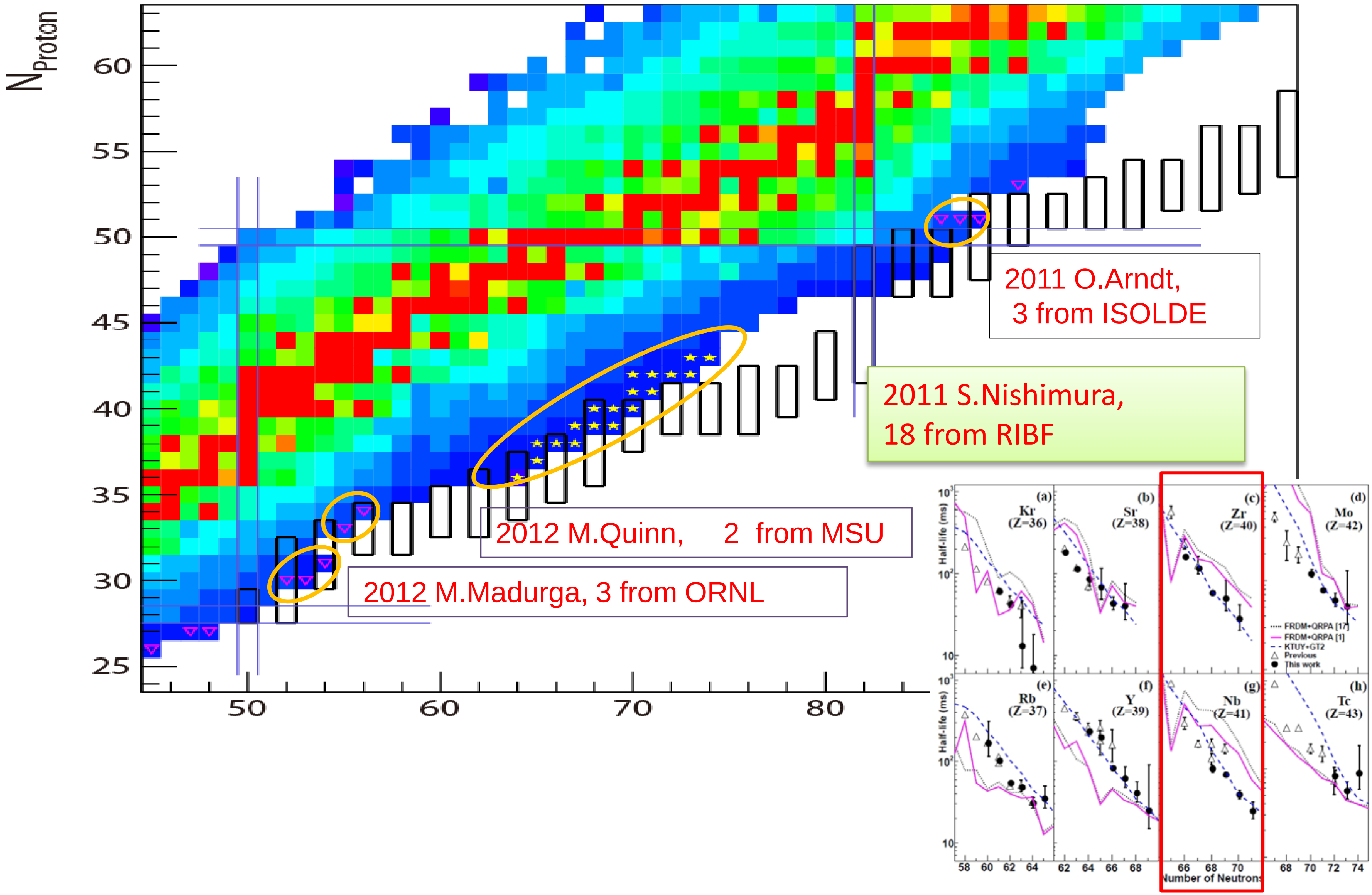
(EUROBALL RIKEN Cluster Array)



2011 Nov.

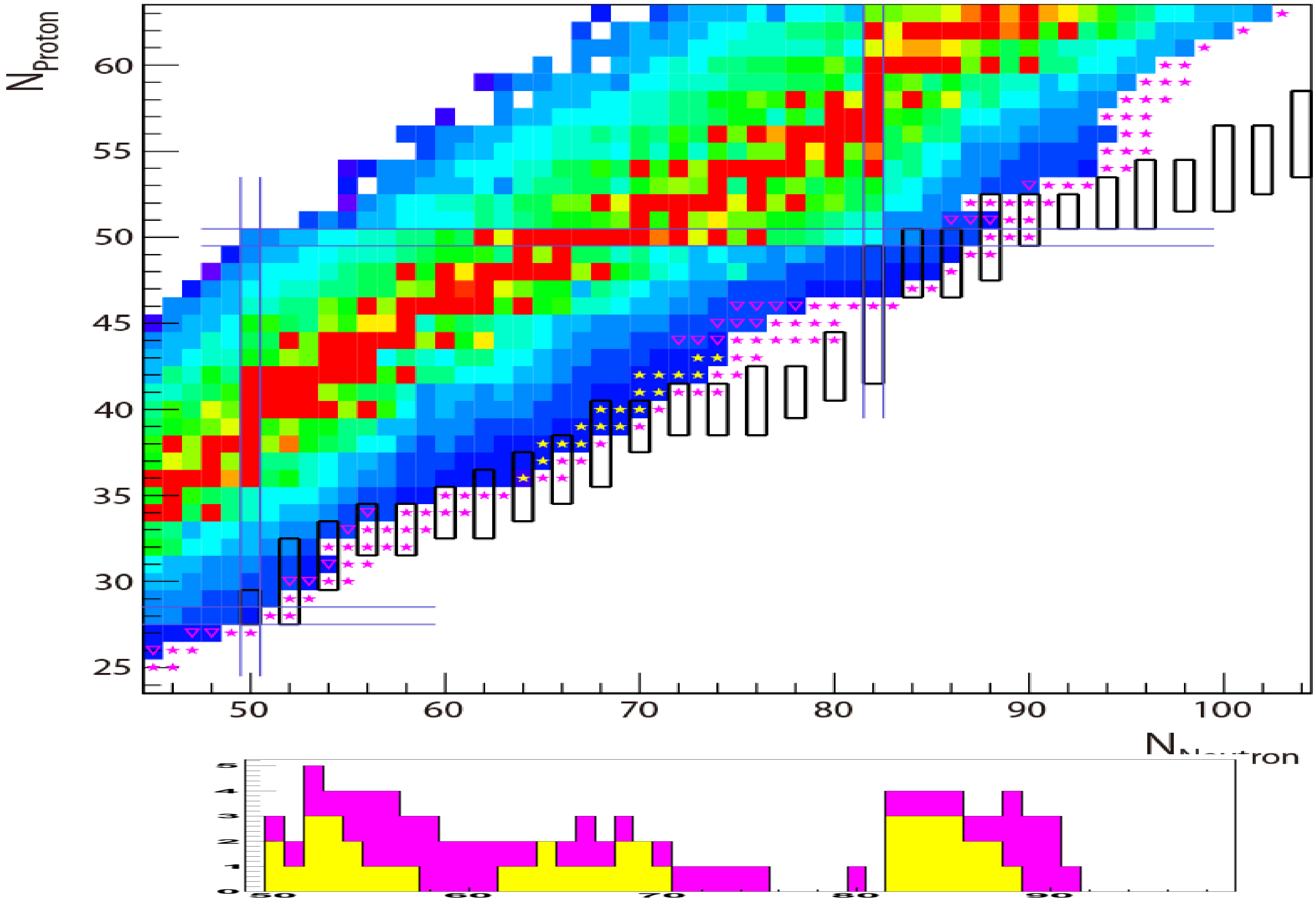


Beta-decay half-lives measured 2007-2012



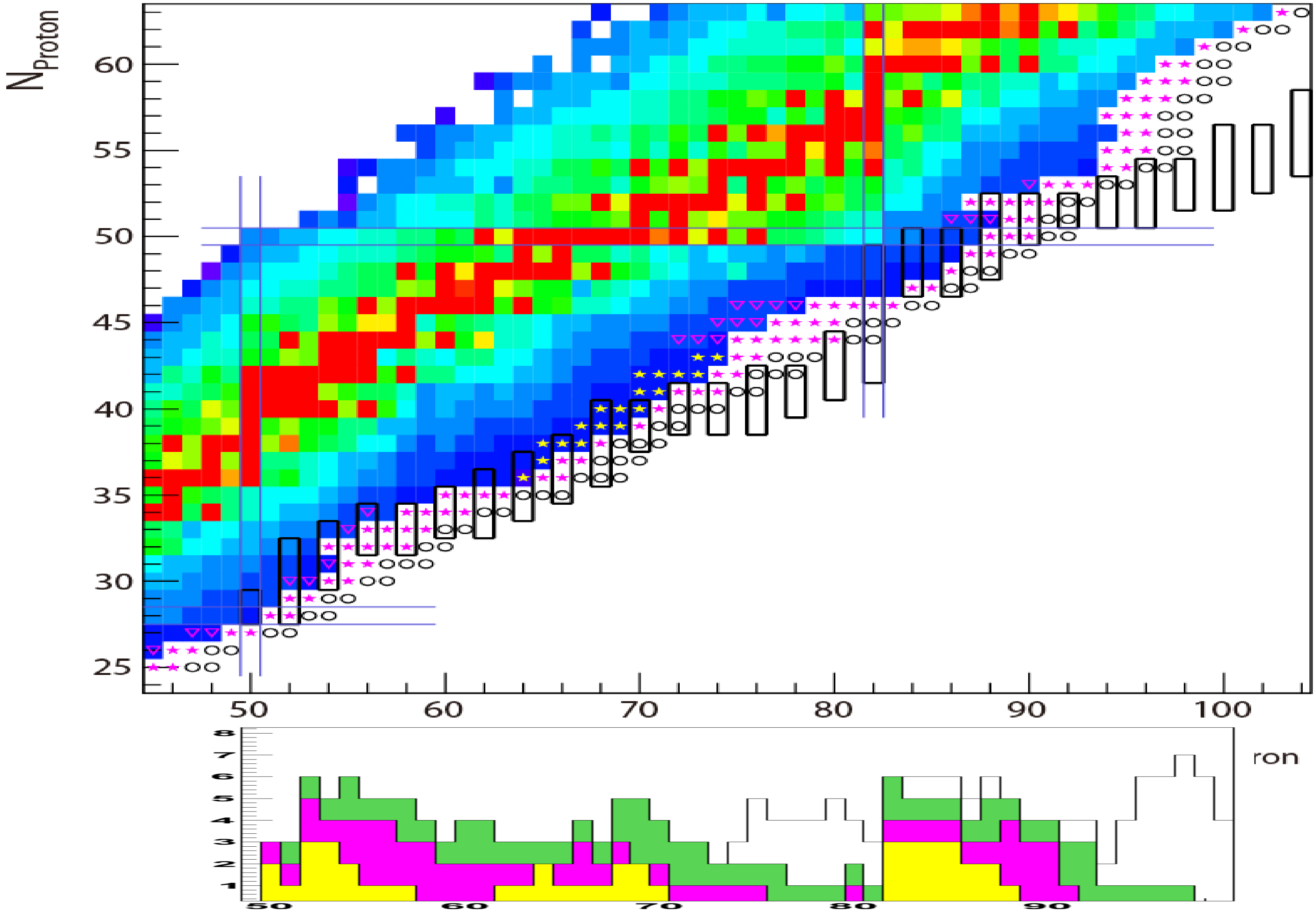
Decay Spectroscopy with EURICA

U-beam intensity ~ 5 pnA



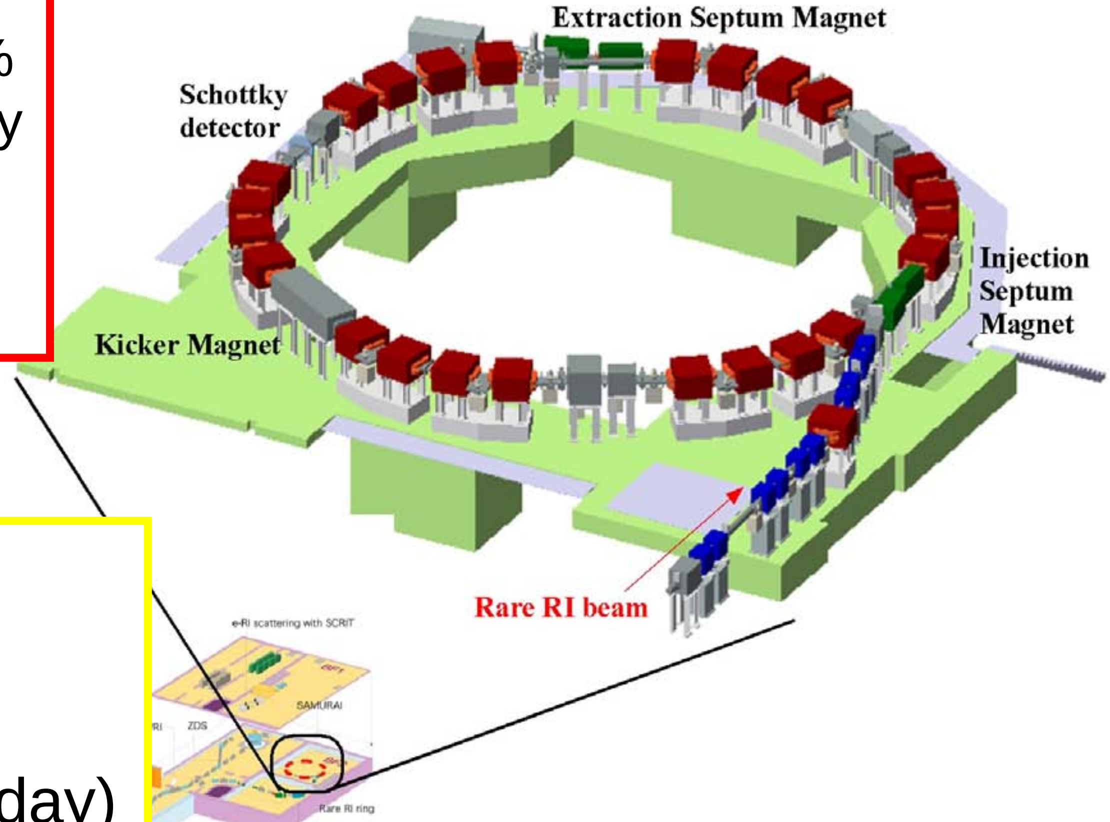
Decay Spectroscopy with EURICA in 5 Years

U-beam intensity I > 100 pnA



“Rare RI Ring” 24 sector RING Cyclotron

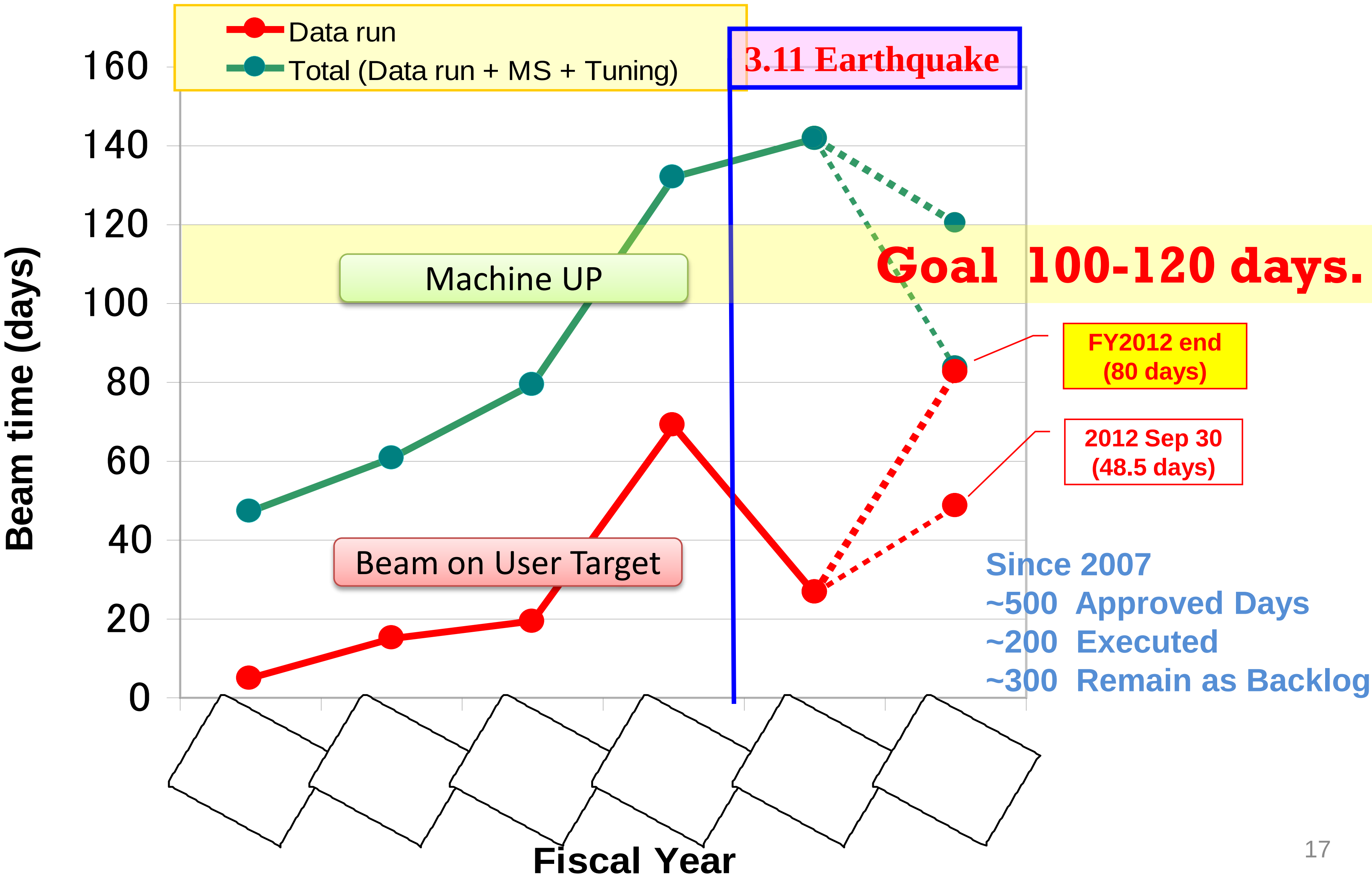
Key technologies:
- Isochronous ring
  - $\Delta T/T < 10^{-6}$ for $\delta p/p = \pm 0.5\%$
- Individual injection triggered by a detector at BigRIPS, kicked into the right orbit.



mass measurements
for
- r-process nuclei
- Low production rate(~1/day)
- Short life time (<50ms)

Schedule:
- **2014 Commissioning run**
- **2015~ Mass measurements of RI**

Beam time for BigRIPS experiments



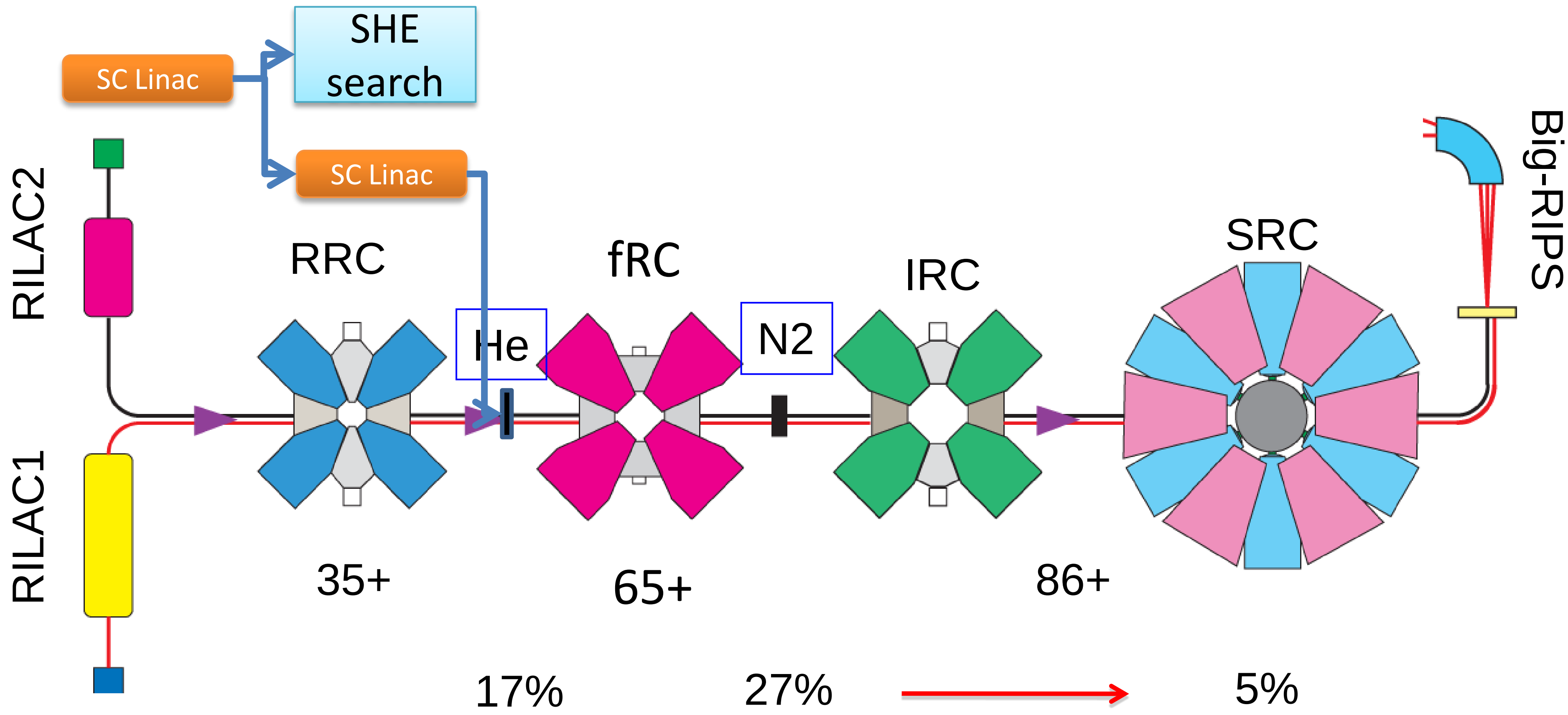
Since 2007
~500 Approved Days
~200 Executed
~300 Remain as Backlog

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

Option 0: ISOL or 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)



RIKEN RIBF Prospects

- Super Heavy Element: Start an experiment to hunt Z>119
- RIBF Accelerator / Facility
  - 345MeV/A U beam reaching 100pnA (20 times to go)
  - 100-120 days user beam time par year (Budgetary challenge after Fukushima problem)
- Measure major characteristics of “key” unstable nuclei close/beyond to R-process path.
- Future Project

		RIBF Present	**RIBF 2015**	**RIBF Option 1**	**RIBF Option 2**	**FRIB Goal**
Current (pnA)	Heavy(Xe-U)	3.8-37.0	50-100	1,000	10,000 (exceed present facility rad. limit)	8,000
	Medium (^{48}Ca)	415	1,000			
	Light(^{18}O)	1,000	1,000			
Uranium Wattage		0.3kW	4kW	80kW	800kW	400kW
Beam Energy/nucleon		345MeV	345MeV	345MeV	345MeV	200MeV
#stripper		2(C/C)	2(He/N2)	1(Gas)	2(Gas)	0
Config.		RILAC2 fRC(69+) IRC,SRC	RILAC2 fRC(65+) IRC.SRC	RILAC2 SC-fRC IRC,SRC	SC-LINAC fRC IRC,SRC	SC-LINAC

Choose either ?

Oh NO!

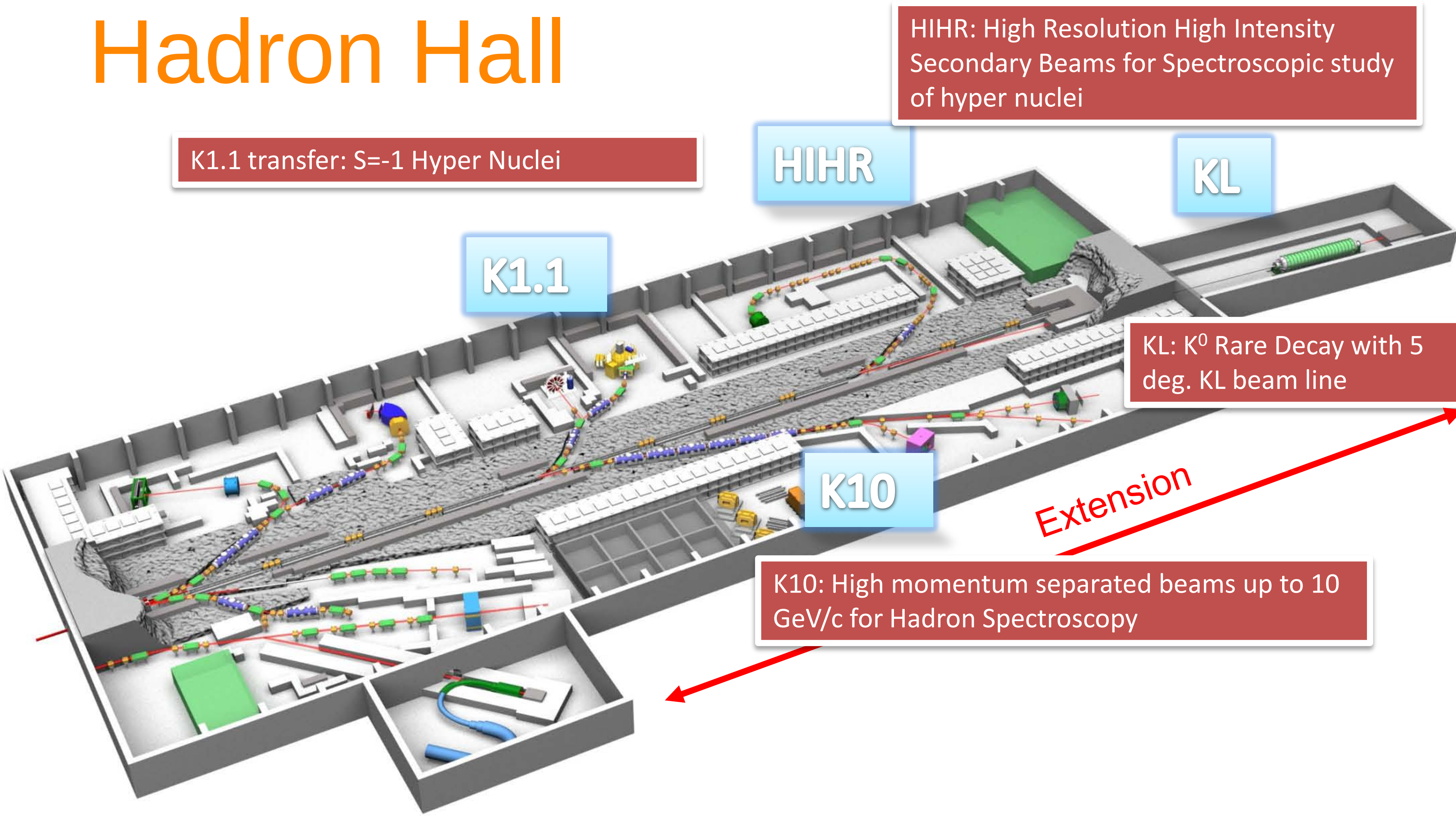
Both are too good

Keep them going until happy *physical* retirement

backup

201x～

Extension of J-PARC Hadron Hall

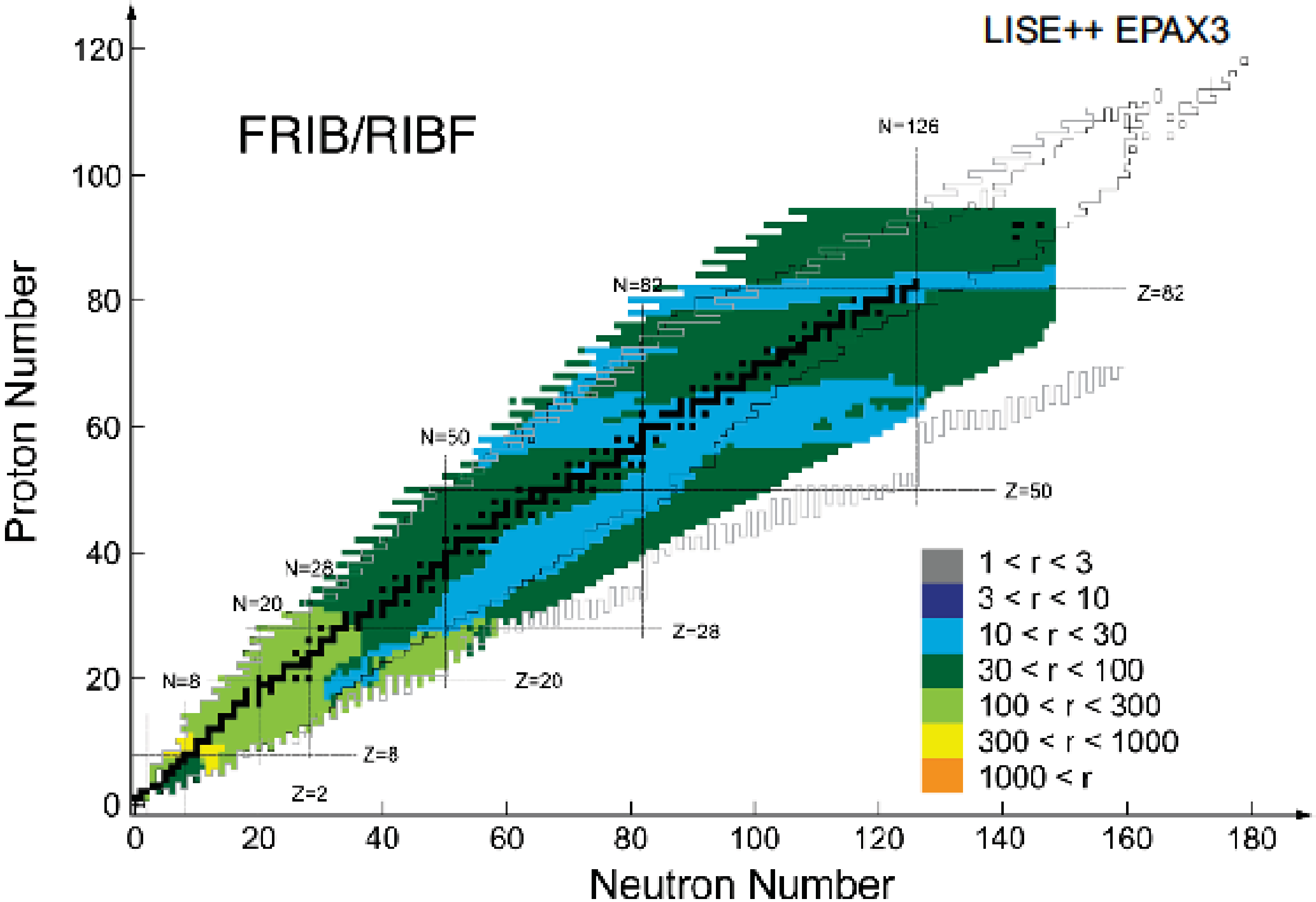


Slide by Hadron group

FRIB Compared to RIKEN RIBF

G (6)

- RIBF is based on cyclotrons and is operational now
- Intensity is limited by stripping of ions between cyclotrons (3 times)
- No reaccelerated beams



FRIB has up to 1000x higher rates than RIBF

RBRC

Scientific Review Committee

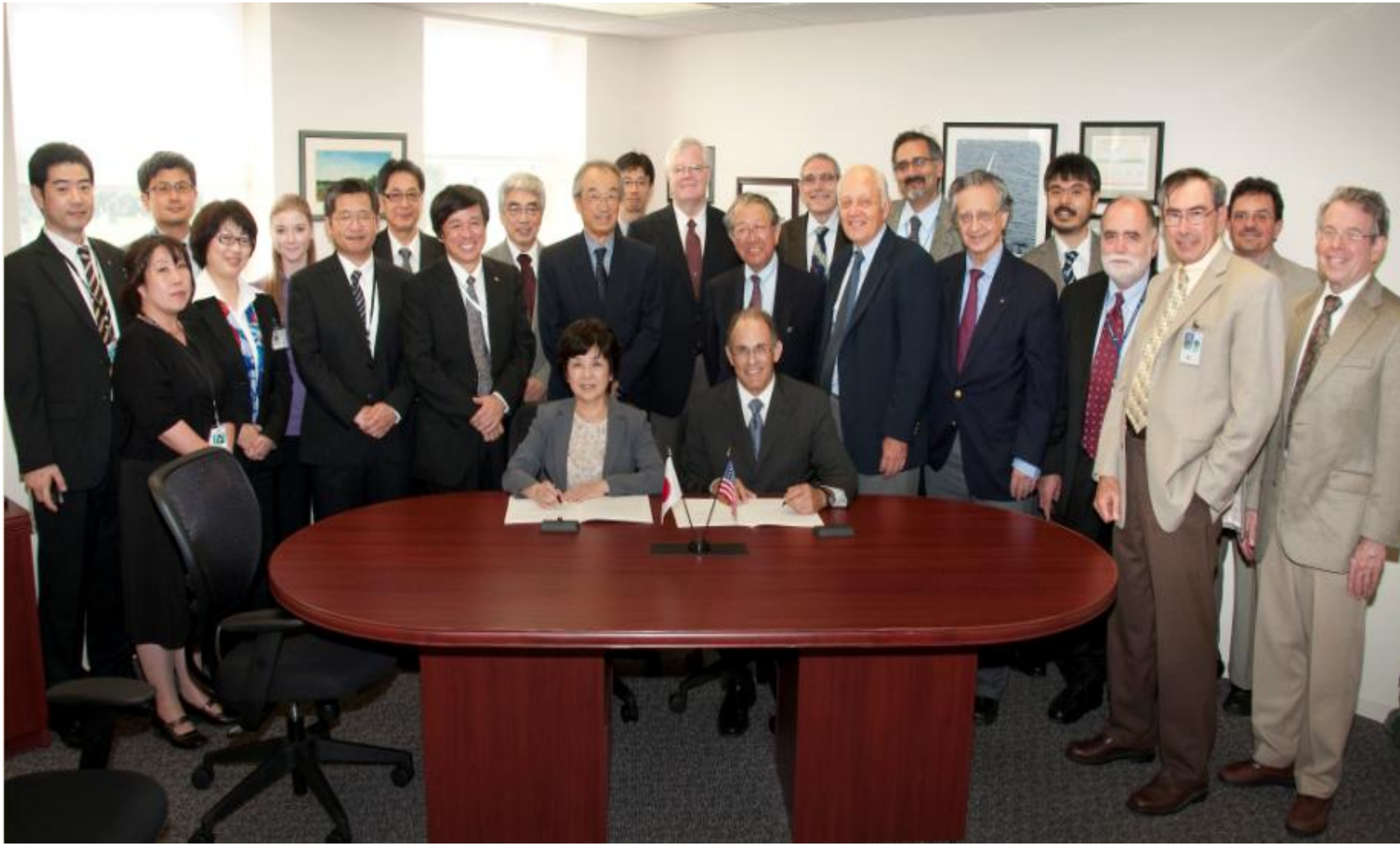
RBRC Overview

Nicholas P. Samios

November 7, 2012

Brookhaven National Laboratory

Memorandum of Understanding
Between
RIKEN
And
Brookhaven National Laboratory
Concerning the Collaborations
On the Spin Physics Program
At the Relativistic Heavy Ion Collider (RHIC)
And
RIKEN BNL Research Center
Implementation Agreement
Renewed on May 29, 2012
For six (6) years until August 29, 2018
Signed by: Samuel Aronson (BNL) and
Maki Kawai (RIKEN) [for R. Noyori]



Administration

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

Scientific Personnel: Theory Fellows

Recent Graduates:			Tenure
Molnar	Purdue	8/2010	2011
Tuchin	Iowa State	8/2010	2011
Fries	Texas A&M	9/2011	2011
Lunardini	Arizona State	9/2012	2012
Y. Aoki	BNL	7/2011	

Present:		
Teaney	SUNY	3/2013
Stasto	Penn State	7/2013
Dumitru	CUNY	8/2013
Izubuchi	BNL	9/2013
Ishikawa	BNL	8/2016

New:		
Bezrukov	UConn	9/2016
Tiburzi	CCNY	9/2016
Liao	Indiana	9/2016
Yee	Illinois	9/2017

Future:

Colorado

North Carolina State

Fukushima received the Nishinomiya Yukawa Award 2012

Scientific Personnel: Experimental Fellows

Graduates:			Tenure
Kawall	U of Mass	9/2010	
Seidl	BNL	8/2010	2011

Present:		
Bathe	CUNY	1/2015
Boyle	BNL	4/2016
Seele	BNL	6/2016
Wang	NMSU	3/2017

Scientific Personnel: Theory Post Doc's

Graduates:

Kang	4/2012	

Present:

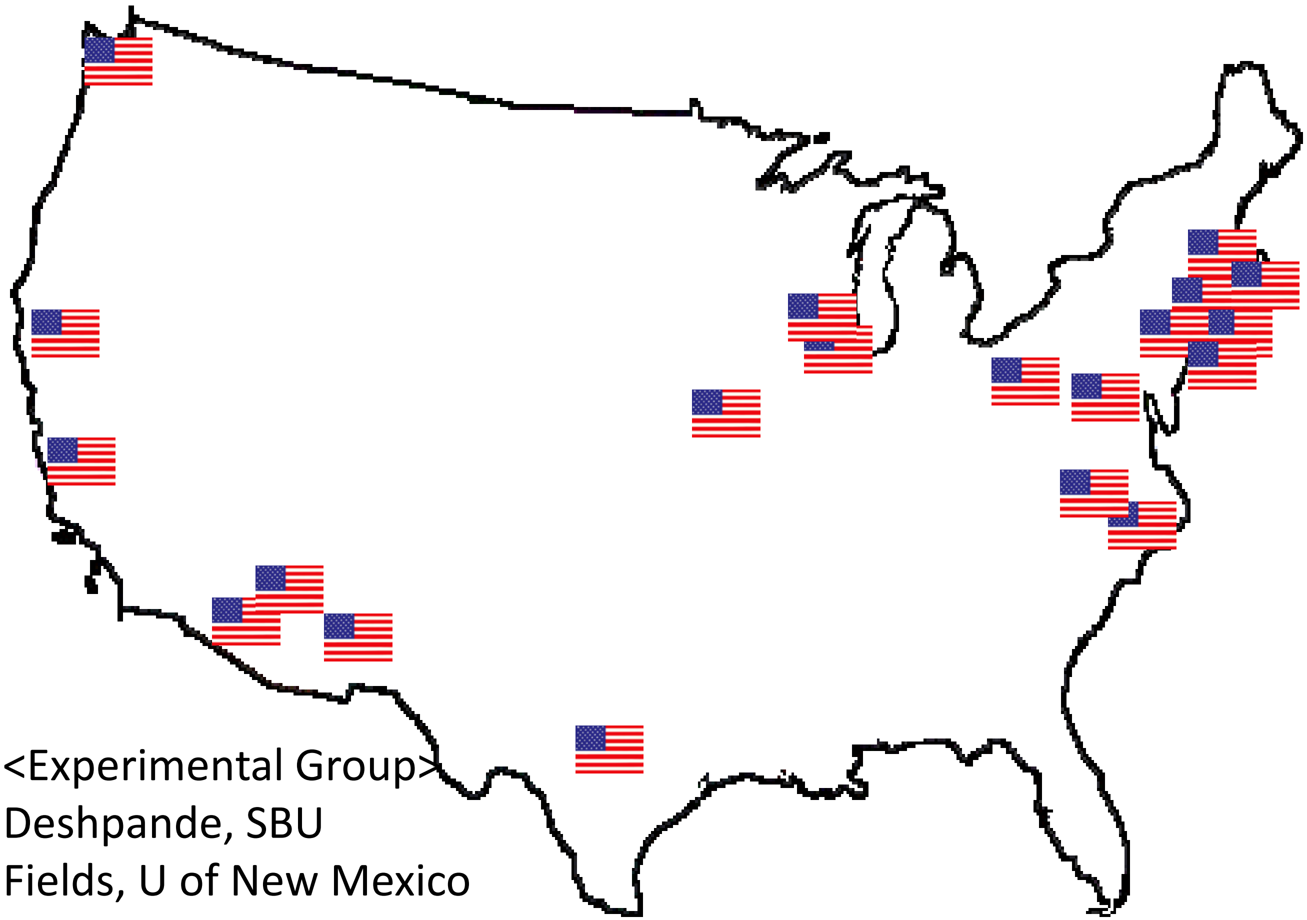
Shintani	9/2013	
Lehner	9/2013	FPR
Lin	3/2015	FPR
Bzdak	9/2013	
Syritsyn	9/2014	FPR
Kelley	9/2014	FPR

Scientific Personnel: Experimental Post Doc's

Present:

Koster	9/2013	FPR
Chen	5/2013	

RBRC Graduates have tenured positions in the U.S.



<Theory Group>
Bass, Duke U
Blum, U of Connecticut
Kharzeev, BNL
Son, U of Washington
Schaefer, NCSU
Stephanov, U of Illinois
Van Kolck, U of Arizona
Venugopalan, BNL
Tuchin, Iowa S U
Kusenko, UCLA
Fries, Texas A&M
Molnar, Purdue
Lunardini, Arizona State
Petreczky, BNL
Orginos, William & Mary
Yuan, Berkeley

<Experimental Group>
Deshpande, SBU
Fields, U of New Mexico
Grosse-Perdekamp, U of Illinois
Bazilevsky, BNL

RBRC Graduates have tenured positions in the World.

<Experimental Group>

Heuser, GSI

<Theory Group>

Bodeker, Bielefeld U

Jeon, McGill U

Rischke, FIAS

Vogelsang, Tubingen U

Wettig, U of Regensburg

Boer, U of Groningen

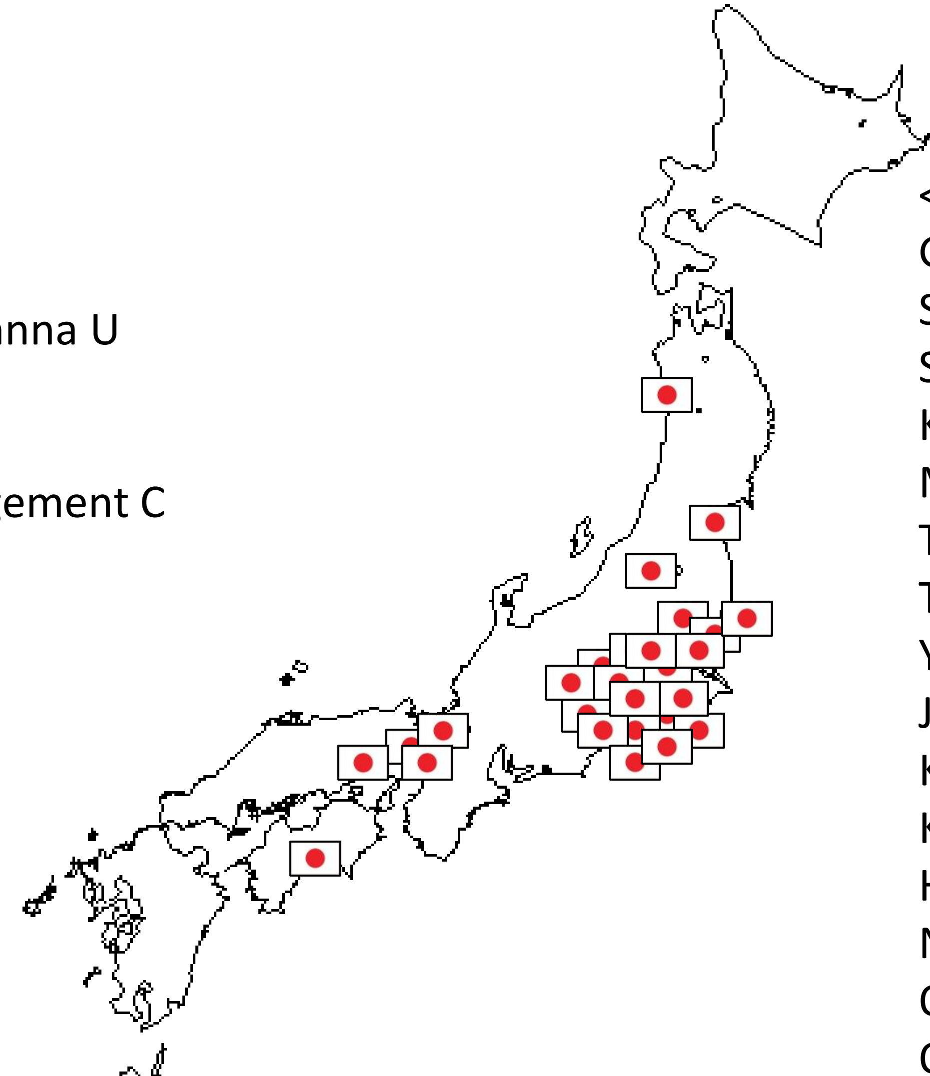
Schaffner-Bielich, Heidelberg U

Wingate, U of Cambridge

Wiedemann, CERN

RBRC Graduates have tenured positions in Japan.

<Theory Group>
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 C
Hirano, U of Toyko
Fukushima, Keio
Doi, RIKEN
Hidaka, RIKEN
Nara, Akita Int. 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)

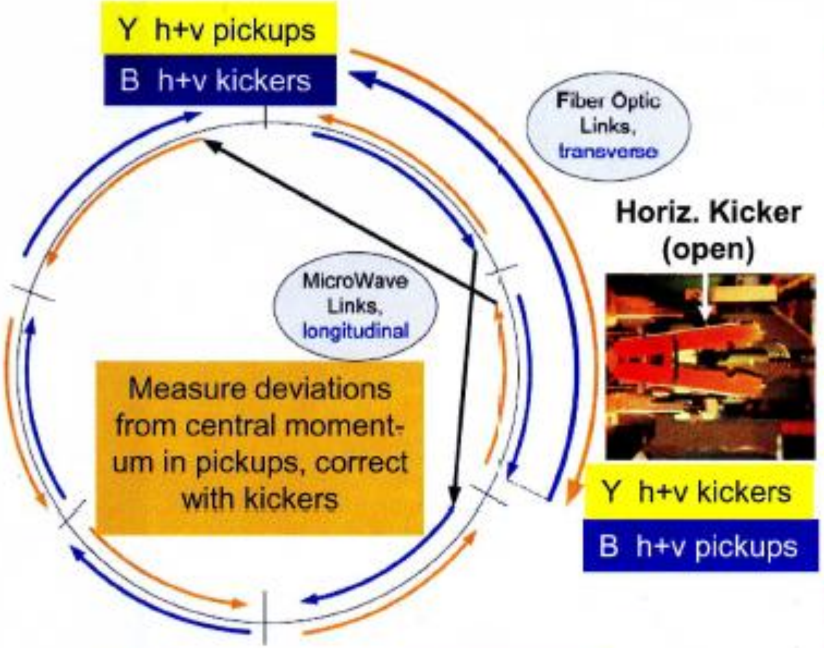
Accelerator

Run 11	26 Cryo Weeks		
$\vec{p}\,\vec{p}$	500 GeV	80 pb^{-1}	50% pol
Au x Au	200 GeV/$_A$	5,000 μb^{-1}	
	19.3 Gev/$_A$	20 μb^{-1}	

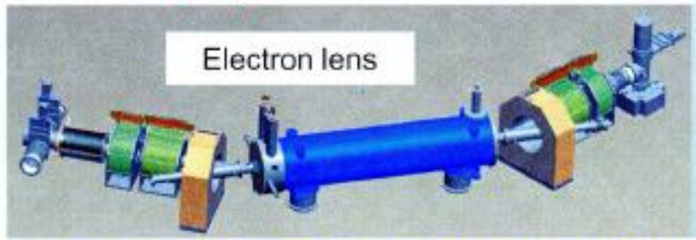
Fantastic Year: EBIS, Stochastic Cooling (b planes)

Run 12	23 Cryo Weeks		
$\vec{p}\,\vec{p}$	200 GeV	35 pb^{-1}	52% pol
	510 GeV/$_A$	130 pb^{-1}	59% pol
U U	193 GeV/$_A$	350 μb^{-1}	
Cu x Au	200 GeV/$_A$	14 nb^{-1}	
Au x Au	5 GeV/$_A$	test	

RHIC-II Era is Here, Done Very Cost-Effectively !

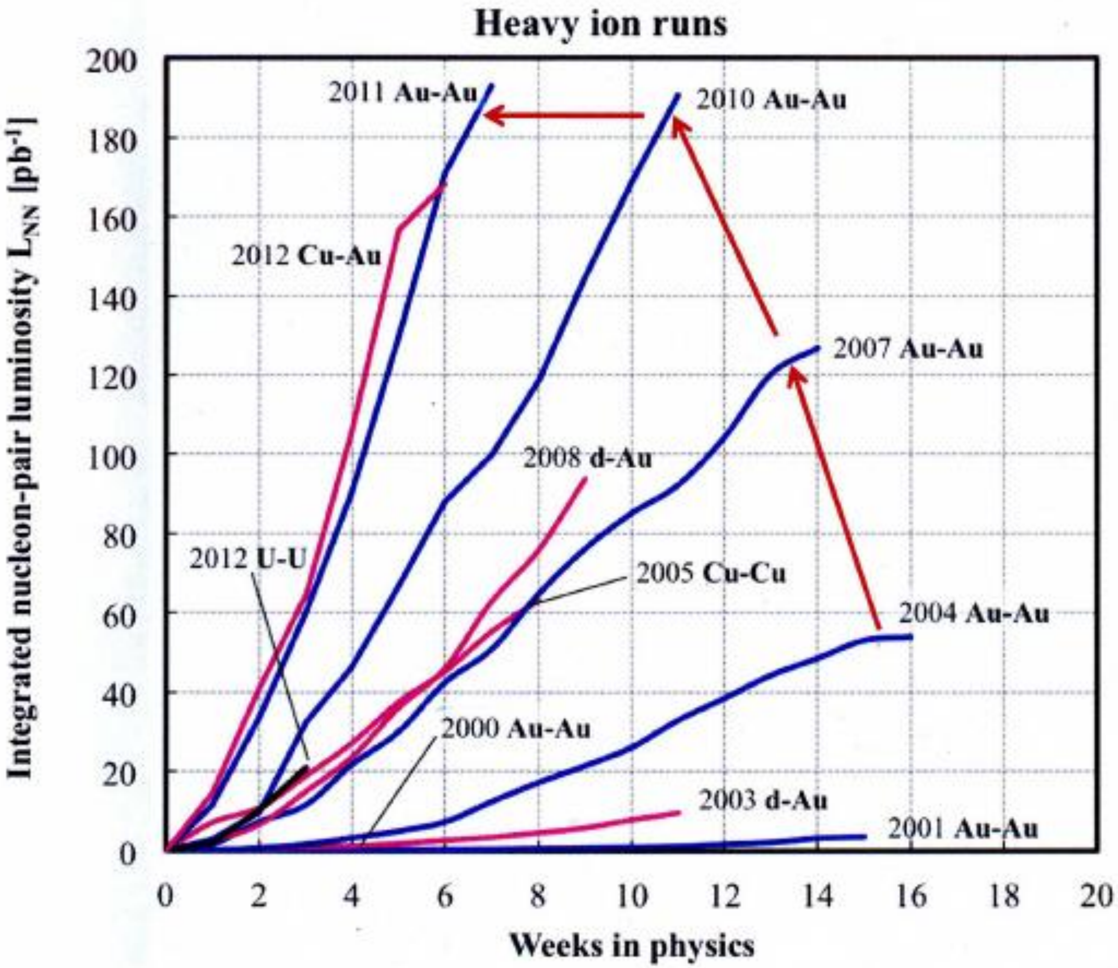


- **RHIC breakthrough in bunched-beam stochastic cooling facilitates ~x10 improvement in heavy-ion collision rates, 5 years earlier and at ~1/7 the cost envisioned in 2007 NP Long Range Plan, saving ~$80M**
- **All (6 planes of pickups & kickers) of the new system commissioned during 2010-12, new 56 MHz SRF cavity anticipated for 2014 run.**
- **Electron lenses to be installed for 2013 run to improve polarized pp luminosity by factor ~2**



- **New Electron Beam Ion Source (EBIS, 2012) expands range of ions available (e.g., U) and enhances cost-effectiveness of operations**

RHIC heavy ions – luminosity evolution to date



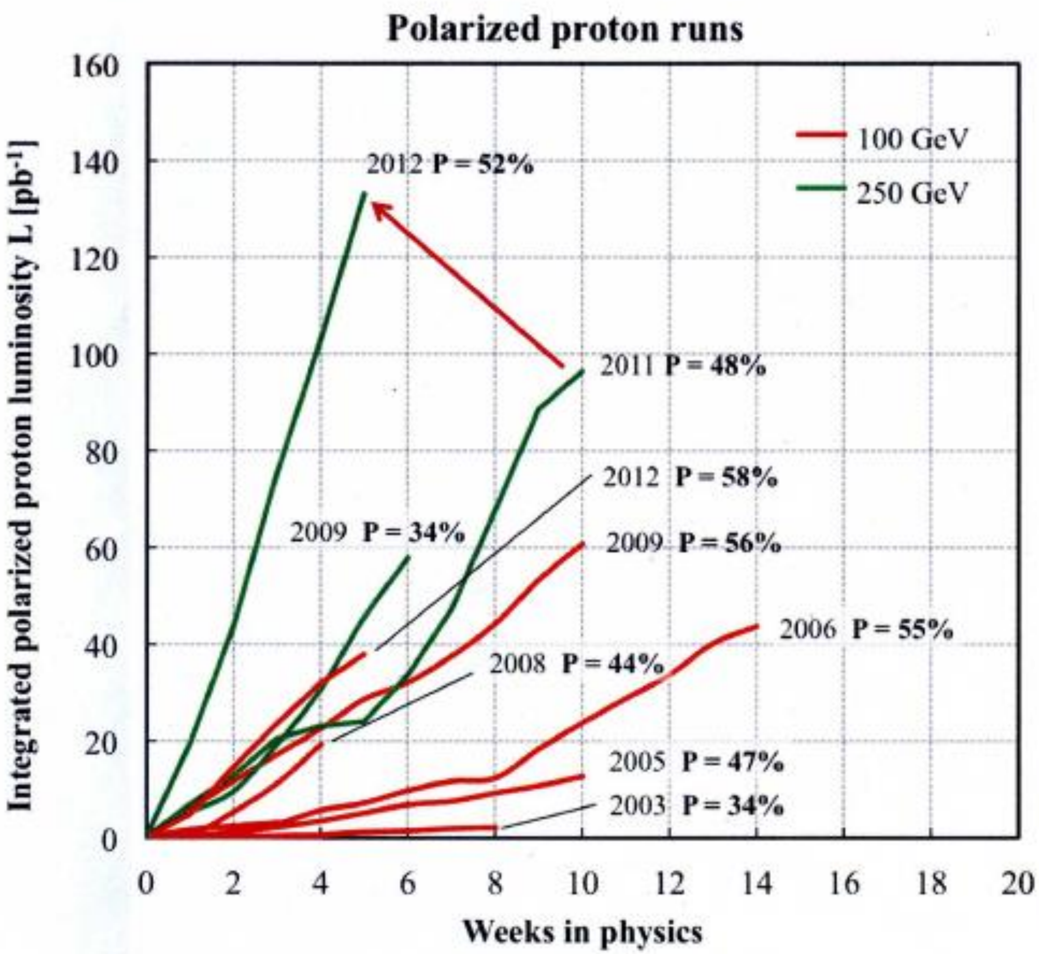
<L> = 15x design in 2011

About 2x increase in L_{int}/week each

- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

$\mathbf{L_{NN} = L\,N_1N_2}$ (= luminosity for beam of nucleons, not ions)

RHIC polarized protons – luminosity and polarization



At 255 GeV in 2012

L_{avg} = 105x10^{30}cm^{-2}s^{-1}

P_{avg} = 52%

L_{avg} +15% relative to 2011

P_{avg} +8% relative to 2011

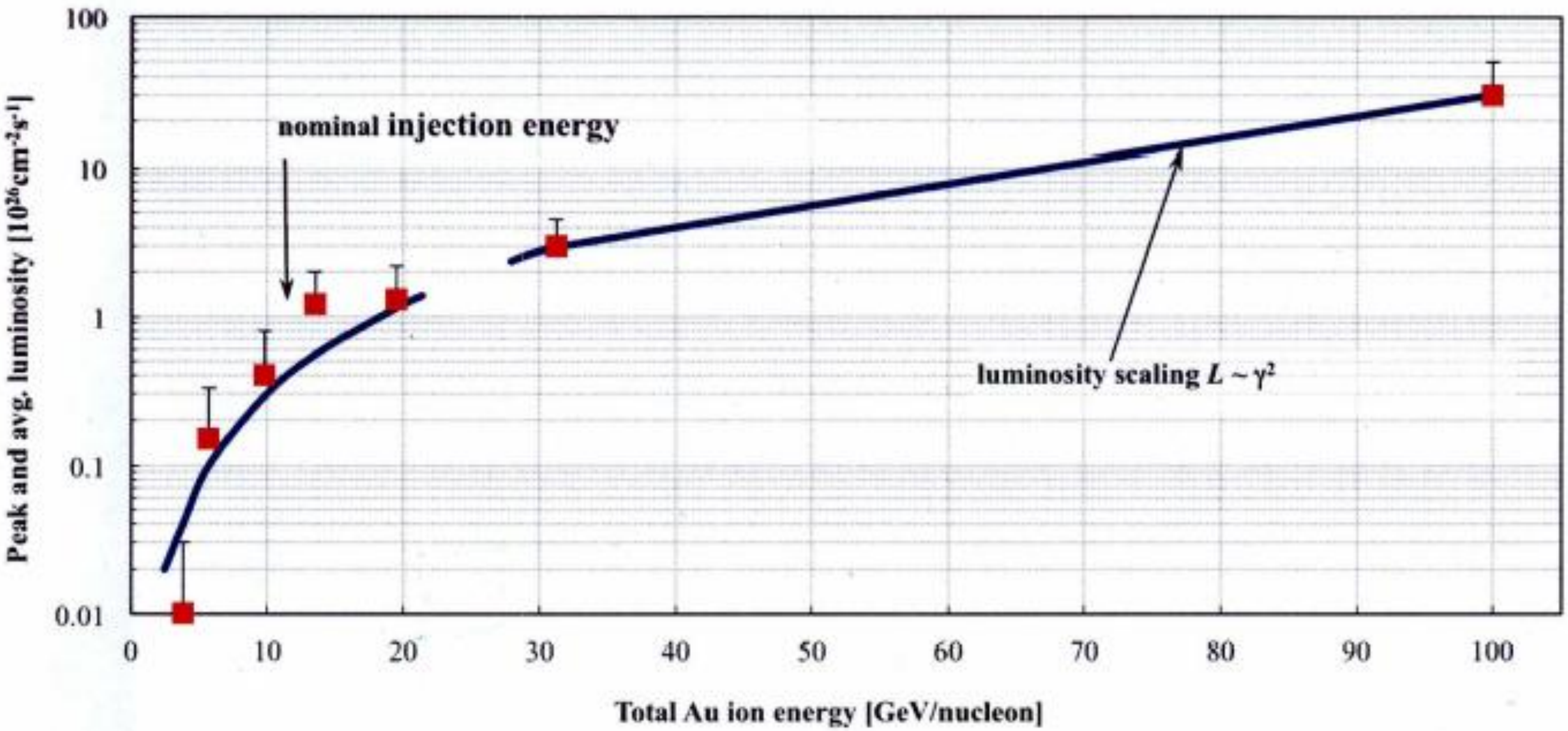
FOM = LP²

(single spin experiments)

FOM = LP⁴

(double spin experiments)

Au-Au energy scan to date



Peak and average luminosities fall faster than $1/\gamma^2$ at lowest energies
Need cooling at low energies to significantly increase luminosities

Physics

Phenix – Detectors

Mu – Trigger
Vertex – Silicon Trackers } Operational

R_{AA} – Nuclear Modification Factors

$\pi°, \eta, \phi, J/_{\psi}, \gamma$

up to $p_T \approx 20$ GeV

CMS – jets

p_T 40 - 250 GeV

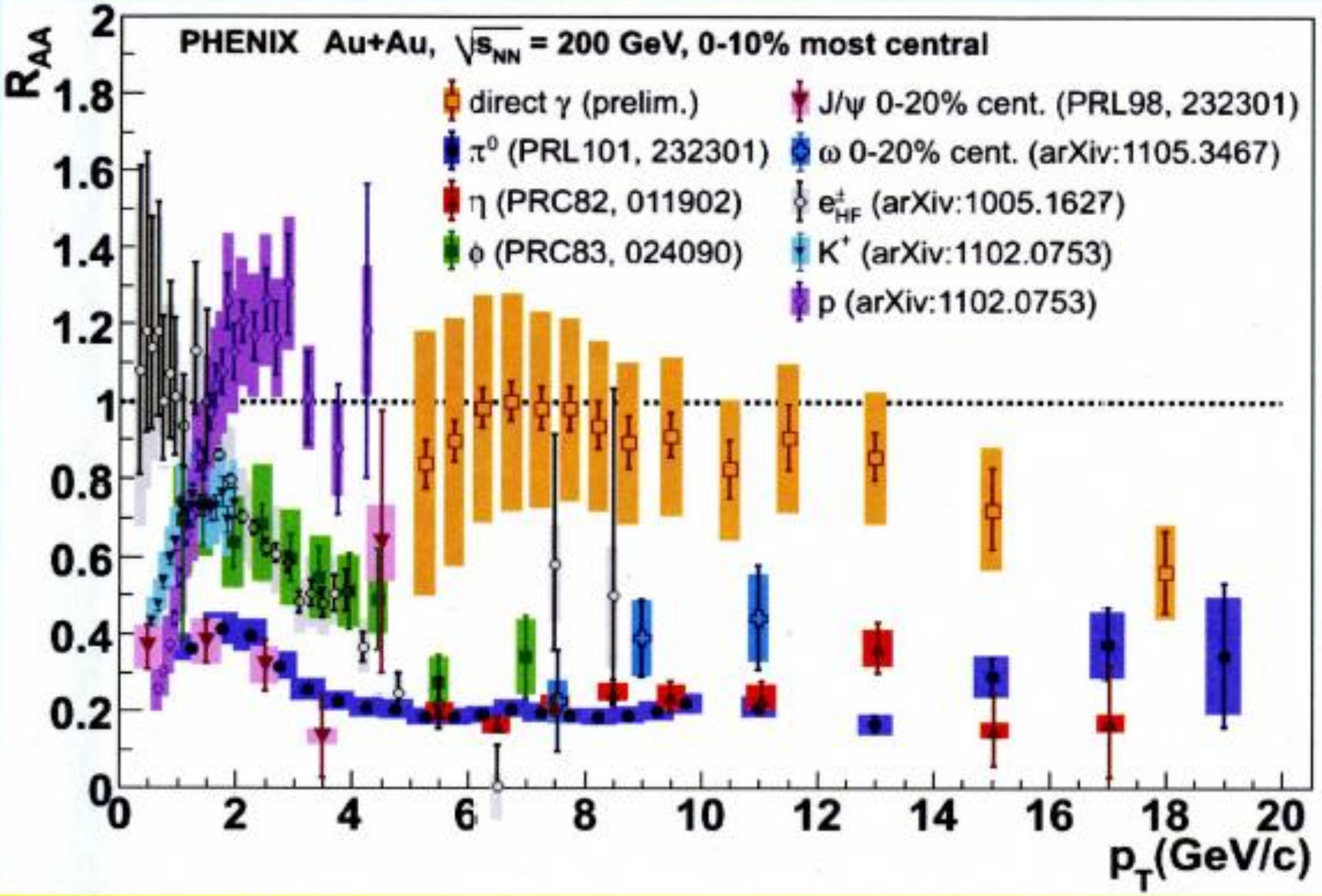
Harmonic Flow

v_n – higher harmonics damped

η/s .08 RHIC

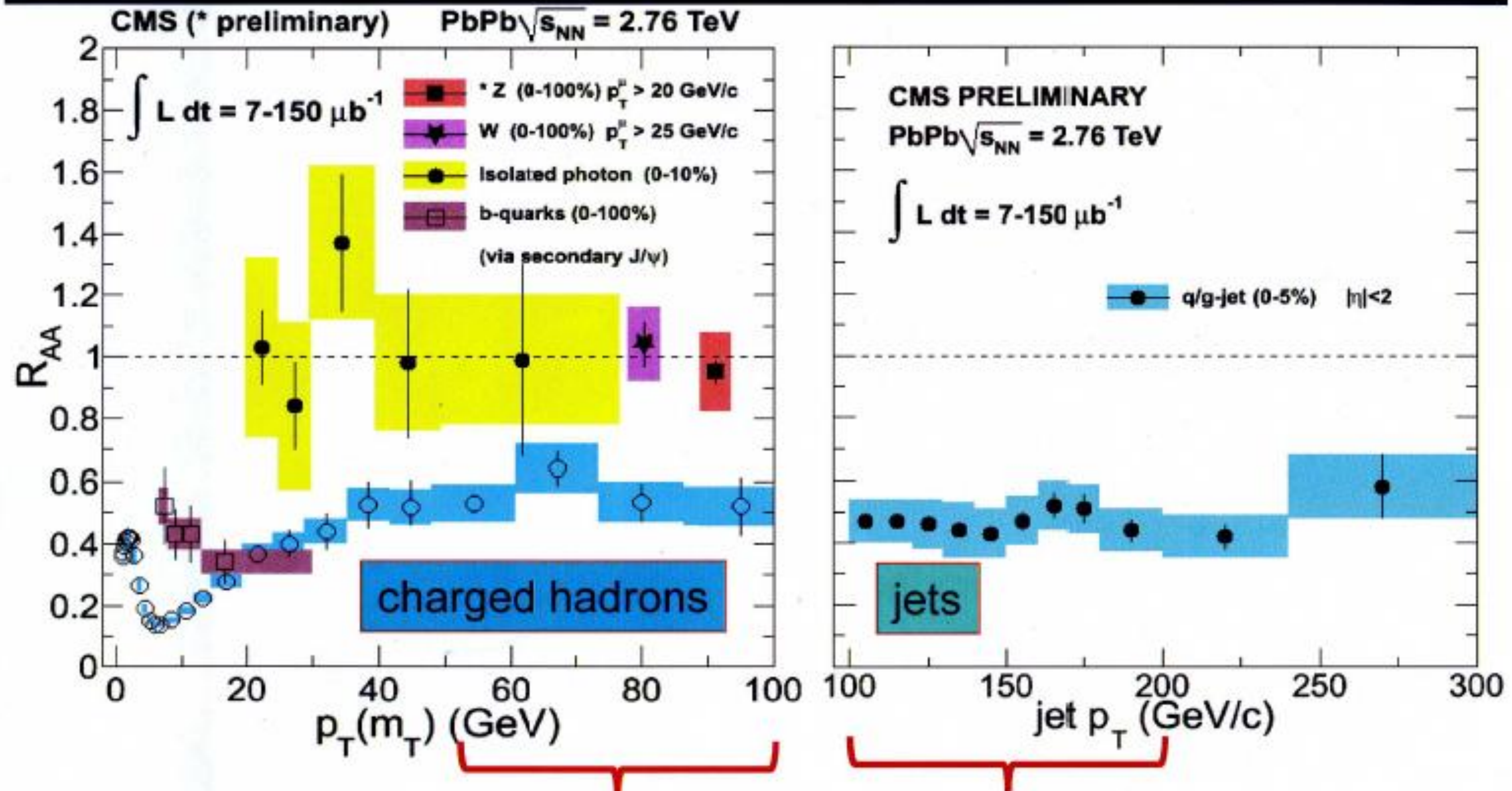
.20 LHC

PHENIX: unprecedented reach and precision



Superb particle ID, high rate capability and excellent trigger: broad physics capabilities over a large kinematic range

Nuclear modification factors



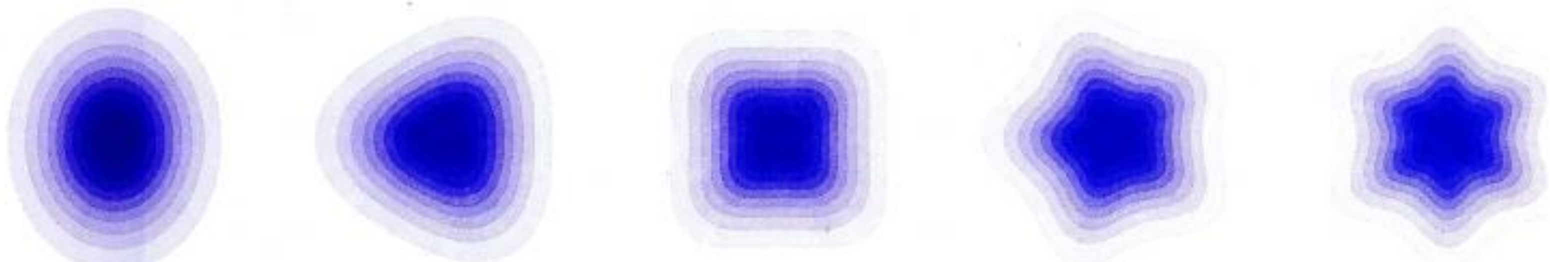
Sampling the ~same parton p_T range

Note: jets fragment into high-p_T particles in pp and PbPb the same way – *see later*..

Higher harmonic flow

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n (2v_n \cos[n(\phi - \psi_n)]\right)$$

When including fluctuations, all moments appear:

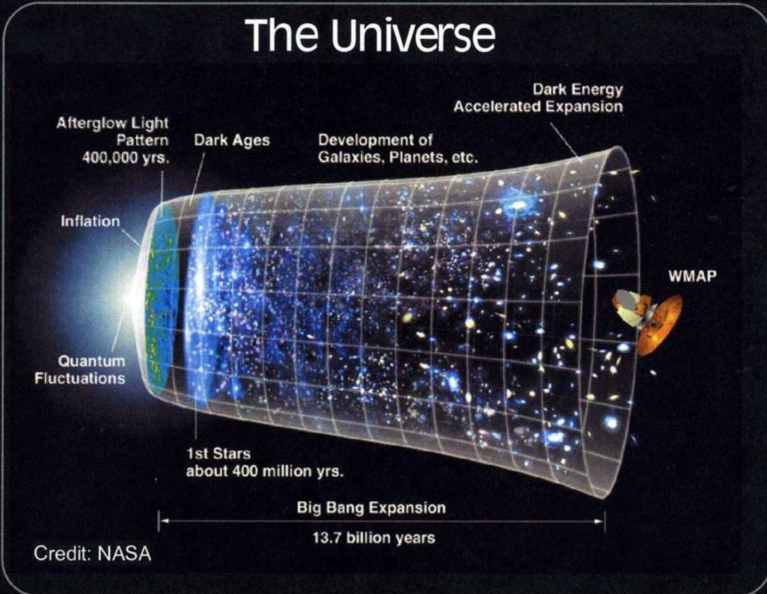


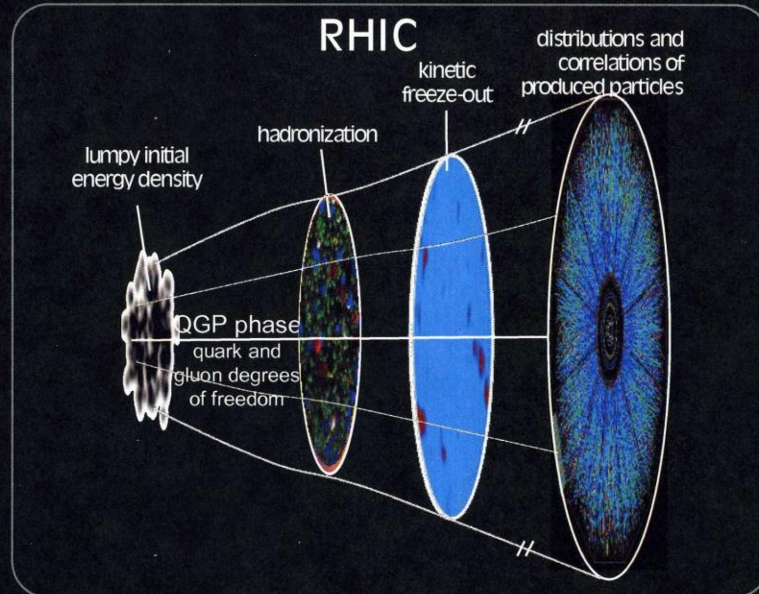
$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$

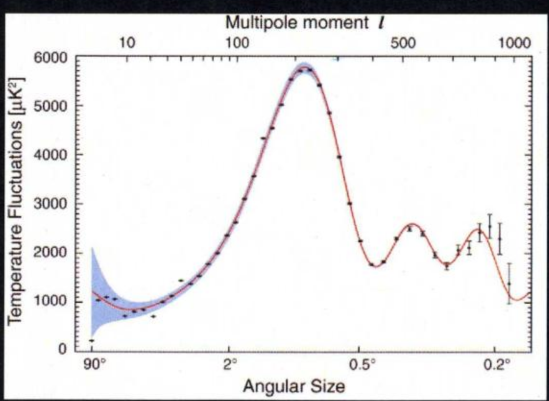
also v_1 and $n > 6$

Compute $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$
with the event-plane angle $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$

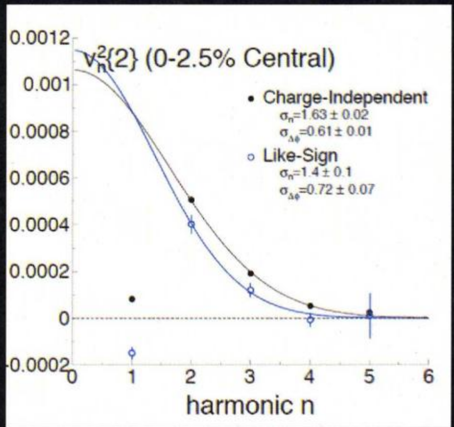
The Evidence Validates this Analogy







WMAP

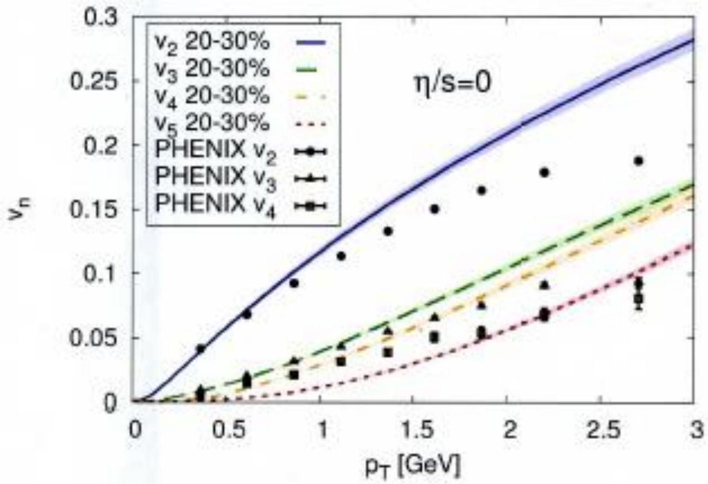


RHIC

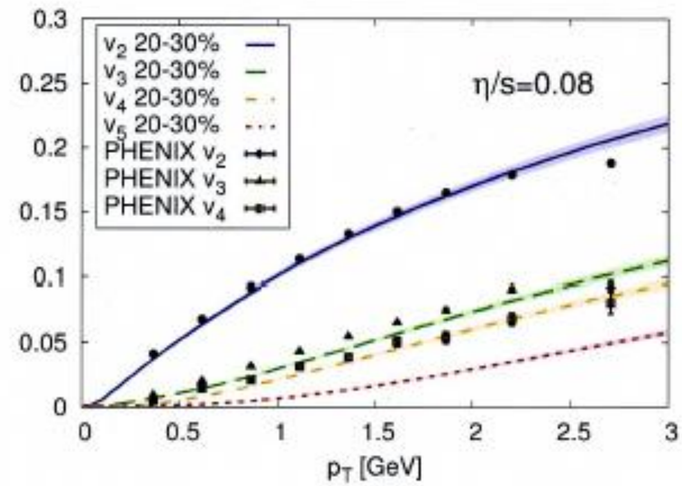
Using higher harmonics to determine η/s

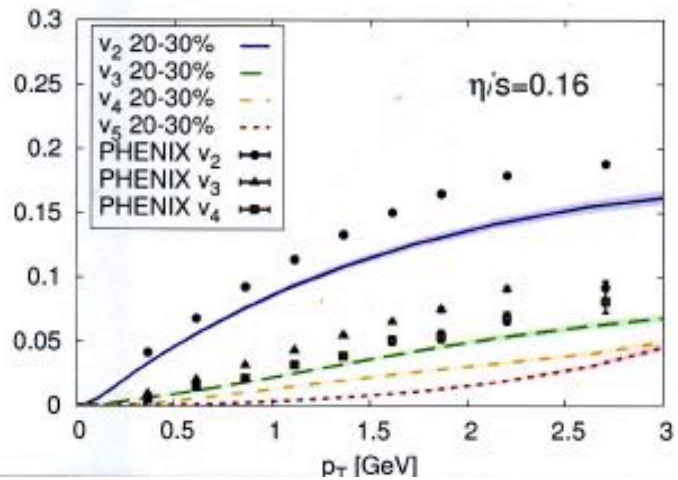
B. Schenke, S. Jeon, C. Gale, arXiv:1109.6289

Data is from event-plane method. Calculations are $\sqrt{\langle v_n^2 \rangle}$.



MC-Glauber initial conditions

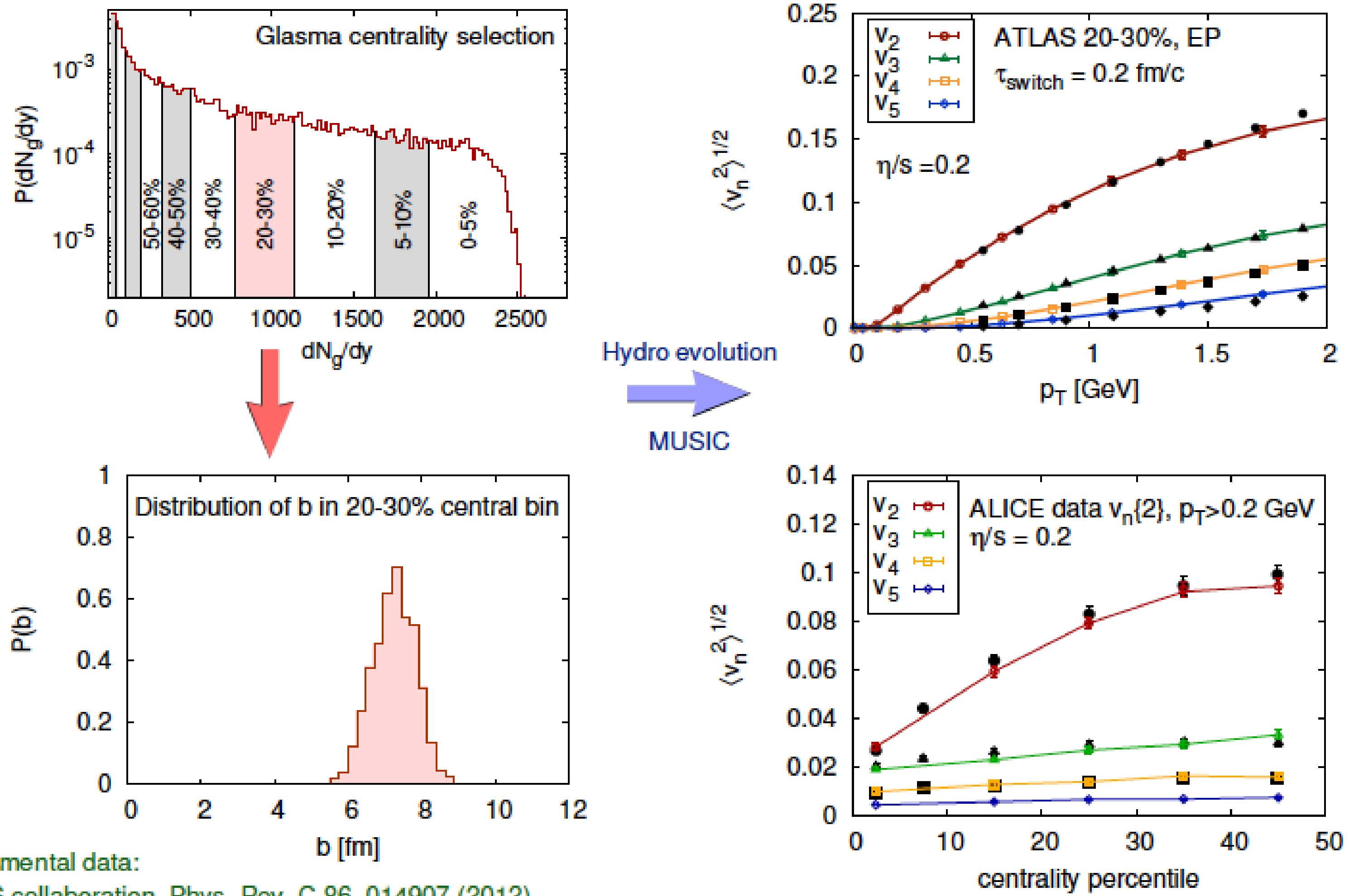




This is promising.
Need systematic study of all v_n as function of initial conditions, granularity, η/s, ...

Experimental data: PHENIX, arXiv:1105.3928

Centrality selection and flow

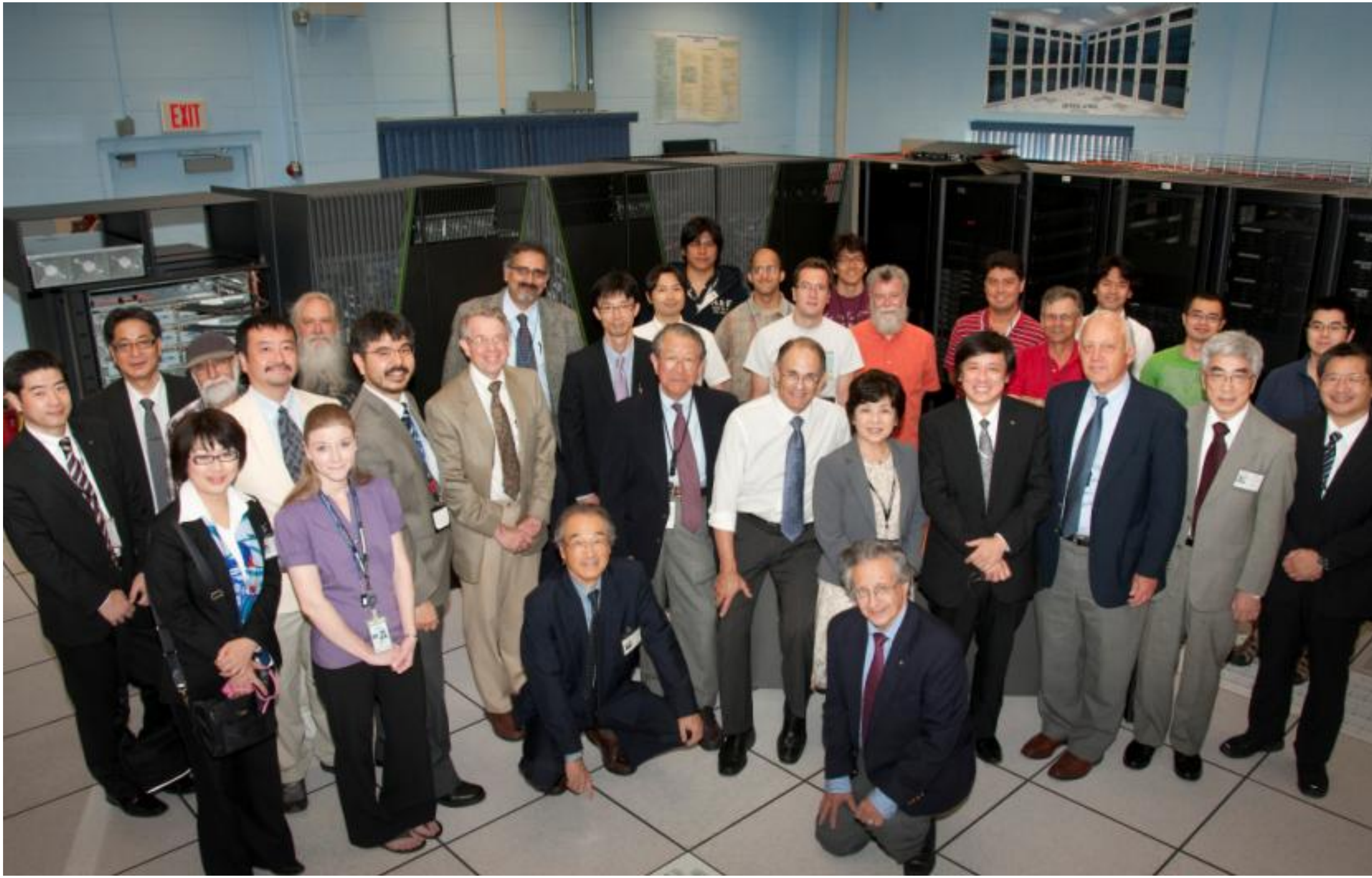


Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

Computing History

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

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


EXIT

Workshops

- Polarized Drell-Yan Physics (LANL – Sante Fe)
  October 31, 2010 – November 1, 2010
- Initial State Fluctuations and Final-State Particle Correlations
  February 2-4, 2011 (Vol. 102)
- Opportunities for Drell-Yan Physics at RHIC
  May 11-13, 2011 (Vol. 103)
- Quarkonium Production in Elementary and Heavy Ion Collisions
  June 6-17, 2011 (Vol. 104)
- Opportunities for Polarized He-3 in RHIC and EIC
  September 28-30, 2011 (Vol. 105)
- Fluctuations, Correlations and RHIC Low Energy Runs
  October 3-5, 2011 (Vol. 106)
- Future Directions in High Energy QCD (RIKEN - Wako, Japan)
  October 20-22, 2011 (Vol. 107 – new format)
- Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions
  February 29, 2012 – March 2, 2012 (Vol. 108)
- New Horizons for Lattice Gauge Theory Computations
  May 14-18, 2012 (Vol. 109 – new format)
- P- and CP-odd Effects in Hot and Dense Matter
  June 25-27, 2012 (Vol. 110 – new format)
- Forward Physics at RHIC
  July 30, 2012 – August 1, 2012 (Vol. 111 – new format)

Committees

- Theory Advisory Committee:
  - Larry Mc Lerran
  - Anthony Baltz
  - Michael Creutz
  - Frithjof Karsch
  - Dmitri Kharzeev
  - Miklos Gyulassy
  - Robert Oswald-Pisarski
  - Jianwei Qiu

- Experimental Advisory Committee:
  - Akira Masaike
  - Kenichi Imai
  - Yousef Makdisi

- Lattice Gauge Advisory Committee:
  - Michael Creutz
  - Robert Oswald-Pisarski
  - Sinya Aoki

Publications

Theory: 119

Experimental: 50

Seminars

- Wednesday – RBRC/BNL/SUNY
- Thursday – RBRC/Lunch
- Friday – RBRC/Spin
- Friday – RBRC/BNL

Safety Update

RBRC has maintained a perfect safety record for the past 15 years.

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

Y. Akiba

RBRC SRC review
2012/11/07

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 in “reaping harvest”.

RBRC Experimental Group

Group Leader

Y. Akiba

Deputy GL

A. Deshpande

University Fellow

S. Bathe
Baruch
CCNY

X. Wang
New Mexico
State Univ.
started this
August

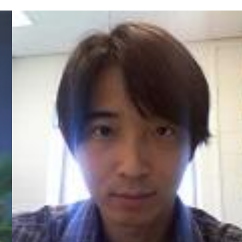
Fellow

K. Boyle

J. Seele

PostDoc

J. Koster



M. Kurosawa

C-H Chen

RIKEN/RBRC @

R. Seidl

Y. Goto

I. Nakagawa

A. Taketani

T. Hachiya

Y. Imazu

- Plus Many Students and Visitors
- K. Okada moved to Spring-8 as a tenured researcher

K.Okada

Visitors/Collaborators/students

RIKEN/BNL

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

Students

A Takahara	Katsuro Nakamura	Hidemitsu Asano
Ryoji Akimoto	Masaya Nihashi	Takahiro Todoroki
Megumi Sekine	Sanshiro Mizuno	Hideyuki
Oide Sangwa Park		

Visiting Scientist

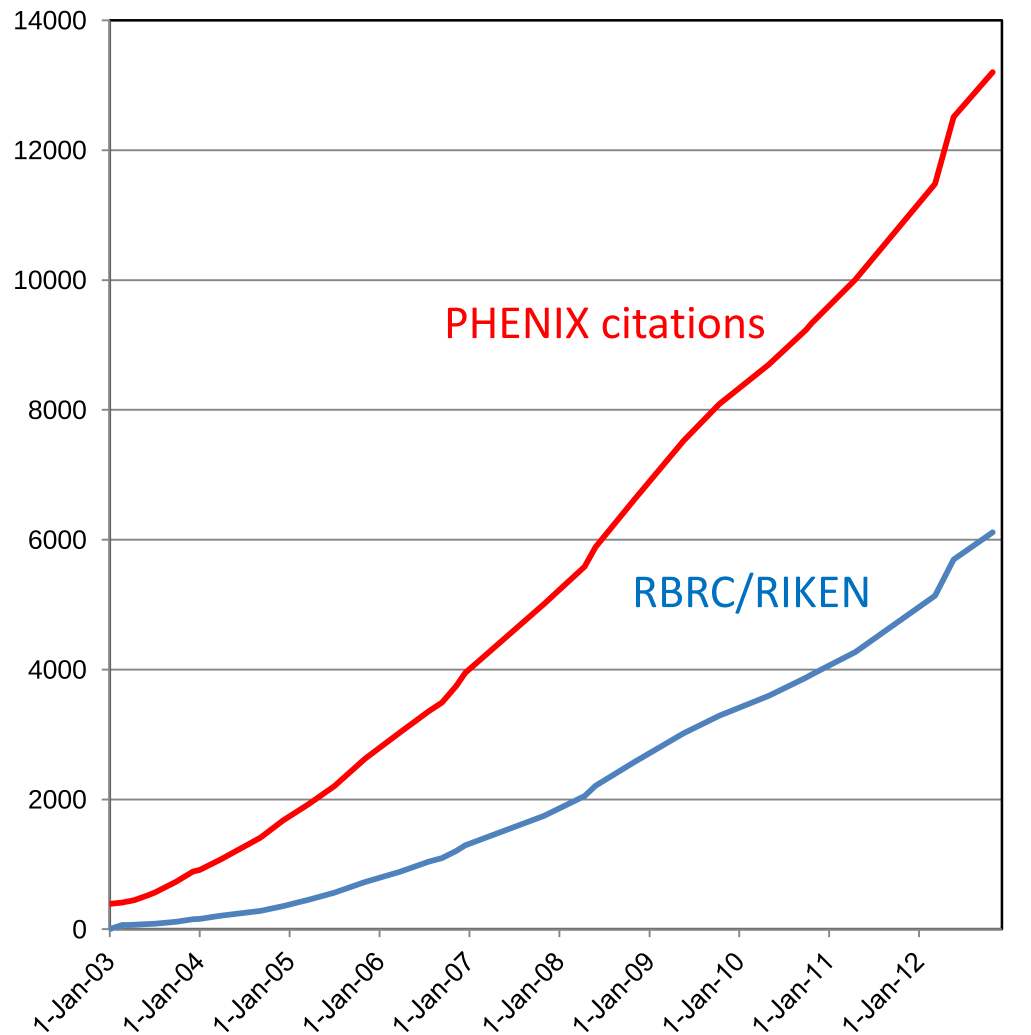
Zheng Li	Kiyoshi Tanida	Akio Ogawa
Naohito Saito		

Collaborating Scientist

Masahiro Okamura Rachid Nouicer

PHENIX publications and RBRC

- 115 (46)papers published since 2001
  - Phys. Rev. Lett. 60 (25)
  - Phys. Rev. C 35 (13)
  - Phys. Rev. D 15 (6)
  - Phys. Letter B 4 (1)
  - Nucl. Phys. A 1 (1)
- Total citation: ~13100
  - Topcite 500+ 3 (2)
  - 250-500 6 (3)
  - 100-250 19 (13)
  - 50-100 27 (13)
- 22 (9) papers published since last SRC (Oct 2010)
  - PRL 7 (3)
  - PRC 9 (4)
  - PRD 6 (2)



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

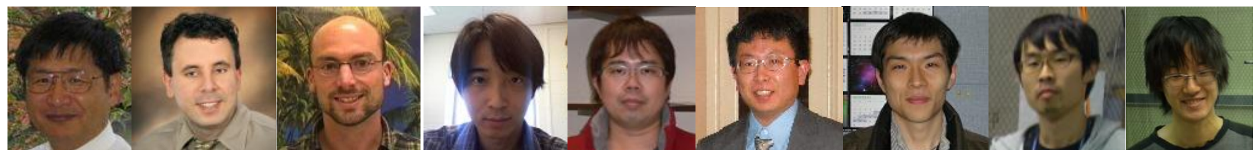
Exp Group Activities

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

  RBRC/RIKEN studies sQGP using penetrating probes

  - High p_T physics

  - Heavy quark



  - Low p_T direct photon and low mass dielectrons

- PHENIX detector Upgrade (completed)
  - Silicon Vertex Tracker (VTX) upgrade Lead by RIKEN/RBRC

+ many more

  - Muon Trigger Upgrade strong support by RIKEN/RBRC

+ 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 → e, mu analysis

– A_N at RHIC

QGP physics: thermal photon measurement

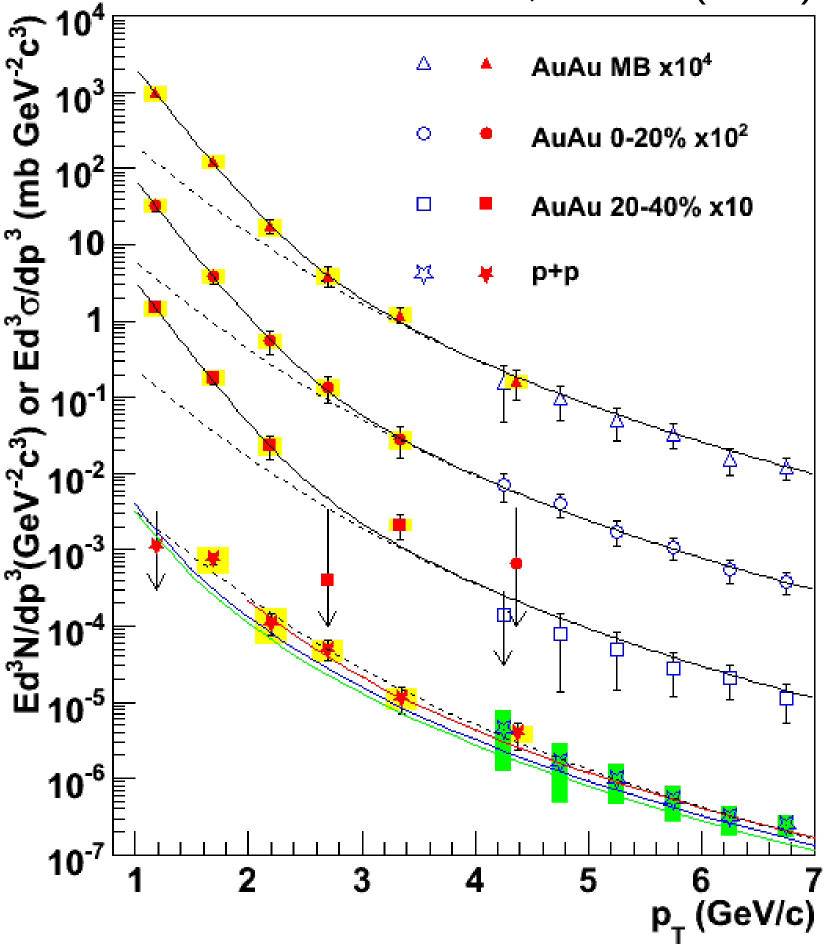
Large enhancement of low p_T direct photon in Au+Au

First measurement of thermal photon from QGP

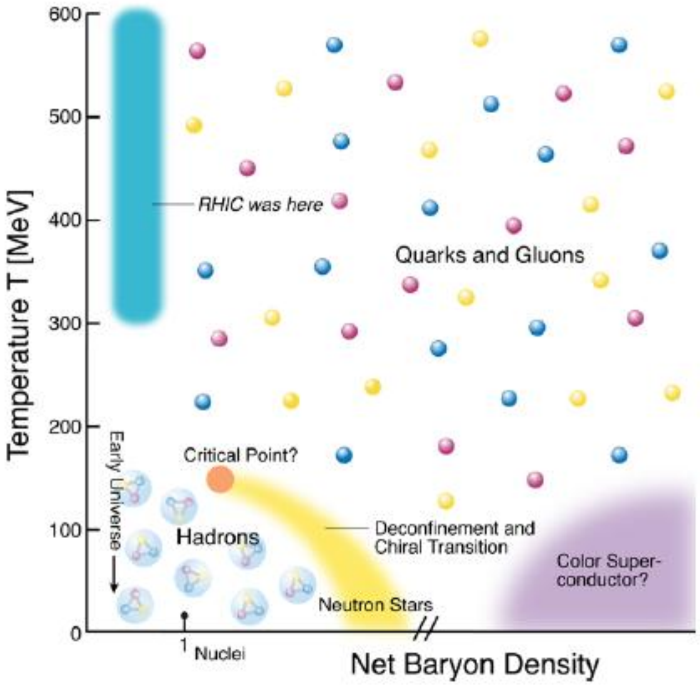
From theory comparison, initial temperature of 300 – 600 MeV is achieved at RHIC, well above the transition temperature to QGP

SPIRES138 cites

PRL104, 132301(2010)



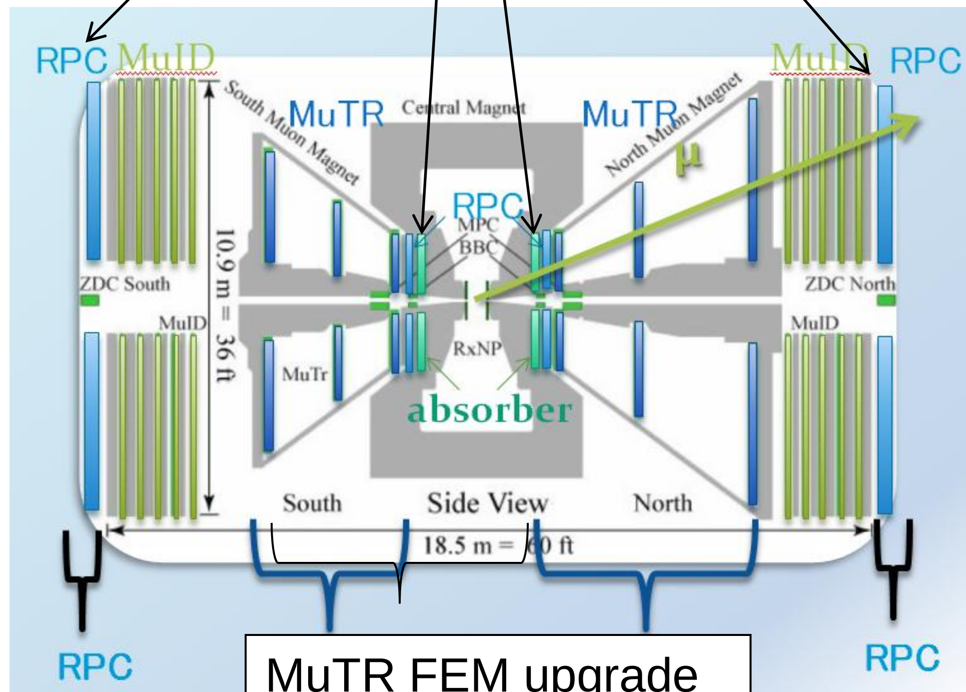
2011 Nishina Memorial Prize to YA



PHENIX Uprade: W → mu trigger

- muTRIG upgrades increase the trigger rejection factor by selecting high pT.
  - Essential for W measurement.
- Two trigger projects:
  - RPC trigger
    led by M.G.Perdekamp
    (UIUC/former RBRC fellow)
    R. Seidl (RBRC fellow)
  - Muon tracker FEE
    led by N. Saito (KEK/RBRC)
    I. Nakagawa (RIKEN/RBRC)
- New muon absorbers
  - Reduce background by a factor of ~10

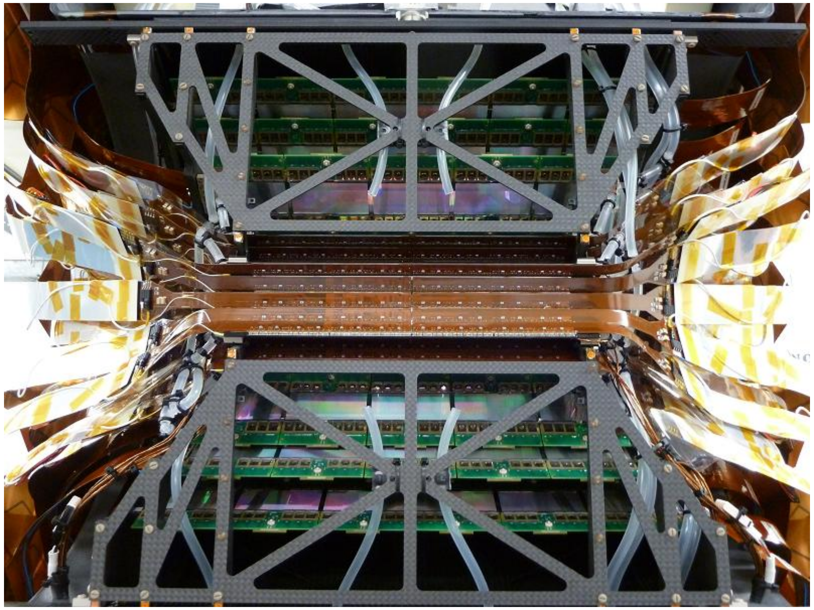
RPC trigger detector
Funded by NSF
M.G. Perdekamp (UIUC)

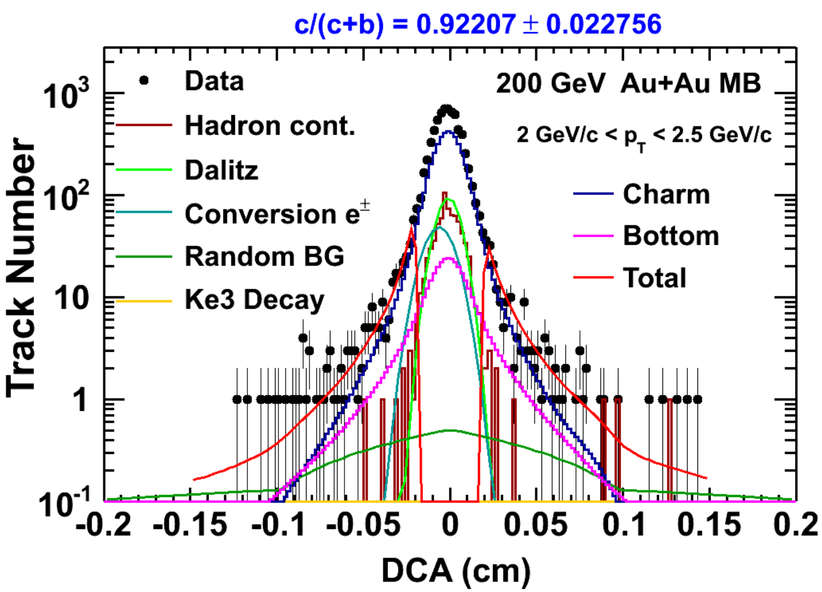


MuTR FEM upgrade
Funded by JSPS
N. Saito (KEK/RBRC)

muTrig completed.
First data in RUN11(~25/pb) and more data in RUN12(~50/pb).

PHENIX Upgrade: VTX silicon tracker

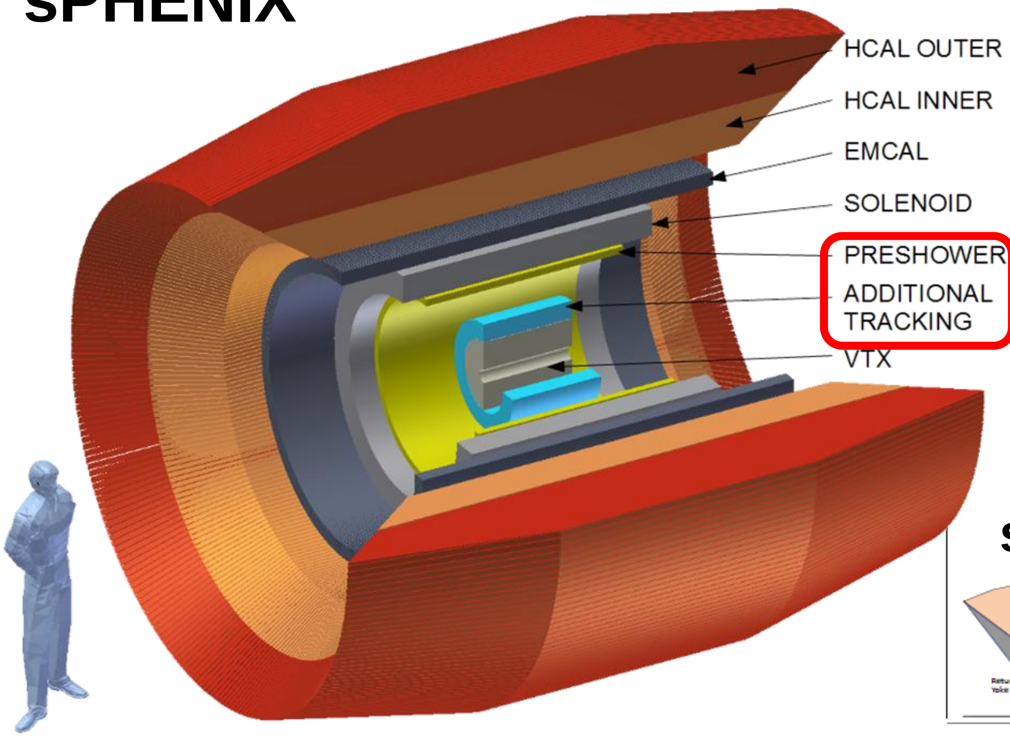


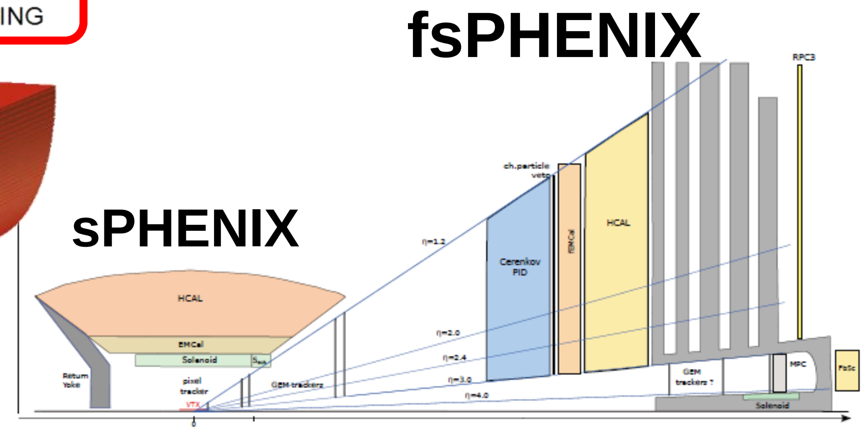


- Key device to improve heavy quark measurement at RHIC/PHENIX
  - Identify charm/bottom decay by precision tracking ($\sigma \sim 50\mu$)
  - Provides near 4π acceptance
- ~100 collaborators working on the project
- Project is lead by RIKEN/RBRC
  - Y. Akiba (RIKEN) : project manager
  - A. Taketani (RIKEN): pixel manager
  - A. Deshpande (StonyBrook/RBRC) strip manager
  - R. Nouicer (BNL/RBRC): strip detector
- The US side of the project
  - $4.7M from FY07 to FY10
- Completed in November, 2011
- First data in Run11 Au+Au
- First physics results presented in QM2012 in August 2012

sPHENIX and forward sPHENIX

sPHENIX





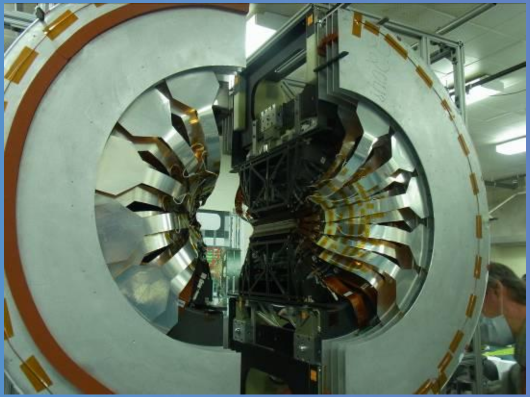
- sPHENIX: large upgrade of PHENIX for jet measurements
  - DOE MIE proposal for ~$24M
  - BNL internal review on 10/5-6
  - RIKEN/BRRC has strong interest on additional tracking system
- fsPHENIX: upgrade at forward rapidity for spin and small-x
  - Talk by J. Seele

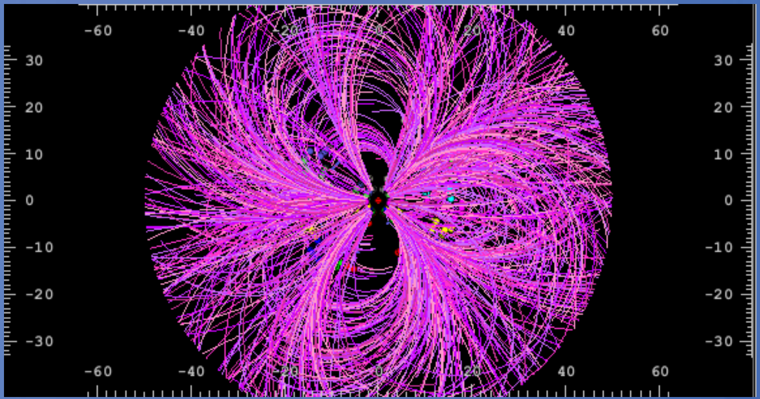
Summary

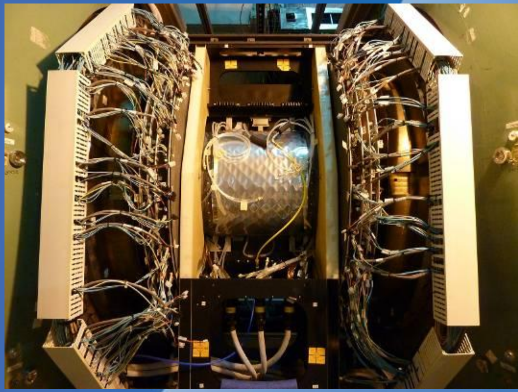
- Three pillars of RBRC Experimental Group Activity

  Spin Physics/HI Physics/PHENIX Upgrade
- Spin Physics
  - Main activity of the group
  - Strong constraint on $\Delta G(x)$
  - First 500 GeV run → First signal of W
- Heavy Ion Physics
  - Study of QGP with penetrating probes
  - Important heavy ion results from RBRC
- Upgrade of PHENIX detector to explore the full physics opportunities at RHIC
  - Two major upgrades, VTX and Muon Triggers, completed
  - Next: sPHENIX and fsPHENIX
- RBRC experimental group plays leading roles in Spin Physics, HI physics and PHENIX upgrades

Probing Hot and Dense Matter with Charm and Bottom Measurements with PHENIX VTX Tracker







Rachid Nouicer

Brookhaven National Laboratory

Research Affiliate of RIKEN-BNL Research Center

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

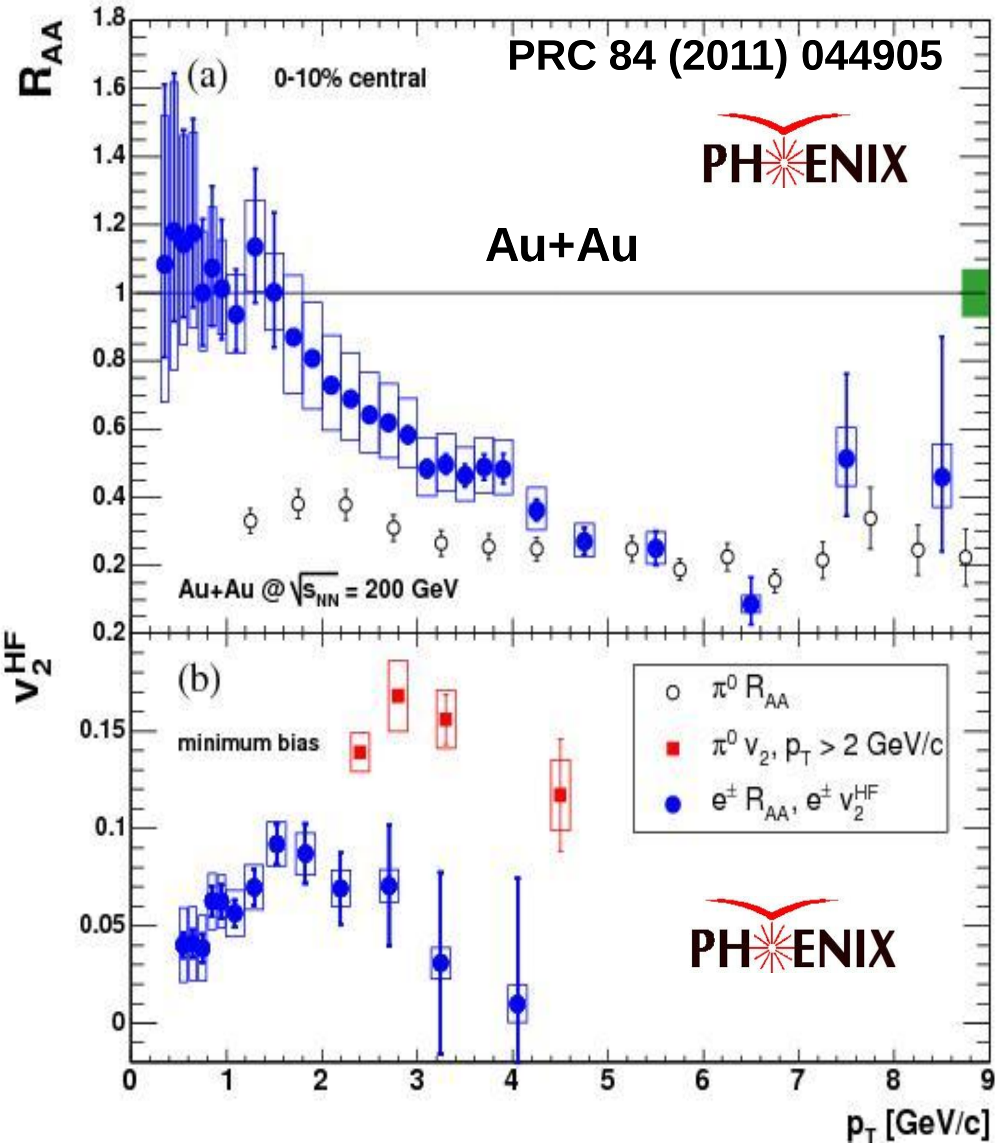
RIKEN BNL Research Center

Annual RBRC Scientific Review,
November 7th, 2012

One of the most surprising results from RHIC

- **Electrons from Heavy quarks suppressed, and they flow.**
- **Collective behavior is apparent in e^{HF}; but HF v_2 is lower than v_2 of π^0 for p_T > 2 GeV/c.**

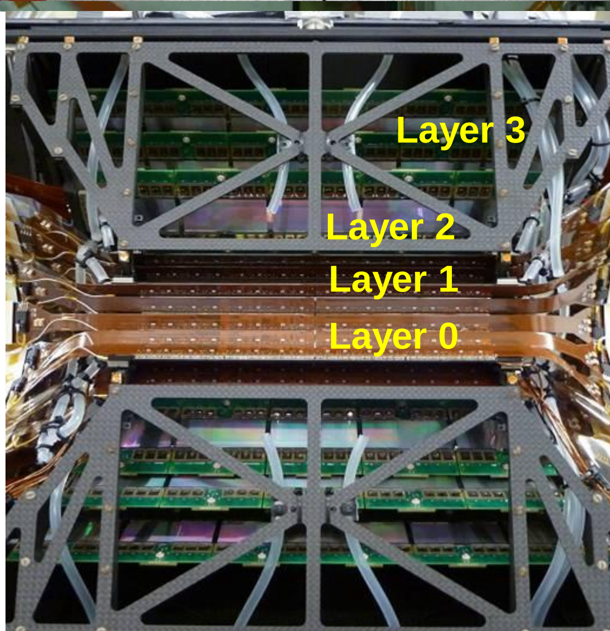
✧ **Separating charm and bottom is the key to understand the mass hierarchy of energy loss.**

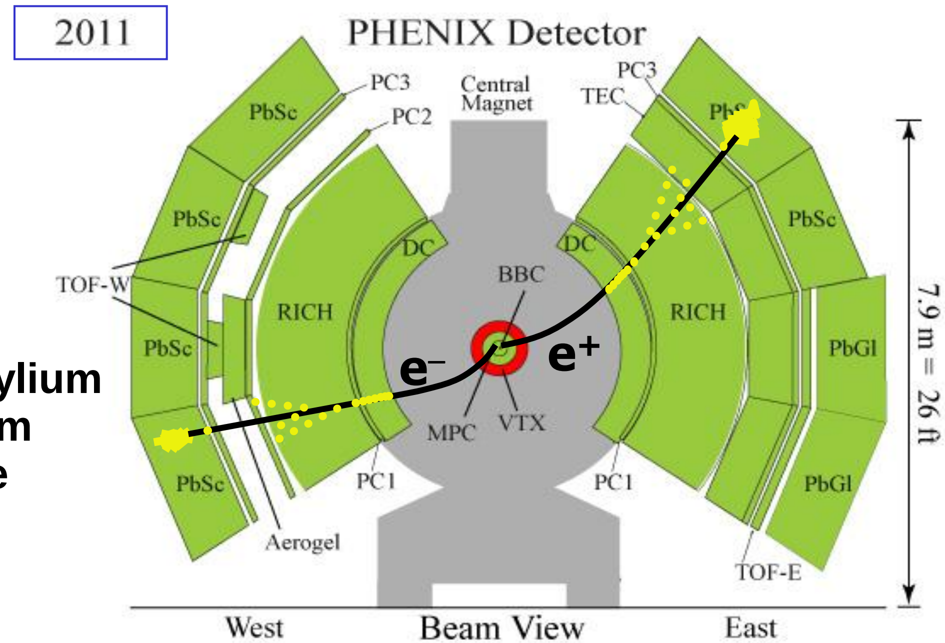


Silicon Vertex Tracker

VTX: Silicon Barrels ~ 2π

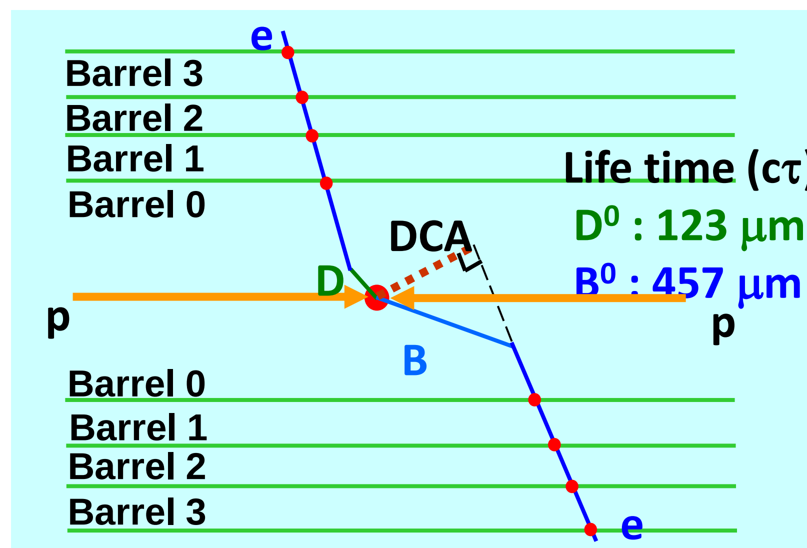
Berylium beam pipe





Main

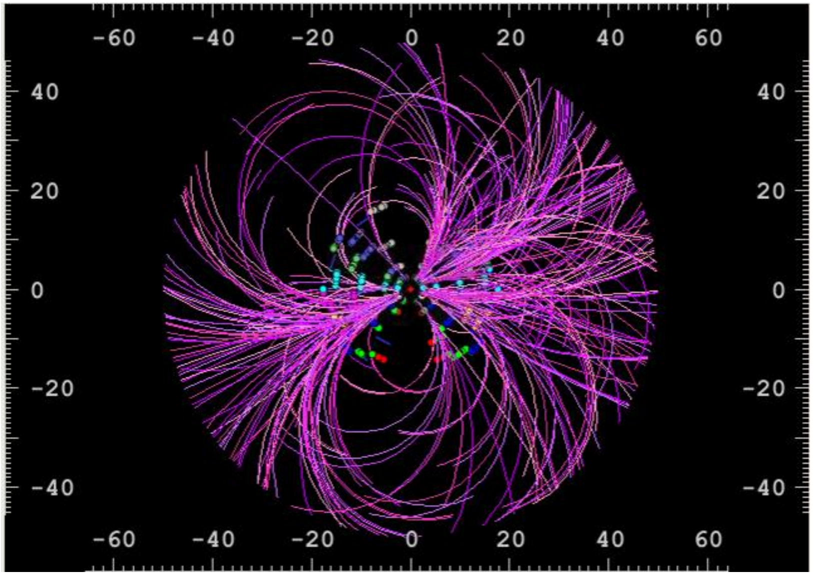
Goal



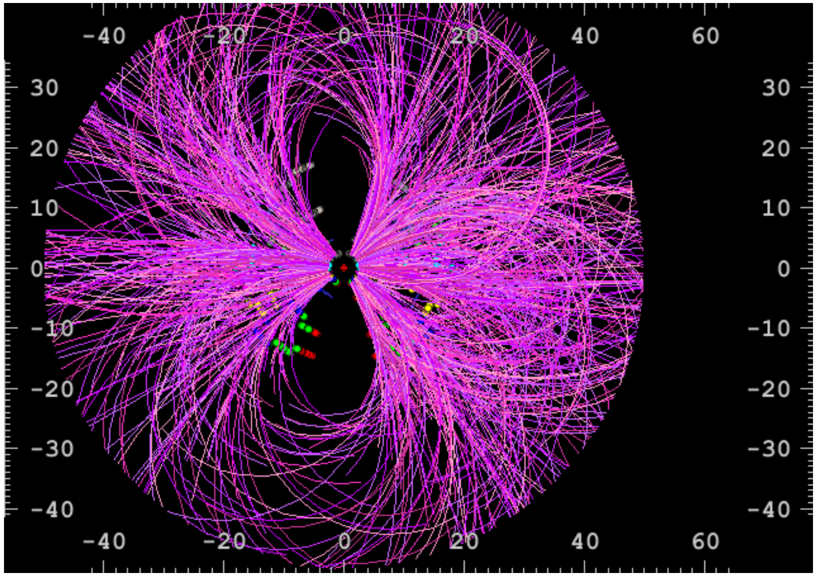
PHENIX-VTX in Action at RHIC

- **Run -11**
  - **Commissioned in p+p at 510 GeV**
  - **data: Au+Au at 19.6 GeV**
  - **Au + Au at 200 GeV**
  - **Au + Au at 27 GeV**
- **Run-12**
  - **p + p at 200 GeV**
  - **p + p at 510 GeV**
  - **Cu+ Au at 200 GeV**
  - **U + U at 200 GeV**

VTX in Run 2011: Au+Au at 19.6 GeV

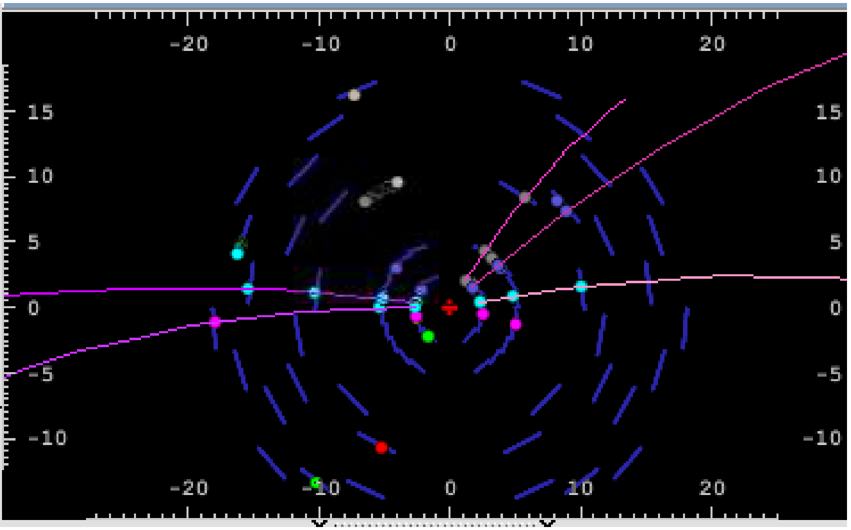


VTX in Run 2012: U+U at 200 GeV

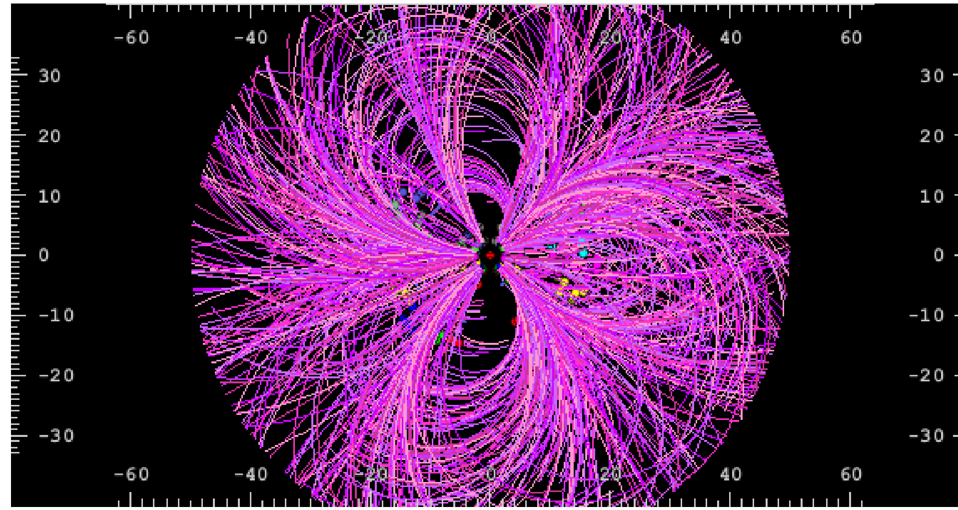


PHENIX-VTX in Action at RHIC

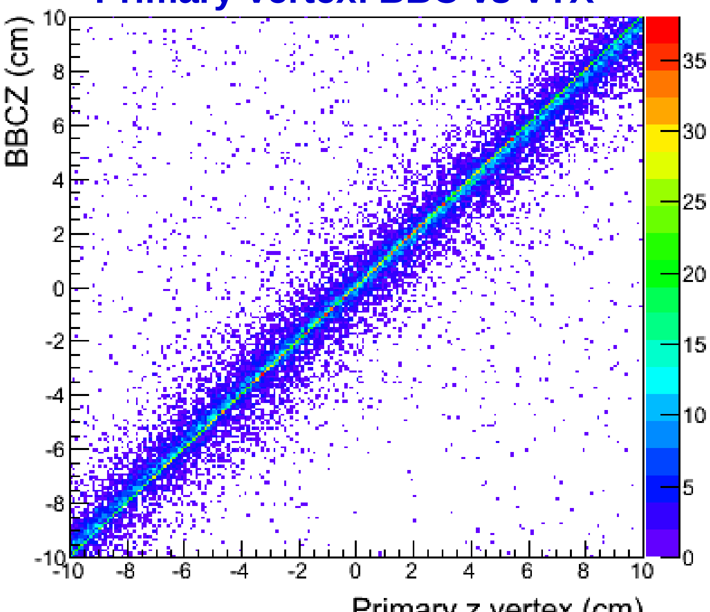
VTX in Run 2012: p+p at 200 GeV



VTX in Run 2011: Au+Au at 200 GeV



Primary Vertex: BBC vs VTX

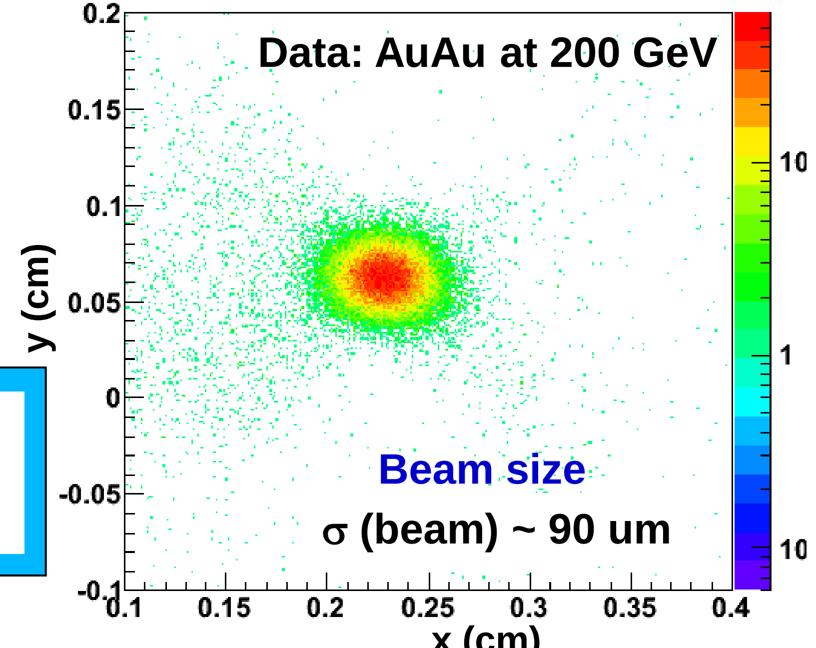


Primary Vertex Resolution

central (0-5%)

AuAu 200 GeV

$\sigma_x = 54 \pm 2\ \mu m$
$\sigma_y = 37 \pm 2$ mm
$\sigma_z = 68 \pm 2\ \mu m$



Conversion Electron Background Subtraction

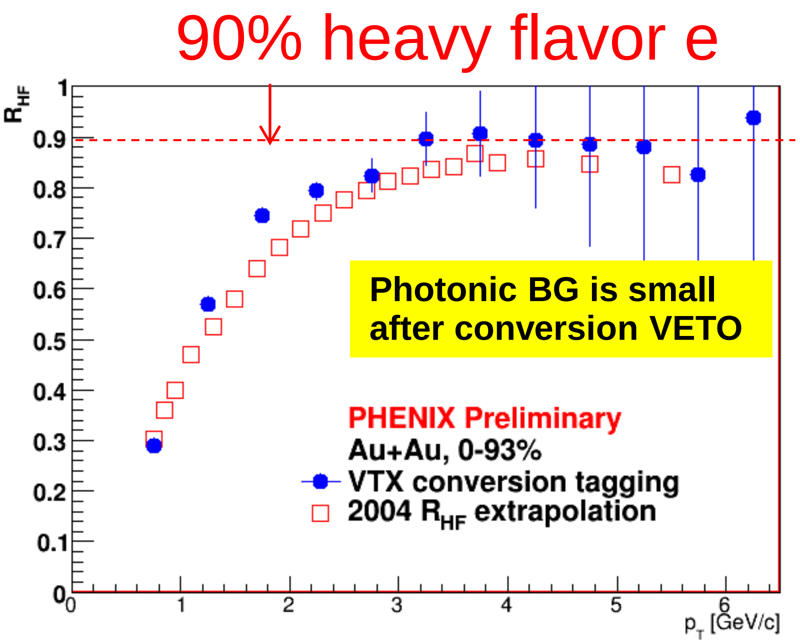
- Challenge in the DCA measurement of single electrons is the Conversion Electron Background (CEB).

- Most conversions happen in the outer layers (total radiation length = 12 % (B0: 1.3%, B1: 1.3%, B2:4.7% and B3: 4.7%). They are suppressed by requiring a hit in inner silicon layer B0.

- Conversions in the beam pipe and B0, and Dalitz are suppressed by rejecting electron tracks with a nearby hit : Conversion Tag and Veto.

- Yield of the remaining conversions and Dalitz are estimated using the veto efficiency.

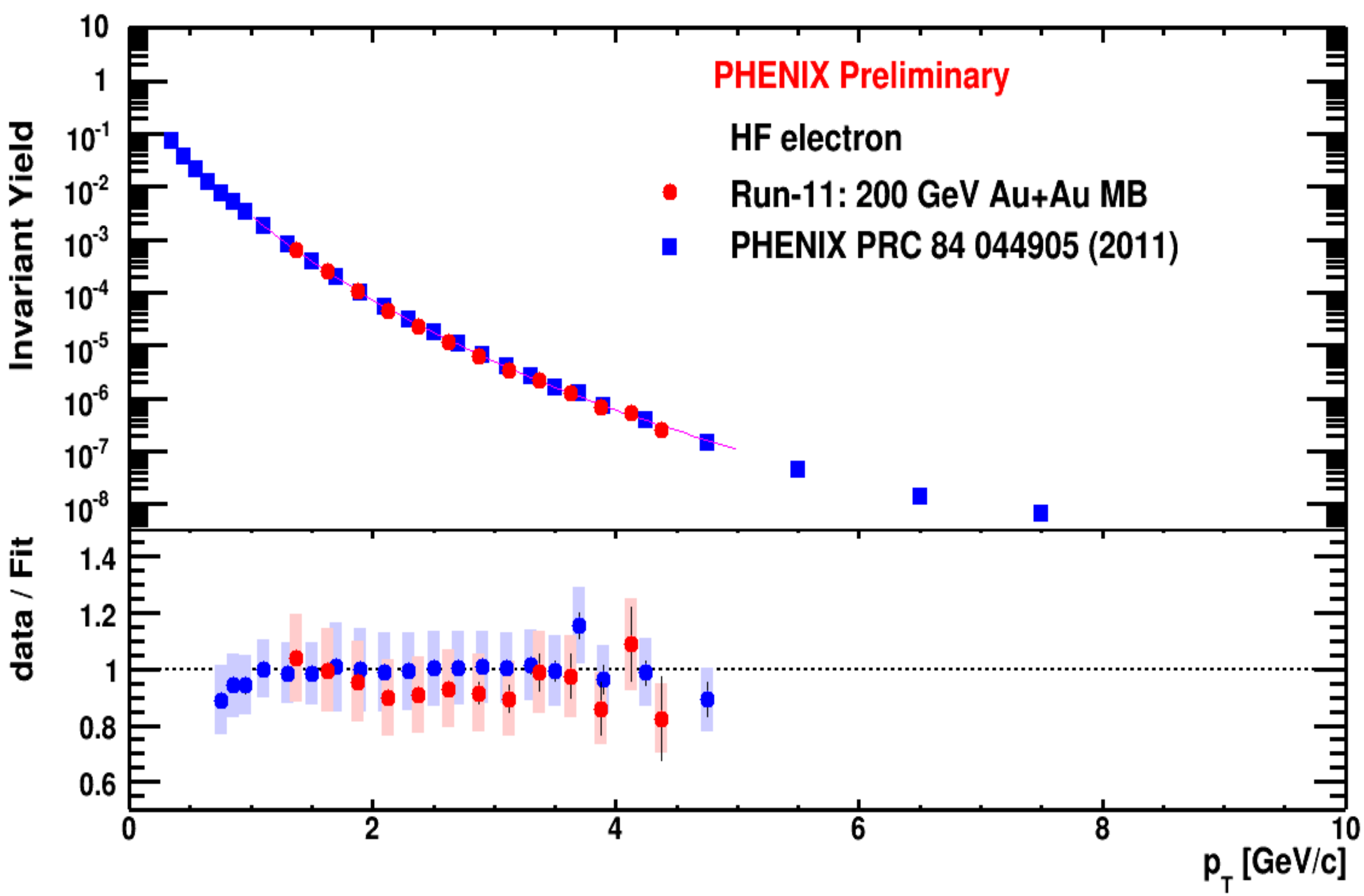
Fraction of HF electron after conversion Veto



HF Invariant Yield in Au + Au

- **Using VTX to tag Dalitz and conversion electrons, we measure the heavy flavor (HF) electron spectra**

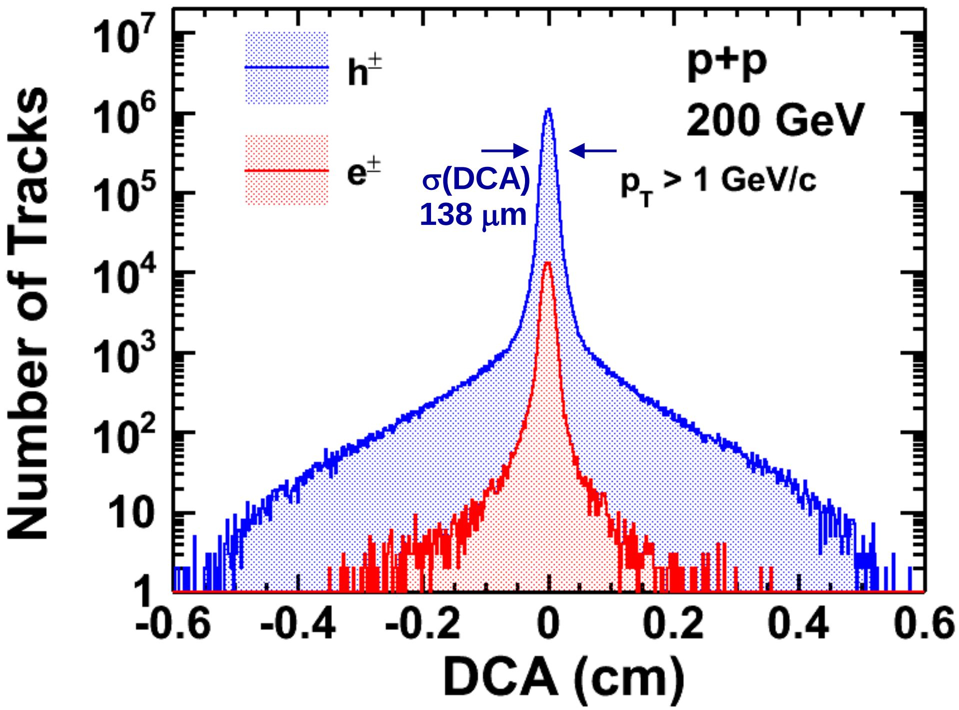
Run 2011 HF spectrum consistent with **previously published HF** by PHENIX

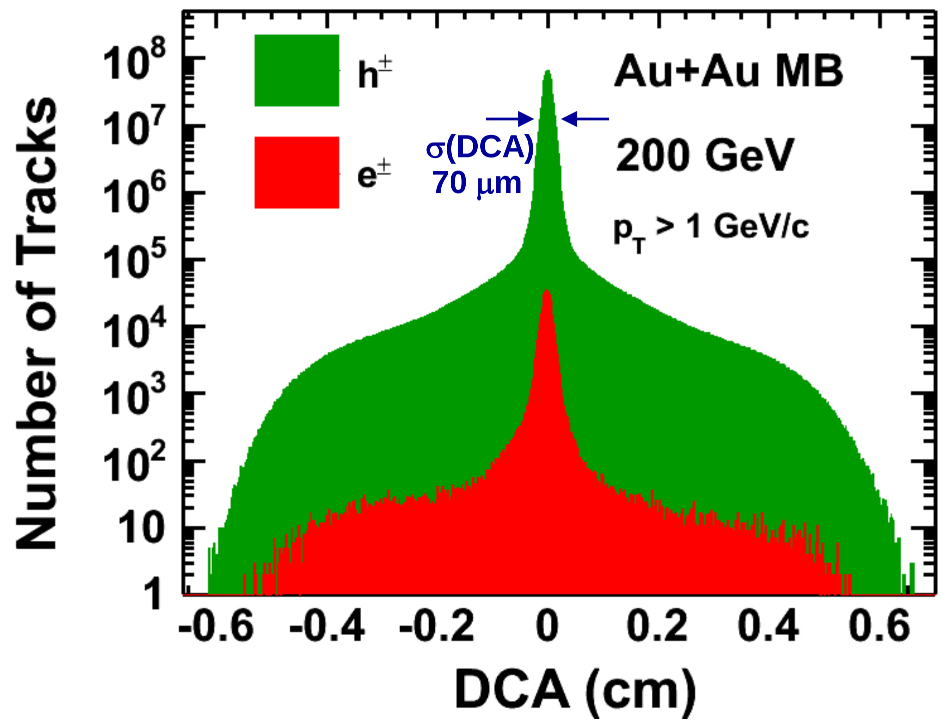


Raw DCA distributions for charged hadrons and electrons

p+p and Au+Au MB at 200 GeV

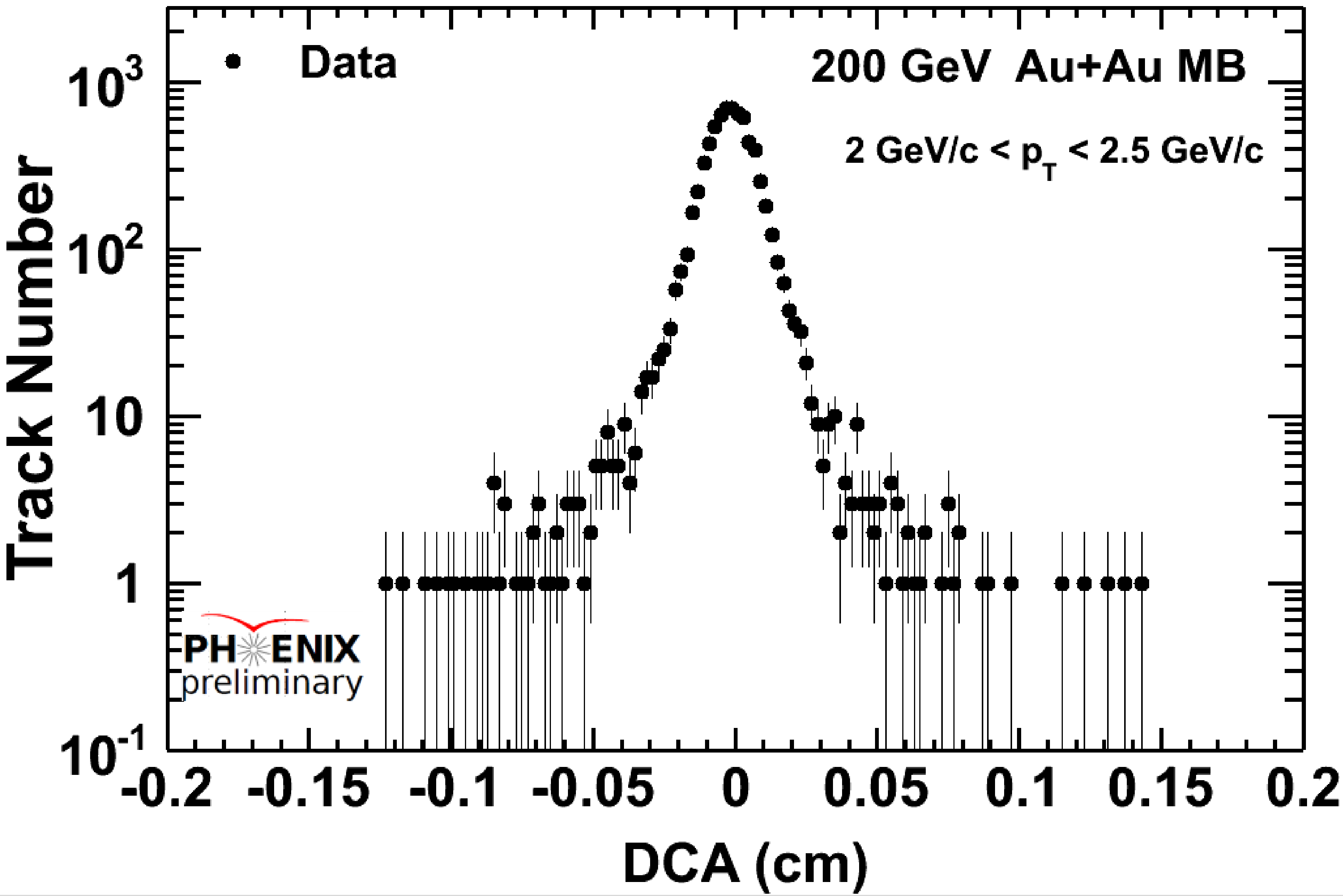
σ(DCA) ~ 70 μm





Note: **hadron contamination** for electron DCA distributions is not subtracted in these plots

Electron Distance of Closest Approach (DCA)



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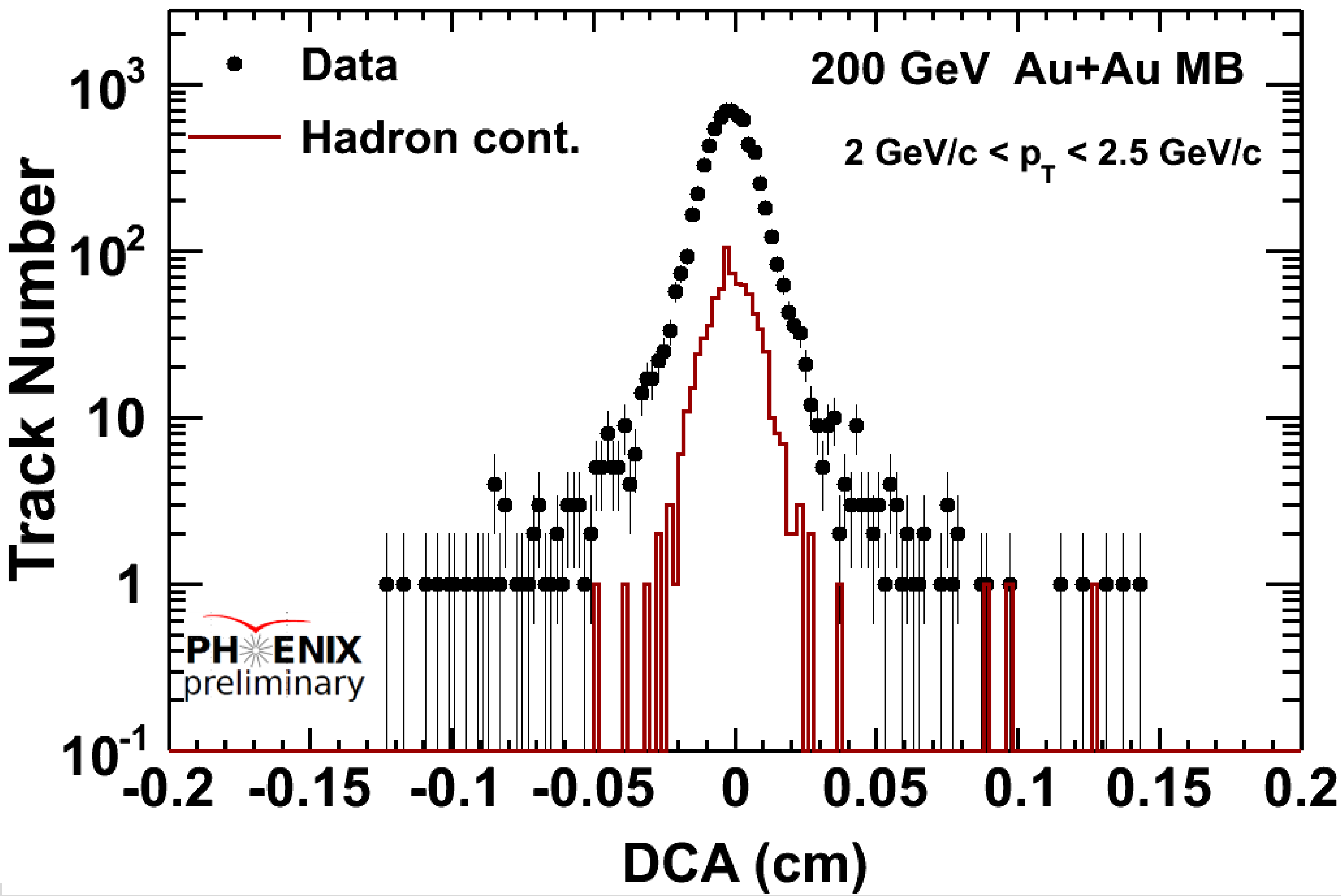

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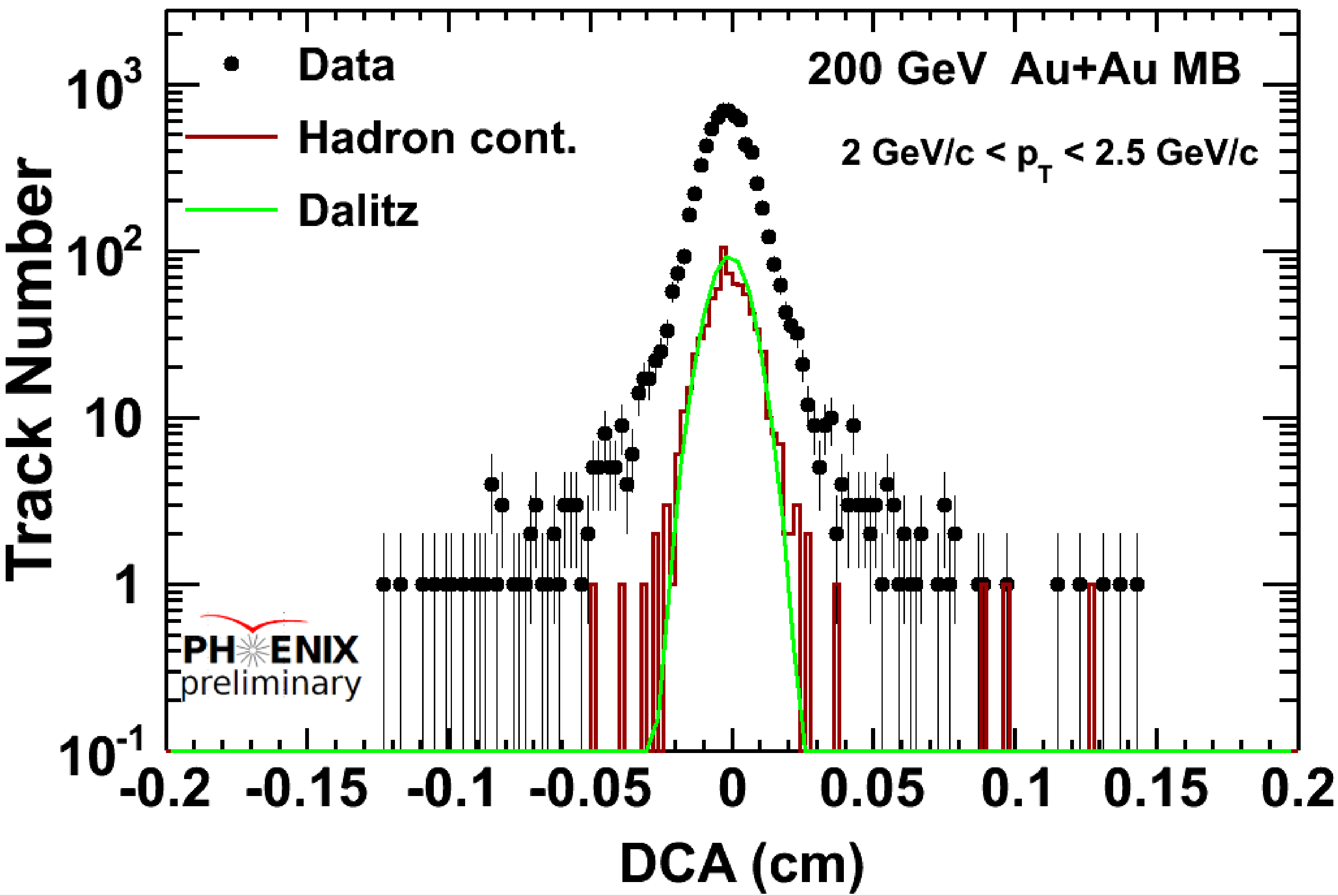

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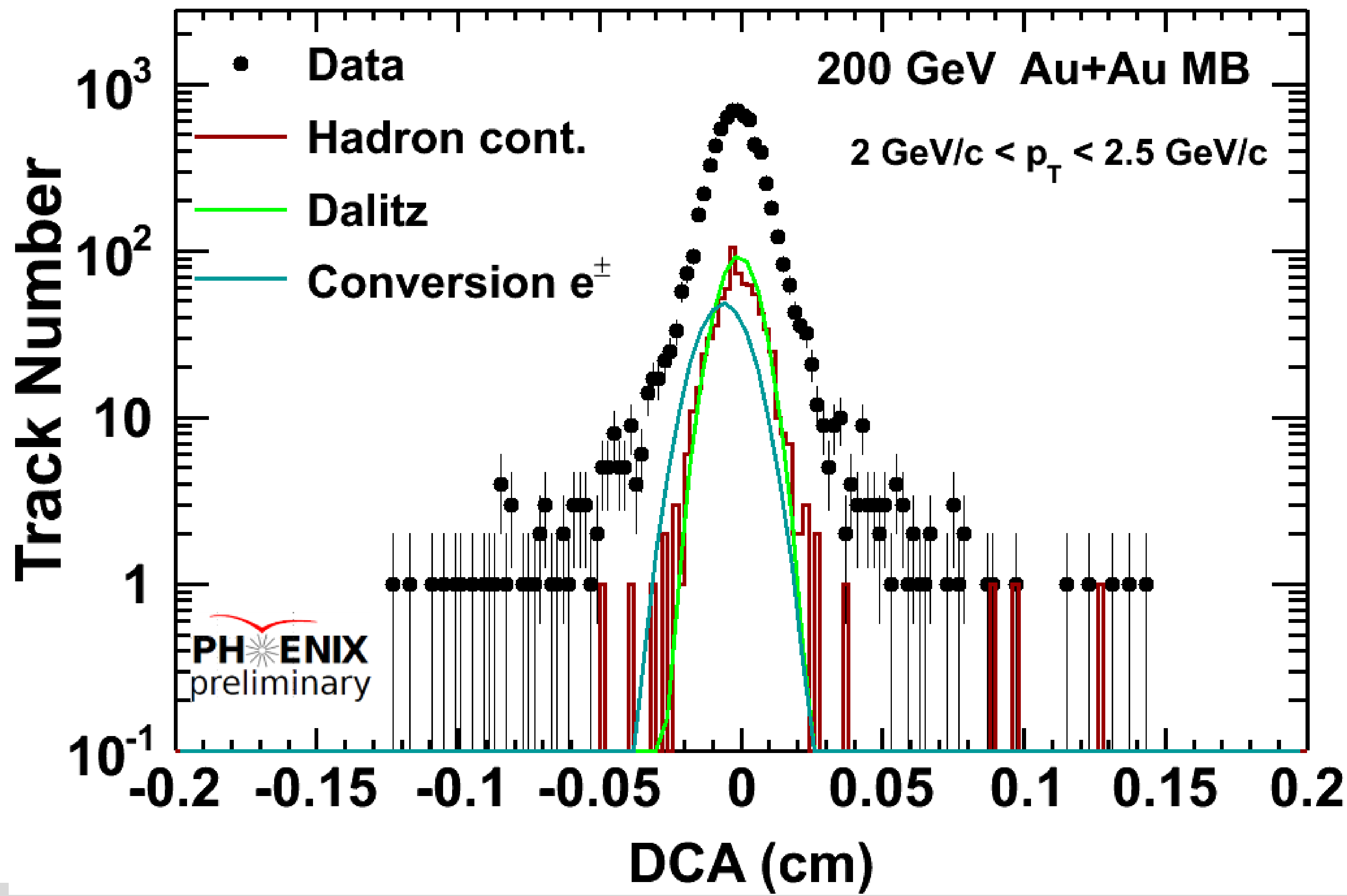

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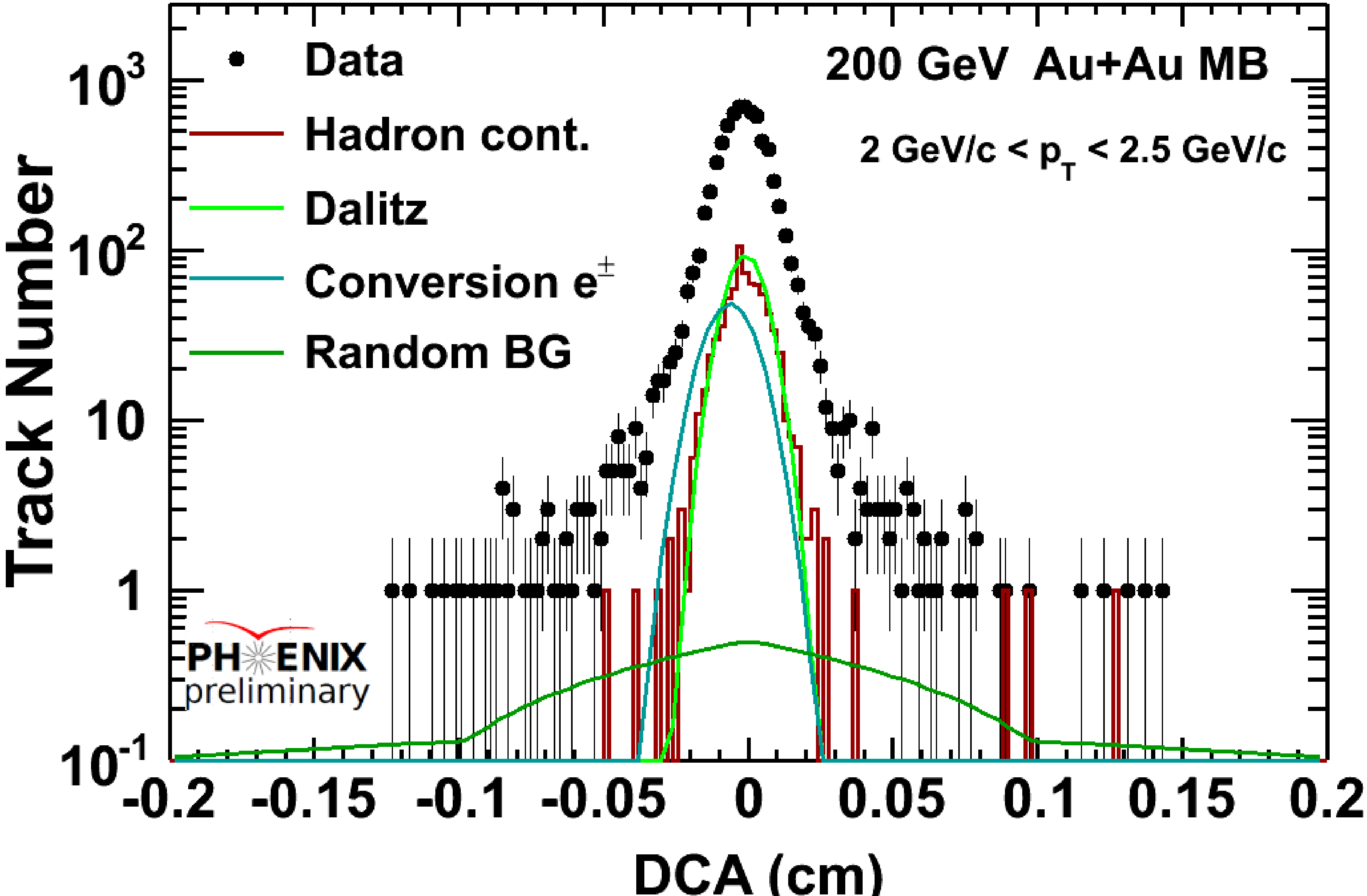

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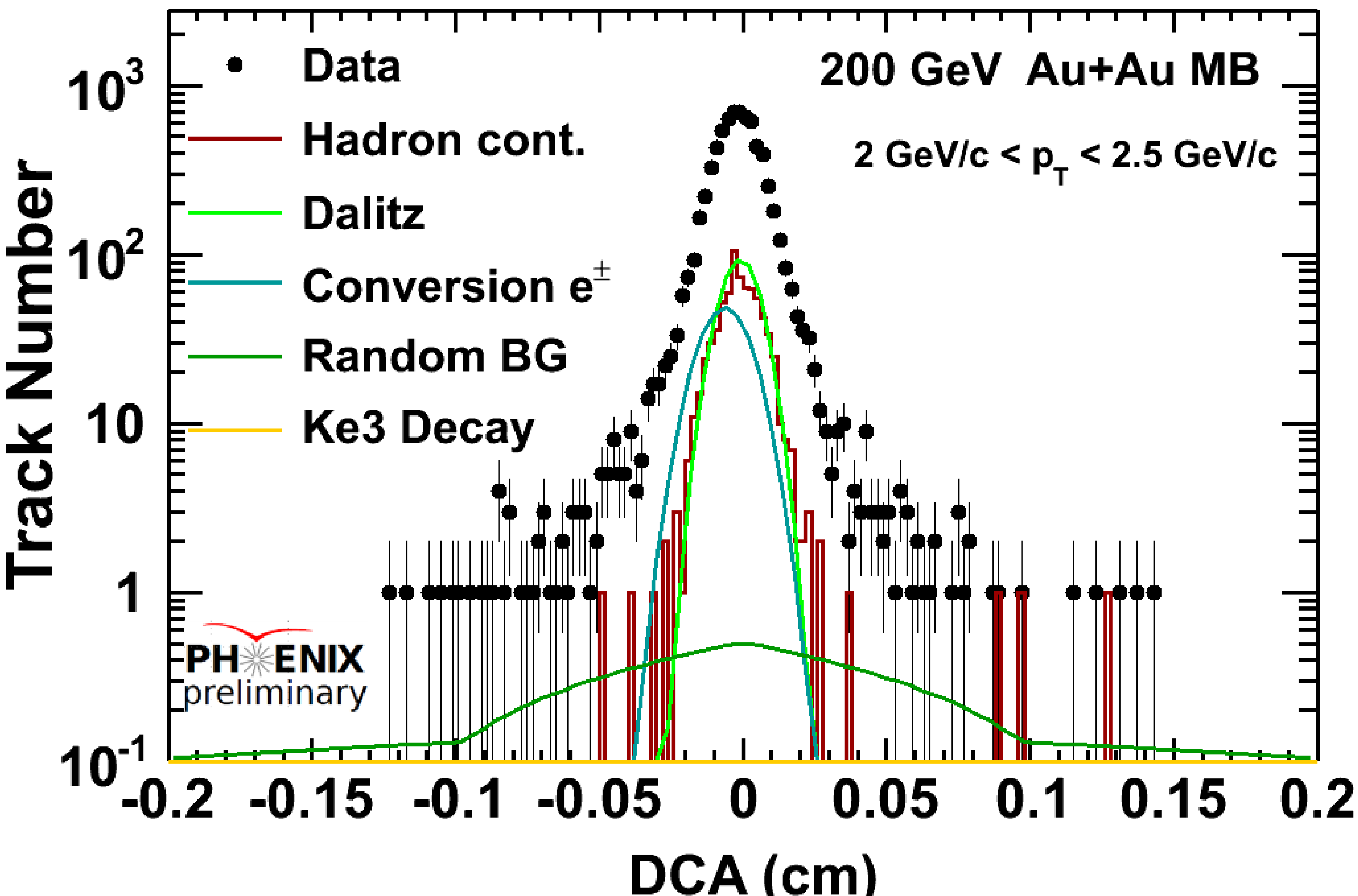

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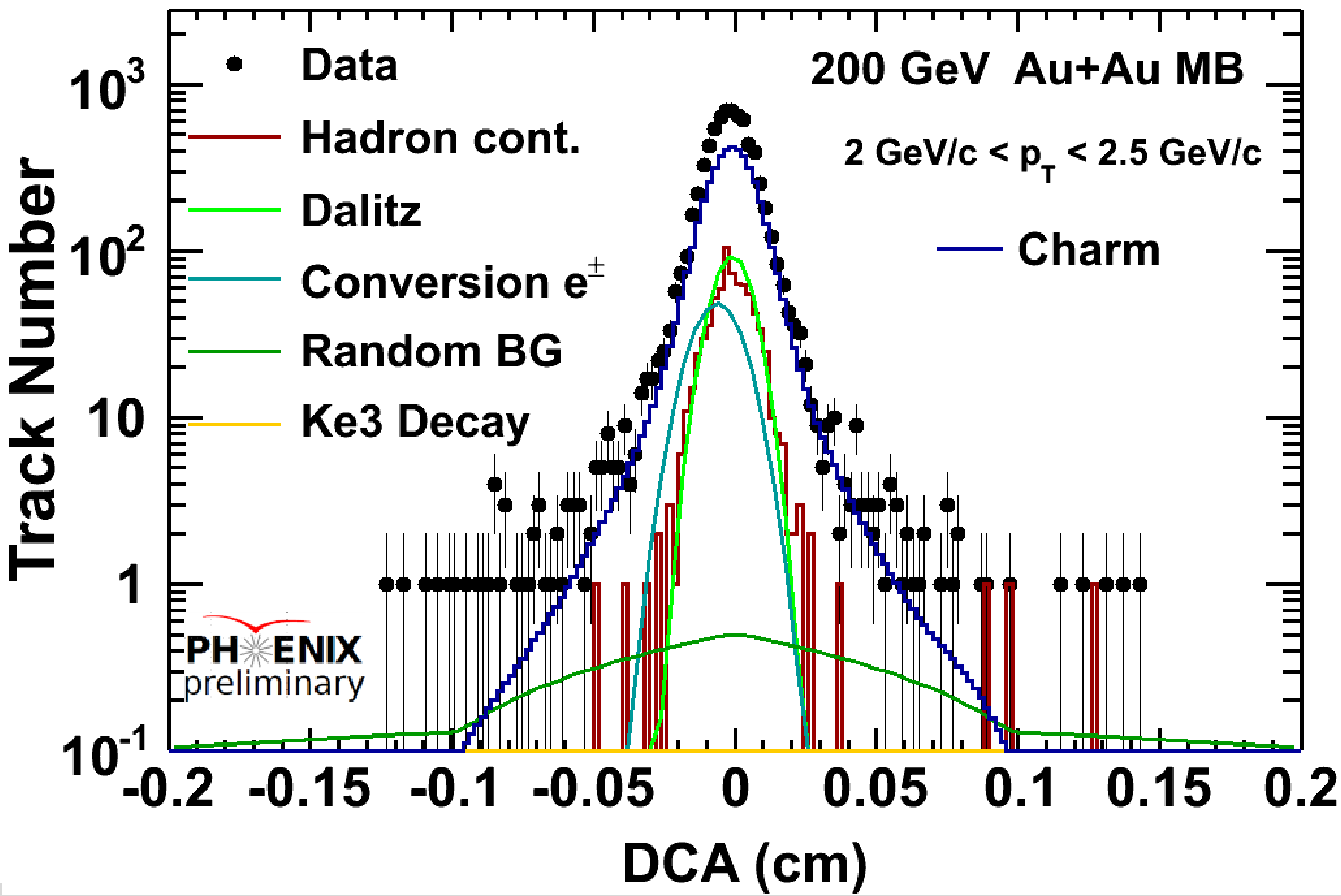

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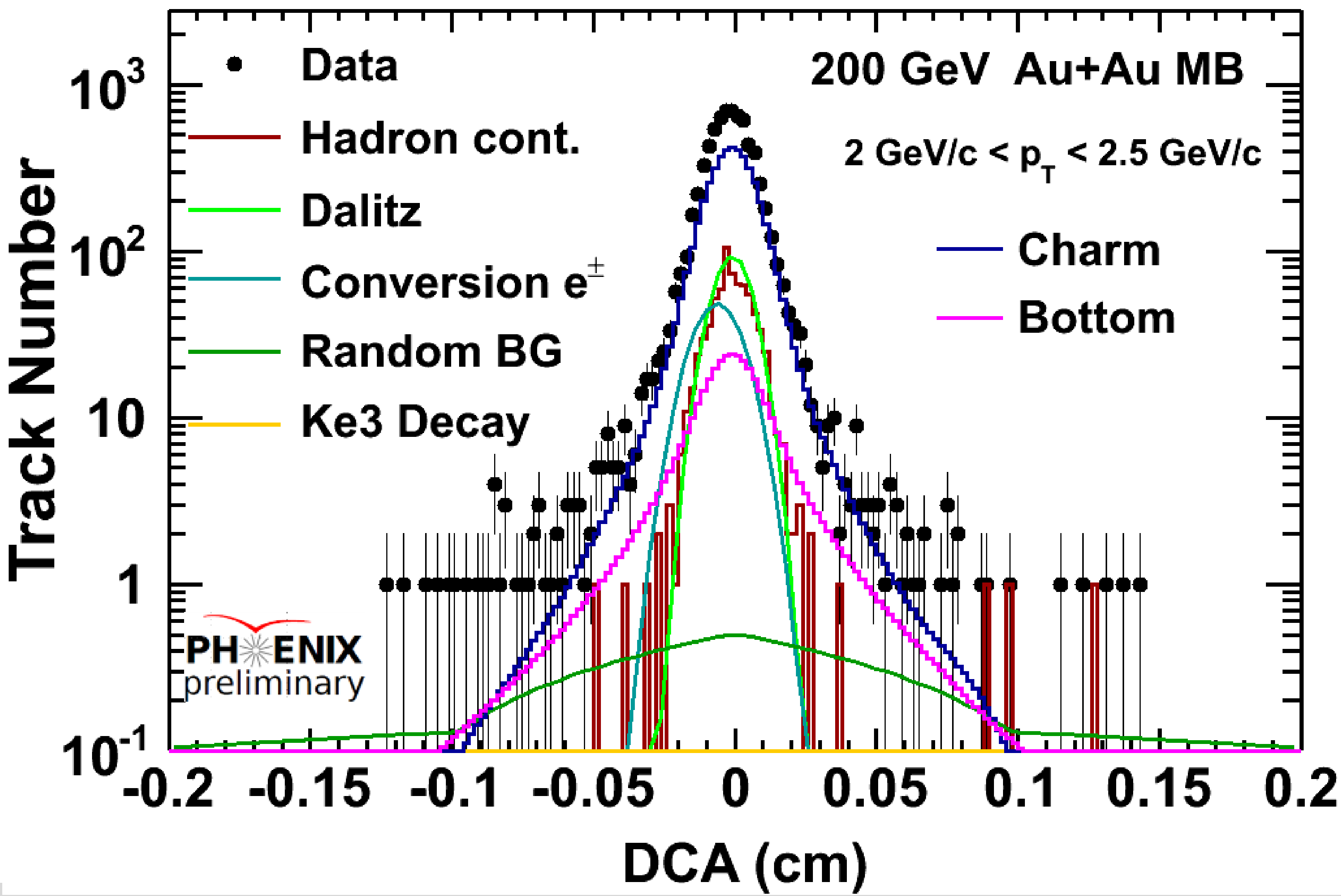

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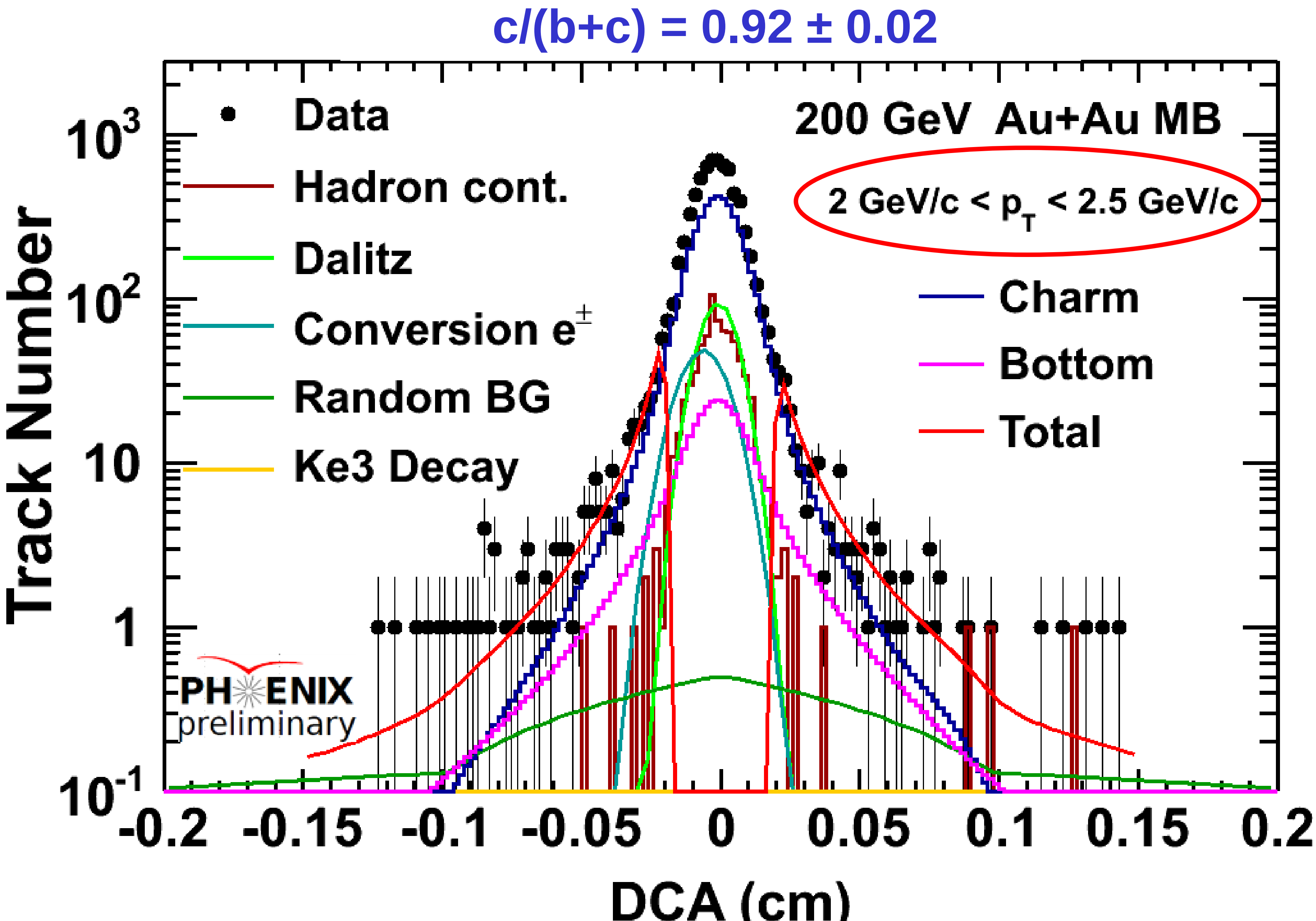

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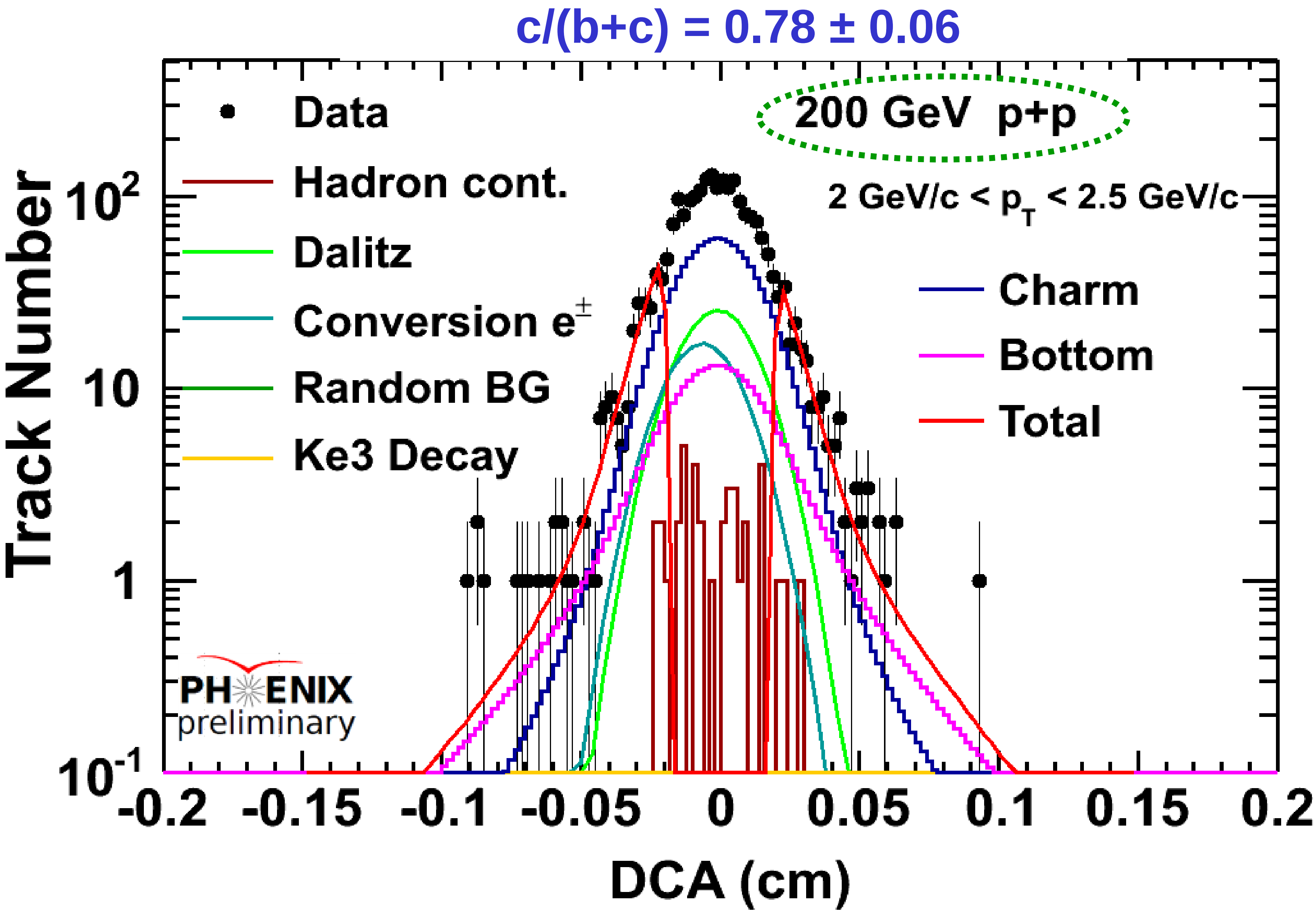
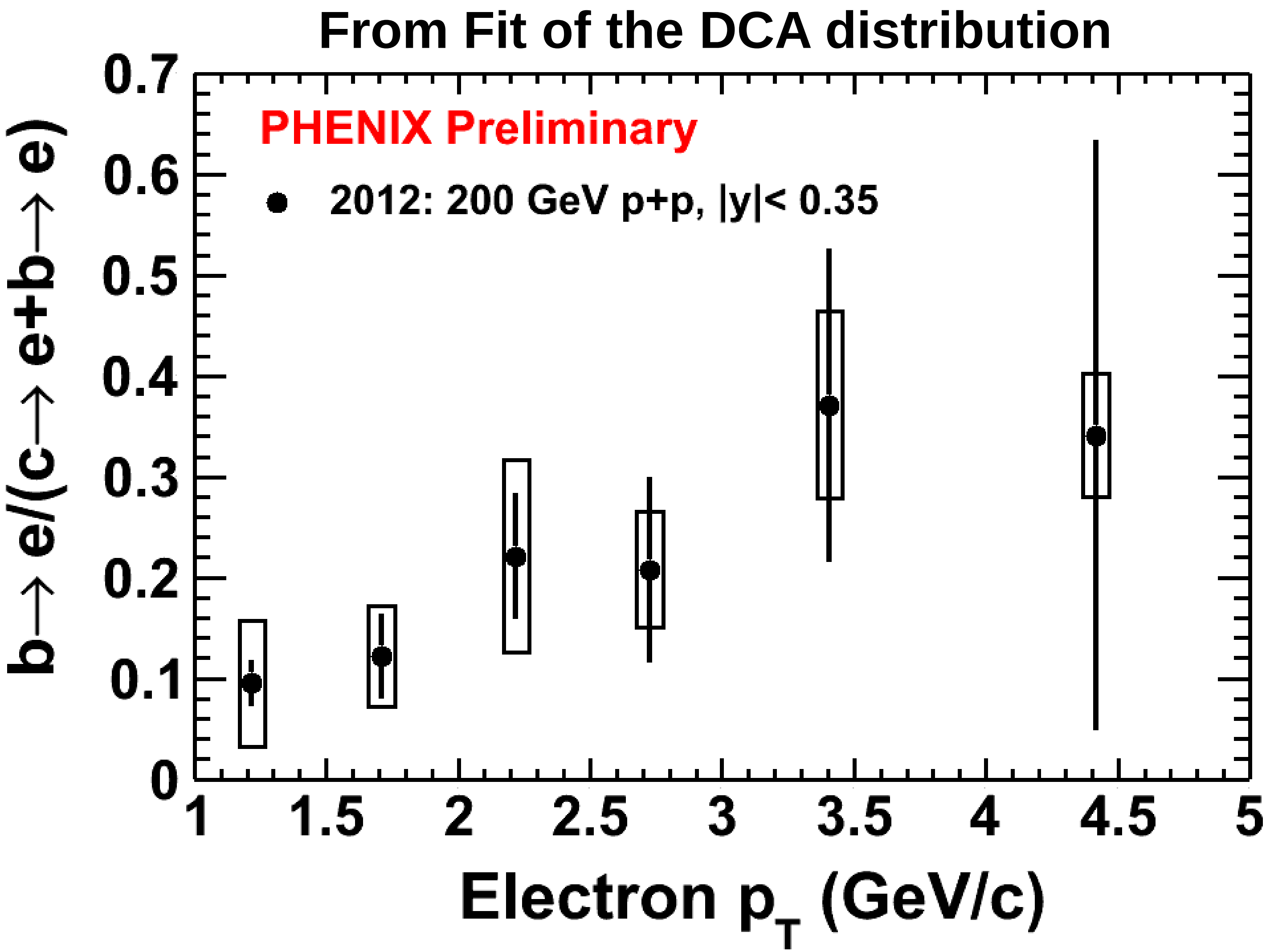


First direct measurements of bottom production in p+p at RHIC

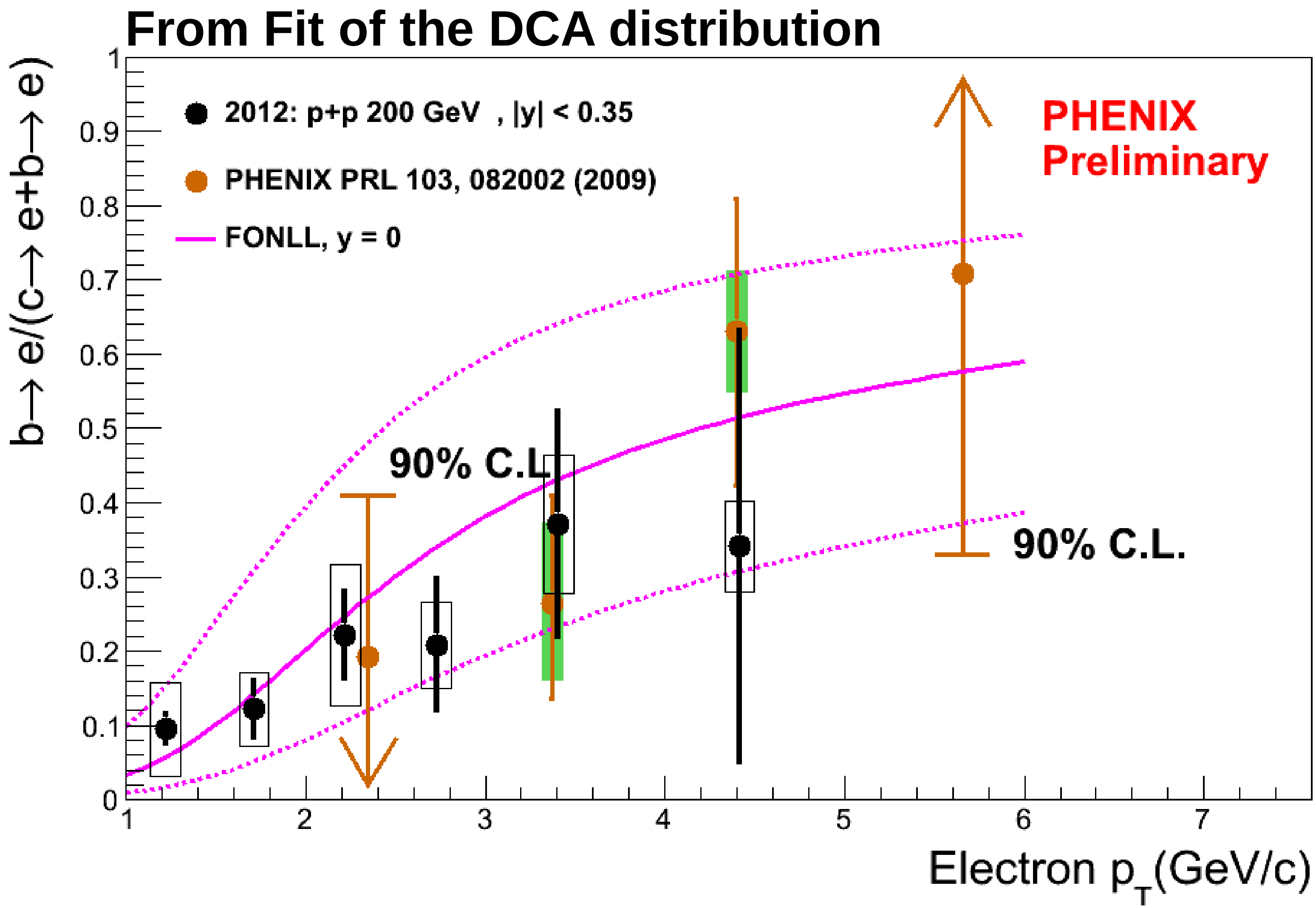


Results: Bottom Production in p+p 200 GeV

VTX direct measurement of b/b+c using DCA confirms published results using e-h correlation

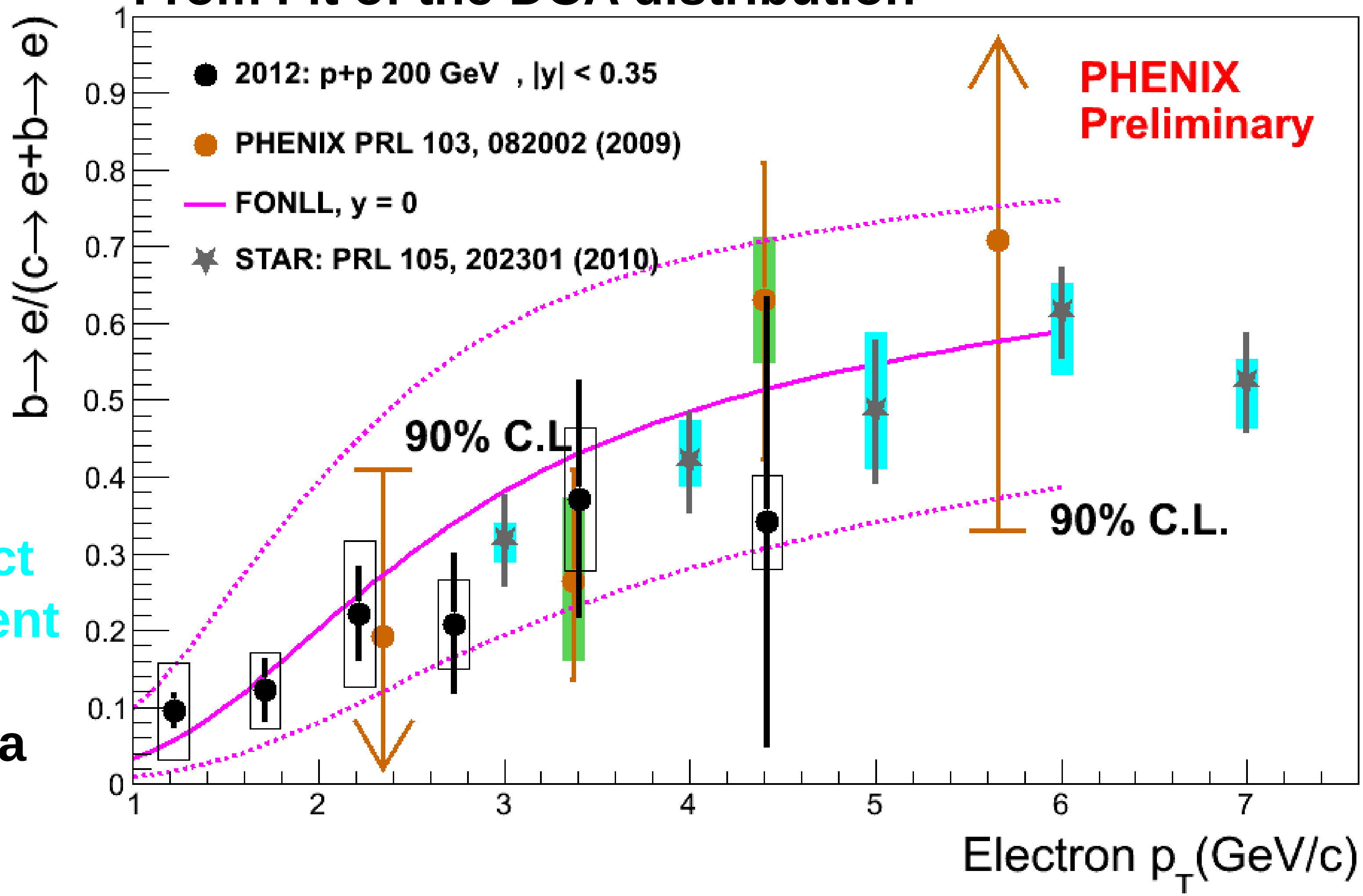
PHENIX Published data agree With new data

FONLL agree with data



First direct measurement of bottom production in p+p at RHIC

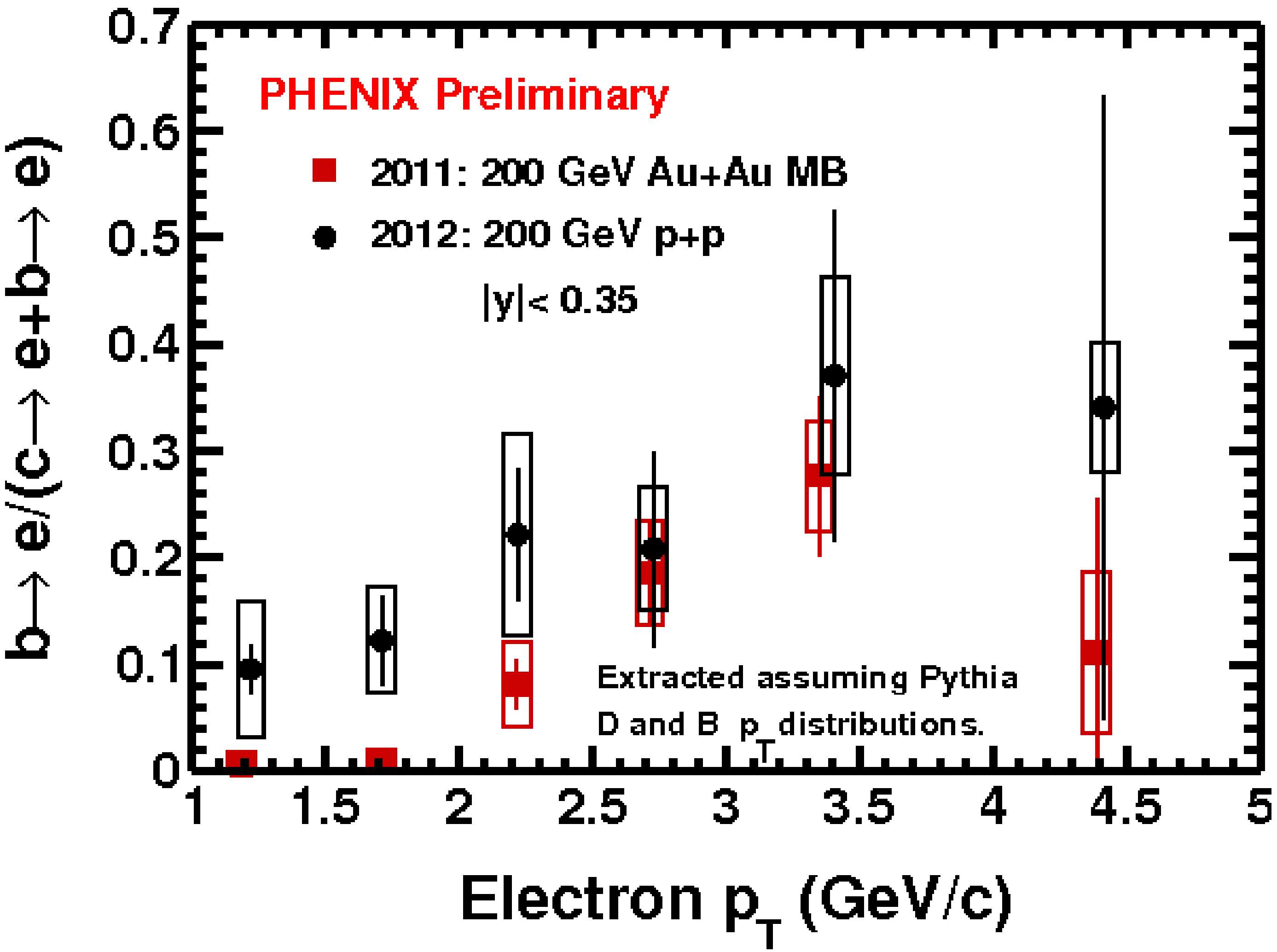
From Fit of the DCA distribution



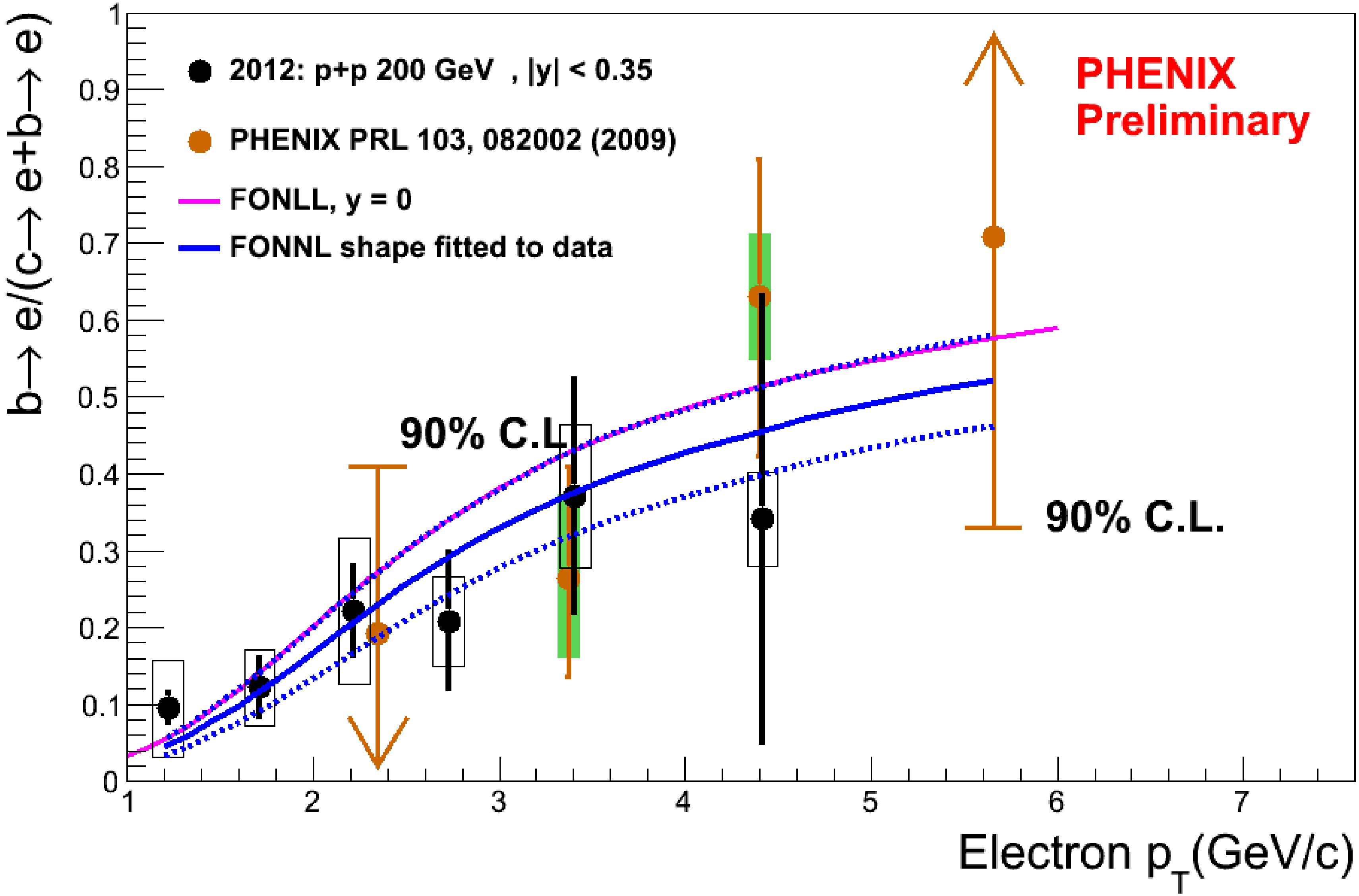
STAR indirect measurement consistent with our data

Results: Bottom Production in Au+Au and p+p

b→e /(b→e+ c→e) in 200 GeV Au+Au vs p+p
From Fit of the DCA distribution

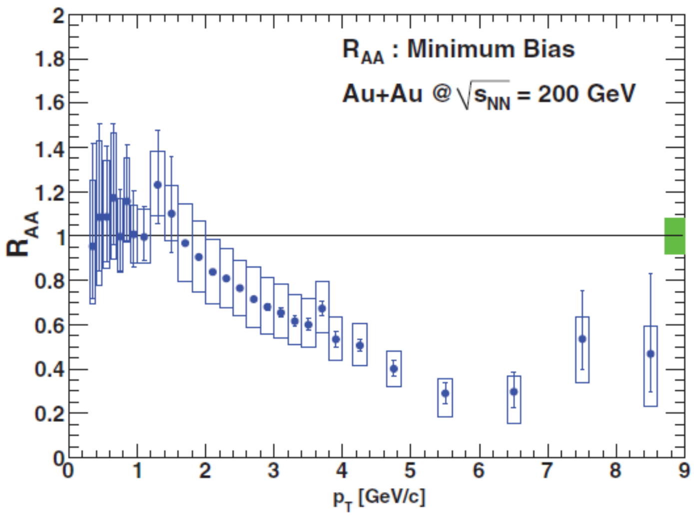


p+p: b/(b+c) Fitted by FONNL



R_{AA} of Bottom Extraction

$$R_{AA}{}^{b\to e} = R_{AA}{}^{b+c\to e}\frac{\left(\frac{b\to e}{b+c\to e}\right)^{AA}}{\left(\frac{b\to e}{b+c\to e}\right)^{pp}}$$

R_{AA} (b→e) = 

X ————————

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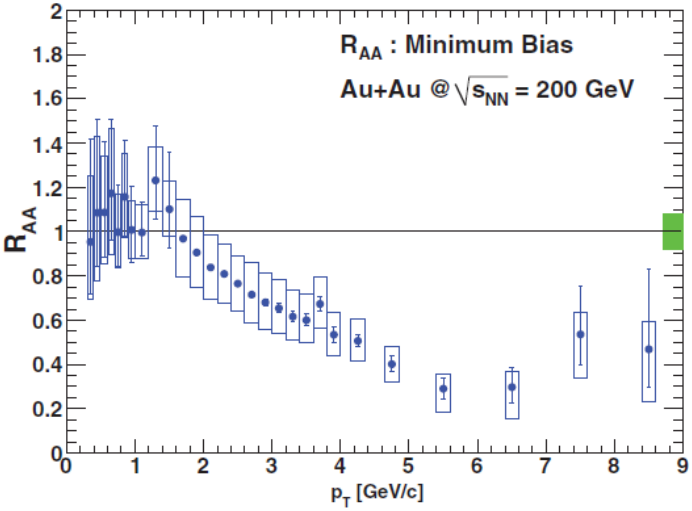
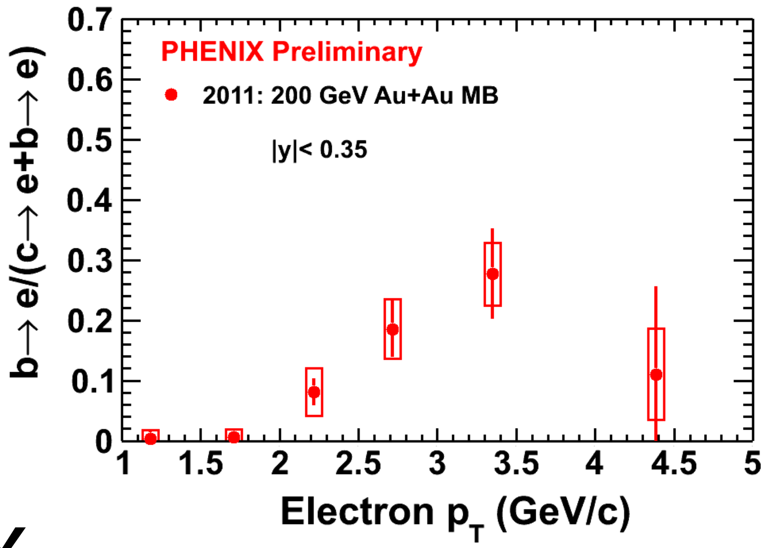
R_{AA} (b→e) = 

X 

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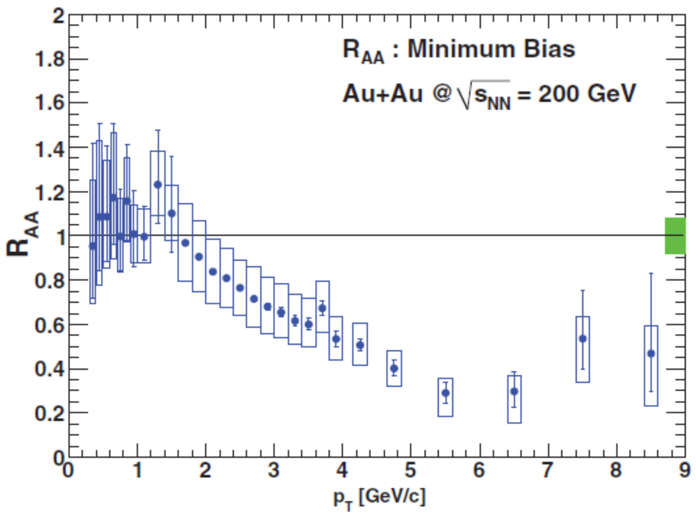

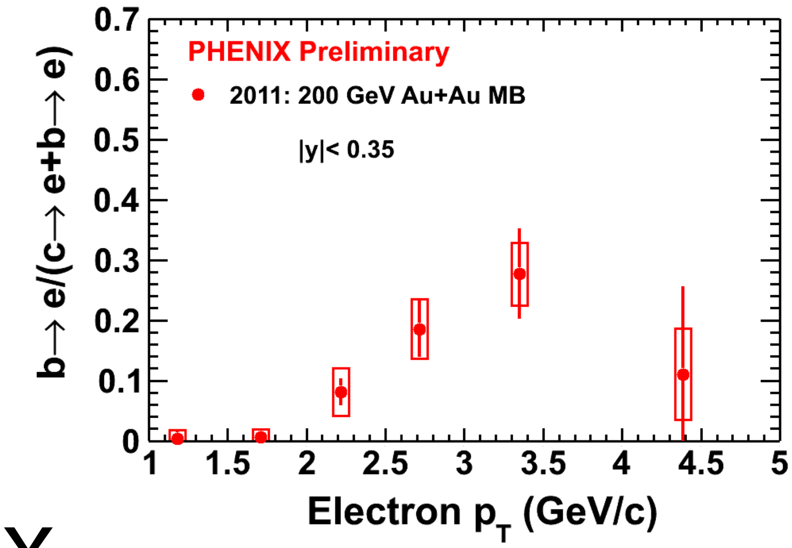

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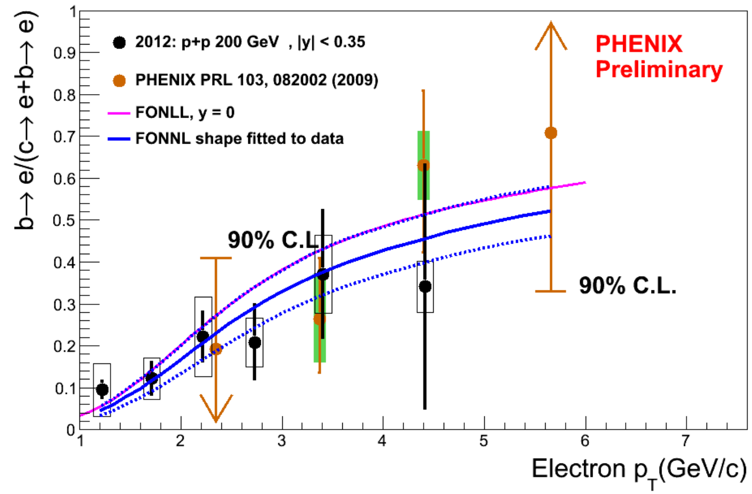

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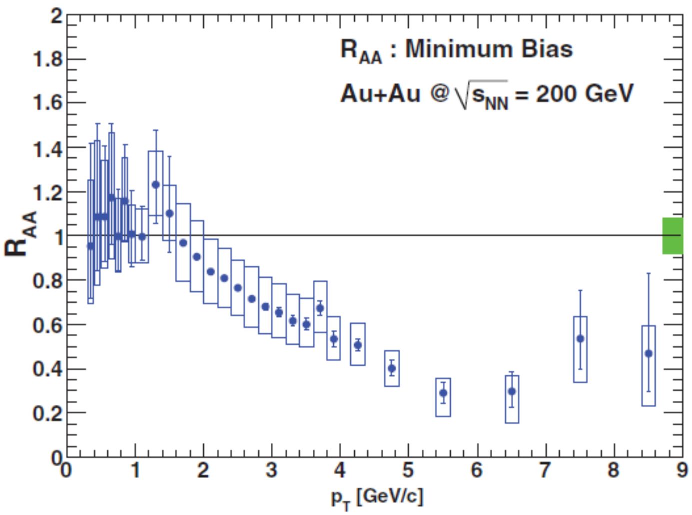

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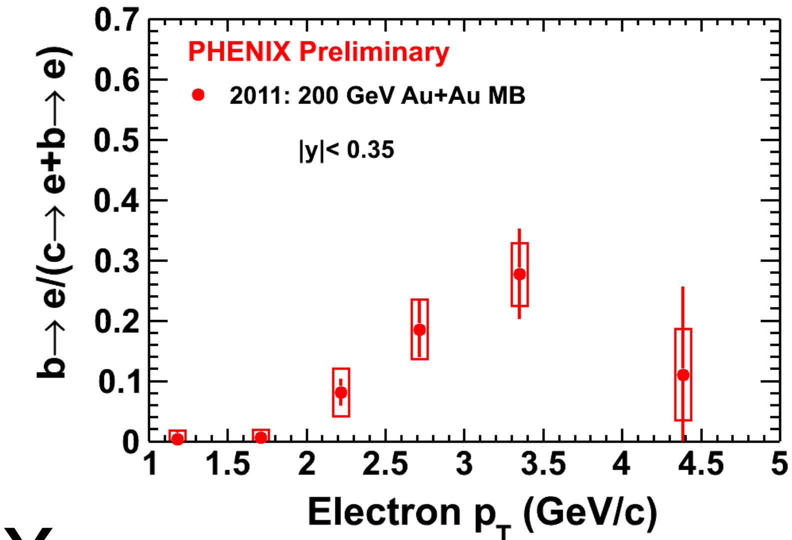
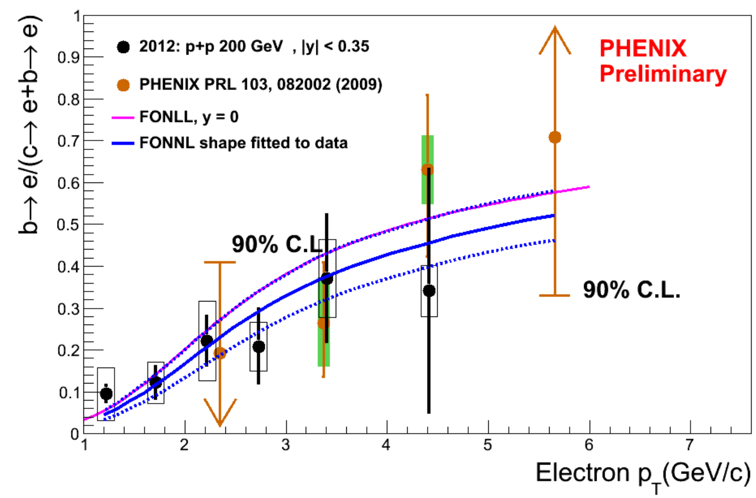
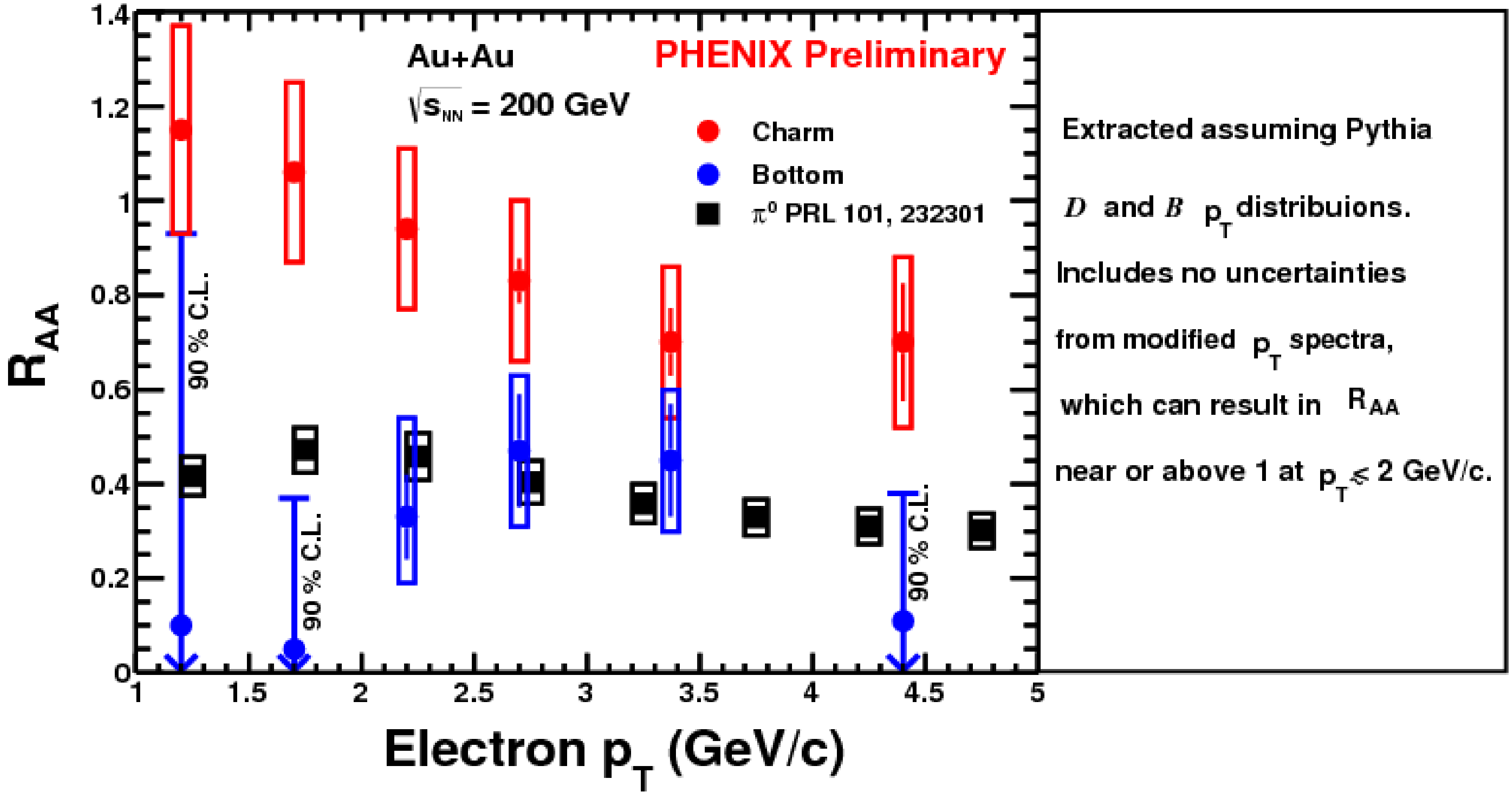




$$R_{AA}{}^{c\to e} = R_{AA}{}^{b+c\to e}\frac{1-\left(\dfrac{b\to e}{b+c\to e}\right)^{AA}}{1-\left(\dfrac{b\to e}{b+c\to e}\right)^{pp}}$$

Nuclear Modification of Charm and Bottom



- We observe that the nuclear modification of c→e is less than that for π^0 s (R_{AA} (c->e) > R_{AA} (π^0))

- These results imply that either a large suppression of b → e or a large modification of B meson p_T distributions, which implies a very interesting physics of B mesons in Au+Au collisions.

We are actively working on evaluation of these uncertainties.

Summary

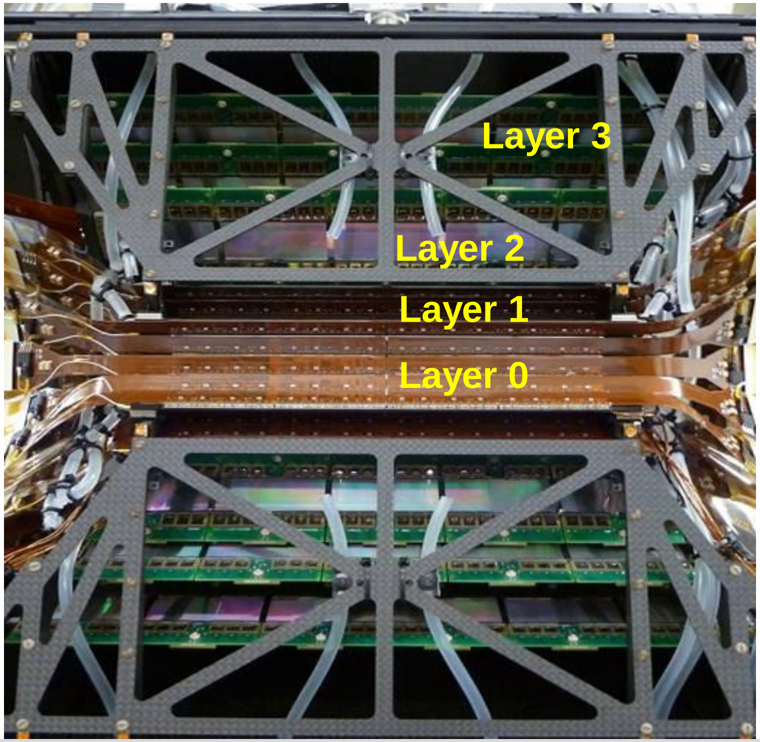
- First measurements of Charm and Bottom separately in heavy ion collisions at RHIC achieved
- In p+p, FONLL prediction of b/(b+c) agrees with the data
- In Au+Au, the data imply a large suppression of b→ e or a large modification of B meson p_T distributions, which implies a very interesting physics of B mesons in Au+Au collisions. We are actively working on evaluation of these uncertainties.
- PHENIX-VTX opens new era of heavy flavor physics at RHIC: Cu+Au and U+U

Auxiliary Slides

Conversion Electron Background Subtraction

- Challenge in the DCA measurement of single electrons is the Conversion Electron Background (CEB).

- Most conversions happen in the outer layers (total radiation length = 12 % (B0: 1.3%, B1: 1.3%, B2:4.7% and B3: 4.7%). They are suppressed by requiring a hit in inner silicon layer B0.



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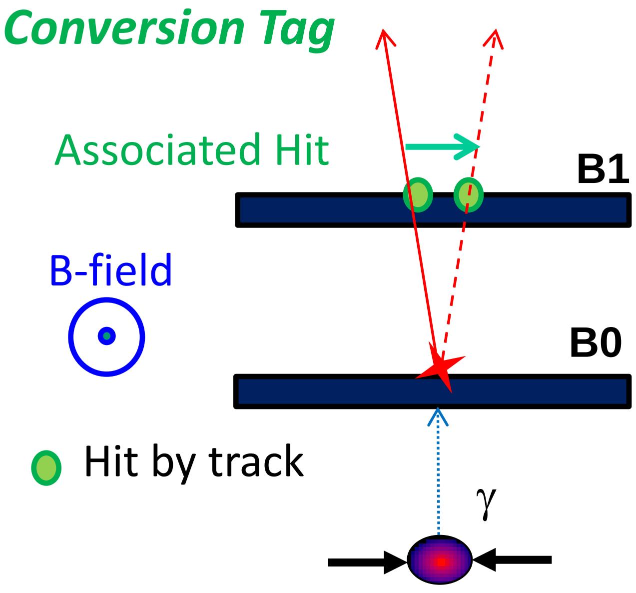
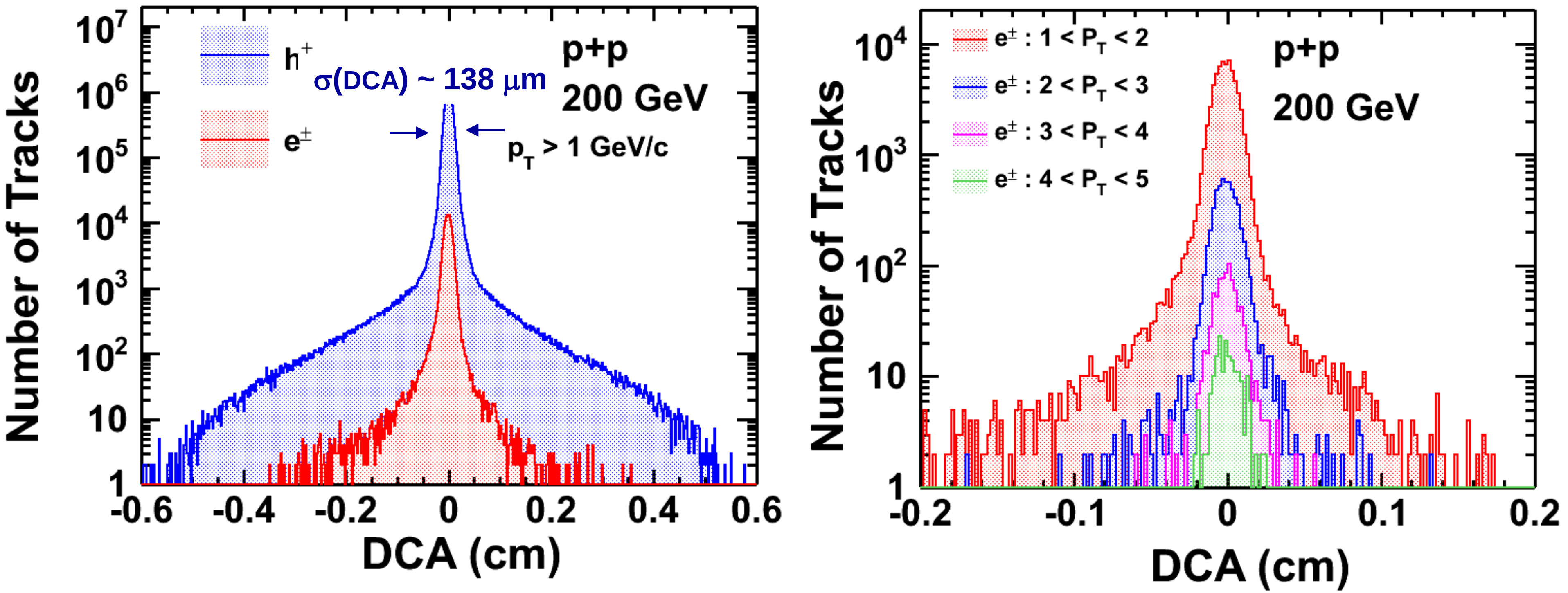


Decomposition of the DCA Distributions

- VTX provides another new capability:
  - Measure distance of closest approach to separate charm and bottom components of heavy flavor spectra

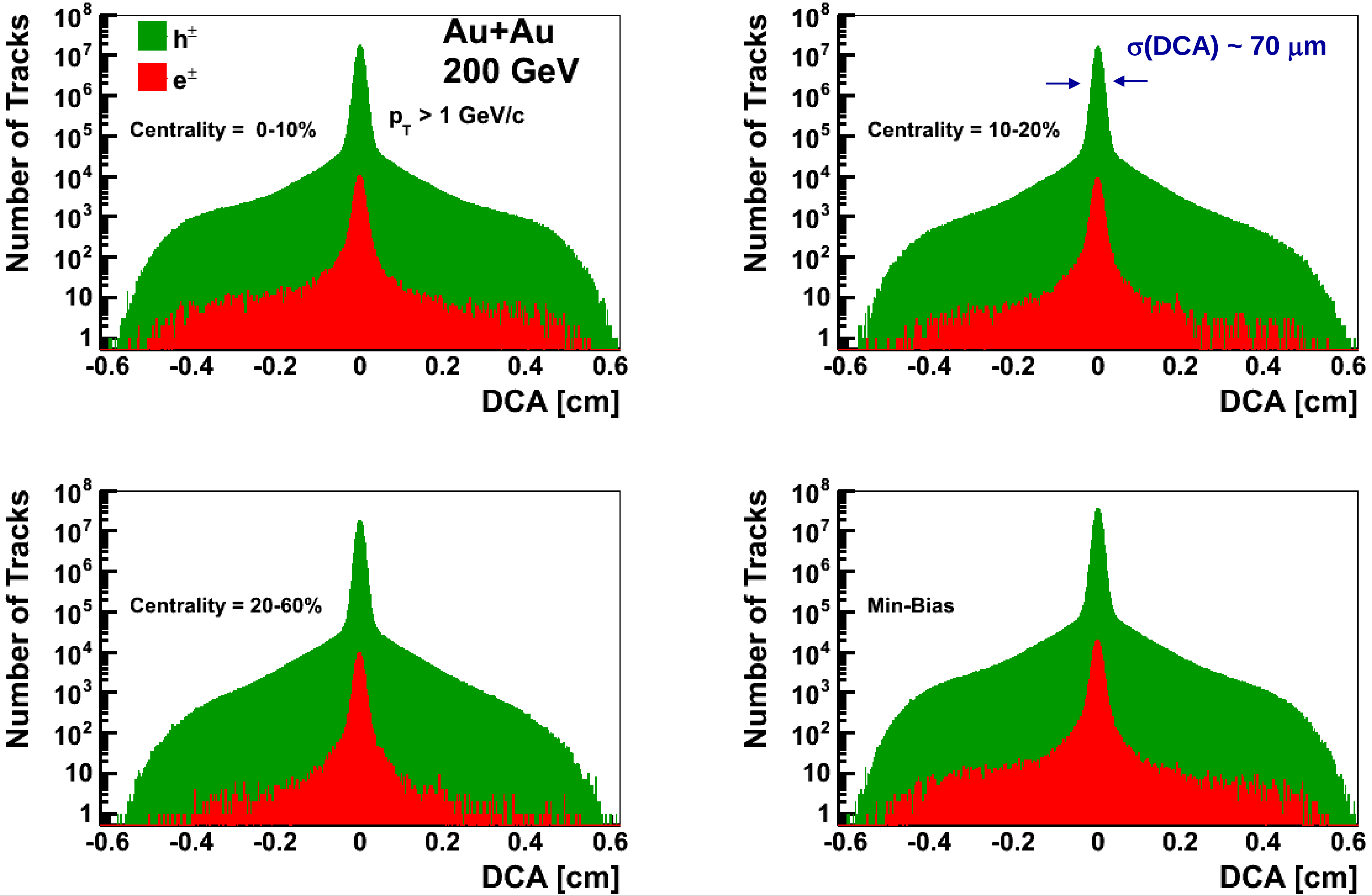
- Charm to bottom ratio is obtained from the fit to the DCA distribution of measured electrons:
  - Charm and Bottom events generated by PYTHIA are convoluted with DCA resolution to obtained expected DCA distribution <u>shapes</u>.

Raw DCA distributions for charged hadrons and electrons p+p at 200 GeV



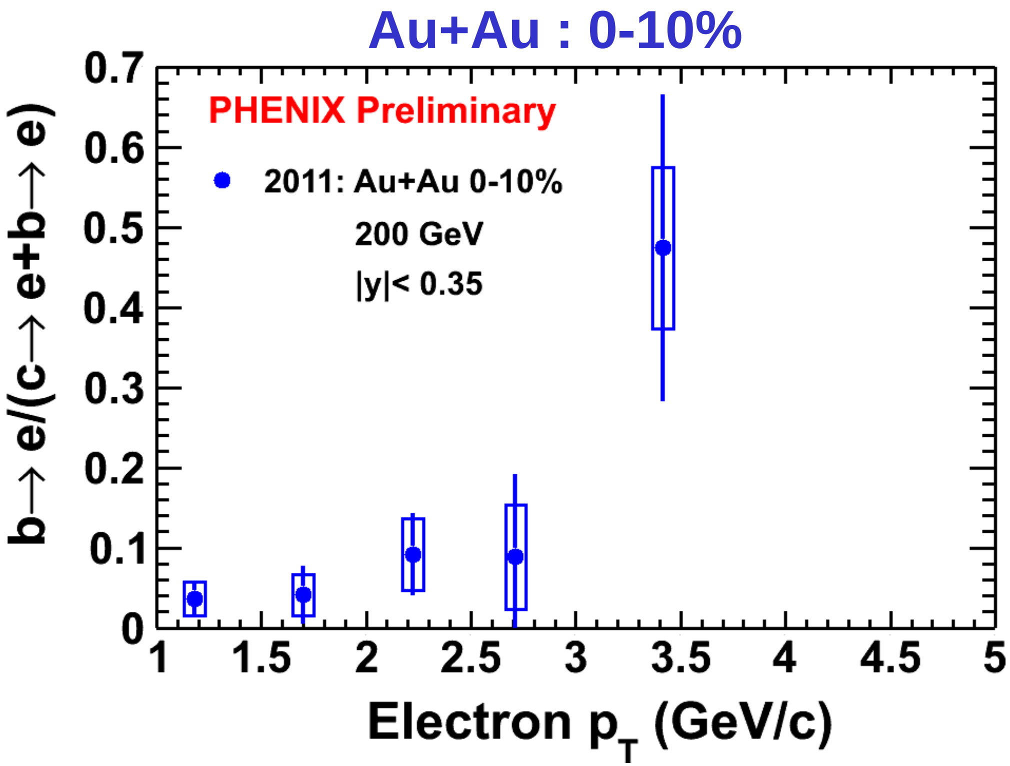
Note: **hadron contamination** for electron DCA distributions is not subtracted in these plots

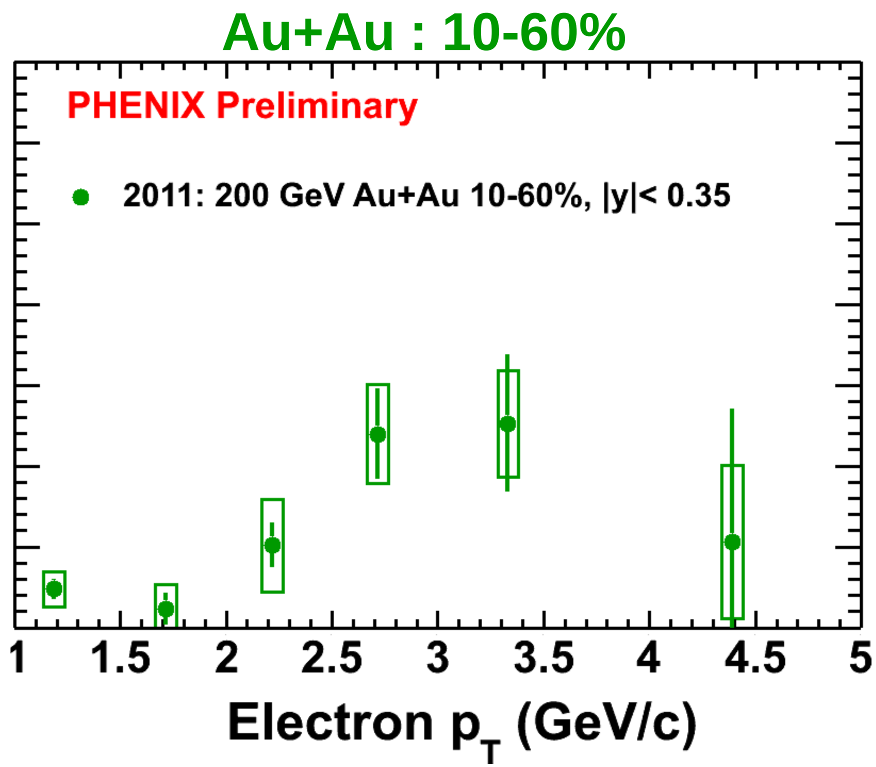
Distance of Closest Approach (DCA): **Au+Au**



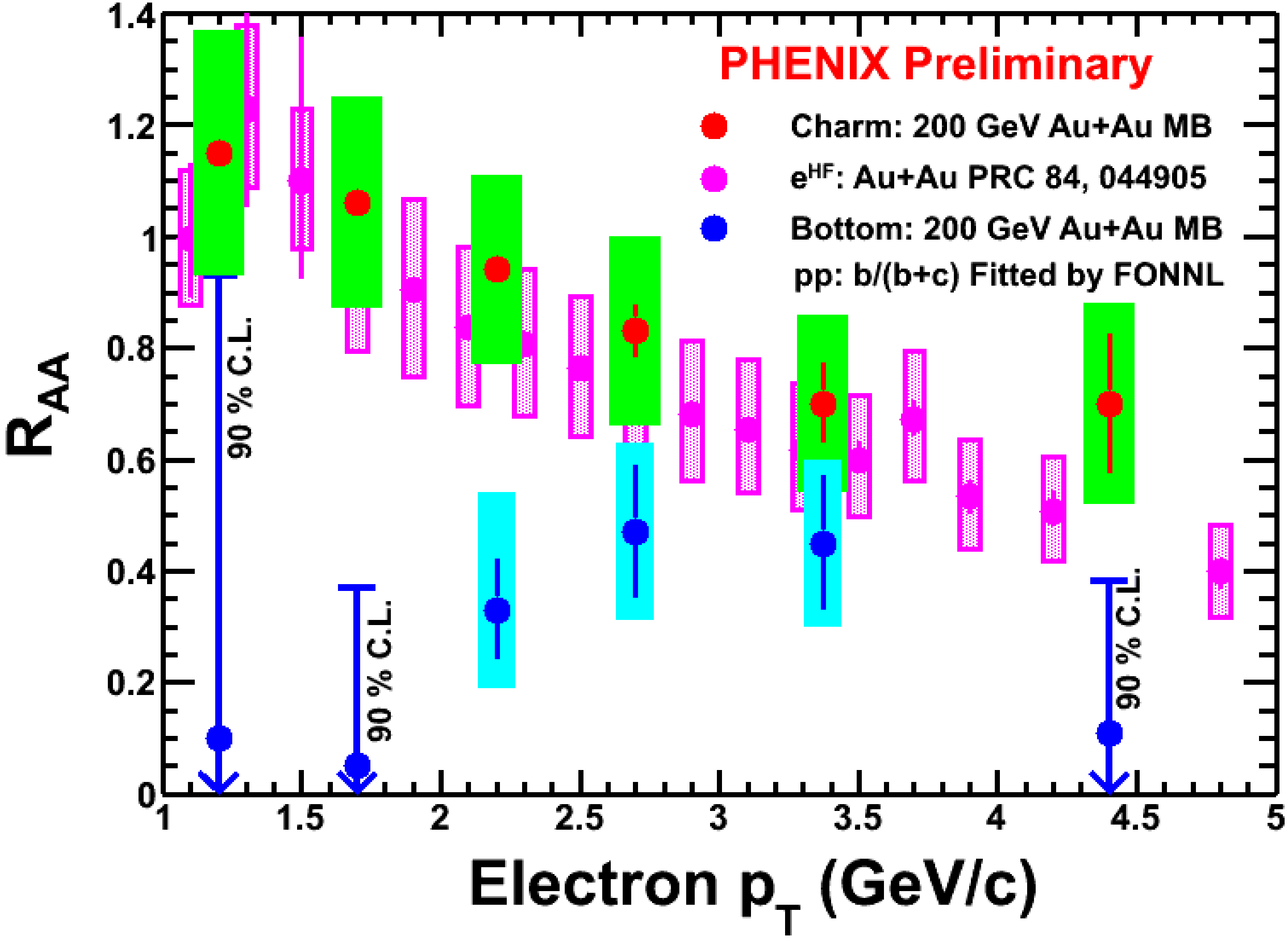
First direct measurements of bottom production in Au+Au at RHIC

b→e /(b→e+ c→e) in 200 GeV Au+Au vs Centrality
From Fit of the DCA distribution



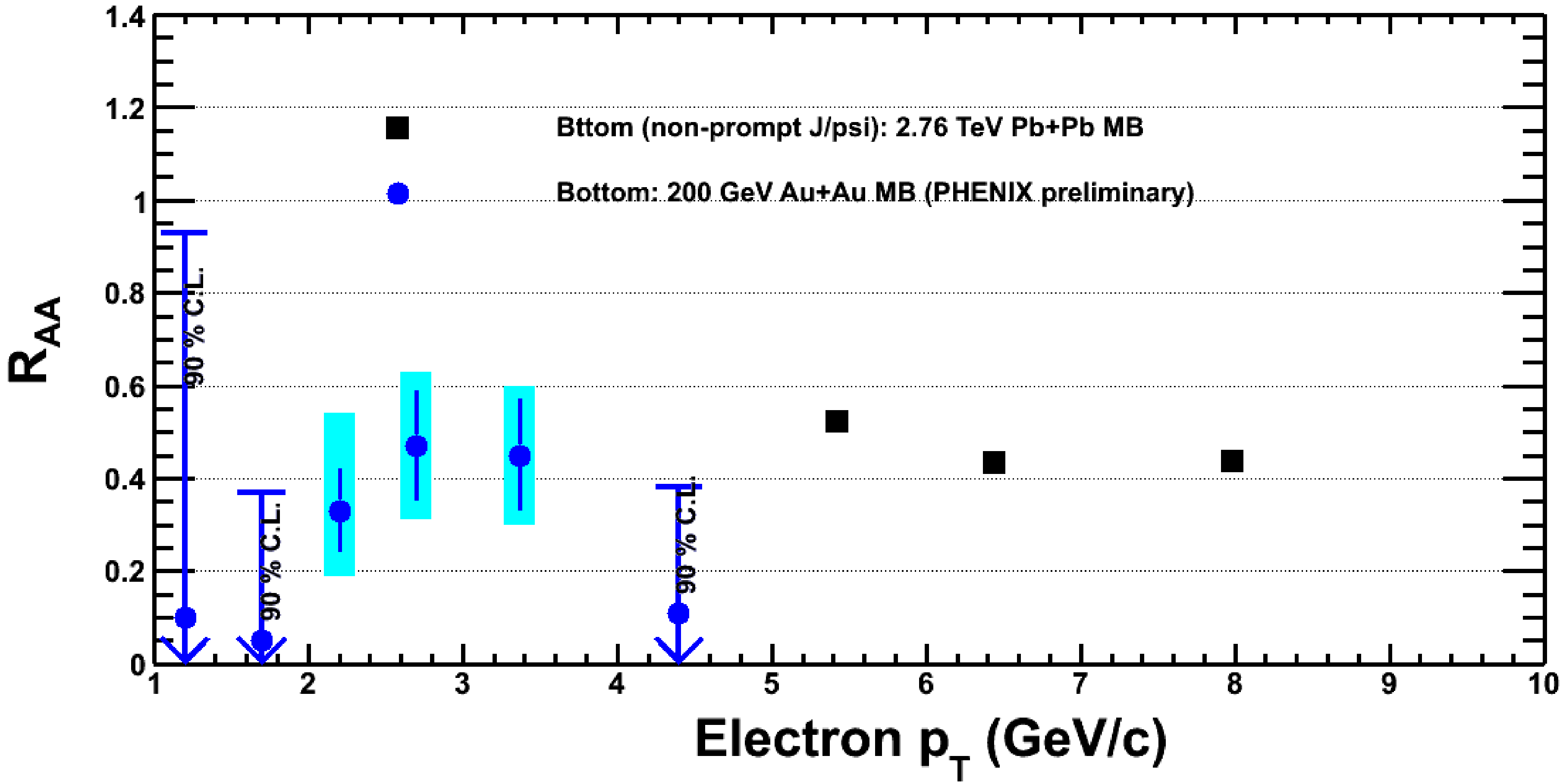


R_{AA} of Bottom, Charm and published e^{HF} in Au+Au MB



Bottom : PHENIX and CMS

Note: For comparison : CMS pt was scaled by factor 1/1.5 because of kinematic



Results are comparable: same magnitude

R_{AA} of Bottom Extraction

$$Y_{AA}{}^{b\rightarrow e} = Y_{AA}{}^{b+c\rightarrow e} R_b{}^{AA}$$

$$Y_{pp}{}^{b\rightarrow e} = Y_{pp}{}^{b+c\rightarrow e} R_b{}^{pp}$$

$$\frac{Y_{AA}{}^{b\rightarrow e}}{Y_{pp}{}^{b\rightarrow e}} = \frac{Y_{AA}{}^{b+c\rightarrow e}}{Y_{pp}{}^{b+c\rightarrow e}} \frac{R_b{}^{AA}}{R_b{}^{pp}}$$

$$\langle N_{coll}\rangle R_{AA}{}^{b\rightarrow e} = \langle N_{coll}\rangle R_{AA}{}^{b+c\rightarrow e} \frac{R_b{}^{AA}}{R_b{}^{pp}}$$

$$R_{AA}{}^{b\rightarrow e} = R_{AA}{}^{b+c\rightarrow e} \frac{R_b{}^{AA}}{R_b{}^{pp}}$$

Flow measurement of charged hadrons and heavy flavor electrons with PHENIX VTX tracker

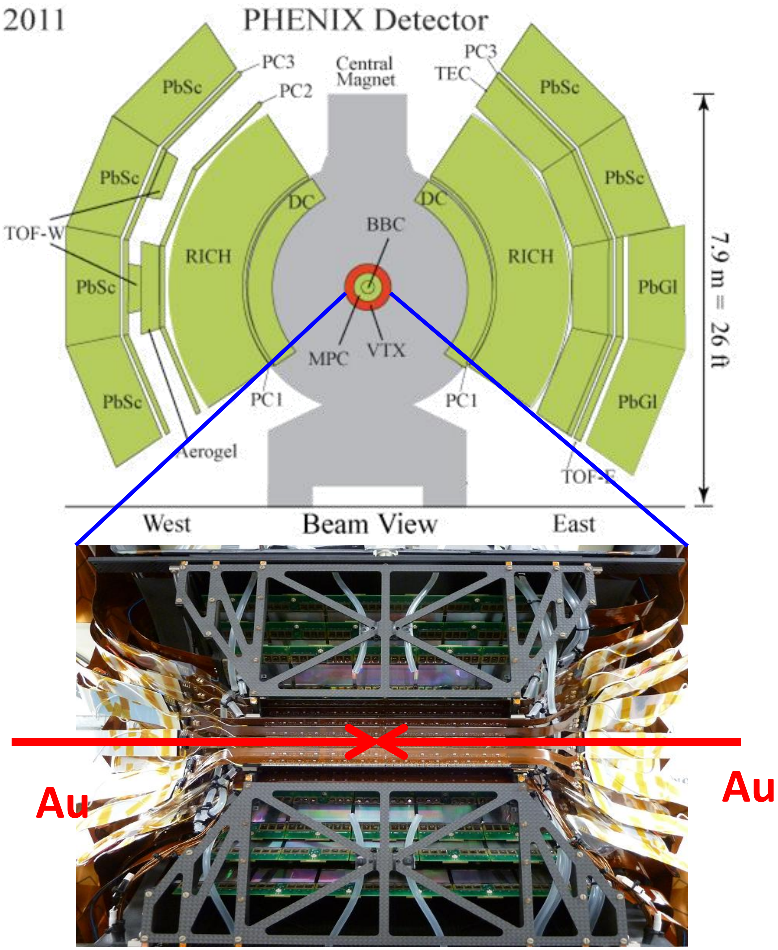
Maki KUROSAWA
for PHENIX collaboration

Outline of the Talk

1. **Introduction**
2. **Method of Azimuthal anisotropy Measurements**
3. **Charged Hadron v_2 and v_3 in AuAu 200 GeV Transvers momentum and η dependence.**
4. **Heavy Flavor Decomposition**
5. **First Measurements of Charm v_2**
6. **Summary**

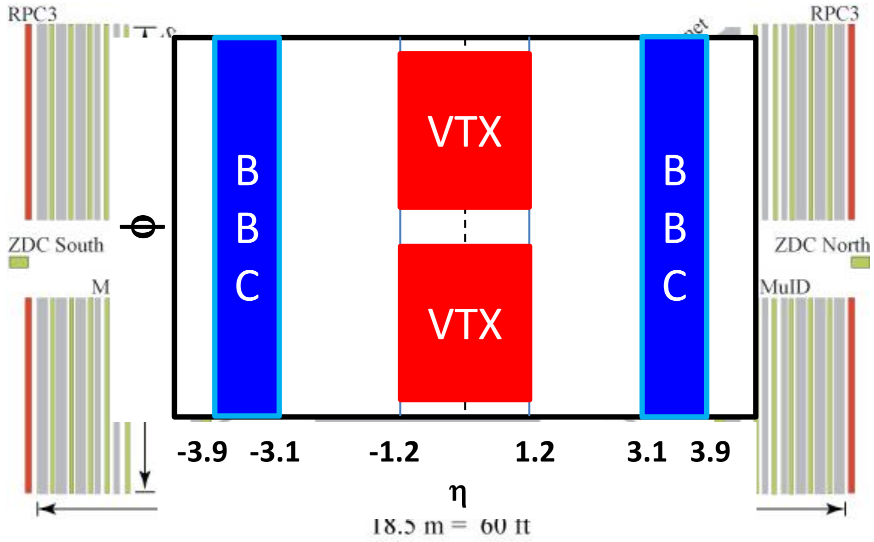
1. Introduction

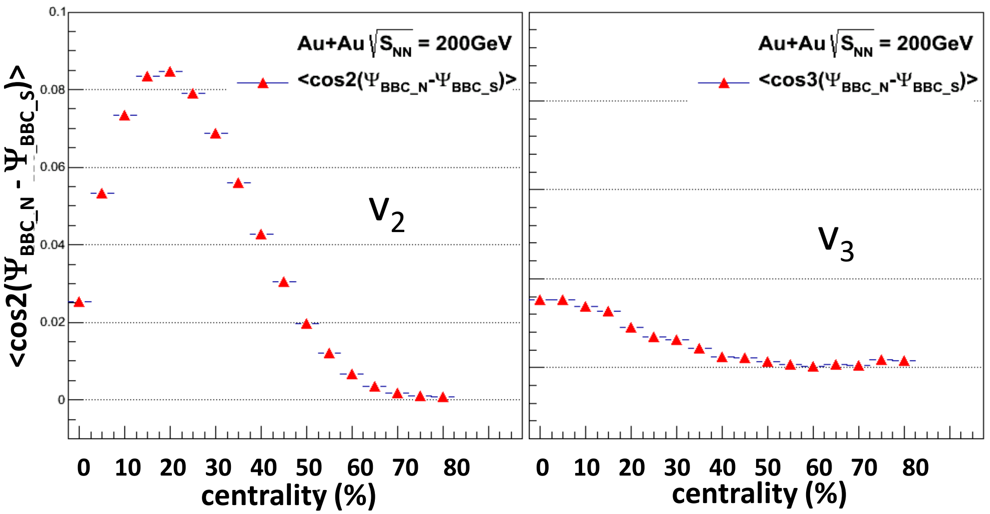
- **Physics motivation to measure heavy flavor**
  - Initial state of QGP.
  - Detail study of QGP due to large mass.
- **Silicon vertex tracker (VTX) upgrade for PHENIX**
  - Heavy flavor tagging
    - ✓ spatial resolution → σ ~ 77μm
    - ✓ Large acceptance → $|\eta| < 1.2$, $\Delta\phi \sim 2\pi$
- **Physics observables with VTX**
  - Nuclear modification factor for heavy flavor R_{AA}
  - **Azimuthal anisotropy for heavy flavor**



2. Method (1)

Event Plane Method : Beam Beam Counter (to avoid auto-correlation effects)



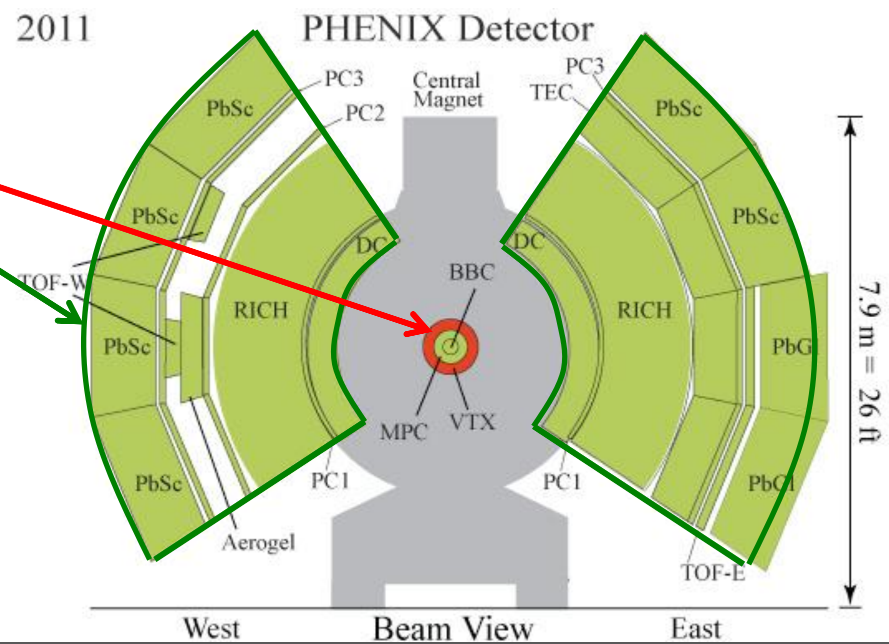


Track reconstruction

- VTX (high position resolution)
  + Central Arm (high momentum resolution)
- Central Arm track was associated with stand-alone track of VTX

Electron Identification

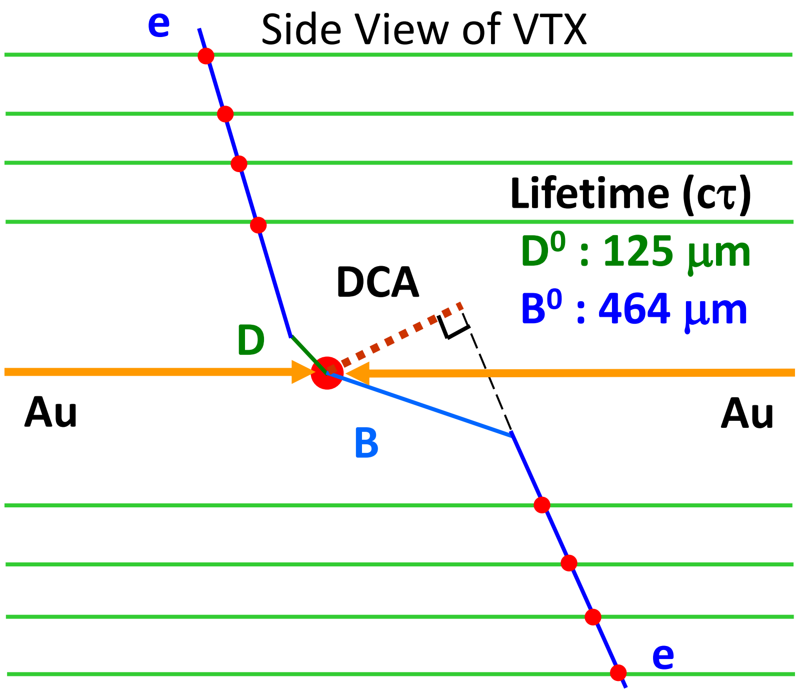
- Electron identification detector of central arm were used.

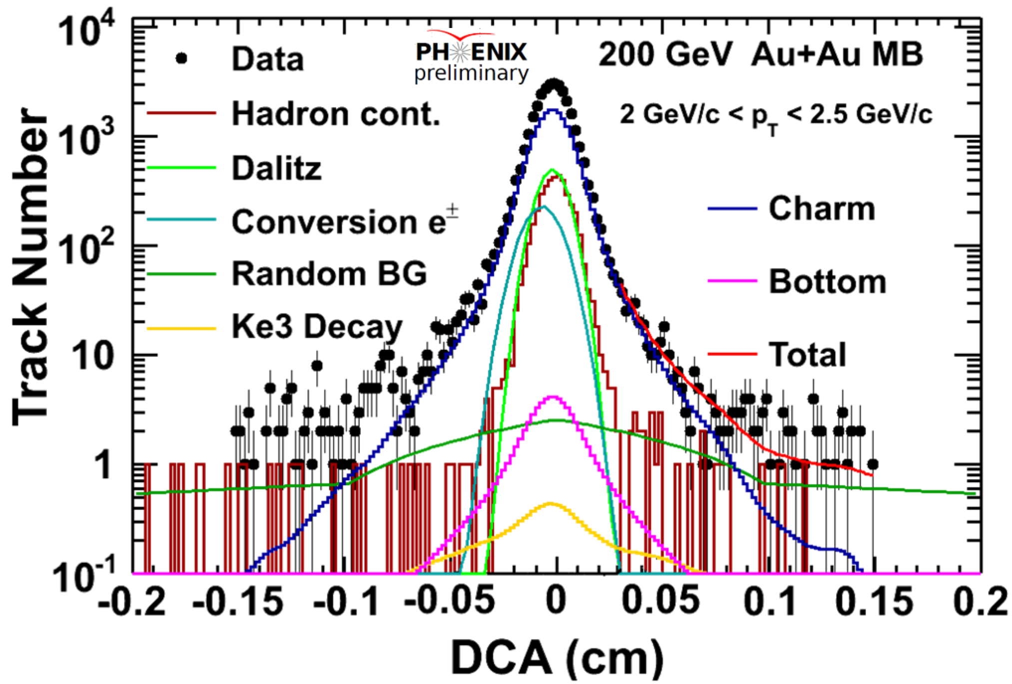


2. Method (2)

DCA decomposition of charm and bottom

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

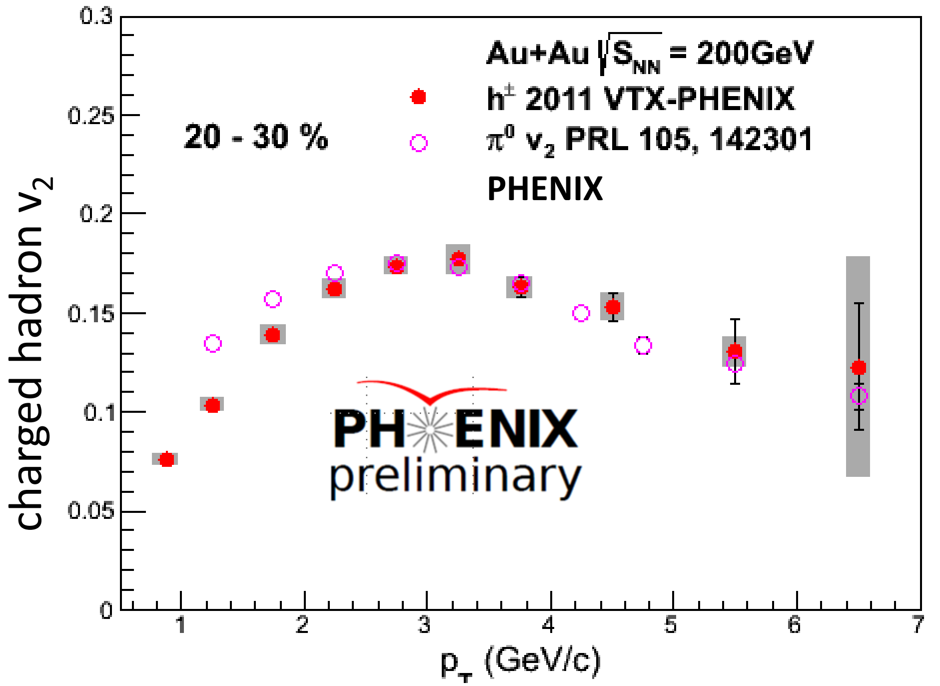




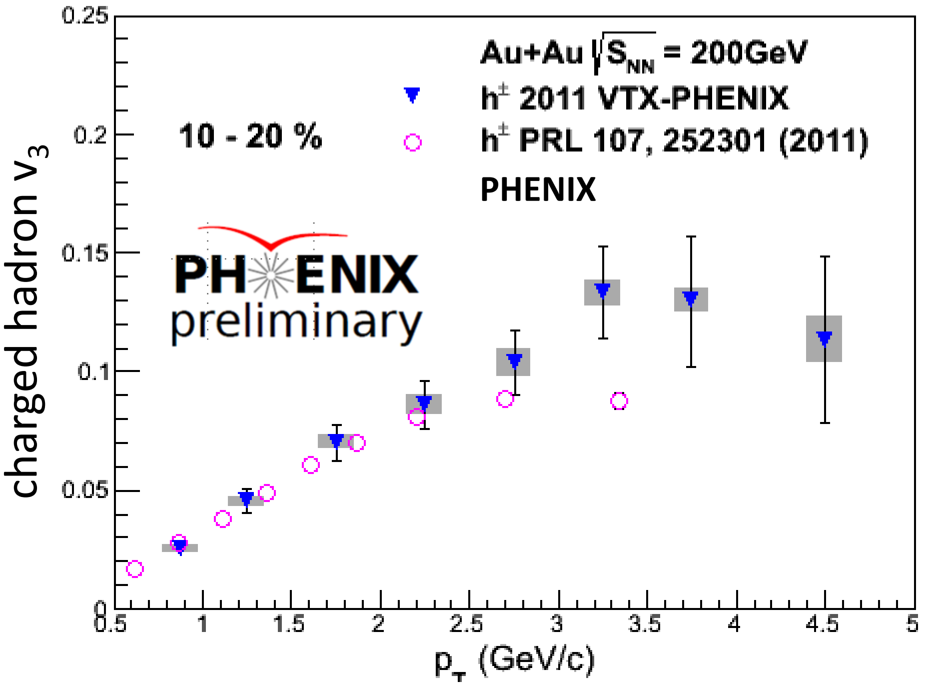
- We know the shape of each component from Montecarlo simulation.
- By simultaneous fitting of DCA distribution, each component can be separated statistically.

Charged Hadron v2 and v3

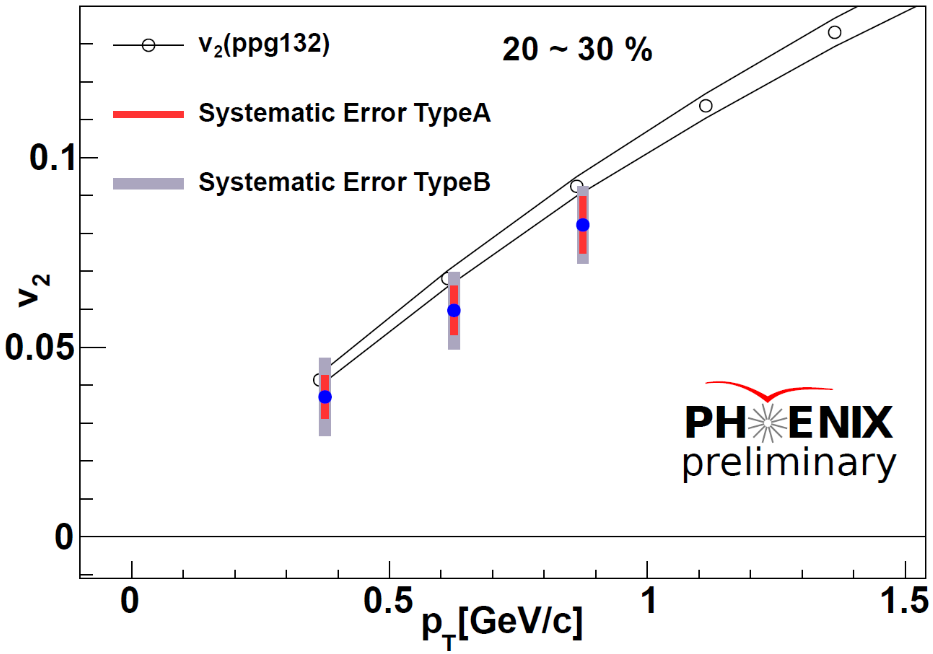
- v_2 and v_3 of $h^{\pm}$ has reduced background by application of DCA cut < 200um.
- v_2 are consistent with previous measurements of π^0 v_2 in high p_T region.

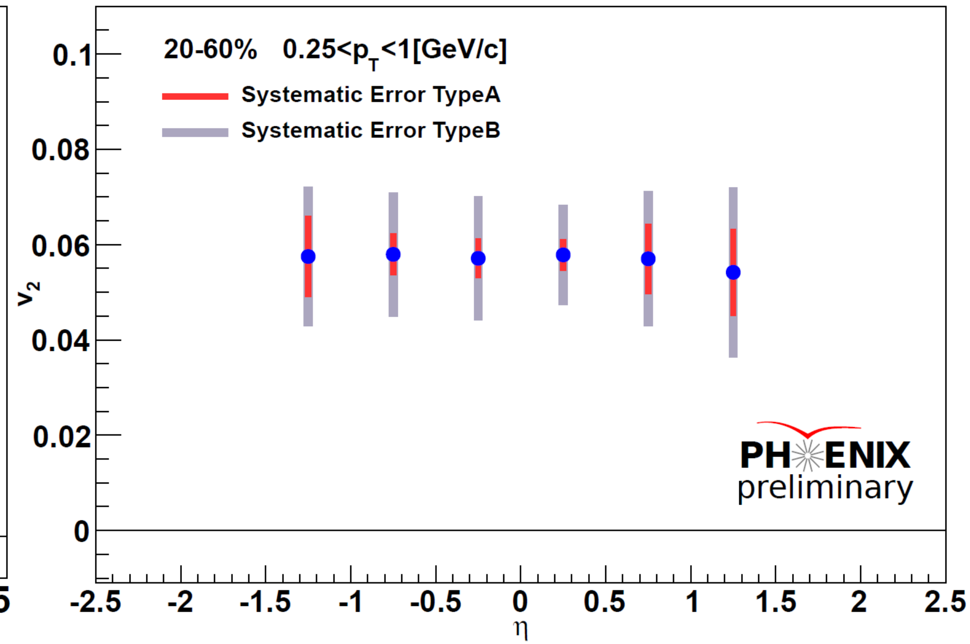


- Extend to high p_T region for v_3.
    - Good agreement with previous data in low p_T region.
- A non-zero v_3 is still observed in high p_T region.

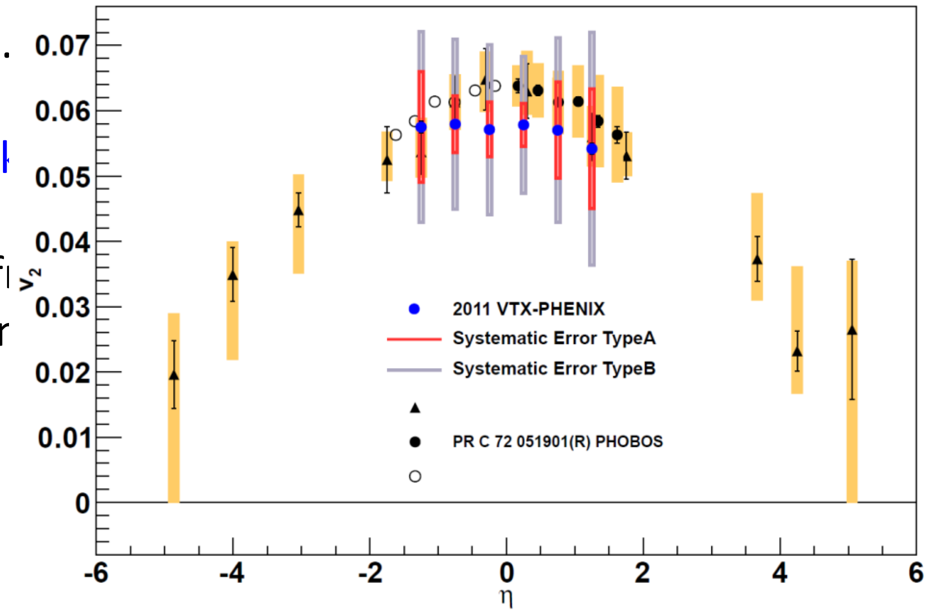


Eta Dependence of v_2 for Charged Hadron (VTX Stand-Alone Tracking)



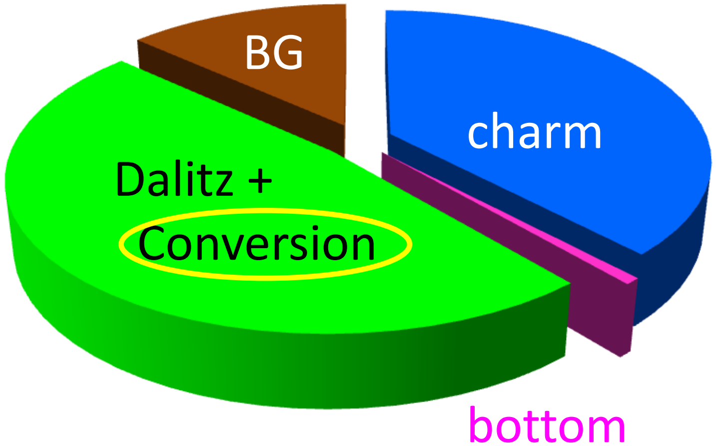


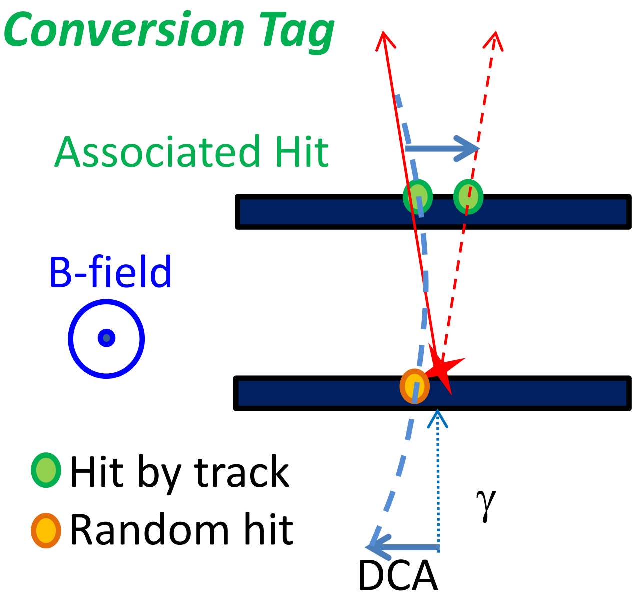
- Charged hadron v2 was measured with VTX.
  - Event plane : BBC
  - Track reconstruction : stand-alone track
- Good agreement with the previous results f
  - Analysis using multi-particle correlatior possible in the future analysis.
- No η dependence observes within |η| < 1.2 at low p_T region.



3. Electron v2 (Conversion Electron)

Inclusive electron components



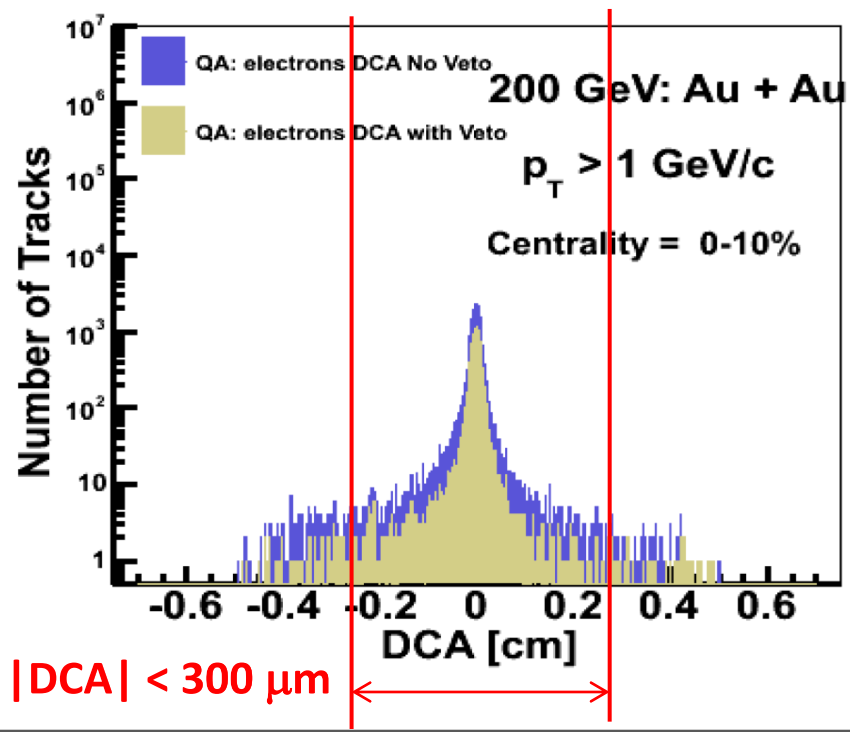


Large background is conversion electron

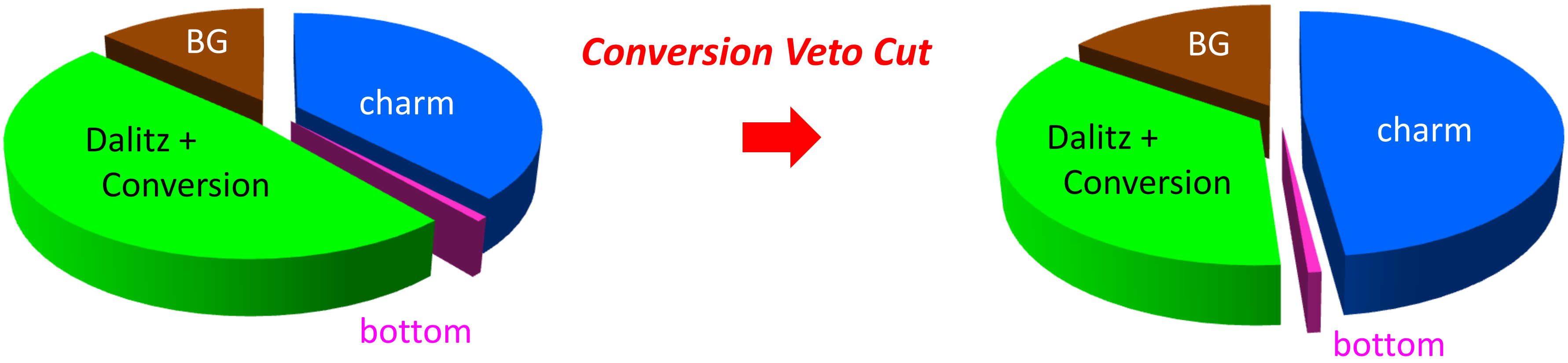
- ***Conversion tagged*** electrons :
  - Require **another hits** around track associated hit.

- **Conversion electron events** can be selected by applying

conversion tag cut + |DCA| < 300 μm



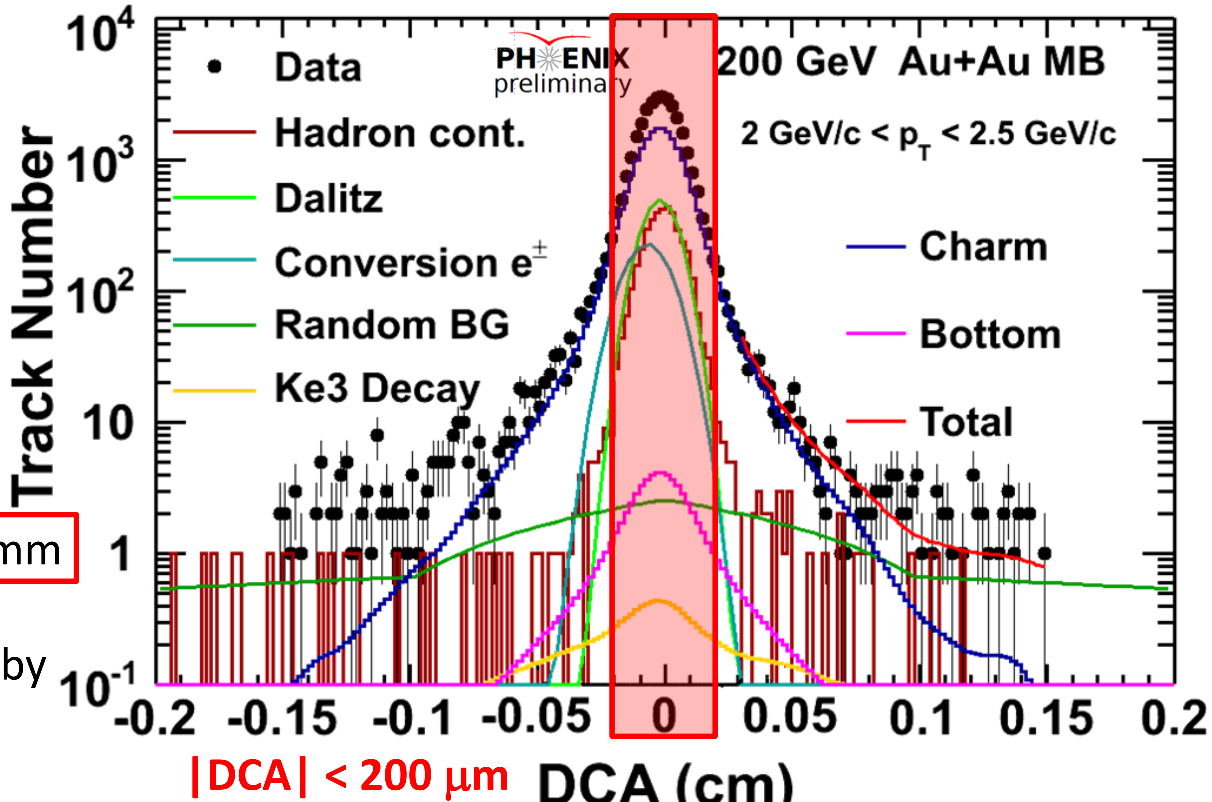
3. Electron v2 (Conversion BG Rejected Electrons)



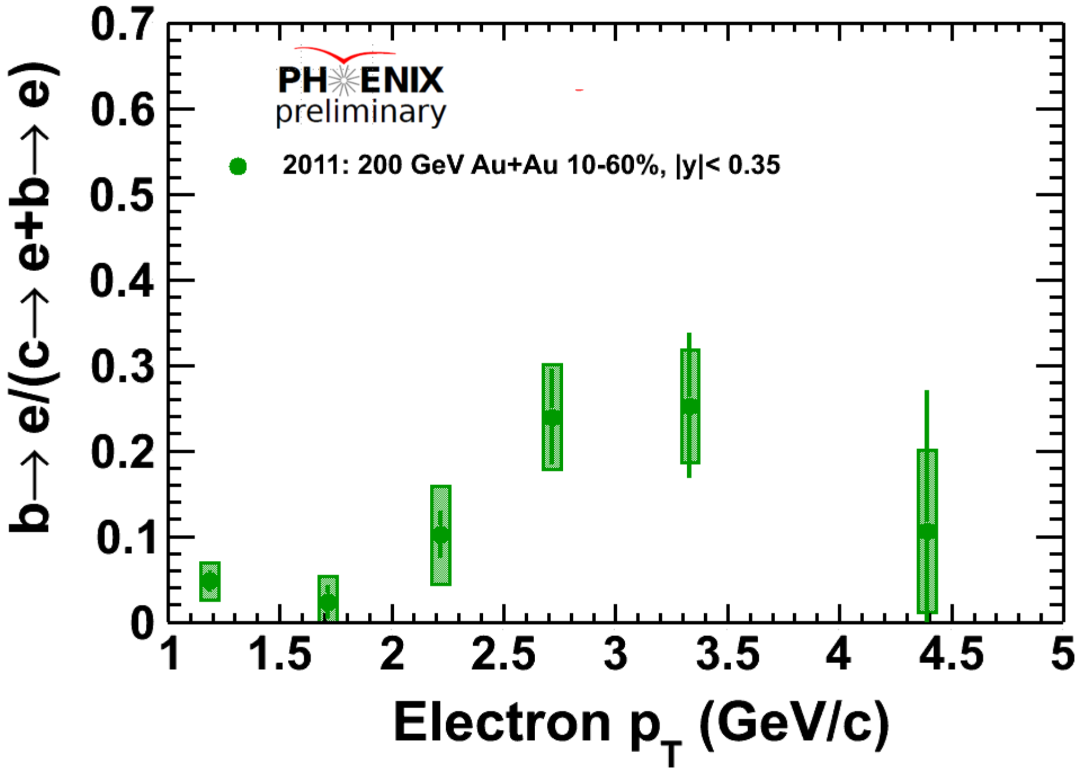
- ***Conversion veto*** electrons :
  - Require **no hit** around track associated hit.
- **Charm enhanced events** can be selected by applying

Conversion veto cut + |DCA| < 200mm

Each components are decomposed by using DCA distribution.



Electron v2



$$v_2^{c\,enhance} = R^c \cdot v_2^c + R^b \cdot \boxed{v_2^b} + R^\gamma \cdot v_2^\gamma + R^h \cdot v_2^h$$

R^x : Ratio of each components. Those values can be derived from DCA decomposition.

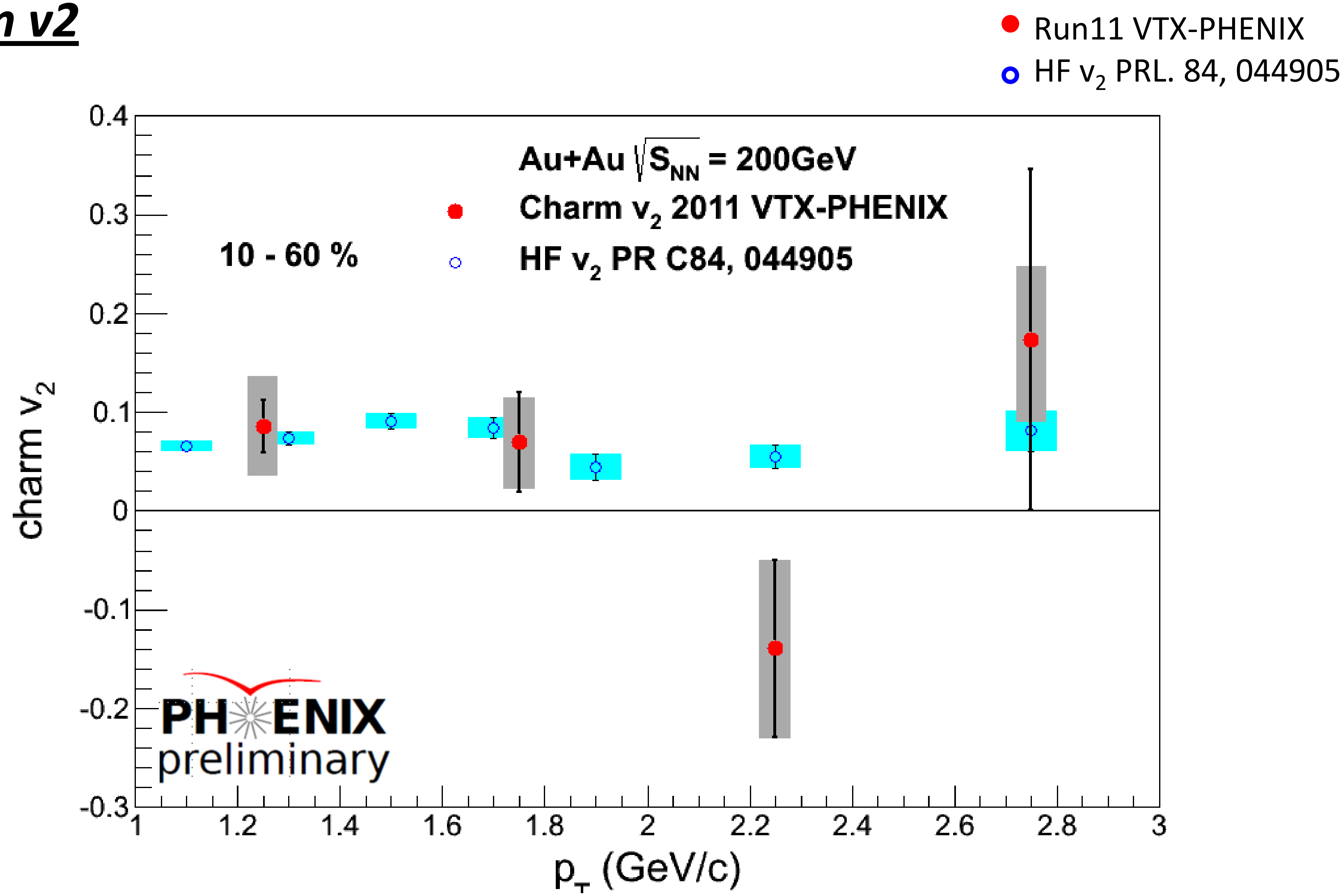
$v_2^{c\,enhance}$: charm enhanced v_2 (VTX-PHENIX)

v_2^h : charged hadron v_2 (VTX-PHENIX)

v_2^γ : PR C 84, 044905

v_2^b : used three kinds of value (-0.2, 0., 0.2). Fluctuation were included in sys. error

5. Charm v2



- Non-zero v_2 of charm was observed.
- Obtained charm v_2 was consistent with previous HF v_2.
  - Because of small fraction of bottom at low p_T, HF v2 is thought as charm v_2.

6. Summary

- Azimuthal anisotropy measurements had been done with VTX in AuAu 200 Gev.
  - Used generalized event plane method.
  - Extend to high p_T region with low background.

- Measured charged hadron v2 and v3.
  - Charged hadron v_2 at high p_T region were consistent with previous results of π^0 v_2.
  - Non-zero v_3 was observed at high p_T region.

- η dependence of charged hadron v_2 was measured using stand-alone track of VTX.
  - η dependence was not observed within $|\eta| < 1.2$ at low p_T region.

- With the DCA decomposition, first measurements of charm v_2 had been done.
  - Non-zero v_2 of charm was observed.

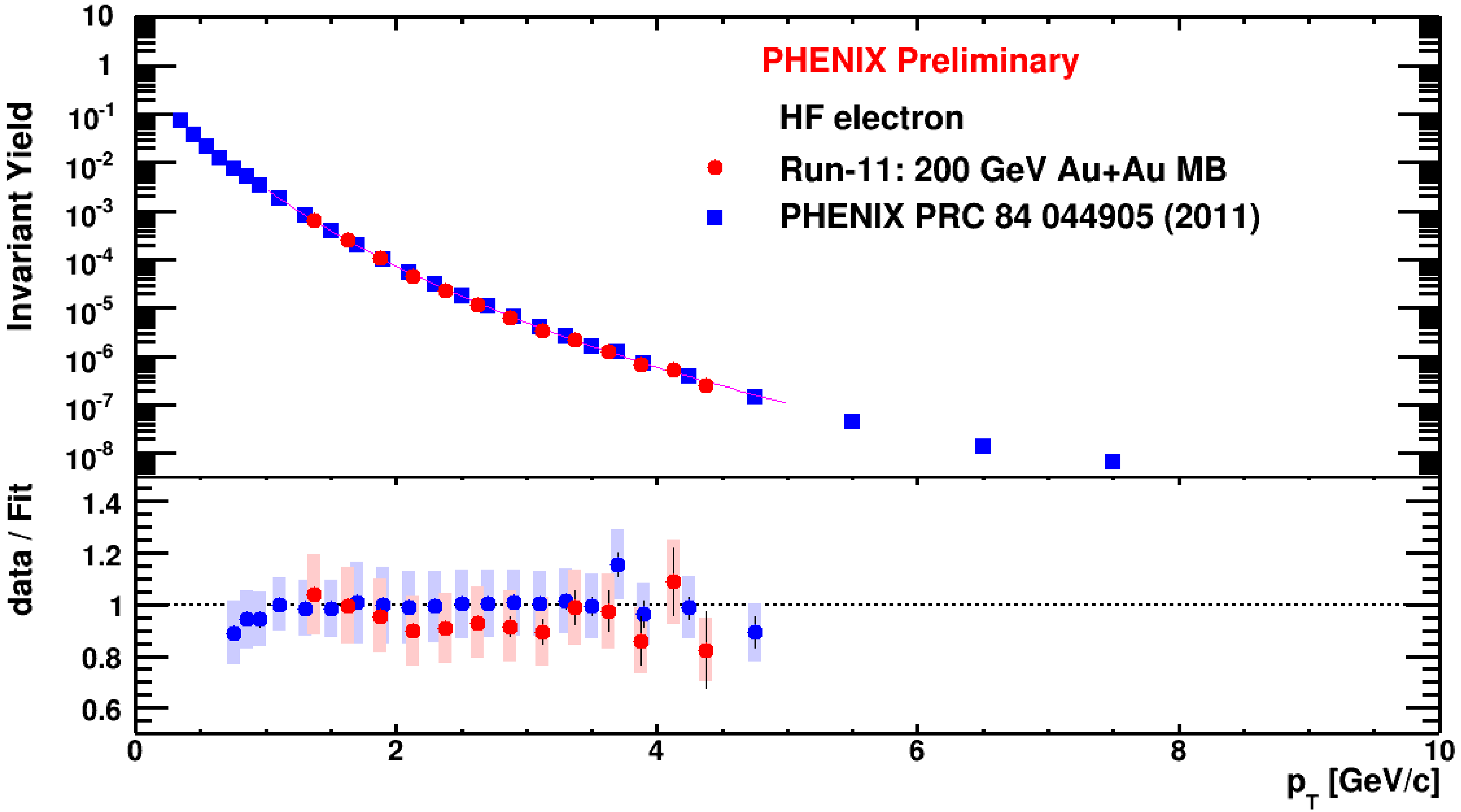
- Next Step:
  - Statistic error can be improved by using remaining data and fine tuning the analysis.
  - Bottom v_2 will be obtained by using more statistics.

→ We are working on remained work.

Back Up Slides

HF electrons in Au+Au at 200 GeV

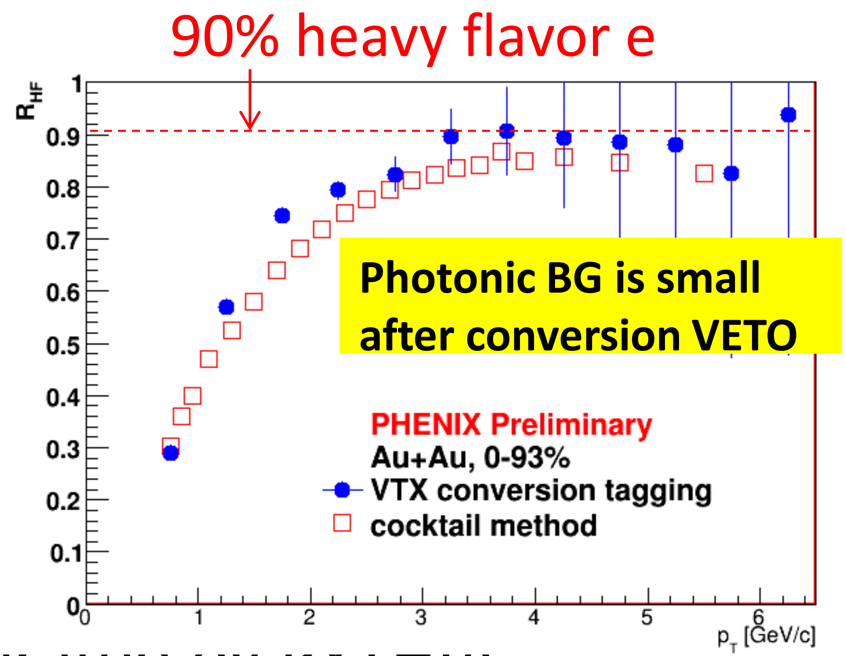
Use VTX to tag Dalitz and conversion electron
→Determine HF components in inclusive electron



Decomposition of the DCA Distributions
Charm and Bottom Measurements

- Our π^0 measurements give us a the photonic background

- In addition, most conversion el are tagged and vetoed.

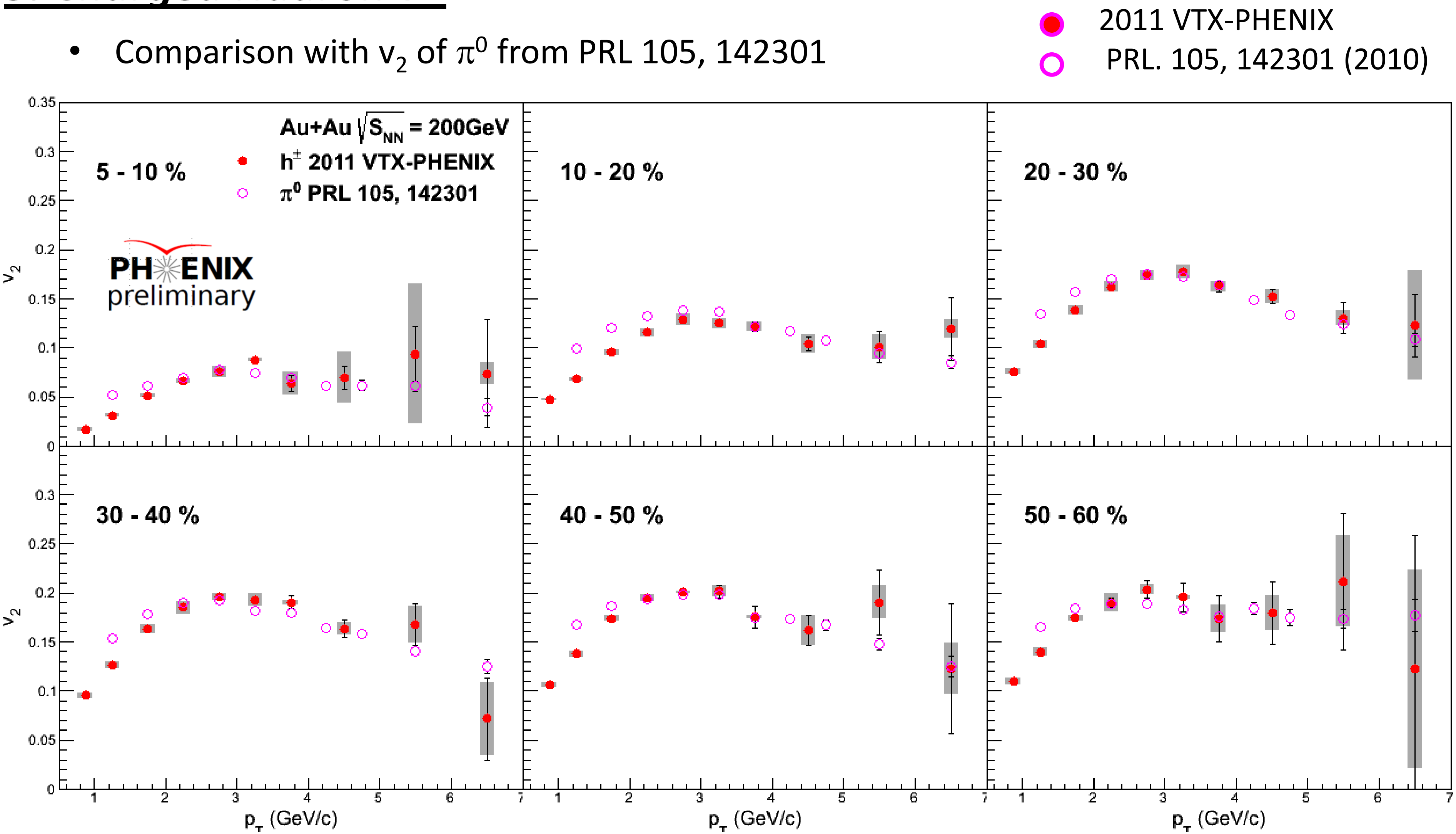


- Charm and Bottom events generated by PYTHIA run through full GEANT simulation determine the DCA shape of charm and bottom decays

- Charm to bottom ratio is obtained from the fit to the DCA distribution of measured electrons

3. Charged Hadron v2

- Comparison with v_2 of π^0 from PRL 105, 142301

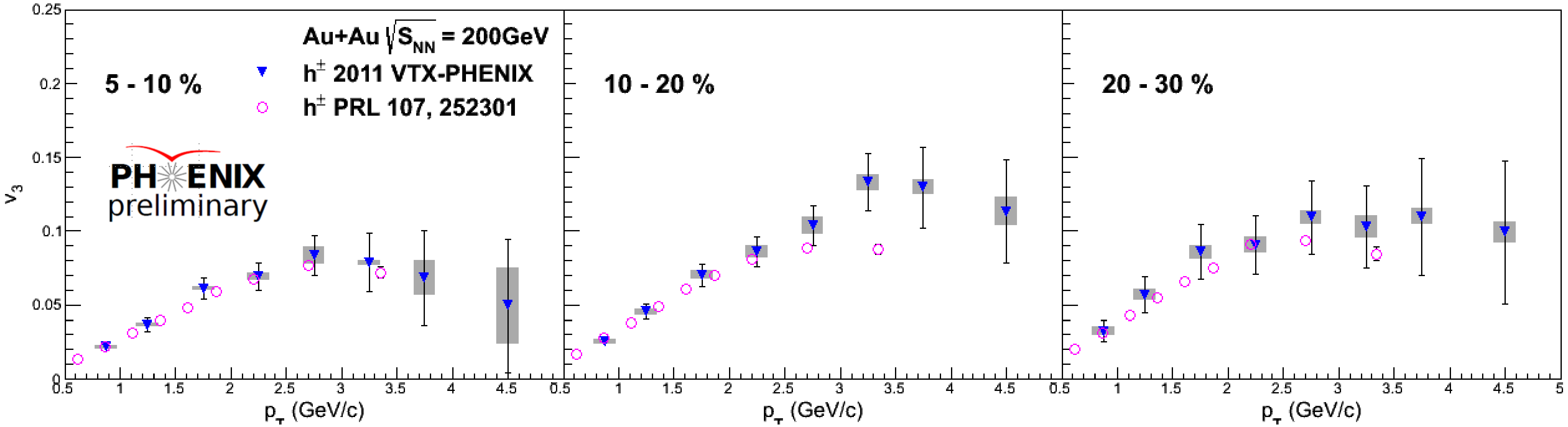


- v_2 of $h^{\pm}$ has reduced background by application of DCA cut < 200um.

- Results are consistent with previous measurements of π^0 v_2 in high p_T region.

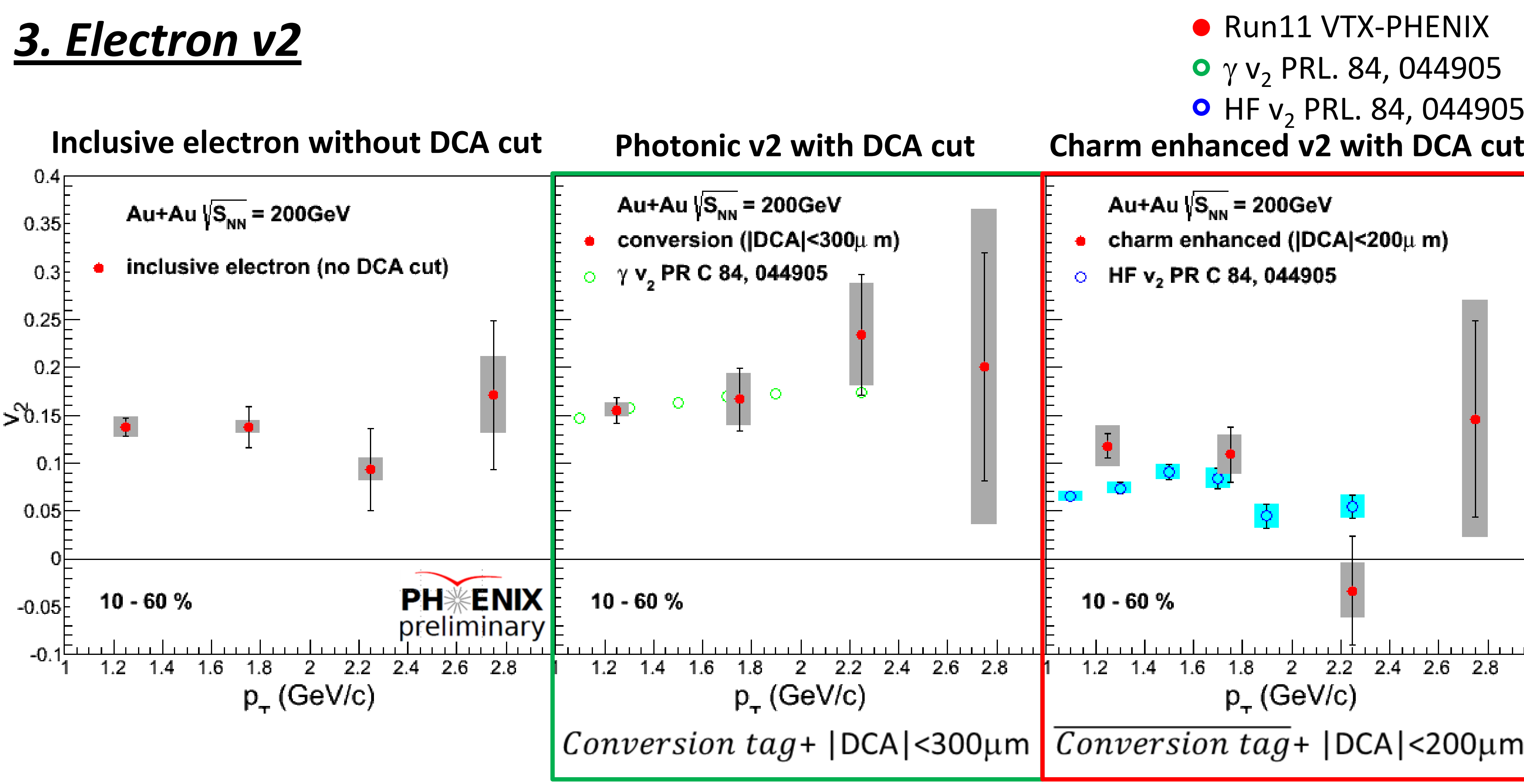
Charged Hadron v3

▼ 2011 VTX-PHENIX
○ PRL. 107, 252301



- Comparison with v_3 of charged hadrons from PRL 107, 252301.
  - Good agreement with previous data in low p_T region.
- In high p_T region, a non-zero v_3 is still observed.

3. Electron v2



$$v_2^{c\,enhance} = R^c \cdot v_2^c + R^b \cdot v_2^b + R^\gamma \cdot v_2^\gamma + R^h \cdot v_2^h$$

R^x : Ratio of each components. Those values can be derived from DCA decomposition.

v_2^b : used three kinds of value (-0.2, 0., 0.2). Fluctuation were included in sys. error

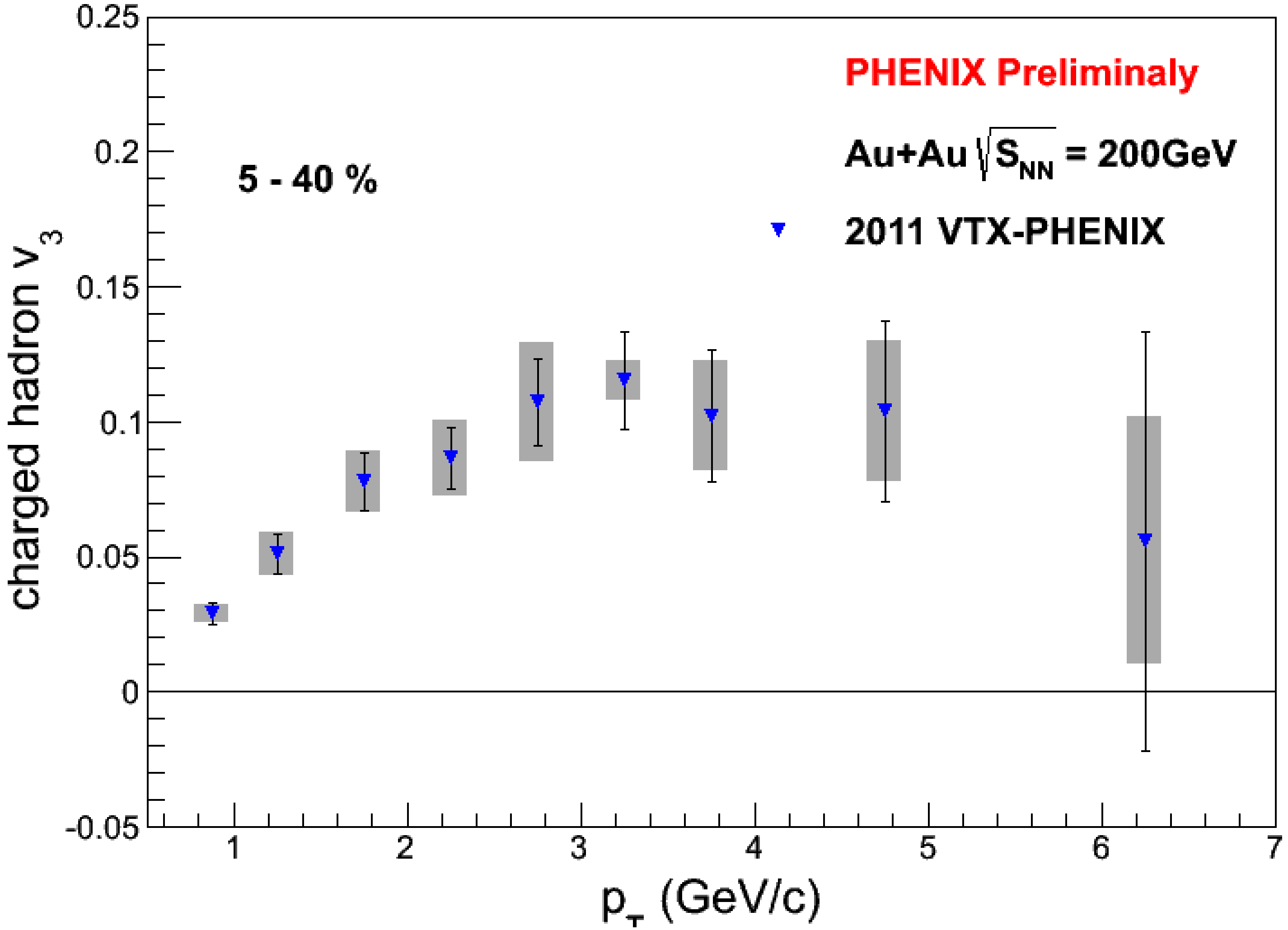
$v_2^{c\,enhance}$: charm enhanced v_2 (VTX-PHENIX)

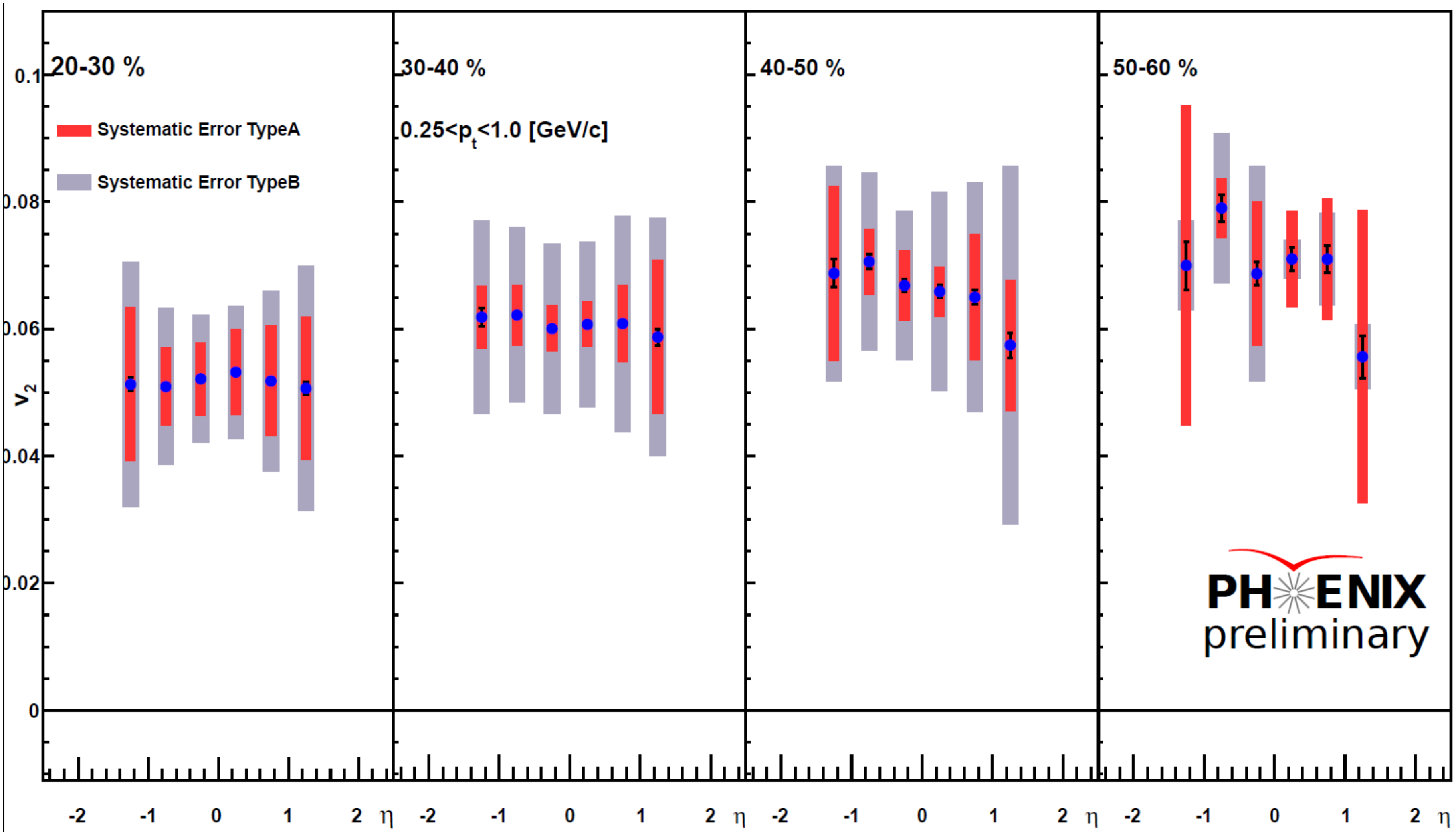
v_2^γ : PR C 84, 044905

v_2^h : charged hadron v_2 (VTX-PHENIX)

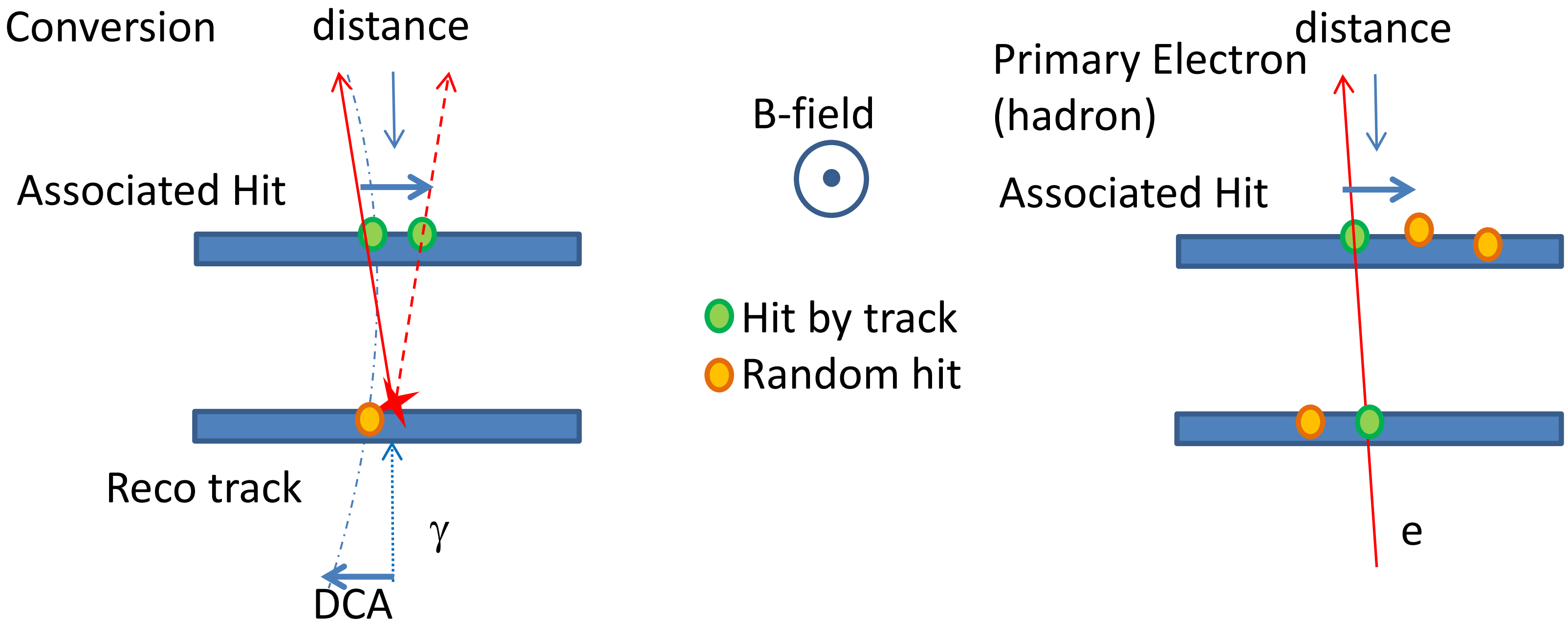
3. Charged Hadron v3

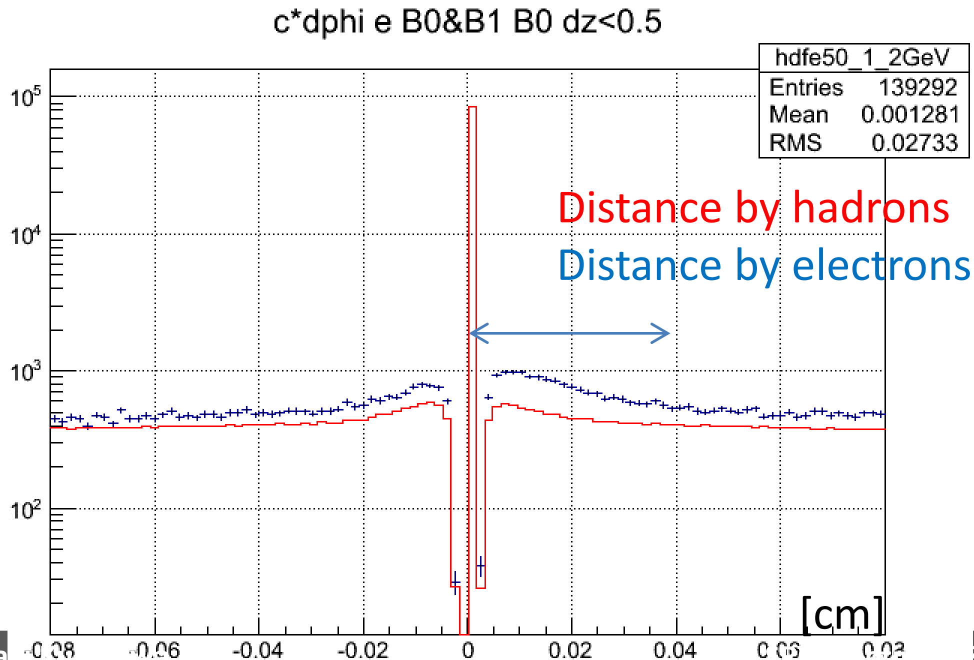
Run11 VTX-PHENIX
Phys. Rev. Lett. 105, 142301 (2010)




20-30 %
Systematic Error TypeA
Systematic Error TypeB
30-40 %
0.25<p_t<1.0 [GeV/c]
40-50 %
50-60 %
PHENIX
preliminary
v2
η

Conversion Tagging (Isolation Cut)





Hadrons

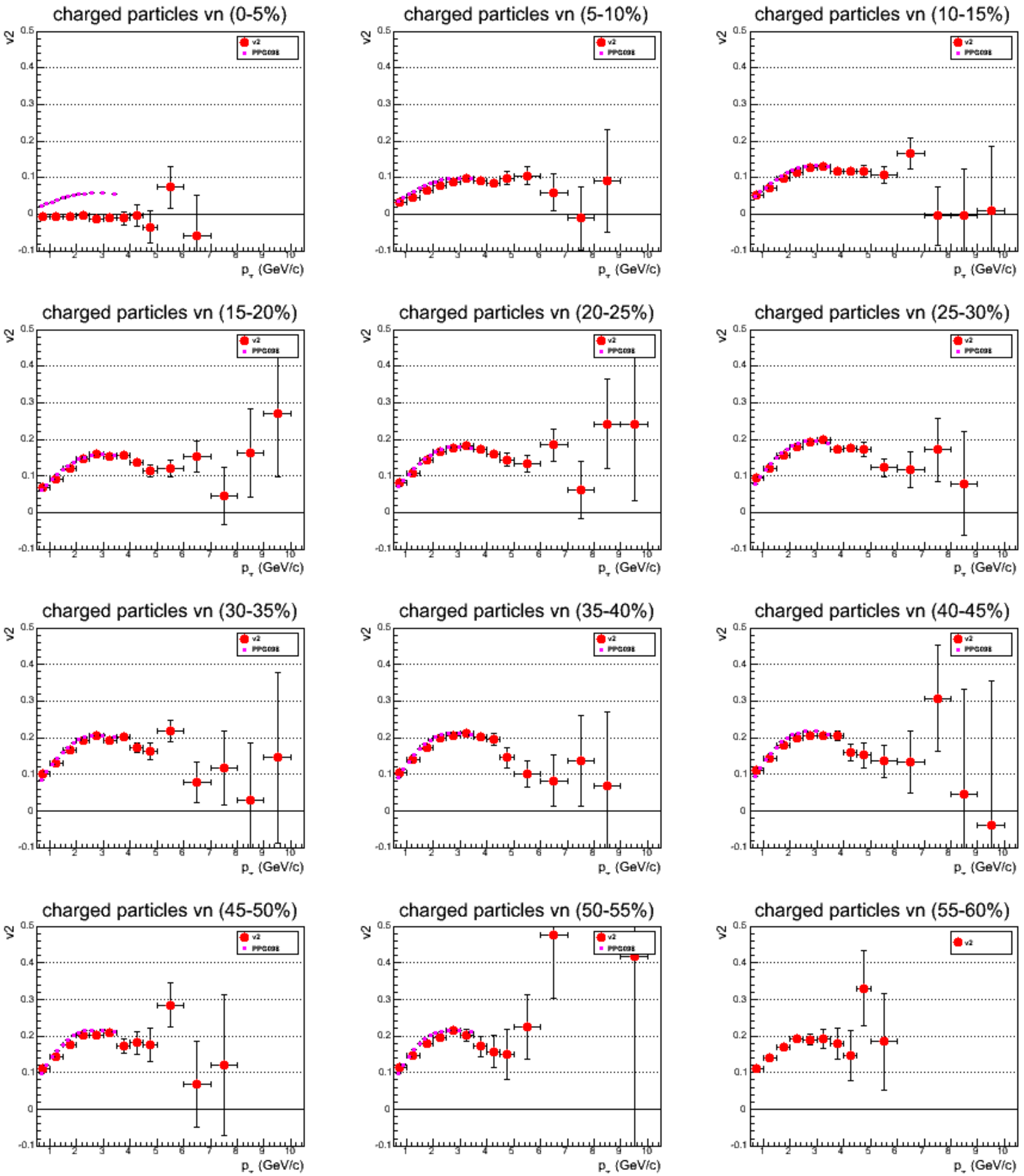
- Symmetric shape → random associate

Eletrons

- Asymmetric shape → pair

Same shape for all layers.
Determine isolation cut by using all layers.

Charged Hadron v2



- ● Run11 VTX-PHENIX
- ○ Phys. Rev. Lett. 105, 062301 (2010) ppg098

Centrality dependence of v2 as a function of pT.
5% centrality step

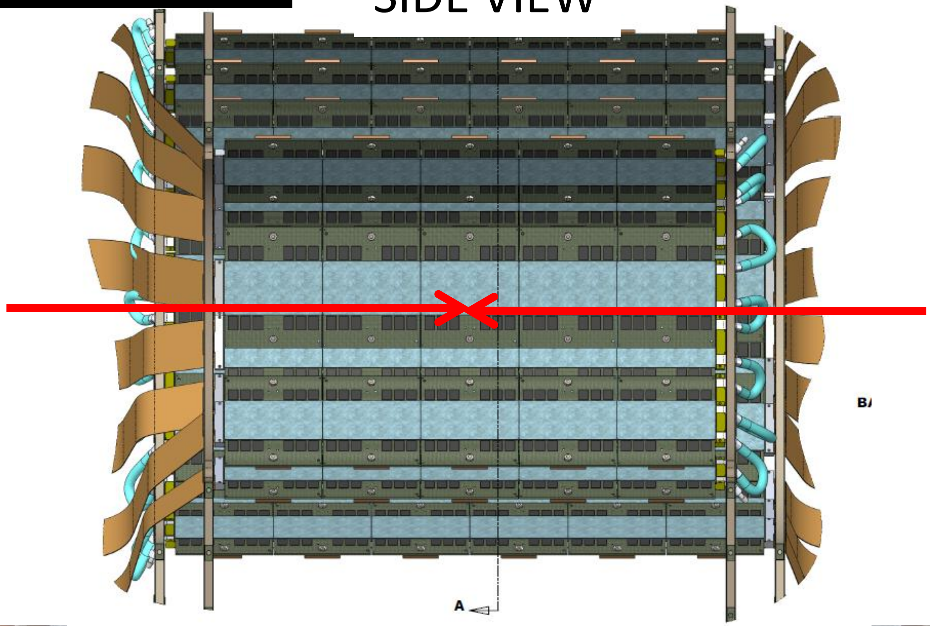
CNT track was associated with VTX.

Required isolation cut and |DCA| < 700 μm to reduce miss-association tracks except for 0-5% centrality bin.

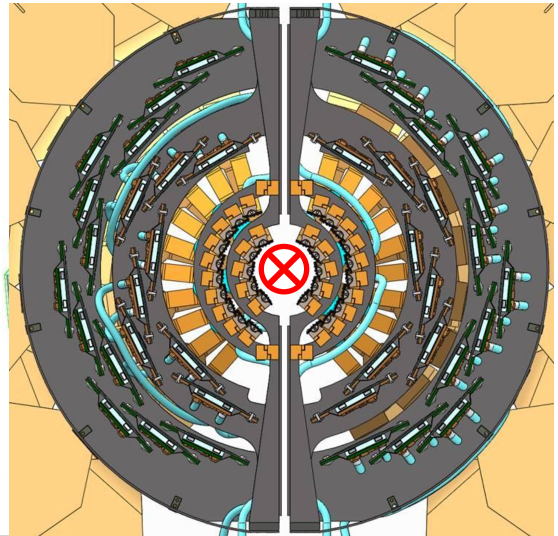
Our data is consist with the results from PPG098.

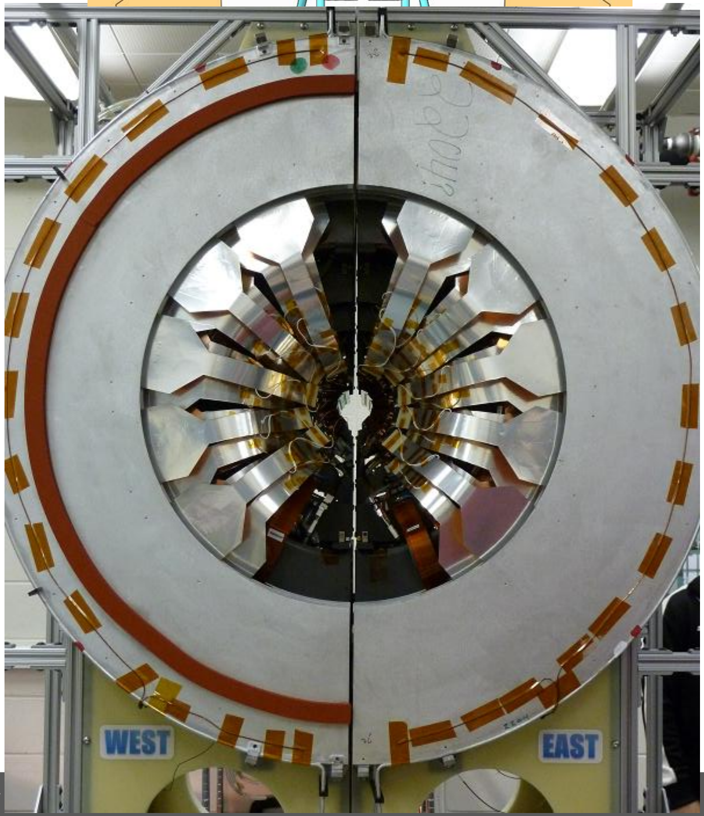
VTX Barrel

SIDE VIEW



BEAM VIEW



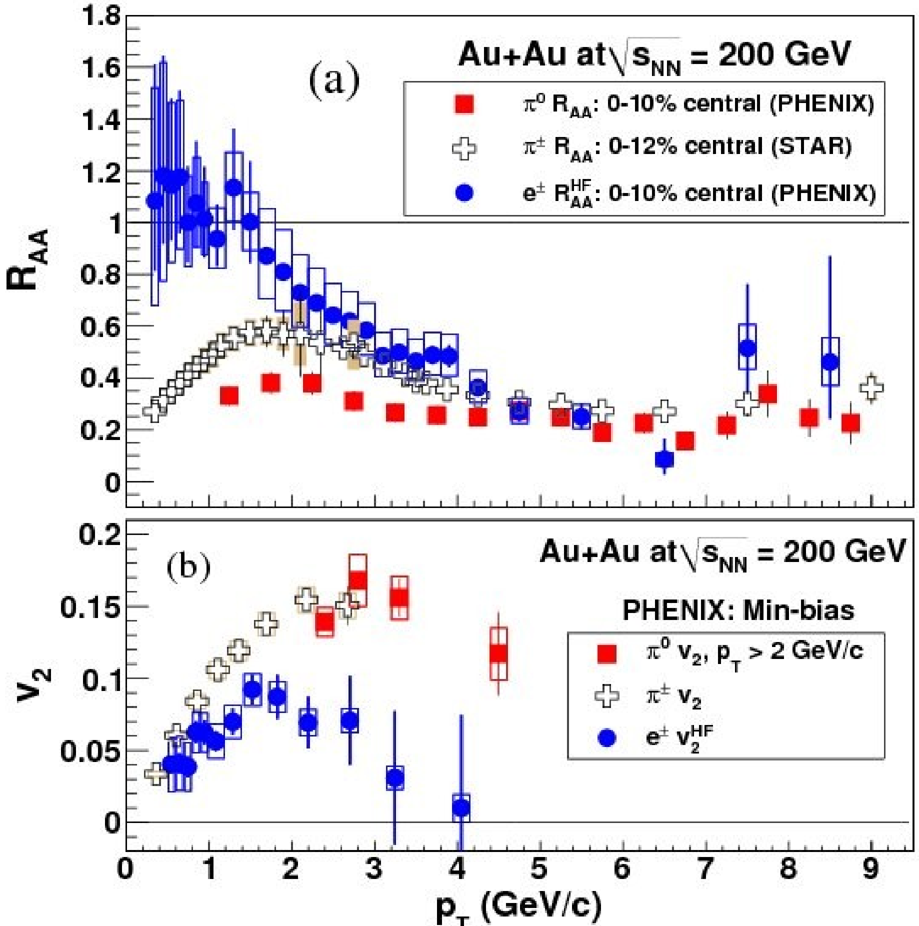


Measuring the charged hadrons and heavy flavor electrons with VTX

John Chin-Hao Chen
RBRC

2012/11/07

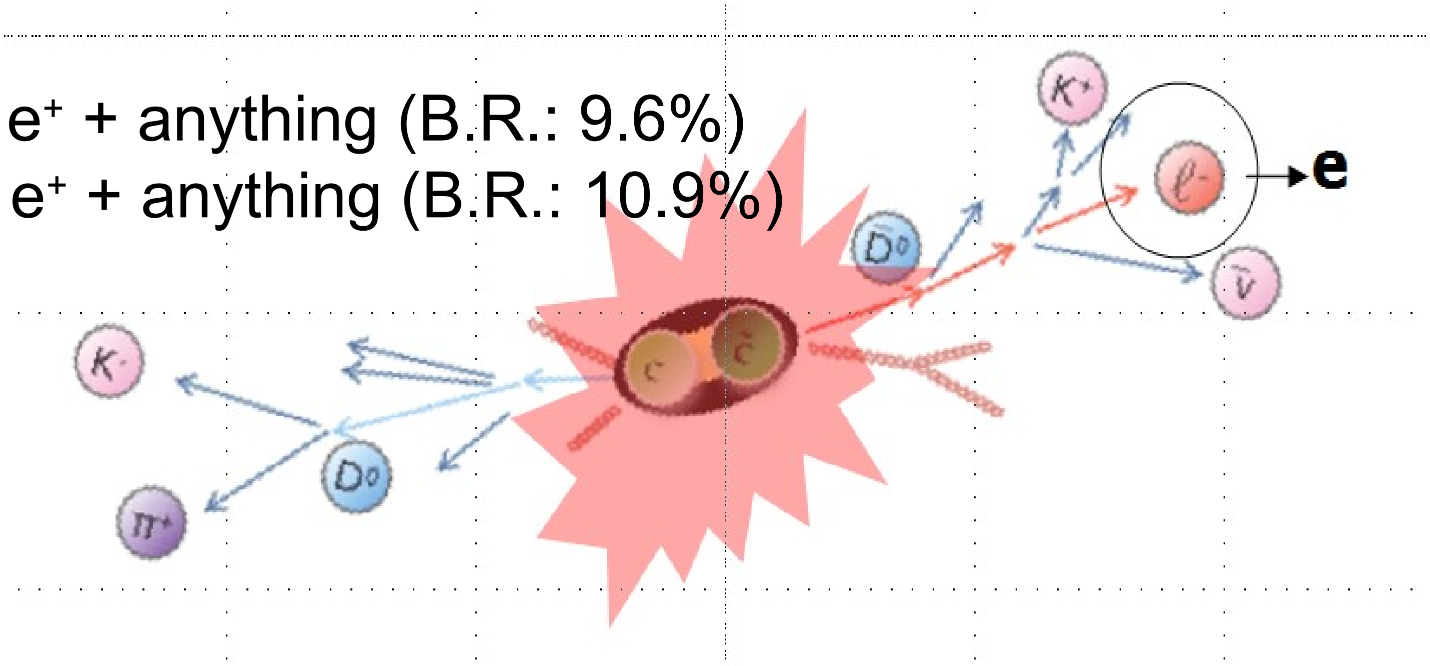
Why Heavy Flavor Quarks?



- Heavy flavor is highly suppressed in QGP
- Like lighter mesons, heavy flavor electrons also flow in QGP
- Separating charm/bottom quarks is crucial in understanding the energy loss mechanism of heavy flavor quarks

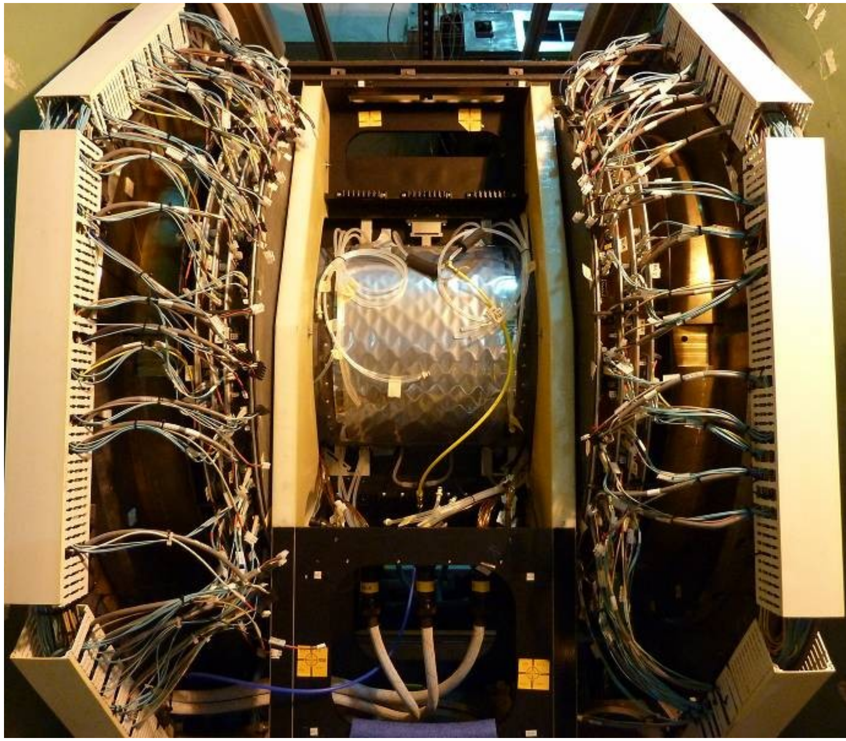
Measuring Heavy Flavor Mesons via single electrons

c -> e^+ + anything (B.R.: 9.6%)
b -> e^+ + anything (B.R.: 10.9%)

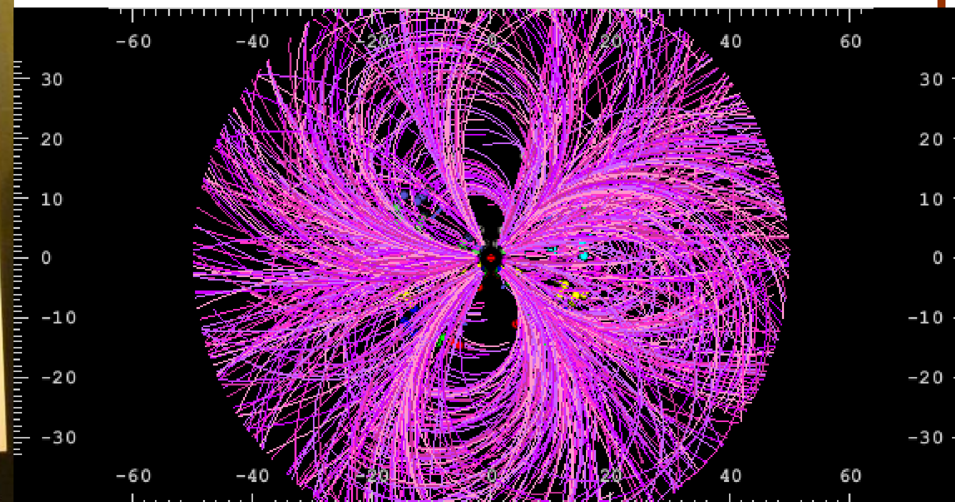


- Heavy flavor mesons (D or B) has large branch ratio in semi-leptonic decay mode
- By measuring the single electrons coming from semi-leptonic decay, we can measure the D/B meson indirectly
- With different DCA of electrons, we can separate c/b

Silicon Vertex Detector (VTX)

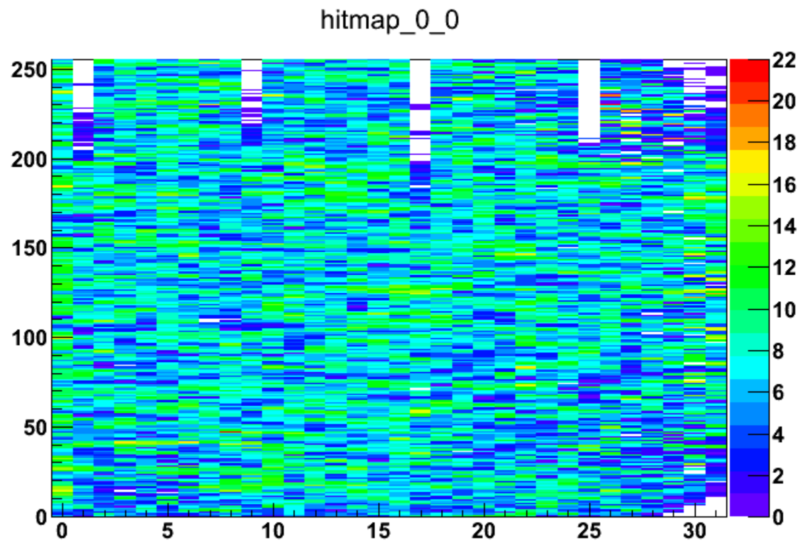


VTX in Au+Au @ 200GeV



- VTX detector is used to measure the vertex of the electron precisely
- Installed in 2011 and fully functioning in 2011 and 2012

Determine the dead/hot map of pixel layers



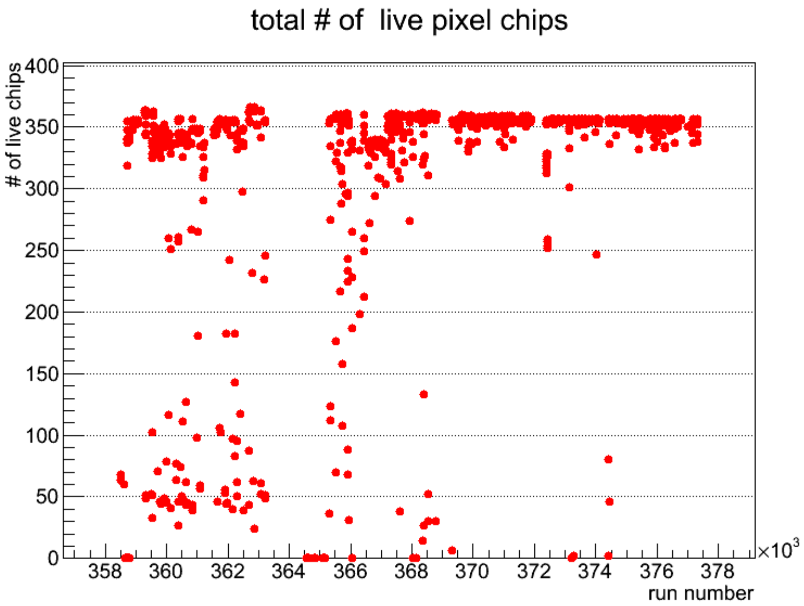
From run 363228
(p+p @ 200 GeV)

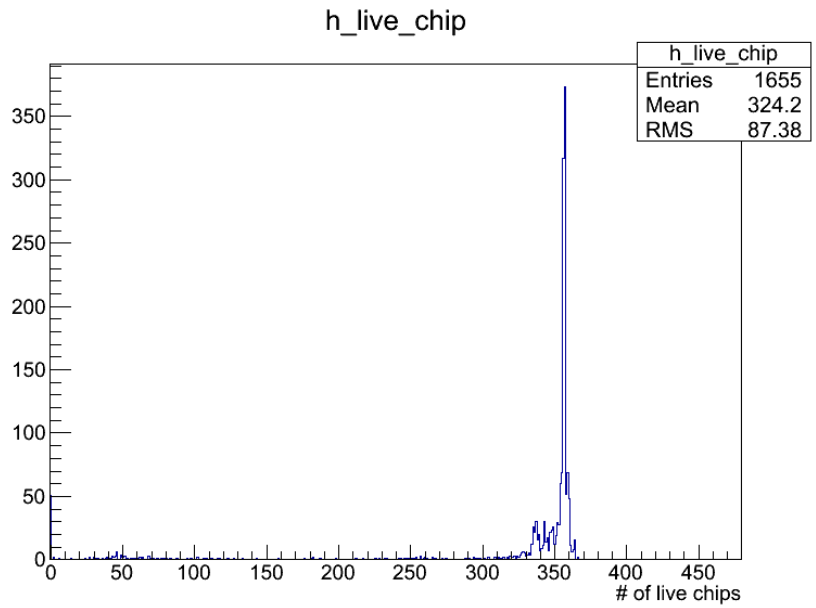
- 2 layers, 20 (40) modules in each layer, 8 chips per module, 8192 pixels per chip
- The basic for every vtx measurement
  - Clusterizing
  - Tracking
- Produce
  - chip-by-chip map for each run
  - Pixel-by-pixel map of each chip during the run period

Steps of making dead/hot map

- Calculate the “# of hits per “good pixel” of each chip
- Determine the status of the chip through the run period
- Determine the pixel status of the chip through the run period

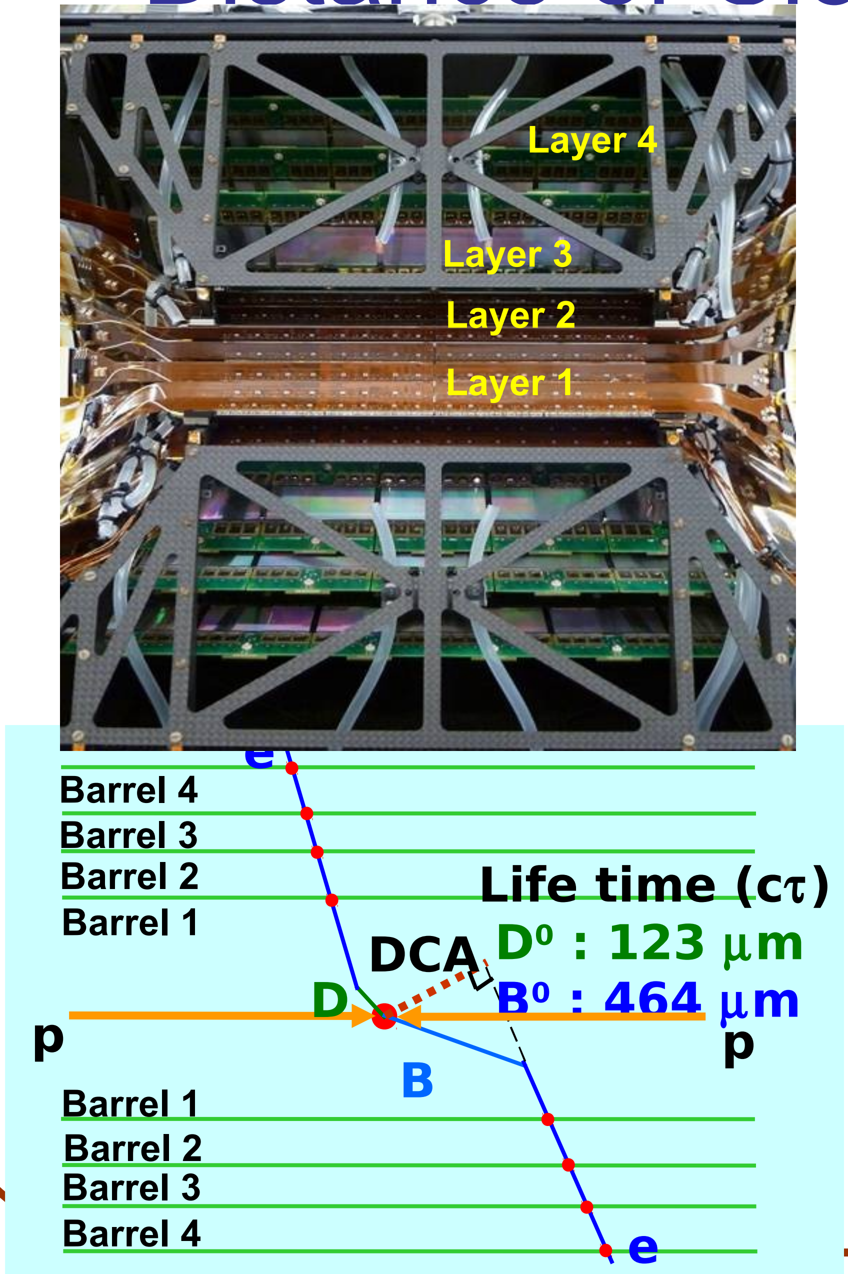
Summary on dead/hot chips





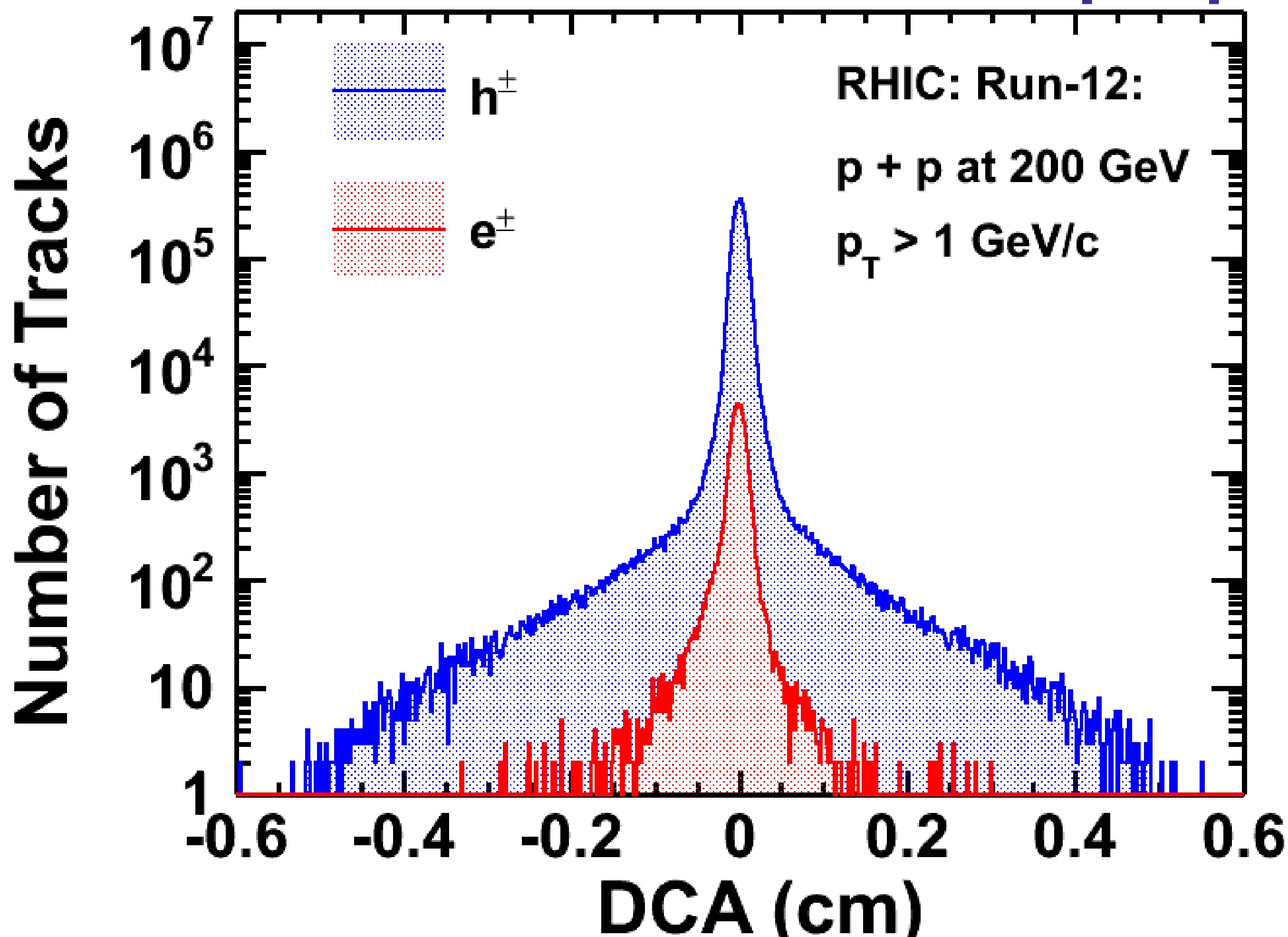
- Pixel layers are pretty stable throughout run12
- 89% of the runs in run12 has live chips >300

Distance of Closest Approach



- Because of large τc of heavy meson, semi-leptonic decay has a secondary vertex
- Four different layers in VTX can determine the DCA precisely
- DCA can be used to separate electrons from c/b decay

DCA distribution in p+p

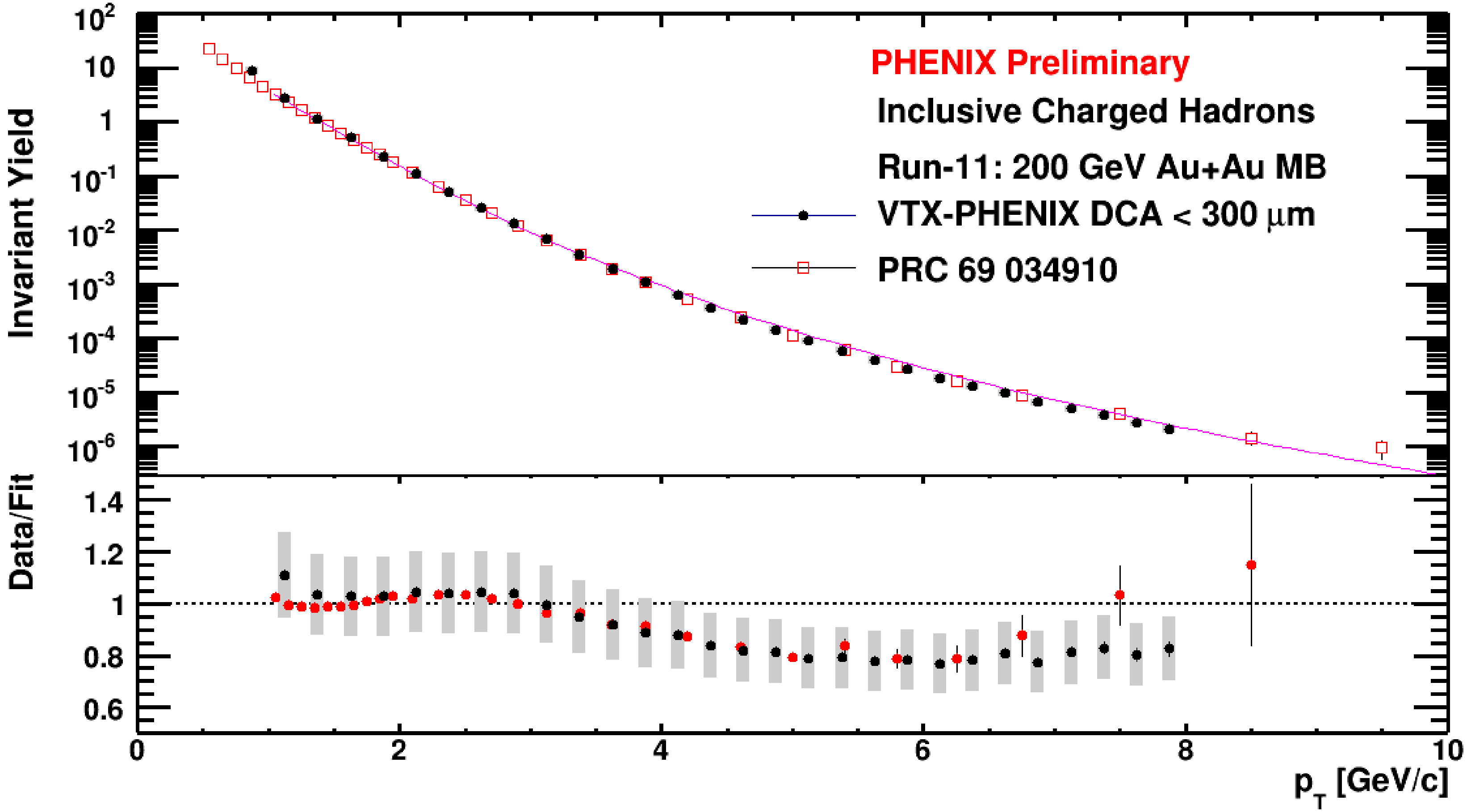


- The DCA distribution of hadrons and electrons, where DCA of hadrons extend to large values.

Measuring the spectra of charged hadron and heavy flavor electron

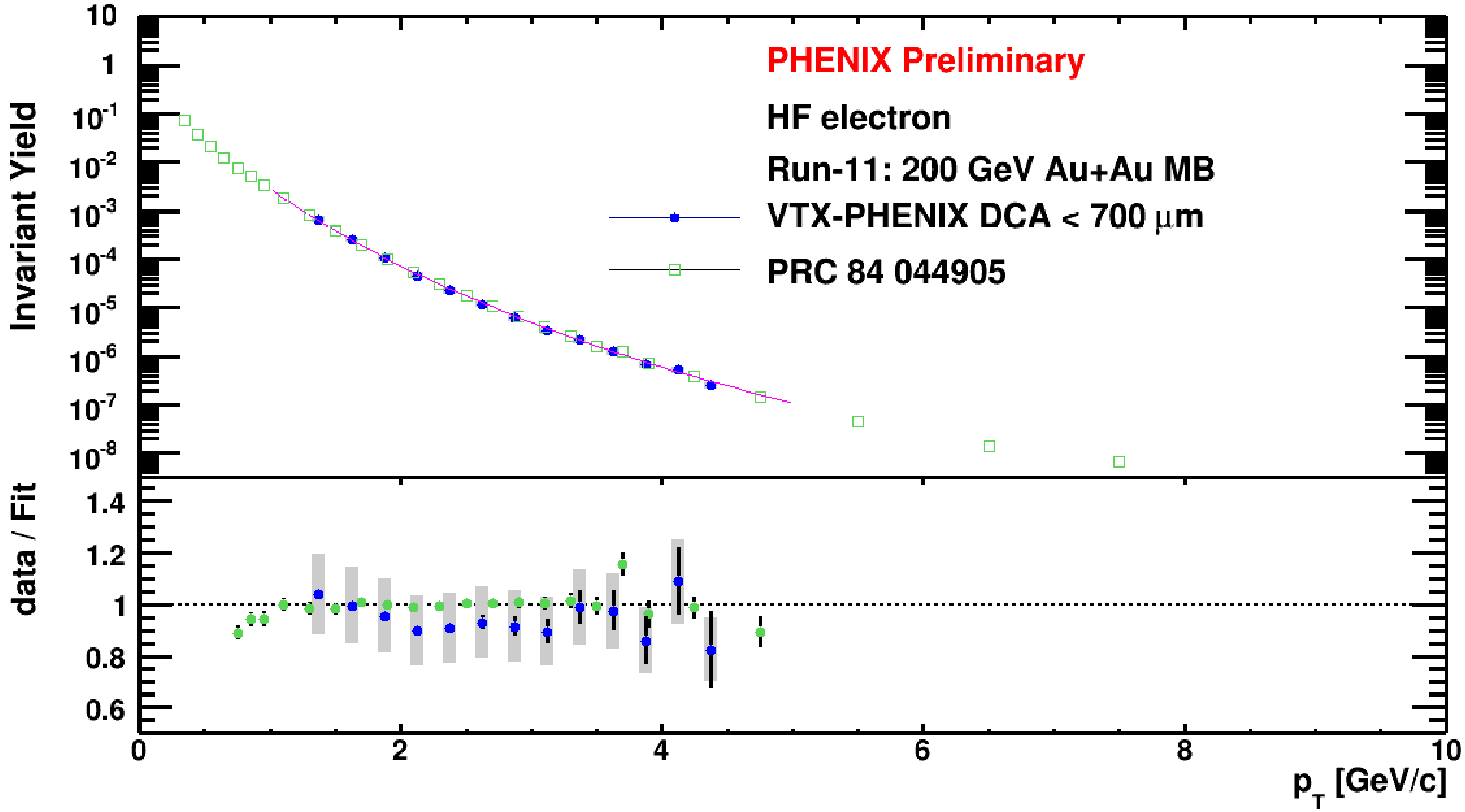
- Charged hadron:
  - track quality cuts,
  - fiducial cuts
  - At least 3 hits in VTX while 2 hits at pixel layers
- Electron: same as hadron cuts and
  - rich cut,
  - Dca < 700um
- Acceptance correction

Spectra of Inclusive Charged Hadrons



- The hadron spectra is consistent with previous PHENIX measurement

Spectra-HF electron



- The inclusive heavy flavor electron spectra is consistent with previous PHENIX measurement

Summary

- VTX is installed in PHENIX in run 11 (2011) and works well in run 12 (2012)
- From dead/hot map, pixel layer is stable during run12
- Inclusive charged hadrons and inclusive heavy flavor electrons in min-bias Au+Au is measured, and agrees well with previous PHENIX measurement

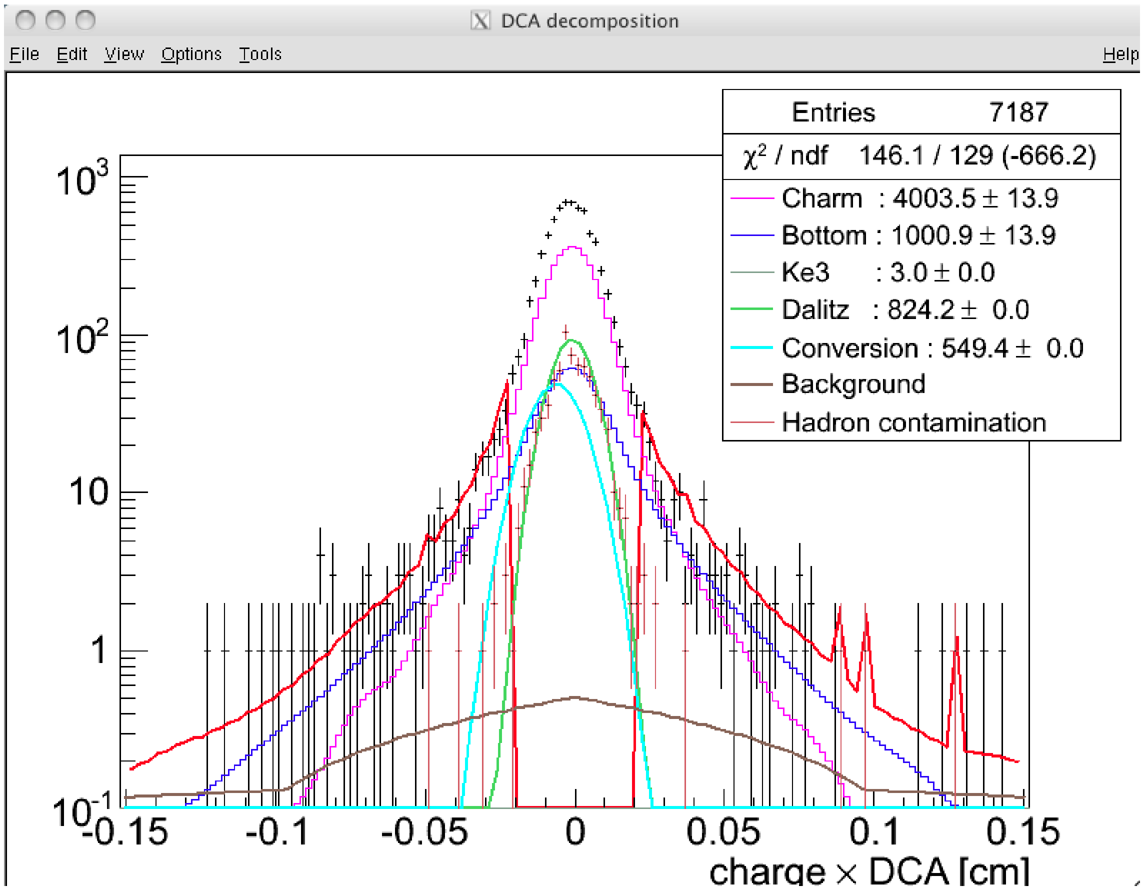
Backup slides

Different sources in DCA distribution

- Signal:
  - single electrons from heavy flavor meson decay
- Background:
  - photon conversions
  - Dalitz decay
  - Ke3 decay
  - Hadronic contributions

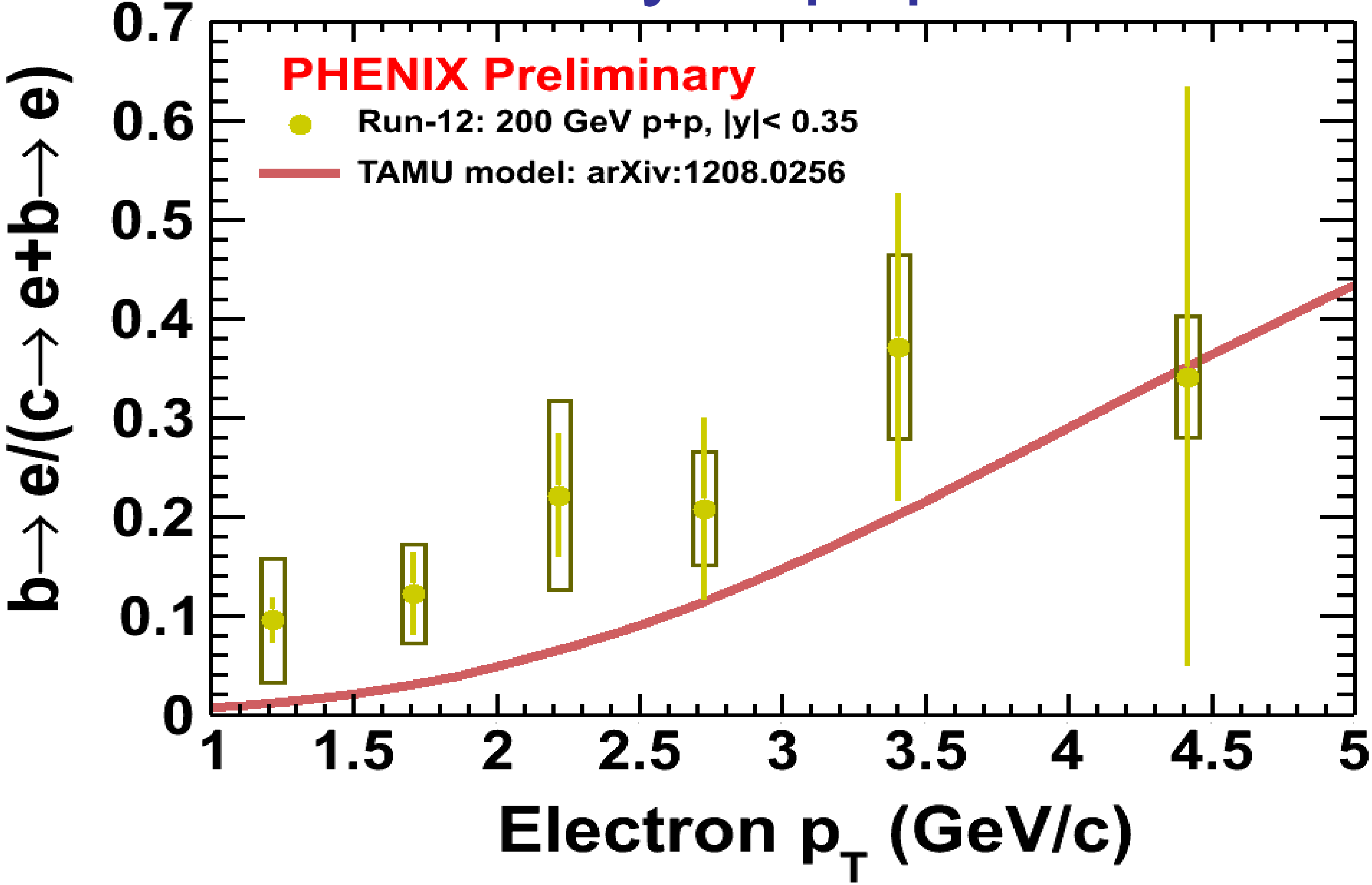
- Use fitting method to decompose contribution from each source

DCA distribution in p+p



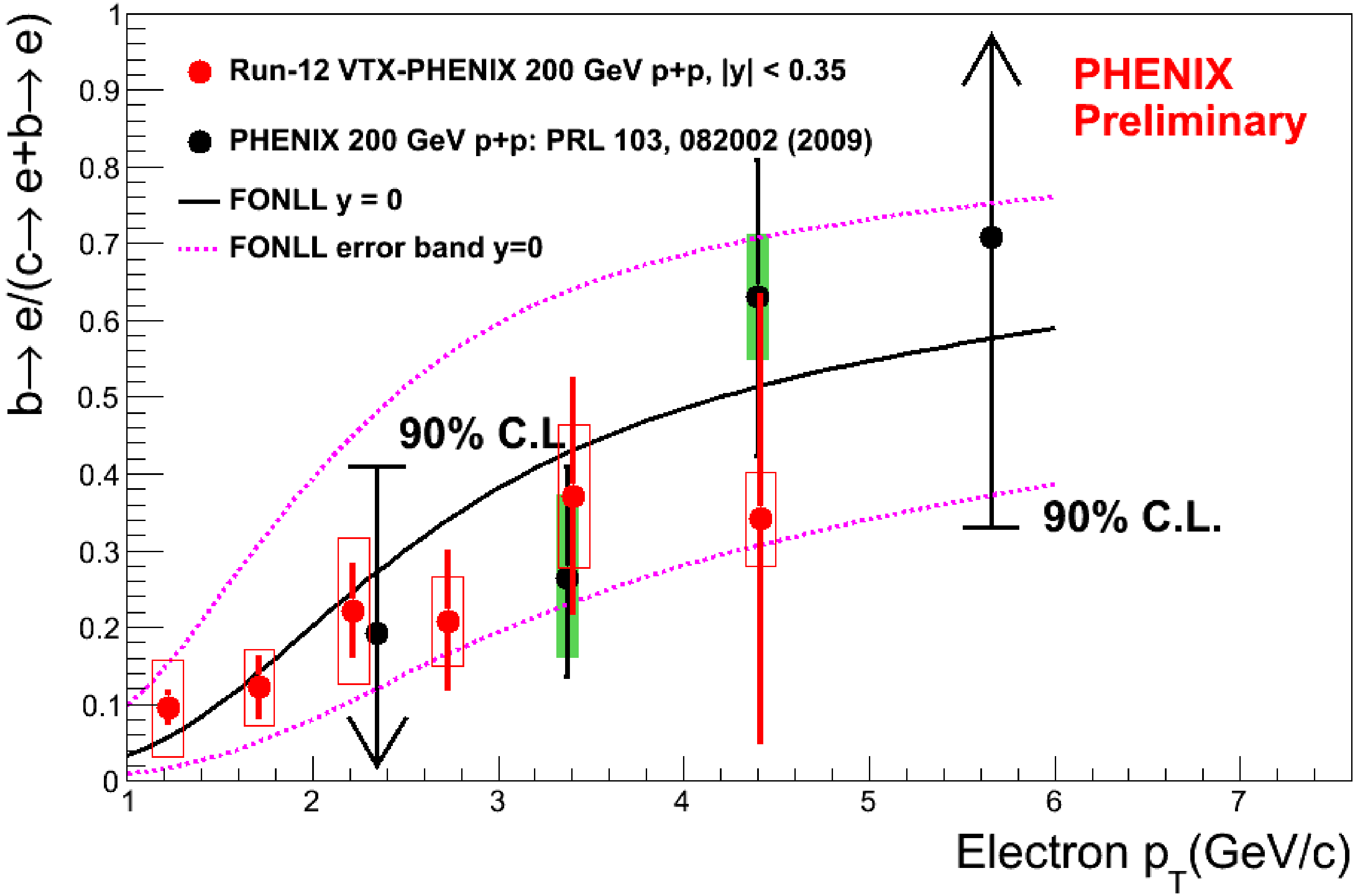
- By fitting decomposition, we can separate DCA contributions from different sources

Beauty in p+p

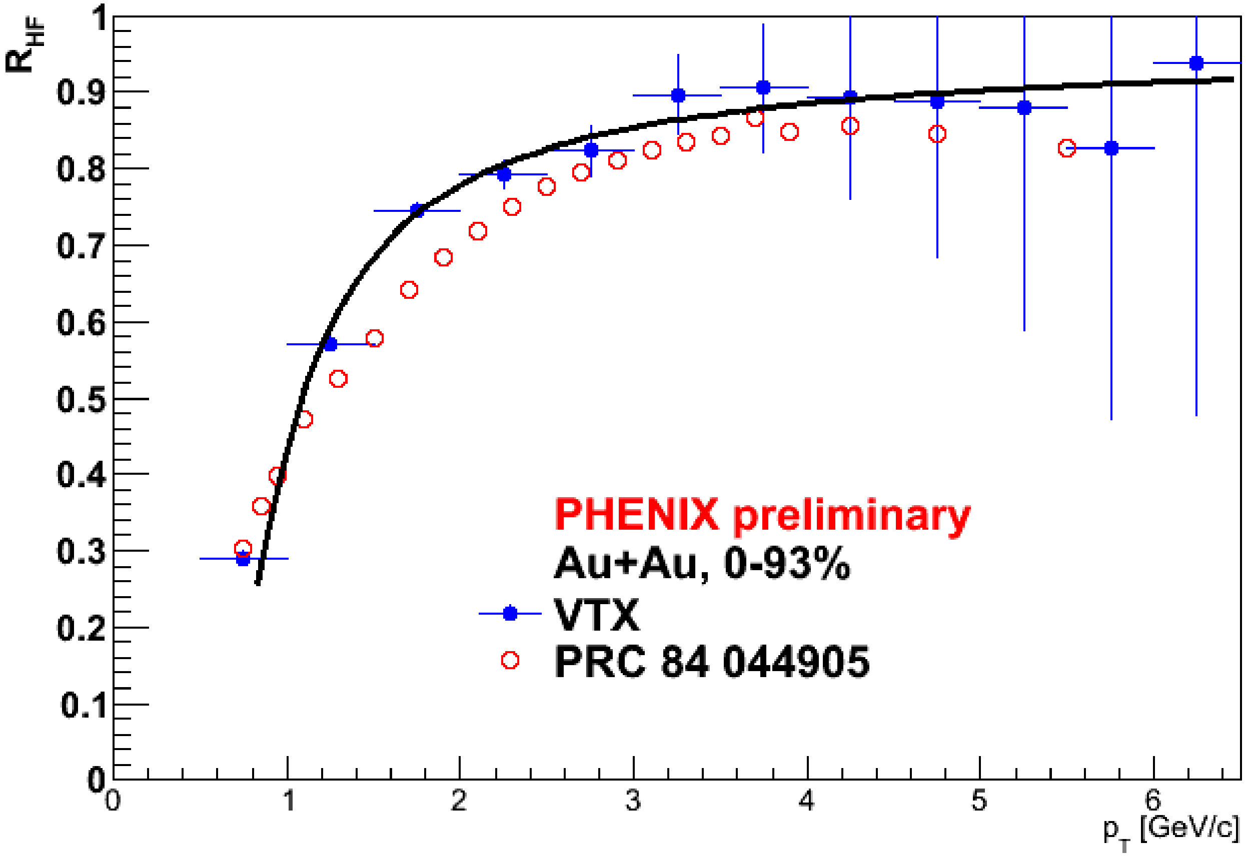


PHENIX Preliminary
Run-12: 200 GeV p+p, |y|< 0.35
TAMU model: arXiv:1208.0256
b→ e/(c→ e+b→ e)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
1.5
2
2.5
3
3.5
4
4.5
5
Electron p_T (GeV/c)

Ratio of Beauty is consistent with FONLL



RHF



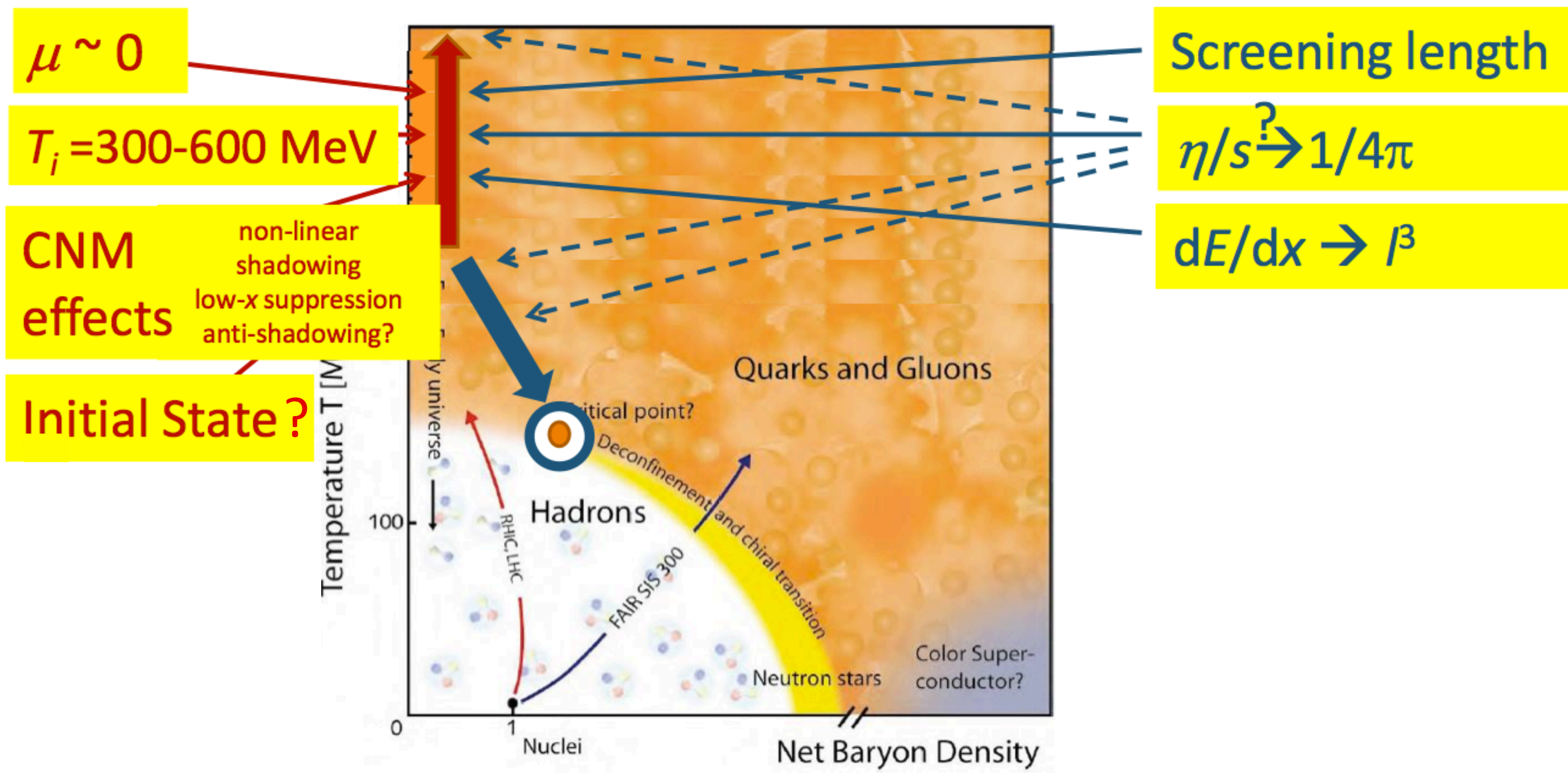
- The inclusive electron spectra has photonic electron contamination. By using $R_{HF} = (\#e^{HF})/(\#e^{HF}+\#e^{PE})$, we can extract the spectra of HF electrons

High p_T hadrons with the PHENIX VTX detector

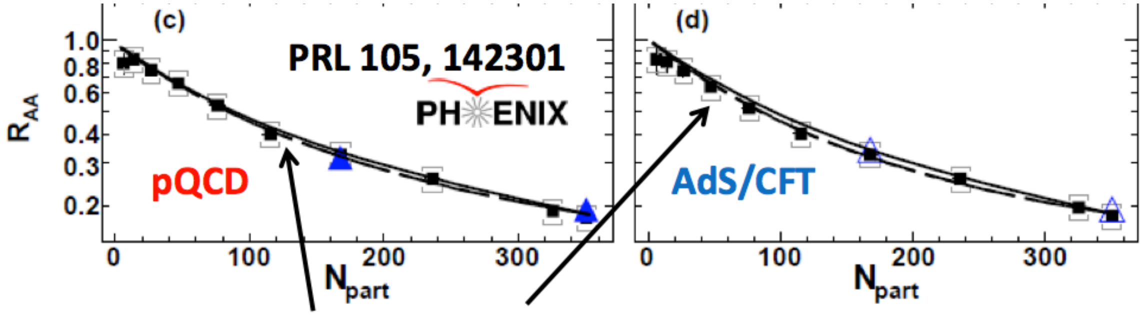
Stefan Bathe

Measuring QGP Properties

Conditions ⟹ Properties



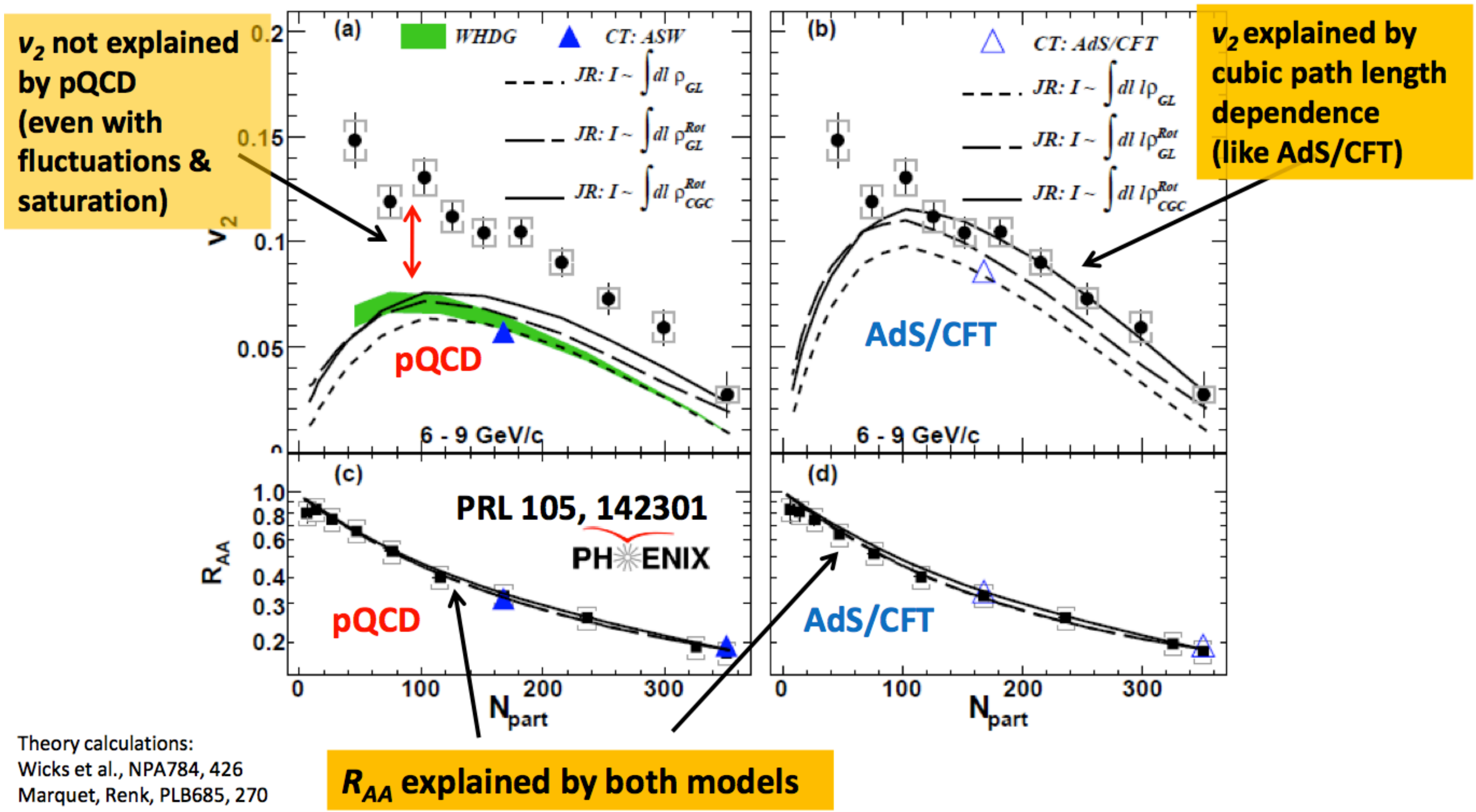
Path-length dependence of E loss:



R_{AA} explained by both models

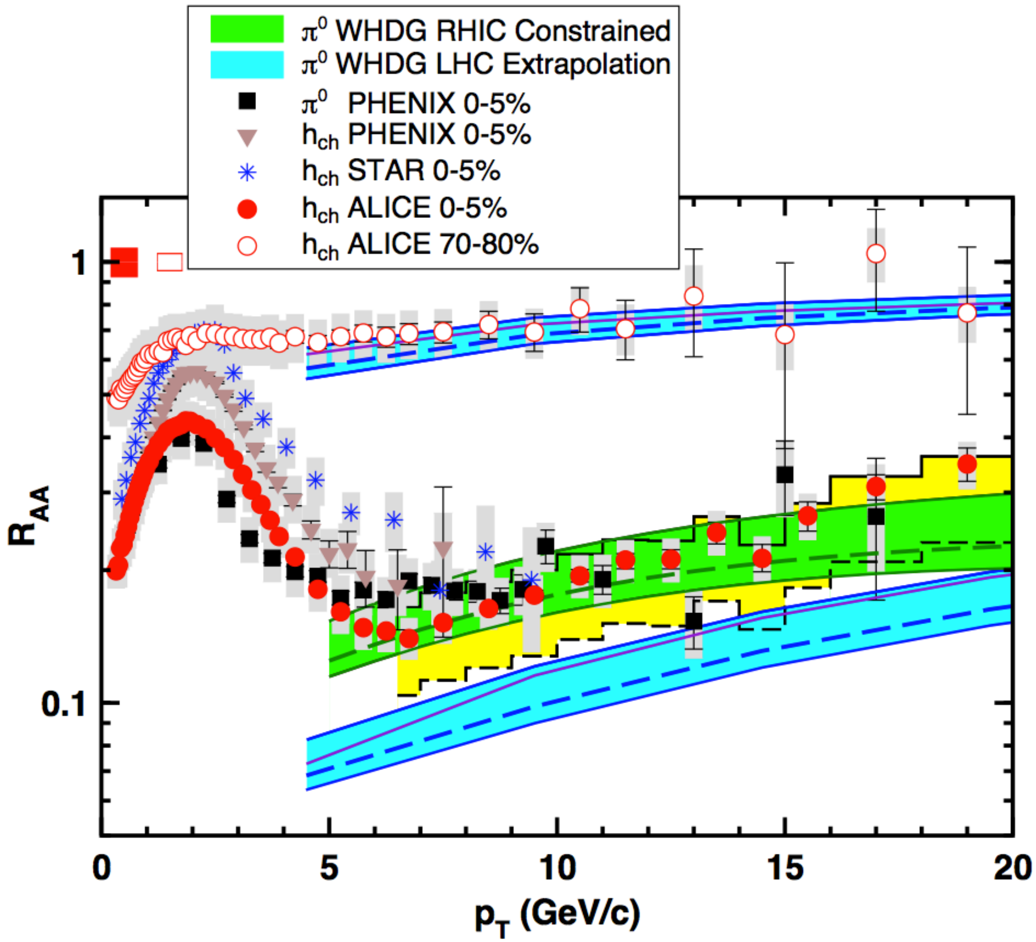
Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

Path-length dependence of E loss: cubic!



Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

"The surprising transparency of the sQGP at LHC*"



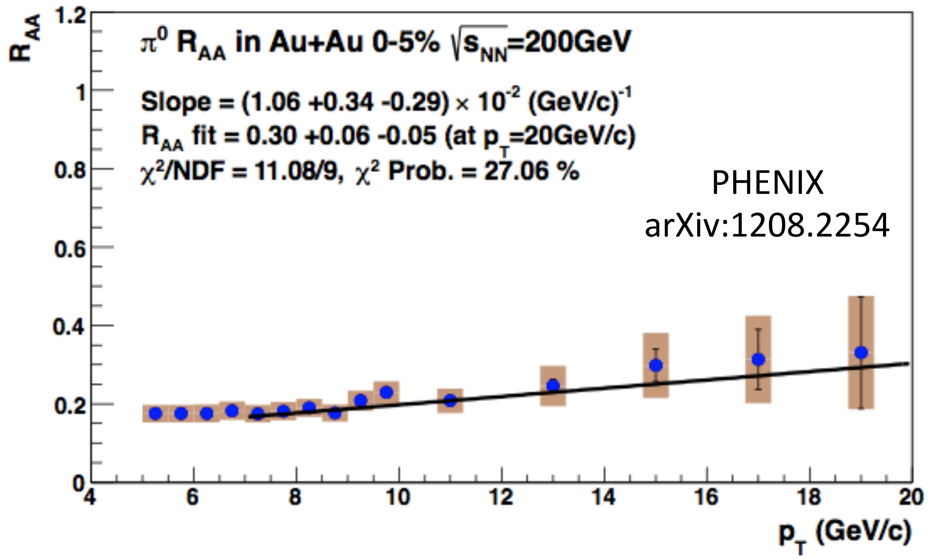
*Plot: W. Horowitz, M. Gyulassy
Nucl.Phys. A872, 265 (2011)

WHDG: Wicks, Horowitz, Djordjevic, Gyulassy,
Nucl.Phys. A784, 426 (2007)

ALICE data: K. Aamodt et al.,
Phys.Lett. B696, 30 (2011)

PHENIX data: A. Adare et al.,
Phys. Rev. C77, 064907 (2008)

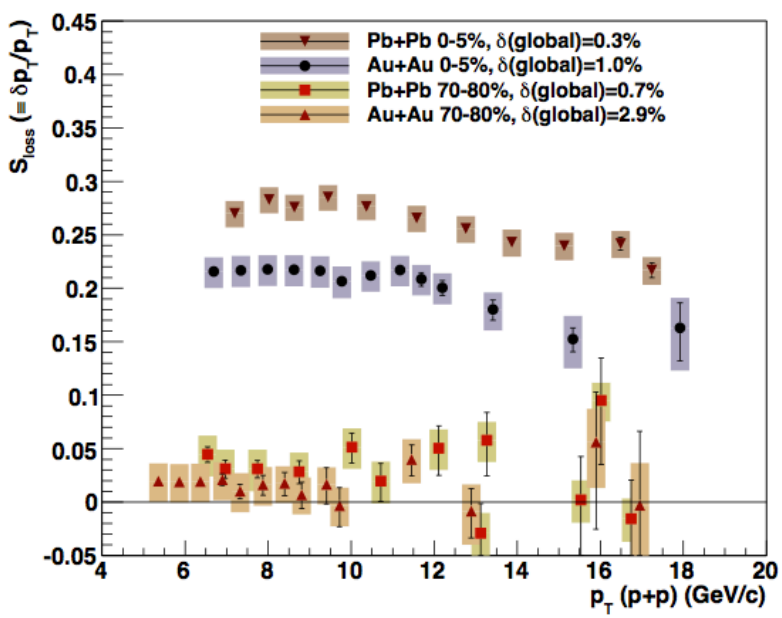
Significant slope of R_{AA} observed



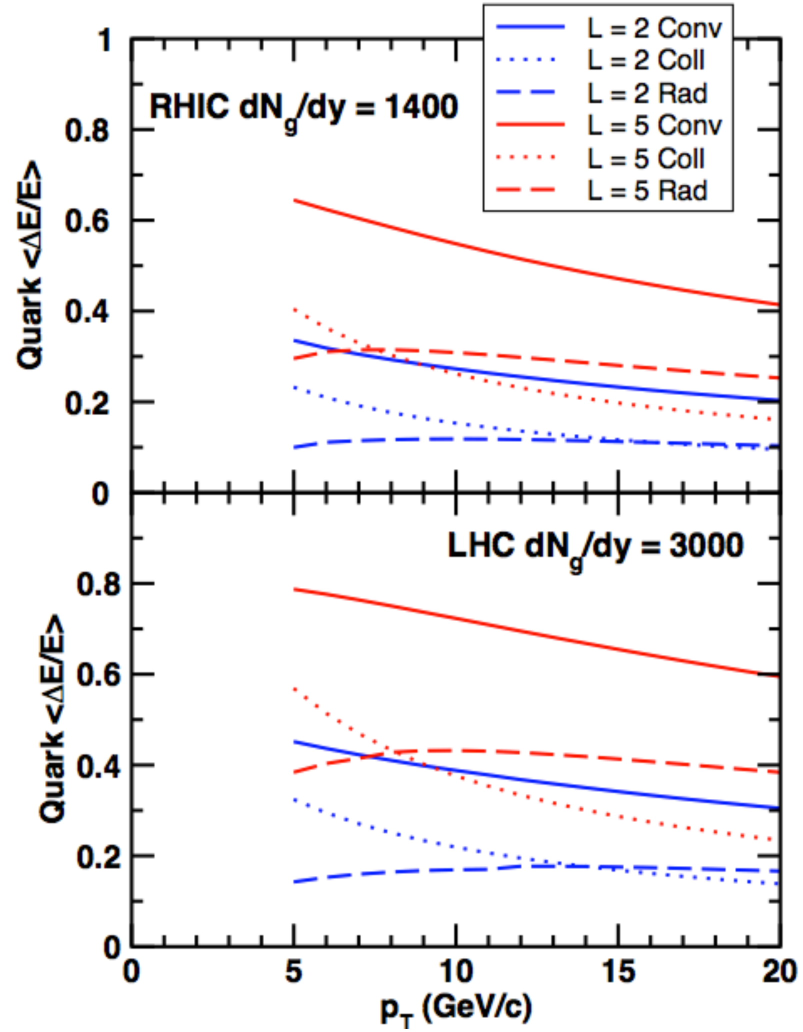
Recent progress!

$$f(p_T) = A \times (p_T(1 + \delta p_T/p_T))^{-n}$$

Fractional E loss

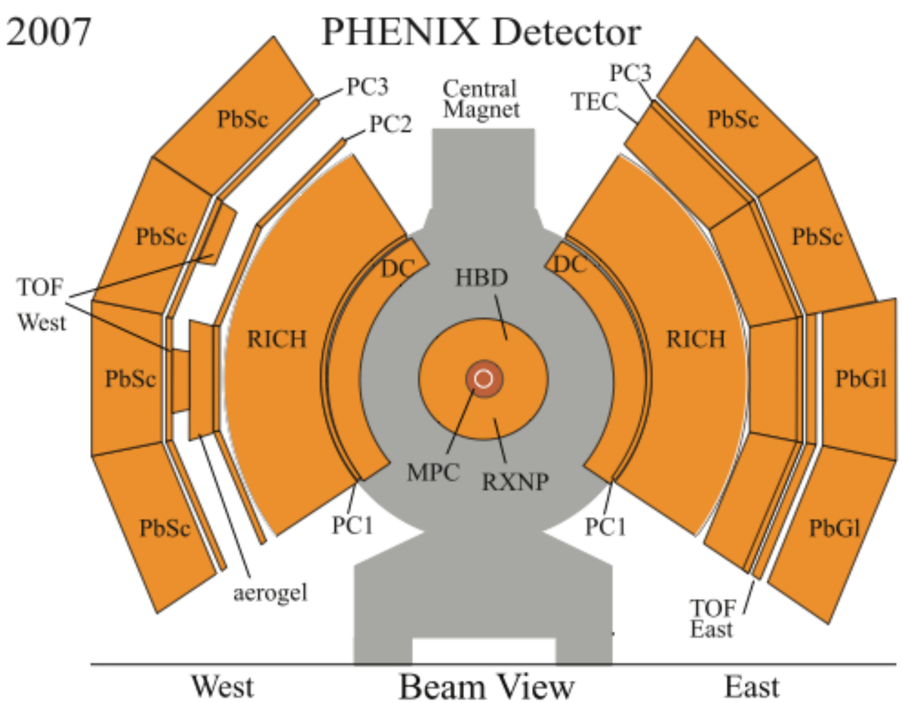


PHENIX
arXiv:1208.2254



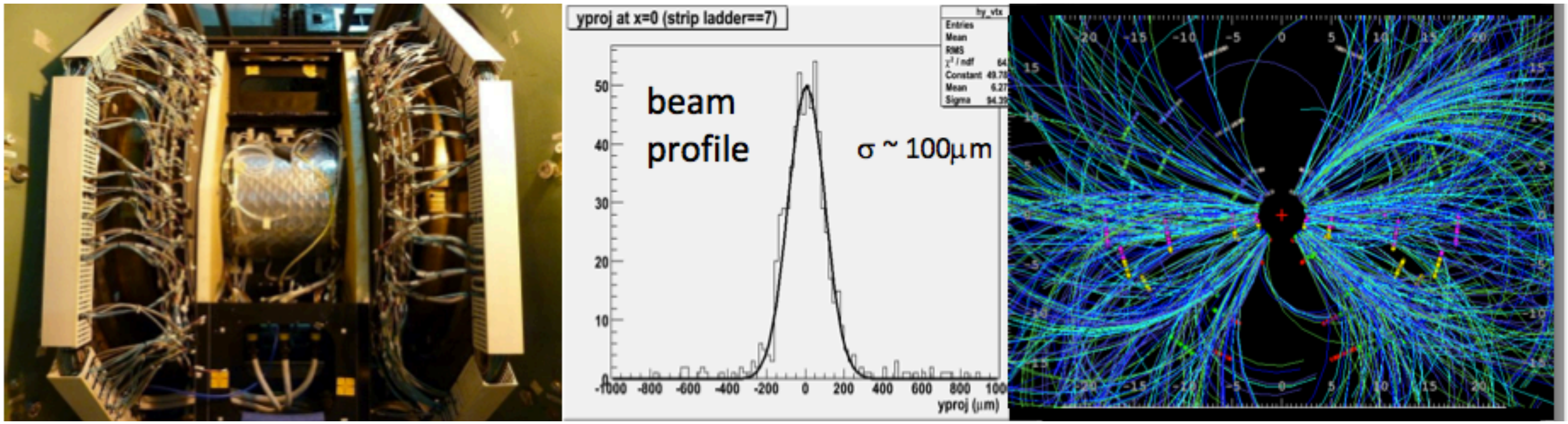
W. Horowitz, M. Gyulassy
Nucl.Phys. A872, 265 (2011)

Limits of current measurement



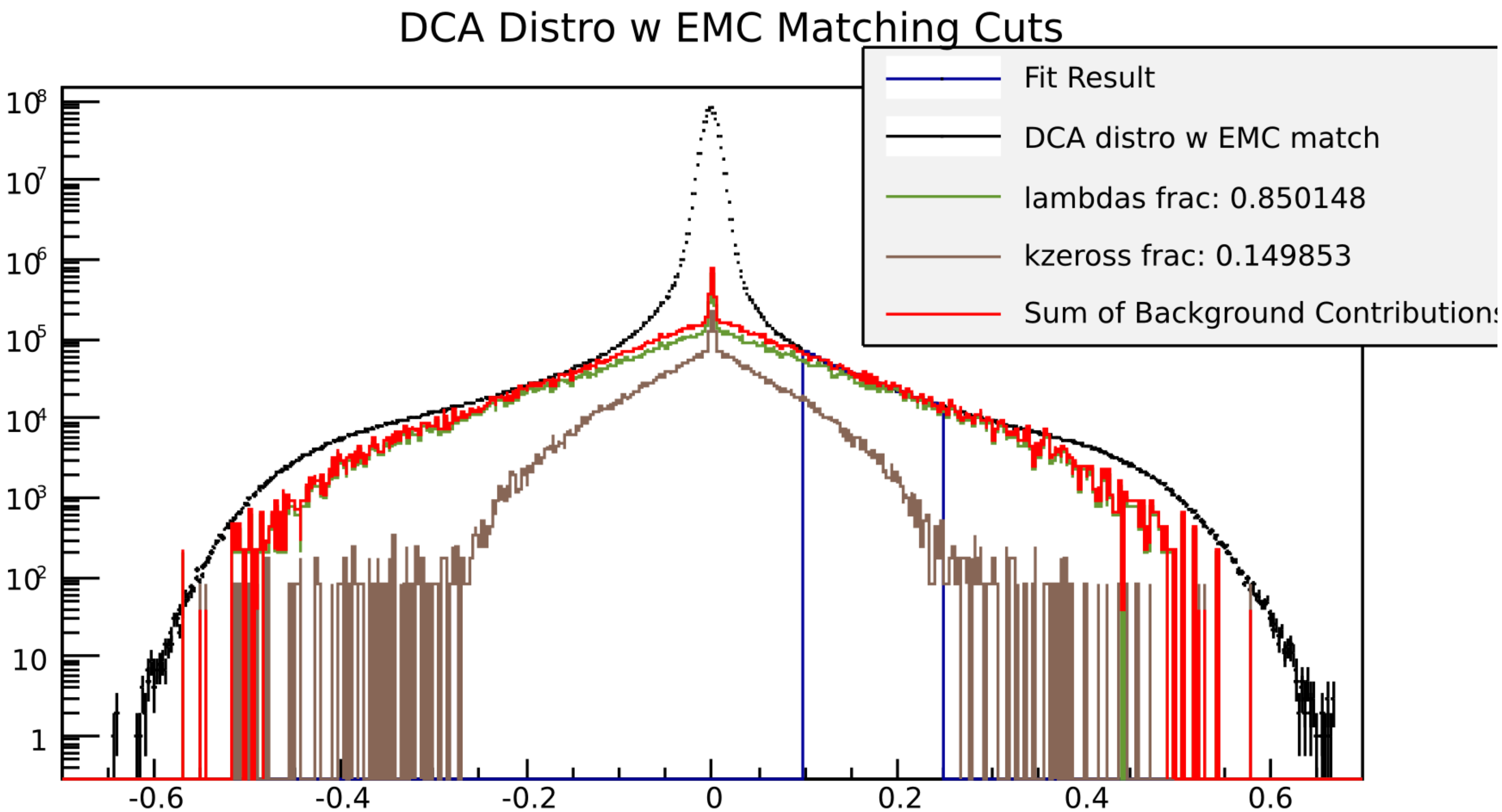
- Dominating systematics of π^0's at high p_T: cluster merging in EMCal
  - η mesons don't suffer this, but factor 5 less statistics
- Charged hadrons limited to $p_T < 8$ GeV due to off-vertex background

New capabilities: VTX detector

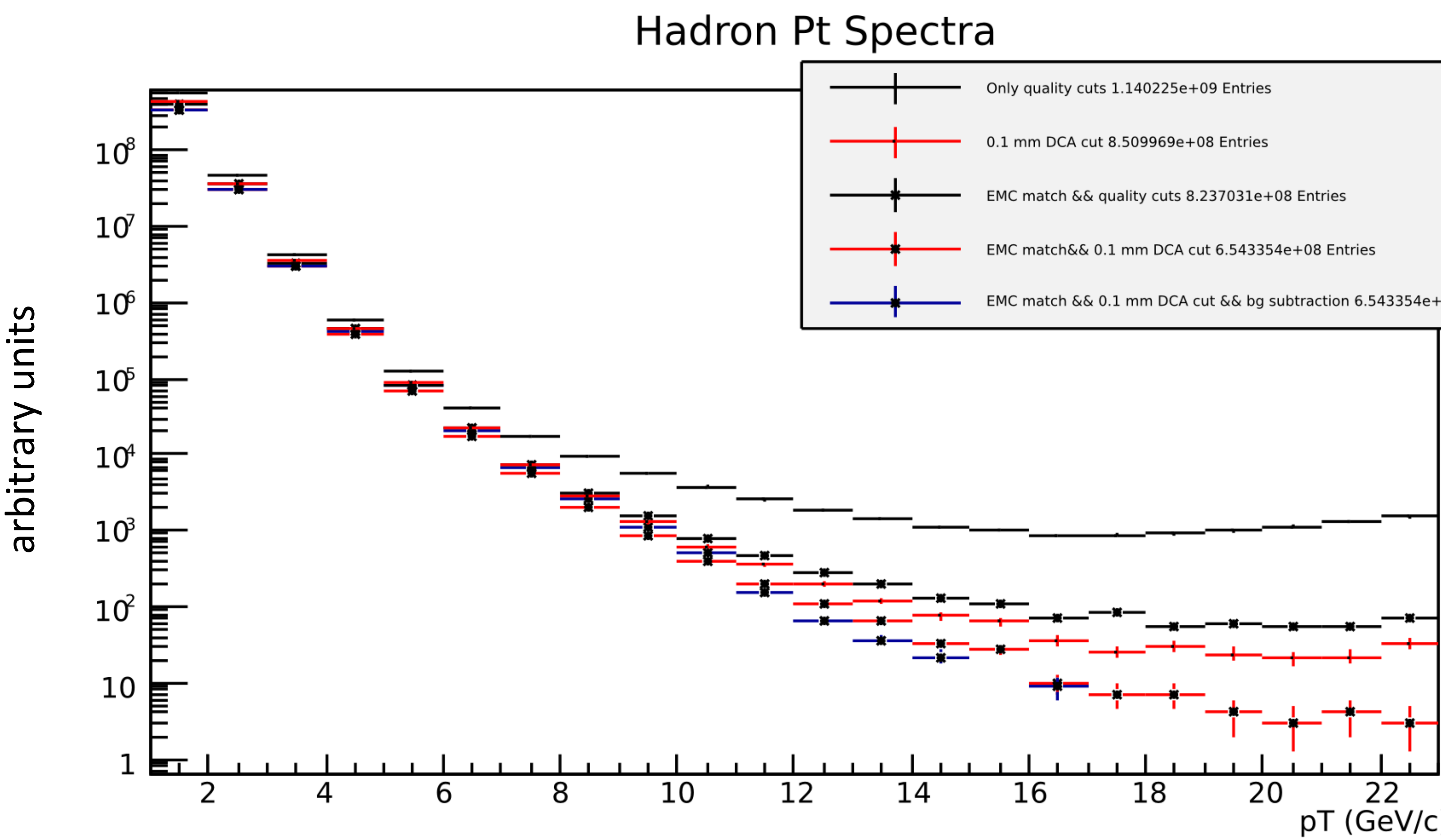


- VTX confirms charged track at event vertex
- VTX measures RxNP (for path length)
- RICH identifies pions (threshold: $\gamma = 35$ ($p_T = 5$ GeV for pions, 17 GeV for kaons)

Transverse DCA for $h^{\pm}$ candidates

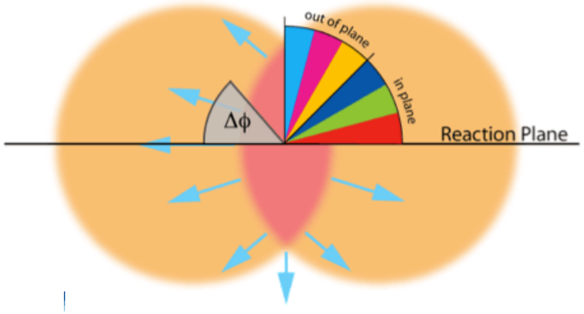


h± candidate p_T for various purity cuts



Next steps

- Estimate random background
  - From DCA_z distribution
- Estimate conversion contribution
  - Measured from $\Delta\phi$ correlations
- Reference measurement in *p*+*p*
  - Using EMCal RICH trigger for pions
- Path length dependence via RxNP dependence (measured with VTX)



Acknowledgements

- I would like to thank
  - Yasuyuki Akiba for many ideas and discussions
  - My student Jason Bryslawkyj for doing all the work
  - The rest of the VTX group for providing code, calibrations, etc.
  - The PHENIX collaboration for data taking and operation
  - RIKEN and DOE for support

RBRC Spin Group's Current Activities & Future Directions

Status of RHIC Spin program

- Polarized protons in RHIC
- Recent physics highlights

Open questions leading to future plans

- sPHENIX-forward
- ePHENIX at eRHIC

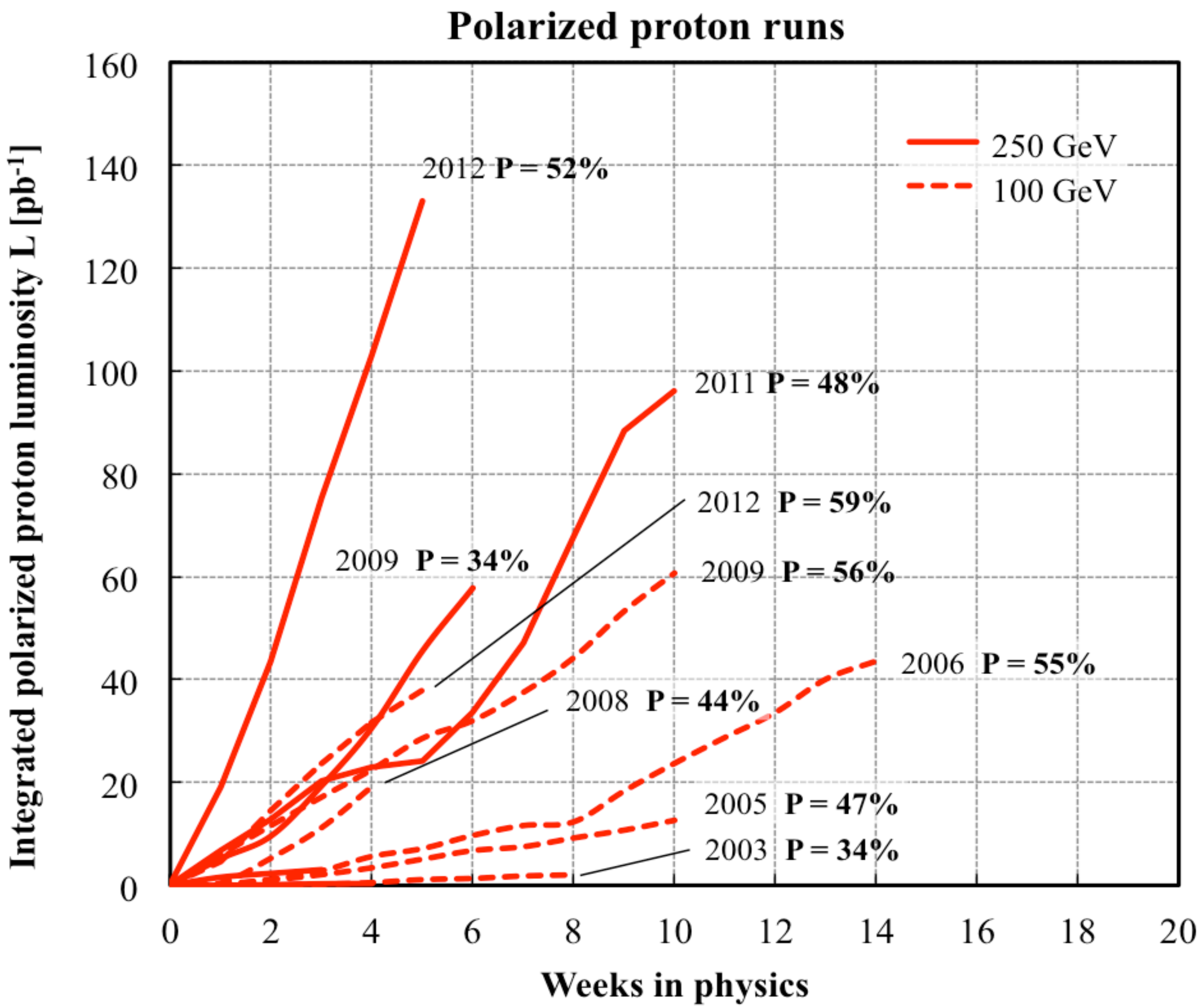
Abhay Deshpande
Stony Brook University & RBRC

Stony Brook University

RIKEN BNL Research Center

The polarized p-p program comes of age!

Continious and deliberate effort by the CAD Run 2012

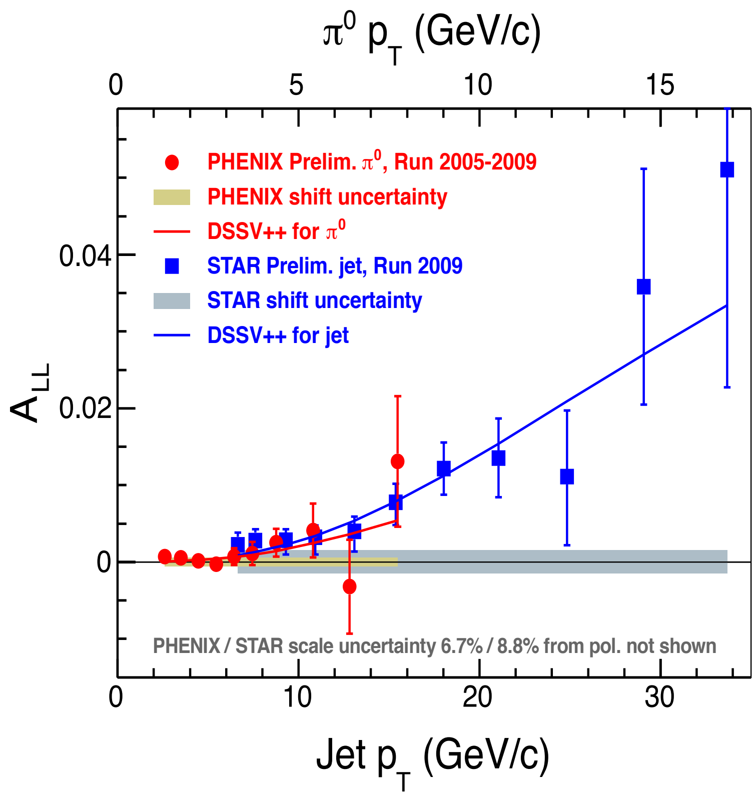


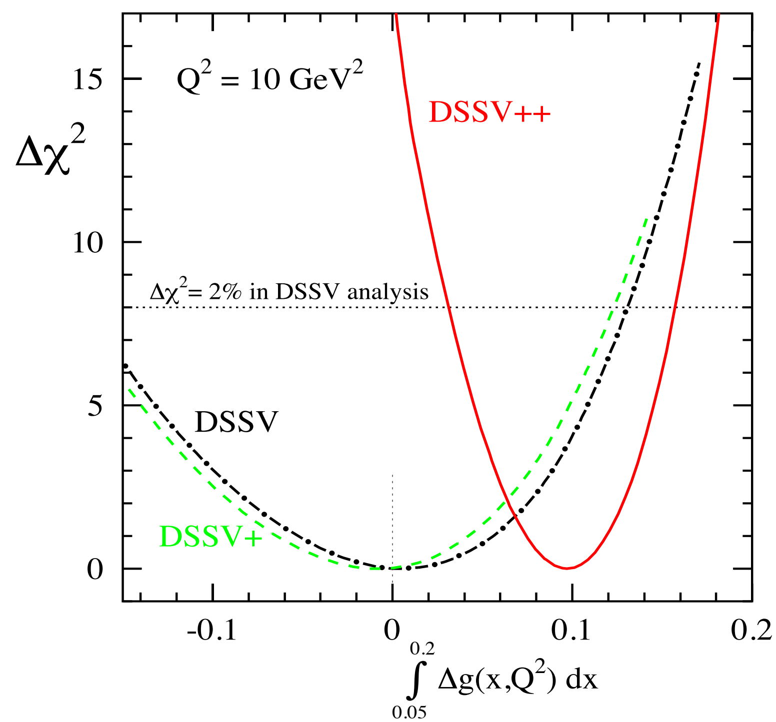
The RHIC Spin Program

- 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

RHIC-Spin White Paper, 2012

Status of ΔG with RHIC Data





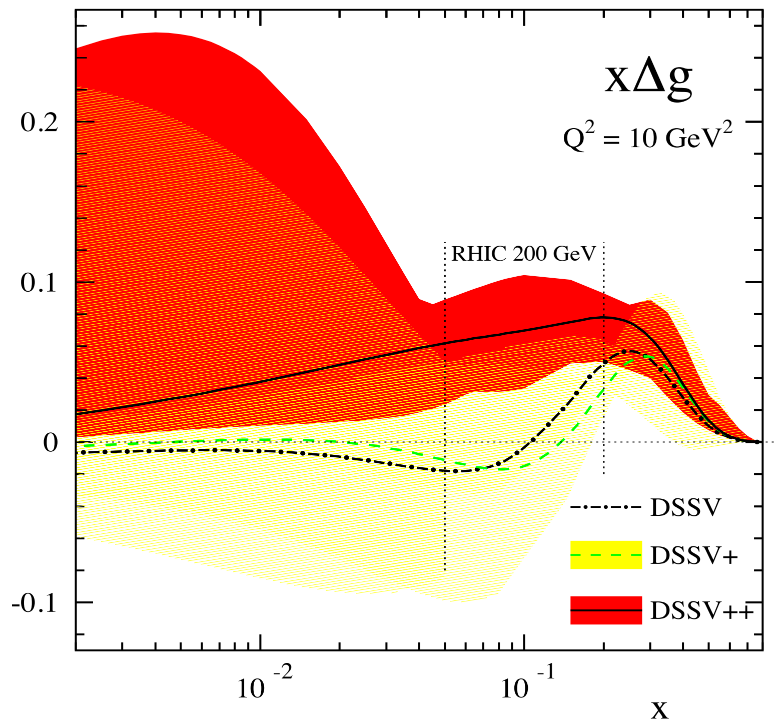
PHENIX data: Ph.D. theses
2006 Data Ph.D. SBU **Kieran Boyle** (now RBRC)
2009 Data Andrew Manion (SBU grad. student)

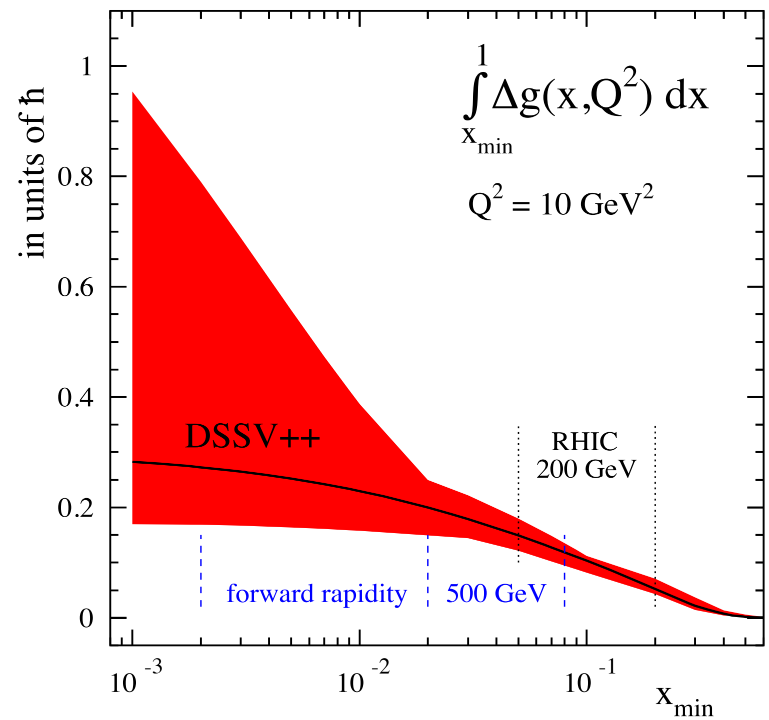
Global fit DSSV++ by
Sassot & Stratmann

Stony Brook University

RIKEN BNL Research Center

ΔG Status and future needs…. (low-x)



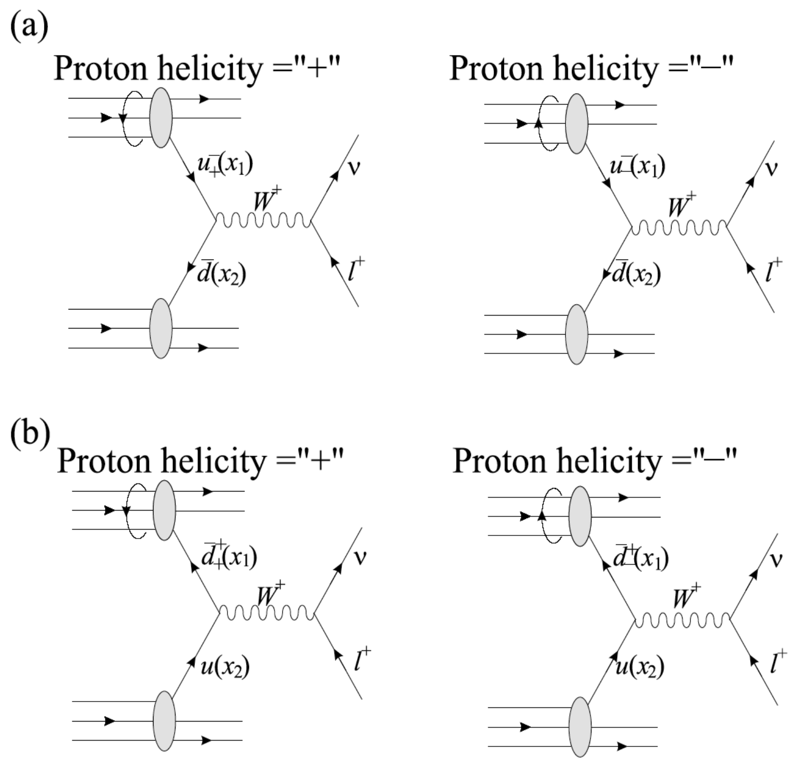


Low x uncertainty reduction requires higher energy & forward rapidity studies

Effort limited by systematic uncertainties in measurements:

Novel ideas being tried by **Kieran Boyle (RBRC)** and Grad. Student (Andrew Manion, SBU) ➔ See details of such a study in Kieran's talk.

Anti-Quark Polarization



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

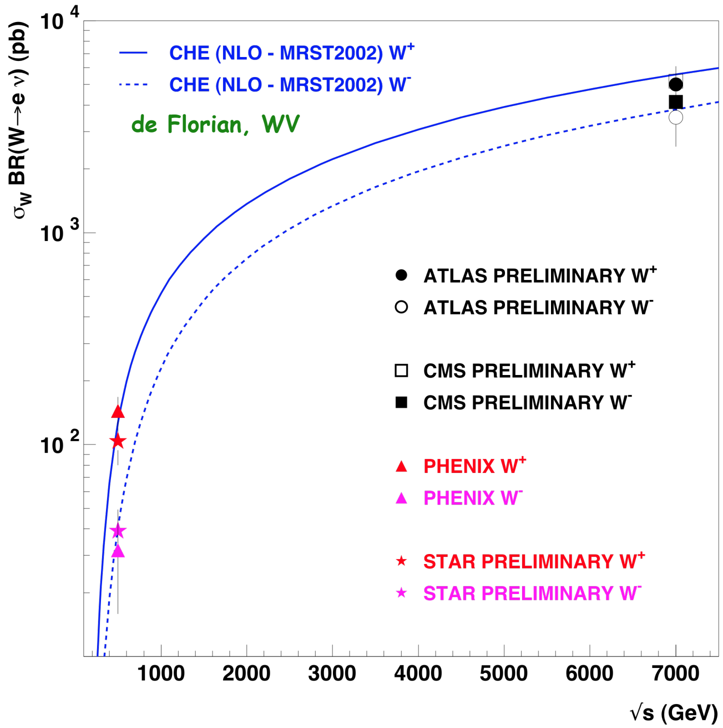
Produced W's decay in to a lepton and a neutrino

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

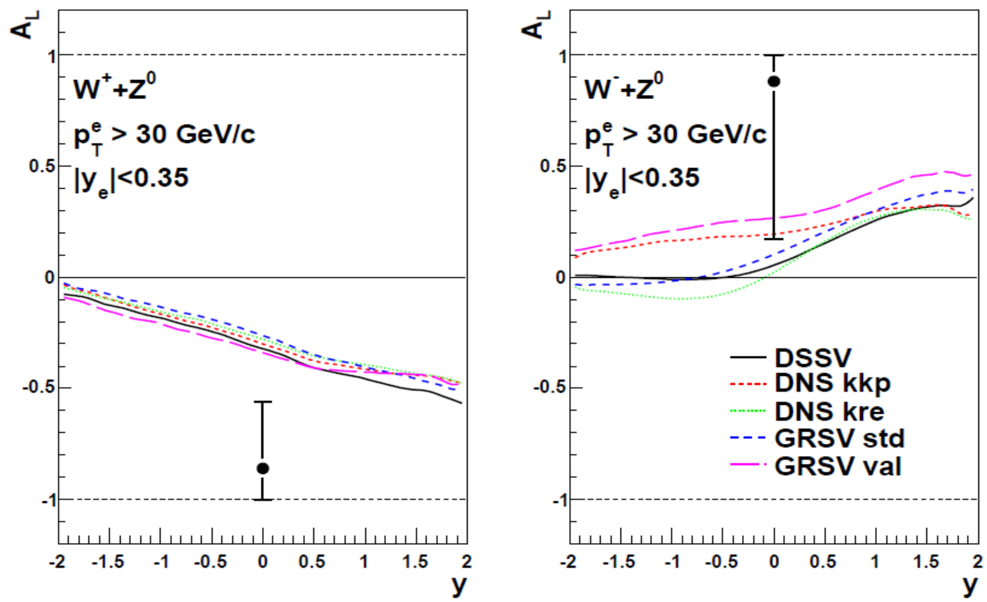
- The charge of the high p_T lepton
- Isolate the lepton from leptons decayed from other mesons
- Background subtraction a challenge

PHENIX Central arm results published last year, with electron in the final state
➔ **K. Okada (RBRC) et al.**
Forward arm detector/trigger upgrade just completed
➔ More on this by **Itaru Nakagawa (RIKEN)** in the following talk

PHENIX central arm: Run-11



Phy. Lett. 106 062001 (2011)
Led by **Kensuke Okada (RBRC)**



Run 12 Analysis in progress: C. Gal (SBU),M. Stepanov (U. Mass),
S. Bandara (Run-13), **K. Okada (RBRC), D. Kawall (U. Mass), AD (SBU)**

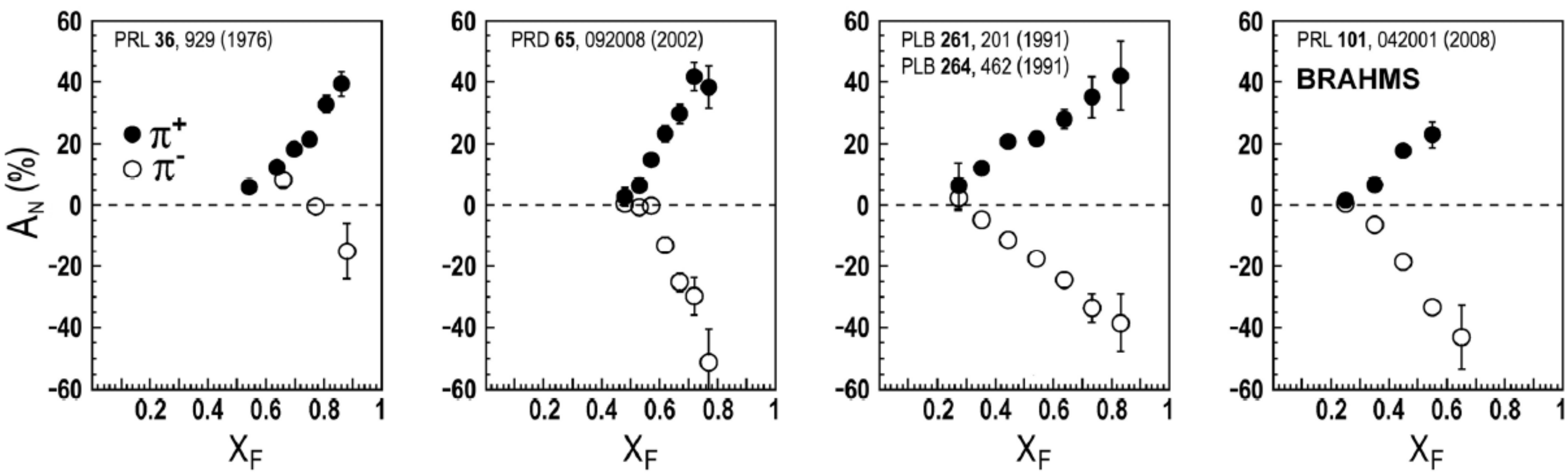
Ongoing effort on Forward Muon Upgrade: I. Nakagawa's (RIKEN) talk

Transverse Spin asymmetries:

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

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

Measured from ZGS to early measurements at RHIC (Shown here: Brahms)



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

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

➔ **Yuji Goto (RIKEN)** (Neutron asymmetries),

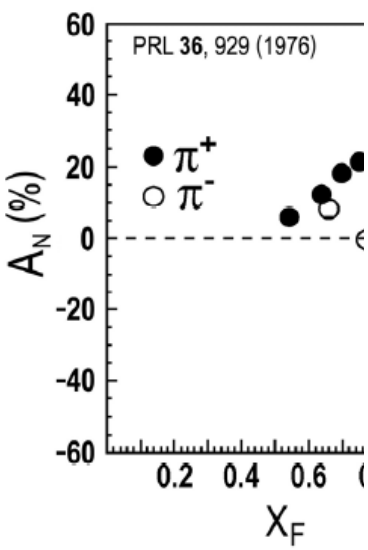
➔ **Xiaorang Wang (RBRC-NMSU)** (heavy Q with Forward-VTX)

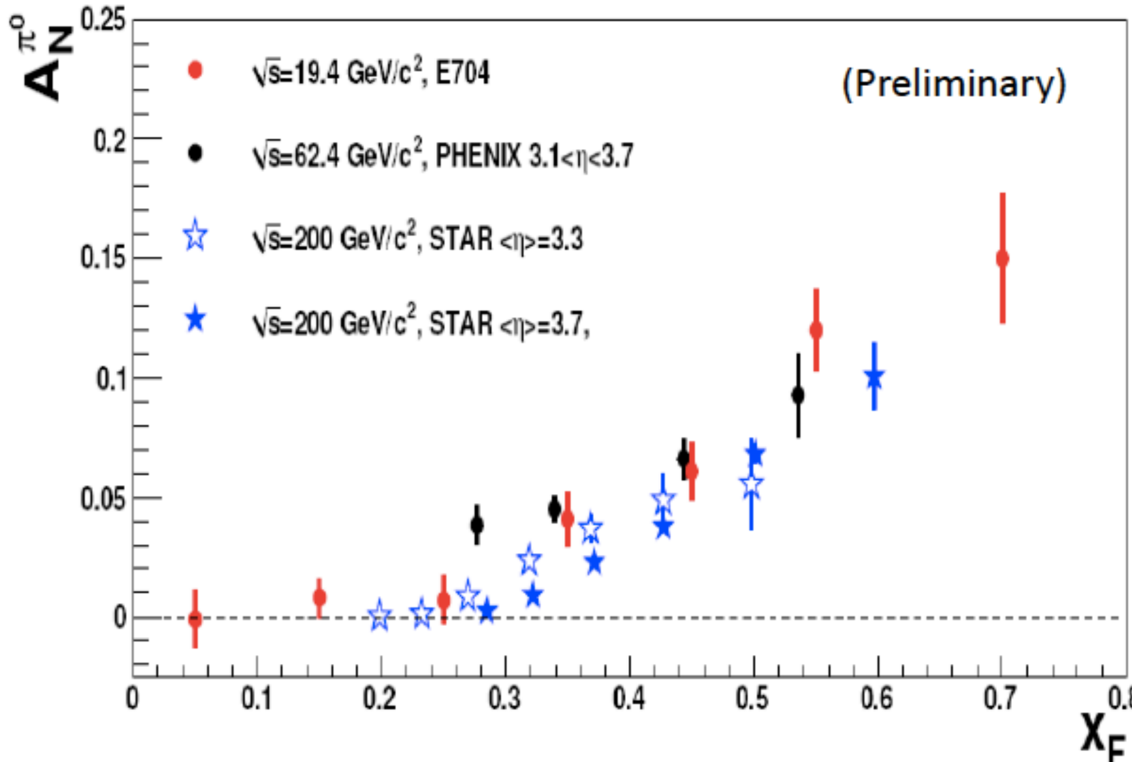
Transverse Spin asymmetries:

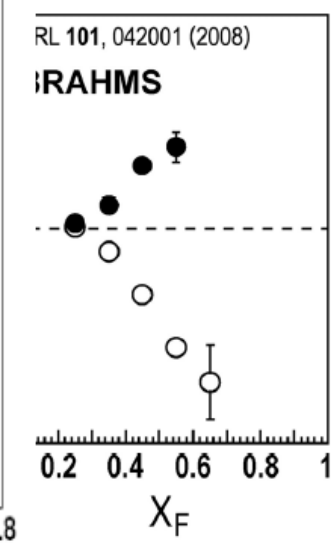
$$x_F = \frac{2p_l}{\sqrt{s}}$$

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
➔ **Yuji Goto (RIKEN)** (Neutron asymmetries),
➔ **Xiaorang Wang (RBRC-NMSU)** (heavy Q with Forward-VTX)

PHENIX → sPHENIX → sPHENIX-forward

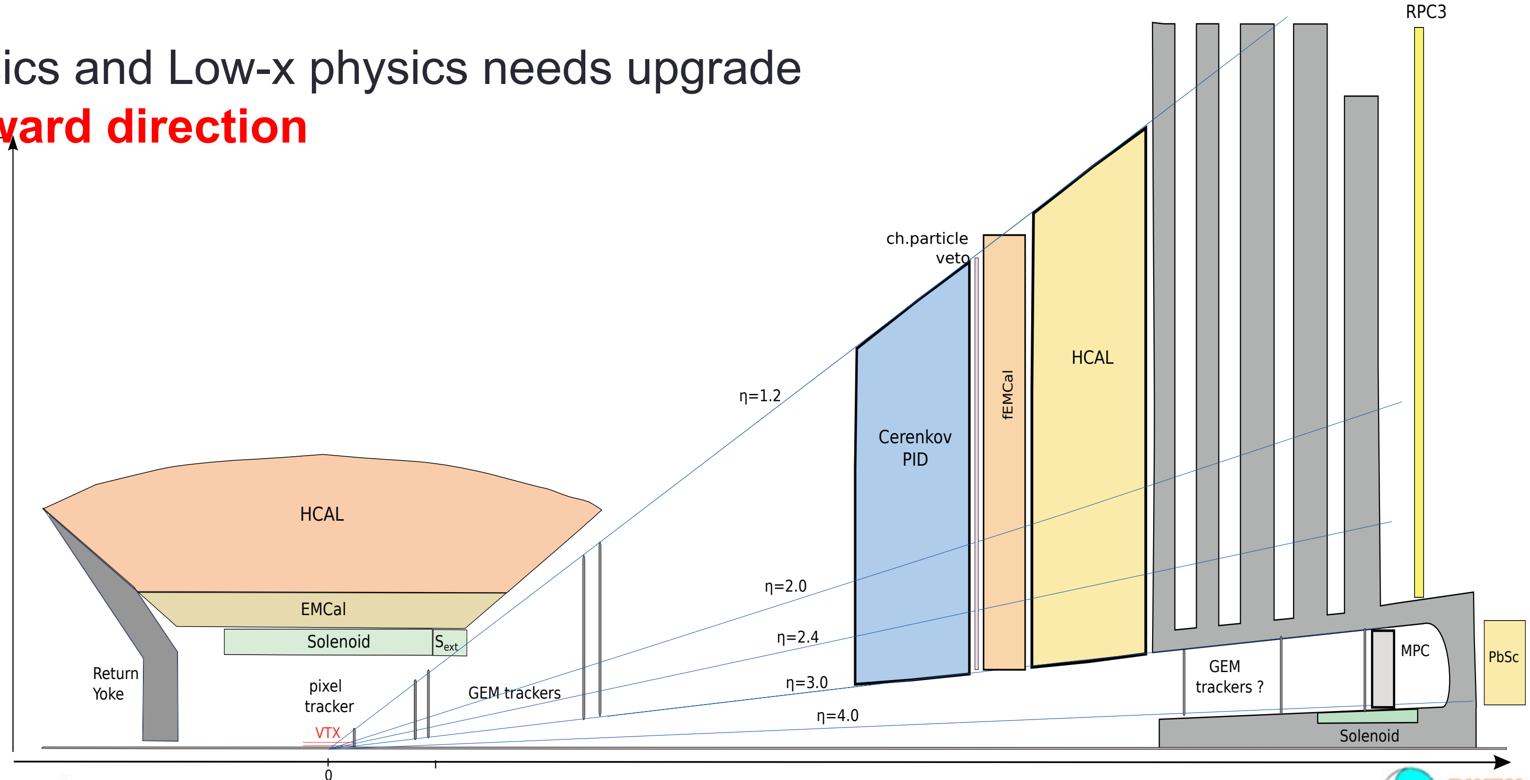
An upgrade proposal by PHENIX to BNL management

➔ Focus on central arm (jets and heavy quarks in HI collisions)

➔ BNL Review positive

Spin Physics and Low-x physics needs upgrade in the **forward direction**

Details in Joe Seele's talk

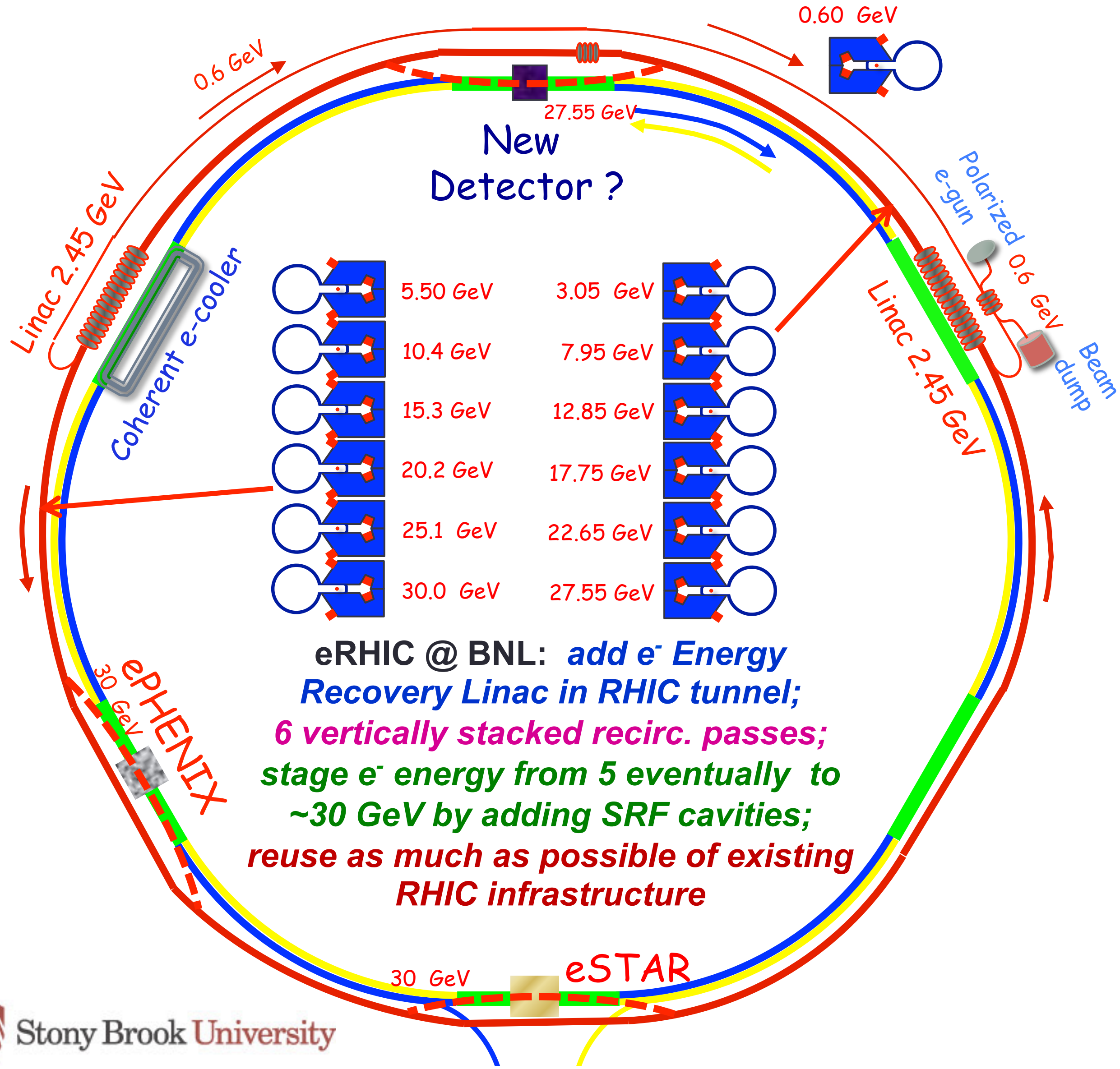


Far Future: eRHIC

Add an electron beam facility to collide with one of the beams of RHIC

Other option under consideration at Jefferson Laboratory

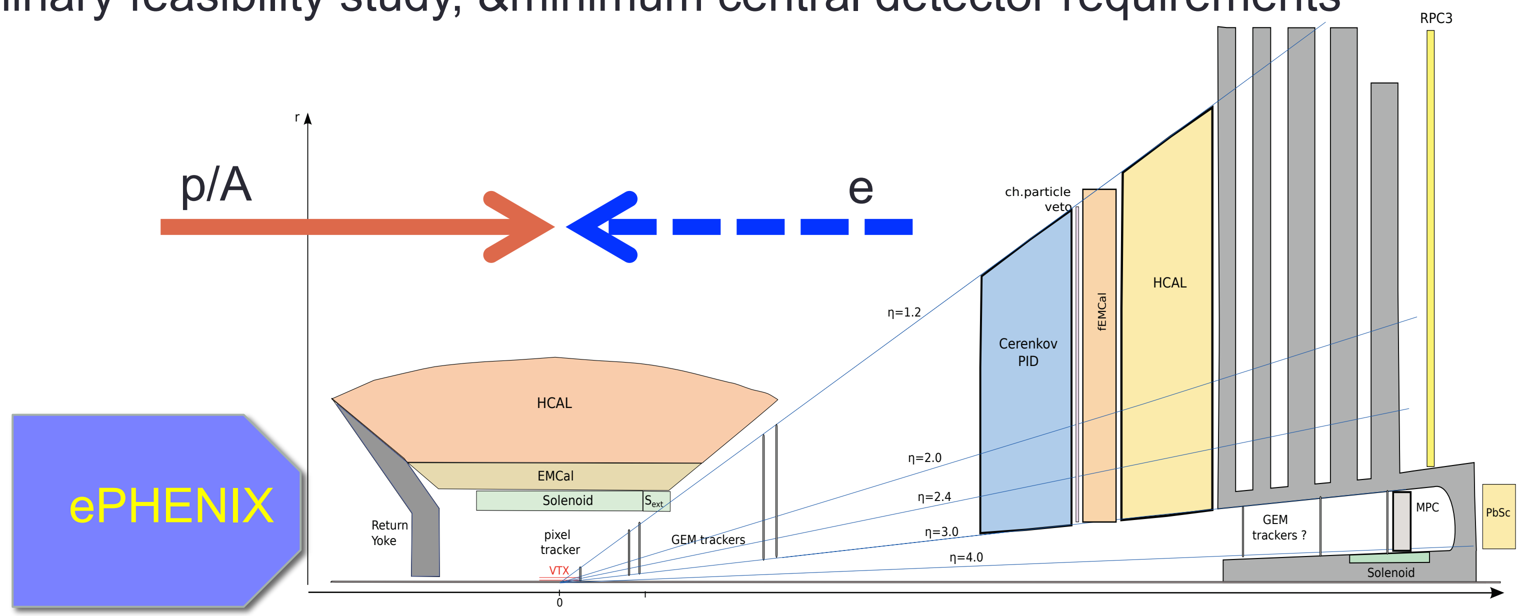
eRHIC at BNL



- Meets performance requirements & has straightforward upgrade path
- Vigorous R&D to demonstrate various novel aspects
- Stage 1 can fit in the DOE guidance
- Technical review in Aug.'11, Cost review soon

sPHENIX → ePHENIX at eRHIC

ePHENIX: sPHENIX (PID, B-field studies & tracking) + e-detection
Preliminary feasibility study, &minimum central detector requirements

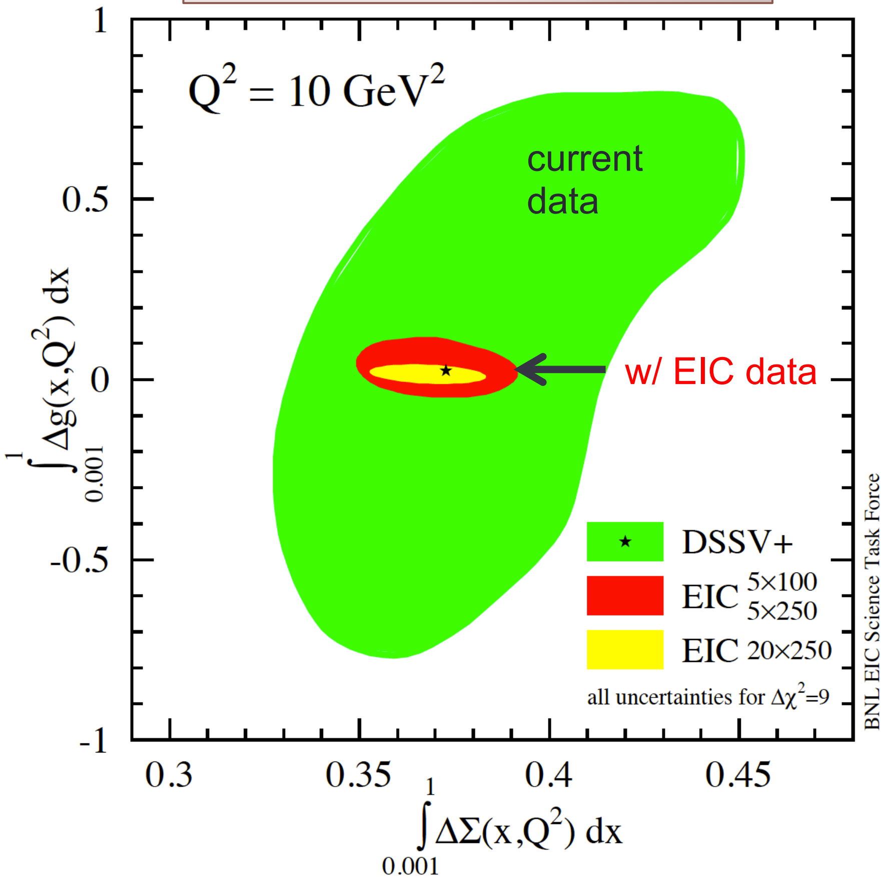


ePHENIX Task Force:
C. Aidala, K. Barish, A. Bazilevsky*, **K. Boyle, A. Deshpande (Chair)**, T. Hemmick, D. Morrison, **I. Nakagawa, Joe Seele, Ralf Seidl**, Craig Woody

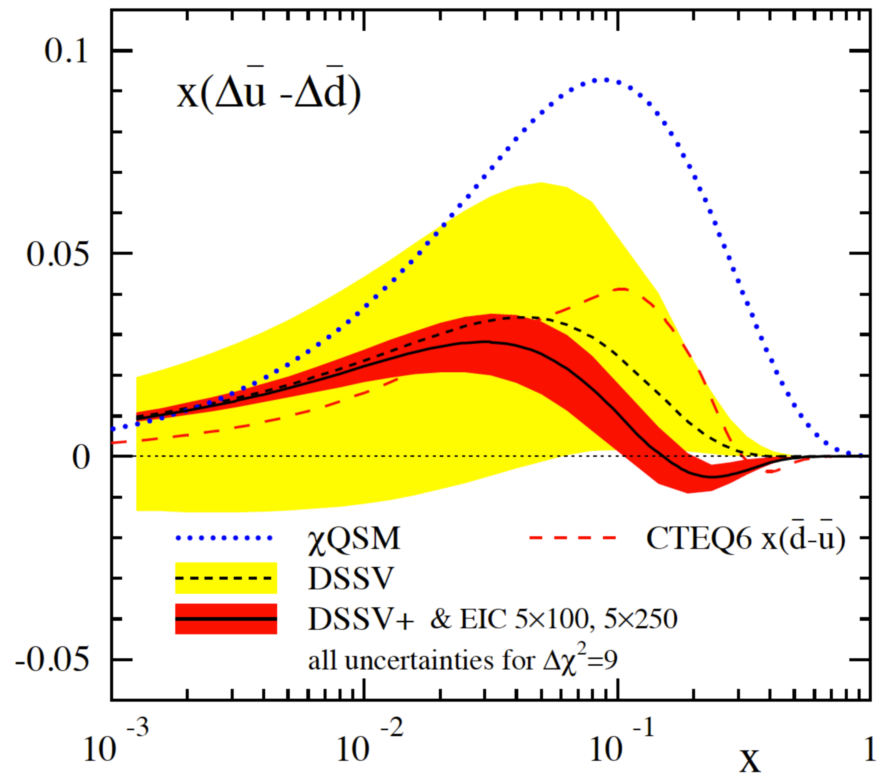
* Past RBRC Fellow

Precision: Gluon & Sea Quark *polarization:*

ΔG and ΔΣ in helicity sum
~5% measurement



Are the sea quark polarizations different?



EPJ A
Hadrons and Nuclei
EPJ.org
your physics journal

Eur. Phys. J. A (2012) 48: 92 DOI 10.1140/epja/i2012-12092-7

The Electron Ion Collider:

The QCD Frontier

Understanding the Glue that Binds us all

The EIC White Paper
Released for comments
Being Finalized by Nov. 15
Editors:
A. Deshpande, J. Qiu, Z. Meziani

US/Int Nucl. Phys. Community

EPJ A
Hadrons and Nuclei
EPJ.org
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Eur. Phys. J. A (2011) 47: 35 DOI: 10.1140/epja/i2011-11035-2

Transverse-momentum–dependent parton distri-

INT Report on EIC Science

The EIC Science case: a report on the joint BNL/INT/JLab program

Gluons and the quark sea at high energies: distributions, polarization, tomography

Institute for Nuclear Theory • University of Washington, USA
September 13 to November 19, 2010

Editors:
D. Boer
Rijksuniversiteit Groningen, The Netherlands
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R. Milner
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Universität Tübingen, Germany

550+ Authors 2011

The US EIC being prepared for the NSAC LRP

Summary

- RBRC Spin group members are significantly involved and have leadership roles in the current and future physics at RHIC:
  - PHENIX ongoing upgrades & analyses and operations *(J. Koster, recent Run Coordinator)*
  - PHENIX upgrades to sPHENIX-forward
  - RHIC upgrade to eRHIC
- We remain optimistic and enthusiastic about near and far future of RHIC as a polarized collider

Reducing systematic uncertainties: Understanding false asymmetries from beam dynamics at PHENIX

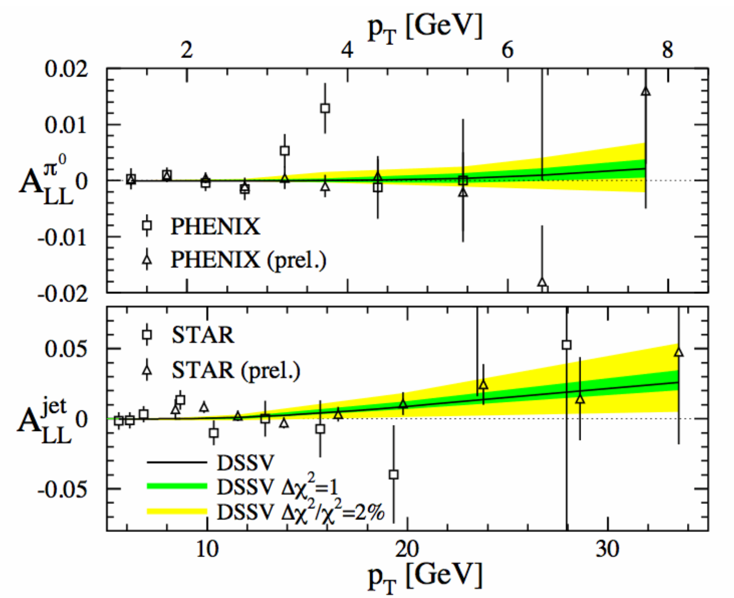
Kieran Boyle (RBRC)

*Work done with Andrew Manion (SBU)

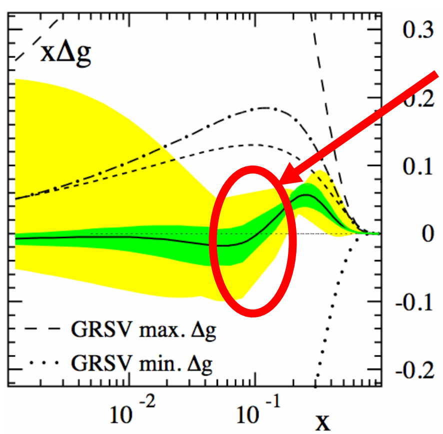
Proton Helicity Structure

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{z,q} + L_{g,z}$$

- ½ΔΣ: Quark spin contribution, ~0.15 (30%)
- ΔG: Gluon spin contribution, poorly known before RHIC
- $L_{q,g}$: Quark and gluon orbital angular momentum



+DIS
+SIDIS



RHIC region

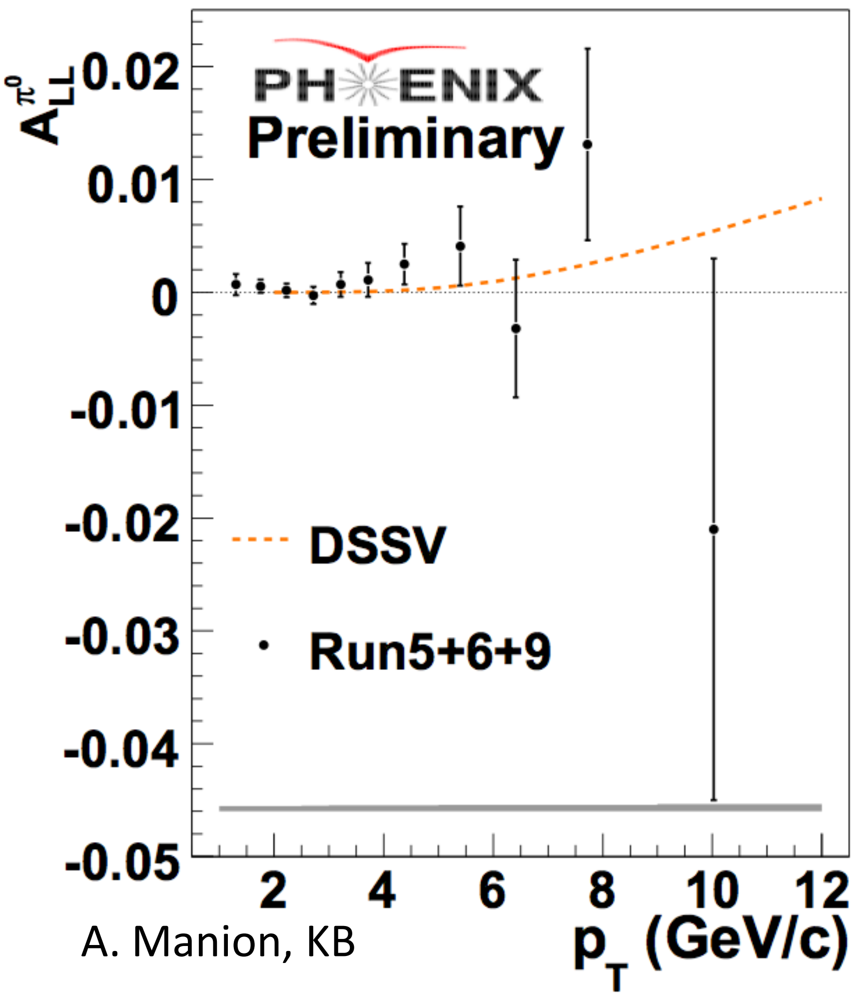
$$\int_{0.05}^{0.2} \Delta g(x) = 0.005 \pm^{0.129}_{0.164}$$

$$\int_{0.001}^{1.0} \Delta g(x) = 0.013^{+0.702}_{-0.314}$$

De Florian, et al (DSSV), PRL101:072001, 2008

ΔG~0 with **LARGE** uncertainties

Add 2009 π^0 A_{LL}



A. Manion, KB

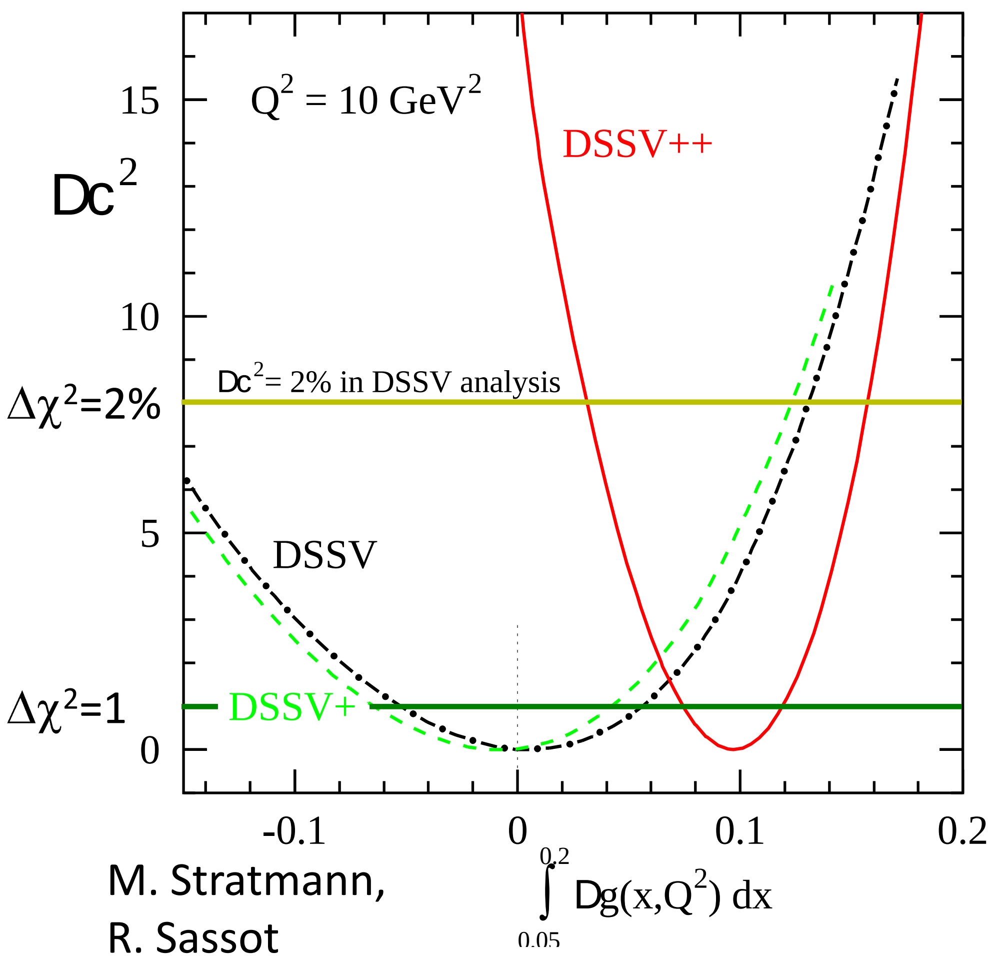
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$$= \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

$$R = L_{++}/L_{+-}$$

- With 2009 √s=200 GeV RHIC run, PHENIX above DSSV best fit
  - STAR results similarly above DSSV

Impact of Run9



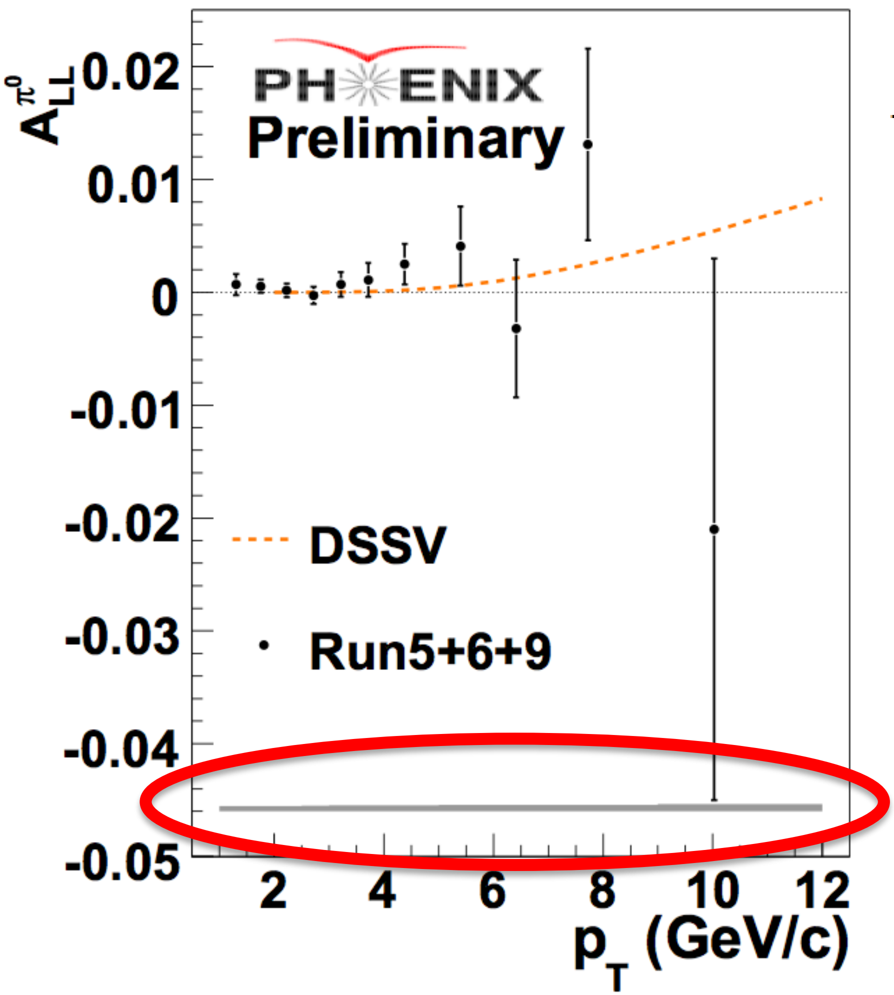
M. Stratmann, R. Sassot

- DSSV have recently redone their fit with RHIC run9 data included.
  - Greatly reduced uncertainty

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

- Simple Error treatment ignores systematic correlations:
  - Important for PHENIX and STAR Relative Luminosity uncertainties
  - Group of experimentalists working to include these properly:
    - C. Gal, P. Kline, S. Taneja, A. Deshpande, KB

Add 2009 π^0 A_{LL}



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$$= \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

$$R = L_{++}/L_{+-}$$

- Relative Luminosity in 2009 limiting uncertainty
  - Factor ~3 times stat uncertainty

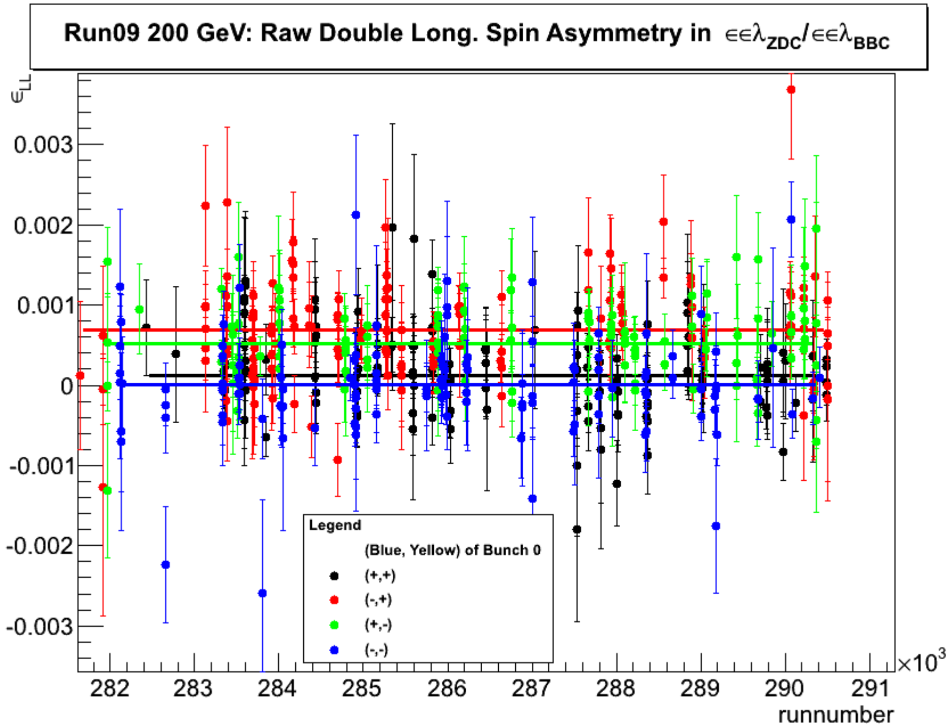
Relative Luminosity Uncertainty

- Scale by relative luminosity (RL) to account for variations in luminosity between spin combinations
- Possible sources of uncertainty on A_{LL} from RL
  - **Miscounting** due to variations from bunch to bunch
    - Rate effects affect high lumi. bunches more
    - Width variations coupled with detector smearing

    → Rate and width corrections
  - **Real physics asymmetry**

    → Find another luminosity monitor without an asymmetry
  - **False asymmetries**
    - Other asymmetry mimicking the asymmetry being studied

2009 RL Uncertainty



- Nonzero asymmetry seen, after corrections applied
  - ~ (1.2±0.2)x10^{-3}

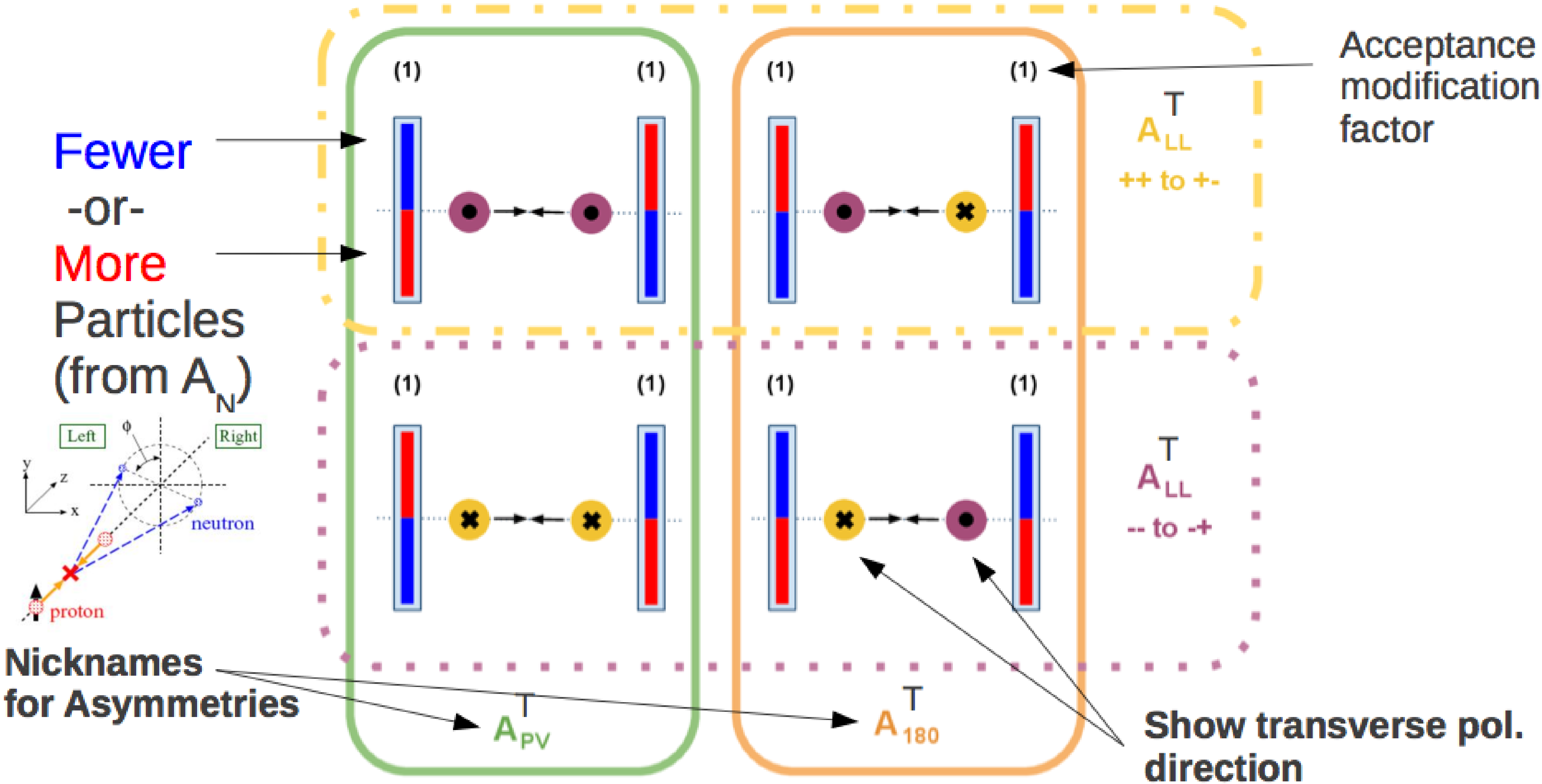
→ "Real" asymmetry?
  - Year to year results not consistent
  - Spin pattern dependence

  → Unlikely real physics A_{LL} in luminosity monitors

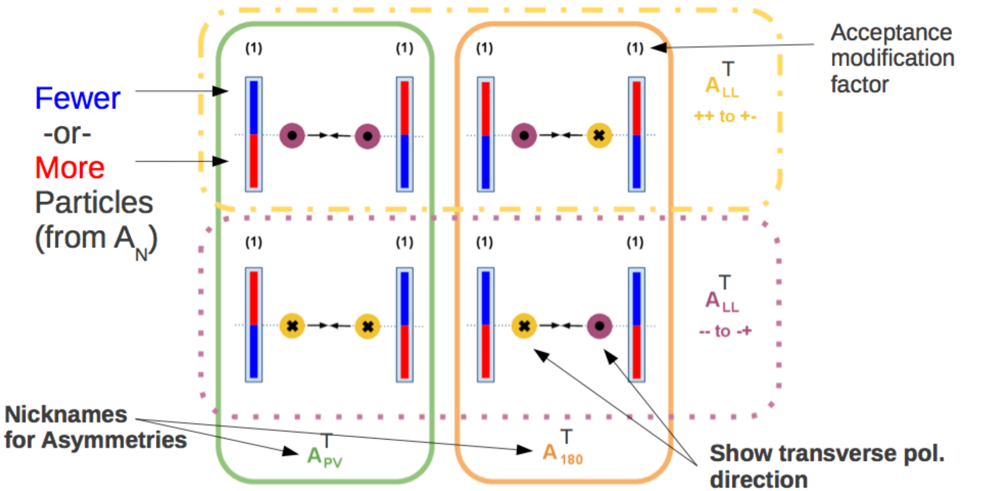
- Proposal: False asymmetry caused by transverse spin effects coupled with beam angles/offsets w.r.t. the detectors

Beam effects

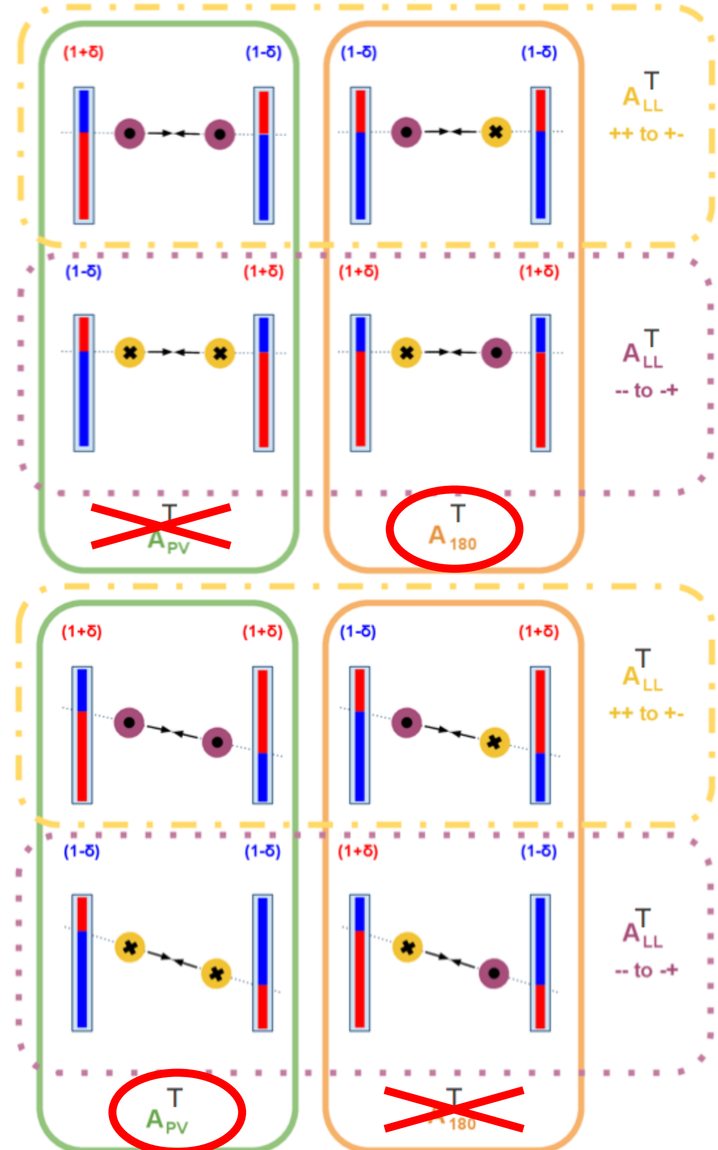
- Basic concept:



Beam effects



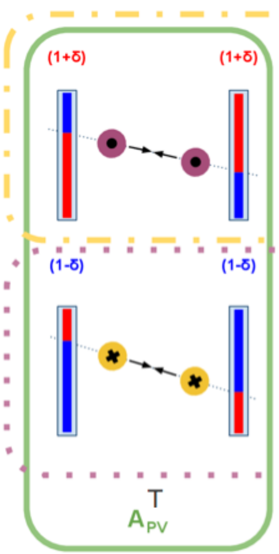
Offsets:
Big A_{180},
no A_{PV}

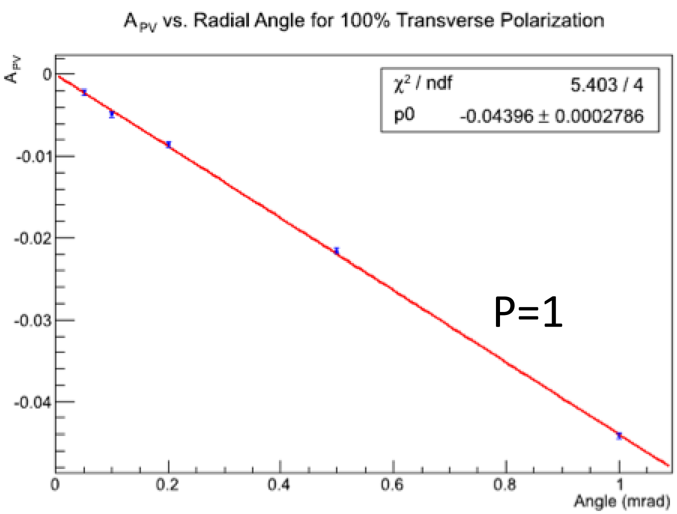


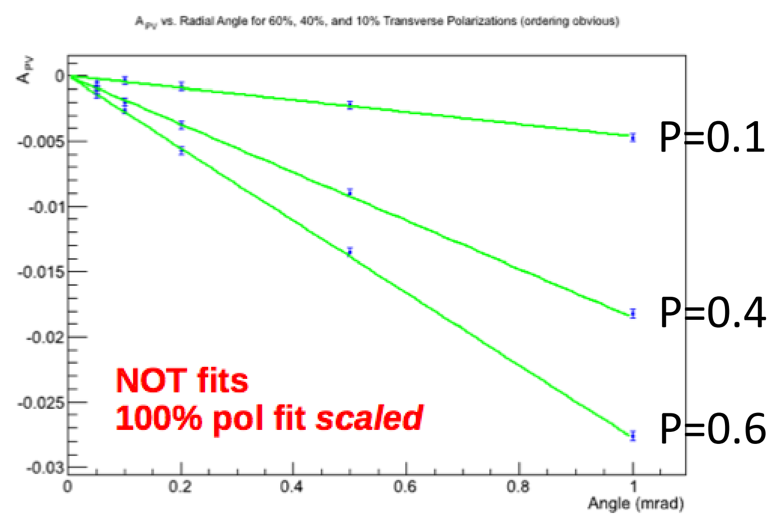
Collinea rAngles:
Big A_{PV},
no A_{180}

Toy MC

- Describe beam collision distribution based on beam paths through IR
- Generate particles based on charged particle and neutron measurements at RHIC (xsec., asym.)
- Add fiducial volume for luminosity detectors (BBC, ZDC)



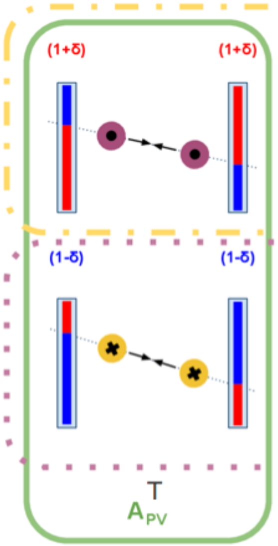


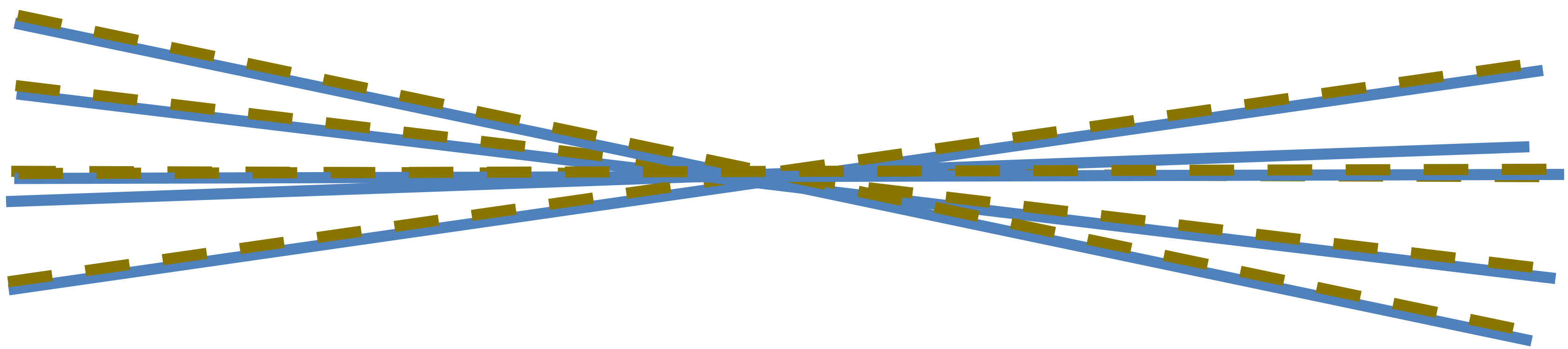


Single Spin effect: $\sim 1/p$, not $\sim (1/p)^2$

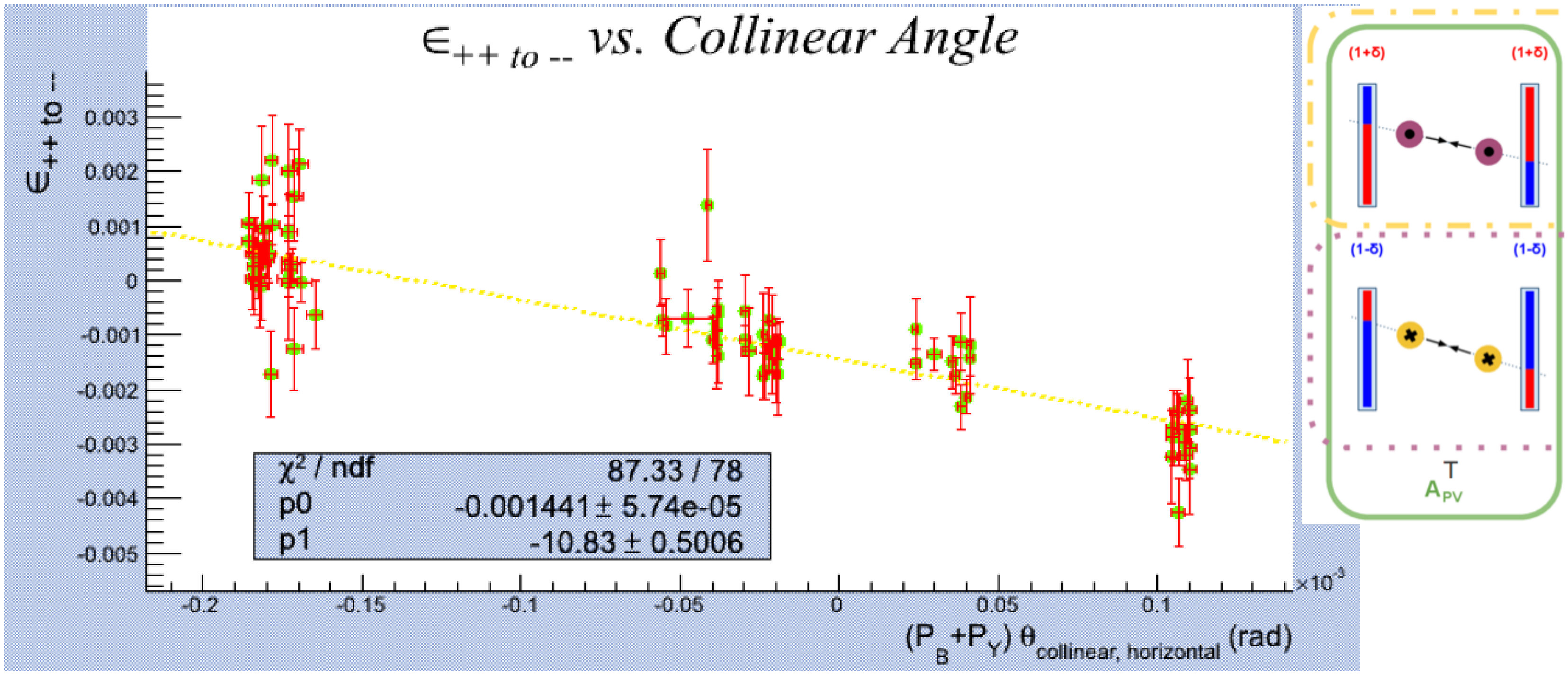
Study in RHIC: 2012

- Did Beam (Collinear) Angle Scan:
  - Use 200 GeV data with transverse polarization (reduce measurement time needed)
  - CAD changed angles of the two beams while keeping them collinear.
    1. Scan beams to get maximum collinear
    2. Measure at starting point
    3. Change angle of beams through the IR +Δθ, -Δθ
    4. Check linearity with ½Δθ.



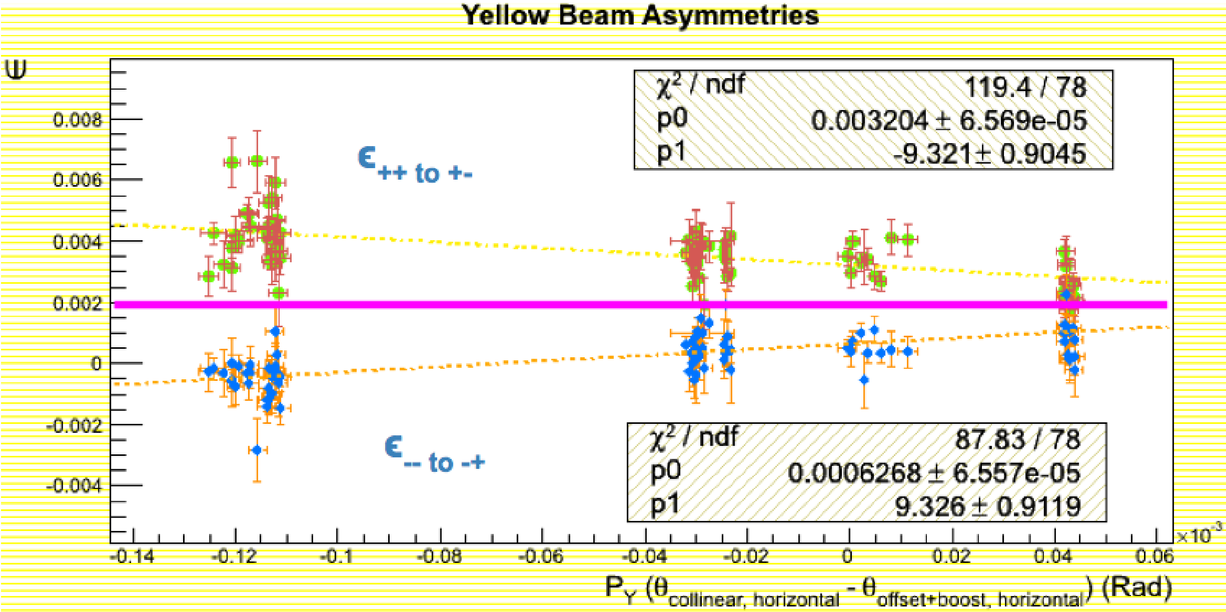


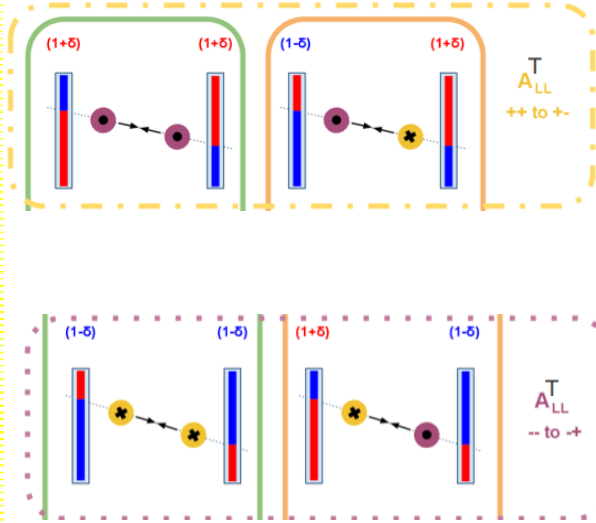
Beam Angle Study Results



- Clear asymmetry is seen as expected
  - Beam path through IR can generate false asymmetries
  - What about other asymmetries?
    - A_{180} unaffected as expected

Beam Angle Study Results

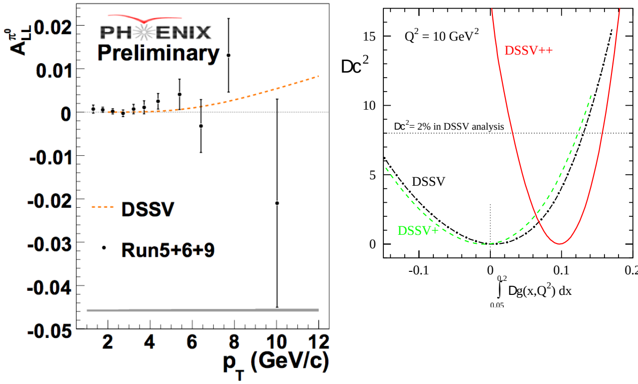


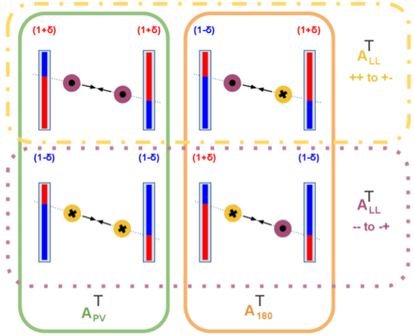


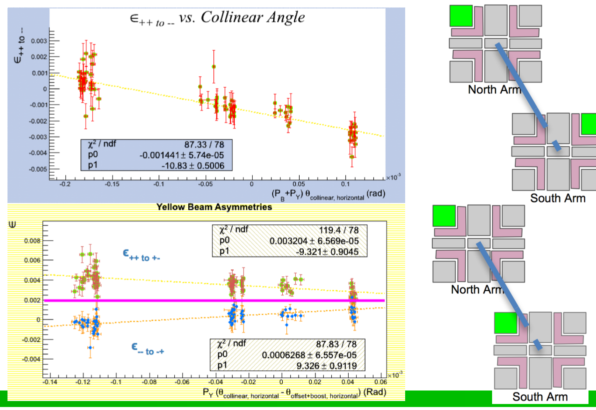
- ++ vs +-, -- vs -+
  - Expect equal and opposite slopes, which we find
  - Non-zero intercept still being studied

Conclusion

- RHIC data from 2009 including PHENIX π^0 A_{LL} significantly constrain ΔG
- 2009 measurements at PHENIX systematically limited, due to RL systematic
- Proposed false asymmetry due to angles and offsets of beam in IR
- In 2012, performed beam angle scan
  - Results show false asym. effect clearly
  - Study ongoing to explain false A_{LL}
- New detector readout in Run13 to measure offset and angle effect every run parasitically

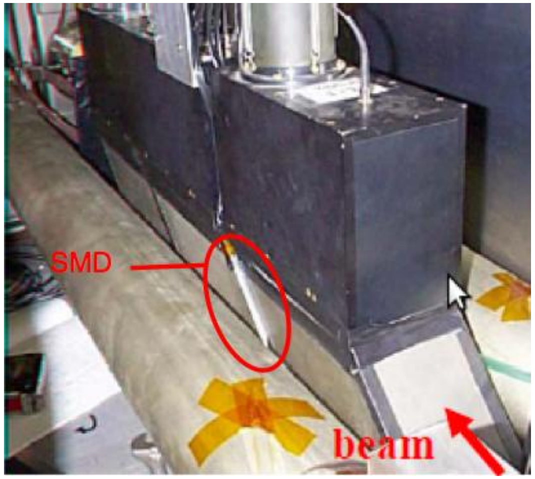


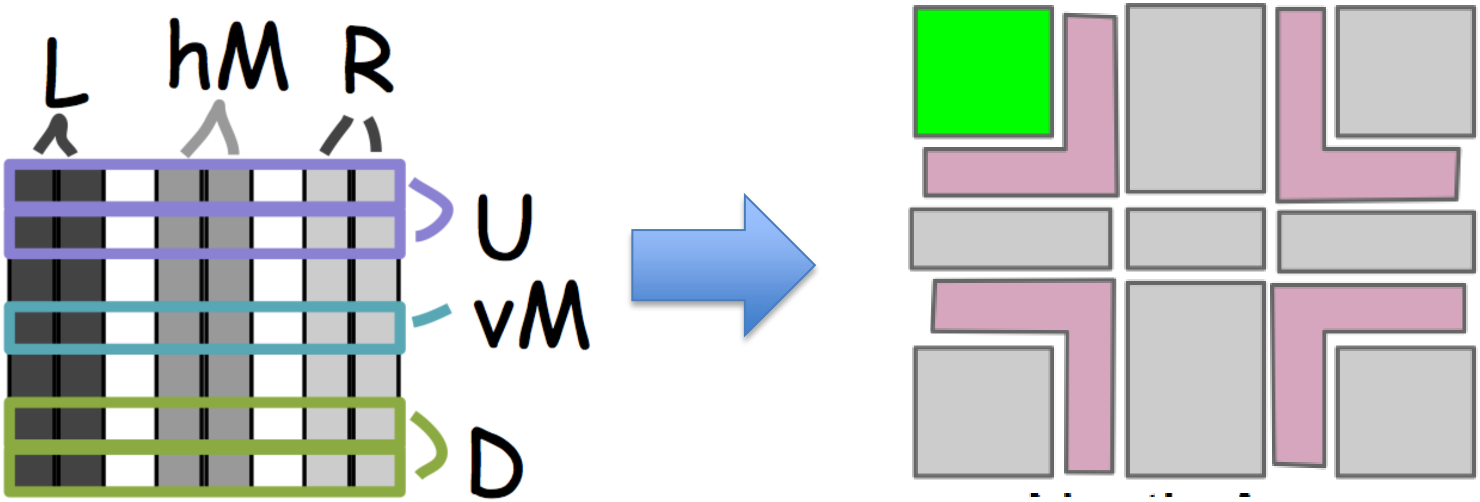




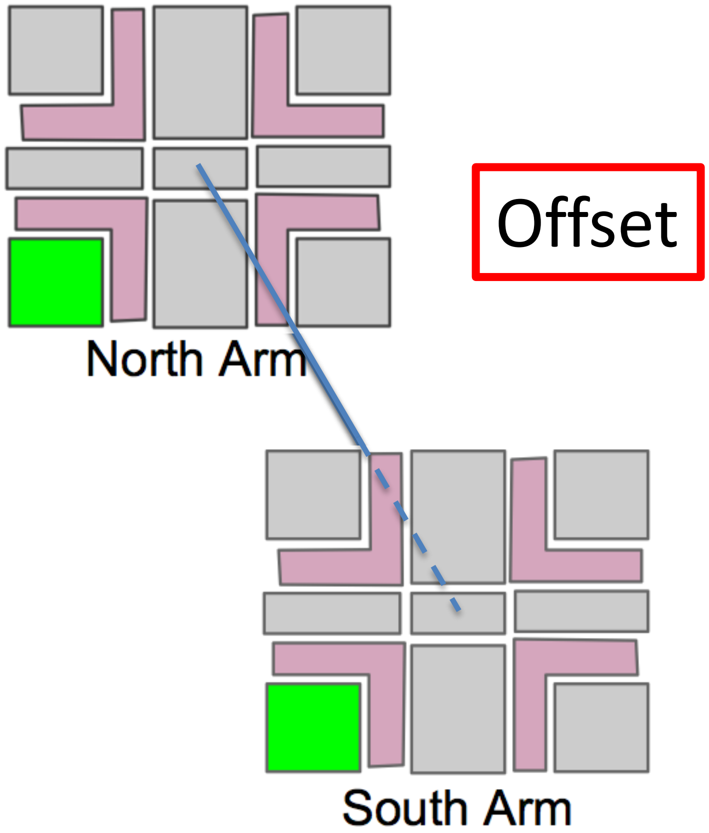
Plan for 2013

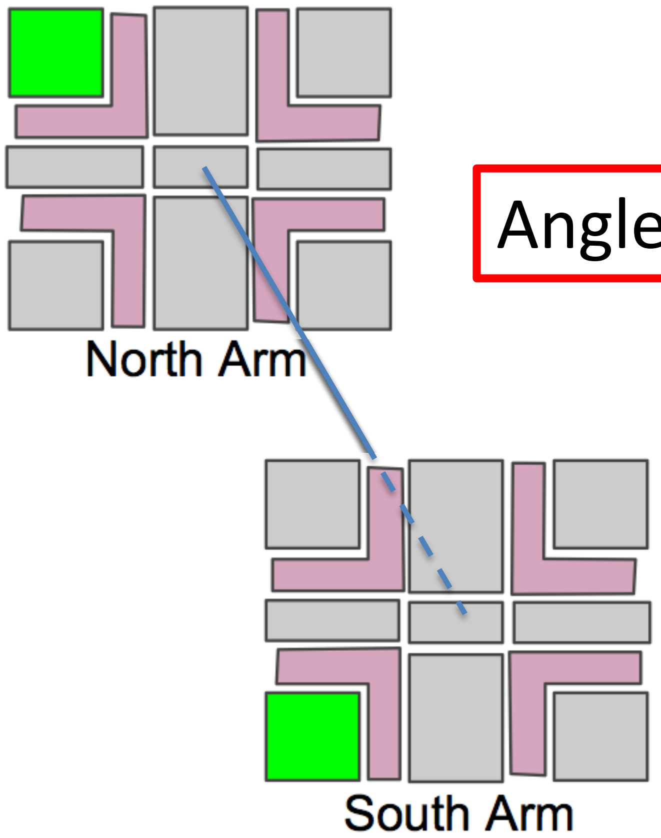
- Will be longitudinal running, making quick (1-2 fills) measurements difficult
- Another solution:
  - Segmented readout of SMD
  - Input into scalar board readout
  - Boards give all possible combinations of scalars





Multiple Angles and Offsets





- Comparing different sections is equivalent to moving beams

→ Can look at ***multiple*** angles and offsets in ***every*** run in both dimensions

The sPHENIX Forward Upgrade

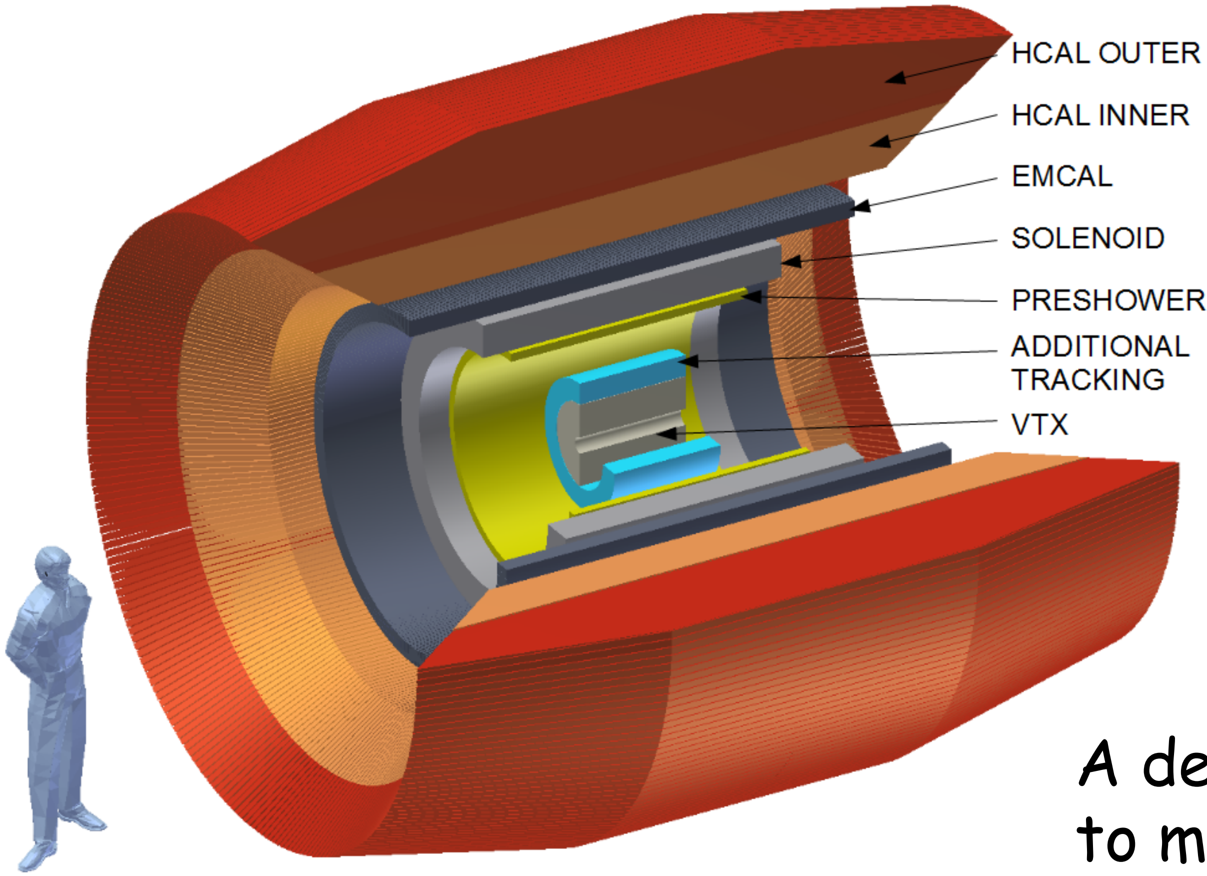
RBRC SRC

Joe Seele
(RIKEN BNL Research Center)

Duties in PHENIX

- I serve in two positions in PHENIX
  - Computing Coordinator
    - Maintain/upgrade large PHENIX codebase/software stack
    - Solve computing issues as they arise (and there are many!)
    - Highlight : Sped up PHENIX data production ~5x in the last year (largest dataset can be produced in < 2 weeks, p+p in 3 days)
    - Currently : Working to automate access to large datasets to increase analysis throughput of collaboration as well as exploring different technologies/platforms for information storage and retrieval (both data and collaboration knowledge)
  - Forward sPHENIX working group convener
    - Working to develop a strong physics case
    - Designing a detector for the physics that can also be used for ePHENIX (working with Stony Brook student on GEANT simulations)
    - Current physics case : The rest of this talk

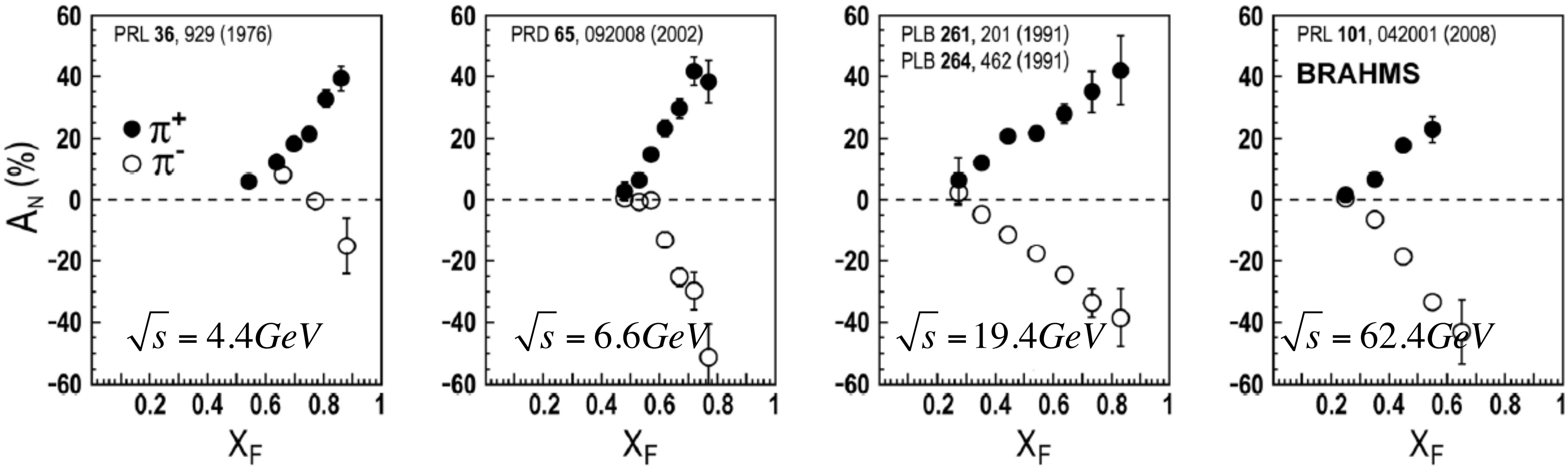
sPHENIX



A detector optimized to measure jets and dijets in heavy ion collisions, but it will make the current muon arms useless.

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

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

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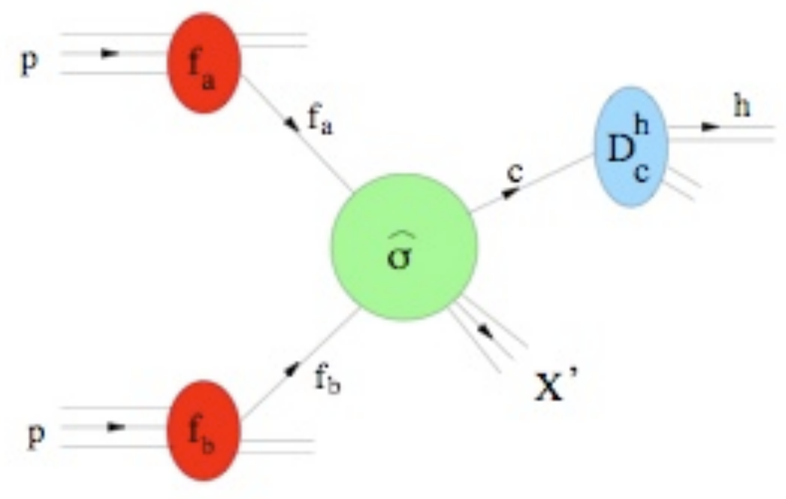
Forward Spin Physics - II



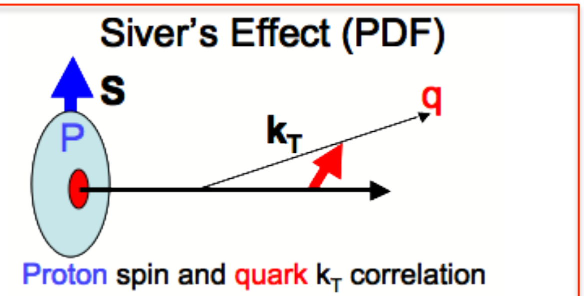
Since the mid to late 90's new extended factorization schemes (TMD and Twist-3) have provided a new mechanism to generate single spin asymmetries in these collisions.

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

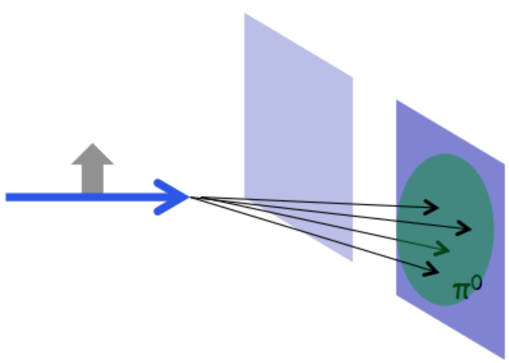
$$A_N \sim (\text{Initial State Piece}) + (\text{Final State Piece}) + (\text{h.o.t.})$$

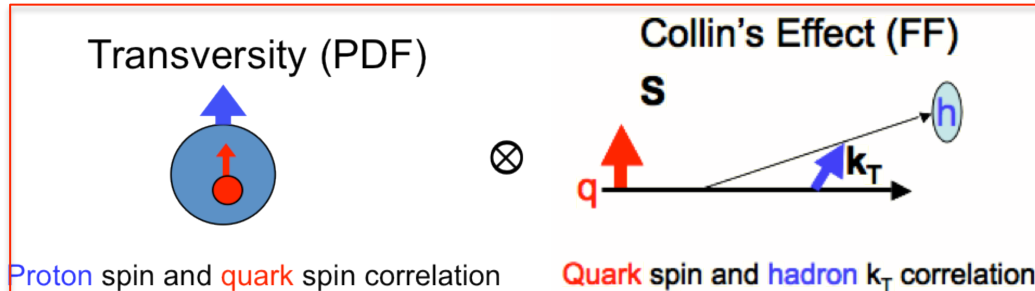
Forward Spin Physics - III

- Source of large SSA seen at RHIC uncertain
- May be Sivers, Collins, or some combination
  - ➜ Need to make measurements to separate them

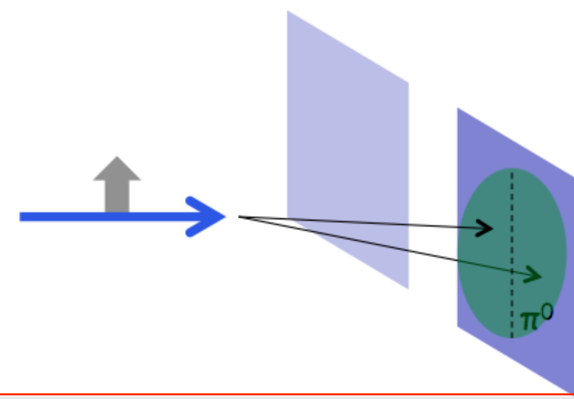


Signature is Jet Asymmetry

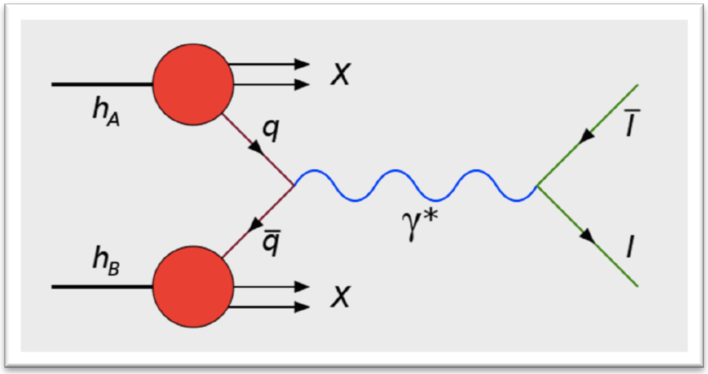


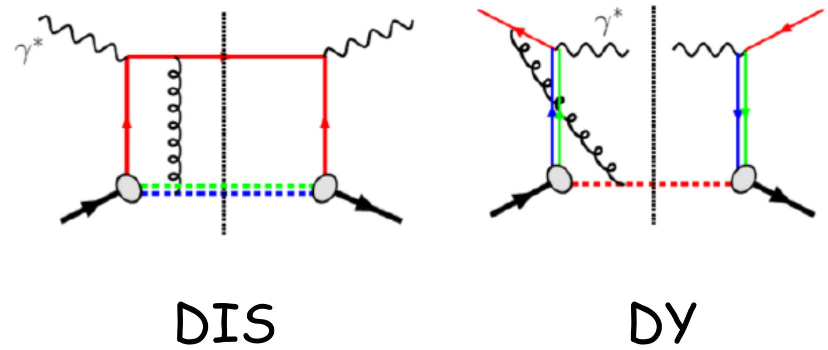


Signature is Hadron Asymmetry about jet axis



Forward Spin Physics - IV



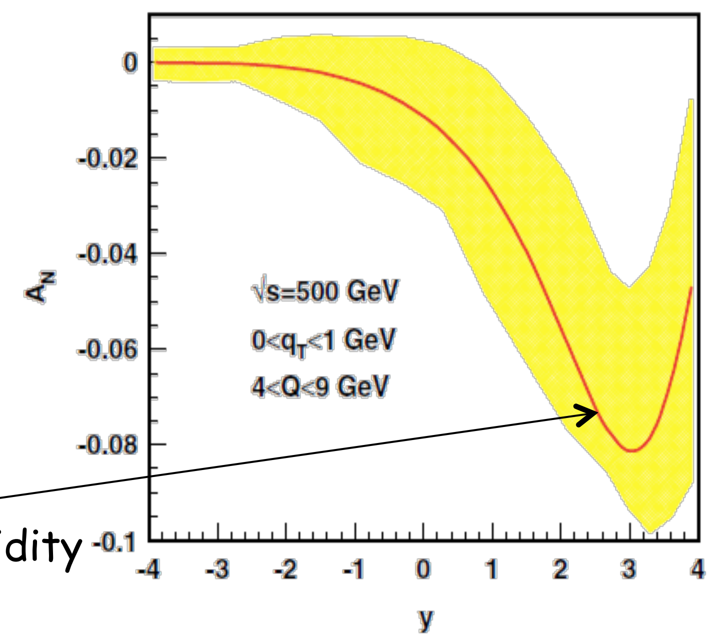


There is a prediction that the Sivers function measured in DY should be opposite that measured in SIDIS.

$$(\text{Sivers})_{SIDIS} = -(\text{Sivers})_{DY}$$

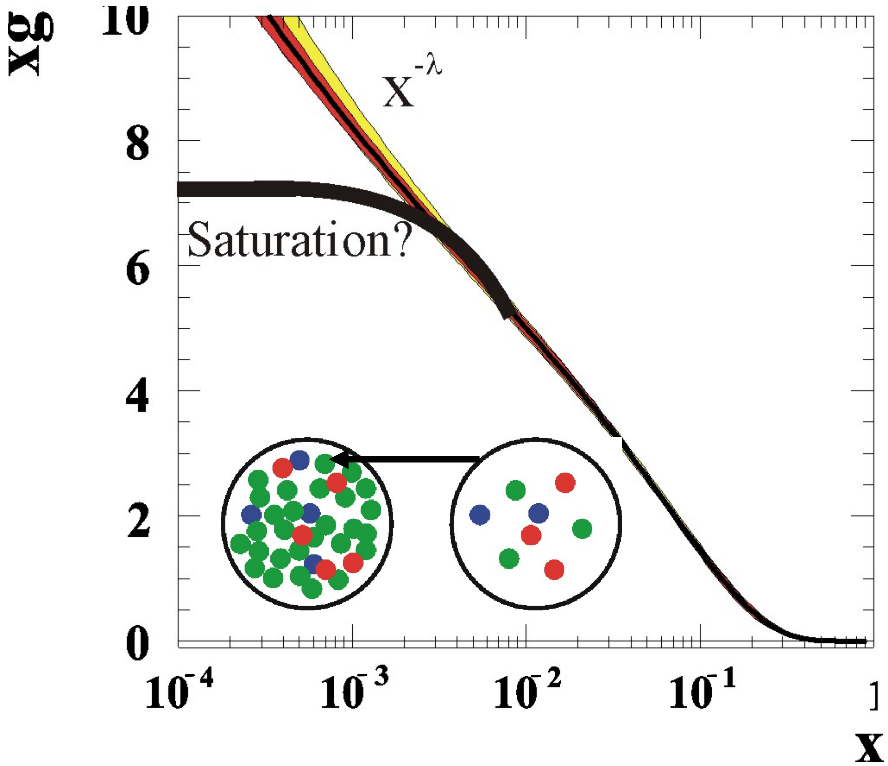
DY is a very clean process. The A_N is directly related to the Sivers function as there is no uncertainty/smearing due to fragmentation.

BUT, all the interesting asymmetry is at large rapidity



Forward CNM Physics - I

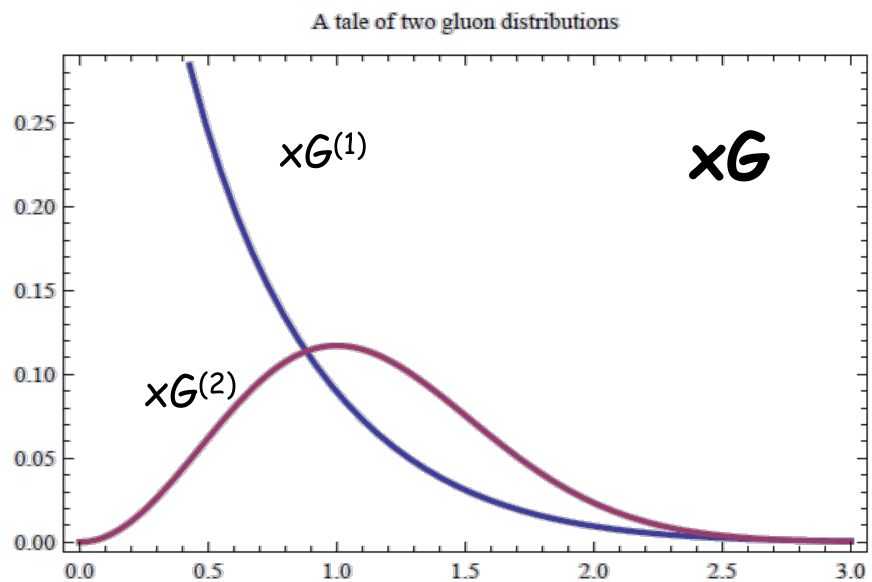
- The forward region also corresponds to the low-x region where saturation is expected (below a scale Q_S) and/or a CGC description of the data is relevant
- As in other QCD related phenomena, many measurements will be needed to substantiate and understand the validity of a CGC as the description of gluons in the nucleus.
- A single unified framework should be able to explain phenomena seen both at RHIC and the LHC.



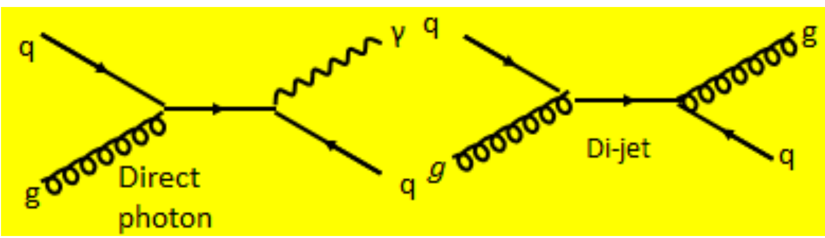
A major push is to observe saturation experimentally, and understand and map out the x and saturation scale, Q_S, dependencies

Forward CNM Physics - II

- G now comes in two flavors $G^{(1)}$ and $G^{(2)}$ in the low-x limit
- All CS described using $G^{(1)}$ and $G^{(2)}$
- Measure G's via γ-jet, dijet



q_T^2 / Q_s^2



PRD 49, 2233, 3352
NPB 529, 451

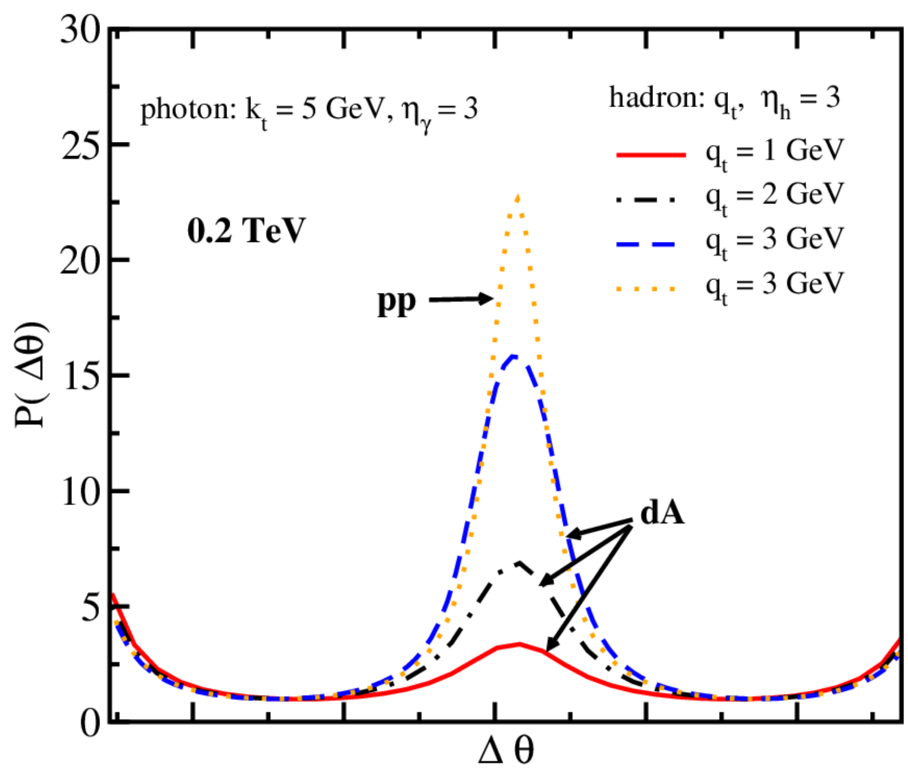
	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$G^{(1)}$ (WW)	×	×	×	×	√	√
$G^{(2)}$ (dipole)	√	√	√	√	×	√

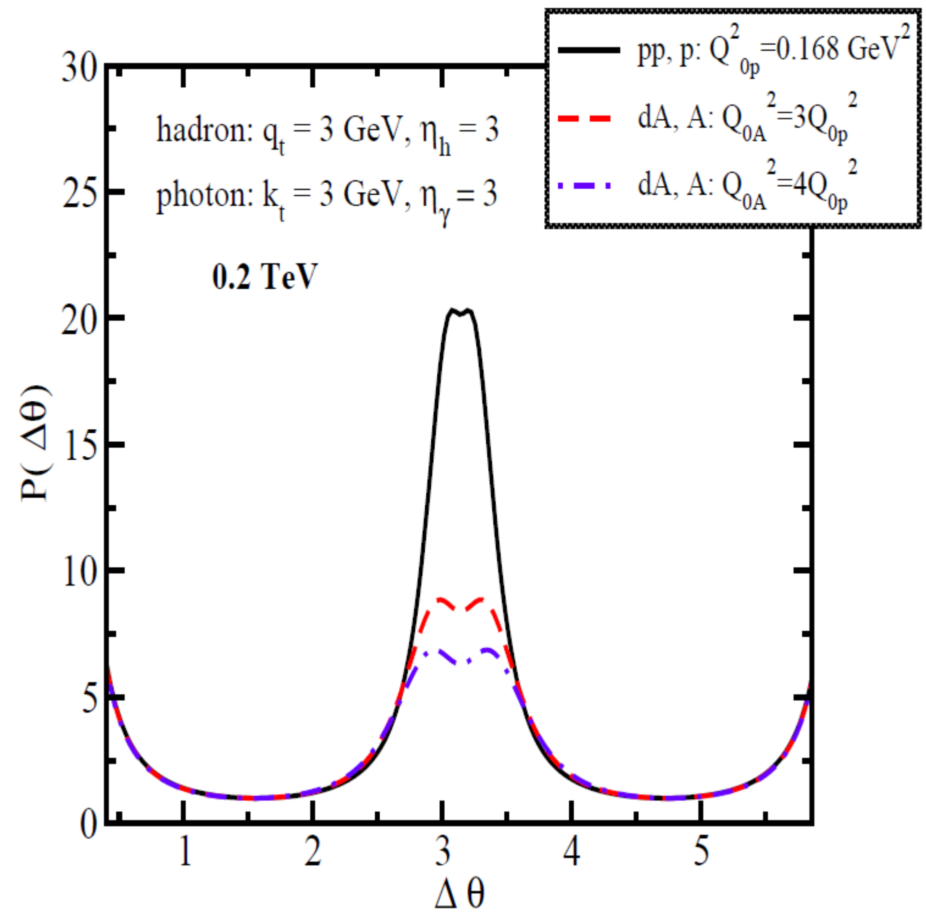
Both real and virtual (DY) photons

Forward CNM Physics - III

STAR has already observed suppression of the away side peak in the forward region in d+Au collisions

Q_S via direct photon+hadron correlations (DY also), in pA, pp





Rezaein, jalilian-Marian

A Link Between CNM and Spin

RHIC is unique in its ability to collide polarized protons with nuclei

Exploiting the link between the TMD and CGC framework, it has been shown that transverse single spin asymmetries in polarized p+A collisions are sensitive to the saturation scale in the nucleus

$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h << Q_s^2}{\approx} \frac{Q_{s,p}^2}{Q_{s,A}^2} f(p_T^h) \qquad \frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h >> Q_s^2}{\approx} 1$$

[Kang, Yuan, PRD84 034019]

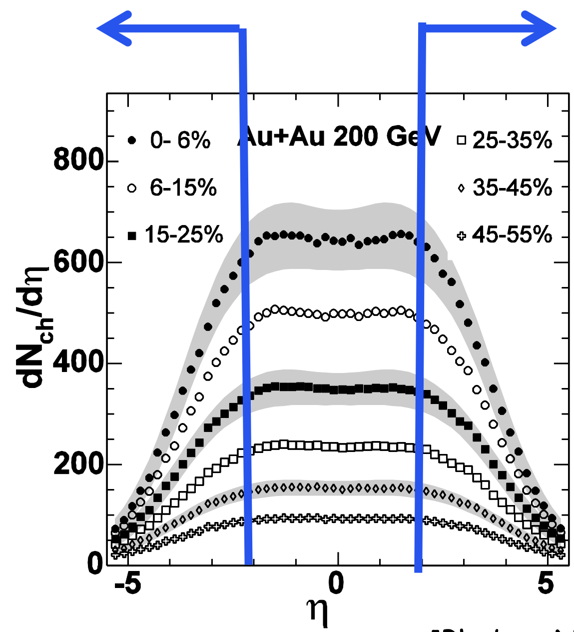
A_N measures the azimuthal modulation of particle/jet production with respect to the proton's spin

These spin effects are large. Spin "R_{AA}" could be ~O(0.5)

Forward Heavy Ion Physics

An area largely pioneered by PHOBOS and BRAHMS. We hope to expand upon their measurements (away from Bjorken plateau)

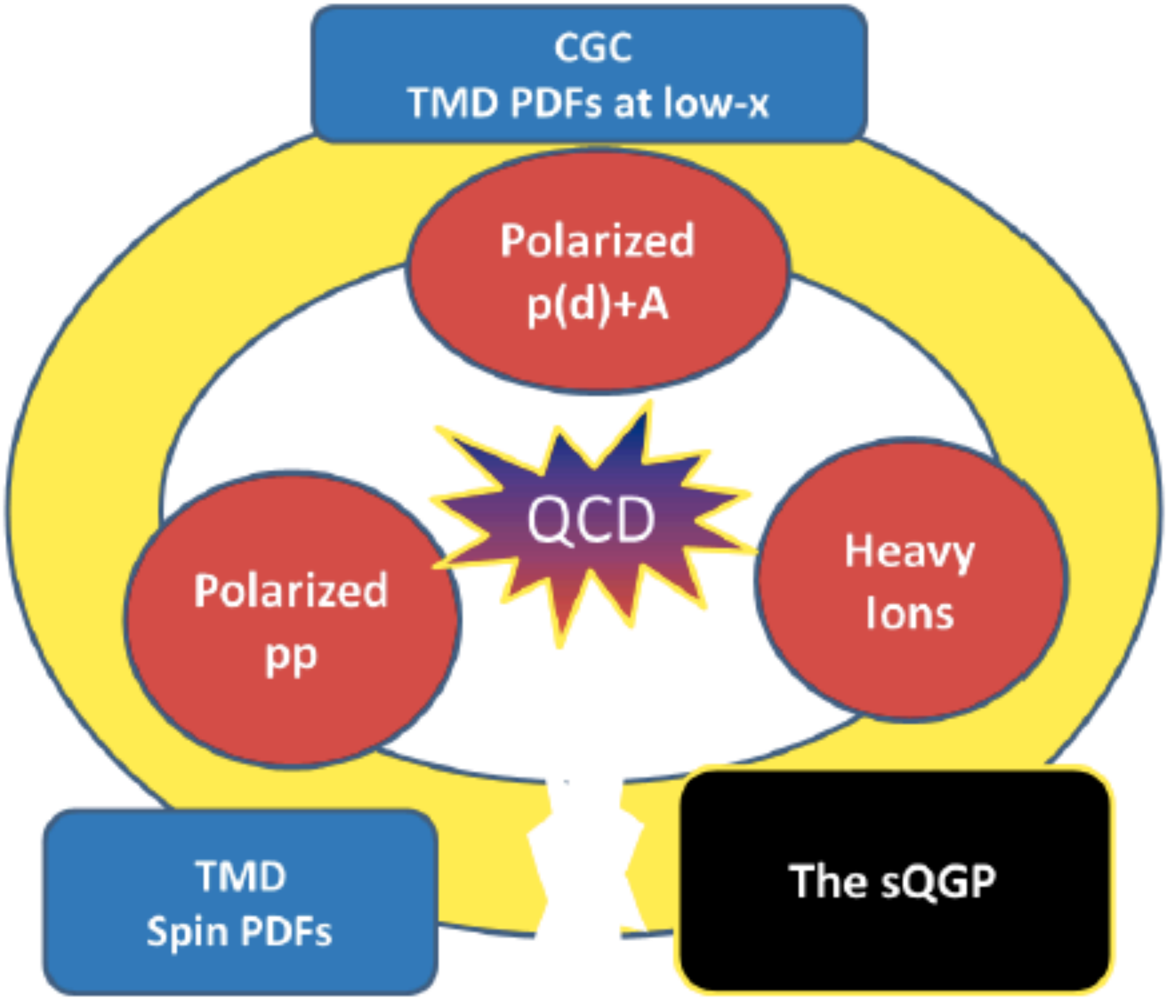
At forward rapidities
- Direct photons can give information about the expansion of the medium
- Correlation measurements can test models of longitudinal expansion (3d hydro)
- Extended (di-)jet coverage to study jet energy loss in the medium



[Phobos NPA 757]

Currently it is question of how far forward the measurements will be able to be made

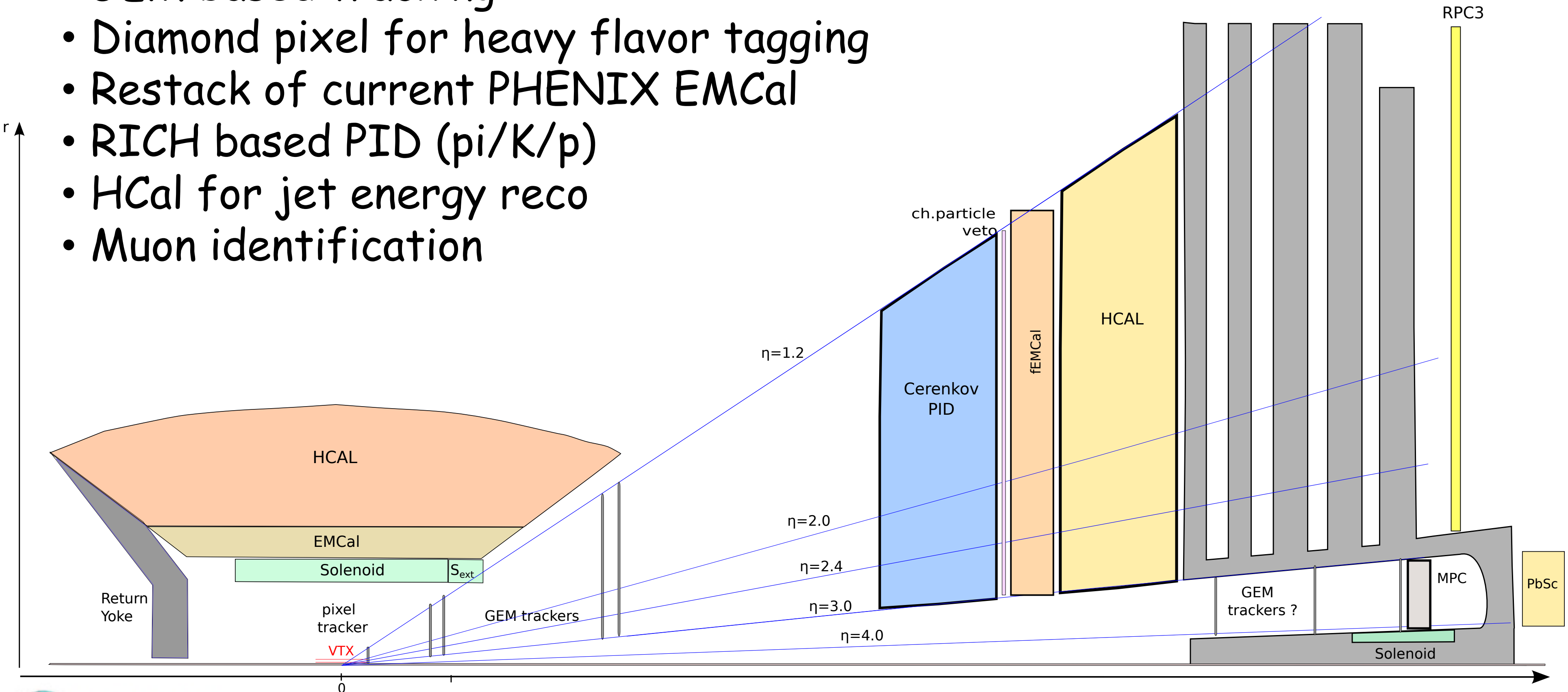
Physics at RHIC



Forward sPHENIX

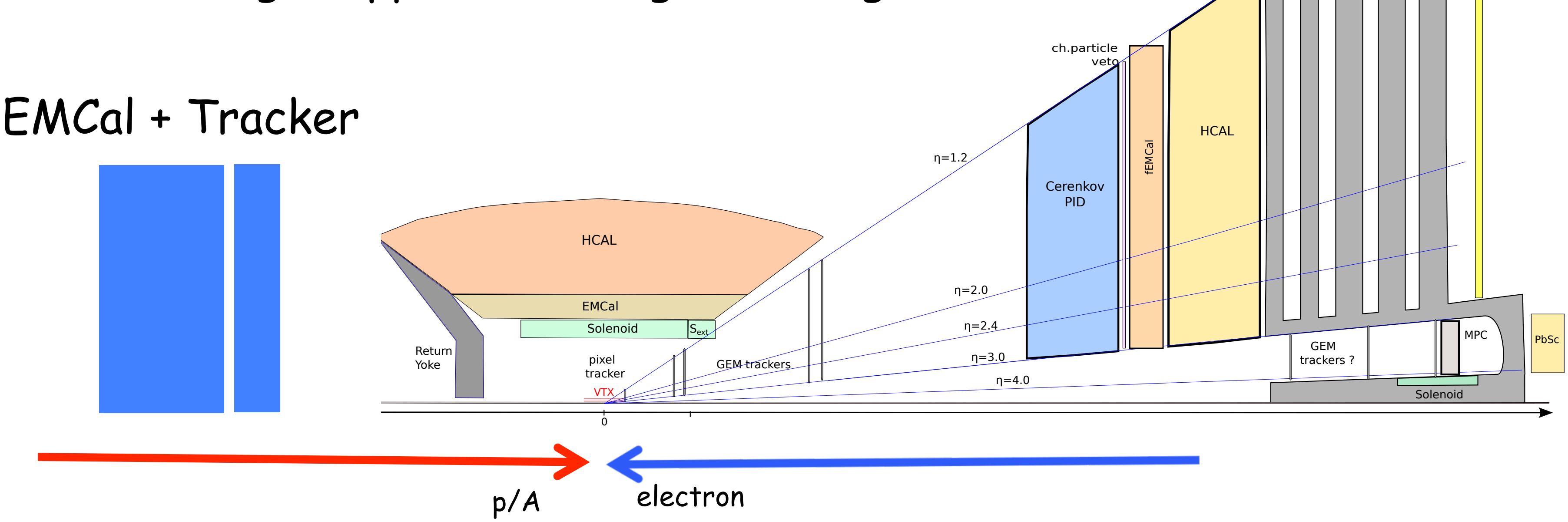
Optimized for jets and photons/DY over a large range in rapidity (η~4)

- Extension/modification of the central solenoid for B field
- GEM based tracking
- Diamond pixel for heavy flavor tagging
- Restack of current PHENIX EMCal
- RICH based PID (pi/K/p)
- HCal for jet energy reco
- Muon identification



sPHENIX to ePHENIX

- Many studies were done to test the central barrel design for the phase I of eRHIC (electron beam momentum <= 10 GeV) [arXiv:1207.6378] and the current designs appears to be good enough



- Forward sPHENIX is being designed with ePHENIX in mind
- A forward EMCal + tracker on the opposite side will need to be added for ePHENIX

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Conclusions

- PHENIX is embarking on an ambitious suite of upgrades
- There is much to do that can only be accessed by going to the forward direction.
- Forward sPHENIX is being designed and optimized to study forward jets, photons and DY
- Sensitivity studies are ongoing
- An evolution of sPHENIX to ePHENIX is being planned for in the design of sPHENIX

SPIN Measurement with FVTX

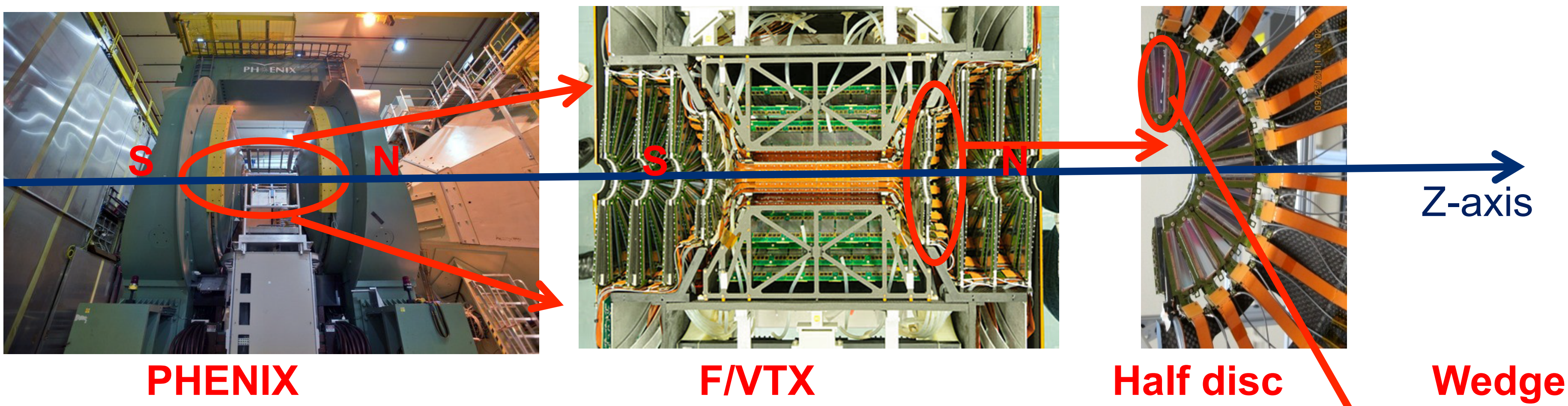
Xiaorong Wang
NMSU/RBRC

- **Introduction**
- **FVTX status**
- **Open Heavy Flavor Single Spin asymmetry**
- **Forward *W* Background Reduction with FVTX**
- **Summary and Outlook**

Introduction

- **2012 Fall: Assistant professor, New Mexico State University and RBRC Fellow**
- **Previous work**
  - Muon Arm data analysis
  - FVTX simulations
- **Physics interest**
  - Single spin asymmetry through heavy-flavor channel (J/Ψ, open Heavy Flavor)
  - Deduct W background using new installed FVTX
- **NMSU/PHENIX group**
  - Senior Faculties: Steve Pate and Vasili Papavasilliou
  - Students: Abraham Meles: W background
    Darshana Perera: Drell – Yan A_{LL}
    Joengsu Bok: b and c separation
  - Postdoc: Feng Wei

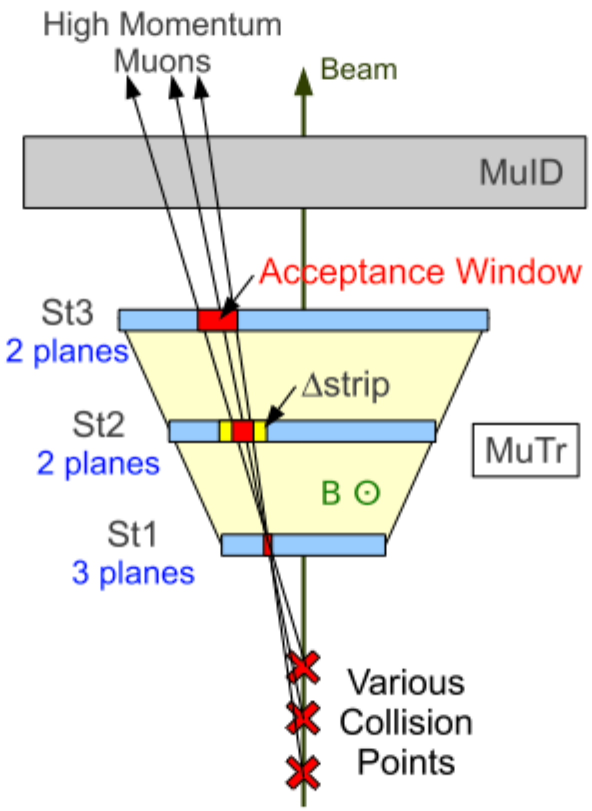
Forward Silicon VerTeX Detector (FVTX)



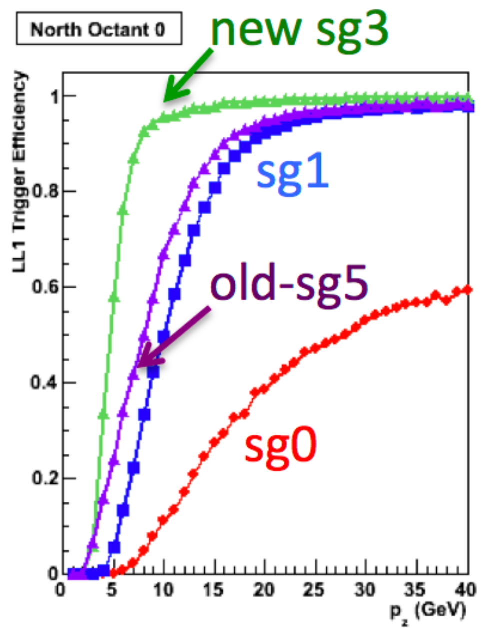
- FVTX has N and S arms. Each arm contains 4 discs perpendicular to the beam axis. located at 18.5 cm < |z| < 38 cm.
- Each disc contains 48-"wedges" made of Silicon mini-strips.
- 1.1 Million strips (75 µm radial, 3.75° staggered in φ).
- It covers 1.2 < |η| < 2.4, 2π in φ
- Completed in 2011.
- 90% of detector is operational in 2012 (*p-p, U-U, Cu-Au*)
- 510 GeV *p-p* 3.3 billion events

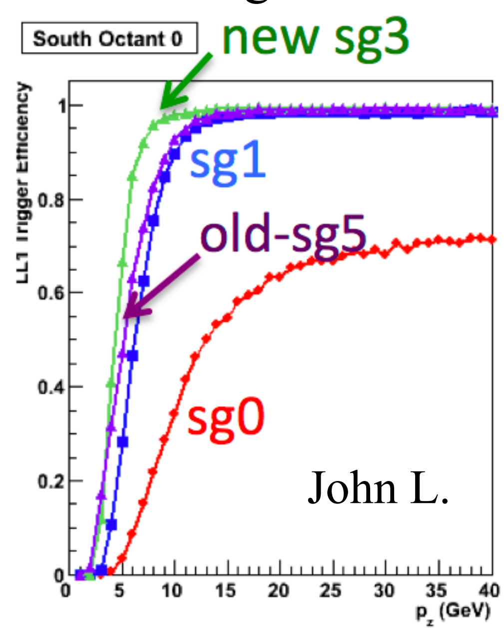
NM STATE UNIVERSITY RIKEN BNL Research Center

HF SG3 Trigger Development for Run12



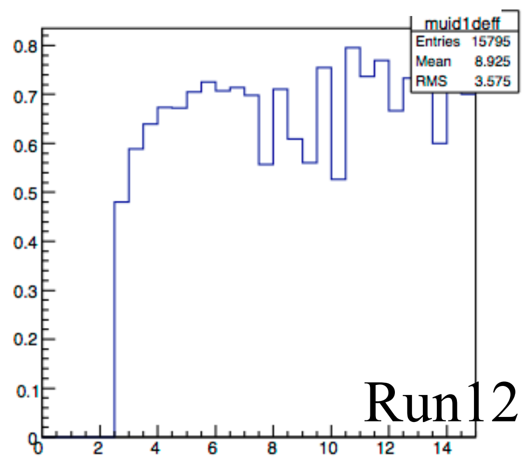
X. Jiang and X. Wang

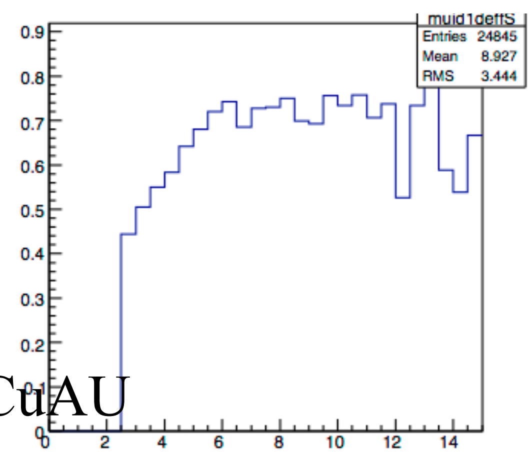




North SG3 &&MuID

South SG3 &&MuID





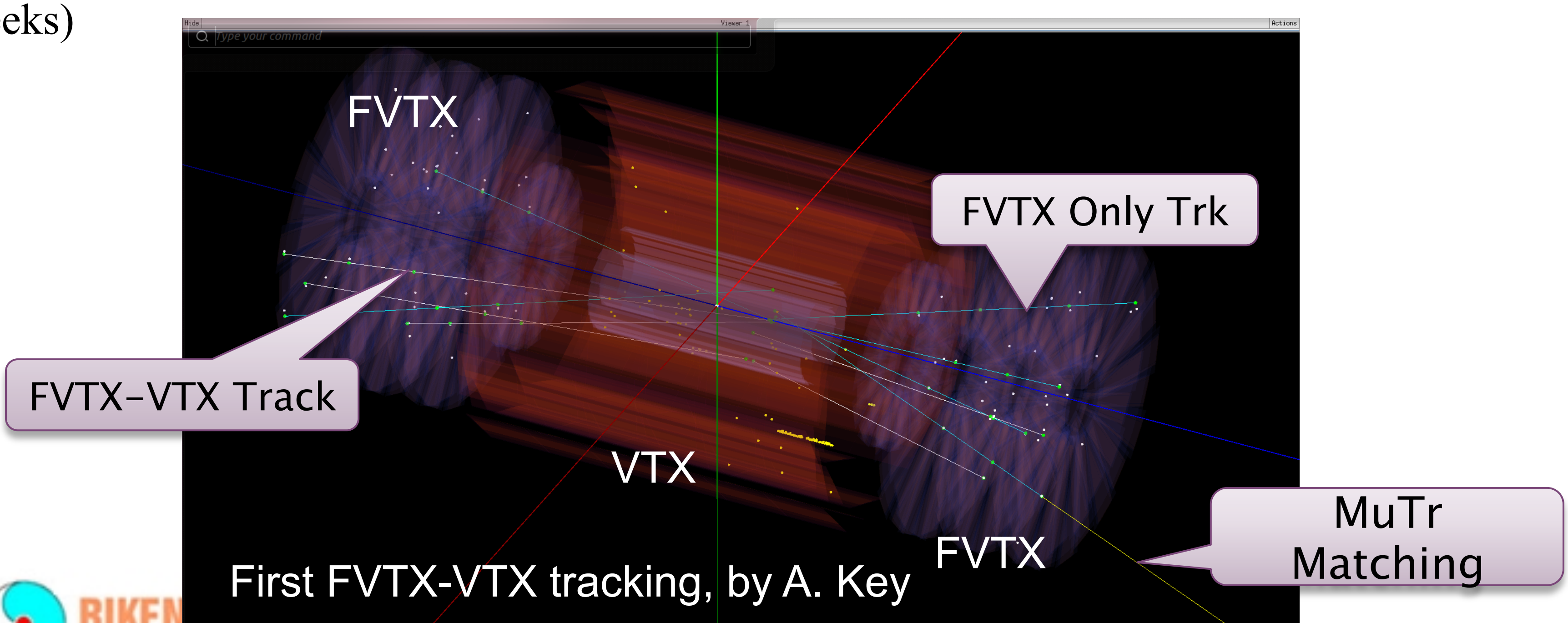
Run12 CuAU

Good efficiency achieved.
Further improvement of rejection factor needed.
(combine with RPC1)

FVTX software workshop

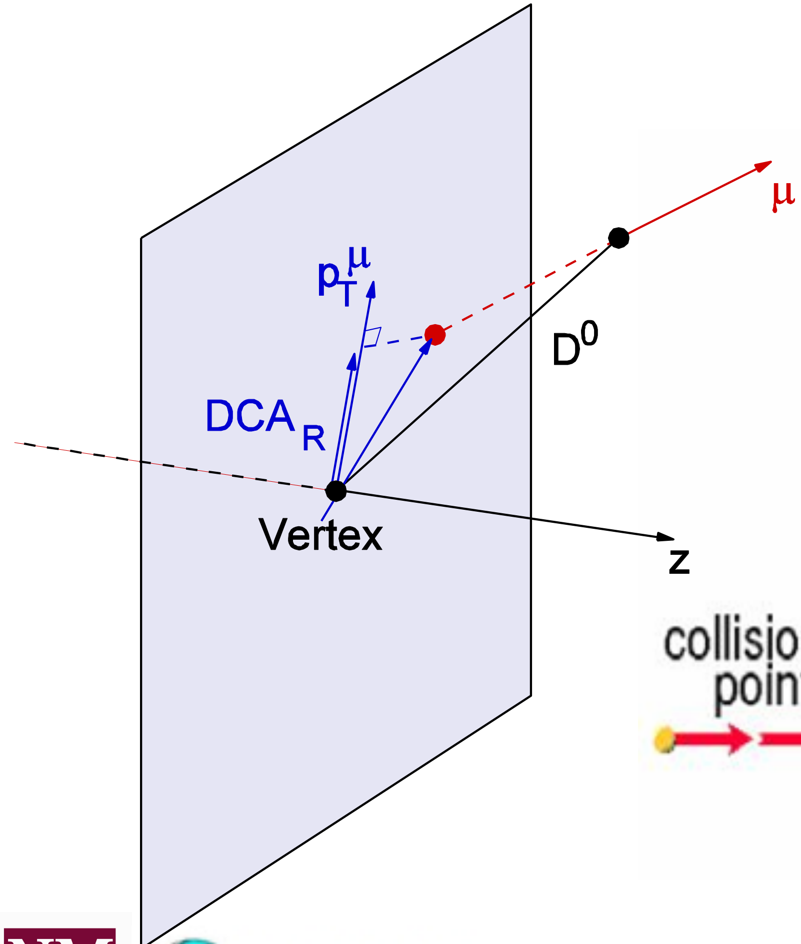
(October 29-31, 2012 NMSU)

- **Reconstruction software is ready**
  Includes: Decoder/Clustering/VTX-FVTX joint tracking/Kalman filter/ (F)VTX – MuTr joint fitting
- **nDST framework is ready**
  need to save simplified version of all FVTX tracklets ~5trks/event (a few weeks)
- **Dead/hot channel map (a few weeks)**
- **Geometry alignment in Run12**
  FVTX self-alignment is ready
  VTX-FVTX-MuTr global alignment is in progress
- **Joint VTX-FVTX vertex finding**

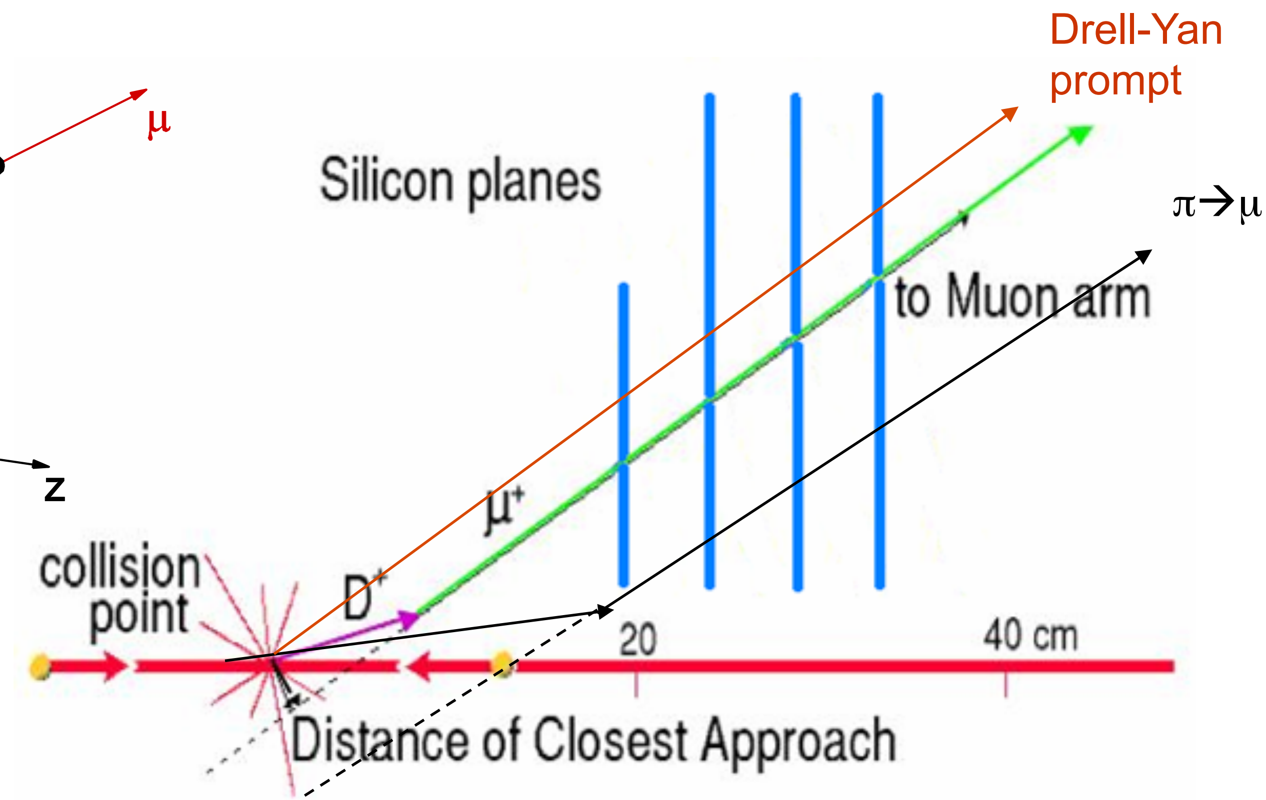


FVTX Improve Forward Muon Probes

Projected reconstructed vertex onto reconstructed p_T

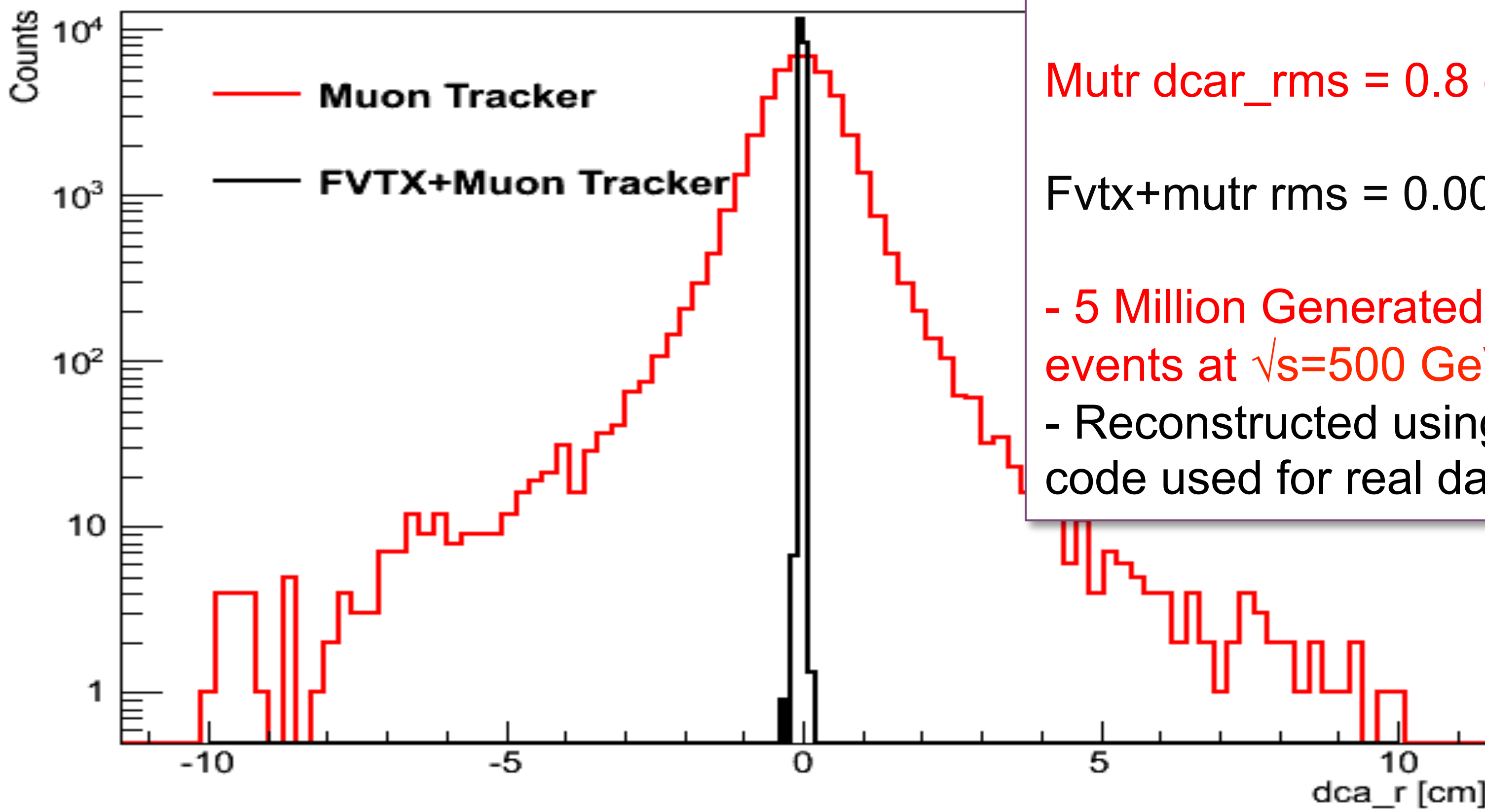


- Charm/Beauty Measurements
- Drell-Yan, J/ψ …
- *W/Z*



Improved DCA_R Measurement

Abraham Meles, X. Wang



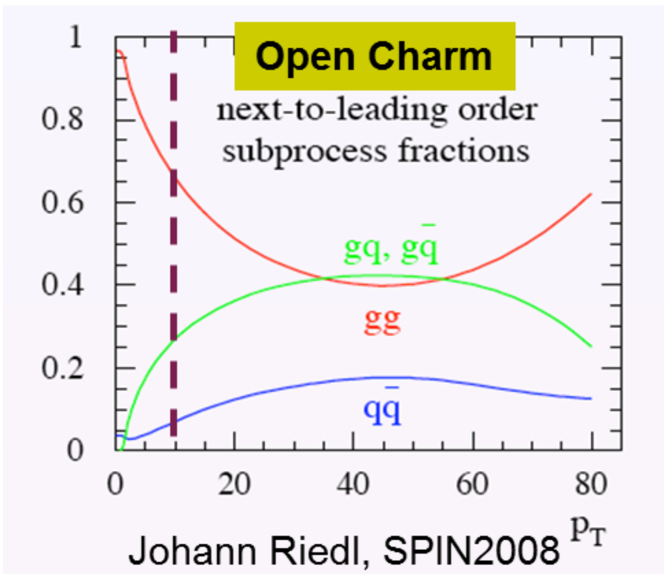
Mutr dcar_rms = 0.8 cm

Fvtx+mutr rms = 0.006 cm

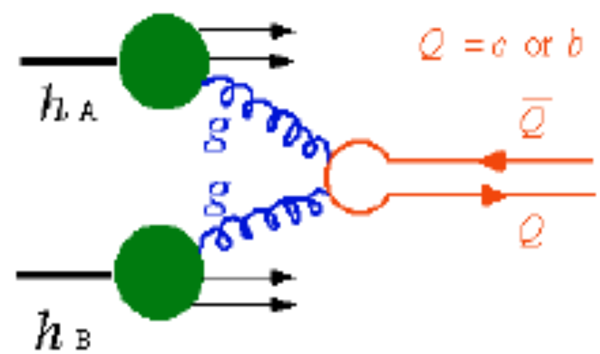
- 5 Million Generated single muon events at $\sqrt{s}$=500 GeV *p-p.*
- Reconstructed using the actual code used for real data.

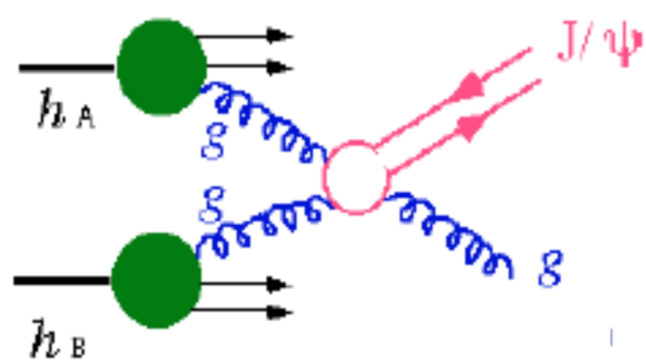
Heavy Flavor TSSA (J/Ψ and OHF)

- Gluon fusion dominates at NLO



Gluon Fusion





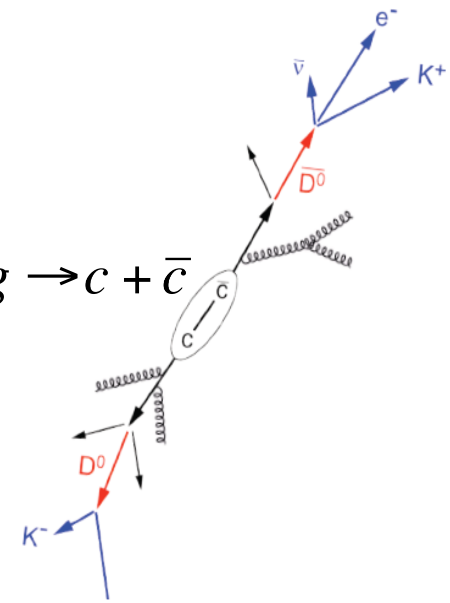
- Gluon Sivers in TMD framework

- Twist-3 Tri-gluon correlation function

Heavy Quark TSSA at RHIC
Twist-3 tri-gluon correlation funs

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right) \frac{1}{\tilde{u}}$$
$$\times \left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \right) \hat{\sigma}^{N1} \right].$$

$g + g \to c + \bar{c}$

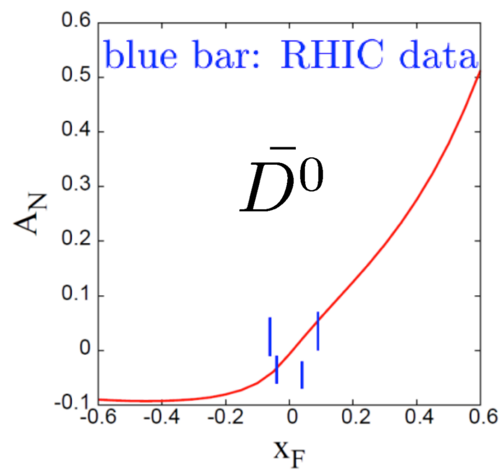


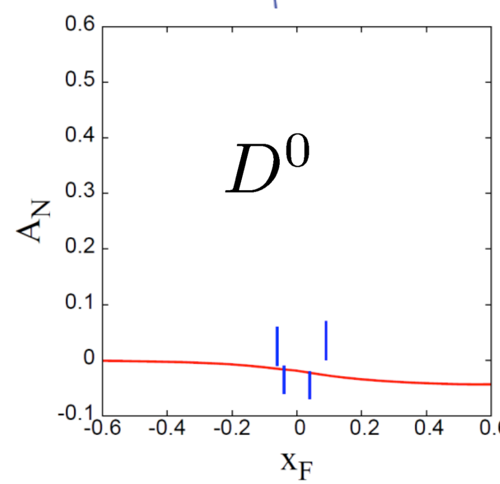
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

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

Model 1:
$O(x) = 0.004xG(x)$

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



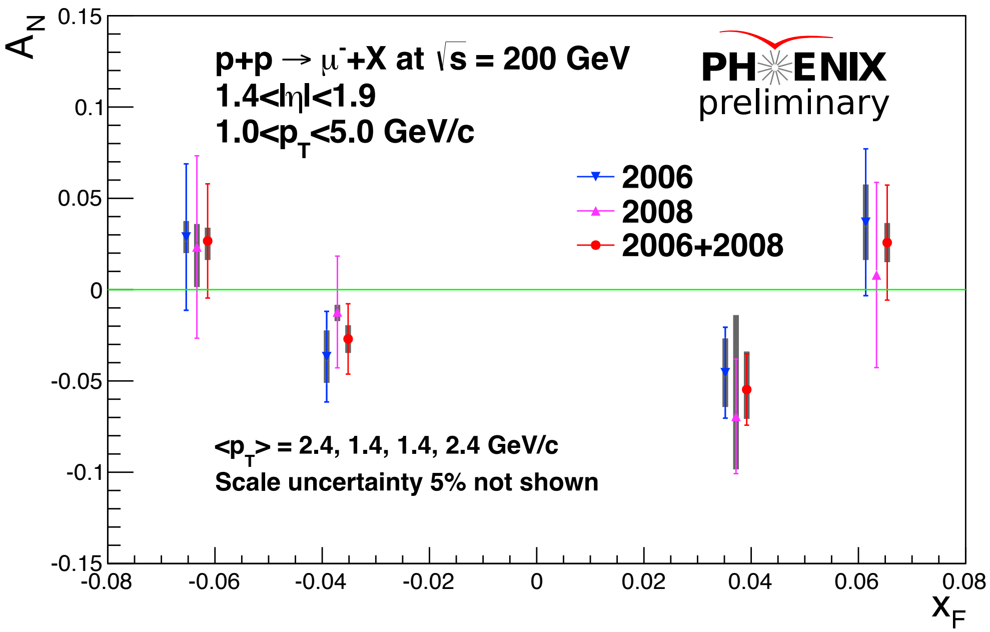


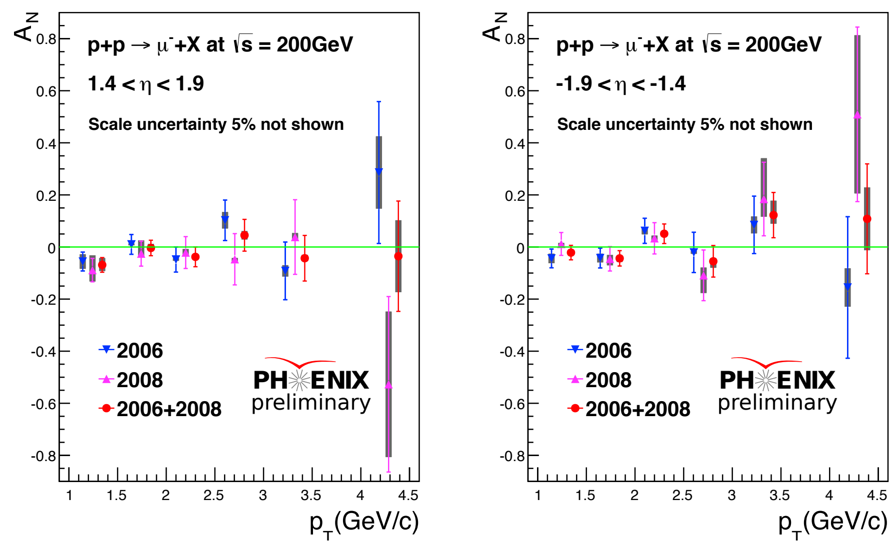
Open Heavy Quark A_N

- **Forward muon arms** $1.2 < |\eta| < 2.4$
  - Run6 and run8 data
  - Systematics limited (poor S/B)
- **Run12 with FVTX**

  work in progress

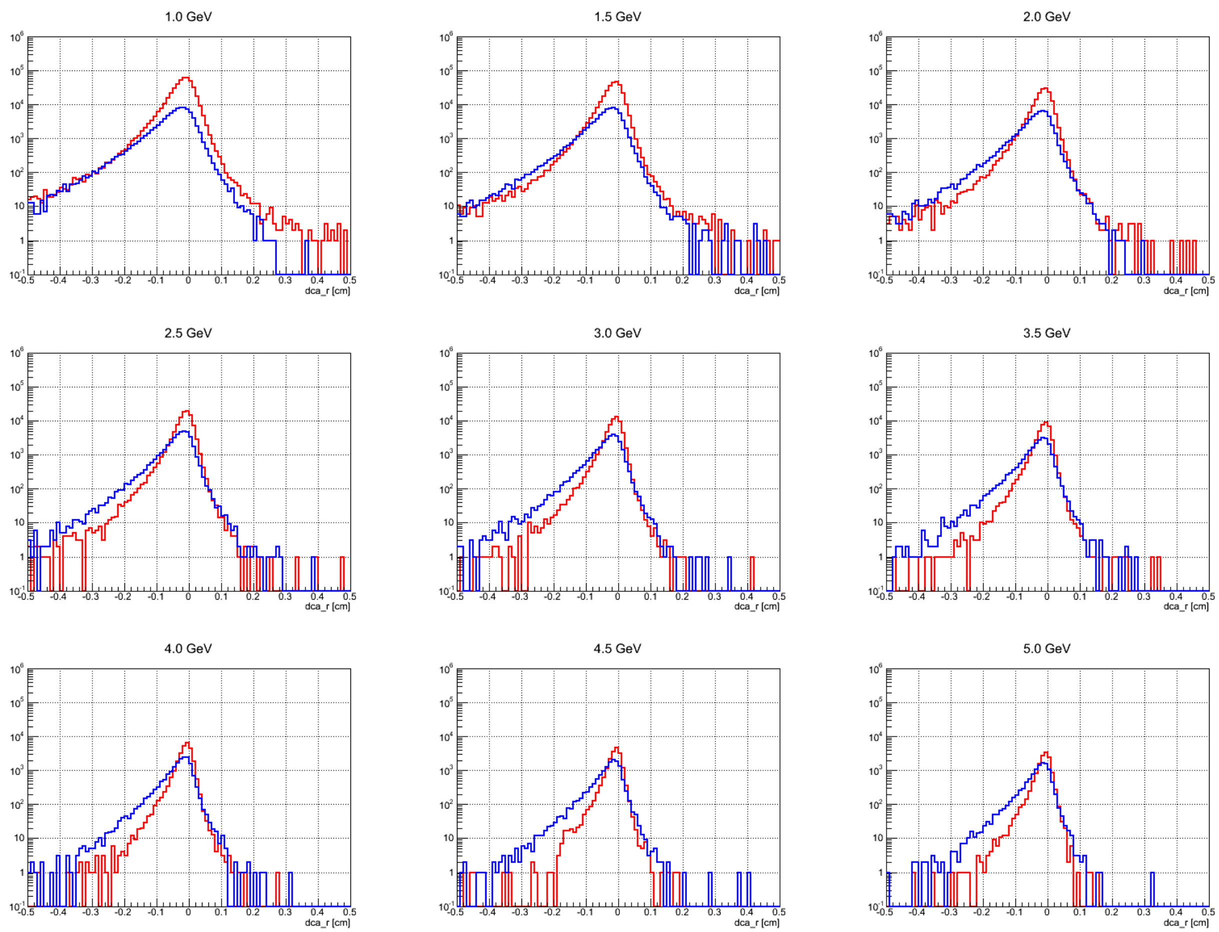
F. Wei, M. Liu, X. Wang





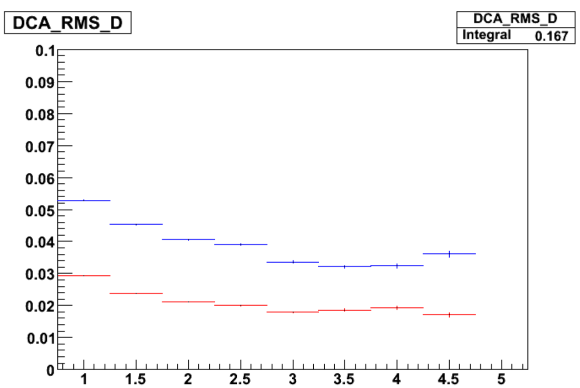
FVTX: B and D DCA$_R$ in p+p 510 GeV

Joengsu Bok, X. Wang

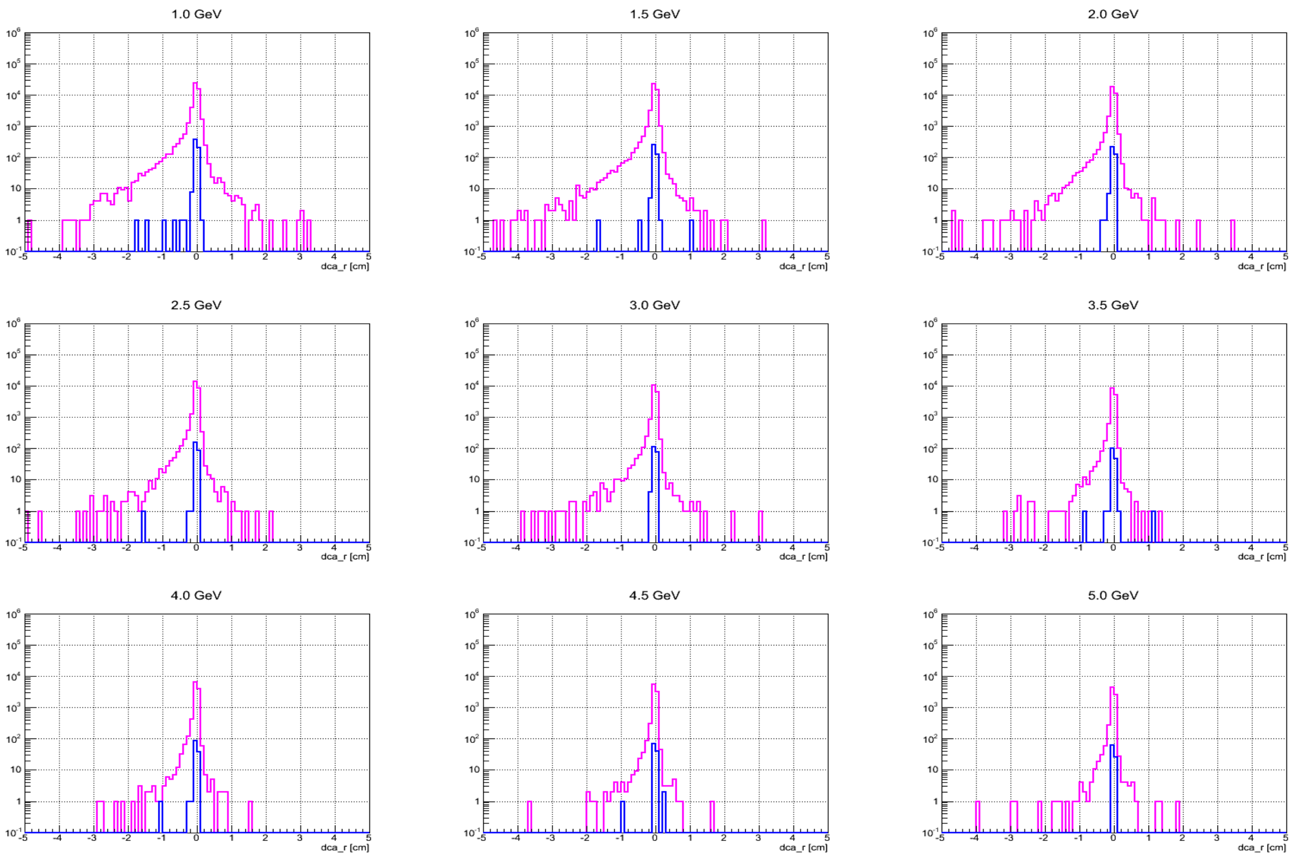


Blue : 50 mil B events
Red : 900mil D events

Using actual reconstruction code used for real data



FVTX: Background DCA_R



Joengsu Bok, X. Wang

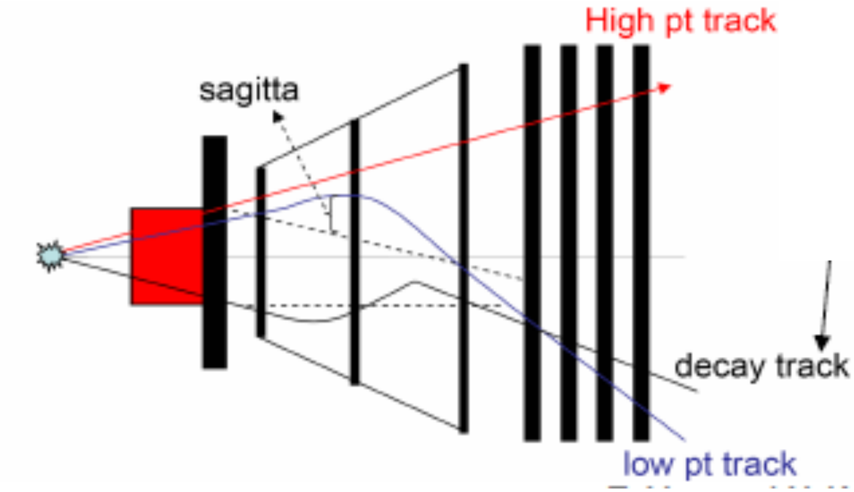
190mil $\pi^{\pm}$

Blue : stopped hadron
magenta : deeply penetrating
(decay muon including punch-through)

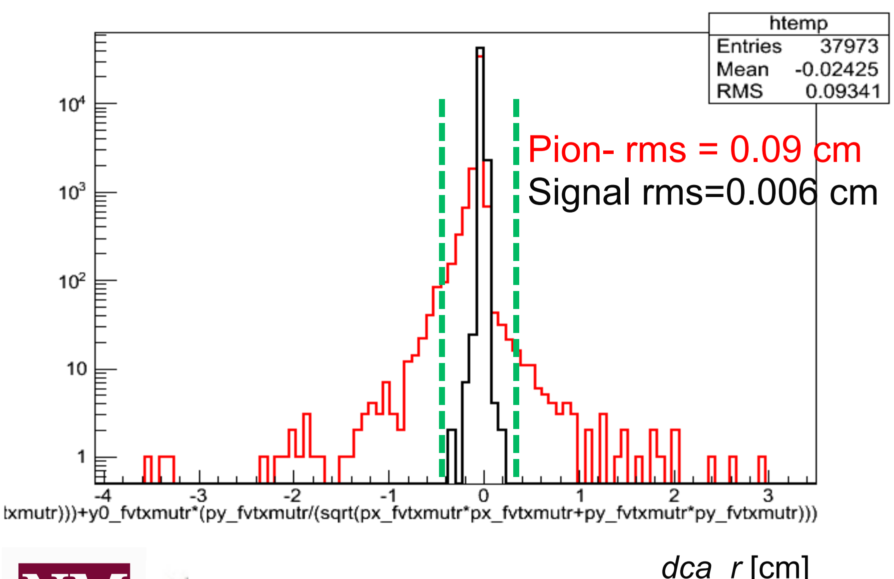
DCA_R (background) > 10 × DCA_R (muons from B,D)

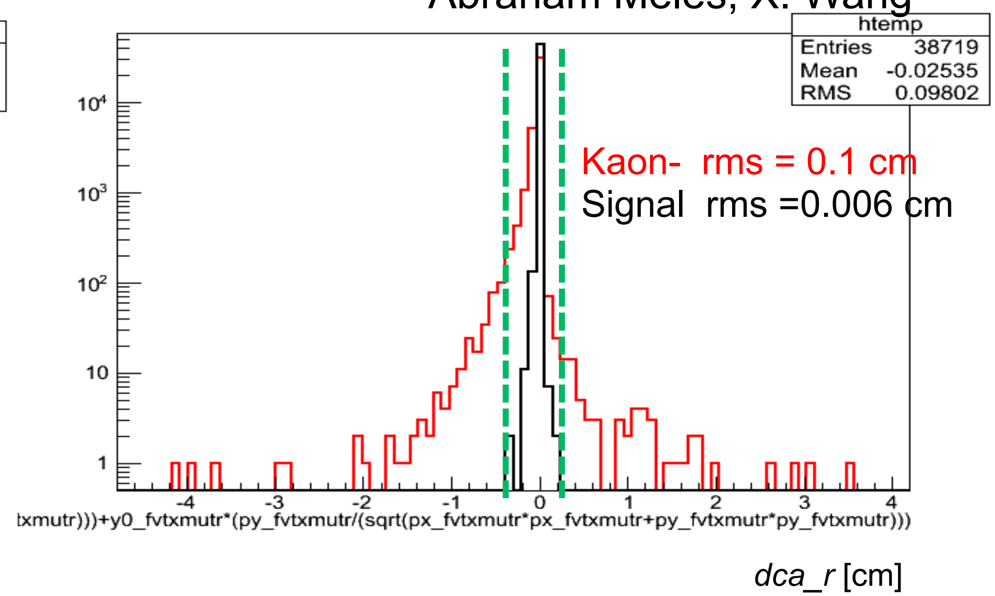
W Background from Low p_T Hadrons

- The background in W production is dominated by the low p_T light hadrons π and K. (mis)reconstructed to higher momentum, because of their kink trajectory.
- Fake high p_T muons have much bigger DCAs compare with W signals.
- FVTX Simulations (W, K and π)



Abraham Meles, X. Wang





SUMMARY and OUTLOOK

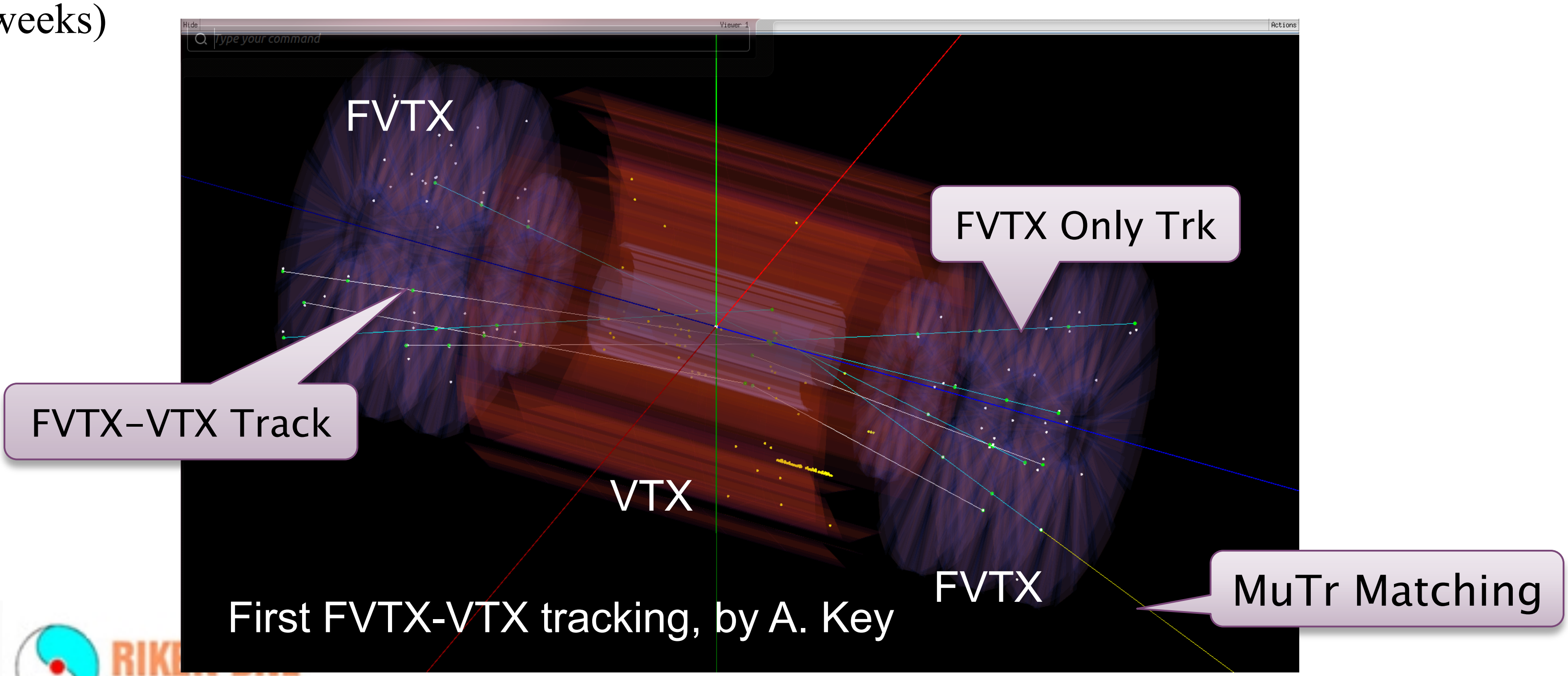
- Newly installed FVTX detector has successfully commissioned into PHENIX data taking. New heavy flavor trigger (SG3) is implemented. Further possibility to improve the rejection power by combining with RPC1 is in progress.

- Heavy flavor is unique channel to understand gluon Sivers and tri-gluon correlation function. Run 8 new preliminary result consistent with Run6. Run12 heavy flavor A_N with FVTX is working in progress.

- Addition to improve heavy flavor measurement, FVTX will make contribution to improve signal to background ratio for *W* measurement within 10 cm vertex range. Run12 *W* background study is working in progress.

FVTX Software Status

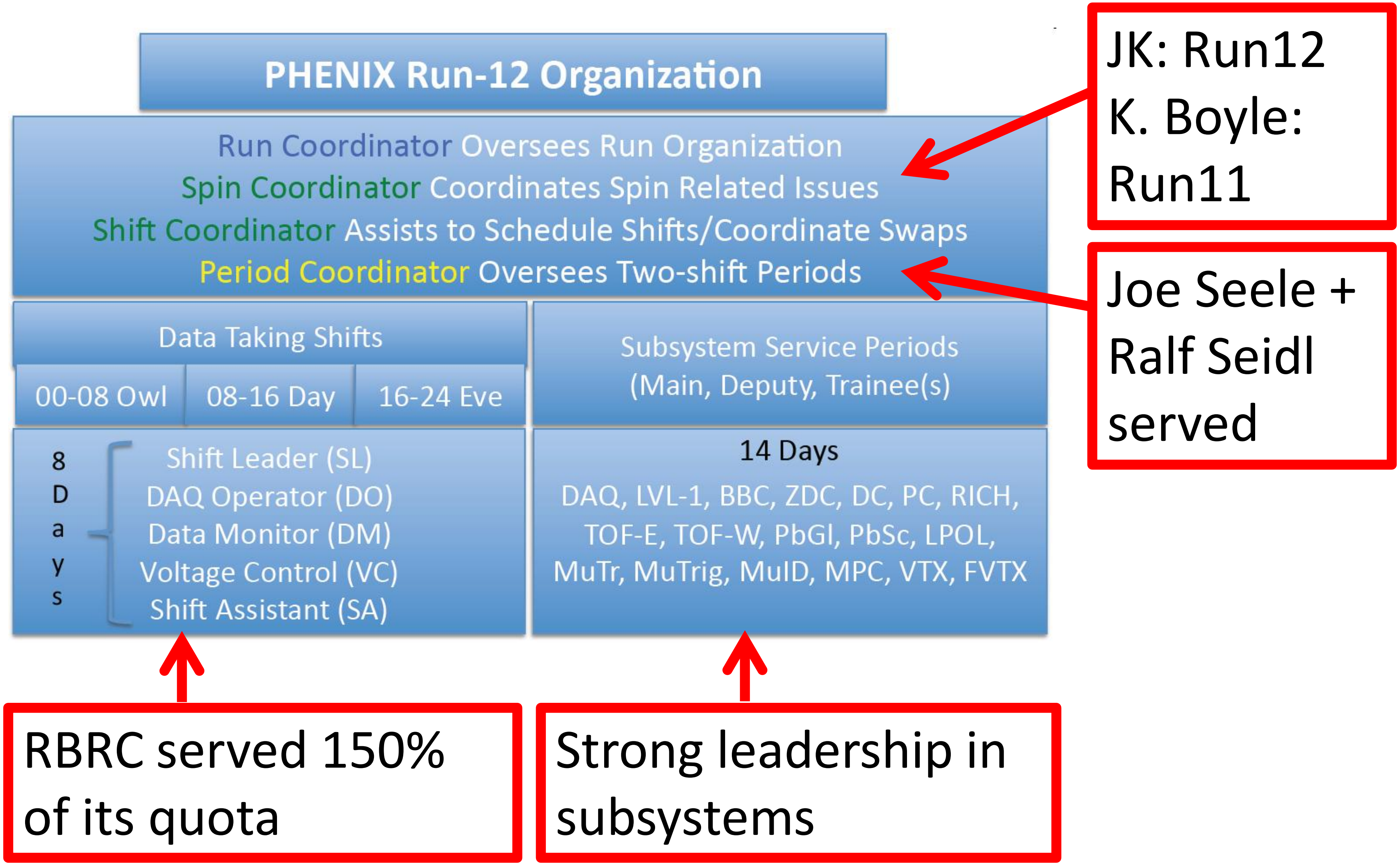
- **Reconstruction software is ready**
  Includes: Decoder/Clustering/VTX-FVTX joint tracking/Kalman filter/(F)VTX – MuTr joint fitting
- **nDST is ready**
  need to save simplified version of all FVTX tracklets ~5trks/event (a few weeks)
- **Dead/hot channel map (a few weeks)**
- **Geometry misalignment in Run12**
  FVTX self-alignment is ready
  VTX-FVTX-MuTr global alignment is in progress
- **Joint VTX-FVTX vertex finding**



Run12 Spin PHENIX Report

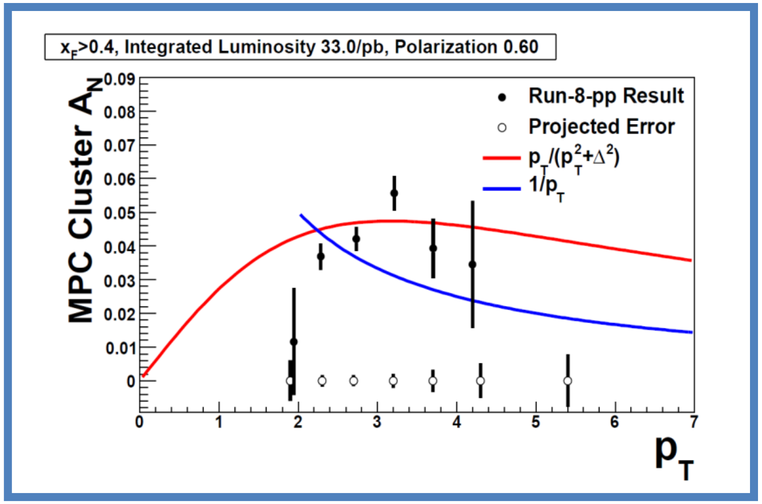
John Koster
RBRC Review
2012/11/07

PHENIX Run-12 Organization



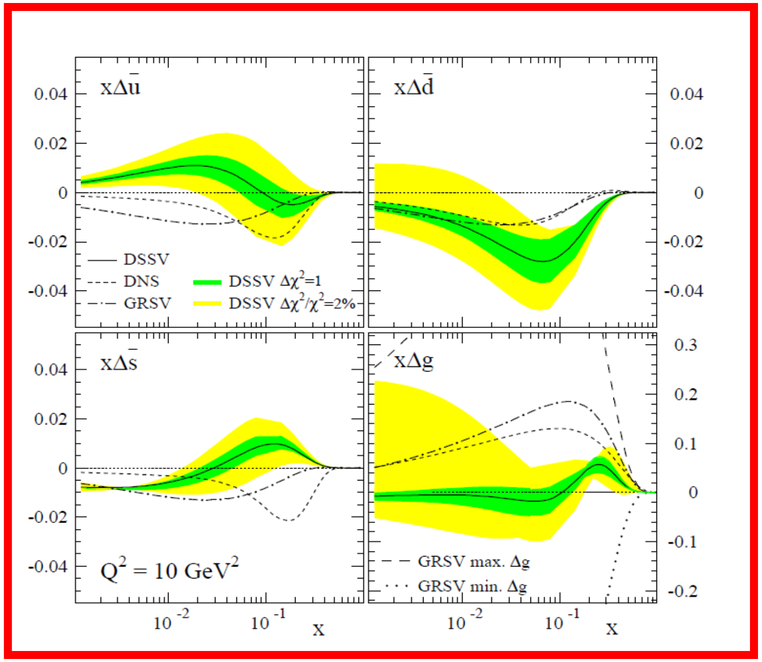
Achieving the Physics Goals

Reduction of statistical uncertainties **essential** for all measurements.

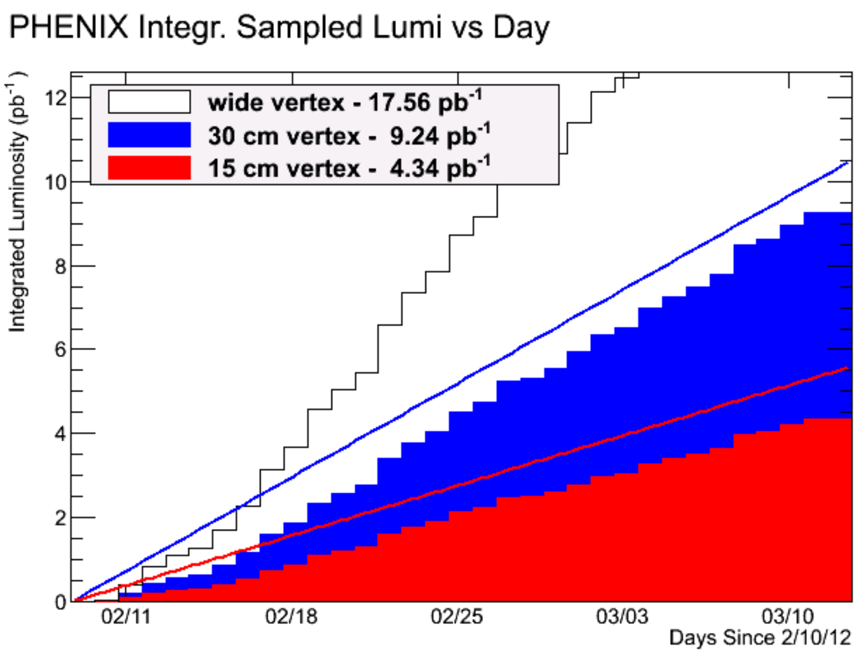


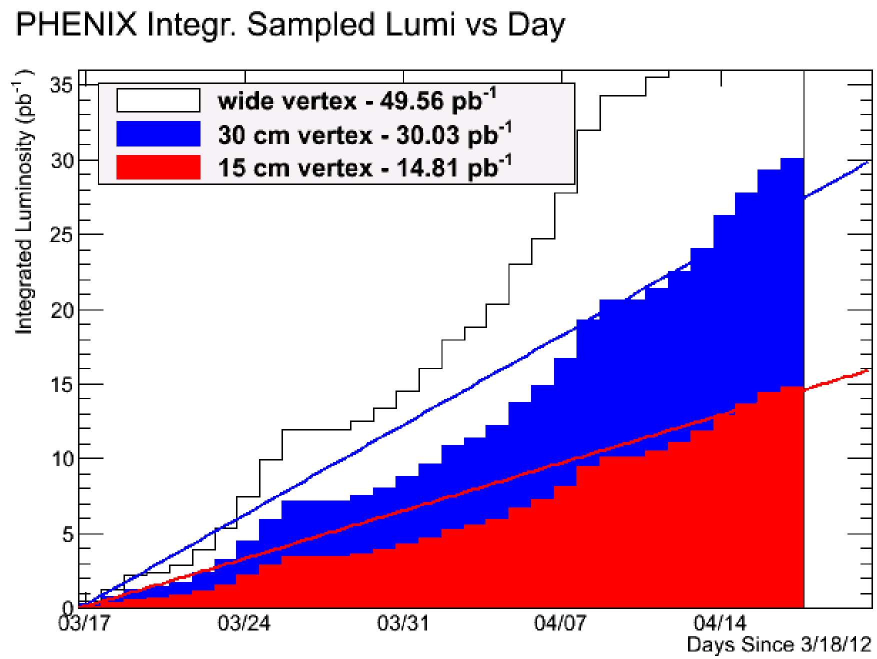
- Transverse p+p √s=200 GeV
  - (A_N) Upgrade electronics
- Longitudinal p+p √s=500 GeV

  Implement longitudinal spin
  - ($\Delta\bar{u}$,$\Delta\bar{d}$) Finalize W→μ trigger
  - (ΔG) Systematic errors on A_{LL}



Run12pp Integrated Luminosity





√s=200 GeV

P_{blue} =61.8%

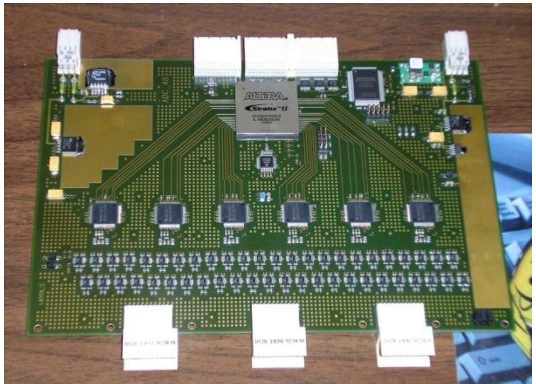
P_{Yellow}=56.6%

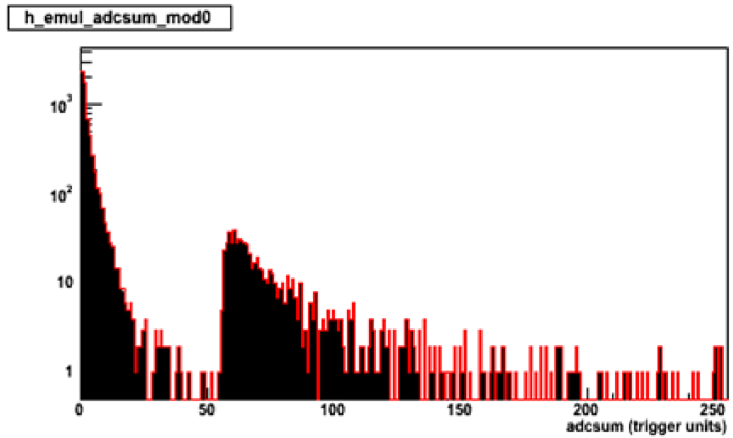
√s=510 GeV

P_{blue} =50.3%

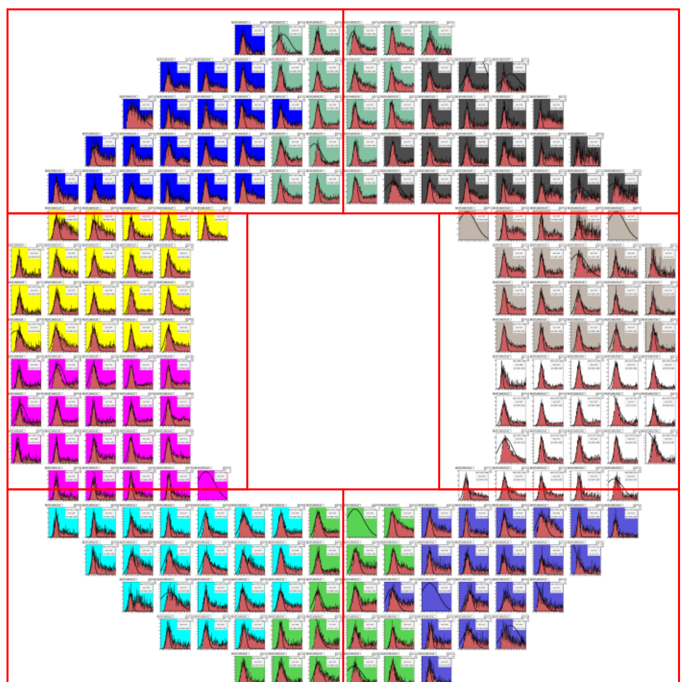
P_{yellow}=53.5%

MPC Electronics Upgrade





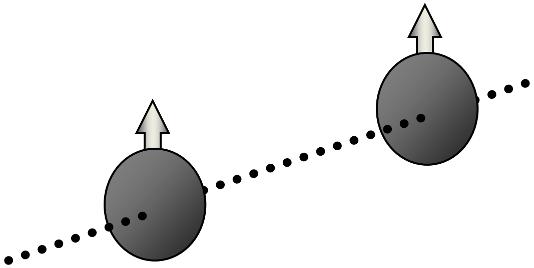
Sharp (Digital) Trigger Threshold



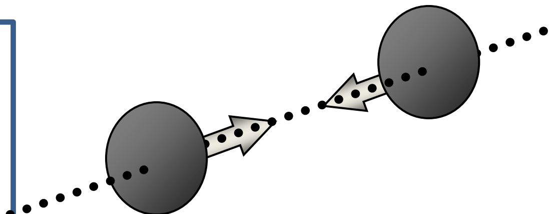
π^0 tower-by-tower calibration

Made possible by rapid analysis

PHENIX Online Polarimetry



For Longitudinal Running:
Spin direction needs to be rotated from perpendicular to parallel to proton beam
Setting magnets rely on PHENIX pol.



Neutron A_N Physics Measurement

(Y. Goto later today)

$$A_N = \varepsilon_N / P_{Transverse}$$

- A_N → Physics quantity
- ε_N → Measured “raw” asymmetry
- $P_{Transverse}$ → Transverse beam component

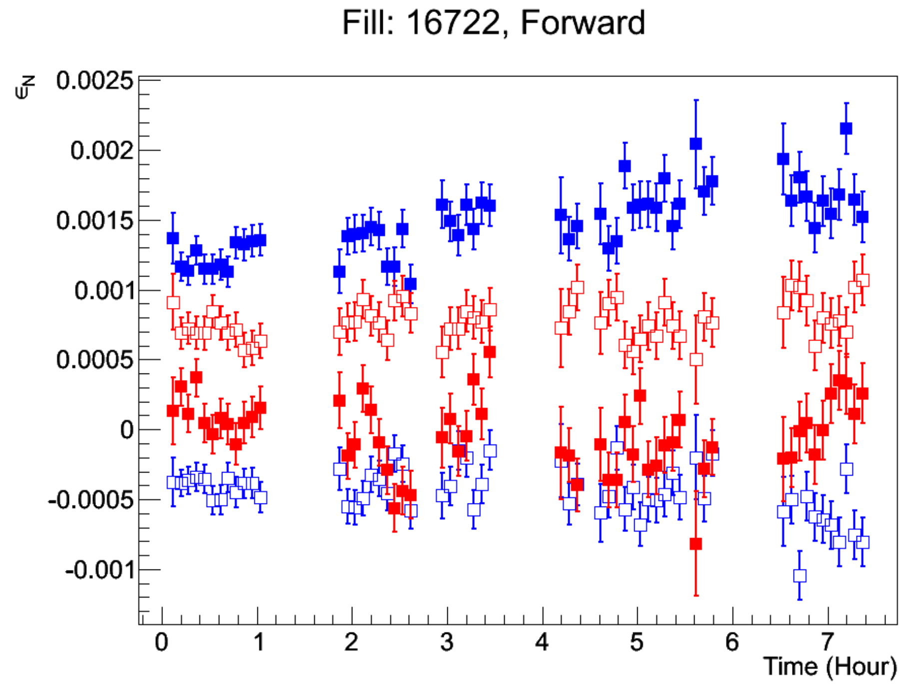
Residual Polarization Measurement at PHENIX

$$P_{Transverse} = \varepsilon_N / A_N$$

Measure residual transverse polarization using our published asymmetries (A_N) and raw asymmetries (ε_N)

Online Local Polarimetry

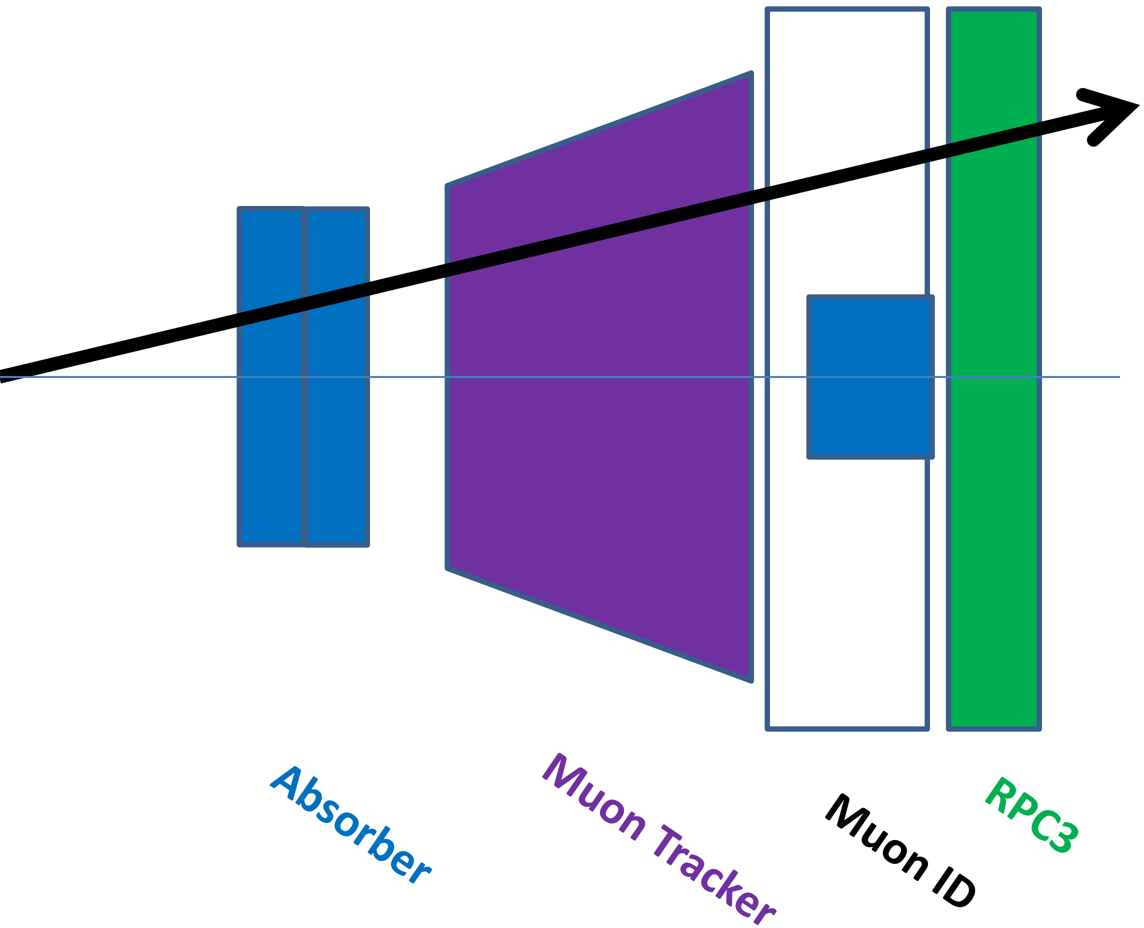
- Scaler based analysis
  - New tool for Run12
  - Gives us tremendous precision and speeds up analysis.
- Blue and yellow beams tracked independently
- Polarization direction tracked, i.e. Up/Down or Into/Out ring



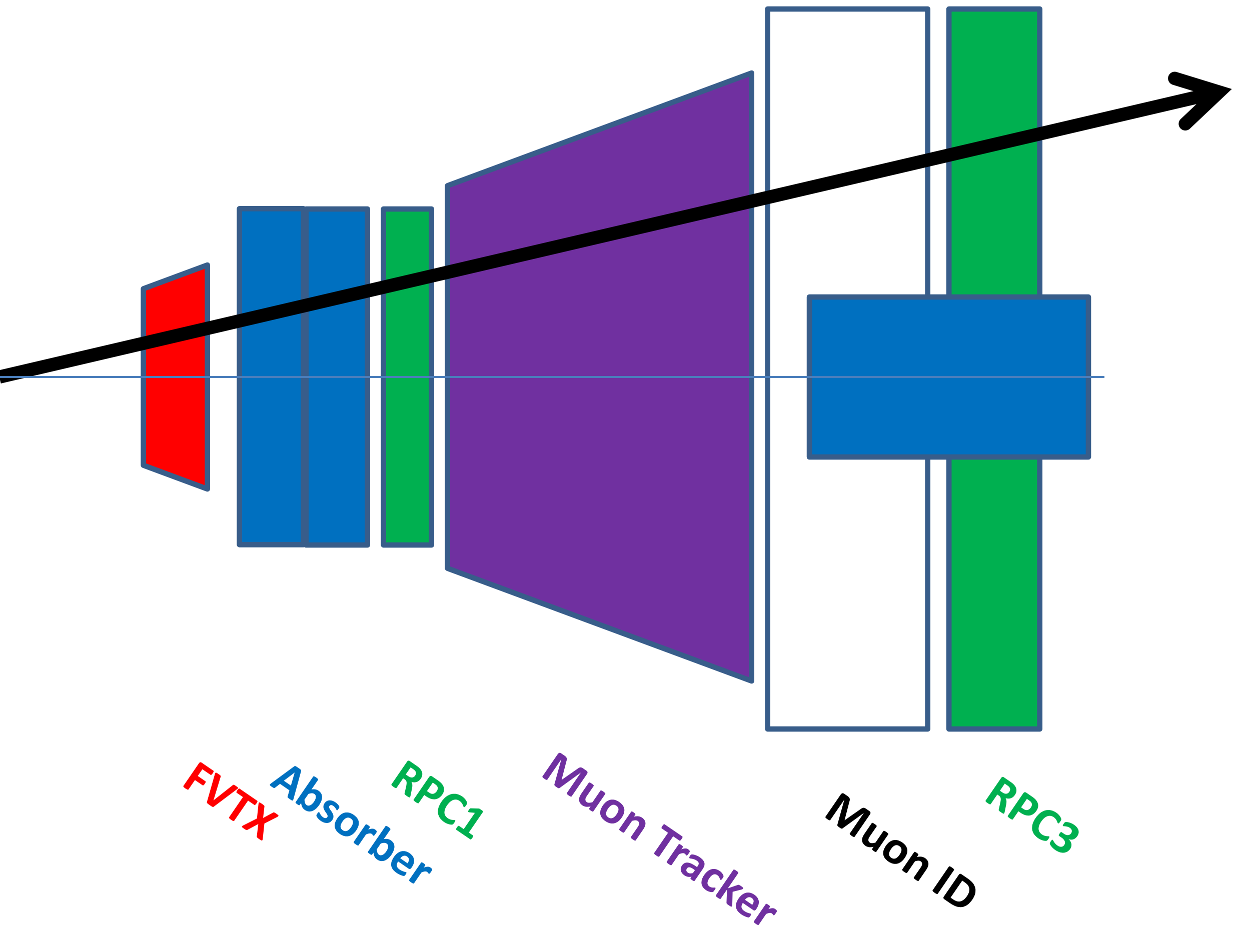
Blue and Yellow beam residual for one fill

Results from C. Gal, S. Park, J. Perry

Run11 Muon Trigger Hardware



Run12 Muon Trigger Hardware



FVTX Upgrade

+Adds tracking

RPC1

+Adds acceptance

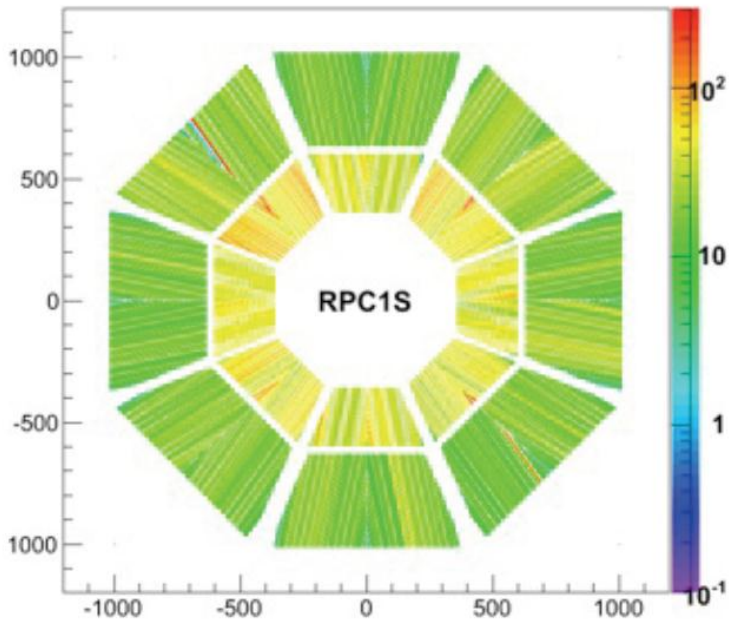
+Adds trigger rejection

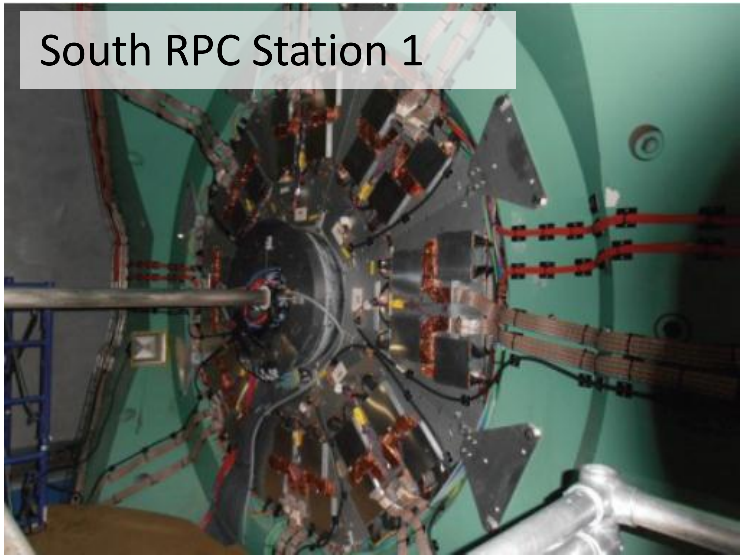
Additional Absorber

+Shields detector from in-time backgrounds

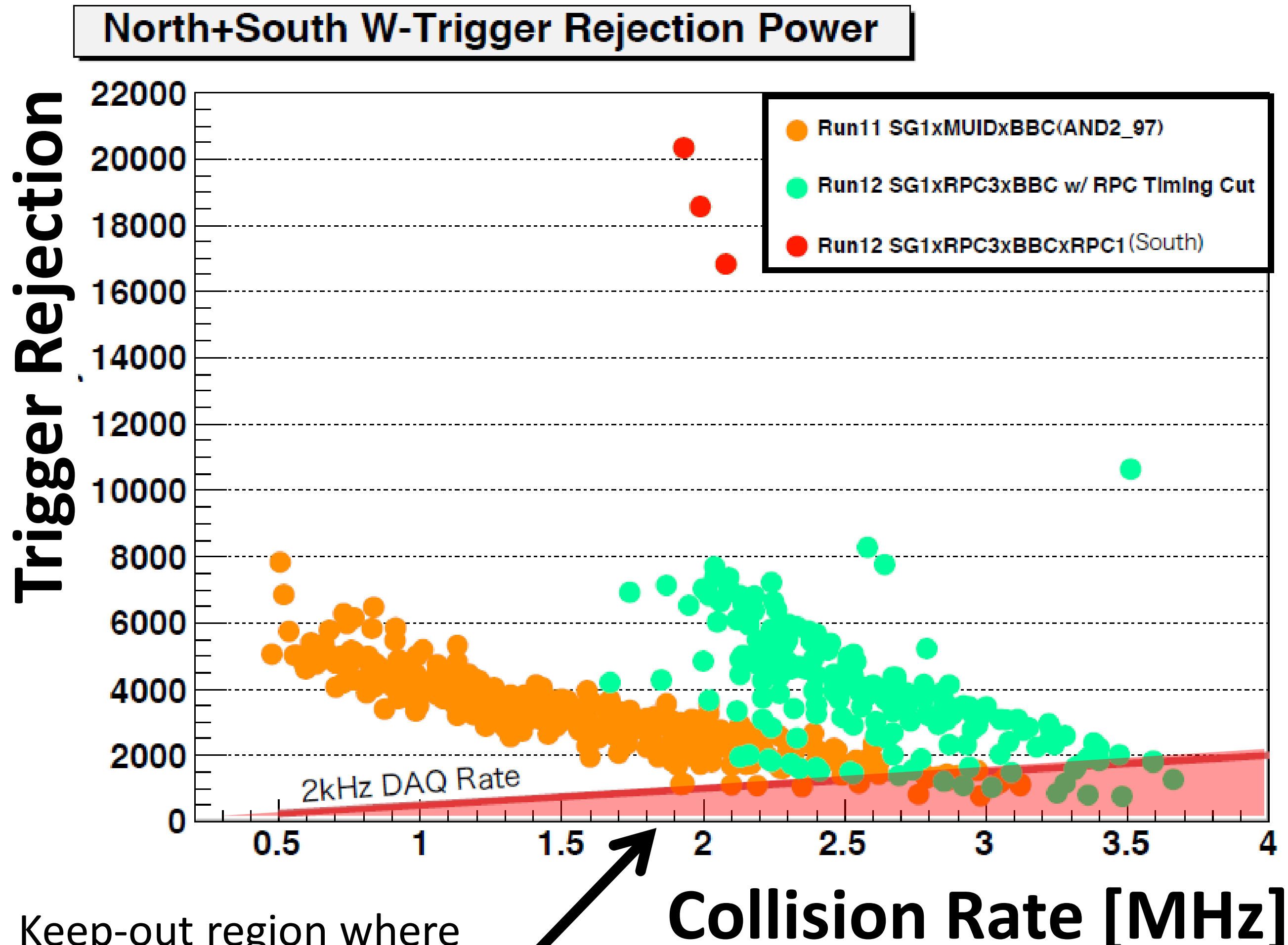
W→μ: RPC1 Commissioning

- RPC1 Successfully installed for Run-12
- Offline readout working during 510 GeV period



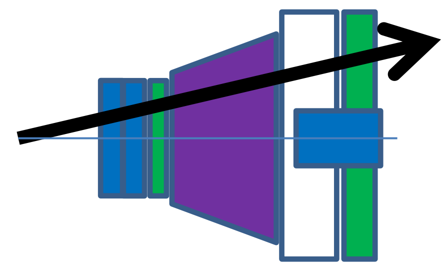


W→μ: Trigger Commissioning

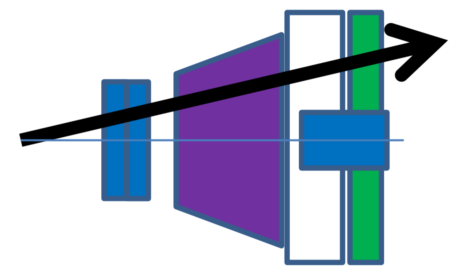


Keep-out region where trigger will take too much DAQ bandwidth

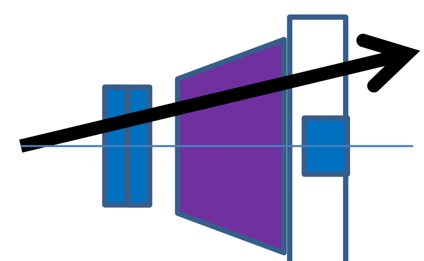
Run13 Production Trigger



Run12 Production Trigger



Run11 Production Trigger

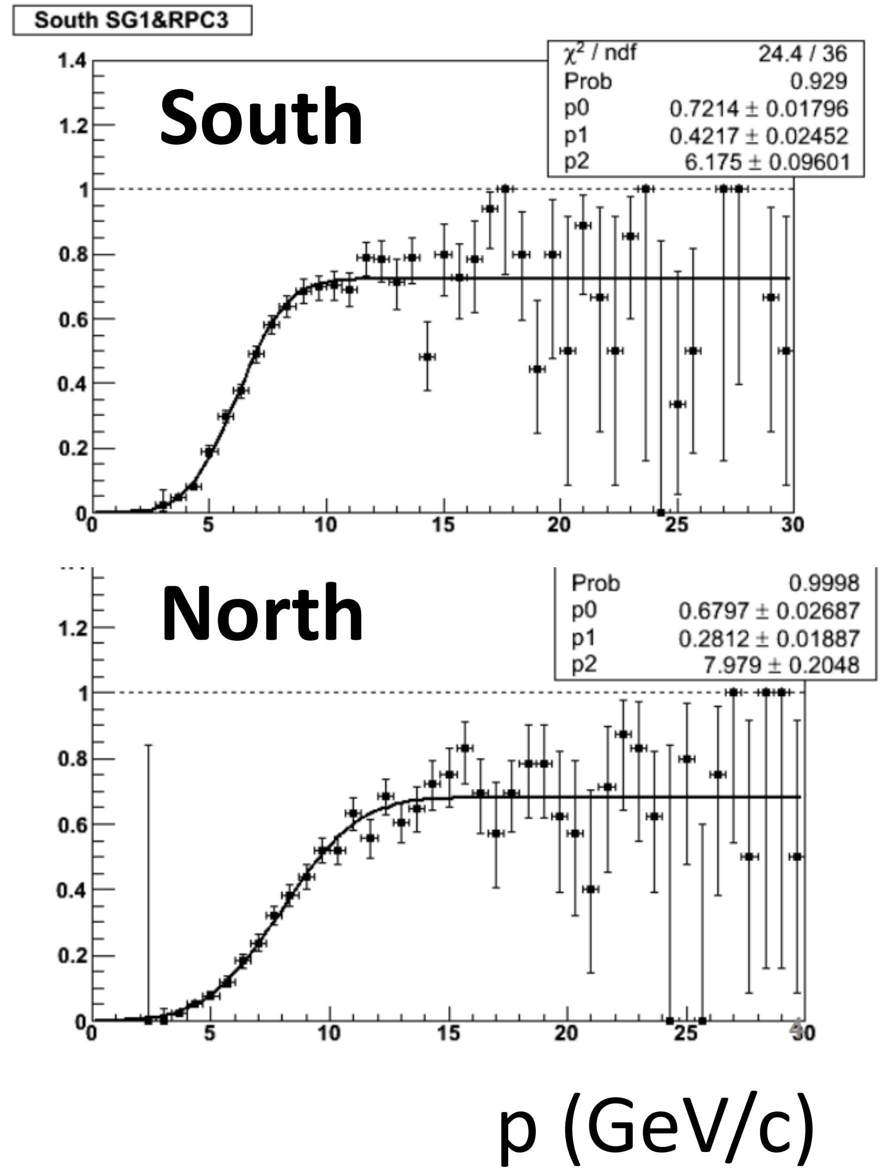


Results from Y. Imazu, S. Park, I. Nakagawa

W→μ: Trigger Commissioning

- Run12 Muon-like track turn on curve
- Yield (Production Trigger) / Yield (Minimum Bias)

Trigger maintains high rejection and selects high momentum tracks



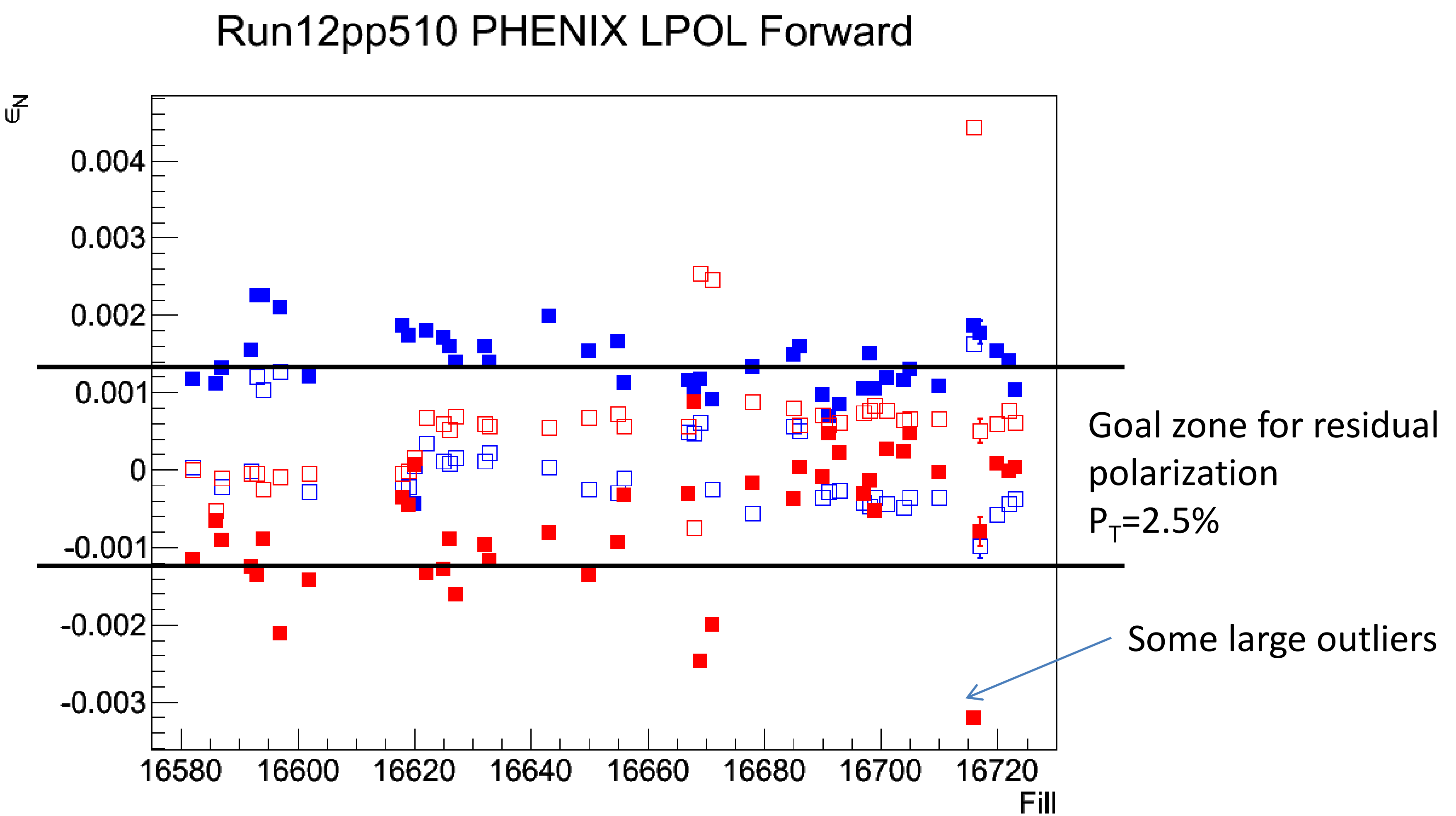
Results from Y. Imazu, S. Park, I. Nakagawa

Summary

- Run12 – Huge success for RHIC/AGS
- Great dataset collected at PHENIX
  - Large Transverse dataset opens window to high statistics A_N
  - New local polarimetry effort successful
  - ΔG: Limiting systematic errors studied (K. Boyle's talk)
  - $\Delta\bar{u}$, $\Delta\bar{d}$:
    Muon Trigger hardware in place, tested and implemented.
    Trigger was active for 510 GeV data-taking.

Extra Material

Online Local Polarimetry



Blue and Yellow beam residual

Results from C. Gal, S. Park, J. Perry

PHENIX BUP Run13

15+5 cryo-week proposal for Run-13:

1. 500 GeV $p+p$ for 10 weeks
2. 500 GeV $p+p$ for 1-5 additional weeks, if needed to reach 250 pb^{-1} sampled inside $\pm$ 30 cm
3. 200 GeV $p+p$ if 3-4 weeks remain following the 500 GeV run
4. if fewer than 3 weeks remain following the 500 GeV Run, we request 4.2 pb^{-1} delivered of 39 GeV $p+p$ ($\approx$ 1 week)

PHENIX BUP Run14

15+5 cryo-week proposal for Run-14, assuming 200 GeV $p+p$ is done

in Run-13:

1. 200 GeV Au+Au for 6-8 weeks, to collect 1 nb^{-1} in $\pm$ 10 cm
2. 200 GeV d+Au for the remainder of the Run

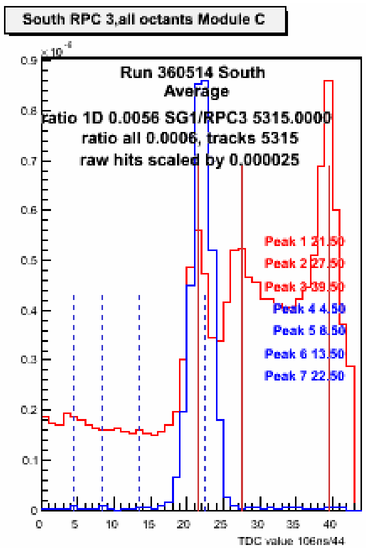
15+5 cryo-week proposal for Run-14, assuming no 200 GeV $p+p$ in Run-13:

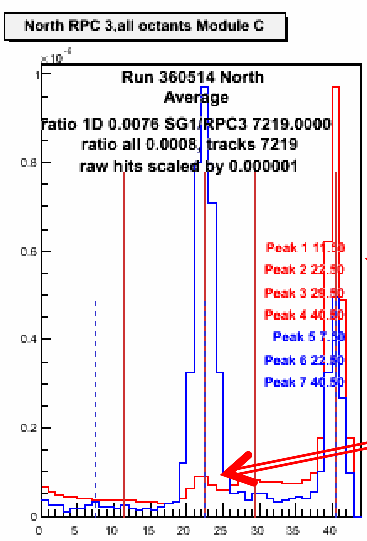
1. 200 GeV Au+Au for 6-8 weeks, to collect 1 nb^{-1} in $\pm$ 10 cm
2. 200 GeV $p+p$ for 4 weeks
3. 200 GeV d+Au for the remainder of the Run

Slide by Ralf Seidl

Overall RPC timing and BG

200 GeV





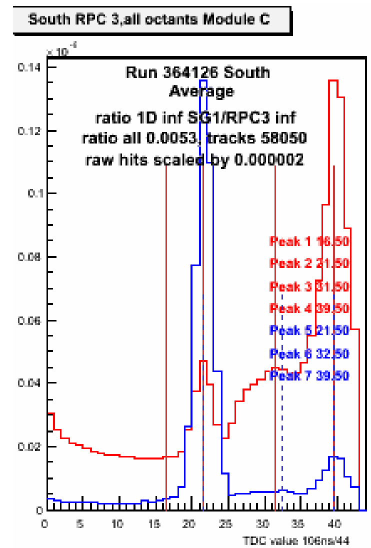
- Outer RPC3s in the tunnel most sensitive to incoming BG
- Blue (North) sees more background at 510 GeV
- However beam conditions change very much – study Collimator and Vernier scan data

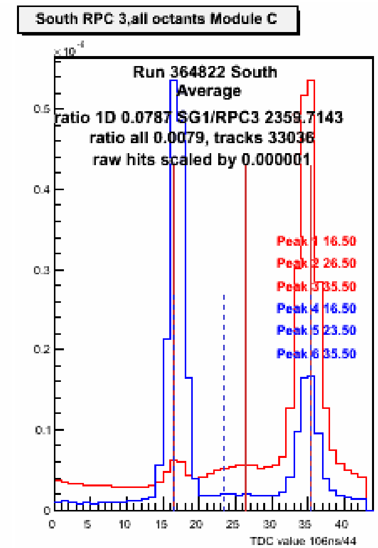
Incoming Background

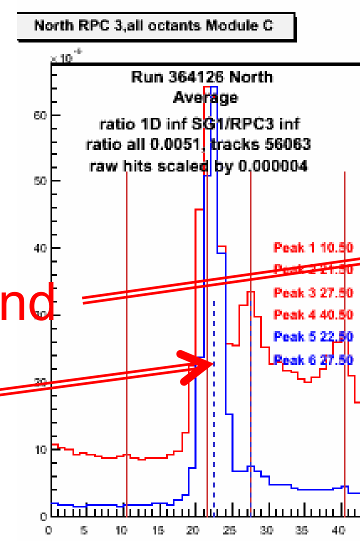
Collision related

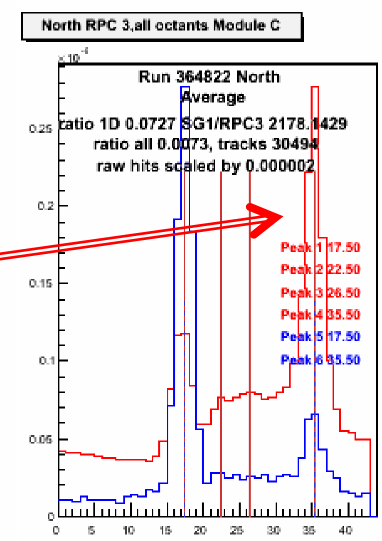
Muon arm track related hits (different scale)

510 GeV





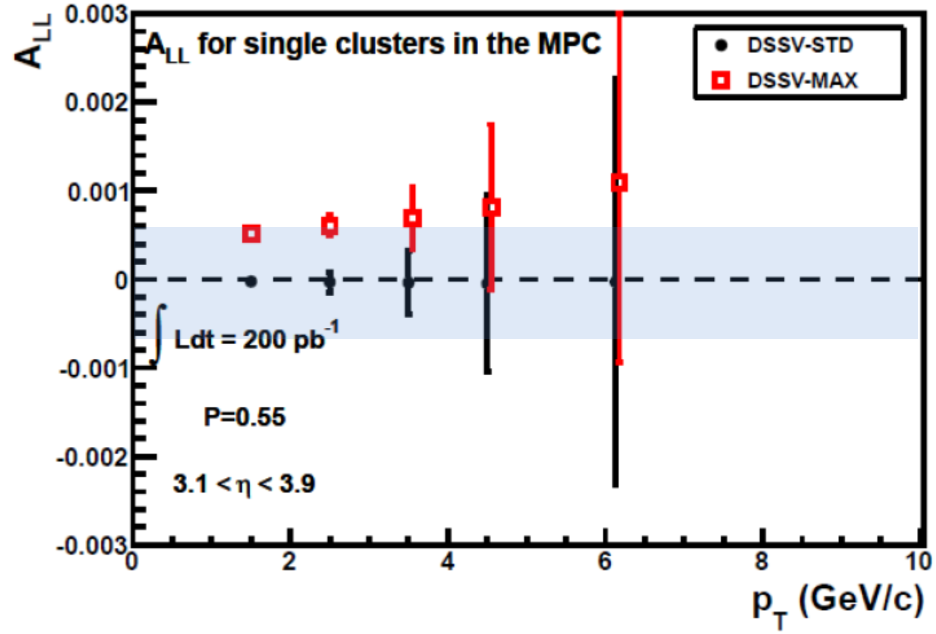




Reducing A_{LL} Systematic Errors

- Important for PHENIX reduce its limiting A_{LL} systematic errors.
- One theory:
  1. Single transverse spin asymmetry in neutron production
     Phys.Lett.B650:325-330,2007
  2. Residual transverse spin component during Longitudina running
  3. Acceptance effects in the PHENIX ZDC

Projected asymmetry and statistical errors

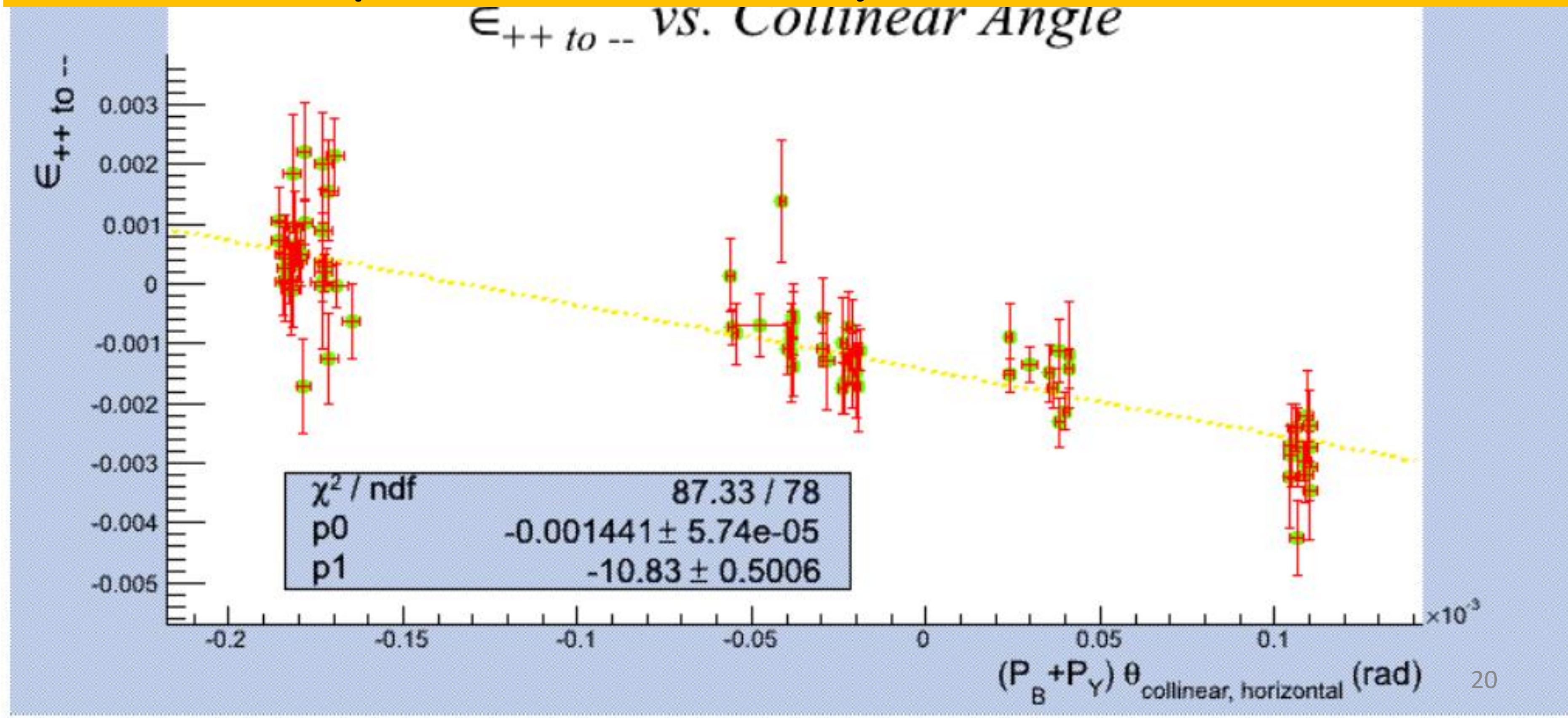


1+2+3 = Large (~10^{-3}) systematic error?

Approach:
Vary the acceptance effect by changing the beam angle

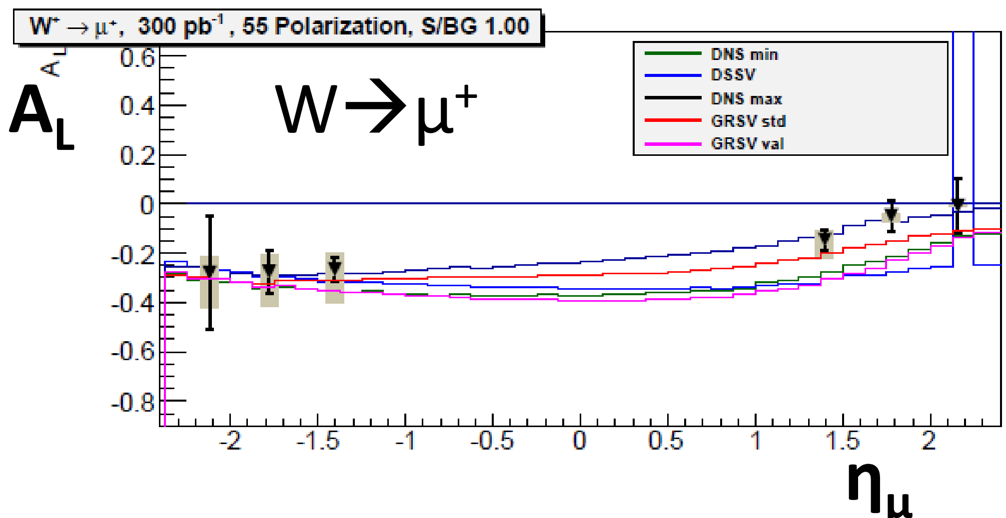
Reducing A_{LL} Systematic Errors

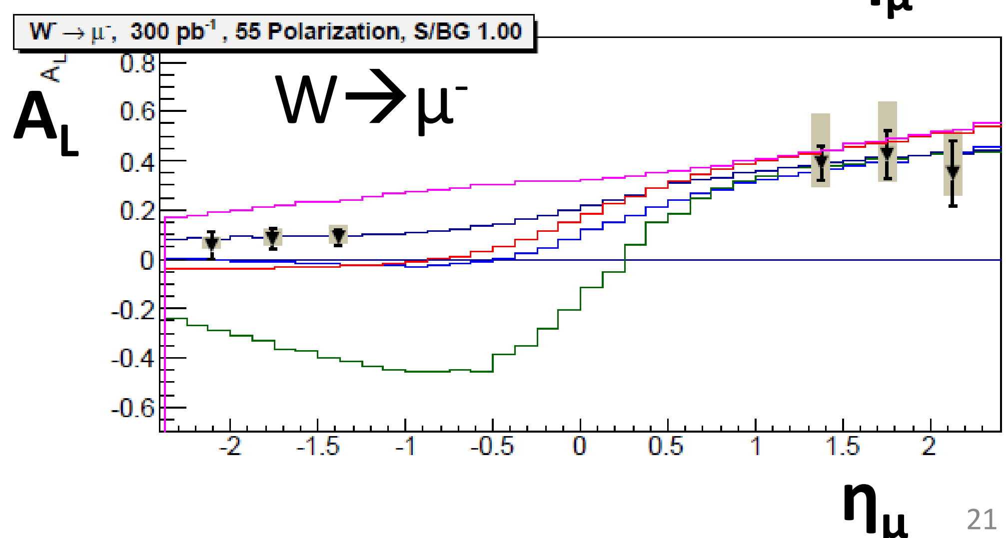
Results scale with the beam angle linearly, as expected by toy Monte-Carlo.
More tests planned for next year.



Accessing the sea quark polarization

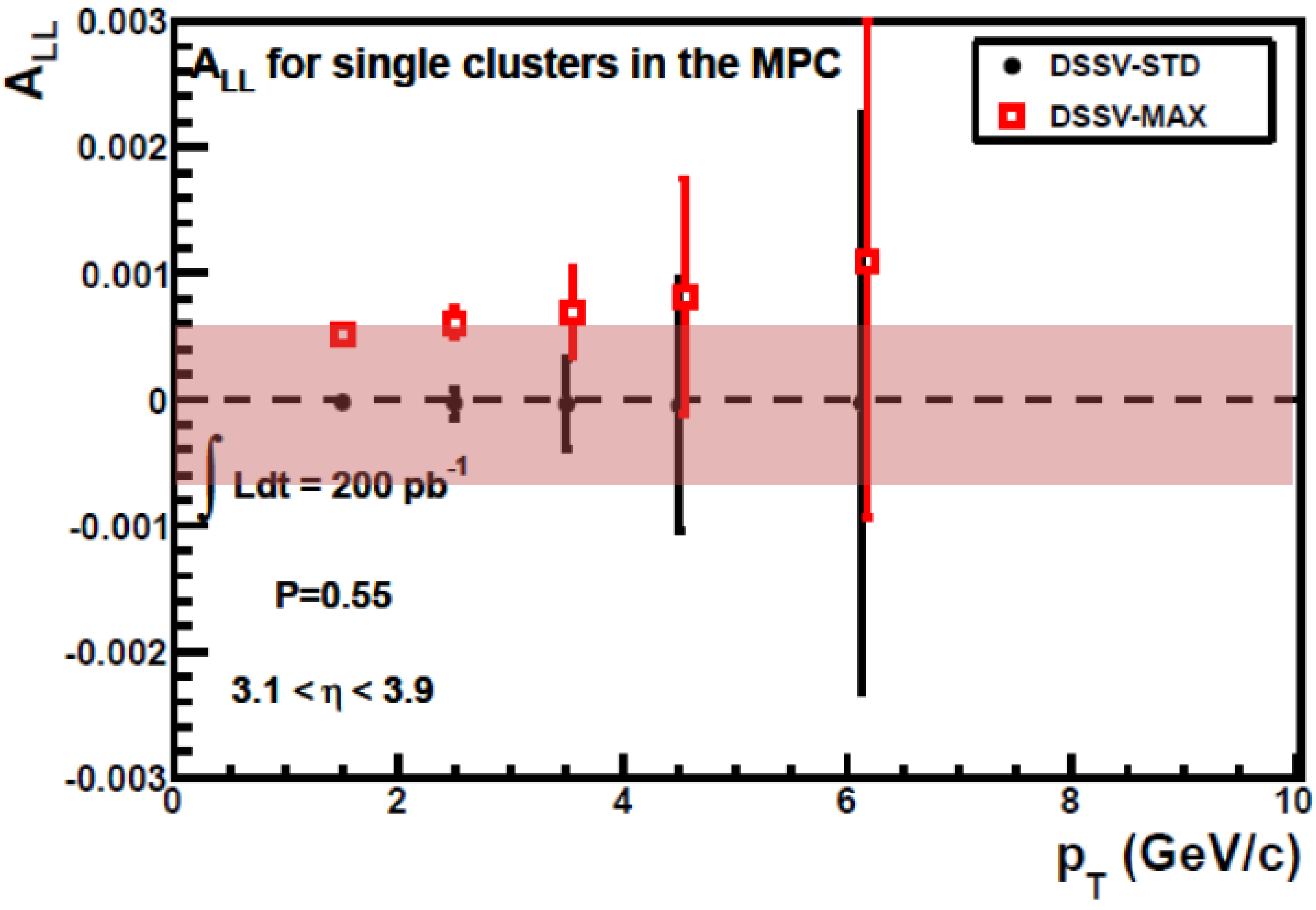
- Projections based on 300 pb^{-1} at 55% polarization
- High luminosity and polarization are important for hitting goals.
- Hardware for efficient triggering in place for forward muons





DSSV: *Phys.Rev.Lett.101:072001,2008*

Projected asymmetry and statistical errors



Sea Quark Polarization Measurement in Forward Rapidity via W-Boson Production

Itaru Nakagawa
On behalf of Forward Upgrade Group
RBRC/RIKEN

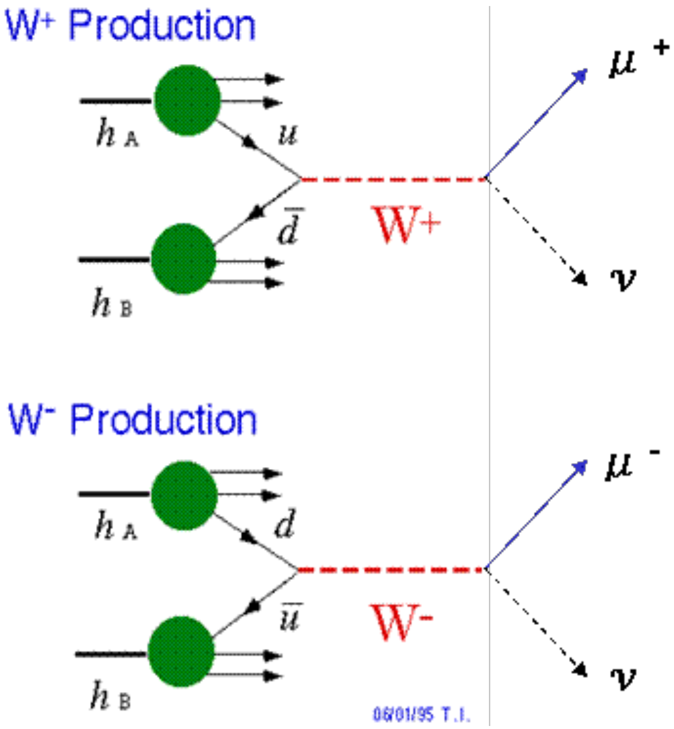
Forward Upgrade Members

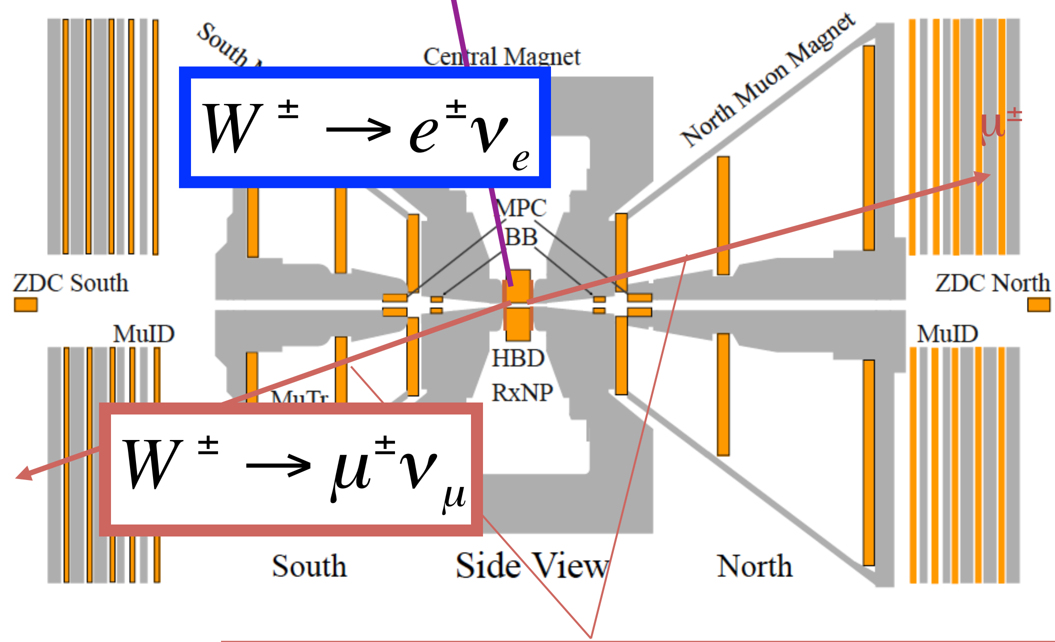
- Ralf Seidl (Scientist, RIKEN/RBRC)
- Itaru Nakagawa (Scientist, RIKEN/RBRC)
- Yoshimitsu Imazu (Postdoc, RIKEN)
- Yoshinori Fukao (Postdoc, RIKEN->KEK)
- Hideyuki Oide* (Student, Tokyo/RIKEN)
- Sanghwa Park (Student, Seoul National University/RIKEN)
- Katsuro Nakamura (Student, Kyoto University/RIKEN)
- Kentaro Watanabe (Student, Rikkyo/RIKEN)
- Takeru Iguri (Student, Rikkyo/RIKEN)

*Thesis Topic for Run11 510GeV p-p

sqrt(s)=500 GeV @ RHIC

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



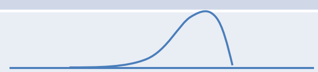
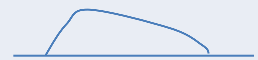


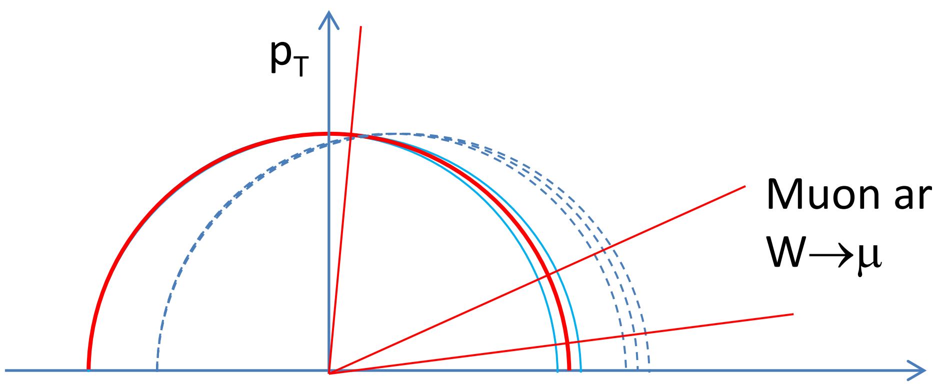
Parity Violation Asymmetry
Clean flavor separation
w/o fragmentation uncertainty

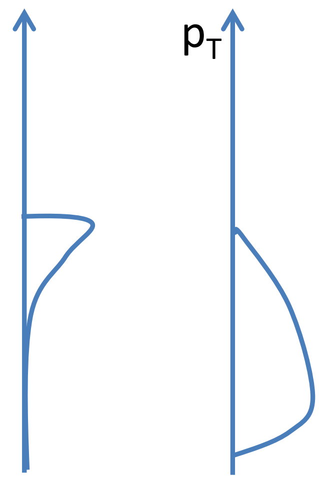
$$A_L^{W^+} \approx -\frac{\Delta u(x_1, M_W^2)}{u(x_1, M_W^2)} \quad , \; x_1 > x_2 \;\; (y_W >> 0)$$

$$A_L^{W^+} \approx \frac{\Delta\bar{d}(x_1, M_W^2)}{\bar{d}(x_1, M_W^2)} \quad , \; x_1 < x_2 \;\; (y_W << 0)$$

W→e (central), W→μ (forward)

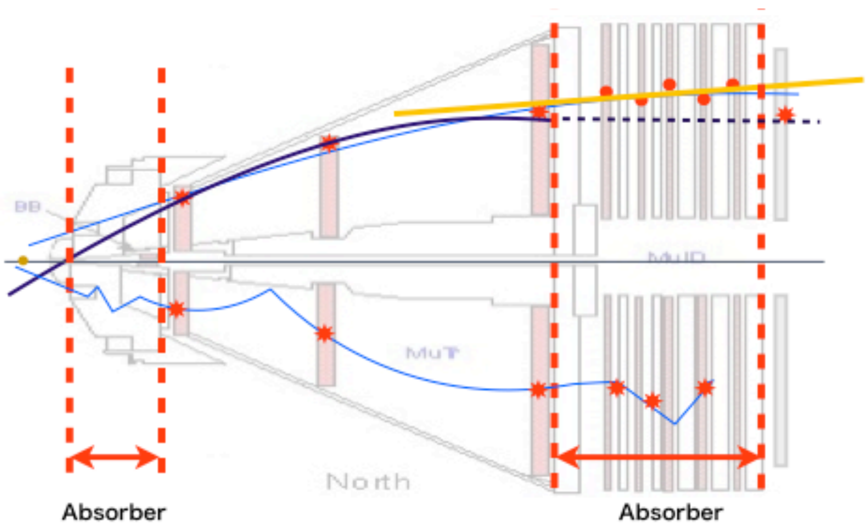
	Central arm	Muon arm
Triggered by	energy	momentum
momentum	E_{dep} in EMCal	Tracking in B field
charge	Tracking in B field	Tracking in B field
pT shape		

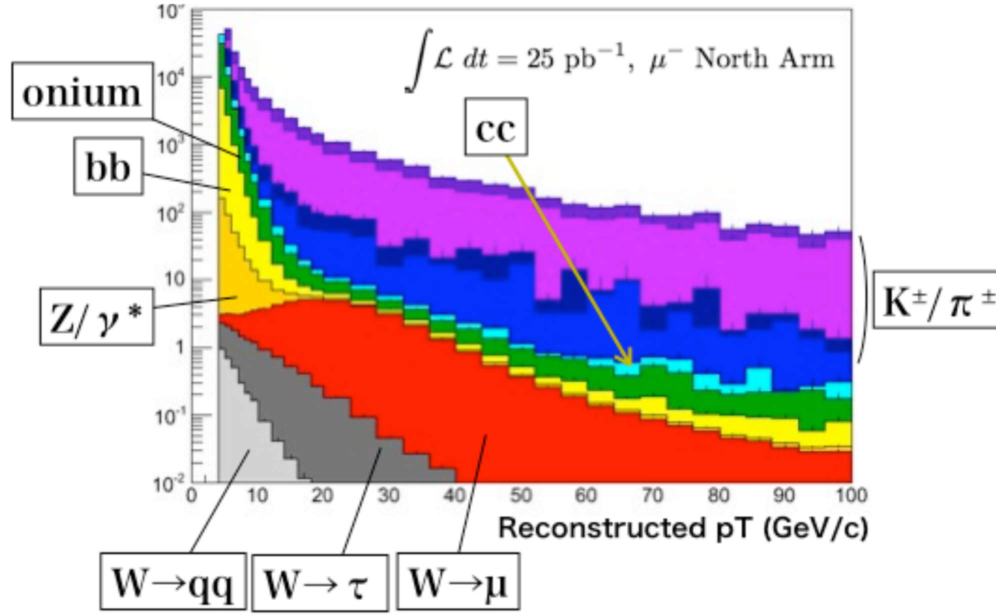




W→μ is more challenging.

Forward W-> μ Analysis





Signal: high pT single muon

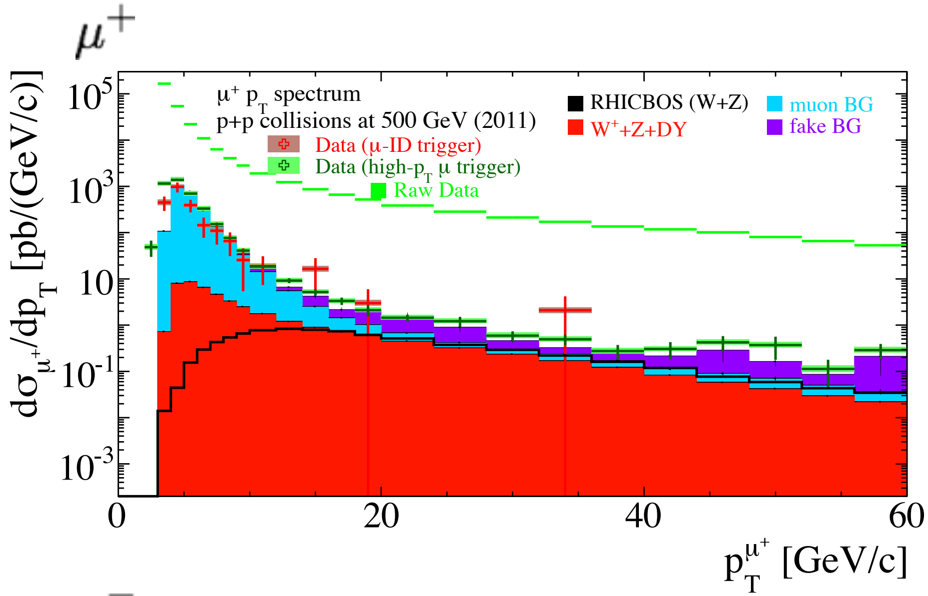
Backgrounds:
- Heavy flavor, onium (true muon, irreducible)
- "Fake high pT" caused by decayed hadrons

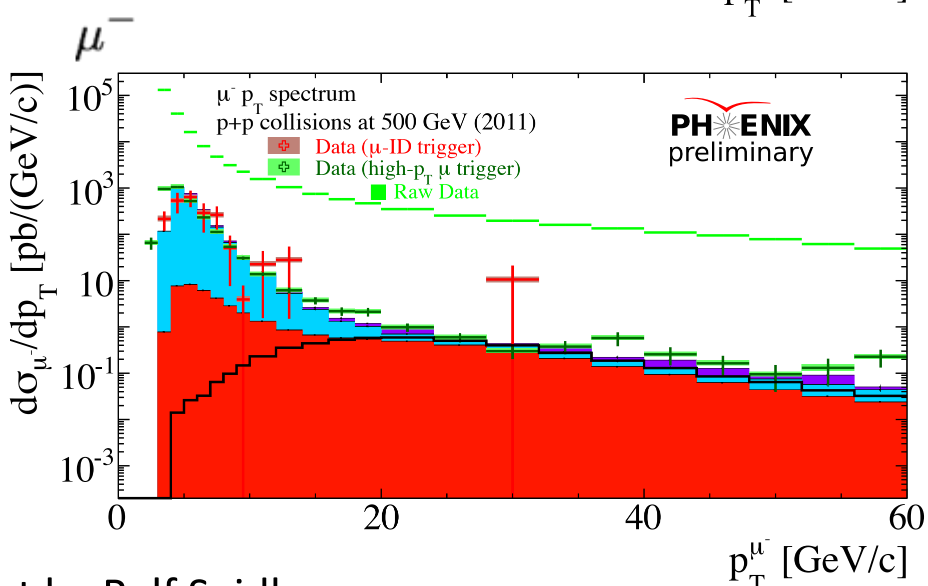
Tight cuts are applied for "consistency of true high pT muon".
- small multiple scattering : MuTr/MuID/RPC matching
- vertex requirement : Track/vertex(BBC) matching

Resolution plays key role in S/N
- Alignment
- Charge sharing model
- X-talk
- Etc.

Yoshimitsu Imazu

Single Muon P_T Spectra





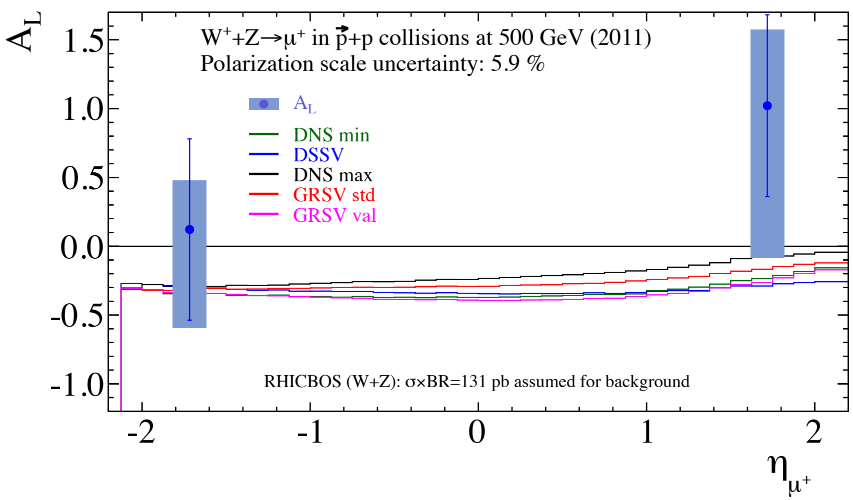
Plot by Ralf Seidl

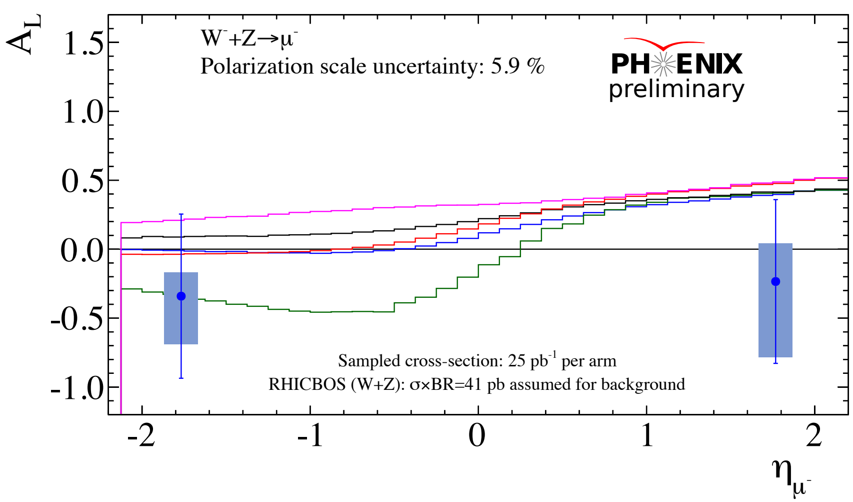
- ☑ Efficiency corrections
- ☑ W/Z cross section employed RHICBOS NLO
- ☑ S/B estimation from fixed W/Z cross section (RHICBOS NLO)

S/B ~ 1/3

- ☐ Background estimation in **data driven manner**
- ☐ Resolution Improvement for better S/N

The First Forward A_L^W Results





- $\sqrt{s}$ = 500 GeV
- Luminosity: ~25 pb-1
- Pol. : ~50%

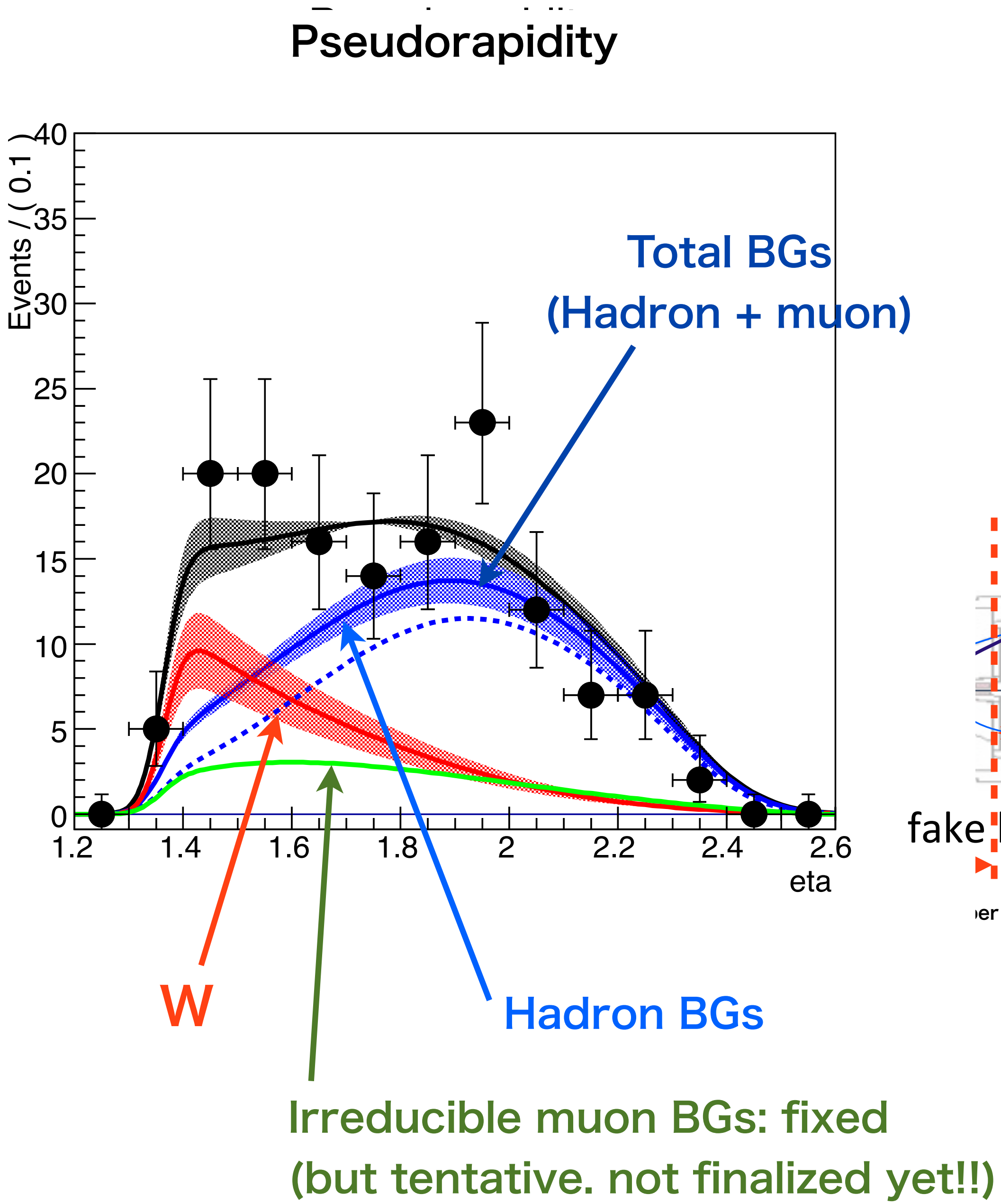
First Forward W Asymmetry Results!

More to come!

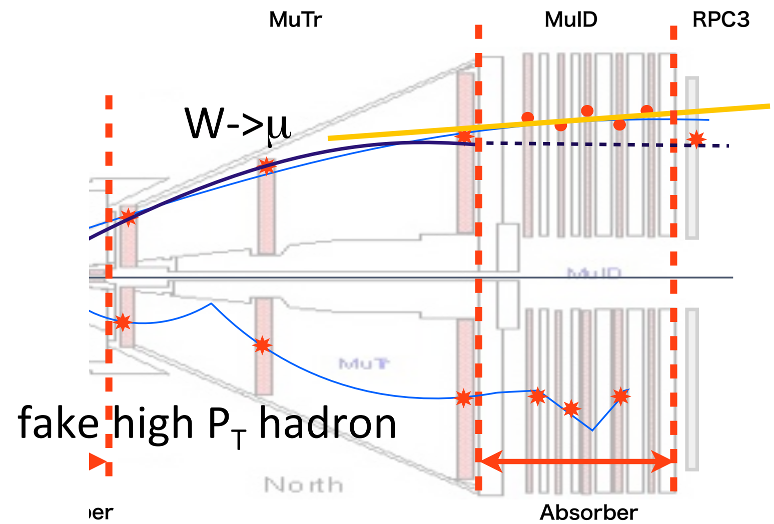
	Run11	Run12
Luminosity	25	50

Plot by Ralf Seidl

Data Driven Approach



- $16<P_T<60$ GeV



Matching between track and MuiD track can be quite different due to multiple Scattering

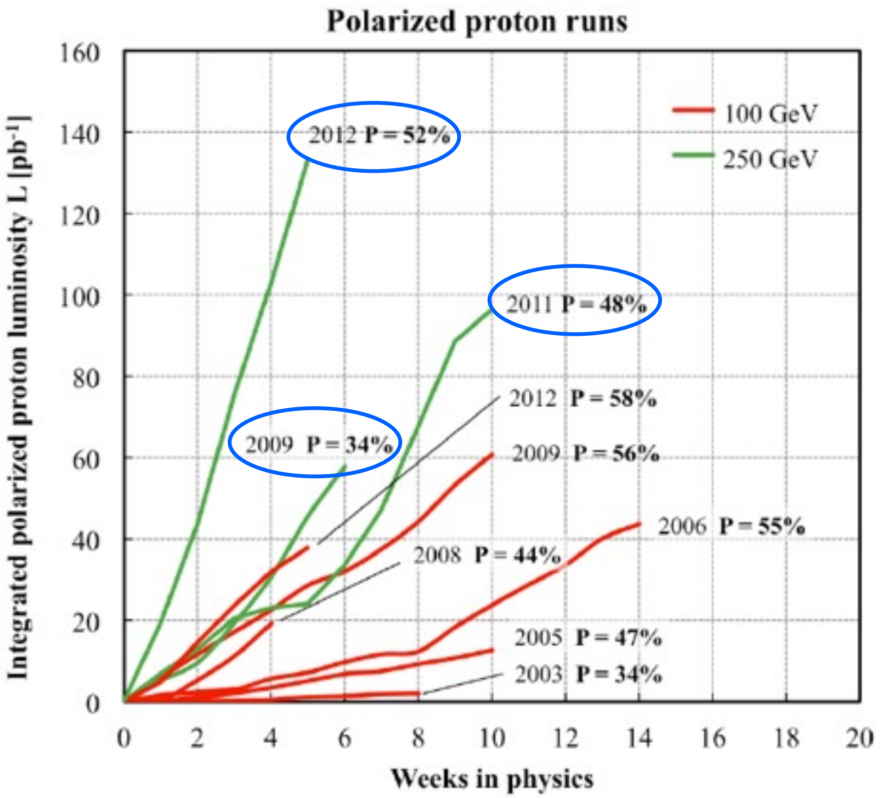
Plot by Hideyuki Oide

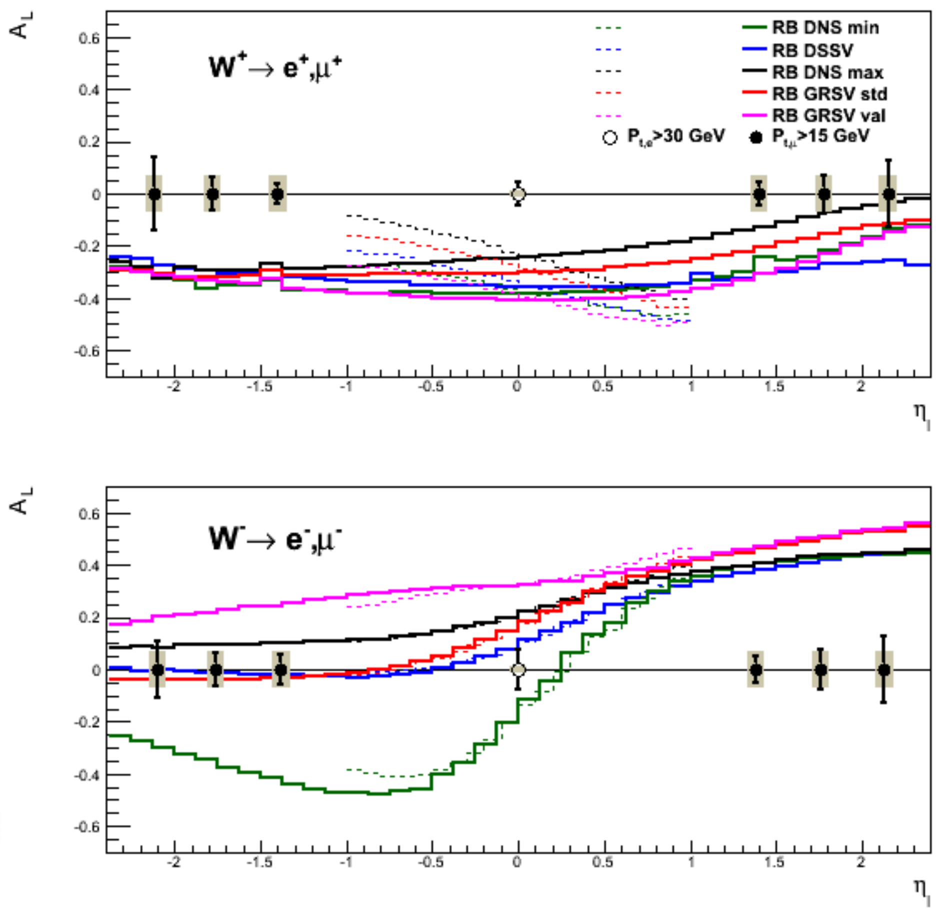
Analysis is underway towards final results

W measurement Run13 Projections

Goal : 250 pb^{-1} on tape ($-30<z_{vtx}<30$cm)

Delivered Luminosity





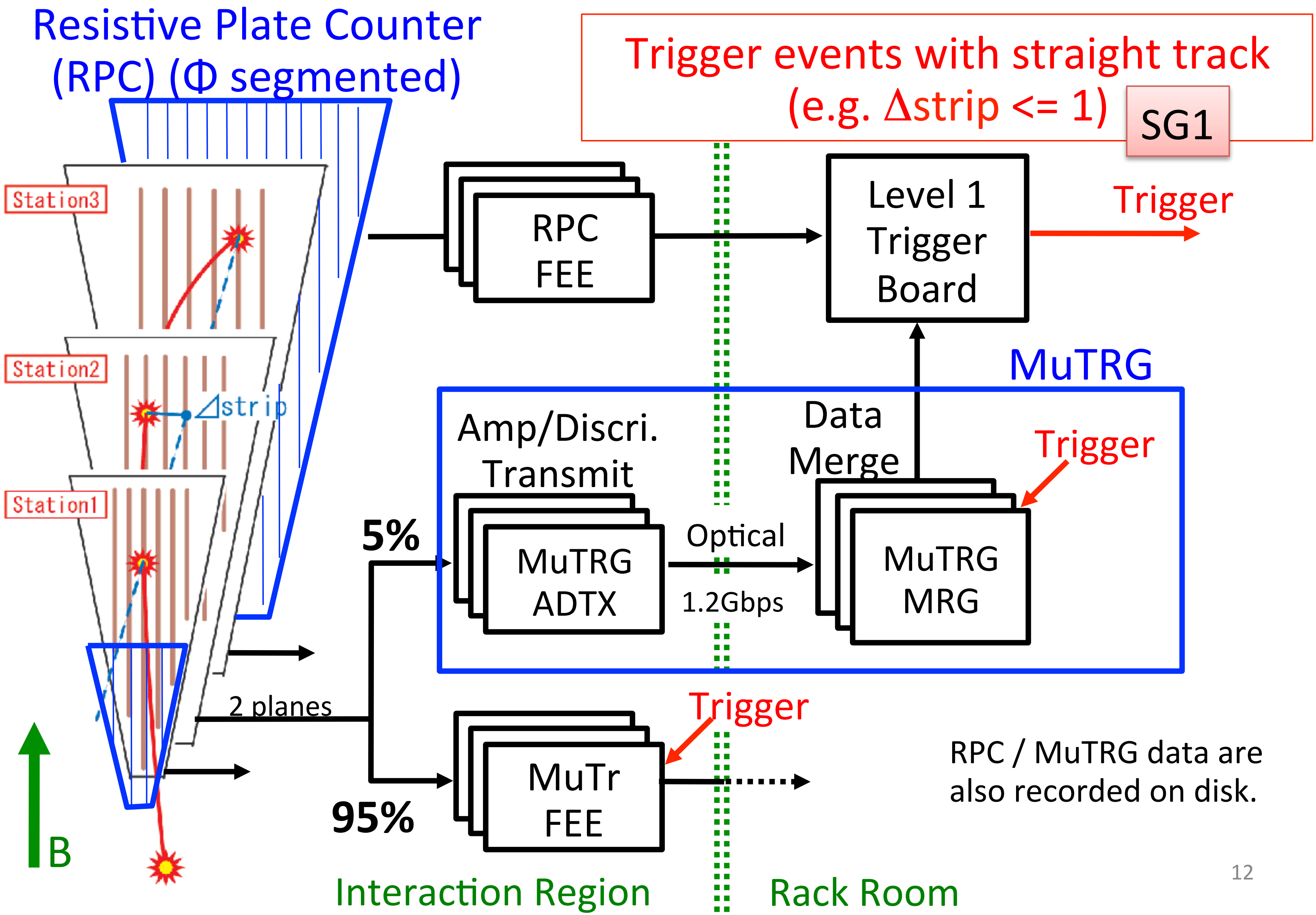
Improving Performance of RHIC

Summary

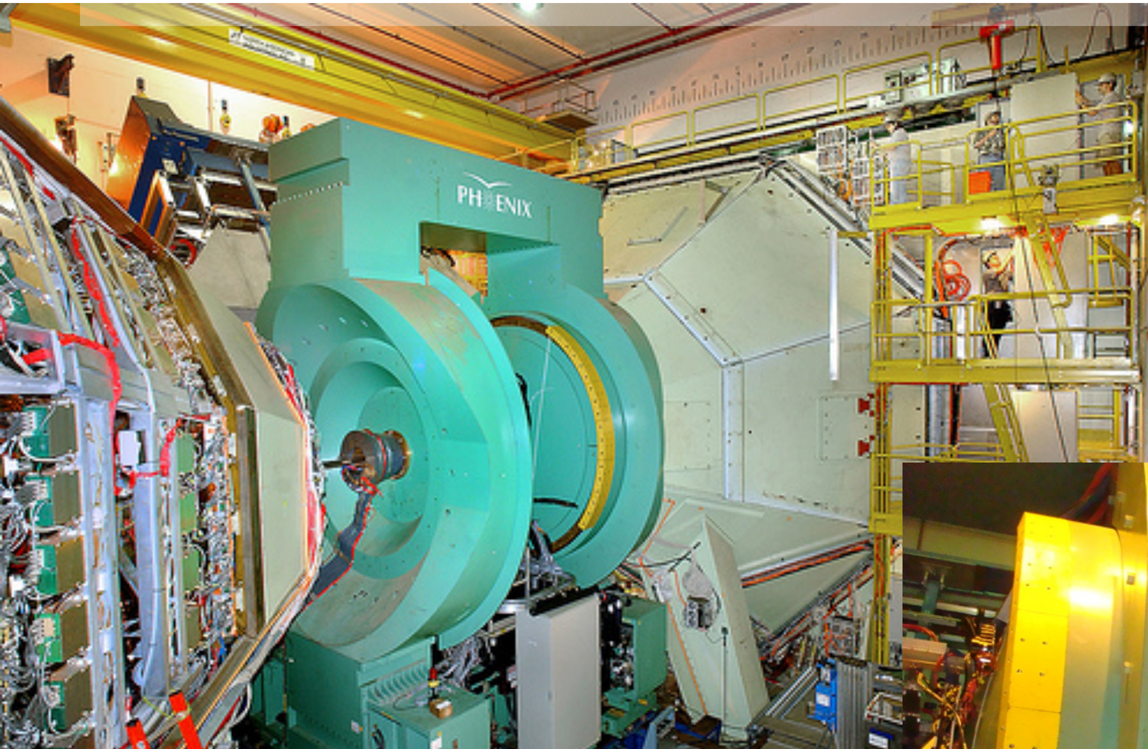
- Past several years, RBRC played key role to make W measurement feasible.
  - High Momentum Trigger (R&D, Production, Operation)
  - MC Simulation
  - Offline Analysis
- Run11 Results are close to be final
- Run12 analysis underway
- Significantly higher statistics Run13 to achieve our goal.

BACKUP SLIDES

W Trigger System

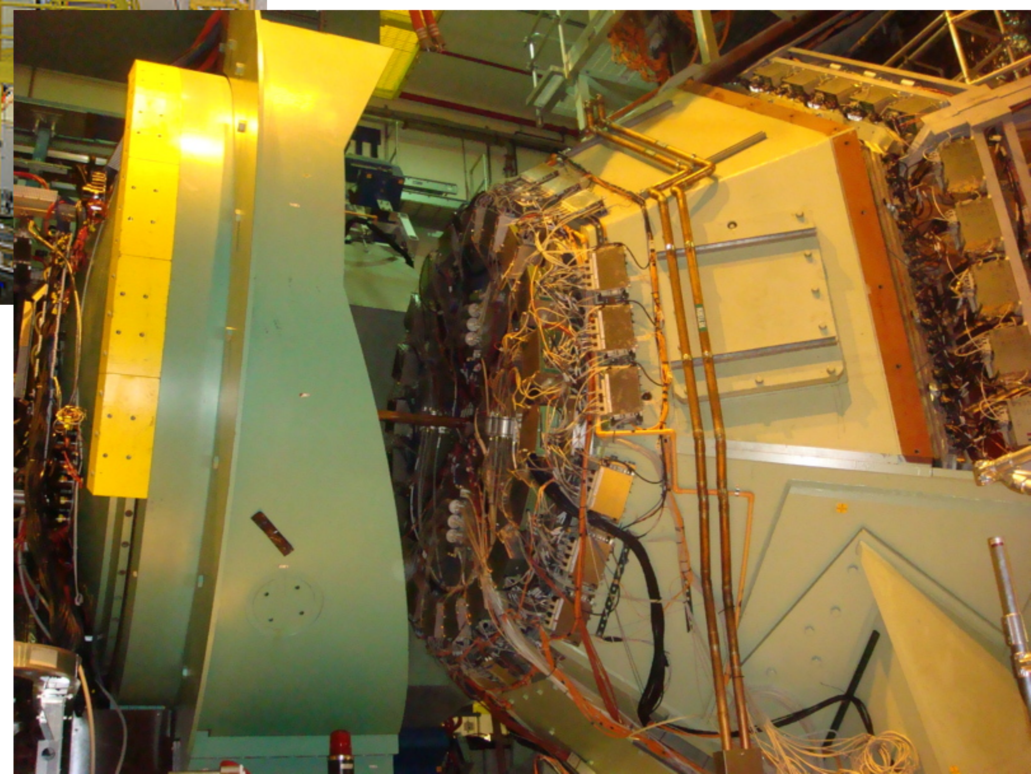


New MuTRIG-FEE in North Arm

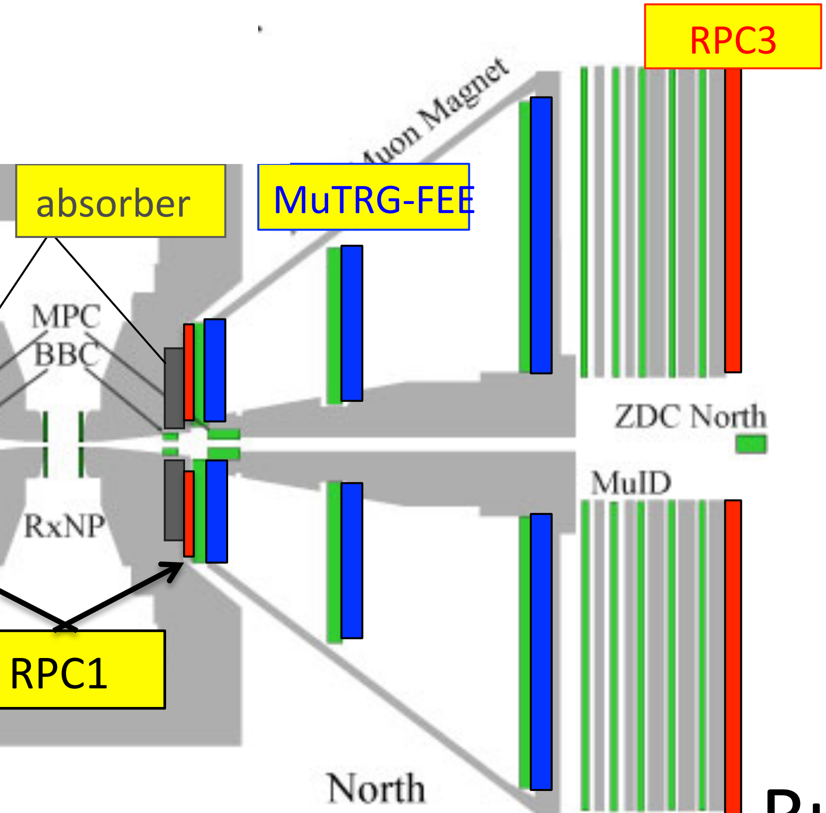


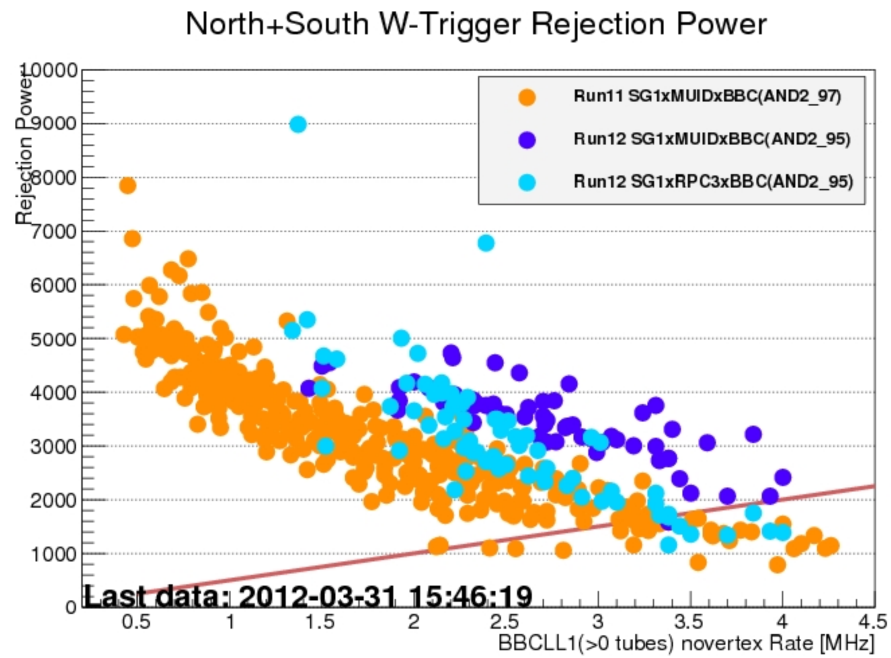
↑ Before Install

2008 Install→



MuTrig-FEE Run11/Run12 Reiection



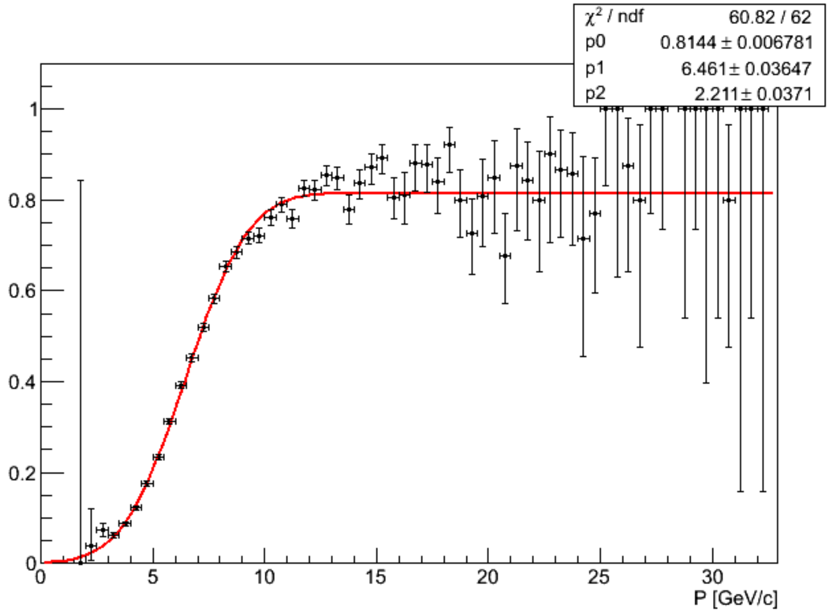


Run11 : SG1 x MuID x BBC

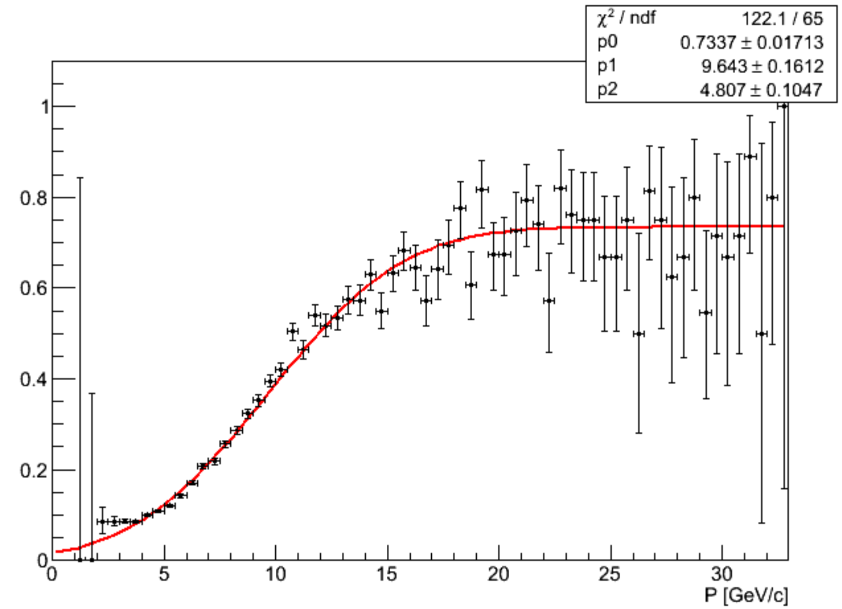
Run12 : SG1 x RPC3 x BBC

Run13 : SG1 x RPC1 x RPC3 x BBC

SG1 Efficiency



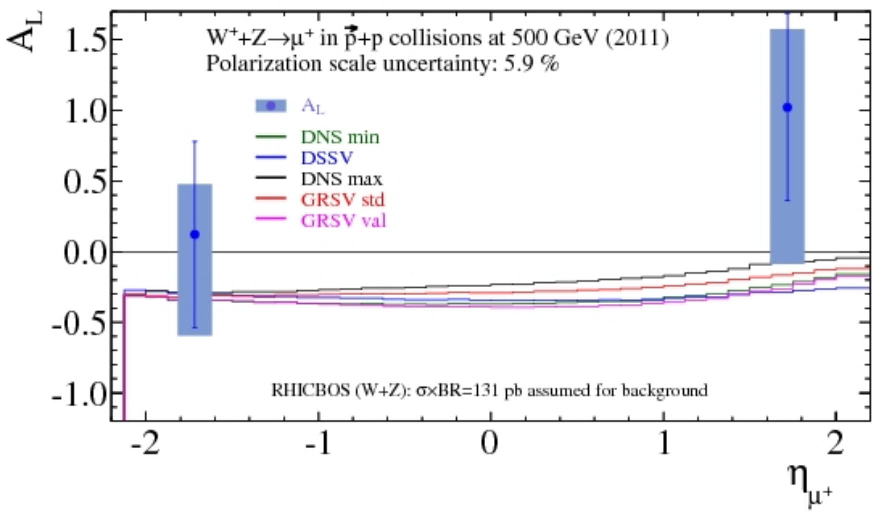
SG1 South Trigger Efficiency

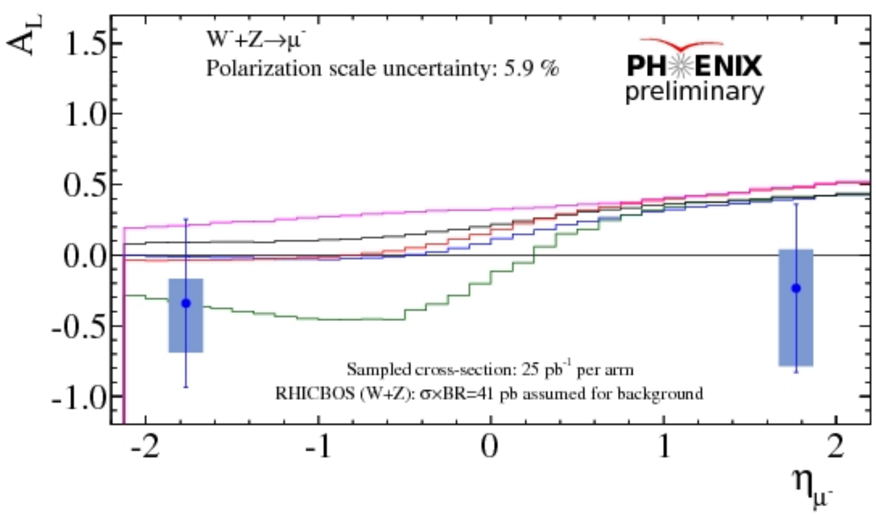


SG1 North Trigger Efficiency

Arm	Efficiency at Plateau [%]	Turn-on Point [GeV/c]
South	81.4	6.5
North	73.4	9.6

First Forward Rapidity A_L^W





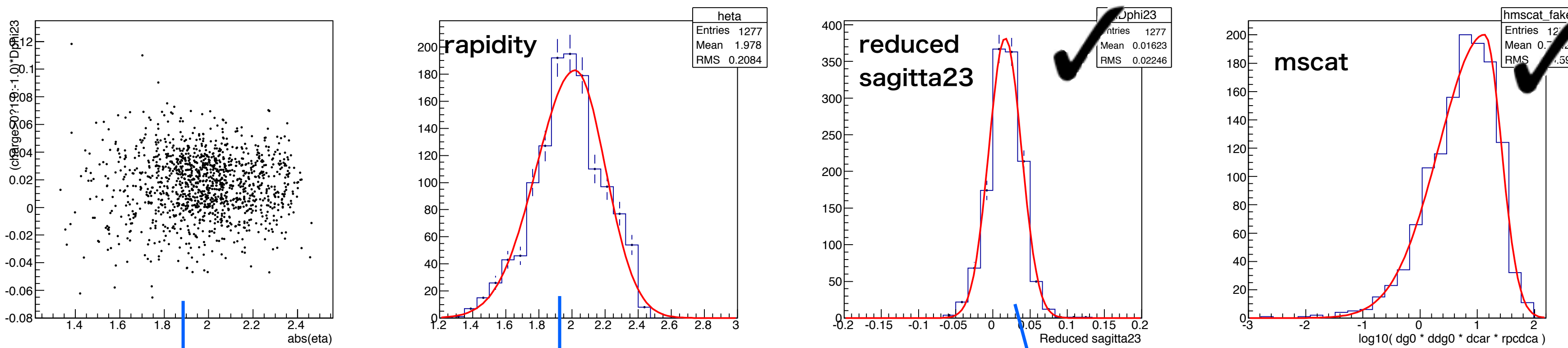
The first W asymmetry measurement in forward rapidity

The statistical precision will be improved in Run11, Run12

Run	Integ. Lumi [pb^{-1}]
11	30
12	50
13	250

Hadron BG distribution

Last week: applied simulation-based distribution

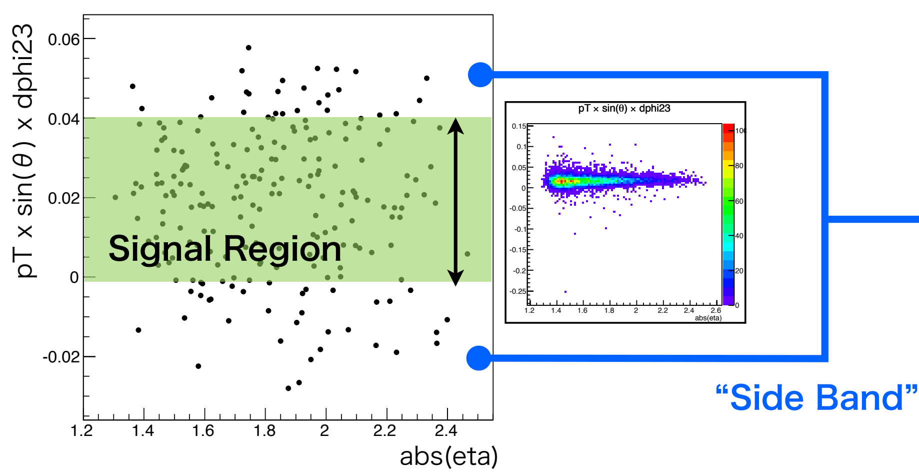


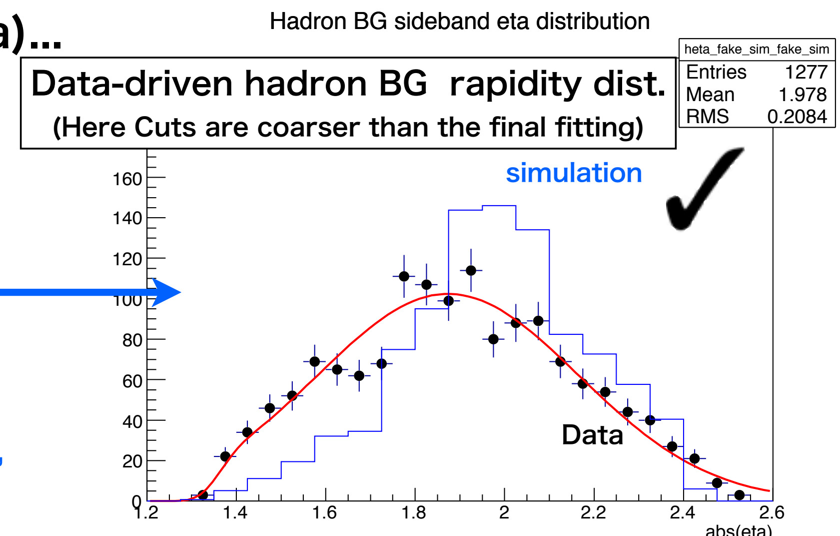
Indication: weak correlation between eta and dphi23

Still, reliability of eta distribution is not so clear.

The width basically agreed between data (prev. page)

Looking at signal candidates (real data)...





Inclusive cross section and single transverse-spin asymmetry of very forward neutron production

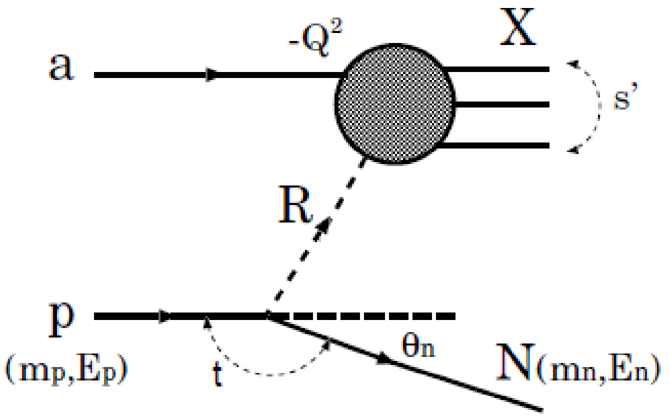
RBRC-SRC Meeting

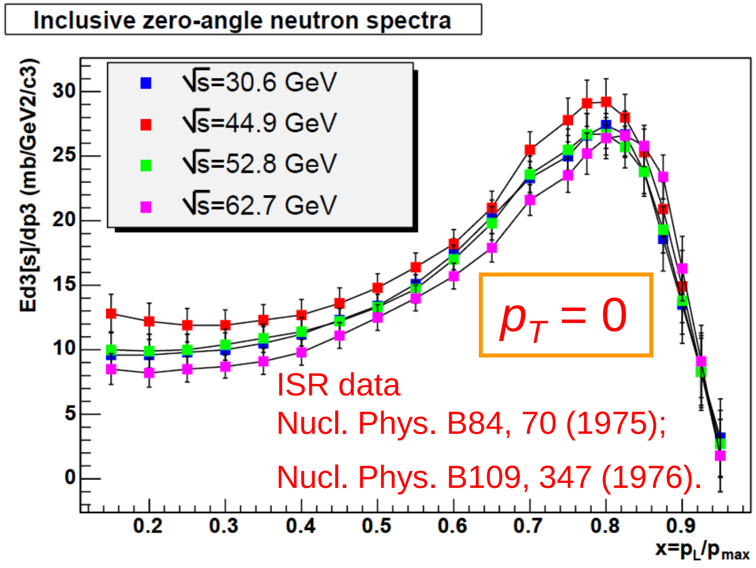
November 7th, 2012

Yuji Goto (RIKEN)

Forward neutron production

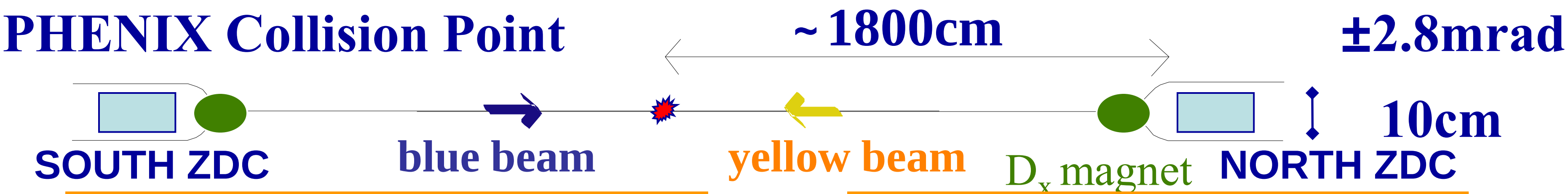
- Cross section measurement at ISR/FNAL
  - Forward peak in the x_F distribution
    - around x_F~0.8
  - Only a small √s dependence
- OPE (one-pion exchange) model gives a reasonable description
- Cross section measurement at HERA(e+p)/NA49(p+p)
  - √*s* dependence indicated
  - Suppression of the forward x_F peak at high √*s*?
- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input
  - Local polarimeter to monitor beam polarization and polarization direction





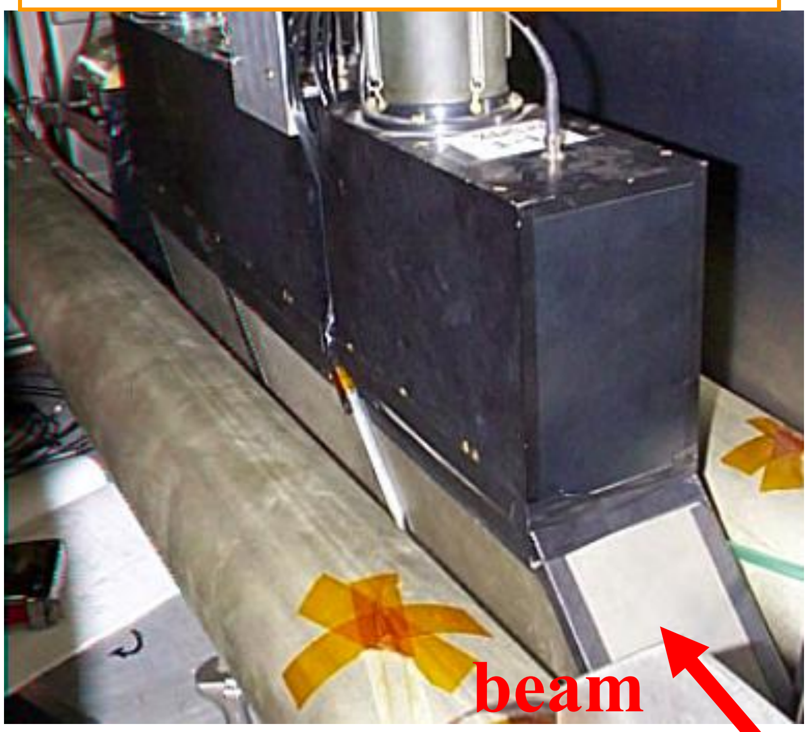
Cross section and single transverse-spin asymmetry measurements at PHENIX: arXiv:1209.3283 [nucl-ex].

PHENIX ZDC and SMD



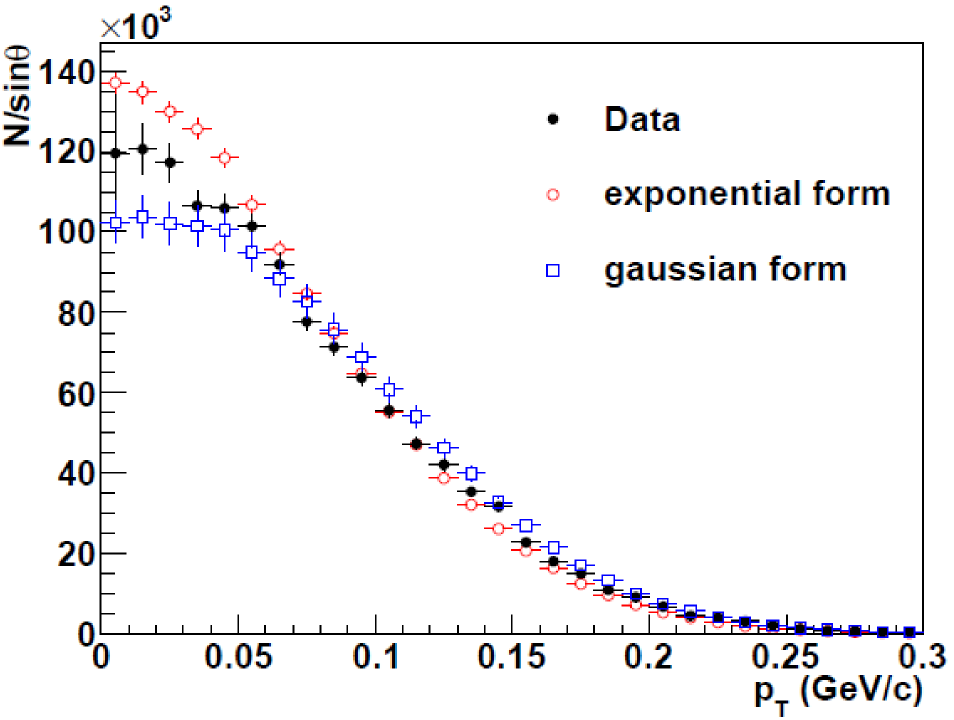
ZDC (Zero Degree Calorimeter)
hadron sampling calorimeter made of Tungsten plate and fibers
$5.1\lambda_T$ $149X_0$ (3 ZDCs)
energy resolution ~ 20% @ 100GeV

SMD (Shower Maximum Detector)
x: segmented by 7
y: segmented by 8
position resolution ~1cm
@ 50GeV neutron (simulation study)



Inclusive cross section at $\sqrt{s}$ = 200 GeV

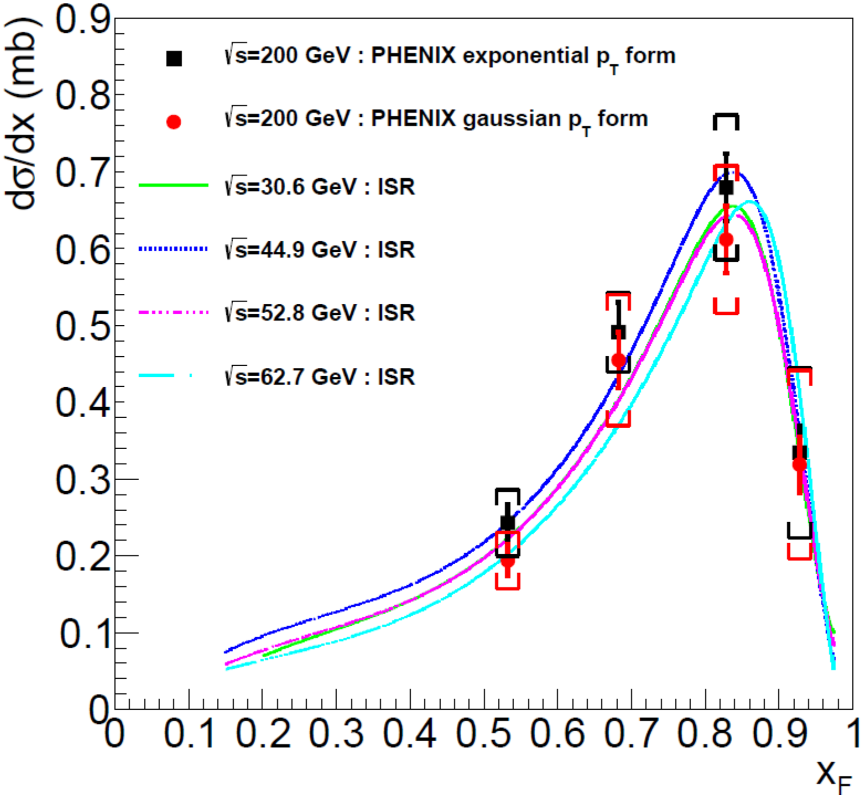
- x_F distribution measurement
  - With hadron calorimeter
- p_T range & resolution limited
  - $0 < p_T < 0.11\ x_F$ GeV/c
  - Limited by ZDC acceptance
  - Limited by SMD position resolution
- p_T shape assumed
  - gaussian form (HERA form)
  - exponential form (ISR form)
- Comparison of p_T distribution from experimental data and two simulations including p_T resolution



Difference between data and two simulations are not large

Inclusive cross section at √s = 200 GeV

- Systematic uncertainties
  - p_T distribution form
  - Beam center shift
    - Possible ~1 cm shift
  - Proton background
    - Scattered forward proton could hit the DX magnet or beam pipe
  - Multiple hit
- Absolute normalization
  - 9.7% (22.9±2.2 mb for the BBC trigger cross section)
- Energy unfolding
  - ref. V. Blobel, arXiv:hep-ex/0208022

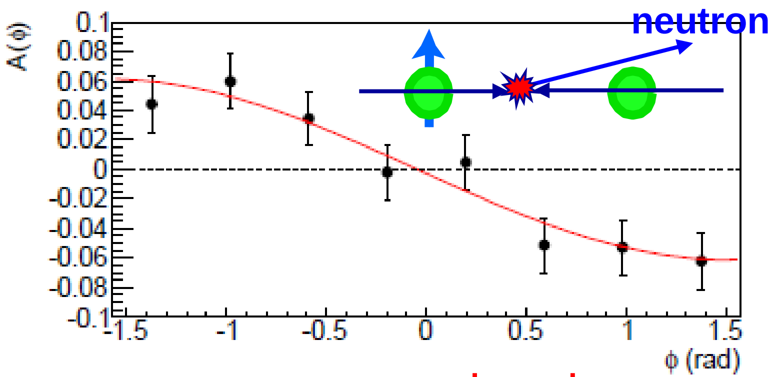


Consistent with x_F scaling from ISR results

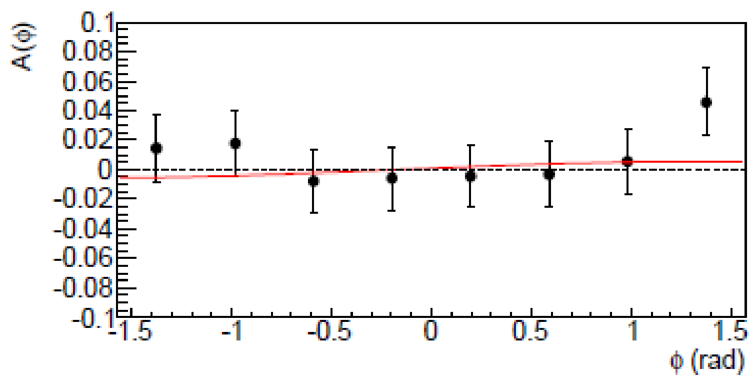
Single transverse-spin asymmetry at $\sqrt{s}$ = 200 GeV

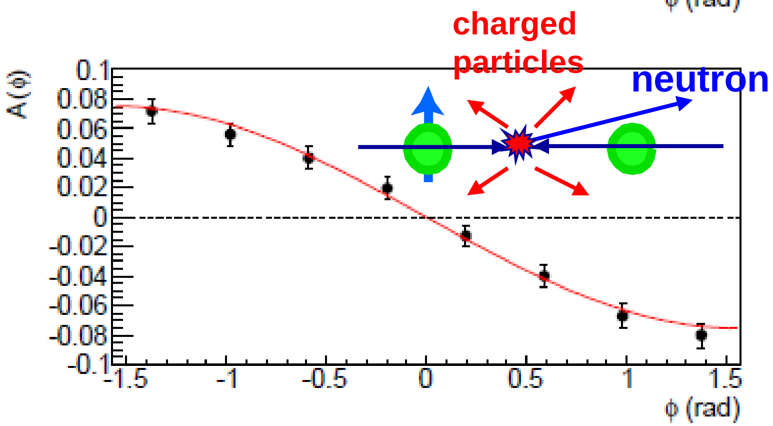
Inclusive neutron trigger (ZDC trigger)

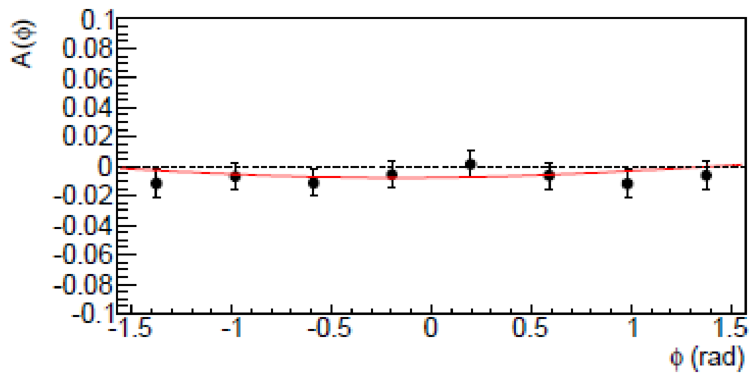
Forward asymmetry
$A_N = -0.061 \pm 0.010(\text{stat}) \pm 0.004(\text{syst})$



Backward asymmetry
$A_N = -0.006 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$







Interaction trigger with charged particles in beam-beam counter (ZDC⊗BBC trigger)

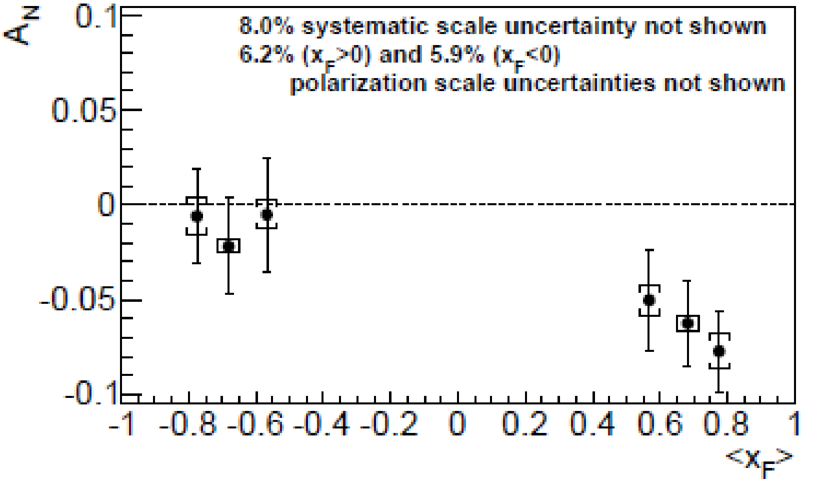
Forward asymmetry
$A_N = -0.075 \pm 0.004(\text{stat}) \pm 0.004(\text{syst})$

Backward asymmetry
$A_N = -0.008 \pm 0.005(\text{stat}) \pm 0.004(\text{syst})$

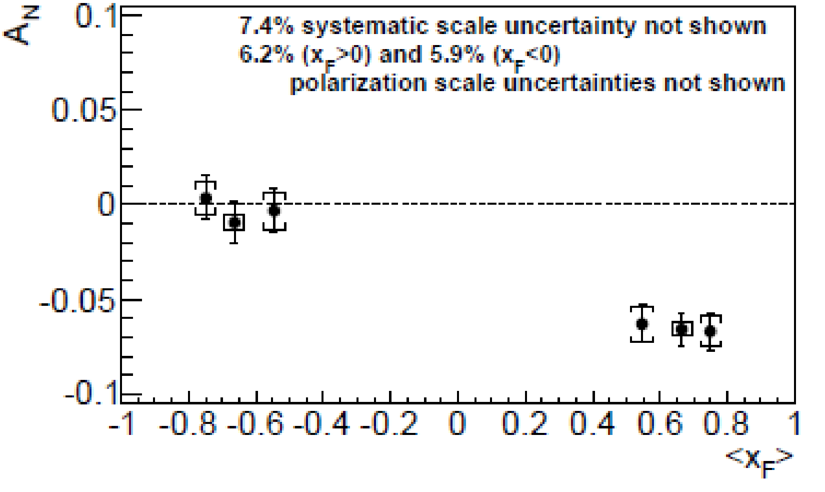
Single transverse-spin asymmetry at $\sqrt{s}$ = 200 GeV

- Comparison to IP12 experiment
  - ZDC⊗BBC trigger results
  - PHENIX
    - $A_N = -0.075 \pm 0.004(\text{stat}) \pm 0.004(\text{syst})$
  - IP12
    - $A_N = -0.090 \pm 0.006(\text{stat}) \pm 0.009(\text{syst})$
  - Consistent within the errors
  - Higher precision
- x_F dependence
  - Significant negative A_N in the forward region
    - No x_F dependence within the uncertainties
  - No significant backward asymmetry

ZDC trigger



ZDC⊗BBC trigger

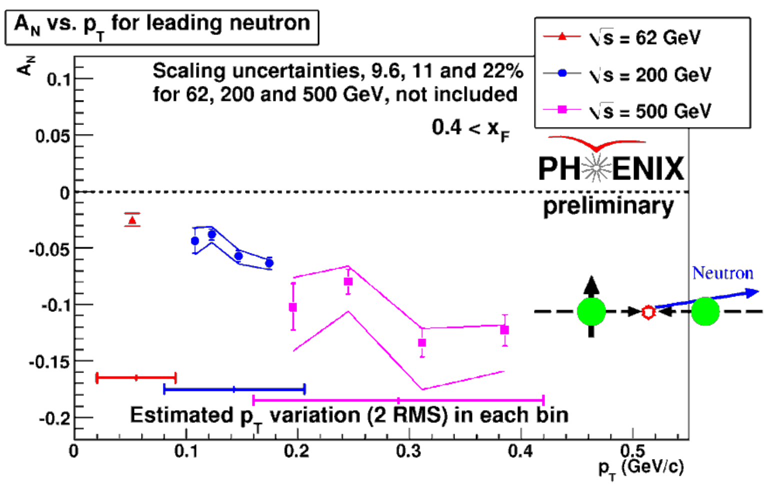


√s dependence

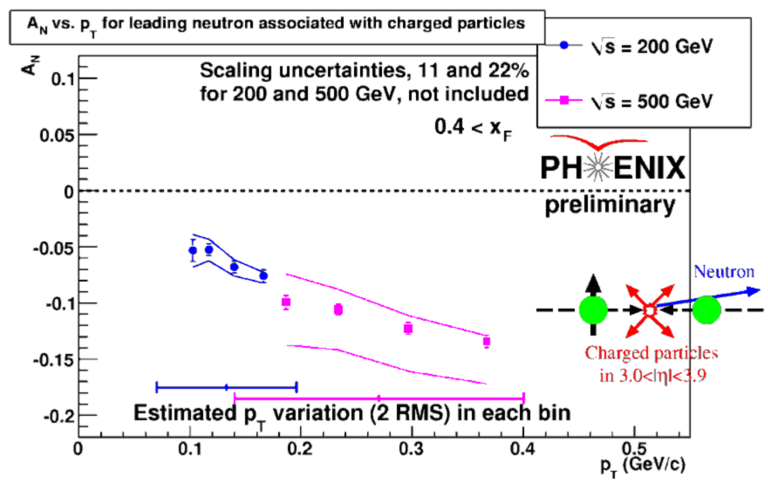
- p_T distribution
  - $p_T \sim x_F \cdot \sqrt{s} / 2 \cdot \theta$
  - Assuming p_T shape of ISR
  - No smearing correction (no-unfolding)
    - wide p_T deviation for each bin

PHENIX preliminary data
J. Phys. Conf. Ser. 295, 012097 (2011).

Inclusive neutron



Neutron with charged particles



- A_N(62 GeV) < A_N (200 GeV) < A_N (500 GeV)
- √s dependence or p_T dependence?

Forward neutron production

- Interference between spin-flip and non-flip with a relative phase

$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{|f|^2 + |g|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

- Pion exchange
  - Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 78 (2008) 014031.
  - Spin-flip amplitude and non-flip amplitude have the same phase
    - No single transverse-spin asymmetry can appear
  - Absorption correction for a relative phase
    - Initial/final state interaction
    - Also important for cross section calculation
    - Gained shift between spin-flip and non-flip amplitudes is too small to explain the large asymmetry
- Interference with other Reggeons
  - Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012.
  - a_1 axial-vector meson
    - Pion-a_1 interference
    - π-ρ in 1^+S state instead of a_1

Forward neutron production

- Pion-a_1 interference: results
  - The data agree well with a linear dependence on q_T and indicate an energy-independent A_N
- The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012.

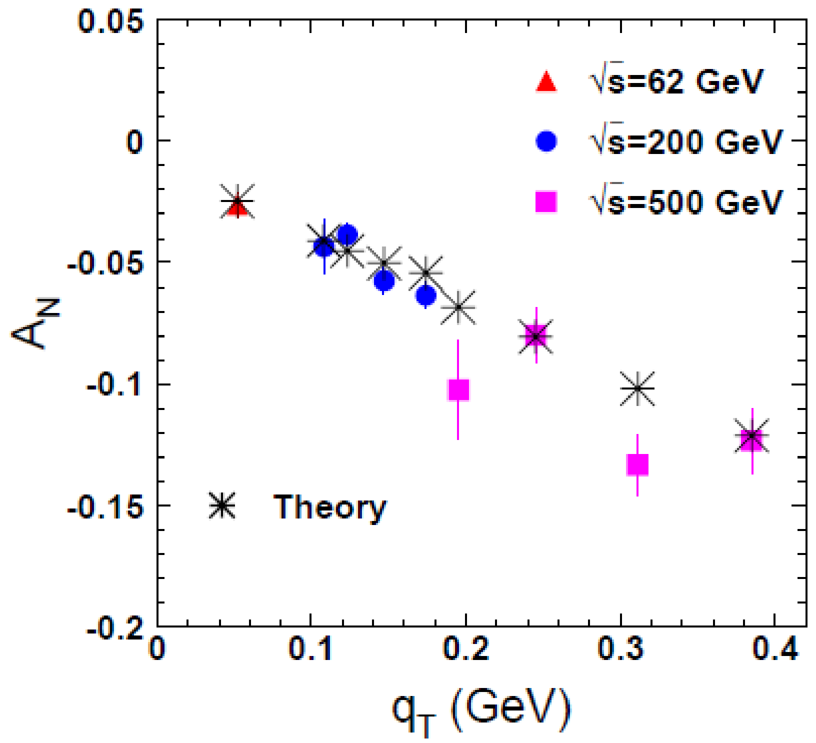
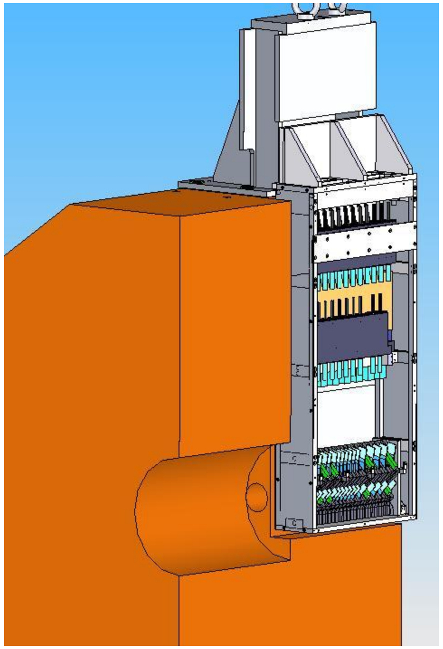
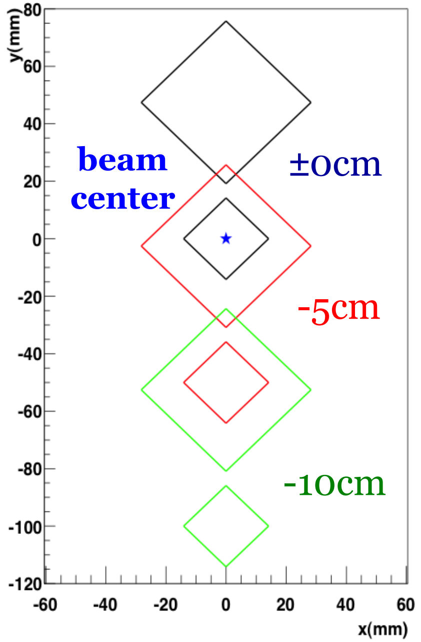


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

Future outlook

- Possible collaboration with LHCf experiment
  - Interest in understanding air-shower development of very-high energy cosmic-ray
  - EM calorimeter with good energy resolution and position resolution
  - Possible installation in front of ZDC at RHIC
  - Interest in d-N (or p-N) collisions
- New collaborators are very welcome





Summary

- Very forward (and backward) neutron production in polarized *p+p* collisions at PHENIX
  - Inclusive cross section at $\sqrt{s}$ = 200 GeV
    - consistent with x_F scaling from ISR results
  - Single transverse-spin asymmetry at $\sqrt{s}$ = 200 GeV
    - consistent with IP12 measurement with higher precision
    - x_F dependence
  - Single transverse-spin asymmetry at $\sqrt{s}$ = 62.4 GeV, 200 GeV and 500 GeV
    - $\sqrt{s}$ dependence or p_T dependence
- Production mechanism
  - Pion-a_1 interference (Kopeliovich et al.)
  - Sensitivity of asymmetry measurement to presence of different mechanism
- Future outlook
  - Possible collaboration with LHCf experiment
  - Diffraction physics with central detectors and Roman-pot option

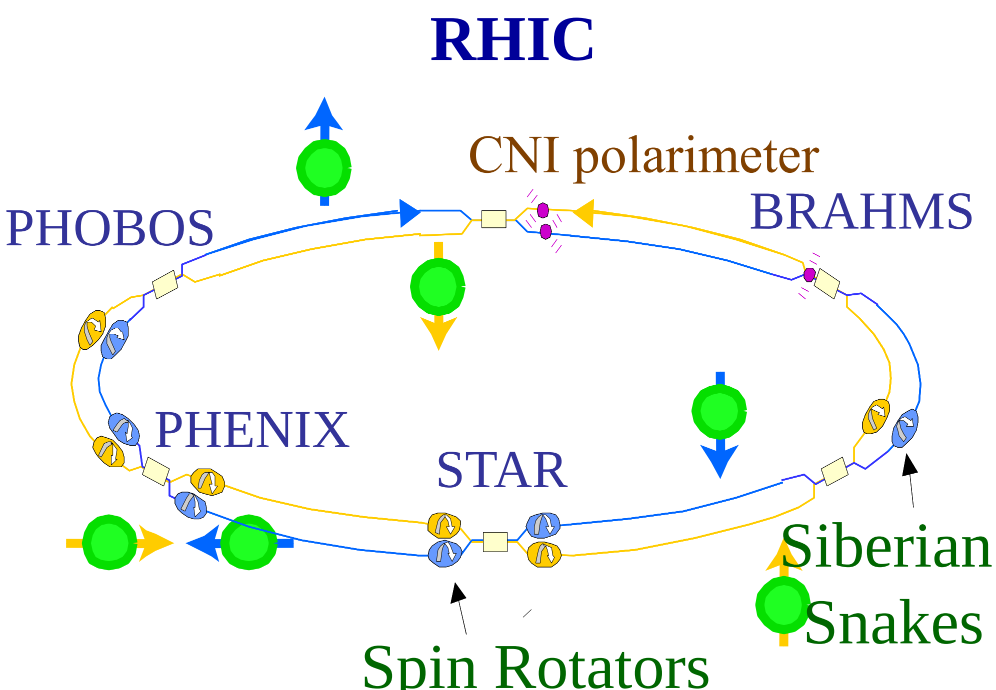
Backup Slides

Outline

- Very forward (and backward) neutron production in polarized *p+p* collisions at RHIC-PHENIX
- Inclusive cross section and single transverse-spin asymmetry at $\sqrt{s}$ = 200 GeV
  - x_F dependence
  - 2005 result
  - arXiv:1209.3283 [nucl-ex]
- Single transverse-spin asymmetry at $\sqrt{s}$ = 62.4 GeV, 200 GeV and 500 GeV
  - $\sqrt{s}$ dependence
  - 2006 (62.4 GeV) & 2009 (500 GeV) preliminary results

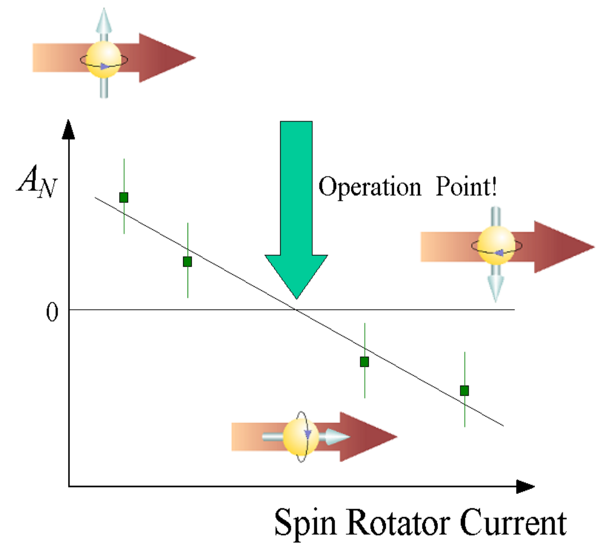
Introduction

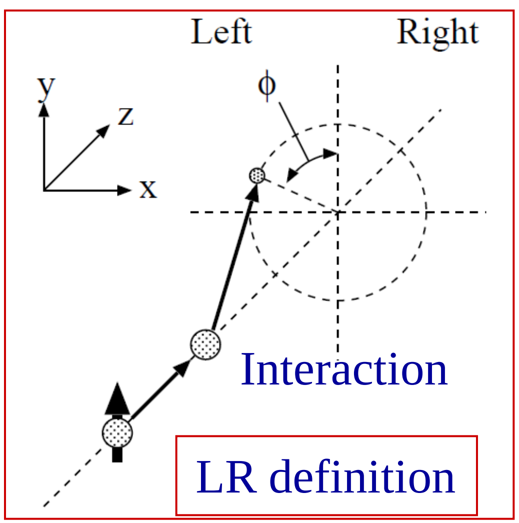
- For A_{LL} measurement at RHIC, we need a good local polarimeter at the IP (interaction point)
- At RHIC, protons are stored with transverse polarization
  - Monitored by the CNI polarimeter and polarized Hydrogen gas-jet polarimeter
- Spin rotator magnets rotate the proton polarization into the longitudinal direction at PHENIX (IP8) and STAR (IP6)



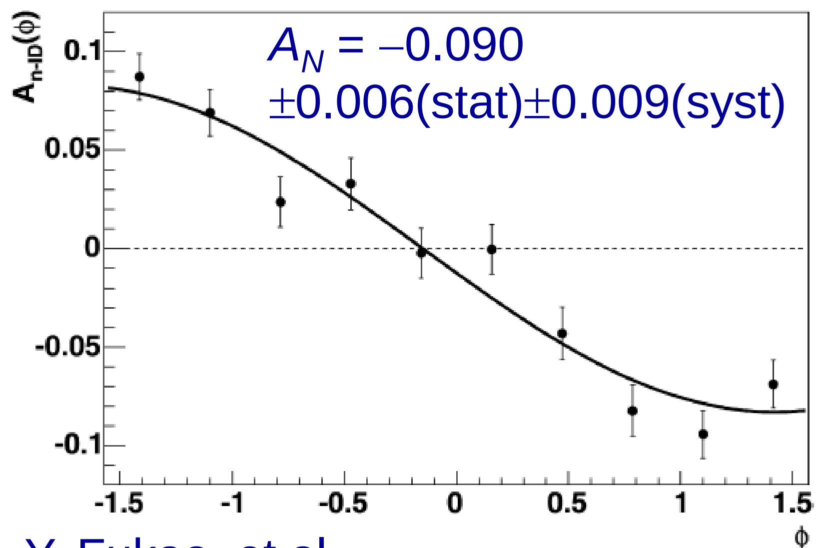
Introduction

- Longitudinal-spin is monitored by the local polarimeter by using physics processes with left-right asymmetry (A_N)
- A_N of forward π^0 found at FNAL-E704
  - Only very forward region was available at PHENIX
  - But, there was no measurement at very forward
- Measurement at IP12 in Run2 (2001-02)
  - With EM calorimeter to measure A_N of photons mainly from π^0 decay $\rightarrow$ too small to measure
  - Very large asymmetry of very forward neutron was found





$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$

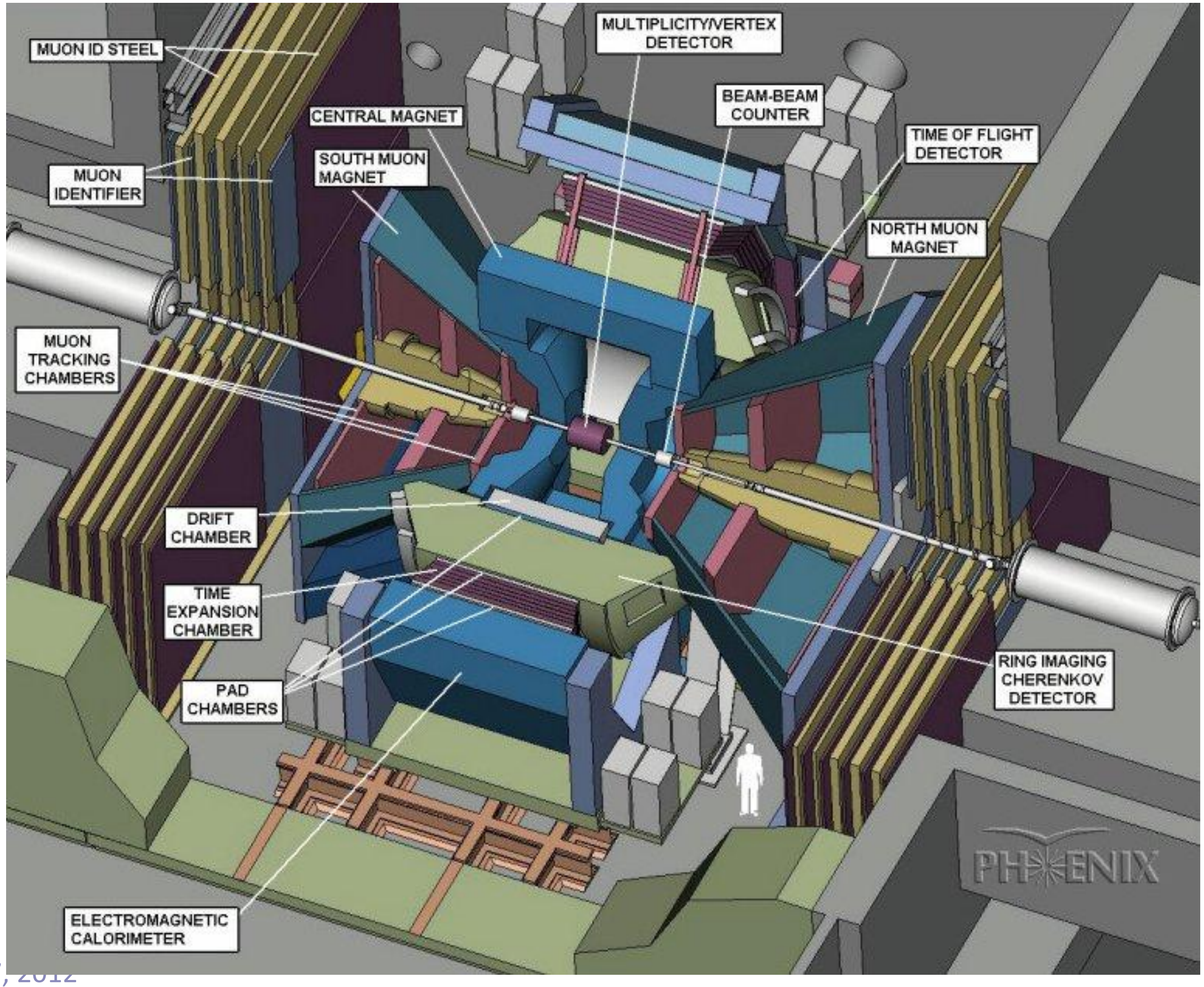


Y. Fukao, et al.,
Phys. Lett. B 650 (2007) 325.

PHENIX local polarimeter

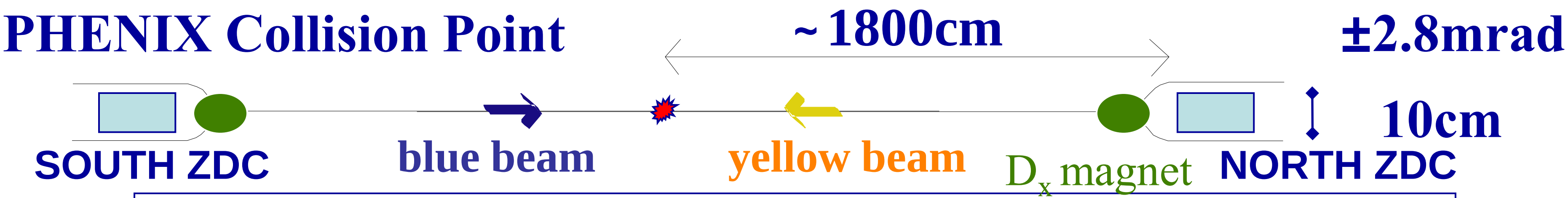
- There have existed ZDCs (Zero Degree Calorimeter) to detect neutrons at PHENIX
- SMDs (Shower Maximum Detector) were added to measure the hit position of neutrons

ZDC



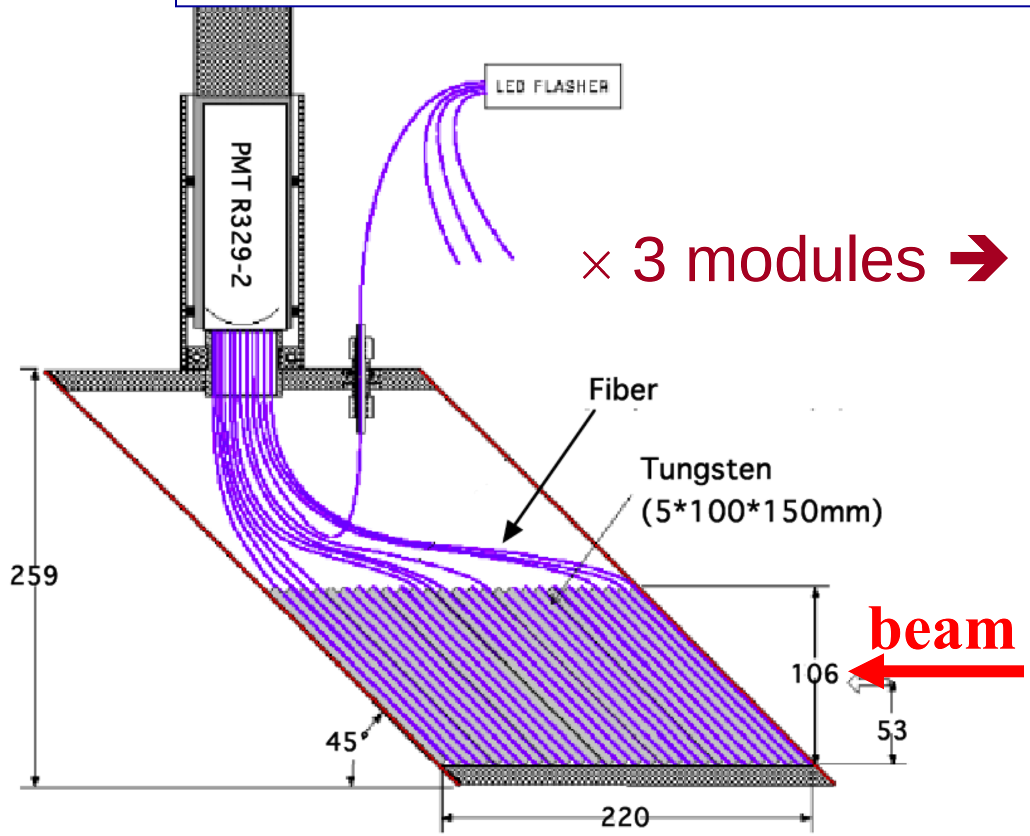
ZDC
@ 18m away from the IP

ZDC (Zero Degree Calorimeter)

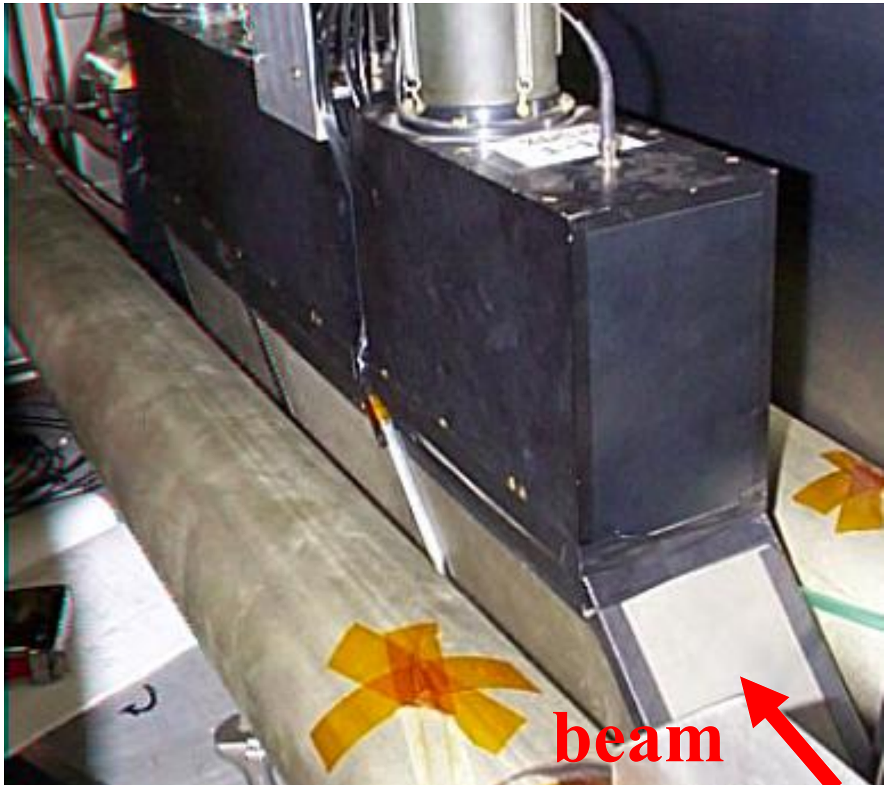


hadron sampling calorimeter made of Tungsten plate and fibers

5.1λ_T 149X_0 (3 ZDCs), Energy resolution ~ 20% @ 100GeV

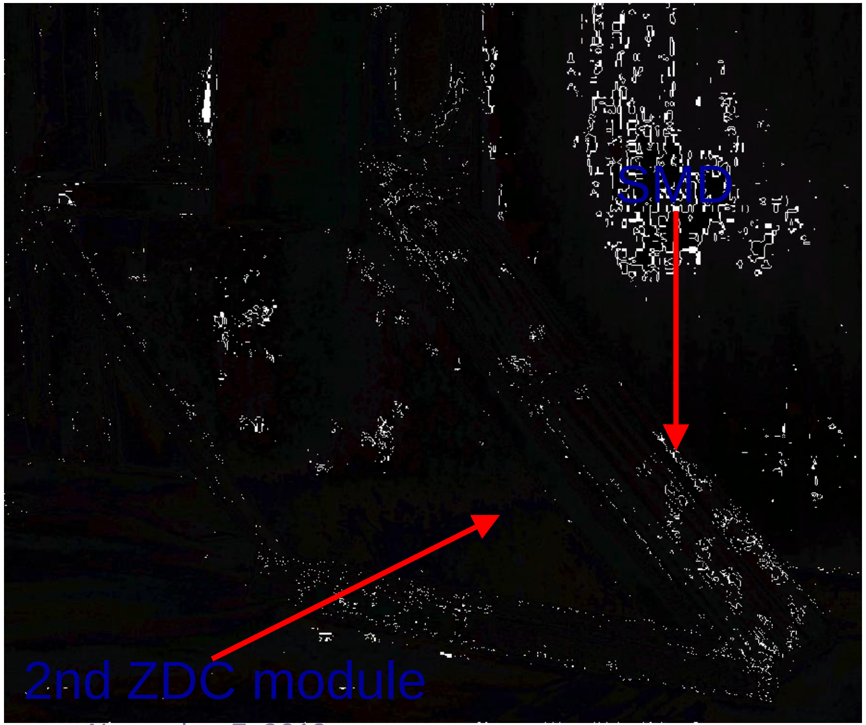


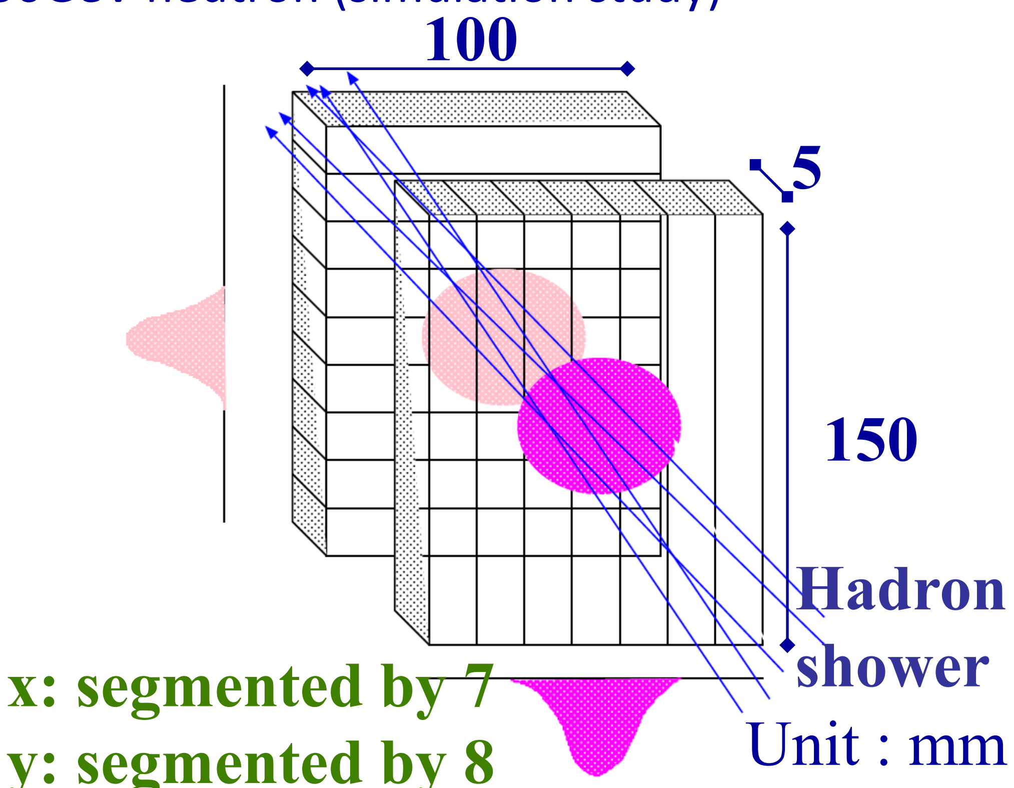
× 3 modules →



Shower Maximum Detector

- To measure the neutron hit position, SMDs (Shower Maximum Detector) were installed between 1st and 2nd modules of ZDC
  - arrays of plastic scintillators
  - giving a position by calculating the center of gravity of shower generating in the 1st ZDC module
  - position resolution ~1cm @ 50GeV neutron (simulation study)



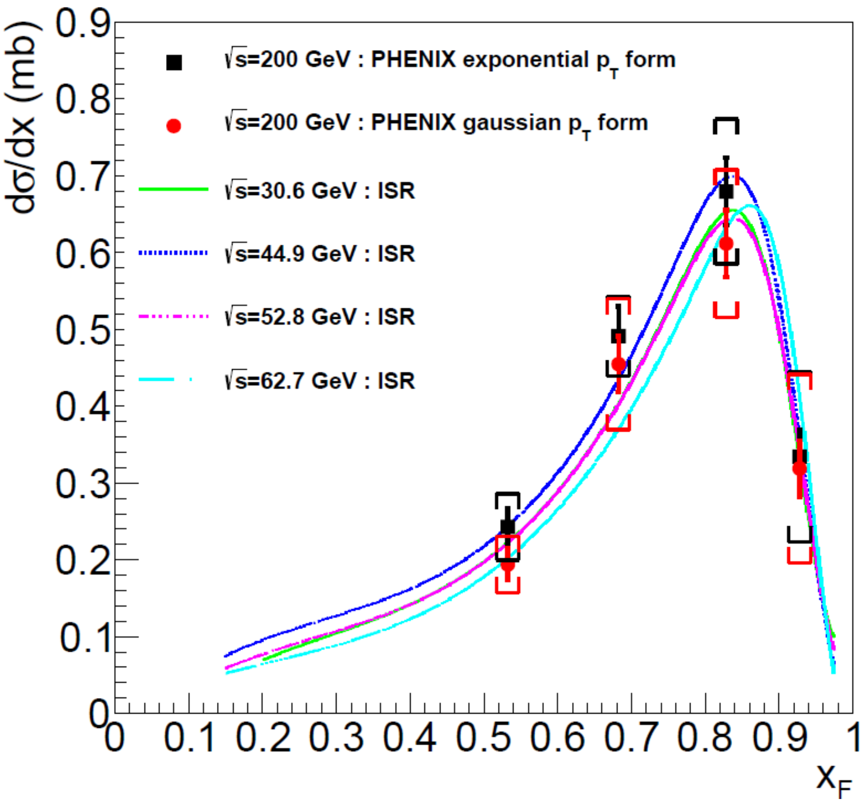


Inclusive cross section at √s = 200 GeV

- Systematic uncertainties
  - p_T distribution form
  - Beam center shift
    - Possible ~1 cm shift
  - Proton background
    - Scattered forward proton could hit the DX magnet or beam pipe
  - Multiple hit
- Absolute normalization
  - 9.7% (22.9±2.2 mb for the BBC trigger cross section)
- Energy unfolding
  - ref. V. Blobel, arXiv:hep-ex/0208022

TABLE II: Systematic uncertainties for the cross section measurement. The absolute normalization error is not included in these errors. The absolute normalization uncertainty was estimated by BBC counts to be 9.7% (22.9±2.2 mb for the BBC trigger cross section).

	exponential p_T form	Gaussian p_T form
p_T distribution	3 – 10%	7 – 22%
beam center shift	3 – 31%	
proton background	3.6%	
multiple hit	7%	
total	11 – 33%	16 – 39%



Consistent with x_F scaling from ISR results

Single transverse-spin asymmetry at √s = 200 GeV

- Square-root formula
  - *P*: polarization, C_ϕ: smearing correction
  - sine fit → A_N
- Systematic uncertainties
  - p_T correlated
    - Beam center shift
  - Scale uncertainties
    - Proton background
    - Multiple hit
    - Smearing by position resolution
- Polarization scale uncertainties from RHIC polarimeters
  - 6.2% for the Yellow beam
  - 5.9% for the Blue beam

$$\epsilon_N(\phi) = \frac{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} - \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} + \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}$$

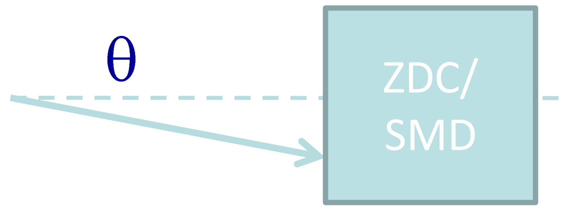
$$A(\phi) = \frac{1}{P}\frac{1}{C_\phi}\epsilon_N(\phi)$$

$$A(\phi) = A_N \sin(\phi - \phi_0)$$

TABLE IV: Scale uncertainties for the A_N measurements.

	ZDC trigger	ZDC⊗BBC trigger
proton background	2.1%	1.5%
multiple hit	6.5%	5.9%
smearing	4.2%	
total	8.0%	7.4%

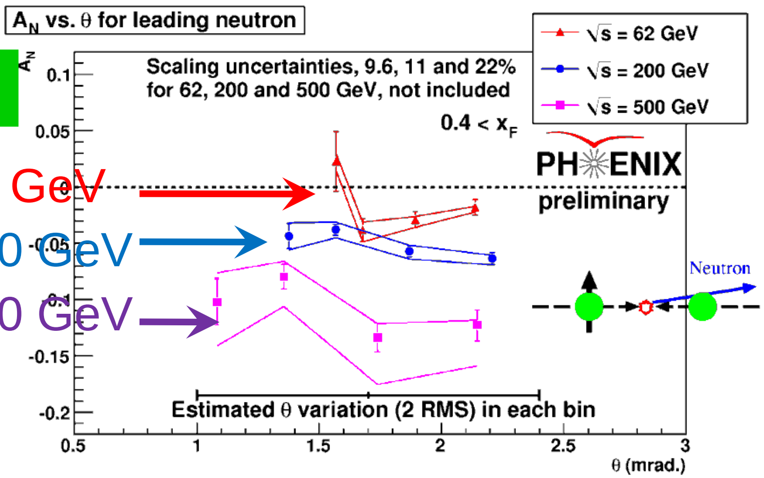
√s dependence

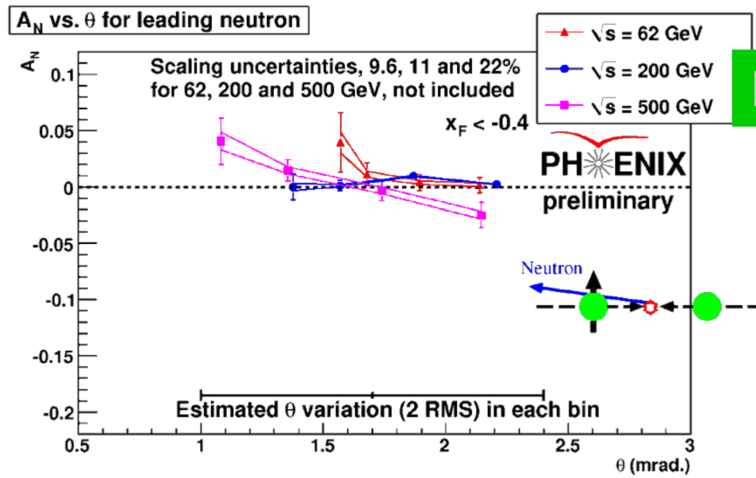


- *θ* distribution
  - Inclusive neutron

forward

√s = 62 GeV
√s = 200 GeV
√s = 500 GeV

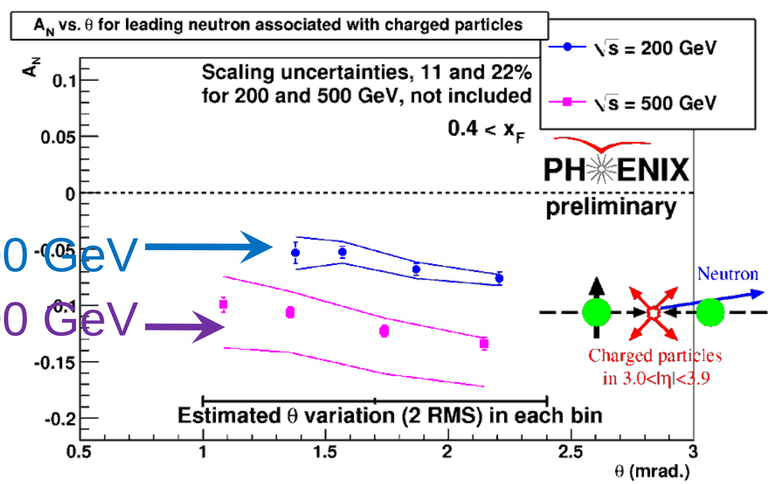


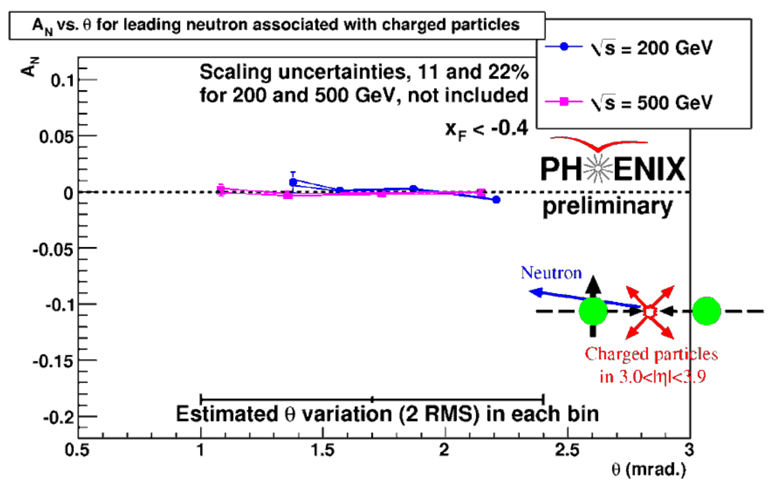


backward

  - Neutron with charged particles (in beam-beam counter)

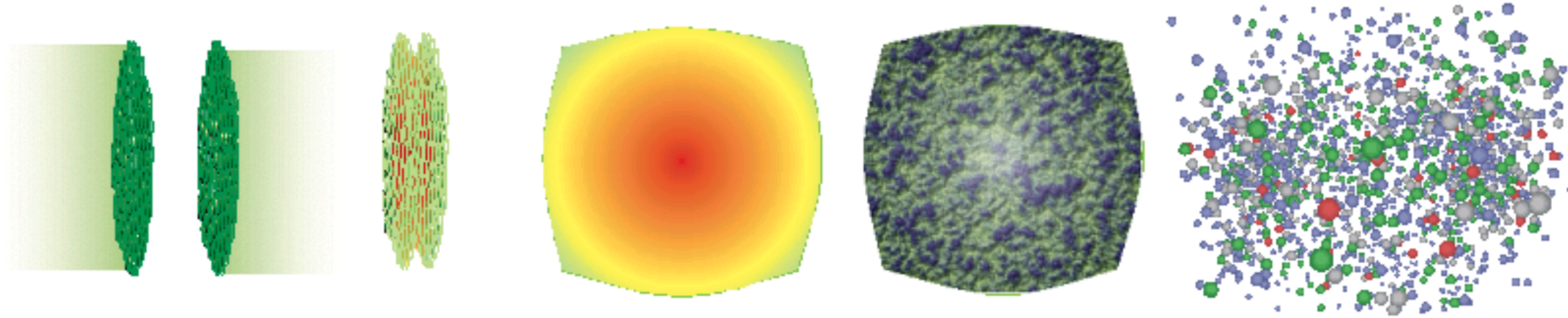
√s = 200 GeV
√s = 500 GeV





Theory at RBRC

I: QCD Matter at High Energy Density

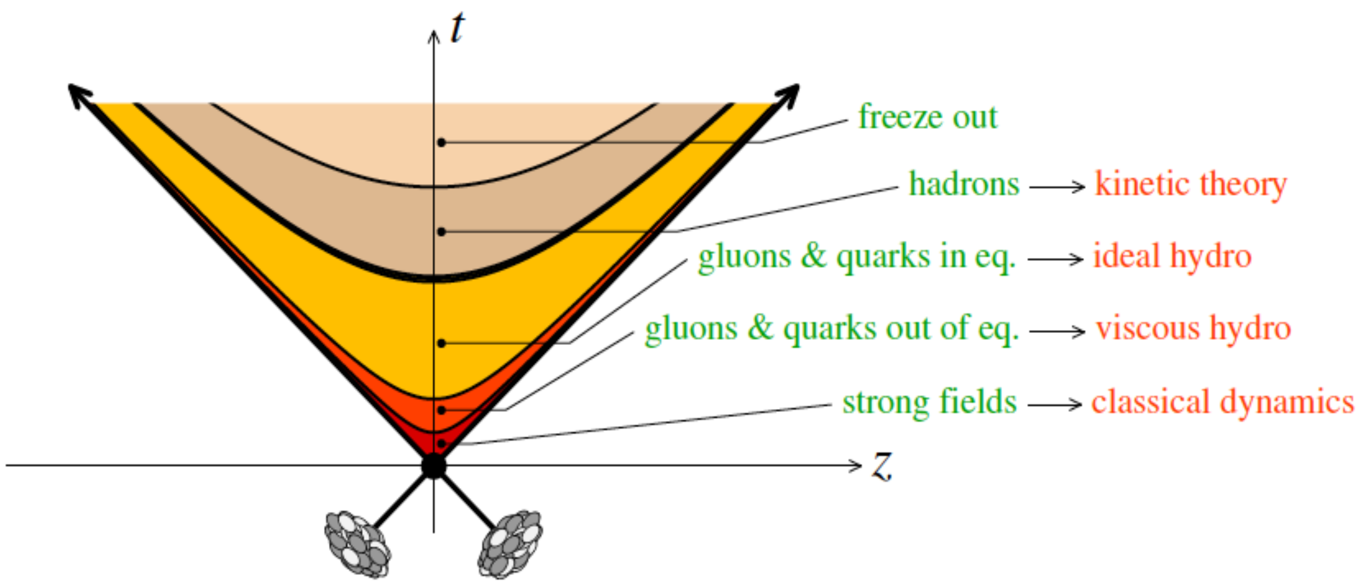


CGC | Initial Singularity | Glasma | Thermalized sQGP | Hadron Gas

<--------------sQGP ------------->

What are the properties of the CGC, the Glasma and the thermalized QGP?
When is the matter produced in heavy ion collisions a Glasma or a thermalized sQGP?

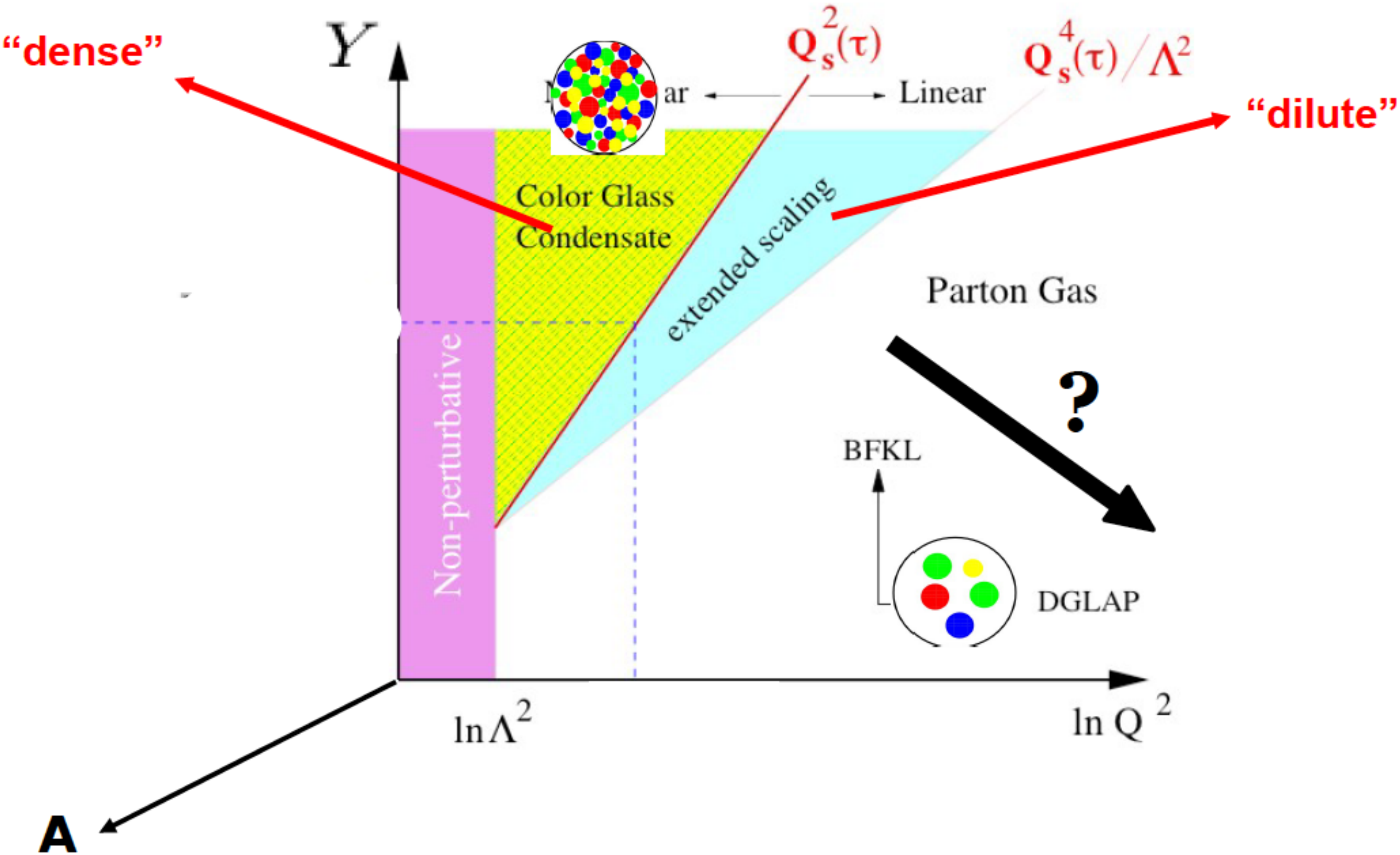
RIKEN BNL Research Center | RIKEN | RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG | HUAZHONG UNIVERSITY



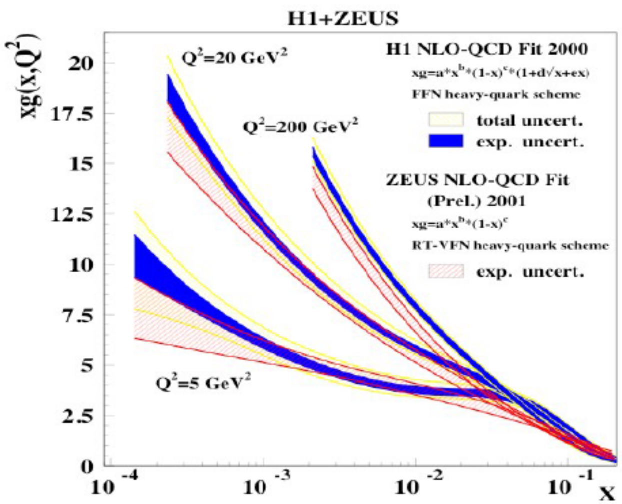
Color Glass Condensate:
The High Density Gluonic States of a high energy hadron that dominate high energy scattering.

Glasma:
Highly coherent gluon fields arising from the Glasma that turbulently evolve into the thermalized sQGP while making quarks

Thermalized sQGP:
Largely incoherent quark and gluons that are reasonably well thermalized



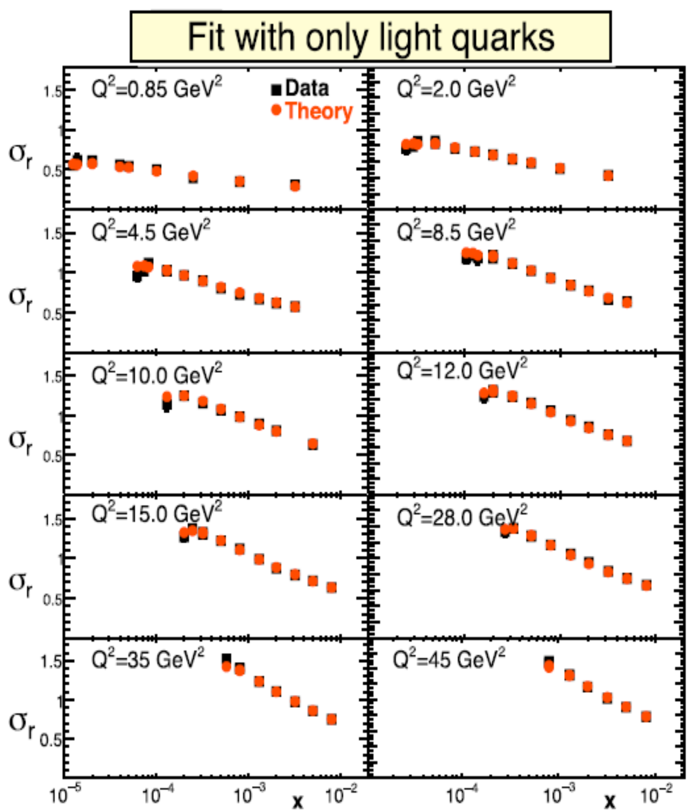
The CGC is a consequence of QCD at some energy and some A: Are we there yet?

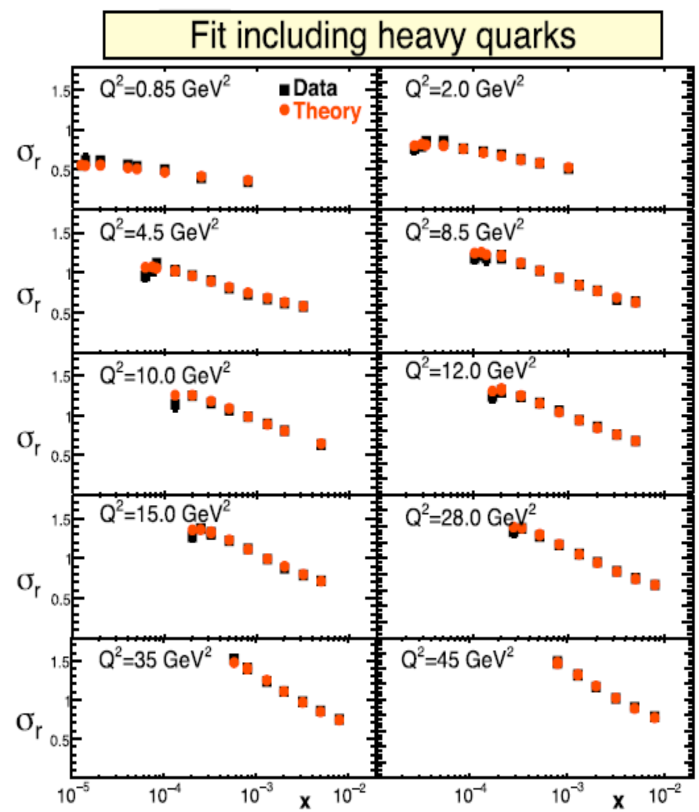


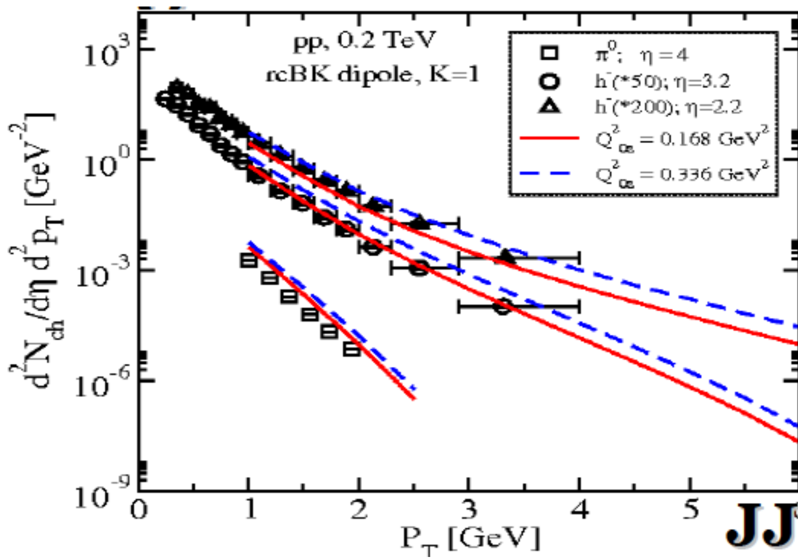
Motivated by the dominance and increase of the gluon density for small x

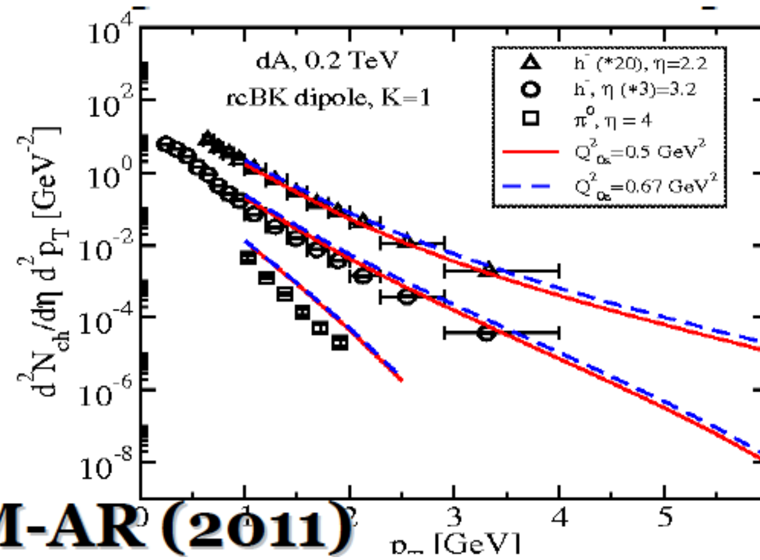
Provides a good description of deep inelastic scattering and diffraction from protons and nuclei at small x

Precision tests in Electron Ion Collider







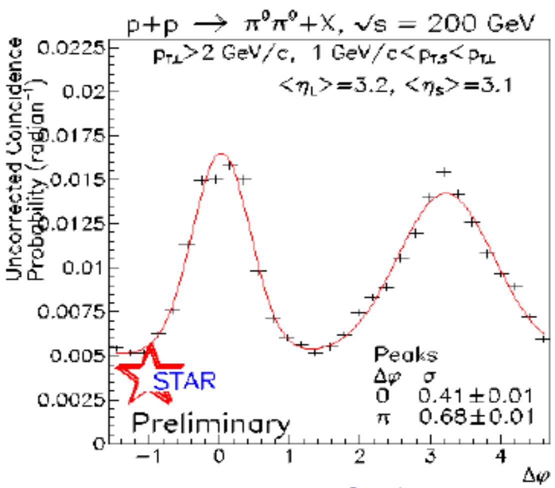


JJM-AR (2011)

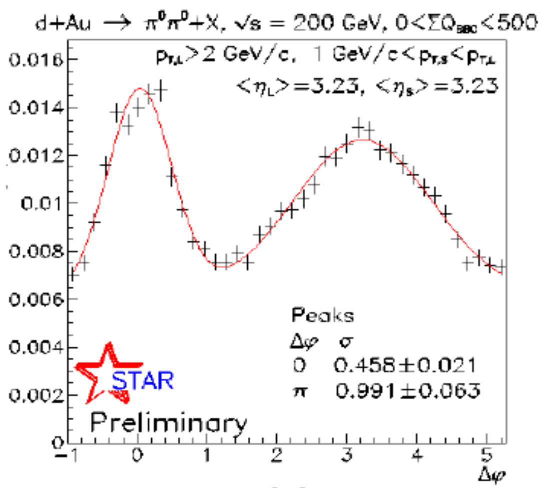
Provided semi-quantitative description of forward particle production in AA and dA collisions at RHIC

Leading P_T π^0 > 2 GeV

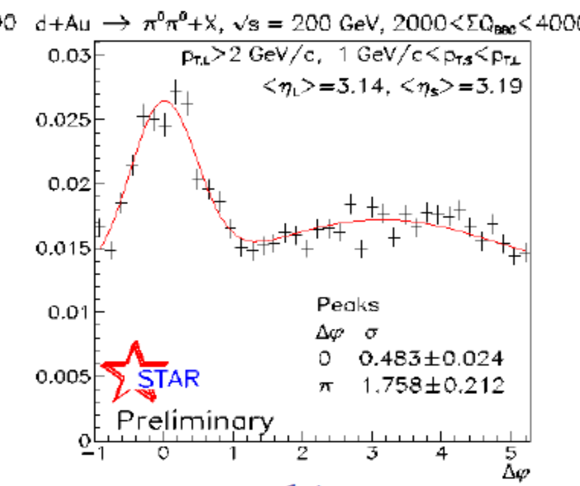
arXiv:1005.2378



pp data



dAu peripheral

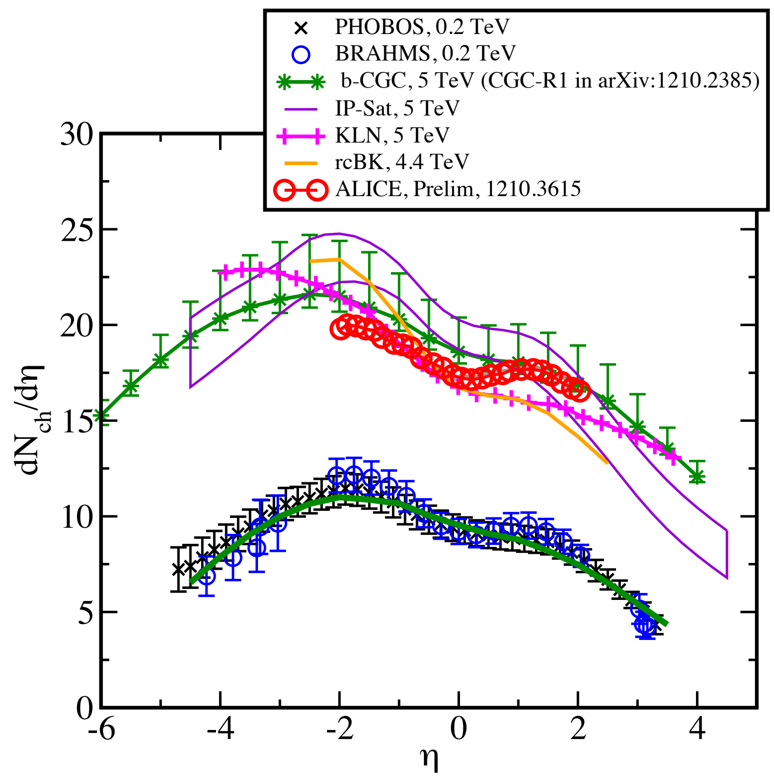


dAu central

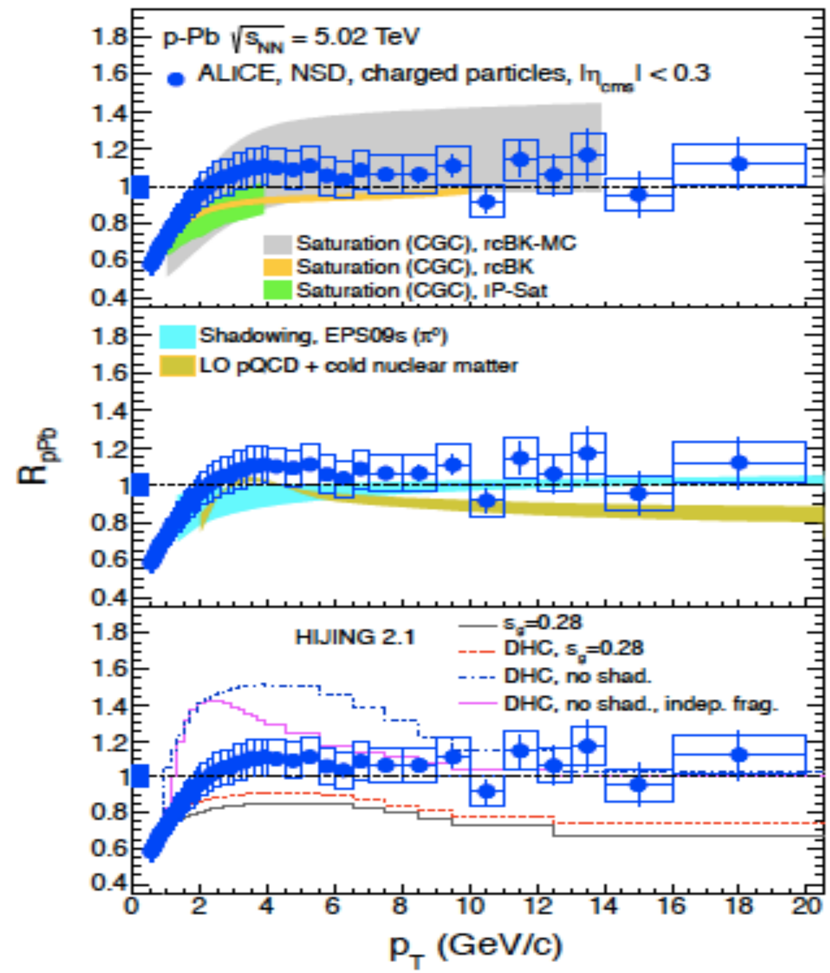
Talk by Stasto

Many tests with the extraordinary reach in pt and y at LHC

15 years ago: Theorists would claim that one cannot compute multiplicity!

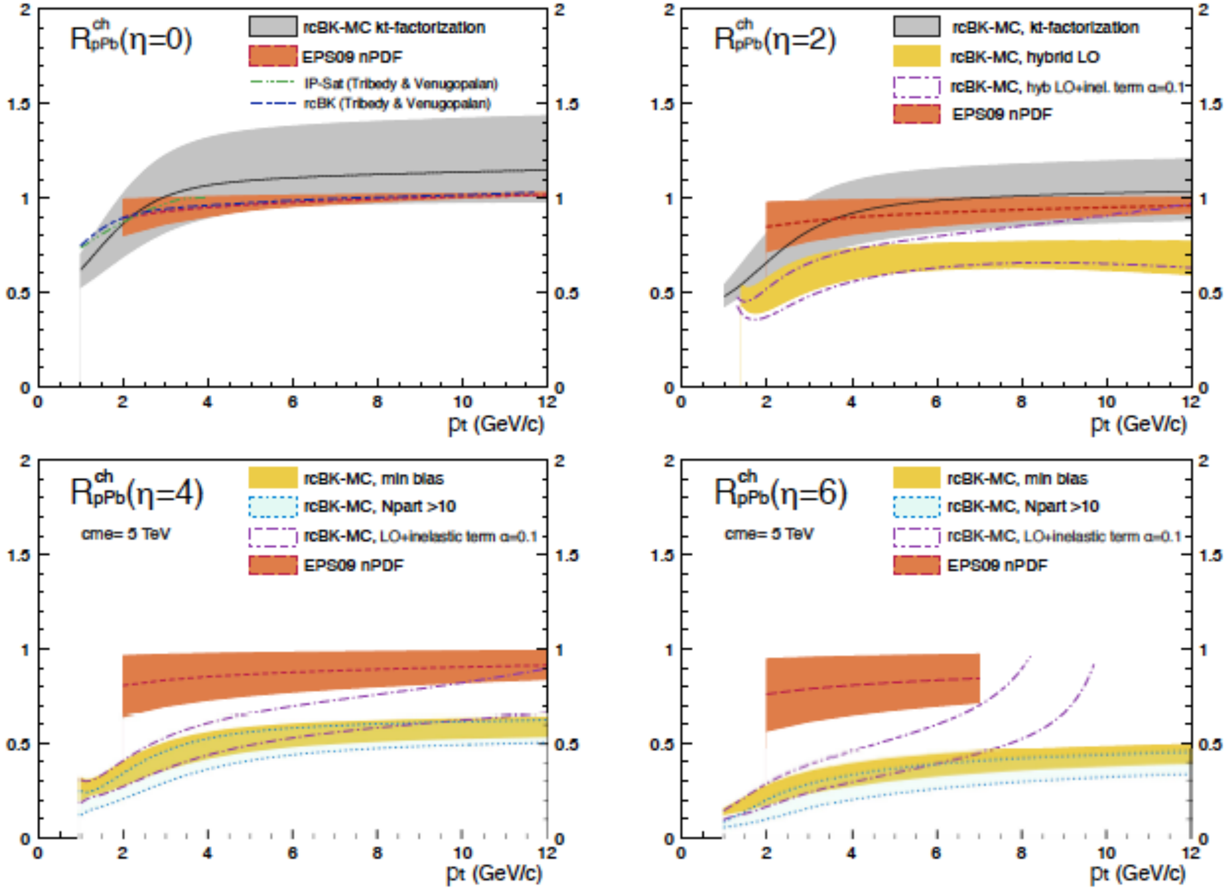


Too steep a dependence of the saturation momentum on y. NLO effects?



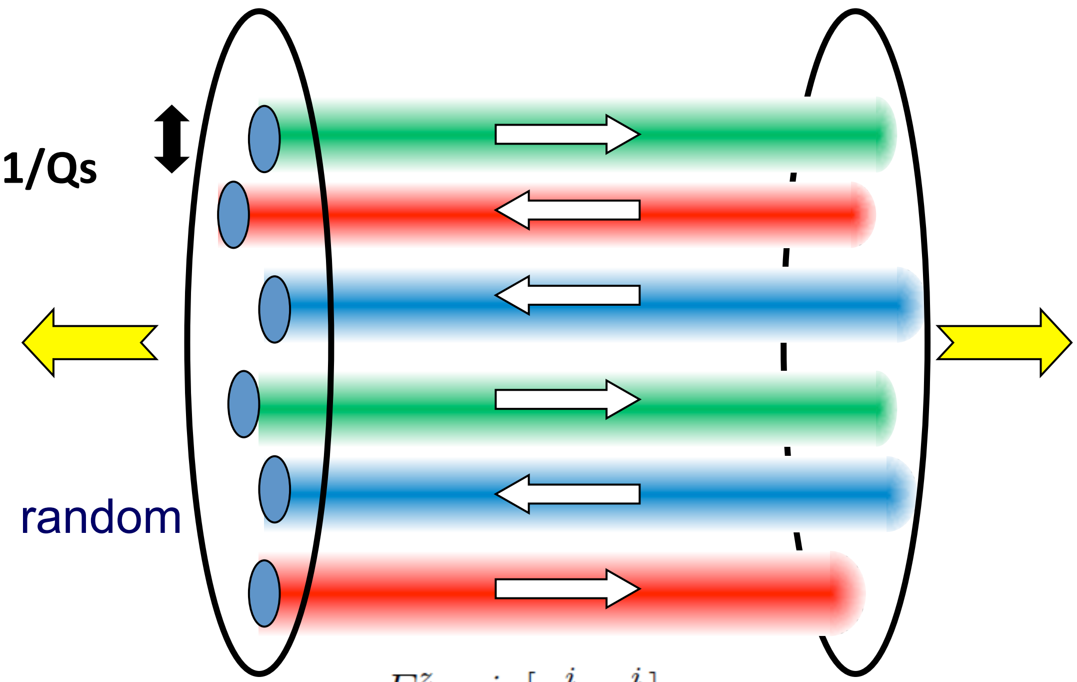
Rapidity and centrality dependence?

Talk by Dumitru

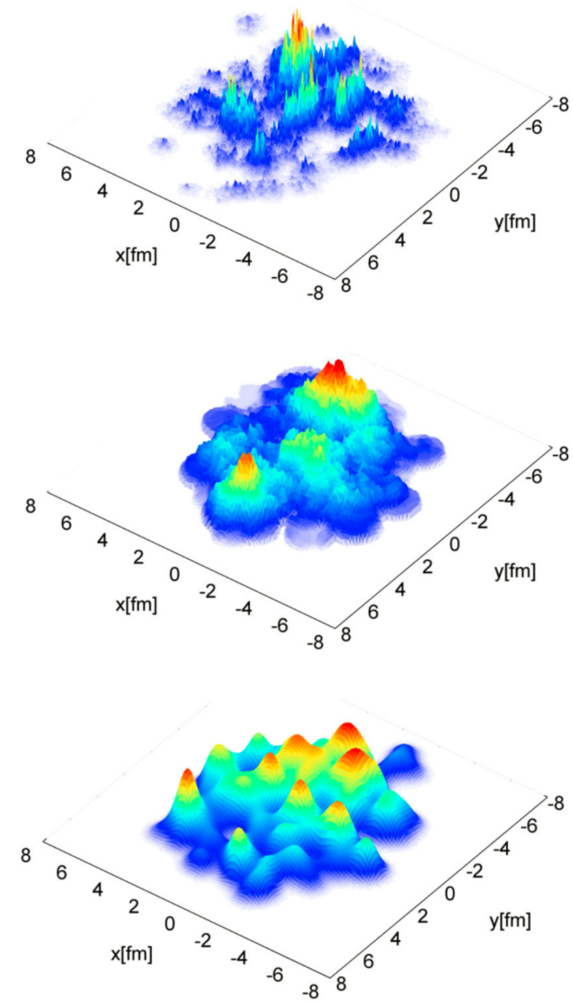


Much exciting physics to come:
Centrality and rapidity dependence of R_pA, J/Psi and heavy quark production, two particle correlations, photon triggered correlations, Drell Yan….

The Glasma



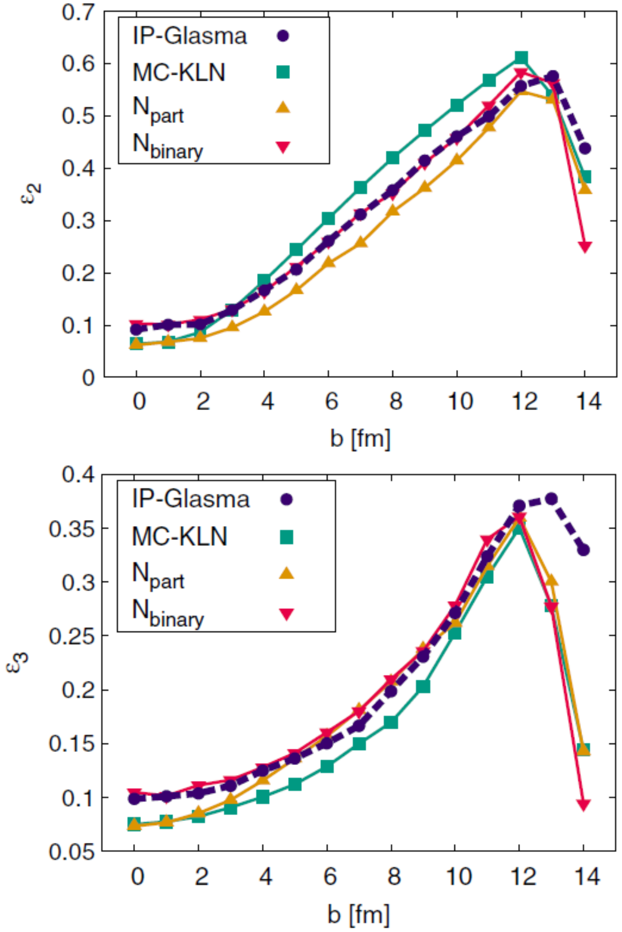
$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$



Typical configuration of a single event
just after the collision

Highly coherent colored fields:
Stringlike in longitudinal direction
Stochastic on scale of inverse saturation momentum in transverse direction
Multiplicity fluctuates as negative binomial distribution

Fluctuations in positions of sources of color field and in multiplicity of production from individual source will make v_n



Scale in transverse size is sub-nucleonic:

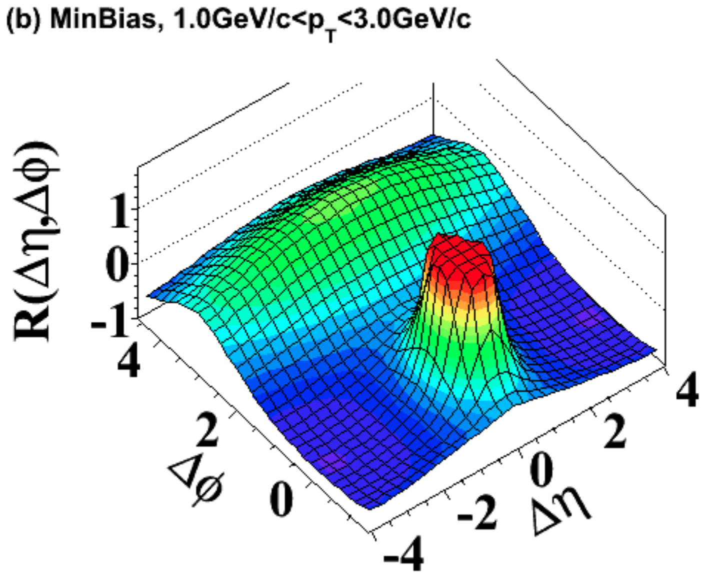
If there is flow in pp, would generate v_n

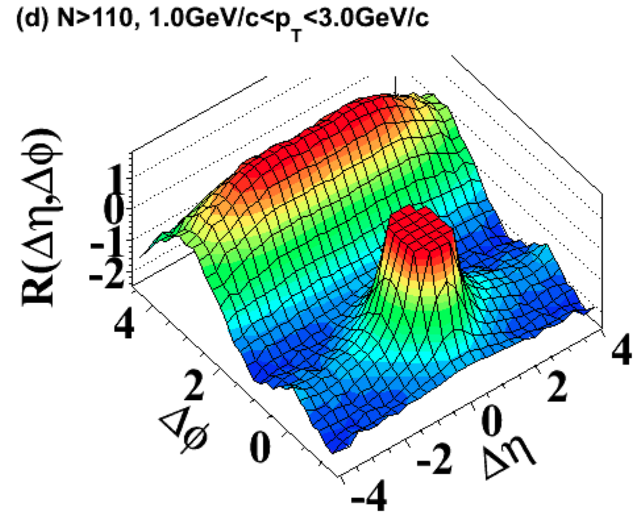
Without flow there are intrinsic correlations that would generate two and multiparticle correlations

Strongest in high multiplcity events

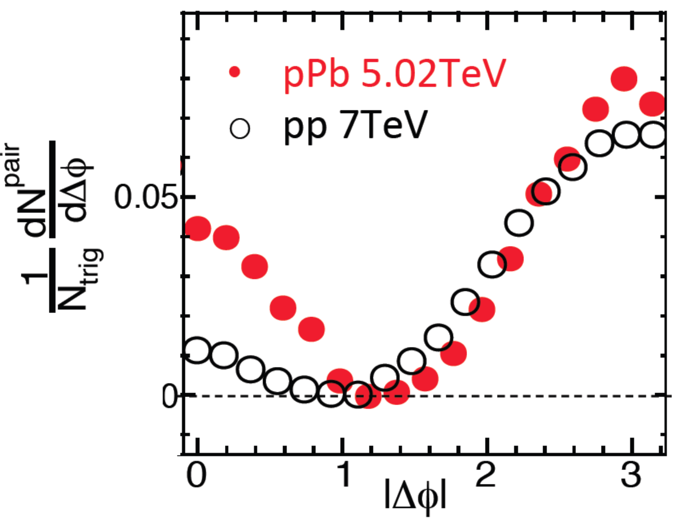
Transverse momentum scale associated with saturation momentum

$$Q_s^2 \sim \frac{1}{\pi R^2} \frac{dN}{dy}$$





pp Ridge

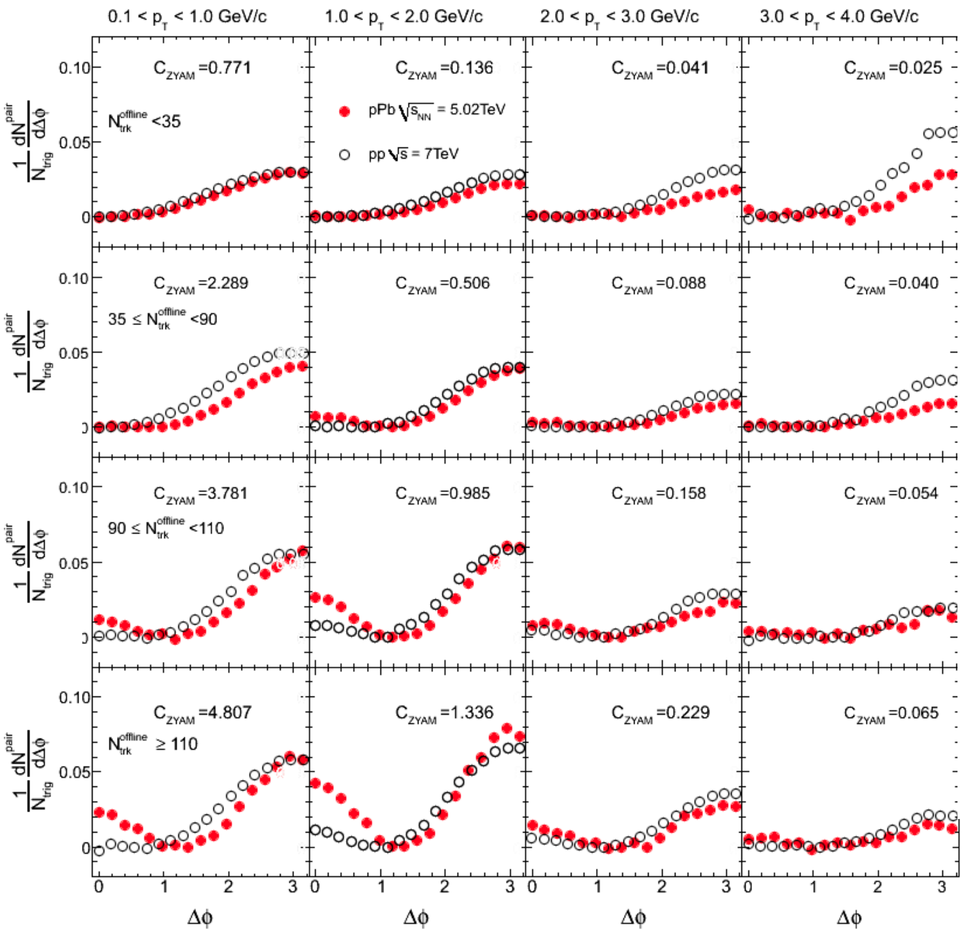


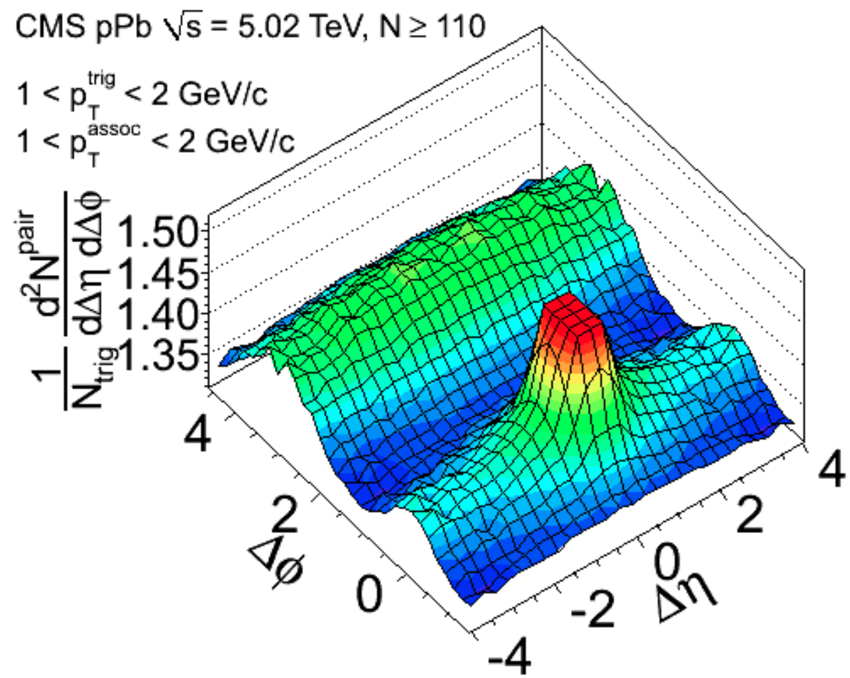
High Multiplicity

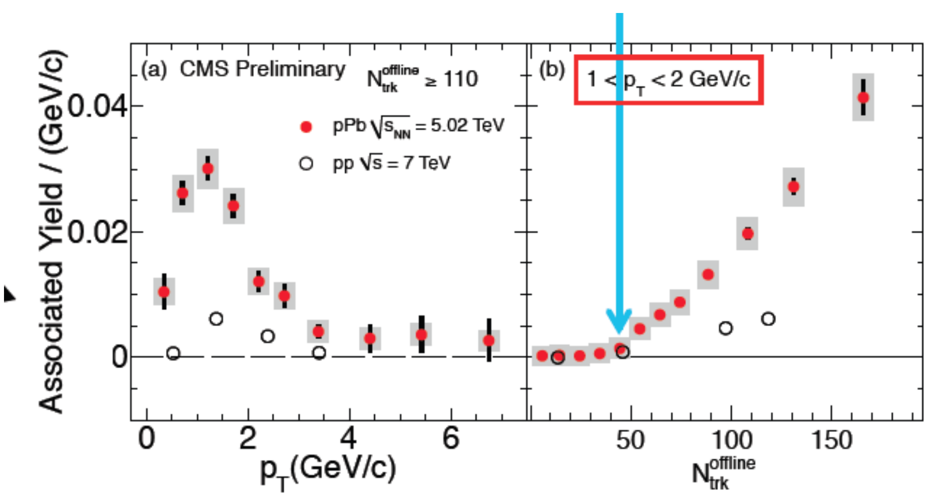
Ridge seen in high multiplicity pp in CMS

Now seen in high multiplicity pA in CMS

For fixed multiplicity cut, pA ridge appears to be stronger than in pp







What causes the apparent increase in strength of pA ridge relative to pp for fixed multiplicity?

Is there a threshold in multiplicity?

Alternative explanations such as Wong's?

See Dusling and Venugopalan

Talk by Liao

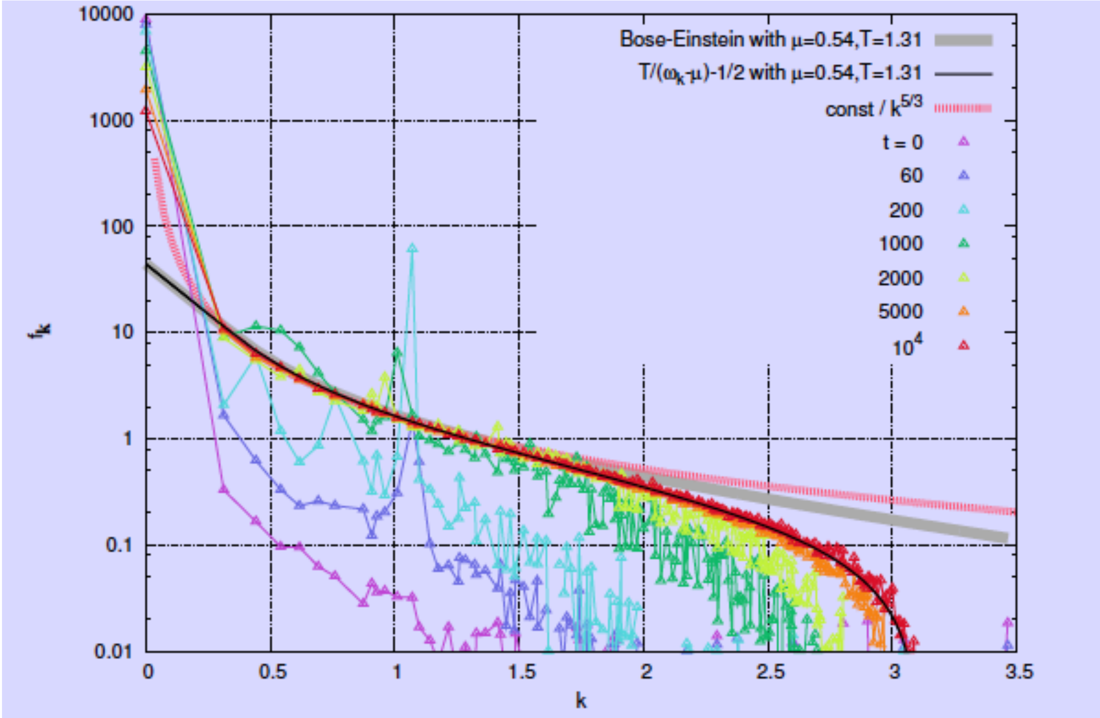
The Glasma:

Weak coupling but strongly interacting due to coherence of the fields
In transport or classical equations, the coupling disappears!
Two scales

$$\Lambda_{coh}(t_{in}) \sim \Lambda_{UV}(t_{in}) \sim Q_{sat}$$

But it takes time to separate the scales and make a thermal distribution

$$\Lambda_{coh}(t_{therm}) \sim \alpha_s \Lambda_{UV}(t_{therm}) \sim \alpha_s T_{init}$$



How long does it take to thermalize?

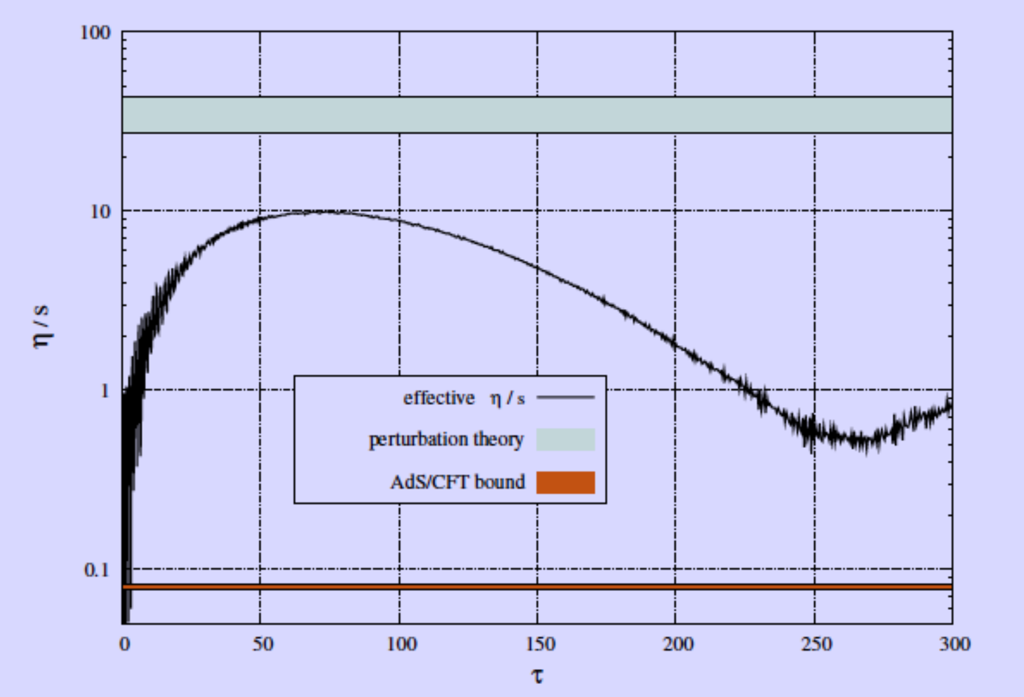
Are there Bose-Einstein Condensates formed?

For how long is the system in homogeneous with longitudinal pressure not equal to transverse?

Cane we measure a difference between longitudinal and transverse pressure?

Gelis: Scalar field

Order parameters: Electric and magnetic confinement



In scalar field theory:

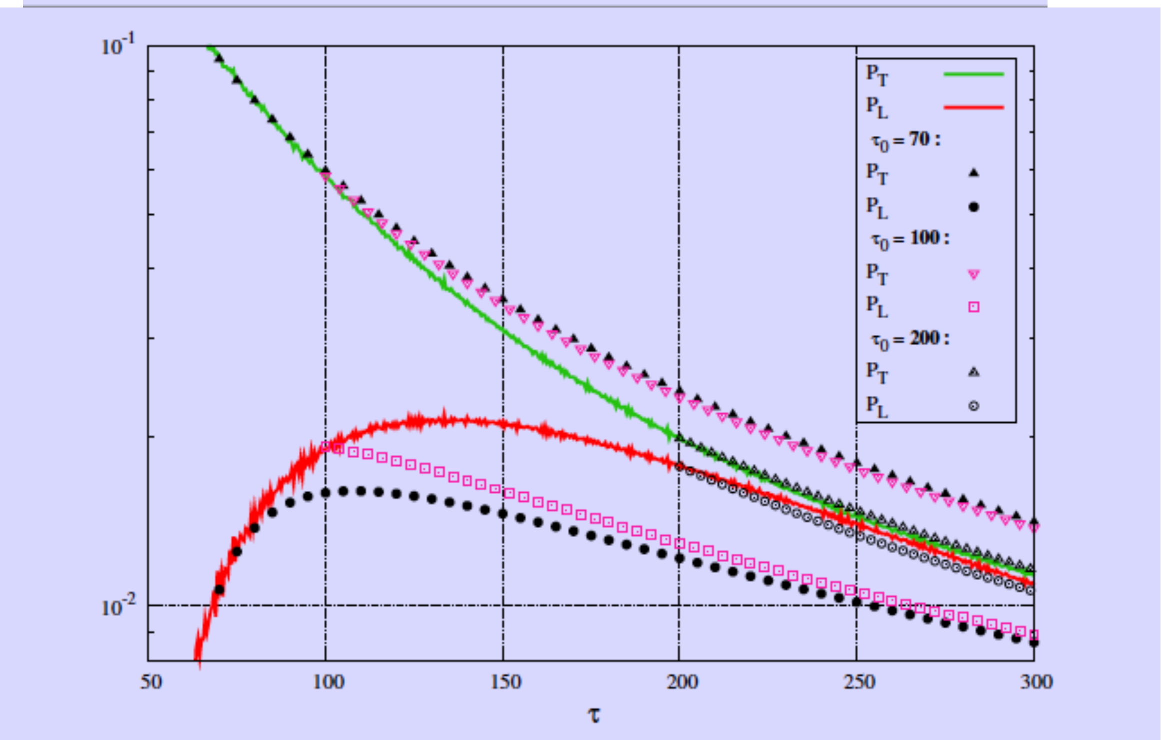
Smallish viscosity

Eventual equilibration of longitudinal and transverse pressure

Longish time for thermalization

Yang Mills theory with realistic numbers?

What condenses?



The Glasma and turbulent coherent fields is generically a new type of matter:

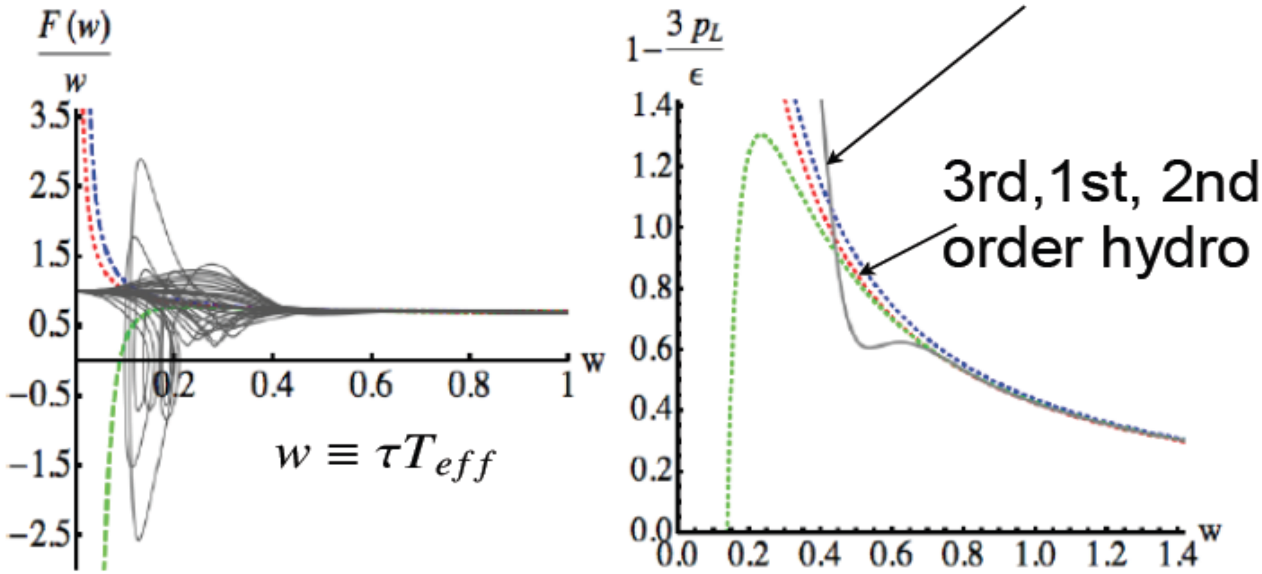
There may be genuinely new phenomenon associated with electric and magnetic confinement and perhaps superfluidity

Vacuum ~ Turbulent Fluctuations?

Holographic description of a boost invariant plasma

(Heller, Janik, Witaszczyk, 2011)

Talk by Teaney and Lin



Viscous hydro can cope with partial thermalization, and large differences between longitudinal and transverse pressures

In fact, there is little experimental evidence that complete local equilibrium is reached in nuclear collisions

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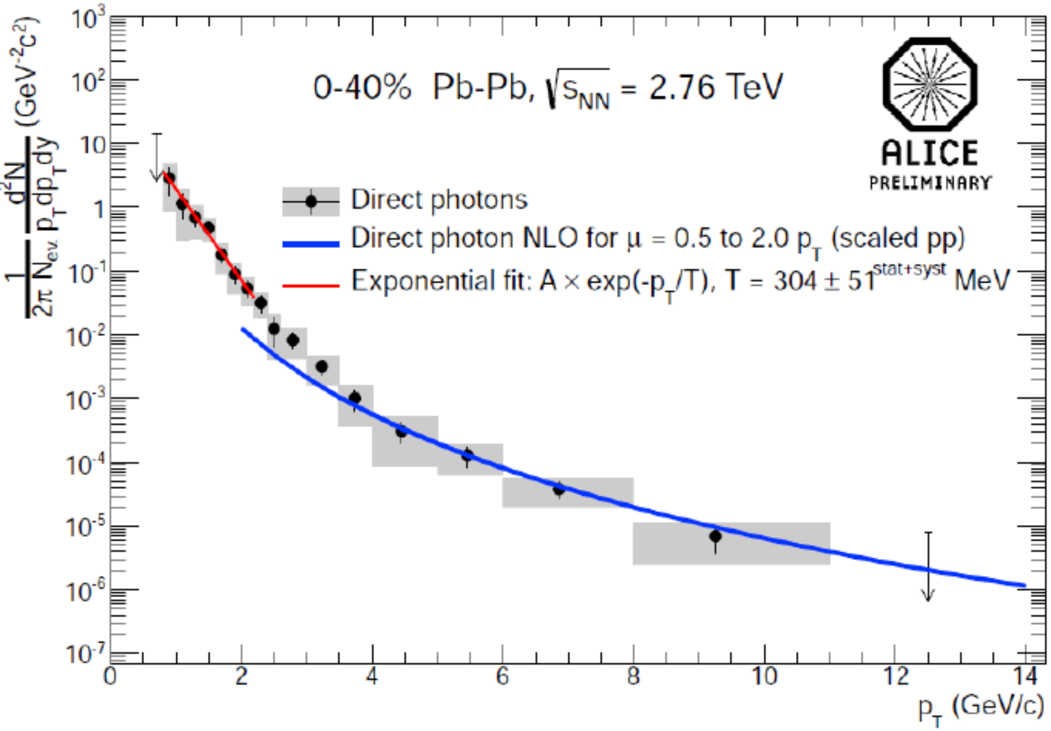
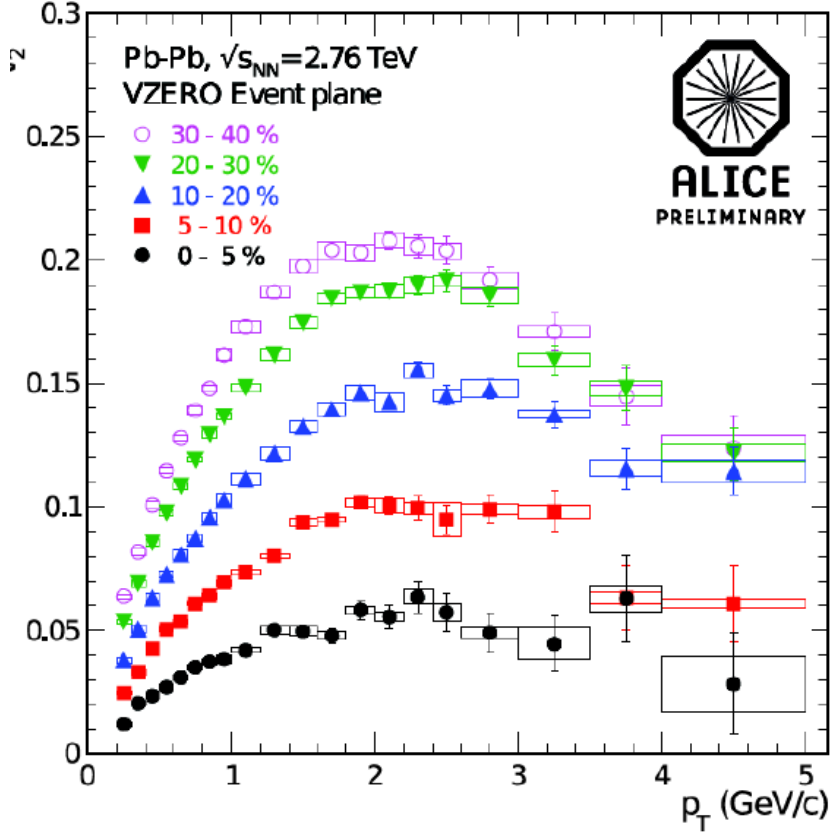
The Glasma may be a nearly perfect fluid, even though it is not a thermalized sQGP. It is certainly a sQGP





High pT suggests photons comes from early time

V2

and

geometric scaling of multiplicity dependence seen in Phenix suggest photons did not arise from a very hot thermalized QGP

Talk by Fries

Possible New Phenomena Associated with High Energy Density Matter:
Chiral Magnetic Effect, Photon Flow?

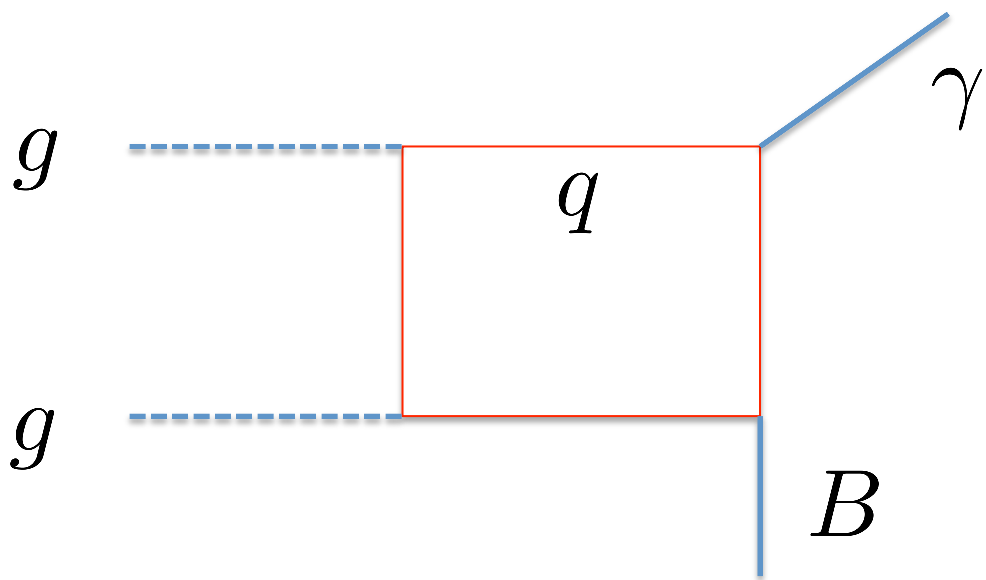
P and CP Violating Fluctuations (Instantons, Sphalerons) generate net helicity for quarks

Magnetic field due to moving charges in collisions couples to helicity and generates an electromagnetic current

Waves associated with quadrupole moment?

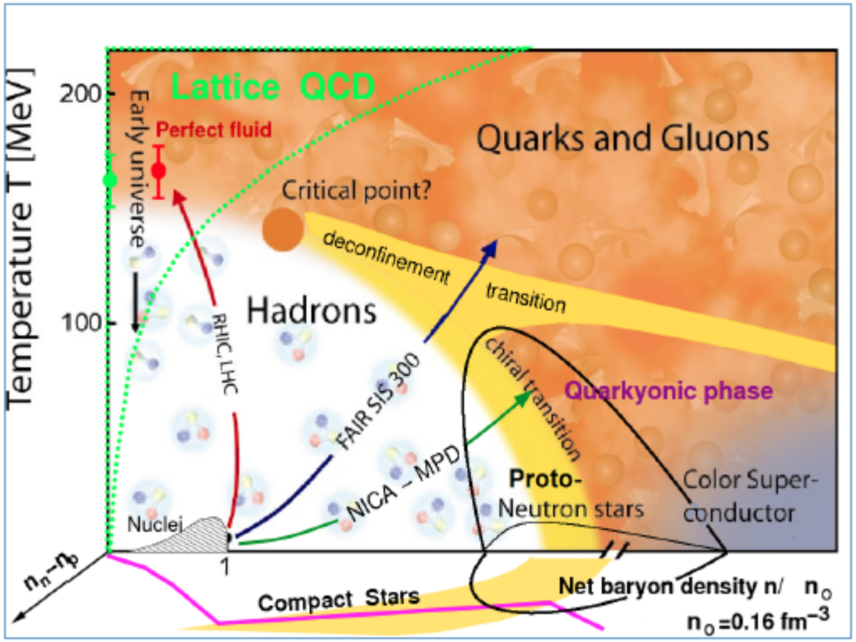
Talk by Yee

Photon Flow by Coupling to Magnetic Field?



Matter in Thermal Equilibrium

Talks by Liao and Kashiwa



"Triple point"

Where the quark gluon plasma, quarkyonic matter and confined mesonic matter coexist

"Critical End Point"

Where first order phase transition end, assuming there is a region with first order phase transitions

"Quark Gluon Plasma"

Deconfined quarks and gluons. Theoretically studied using lattice gauge theory

"Quarkyonic Matter"

A quark Fermi sea with a confining Fermi surface and confined thermal excitations. Mass generation by chiral spirals that break translational invariance and parity. Rich phase structure associated with Fermi surface

Color Superconductivity:

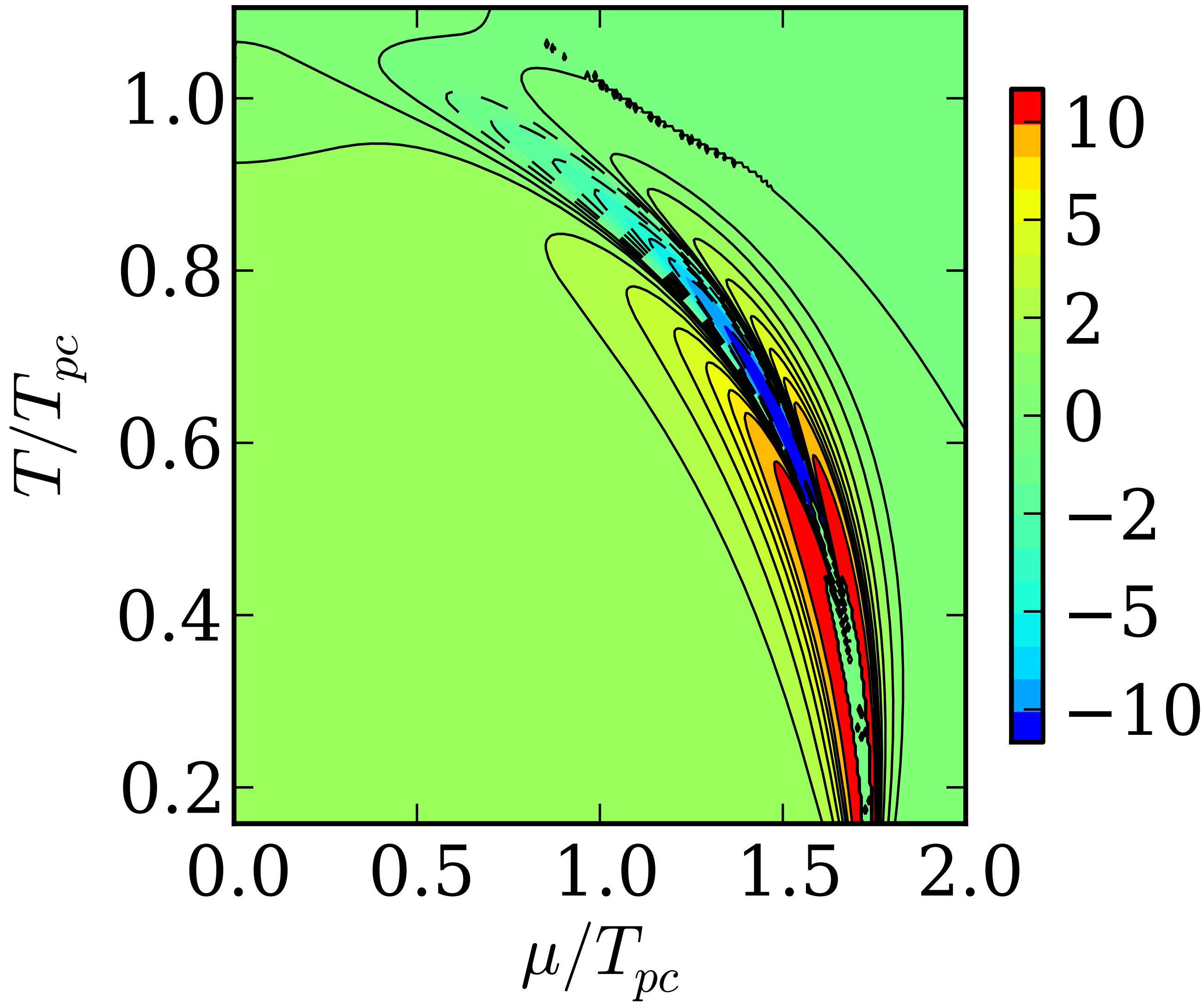
At very high density and low temperature, should be colored Cooper pairs analogous to Cooper pairs of ordinary matter.

Fluctuations: Ratios of Moments of Distributions:

Fluctuations in conserved quantities such as energy or baryon number

Big numbers because the pion is small.

Approximate singularity along line where there was a chiral tranisition if pion mass was zero.



Talk by Bzdak

The Standard Model and Cosmology:

Within the standard model and its trivial extensions to include heavy right handed neutrinos:
Can one have acceptable:

Talk by Bezrukov

Baryogenesis:
Yes with sphalerons

Dark Matter:
Yes with heavy right handed neutrinos

LDM, Pisarski and Skokov

Dark Energy
Yes, if include an electroweak axion

$$\nu MSM$$

was shown by Shaposhnikov and Wetterich to be consistent up to the Planck scale if the Higgs mass is close to that seen at LHC

CGC predictions for LHC energies

Adrian Dumitru

RIKEN BNL
Baruch College/CUNY

RIKEN Scientific Review 2012

$k_\perp$ factorization with rcBK UGDs

BK equation (incl. non-linear terms → saturation of scattering amplitude!)

$$\frac{\partial \mathcal{N}(r,Y)}{\partial Y} = \int d^2 r_1 \, K(r,r_1,r_2) \left[\mathcal{N}(r_1,Y) + \mathcal{N}(r_2,Y) - \mathcal{N}(r,Y) - \mathcal{N}(r_1,Y)\,\mathcal{N}(r_2,Y)\right]$$

running-coupling kernel (Balitsky prescription)

$$K(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{r^2}{r_1^2\, r_2^2} + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

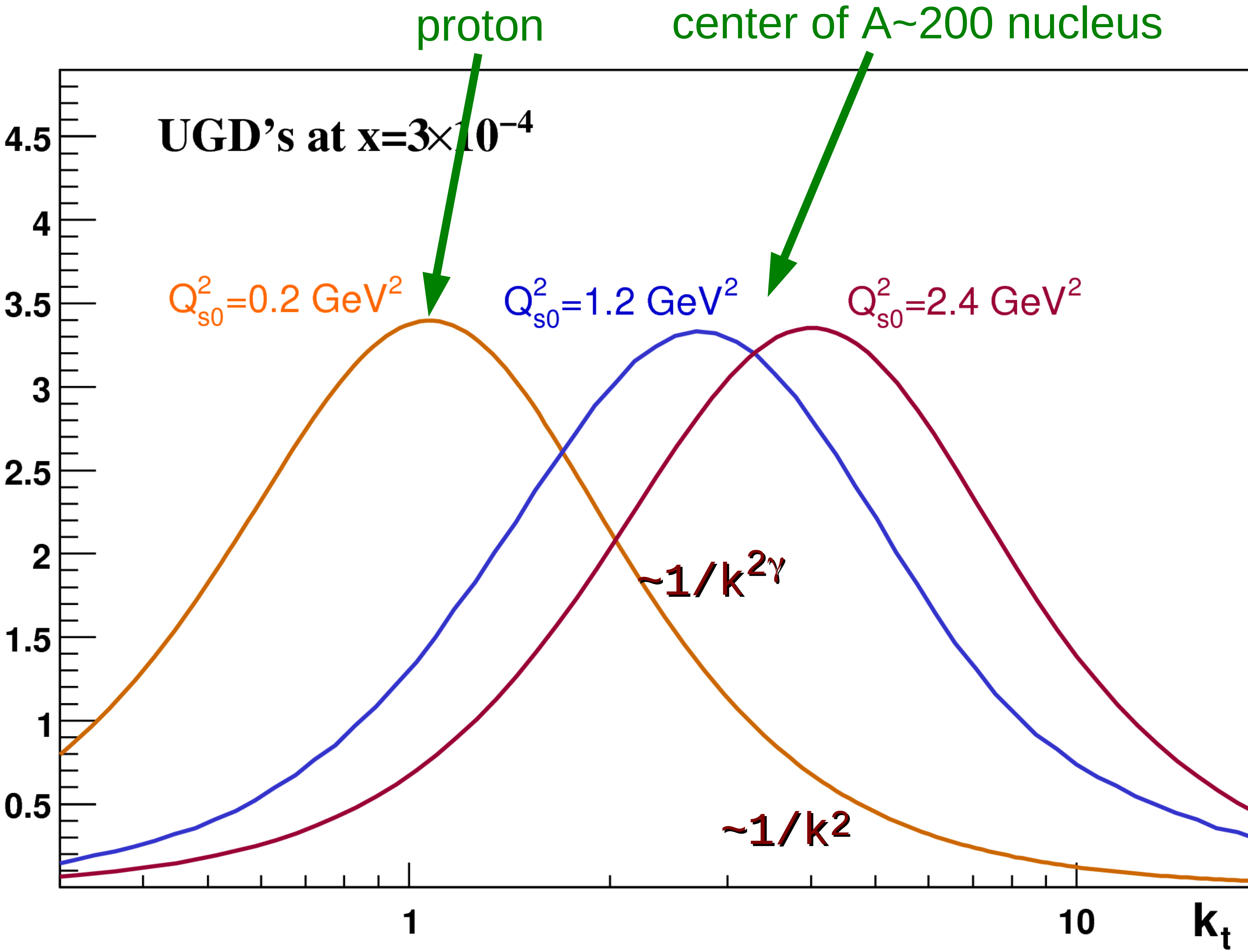
dipole scattering amplitude in adj. rep.

$$\mathcal{N}_A = 2\,\mathcal{N}_F - \mathcal{N}_F^2$$

(dipole) unintegrated gluon distribution:

$$\varphi(k,Y;b,A) = \frac{C_F\,k^2}{\alpha_s(k)} \int \frac{d^2\mathbf{r}}{(2\pi)^3}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \mathcal{N}_A(r,Y;b,A)$$

uGD at $x = 3x10^{-4}$ (e.g. pt=2GeV, y=0, √s=7TeV)



$k_\perp$-factorization, multiplicity in A+B --> g+X

$$\frac{dN}{dy} \;=\; K\,\frac{1}{2C_F}\int d^2r_t \int \frac{d^2p_t}{p_t^2}\int^{p_t} d^2k_t$$
$$\alpha_s(Q)\,\varphi\left(\frac{|p_t+k_t|}{2},x_1\right)\,\varphi\left(\frac{|p_t-k_t|}{2},x_2\right)$$

(insert FF for hadron pt distribution)

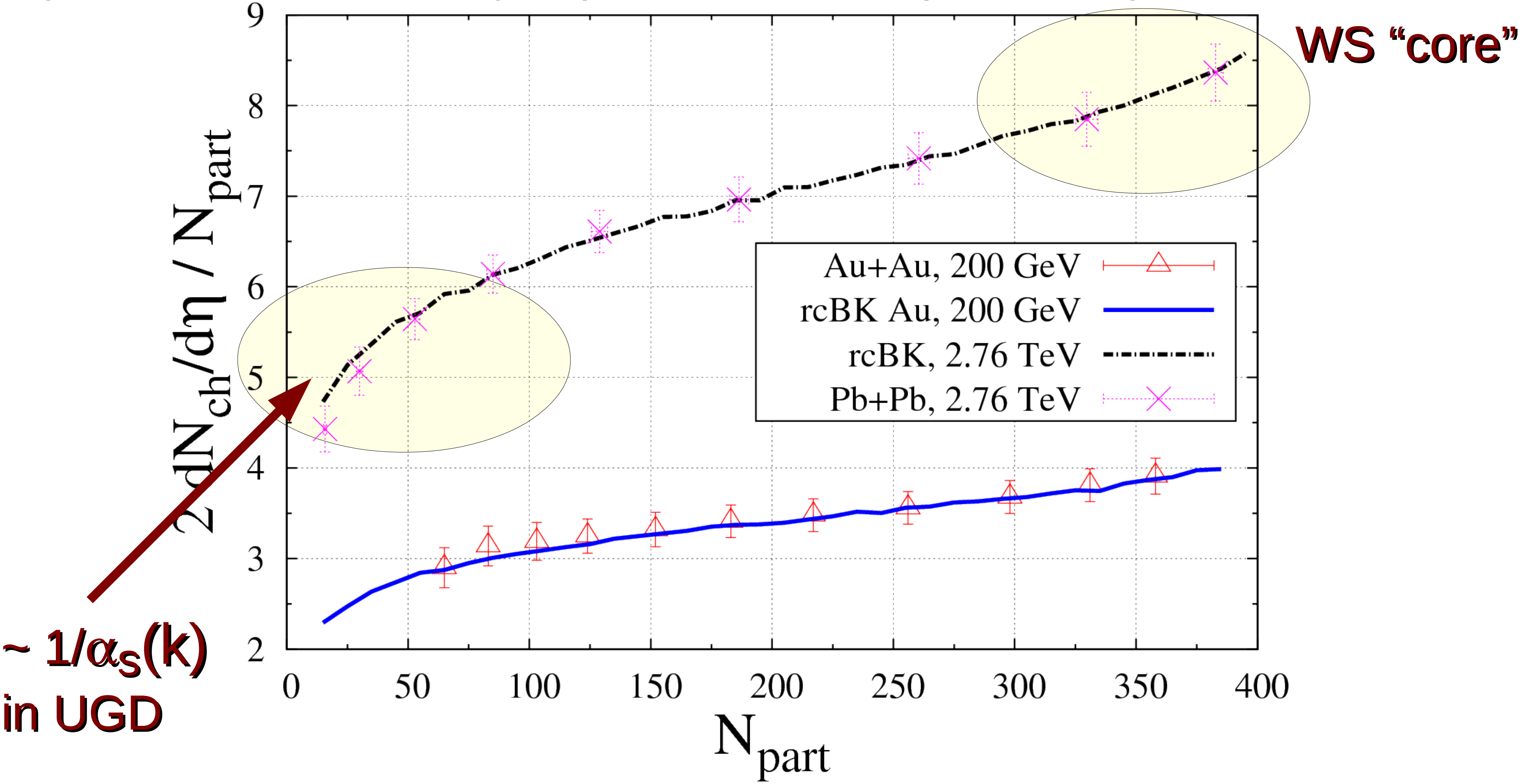
Notes:

- finite at $p_t \to 0$ if UGD does not blow up
- $x_{1,2} = (p_t/\sqrt{s})\exp(\pm y)$; $Y_{1,2}=\log(x_0/x_{1,2})$
  where $x_0=0.01$ is assumed onset of rcBK evol.

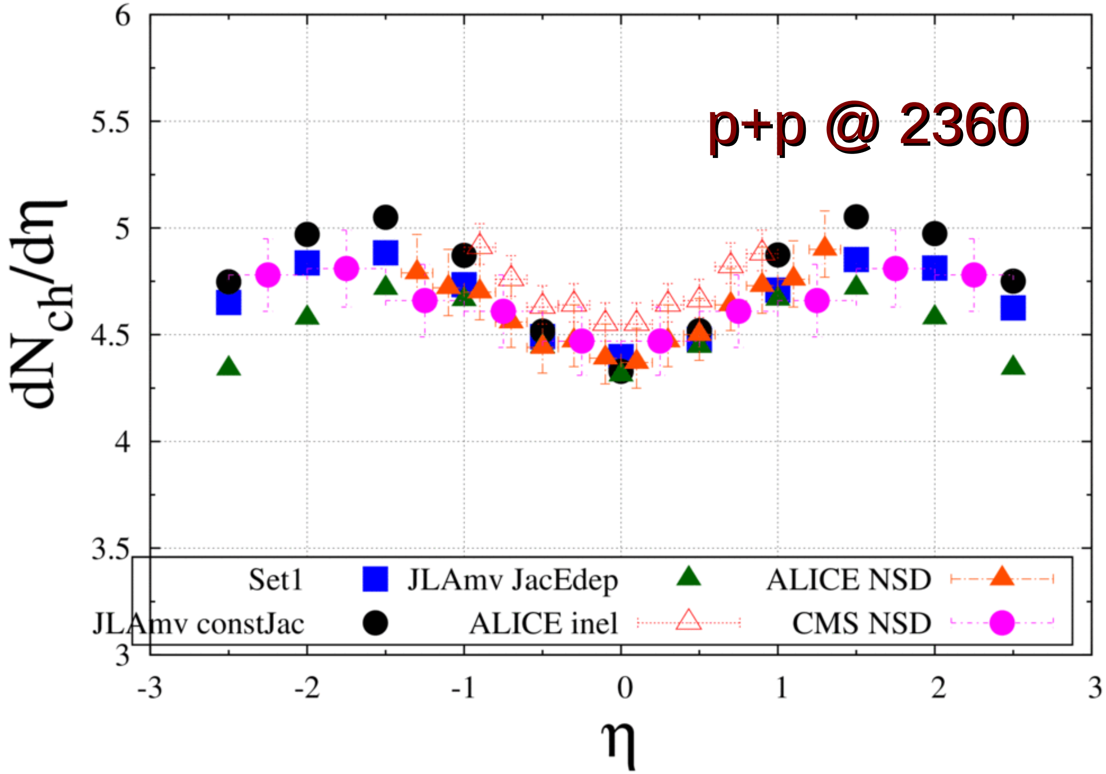
AA : centrality and energy dependence of multiplicities

Albacete & Dumitru: arXiv:1011.5161

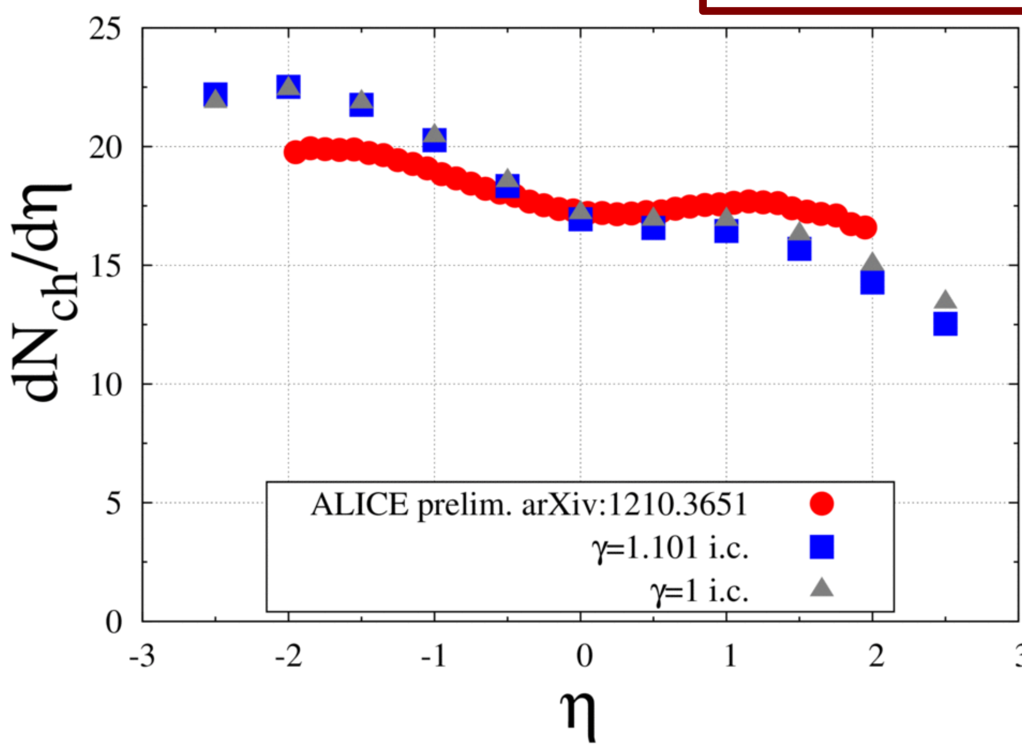
(Pb+Pb@LHC centrality dependence was a prediction!)



- assumes $N_{hadr} \sim N_{glue}$

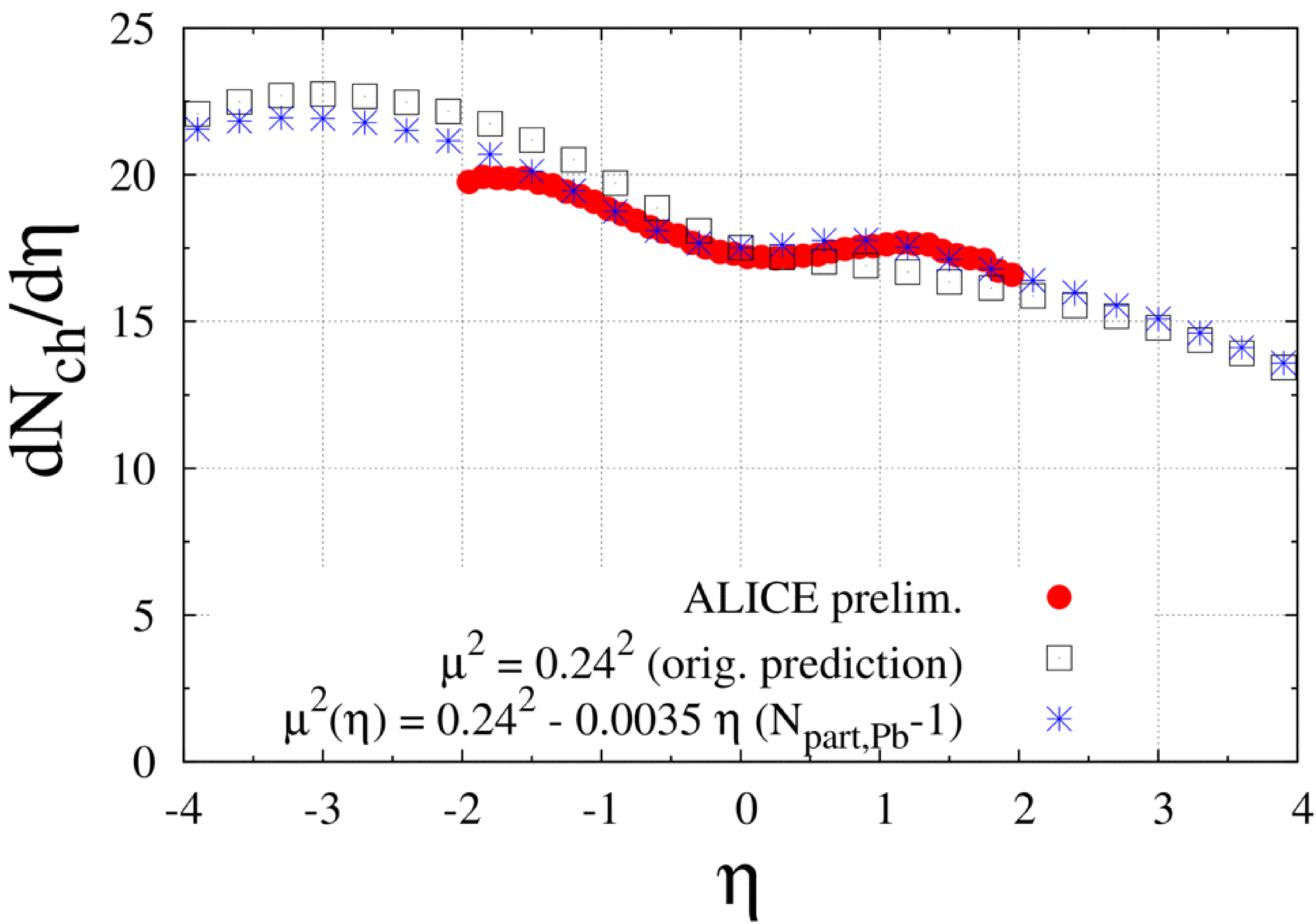


p+Pb @ 5000 prediction



dN/dη works out: we have a very economical description of multiplicities in terms of single scale $Q_s(A,\sqrt{s})$

for those who're worried about the “discrepancy” of the shape: tune within KLN model



what is the initial condition for rcBK evolution ?

- needs to be set at "sufficiently" small x_0 so that rcBK can take it from there; in practice, x_0=0.01 ?

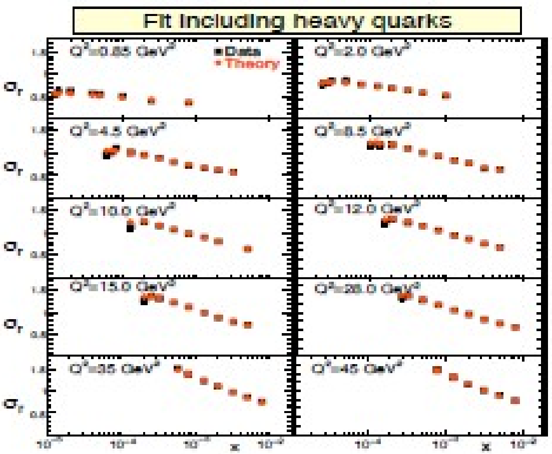
- for large A, MV model may provide a decent ini. cond. :

$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{r^2\, Q_{s0}^2(b)}{4}\,\ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

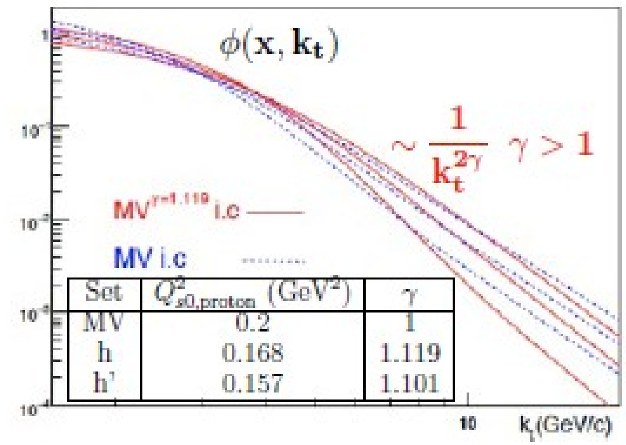
- alternative I.C. (AAMQS 2011, γ>1 !):

$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{\left[r^2\, Q_{s0}^2(b)\right]^\gamma}{4}\,\ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

1. Global fits to e+p data at small-x

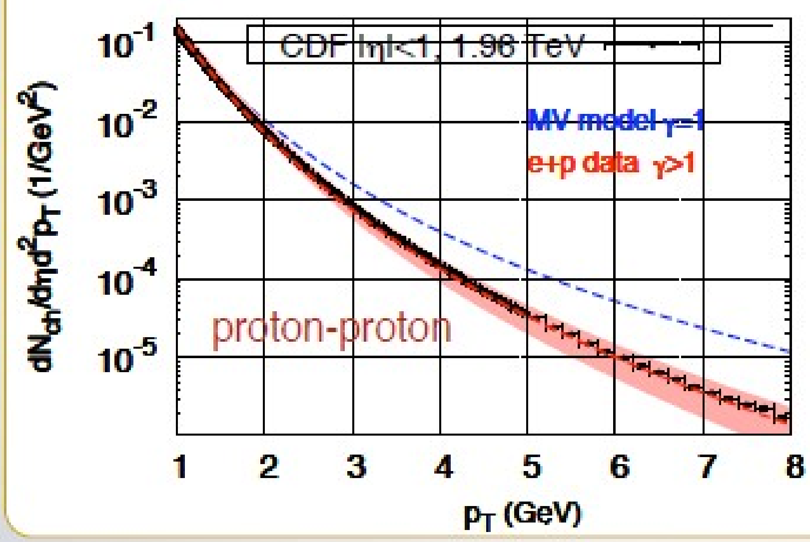


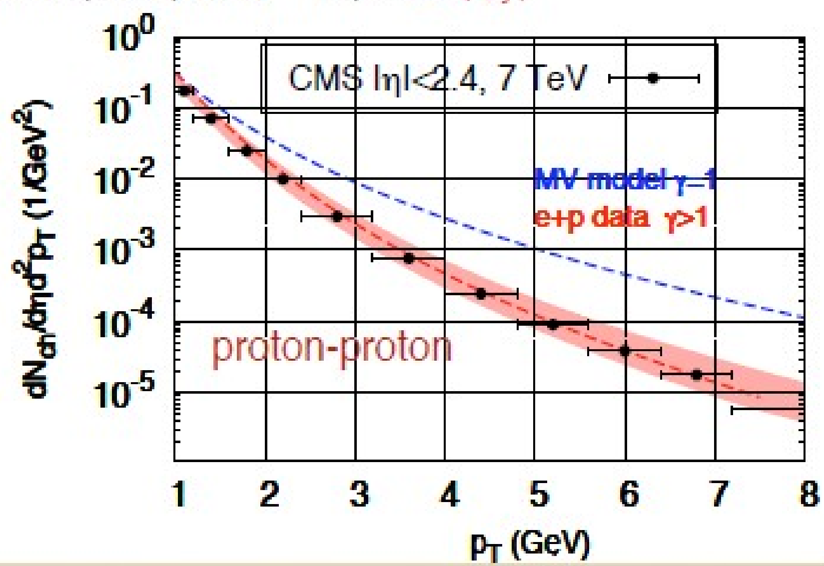
2. Extract NP fit parameters



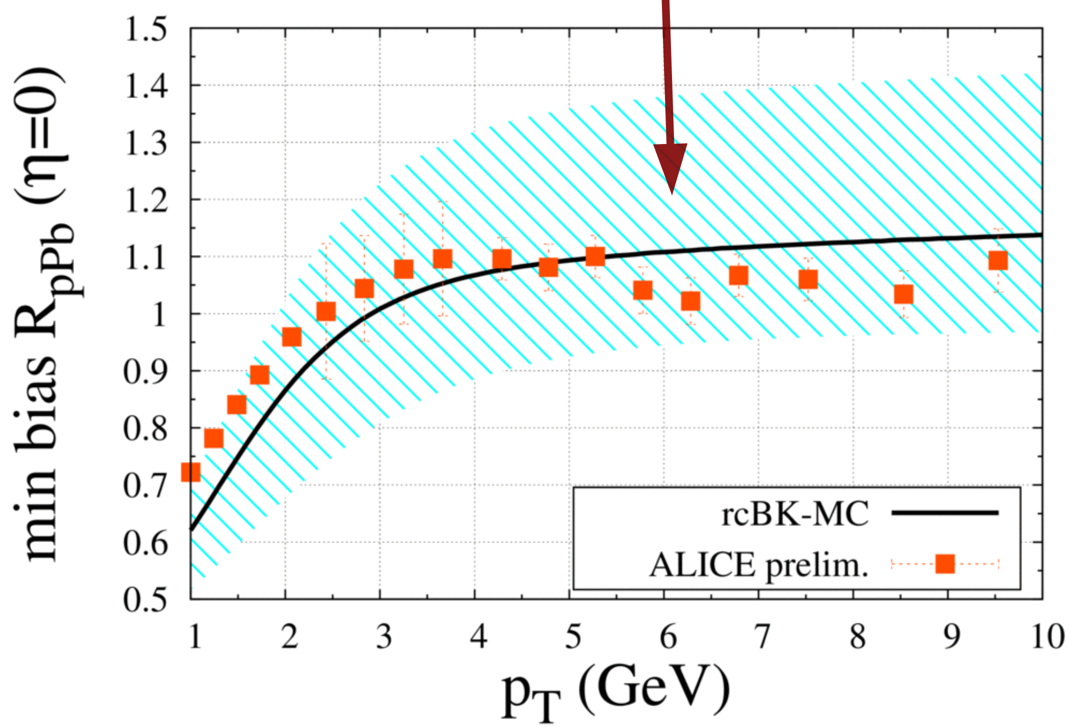
4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

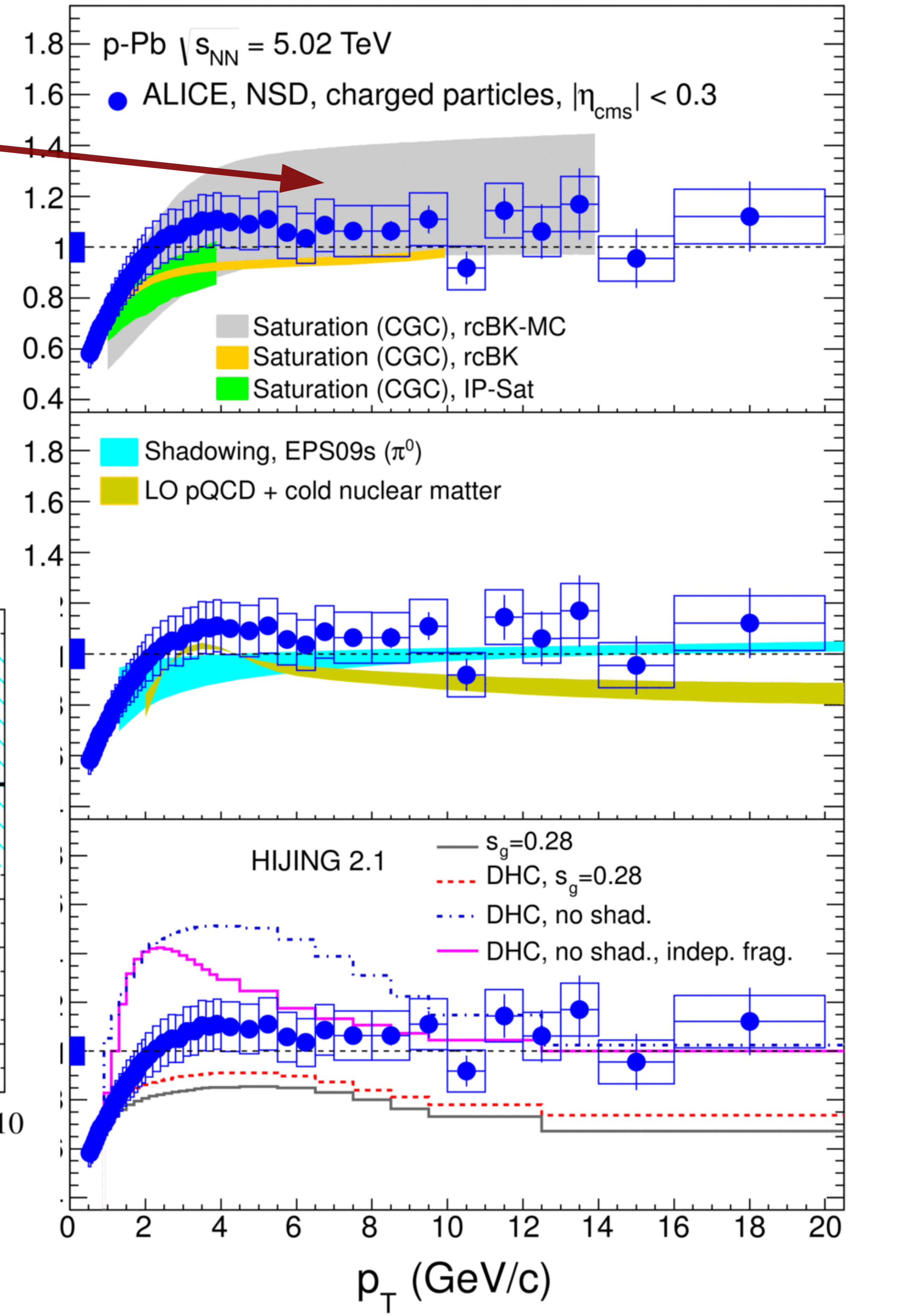
LO kt-factorization: $$\frac{\mathbf{dN^g}}{\mathbf{d\eta d^2 p_t}} \sim \mathbf{K}\, \alpha_s(\mathbf{Q_r^2})\, \phi(\mathbf{x_1}, \mathbf{k_t}) \otimes \phi(\mathbf{x_2}, \mathbf{k_t} - \mathbf{pt}) \otimes \mathrm{FF}(Q_f^2)$$



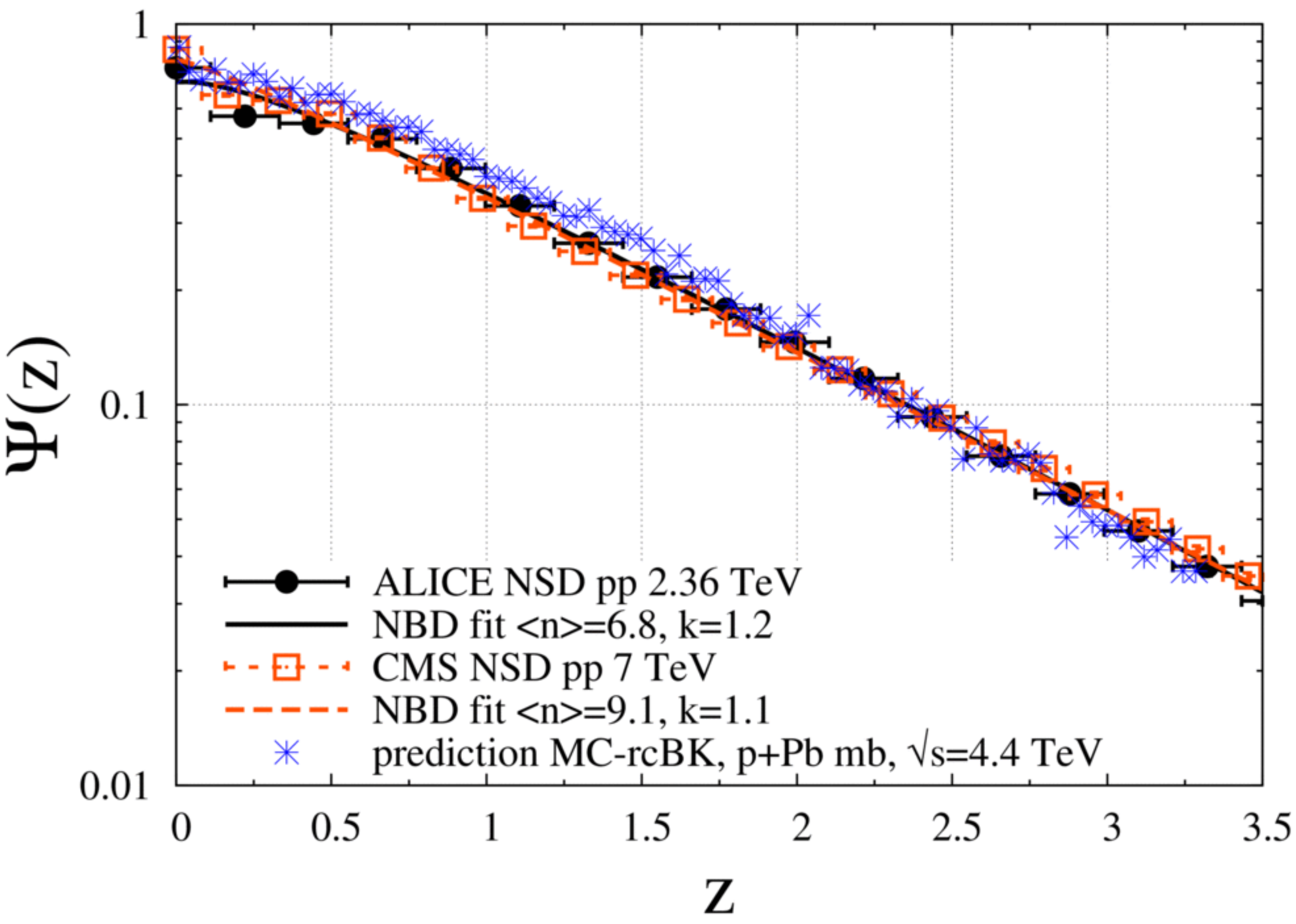


predicted R_{p+Pb} at 5 TeV





KNO scaling of multiplicity fluctuations in pp, pA: *precursor of ε_n fluctuations in AA!*



- scaling prediction for p+Pb @ LHC:
  Dumitru, Nara: PRC 85 (2012)

- scaling in pp → Gaussian action for color charge fluctuations &
  high occupation number of x«1, p_T~Q_s gluons !
  Dumitru, Petreska: arXiv:1209.4105

Open source code package available at

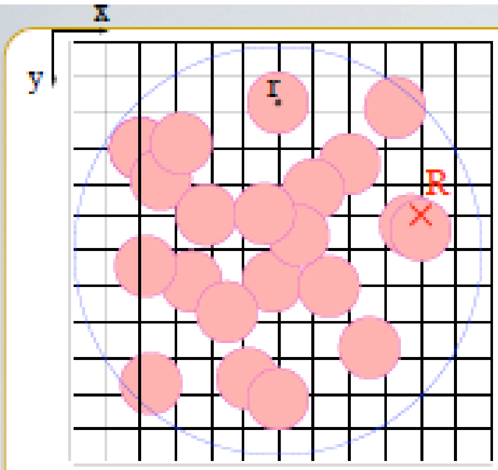
http://faculty.baruch.cuny.edu/naturalscience/physics/dumitru/

Developed & maintained in collaboration with

- J. Albacete (CEA Saclay)
- H. Fujii (U. of Tokyo)
- *Y. Nara* (Akita Intl U.)

Backup Slides

fluctuations of valence partons in ⊥ plane



1. Initial conditions for the evolution (x=0.01)

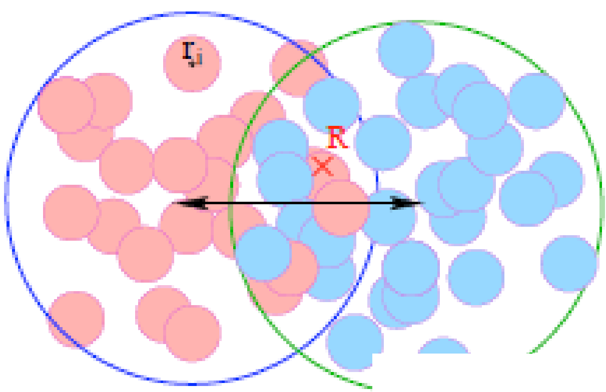
$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \longrightarrow Q^2_{s0}(\mathbf{R}) = N(\mathbf{R})\, Q^2_{s0,\,\mathrm{nucl}}$$

$$\varphi(x_0 = 0.01, k_t, R)$$

2. Solve local running coupling BK evolution at each transverse point

rcBK equation or KLN model

$$\varphi(x, k_t, R)$$



3 Calculate gluon production at each transverse point according to kt-factorization

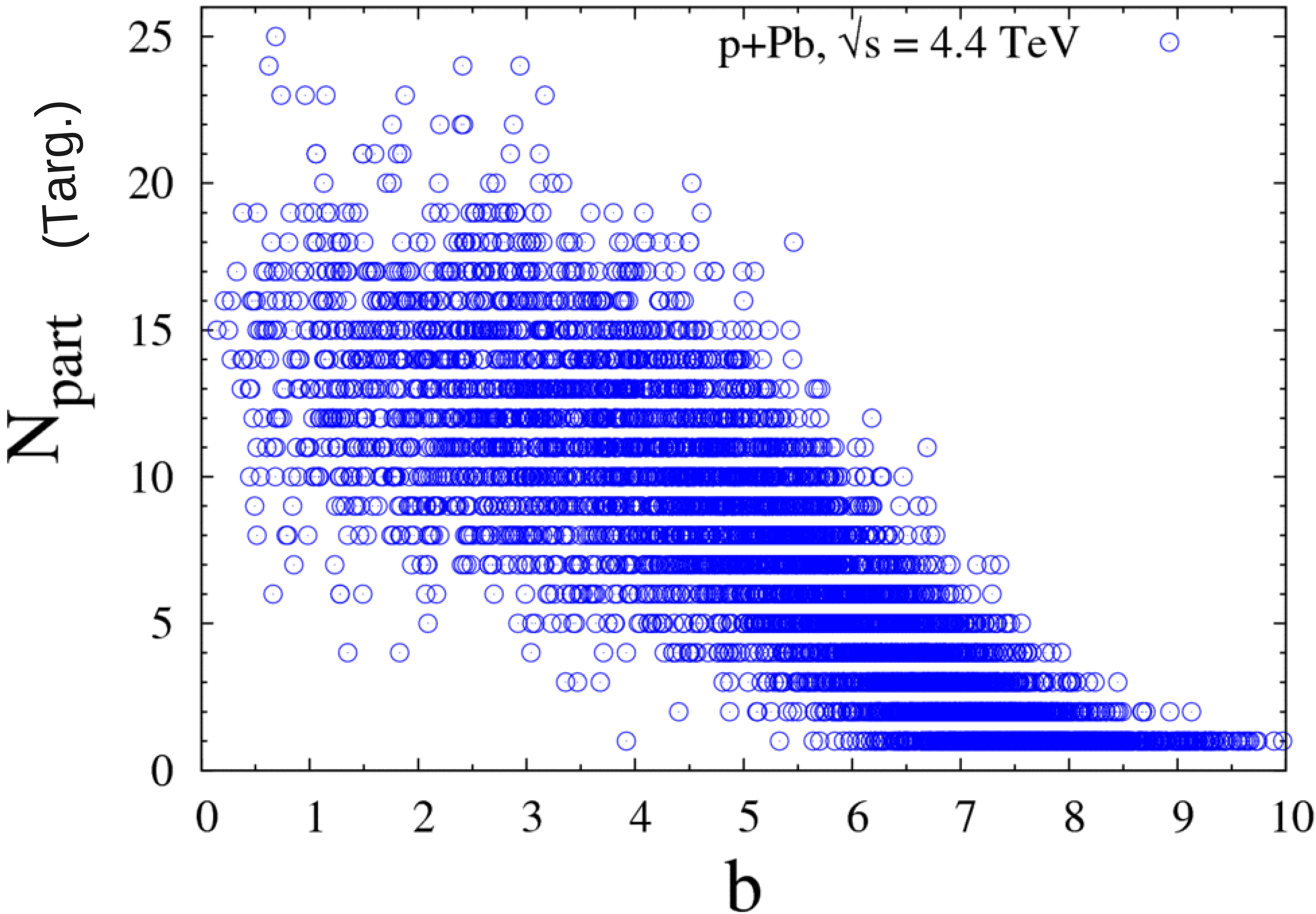
INPUT: $\varphi(\mathbf{x} = \mathbf{0.01}, \mathbf{k_t})$ FOR A SINGLE NUCLEON:

$$N_{\mathrm{part,A}}(\vec{b}) = \sum_{i=1\cdots A} \Theta\left(P(\vec{b} - \vec{r}_i) - \nu_i\right) \; .$$

$$P(b) = 1 - \exp[-\sigma_g T_{pp}(b)], \qquad T_{pp}(b) = \int d^2s\, T_p(s)\, T_p(s-b)$$

$$T_p(r) = \frac{1}{2\pi B} \exp[-r^2/(2B)] \qquad \sigma_{NN}(\sqrt{s}) = \int d^2b\, (1 - \exp[-\sigma_g T_{pp}(b)])$$

N_{part} fluctuations in p+Pb:



Particle correlations in hadron-nucleus collisions as a signature of high parton density

Anna Stasto
Penn State & RIKEN BNL

Outline

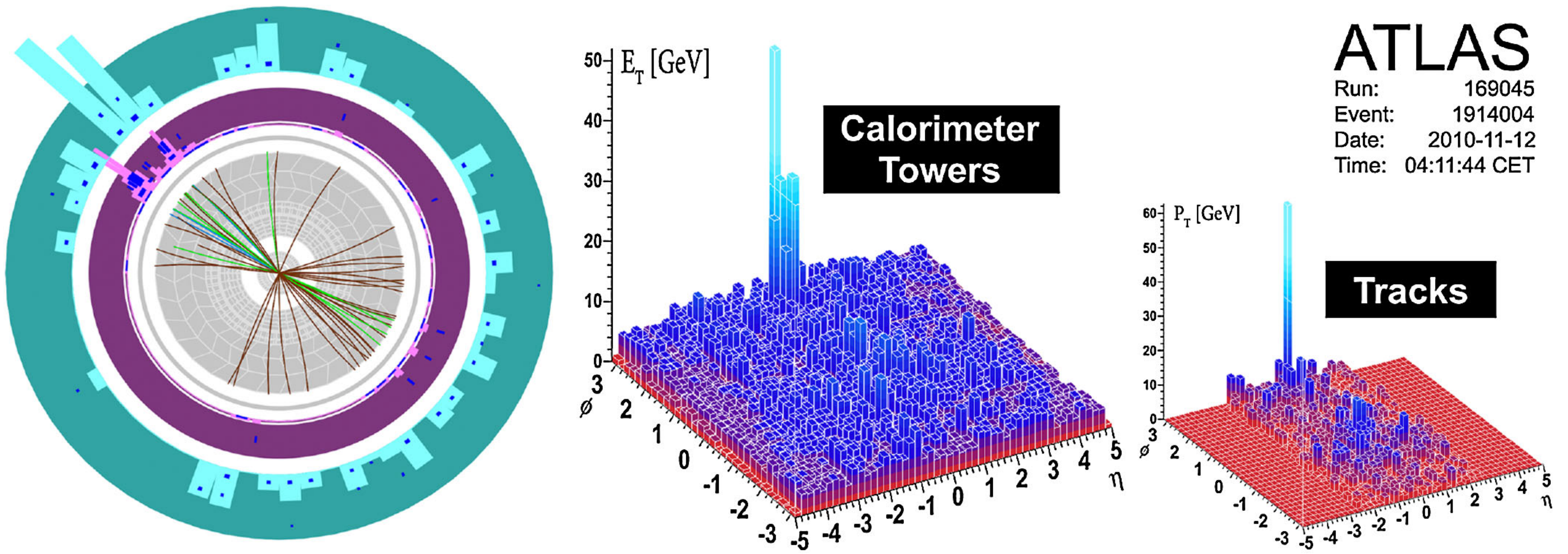
- Dihadron correlations in pA (dA) (RHIC)
- Drell-Yan - hadron correlations in pA (RHIC,LHC)

Topics of research

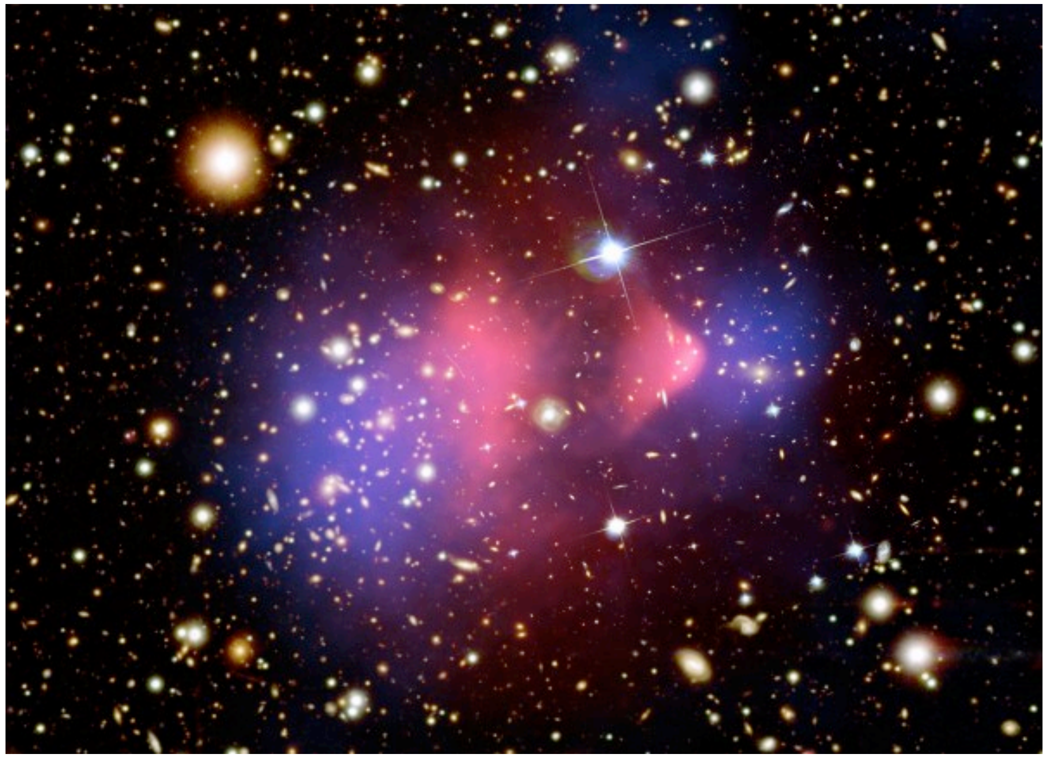
- Correlations in proton-ion collisions as a sign of the high parton density (AMS, B.Xiao, F.Yuan, D.Zaslavsky; **Phys.Rev. D86 (2012) 014009**, **Phys.Lett. B716 (2012) 430-434**)
- Impact parameter dependence in small x evolution (J.Berger, AMS; **Phys.Rev. D84 (2011) 094022**, **arXiv:1205.2037**)
- MHV amplitudes on the light-front (C.Cruz-Santiago, AMS; to be published
- Saturation effects and resummation of higher order corrections (E.Avsar, D.Triantafyllopoulos, AMS, D.Zaslavsky, **JHEP 1110 (2011) 138)**
- Multi-particle production at high energies (F.Dominguez, C.Marquet, AMS, B.Xiao); **arXiv:1210.1141)**

Examples of (de)correlations and distortions of a probe as a tool to analyze the properties of the medium

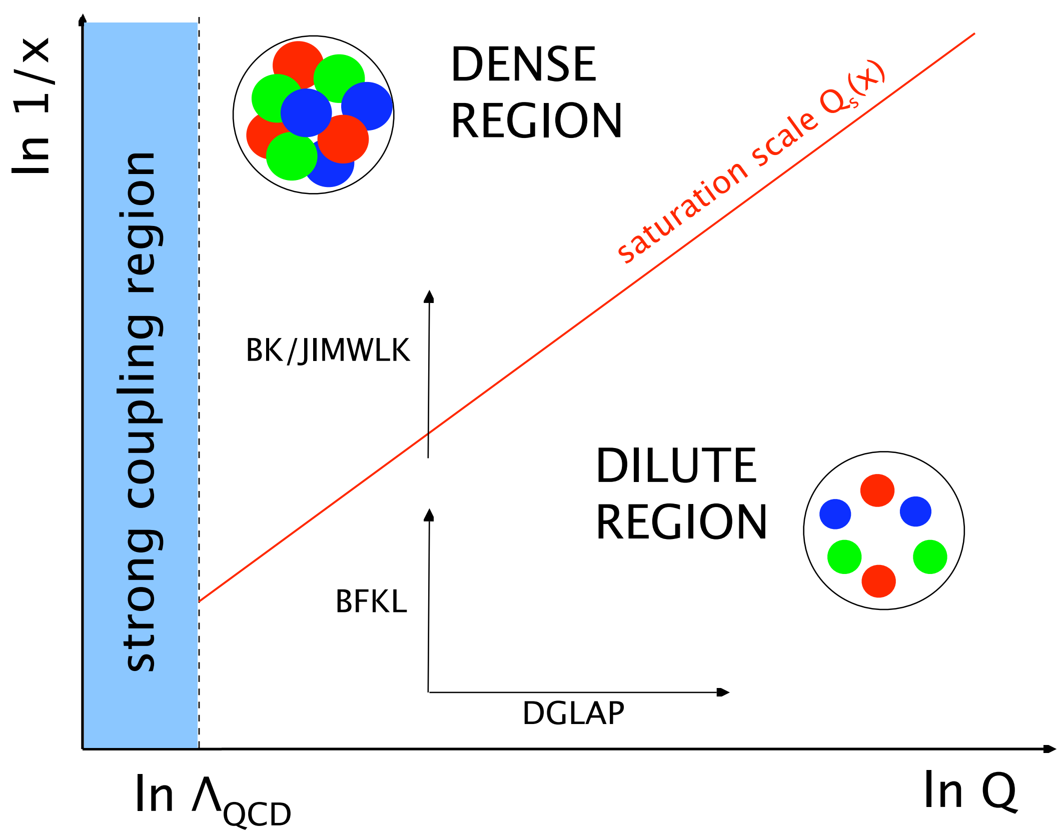
Jet quenching as a probe of dense medium in heavy ion collisions



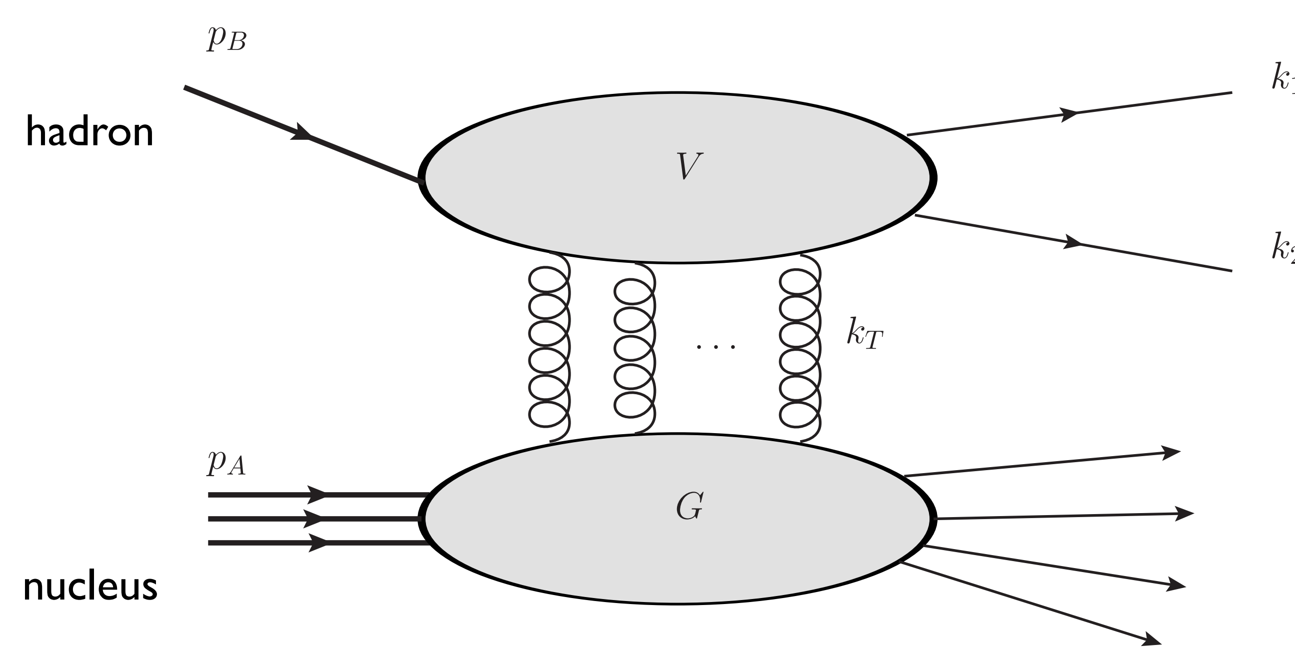
Gravitational lensing as a measure of dark matter distribution



Measure the properties of the gluon distribution in the nucleus through correlations



Observables sensitive to parton transverse momentum can establish the size of saturation scale and constrain the unintegrated gluon density in the nucleus.



Two processes studied:

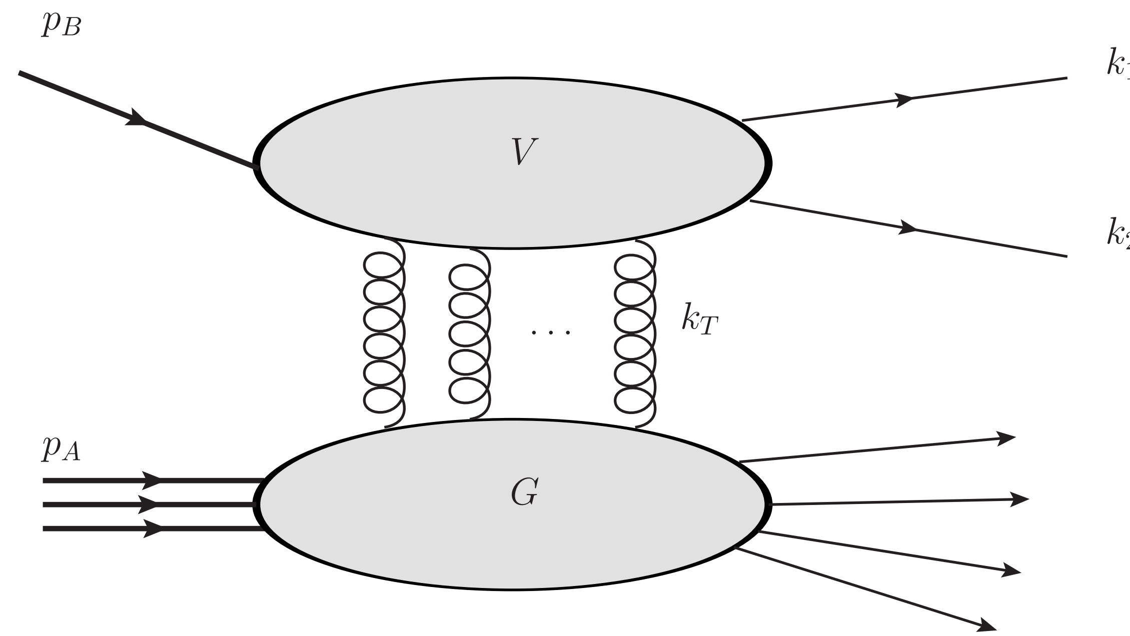
Dihadron correlations in p(d)A

Drell-Yan lepton pair-hadron correlations in pA

Dihadron correlations in p(d)A

(Albacete,Marquet)

$$p + A \to h_1 + h_2 + X \ ,$$



- Forward rapidity
- Sensitivity to small x gluon distribution in the nucleus
- Involves two gluon distribution functions
- Cross section for this process evaluated using kT factorization formula for two particle production.

Unintegrated gluon distribution convoluted with coefficient functions and fragmentation functions

$$\frac{d\sigma_{\mathrm{corr.}}^{(pA\to h_1 h_2)}}{dy_{h_1} dy_{h_2} d^2p_{1\perp} d^2p_{2\perp}} = \int \frac{dz_1}{z_1^2}\frac{dz_2}{z_2^2}\frac{\alpha_s^2}{\hat{s}^2}\left[x_p q(x_p)\mathcal{F}_{qg}^{(i)}\right.$$

$$\times H_{qg}^{(i)}\left(D_{h_1/q}(z_1)D_{h_2/g}(z_2) + D_{h_2/q}(z_1)D_{h_1/g}(z_2)\right)$$

$$\left. + x_p g(x_p)\mathcal{F}_{gg}^{(i)} H_{gg}^{(i)} D_{h_1/g}(z_1) D_{h_2/g}(z_2)\right] \ ,$$

Need to estimate the uncorrelated piece

$$d\sigma^{(pA\to h_1h_2)} = d\sigma^{(pA\to h_1h_2)}_{\rm corr.} + d\sigma^{(pA\to h_1h_2)}_{\rm uncorr.}$$

Comes from independent double parton scattering

$$\frac{d\sigma^{(pA\to h_1h_2)}_{\rm uncorr.}}{d^2b\,dy_{h_1}dy_{h_2}d^2p_{1\perp}d^2p_{2\perp}} = \int \frac{dz_1}{z_1^2}\frac{dz_2}{z_2^2}D(z_1)D(z_2) \times \sum_{ij} x_pf_i(x_p)x'_pf_j(x'_p)F^{(i)}_{x_g}(k_{1\perp})F^{(j)}_{x'_g}(k_{2\perp}) \ ,$$

To compare with experimental data need to compute the correlation function

$$C(\Delta\phi) = \frac{\int_{|p_{1\perp}|,|p_{2\perp}|} \frac{d\sigma^{pA\to h_1h_2}}{dy_1dy_2d^2p_{1\perp}d^2p_{2\perp}}}{\int_{|p_{1\perp}|}\frac{d\sigma^{pA\to h_1}}{dy_1d^2p_{1\perp}}} \ ,$$

Together with the single inclusive cross section

Forward di-pion correlation

$$y_1 \sim y_2 \sim 3.2$$

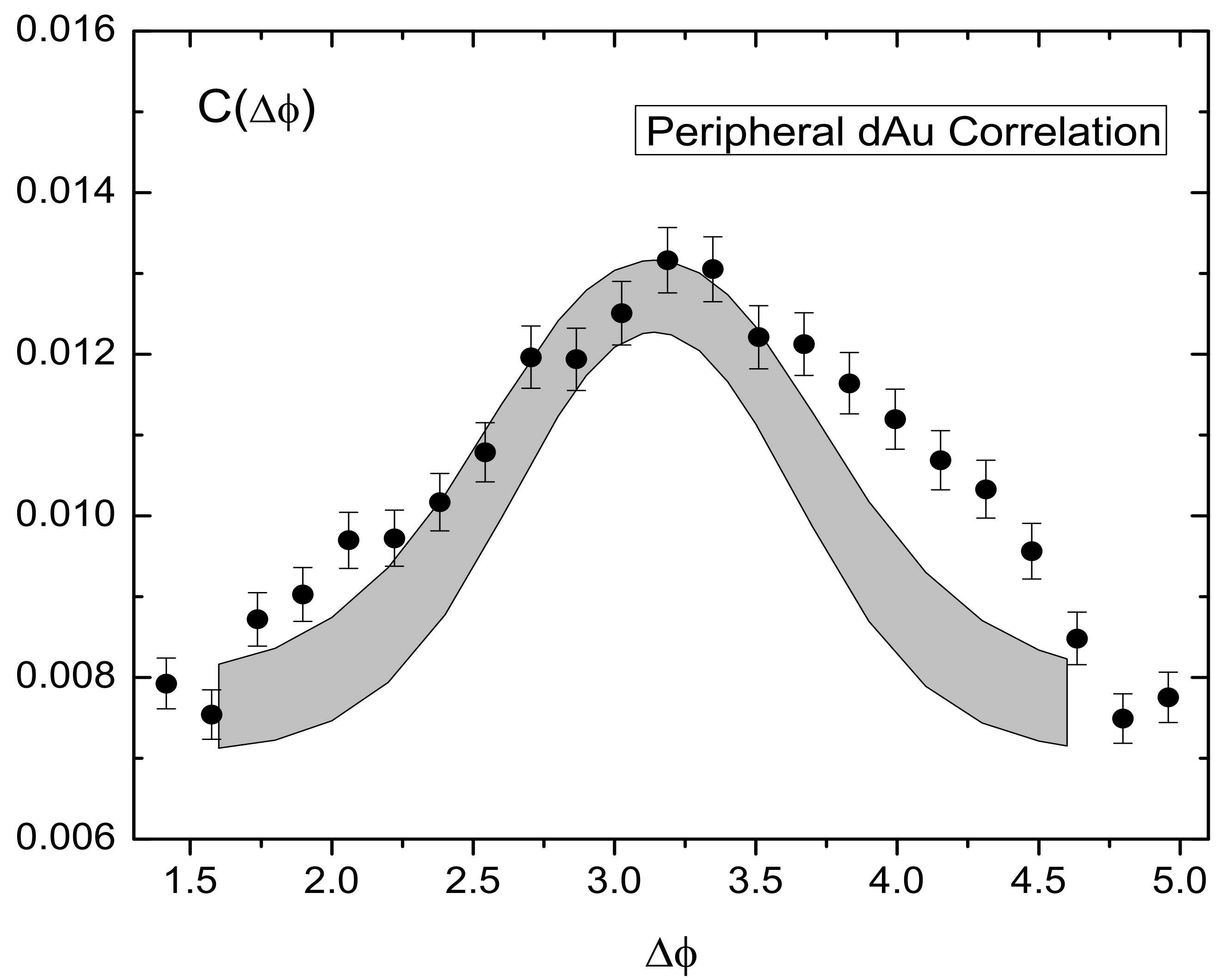
Average impact parameter:

$$\bar{b} \sim 6.7\ \mathrm{fm}$$

$$p_{1\perp}^{\mathrm{trig}} > 2\ \mathrm{GeV}$$

$$1\ \mathrm{GeV} < p_{2\perp}^{\mathrm{asso}} < p_{1\perp}^{\mathrm{trig}}$$

STAR measurement



Clear peak for peripheral collisions

GBW model with geometrical scaling

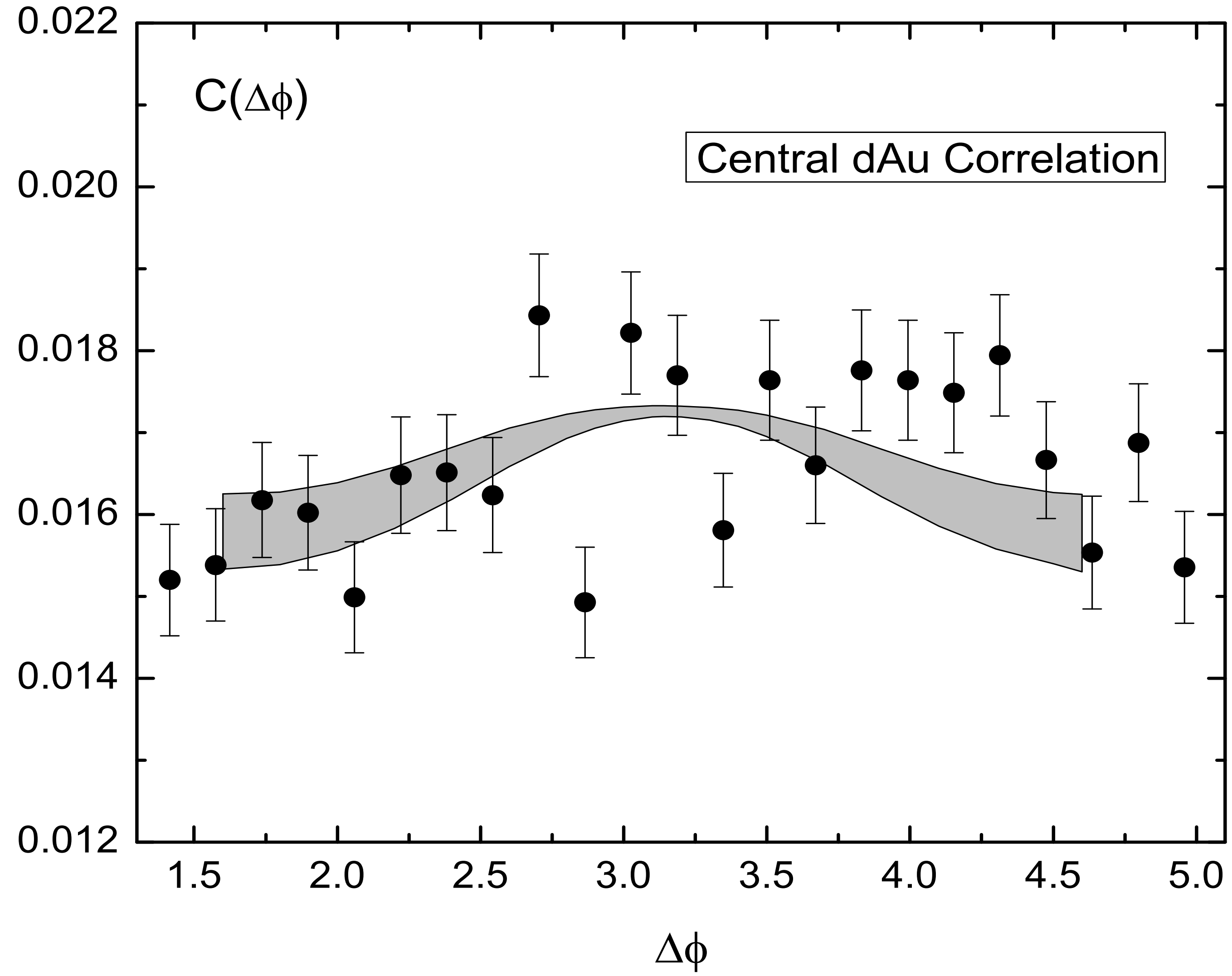
$$Q_s^2(x) = Q_{s0}^2(x/x_0)^{-\lambda} \text{ with } Q_{s0} = 1\,\mathrm{GeV},\ x_0 = 3.04 \times 10^{-3} \text{ and } \lambda = 0.288$$

$$Q_{sA}^2 = c(b) A^{1/3} Q_s^2(x)$$

Average impact parameter:

$$\bar{b} \sim 2.7 \text{ fm}$$

STAR measurement



Peak disappears for central collisions

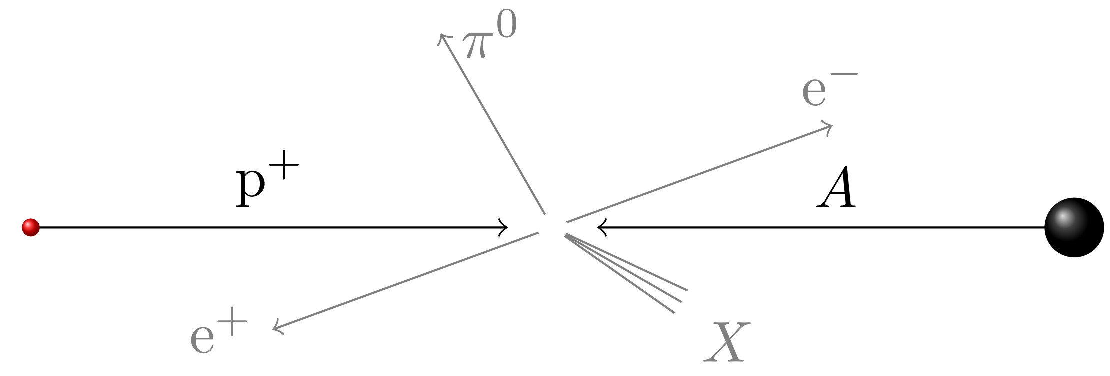
The saturation scale must be of an order of the transverse momentum of the probe

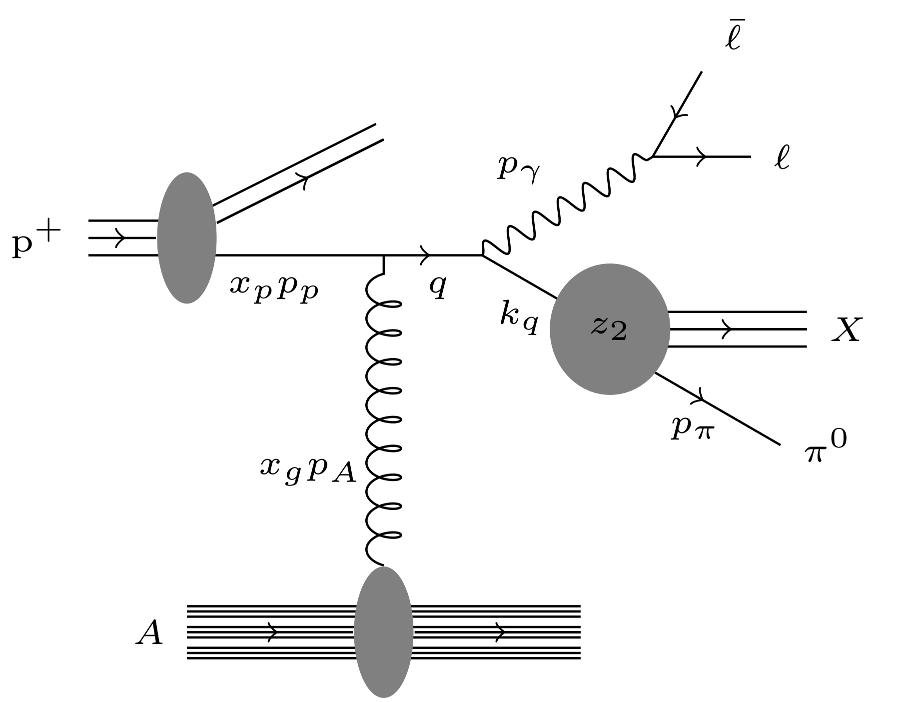
$Q_s \sim 2 \text{ GeV}$ at $x_g \sim 6 \times 10^{-4}$

in the center of gold nucleus

The width of the peak directly sensitive to the value of the saturation scale

Drell-Yan lepton pair-hadron correlations in p(d)A





Exclusive cross section

$$\frac{\mathrm{d}\sigma^{pA\to\gamma^*\pi^0X}}{\mathrm{d}Y_\gamma \mathrm{d}Y_\pi \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2\mathbf{p}_{\pi\perp}\mathrm{d}^2b} = \int_{\frac{z_{h2}}{1-z_{h1}}}^{1} \frac{\mathrm{d}z_2}{z_2^2}\sum_f D_{\pi^0/f}(z_2,\mu)x_p q_f(x_p,\mu)\frac{\alpha_{\mathrm{em}}e_f^2}{2\pi^2}(1-z)F_{x_g}(q_\perp)$$
$$\times\left\{[1+(1-z)^2]\frac{z^2q_\perp^2}{[\tilde{P}_\perp^2+\epsilon_M^2][(\tilde{\mathbf{P}}_\perp+z\mathbf{q}_\perp)^2+\epsilon_M^2]} - z^2(1-z)M^2\left[\frac{1}{\tilde{P}_\perp^2+\epsilon_M^2}-\frac{1}{(\tilde{\mathbf{P}}_\perp+z\mathbf{q}_\perp)^2+\epsilon_M^2}\right]^2\right\}$$

Inclusive cross section

$$\frac{\mathrm{d}\sigma^{pA\to\gamma^*X}}{\mathrm{d}Y_\gamma \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2b} = \int_{z_{h1}}^{1}\frac{\mathrm{d}z}{z}\iint \mathrm{d}^2\mathbf{q}_\perp\sum_f x_p q_f(x_p,\mu)\frac{\alpha_{\mathrm{em}}e_f^2}{2\pi^2}F_{x_g}(q_\perp)$$
$$\times\left\{[1+(1-z)^2]\frac{z^2q_\perp^2}{[p_{\gamma\perp}^2+\epsilon_M^2][(\mathbf{p}_{\gamma\perp}-z\mathbf{q}_\perp)^2+\epsilon_M^2]} - z^2(1-z)M^2\left[\frac{1}{p_{\gamma\perp}^2+\epsilon_M^2}-\frac{1}{(\mathbf{p}_{\gamma\perp}-z\mathbf{q}_\perp)^2+\epsilon_M^2}\right]^2\right\}$$

This process provides a way to measure dipole gluon distribution in the nucleus at small x

Correlation is computed as the ratio of the two cross sections

$$C^{\mathsf{DY}}(\Delta\phi) = \frac{\underset{p_{\{\gamma,\pi\}\perp} > p_{\perp\mathsf{cut}}}{\int\cdots\int} \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2\mathbf{p}_{\pi\perp}\frac{\mathrm{d}\sigma^{pA\to\gamma^*\pi^0 X}}{\mathrm{d}Y_\gamma \mathrm{d}Y_\pi \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2\mathbf{p}_{\pi\perp}\mathrm{d}^2 b}}{\underset{p_{\gamma\perp} > p_{\perp\mathsf{cut}}}{\int} \mathrm{d}^2\mathbf{p}_{\gamma\perp}\frac{\mathrm{d}\sigma^{pA\to\gamma^* X}}{\mathrm{d}Y_\gamma \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2 b}}$$

$$C^{\mathsf{DY}}(\Delta\phi) = \frac{\sigma^{pA\to\gamma^*\pi^0 X}}{\sigma^{pA\to\gamma^* X}}$$

$\Delta\phi = \pi$ sensitivity to low q_T

$\Delta\phi \sim 0, 2\pi$ sensitivity to high q_T

Exclusive cross section vanishes when $q_T = 0$

Expect double peak structure with a minimum at $\Delta\phi = \pi$

Use MSTW2008 for integrated parton distribution functions

Use DSS 2007 for fragmentation functions

Need to model gluon distribution in the nucleus at small x

GBW model:

$$\phi(k^2,Y) = \frac{1}{2}\Gamma\left(0, \frac{k^2}{Q_{sA}^2(Y)}\right)$$

$$F_{x_g}(k^2,Y) = \frac{1}{\pi Q_{sA}^2(Y)} e^{-k^2/Q_{sA}^2(Y)}$$

where

$$Q_{sA}^2 = Q_{s0}^2\left(\frac{x_0}{x}\right)^\lambda$$

Here $Q_{s0} = 1\,\mathrm{GeV},\ \lambda = 0.288,\ x_0 = 3.04 \times 10^{-4}$

BK equation:

$$\frac{\partial \phi(k,Y)}{\partial Y} = \bar{\alpha}_s K \otimes \phi(k) - \bar{\alpha}_s \phi^2(k)$$

Normalized gluon distribution

$$F_{x_g}(\mathbf{k},\mathbf{b}) = \frac{1}{2\pi}\nabla_{\mathbf{k}}^2 \phi\big(\mathbf{k},\mathbf{b},Y(x_g)\big) + \delta^2(\mathbf{k})$$

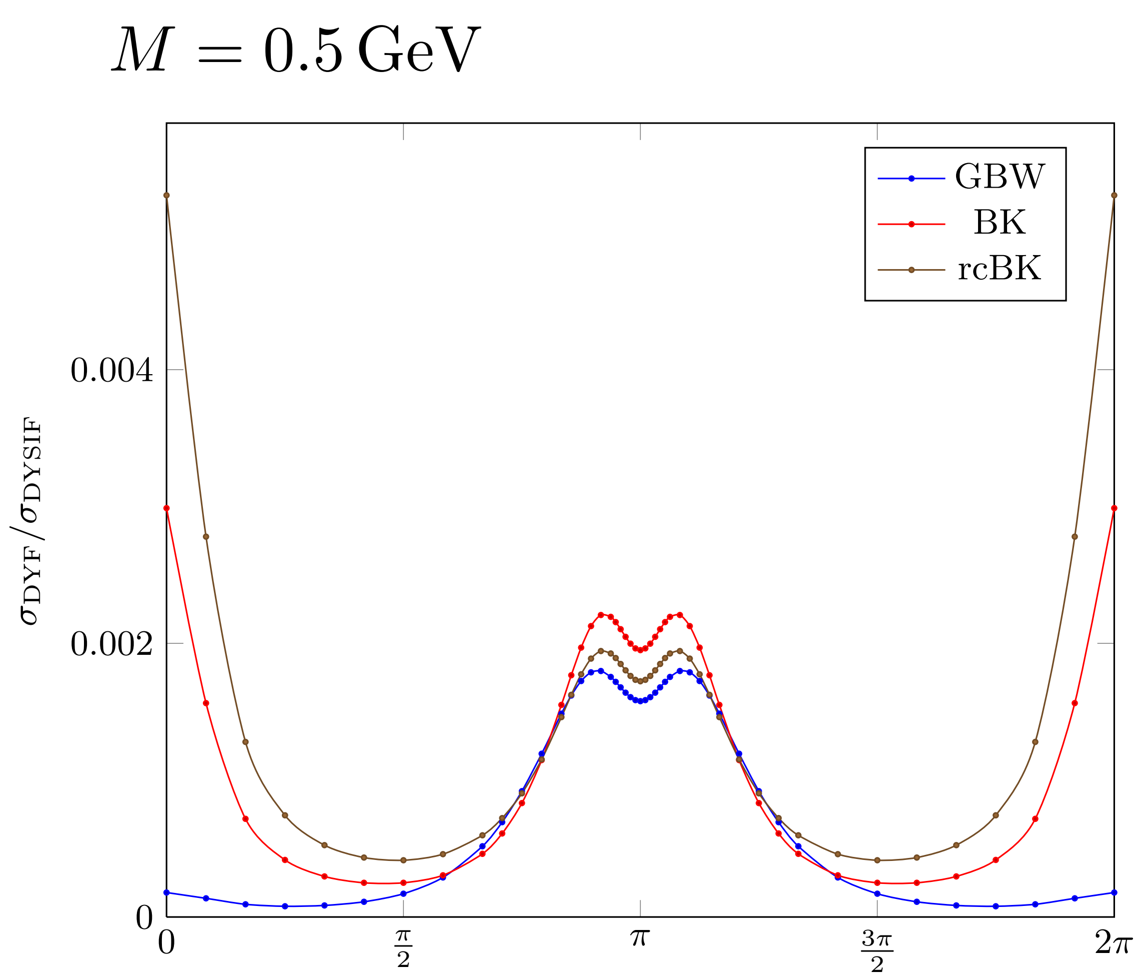
with (simplified) and regularized running coupling:

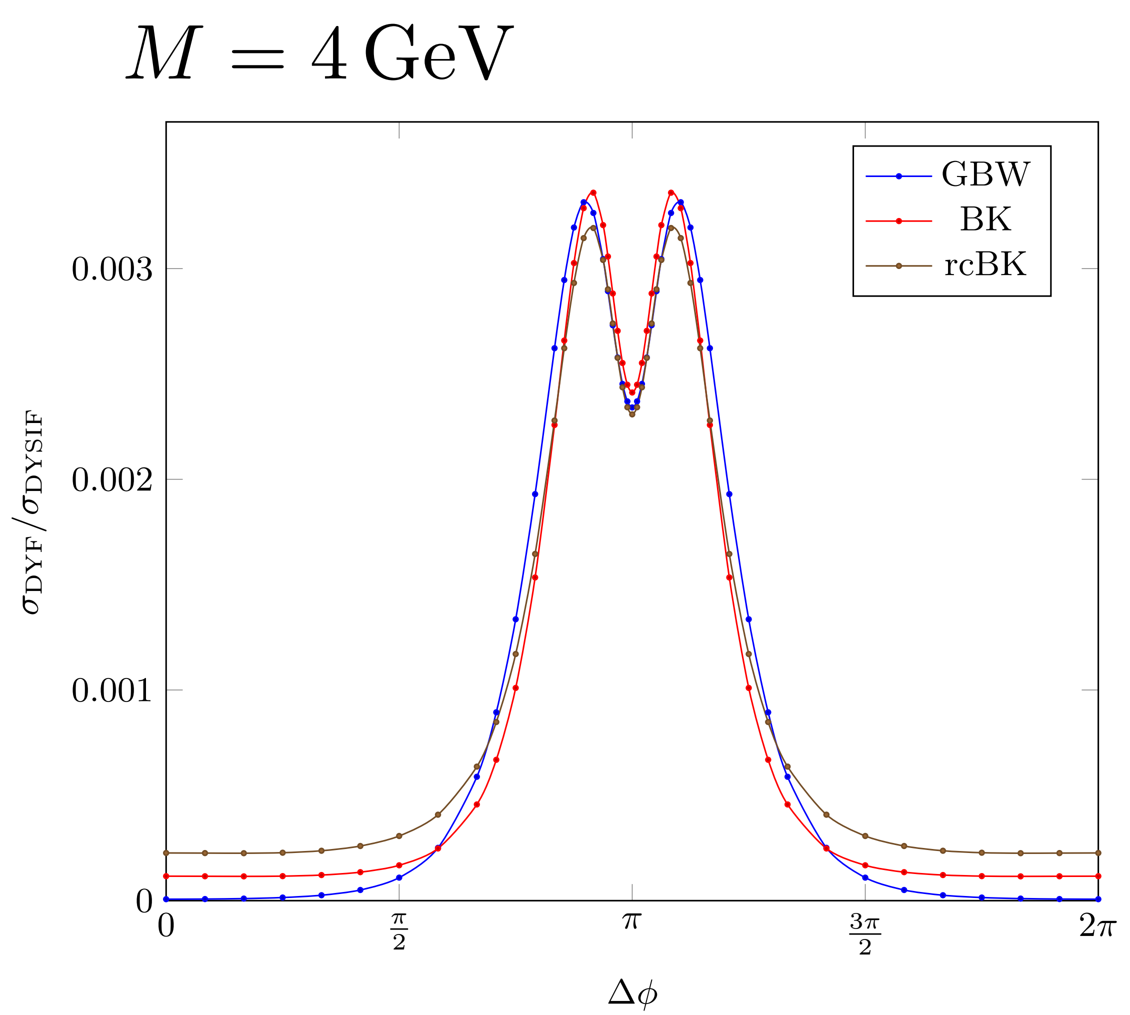
$$\bar{\alpha}_{\mathrm{s}}(k^2) = \frac{1}{\beta \ln \frac{k^2+\mu^2}{\Lambda_{\mathrm{QCD}}^2}}$$

Parameters for the calculation:

		RHIC	LHC
virtual photon mass	M	$0.5\,\mathrm{GeV}, 4\,\mathrm{GeV}$	$4\,\mathrm{GeV}, 8\,\mathrm{GeV}$
photon rapidity	Y_γ	2.5	4
pion rapidity	Y_π	2.5	4
centrality coefficient	c	0.85	0.85
mass number	A	197	208
CM energy per nucleon	$\sqrt{s_{NN}}$	$200\,\mathrm{GeV}$	$8800\,\mathrm{GeV}$
transverse momentum cut	$p_{\perp\mathrm{cut}}$	$1.5\,\mathrm{GeV}$	$3\,\mathrm{GeV}$
projectile type		deuteron	proton

Calculation for RHIC

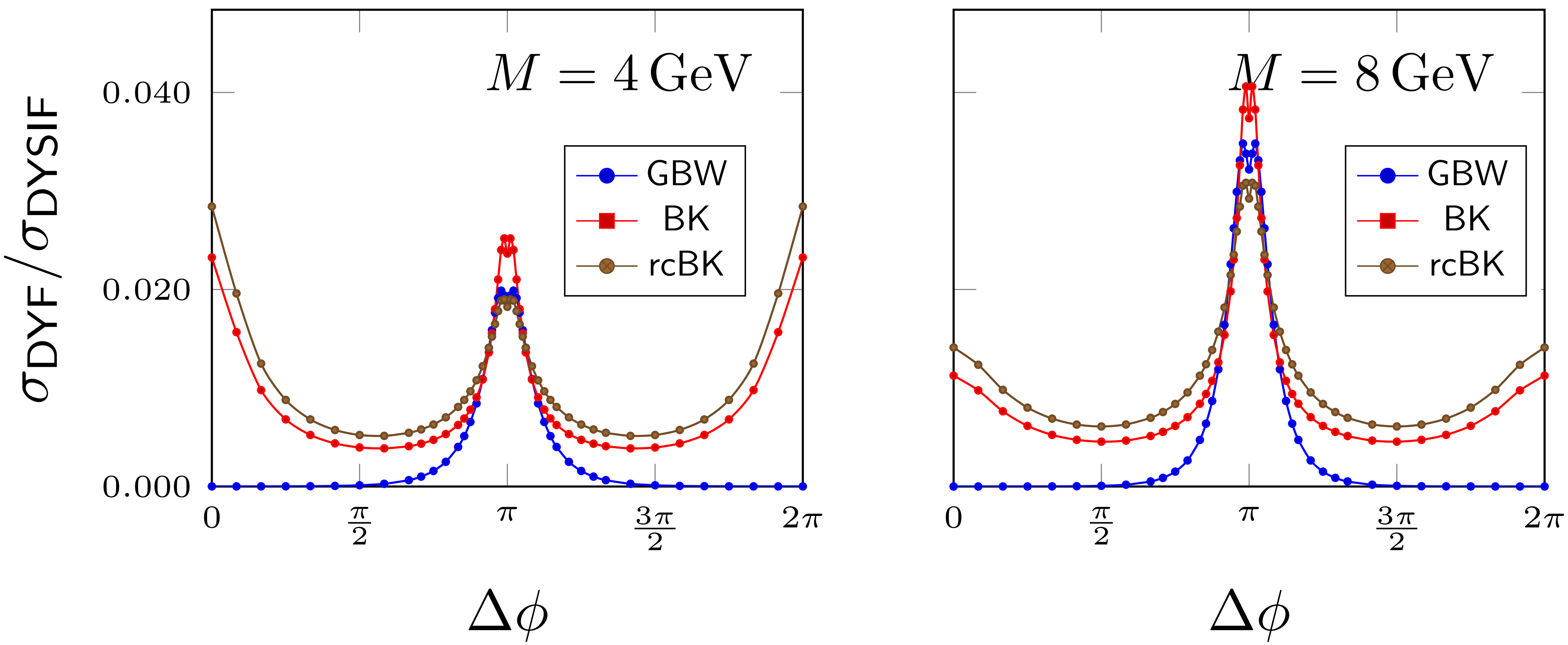




Strong enhancement of the near side peak for the case of the gluon distribution from BK equation.

Small differences between GBW and BK in the away side peak structure.

Calculation for LHC



Strong enhancement of the near side peak for the case of the gluon distribution from BK equation as compared with GBW. This is related with markedly different shape of the gluon distribution in the region of large transverse momenta.

Summary

- Dihadron correlations in dA.
- Good description of the RHIC data. Direct sensitivity to saturation scale of the nucleus.
- Can use similar process in electron-ion collider like EIC,LHeC to constrain WW gluon distribution in the nucleus.
- Drell-Yan lepton pair - hadron correlations.
- Sensitivity to the dipole gluon distribution.
- Double peak structure, notable differences between models which differ by large kT behavior.

RBRC Review 2012
Brookhaven National Laboratory, November 7, 2012

Electromagnetic and Heavy Flavor Probes of Quark Gluon Plasma

Rainer Fries

Texas A&M University

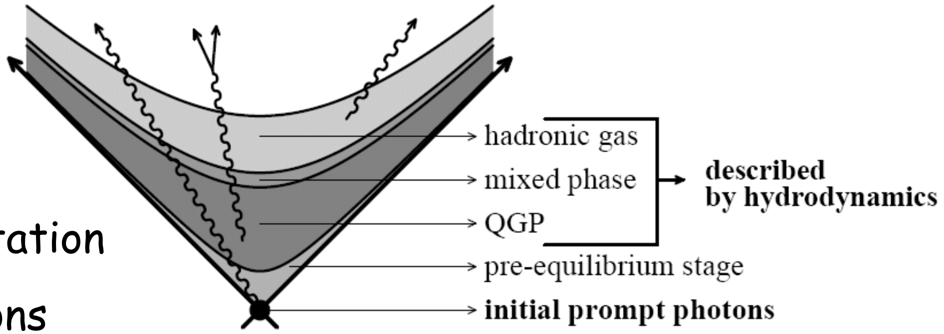
Overview

- Electromagnetic Probes: Measuring jet-triggered back-scattering photons
  - With Somnath De, Dinesh Srivastava (VECC)
  - arxiv:1208.6235

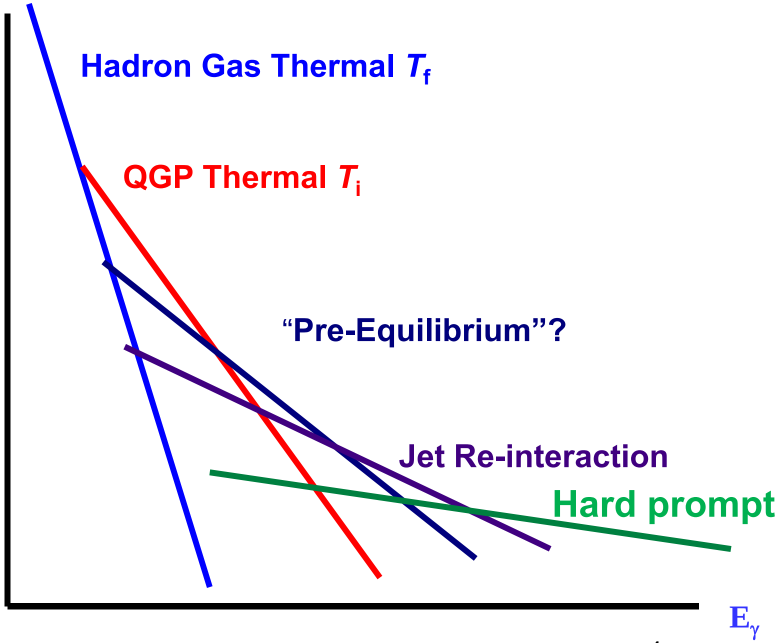
- Heavy Flavor Probes: A consistent framework for open heavy flavor in the kinetic regime
  - With Min He (Hunan University) and Ralf Rapp (Texas A&M University)
  - Phys.Lett. B701 (2011) 445
  - Phys.Rev. C86 (2012) 014903
  - arXiv:1204.4442
  - arXiv:1208.0256

Back-Scattering Photons

Direct Photons in Heavy Ion Collisions

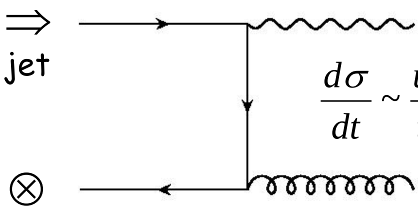


- Sources:
  - Initial hard photons + jet fragmentation
  - Pre-equilibrium + jet-medium photons
  - Thermal radiation from QGP, HRG and hadronization



- Goals:
  - Separate sources experimentally
  - Put constraints on QGP/QCD properties

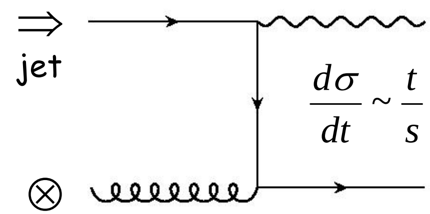
Back-Scattering Photons



$$\frac{d\sigma}{dt} \sim \frac{u}{t} + \frac{t}{u}$$

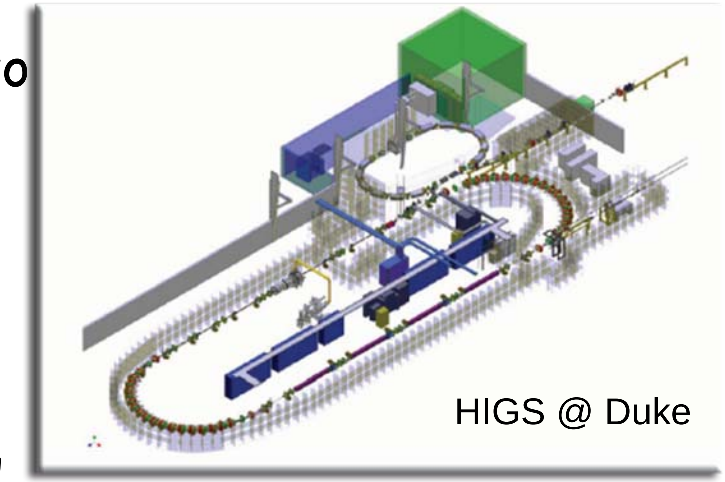
$$\vec{p}_\gamma \approx \vec{p}_{jet}$$

$$\vec{p}_\gamma \approx \vec{p}_{jet}$$



$$\frac{d\sigma}{dt} \sim \frac{t}{s} + \frac{s}{t}$$

- Same diagrams in QED: routinely used to electron beams into gamma-ray beams
  - E.g. HIGS and ALICE facilities
  - (~1 eV) γ + (~1 GeV) e $\rightarrow$ (~1 GeV) γ + e



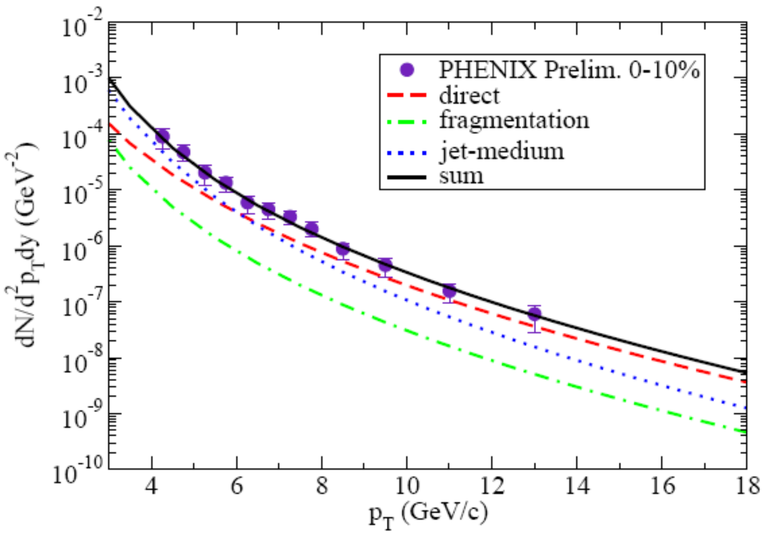
- Here:
  - (~200 MeV) g+ (~10 GeV) q $\rightarrow$ (~ 10GeV) γ + q
- Yield for jet phase space distribution *f* and QGP with temp. *T*:

$$E_\gamma \frac{dN_\gamma}{d^3 p_\gamma} = \frac{\alpha \alpha_s}{8\pi^2} \int d^4x \frac{2}{3} \left[f_q(p_\gamma) + f_q(p_\gamma) \right] T^2 \left(\ln \frac{4E_\gamma T}{m^2} + C \right)$$

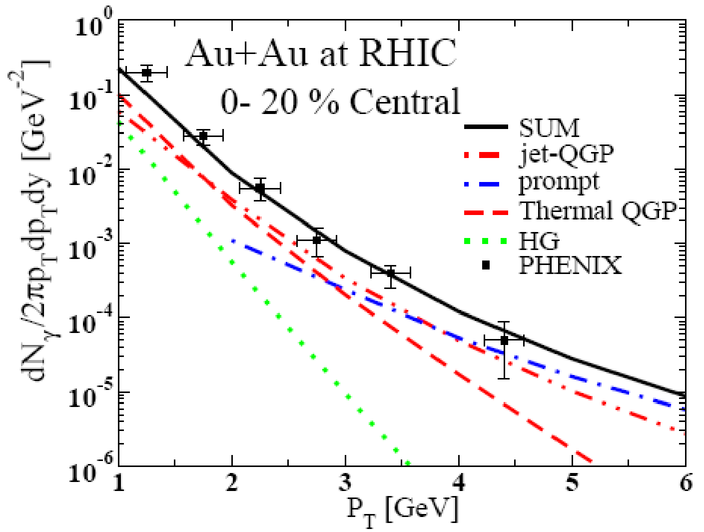
[RJF, Müller & Srivastava, PRL 90 (2003)]

How to Measure Those Photons?

- Inclusive yield and R_{AA}: hopeless



[Qin, Ruppert, Gale, Jeon & Moore, PRC 80 (2009)]



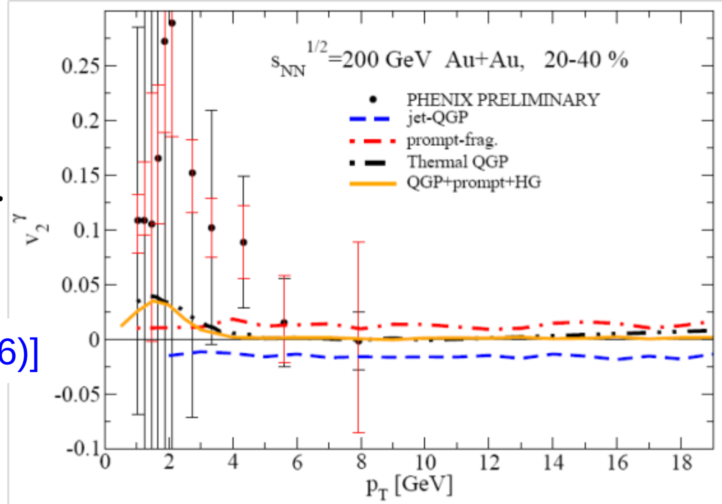
[Turbide, Gale, Frodermann & Heinz, PRC 77 (2007)]

- Negative v_2 for jet-medium photons!

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

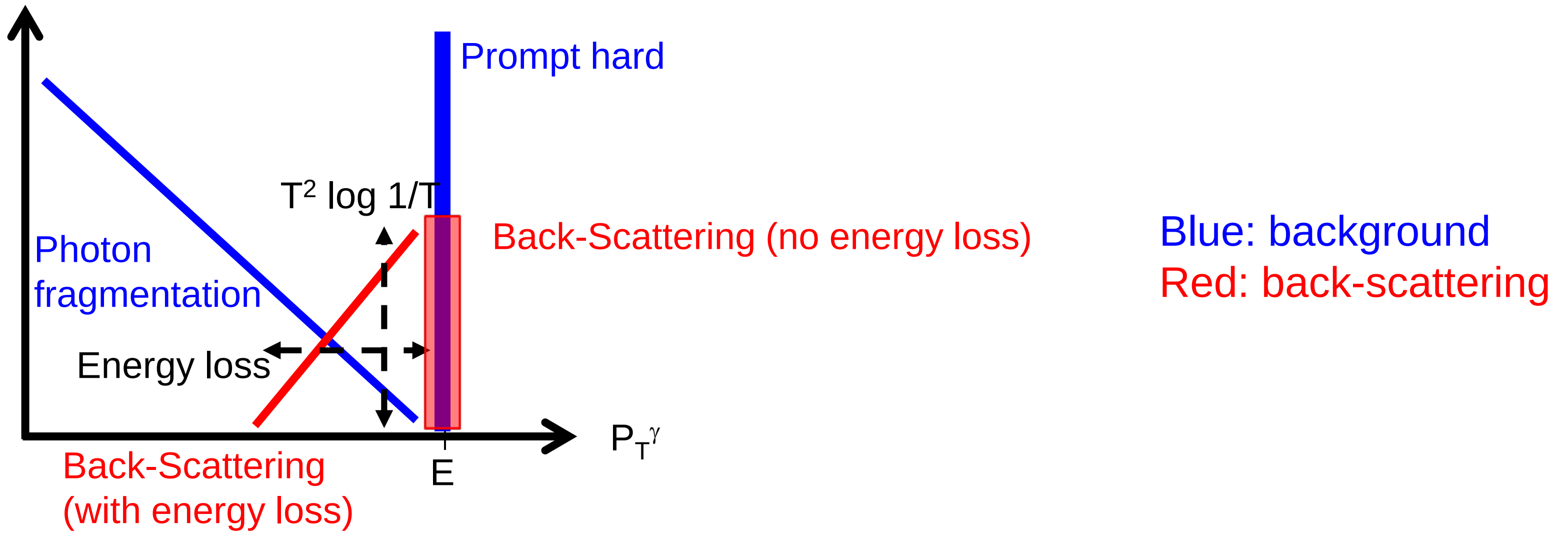
- Expected signal too small for current experimental resolution.

[Chatterjee, Frodermann, Heinz, Srivastava, PRL 96 (2006)]



Jet-Triggers for Photons

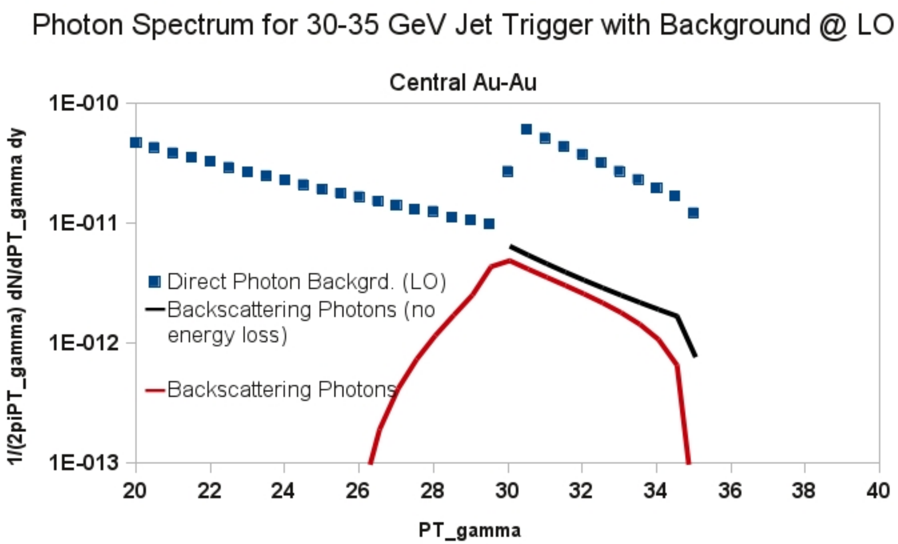
- Idealized picture: photons opposite a jet of fixed energy E in leading order (LO) kinematics.

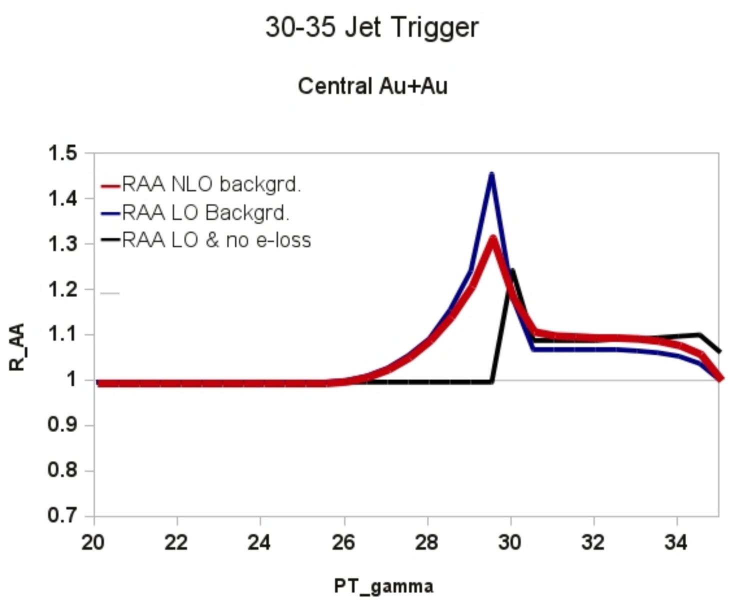


- Important information stored in those photons: Perturbative mechanism? Medium Temperature? Parton energy loss?
- Is nature kind? Have to account for finite trigger windows, kinematics beyond LO, etc.

Jet-Triggered Photons: RHIC

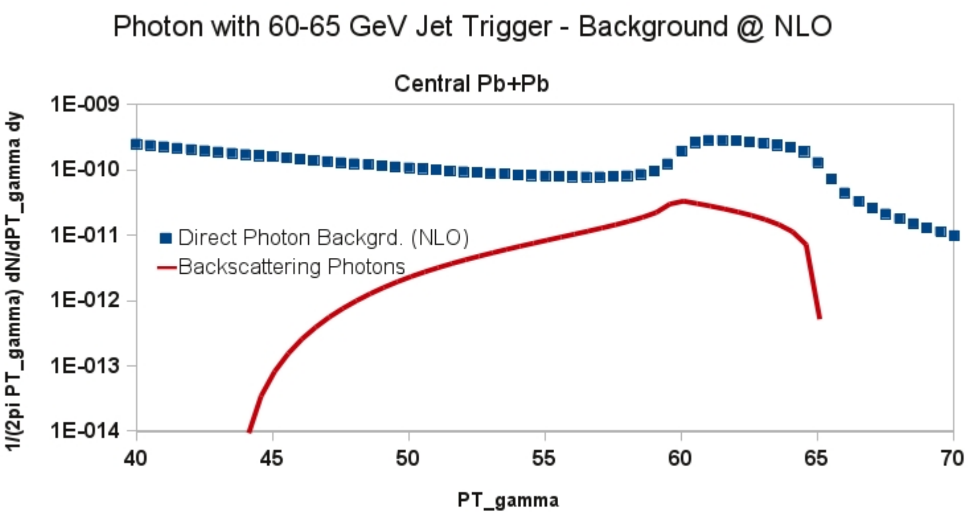
- Study with 30-35 GeV trigger jet in central Au+Au @ 200 GeV, look for photons on away side ±15° from trigger jet direction.
- Backscattering photons underneath "trigger peak"
- Energy loss: leakage of signal to smaller momenta
- R_{AA}: clear backscattering peak despite finite trigger interval.
- NLO: smoothened out "trigger peak".

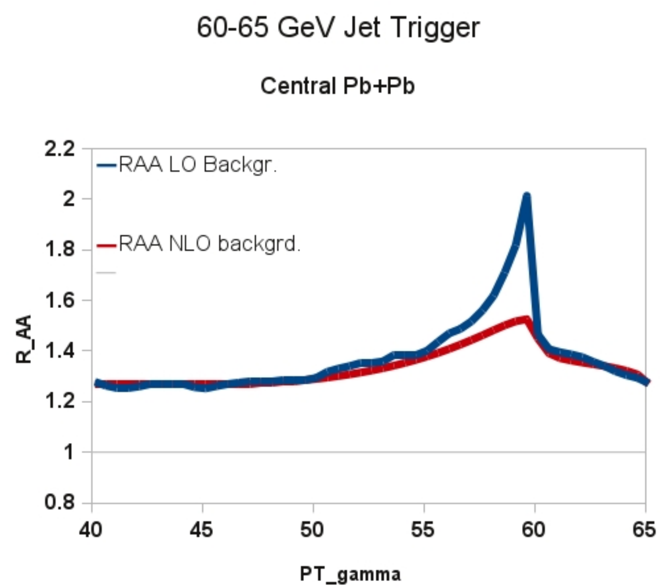




Jet-Triggered Photons: LHC

- Study with 60-65 trigger jets in central Pb+Pb @ 2.76 TeV., look for photons on away side ±15° from trigger jet direction.





Open Heavy Flavor

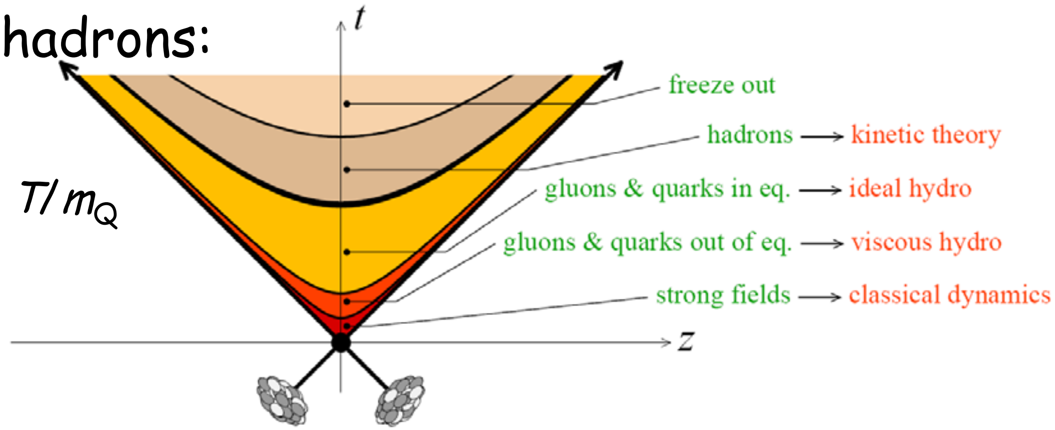
- Novel ingredients:
  - Heavy meson diffusion in hadronic phase
  - Hadronization rate compatible with heavy quark scattering rate in medium
  - Hydro tuned to describe flow around Tc.

Heavy Flavor Probes

- Our commonly accepted picture for heavy ion collisions:
  - A thermalized quark gluon plasma is created ~ 1fm/c after the collision of two heavy nuclei at RHIC or LHC energies.
- Heavy quarks Q and heavy hadrons:
  - Kinetic equilibration rates

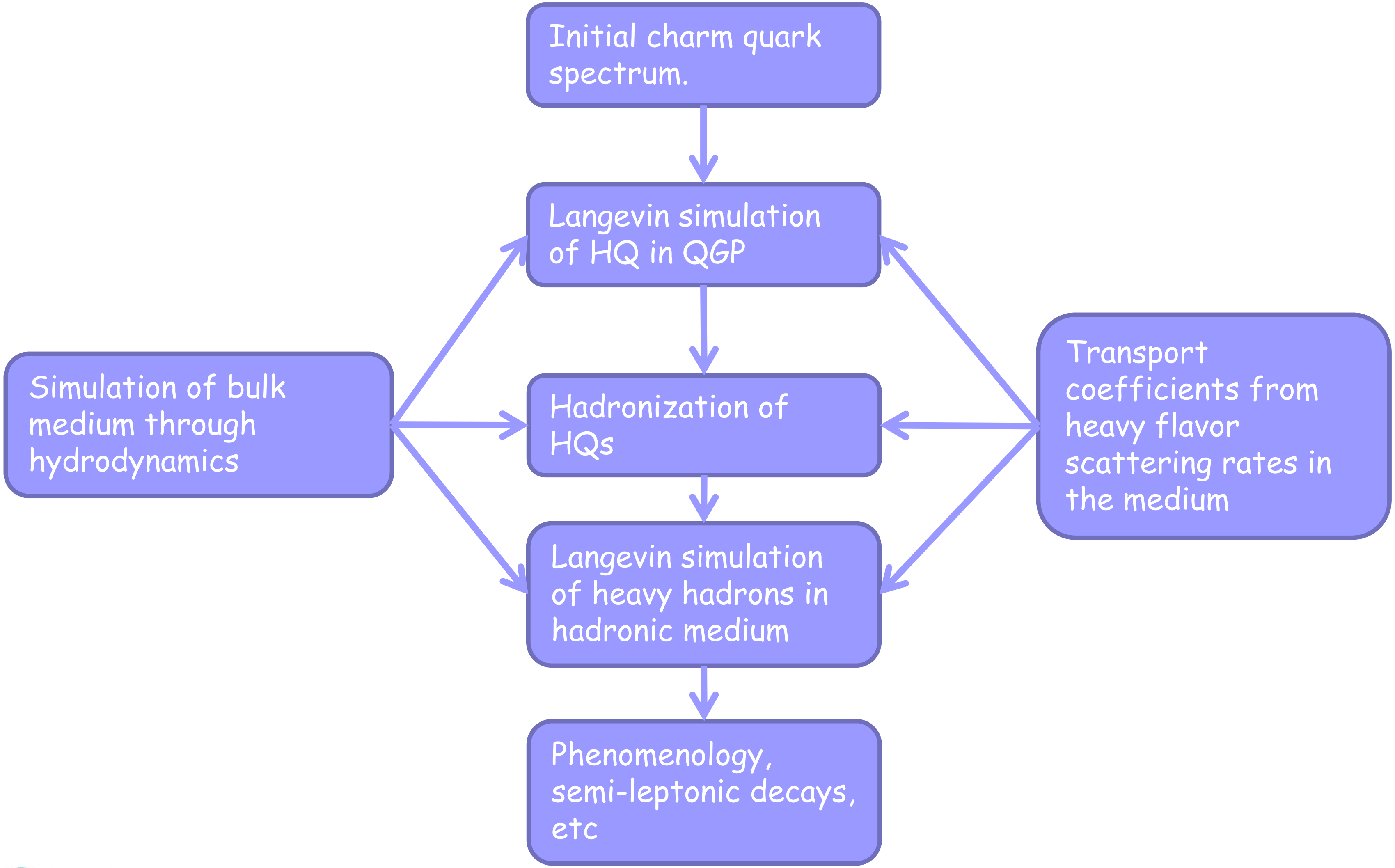
    parametrically suppressed by T/m_Q
  - Equilibration times

    ~ lifetime of the medium



- Degree of thermalization and collective motion (flow) = measure for HQ-medium interactions.
- Here open heavy flavor at low to intermediate P_T.

Work Flow in our Framework

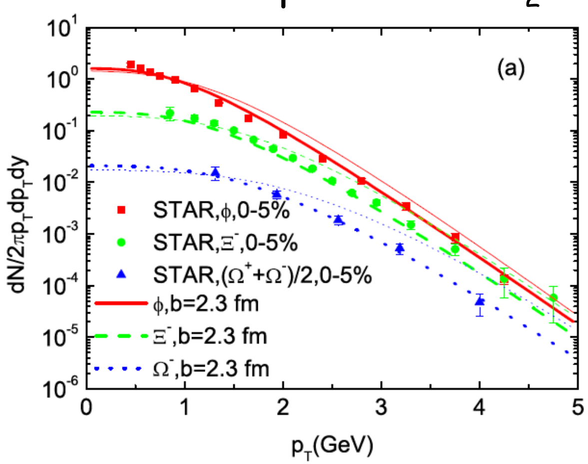


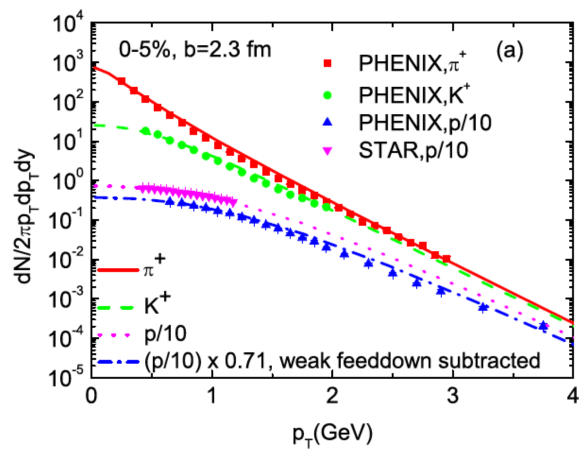
Langevin Simulation in Hydro

- Fokker-Planck equation: Stochastically realized by Langevin equation
  - Drag force and Brownian motion.
  - ρ = Gaussian noise term.

$$d\mathbf{x} = \frac{\mathbf{p}}{E}dt,$$
$$d\mathbf{p} = \boxed{-\Gamma(p)\mathbf{p}dt} + \boxed{\sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\rho}$$

- Use 2+1 ideal hydro code AZHYDRO as background
  - Standard AZHYDRO does not have enough flow at T_c. We have developed our own tune: Lattice-based PCE EOS, initial flow, steep initial profile.
  - Fit to: bulk hadron multiplicites, spectra and v_2 at 110 MeV, multi-strange hadron spectra and v_2 at 160 MeV.



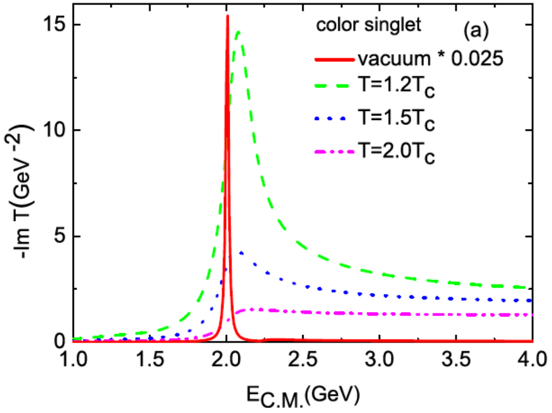


[M. He, RJF and R. Rapp, Phys. Rev. C85, 044911 (2012).]

Transport Coefficients

- Heavy quark relaxation rates in QGP from elastic scattering
  - Non-perturbative *T*-matrix approach for Q-q and Q-g interaction.
  - Resonant correlations up to 1.5 T_c.

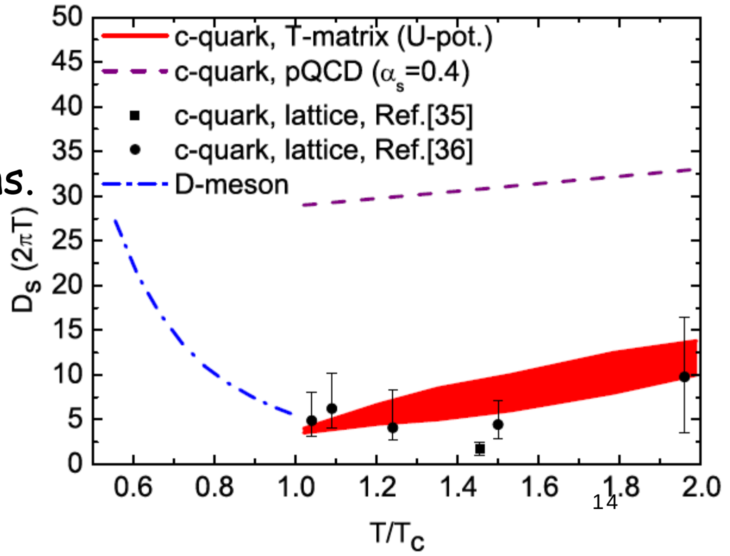
  [F. Riek and R. Rapp, Phys. Rev. C 82, 035201 (2010)]
  [K. Huggins and R. Rapp, arXiv:1206.6537]



- *D*-relaxation rates in hot hadron gas.
  - Constrained by chiral effective theory and BELLE *D*-resonance measurements.

    [C. Fuchs et al., PRC 73, 035204 (2006)]
  - *D* scattering off kaons, vector mesons, baryons.

  [M.F.M. Lutz and C. L. Korpa, Phys. Lett. B633, 43 (2006)]
  [D. Gamermann and E. Oset, Eur. Phys. J. A33, 119 (2007)]



- Open charm diffusion coefficient:

Hadronization of Heavy Quarks

- Resonance recombination ideal for systems close to equilibrium:

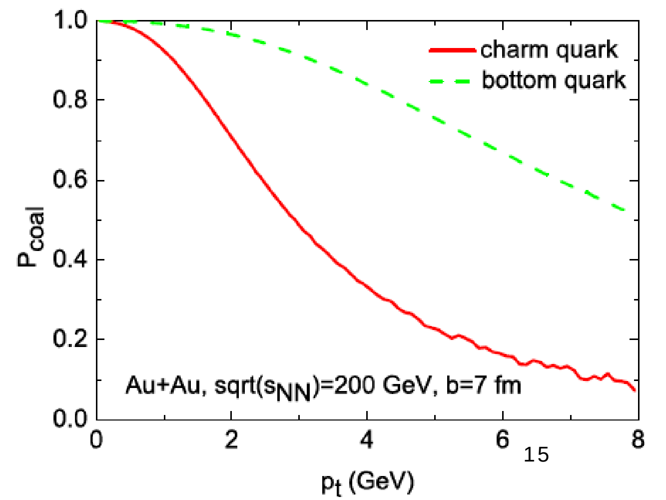
  Energy conservation + detailed balance + equilibrated quark input $\rightarrow$ equilibrated hadrons! [M. He, RJF and R. Rapp, PRC 82 (2010)]

- How to decide recombination vs fragmentation rate?

  NEW: **Q-q recombination rate ~ Q-q in-medium scattering rate!**

$$P_{\rm coal}(p) = \Delta\tau_{\rm res}\ \Gamma_Q^{\rm res}(p)$$

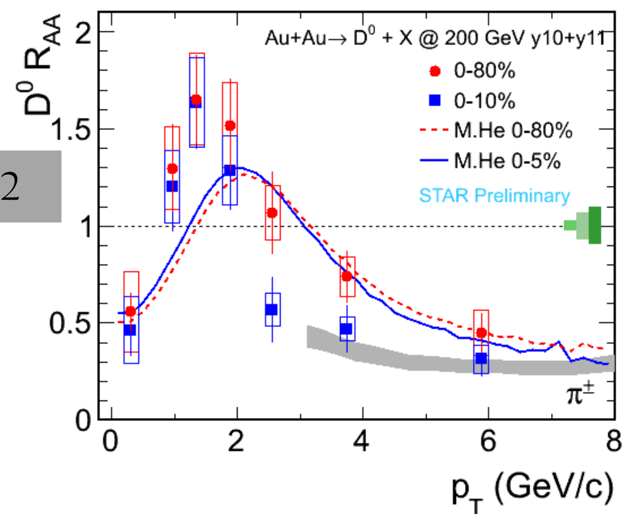
- Usually two extreme assumptions about $\Delta\tau$:
  - Corresponding to P_{coal} =1 or 1-e^{-1} at p=0.
- Total recombination probability averaged over fluid cells in lab frame:

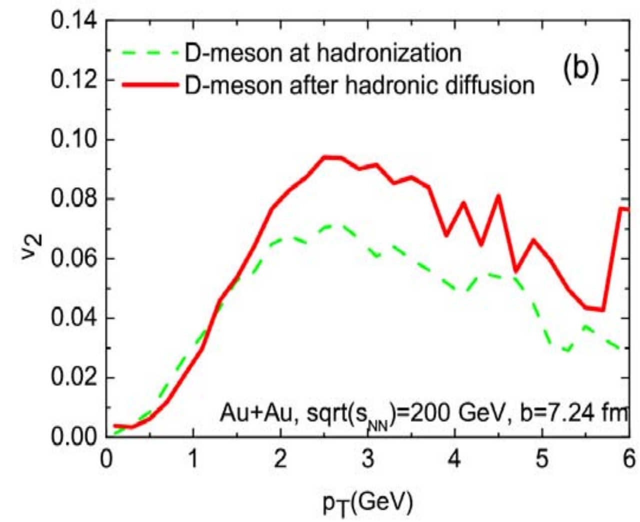


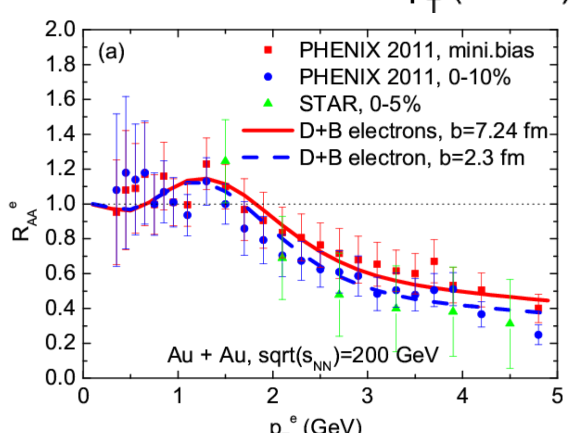
Comparison to RHIC Data

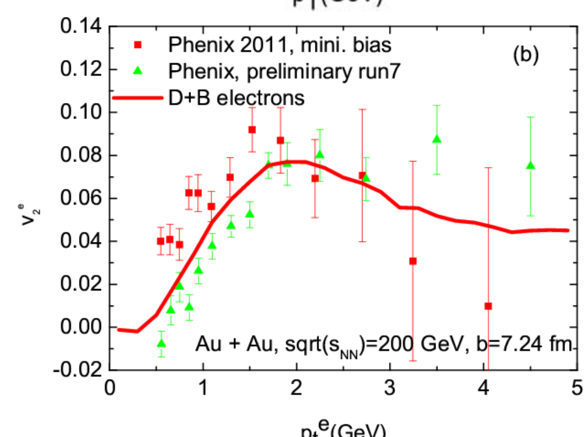
- STAR "flow bump" described.
- *D* mesons pick up significant elliptic flow in the hadronic phase.

W. Xie, QM 12



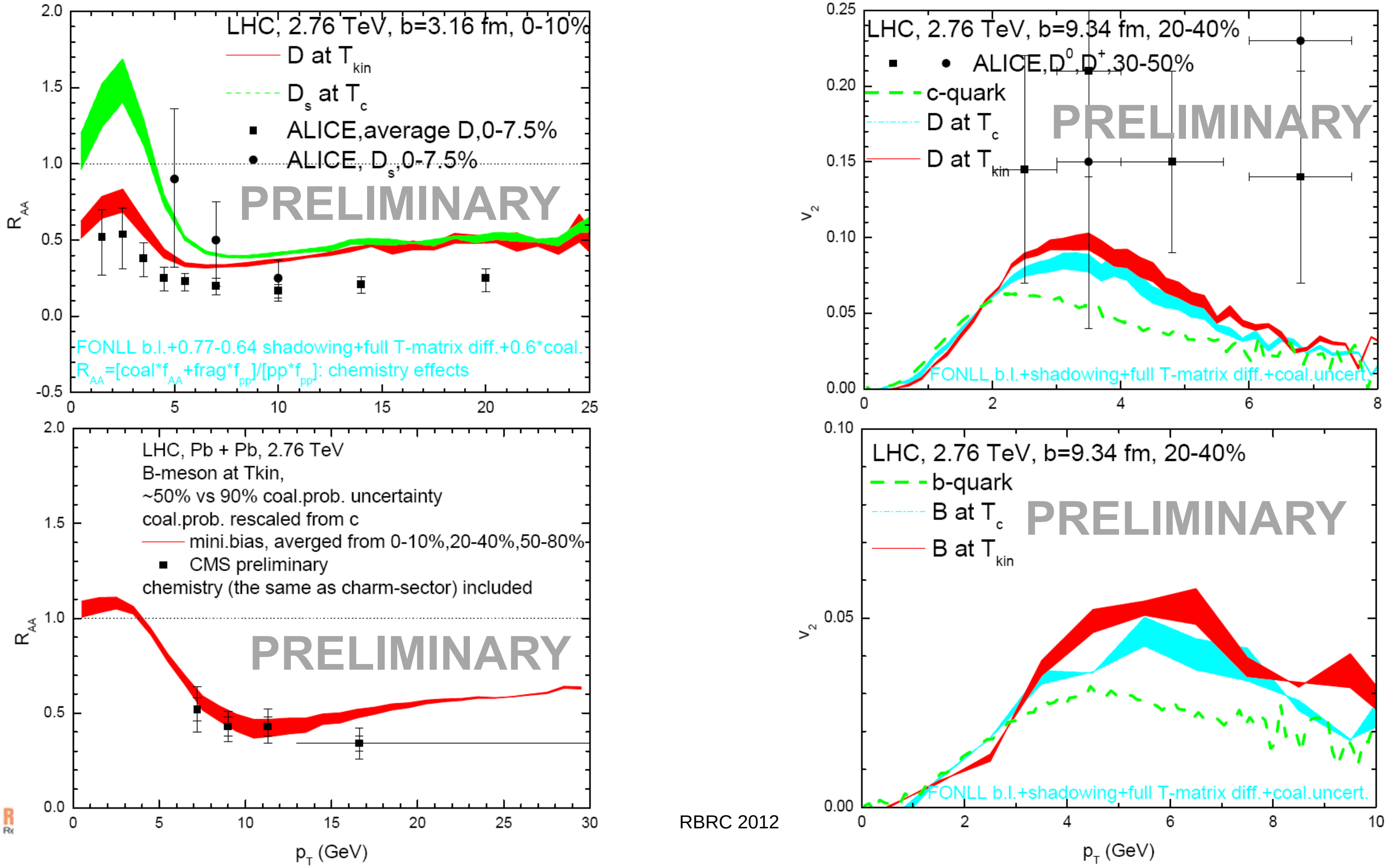






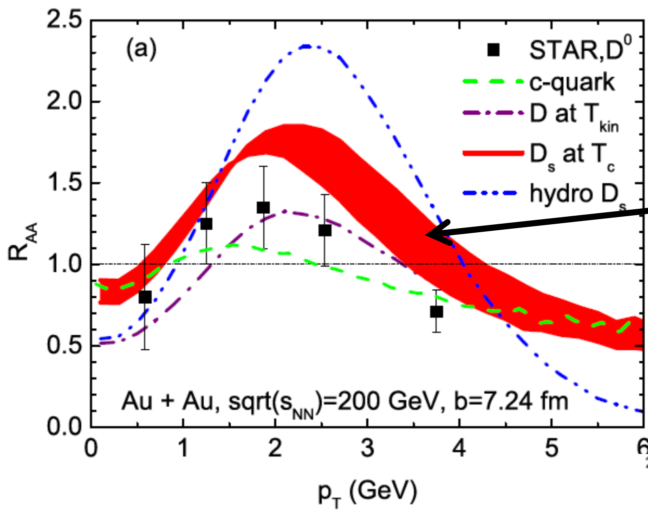
Comparison to LHC Data

- Caveats: AZHYDRO tune not as well constrained, measurements extend to high P_T: where radiative energy loss is important,

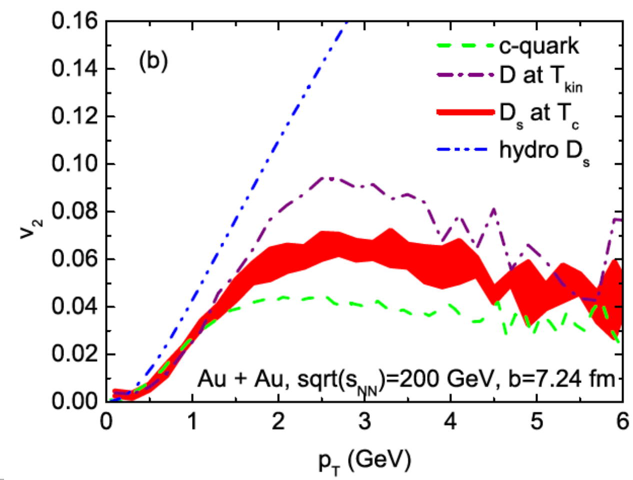


The Power of D_s vs D Measurements

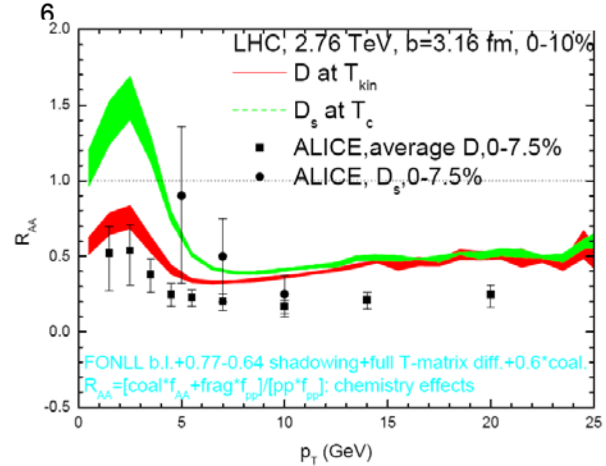
- Signature 1: *D_s vs D R_{AA}* is a measure for strength of recombination vs fragmentation.
- Signature 2: *D_s vs D v_2* can measure the relative strength of *D_s* vs *D* interactions in the hadronic phase.



Ds enhancement predicted



- First measurement by ALICE!



[M. He, RJF and R. Rapp, arxiv:1204.4442]

Overview of Current Research

Derek Teaney

SUNY Stony Brook and RBRC Fellow

Stony Brook University

Outline:

- Transport at NLO in Weakly-Coupled Plasmas
  - In preparation with Jacopo Ghiglieri, Juhee Hong, Aleski Krukela, Egang Lu, Guy Moore
- Non-linear response in hydrodynamics
  - DT and Li Yan, Phys. Rev. C., arXiv:1206.1905
- Thermalization of Hawking Radiation in AdS/CFT
  - Paul Chesler and DT, arXiv:1112.6196, submitted to PRL

Photon Production

$$2k(2\pi)^3\frac{\mathrm{d}\Gamma}{\mathrm{d}^3k} = \text{Photon emission rate per phase-space}$$

The photon emission rate at weak coupling:

- The rate is function of the coupling coupling constant and k/T:

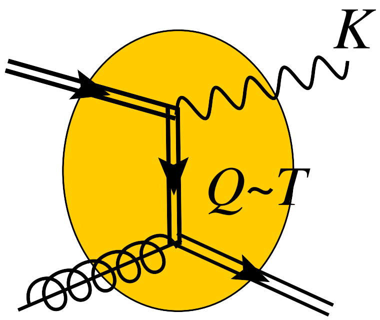
$$2k(2\pi)^3\frac{\mathrm{d}\Gamma}{\mathrm{d}^3k} \propto e^2T^2\Big[\underbrace{O(g^2\log) + O(g^2)}_{\text{LO AMY}} + \underbrace{O(g^3\log) + O(g^3)}_{\text{From soft } gT \text{ gluons, } n_B \simeq \frac{T}{\omega} \simeq \frac{1}{g}} + \ldots$$

$O(g^3)$ is closely related to open issues in energy loss:

- At NLO must include drag, collisions, bremsstrhalung, and kinematic limits

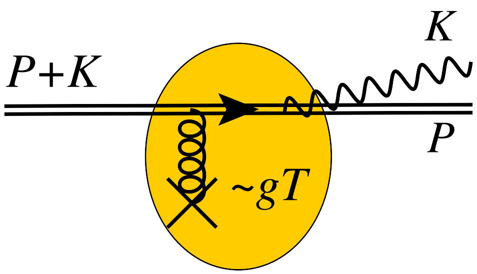
Three rates for photon production at Leading Order — Baier, Kapusta, AMY

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



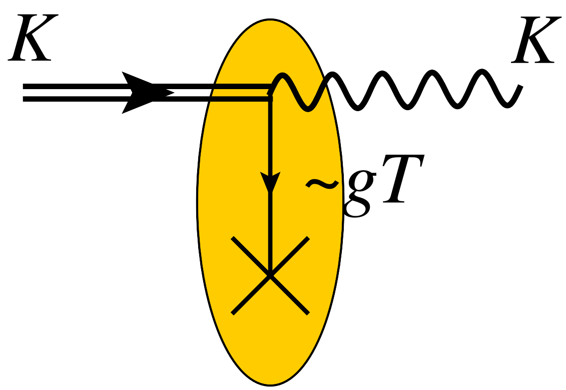
$$\sim e^2 \underbrace{m_\infty^2}_{g^2 C_F T^2/4} \times \underbrace{n_F(k)}_{\text{fermi dist.}} \times \left[\log(T/\mu) + C_{2\text{to}2}(k) \right]$$

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

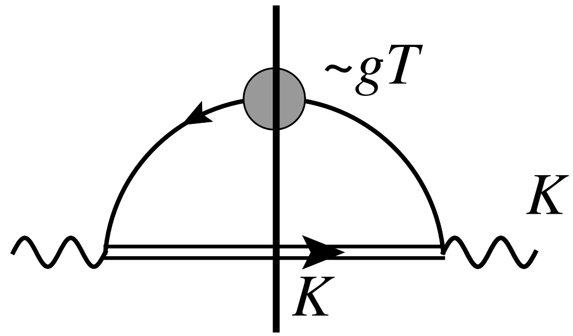


$$\sim e^2 \, m_\infty^2 n_F \left[\underbrace{C_{\text{bremm}}(k)}_{\text{LPM + AMY and all that stuff!}} \right]$$

3. Quark Conversions – $1 \leftrightarrow 1$ processes (analogous to drag)



or



$$= \sim e^2 m_\infty^2 n_F \left[\log(\mu_\perp/m_\infty) + C_{\rm cnvrt}\right]$$

Full LO Rate is independent of scale $\mu_\perp$:

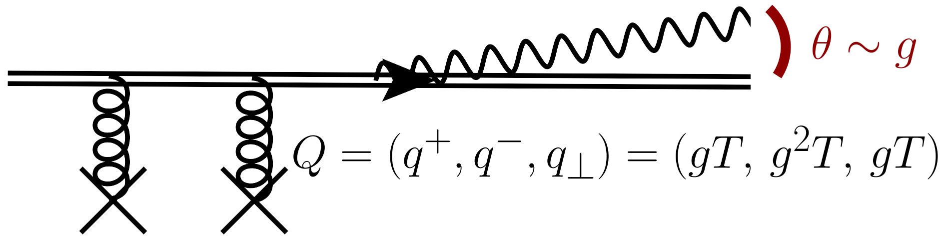
$$2k\frac{d\Gamma}{d^3k} \propto e^2 m_\infty^2 n_F \left[\log\left(T/m_\infty\right) + \underbrace{C_{\rm cnvrt} + C_{\rm bremm}(k) + C_{\rm 2to2}}_{\equiv C_{LO}(k)}\right]$$

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

1. No corrections to Hard Collisions:

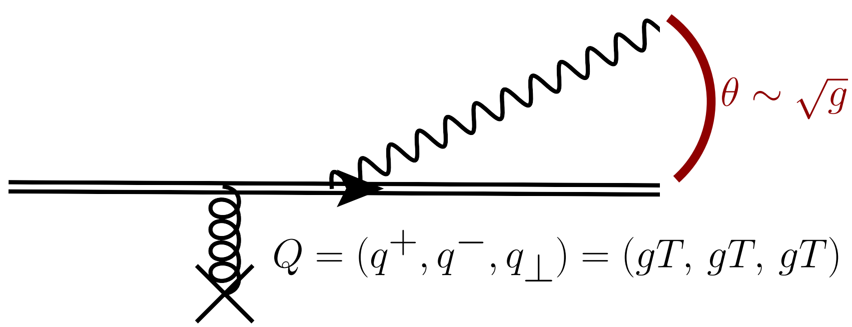
2. Corrections to Bremm:

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

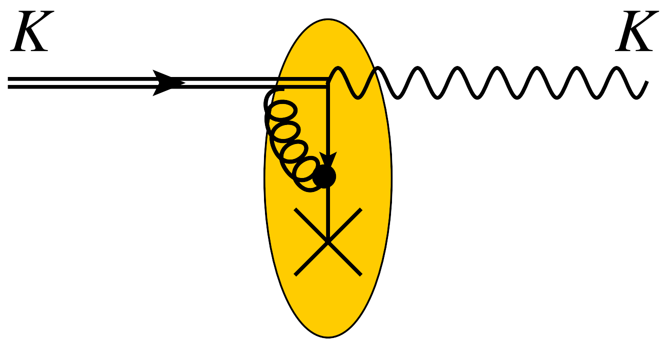


$$C_{LO}[q_\perp] = \frac{Tg^2m_D^2}{q_\perp^2(q_\perp^2 + m_D^2)} \rightarrow \text{A complicated but analytic formula}$$

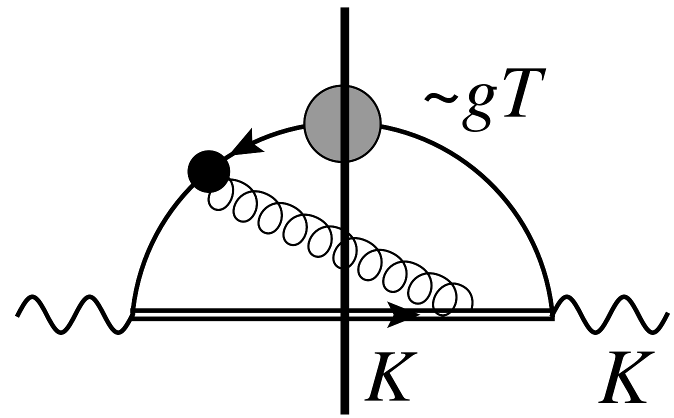
   (b) Larger angle bremm. Include collisions with energy exchange, $q^- \sim gT$.



3. Corrections to Conversions:



or



Simon Caron-Huot

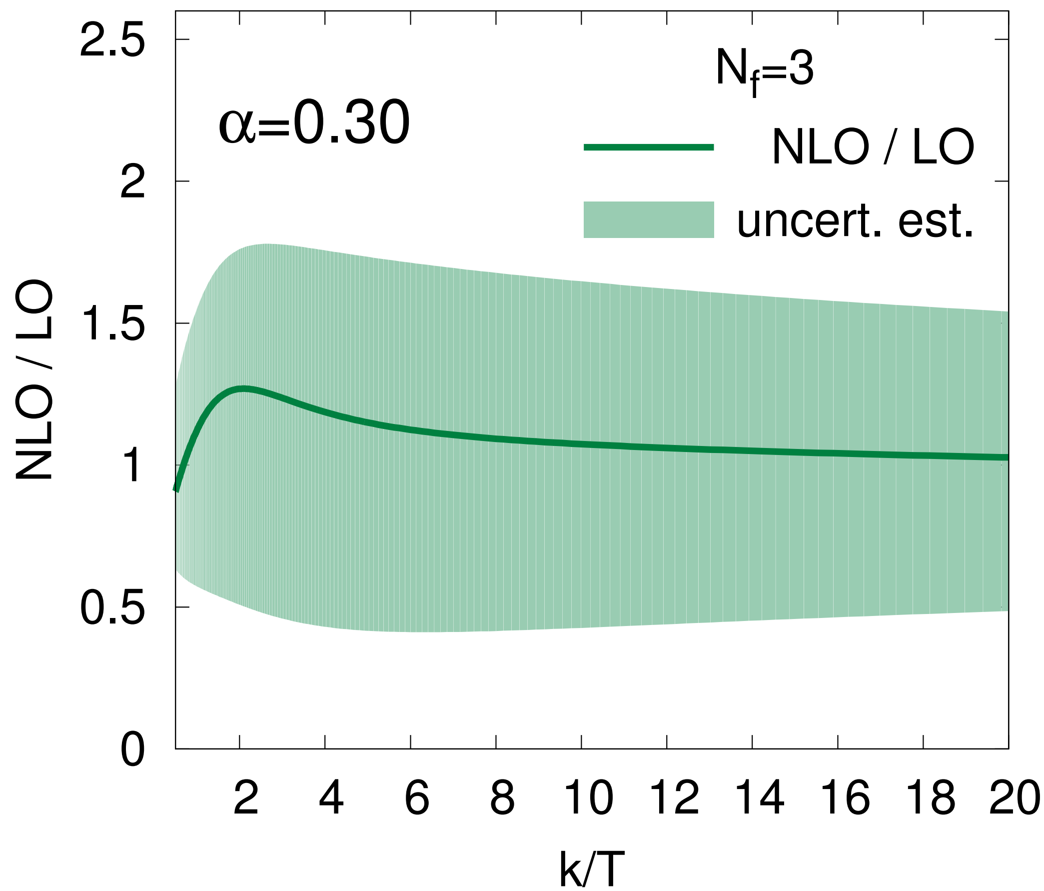
- Doable because of HTL sum rules (light cone causality)
- Gives a numerically small and momentum indep. contribution to the NLO rate

Full results depend on all these corrections.

These rates smoothly match onto each other as the kinematics change.

NLO Results: $\Gamma_{NLO} \sim \mathrm{LO} + g^3 \log(1/g) + g^3$

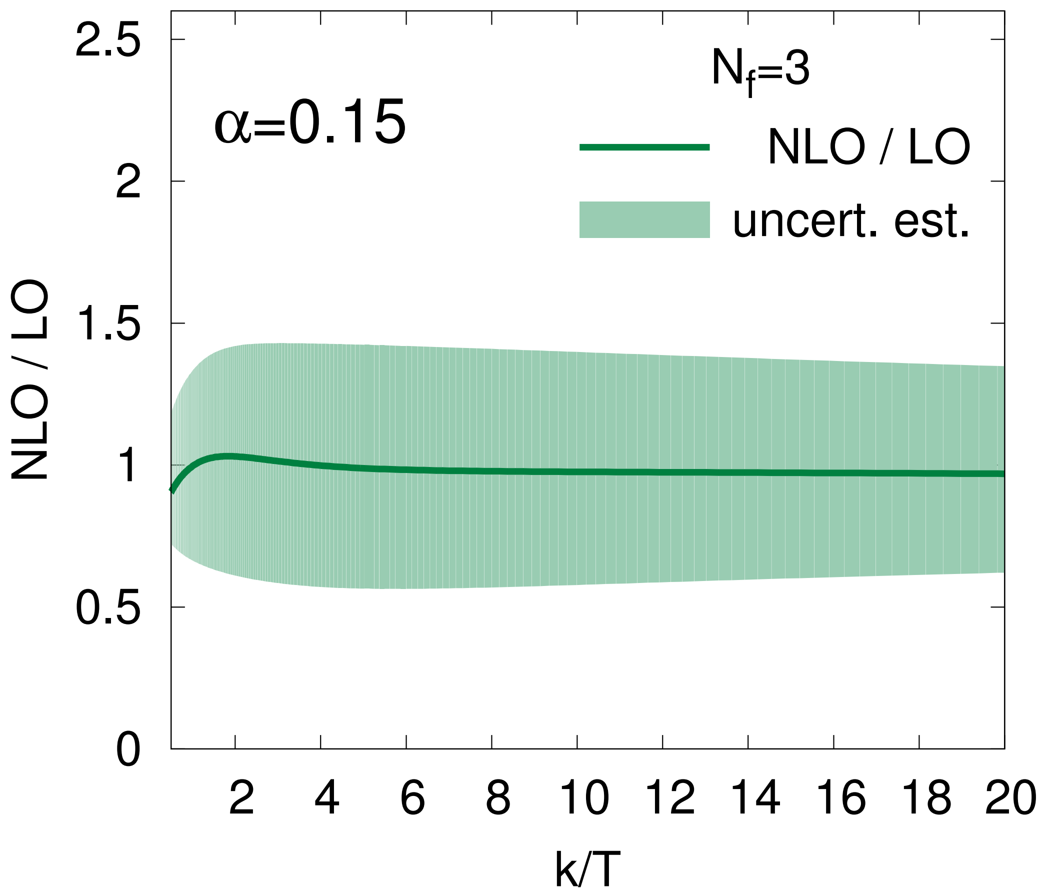
$$2k\frac{\mathrm{d}\Delta\Gamma_{NLO}}{\mathrm{d}^3k} \propto e^2 m_\infty^2 n_F(k)\Big[\overbrace{\frac{\delta m_\infty^2}{m_\infty^2}\log\left(\frac{\sqrt{2Tm_D}}{m_\infty}\right)}^{\text{conversions}} + \overbrace{\frac{\delta m_\infty^2}{m_\infty^2}C_{\mathrm{large}-\theta}(k)}^{\text{large-}\theta\text{-bremm}} + \overbrace{\frac{g^2 C_A T}{m_D}C_{\mathrm{small}-\theta}(k)}^{\text{small-}\theta\text{-bremm}}\Big]$$



Corrections are small and k independent

NLO Results: $\Gamma_{NLO} \sim \mathrm{LO} + g^3 \log(1/g) + g^3$

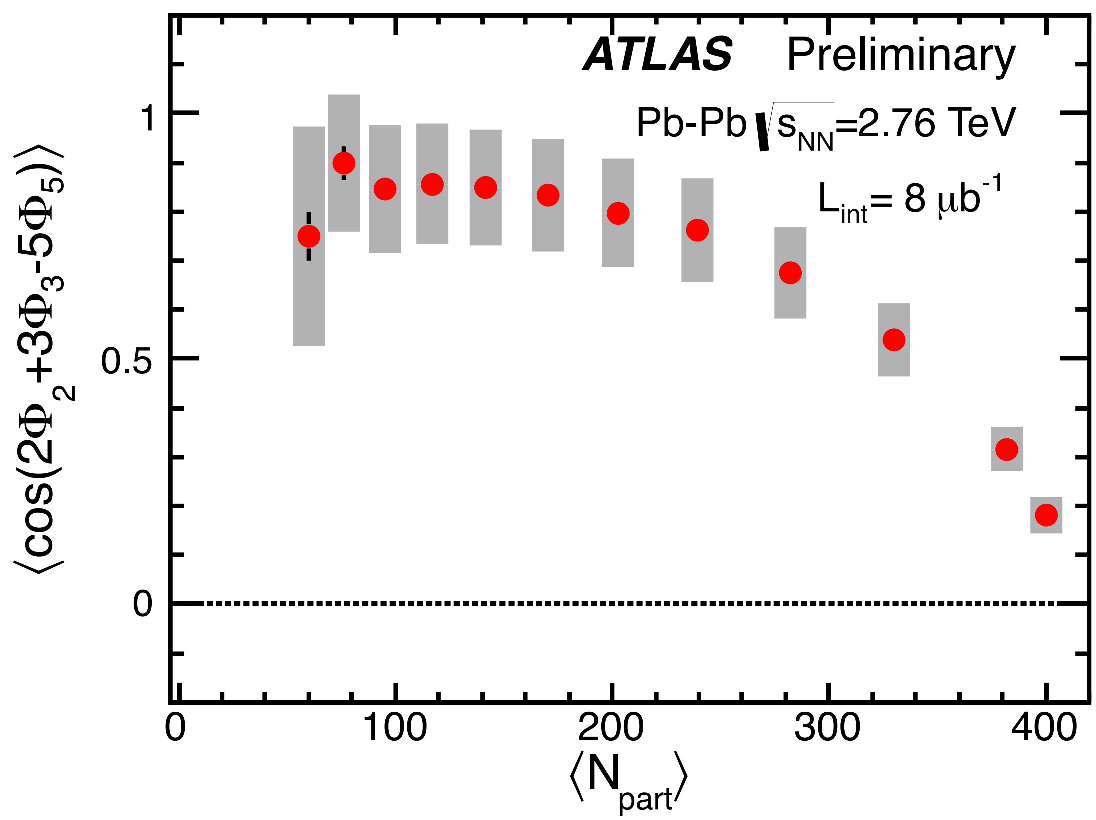
$$2k\frac{\mathrm{d}\Delta\Gamma_{NLO}}{\mathrm{d}^3k} \propto e^2 m_\infty^2 n_F(k)\Big[\overbrace{\frac{\delta m_\infty^2}{m_\infty^2}\log\left(\frac{\sqrt{2Tm_D}}{m_\infty}\right)}^{\text{conversions}} + \overbrace{\frac{\delta m_\infty^2}{m_\infty^2}C_{\mathrm{large}-\theta}(k)}^{\text{large-}\theta\text{-bremm}} + \overbrace{\frac{g^2 C_A T}{m_D}C_{\mathrm{small}-\theta}(k)}^{\text{small-}\theta\text{-bremm}}\Big]$$



Corrections are small and k independent

Hydro

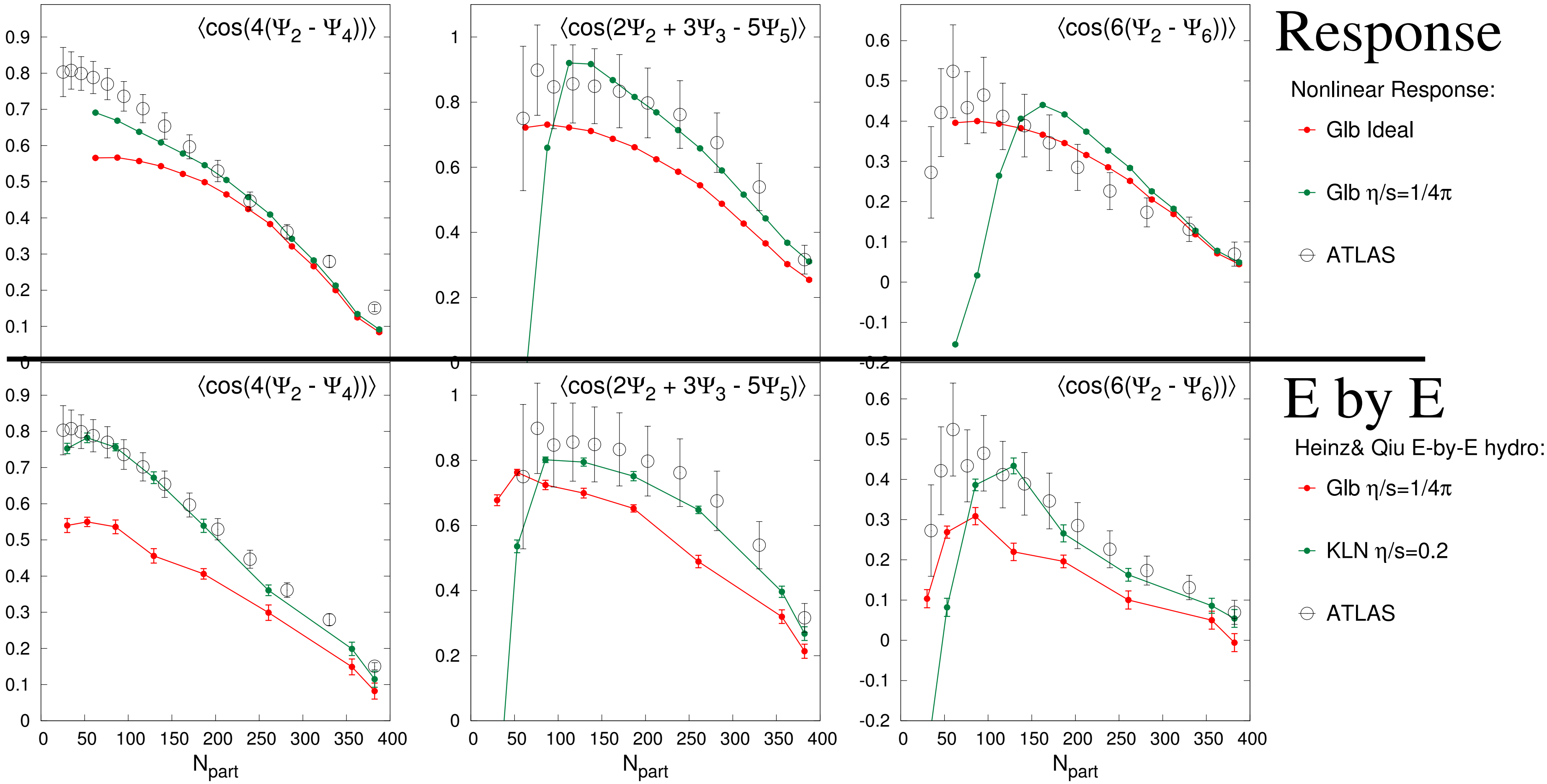
Observed correlations between Elliptic, Triangular, and Pentagonal flow



The correlations are due mixing between triangular and elliptic flow

(Heinz and Qiu, and Gardim et al)

A response theory for this non-linear mixing and (prelim) comparison with EbyE hydro



With a quadratic non-linear response formalism

we reproduce the *all* the trends of E-by-E hydro

Outlook:

- Transport at NLO in Weakly-Coupled Plasmas
  - Compute the shear viscosity at NLO and other quantities
  - Use a 3D Euclidean formulation to compute $\hat{q}$
- Non-linear response in hydrodynamics
  - Fully compare our results to data and simulation
- Thermalization of Hawking Radiation in AdS/CFT
  - Understand the back-reaction of hawking radiation on the metric.

The Ubiquitous Chiral Magnetic Waves

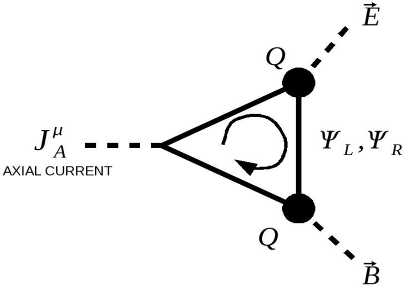
Ho-Ung Yee

University of Illinois at Chicago/RIKEN-BNL Research Center

Scientific Research Committee Meeting, RBRC, November 6-8, 2012

Triangle Anomaly

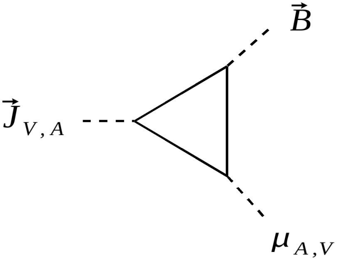
$$\partial_\mu J_A^\mu = \frac{N_F}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} = \frac{N_F}{4\pi^2}\vec{E}\cdot\vec{B}$$



The full consequences of $\langle AVV \rangle$ may not have been explored completely in various situations

Chiral Magnetic Effect

Kharzeev-McLerran-Waringa, Fukushima-Kharzeev-Warringa, Vilenkin

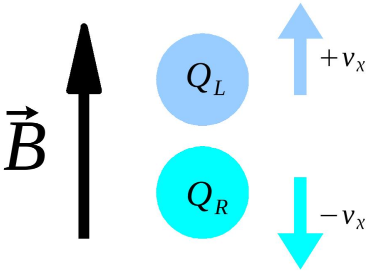


$$\vec{J}_V = \frac{N_c e\vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e\vec{B}}{2\pi^2}\mu_V$$

Charge current along the magnetic field is induced by chemical potential

CHIRAL MAGNETIC WAVE (Kharzeev-HUY)

New propagating charge waves along magnetic field originating from triangle anomaly



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

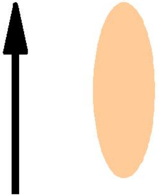
A possible experimental consequence of chiral magnetic waves

Charge dependent elliptic flow v_2 of pions

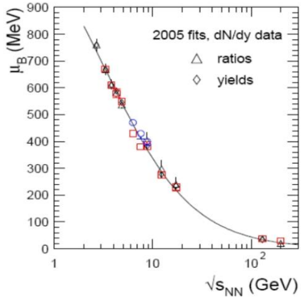
(Burnier-Kharzeev-Liao-HUY)

$$v_2(\pi^-) > v_2(\pi^+)$$

Essential physics mechanism



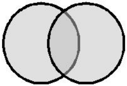
$\vec{B}$



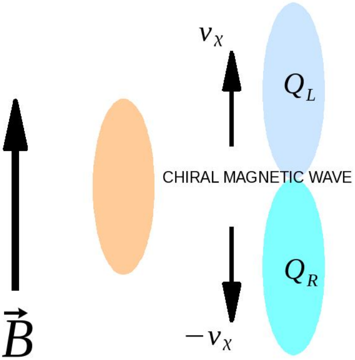
$$Q = Q_L + Q_R > 0$$

$$Q_A = Q_L - Q_R = 0$$

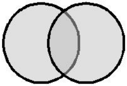
NON-CENTRAL COLLISION



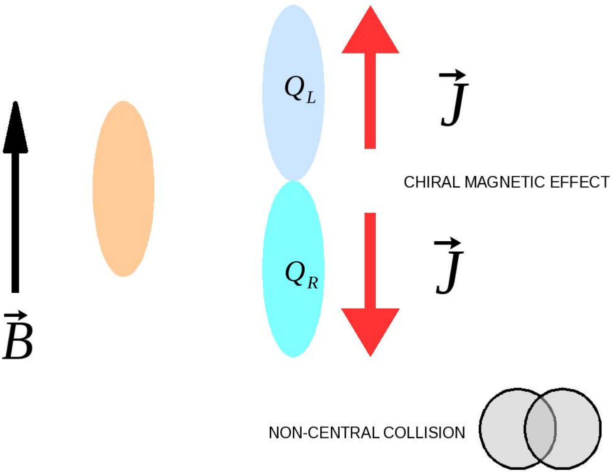
Essential physics mechanism



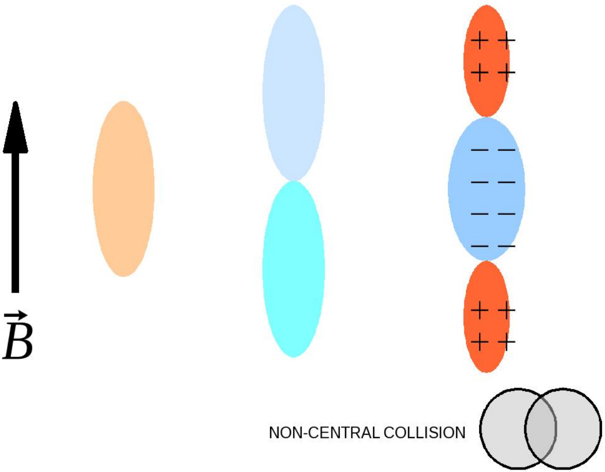
NON-CENTRAL COLLISION



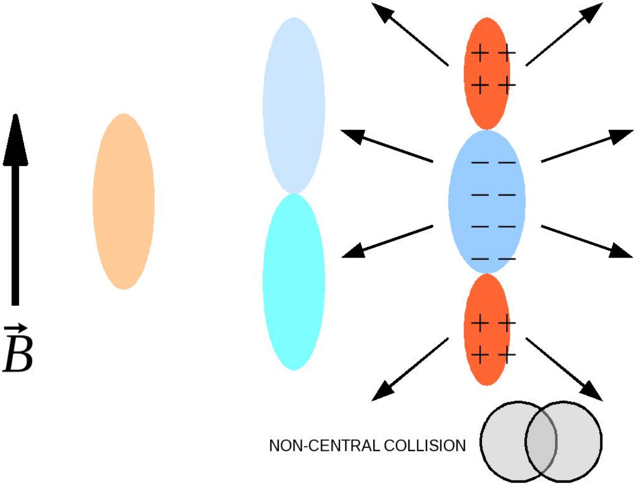
Essential physics mechanism



Essential physics mechanism

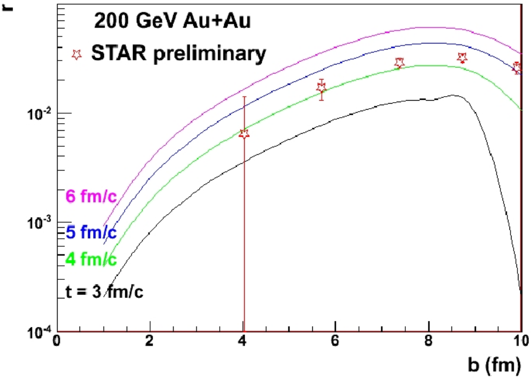


Essential physics mechanism



Charge dependent elliptic flow

Theory: Burnier-Kharzeev-Liao-HUY : **PRL** 107 (2011) 052303; 1208.2537
Data from **STAR** : 1210.5498

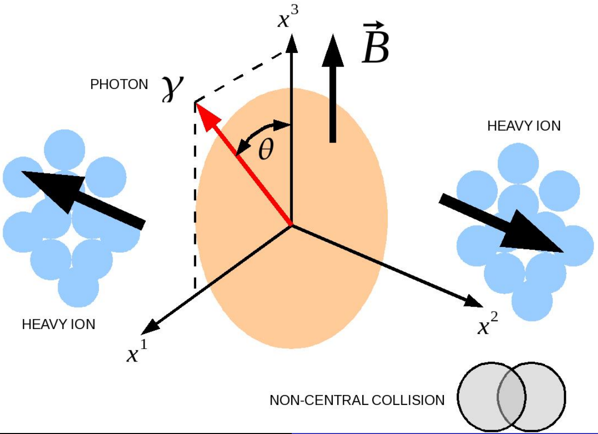


$$v_2^{\pm} = v_2 \mp A * r \quad , \quad A \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

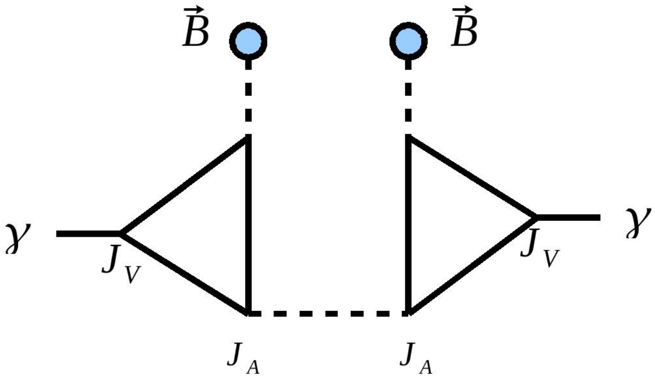
Photon Emission and the Chiral Magnetic Wave in Strongly Coupled Regime

Photon emission rate in the presence of magnetic field

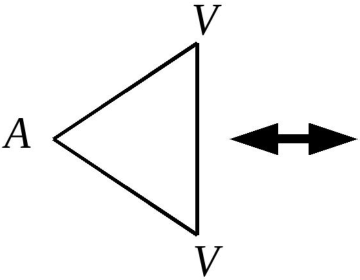
$$\frac{d\Gamma_\gamma}{d^3k}(\epsilon^\mu) = \frac{e^2}{(2\pi)^3}\frac{1}{2\omega}\frac{-2}{e^{\frac{\omega}{T}}-1}\mathrm{Im}\left[\epsilon^\mu\epsilon^{\nu*}G^{\mathrm{RET}}_{\mu\nu}(k)\right]$$



Why Triangle Anomaly in Photon Emission Rates ?



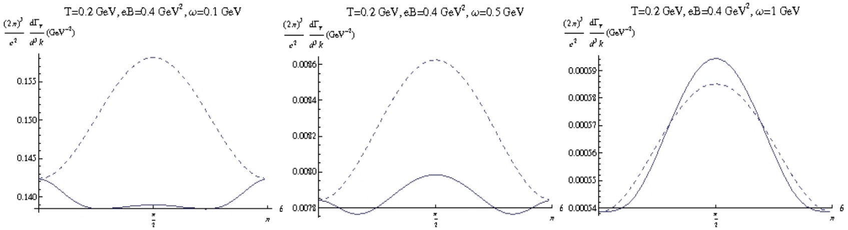
Strong Coupling Computation in Holographic QCD



$$A \wedge dV \wedge dV$$

4D QCD 5D $HQCD$

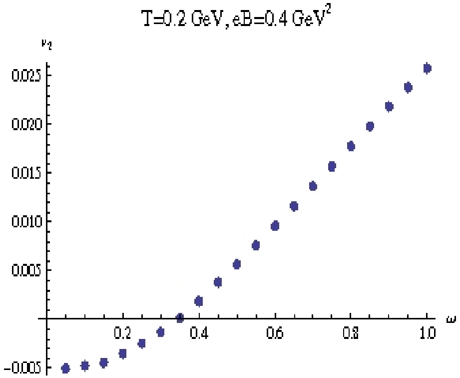
Azimuthal Dependence of Emission Rates

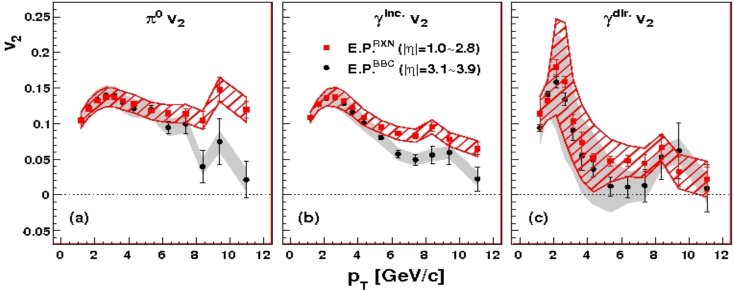


T=200 MeV, eB=0.4 GeV^2, $\omega = 0.1$, 0.5, 1 GeV

Dashed line : Results without triangle anomaly

Non-trivial v_2 Dependence with Energy



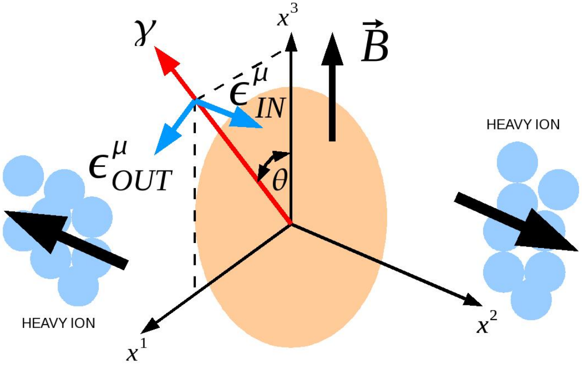

π^0 v_2
$\gamma^{inc.}$ v_2
$\gamma^{dir.}$ v_2
E.P.^{RXN} ($|\eta|$=1.0~2.8)
E.P.^{BBC} ($|\eta|$=3.1~3.9)
v_2
(a)
(b)
(c)
p_T [GeV/c]

(PHENIX)

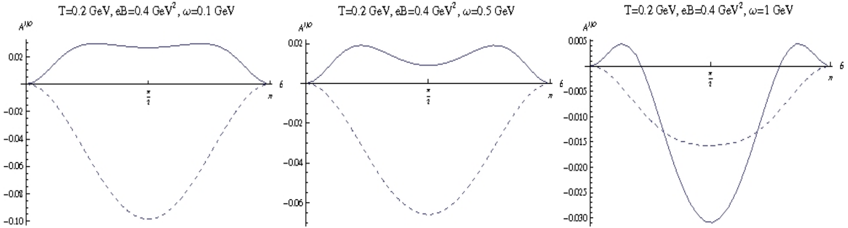
New observable

: IN/OUT PLANE POLARIZATION ASYMMETRY

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



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



T=200 MeV, eB=0.4 GeV^2, $\omega = 0.1$, 0.5, 1 GeV

Dashed line : Results without triangle anomaly

Chiral Magnetic Wave in Cold Weyl Liquid

(In progress with Gorsky and Kharzeev)

Landau's Kinetic Theory of Fermi Liquid

$$\frac{\partial f}{\partial t} + \dot{\vec{x}} \cdot \frac{\partial f}{\partial \vec{x}} + \dot{\vec{p}} \cdot \frac{\partial f}{\partial \vec{p}} = 0$$

with

$$\dot{\vec{x}} = \frac{\partial H}{\partial \vec{p}} \quad , \quad \dot{\vec{p}} = -\frac{\partial H}{\partial \vec{x}}$$

Background :

$$f = \theta\left(p_F - |\vec{p}|\right) \equiv f_0 \quad , \quad H = H_0\left(|\vec{p}|\right)$$

Study Dispersion Relation of Fluctuations : Zero Sound

- Fluctuations are localized on the Fermi surface

$$\delta f = \frac{\delta\left(|\vec{p}| - p_F\right)}{v_F}\delta n(\Omega, \vec{x})$$

- δH is assumed to include 2-body collective interactions between fluctuations

$$\delta H = \int \frac{d\Omega'}{4\pi} F(\Omega, \Omega')\delta n(\Omega', \vec{x})$$

with $F(\Omega, \Omega') = F_0$ for simplicity

We get the integral equation for the dispersion relation of (ω, k),

$$\left(\frac{\omega}{v_F k} - \cos\theta\right)\delta n(\theta) = F_0 \cos\theta \int \frac{d\Omega'}{4\pi}\delta n(\theta')$$

Let's do it again for the kinetic equation with triangle anomaly in the presence of magnetic field (Gorsky-Zayakin)

PROBLEMS :

- The kinetic equation is not completely correct
- No chiral magnetic wave was observed

A KEY FACT :

One needs a relaxation term to have the chiral magnetic wave

$$\frac{\partial f}{\partial t} + \dot{\vec{x}} \cdot \frac{\partial f}{\partial \vec{x}} + \dot{\vec{p}} \cdot \frac{\partial f}{\partial \vec{p}} = -\frac{1}{\tau} \delta f$$

We expect that chiral magnetic wave appears when

$$\omega \sim k \ll \tau^{-1}$$

Kinetic equation with triangle anomaly(Stephanov-Yin)

$$\sqrt{G}\,\dot{\vec{x}} = \frac{\partial H}{\partial \vec{p}} - \frac{\partial H}{\partial \vec{x}} \times \vec{b} + \vec{B}\left(\frac{\partial H}{\partial \vec{p}} \cdot \vec{b}\right)$$

$$\sqrt{G}\,\dot{\vec{p}} = -\frac{\partial H}{\partial \vec{x}} + \frac{\partial H}{\partial \vec{p}} \times \vec{B} - \vec{b}\left(\frac{\partial H}{\partial \vec{x}} \cdot \vec{B}\right)$$

where $\sqrt{G} = (1 + \vec{B} \cdot \vec{b})$ with $\vec{b} = \frac{\hat{p}}{2|\vec{p}|^2}$

Collision term should preserve the local particle density

$$n(\vec{x}) = \int \frac{d^3\vec{p}}{(2\pi)^3}\sqrt{G}\, f(\vec{x}, \vec{p})$$

so that we should have

$$\mathcal{C}[f] = -\frac{1}{\tau}\delta f = -\frac{1}{\tau}\frac{\delta(|\vec{p}| - p_F)}{v_F}\left(\delta n(\theta) - \int \frac{d\Omega'}{4\pi}\sqrt{G'}\delta n(\Omega')\right)$$

The new integral equation for the dispersion relation is

$$\left(-\omega+\frac{v_F k}{1+\tilde{B}t}(t+\tilde{B})-\frac{i}{\tau}\right)\delta n(t)$$
$$+\quad \frac{v_F k}{1+\tilde{B}t}(t+\tilde{B})\left[F_0\int_{-1}^{1}\frac{dt'}{2}\,\delta n(t')+F_1 t\int_{-1}^{1}\frac{dt'}{2}\,t'\delta n(t')\right]$$
$$+\quad \frac{i}{\tau}\int_{-1}^{1}\frac{dt'}{2}\,(1+\tilde{B}t')\delta n(t')=0$$

where $\tilde{B}\equiv\frac{B}{2p_F^2}$ and $t\equiv\cos\theta$

For $\omega\sim k\ll\tau^{-1}$, one can analytically show

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

with $v_\chi=(1+F_0)\frac{v_F}{2p_F^2}B=\frac{1}{4\pi^2}(\frac{\partial\mu}{\partial n})B$, precisely the CMW

The Higgs boson mass
—
its meaning for the Standard Model?

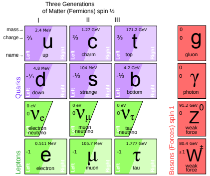
Fedor Bezrukov

University of Connecticut
&
RIKEN-BNL Research Center

RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510, Room 2-160
November 6, 7, 8, 2012

Outline

Standard Model – describes nearly everything



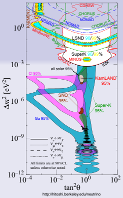
\+ Einstein gravity

Describes

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

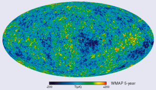
Experimental problems:

- Laboratory
  - ? Neutrino oscillations



- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter

  - ? Inflation

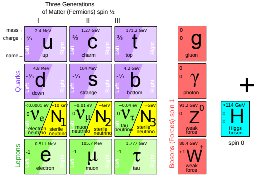


  - ? Dark Energy

Can we describe everything with as small extension as possible?

- Minimal number of new particles
- No new scales before inflation/gravity

νMSM+inflation – describes everything



+

Einstein gravity

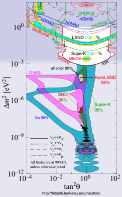
with νMSM

- Right handed neutrinos
  - generation of active neutrino masses
  - keV scale DM
  - Baryogenesys via very low scale leptogenesys

+ comological constant

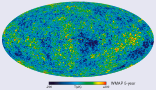
Experimental problems:

- Laboratory
  - ✓ Neutrino oscillations



- Cosmology
  - ✓ Baryon asymmetry of the Universe
  - ✓ Dark Matter

  - ? Inflation



  - ✓ Dark Energy

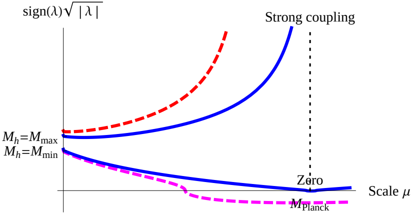
SM everywhere?

What happens if there is nothing else up to the Planck scales?
(or at least up to the scale of inflation)

Renormalization evolution of the Higgs self coupling λ

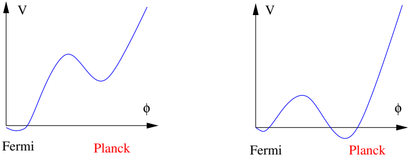
$$(4\pi)^2\beta_\lambda = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2+g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$

Coupling constant evolution:



- High M_h – strong coupling
- Low M_h – our (EW) vacuum is metastable.
- Boundary situation – $M_h = M_{\rm min}$

Higgs effective potential $V(\varphi) \simeq \lambda(\varphi)\frac{\varphi^4}{4}$



$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\mu_0) \equiv \mu\frac{d\lambda}{d\mu} = 0$$

Which case is realized?

The boundary case defines both M_h and $\mu_0 \sim M_P$

Let us fix all the SM constants, except for the Higgs mass:

$$\alpha, M_W, M_Z, \alpha_S, M_t$$

Then *two* requirements:

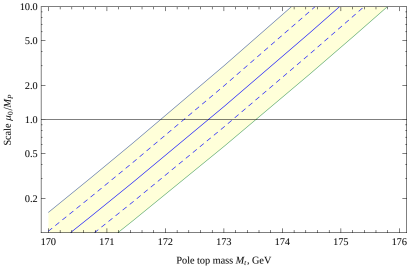
$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\mu_0) \equiv \mu \frac{d\lambda}{d\mu} = 0$$

define *two* parameters:

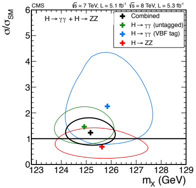
$$m_H, \quad \mu_0$$

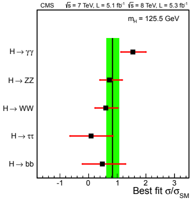
Planck scale!

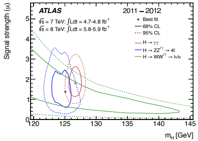
SM with $m_t \sim 173\,\text{GeV}$ leads to $\mu_0 \sim M_P$

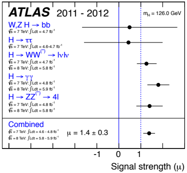


CMS&ATLAS "new boson" results









CMS

$$M_h = 125.3$$
$$\pm\, 0.4(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV}$$

[CMS'12]

ATLAS

$$M_h = 126.0$$
$$\pm\, 0.4(\text{stat}) \pm 0.4(\text{syst})\,\text{GeV}$$

[ATLAS'12]

Calculation steps

Experiment

constants: α, $\sin\theta_W$, α_S

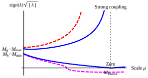
Pole masses: M_h, M_t

$\overline{\text{MS}}$ constants (at EW scale $\mu \sim M_t$):

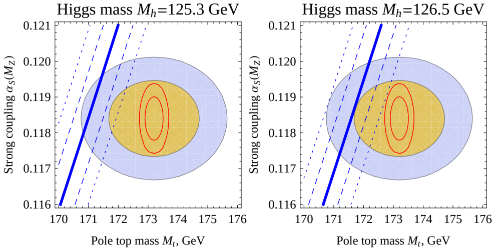
$$y_t(\mu) = 2^{3/4}\sqrt{G_F}M_t \times \left[1 + \delta y_t(M_t, \alpha_S, \alpha, s_W^2, M_Z; \mu)\right]$$

$$\lambda(\mu) = \sqrt{2}G_F M_h^2 \times \left[1 + \delta\lambda(M_t, \alpha_S, \alpha, s_W^2, M_Z; \mu)\right]$$

RG running: $\frac{d\lambda}{d\ln\mu} = \beta_\lambda(\lambda, y_t, g_i), \ldots$

High scale behavior of constants: 

Do we have the critical Higgs mass?



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

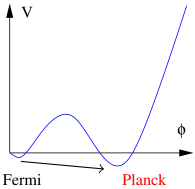
We do not really know now! Yet to be done:

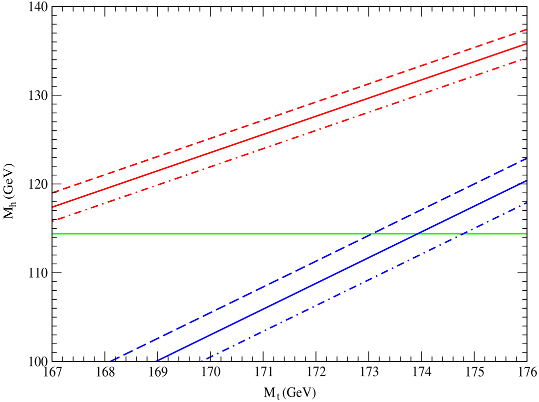
- Build a lepton collider at $\gtrsim 350$ GeV! (Higgs *and* top masses)
- Calculate higher order relations between $\overline{\text{MS}}$ parameters and masses

Outline

No new physics is required even for light Higgs boson

Will the vacuum decay?





[Espinosa, Giudice, Riotto’07]

EW vacuum lifetime $> \tau_{\text{Universe}}$

$M_h > 111\,\text{GeV}$

Asymptotic safe model predicts M_h

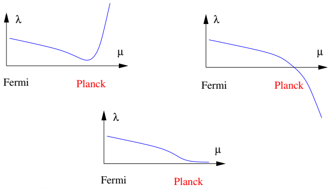
Above Planck scale beta functions for coupling constant $h \in \{g_1, g_2, g_3, \lambda, y_t\}$ get additional terms

$$\beta_h^{\text{grav}} = \frac{a_h}{8\pi} \frac{\mu^2}{M_P^2 + 2\xi 0\mu^2} h$$

leading to a *fixed point* at high energies

$a_\lambda > 0$ leads to the prediction $M_h = M_{\text{min}}$

(up to a difference of 0.1–0.2 GeV)

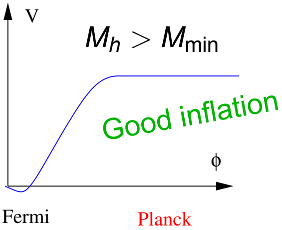


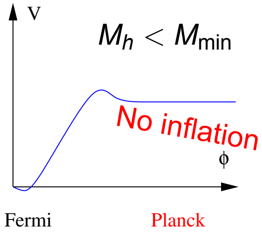
[Shaposhnikov, Wetterich’09]

For other M_h no finite fixed point for λ

Higgs inflation works only for $M_h > M_{min}$

$$S_J = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \xi\frac{h^2}{2}R + g_{\mu\nu}\frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4}(h^2 - v^2)^2 \right\}$$





Bound on the Higgs mass

$$M_h > M_{\rm min}$$

Up to a difference of 0.1–0.2 GeV

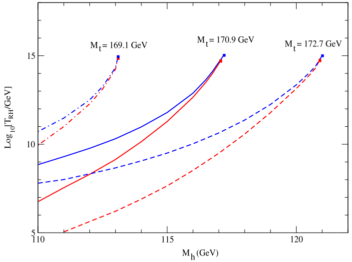
[FB, Shaposhnikov'09]

Modifying the gravity action gives inflation for any M_h

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R + \frac{\zeta^2}{4}R^2\right\} + S_{SM}$$

[Starobinsky'80]

The electroweak vacuum may decay at high temperature. But reheating is due to M_P suppressed operators $\Rightarrow$ temperature is low
$T_r \sim 10^7 - 10^9$ GeV



[Espinosa, Giudice, Riotto'07]

Higgs mass bounds in R^2 is weak

$$m_H > 116\,\text{GeV}$$

Summary

Coincidence in Standard Model

- $\lambda(M_P) = \left.\frac{d\lambda}{d\mu}\right|_{\mu=M_P} = 0$
  Higgs self couling is vanishing with its derivative at Planck scale
- for $M_h = M_{\rm min} =$
  $$\left[129.5 + \frac{M_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right]\text{GeV}$$

- We may be learning about Planck scale physics!

To disprove/confirm this the following is needed

- e^+e^- collider up to $\gtrsim 350\,\text{GeV}$
  - Higgs factory — M_H
  - top factory — M_t

- FB, M. Kalmykov, B. Kniehl, M. Shaposhnikov, arXiv:1205.2893 [hep-ph]
- G. Degrassi, S. Di Vita, J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori, A. Strumia arXiv:1205.6497 [hep-ph]
- A.Starobinsky, Phys.Lett. B91 (1980) 99
- J. R. Espinosa, G. F. Giudice and A. Riotto, JCAP **0805** (2008) 002
- K. G. Chetyrkin and M. Steinhauser, *Phys. Rev. Lett.* **83** (1999) 4001
- K. Melnikov and T. v. Ritbergen, *Phys. Lett.* **B482** (2000) 99
- L. N. Mihaila, J. Salomon, and M. Steinhauser, *Phys. Rev. Lett.* **108** (2012) 151602
- K. G. Chetyrkin and M. F. Zoller, `arXiv:1205.2892`.
- FB, M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)
- FB, M. Shaposhnikov, JHEP **0907** (2009) 089
- M. Shaposhnikov and C. Wetterich, Phys. Lett. B **683** (2010) 196

CMS Collaboration, [arXiv:1207.7235 [hep-ex]]

ATLAS Collaboration, [arXiv:1207.7214 [hep-ex]]

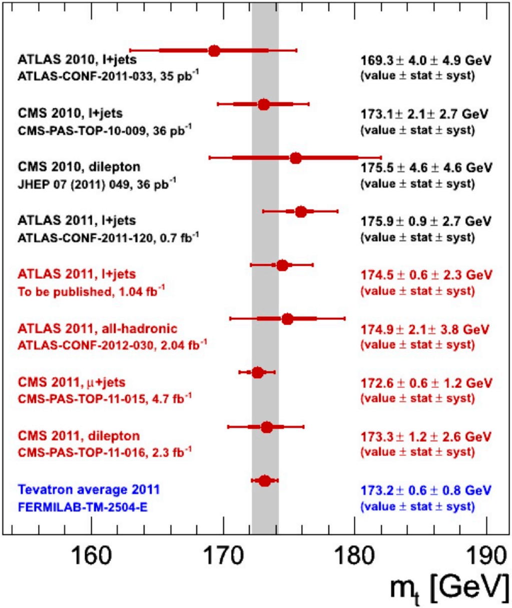
Exact effective potetnial definition

$$V(\varphi) = \lambda(\mu)\varphi^4 \left[1 + \sum \left(\frac{M_i^4(\varphi)}{64\pi} \log(M_i^2/\mu^2) \right)\right],$$

choosing μ to minimize logarithms

$$V(\varphi) \propto \lambda(\varphi)\varphi^4 \left[1 + O\left(\frac{\alpha}{4\pi} \log(M_i/\varphi)\right)\right],$$

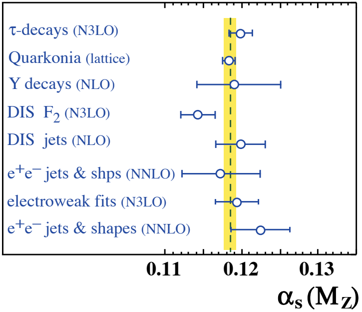
Top mass determination

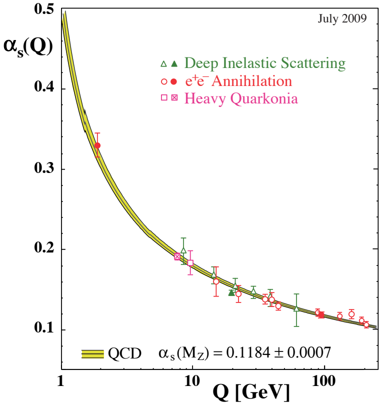


In addition:

- Problems with relation of M_{Pythia} and M_{pole} – up to ~ 1 GeV

α_s determination





Calculation steps: state of the art

- Convert to $\overline{\text{MS}}$ constants $\lambda(\mu)$, $y_t(\mu)$ at a scale μ between M_Z and M_t

  δy_t Up to $O(\alpha_s^2)$, $O(\alpha)$

  $O(\alpha_s^3)$ [Chetyrkin, Steinhauser'99, Melnikov,Ritbergen'00]

  $O(\alpha\alpha_s)$ [FB, Kalmykov, Kniehl, Shaposhnikov'12]

  $\delta\lambda$ Up to $O(\alpha)$

  $O(\alpha\alpha_s)$ [FB, Kalmykov, Kniehl, Shaposhnikov'12]

  $O(y_t^4)$ (Yukawa part of $O(\alpha^2)$)

  [Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia'12]

- Evolve with RG up to Planck scales

  β_{g_i} two loops

  three loops [Mihaila, Salomon, Steinhauser'12]

  β_{y_t}, β_λ two loops

  three loops (no EW gauge contributions)

  [Chetyrkin, Zoller'12]

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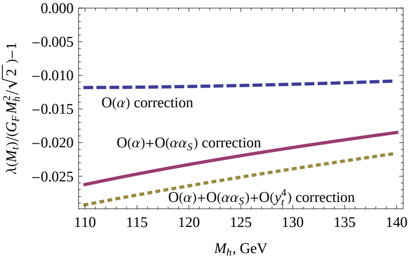
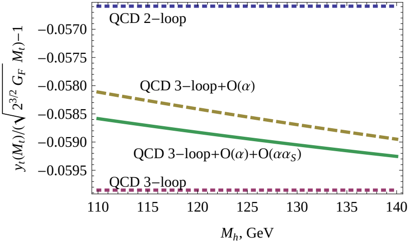
  three loops (no EW gauge contributions)

  [Chetyrkin, Zoller'12]

Size of contributions to $M_{\min}$

Contribution	$\Delta M_{\min}$, GeV
Three loop	
beta functions	-0.23
$\delta y_t \propto O(\alpha_s^3)$	-1.15
$\delta y_t \propto O(\alpha\alpha_s)$	-0.13
$\delta\lambda \propto O(\alpha\alpha_s)$	0.62
$\delta\lambda \propto O(y_t^4)$	0.2





Error budget

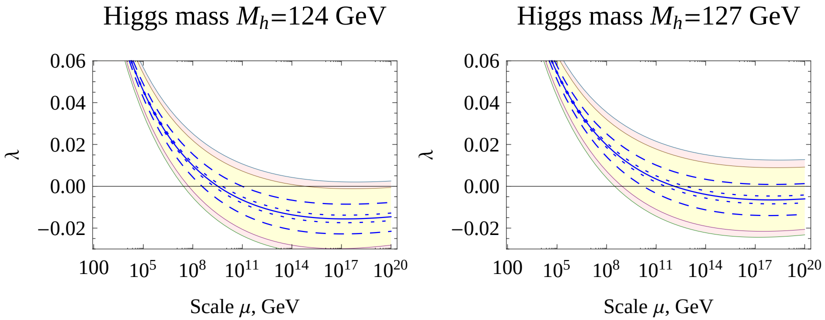
Theoretical

Source of uncertainty	Nature of estimate	$\Delta_{\text{theor}} M_{\text{min}}$, GeV
3-loop matching λ	Sensitivity to μ	1.0
3-loop matching y_t	Sensitivity to μ	0.2
4-loop α_s to y_t	educated guess	0.4
confinement, y_t	educated guess	0.5
4-loop RG $M_W \to M_P$	educated guess	< 0.2
total uncertainty	sum of squares	1.2
total uncertainty	linear sum	2.3

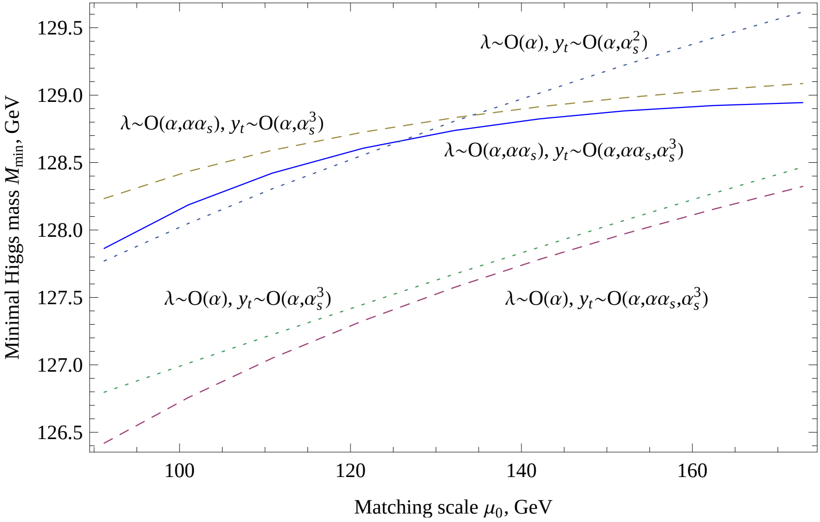
Experimental

Source of uncertainty		$\Delta_{\text{exp}} M_{\text{min}}$, GeV
M_t		~ 2
α_s		~ 0.6
total uncertainty	sum of squares	2.1

Scale for λ turning negative is high



RG scale dependence



Baryon number conservation and limited acceptance vs. cumulants of net proton distribution

Adam Bzdak

RIKEN BNL

AB, V. Koch, V. Skokov, to appear in Phys.Rev. C

AB, V. Koch, Phys.Rev. C86 (2012) 044904

Outline

- Short introduction
- Baryon number conservation
  - calculation
  - new observable
- Limited acceptance
  - required vs. actual acceptance
  - results, problems and hopes
- Conclusions
- Backup with equations

Introduction

To make a long story short we hope to see a minimum and a maximum of net baryon/proton or charge cumulant ratios as a function of energy

$$c_1 = \langle N_B - N_{\bar{B}} \rangle$$

$$c_2 = \langle (N_B - N_{\bar{B}})^2 \rangle - \langle N_B - N_{\bar{B}} \rangle^2$$

$c_3, c_4, c_5, c_6, \ldots$ or $B \rightarrow Q$

Baryon number conservation

AB, V. Koch, V. Skokov, to appear in Phys.Rev. C

Calculation

$$P(n_B, n_{\bar{B}}) = P(n_B)P(n_{\bar{B}})$$

↓

$P_\Delta(n_B - n_{\bar{B}})$ Skellam distribution

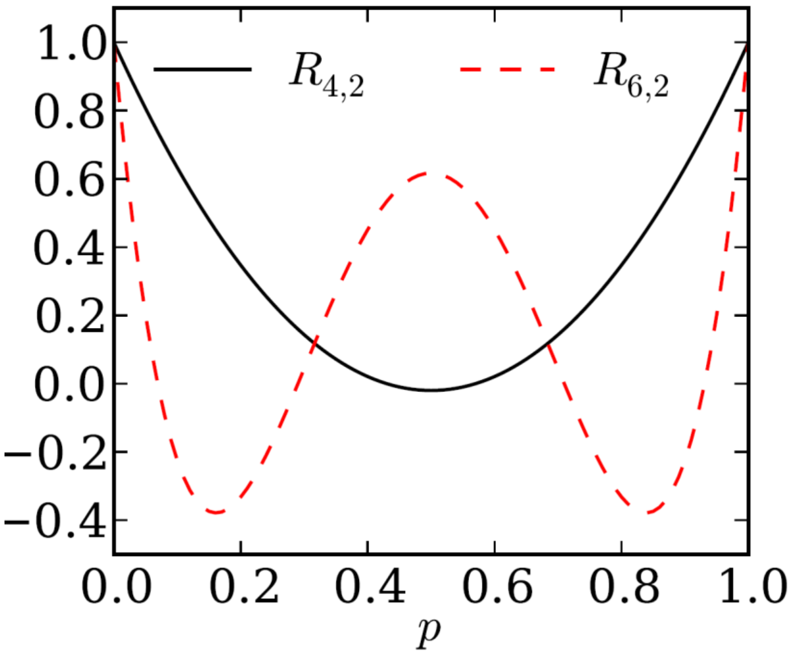
$$P_B(n_B, n_{\bar{B}}) \sim \sum P(N_B)P(N_{\bar{B}})\delta_{N_B - N_{\bar{B}} - B} \times$$

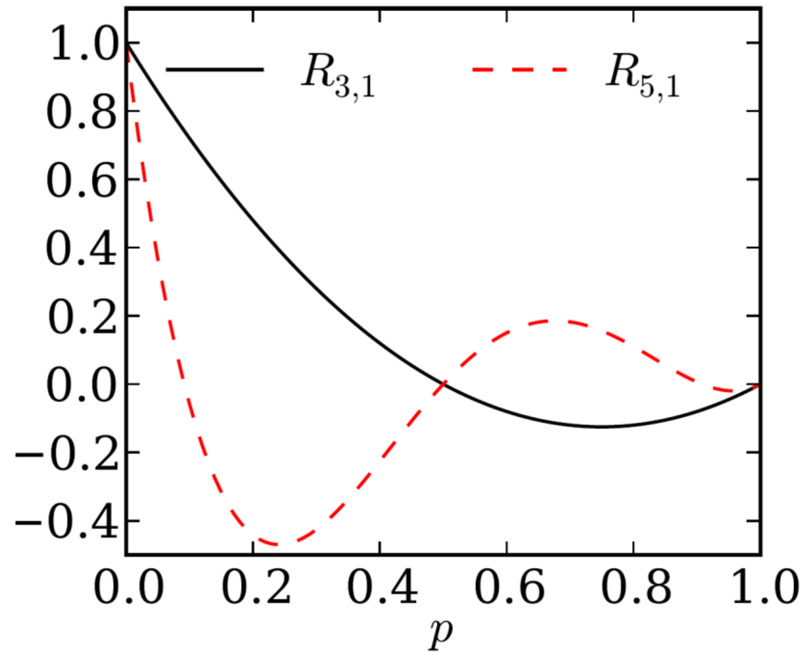
$$\times B(N_B, n_B; p_B)B(N_{\bar{B}}, n_{\bar{B}}, p_{\bar{B}})$$

$P(x)$ – Poisson dist., $B(\ldots)$ – Binomial dist.

N_B – total # of baryons, n_B – measured # of baryons

Results for $\langle N_B \rangle = 400,\ \langle N_{\bar{B}} \rangle = 100$



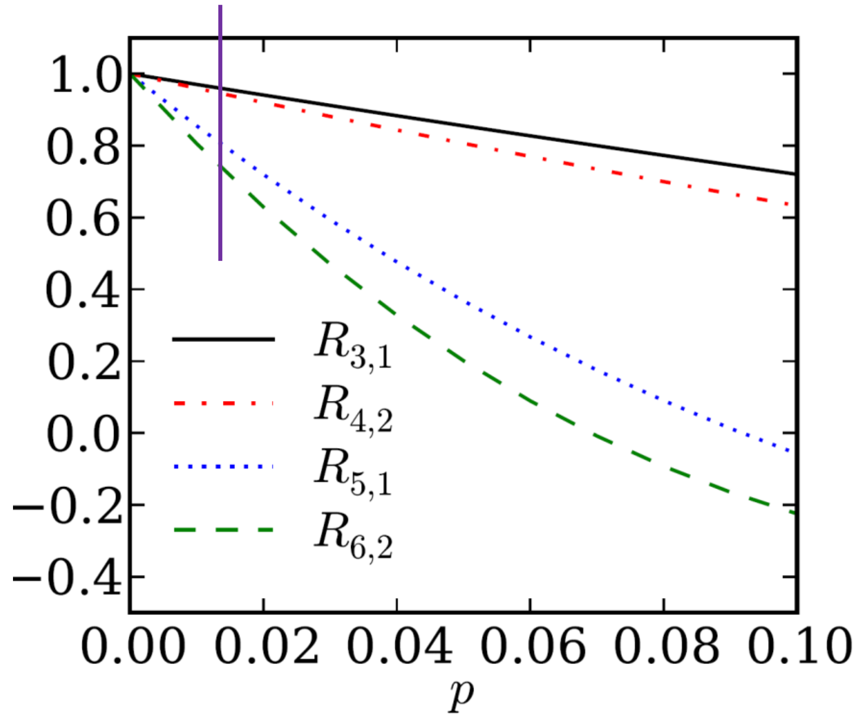


$$R_{n,m} = \frac{c_n}{c_m}$$

$$p = \frac{\#\ of\ measured\ protons/baryons}{total\ \#\ of\ baryons}$$

… for small *p*

STAR, 200 GeV



We obtain:

200 GeV: $R_{4,2} \approx 0.95,\ \ R_{6,2} \approx 0.77$

5 GeV: $R_{4,2} \approx 0.85,\ \ R_{6,2} \approx 0.32$

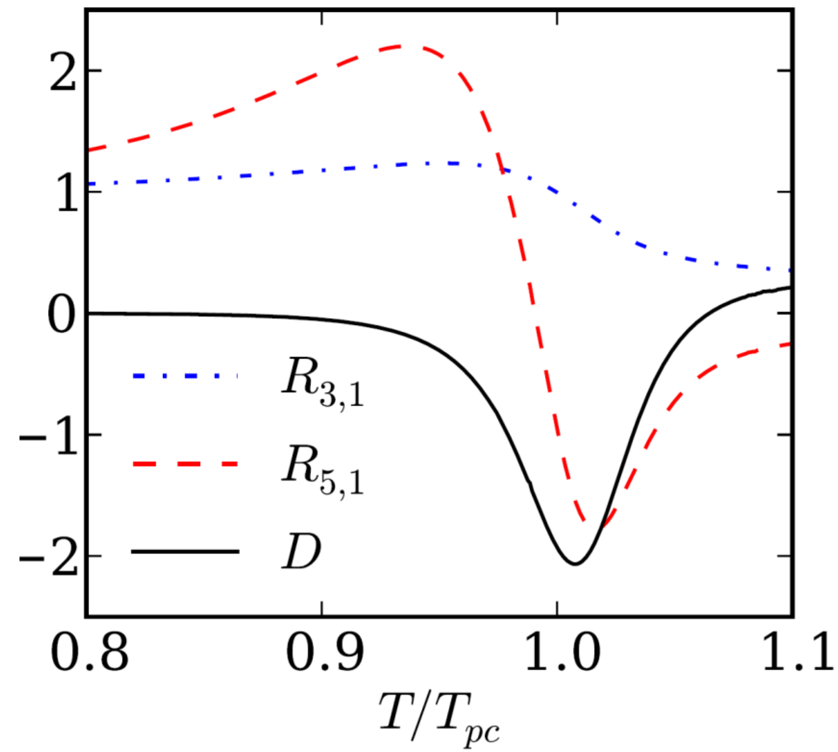
New observable

$$D = R_{5,1} - R_{3,1}\left[1 - \frac{3}{4}(1+\gamma)(3-\gamma)\right]$$

$$\gamma = \sqrt{1 + 8R_{3,1}}$$

$D = 0$ for a system with only baryon conservation

PQM calculation →



$\mu_B/T = 0.5$

T_{pc} – crossover temperature

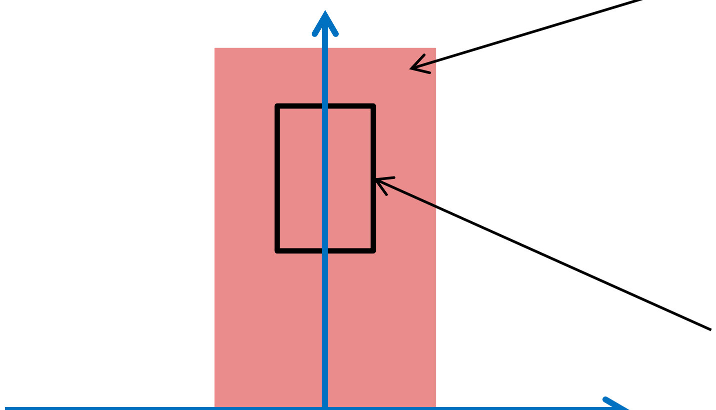
Limited acceptance

M. Kitazawa, M. Asakawa, Phys.Rev. C86 (2012) 024904

AB, V. Koch, Phys.Rev. C86 (2012) 044904

Definitions

p_t − trans. mom.



y − (pseudo)rapidity

Required acceptance.
If we measure all relevant particles in this acceptance we will capture the desired physics.

Actual acceptance. In addition we usually cannot measure all relevant particles, e.g., neutrons.

$$p = 1:\ c_n = K_n$$

K_n − cumulants in the required acceptance

c_n − cumulants in the actual acceptance

Calculation

$$p(n_1, n_2) = \sum P(N_1, N_2)\, B(N_1, n_1; p_1) B(N_2, n_2, p_2)$$

↓ c_n — what we measure

↓ $K_n,\ F_{i,k}$ — what we would like to measure

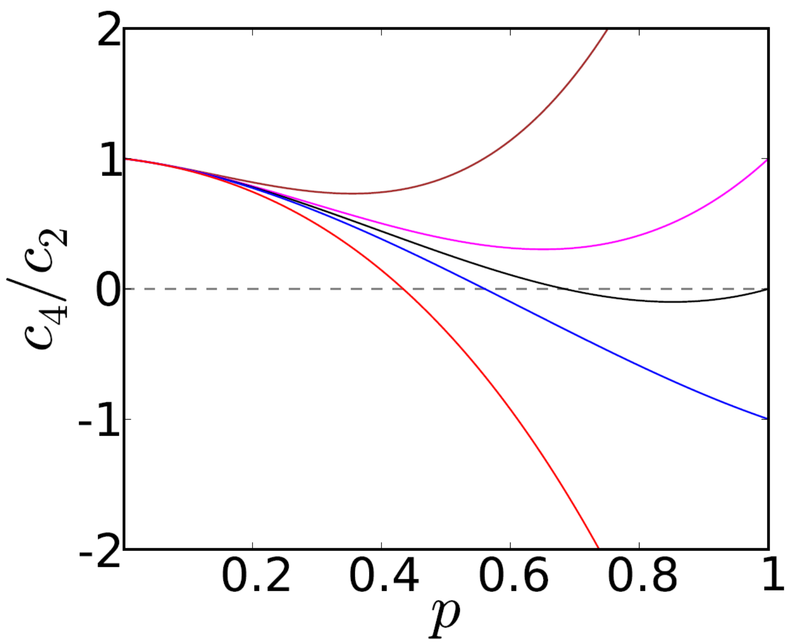
$$p_1 = p_2 = 1\text{:}\ c_n = K_n$$

factorial moments $F_{i,k} = \left\langle \frac{N_1! N_2!}{(N_1 - i)!(N_2 - k)!} \right\rangle$

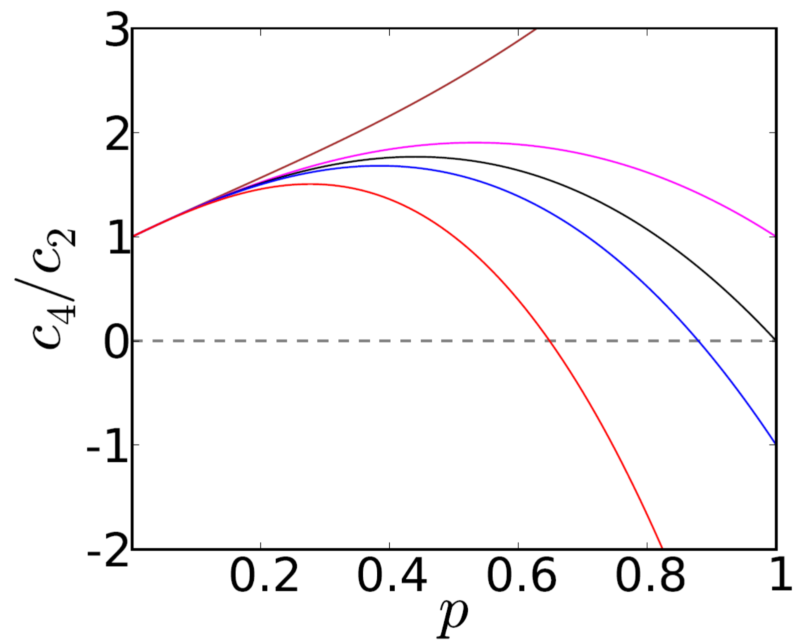
$B(\ldots) -$ binomial dist.

Results

multiplicity distr. narrower than Poisson



multiplicity distr. broader than Poisson



$$p = \frac{\#\ of\ measured\ particles}{total\ \#\ of\ particles\ that\ should\ be\ measured}$$

STAR: $p < 1/2$ and probably $p \approx 1/5$ (nobody really knows)

Can we do something? Yes

We can extract K_n, e.g.,

$$pK_1 = c_1$$

$$p^2 K_2 = c_2 - n(1-p)$$

n – measured number of protons and anti-protons

See our paper for $K_{3,4,5,6}$. However, the smaller p the better precision of measurement is needed.

What about net charge? There is no problem to have $p > 1/2$

Conclusions

- Baryon number conservation results in a comparable signal as the experimental data for net proton cumulants

- Limited acceptance, especially inability to measure neutrons, is the most serious problem that makes the interpretation of net proton cumulants <u>very</u> challenging. Net charge is more promising.

Backup

Modified (baryon conservation) Skellam distribution:

$$P_B(n) = \left(\frac{p_B}{p_{\bar{B}}}\right)^{n/2} \left(\frac{1-p_B}{1-p_{\bar{B}}}\right)^{(B-n)/2} \times \frac{I_n\left(2z\sqrt{p_B p_{\bar{B}}}\right) I_{B-n}\left(2z\sqrt{(1-p_B)(1-p_{\bar{B}})}\right)}{I_B(2z)}$$

$n = n_B - n_{\bar{B}}$ (net baryon)
or $n = n_p - n_{\bar{p}}$ (net proton)

$$\langle N_{B,\bar{B}} \rangle_{\mathrm{C}} = z\frac{I_{B\mp1}(2z)}{I_B(2z)}$$

Cumulants ($p_B = p_{\bar{B}} = p$; $q = 1 - p$):

$$\begin{aligned} c_1 &= pB, \\ c_3 &= c_1(1-p)(1-2p), \\ c_5 &= c_3\left(1 - 12p(1-p)\right). \end{aligned}$$

$$\begin{aligned} c_2 &= p(1-p)\langle N \rangle_C, \\ c_4 &= c_2 + 3(p^2q^2B^2 - c_2^2) + 6pq(2z^2pq - c_2), \\ c_6 &= c_4 + 4(c_4 - c_2) - 10(2pq + c_2)(c_4 - c_2) \\ &\quad -30pq(p^2q^2B^2 + c_2^2), \end{aligned}$$

Relations between K_n and c_n (required vs. actual acceptance).
Here $p_1 = p_2 = p$.

$$
\begin{aligned}
pK_1 &= c_1, \\
p^2 K_2 &= c_2 - n(1-p), \\
p^3 K_3 &= c_3 - c_1(1-p^2) - 3(1-p)(f_{20} - f_{02} - nc_1),
\end{aligned}
$$

$$
\begin{aligned}
p^4 K_4 \;=\; & c_4 - np^2(1-p) - 3n^2(1-p)^2 - 6p(1-p)(f_{20} + f_{02}) + 12c_1(1-p)(f_{20} - f_{02}) \\
& -(1-p^2)(c_2 - 3c_1^2) - 6n(1-p)(c_1^2 - c_2) \\
& -6(1-p)(f_{03} - f_{12} + f_{02} + f_{20} - f_{21} + f_{30}).
\end{aligned}
$$

$f_{i,k}$ – measured factorial moments

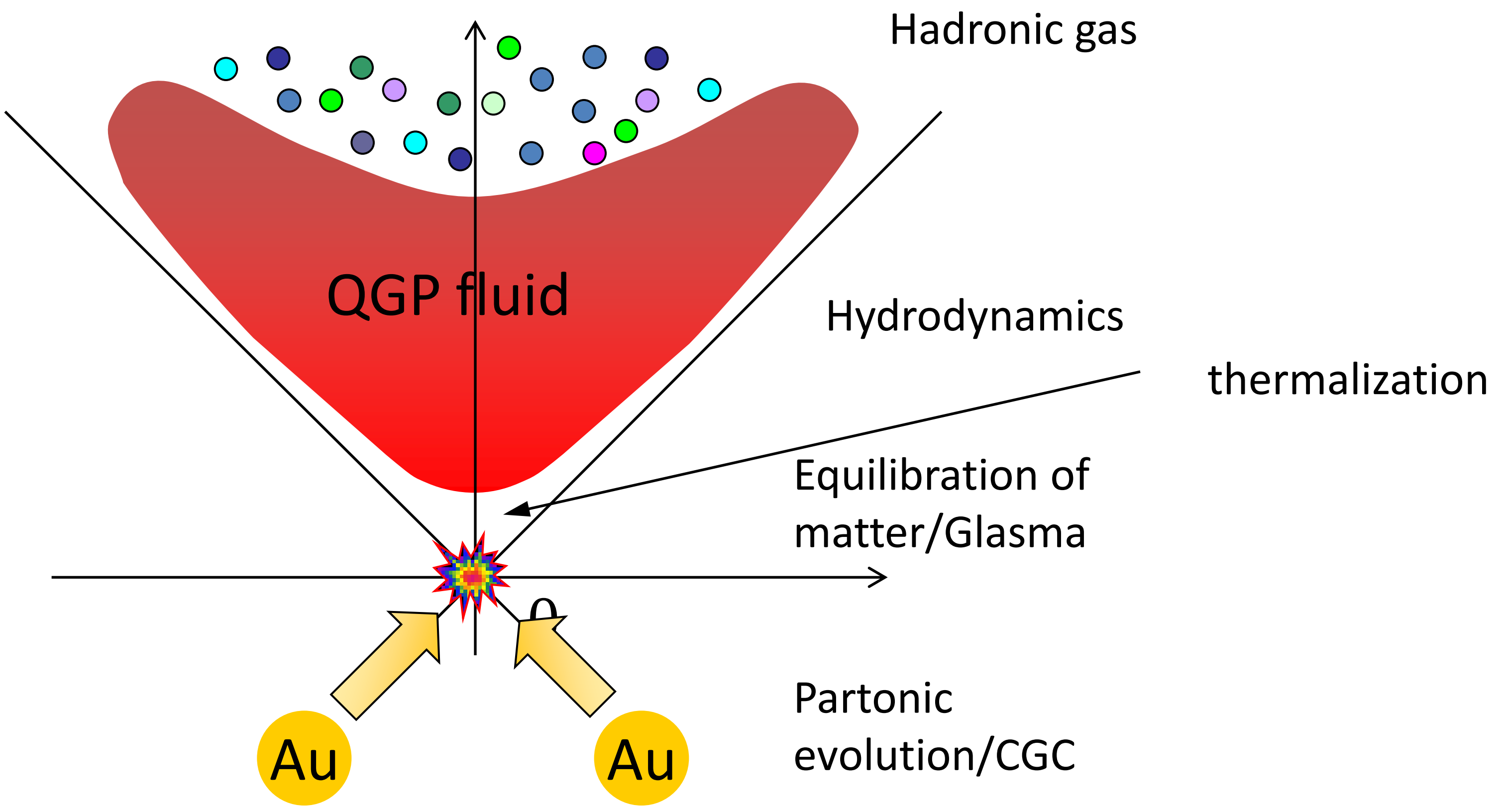
General case $p_1 \neq p_2$, see Phys.Rev. C86 (2012) 044904

Evolution of singularities in thermalization of strongly coupled gauge theory

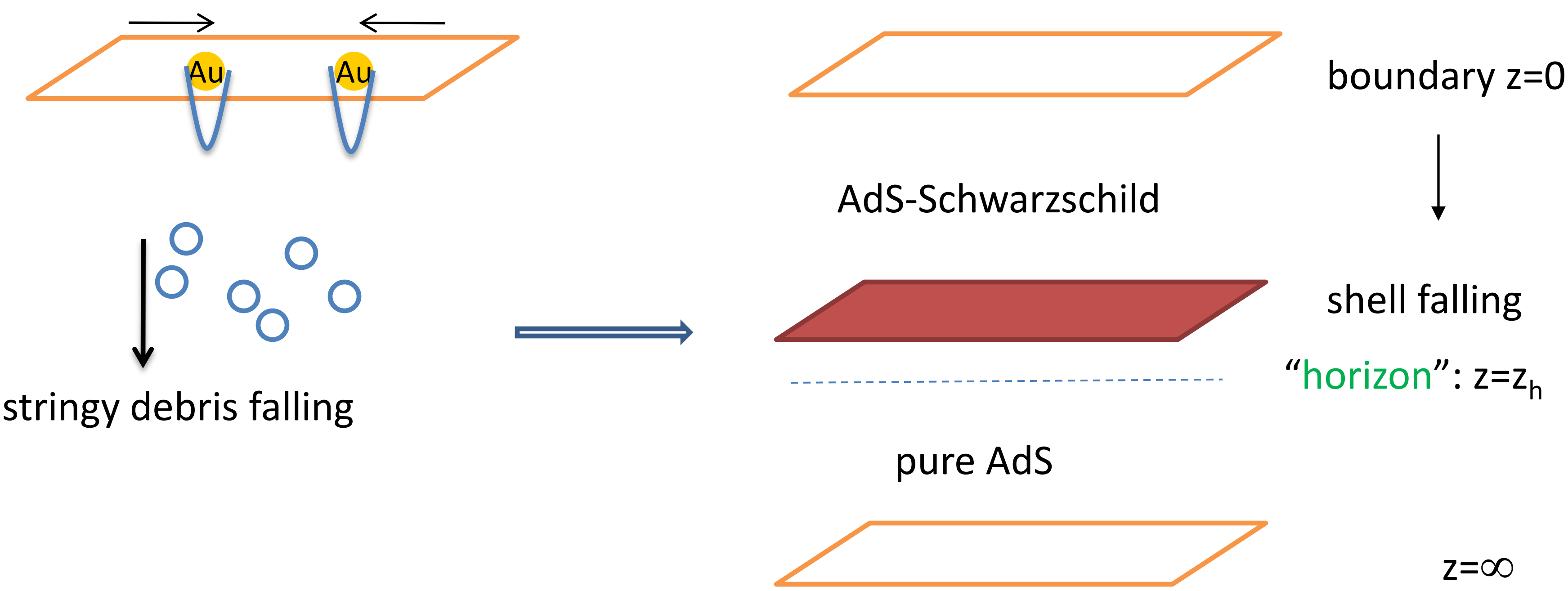
Shu Lin
RBRC

J. Erdmenger, SL: **JHEP 1210 (2012) 028**
J. Erdmenger, C. Hoyos, SL: **JHEP 1203 (2012) 085**
J. Erdmenger, SL, H. Ngo: **JHEP 1104 (2011) 035**
SL, E. Shuryak: **Phys.Rev. D78 (2008) 125018**

Stages of heavy ion collisions



Gravitational collapse model dual to thermalization



$$T_{\mu\nu} = diag(\varepsilon, p, p, p)$$

Sin, Shuryak & Zahed hep-th/0511199
SL, E. Shuryak **0808.0910** [hep-th]

Homogeneous and isotropic but not thermalized

Trajectory of falling shell from Israel junction condition

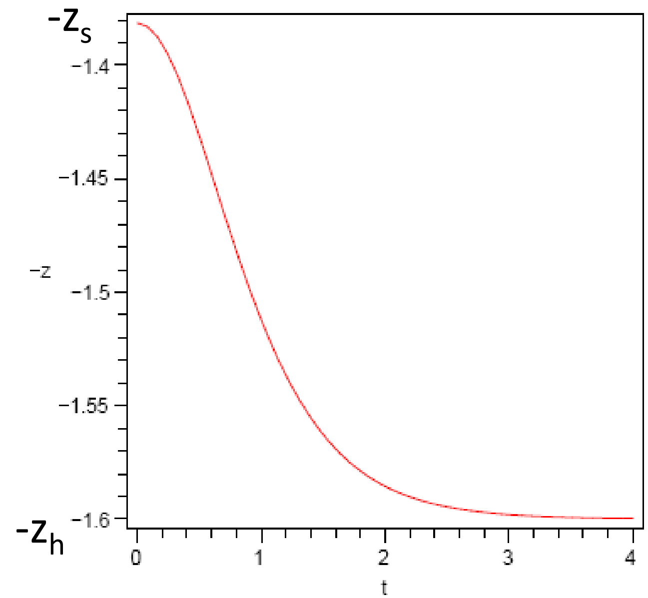
Israel junction condition

$$[K_{ij} - \gamma_{ij} K] = \kappa S_{ij}\,, \qquad \{K_{ij}\} S^{ij} = 0.$$

K_{ij}: extrinsic curvature
γ_{ij}: intrinsic curvature

$$S_{ij} = (\epsilon(z) + p(z)) u_i u_j + p(z) \gamma_{ij}.$$

Equation of state $\epsilon = \frac{p}{a}$

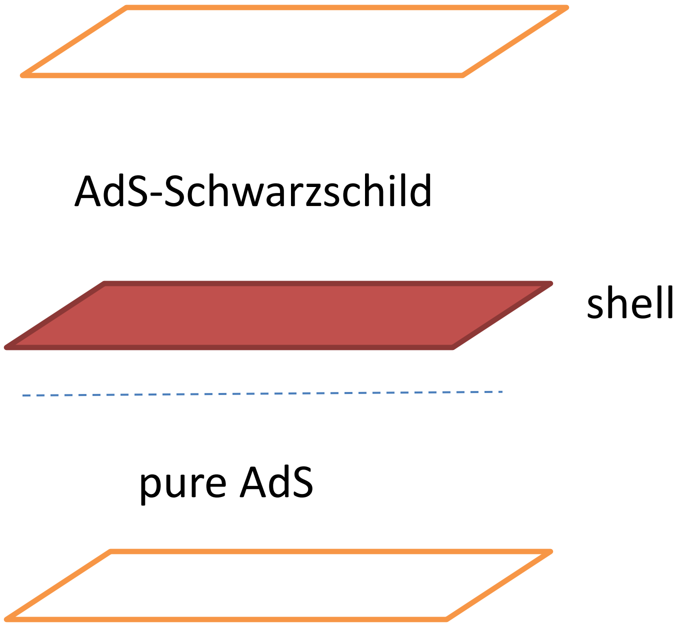


$$\Longrightarrow \quad \dot{z} = \sqrt{\frac{1}{4}\left(bz^4 + \frac{1}{bz_h^4}\right)^2 - 1}\,, \quad \dot{t}_f = \frac{\sqrt{f + \dot{z}^2}}{f} = \frac{\frac{1}{bz_h^4} - bz^4}{2f}.$$

$$bz_s^4 + \frac{1}{bz_h^4} = 2.$$

z_s: initial shell position (intrinsic scale)
b: "energy density"
z_h: horizon position (temperature)

Quasi-static state & beyond



quasi-static state (adiabatic): shell at $z=z_s<z_h$

$\langle O(t,x)O(t',0)\rangle = \langle O(t-t')O(x)\rangle$

$$G^R(\omega,k)=\int dt\,d^3x\,e^{-i\omega t+ikx}\theta(t-t')\langle[O(t-t',x),O(0,0)]\rangle$$

$$\phi(\omega,k,z)\to G^R(\omega,k)$$

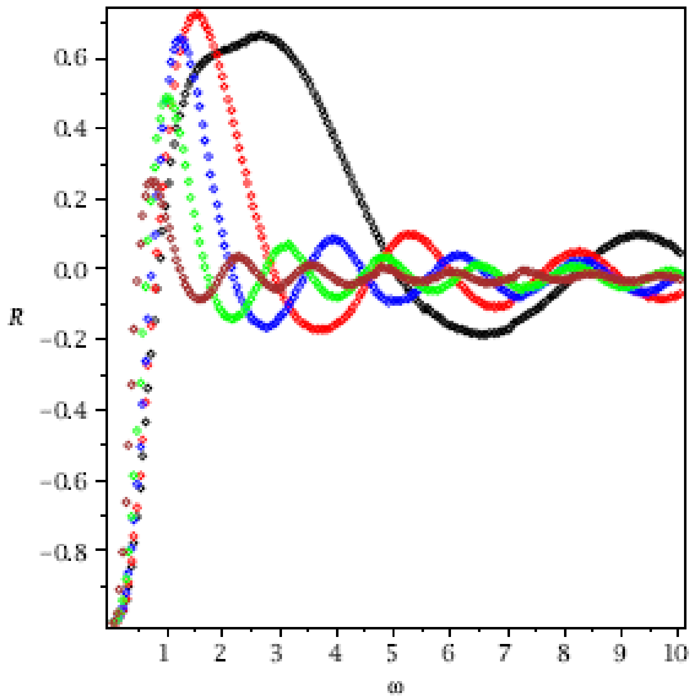
Beyond quasi-static (nonadiabatic):
falling shell $z=z_s(t)$

$\langle O(t,x)O(t',0)\rangle \neq \langle O(t-t')O(x)\rangle$

$$G^R(t,t',k)=\int d^3x\,e^{ikx}\theta(t-t')\langle[O(t,x),O(t',0)]\rangle$$

$$\phi(t,t',k,z)\to G^R(t,t',k)$$

Deviation from thermal spectral function for quasi-static state



glue ball spectral function

$$\chi = -2\,\mathrm{Im}\,G^R(\omega)$$

$$R = \frac{\chi - \chi_{thermal}}{\chi_{thermal}}$$

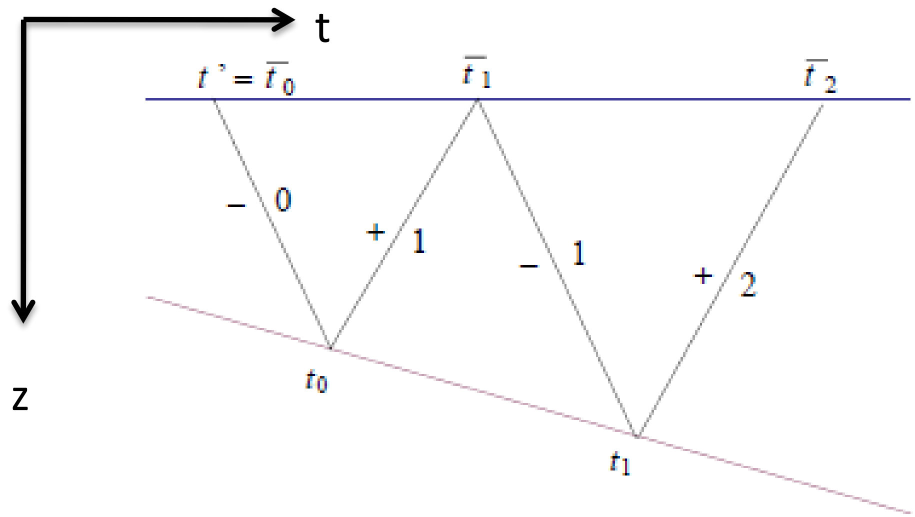
Spectral function for quasi-static state oscillate around thermal spectral function

$\Delta\omega$ and oscillation amplitude shrinks as the shell is lowered toward the horizon

Shell falling →

	black	red	blue	green	brown
f	0.99	0.91	0.75	0.51	0.19

Beyond quasi-static state



Focus on large frequencies in the bulk   ω>>R, ω>>T
➔ Geometric optics.

Bulk scalar singular along the trajectory of the light ray

➔singularities in the correlator.

$$G^R(t,t') = \int d^3x\,\theta(t-t')\langle[O(t,x),O(t',0)]\rangle$$

zero momentum glue ball correlator

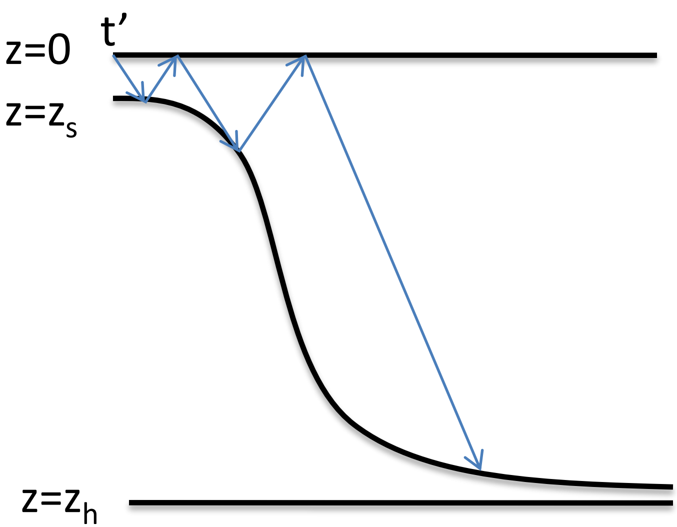
$$G^R(t \to \bar{t}_n, t') \sim \frac{A_n(-i)^{n-1}}{(-t+\bar{t}_n+i\varepsilon)^{5-n}} - \frac{A_n i^{n-1}}{(-t+\bar{t}_n-i\varepsilon)^{5-n}}$$

splitting between positive/negative frequency contributions

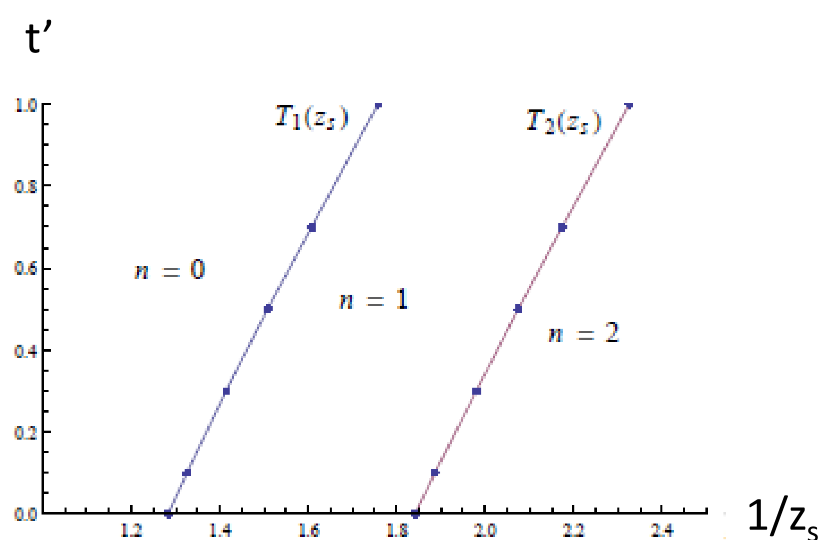
J. Erdmenger, C. Hoyos, SL **JHEP 1203 (2012) 085**
J. Erdmenger, SL **JHEP 1210 (2012) 028**

Light ray bouncing in collapse background

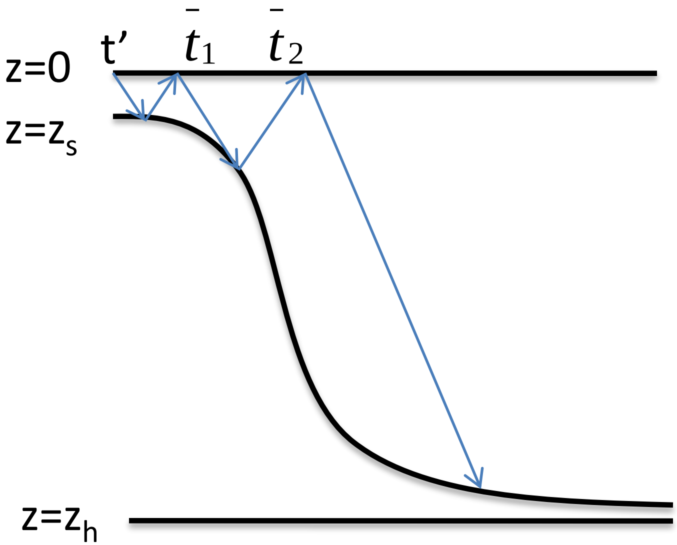
Expectation from geometric optics picture suggests singularities of $G^R(t,t')$ when the light ray starting off at t' returns to the boundary



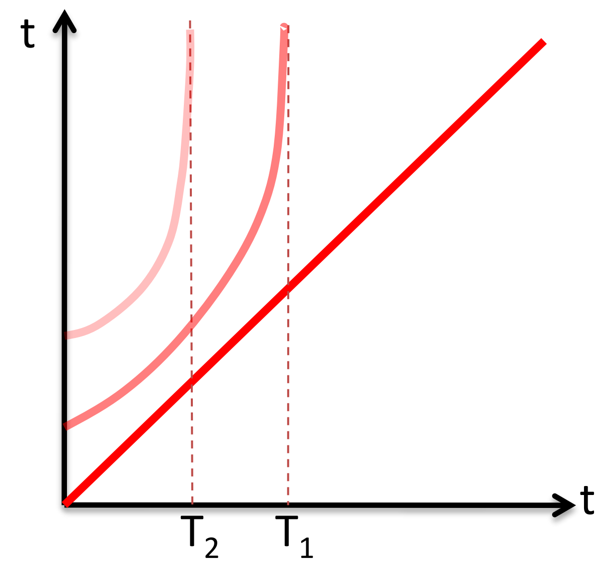
Only finite bouncing is possible:
The warping factor freezes both the shell and the light ray near horizon



Divergence matching in collapse background



Geometric Optics:
ω>>R, ω>>T



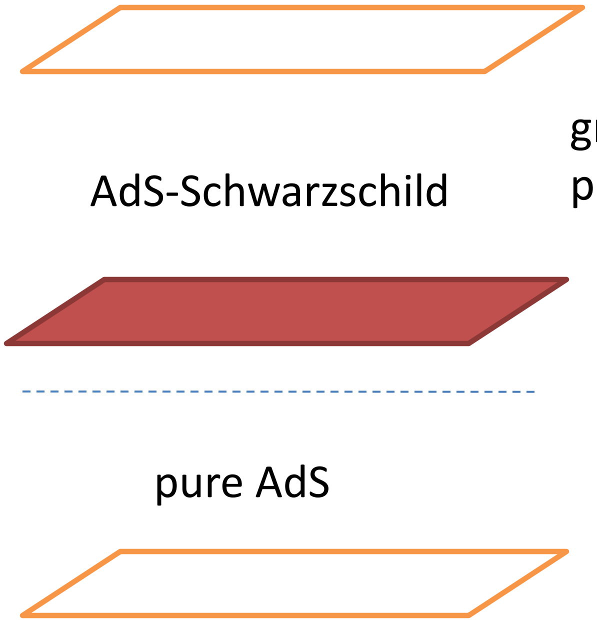
$$G^R_>(t \to \bar{t}_n) = \frac{A_n(-i)^{n-1}}{(-t+\bar{t}_n+i\varepsilon)^{5-n}}, G^R_<(t \to \bar{t}_n) = \frac{A_n i^{n-1}}{(-t+\bar{t}_n-i\varepsilon)^{5-n}}$$

$\bar{t}_n \to +\infty$ as $t' \to T_n(z_s)$

"Time scale for temporal decoherence"

$$t_{td} = \frac{T_1(\pi T z_s)}{\pi T} \sim \frac{O(1)}{\pi T}$$

Singularities in correlator of stress tensor from metric perturbation



graviton wave perturbation

$$G_R^{\mu\nu,\rho\sigma}(t,t') = \int d^3x\,\theta(t-t')\langle[T^{\mu\nu}(t,x),T^{\rho\sigma}(t',0)]\rangle$$

Same pattern of singularities dictated by geometric optics

Same "time scale for temporal decoherence" $t_{td} = \frac{T_1(\pi T z_s)}{\pi T} \sim \frac{O(1)}{\pi T}$

work in progress

Summary

- Within a gravitational collapse model, we studied spectral function of the glue ball correlator for quasi-static state, and the singular part of the correlator for thermalizing state.
- The singularities are consistent with bouncing light ray in collapse background: Finite singularities; singularities set scale for temporal decoherence and eventually disappear at late stage of thermalization.
- Similar singularities structure for stress tensor correlator, leading to the same temporal decoherence time.

Columbia plot and QCD thermodynamics in effective model

Kouji Kashiwa

RIKEN BNL Research Center

Collaborators : R. D. Pisarski, V. V. Skokov (Brookhaven National Laboratory)

M. Yahiro, [1]H. Kouno, T. Sasaki (Kyushu University, [1]Saga University)

W. Weise, T. Hell (Technical University of Munich)

K. Fukushima (Keio University)

Y. Maezawa (Brookhaven National Laboratory)

Last year

- Phys. Rev. D 83 (2011) 117901,
『Entanglement between chiral and deconfinement transitions under strong uniform magnetic background field』
K.K..

This year

- hep-ph/1208.2283,
『Two-color QCD at imaginary chemical potential and its impact on real chemical potential』
K.K., T. Sasaki, H. Kouno, M. Yahiro.
- hep-ph/1206.0685,
『Polyakov loop and QCD thermodynamics from the gluon and ghost propagators』
K. Fukushima, **K.K.**.
- Phys. Rev. D 85 (2012) 114029,
『Critical endpoint for deconfinement in matrix and other effective models』
K.K., R. D. Pisarski, V. V. Skokov.

In progress:

- 『(tentative title) Impact of nonderivative vector-type interaction on the QCD phase diagram』
T. Hell, **K.K.**, W. Weise.
- 『(tentative title) Colombia plot and QCD thermodynamics at imaginary chemical potential』
K.K., R. D. Pisarski.
- 『 (tentative title) Quark back reaction to deconfinement transition via gluon propagator』
K.K., Y. Maezawa.

Introduction: QCD phase diagram

QCD phase diagram

Lattice QCD has the sign problem.

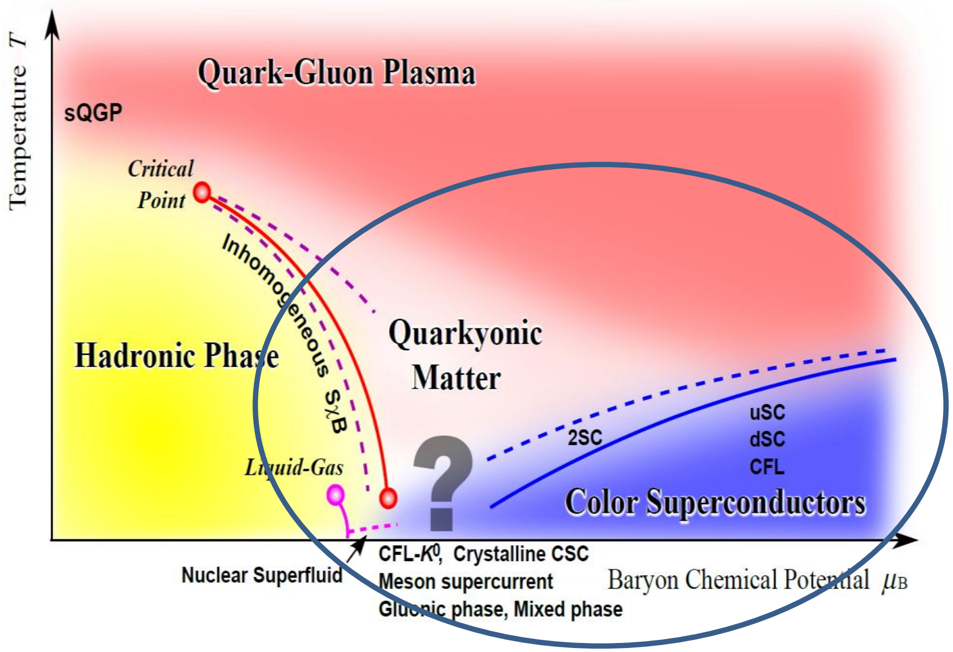
Effective models have large ambiguities.

At the present, we can not obtain any reliable QCD phase diagram.

Construction of reliable effective model is important.

- To investigate the QCD phase structure at finite μ_R
- To extract the physical meaning and picture form LQCD data

K. Fukushima and T. Hatsuda, Rept.Prog.Phys.74 (2011) 01400



How to construct the reliable effective model of QCD?

How to check the model reliability?

K.K., R. D. Pisarski, V. V. Skokov, Phys. Rev. D 85 (2012) 114

- Polyakov-loop effective potential

$$\frac{\mathcal{U}(\bar{\Phi},\Phi;T)}{T^4} = -\frac{1}{2}b_2(T)\,\bar{\Phi}\,\Phi + b_4(T)\,\ln[1-6\,\bar{\Phi}\,\Phi + 4(\bar{\Phi}^3+\Phi^3) - 3(\bar{\Phi}\,\Phi)^2]$$

It is widely used to investigate the QCD phase structure.

- Matrix model for deconfinement

Perturbative part

$$\mathcal{V}^g_{\rm pt} = \frac{2\pi^2 T^4}{3}\sum_{i,j=1}^{N} q_{ij}^2(1-|q_{ij}|)^2 - (N_c^2-1)\frac{\pi^2 T^4}{45}$$

Non-perturbative part

$$+\ \mathcal{V}^g_{\rm npt} = T^2 T_c^2 \sum_{i,j=1}^{N}\left[c_1|q_{i,j}|(1-|q_{ij}|) + c_2 q_{ij}^2(1-|q_{ij}|)^2 \ + c_3\right]$$

This model is based on the perturbative transverse gluon potential.

It is easy to extend to arbitral color number.

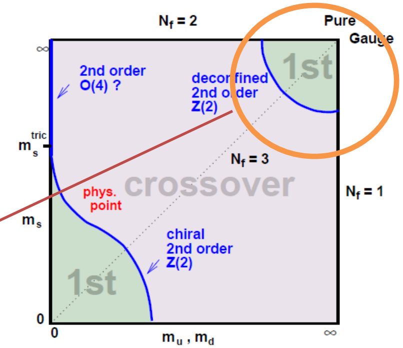
Numerical results: Matrix model for deconfinement transition

K.K., R. D. Pisarski, V. V. Skokov, Phys. Rev. D 85 (2012) 114

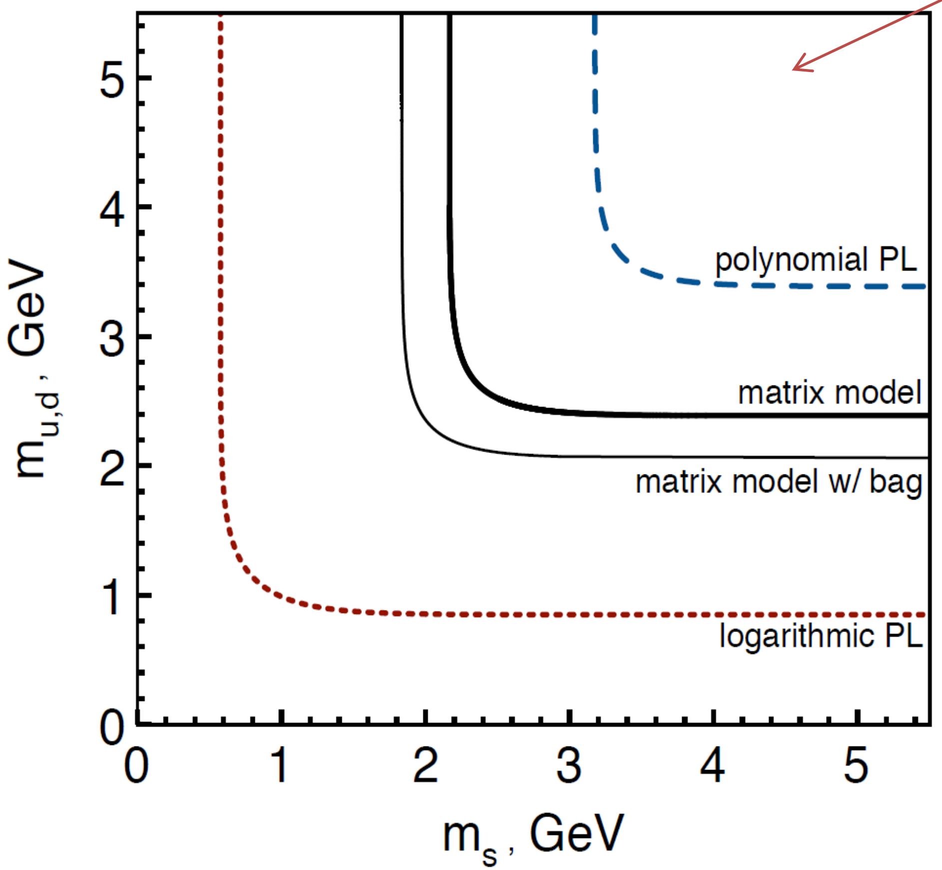
Matrix model for deconfinement

A. Dumitru, Y. Guo, Y. Hidaka, C. P. K. Altes, and R. D. Pisarski, Phys. Rev. D 83 (2011) 034022,

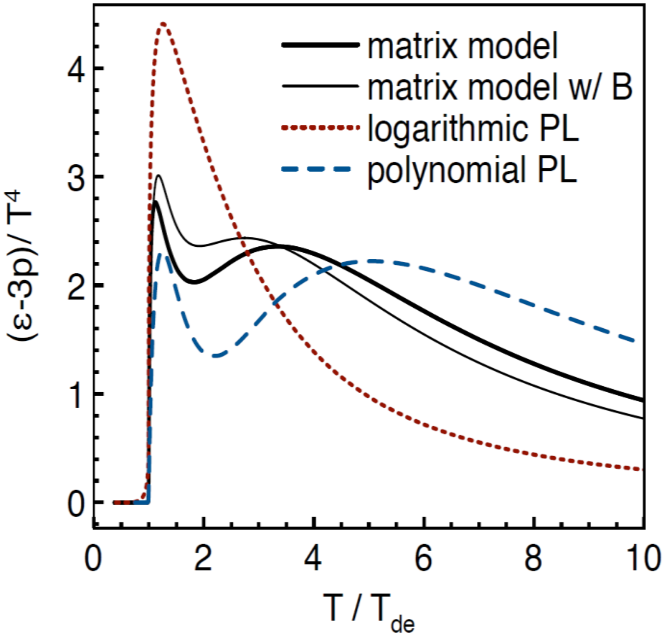
Model unclearness for gluonic sector



2-d Clombia plot



Interaction measure



Model dependence is quite large!

Introduction: Effective models

K. Fukushima, **K.K.**, hep-ph/1206.068

It is well known that the confinement can be discussed from the gluon and ghost propagator.

It is possible to describe the deconfinement transition from the gluon and ghost propagator.

Fit the LQCD gluon and ghost propagator by analytic function
(Gribov-Stingl form)

↓ Calculate the effective potential

↓ Minimize the potential respect to order-parameter

- Explicit form of the effective potential

$$\beta\Omega_{\text{glue}} \simeq \boxed{-\frac{1}{2}\text{tr}\ln D_A^{-1}} + \boxed{\text{tr}\ln D_C^{-1}}$$

Gluon contribution Ghost contribution

This approach is convenient to include the quark back reaction!

(Actual inclusion is in progress)

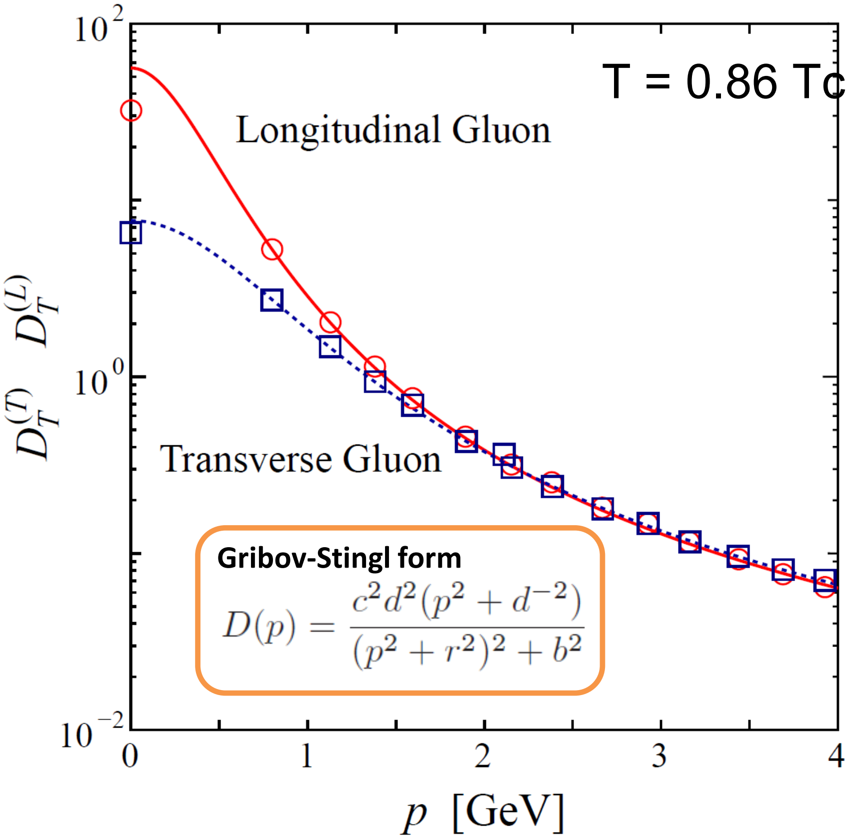
Numerical results: Gluon and ghost potential in Landau gauge

K. Fukushima, **K.K.**, hep-ph/1206.068

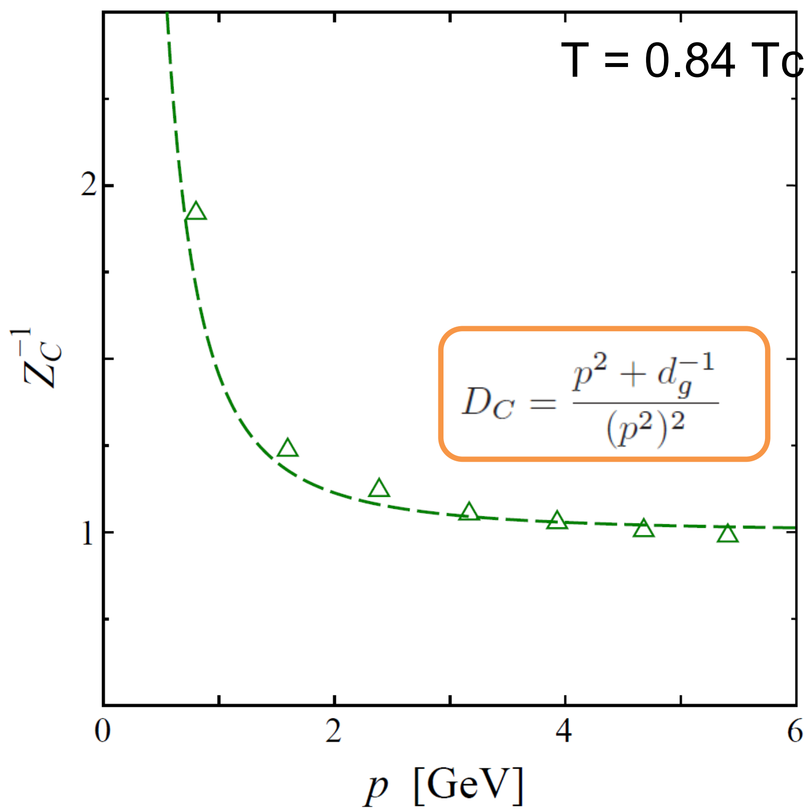
Effective potential
from gluon and ghost propagator

$$\beta\Omega_{\rm glue} \simeq -\frac{1}{2}{\rm tr}\ln D_A^{-1} + {\rm tr}\ln D_C^{-1}$$

Gluon propagator



Ghost dressing function



Lattice data: R. Aouane et al., PRD 85 (2012) 034501

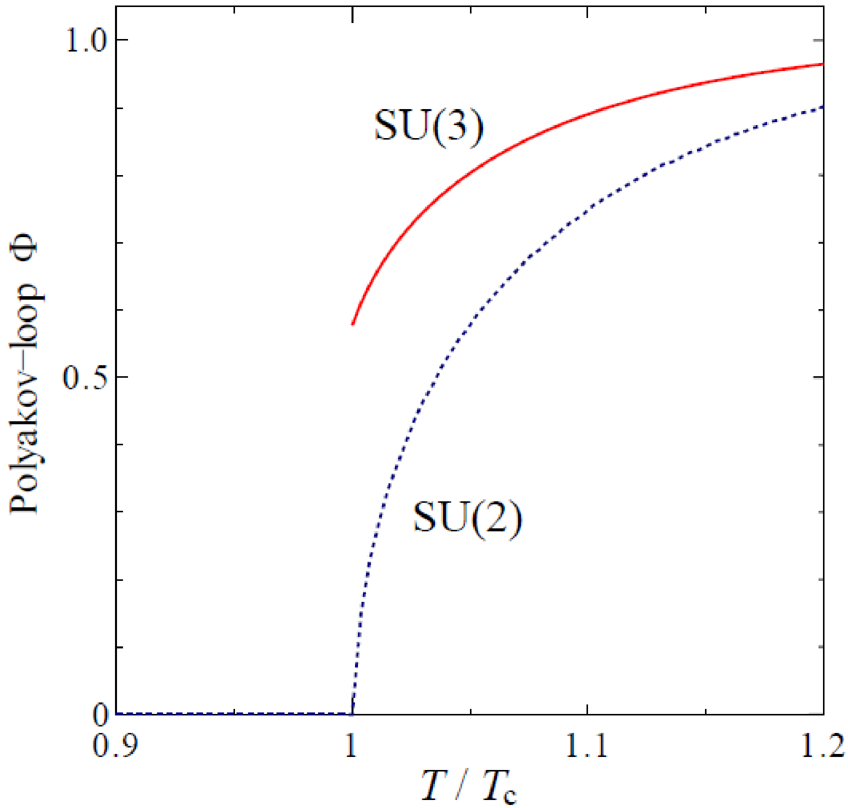
By using above fitting results, we can calculate the effective potential from gluon and ghost propagator!

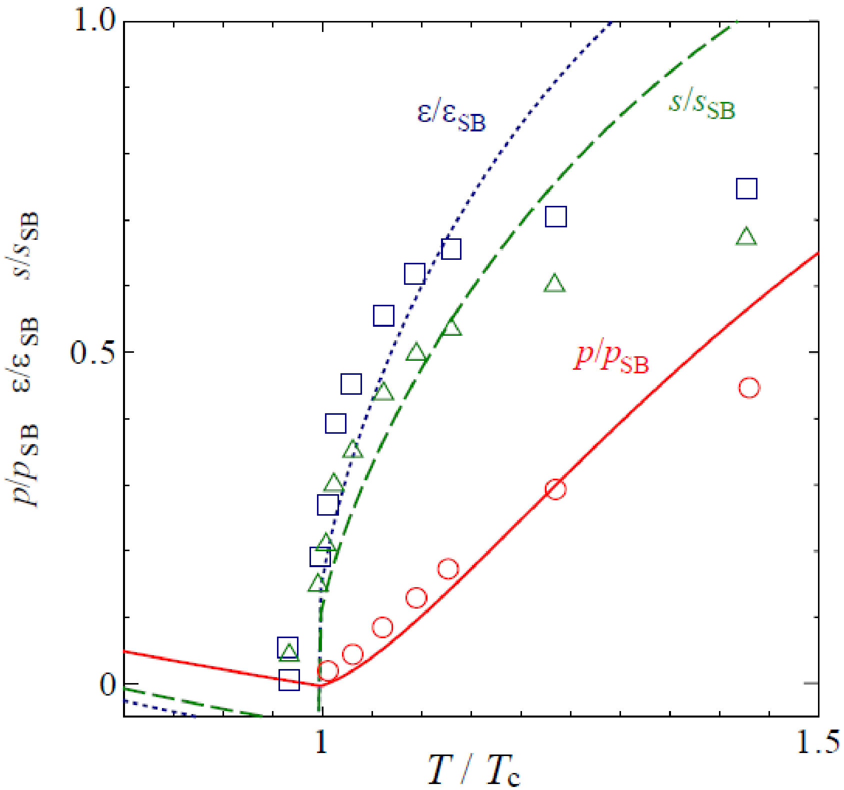
Numerical results: Gluon and ghost potential in Landau gauge

K. Fukushima, **K.K.**, hep-ph/1206.068

Result In this approach, we can clearly treat the **microscopic properties of QCD**.

Pure gauge limit





Lattice data: S. Datta and S. Gupta, PRD 82 (2010) 114505

Actual value is 286 MeV

Near Tc, this approach can **reproduce LQCD data very well near Tc**.

Summary

K.K., R. D. Pisarski, V. V. Skokov, Phys. Rev. D 85 (2012) 114029.

We investigate the model ambiguities at heavy quark mass region.

There is the **large difference** on the upper part of the Columbia plot.

The **interaction measure** is sensitive against the model ambiguities.

How about in imaginary chemical potential region?

→ **K.K.**, R. D. Pisarski, in progress.

K. Fukushima, **K.K.**, hep-ph/1206.0685.

The gluonic sector of QCD is constructed by the gluon and ghost propagator.

LQCD data is fitted by the **Gribov-Stingl form** and then LQCD data are well reproduced.

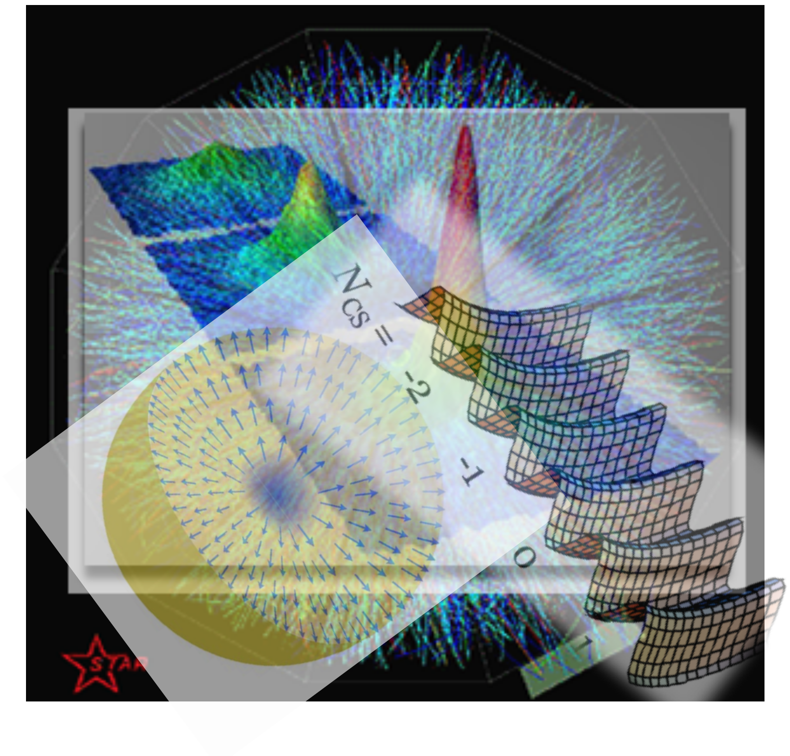
The gluon and ghost propagator is fundamental quantities of QCD, and thus
It is promising approach to describe the QCD thermodynamics.

We can expect that the **quark back reaction** can be naturally
introduced in this approach.

→ **K.K.**, Y. Maezawa, in progress

RBRC Review Nov 7-8, 2012

Strongly Interacting Matter in Heavy Ion Collisions



Jinfeng Liao

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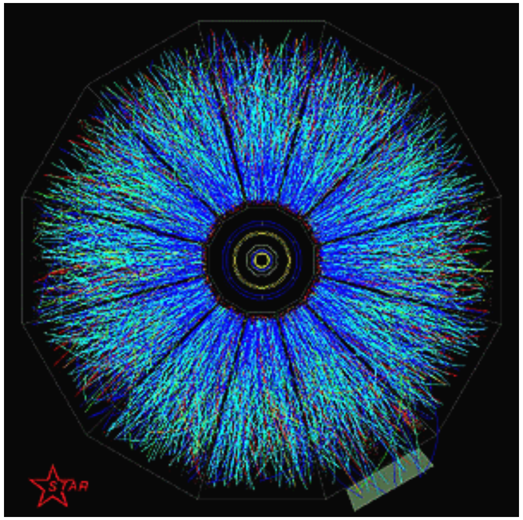
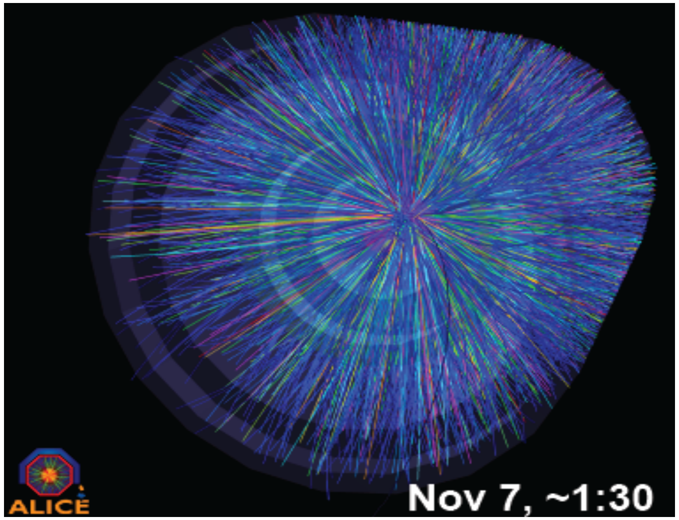
Outline

- Strongly Interacting Glasma & Thermalization
- Near-Tc Matter and Confinement
- Hard Probe of the geometry and fluctuations at RHIC + LHC: Jet Mono-graphy
- In search of topological effects (CME,CMW,Geometry & fluctuations in strong B-field effects.)
- Summary; Miscellaneous items

Strongly Interacting Matter





A strongly interacting matter has been created at RHIC & LHC: rapid thermalization, strong collective flow, jet quenching, …

But unsatisfactory understanding on:

How such strongly interacting nature arises from underlying QCD dynamics in the hot dense environment?

Connected phenomenological puzzles:

How thermalization occurs?

Opaqueness evolution & jet quenching anisotropy?

From Weakly to Strongly Interacting

A weakly coupled and weakly interacting QGP (at very high temperature):
characterized by a well separated hierarchy of scales

$$E \sim T >> E_D \sim gT >> E_M \sim g^2 T$$

Matter becomes strongly interacting upon collapse of all these scales

$$E \sim E_D \sim E_M$$

This may occur in two ways:

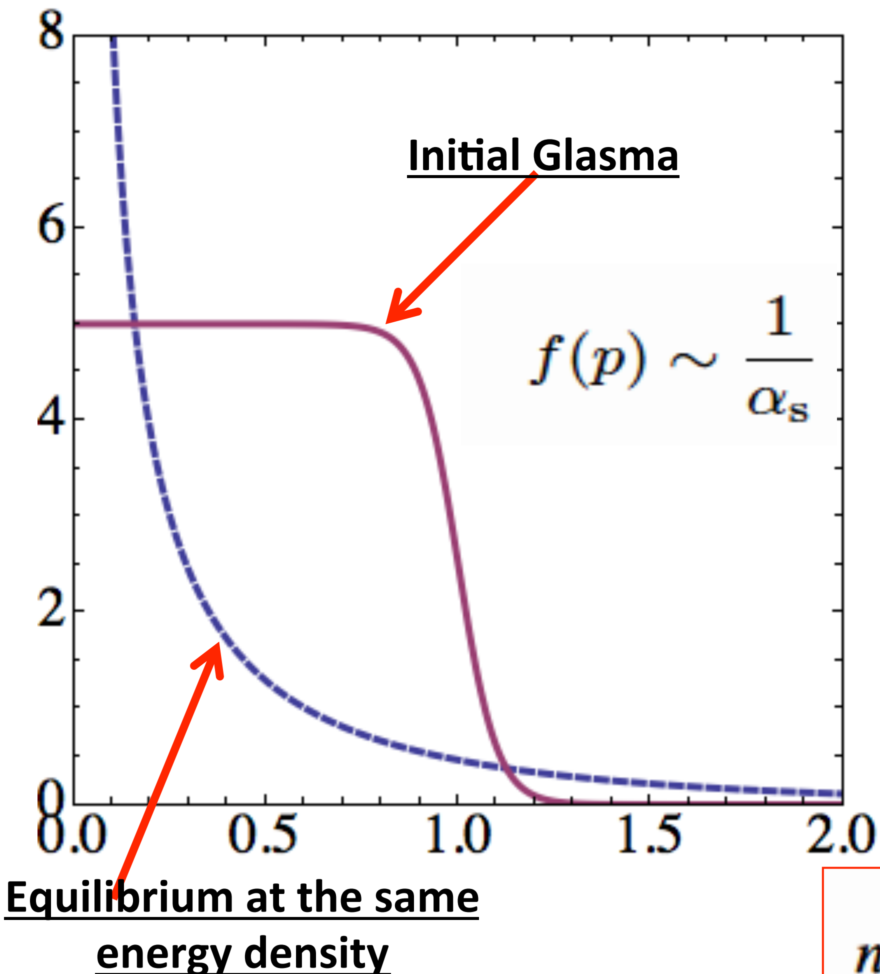
(1) When a weakly-coupled system is brought far away from equilibrium → f ~ 1/g^2:
weakly coupled but strongly interacting as an emergent property
--- this is the case for the pre-equilibrium glasma and may hold the key of thermalization

(2) When the coupling itself becomes strong g→ 1
strongly coupled, and expect change into emergent degrees of freedom
--- this is the case for the matte near Tc, T→ Tc ~ Lambda_QCD and thus a thermal sQGP

My research focus on understanding strongly interacting matter in both cases and their implications for observed heavy ion collision phenomena.

Overpopulation → Thermalization

Initial Glasma: far from equilibrium and highly overpopulated!



- **Very strong scattering**

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

- **Only one scale: emergent strongly interaction; require separation**

$$\Lambda_s \sim \Lambda \sim Q_s$$

In contrast with: $\Lambda_s^{th} \sim \alpha_s T \quad \Lambda^{th} \sim T$

- **Strong overpopulation: → condensation!**

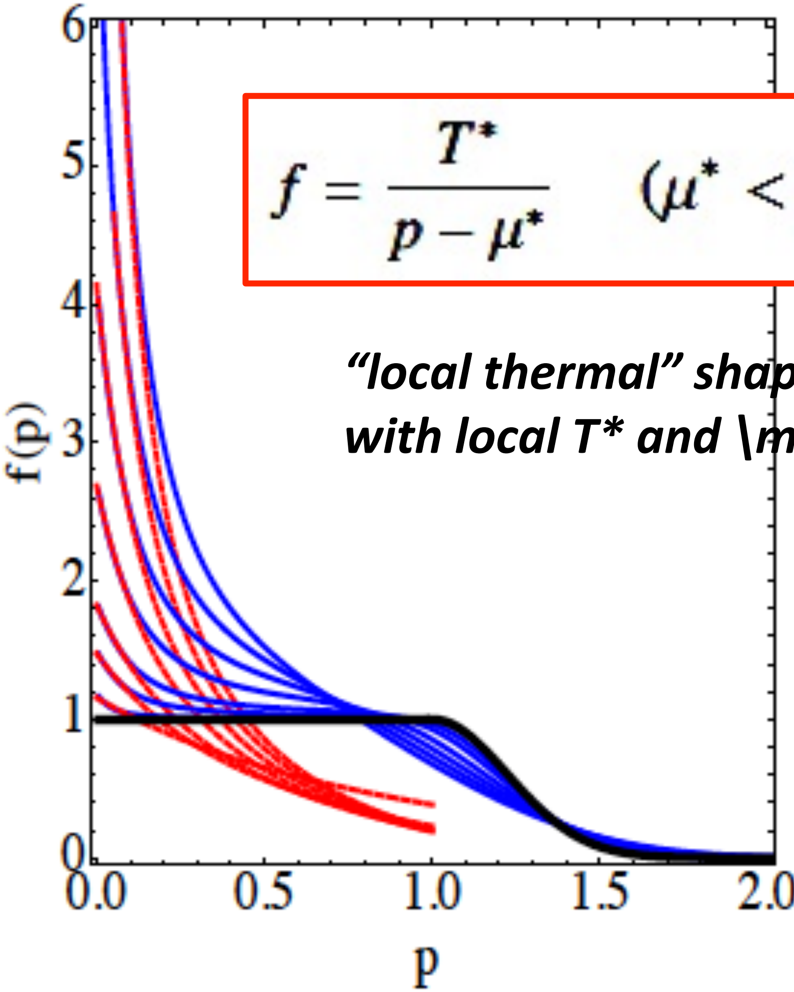
$$n_0\, \epsilon_0^{-3/4} \sim 1/\alpha_s^{1/4} \quad >> \quad n_{eq} \epsilon_{eq}^{-3/4} \sim 1$$

Kinetic approach developed and scaling solutions found for thermalization.

Blaizot, Gelis, JL, McLerran, Venugopalan, arXiv:1107.5296[NPA2012]

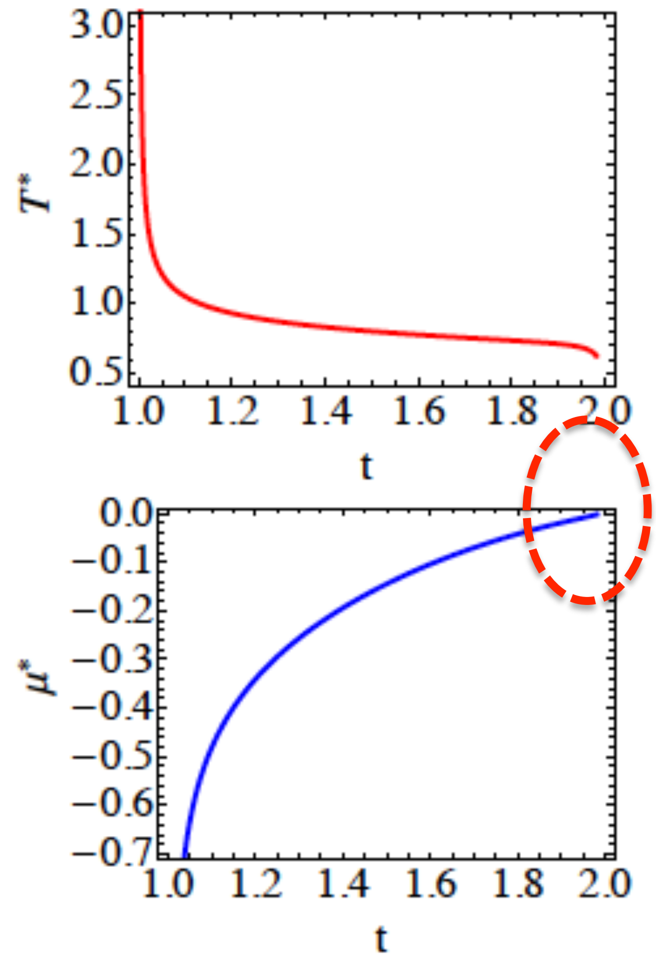
Onset of BEC in Overpopu. Glasma

It is very important to understand dynamically how condensation occurs.



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

"local thermal" shape
with local T and \mu**

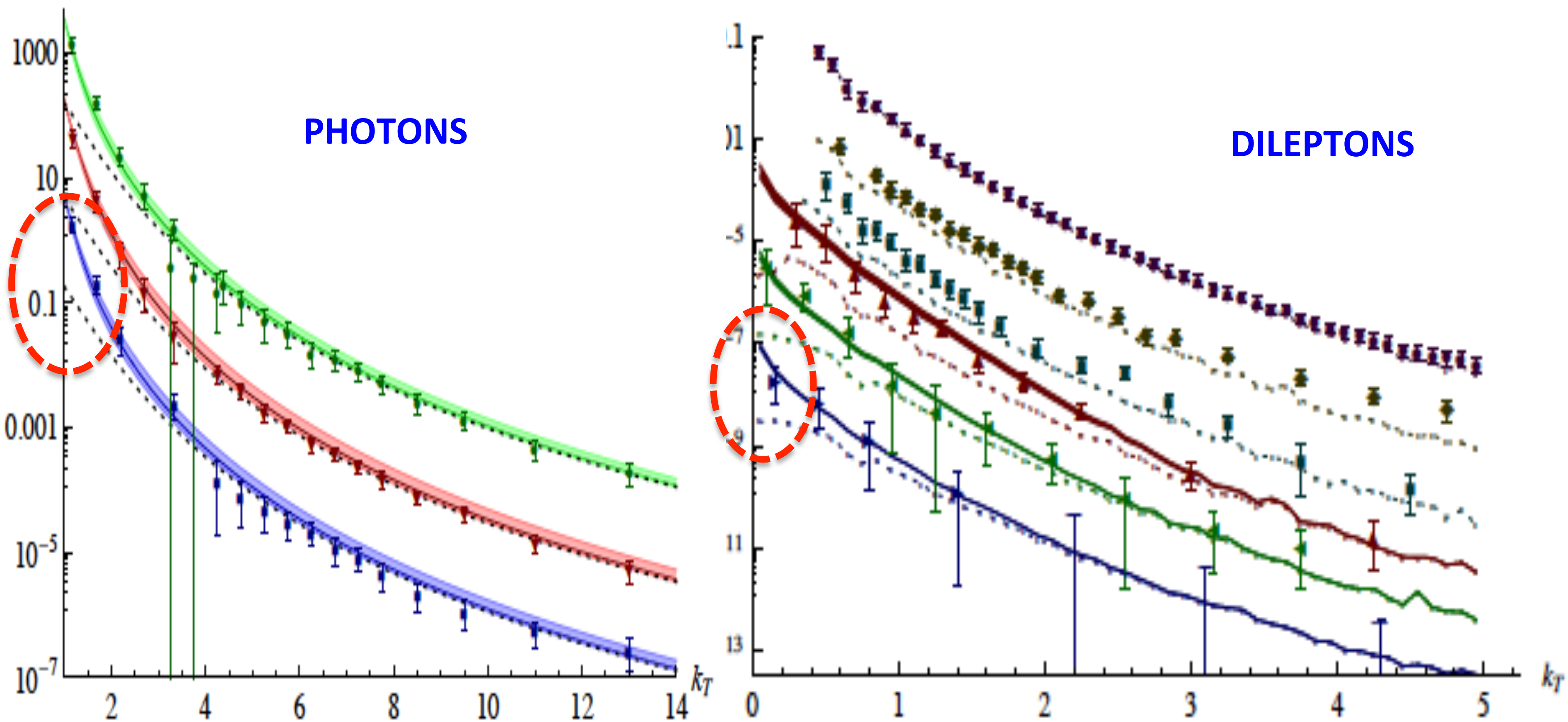


The link from overpopulation to onset of condensation is VERY ROBUST, despite:
any shape of initial distribution; possible initial anisotropy; longitudinal expansion.

Blaizot, JL, McLerran, in final preparation

Pre-Equilibrium Phenomenology

One example of pre-equilibrium phenomenology:
there are important contributions to EM production from the thermalizing Glasma!



Chiu, Hemmick, Khachatryan, Leonidov, JL, McLerran, arXiv:1202.3679 [nucl-th].

Emergent QCD Matter Near Tc

T<< Lambda_QCD

T ~ Lambda_QCD

T>> Lambda_QCD

Vacuum: confined

Tc

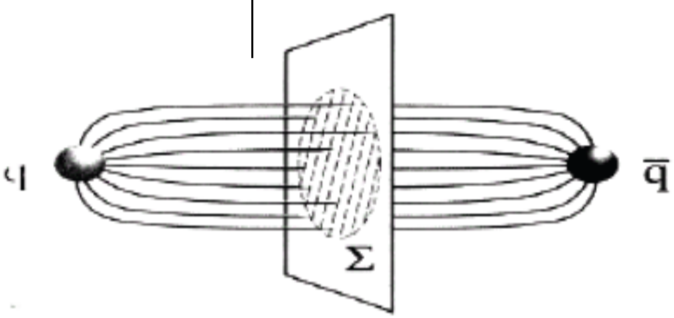
sQGP

wQGP: screening

T

RHIC

LHC

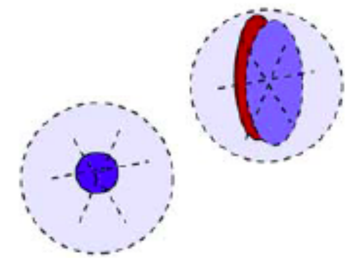


Electric Flux Tube in Magnetic Condensate

Dual superconductor
't Hooft-Mandelstam in 70's
Manifested in Seiberg-Witten

?

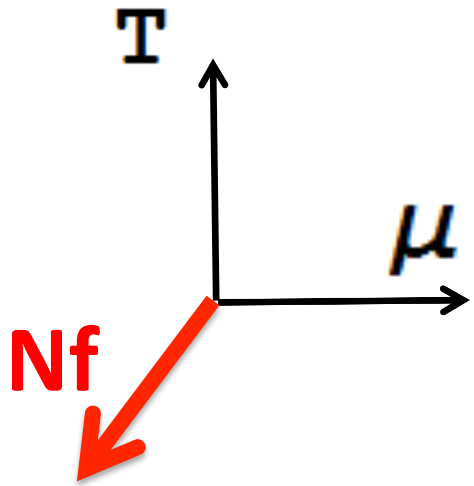
Our proposal →
one more level of emergence near Tc:
Plasma of magnetic monopoles (the dual normal conductor)



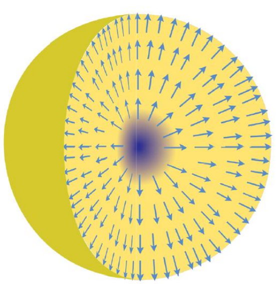
Plasma of E-charges
E-screening: g T
M-screening: g^2 T

JL, Shuryak, PRC2007,PRL2008

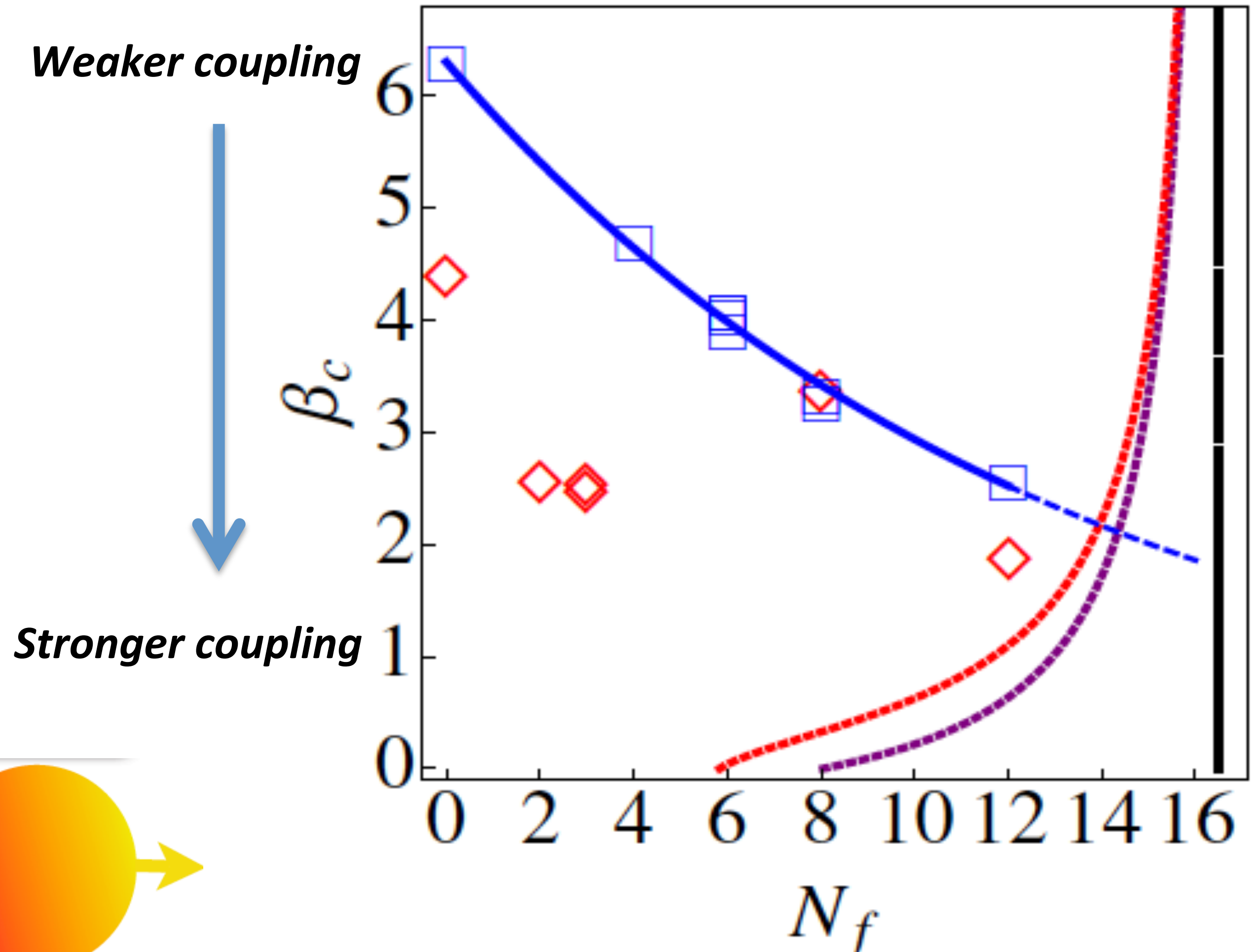
How Fermions affect the Confinement Transition



Magnetic Monopoles



Monopole-quark from zero modes

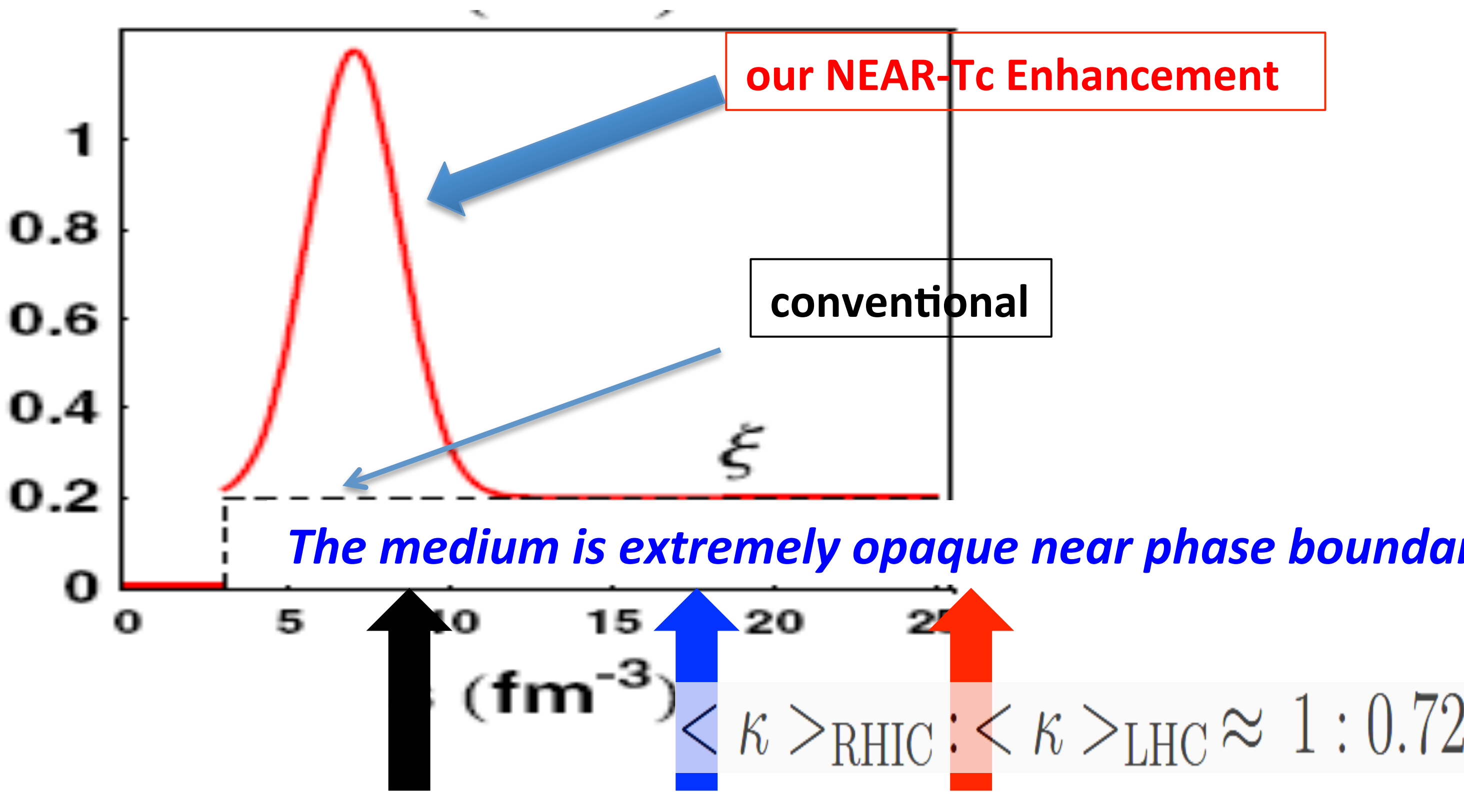


$$\beta_c(N_f) = \beta_0(1+f)^{-8N_f N_M/15}$$

JL, Shuryak, arXiv:1206.3989[PRL2012]

Near Tc Matter is Extremely Opaque

Strong emergent magnetic component near Tc → strong magnetic quenching of electric jet!

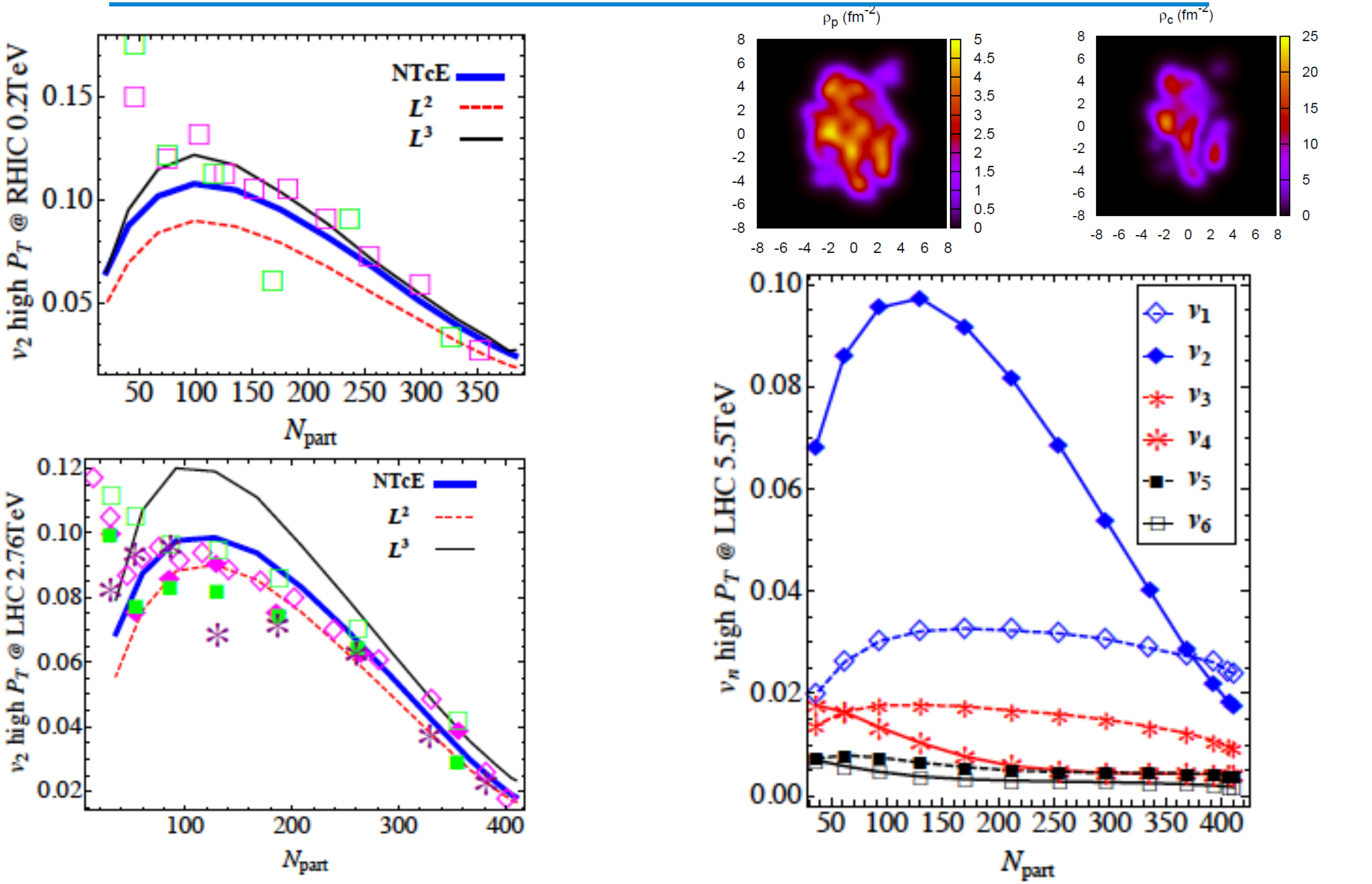


Unique prediction for medium opaqueness evolution with collision beam energy:
--- nontrivial convolution of jet-medium interaction with fireball density

- **LHC fireball is on average 30% less opaque --- LHC data indeed suggests so!**
- **RHIC lower energy (62,39GeV) fireball should be more opaque than 200GeV**
  --- most recent PHENIX data suggests so, too!

JL, arXiv:1109.0271; JL, Zhang, arXiv:1208.6361, 1210.1245

Hard Probe of Geo. & Fluc.

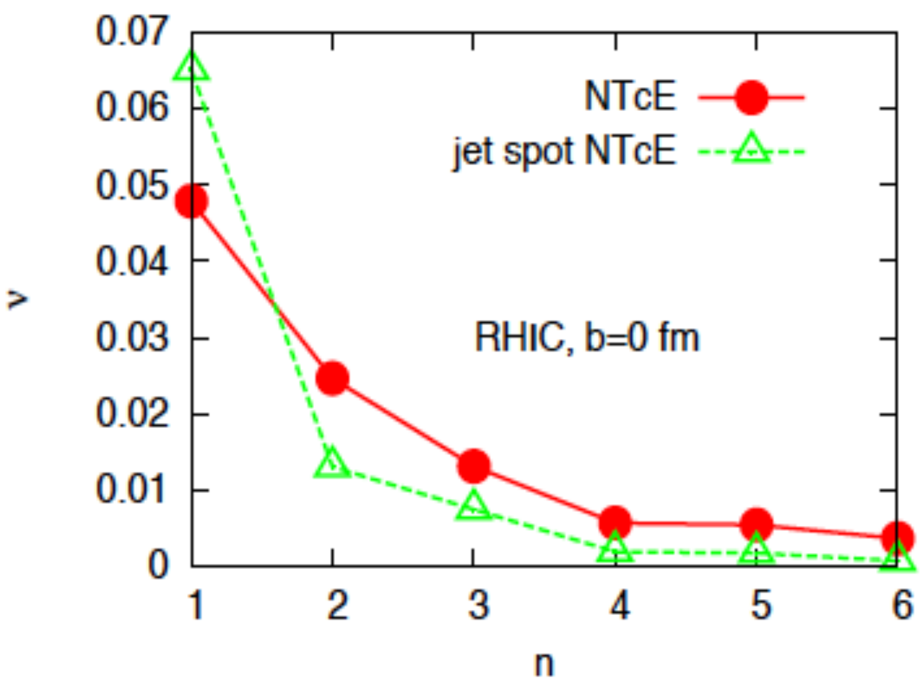


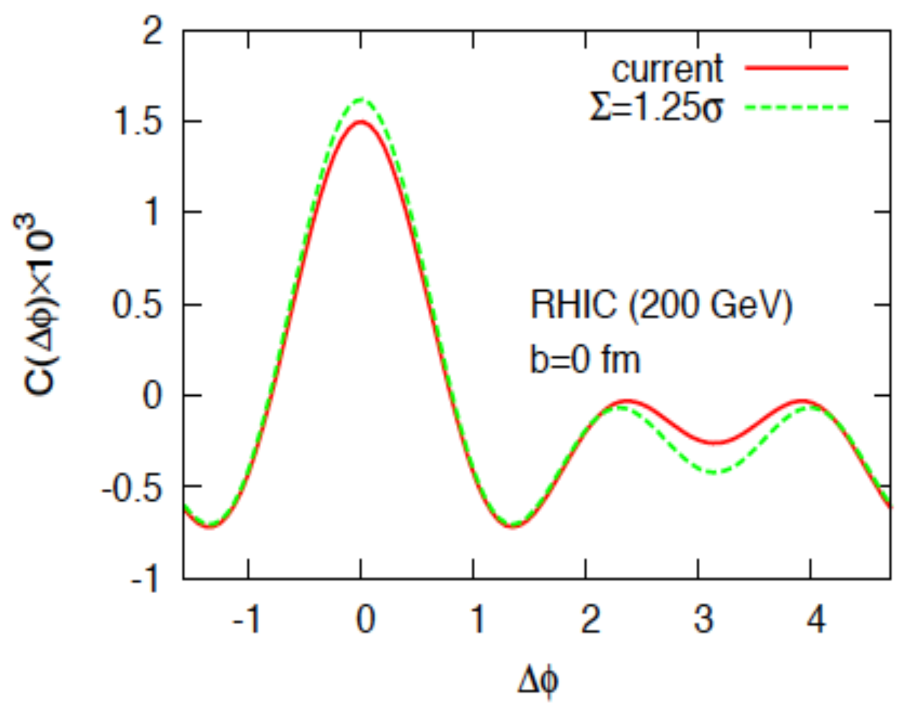
RHIC+LHC geometric data: L^2 path-length dependence + Near Tc Enhancement!

JL, arXiv:1109.0271; JL, Zhang, arXiv:1208.6361, 1210.1245

Hard-Soft Correlation from Fluctuating Geometry

SOFT Response ← Fluctuating Geometry → HARD Response



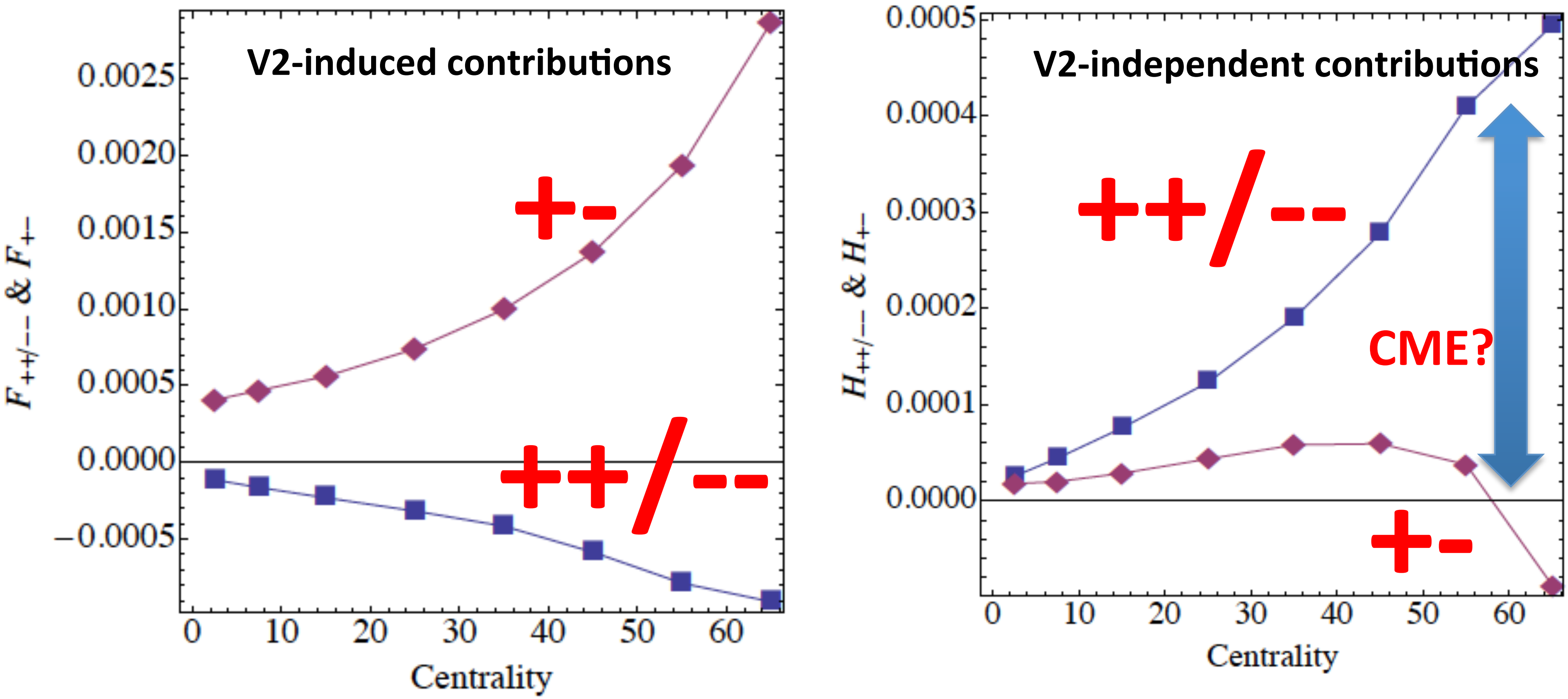


$$C[\Delta\phi] = \sum_{n=1,2,3,\ldots} 2 < v_n^h v_n^s > \cos(n\Delta\phi)$$

JL, Zhang, arXiv:1202.1047[PLB2012], 1210.1245

In Search of Topo-Effects: CME

$$\gamma_{\alpha,\beta} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \qquad \delta_{\alpha,\beta} = \langle\cos(\phi_\alpha - \phi_\beta)\rangle$$



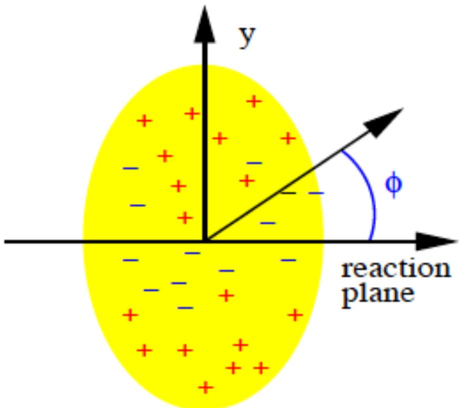
New decomposition efforts indicate a possible scenario:
V2-induced contributions --- Trans. Momentum Cons. + Local Charge Cons.
V2-independent contributions --- Dipole Asym. Fluct. + Chiral Magnetic Effect

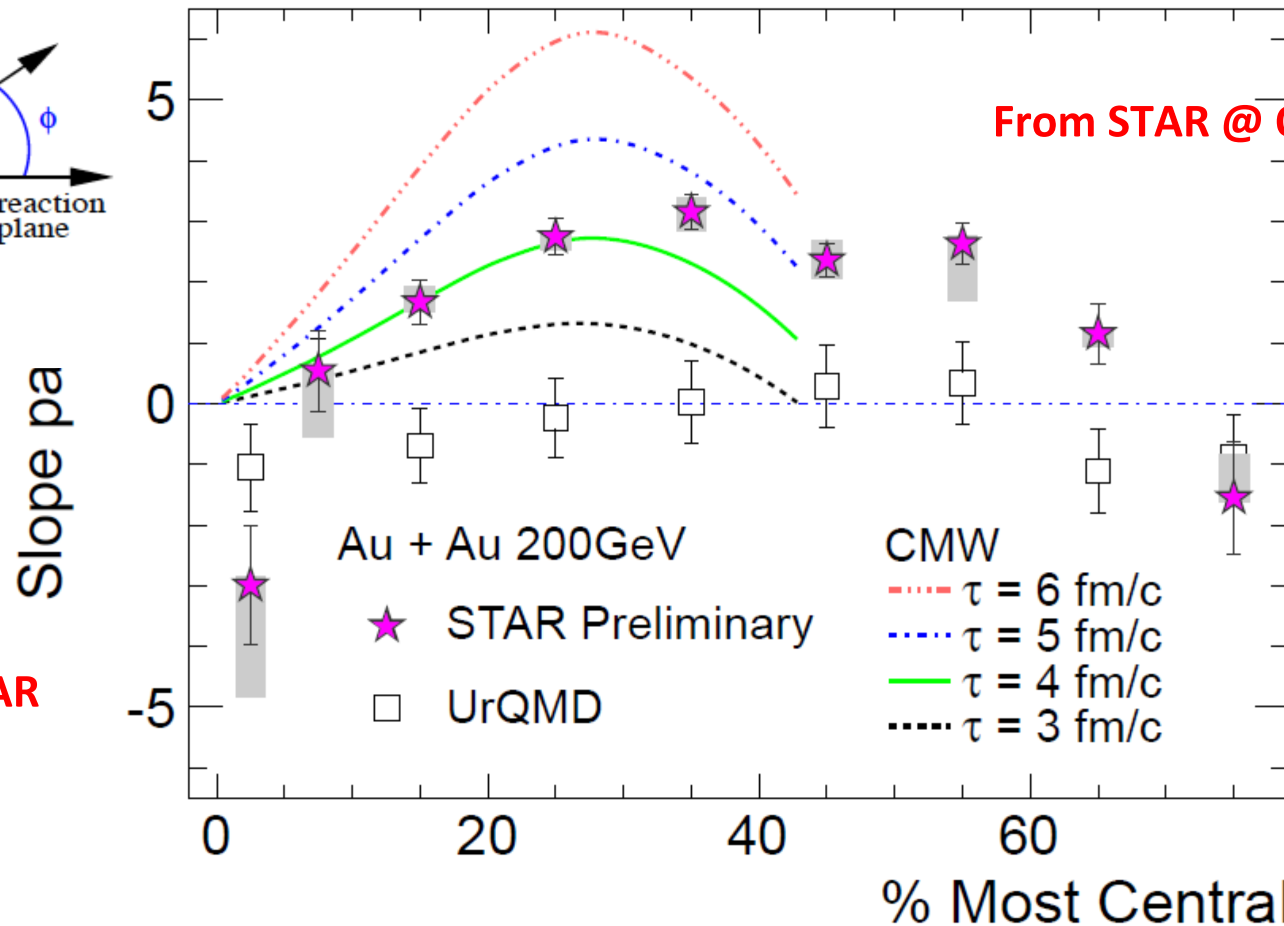
Bzdak, Koch, JL, arXiv:1207.7327

In Search of Topo-Effects: CMW

CME+CSE → CMW → Quadrupole Charge Distribution→

$$v_2^{\pm} = v_2 \mp \frac{rA_{\pm}}{2}.$$



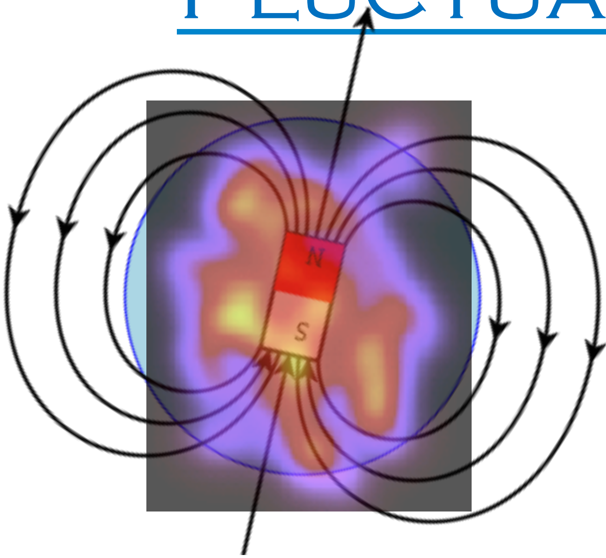


From STAR @ QM2012

The predicted flow splitting is found by STAR in quantitative agreement!

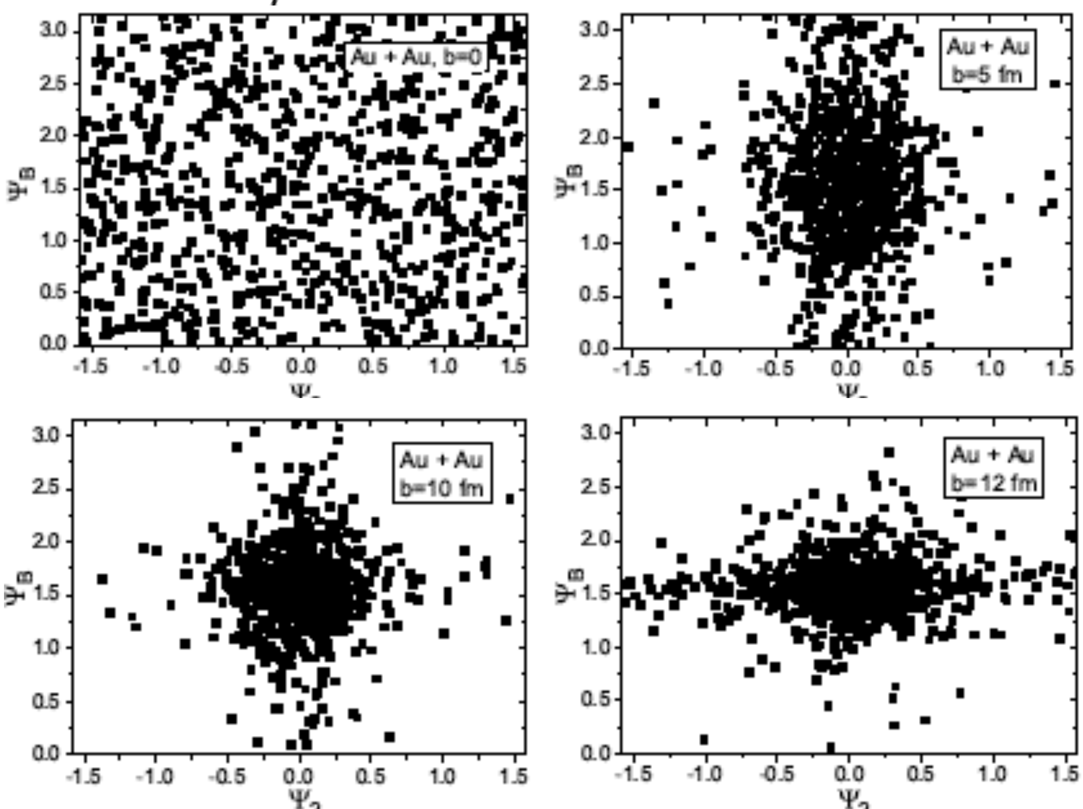
Burnier, Kharzeev, JL, Yee, arXiv:1103.1307[PRL2011]; arXiv:1208.2537

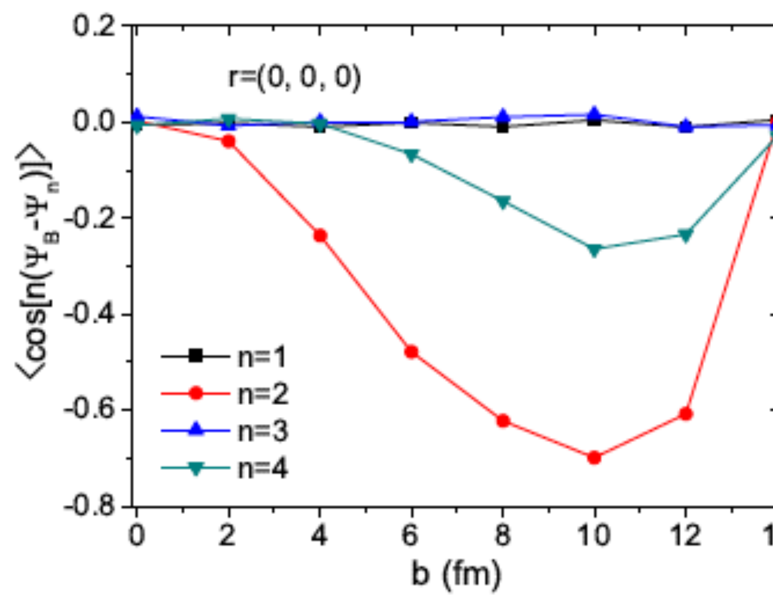
Fluctuating B-field & Matter



Fluctuations in both the
MATTER GEOMETRY
and the
B FIELD STRENGTH AND DIRECTION
(important for measuring/interpreting all the B-field related effects!)

$$\Psi_B - \Psi_2$$





Strong "mismatch" in very central and very peripheral collisions!

Bloczynski, Huang, Zhang, JL, arXiv:1209.6594

Summary: Strongly Interacting Matter

Matter becomes strongly interacting upon collapse of all these scales

$$E \sim E_D \sim E_M$$

(1) When a weakly-coupled system is brought far away from equilibrium → f ~ 1/g^2:

weakly coupled but strongly interacting as an emergent property

--- this is the case for the pre-equilibrium glasma and may hold the key of thermalization

- Important role of initial overpopulation identified and demonstrated to be essential for thermalization
- Kinetic approach developed and scaling solutions found
- Dynamical Bose condensation predicted, understood, and shown to be very robust
- Glasma production of photons and dileptons may explain "excess"

(2) When the coupling itself becomes strong g→ 1

strongly coupled, and expect change into emergent degrees of freedom

--- this is the case for the matte near Tc, T→ Tc ~ Lambda_QCD and thus a thermal sQGP

- Emergent monopole plasma near Tc and their condensation leads to confinement
- Naturally explains the fermion influence on confinement transition via zero modes
- Strongly enhanced jet quenching in near Tc matter that is essential for explaining the medium opaqueness evolution and jet quenching anisotropy and hard-soft correlation
- Progresses in search of topological effects

"More is different", and more progress to come soon!

Publication in the Past Year

- **arXiv:1202.3679** --- EM emission in pre-equilibrium matter [with Chiu, Hemmick, Khachatryan, Leonidov, McLerran]
- **arXiv:1210.1245;**
  arXiv:1208.6361;
  arXiv:1202.1047[PLB]
  --- jet quenching [with Zhang]
- **arXiv:1206.3989[PRL]** --- confinement [with Shuryak]
- **arXiv:1208.2537** --- Chiral Magnetic Wave [with Burnier, Kharzeev, Yee]
- **arXiv:1209.6594** --- fluctuating geometry and B field [with Bloczynski, Huang, Zhang]
- **arXiv:1207.7327** --- invited review on charge-dependent correlatiosn & CME [with Bzdak, Koch]
- Proceedings:
  arXiv:1210.6838[QM2012]; arXiv:1209.2998[NN2012];
  arXiv:1209.1052[CIPANP2012]
- Two more in final preparation:
  on Glasma transport [with Blaizot, McLerran]
  on baryonic susceptibilities in holography [with Shi]

RBRC Workshop: CPODD2012

- Thanks for RBRC support
- Organizers: Kharzeev, Liao, Shuryak, Yee
- 3 days June 25-27
- 68 registered attendees
- 34 talks covering interdisciplinary topics
- vibrant discussions and important progresses

http://www.bnl.gov/pcp2012/

POETIC2012 Workshop

International Workshop on

Physics
Opportunities
@ an
ElecTron
Ion Collider
(POETIC 2012)

August 20-22, 2012
Bloomington, IN, USA

Organizers:
K. Hafidi, M. Lamont, J. Liao,
T. Londergan, W. Melnitchouk,
A. Szczepaniak, R. Venugopalan,
W. Vogelsang, F. Yuan

http://www.indiana.edu/~ntceic/

I gratefully acknowledge
the generous & essential
support from RBRC.

My particular thanks to
Larry, Rob, and Nick
for support, advices, and encouragement.

Thank you all !

Computing Group

Overview

Taku Izubuchi

RIKEN BNL Research Center

BROOKHAVEN NATIONAL LABORATORY

RIKEN

RBRC Scientific Review Committee Meeting 2012/11/8

Contents

- Organization
- Overview of past years (other than physics)

- muon anomalous magnetic moment $(g-2)_\mu$
- Other Intensity Frontier quantities
- A new class of error reduction techniques (AMA)

- Summary

Computing Group

- Group Leader : Taku Izubuchi (BNL)
- University Fellow : Brian Tiburzi (CCNY)
- Fellow : Tomomi Ishikawa
- PostDocs : Christoph Lehner (Foreign PostDoc) → BNL from 2013
  Eigo Shintani
  (C. Kelly, S. Seryzin FPR from 2013)
- Visiting students :

  Michael Abramczyk (Connecticut)
  Taichi Kawanai (Tokyo)

- Visiting scientists :

  Yasumichi Aoki (Nagoya)
  Thomas Blum (Connecticut)
  Chulwoo Jung (BNL)
  Meifeng Lin (Yale → Boston)
  Robert Mawhinney (Columbia)
  Shigemi Ohta (KEK)

Computing Group Collaborations

- RIKEN-BNL Research Center

  2 fellows, 2 PostDocs
  + visiting scientists / students

  RIKEN BNL Columbia (RBC) Collaboration (1998-)

- Columbia University
  2 faculty, 1 PostDoc,
  7+2 Students

- University of Connecticut
  1 faculty, 1 Students

- BNL HEP Theory
  3+1 scientists, 1+2 PostDocs,
  1 student (SciDAC, LDRD, JSPS)

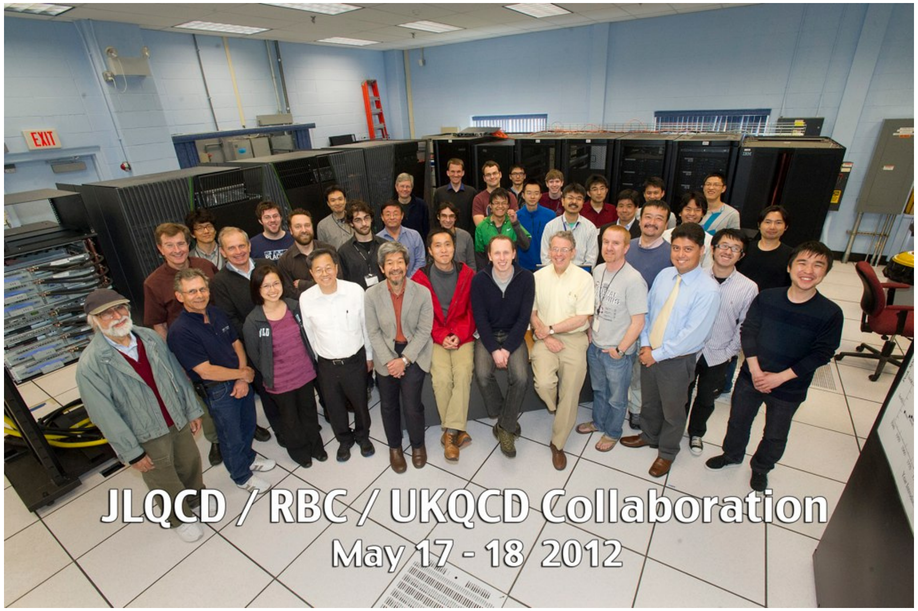
- BNL LG Theory
  3 scientists, 3+1 PostDocs (SciDAC)

15 current students,
~22 PhD theses since 2005

- + UKQCD Collaboration (2005-)
  - Univ. of Edinburgh
    1 faculty, 2 PostDocs, 2+1 students
  - Univ. of Southampton
    3 faculty, 2+1 Postdoc, 4 students

- + JLQCD (2012- , collaborating for physics measurement methods)
  - KEK, Tsukuba & Osaka Univ

(# of personnel: accumulation of last 3 years)
(#(current) + #(just left, but still collaborating))



RIKEN RICC ('09) ~ 110 Tflops peak

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

RBRC Computing

RIKEN/ Nishina

BNL

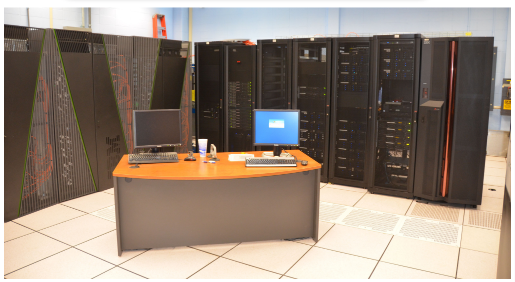
HEP/NP/LGT

US Universities
Columbia
Connecticut
CCNY (Colorado)

IBM

RIKEN-BNL Research Center

UKQCD
Edinburgh Southampton
JLQCD
KEK, Tsukuba



QCDCQ('12) ~ 600Tflops peak

NYBlue('07)~ 130 Tflops peak

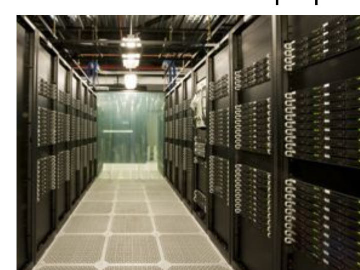
NYCCS

CCS/ITD

USQCD

ANL Mira ('12) ~100 Pflops peak

FNAL/Jlab ~ 160 Tflops peak

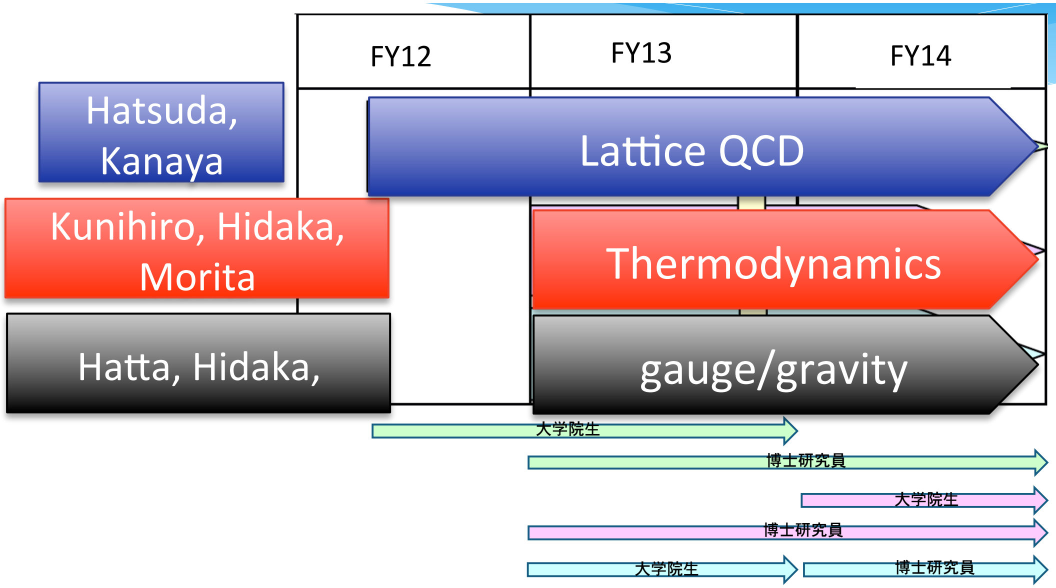


2.5 years Visiting program between BNL Theory groups and Tsukuba, Kyoto, RIKEN/Wako,

✔ クォーク・ハドロン分野で世界最大の理論グループ
かつ極めて高い研究実績　http://thy.phy.bnl.gov/

BNL側受入代表： R. Venugopalan博士

高エネルギー理論グループ	18名	(リーダー A. Soni博士)
格子ゲージ理論グループ	8名	(リーダー F. Karsch博士)
原子核理論グループ	12名	(リーダー R. Venugopalan博士)
計算物理グループ(RBRC)	7名	(リーダー T. Izubuchi博士)
理論物理グループ(RBRC)	14名	(リーダー L. McLerran博士)



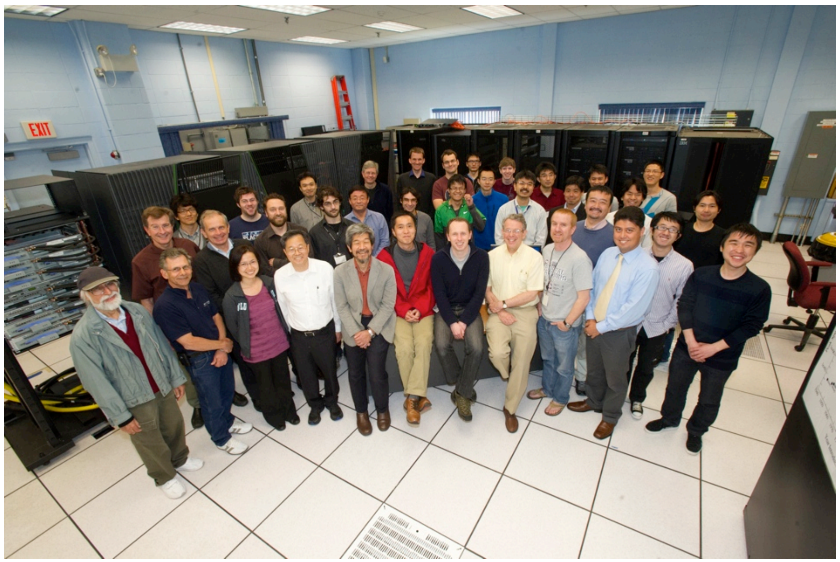
[T. Hatsuda]

Past years : (some of) plenary talks / invited lectures

- LATTICE 2011
  - Eigo Shintani, "Determination of α_s from lattice QCD"
  - Robert Mawhinney, "Direct and Indirect Kaon Physics Directly Below KT-22: A Lattice 2011 Review"
- LATTICE 2012
  - Taku Izubuchi, "Lattice QCD+QED – from Isospin breaking to g-2 light-by-light"
  - Norman Christ, "Calculating the two-pion decay and mixing of neutral K mesons"
  - Thomas Blum, "Hadronic contributions to the muon g-2"
- Chiral Dynamics 2012
  - Taku Izubuchi, "Isospin breaking studies from lattice QCD+QED"
- INT Summer School on Lattice QCD for Nuclear Physics
  - Brian Tiburzi, "Chiral Perturbation Theory"
  - Taku Izubuchi, "Lattice QCD+QED"
- press releases
  (QCDOC, $K \to \pi\pi$, QCDCQ)
- 2012 Ken Wilson Lattice Awards

Past years: workshops/meeting organizations, etc.

- RBRC Workshop, "New Horizons for Lattice Computations with Chiral Fermions", May 14-16, 2012, Thomas Blum, Tomomi Ishikawa, Taku Izubuchi, Amarjit Soni
- JLQCD/RBC/UKQCD collaboration meeting, BNL, May 17-18, 2012, Shoji Hashimoto, Taku Izubuchi, Peter Boyle




- USQCD
  Executive Committee : Norman Christ
  Scientific Program Committee : Taku Izubuchi
- XSEDE
  Resources Allocation Committee : Thomas Blum, Robert Mawhinney
- Thomas Blum : Convener/Coorganizer of INT Workshop on the Hadronic Light by Light contribution to muon anomaly, New Frontiers in Lattice Gauge Theory (Florence, GGI), Project X Summer Study (Lattice QCD Working Group), Snowmass Meeting: Computational Frontier (Lattice QCD subgroup)
- LATTICE 2014 at Columbia, Robert Mawhinney, Norman Christ

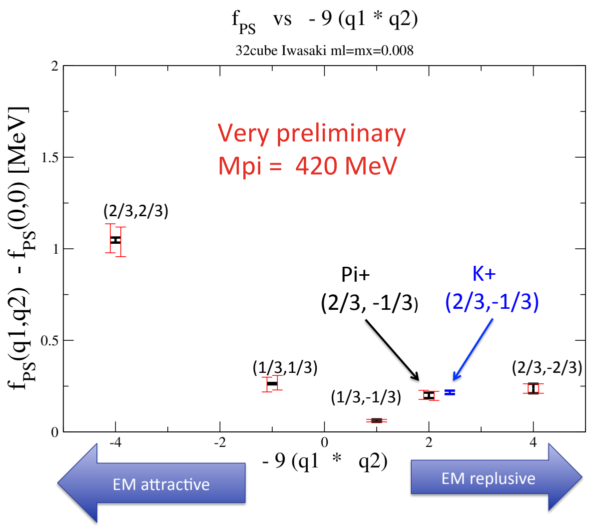
Physics Highlights

- K→ππ I=2 & I=0, $\Delta M(K_L - K_S)$ [Norman Christ]
- QCDOC → QCDCQ : on-physics point (Mπ=135 MeV) large volume ~$(5\ \mathrm{fm})^3$, QCD ensembles with DWF
  [Robert Mawhinney]
- QCD + Electromagnetism :
  Hadron's polarizabilities [Brian Tiburzi]
  QCD + dynamical QED [Tomomi Ishikawa]
- Nucleon Electric Dipole Moments
  [Eigo Shintani]
- CKM (K & B), Computer Algebra System for perturbation
  [Christoph Lehner]

QCD+QED simulation

[T. Blum, TI et al.]   [Tomomi Ishikawa's talk]

- EM effects on PS decay

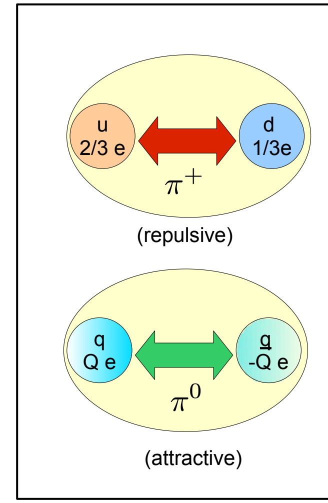


- Statistically well resolved by +e/-e averaging.
- c.f. [Bijnens Danielsson 2006]

$$f_{\pi^+,\mathrm{NLO}}/F_0 = 0.0039$$

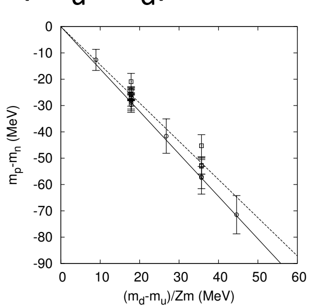
$$f_{K^+,\mathrm{NLO}}/F_0 = 0.0056$$

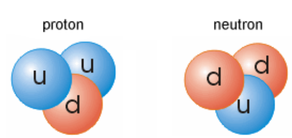
- EM turned on, but mu = md
- Iwasaki-DWF Nf=2+1,
- (2.7 fm)^3, a^{-1} ~ 2.3 GeV



- Proton / Neutron mass difference

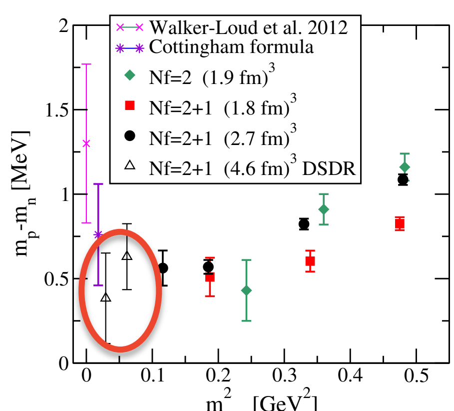
(m_u-m_d) effect





DSDR DWF Nf=2+1
(4.6 fm)^3,
a^{-1} ~ 1.4 GeV

EM effect



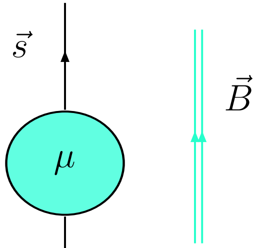
	$m_u - m_d$	EM
NPLQCD	2.26(72)	
BLUM	2.51(71)	0.54(24)
RM123	2.80(70)	
QCDSF-UKQCD	3.13(77)	
	2.68(35)	0.54(24)

$$\Longrightarrow M_N - M_p| = 2.14(42) \ \ \mathrm{MeV}$$

(experiment: 1.2933321(4) MeV)

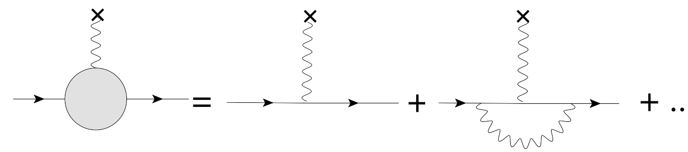
Muon anomalous magnetic moment

[T. Blum, T. Ishikawa, TI, E. Shintani et al.]



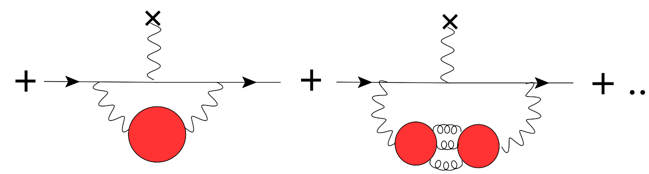
$E = -g_\mu \frac{e}{2m_\mu} \vec{s} \cdot \vec{B}$

$$a_l = \frac{g_l - 2}{2}$$

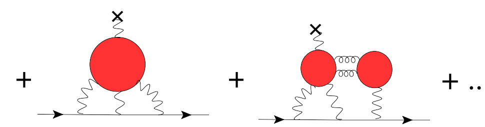


QED (5-loop)

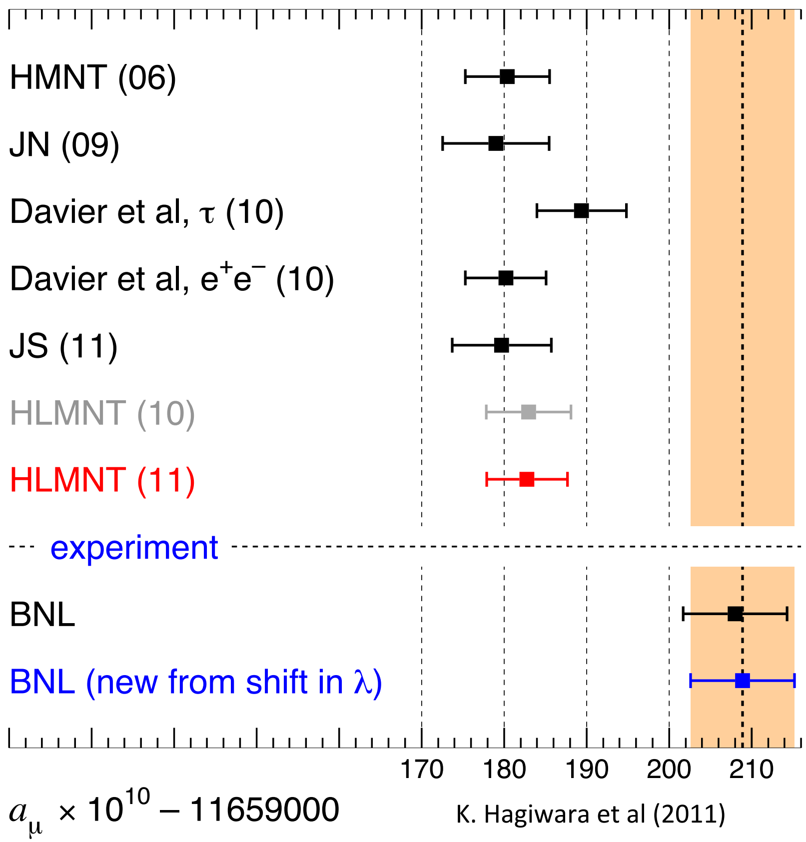
$1/\alpha$ = 137.035 999 166 (34) [Aoyama et al. (12)]



Hadronic Vacuum Polarization (HVP)



Hadronic Light-by-light (HLbL)



$$a_\mu^{\rm SM} = (11 \quad 659 \quad 182.8 \quad \pm 4.9 \quad) \times 10^{-10}$$

$$a_\mu^{\rm QED} = (11 \quad 658 \quad 471.808 \quad \pm 0.015 \quad) \times 10^{-10}$$
$$a_\mu^{\rm EW} = (\quad 15.4 \quad \pm 0.2 \quad) \times 10^{-10}$$
$$a_\mu^{\rm had,LOVP} = (\quad 694.91 \quad \pm 4.27 \quad) \times 10^{-10}$$
$$a_\mu^{\rm had,HOVP} = (\quad -9.84 \quad \pm 0.07 \quad) \times 10^{-10}$$
$$a_\mu^{\rm had,lbl} = (\quad 10.5 \quad \pm 2.6 \quad) \times 10^{-10}$$

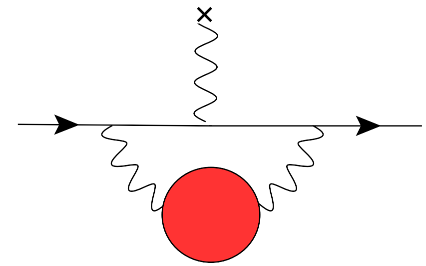
FNAL E989, J-PARC aim for x 4-5 accuracy

$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$ ~3 σ discrepancy

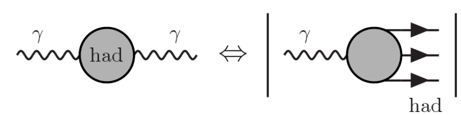
Hadronic Vacuum Polarization

- Currently estimated by σ (e+e-)
  <u>0.6 % accuracy</u>

$$a_\mu^{\rm HVP} = \frac{1}{4\pi^2}\int_{4m_\pi^2}^{\infty} ds K(s)\sigma_{\rm total}(s)$$



$$a_\mu^{\rm had,LOVP} = (\; 694.91 \;\; \pm 4.27 \;) \times 10^{-10}$$
$$a_\mu^{\rm had,HOVP} = (\; -9.84 \;\; \pm 0.07 \;) \times 10^{-10}$$

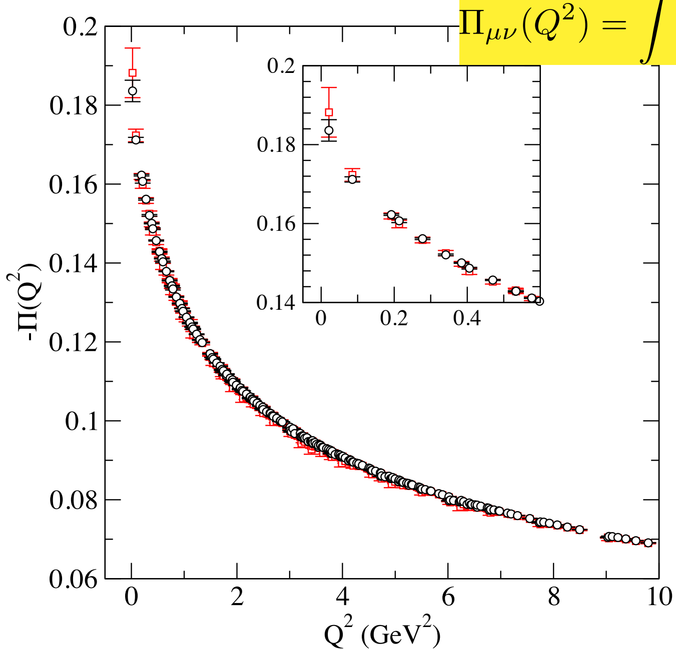


- Lattice calculation [T.Blum (2003)]

$$\Pi_{\mu\nu}(Q^2) = \int dx \langle V_\mu(x)V_\nu(0)\rangle e^{-q(x-y)}$$

$$a_\mu^{\rm HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2)\Pi(Q^2)$$

$$\Pi_{\mu\nu}(Q) = \left(g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2}\right)\Pi(Q^2)$$



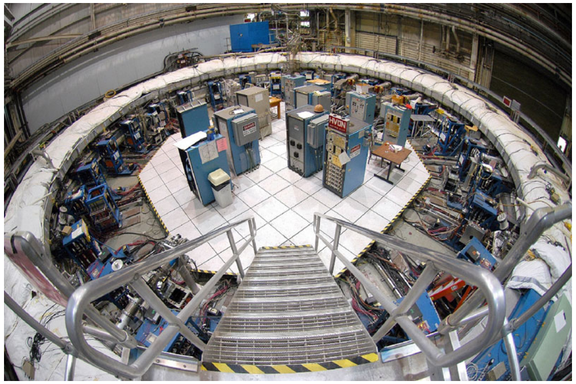
- Use new error reduction technique All Mode Averaging (AMA) <u>x 4- 20 improvements</u>
  [T.Blum, TI, E. Shintani (2012)]

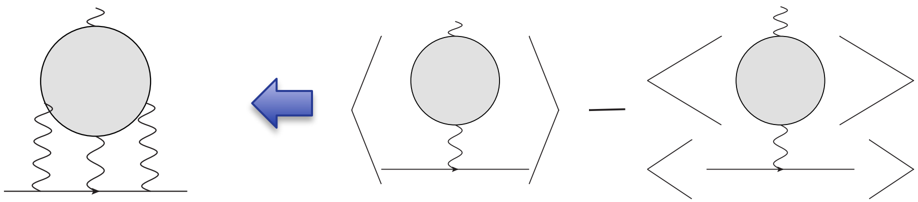
- accurate π(Q^2) at $Q^2 \to 0$ is needed :
  twisted boundary condition and/or Analytic continuation to Minkowski momentum

to be competitive : O(5-10%) → < O(1%)

Hadronic light-by-light
[T. Blum LAT12]

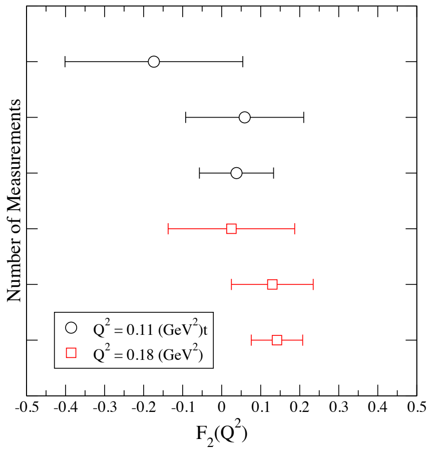
- Compute whole diagram using lattice QCD+QED
- LbL is a part of O(α 3) : need subtraction
  [M. Hayakawa, T.Blum, TI, N. Yamada (2005)]





The First signal (preliminary) using AMA

$F_2(Q^2)$ stable with additional measurements ($20 \to 40 \to 80$ configs)

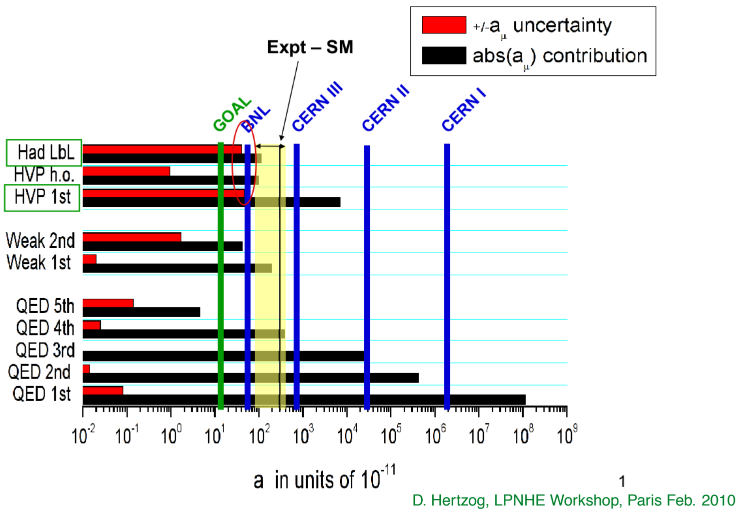


24^3 lattice size

$Q^2 = 0.11$ and $0.18\ GeV^2$

$m_\pi \approx 329$ MeV

$m_\mu \approx 190$ MeV

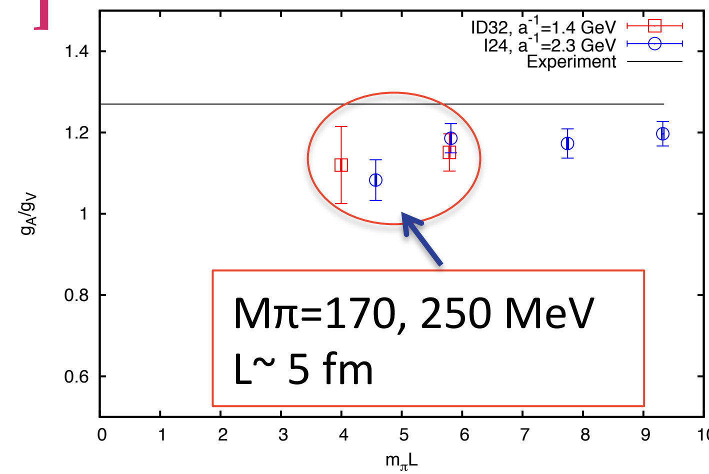


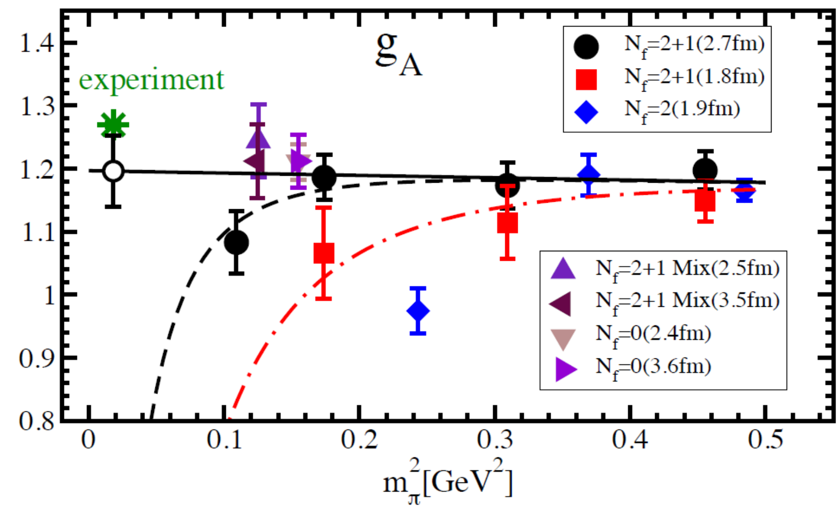
- Very encouraging first results
  order of mag ~ model
- Unphysical mass / momentum
- Disconnected diagrams

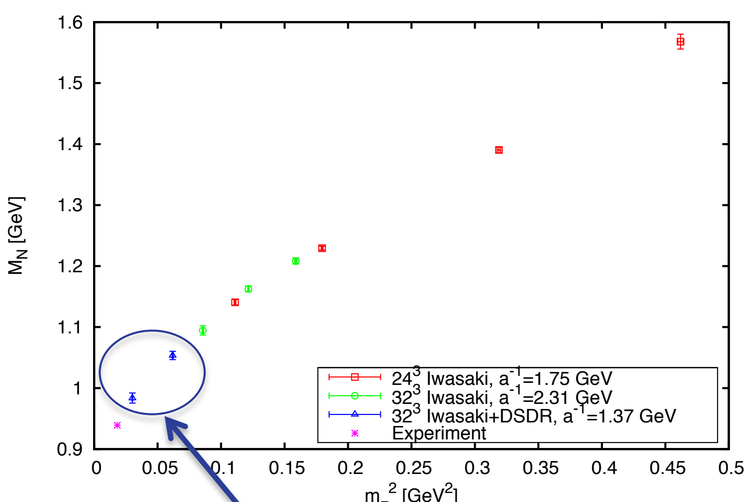
Nucleon calclations

[Meifeng Lin, Y. Aoki, T.Blum, TI, C. Jung, S. Ohta E. Shintani]

- Nucleon axial charge g_A
  - Finite Volume Effect ?
  - Excited contamination ?
- Strangeness in Nucleons $\langle N|\bar{q}q|N\rangle$
  [C. Jung]
- Proton Decay Matrix Elements
  [Y. Aoki, E. Shintani, TI. A. Soni]
- Nucleon Electric Dipole Moment
  [Eigo Shintai's talk]







Mπ=170, 250 MeV
L~ 5 fm

- Advantages of chiral lattice quark
- More demanding calculations
- limited by statistical error

A new class of error reduction CAA/AMA

- Many interesting physics are limited by statistical error

$$\mathrm{err} \approx C \times \frac{1}{\sqrt{N_{\mathrm{meas}}}}$$

- Do more number of measurements, N_{meas}

- Change to observable with smaller fluctuation, C

- Covariant Approximation Averaging (CAA)
  Combine the above using
  - symmetries of the lattice action
  - (crude) approximations

Covariant Approximation Averaging (CAA)

- Original observable $\mathcal{O}$

- Covariant approximation of the observable $\mathcal{O}^{(\mathrm{appx})}$ under a lattice symmetry $g \in G$

$$\langle \mathcal{O}^{(\mathrm{appx})} \rangle = \langle \mathcal{O}^{(\mathrm{appx}),g} \rangle$$

- Unbiased improved estimator

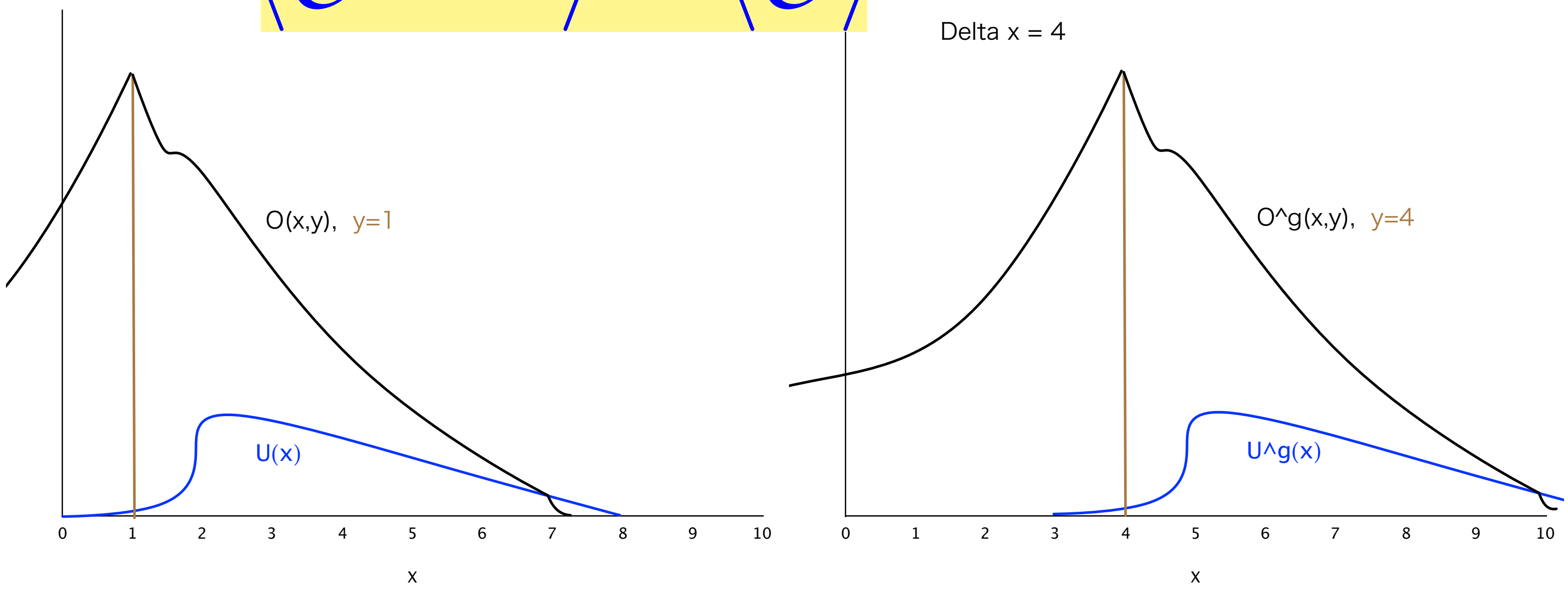
$$\mathcal{O}^{(\mathrm{rest})} = \mathcal{O} - \mathcal{O}^{(\mathrm{appx})}$$

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

Covariant approximation

- $O^{(appx)}$ needs to be precisely (to the numerical accuracy required) covariant under the symmetry of lattice action to avoid systematic errors.

$$\langle \mathcal{O}^{(\mathrm{imp})} \rangle = \langle \mathcal{O} \rangle$$



One should check in the code using explicitly shifted gauge configuration

Why expect improvements ?

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

Lattice Symmetry

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

Expensive : infrequently measured

Cheap : frequently measured

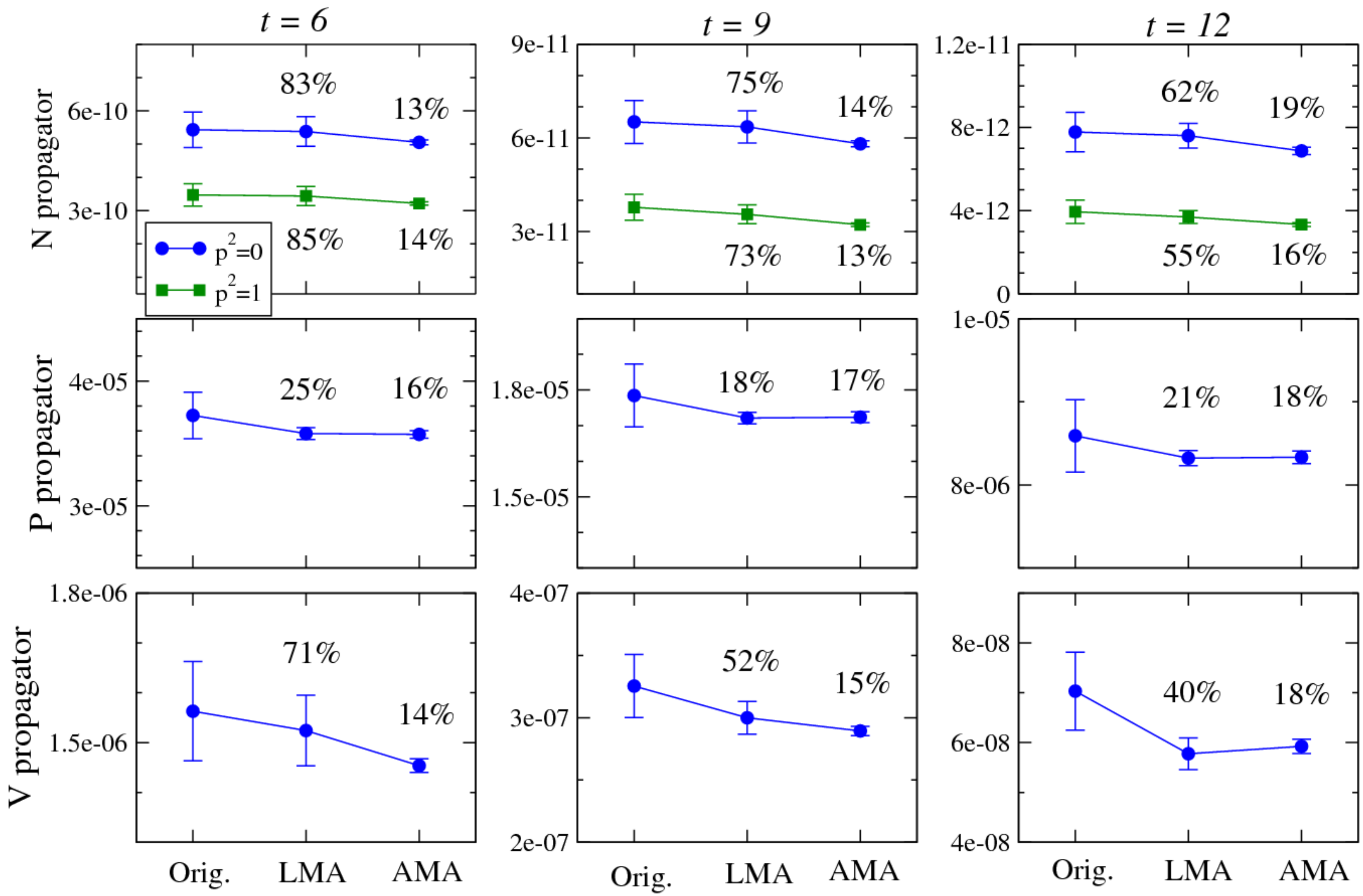
- $O^{(\mathrm{imp})}$ has smaller error, smaller C
  <= accuracy of approximation controls error,
  need not to be too accurate

  N_G suppresses the bulk part of noise cheaply

$$\mathrm{err} \approx C \times \frac{1}{\sqrt{N_{\mathrm{meas}}}}$$

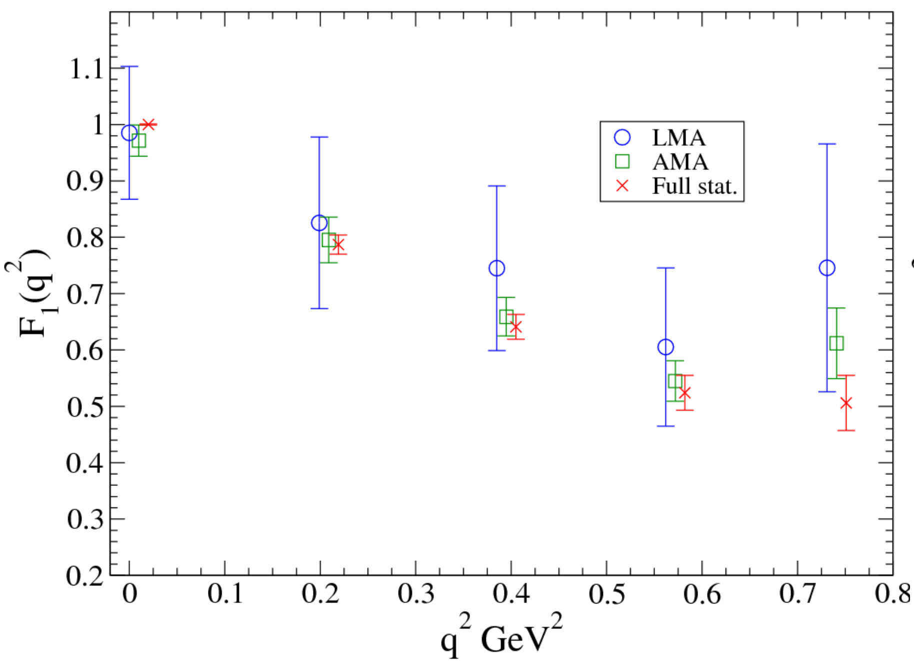
Valence version of Hasenbushing in HMC

AMA results for hadron 2pt functions [E. Shintani]

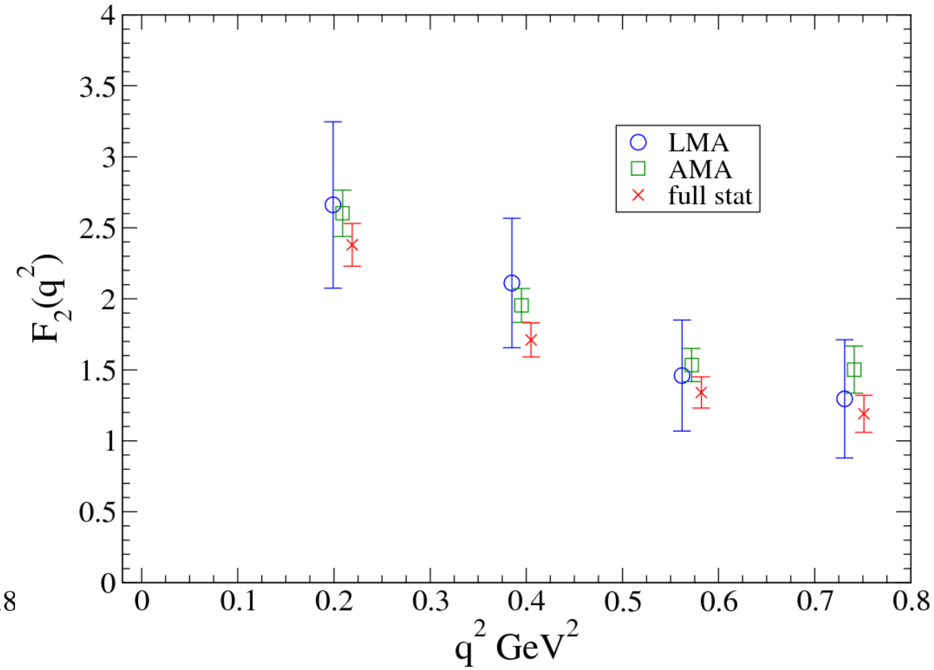


Comparison of isovector $F_{1,2}$ [E. Shintani]

m=0.01



m=0.01



- Results are well consistent with full statistics.
- Statistical error is much reduced in AMA rather than LMA.
- Compared to full statistics, AMA results (m=0.01) have still 1.2 -- 1.5 times larger statistical error (except for $F_1(0)$).
- This may be due to correlation between different source points.

Cost comparison for test cases

- x 16 for DWF Nucleon mass (M_{PS}=330MeV, 3fm)
- x 2- 20 for AsqTad HVP (MPS=470 MeV, 5 fm)
- should be better for lighter mass & larger volume !

	N_{conf}	N_{meas}	LM	$\mathcal{O}$	$\mathcal{O}_G^{(\text{appx})}$	Tot.	scaled cost	
m_N	$m = 0.005$, 400 LM						gauss	pt
AMA	110	1	213	18	91+23	350	0.063	0.065
LMA	110	1	213	18	23	254	0.279	0.265
Ref. [2]	932	4	-	3728	-	3728[a]	1	1
	$m = 0.01$, 180 LM							
AMA	158	1	297	74	300+22	693	0.203	0.214
LMA	158	1	297	74	22	393	0.699	0.937
Ref. [2]	356	4	-	1424	-	1424	1	1
HVP	$m = 0.0036$, 1400 LM						max	min
AMA	20	1	96	11	504+420	1031	0.387	0.050
LMA	20	1	96	11	420	527	10.3	3.56
Ref. [1]	292	2	-	584	-	584	1	1

✓ x 20 is observed more to expect
✓ Other type "approximations" Mobius fermion
✓ other quantities g-2, EDM, Nucleon Form Factors, K_L-K_S

Summary

- New Generation of QCD simulations
- On physics point (M_π=135 MeV) large volume~ (5 fm)^3 QCD ensembles are being generated to avoid systematic errors
- Unprecedented precisions < O(1%)
  EM corrections, EM Polarizabilities,
  quark masses, decay constants, B_K, B & D,
  $K\rightarrow(\pi\pi)_{I=2}$, (g-2) HVP, Proton decay, ….
- Unprecedented physics computations
  $K\rightarrow(\pi\pi)_{I=0}$, $\Delta M(K_L-K_S)$, Kaon rare decays,
  (g-2) LbL, EDM, Hadronic Parity Violation,….
- Enabling technologies
  New resources : QCDCQ, K computer, GPU, …. x 20
  New algorithms : AMA, A2A, Mobius, EigCG, … x 20

Multiple timestep in HMC

- Multiple time steps in MD integrators
- Sexton & Weingarten trick

- Hasenbusch trick : introduce intermediate mass

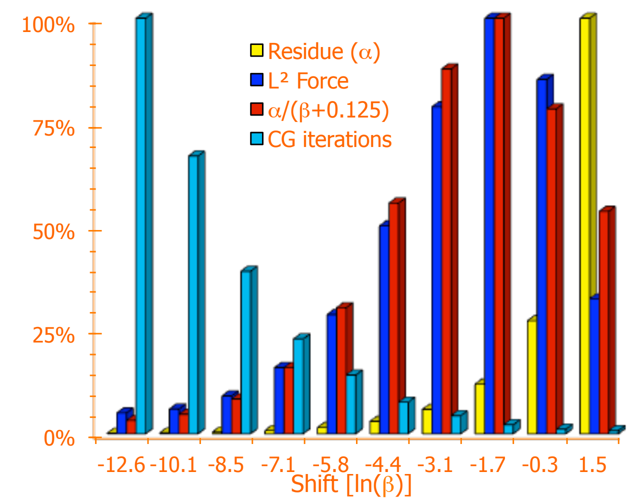
$$\det[D(m)] = \overbrace{\det[D(m_I)]}^{\text{cheap mode}} \times \overbrace{\det\left[D(m)D(m_I)^{-1}\right]}^{\text{expensive mode}}$$

- Clark & Kennedy RHMC (quotient force term)

Berlin Wall was torn down
by Smart Work Sharings

Similar tricks for valence ?

A. Kennedy 06



Unbiasness proof

- Consider a element g of lattice symmetry G e.g. $x_\mu \to x + \Delta x_\mu^{(g)}$
- transformation of fields

$$U_\mu(x) \to U_\mu^g(x) = U_\mu(x - \Delta x^{(g)})$$

$$\begin{aligned}\mathcal{O}[U_\mu] \to & \mathcal{O}^g[U_\mu^g](x_1, x_2, \cdots, x_n) \\ & = \mathcal{O}[U_\mu^g](x_1 - \Delta x^{(g)} x, x_2 - \Delta x^{(g)} x, \cdots, x_n - \Delta x^{(g)} x),\end{aligned}$$

- Observable (and its approximation) is called to have covariance under g iff

$$\mathcal{O}^g[U_\mu^g](x_1, x_2, \cdots, x_n) = \mathcal{O}[U_\mu](x_1, x_2, \cdots, x_n)$$

or, more explicitly,

$$\mathcal{O}[U_\mu^g](x_1 - \Delta x^{(g)}, x_2 - \Delta x^{(g)}, \cdots, x_n - \Delta x^{(g)}) = \mathcal{O}[U_\mu](x_1, x_2, \cdots, x_n) \quad .$$

- When g is a symmetry of lattice, and $O^{(appx)}$ is covariant $\langle \mathcal{O}^g \rangle = \langle \mathcal{O} \rangle$

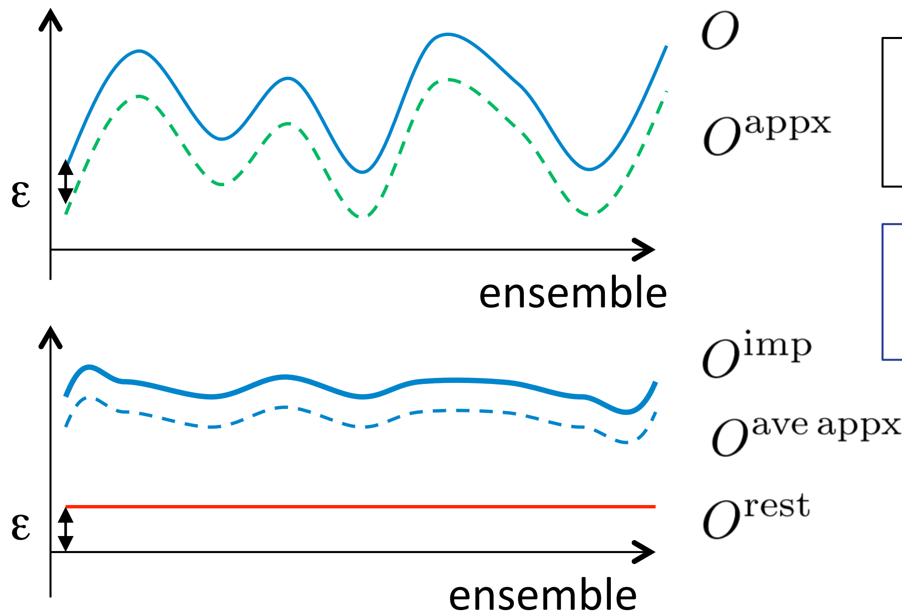
$$\mathcal{O}^{(\mathrm{rest})} = \mathcal{O} - \mathcal{O}^{(\mathrm{appx})}$$

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

$$\langle \mathcal{O}^{\mathrm{imp}} \rangle = \langle \mathcal{O} \rangle$$

AMA : a smart work sharing

- Ideal approximation



O^{appx} is <u>*strongly correlated*</u> with original one.

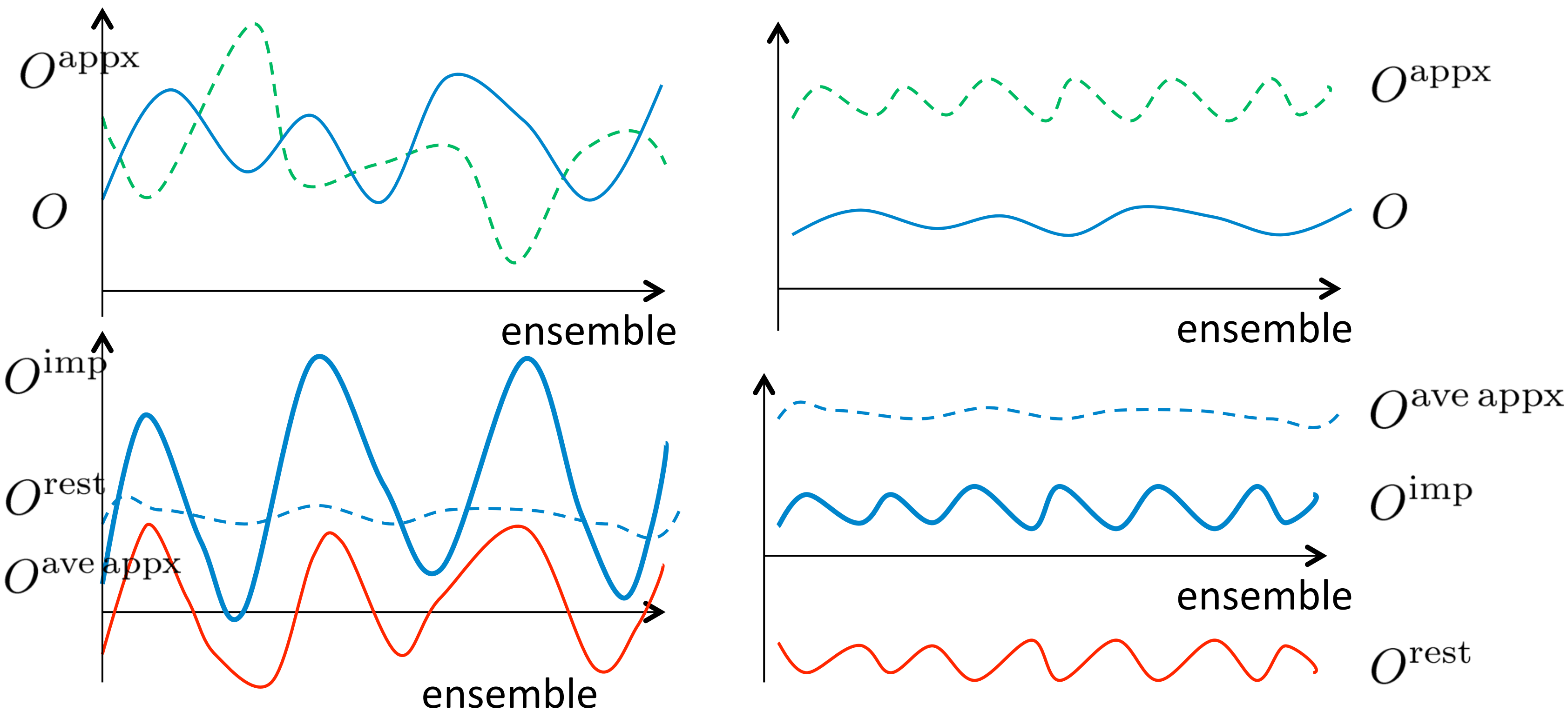
R(corr) b/w O and $O^{(appx)}$ needs to be larger than 0.5 [C. Lehner]

$$\mathrm{err}^{\mathrm{imp}} \simeq \mathrm{err}/\sqrt{N_g}$$

- ε, accuracy of approximation should be smaller than $O^{\text{ave appx}}$
- ΔO^{rest} which is statistical error of O^{rest} depends on the strength of correlation.
- The computational cost of O^{appx} should be much smaller than original.

AMA : not working

- Nightmare case
  - Anti-correlated or bad approximation



$$\mathrm{err}^{\rm imp} \gg \mathrm{err}$$

Examples of covariant approximations

- Low mode approximation used in the Low Mode Averaging (**LMA**)

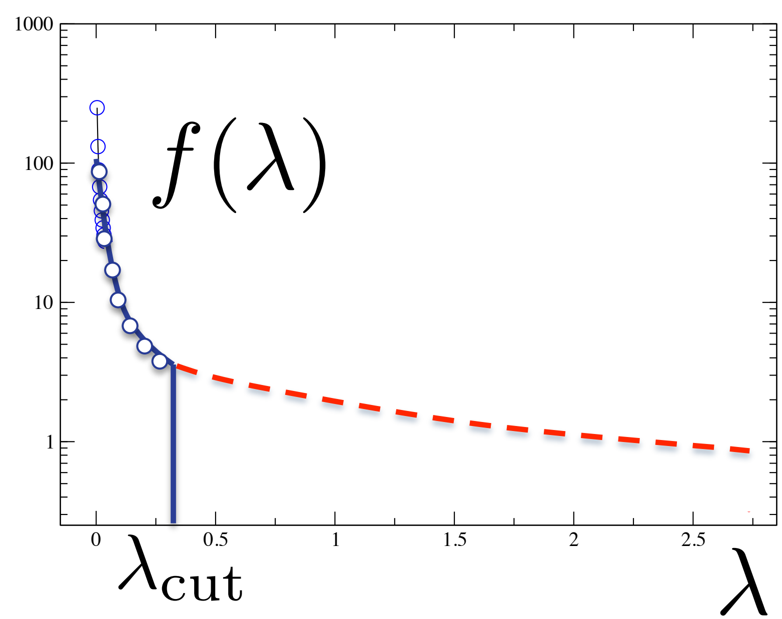
L. Giusti et al (2004), see also T. DeGrand et al. (2004)

accuracy control : # of eigen mode

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

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

$$f(\lambda) = \frac{1}{\lambda}\theta(\lambda_{\mathrm{cut}} - |\lambda|)$$



Deflation using low eigenmodes from Lanczos [Neff et al, JLQCD]

- 4D even/odd preconditioning

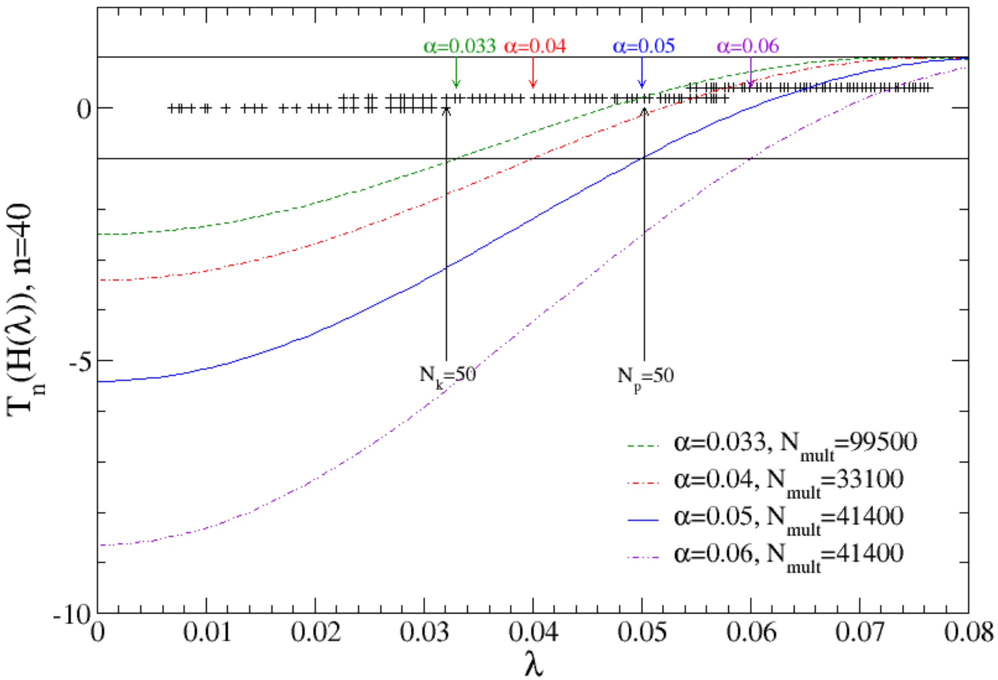
  [R. Arthur]

$$D_{DW} = \begin{pmatrix} M_5 & K(M_4)_{eo} \\ K(M_4)_{oe} & M_5 \end{pmatrix}$$

$$\begin{aligned} D_{DW}^{-1} &= \begin{pmatrix} 1 & 0 \\ -KM_5^{-1}(M_4)_{oe} & M_5^{-1} \end{pmatrix} \begin{pmatrix} D_{ee}^{-1} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -K(M_4)_{eo}M_5^{-1} \\ 0 & 1 \end{pmatrix} \\ D_{ee} &= M_5 - K^2(M_4)_{eo}M_5^{-1}(M_4)_{oe} \end{aligned}$$

- Polynomial accelerated
  P_n(H_DWF)
- With shift
  H-> H-c
- eigen Compression
  / decompression

$$\psi = v_1 + v_2$$
$$H(\psi) = \lambda_1 v_1 + \lambda_2 v_2$$



Low-mode decomposition

- 4D even-odd decomposition

$$D_{DW} = \begin{pmatrix} M_{5\,ee} & KM_{4\,eo} \\ KM_{4\,oe} & M_{5\,oo} \end{pmatrix}$$

M_5 : with 5D differential, 4D diagonal
M_4 : with 4D differential, 5D diagonal

$$= \begin{pmatrix} 1 & KM_{4\,eo}M_{5\,oo}^{-1} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} D_{ee} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ KM_{4\,oe} & M_{5\,oo} \end{pmatrix}$$

$$D_{ee} = M_5 - K^2 M_{4\,eo} M_{5\,oo}^{-1} M_{4\,oe}$$

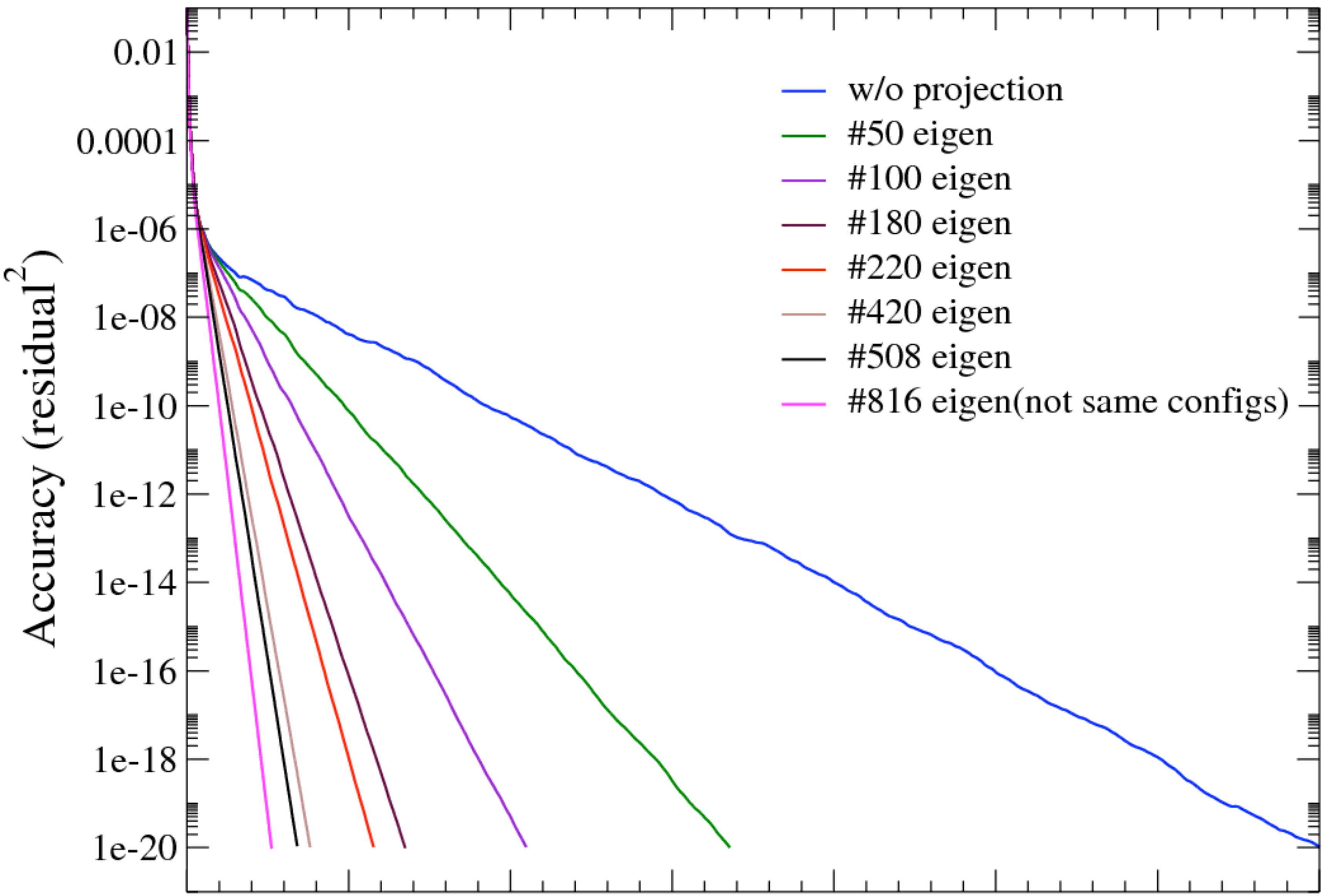
$$D_{DW}^{-1} = \begin{pmatrix} 1 & 0 \\ -KM_{5\,oo}^{-1}M_{4\,oe} & M_{5\,oo}^{-1} \end{pmatrix} \begin{pmatrix} D_{ee}^{-1} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -KM_{4\,eo}M_{5\,oo}^{-1} \\ 0 & 1 \end{pmatrix}$$

- Low mode decomposition

$$D_{ee}^{-1} = D_{\text{low}\,ee}^{-1} + D_{\text{high}\,ee}^{-1}$$

$$D_{\text{low}\,ee}^{-1} = H_{\text{low}\,ee}^{-2} D_{ee}^{\dagger} = \sum_k \frac{1}{\lambda_k^2} \psi_k (D_{ee}\psi_k)^{\dagger}, \quad H_{ee}\psi_k = \lambda_k \psi_k, \quad H_{ee} = \Gamma_5 D_{ee}$$

$$D_{\text{low}\,DW}^{-1} = \begin{pmatrix} 1 & 0 \\ -KM_{5\,oo}^{-1}M_{4\,oe} & M_{5\,oo}^{-1} \end{pmatrix} \begin{pmatrix} D_{\text{low}\,ee}^{-1} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -KM_{4\,eo}M_{5\,oo}^{-1} \\ 0 & 1 \end{pmatrix}$$



Accuracy (residual^2)
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
w/o projection
#50 eigen
#100 eigen
#180 eigen
#220 eigen
#420 eigen
#508 eigen
#816 eigen(not same configs)

Examples of Covariant Approximations (contd.)

- **All Mode Averaging AMA**

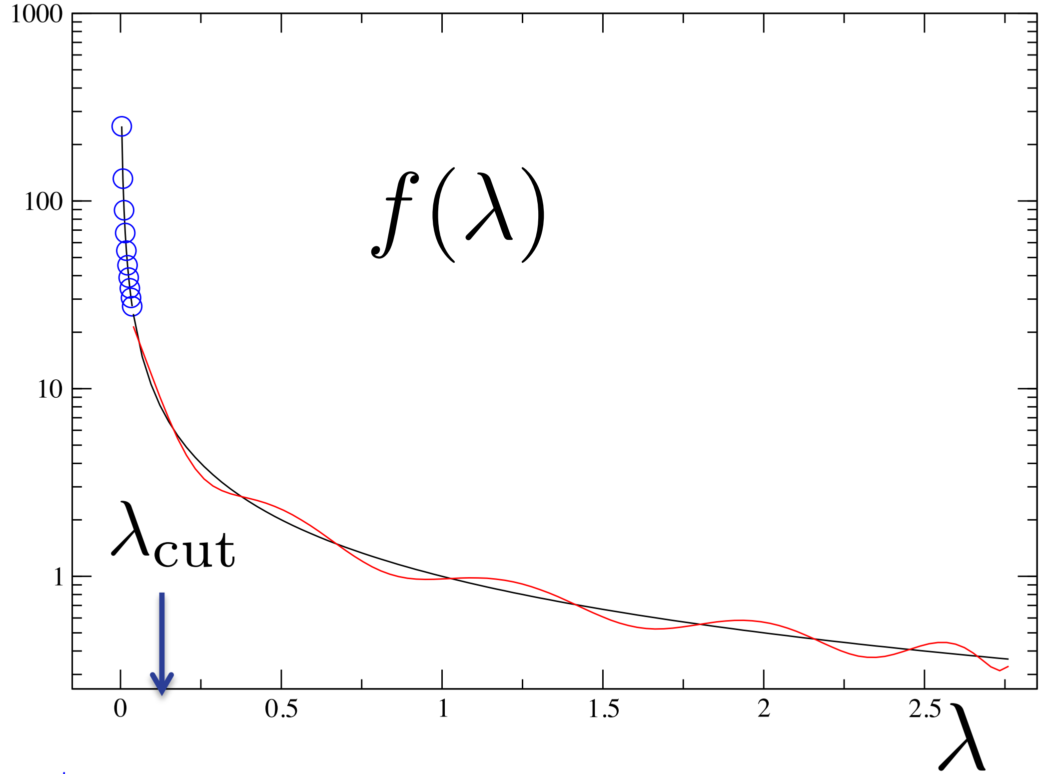
  Sloppy CG or Polynomial approximations

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

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

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

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

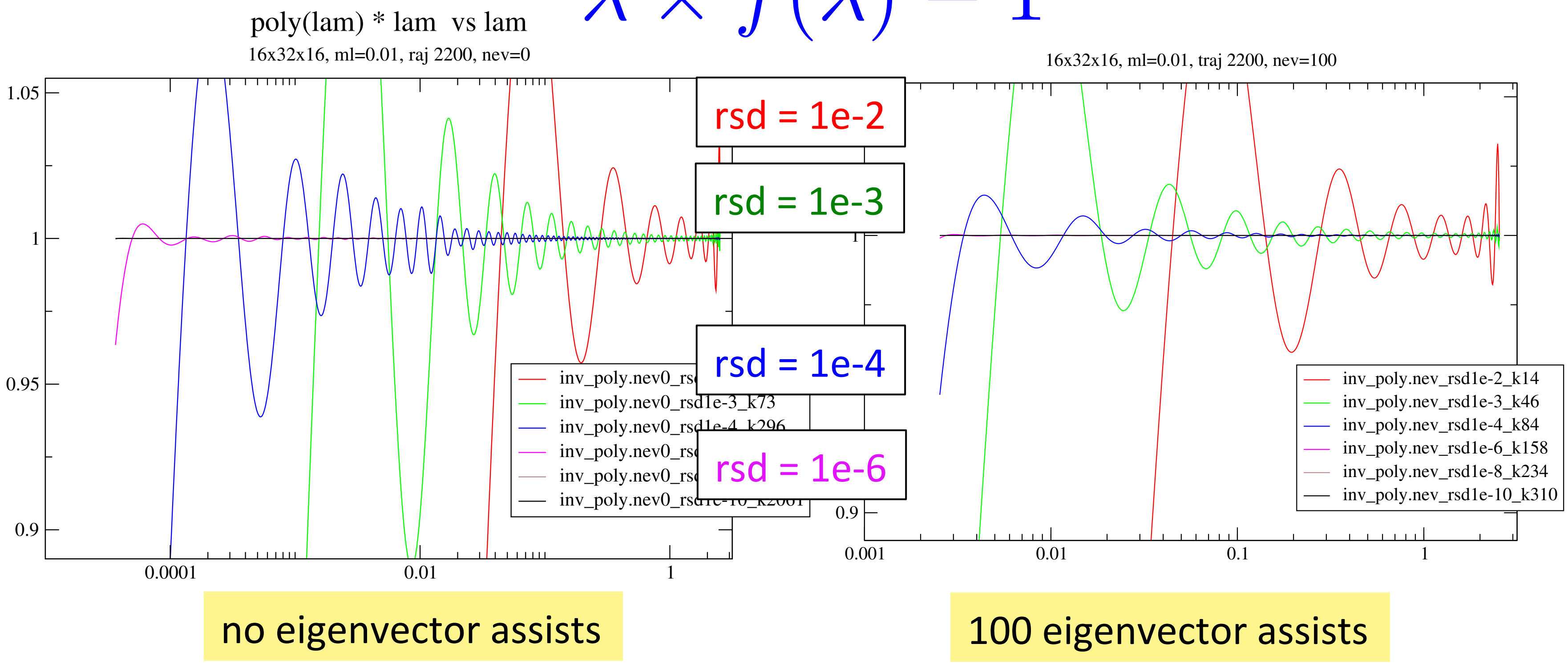


accuracy control :

- low mode part : # of eig-mode
- mid-high mode : degree of poly.

All mode approximation via sloppy CG

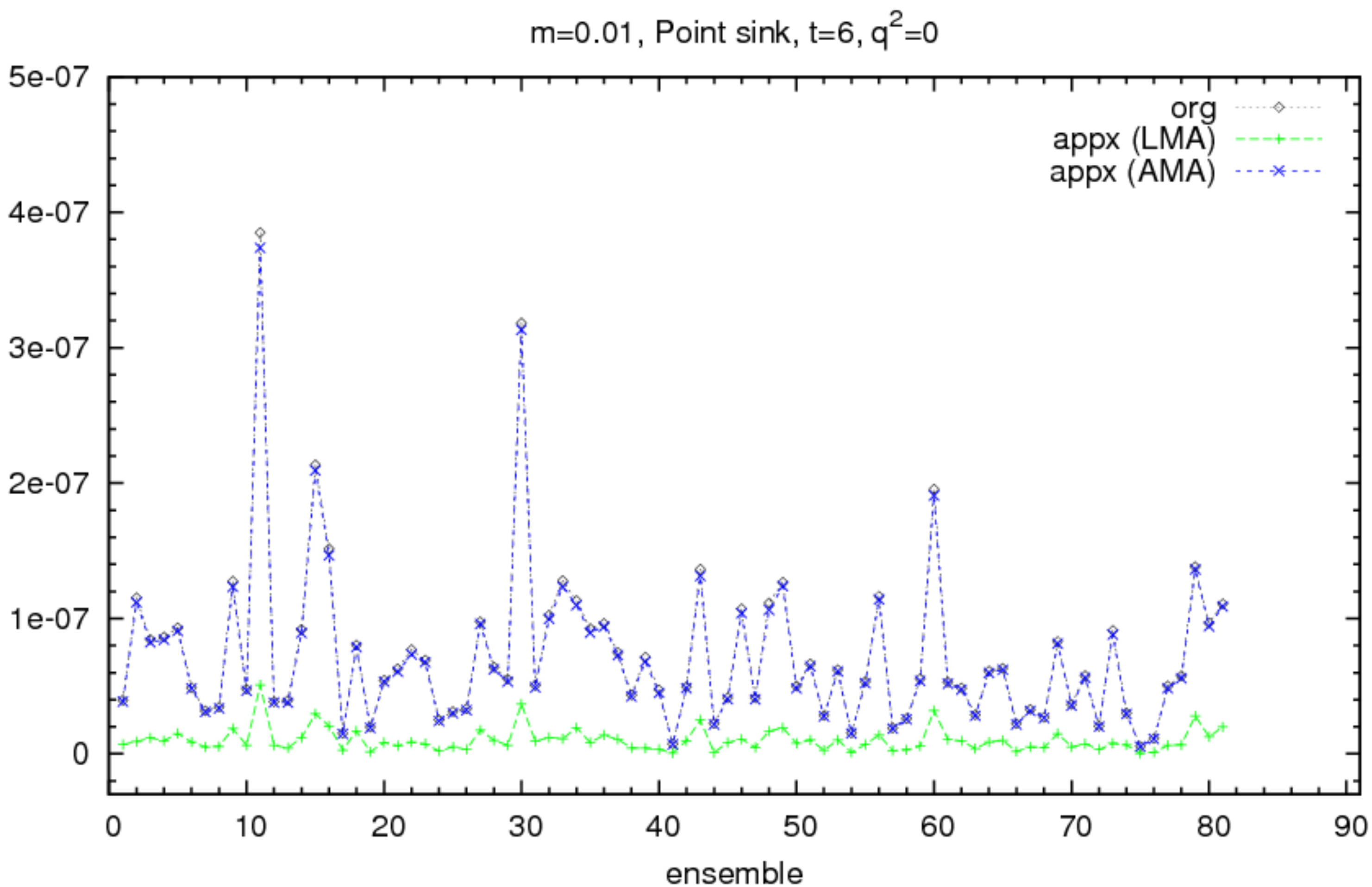
$$\lambda \times f(\lambda) - 1$$



- Conjugate residual with sloppy convergence criteria, which is equivalent to construct a polynomial approximating 1/λ
- The starting vector needs to be translation invariant to be a covariant approx.
- low eigenvectors reduces the size of the dynamic range of 1/λ
  - → Better approximation with smaller polynomial degrees
- low λ region has larger relative errors
- One could employ other construction of polynomial approximation for 1/λ, such as min-max, conjugate rasidual

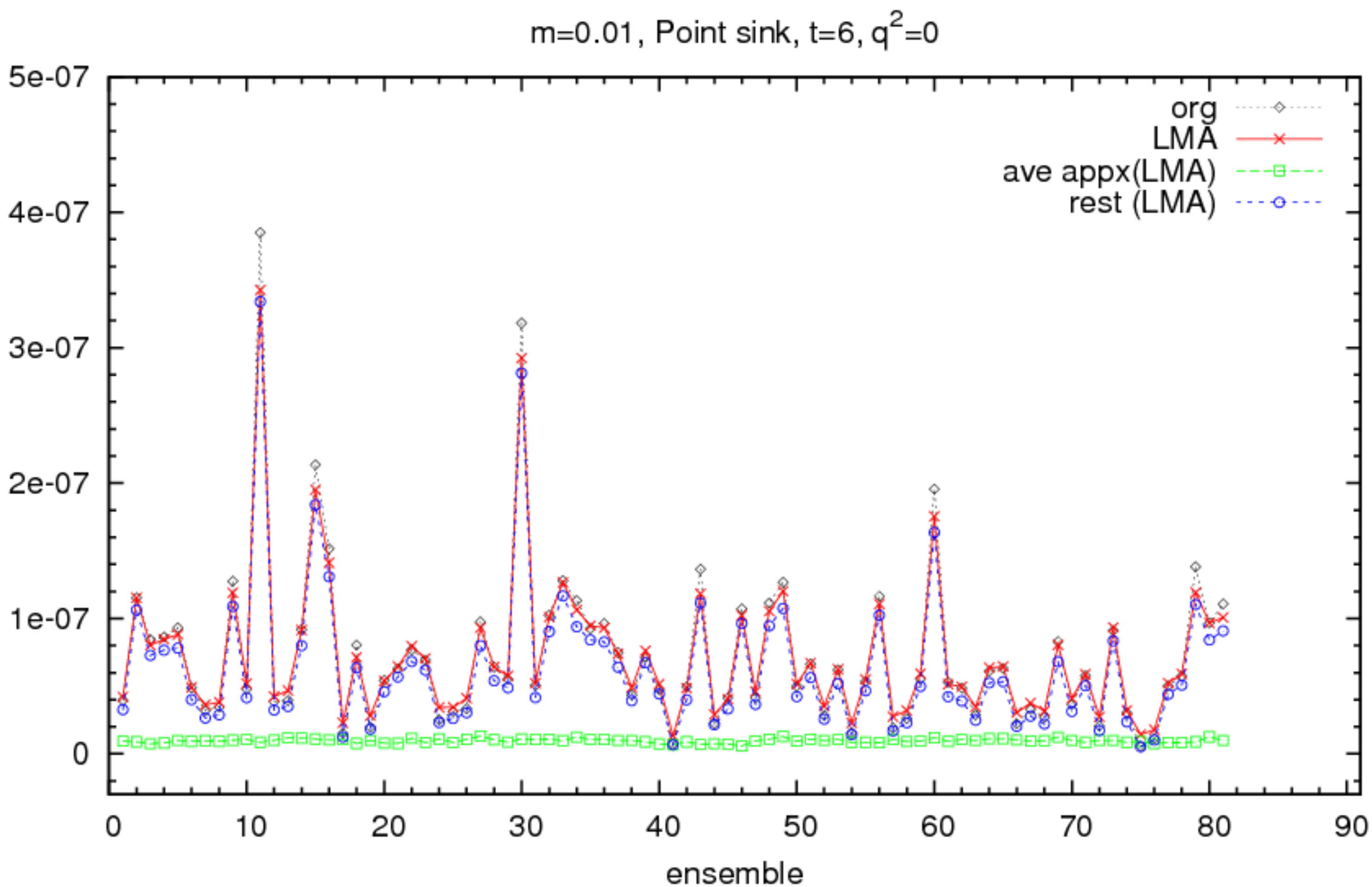
Correlation

- NN propagator at short time-slice



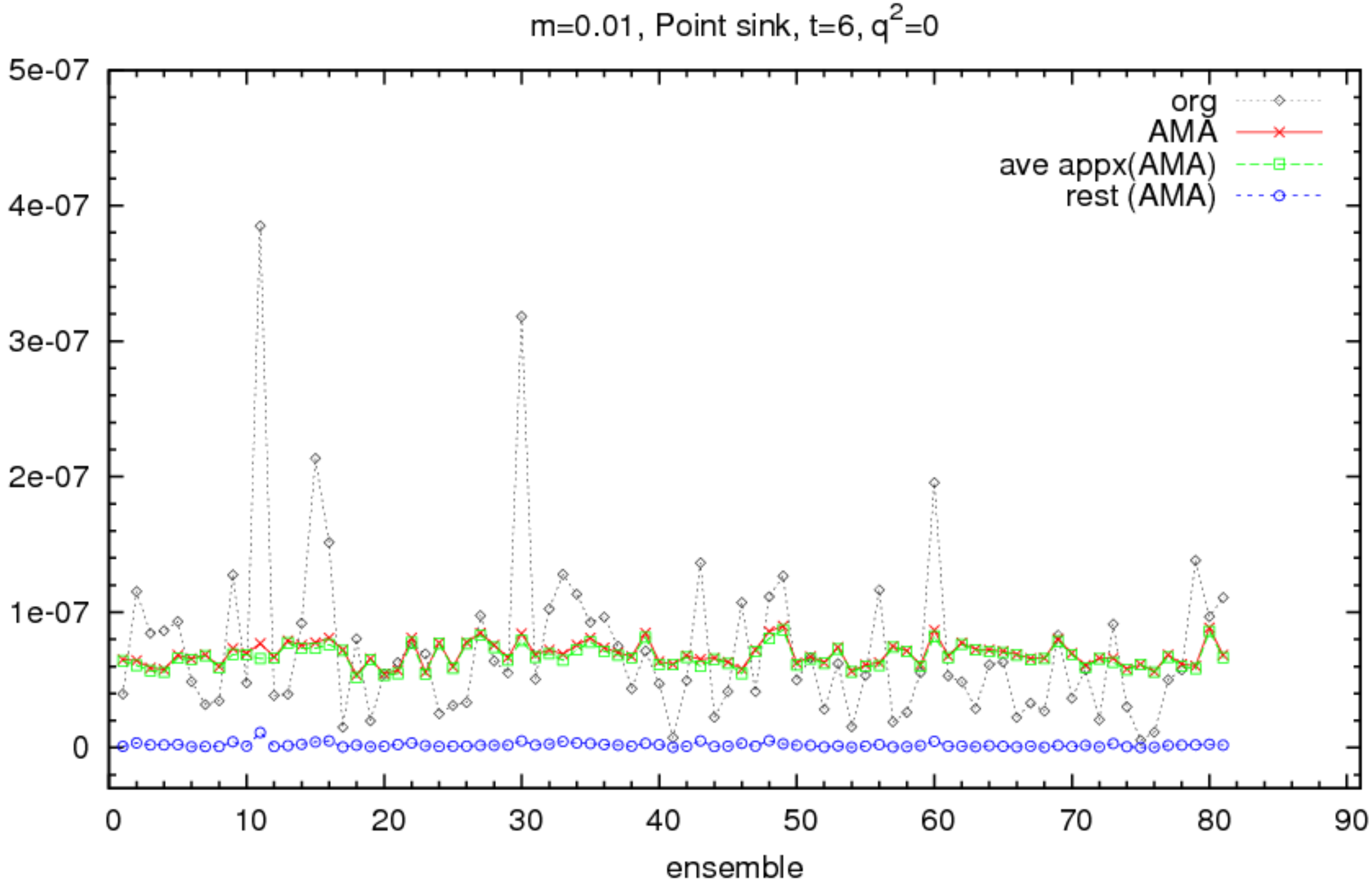
Correlation

- NN propagator (LMA) at short time-slice



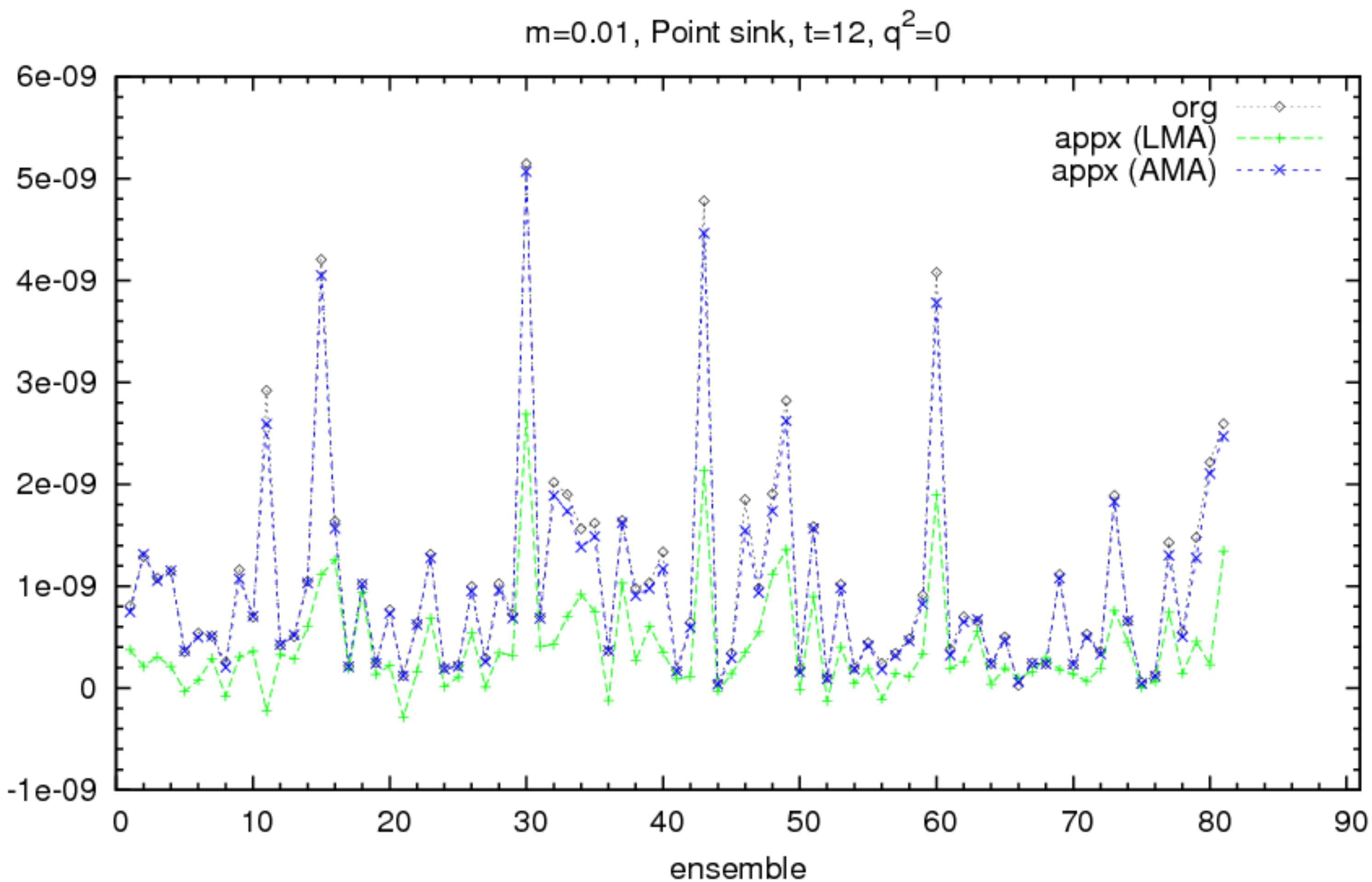
Correlation

- NN propagator (AMA) at short time-slice



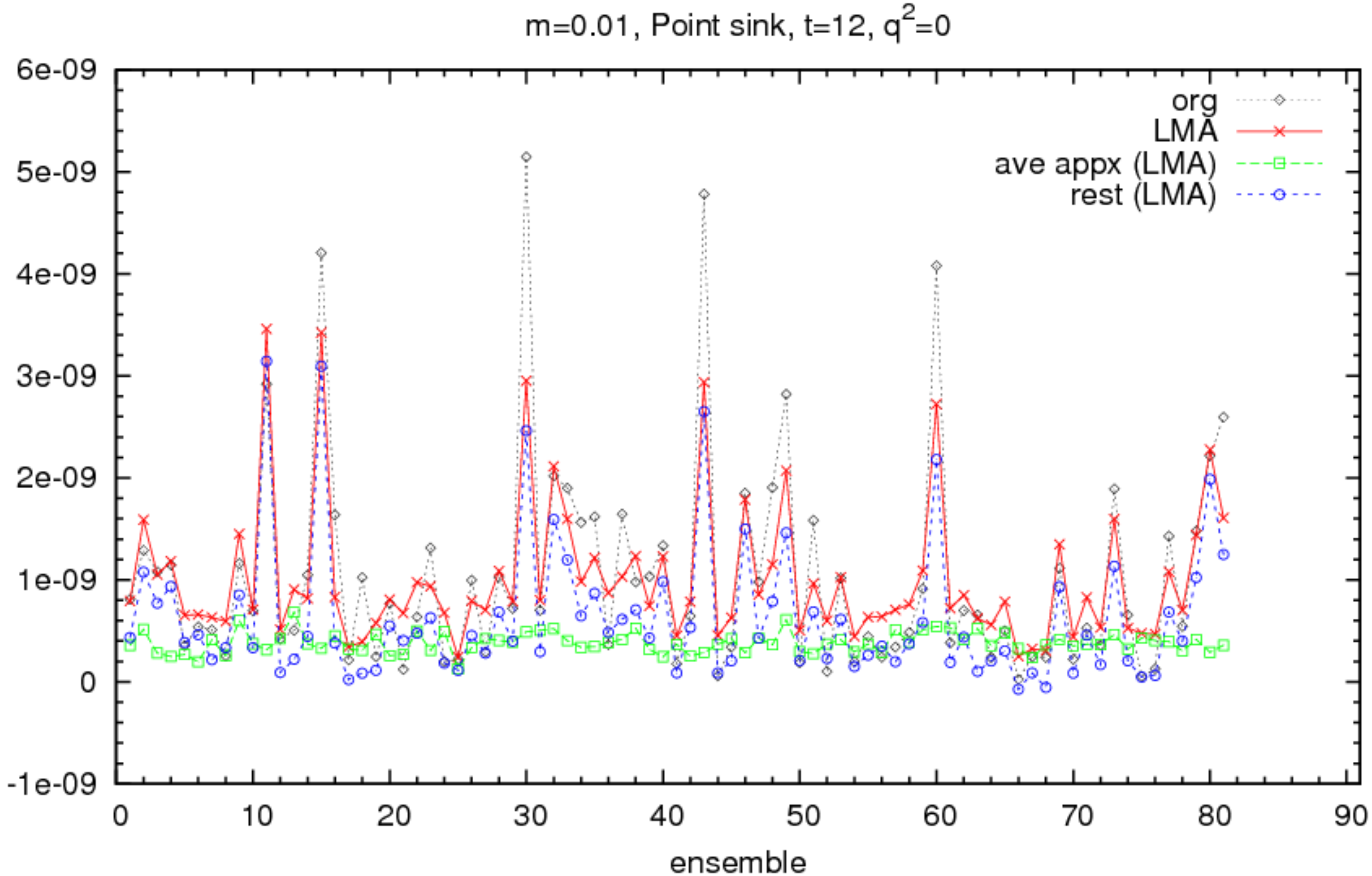
Correlation

- NN propagator at long time-slice



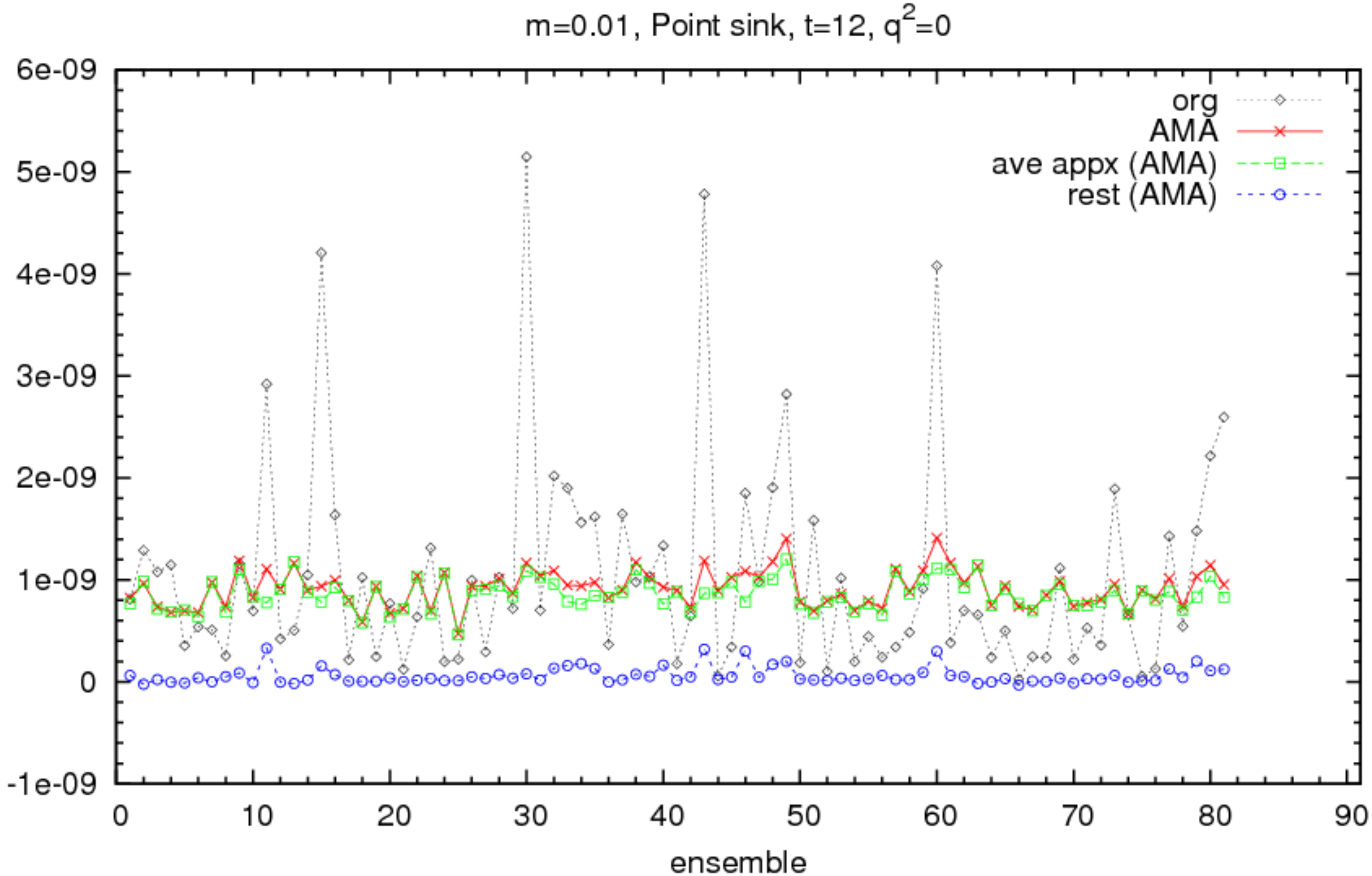
Correlation

- NN propagator (LMA) at long time-slice

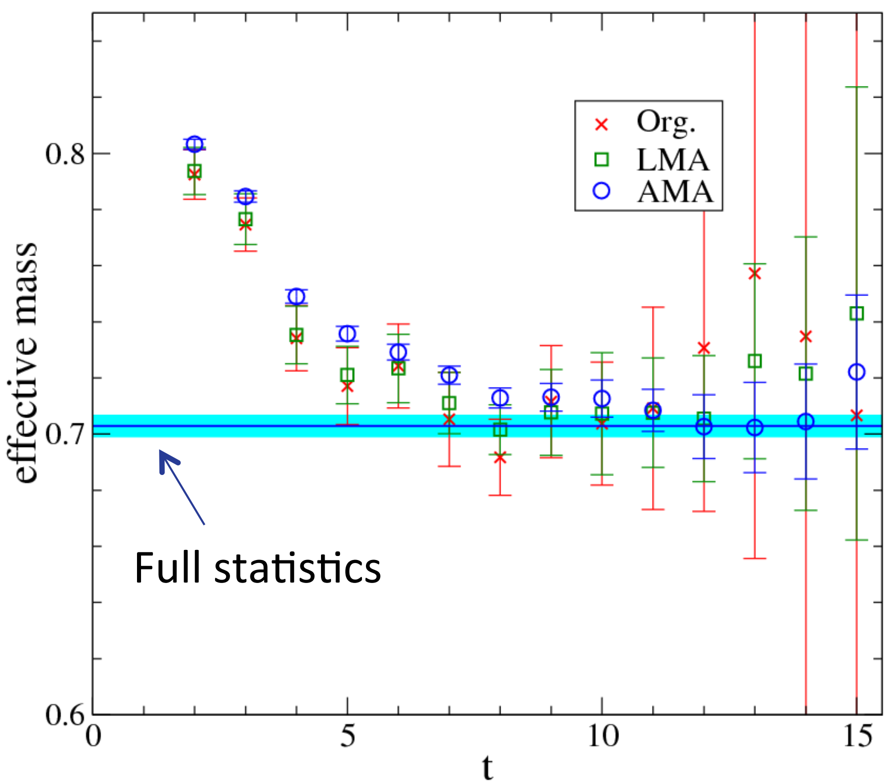


Correlation

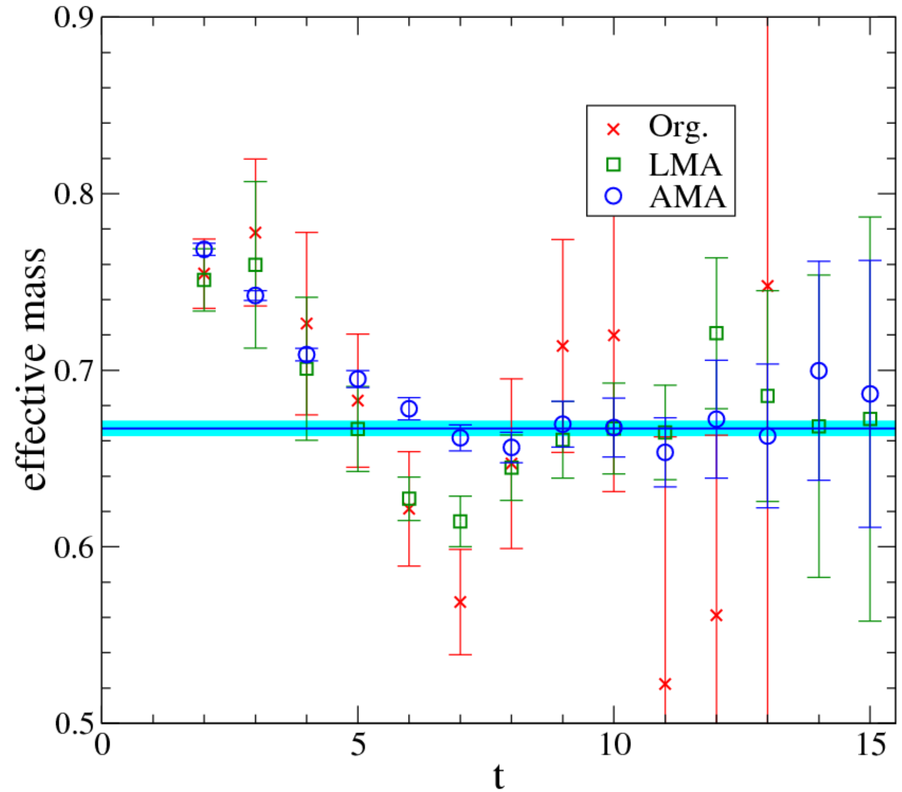
- NN propagator (AMA) at long time-slice



N, m=0.01, point sink



N, m=0.005, point sink



	LMA [7,15]	AMA [7,15]	statistics	Full statistics (Gaussian sink)
m = 0.01	0.712(16)	0.710(5)	N_{conf}=80, N'_{mes}=32	0.703(4), N_{conf} = 356, N_{mes}=4
m = 0.005	0.673(22)	0.666(13)	N_{conf}=26, N'_{mes}=32	0.663(4), N_{conf} = 932, N_{mes}=4

Yamazaki et al., PRD79, 114505 (2009)

Cost (in the case of 24cube m=0.01)

Use of unit of quark propagator "prop" in full CG w/o deflation

Yamazaki et al., PRD79, 114505 (2009)

- Case of full statistics

  In N_{conf} = 356, N_{mes}=4,

  Total： 356×4 = 1424 prop

- Case of AMA w/o deflation

  Since calculation of O^{appx} need 1/50 prop, then in N_{conf}=81, N'_{mes}=32

  Total： 80 + 80×32/50 = 131 prop ⇒ 10 times fast

- Case of AMA w/ deflation

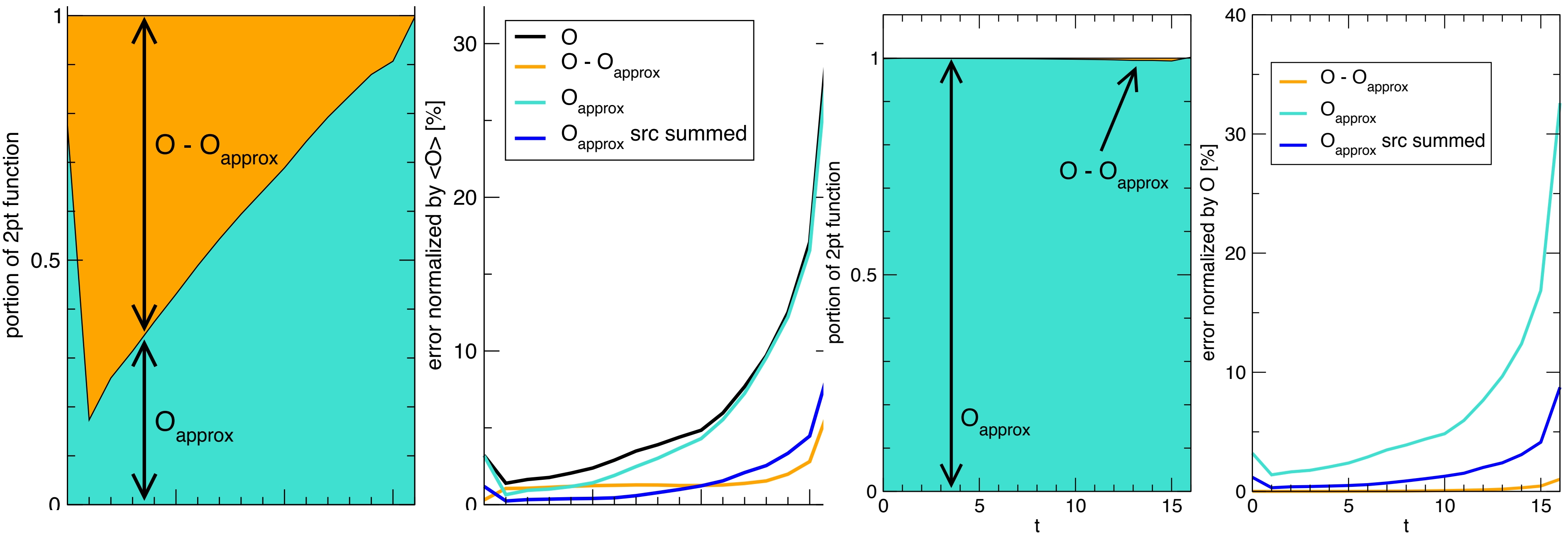
  When using 180 eigenmode, calculation of O^{appx} need 1/80 prop, but in this case the calculation of lowmode is ~1 prop/configs. Deflated CG makes reduction of full CG to 1/3 prop, then

  Total： 80/3 + 80×32/80 + 80 = 138 prop ⇒ 10 times fast

  Note that stored eigehmode is useful for other works.

AMA in USQCD Static-light
[PI Tomomi Ishikawa]

16^3x64x16, 20 conf, 100 eigenvectors



LMA

AMA

3pt function [E. Shintani]

- Application to the form factor measurement
  - CP-even and CP-odd nucleon EM form factor

$$\langle n(P_1)|J_\mu^{\rm EM}|n(P_2)\rangle_\theta = \bar{u}_N^\theta \Big[\underbrace{\frac{F_3^\theta(Q^2)}{2m_N}\gamma_5\sigma_{\mu\nu}Q_\nu}_{\rm P,T\text{-}odd} + \underbrace{F_1\gamma_\mu + \frac{F_2}{2m_N}\sigma_{\mu\nu}Q_\nu}_{\rm P,T\text{-}even} + \cdots \Big] u_N^\theta$$

  - Complicated structure in the ratio method

Cf. Yamazaki et al., PRD79, 114505 (2009)

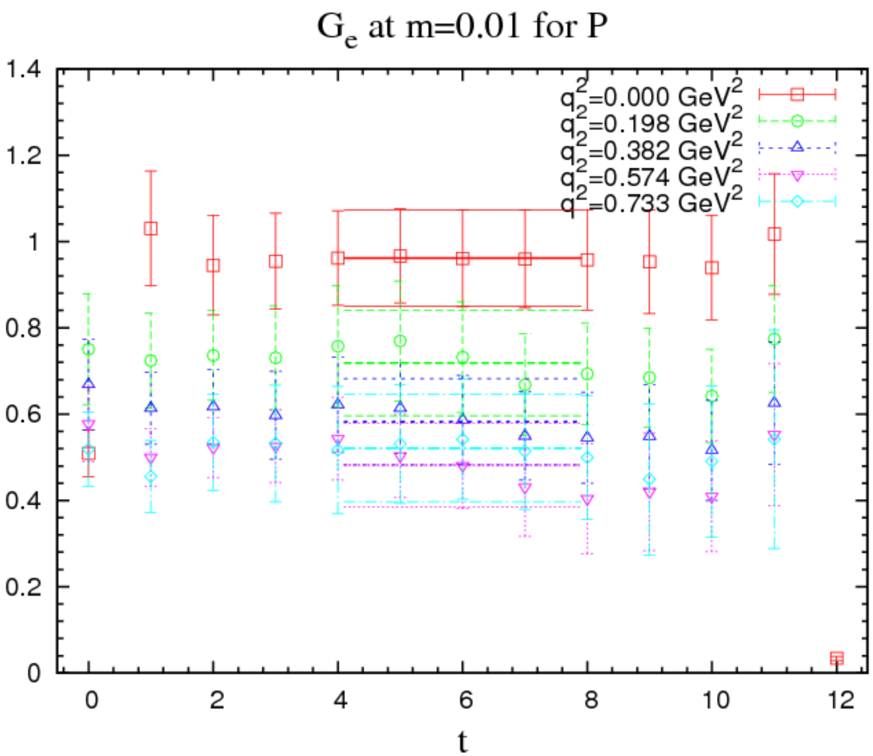
$$R_{J_\mu}(t,\vec{q}) = \sqrt{\frac{m_N}{2(E_N+m_N)}}\frac{\langle \eta_N^g J_\mu \bar{\eta}_N^g\rangle(t,\vec{q})}{\langle \eta_N^l \bar{\eta}_N^g\rangle(t_{\rm snk}-t_{\rm src},0)} R(t,\vec{q}),$$

$$R(t,\vec{q}) = \left[\frac{\langle \eta_N^l \bar{\eta}_N^g\rangle(t_{\rm snk}-t,\vec{q})\langle \eta_N^g \bar{\eta}_N^g\rangle(t-t_{\rm src},0)\langle \eta_N^l \bar{\eta}_N^g\rangle(t_{\rm snk}-t_{\rm src},0)}{\langle \eta_N^l \bar{\eta}_N^g\rangle(t_{\rm snk}-t,0)\langle \eta_N^g \bar{\eta}_N^g\rangle(t-t_{\rm src},\vec{q})\langle \eta_N^l \bar{\eta}_N^g\rangle(t_{\rm snk}-t_{\rm src},\vec{q})}\right]^{1/2}$$

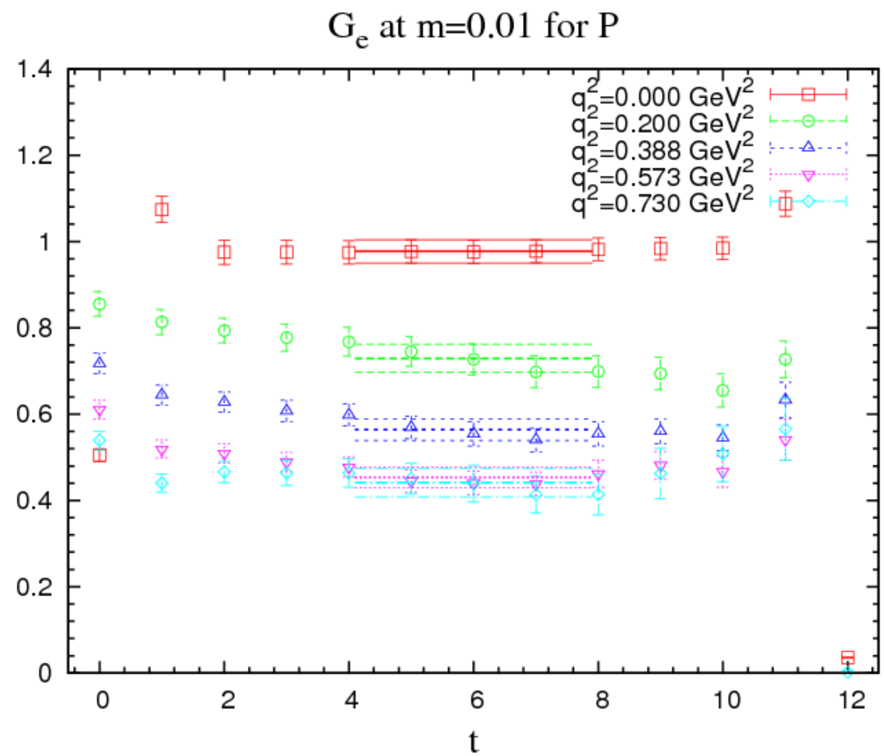
Ratio has complicated combination of both low and high mode,

so AMA has more advantage than LMA even if AMA need larger cost.

LMA



AMA



q^2 GeV^2	G_e (LMA)	G_e (AMA)
0.0	0.96(11)	0.98(3)
0.198	0.72(12)	0.73(3)
0.382	0.58(10)	0.56(3)
0.574	0.48(10)	0.45(2)
0.733	0.52(12)	0.44(3)

Statistical error of AMA is about 3--5 times smaller than LMA.

CP-odd part

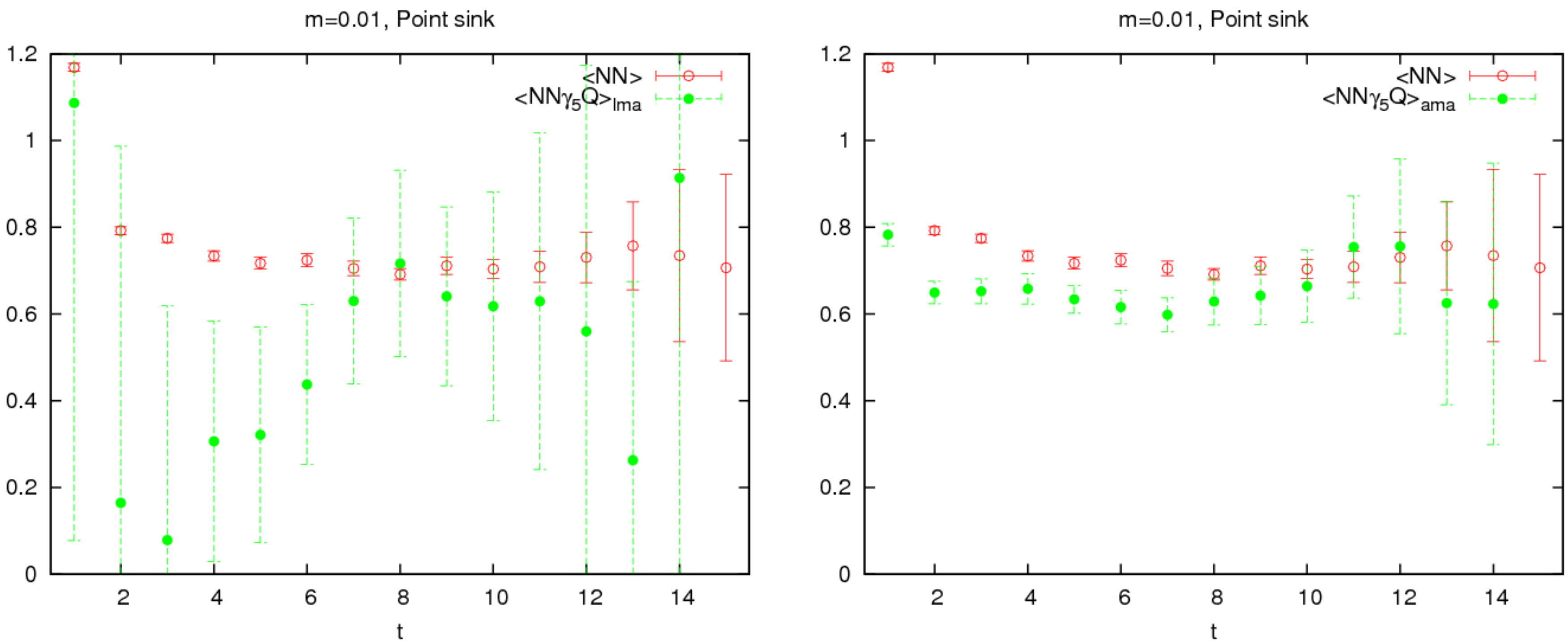
- Nucleon 2pt function with θ reweighting

$$\langle \eta_N \bar{\eta}_N \rangle_\theta(\vec{p}) = Z_N^2 \frac{ip \cdot \gamma + m_N e^{i\alpha(\theta)\gamma_5}}{2E_N}$$

$$\mathrm{tr}\left[\gamma_5 \langle Q \eta_N \bar{\eta}_N \rangle(\vec{p})\right] \simeq Z_N^2 \frac{2m_N}{E_N} \alpha e^{-E_N t}$$

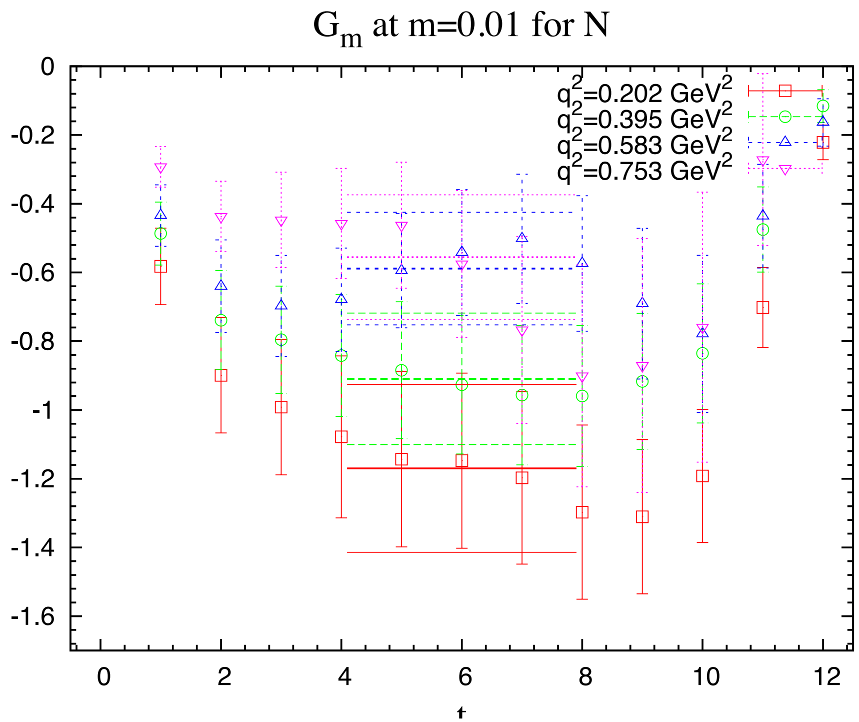
  - Q is topological charge.
  - α which is CP-odd phase is necessary to extract EDM form factor.
  - It is good check of applicability of LMA/AMA to CP-odd sector.
  - Effective mass plot shows the consistency of the above formula

CP-odd part [E. Shintani]

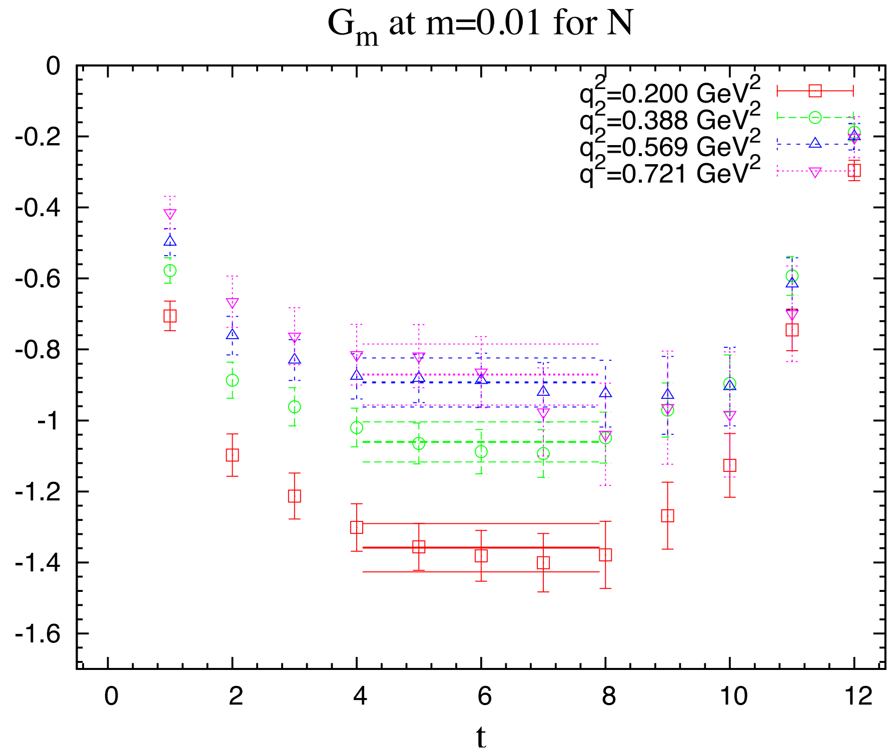


- There is good plateau in AMA, and this figure actually shows CP-odd part has consistent exponent with CP-even(nucleon mass) part as expected.
- CP-odd part has both contribution from high and low lying mode.
- AMA works well even in CP-odd sector !

Nucleon Magnetic formfactor



Original CG



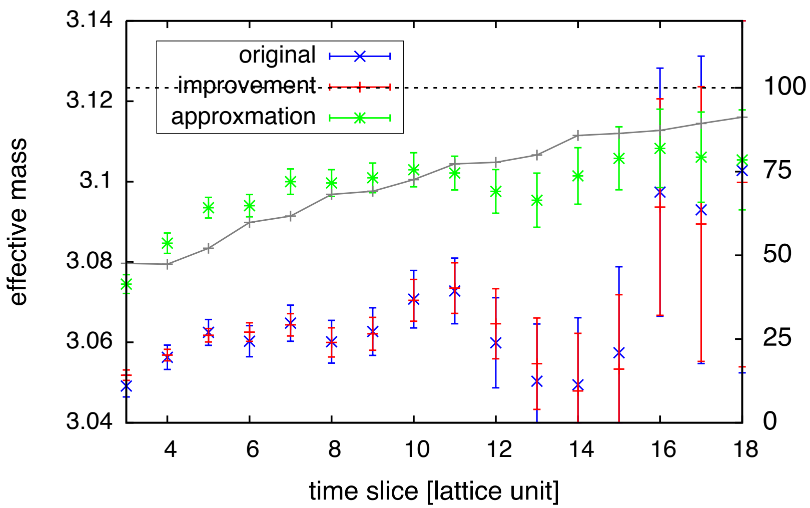
AMA

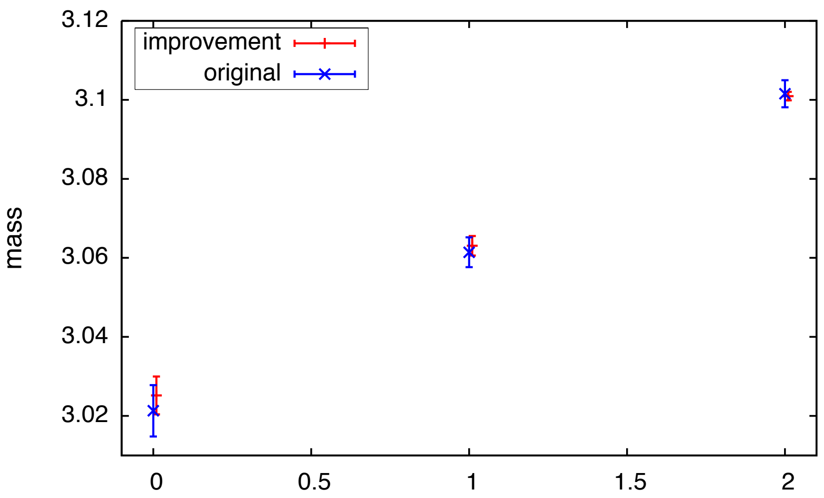
Variants of CAA

- CAA (Covariant Approximation Averaging)
  - Name
    approximation,
    approximation accuracy control
  - LMA (Low Mode Averaging)
    low mode approx of propagator,
    # of eigen vectors
  - AMA (All Mode Averaging),
    low mode (optional)+Polynomial approx,
    (# of eigenV) Polynomial degree
    (also other type of minimization)
  - Heavy quark averaging [T. Kawanai]
    heavier mass quark prop as an approx of light prop
    quark mass
  - ?????

Larger mass as CAA
[Taichi Kawanai]

24^3x64x16, 20 config ,
mf=0.01 (target) mf=0.04 "approximation"





Other Examples of Covariant Approximations

- Less expensive (parameters of) fermions :
  - Larger mf
  - Smaller Ls DWF
  - Mobius
  - even staggered or Wilson …..
- Different boundary conditions
- More than one kinds of approximation (c.f. multi mass Hasenbushing)

Strongly depends on Observables / Physics (YMMV)

Would work better for EXPENSIVE observables and/or fermion, potentially a game changer ?

Other related/similar techniques

- LMA

  L. Giusti, P. Hernandez, M. Laine, P. Weisz and H. Wittig, JHEP 0404, 013 (2004)
  see also H. Neff, N. Eicker, T. Lippert, J. W. Negele and K. Schilling, Phys. Rev. D 64 (2001) 114509 and T. DeGrand and S. Schaefer, Comput. Phys. Commun. 159 (2004) 185

  works for low mode dominant quantities

- Truncated Solver Method (TSM)

  G. Bali, S. Collins, A. Schaefer, Comput. Phys. Commun. 181 (2010) 1570

  uses stochastic noise to avoid systematic error

- All-to-all propagator

  J.Foley, K.Juge, A. O'Cais, M. Peardon, S. Ryan, J-I. Skullerud, Comput.Phys.Commun. 172 (2005) 145

  uses stochastic noise
  could use CAA as a part of A2A

Summary

- CAA , LMA, AMA, ... : Class of Statistical error reduction technique
  - AMA is a valence version of the Hasenbush trick
  - AMA could improve existing data easily

1. Do Full CG for selected config / source
   (existing data : This expensive part is already done)
2. Find a good approximation (accuracy of sloppiness / number of eigenvalue) that reproduce your exact CG result by, say, 95%
   (mathematically find a strongly correlated approximation, R(corr) > 0.5)
3. Subtract the approx obs with same source location as full CG

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

4. Perform many source location using approx obs, average, add back

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

You could use other config.

- YMMV, find a good / cheap / funny approximations

Other technical details

- Implicitly Restarted Lanczos with Polynomial acceleration and spectrum shifts for DWF and staggered in CPS++ [E. Shintani, T. Blum, TI].
- Eigen Vector compression / decompression

- Sea Electric Charge is now controlled by QED reweighting
  [T. Ishikawa et. al. arXiv:1202.6018]
- Aslash-SeqSrc method

The two-pion decay and mixing of neutral *K* mesons

RBRC Review 2012

November 8, 2012

Norman H. Christ

Outline

- QCD thermodynamics with DWF
- Weak interactions on the lattice
- $K \rightarrow \pi\pi$
  - Lattice aspects
  - Results (ΔI = 3/2 and 1/2)
- Second order weak processes
  - Focus on $m_{K_L} - m_{K_S}$
  - Indirect CP violation: ε_K
  - Rare K decays

Overview

- Physical m_π=135 MeV and L = 4 – 6 fm now possible with domain wall fermions.
- Increase accuracy on standard quantities:

  $\boldsymbol{f_\pi, \; f_K, m_{ud}, m_s, B_K, \ldots.}$

- Compute new quantities
  - Avoid mass extrapolations and ChPT
  - Faster computers (K/QCDCQ/Mira/Sequoia)
  - Better algorithms (AMA, A2A, EigCG, ….)

RBC Collaboration

- BNL
  - **Alexei Bazavov**
  - **Heng-Tong Ding**
  - **Prasade Hedge (Taiwan U.)**
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  - **Frithjof Karsch**
  - Taichi Kawanai (Tokoyo)
  - Hyung-Jin Kim
  - Yu Maezawa
  - **Swagato Mukherjee**
  - **Peter Petreczky**
  - Amarjit Soni
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  - Meifeng Lin (Yale → ANL/BU)
  - Qi Liu (Two Sigma)
  - **Robert Mawhinney**
  - Greg McGlynn
  - Hao Peng
  - **Hantao Yin**
  - Jianglei Yu
  - Daiqian Zhang
- Connecticut
  - Tom Blum
  - Michael Abramczyk

QCD phase transition with chiral quarks

(Jasper Lin/Hantao Yin)

$m_\pi = 200$ MeV

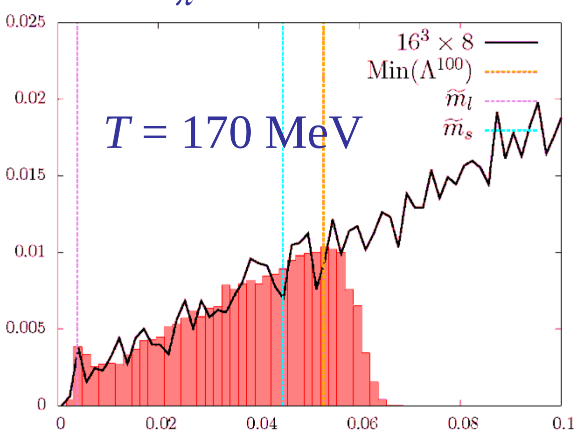


Figure 2: 170 MeV ($N_s = 32$) Dirac Spectrum

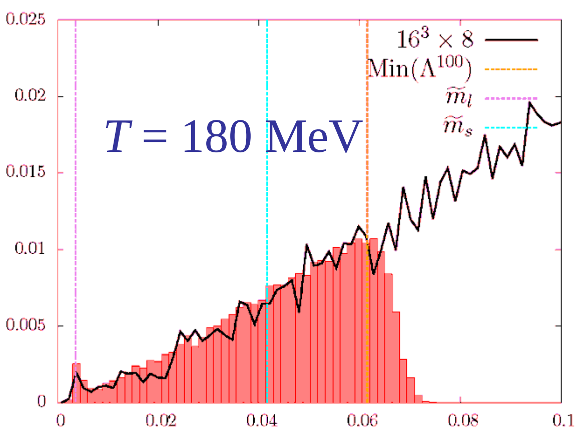
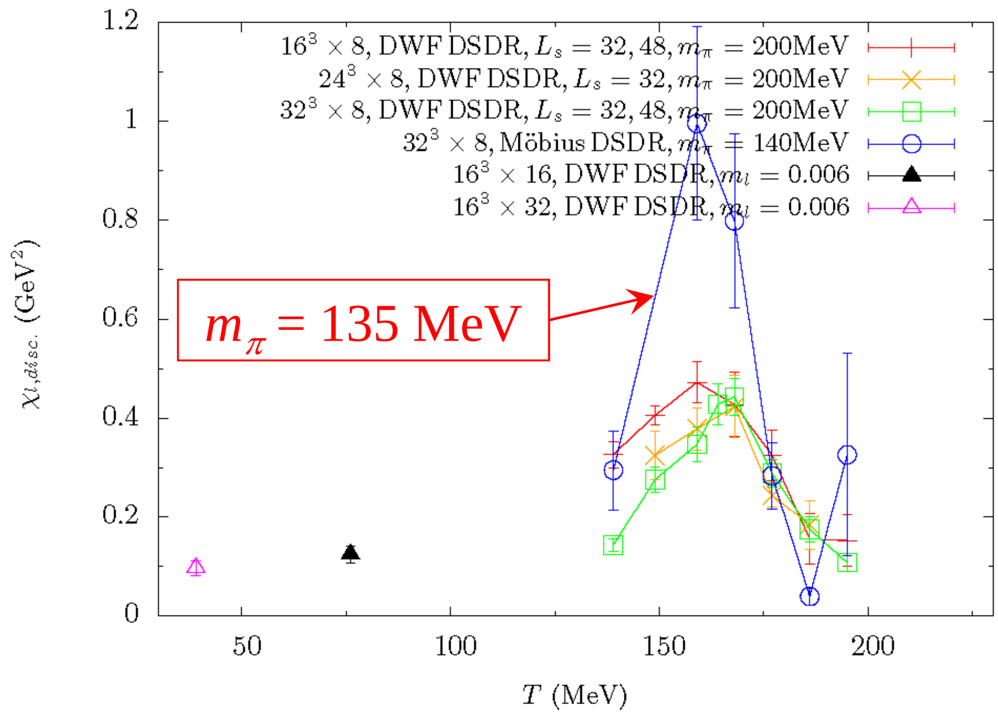


Figure 3: 180 MeV ($N_s = 32$) Dirac Spectrum



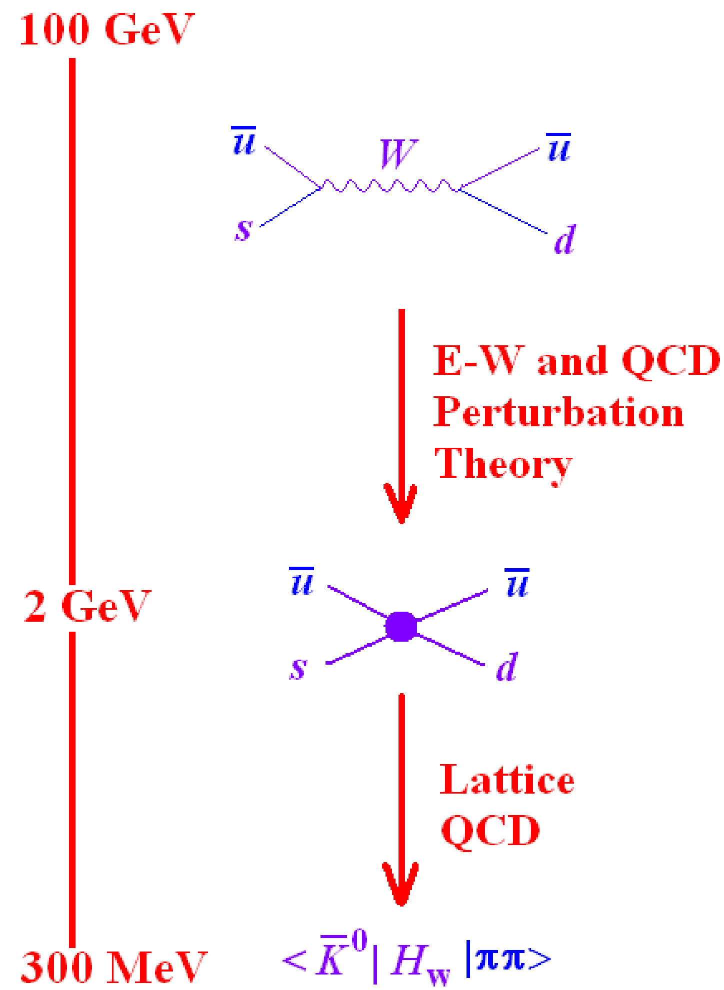
- Evidence for dilute instanton gas model
- χ_{disc} for $T \sim T_c$ for $m_\pi = 135$ MeV
- Hot QCD – LLNL (Sequoia)

Low Energy Effective Theory

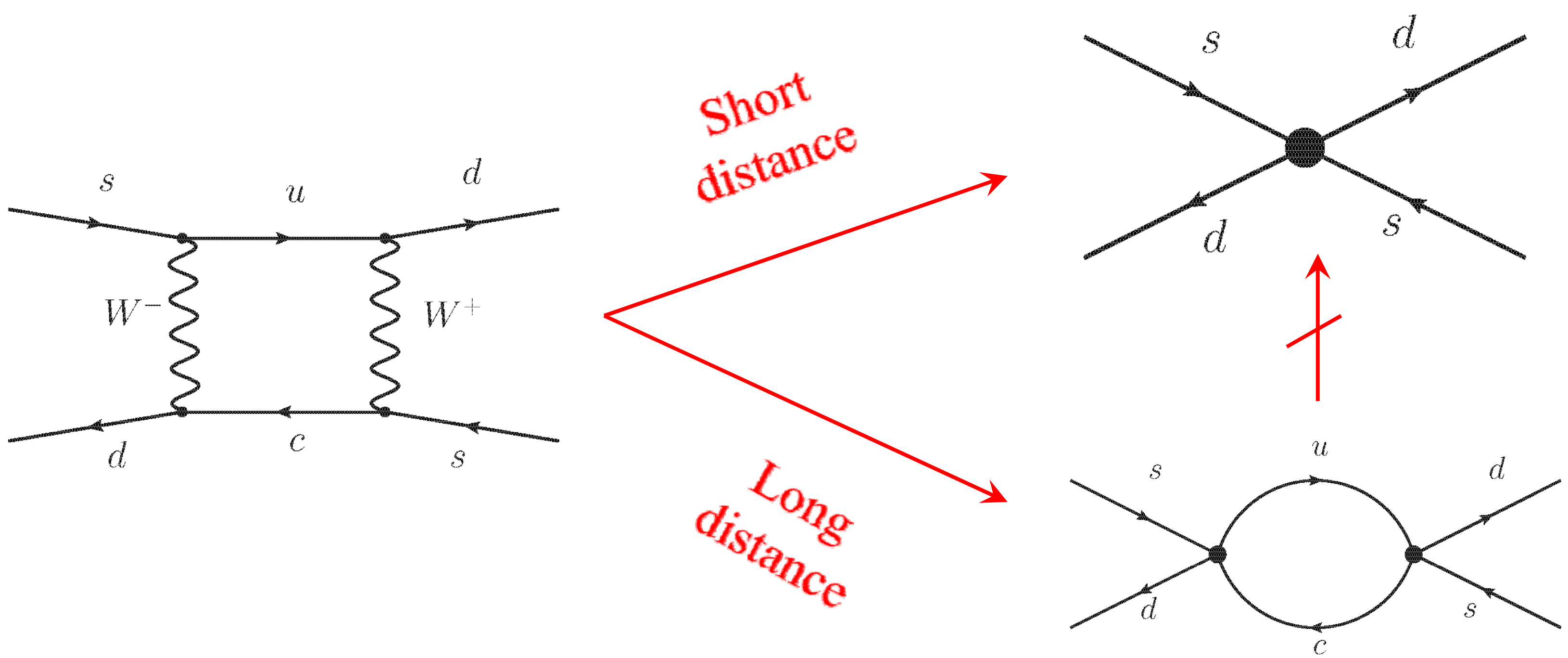
- Represent weak interactions by local four-quark Lagrangian

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

- $V_{qq'}$ – CKM matrix elements
- z_i and y_i – Wilson Coefficients
- Q_i – four-quark operators



Second order weak processes



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  - Jonathan Flynn
  - **Tadeusz Janowski**
  - Andreas Juttner
  - **Andrew Lytle**
  - **Chris Sachrajda**
  - Benjamin Samways

$K \rightarrow \pi\,\pi$ decay

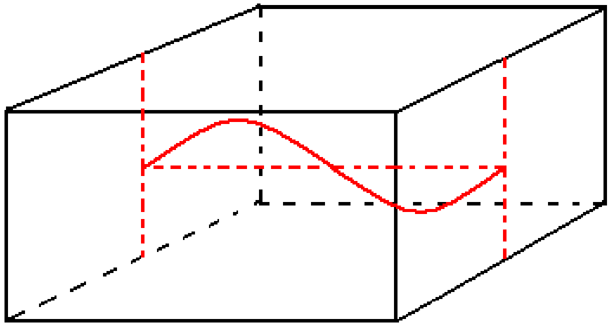
Lattice Aspects

Evaluate $<K|H_W|\pi\pi>$

- Use SU(3) ChPT: $<K|H_W|\pi>$ & $<K|H_W|0>$ → $<K|H_W|\pi\pi>$?
  - m_K too large
  - ~70% errors
- Maiani-Testa no-go theorem (1990):
  - Euclidean space: e^{-Ht} projects onto lowest energy state
  - Gives π - π state with zero relative momentum

Solved by Lellouch-Luscher

- Use finite-volume quantization.
- Adjust volume so 1st or 2nd excited state has correct *p*.
- Requires extracting signal from non-leading large *t* behavior:



$p = 2\pi/L$

$$G(t) \sim c_0 e^{-E_0 t} + c_1 e^{-E_1 t}$$

- Finite volume states correctly include π - π interactions.
- Lellouch-Luscher correction factor compensates for finite volume, $\vec{J}$ non-conservation.

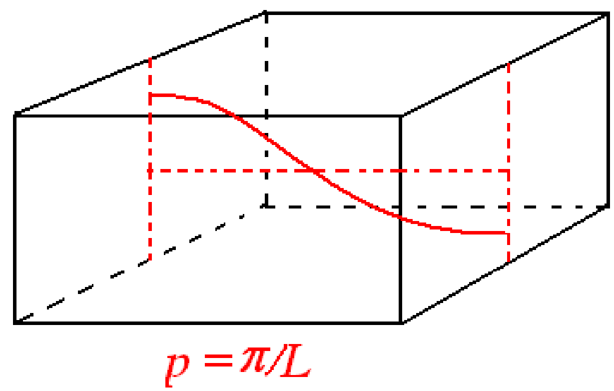
Lattice operators

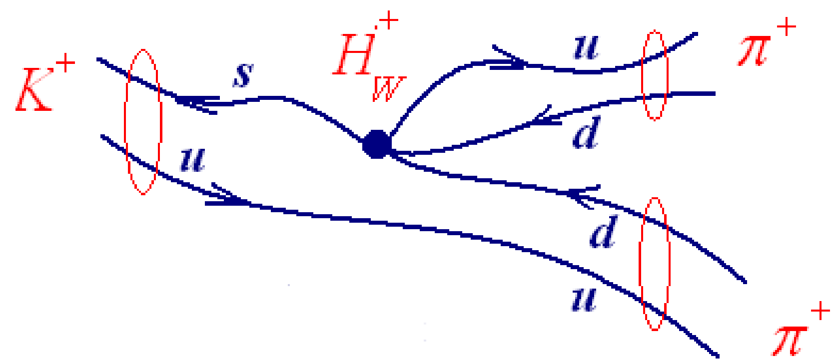
- Use chiral fermions (DWF): short-distance chiral symmetry controls operator mixing (L_s=16 and 32)
- Use non-perturbative methods to convert lattice operators to regularization invariant (RI) scheme at a scale μ.
- Use a series of finer lattice ensembles to non-perturbatively run μ up to 3 GeV.
- Use continuum perturbation theory to convert RI to $\overline{\mathrm{MS}}$

$$\Delta I = 3/2$$

Δ I = 3/2 $K \rightarrow \pi\pi$

- Three operators contribute $O^{(27,1)}$, $O^{(8,8)}$ and $O^{(8,8)m}$.
- Use isospin to relate to $K^+ \rightarrow \pi^+ \pi^+$.
- Use anti-periodic boundary conditions for *d* quark.
  (Changhoan Kim, hep-lat/0210003).
- **Achieve essentially physical kinematics!** (147 configurations)
  - m_π = 142.9(1.1) MeV
  - m_K = 511.3(3.9) MeV
  - $E_{\pi\pi}$ = 492(5.5) MeV

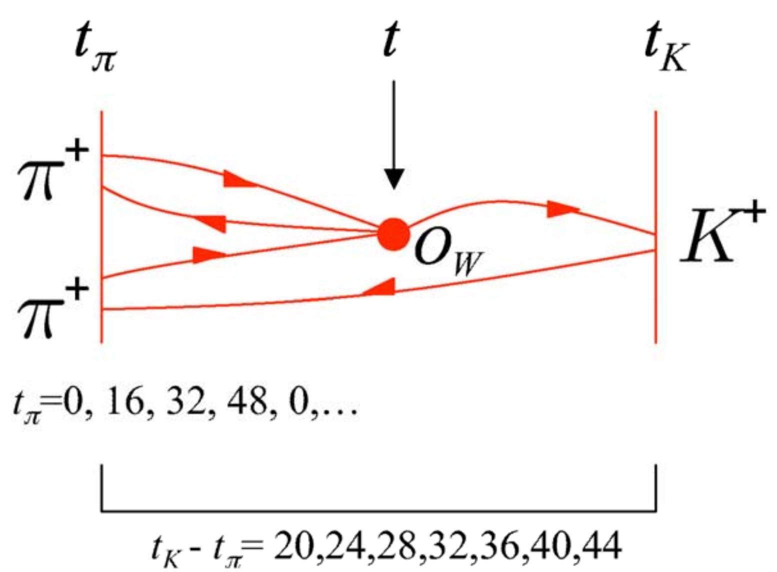




Computational Set-up

(Lightman and Goode)

- Use $32^3 \times 64$, DSDR ensemble: $1/a$=1.36 GeV, L = 4.6 fm.
- Use anti-periodic boundary conditions for d quark in two directions (average over three choices).
- Fix $\pi - \pi$ source at t = 0, vary location of O_W and K source.



Determine physical A_2

- Error estimates:

	$\mathrm{Re}A_2$	$\mathrm{Im}A_2$
lattice artefacts	15%	15%
finite-volume corrections	6.2%	6.8%
partial quenching	3.5%	1.7%
renormalization	1.8%	5.6%
unphysical kinematics	0.4%	0.8%
derivative of the phase shift	0.97%	0.97%
Wilson coefficients	6.6%	6.6%
Total	18%	19%

Results for A_2

- $\mathrm{Re}(A_2) = (1.436 \pm 0.063_{stat} \pm 0.258_{sys})\ 10^{-8}$ GeV

Experiment: $1.479(4)\ 10^{-8}$ GeV

- $\mathrm{Im}(A_2) = -(6.29 \pm 0.46_{stat} \pm 1.20_{sys})\ 10^{-13}$ GeV

The $K \rightarrow \pi\pi_{I=2}$ Decay Amplitude from Lattice QCD, T. Blum, *et al.*, Phys.Rev.Lett. 108 (2012) 141601, arXiv:1206.5142

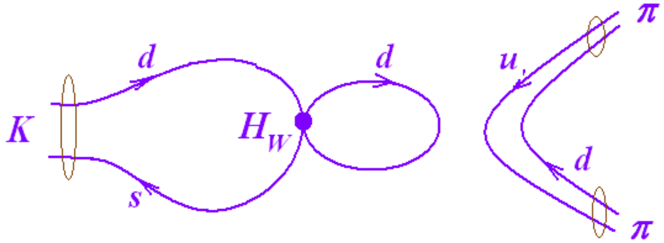
(2012 Ken Wilson Lattice Award)

Lattice determination of the $K \rightarrow \pi\pi_{I=2}$ Decay Amplitude A_2, T. Blum, *et al.*, arXiv:1206.5142 [hep-lat]

$$\Delta I = 1/2$$

$\Delta I = 1/2\ K \to \pi\pi$
(Qi Liu)

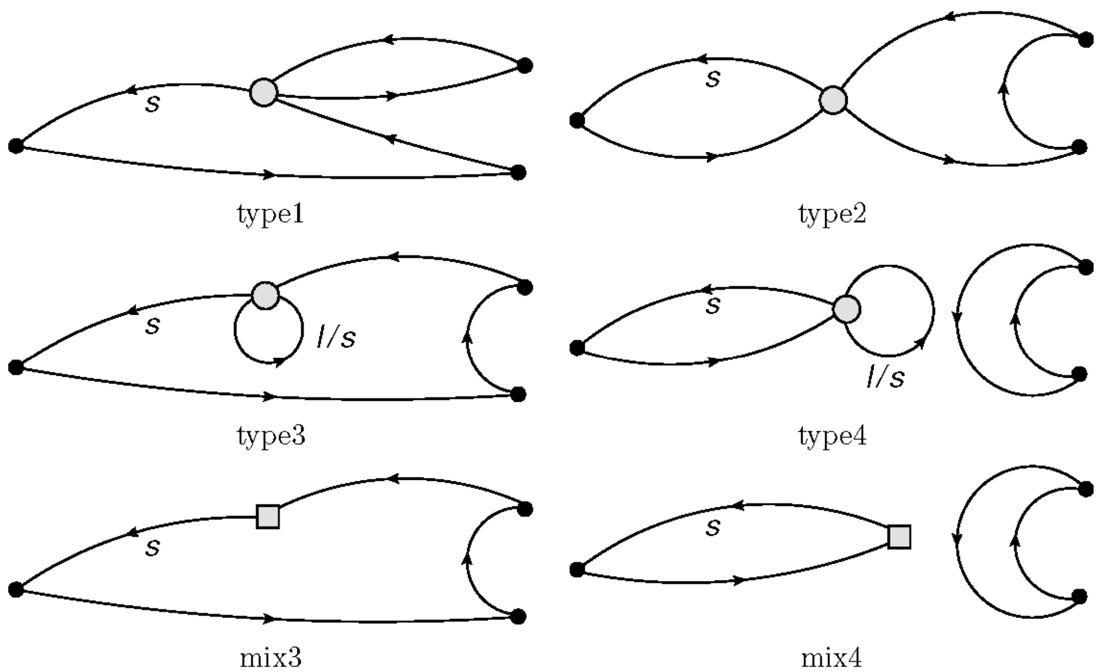
- Made much more difficult by disconnected diagrams:



- <u>16^3 x 32 ensemble</u> (arXiv:1106.2714 [hep-lat])
  - $1/a$ = 1.73 GeV, m_π = 420 MeV, L = 1.8 fm
  - Use 8000 time units, measure every 10 (800 configs.)
- <u>24^3 x 64 ensemble</u> (22 x harder)
  - $1/a$ = 1.73 GeV, m_π = 329 MeV, L = 2.8 fm
  - Use 5520 time units, measure every 40 (138 configs.)
- Adjust valence strange mass for on-shell, threshold kinematics ($\pi\pi$ state is unitary)

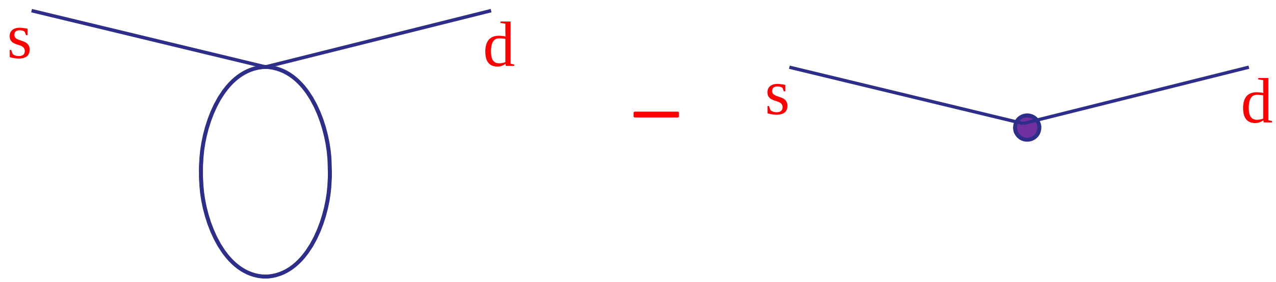
$\Delta I = 1/2 \;\; K \rightarrow \pi\pi$

- Code 50 different contractions of four types:



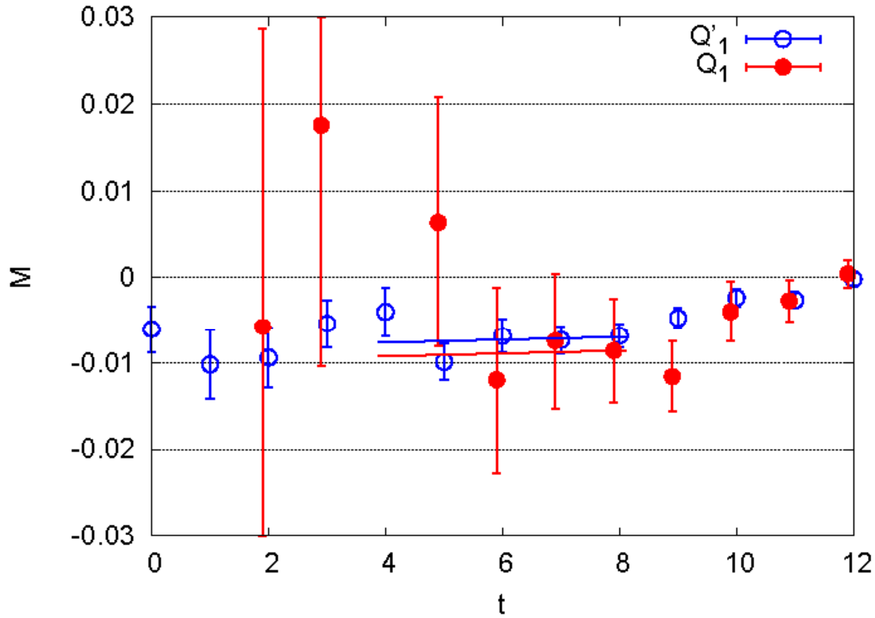
Substantially improved methods

- Improve statistics using sources at each of 32 or 64 times
- Accelerate inversions with low-mode deflation or EigCG
- Reduce vacuum coupling by separating pion sources
- Subtract divergent $\bar{s}d$ and $\bar{s}\,\gamma^5 d$ terms
  - Does not affect on-shell amplitudes
  - Suppress $1/a^2$-enhanced excited state contributions.

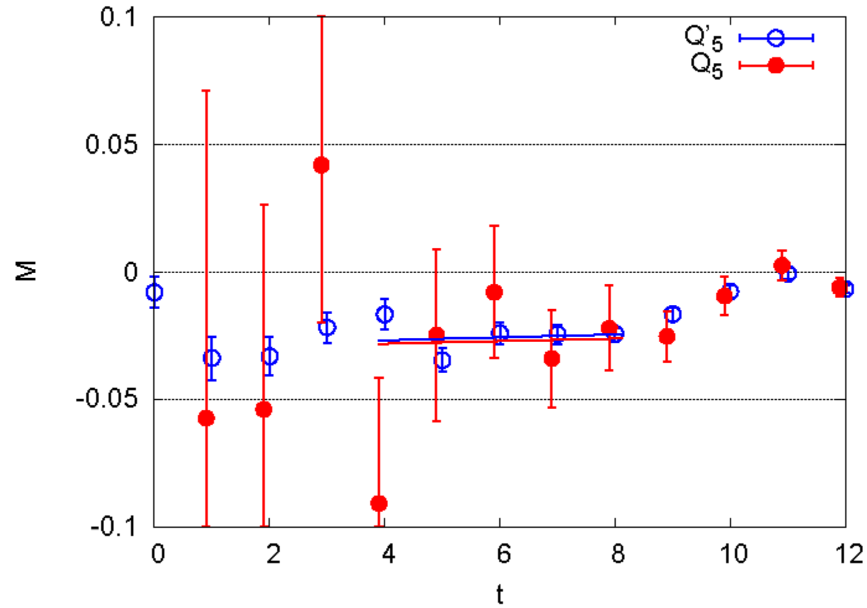


$\Delta I = 1/2 \;\; K \rightarrow \pi\pi \quad 24^3 \times 64$

Q2 - largest part of Re(A_0)



Q6 - largest part of Im(A_0)



$\Delta = 12 \; K - \pi\pi$ separation

Full amplitude

(′) Drop disconnected

m_π(MeV)	m_K(MeV)	Re(A_0)	Re(A_0')	Im(A_0)	Im(A_0')	Re(A_2)	Im(A_2)
329.3	662.1	31.1(4.5)	27.8(0.8)	-33(15)	-36.3(16)	2.668(14)	-0.6509(34)

$\Delta I = 1/2$ $K \rightarrow \pi\pi$: Future

- Goal is a 20% calculation of ε'/ε with all errors controlled
- Repeat $\Delta I = 3/2$ kinematics
  - Use 32^3 x 64 volume with $1/a$ = 1.37 GeV
  - Achieve p = 205 MeV from **G-parity** in 2 directions **(Chris Kelly)**
  - Test 16^3 x 32 G-parity ensembles being generated on **QCDCQ**
- Use "all-2-all" propagators (KEK/Trinity) **(Daiqian Zhang)**

24^3 x 64 – **138** configs. QCDOC	16^3 x 32 – **30** configs. **QCDCQ**
wall sources	all-2-all – point sources
$E_{\pi\pi}$(I=0) = 0.3637(55)	$E_{\pi\pi}$(I=0) = 0.4461(82)

- BG/Q gives 20 x speedup
- Result anticipated in 2 years

$K_L - K_S$ mass difference

$K^0 - \overline{K^0}$ Mixing

- Time evolution of $K^0 - \overline{K^0}$ system given by familiar Wigner-Weisskopf formula:

$$i\frac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} = \left\{ \begin{pmatrix} M_{00} & M_{0\bar{0}} \\ M_{\bar{0}0} & M_{\bar{0}\bar{0}} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{00} & \Gamma_{0\bar{0}} \\ \Gamma_{\bar{0}0} & \Gamma_{\bar{0}\bar{0}} \end{pmatrix} \right\} \begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$$

where:

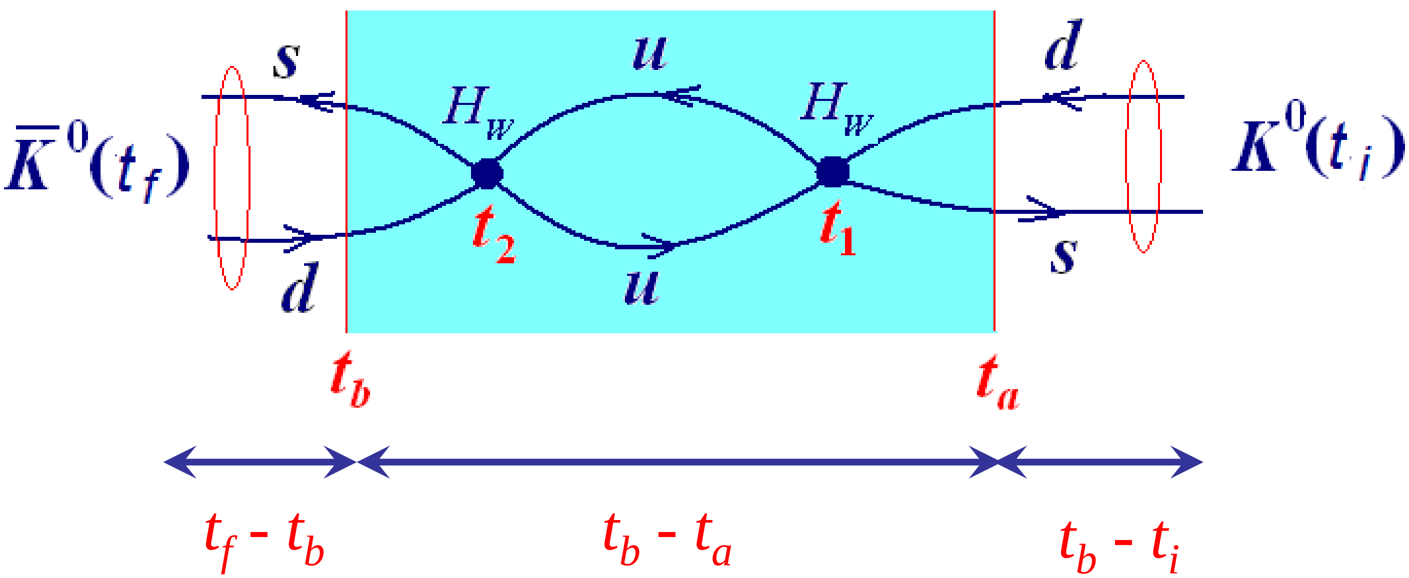
$$\Gamma_{ij} = 2\pi \sum_\alpha \int_{2m_\pi}^\infty dE \langle i|H_W|\alpha(E)\rangle\langle\alpha(E)|H_W|j\rangle\delta(E-m_K)$$

$$M_{ij} = \sum_\alpha \mathcal{P}\int_{m_\pi}^\infty dE \frac{\langle i|H_W|\alpha(E)\rangle\langle\alpha(E)|H_W|j\rangle}{m_K - E}$$

Lattice Version
(Jianglei Yu)

- Evaluate standard, Euclidean, 2nd order $K^0 - \overline{K^0}$ amplitude:

$$\mathcal{A} = \langle 0 | T \left(K^0(t_f) \frac{1}{2} \int_{t_a}^{t_b} dt_2 \int_{t_a}^{t_b} dt_1 H_W(t_2) H_W(t_1) K^{0\dagger}(t_i) \right) |0\rangle$$



Interpret Lattice Result

$$\mathcal{A} = N_K^2 e^{-M_K(t_f-t_i)} \left\{ \sum_{n \neq n_0} \frac{\langle \overline{K}^0 | H_W | n \rangle \langle n | H_W | K^0 \rangle}{M_K - E_n} \left(\underbrace{-(t_b - t_a)}_{1.} \underbrace{- \frac{1}{M_K - E_n}}_{2.} + \underbrace{\frac{e^{(M_K-E_n)(t_b-t_a)}}{M_K - E_n}}_{3.} \right) + \underbrace{\frac{1}{2} \langle \overline{K}^0 | H_W | n_0 \rangle \langle n_0 | H_W | K^0 \rangle (t_b - t_a)^2}_{4.} \right\}$$

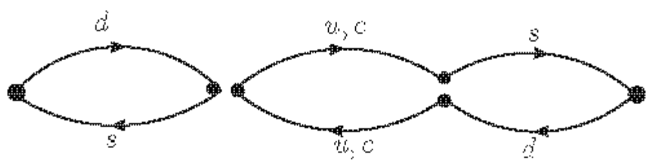
1. Δm_K^{FV}
2. Uninteresting constant
3. Growing or decreasing exponential:
   $E_n > m_K$ must be removed!
4. Degenerate $E_{\pi\pi} = m_K$ state

Lattice setup

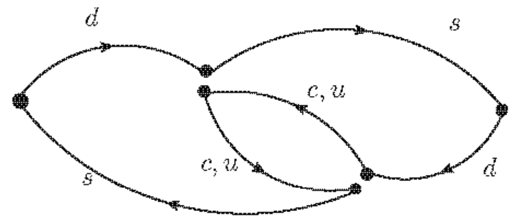
- $N_f = 2{+}1$ and $2{+}1{+}1$, $16^3 \times 32$, $m_\pi = 420$ MeV
- Include type 1 and type 2 graphs:

Include

Type 1

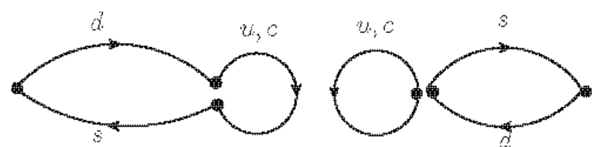


Type 2

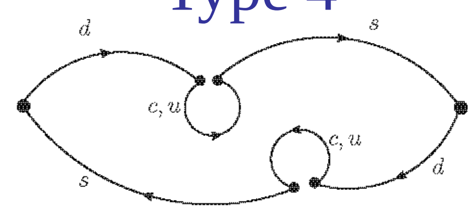


Drop

Type 3

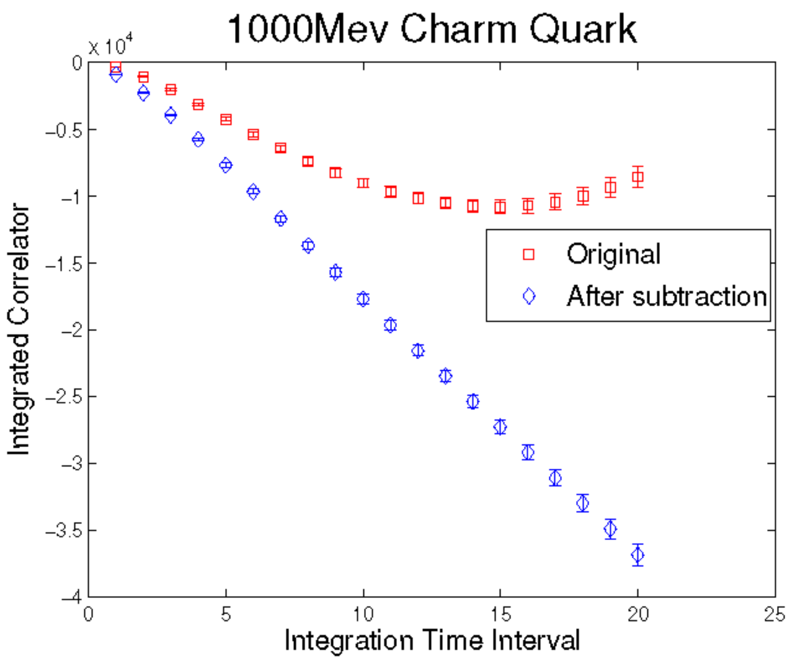


Type 4

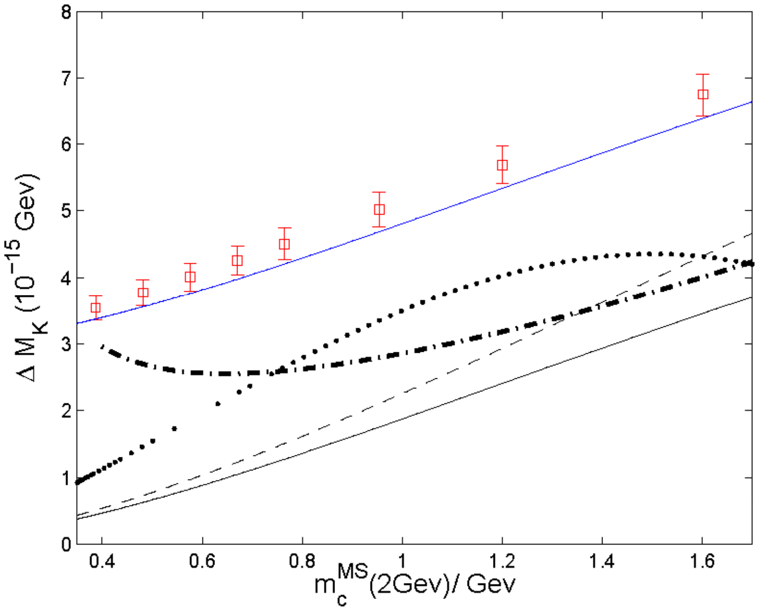


First results
(Jianglei Yu)

- N_f=2+1, 16^3 x 32, m_π = 420 MeV
- Incorporate GIM cancellation



Compare with NLO perturbation theory



- See large constant offset above uncertain perturbative results.

Results

M_K (GeV)	ΔM_K (x 10^{-12} MeV)
563	5.12(24)
707	6.92(37)
775	8.08(49)
834	9.31(65)

- $\Delta M_K^{expt} = 3.483(6)\ 10^{-12}$ MeV
- Unphysical kinematics, $m_\pi = 421$ MeV
- Active charm but $m_c\, a = 0.7$
- 24^3 x 64 calculation using AMA with all diagrams begun!

Kaon physics from lattice QCD
Outlook

- Work at physical quark masses.
- DW fermions and NPR give continuum-like control of operator normalization and mixing.
- Theoretical advances allow π–π rescattering effects to be correctly computed in Euclidean space.
- Many critical quantities can now be computed:
  - $K \to \pi\pi$: ΔI=3/2 and 1/2, ε'/ε
  - $m_{K_L} - m_{K_S}$
  - $K \to \pi l \bar{l}$

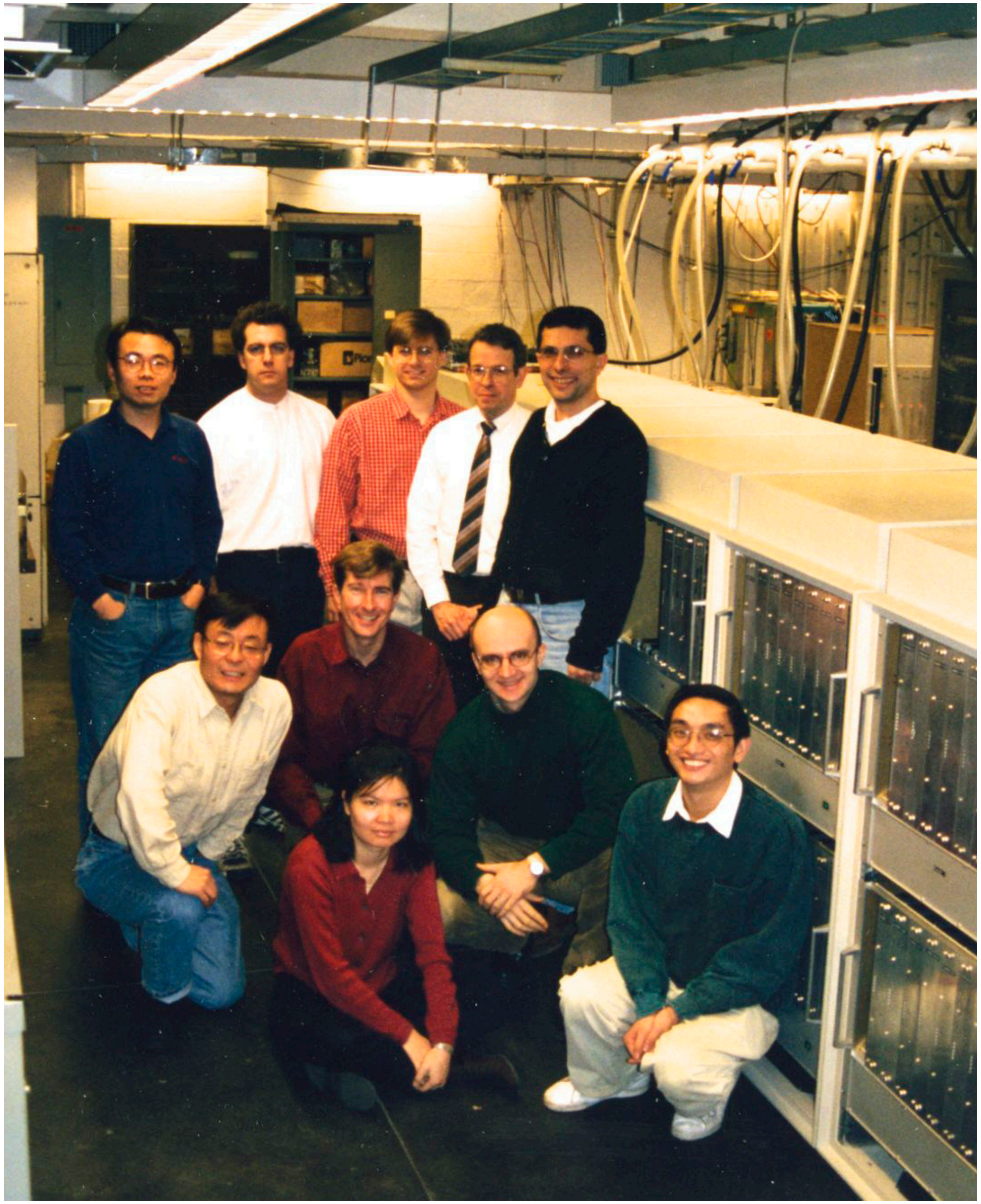
RBRC/BNL BGQ Computers and LQCD Simulations

RBRC Review
Brookhaven National Laboratory
November 8, 2012

Robert Mawhinney
Columbia University

QCDSP Computer

400 GFlop QCDSP at Columbia in 1997

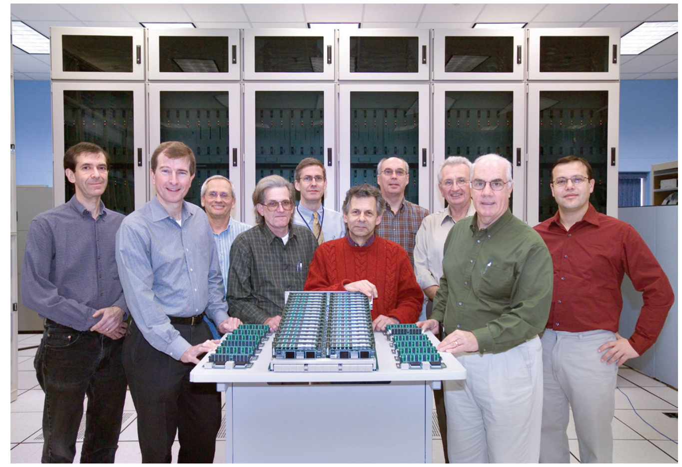


RBRC 600 GFlop QCDSP at BNL
First crates 1997. Completed 1998

RBRC 600 GFlops QCDSP Computer

Shut down on January 31, 2006

RBRC and USDOE 10 TFlops QCDOC Computers



Picture taken on May 11, 2005

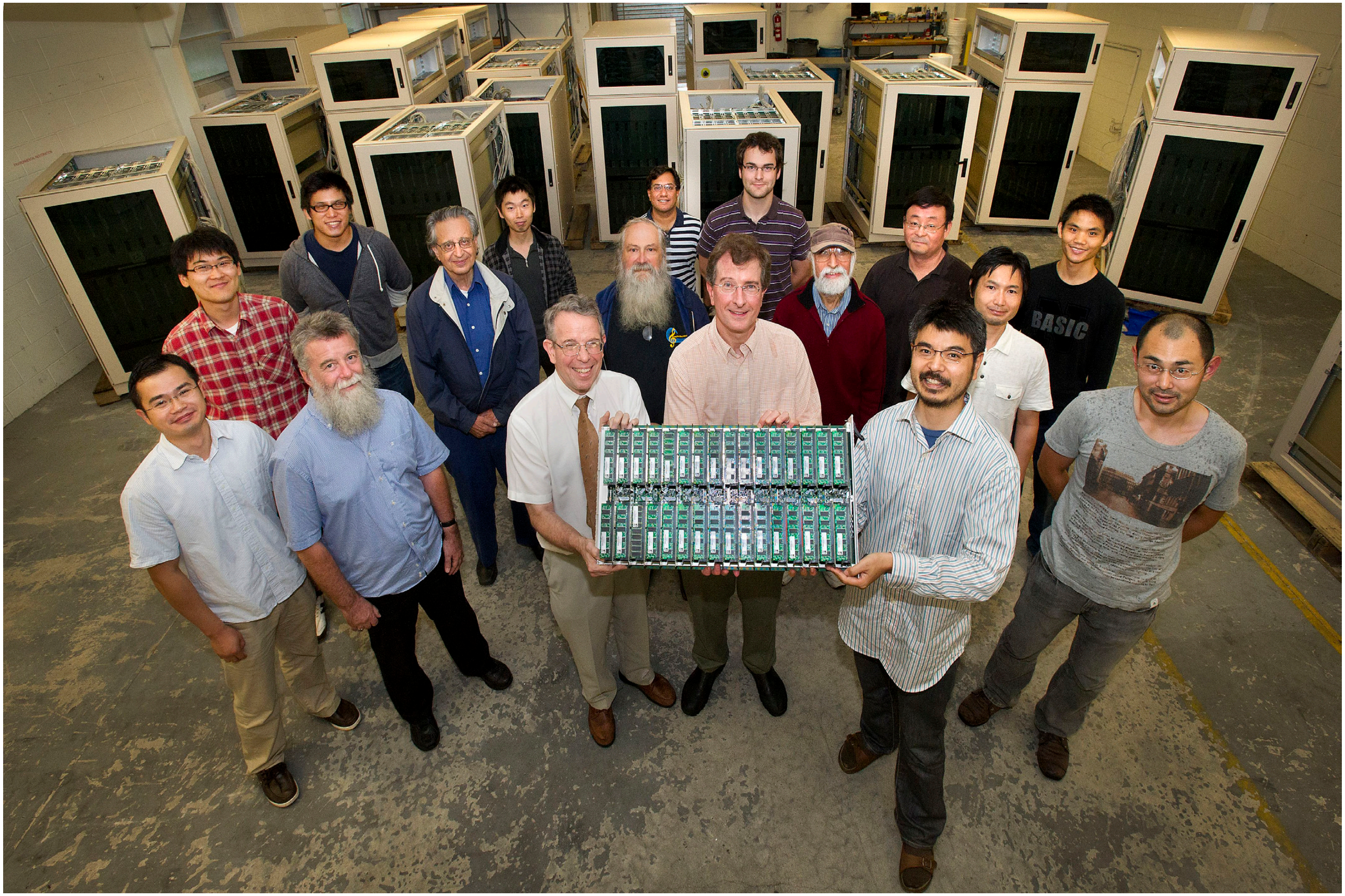
RBRC and USDOE 10 TFlops QCDOC Computers

Shut down on September 19, 2011

QCDOC Disassembly

Parting Pictures

September 29, 2011



QCDCQ Project Using IBM BGQ Computers

December 20, 2011


NO SMOKING
SMOKING IN
PERMITTED AREAS
ONLY


Supercomputing Landscape
Computer Architecture Evolution from IBM
RIKEN • BNL • Columbia
Quantum Chromodynamics (QCD) Project
Quantum Chromodynamics (QCD) Project
Total Peak Speed: 1100.8 Gflops
Awarded 1998
Gordon Bell Prize for
Price Performance!
1 QCDOC
MOTHERBOARD
32 QCDSP
MOTHERBOARDS
as compared to
QCDOC
System on a Chip
EXIT
IBM

QCDCQ Project Using IBM BGQ Computers

May 18, 2012

- Each BGQ rack is 200 TFlops peak.
- Peter Boyle's dirac solver sustains 20-60 GFlops, depending on the local volume

Computer Evolution

CU16 Node: 0.016 GFlops (1985)

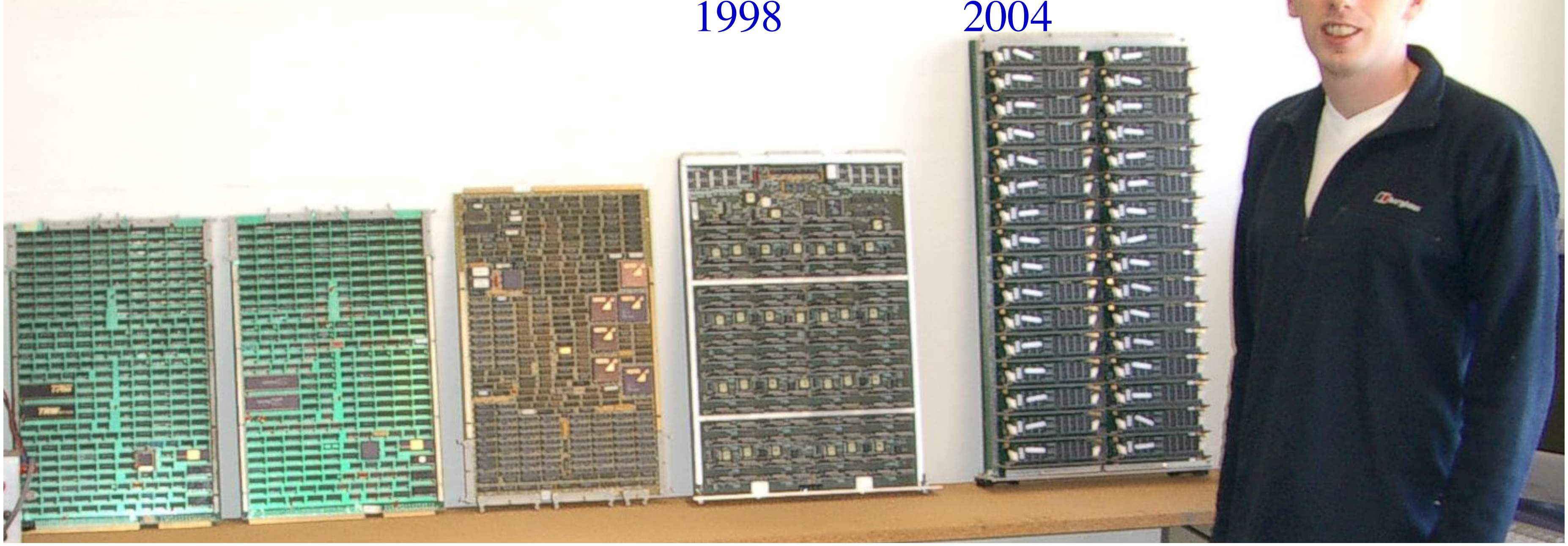
Fermi64 Node: 0.016 GFlops (1987)

Fermi256 Node: 0.063 GFlops (1989)

QCDSP Motherboard: 3.2 GFlops 1998

QCDOC Motherboard: 51.2 GFlops 2004

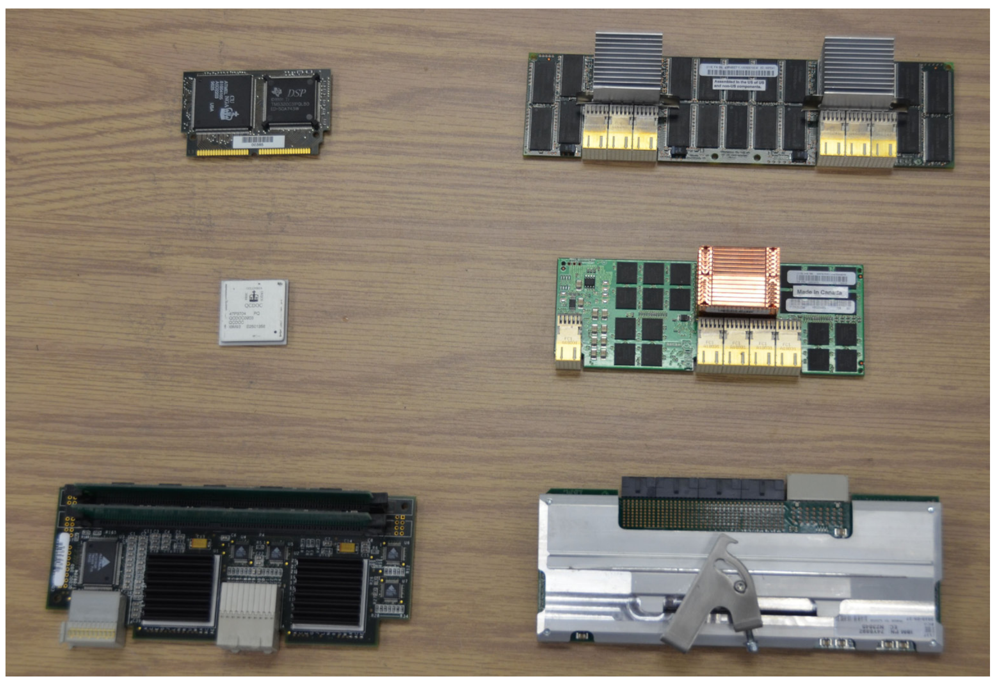
Peter Boyle



QCDSP node: 0.050 MFlops

QCDOC chip: 0.800 MFlops

2 QCDOC nodes: 0.800 MFlops each



2 BG/L nodes: 2.8 GFlops each

BG/P node: 13.6 GFlops

BG/Q node: 204.8 GFlops

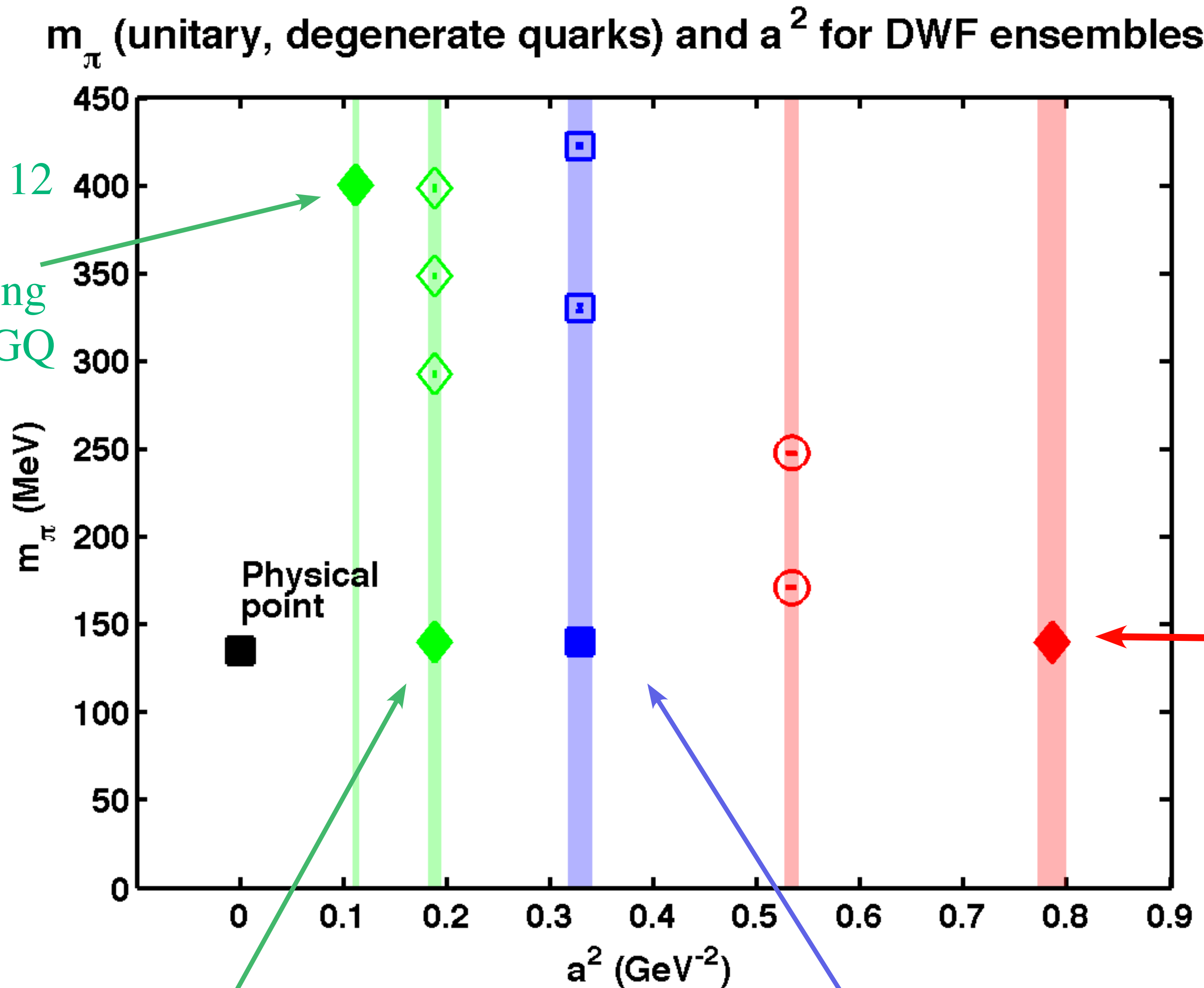
BGQ Status

- DD2 rack running well
  - * IBM XL compilers installed, ESSL libraries here
  - * User access from front end node, SLURM queue system being tested
  - * Allocation committee has given initial allocations - QCD currently dominant use
  - * USQCD gets 10% of this machine, also contribute to operations costs
- DD1 rack in production use and hardware bugs still being fixed
  - * Currently 3 256-node partitions and 9 128-node partitions available
  - * MTBF: 1-3 days
  - * Removed ~30 weak compute cards in July-August, markedly improving MTBF
  - * Current issues are primarily power supply related. IBM helping resolve them
  - * 4 fully populated nodeboards arriving in 2 weeks (in the mail now). Means 128 extra compute nodes as well as 4 nodeboards for spares
  - * Much useful physics being done, but we expect to achieve better reliability.
- BNL BGQ upgraded to IBM's V1R1M1 software driver (V1R1M2 recently released)

BGQ Hardware Tasks

- Replace node boards in DD1 to improve reliability
- Some DD1 power supply problems may be control system reporting errors. We may be able to modify control system to ignore these errors.
- Get queue system up to production standards.
- Purchase parts cache for DD1 and DD2 (thanks to BNL for this support)
- We are currently using NYBlue file systems for the BGQ and are getting quotes for an additional file system dedicated to BGQ (thanks to BNL for this support).
- USQCD has received money for 1/2 rack of BGQ at BNL. Procurement underway

RBC/UKQCD 2+1 flavor DWF ensembles



$32^3 \times 64 \times 12$ DWF Thermalizing on BNL BGQ

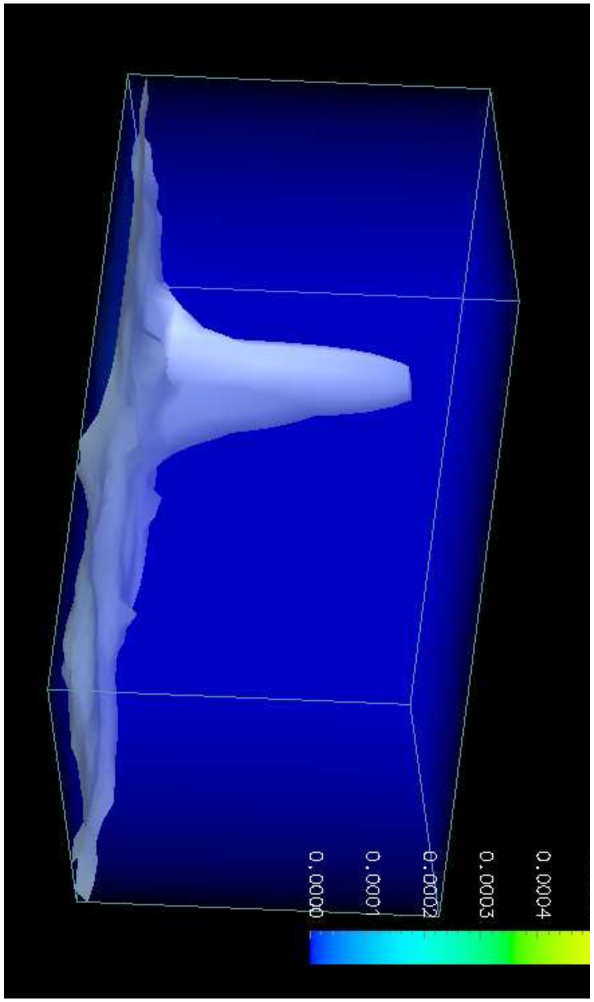
$32^3 \times 64 \times 24$ MDWF T=0 ensemble as part of finite T DWF with HotQCD Started at LLNL Now running at Argonne

$64^3 \times 128 \times 10$, MDWF
Started on BNL BGQ
Then evolved at Edinburgh
Currently evolving at Argonne

$48^3 \times 96 \times 24$, MDWF
Started on BNL BGQ
Currently evolving at Edinburgh

Improving Domain Wall Fermions

- When underlying gauge field changes topology, the DWF modes can extend farther in the fifth dimension
- This gives a non-perturbative contribution to residual chiral symmetry breaking
- Becomes problematic at strong coupling
- Add ratio of determinants of twisted Wilson fermions to suppress these gauge field dislocations
- Tune to minimize residual mass while still preserving toplogical ergodicity



$$\frac{\det\left[D_W(-M+i\varepsilon_f\gamma^5)^\dagger D_W(-M+i\varepsilon_f\gamma^5)\right]}{\det\left[D_W(-M+i\varepsilon_b\gamma^5)^\dagger D_W(-M+i\varepsilon_b\gamma^5)\right]} = \prod_i \frac{\lambda_i^2+\varepsilon_f^2}{\lambda_i^2+\varepsilon_b^2}$$

λ_i are eigenvalues of the Hermitian Wilson operator $\gamma^5 D_W$

Mobius Domain Wall Fermions

- A generalization of DWF with smaller m_{res} for a fixed L_s

$$D_{\mathrm{DW}}(m) =$$
$$\begin{pmatrix} D_+^1 & D_-^1 P_- & & & & -mD_-^1 P_+ \\ D_-^2 P_+ & D_+^2 & D_-^2 P_- & & & \\ & D_-^3 P_+ & \cdots & \cdots & & \\ & & \cdots & \cdots & \cdots & \\ & & & \cdots & \cdots & D_-^{2N-1} P_- \\ -mD_-^{2N} P_- & & & & D_-^{2N} P_+ & D_+^{2N} \end{pmatrix}$$

  - $D_+^i = 1 + b_i D_W$
  - $D_-^i = -1 + c_i D_W$
  - plain DWF is a special case: $b_i = 1$, $c_i = 0$ for all i.

Reference: R.C. Brower, H. Neff and K. Orginos, Nucl. Phys. B(Proc. Suppl.) 153(2006) 191-198.

- Dirac solver supported in Boyle's Bagel assembly code
- Evolution code for Mobius DWF implemented in CPS by my graduate student, Hantao Yin (big job!). DWF evolution code and CPS ported to BGQ by Chulwoo Jung
- Reduces L_s but CG iteration counts increase.
- For $\beta = 2.13$, DWF+I, MDWF cuts m_{res} to $m_l/3$ from DWF value of $2m_l/3$ for same cost

m_{res} versus L_s for DWF and MDWF

1 Results from $24^3 \times 64$, $\beta = 2.13$ lattice.

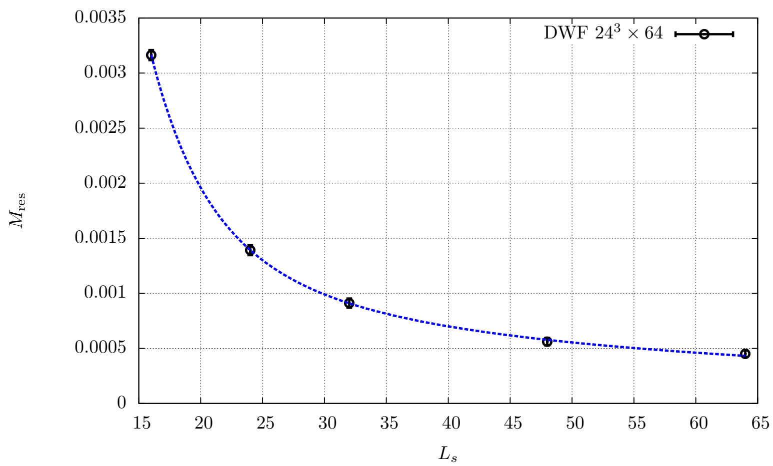


Figure 1: M_{res} as a function of L_s. Measured on $24^3 \times 64$, $\beta = 2.13$, $m_l = 0.005$ ensemble. The measurement uses $m_l = 0.005$ and plain DWF.

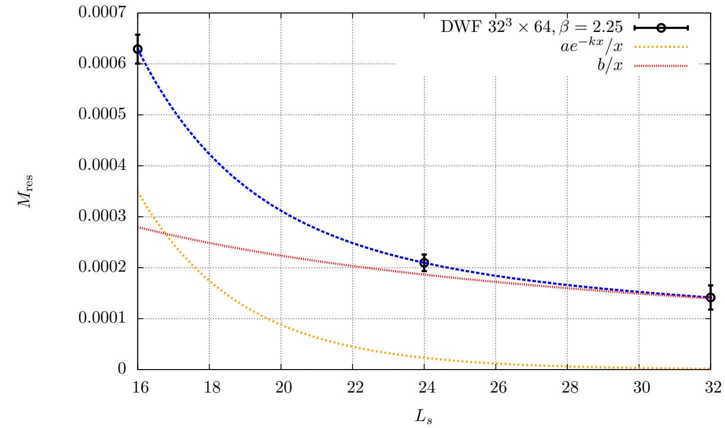


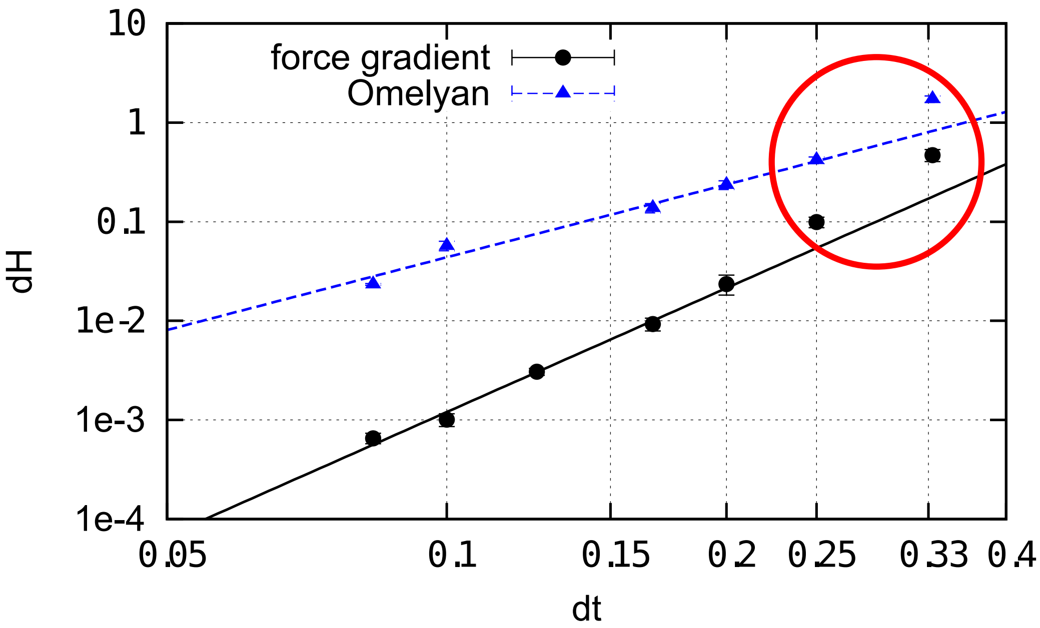
Figure 3: M_{res} as a function of L_s. Measured on $32^3 \times 64$, $\beta = 2.25$, $m_l = 0.004$ ensemble. The measurement uses $m_l = 0.004$ and plain DWF.

Graphs from Hantao Yin

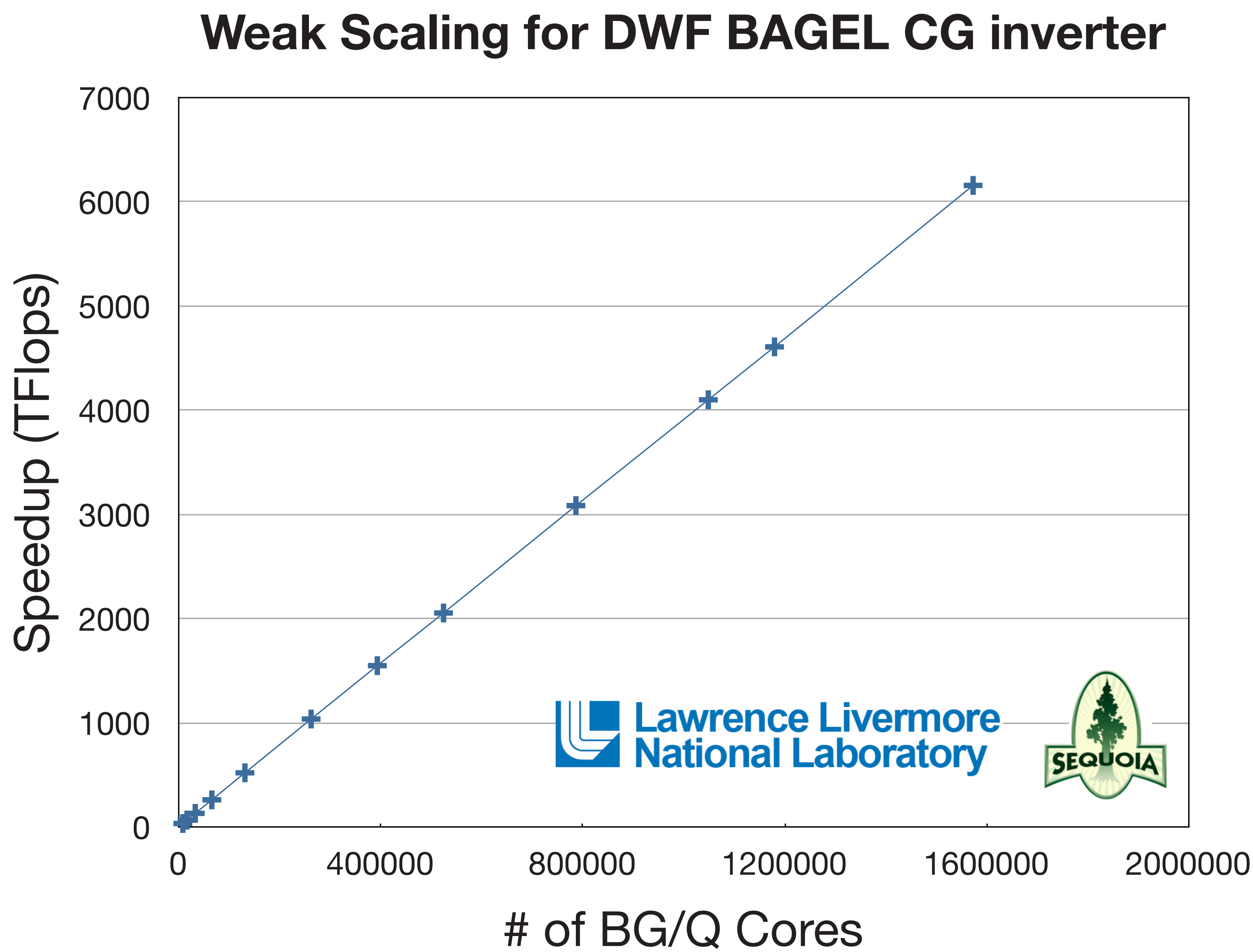
	$48^3 \times 96 \times 48$	$64^3 \times 128 \times 20$	$48^3 \times 96 \times 24$	$64^3 \times 128 \times 10$
	$\beta = 2.13$ (DWF)	$\beta = 2.25$ (DWF)	$\beta = 2.13$ (scaled DWF) $c = 0.5$	$\beta = 2.25$ (scaled DWF) $c = 0.5$
am_{res}	0.00055	0.00031	0.00055	0.00031
m_{ud}(tot)	0.00133	0.000971	0.00133	0.000971
m_s(tot)	0.0367	0.0269	0.0367	0.0269
m_{ud}(input)	0.00078	0.000661	0.00078	0.000661
m_s(input)	0.0362	0.0266	0.0362	0.0266

Force Gradient Integrator

- Proposed by Clark and Kennedy. Implemented (and simplified) in CPS by Hantao Yin
- For $16^3 \times 32 \times 16$ volumes, no speed-up compared to $O(\delta\tau^2)$ Omelyan



- For larger volumes, where δH grows with volume, force gradient may be helpful
- Tests on $48^3 \times 64 \times 16$ with 220 Mev pions using force gradient and retuning Hasenbush masses, 184 minutes/accepted configuration went down to 108 minutes/accepted configuration.



Code developed by Peter Boyle at the STFC funded DiRAC facility at Edinburgh

Code rerun on 96 rack Sequoia BGQ at LLNL on 10/26/12, and achieved 6.16 PF.

Summary

- 3 racks of pre-production BGQ installed at BNL. The 2 RBRC racks are currently running physics jobs while we are working to improve the mean time between failure.
- Procuring disk systems and a USQCD 1/2 BGQ rack is expected in 2-3 months
- The RBC and UKQCD Collaborations are aggressively using additional resources to generate thermalized lattices
- RBRC and BNL BGQ's have played a vital role in this, in that the current production evolution codes (by Chulwoo Jung and Hantao Yin, using Dirac solver of Peter Boyle) were written, tested and initially deployed at BNL. Without this access, our collaboration would not be able to exploit early science time on the large machines at LLNL and ANL. Leverage QCDCQ resources by 10-20×
  - ANL: T = 0 jobs running on 8 and 16 rack systems
  - LLNL: Finite T DWF jobs running on up to seven 1 rack systems many evenings
- Also major effort by RBC members to update measurement codes for BGQ machines.
- BGQ at BNL also supporting thermodynamics work and kaon physics, as discussed by Taku Izubuchi and Norman Christ.
- Peter Boyle, Norman Christ and I are also involved in discussions with IBM about the next generation of computers. Very exciting possibilities.

Electroweak Properties of the Nucleon from Lattice QCD

Brian Tiburzi

8 November 2012

NSF
the City College of New York
CUNY
RIKEN BNL Research Center

Overview

- **Goals**:
  Calculate electroweak properties of hadrons from first principles
  Confront current and future experiments

- **Tools**:
  Lattice QCD
  Chiral Perturbation Theory

- **Focus**:
  Electromagnetic properties of hadrons
  Parity-violating interactions among hadrons

On-going work with: W. Detmold (*MIT*), A. Walker-Loud (*LBNL*), S. Vayl (*CUNY*)

Electromagnetic Properties: Polarizabilities

Electromagnetic Polarizabilities

Chiral Perturbation Theory

$$m_\pi^2 = \lambda\, m_q$$

- Pions are the lightest states in QCD (would be massless)
- Pion interactions (with photons, pions, nucleons) constrained

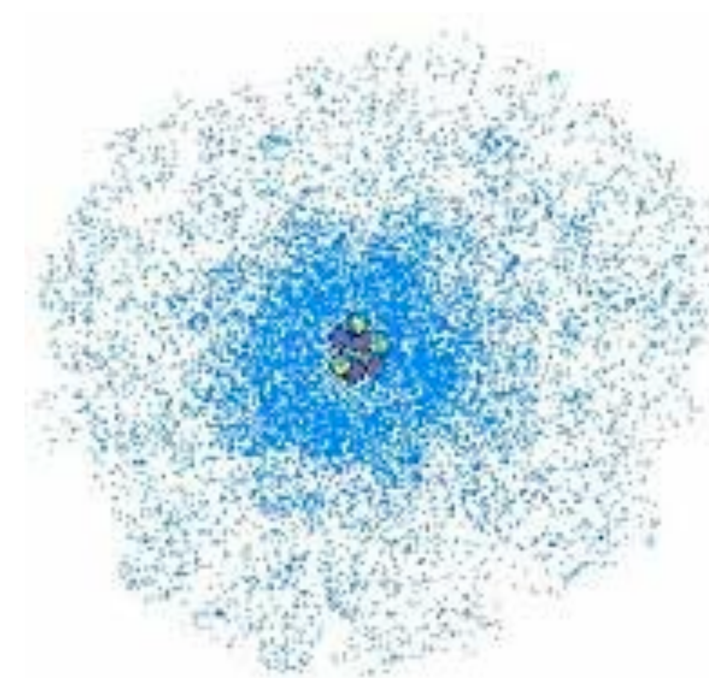
Elegant femtoscale picture of QCD from phenomenology

E.g. chiral electromagnetism of the nucleon

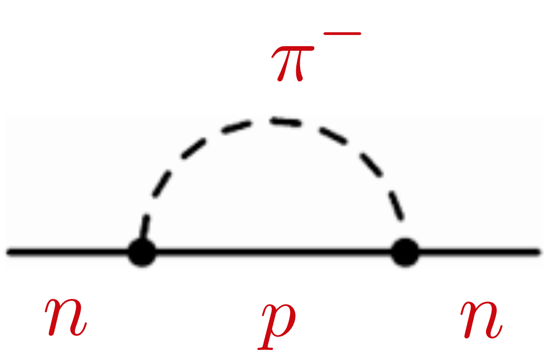
$$H = -\vec{\mu}\cdot\vec{B} - \frac{1}{2}\alpha_E \vec{E}^{\,2} - \frac{1}{2}\beta_M \vec{B}^{\,2}$$

Induced dipole moment in electric field $\vec{p} = -\alpha_E \vec{E}$

$$\alpha_E^{H-\mathrm{atom}} = \frac{27}{8\pi}\left(\frac{4}{3}\pi a_B^3\right) \qquad \alpha_E^N \sim 0.03 e^2 \left(\frac{4}{3}\pi[\mathtt{fm}]^3\right)$$



Second order perturbation theory: nearby states contribute most



$$\alpha_E^N \sim -\frac{e^2 \langle N|\pi N\rangle\langle \pi N|N\rangle}{E_N - E_{\pi N}} = e^2 \frac{g_{\pi NN}^2}{m_\pi}$$

Electromagnetic Polarizabilities

Chiral Perturbation Theory

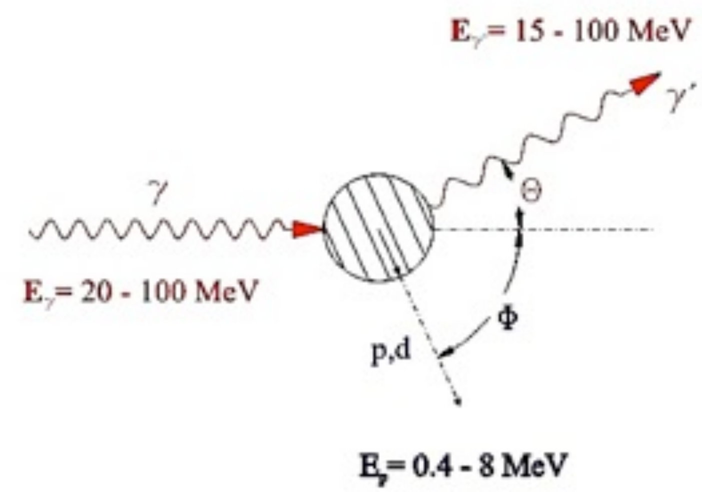
$$m_\pi^2 = \lambda\, m_q$$

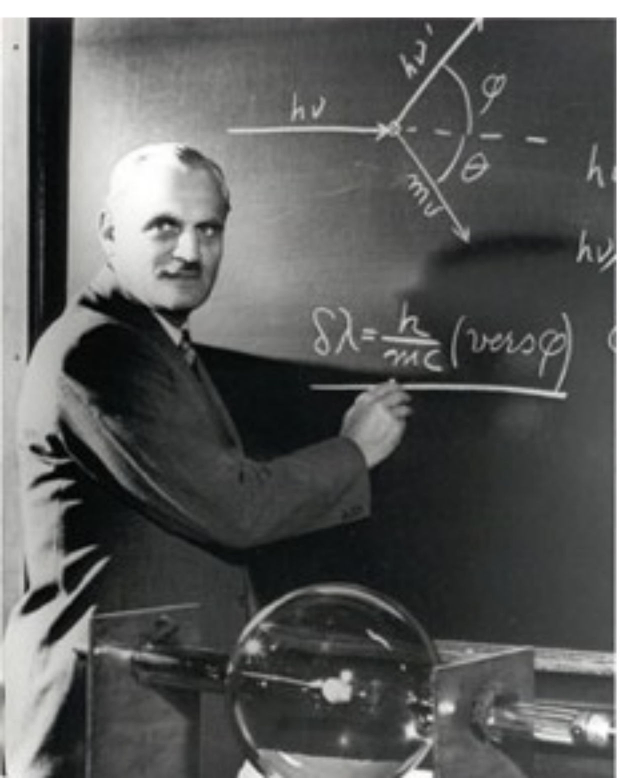
- Pions are the lightest states in QCD (would be massless)
- Pion interactions (with photons, pions, nucleons) constrained

Elegant femtoscale picture of QCD from phenomenology

Compton Scattering Experiments

Motivated by ***discrepancies*** with chiral dynamics: large corrections, relativistic limit poor expansion?





COMPASS expt. (CERN Switzerland)

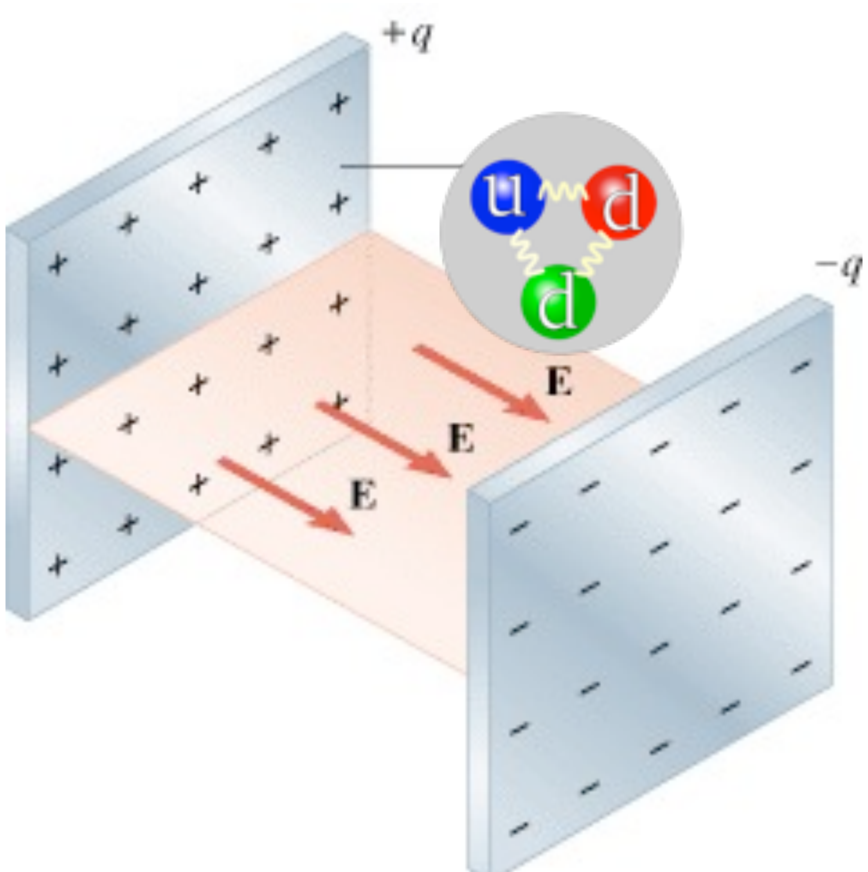
COMPTON expt. MAX-Lab (Lund Sweden) neutron pols from scattering

HIγS @ TUNL (Duke Univ. USA) high precision extraction of all nucleon pols

Polarizabilities from Lattice QCD? Use External Fields

Couple classical electromagnetic fields to quarks and then study hadrons

$$D_\mu = \partial_\mu + ig\,G_\mu + iqA_\mu$$



Gauge links

$$U_\mu(x) = e^{igG_\mu(x)} \in SU(3)$$

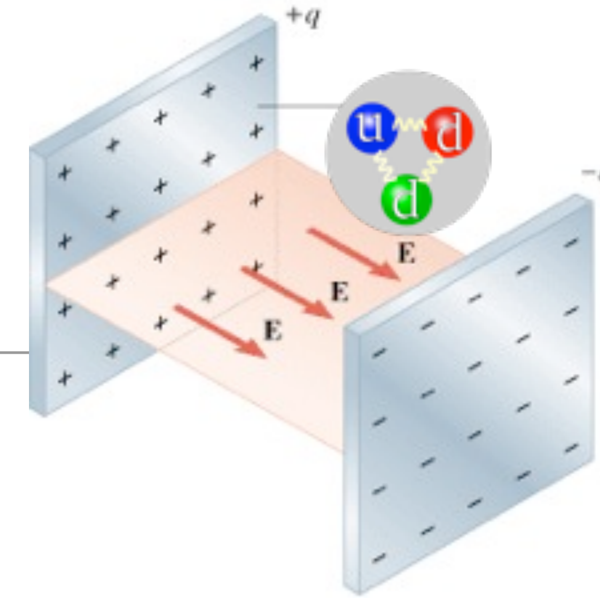
$$U_\mu^{\text{e.m.}}(x) = e^{iqA_\mu(x)} \in U(1)$$

In our exploratory studies:
U(1) field couples only to valence quarks

ChPT predicts the sea quark charge dependence of polarizabilities

Detmold, Tiburzi, Walker-Loud, PRD 73 (2006)　　Hu, Jiang, Tiburzi, PRD 77 (2008)

Lattice QCD in External Fields



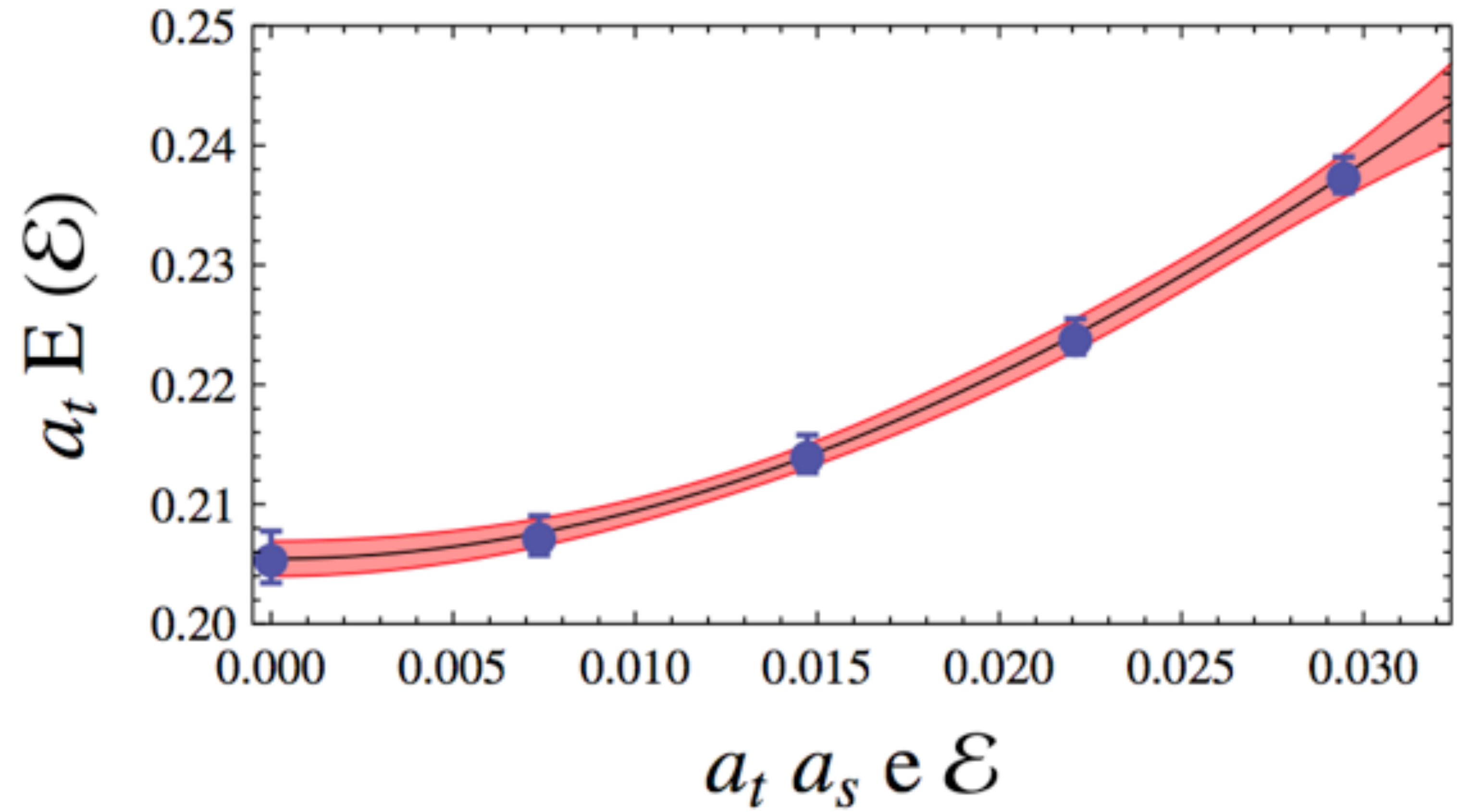
- Neutral QCD bound states in classical E&M fields

$$e|\vec{E}| \sim \mathtt{MeV/fm} = 10^{21}\,\mathtt{eV/m}$$

- Apply long time limit to filter out ground state energy $\sim e^{-E_N \tau}$

$$E_N = M_N - \frac{1}{2}\vec{E}^2\left(\alpha_E - \frac{\mu_N^2}{4M_N^3}\right)$$

NEUTRON



DETMOLD, TIBURZI, WALKER-LOUD, PRD 81 (2010)

First results:

$$\alpha_E^n = 3(1) \times 10^{-4}\,\mathtt{fm}^3$$
$$(\alpha_E^n)_{\text{exp}} = 11(2) \times 10^{-4}\,\mathtt{fm}^3$$

Actually must remove magnetic moment!

$$\vec{B} = \vec{v} \times \vec{E}$$

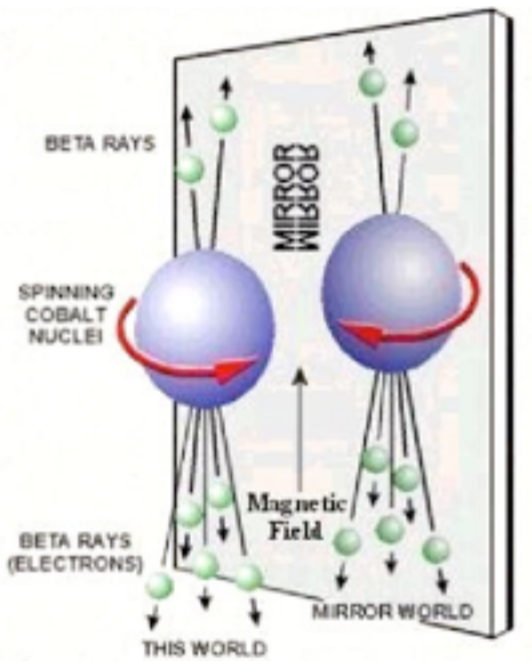
$$\mu_n = -1.6(1)\,[\mu_N]$$
$$(\mu_n)_{\text{exp}} = -1.9\,[\mu_N]$$

Our results have a variety of systematic errors

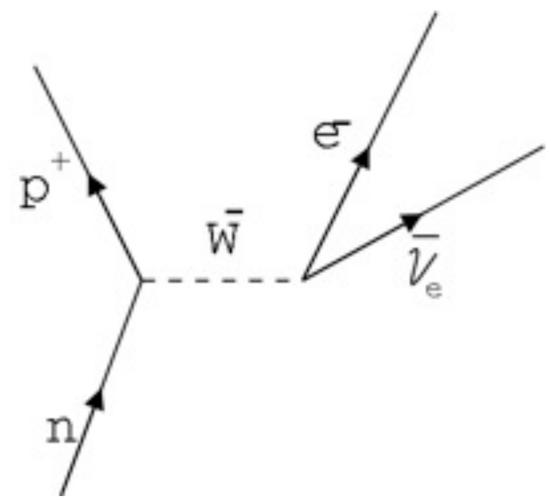
Weak Interactions: Hadronic Parity Violation

Nuclear & Hadronic Parity Violation

- Parity Violation in the Weak Interaction $G_F = \frac{\sqrt{2} g^2}{8 M_W^2} = 10^{-5}/\mathtt{GeV}^2$

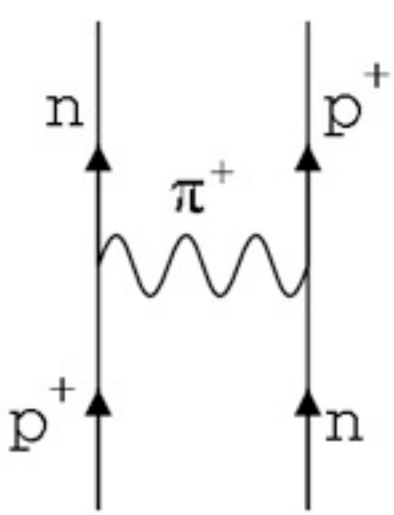


$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left(\overline{u}_L \gamma_\mu d_L\right) \left(\overline{\nu}_L \gamma^\mu e_L\right)$$



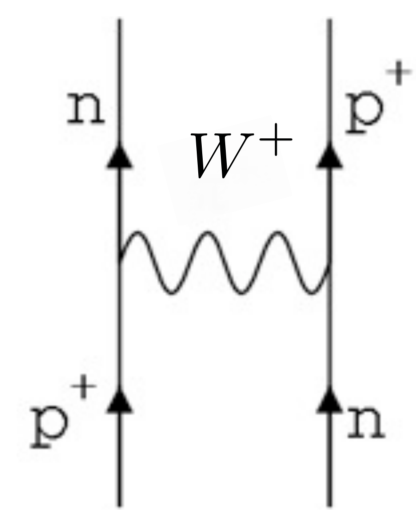
$$\langle p | V | n \rangle \sim g_V$$
$$\langle p | A | n \rangle \sim g_A$$

- Long-Range Nuclear Force from Strong Interactions



$$\sim \left(\frac{g_A}{f_\pi}\right)^2 \frac{q \cdot \sigma_1 \, q \cdot \sigma_2}{q^2 + m_\pi^2}$$

G_F



Nucleon-Nucleon Weak Interactions

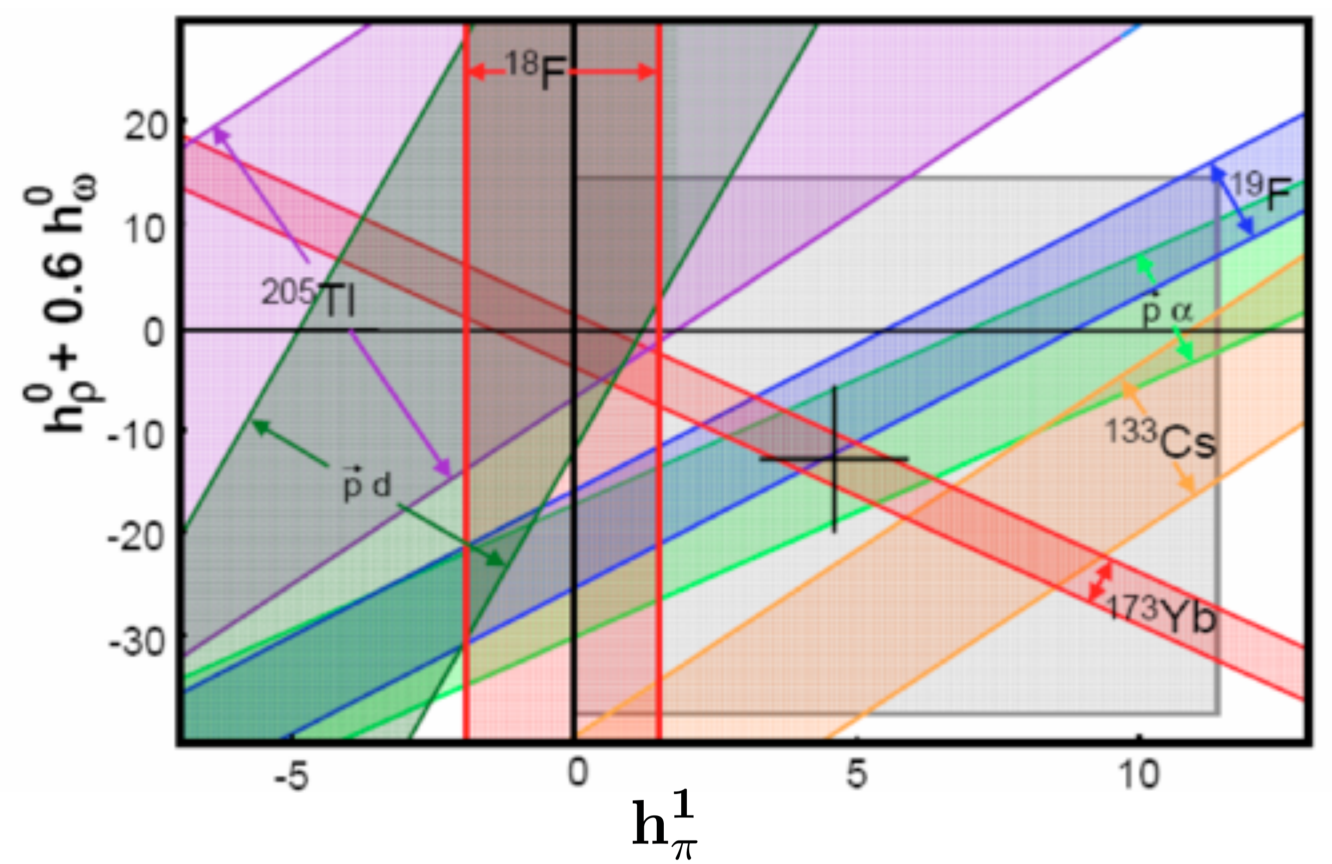
$$G_F f_\pi^2 \sim 10^{-7}$$

Nuclear Parity Violation

Violate strong interaction symmetries to expose weak nuclear force

- (Many) Parity Violating Nuclear reactions have been seen starting in 1967

(*Model Dependent*) **Parity Violating Nuclear Force**



- **Program to remove model dependence in NN, NNN, ...**

Zhu Maekawa Holstein Ramsey-Musolf van Kolck, Phillips Schindler Springer Grießhammer, Shin Ando Hyun, Vanasse, . . .

- New neutron experiments will constrain PV in few-body systems
- Forthcoming: $n + {}^4\mathrm{He}$ $\vec{n}p \to d\gamma$ at NIST and Oak Ridge

Parity Violation from Lattice QCD?

Perturbative QCD: Connect Standard Model to QCD scale

Tiburzi, PRD 85 (2012), & PRD in press

Lattice QCD: Connect Four Quark Ops. to Observables

- **Organize with Effective Theory**

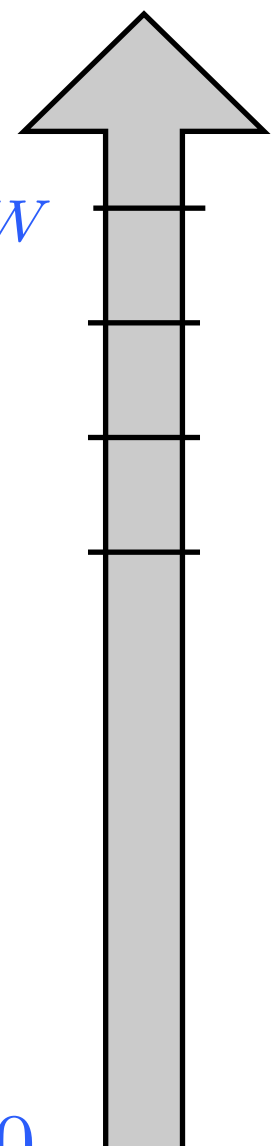
$\Delta F = 1, 2$

Weak Scale PV M_Z, M_W

Fermi Theory PV

m_Q

μ QCD Scale PV Λ_{QCD}



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Weak Scale FC

Fermi Theory FC

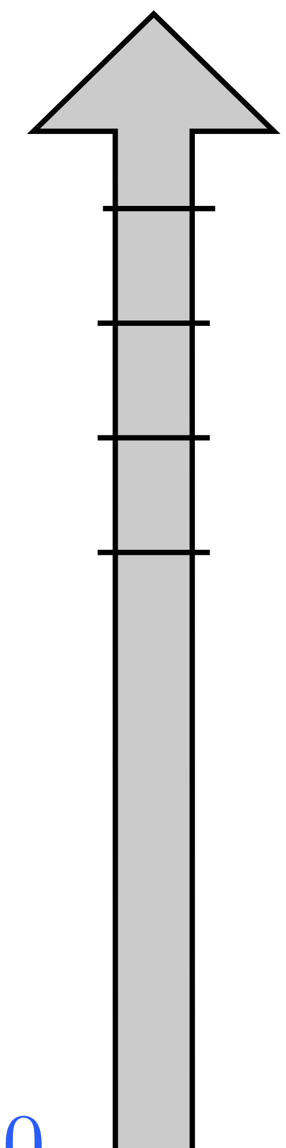
QCD Scale FC

e.g.

$K \to \pi\pi$

$\Delta I = 1/2$

$\cdots$



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Four-Quark Correlations deep inside hadrons

$\sim 1/100\,\texttt{fm}$

Future Directions

- **Electromagnetic Polarizabilities**

  Move beyond exploratory studies: remove systematics, closer to making predictions

  Propose(d) and carry out tests of method for magnetic fields
  Tiburzi, Vayl, arXiv:1210.4464

- **Hadronic Parity Violation**

  Exploratory studies needed: isotensor channel as proving ground?

  Multi-hadron matrix elements are challenging on the lattice, auxiliary fields?

Exploring Full QED Effects through Reweighting

"Full QED+QCD Low-Energy Constants through Reweighting"
T.I, T. Blum, M. Hayakawa, T. Izubuchi, C. Jung and R. Zhou
[Phys. Rev. Lett. 109, 072002 (2012), arXiv:1202.6018]

Tomomi Ishikawa (RIKEN BNL Research Center)

tomomi@quark.phy.bnl.gov

RBRC Scientific Review Committee Meeting
2012/11/6-8, Brookhaven National Laboratory

Lattice QCD + QED

Successful of the lattice QCD

- Lattice QCD calculations have become more and more precise.
  - Increase of computer power (BG/Q, K-computer, GPU, ...)



  - Full QCD simulation (Hybrid Monte Carlo Simulation)
  - Lighter quark mass parameter (Domain Decomposition, Mass precondition, ...)
  - Larger volume, Finer lattice, ...

Including QED as a next step

- Isospin breaking is becoming non-negligible effect.
  - In experiment, isospin breaking effects are measured in high accuracy.
  - QED effects need to be included.

$$(Q_{\mathrm{u}}, Q_{\mathrm{d}}, Q_{\mathrm{s}}) = (0,0,0) \longrightarrow (Q_{\mathrm{u}}, Q_{\mathrm{d}}, Q_{\mathrm{s}}) = (+2/3, -1/3, -1/3)$$

Full QCD + quenched QED

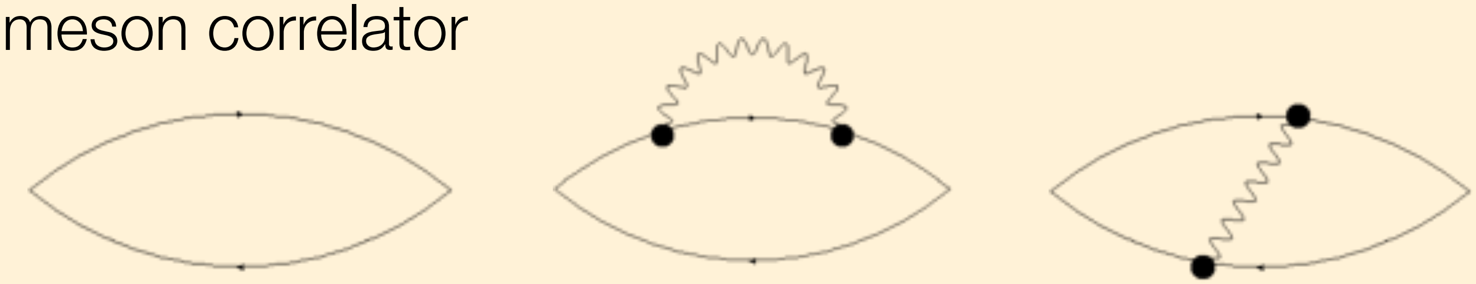
Quenched approximation as a first attempt

- Blum et al.'s work

T. Blum, T. Doi, M. Hayakawa, T. Izubuchi and N. Yamada
[Phys. Rev. D76, 114508 (2007), arXiv:0708.0484]

T. Blum, R. Zhou, T. Doi, M. Hayakawa, T. Izubuchi, S. Uno and N. Yamada
[Phys. Rev. D82, 094508 (2010), arXiv:1006.1311]

e.g. meson correlator



$O(1)$ $O(e^2)$ Sea U(1) charges are neglected.

- U(1) gauge field is superimposed on dynamical domain-wall fermion QCD ensemble.

$$U_\mu[\mathrm{QCD}+\mathrm{QED}] = U_\mu[\mathrm{QCD}] \times U_\mu[\mathrm{QED}]$$

- Non-compact U(1) gauge field

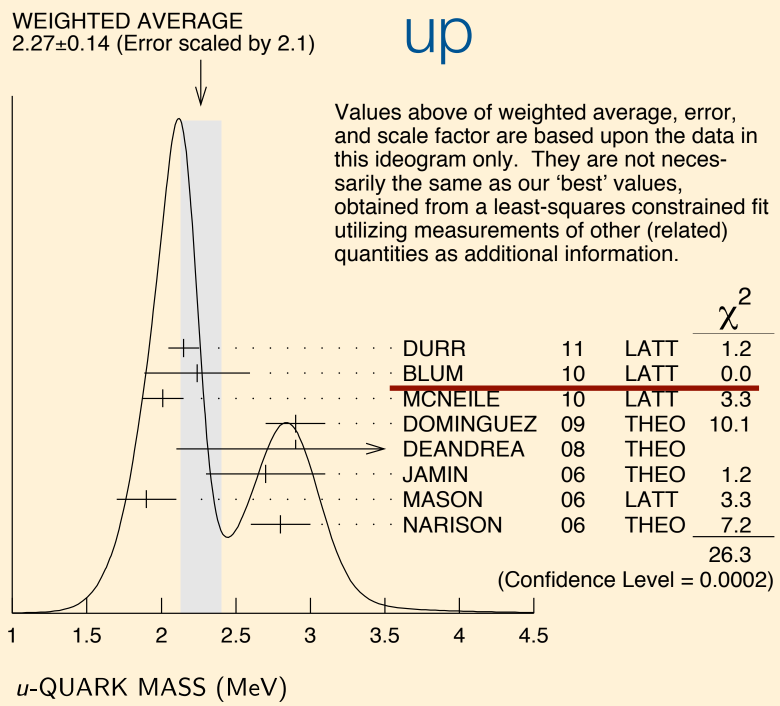
$$S_{U(1)} = \frac{1}{4e^2}\sum(\partial_\mu A_\nu - \partial_\nu A_\mu)^2, \quad U_\mu[\mathrm{QED}] = e^{iQeA_\mu}$$

Full QCD + quenched QED

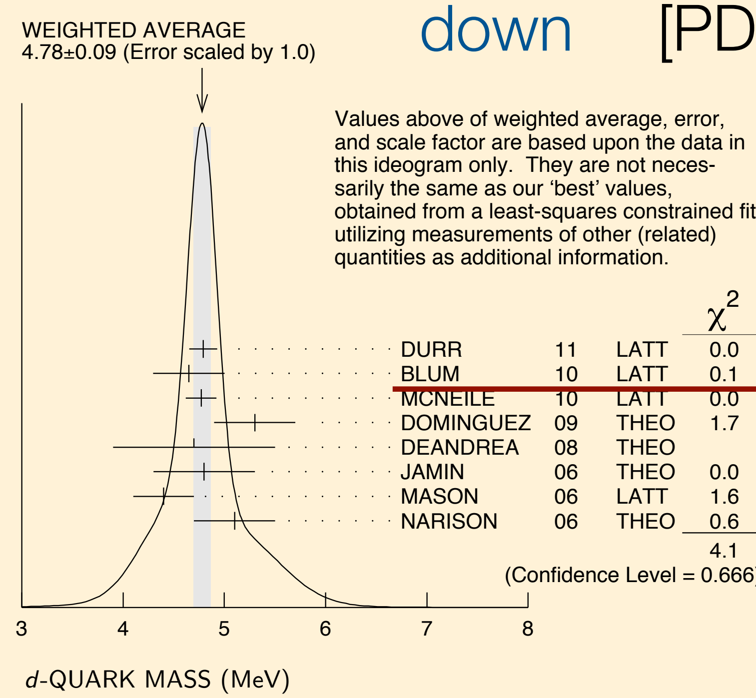
Quenched approximation as a first attempt

- up and down quark masses

up

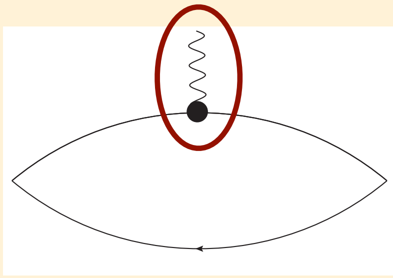


down [PDG (2012)]

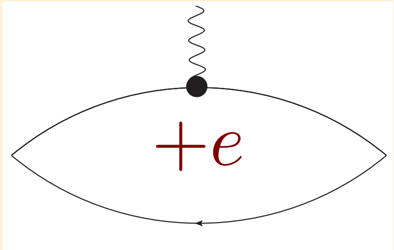


- Valuable technique (+/-e trick)

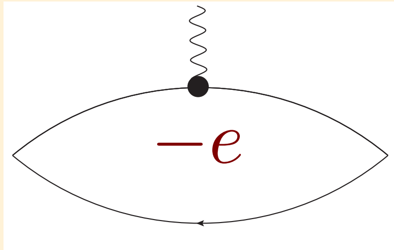
At finite statistics, unphysical contributions could be remained.
They could cause large noise in correlators.



+/-e averaging removes unwanted O(e) contribution.



+



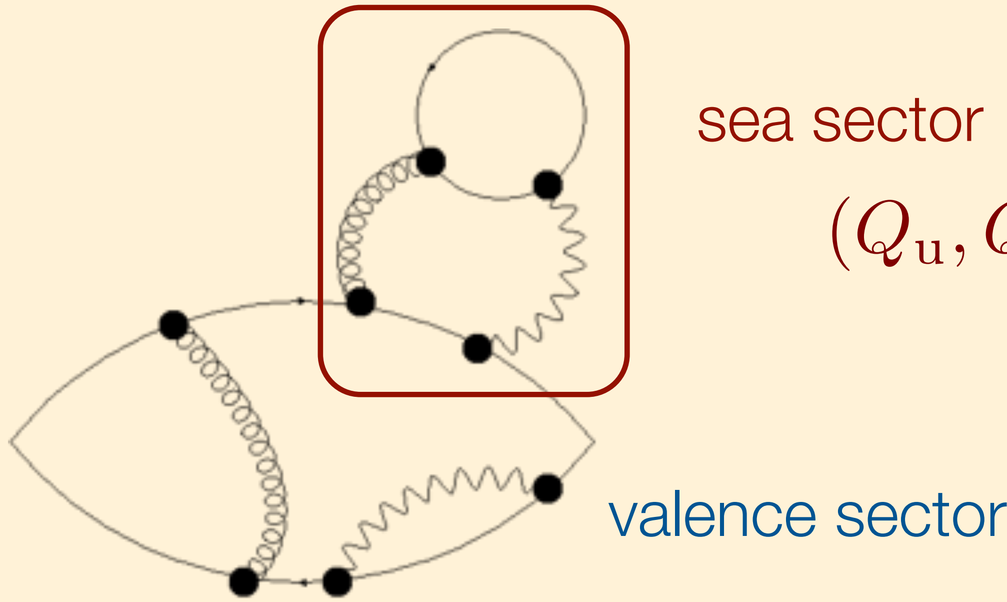
= 0 exact cancelation

It can be extended for full QED.

Full QCD + full QED

Full QED effect

- U(1) charge in sea quark sector



$$(Q_{\rm u}, Q_{\rm d}, Q_{\rm s}) = (+2/3, -1/3, -1/3)$$

(Naive) algorithm for full QED

- Dynamical fermion (Hybrid Monte Carlo)
  - Standard method for full QCD sector
  - Promising way (maybe)
  - But we need to generate gauge ensemble including sea quarks with QED, again.

Reweighting

Full QED from quenched QED

- Reweighting method [Duncan et al. (2005)]

quark det with QCD+QED

$$\langle O\rangle_{\mathrm{QCD+QED}} = \frac{\int \mathcal{D}U\mathcal{D}A O'[\widetilde{U}] e^{\ln \det D[\widetilde{U}] - S_{SU(3)}[U] - S_{U(1)}[A]}}{\int \mathcal{D}U\mathcal{D}A e^{\ln \det D[\widetilde{U}] - S_{SU(3)}[U] - S_{U(1)}[A]}}$$

$$= \frac{\int \mathcal{D}U\mathcal{D}A O'[\widetilde{U}] \frac{\det D[\widetilde{U}]}{\det D[U]} e^{\ln \det D[U] - S_{SU(3)}[U] - S_{U(1)}[A]}}{\int \mathcal{D}U\mathcal{D}A \frac{\det D[\widetilde{U}]}{\det D[U]} e^{\ln \det D[U] - S_{SU(3)}[U] - S_{U(1)}[A]}}$$

quark det only with QCD

Full QED effects are taken into account by the reweighting factor:

$$w[U_{\mathrm{QCD}}, A] = \frac{\det D[U_{\mathrm{QCD}} \times e^{iqeA}]}{\det D[U_{\mathrm{QCD}}]}$$

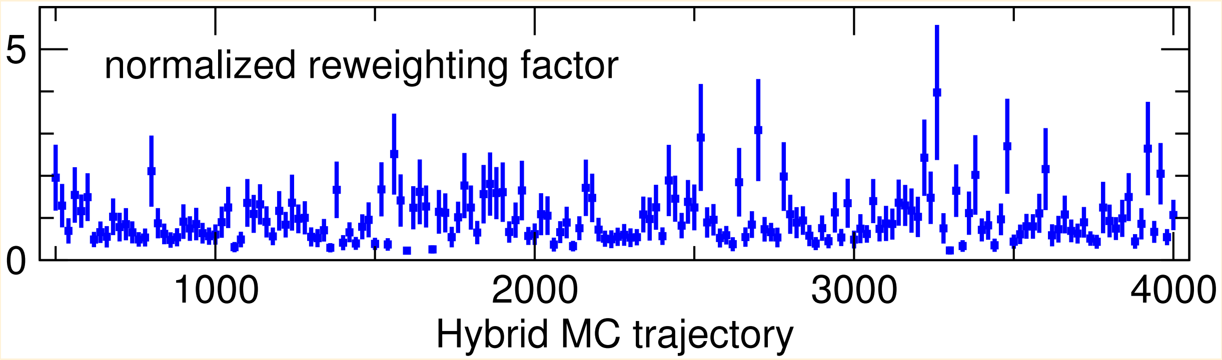
on the dynamical QCD configuration U_{QCD} .

Generation of dynamical QCD+QED ensemble is not needed.

Simulation

- Nf=2+1 dynamical domain-wall fermion + Iwasaki gluon configurations [RBC+UKQCD]
    - $\beta = 2.15 \ (a^{-1} = 1.78 \text{ GeV}), L^3 \times T = 16^3 \times 32 \ ((1.8 \text{ fm})^3)$
    - $[m_{ud}, m_s] = [0.01, 0.04] \ (m_\pi \sim 450 \text{ MeV})$
    - ~60 independent gauge configurations
- Calculation of reweighting factor
    - Stochastic estimation
    - Usually, the distribution of reweight factor in the stochastic estimation is largely skewed. Root-trick is used to avoid the problem.

      [T. I, Y. Aoki and T. Izubuchi (2009)]
    - Not so bad overlap between original ensemble and reweighted ensemble.



Extraction of QED LEC's

Full QED effect in ChPT

- SU(3), NLO, partially quenched formula [Bijnens and Danielsson (2007)]

$$\begin{aligned}\Delta M_{\rm PS}^2 &= M_{\rm PS}^2[\text{full QED}] - M_{\rm PS}^2[\text{quenched QED}] \\ &= -4e_{\rm s}^2 Y_1 \mathrm{tr} Q_{\rm s(3)}^2 \chi_{13} \\ &\quad + e_{\rm s} e_{\rm v} \frac{C}{F_0^4} \frac{1}{8\pi^2} \sum_{i=4,5,6} \left(\chi_{1i} \ln \frac{\chi_{1i}}{\mu^2} - \chi_{3i} \ln \frac{\chi_{3i}}{\mu^2} \right) q_i (q_1 - q_3)\end{aligned}$$

$e_{\rm s}$: sea
$e_{\rm v}$: valence

$$\chi_{ij} = B_0(m_i + m_j), \;\; Q_{s(3)} = \mathrm{diag}(q_4, q_5, q_6)$$
$$(m_1, m_3) = (m_{\rm val1}, m_{\rm val2}), \quad (m_4, m_5, m_6) = (m_{\rm u}, m_{\rm d}, m_{\rm s})$$

- Y_1 : new low-energy constant (LEC) which is related to full QED part.
- C : LEC which is related to Dashen's term (LO QED effect)

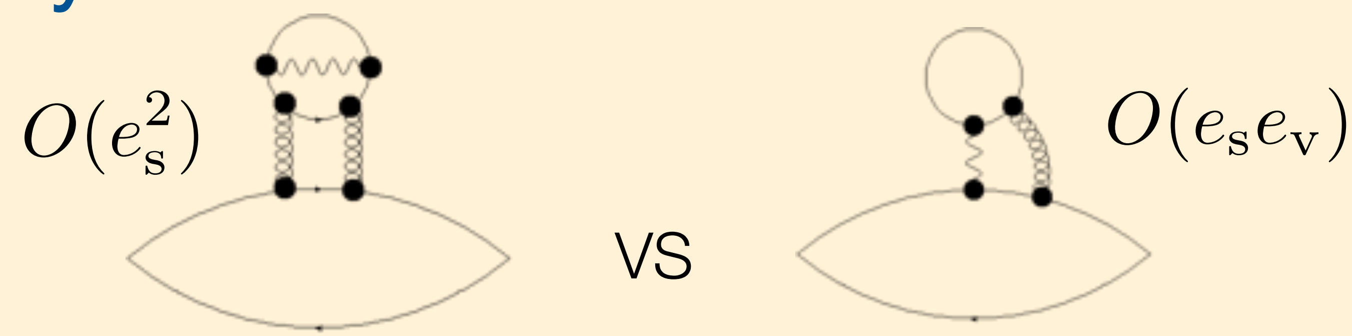
$$M_{\rm PS}^2 = \chi_{13} + e_{\rm v}^2 \frac{2C}{F_0^2} + O(m \ln m, \; e^2 m \ln m, \; e^2 m)$$

It can be obtained from quenched QED. → $10^7 C = 2.2(2.0)$ [Blum et al. (2010)]

LEC C can be used for a validity check of the reweighting procedure.

Extraction of QED LEC's

Large hierarchy



- $O(e_s e_v)$ term can easily get large suppression.
  - When $m_1 \sim m_3$:

$$\left(\chi_{1i} \ln \frac{\chi_{1i}}{\mu^2} - \chi_{3i} \ln \frac{\chi_{3i}}{\mu^2}\right) q_i (q_1 - q_3) \sim 0$$

  - When $m_4 = m_5 \sim m_6$, $q_4 + q_5 + q_6 = 2/3 - 1/3 - 1/3 = 0$:

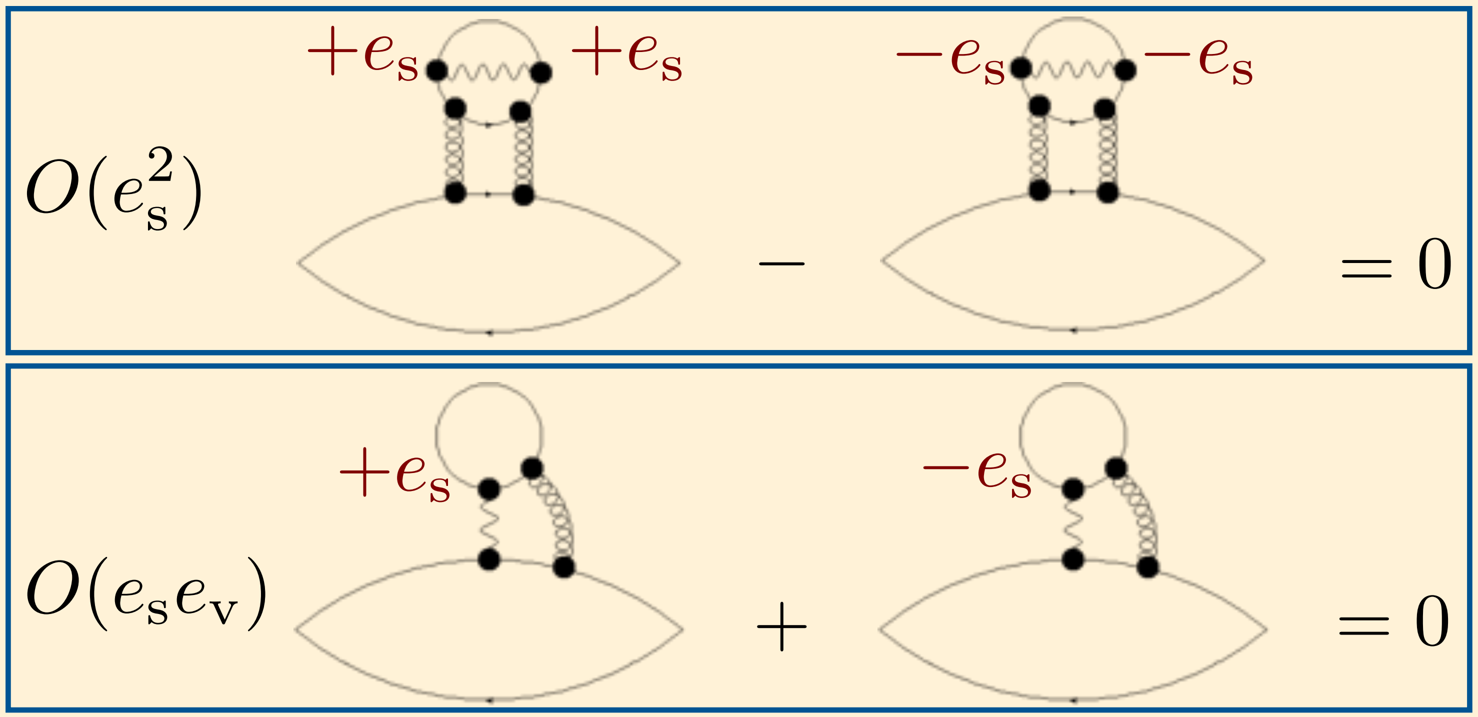
$$\sum_{i=4,5,6} \chi_{1i} \ln \frac{\chi_{1i}}{\mu^2} q_i \sim 0, \quad \sum_{i=4,5,6} \chi_{3i} \ln \frac{\chi_{3i}}{\mu^2} q_i \sim 0$$

The large hierarchy causes a problem in determination of LEC C .

Extraction of QED LEC's

Solving the hierarchy

- Extension of +/- e trick using partially quenched setting



Exact relation.

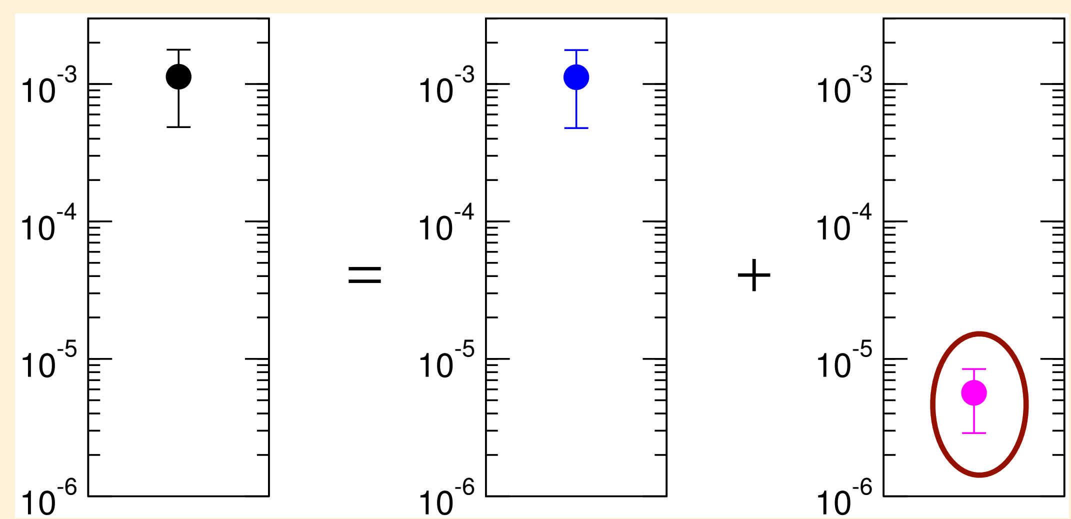
Use this trick to separate $O(e_s^2)$ and $O(e_s e_v)$.

- Actual simulation data

$\Delta m^2_{\pi^+}$

$(m_1,\ m_3) = (0.01,\ 0.03)$

We can easily separate terms with large hierarchy.

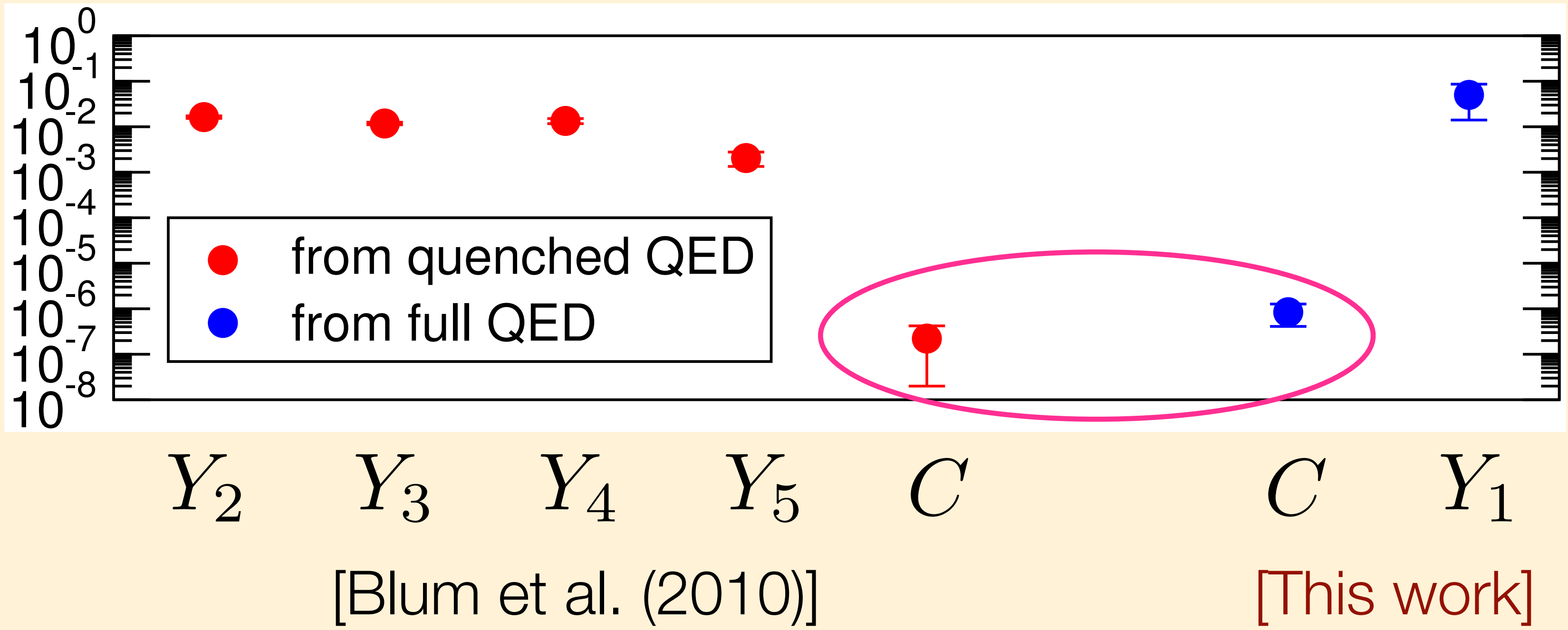


$O(e_s^2)$ $O(e_s e_v)$

Extraction of QED LEC's

QED LEC's obtained

- LEC's in SU(3) ChPT



- LEC C is consistent between quenched QED and full QED.

  → validity of the reweighting

- new LEC (SU(3) ChPT) $10^2 Y_1 = -5.0(3.6)$

- LEC's in SU(2) ChPT can also be obtained. (More LEC's appear.)

Conclusions and future plans

- Full QED effect is included by reweighting method. (a pilot study to address the full QED effect.)
- +/- e trick and its extension for full QED is very powerful in terms of noise reduction and separation of parts in ChPT.
- Observing a consistency of LEC C between quenched QED and full QED, the reweighting seems well controlled.
- While current results still have large uncertainty, they provide valuable inputs and constraints for ChPT in the EM sector.
- Application to larger lattices ($24^3 \times 64, \quad 32^3 \times 64$) is on-going.
- More improvement for estimation of the reweighting factor is needed for precision calculation. Some idea like low-mode averaging and all-mode averaging [T. Blum, T. Izubuchi and E. Shintani (2012)] would improve the signal drastically.
- Precise determination of quark masses including isospin breaking, ...

Nucleon Electric Dipole Moment in Nf=2+1 Lattice QCD

Eigo Shintani (RIKEN-BNL)
for RBC/UKQCD collaboration

RBRC Scientific Review Committee (SRC) Meeting, Brookhaven National Laboratory, Upton, NY, November 6, 7, & 8, 2012

CP symmetry breaking in the SM

- EW
  - CP violation occurs by the phase of CKM matrix
  - K, (D), B meson decay via direct and indirect CP violation
  - Contribution to EDM is very tiny, $\Rightarrow d_N^{\rm KM} \simeq 10^{-30}\text{–}10^{-33}\,{\rm e\cdot cm}$

    6-orders magnitude below the exp. upper limit: $|d_N^{\rm exp}| < 2.9\times 10^{-26}\,{\rm e\cdot cm}$
- QCD
  - θ term in the QCD Lagrangian:

$$\mathcal{L}_\theta = \bar\theta \frac{1}{64\pi^2} G\widetilde{G}, \quad \bar\theta = \theta + \arg\det M$$

    renormalizable and CP-violation comes due to topological charge density.
  - θ term is given as $\bar\theta < 10^{-9\pm1}$

    ⇒ θ and arg det M need to be unnaturally canceled ! (strong CP problem)

Constraint on nEDM

- Close to "exclude" of MSSM

  ~10 new proposals of EDM experiment !

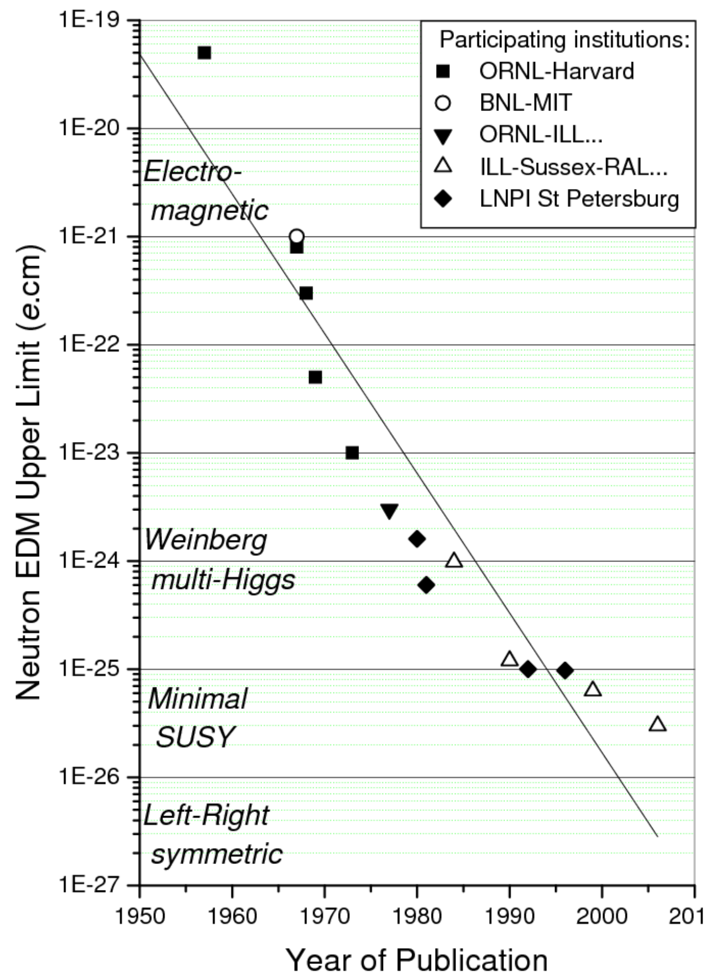
  pEDM experiment @ BNL,
  nEDM experiment @ ORNL, ILL, FRM-2,
  FNAL, PSI/KEK/TRIUMF, …
  Charged particle (d, p)EDM @ COSY
  Lepton EDM @ J-PARC, FNAL

  ⇒ aiming for a sensitivity to 10^{-29} e·cm !

- However, current theoretical bound is based on quark model, then non-perturbative computation of

$$d_n^{QCD}(\theta),\ d_n(\text{qEDM, cEDM})$$

plays an important role !



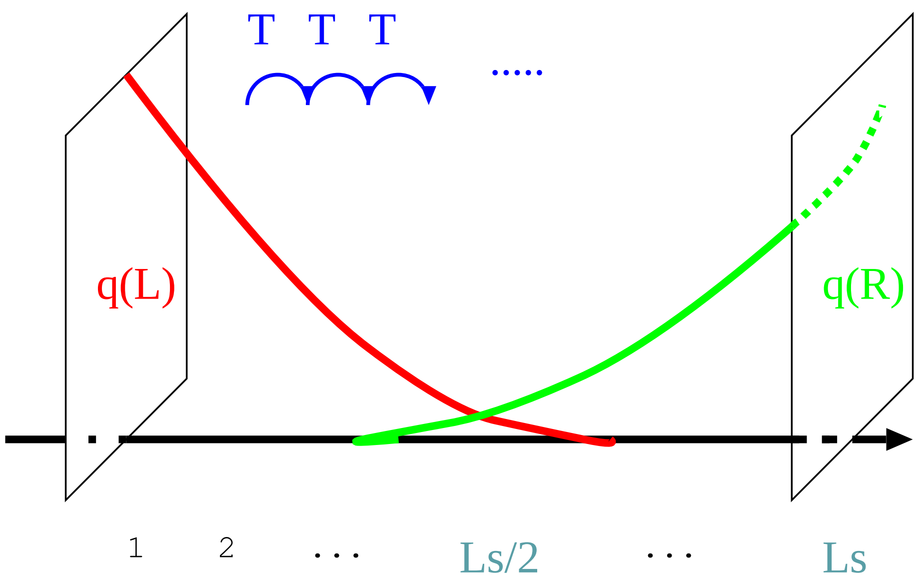
Harris, 0709.3100

Motivation

- Lattice calculation in θ vacuum
  - Using realistic lattice size L ~ 2.5 fm^3
  - Light quark mass, $m_\pi \sim 300$ MeV
  - Domain-wall fermion in full QCD ($N_f = 2+1$)
    - Good chiral symmetry on the lattice
    - Study of the mass dependence of EDM
  - Precise calculation of $d_n^{QCD}(\theta) \simeq d_n^{QCD}\theta + O(\theta^2)$
    - Rigorous bound of θ
    - Check of model dependence
    - Feasible study for other CP-odd source (qEDM, cEDM, et al.) in nucleon EDM

Lattice fermion

- Domain-Wall fermion (DWF) [Blum Soni, (97), CP-PACS(99), RBC(00), RBC/UKQCD. (05--)]
  - L, R fermion is localized on boundaries in 5th dimension
    $\Rightarrow$ Chiral symmetry is realized on the lattice (if $L_s \to \infty$).
  - Even in finite L_s there remains good chiral symmetry ($m_{res} \sim \exp(-L_s)$)
  - Reasonable computational cost compared to Overlap fermion.



Form factor

- Matrix element

$$\langle n(P_1)|J_\mu^{\rm EM}|n(P_2)\rangle_\theta = \bar{u}_N^\theta \Big[\underbrace{\frac{F_3^\theta(Q^2)}{2m_N}\gamma_5\sigma_{\mu\nu}Q_\nu}_{\text{P,T-odd}} + \underbrace{F_1\gamma_\mu + \frac{F_2}{2m_N}\sigma_{\mu\nu}Q_\nu}_{\text{P,T-even}} + \cdots \Big] u_N^\theta$$

$$\sum_s u_N^\theta(s)\bar{u}_N^\theta(s) = \frac{ip\cdot\gamma + m_N e^{i\alpha_N^\theta\gamma_5}}{2E_N}$$

$$\langle\theta|\eta_N J_\mu^{\rm EM}\bar{\eta}_N|\theta\rangle \quad = \quad \langle 0|\eta_N J_\mu^{\rm EM}\bar{\eta}_N|0\rangle + i\theta\langle 0|\eta_N J_\mu^{\rm EM} Q\bar{\eta}_N|0\rangle$$

$$\langle 0|\eta_N(t_1)J_\mu^{\rm EM}(t)Q\bar{\eta}_N(t_0)|0\rangle$$

$$= \frac{\alpha_N}{2}\gamma_5\left[F_1\gamma_\mu + F_2\frac{q_\nu\sigma_{\mu\nu}}{2m_N}\right]\frac{ip\cdot\gamma + m_N}{2E_N} + \frac{1+\gamma_4}{2}\left[F_1\gamma_\mu + F_2\frac{q_\nu\sigma_{\mu\nu}}{2m_N}\right]\frac{\alpha_N}{2}\gamma_5$$

$$+\frac{1+\gamma_4}{2}\left[F_3\frac{q_\nu\gamma_5\sigma_{\mu\nu}}{2m_N} + F_A(iq^2\gamma_\mu\gamma_5 - 2m_N q_\mu\gamma_5)\right]\frac{ip\cdot\gamma + m_N}{2E_N}$$

- Subtraction of CP-odd phase, α_N, in n propagator and CP-even part $F_{1,2}$

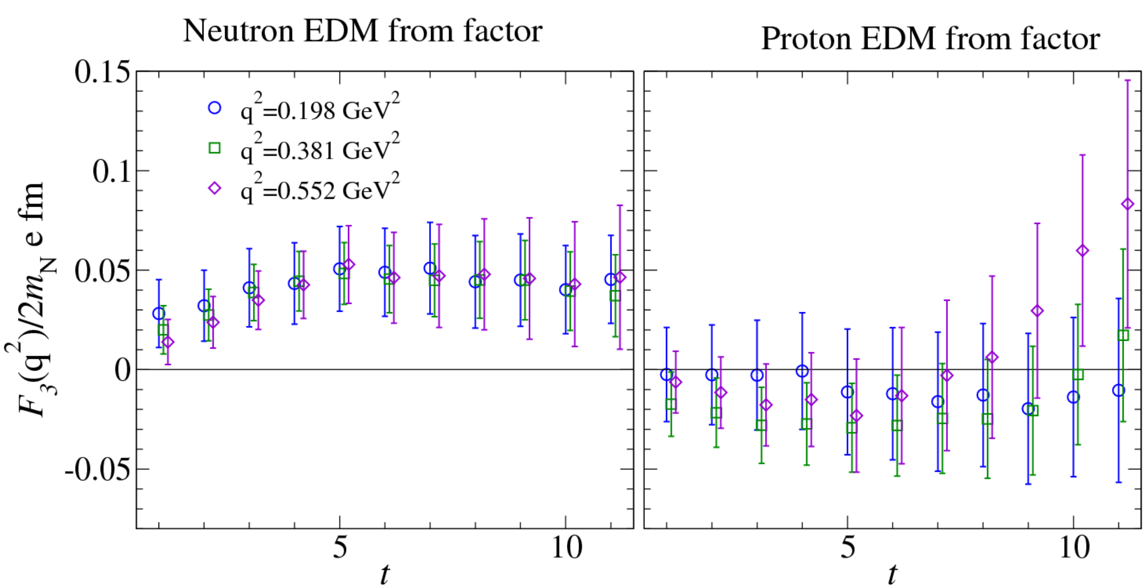
$$d_N = \lim_{Q^2\to\infty} F_3(Q^2)/2m_N$$

Recent results (preliminary)

- Full QCD in 2+1 DWF configurations
  - Development of algorithm — Blum, Izubuchi, ES (2012)

    All-mode-averaging (AMA) which is a new error reduction techniques

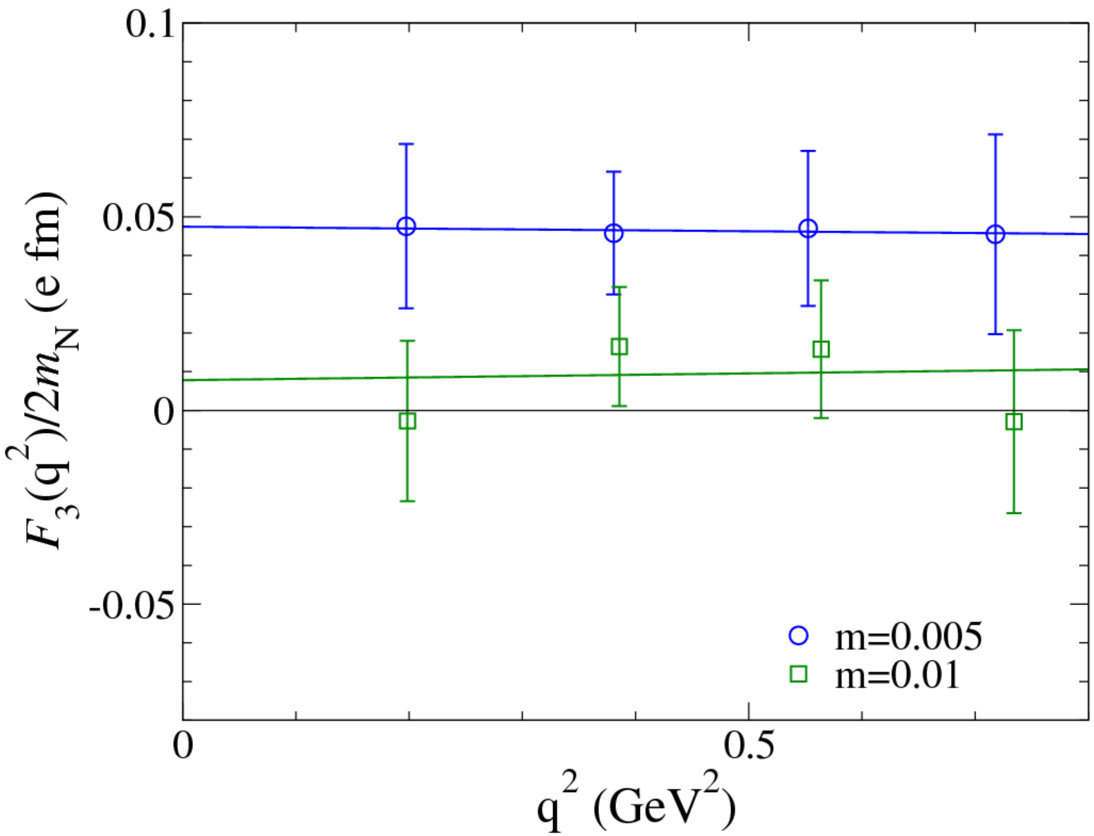
    ⇒ reduction of computational cost is more than 5 times
  - $24^3 \times 64$ lattice (3 fm^3), $m_\pi = 0.3$ GeV, 400 configs with AMA



Using AMA, signal of neutron (and proton) EDM (plateau region) can be observed.

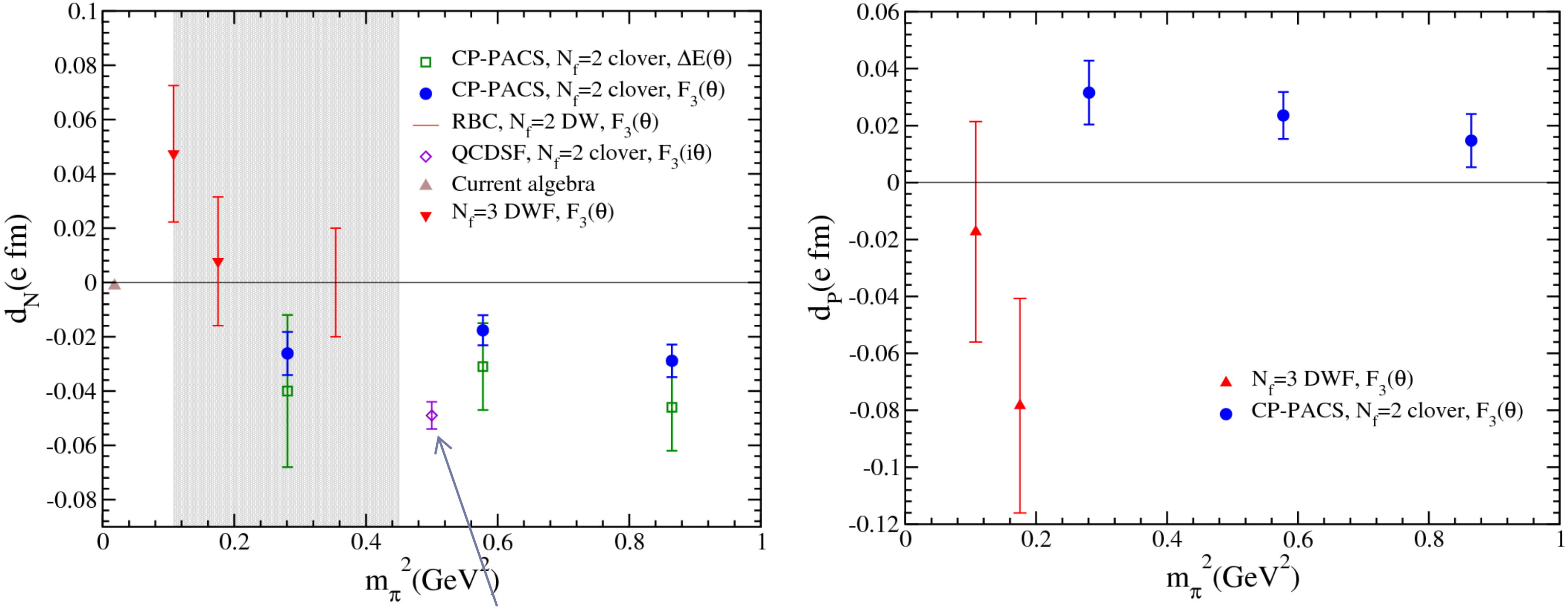
Recent results (preliminary)

- Full QCD in 2+1 DWF configurations
  - Linear extrapolation to zero transfer momentum



Comparison

- Full QCD
  - An order of magnitude is larger than the results of current algebra.
  - N_f = 2+1 DWF configs. near physical pion mass may be available soon.



There may be large systematic error due to chiral symmetry breaking.

Near future plan

- Form factor in DWF configurations
  - Chiral symmetry on the lattice

    Reduction of systematic error coming from finite lattice spacing
  - RBC/UKQCD collaboration

    Generate the ensembles including dynamical up, down, strange quarks
  - Large size and small mass

    Control the finite size and chiral extrapolation ($m_\pi \rightarrow m_\pi^{phys}$)

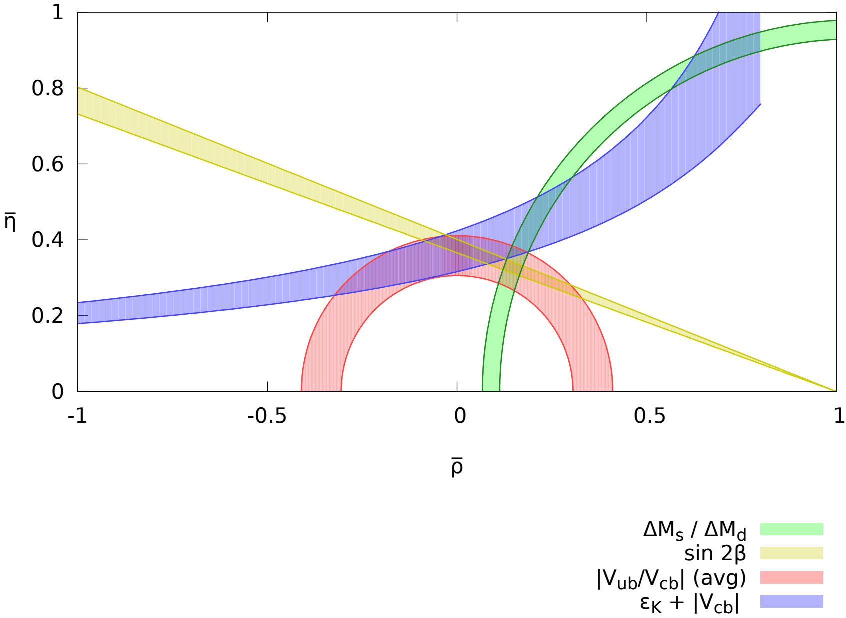
	Lattice size	Physical size	Lattice spacing	L_s	Gauge action	Pion mass
	$24^3 \times 64$	2.7 fm^3	0.114 fm	16	Iwasaki	315 -- 615 MeV
	$32^3 \times 64$	2.7 fm^3	0.087 fm	16	Iwasaki	295 -- 397 MeV
In progress →	$32^3 \times 64$	4.6 fm^3	0.135 fm	32	DSDR	171 -- 241 MeV
	$48^3 \times 96$	5.5 fm^3	0.115 fm	16	Iwasaki	135 MeV

Precise constraints on CP violation from lattice QCD

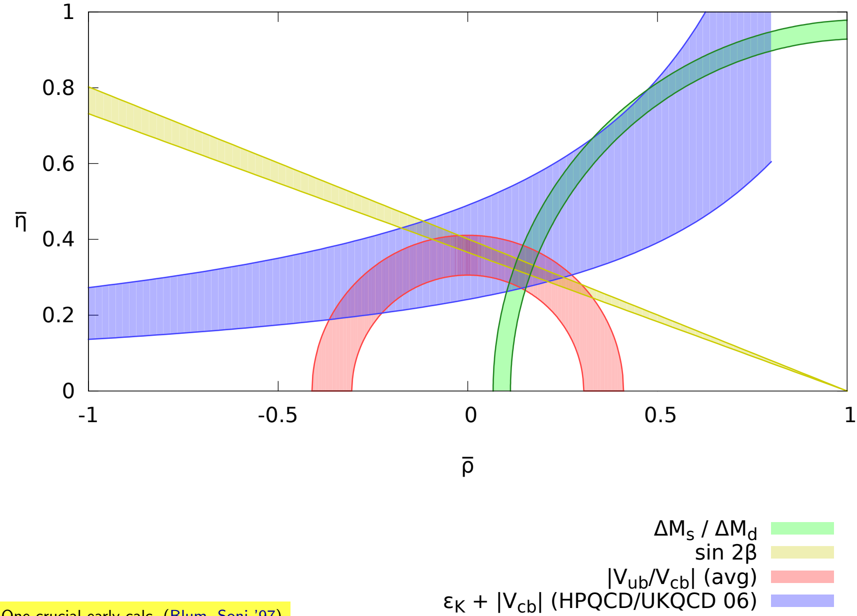
Christoph Lehner
RIKEN/BNL Research Center

SRC – Nov. 8 2012

(PDG, CKMfitter, latticeaverages.org, HFAG)

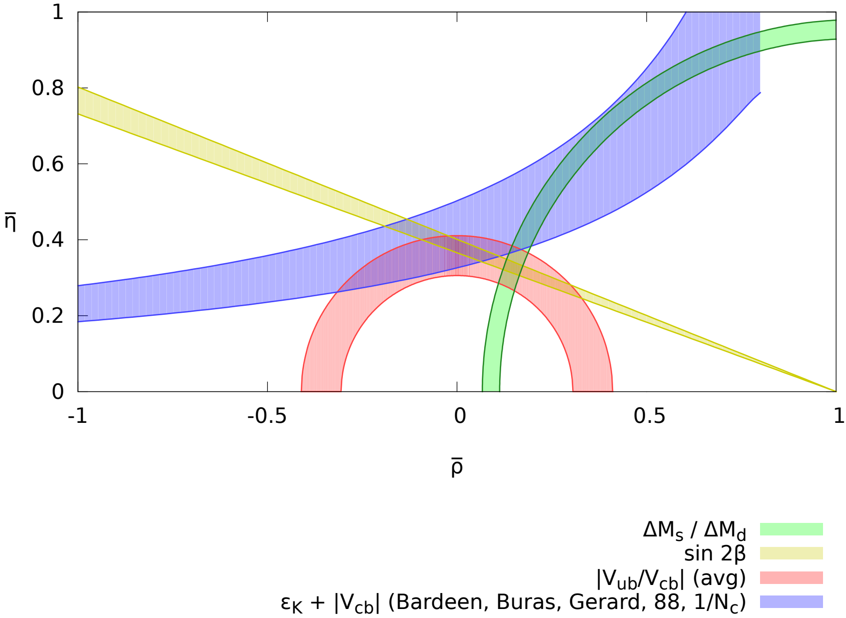


(PDG, CKMfitter, latticeaverages.org, HFAG)

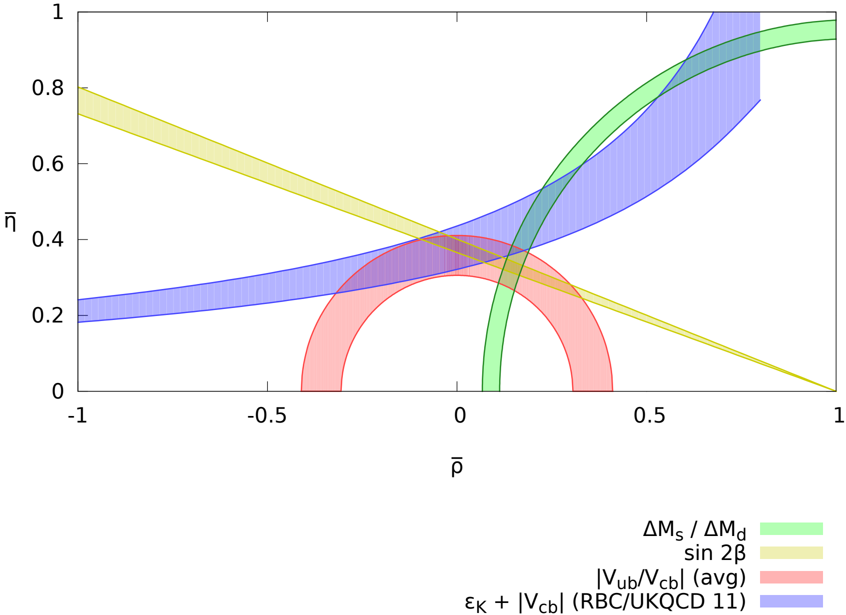


One crucial early calc. (Blum, Soni '97)

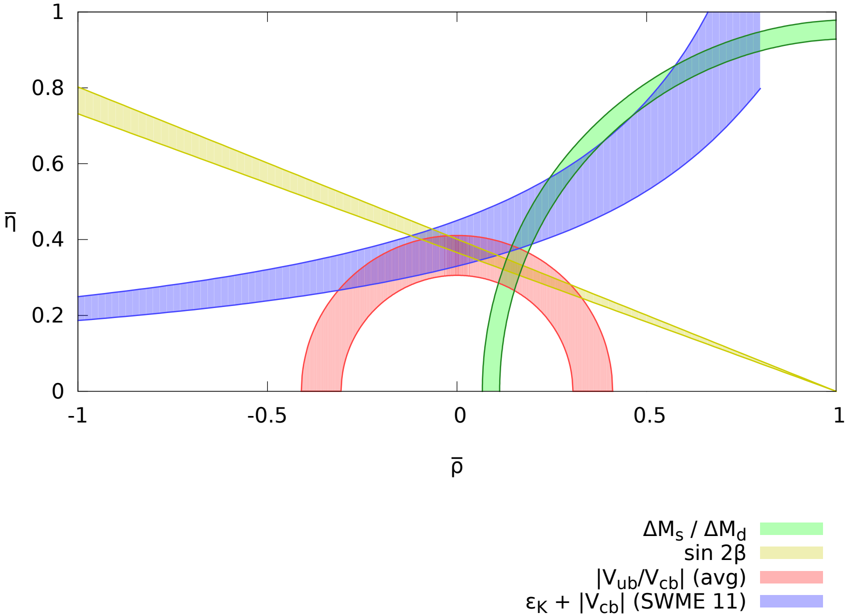
(PDG, CKMfitter, latticeaverages.org, HFAG)



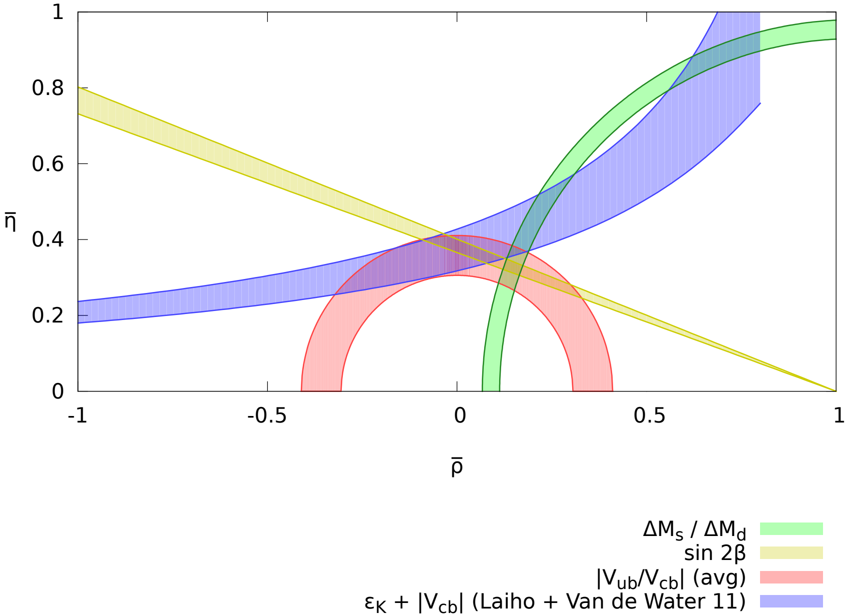
(PDG, CKMfitter, latticeaverages.org, HFAG)



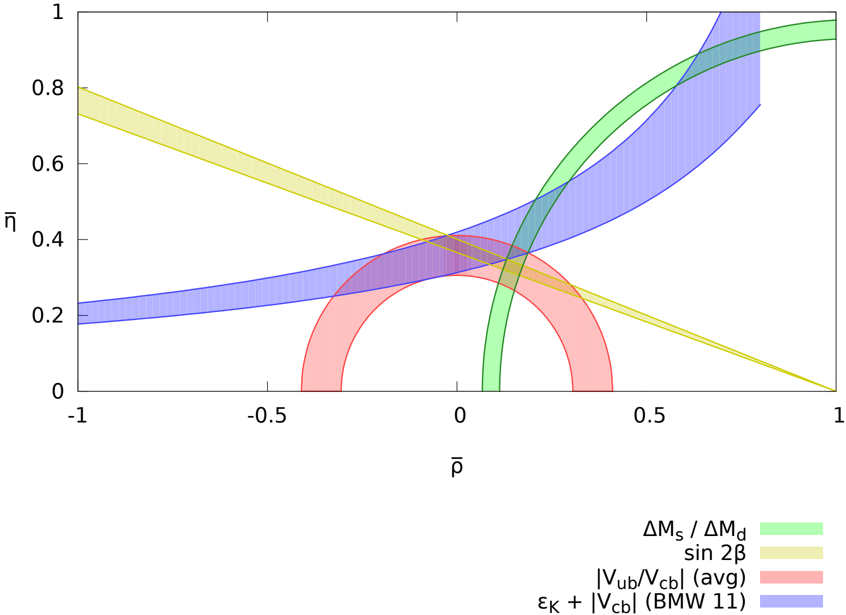
(PDG, CKMfitter, latticeaverages.org, HFAG)

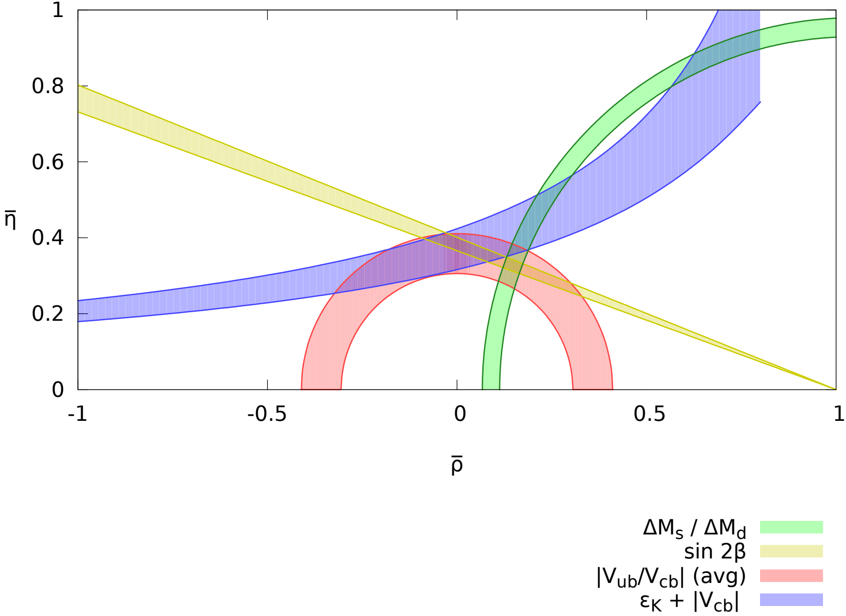


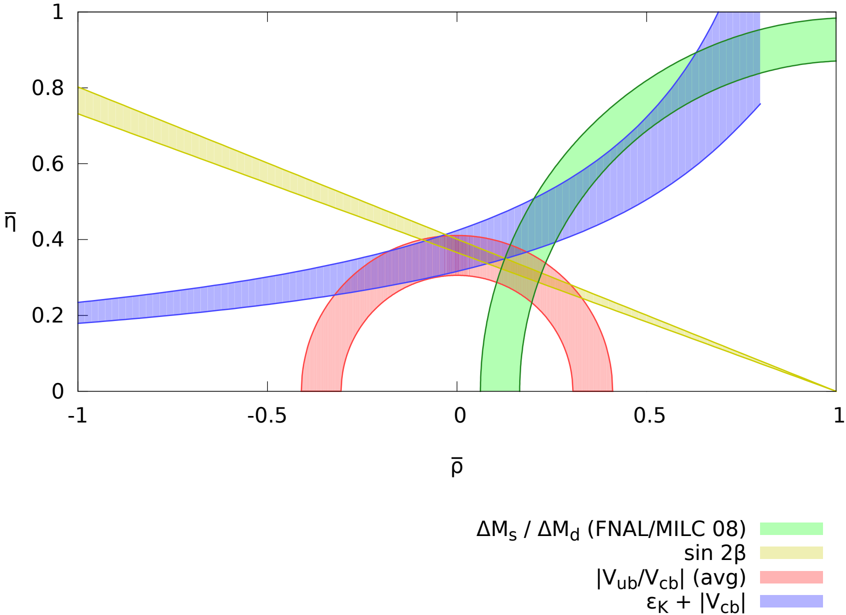
(PDG, CKMfitter, latticeaverages.org, HFAG)



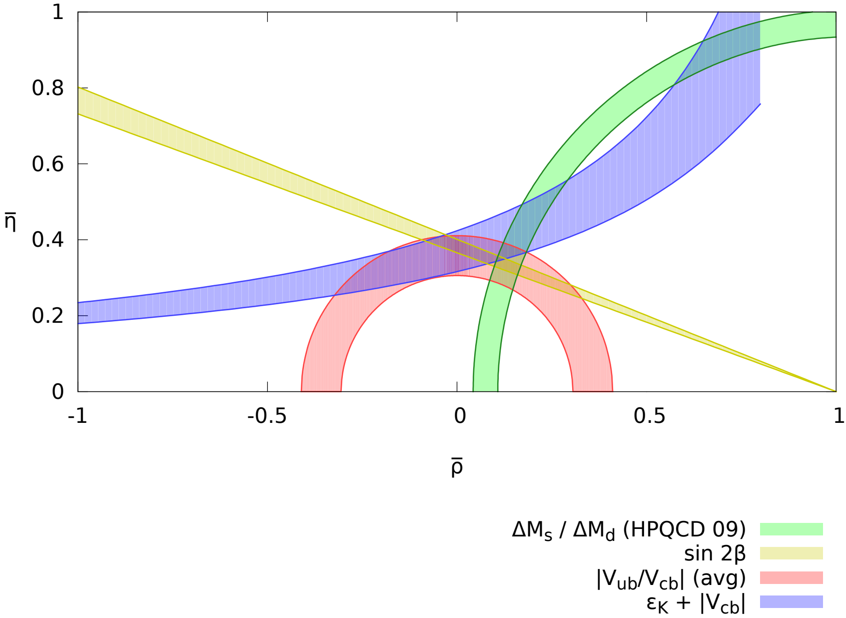
(PDG, CKMfitter, latticeaverages.org, HFAG)



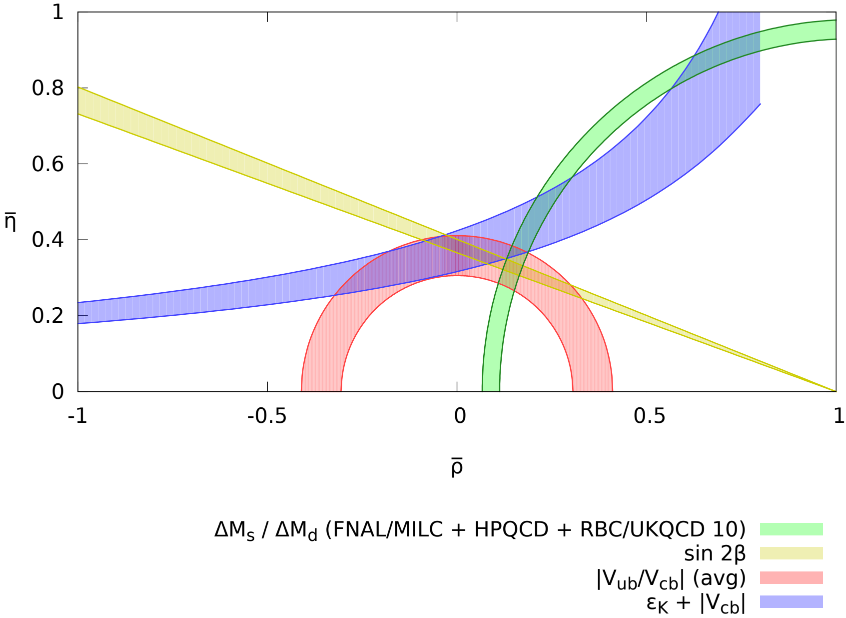

1
0.8
0.6
0.4
0.2
0
η̄
-1
-0.5
0
0.5
1
ρ̄
ΔM_s / ΔM_d
sin 2β
|V_ub/V_cb| (avg)
ε_K + |V_cb|


1
0.8
0.6
0.4
0.2
0
η̄
-1
-0.5
0
0.5
1
ρ̄
ΔM_s / ΔM_d (FNAL/MILC 08)
sin 2β
|V_ub/V_cb| (avg)
ε_K + |V_cb|

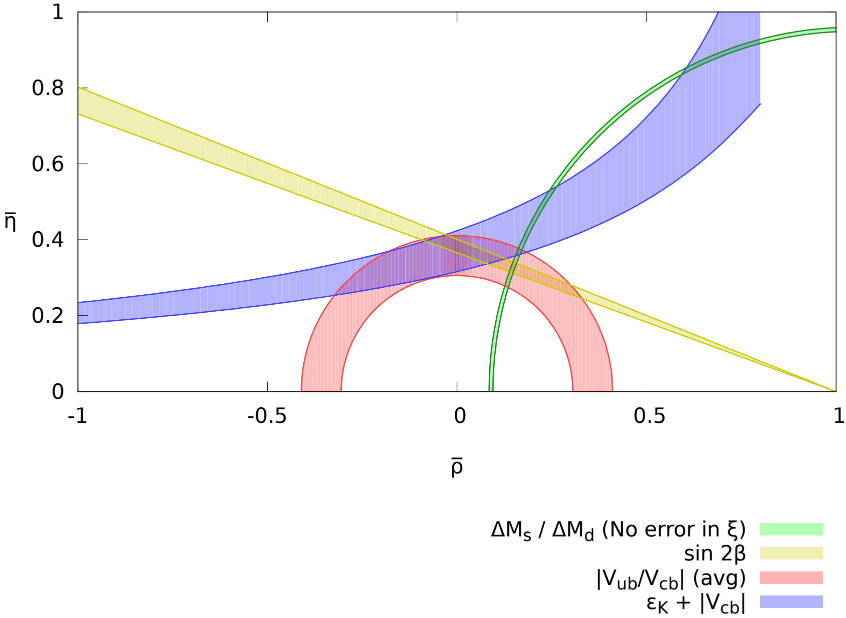
(PDG, CKMfitter, latticeaverages.org, HFAG)



(PDG, CKMfitter, latticeaverages.org, HFAG)



(PDG, CKMfitter, latticeaverages.org, HFAG)



- The potential of the lattice regulator
  - Only non-perturbative regulator; first principles calculations
  - Continuously increasing computing power:

    $\searrow$ statistical uncertainties

    $\searrow$ lattice spacing

    $\rightarrow$ physical quark masses

    $\nearrow$ volume

Need substantial theoretical effort (renormalization, heavy-quark discretization, ...) to fully harness potential

Outline

- Kaon system (ϵ'/ϵ, $A_{0,2}$, ΔM_K)

  $\Delta S = 1$ operator renormalization

- B system ($\Delta M_s/\Delta M_d$, f_{B_q}, B_{B_q}, $B \to \pi l \nu \Rightarrow |V_{ub}|$)

  Discretization of heavy quarks, operator renormalization

Kaon system

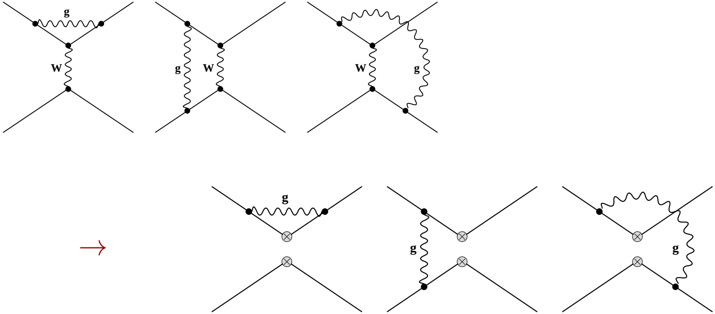
The effective $\Delta S = 1$ Hamiltonian

At low energies weak matrix elements can be obtained from the effective Hamiltonian

$C_i^{\overline{\mathrm{MS}}}$ known

$$\mathcal{H}_{\mathrm{eff}}^{\Delta S=1} = \sum_i C_i^x O_i^x$$

with Wilson coefficients C_i^x (perturbative), four-quark operators O_i^x (non-perturbative), and renormalization scheme x.



RI schemes and NPR

To match the measured matrix elements to $\overline{\mathrm{MS}}$ one can either

1. use lattice PT,
2. or renormalize the lattice operators non-perturbatively in a regularization-independent (RI) scheme.

For 2. continuum PT can be used to calculate matching factors from RI to $\overline{\mathrm{MS}}$.

Higher-loop corrections in continuum PT easier to calculate compared to lattice PT; can run NP to high scales and match there

Non-exceptional RI schemes for $\Delta S = 1$ operators

For $N_f = 3$ (CL and Sturm 2011) and $N_f = 4$ (CL and Sturm 2012):

- RI schemes are defined by projecting physical amplitudes in spinor and color space.
- Classification of RI schemes with respect to projectors:
  - If they do not contain any external momentum, the specifics of the projector are not important. The scheme is unique.
  - If they contain at least one external momentum, independent schemes can be defined.
- Variety of schemes allows for estimate of systematic error associated with matching.

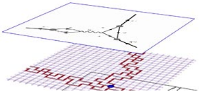
$\Rightarrow$ Define four RI schemes, calculate matching to $\overline{\text{MS}}$ at one loop

Supercomputing the Difference between Matter and Antimatter

Research spurs innovations in computing technology that drive advances to supercomputers

March 29, 2012

UPTON, NY — An international collaboration of scientists has reported a landmark calculation of the decay process of a kaon into two pions, using breakthrough techniques on some of the world's fastest supercomputers. This is the same subatomic particle decay explored in a 1964 Nobel Prize-winning experiment performed at the U.S. Department of Energy's Brookhaven National



PRL **108,** 141601 (2012) PHYSICAL REVIEW LETTERS

$K \to (\pi\pi)_{I=2}$ Decay Amplitude from Lattice QCD

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(RBC and UKQCD Collaborations)

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(Received 8 November 2011; published 4 April 2012)

We report on the first realistic *ab initio* calculation of a hadronic weak decay, that of the amplitude A_2 for a kaon to decay into two π mesons with isospin 2. We find $\mathrm{Re}A_2 = (1.436 \pm 0.063_{\mathrm{stat}} \pm 0.258_{\mathrm{syst}})10^{-8}$ GeV in good agreement with the experimental result and for the hitherto unknown imaginary part we find $\mathrm{Im}A_2 = -(6.83 \pm 0.51_{\mathrm{stat}} \pm 1.30_{\mathrm{syst}})10^{-13}$ GeV. Moreover combining our result for $\mathrm{Im}A_2$ with experimental values of $\mathrm{Re}A_2$, $\mathrm{Re}A_0$, and ϵ'/ϵ, we obtain the following value for the unknown ratio $\mathrm{Im}A_0/\mathrm{Re}A_0$ within the standard model: $\mathrm{Im}A_0/\mathrm{Re}A_0 = -1.63(19)_{\mathrm{stat}}(20)_{\mathrm{syst}} \times 10^{-4}$. One consequence of these results is that the contribution from $\mathrm{Im}A_2$ to the direct *CP* violation parameter ϵ' (the so-called Electroweak Penguin contribution) is $\mathrm{Re}(\epsilon'/\epsilon)_{\mathrm{EWP}} = -(6.52 \pm 0.49_{\mathrm{stat}} \pm 1.24_{\mathrm{syst}}) \times 10^{-4}$. We explain why this calculation of A_2 represents a major milestone for lattice QCD and discuss the exciting prospects for a full quantitative understanding of *CP* violation in kaon decays.

DOI: 10.1103/PhysRevLett.108.141601 PACS numbers: 12.38.Gc, 11.15.Ha, 11.30.Er, 13.25.Es

⇐ Error budget:

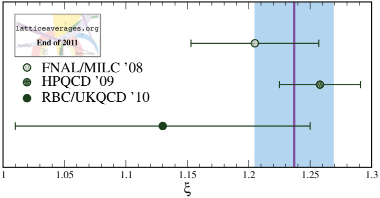
	$\mathrm{Re}A_2$	$\mathrm{Im}A_2$
Lattice artifacts	15%	15%
Finite-volume corrections	6.2%	6.8%
Partial quenching	3.5%	1.7%
Renormalization	1.7%	4.7%
Unphysical kinematics	3.0%	0.22%
Derivative of the phase-shift	0.32%	0.32%
Wilson coefficients	7.1%	8.1%
Total	18%	19%

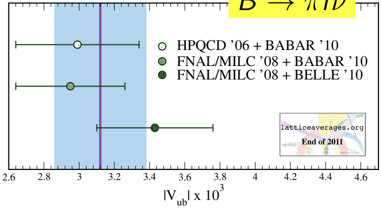
B system

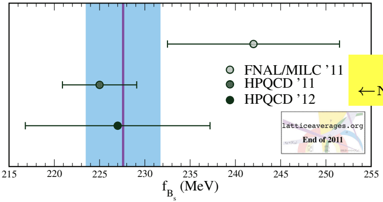
B physics targets

(latticeaverages.org)

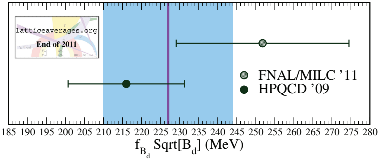
$B \to \pi l \nu$







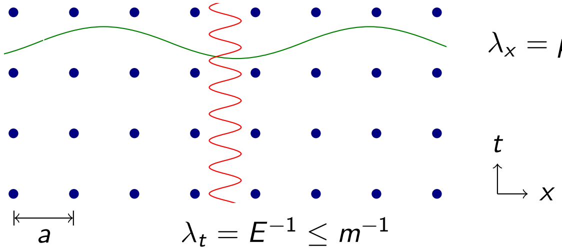
HISQ '11
←NRQCD '12



$\sim 3\sigma$ tension in UT (likely B_d mixing, $B \to \tau\nu$) (Lunghi, Soni '11)

Simulation of heavy quarks on the lattice

- Problem: Heavy mesons "fall through the lattice"



- Mesons with mass m, momentum p, and energy $E=\sqrt{m^2+p^2}$
- Typical scales:
  $a^{-1} \approx 2$ GeV, $m_D \approx 2$ GeV, $m_B \approx 5$ GeV $\Rightarrow am \geq 1$;
  $m_\pi \approx 0.2$ GeV, $L = 32a \Rightarrow m_\pi L \approx 3$

Relativistic heavy quarks

(El-Khadra et al. 1997)
(S. Aoki et al. 2003) (Christ et al. 2006)

- Anisotropic (no $t \leftrightarrow x$ symmetry) clover-improved Wilson action
- Columbia formulation:

$$S = \sum_x \overline{Q}(x)\left((\gamma_0 D_0 - \tfrac{1}{2}D_0^2) + \zeta \sum_{i=1}^{3}(\gamma_i D_i - \tfrac{1}{2}D_i^2) + m_0 + c_P \sum_{\mu,\nu=0}^{3} \tfrac{i}{4}\sigma_{\mu\nu}F_{\mu\nu}(x)\right)Q(x)$$

- Tune coefficients of dimension 4 and 5 operators to remove $|a\vec{p}|$, $(am)^n$, $|a\vec{p}|(am)^n$ errors in on-shell quantities:

$$m_0,\ \zeta,\ c_P$$

- Convert results to $\overline{\mathrm{MS}}$ scheme

Framework for LPT

(CL 2012)

- Wrote from scratch new computer algebra system (CAS) as a C++ library
- Direct access to parsed expression tree in C++
- Speed comparable to FORM, for some applications faster
- Some special features: function map, optimized series expansion, hooks

On top of new CAS: unified LPT, continuum PT framework

Excerpt of RHQ tuning code

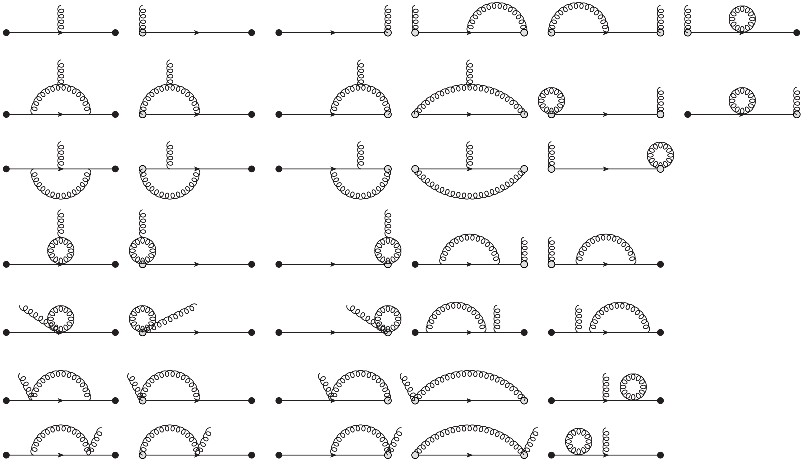
```
Context c;

// use rhq + gauge action
ActionRHQ rhq(&c,"Q");
ActionGAUGE gauge(&c);

// define field rotations
c.coefficients << "d1FT";
const char* QimpD =
 "(1 + sum(i,4)*d1FT(i)*Ngamma(i)*aD(i,x))*Q(x)";
FieldRotationRHQ Qimp(&c,"Q","QimpmomT",QimpD);
const char* QbimpD =
 "Qb(x)*(1 - sum(j,4)*d1FT(j)*Ngamma(j)*aDl(j,x))";
FieldRotationRHQ Qbimp(&c,"Qb","QbimpmomT",QbimpD);

// perform wick contractions
Wick w(&c);
w << rhq << gauge << Qimp << Qbimp;
Expression* vertex = w.contract(
 "sum(k,mom)*QimpmomT(q)*aACmom(mu1,a1,k)*QbimpmomT(-p)",3);
Expression* prop = w.contract(
 "sum(q,mom)*QimpmomT(p)*QbimpmomT(q)",2);
```

One loop vertex graphs



LPT at the precision frontier

- Speed: $\sim$ 10s for calculation of 1-loop corrections to propagator to 10^{-3} accuracy

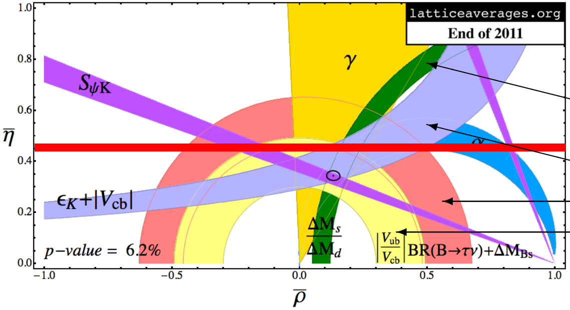
- Two loop calculations feasible $\Rightarrow$ significantly reduce systematic error

- 1-loop PT tuning of all coefficients in an $O(ap)^2$ improved action (Oktay and Kronfeld '08 at tree level)

(CL 2012)

Concluding remarks

- Precise constraints from lattice QCD are crucial to resolve tensions in UT fits.



We work on

- ξ
- ε'/ε
- B_K
- $B \to \tau\nu$ (f_B)
- V_{ub} ($B \to \pi l \nu$)

- We will soon be able to add a new constraint on CP violation for the first time (ε'/ε).

Tension $B \to \tau\nu$, ΔM_{B_s}

Backup slides

Traditional operator basis

Current-current operators:

$$Q_1 = (\bar{s}_a u_b)_{V-A}(\bar{u}_b d_a)_{V-A}\,, \qquad Q_2 = (\bar{s}_a u_a)_{V-A}(\bar{u}_b d_b)_{V-A}\,.$$

QCD penguin operators:

$$Q_3 = (\bar{s}_a d_a)_{V-A}\sum_{q=u,d,s,c}(\bar{q}_b q_b)_{V-A}\,, \quad Q_4 = \text{color mixed } Q_3\,,$$
$$Q_5 = (\bar{s}_a d_a)_{V-A}\sum_{q=u,d,s,c}(\bar{q}_b q_b)_{V+A}\,, \quad Q_6 = \text{color mixed } Q_5\,.$$

Electroweak penguin operators:

$$Q_7 = \frac{3}{2}(\bar{s}_a d_a)_{V-A}\sum_{q=u,d,s,c} e_q(\bar{q}_b q_b)_{V+A}\,, \qquad Q_8 = \text{color mixed } Q_7\,,$$
$$Q_9 = \frac{3}{2}(\bar{s}_a d_a)_{V-A}\sum_{q=u,d,s,c} e_q(\bar{q}_b q_b)_{V-A}\,, \quad Q_{10} = \text{color mixed } Q_9$$

with

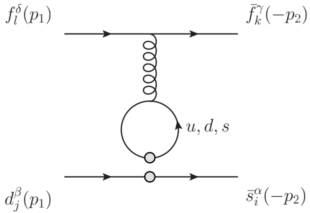
$$e_{u,c}{=}2/3\,, \qquad e_{d,s}{=}-1/3\,, \qquad (\bar{q}q)_{V\pm A}{=}\bar{q}\gamma_\mu(1\pm\gamma_5)q\,.$$

Chiral symmetry

- Only 7 (9) of the 10 operators are independent.
- No charm: the remaining 7 can be decomposed according to irreps. of $\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R$ and isospin:
  - 1 operator in $(27, 1)$ with $\Delta I = 1/2$ and $3/2$,
  - 4 operators in $(8, 1)$ with $\Delta I = 1/2$,
  - 2 operators in $(8, 8)$ with $\Delta I = 1/2$ and $3/2$.
- The $(27, 1)$ and $(8, 8)$ operators of the $\Delta S = 1$ basis can be related to $\Delta S = 2$ operators $(VV + AA, VV - AA, SS - PP)$.

Mixing

The penguin type diagrams



lead to mixing with two-quark operators such as

$$G_1 = \frac{4}{ig^2}\bar{s}\gamma_\nu(1-\gamma_5)[D_\mu,[D^\mu,D^\nu]]d\,.$$

There are three more gauge-invariant dimension 6 two-quark operators that can mix (Buras 1992).

Mixing

- In the on-shell limit these two-quark operators are indistinguishable from linear combinations of four-quark operators.
- Since RI schemes are defined at an off-shell momentum point, however, the two-quark operators must be included (CL and Sturm 2011).
- Non gauge-invariant operators can mix as well.

Framework for perturbative calculation

- Idea: unique framework for
  - automation of LPT
  - automation continuum PT
  - performing complicated contractions for NP lattice calculations
- Combined solution with FORM and Mathematica not satisfactory:
  - FORM optimized for continuum, large overhead for LPT
  - Mathematica is slow, large overhead for LPT
  - Mixing procedural and functional programming (poorly/not implemented in FORM and Mathematica) would be very helpful for generating highly optimized LPT integrator code

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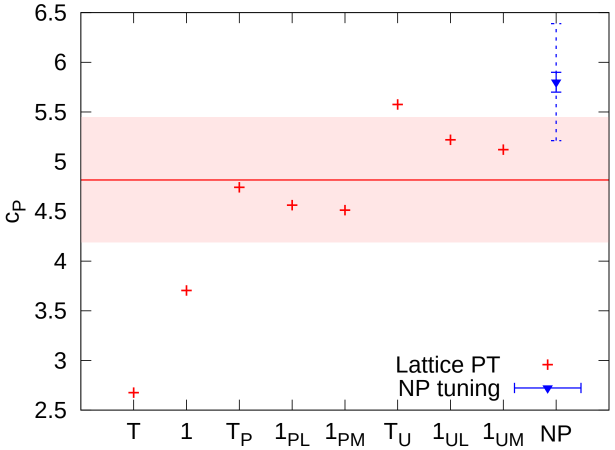
Pattern matching versus direct access to parsed expression tree in C++ code



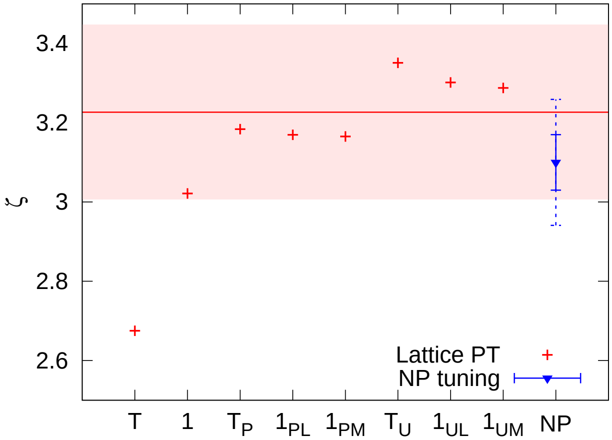
24^3 ensembles

- (T)ree level
- (1) loop
- (P)laquette MF improvement
- Landau gauge (U) link MF improvement
- Expansion in (L)attice coupling
- Expansion in (M)Sbar coupling, $\mu = 1/a$
- NP: non-perturbative tuning result

PT result $= (1_{PM} + 1_{UM})/2$

- PT error is maximum of naive $\alpha_s^2 \sim 5\%$ error and $(1_{UM} - 1_{PM})$
- NP error is stat. (inner) and stat. + syst. in quadrature (outer)

24^3 ensembles



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Test of our framework in B system

	this work	Experiment
M_{η_b}	9350(33)(37)	9390.9(2.8) [28]
M_{Υ}	9410(30)(38)	9460.30(26) [28]
M_{Υ}-M_{η_b}	60(05)(19)	69.3(2.8) [28]
$M_{\chi_{b0}}$	9808(35)(29)	9859.44(52) [28]
$M_{\chi_{b1}}$	9851(35)(29)	9892.78(40) [28]
$M_{\chi_{b1}}$-$M_{\chi_{b0}}$	44(05)(30)	33.3(5) [39]
M_{h_b}	9862(36)(30)	$9898.25\left(^{+1.48}_{-1.51}\right)$ [34]

Lattice error is (stat)(syst)

(Y. Aoki et. al. 2012)

[28] PDG ('10), [34] Belle ('11), [39] Quarkonium Working Group, CERN ('04)

B physics outlook

- Action is tuned
- LPT is in place
- Decay constants, mixing matrix elements, and form factors ($B \to \pi l \nu$) should be available soon

(Y. Aoki, . . . , Izubuchi, CL, Soni, Van de Water, Witzel 2012)

K(662 MeV) $\to$ π(329 MeV)π(329 MeV)

$\Delta I = 1/2$ rule

i	$M_i^{3/2,\mathrm{lat}}(\times 10^{-2})$	$\mathrm{Re}(A_2)$(GeV)	$\mathrm{Im}(A_2)$(GeV)
1	0.1960(7)	-9.461(49)e-09	0
2	$= M_1$	3.630(19)e-08	0
7	4.299(13)	2.433(12)e-11	4.089(21)e-14
8	14.54(5)	-1.937(9)e-10	-8.954(44)e-13
9	$=1.5M_1$	-4.311(22)e-15	2.824(15)e-13
10	$=1.5M_1$	3.324(17)e-12	-7.884(41)e-14
Total	-	2.668(14)e-08	-6.509(34)e-13

i	$M_i^{1/2,\mathrm{lat}}(\times 10^{-2})$	$M_i'^{1/2,\mathrm{lat}}(\times 10^{-2})$	$\mathrm{Re}(A_0)$(GeV)	$\mathrm{Im}(A_0)$(GeV)
1	-1.00(57)	-0.83(11)	6.6(31)e-08	0
2	1.09(24)	0.952(43)	2.59(53)e-07	0
3	-0.9(14)	-0.55(27)	5.4(66)e-10	3.0(37)e-12
4	1.2(12)	1.24((21)	2.3(21)e-09	7.7(69)e-12
5	-3.1(14)	-2.95(24)	4.0(26)e-10	2.1(14)e-12
6	-6.8(24)	-7.29(24)	-7.0(24)e-09	-4.2(15)e-11
7	9.00(48)	8.70(16)	6.29(54)e-11	1.056(90)e-13
8	27.67(92)	27.32(45)	-3.85(13)e-10	-1.877(62)e-12
9	-1.05(36)	-0.985(77)	1.98(62)e-14	-1.30(40)e-12
10	1.08(42)	0.806(74)	1.60(54)e-12	-3.8(13)e-13
Total	-	-	3.21(45)e-07	-3.3(15)e-11
Results without disconnected graph:			2.781(78)e-07	-3.63(16)e-11

Contribution of $Q_i^{\mathrm{RI}}(\mu = 2.15\ \mathrm{GeV})$ (Q. Liu 2012):

- Lattice: $24^3 \times 64 \times 16$, Iwasaki, 2+1 DWF, $a^{-1} = 1.73(3)$ GeV
- I: no disconnected graphs
- $\mathrm{Re}(A_0)/\mathrm{Re}(A_2) = 12.0(1.7)$

  $= 22.2(3.2)$ if we use our $\mathrm{Re}(A_2)$ at physical kinematics
- Unphysical kinematics, pions at rest in kaon rest frame

Applying the new schemes . . .

Realistic calculation of $K \to (\pi\pi)_{I=2}$

(Blum et. al. 2011)

- Lattice: $32^3 \times 64 \times 32$, 2+1 DWF, Iwasaki DSDR, $a^{-1} = 1.375(9)$ GeV, $m_{\pi^+} = 142.9(1.1)$ MeV
- Challenges:
  - Renormalization
  - Finite-volume effects
  - Kinematics (WE-theorem $\pi^+\pi^+ \leftrightarrow \pi^+\pi^0$, d–BC)
- Error budget:

	ReA_2	ImA_2
Lattice artifacts	15%	15%
Finite-volume corrections	6.2%	6.8%
Partial quenching	3.5%	1.7%
Renormalization	1.7%	4.7%
Unphysical kinematics	3.0%	0.22%
Derivative of the phase-shift	0.32%	0.32%
Wilson coefficients	7.1%	8.1%
Total	18%	19%

Results:

	Re(A_2)(10^8/GeV)	Im(A_2)(10^{13}/GeV)
Lat.	1.436(62)(258)	-6.83(51)(130)
Exp.	1.479(4) (K^+)	(n/a)

$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{EWP}} = -6.52(49)(124) \times 10^{-4}$

Errors: (stat)(syst)

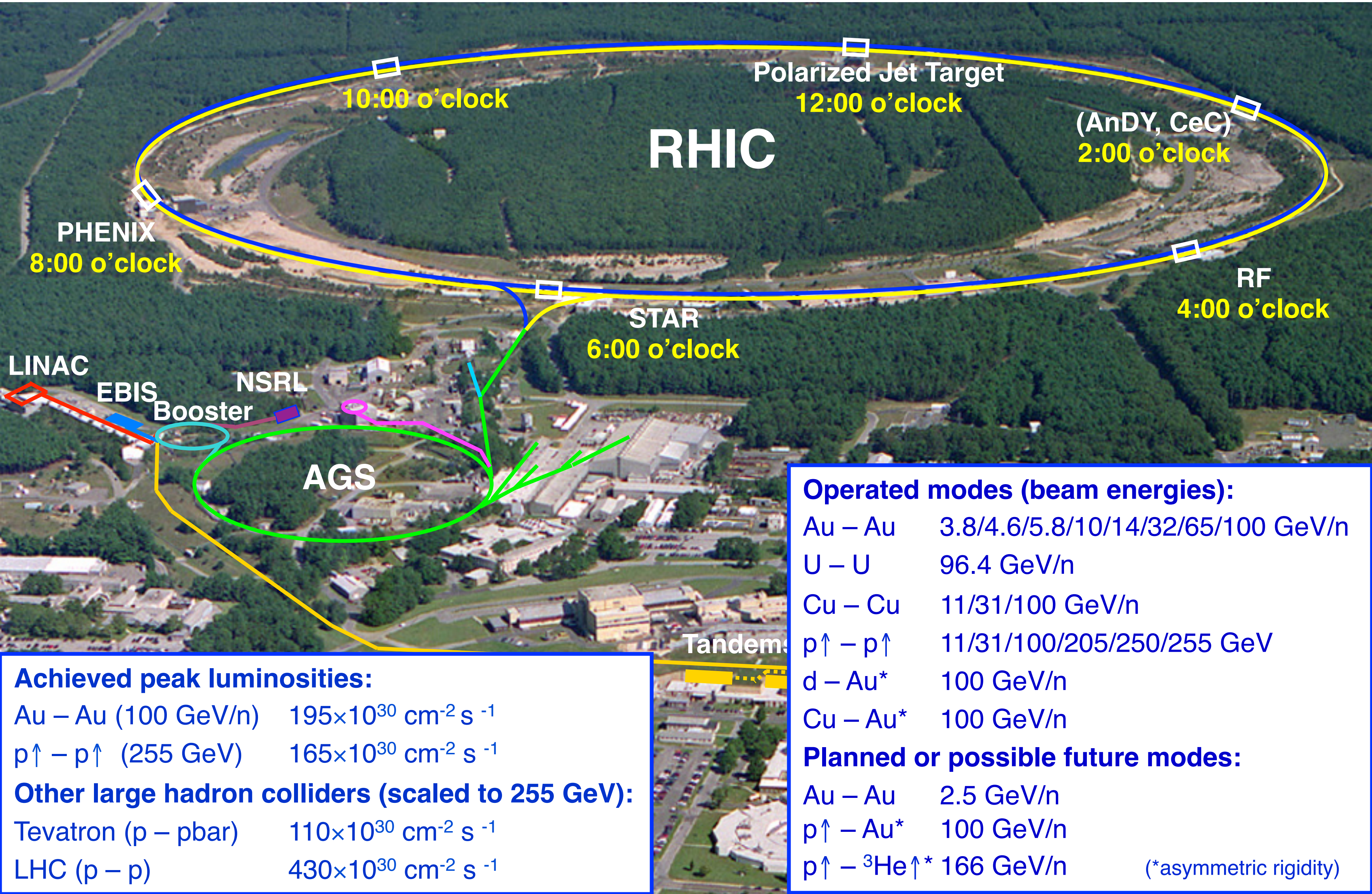
RHIC, the next decade, and eRHIC

- Recent performance of RHIC
- Future plans for RHIC
- Accelerator R&D towards eRHIC
- The next machine: eRHIC

BROOKHAVEN NATIONAL LABORATORY

Thomas Roser, BNL
RBRC SRC
November 8, 2012

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)	165×10^{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)	430×10^{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

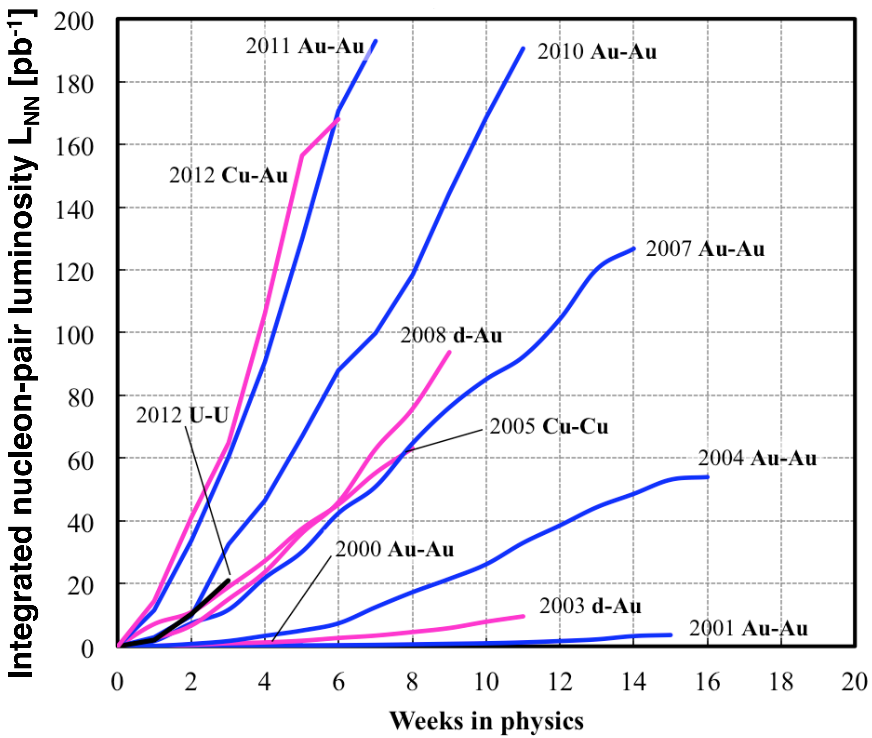
Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

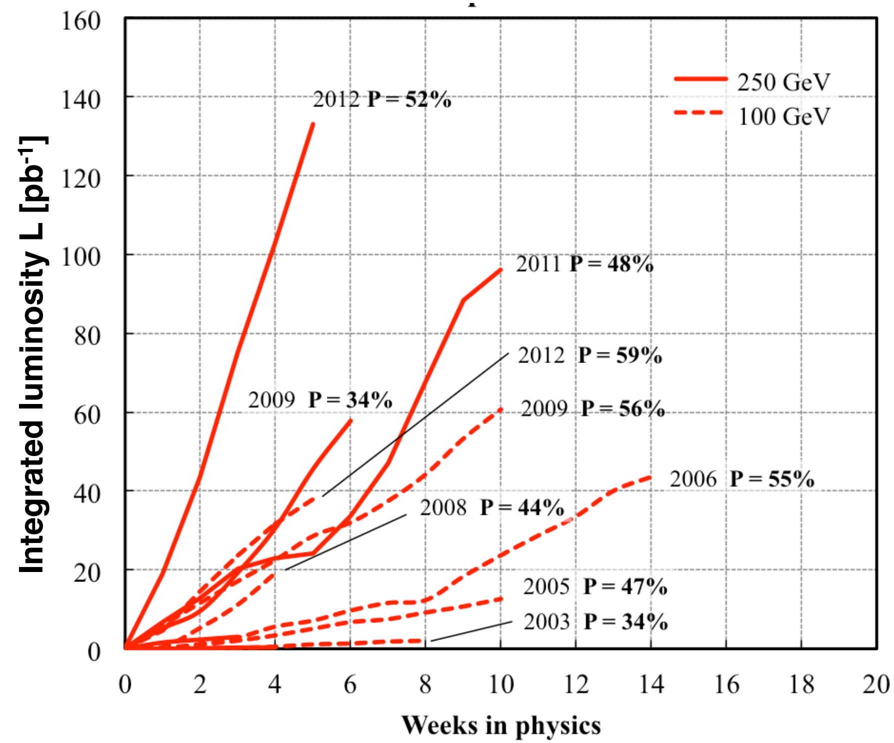
(*asymmetric rigidity)

RHIC Integrated Luminosity and Polarization (RHIC II performance!)

Heavy ion runs



Polarized proton runs



- Further upgrades:
  - 56 MHz SRF system to reduce vertex length
  - Electron lenses to ~ double pp luminosity
  - Polarization goal: 70 %

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

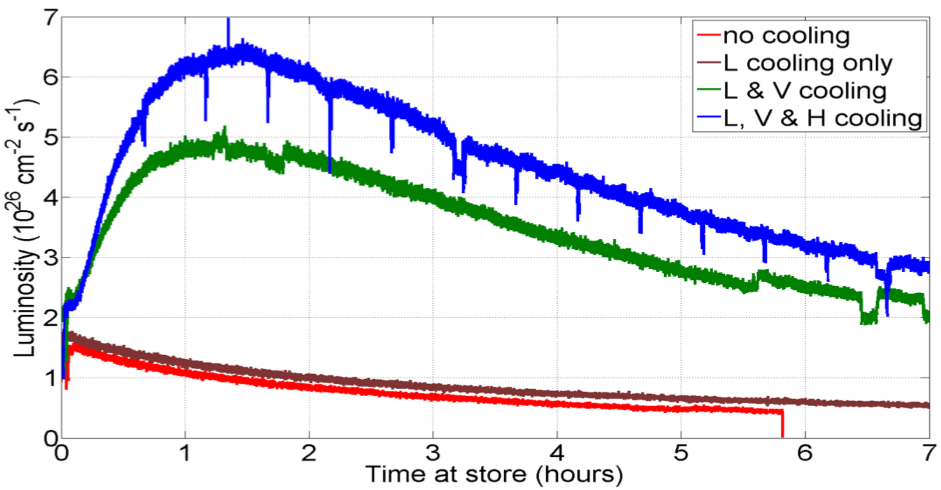
RHIC Facility Upgrade Plans

- EBIS (2012) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)
- RHIC luminosity upgrade (RHIC II) (≥ 2012):
  [Au-Au: 40 × 10^{26} cm^{-2} s^{-1}; 500 GeV p-p: 1.5 × 10^{32} cm^{-2} s^{-1}]
  - 0.5 m β^* for Au – Au and p↑ - p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage SRF system in RHIC
- Further luminosity upgrade for p↑ - p↑ operation (≥ 2014):
  [500 GeV p-p: ~ 3 × 10^{32} cm^{-2} s^{-1}]
  - Electron lens in RHIC for head-on beam-beam compensation (× 2)
  - New high intensity, high polarization polarized source (New OPPIS)
- Low energy ($\sqrt{s}$ = 5…30 GeV) Au-Au collisions for critical point search
  - ~ 1…5 MeV electron cooling of Au beams at injection (≥ 2017)
- eRHIC: high luminosity (~ 1 × 10^{34} cm^{-2} s^{-1}) eA and pol. ep collider using 5-10 GeV and later up to 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (> 2020)
  Exploring gluons at extreme density!

RHIC Run 12 Performance

- Record luminosities and beam polarizations (61.8% (B); 56.6% (Y)) at 100 GeV
- Record luminosities and beam polarizations (50.3% (B); 53.5% (Y)) at 255 GeV
- First acceleration of ^{3}He (unpolarized) in AGS during short test run; Operation of ^{3}He-C CNI polarimeter demonstrated

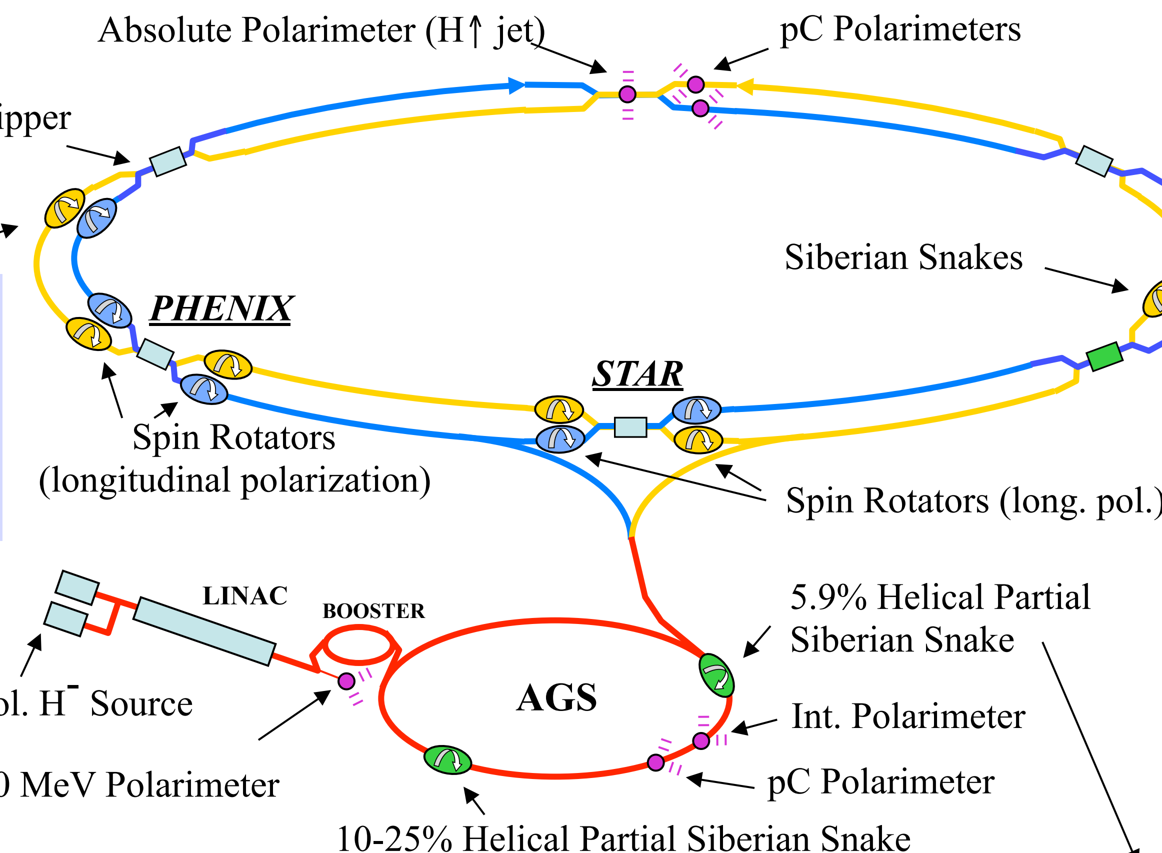
- First U-U collisions; x 5 luminosity from 3-D stochastic cooling
- First Cu-Au collisions; exceeding max. luminosity predictions with record EBIS/ injector performance and 3-D stochastic cooling
- 2.5 GeV Au-Au test with decent beam lifetime
- Very short set-up time due to flawless operation of beam-based feed-back system
- First hadron collider with increasing luminosity!

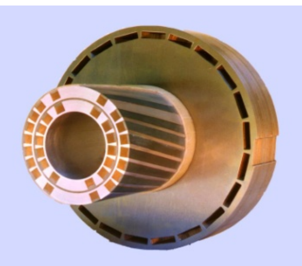


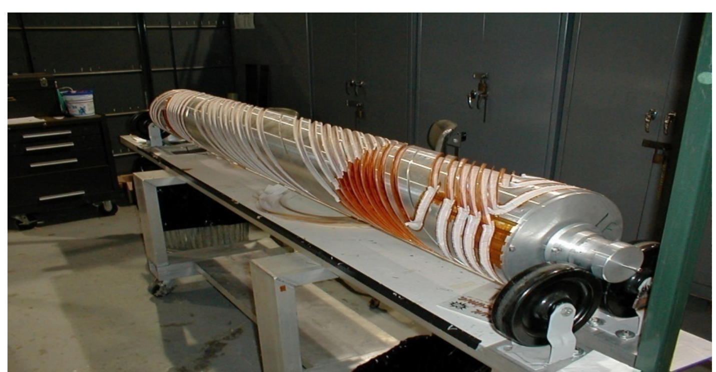
Luminosity in U-U store

Beams cooled to $\varepsilon_{rms,norm} = 0.4\ \mu m$

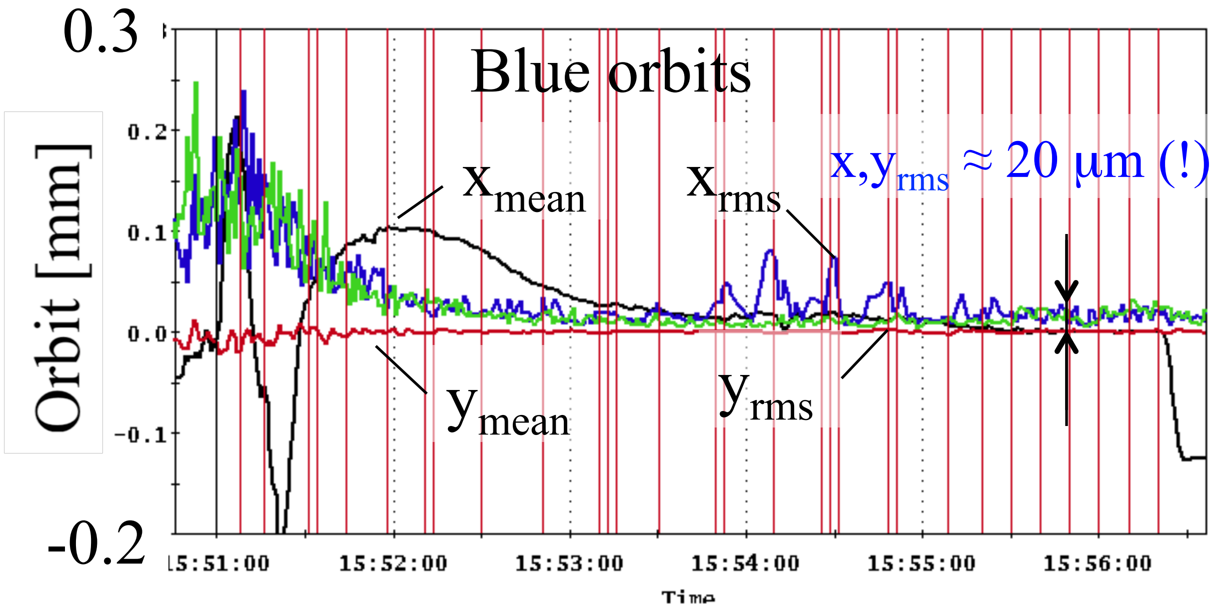
RHIC – First Polarized Hadron Collider

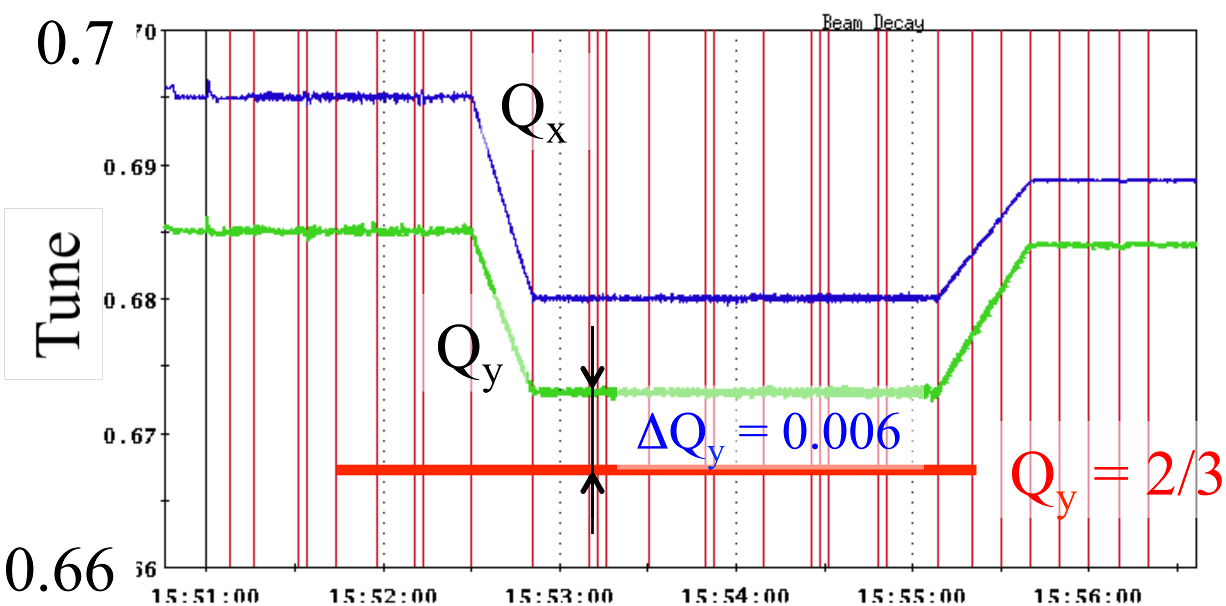






Beam control improvement – feedbacks on ramp

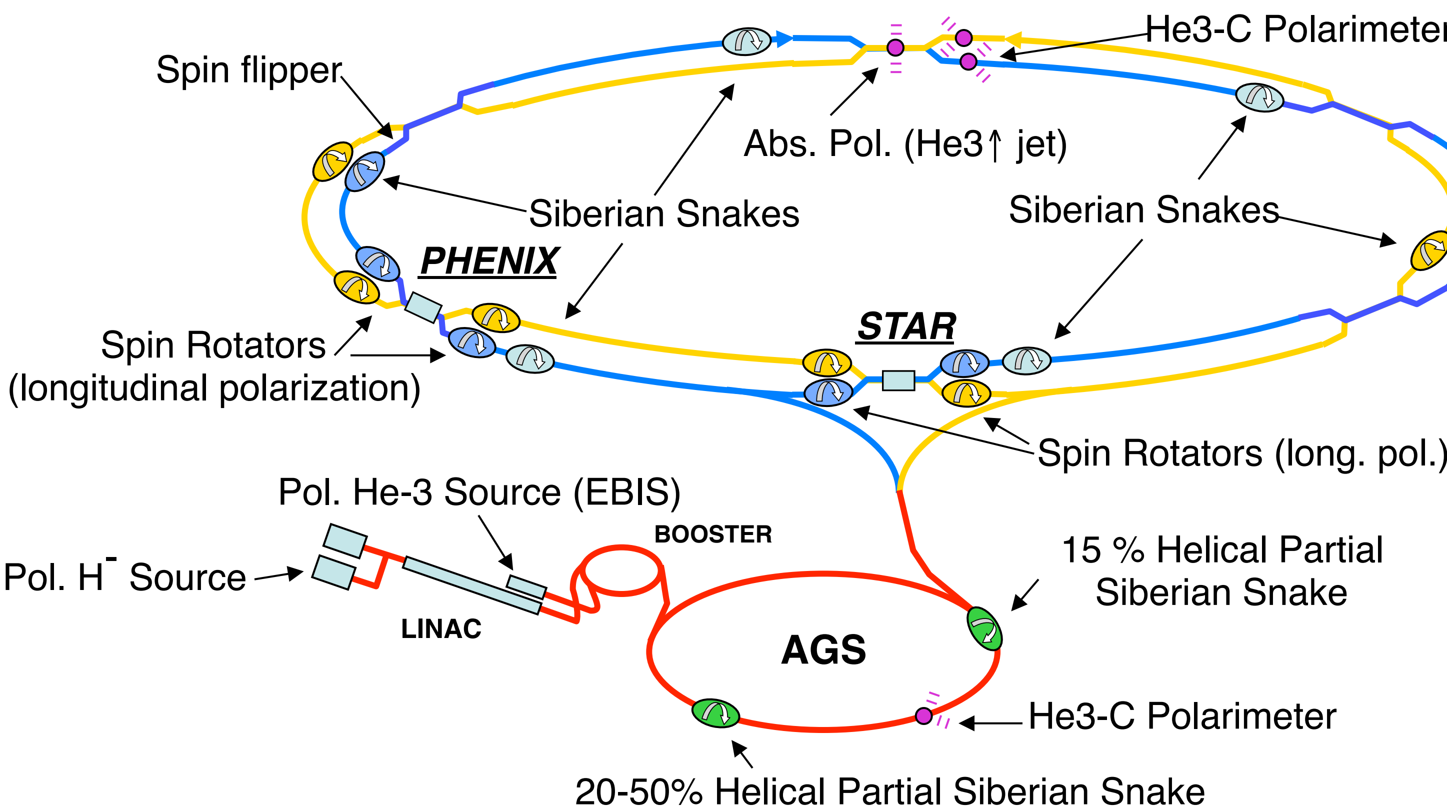




- Slow orbit feedback on every ramp allows for
  - Smaller y_{rms} (smaller imperfection resonance strength)
  - Ramp reproducibility (have 24 h orbit variation)
- Continues fast 10 Hz orbit feedback eliminates effect of vibrating triplets
- Tune/coupling feedback on every ramp allows for
  - Acceleration near $Q_y = ⅔$ with better polarization transmission

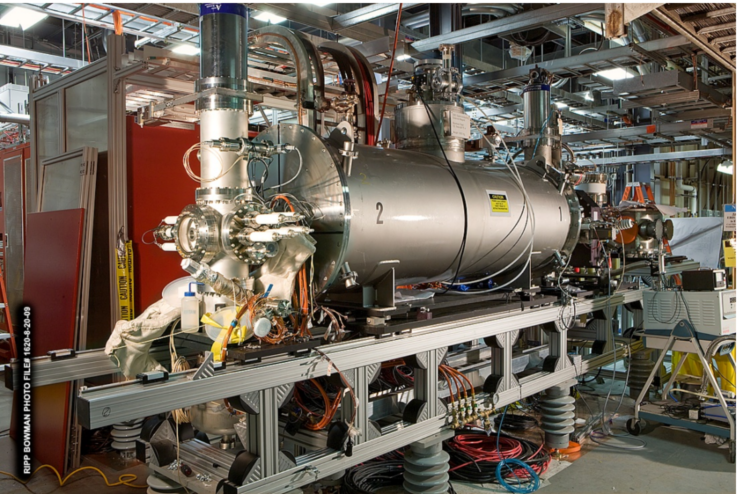
Polarized ³He in RHIC

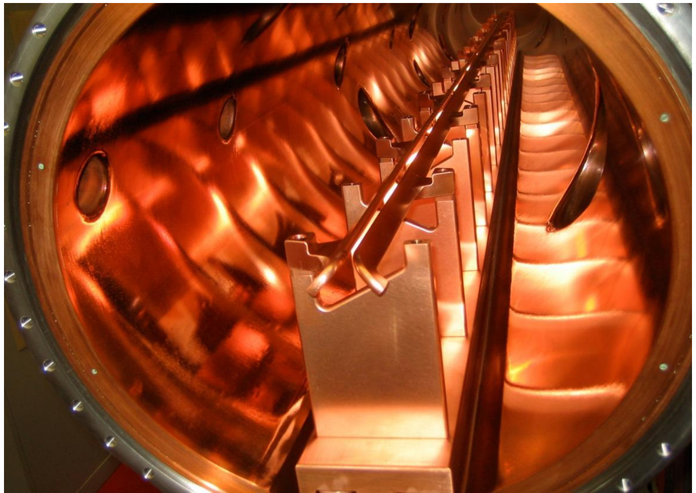
- Polarized ³He possible from new EBIS
- Max. energy in RHIC: 170 GeV/n
- Depolarizing res. are stronger, however no depolarization expected with six snakes in RHIC
- Accelerated unpolarized ³He from EBIS in AGS
- Relative pol.: ³He-C CNI polarimeter; successfully tested with unpolarized ³He
- Absolute pol.: ³He-³He CNI polarimeter using polarized ³He jet?



Electron Beam Ion Source (EBIS) Pre-injector

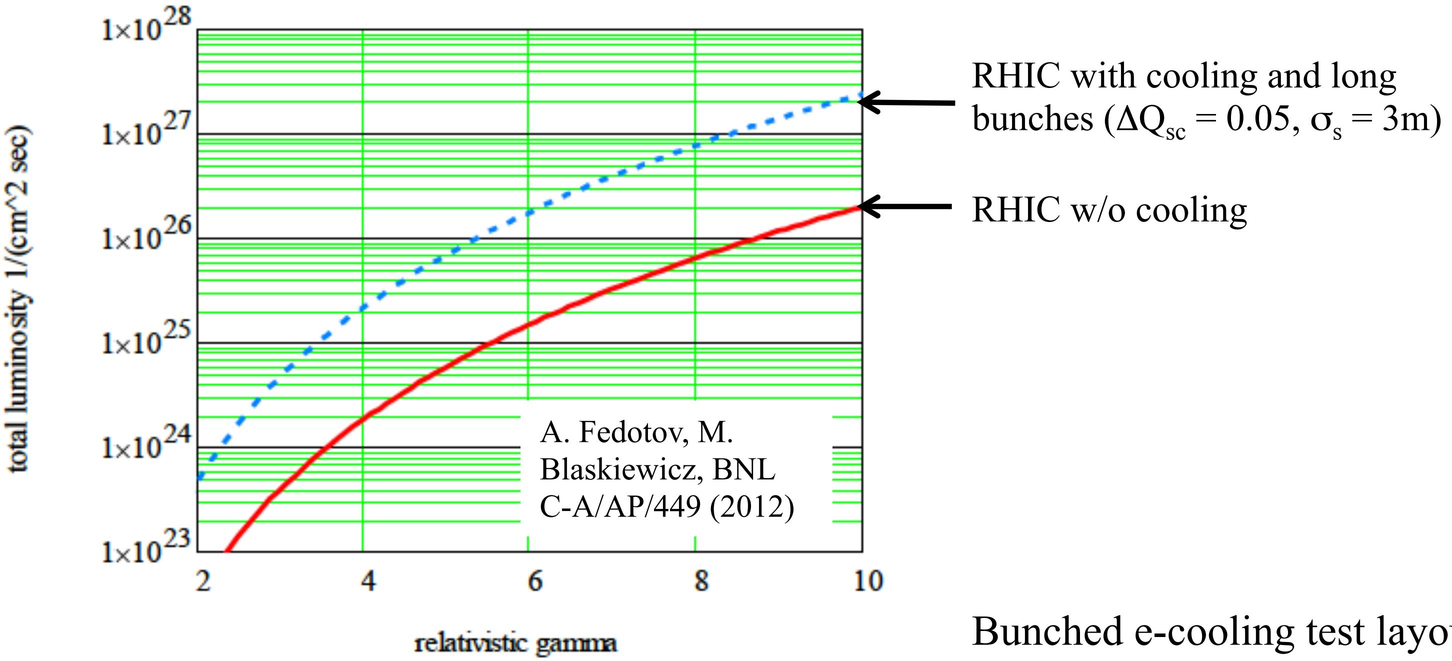
- Very flexible, high brightness ion source for all ion species including noble gas ions (NSRL), uranium (RHIC) and polarized ^3He (eRHIC) (~ 1–2×10^{11} charges/bunch with $\varepsilon_{N,rms}$ = 1–2 μm)
- Operated reliably with He^+, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{10+}, Kr^{18+}, Ti^{18+}, Fe^{20+}, Ta^{33+}, Ta^{38+} for NASA Space Radiation Laboratory and for National Reconnaissance Office
- Operated for RHIC with U^{39+}, Cu^{11+}, Au^{31+} and for AGS test with $^3He^{2+}$
- Design intensity from source; wider charge distribution was compensated by longer effective trap length
- Exceeded previous max. Au bunch intensity in RHIC



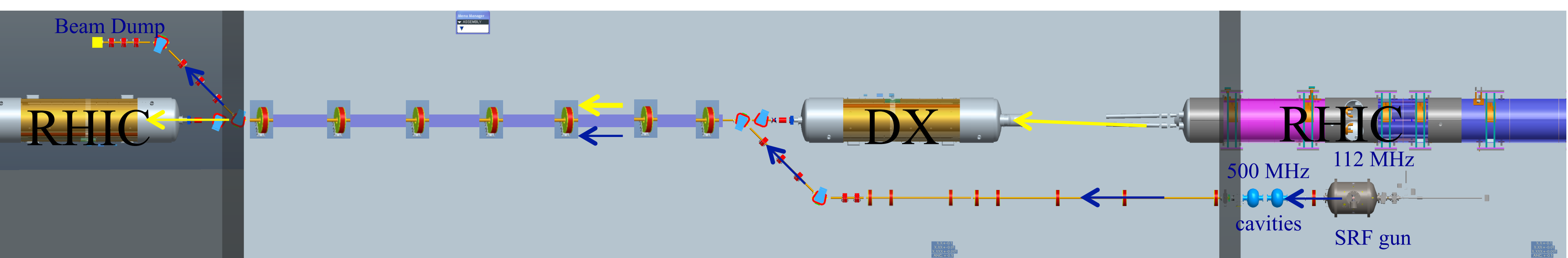


e-cooling for low energy RHIC operation

- Will likely use high brightness SRF electron gun for bunched beam electron cooling; up to ~10x L; ready after 2017 (Fermilab Pelletron (cooled 8 GeV pbar for Tevatron use) is alternative option)
- Can use CeC setup for bunched e-cooling test



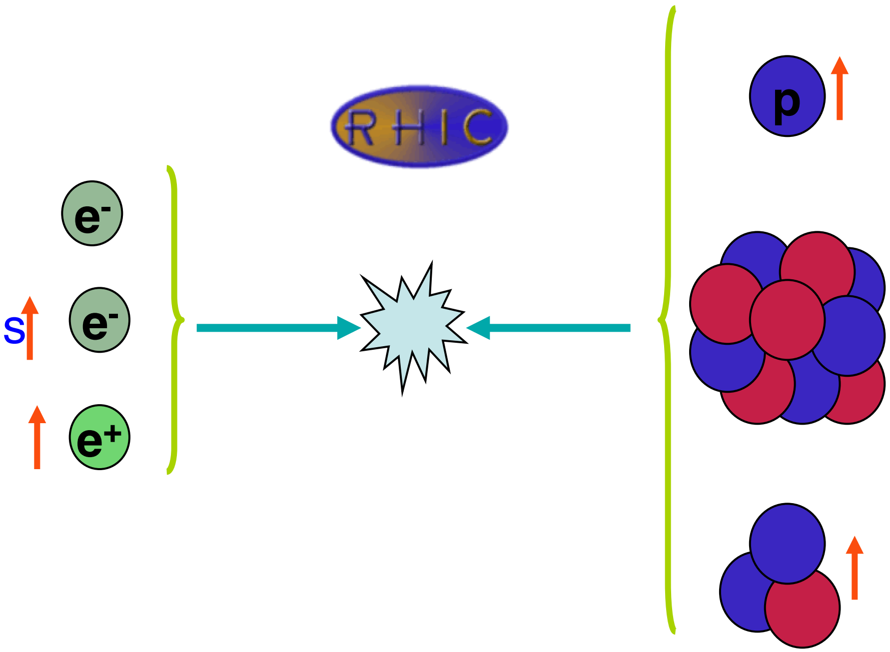
Bunched e-cooling test layout, same as CeC layout



eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing RHIC

Unpolarized and
80% polarized leptons
5 - 30 GeV



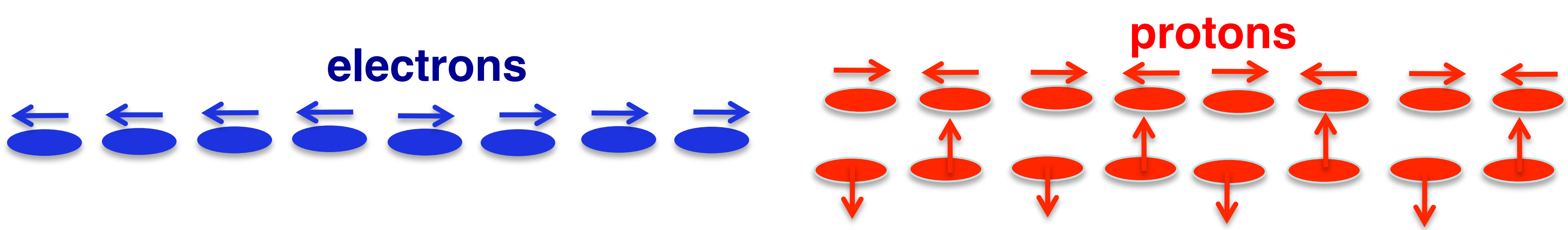
70% polarized protons
50 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
50 - 100 (110*) GeV/u

Pol. light ions (^{3}He)
50 - 167 (184*) GeV/u

Center-of-mass energy range: 30 - 175 GeV

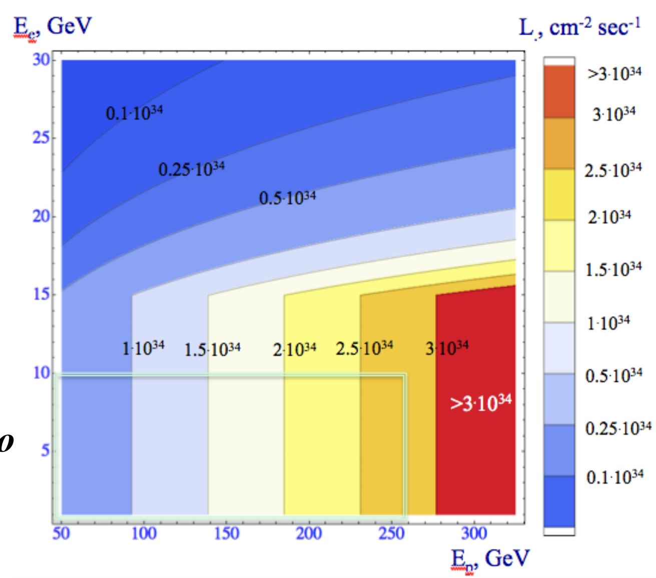
Any polarization direction in lepton-hadrons collisions



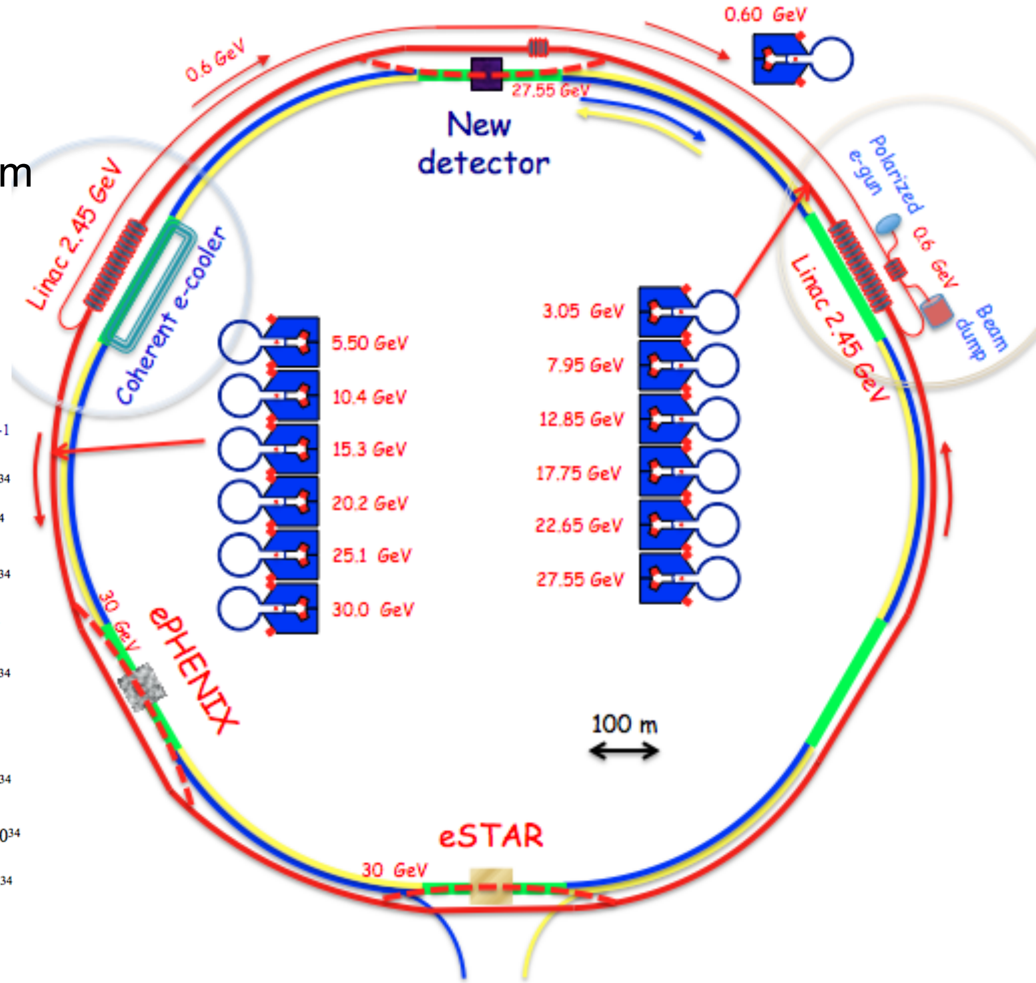
*** We are exploring a possibility of increasing RHIC ring energy by 10% - 30%**

eRHIC design status

- 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 and high luminosity ($L \sim 10^{34}\ cm^{-2}\ s^{-1}$) and full electron polarization transparency
- Accelerator R&D:
  - High current (50 mA) pol. electron gun
  - Multi-pass high average current ERL
  - Coherent electron cooling of hadron beam
- 1st stage: 5-10 GeV electron beam
  - Similar to CEBAF 12 GeV upgrade (1 GeV SRF linac + recirculating arcs)
  - 10 GeV with FFAG arcs?



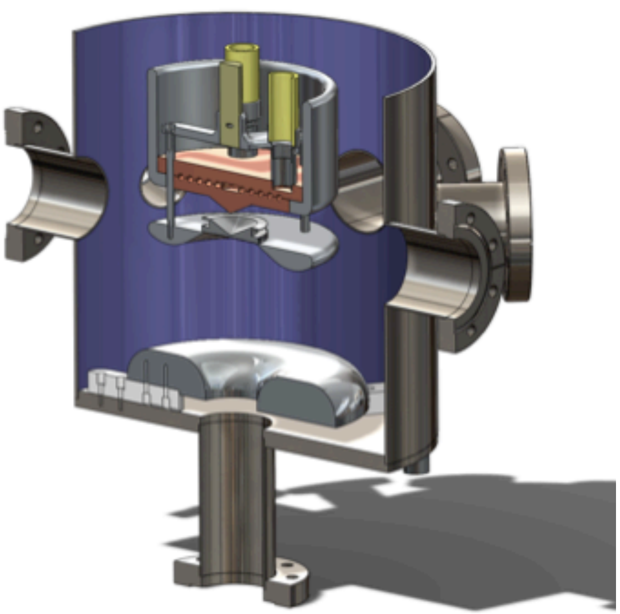
Box area corresponds to the first stage



High CW current (50 mA) polarized electron gun

- Matt Poelker (JLab) achieved 4 mA with good lifetime
- More current with (effectively) larger cathode area

Single large area cathode
(Development at MIT)



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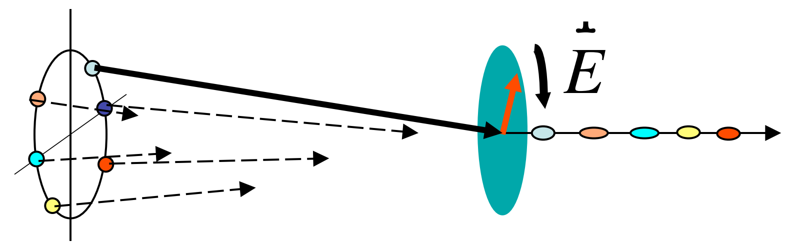
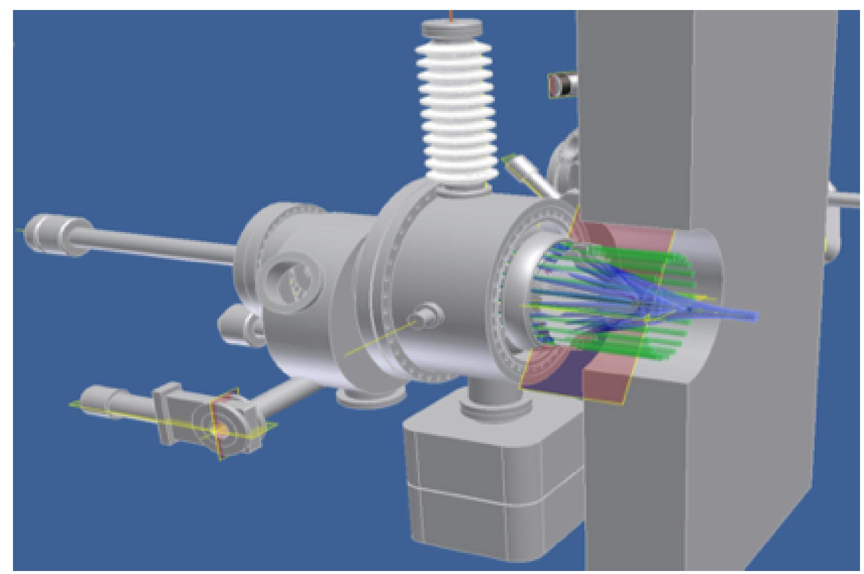
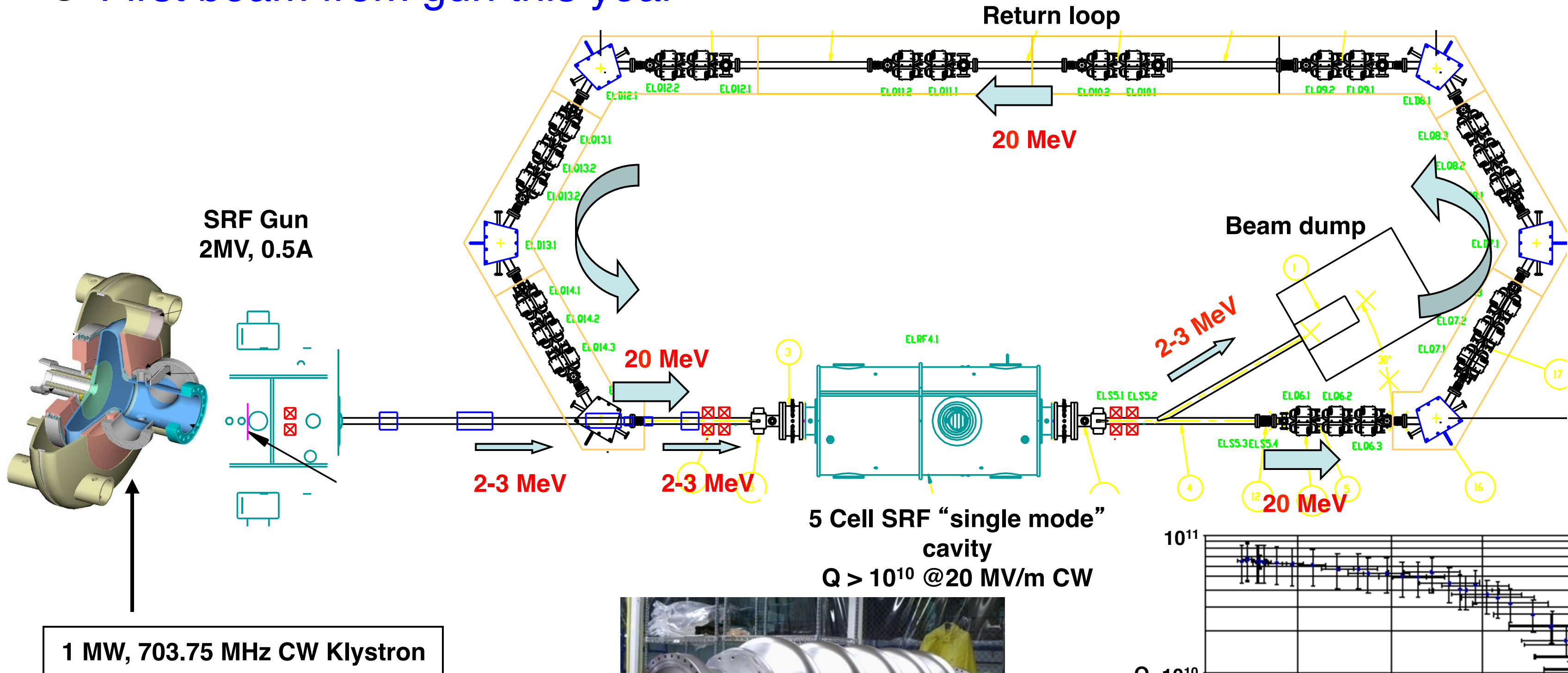
Gatling electron gun: many smaller cathodes
(Development at BNL)

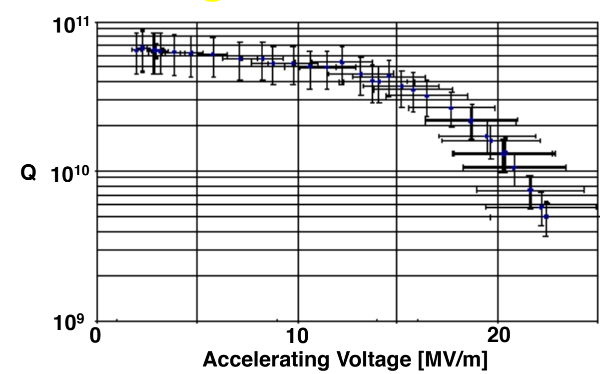




Energy Recovery Linac (ERL) Test Facility

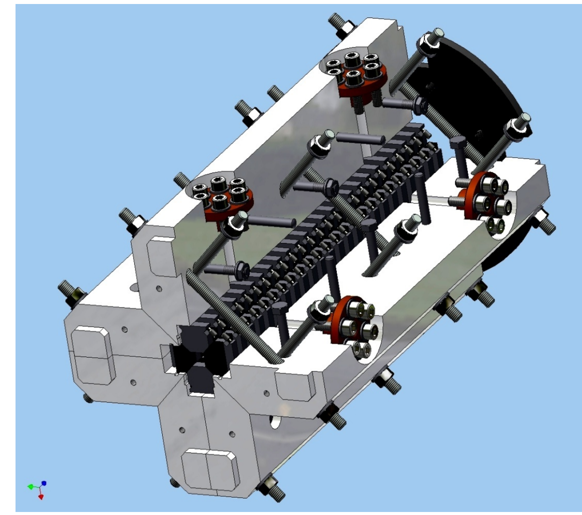
- Test of high current (0.5 A), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Allows for addition of a 2nd recirculation loop
- Similar beam current in cavity as for multi-pass eRHIC ERL
- First beam from gun this year





Coherent electron Cooling (CeC)

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → 10x reduced proton emittance gives high eRHIC luminosity at much reduced electron current
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (commissioning during run 15)

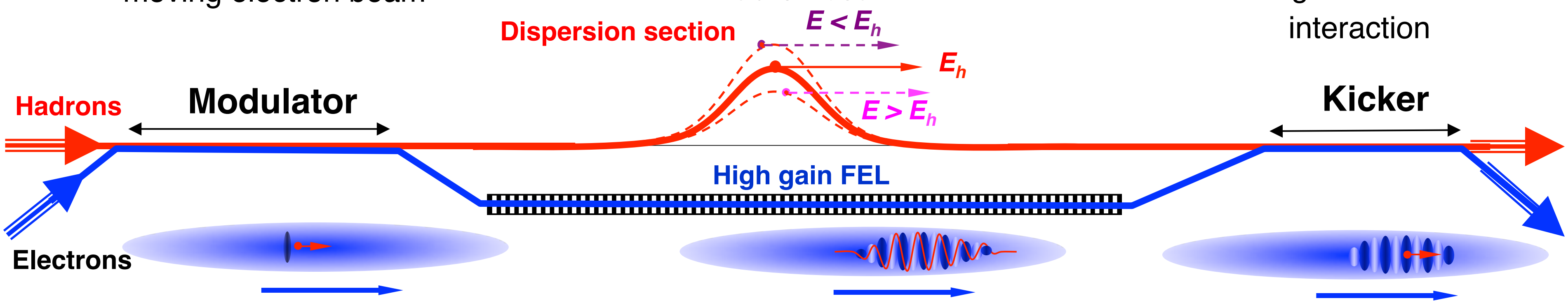


Helical wiggler prototype

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

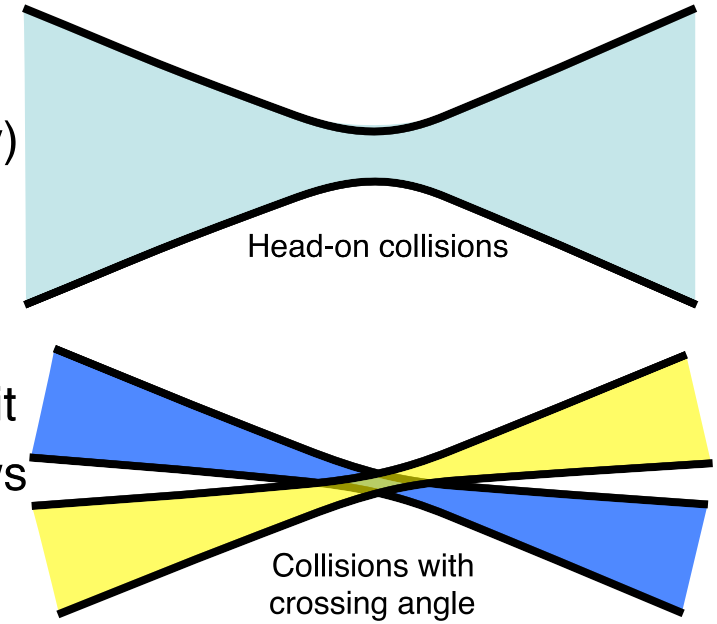
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

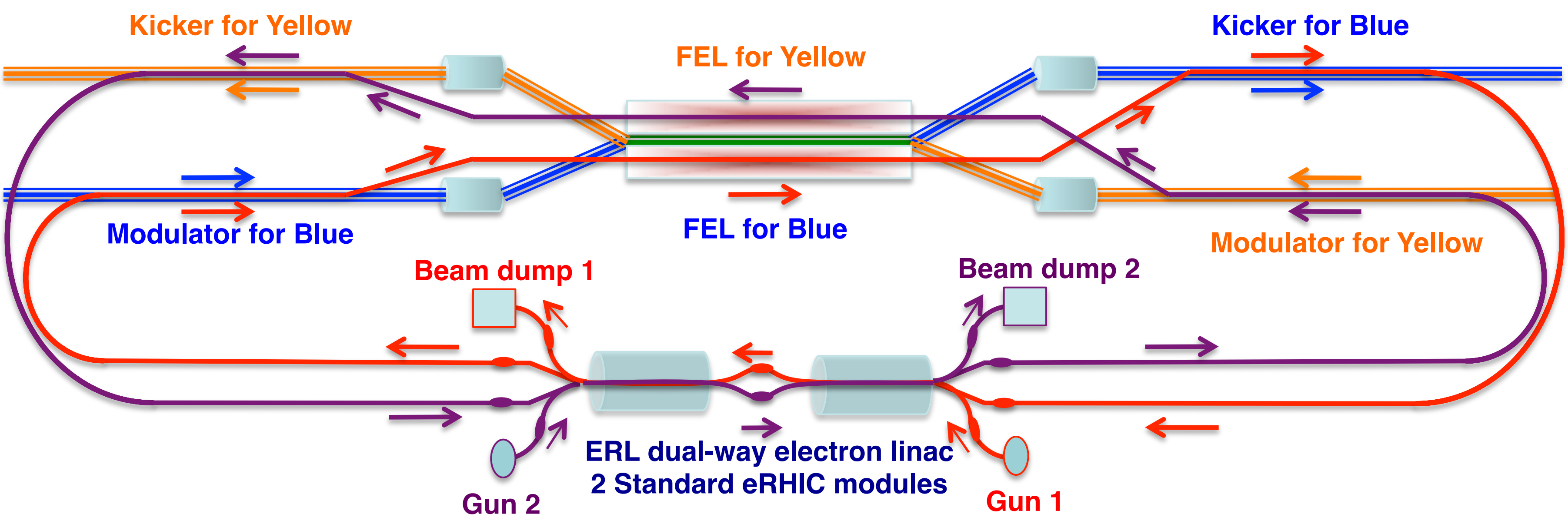
Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



CeC for RHIC: High Luminosity with large Piwinski angle

- If head-on collisions are at beam-beam limit large Piwinski angle collisions with very small emittance can increase luminosity (Super B factory)
- Needs strong cooling: synchrotron rad. or **CeC**
- Separate bunches outside high luminosity region to avoid beam-beam from low luminosity region.
- Reducing beam emittance back to beam-beam limit
- Smaller emittance and shorter overlap region allows for smaller beta-star
- RHIC: overlap length ~ 10 cm, ε_n (95%) ~ 1 π μm , β^* ~ 10 cm → ~ x10 luminosity increase (~ 5 x10^{33} cm^{-2} s^{-1} !)





Summary

- Exceptionally successful RHIC Run-12
- “RHIC II” luminosity upgrade essentially complete and ready for physics running
- Upgrades for the next decade:
  - Increased pp luminosity: new OPPIS, e-lenses,
  - Increased HI luminosity: 56 MHz storage rf, improved stochastic cooling
  - Low energy HI luminosity: low energy electron cooling
- eRHIC design progressing well:
  - First stage electron energy could be increased from 5 GeV to 10 GeV using FFAG arcs
  - Value engineering continuing with goal of a TPC (w/o detector) of ~ $500M

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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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N.P. Samios (RBRC)

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A. Deshpande
T. Izubuchi
R. Pisarski

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K. Boyle
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