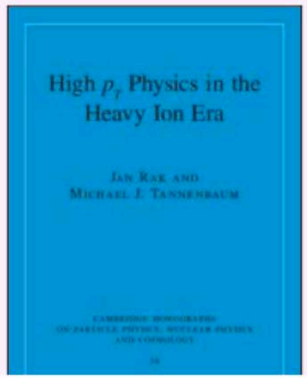
Highlights from BNL and RHIC 2015

For previous years with more details see:

2009: IJMPA **26** (2011)5299 1406.0830

2011-2013: IJMPA **29** (2014)1430017 1406.1100

2014: arXiv1504.02771



High-pT Physics in the Heavy Ion Era
Jan Rak, University of Jyväskylä, Finland
Michael J. Tannenbaum, Brookhaven National Laboratory, New York

Hardback

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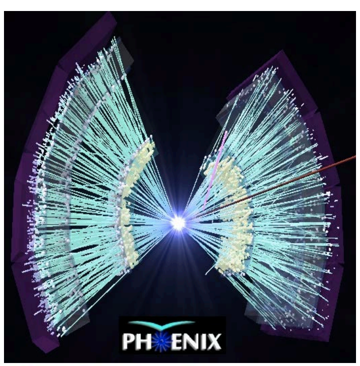
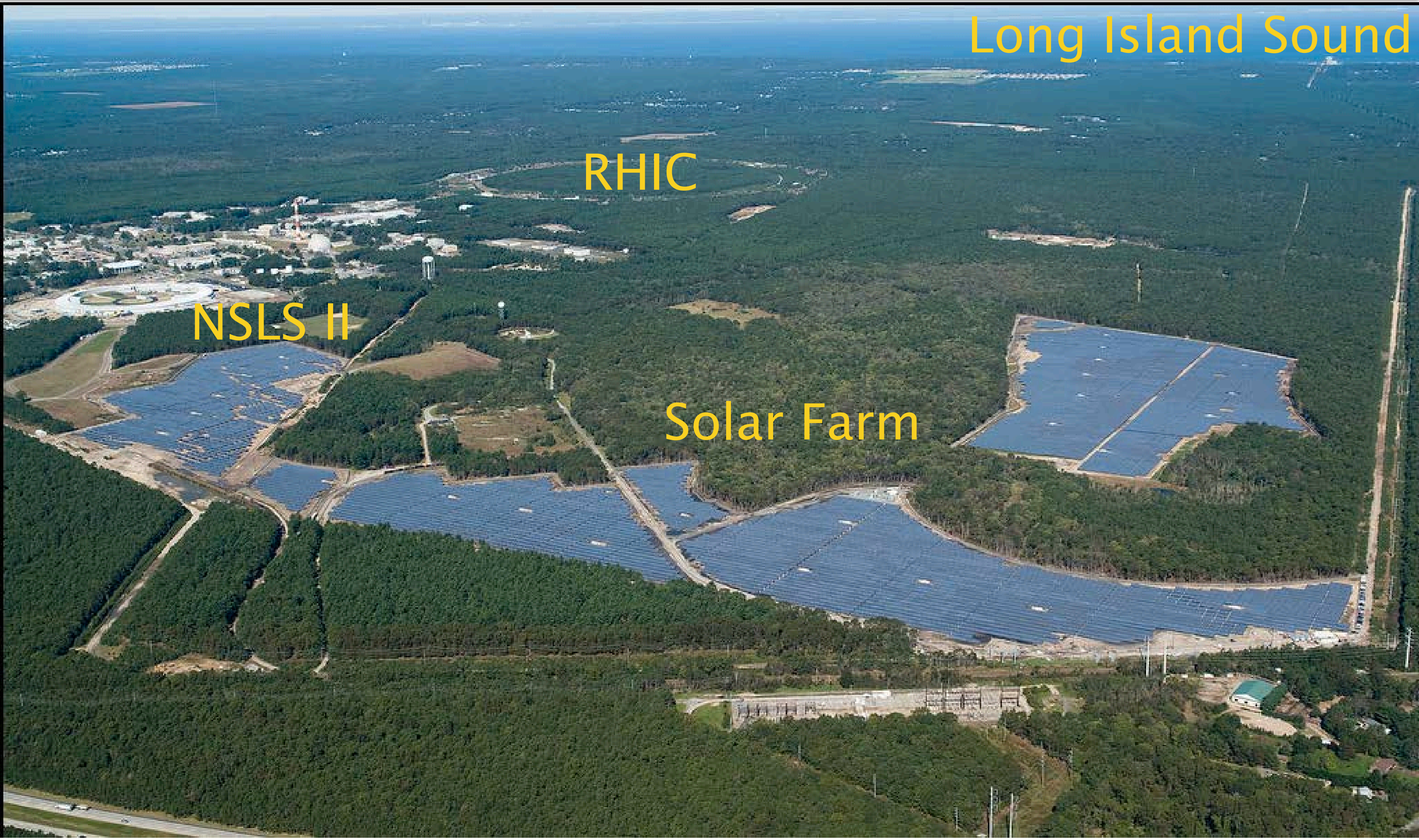
M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



International School of Subnuclear Physics,
"The Future of our Physics Including New Frontiers"
53rd Course-Erice, Sicily, Italy June 24- July 3, 2015

The Relativistic Heavy Ion Collider (RHIC) at BNL is 1 of the 2 remaining colliders-it is visible from space. BNL also has many other facilities

Brookhaven National Laboratory (BNL)



BNL M&O contract awarded to BSA again

By Peter Genzer | January 20, 2015 PRINT

Department of Energy, Brookhaven Science Associates Sign New Brookhaven Lab Management Contract

+ENLARGE

On Dec. 18, 2014, representatives from the U.S. Department of Energy (DOE), Brookhaven Science Associates (BSA), and New York State held a ceremonial signing of a new five-year, $3.25 billion contract for BSA to manage and operate Brookhaven National Laboratory for the DOE.

Established as a partnership between Stony Brook University and Battelle, BSA has managed Brookhaven Lab since 1998. The new contract begins on Jan. 5, 2015, and has a base term of five years, with up to 15 additional years that can be earned through award-term incentives.

National Synchrotron Light Source II Achieves 'First Light'

The National Synchrotron Light Source II detects its first photons, beginning a new phase of the facility's operations. Scientific experiments at NSLS-II are expected to begin before the end of the year.

October 23, 2014

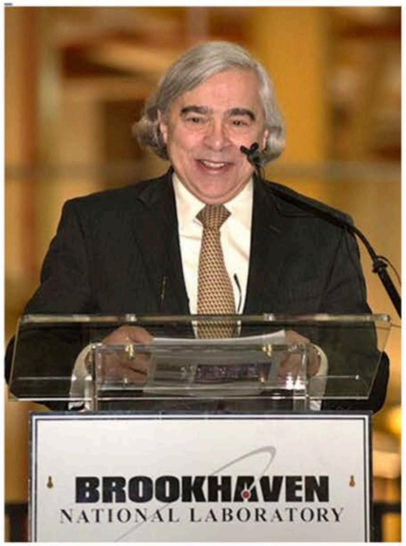
A crowd gathered on the experimental floor of the National Synchrotron Light Source II to witness "first light," when the x-ray beam entered a beamline for the first time at the facility. + ENLARGE

UPTON, NY — The brightest synchrotron light source in the world has delivered its first x-ray beams. The National Synchrotron Light Source II (NSLS-II) at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory achieved "first light" on October 23, 2014, when operators opened the shutter to begin commissioning the first experimental station (called a beamline), allowing powerful x-rays to travel to a phosphor detector and capture the facility's first photons. While considerable work remains to realize the full potential of the new facility, first light counts as an important step on the road to facility commissioning.

Energy Secretary Moniz Dedicates the World's Brightest Synchrotron Light Source

NSLS-II at Brookhaven National Lab will accelerate unprecedented advances in energy, environmental science, and medicine

February 6, 2015



U.S. Department of Energy Secretary Ernest Moniz at the NSLS-II dedication ceremony. + ENLARGE

UPTON, NY – U.S. Department of Energy (DOE) Secretary Ernest Moniz today dedicated the world's most advanced light source, the National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory (BNL). The NSLS-II is a $912-million DOE Office of Science User Facility that produces extremely bright beams of x-ray, ultraviolet, and infrared light used to examine a wide range of materials, including superconductors and catalysts, geological samples, and biological proteins to accelerate advances in energy, environmental science, and medicine.

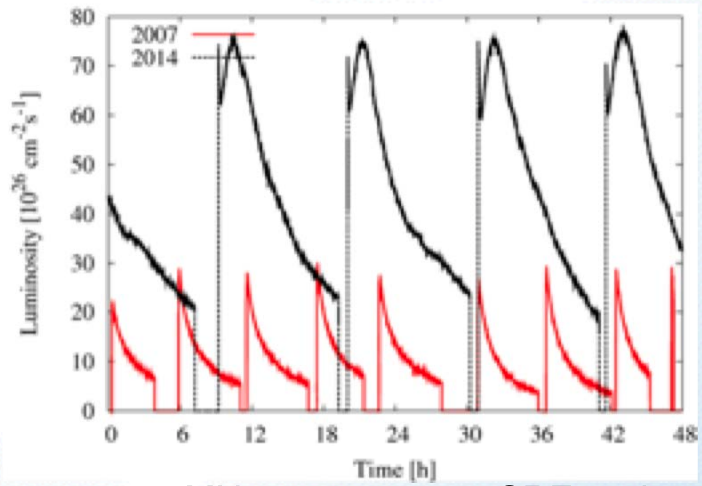
NSLS-II will enable a future generation of scientists to continue building on the 32-year legacy of research at Brookhaven's first light source, NSLS, which directly resulted in two Nobel Prizes and contributed to a third. With $150 million in funding through the American Recovery and Reinvestment Act of 2009, NSLS-II has come online on time and under budget to usher in the next chapter of light source capability. The planning, design,

RHIC – the First Heavy Ion Collider

- After continuous improvements and upgrades RHIC reached 25x design luminosity, exceeding “RHIC II” goal, 3 years early & at 1/7 of estimated cost
- Unparalleled flexibility of operation:
  - Wide energy range ($\sqrt{s_{NN}}$ = 7 – 200 GeV)
  - Capability of colliding different species with detector in center-of-mass frame
  - 8 modes (Au+Au, d+Au, Cu+Cu, Cu+Au, U+U, ^{3}He+Au,p+Au,p+Al) and 15 energies to date
- Ongoing upgrades:
  - 56 MHz SRF cavity to compress vertex and increase usable luminosity (commissioned)
  - Low Energy RHIC electron Cooling: 3 – 10x Au-Au luminosity for $\sqrt{s_{NN}}$ < 20 GeV

BNL Electron Beam Ion Source

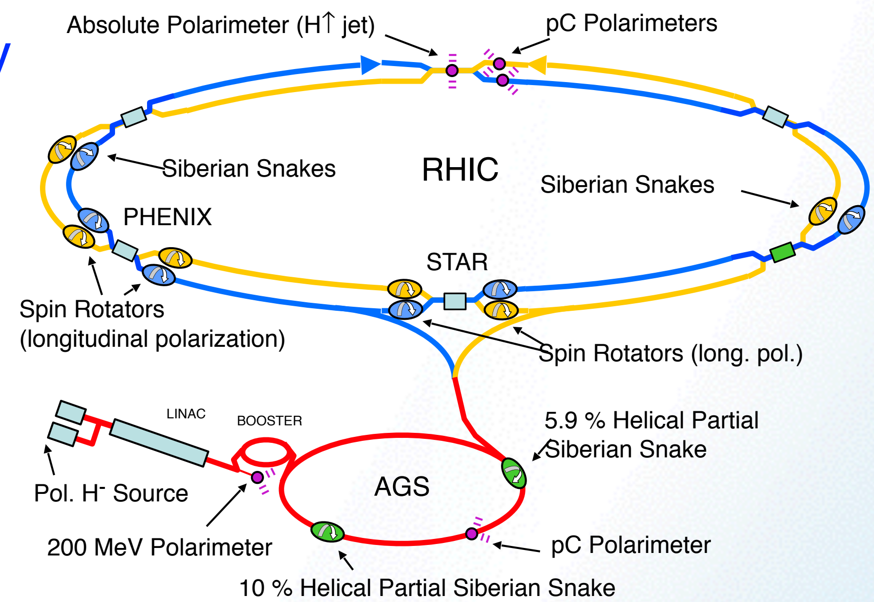
Au-Au luminosity with 3-D cooling



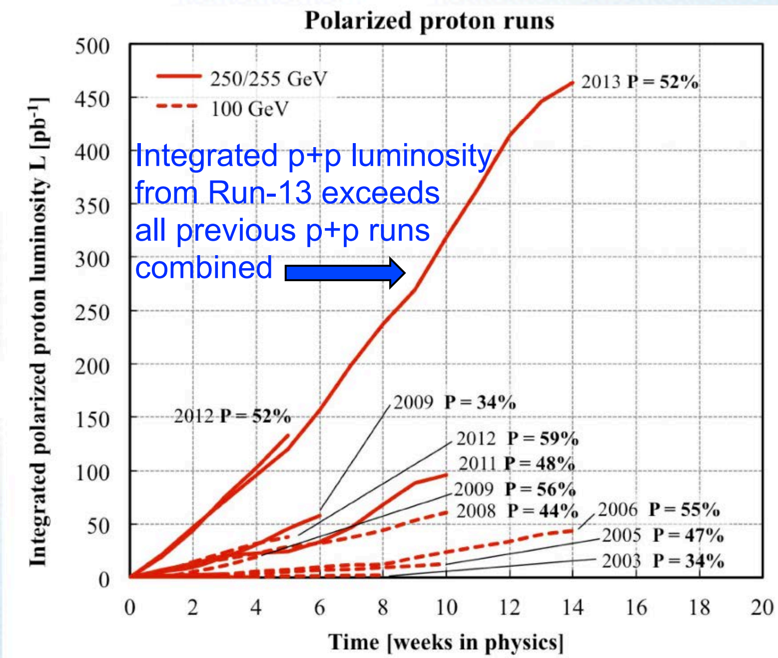
56 MHz quarter wave SRF cavity

RHIC – the First Polarized Proton Collider

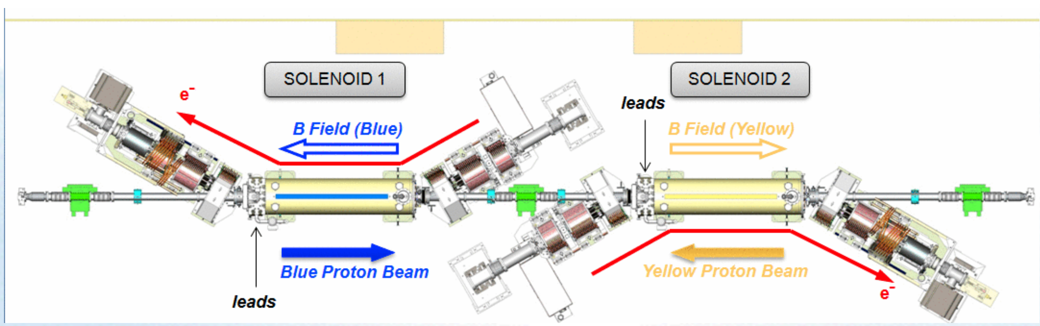
- Successful development of all necessary tools to accelerate polarized protons in the injector and in RHIC (polar. source, [partial] Siberian snakes, polarimeters)



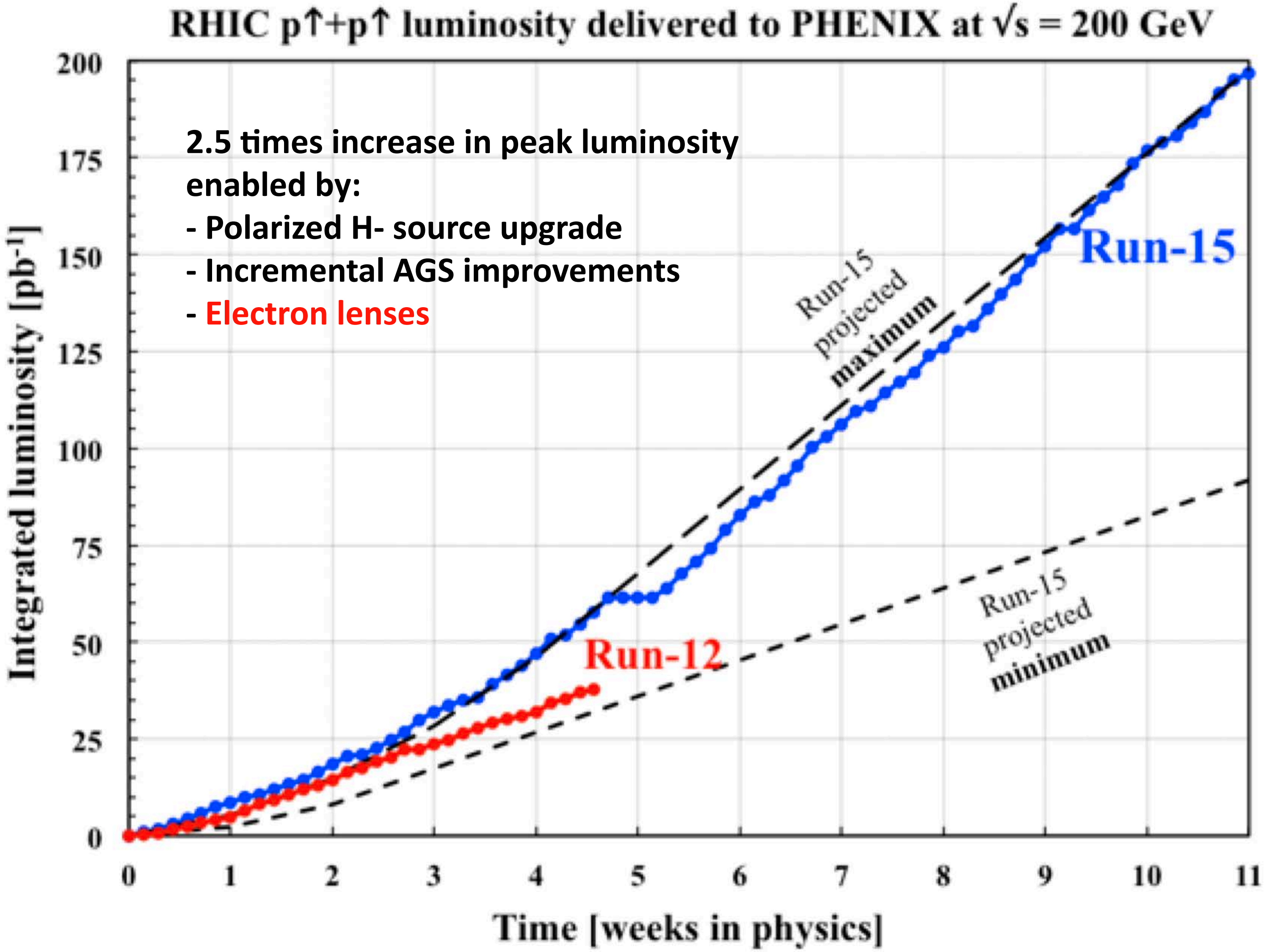
- Polarized proton collisions in RHIC:
  - $\sqrt{s}$=200 GeV: P~59%, L_{peak}~0.5×10^{32} $cm^{-2}s^{-1}$
  - $\sqrt{s}$=510 GeV: P~52%, L_{peak}~2.5×10^{32} $cm^{-2}s^{-1}$



- Luminosity increase with electron lenses
  Compensate for beam-beam interactions
  Successful operation in Run 15



… and even better



2.5 times increase in peak luminosity enabled by:
- Polarized H- source upgrade
- Incremental AGS improvements
- Electron lenses

http://www.bnl.gov/cad/esfd

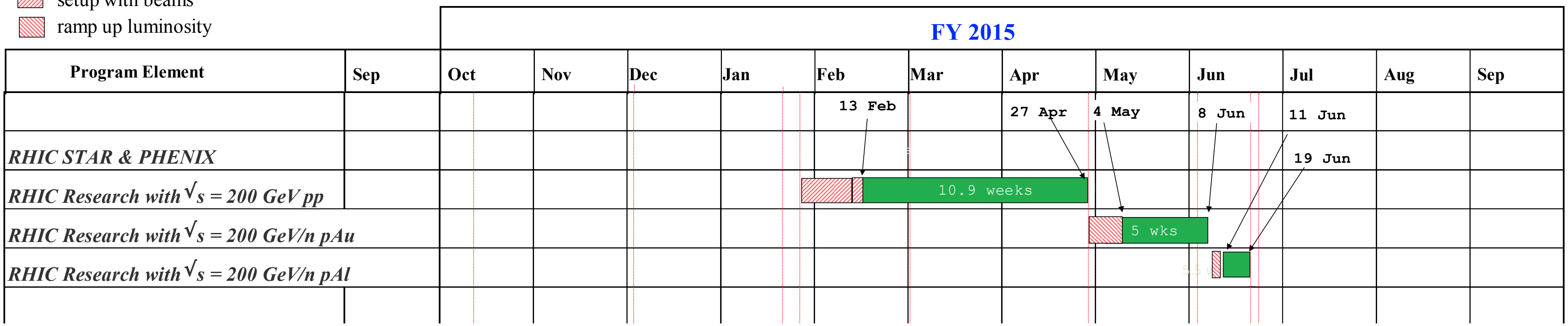
Scheduling Physicist: Makdisi/Pile

C-A Operations-FY15

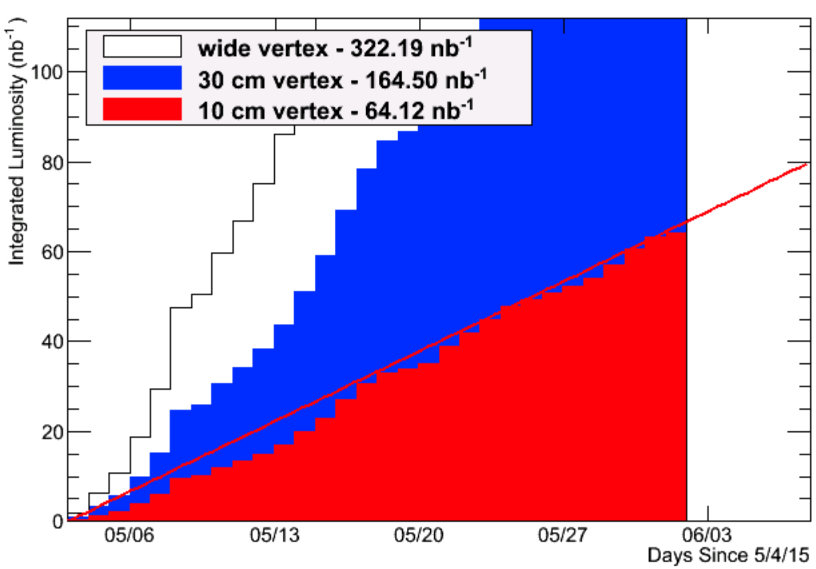
7 May 15

as run,planned

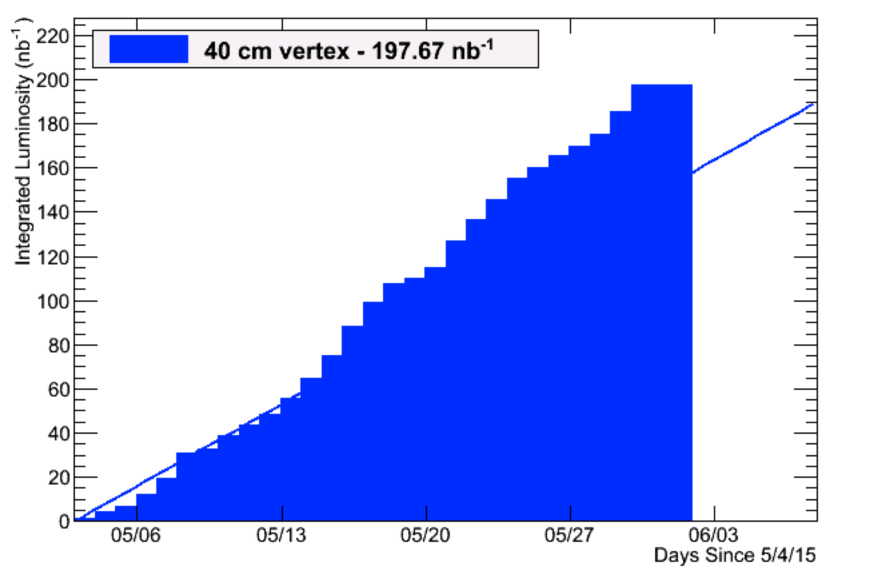
concurrent with RHIC
setup with beams
ramp up luminosity



PHENIX Integr. Sampled Lumi vs Day **Tue Jun 2 09:00:19 2015**

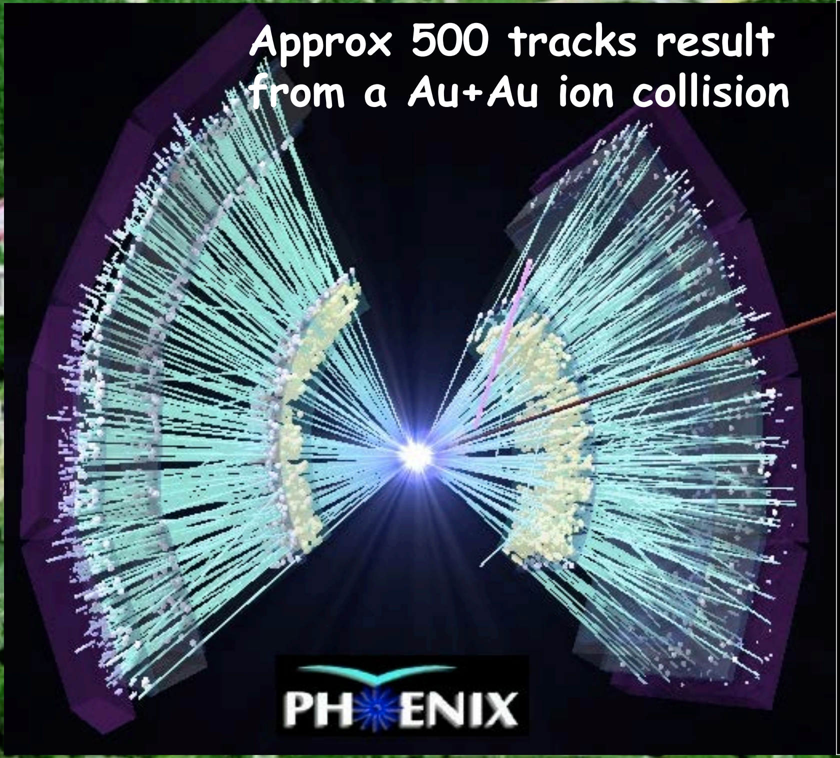


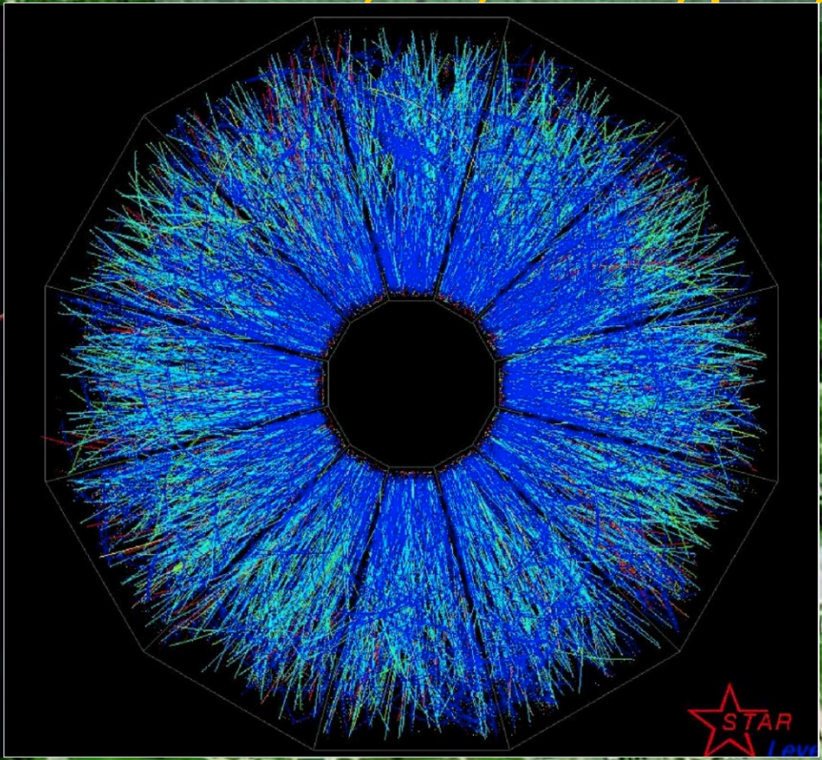
MPC-EX Integr. Sampled Lumi vs Day **Tue Jun 2 09:00:19 2015**



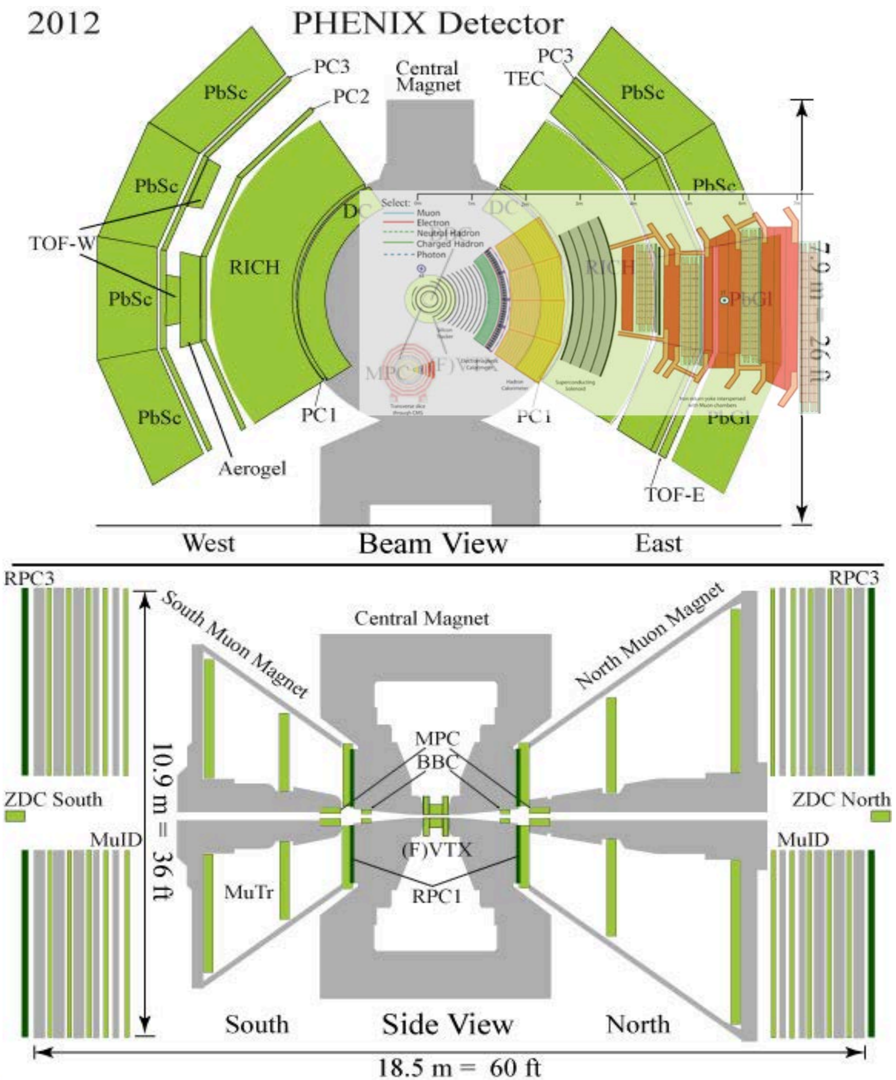
RHIC at BNL

p+p at √s=510 GeV max
Au+Au at √s=200 GeV max
Started at Year 2000
collided various beams
pp, dAu, CuCu, CuAu
AuAu, UU, He^3Au, pAu,pAl





"Mike, is there a 'real collider detector' at RHIC?"---J. Steinberger about PHENIX



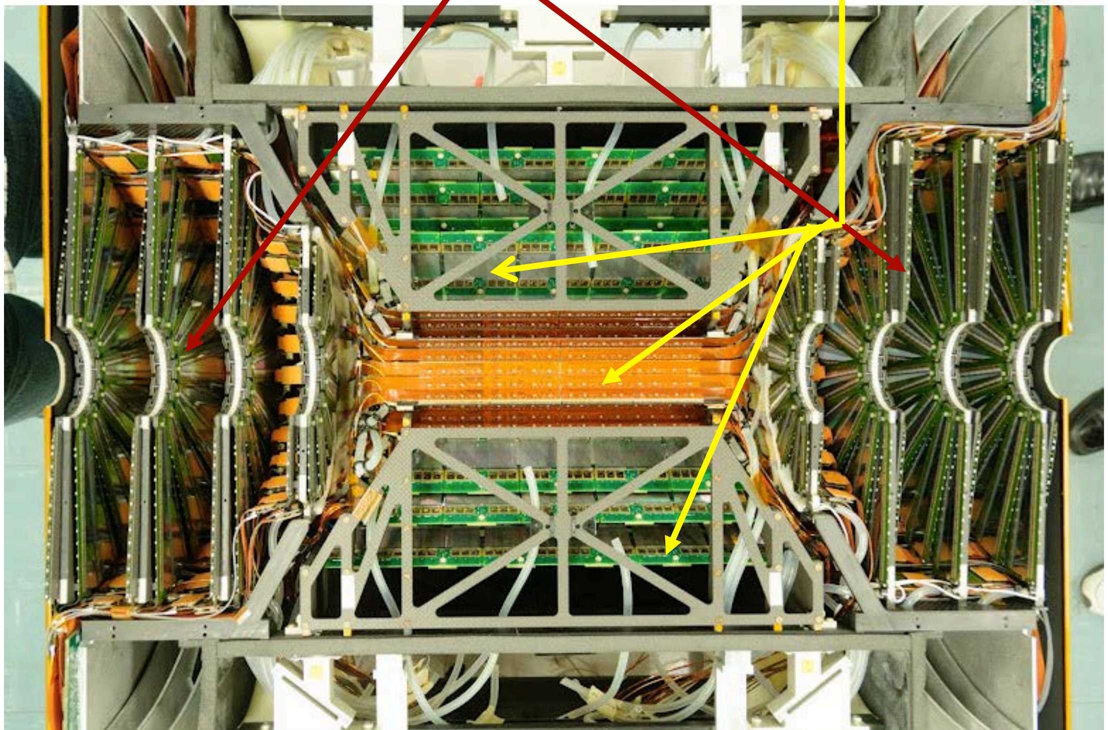
- **PHENIX is a special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**

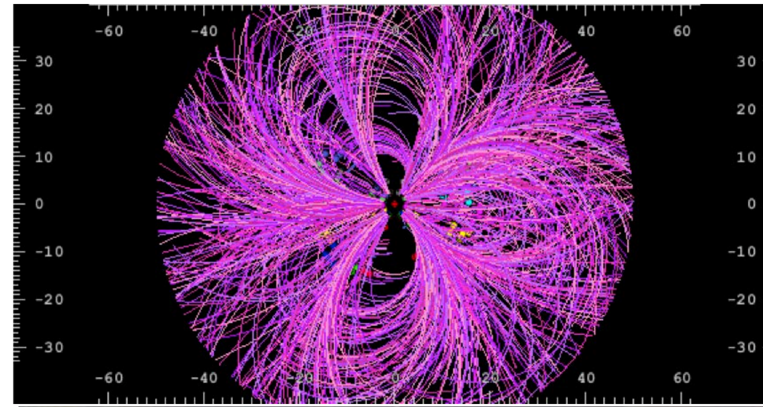
✓ *possibility of zero magnetic field on axis*
✓ *minimum of material in aperture 0.4% X_o*
✓ *EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger*

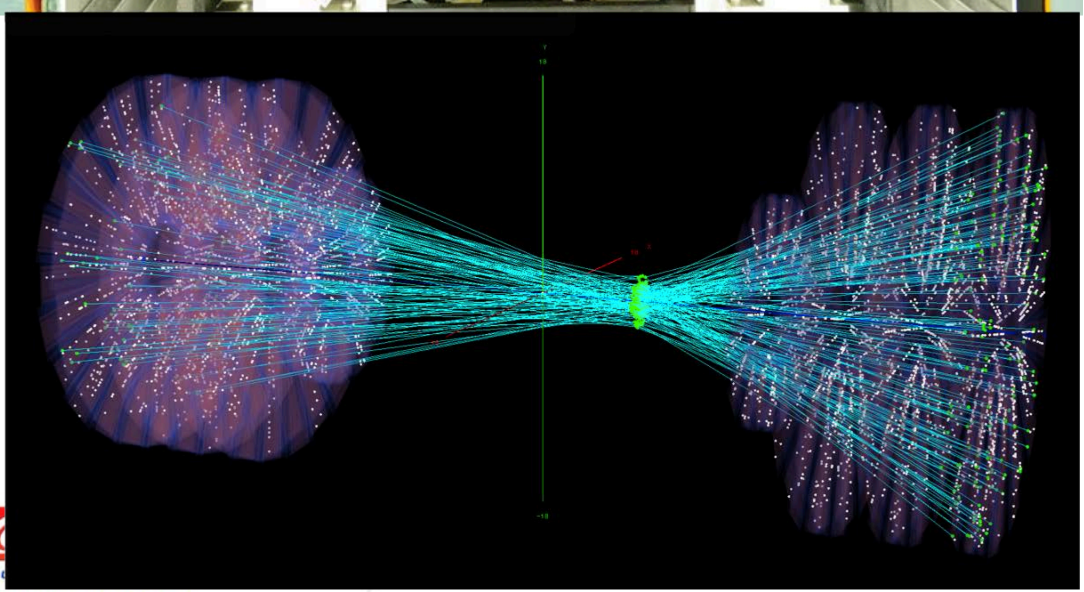
- *γ π^0 separation up to $p_T \sim 25$ GeV/c*
- *EMCAL and precision TOF for $h^{\pm}$ pid*
- *Main Central detector $|\eta|<0.35$*
- *Muon arms $1.1<|\eta|<2.3$*
- *BBC, MPC $3.1<|\eta|<3.9$*

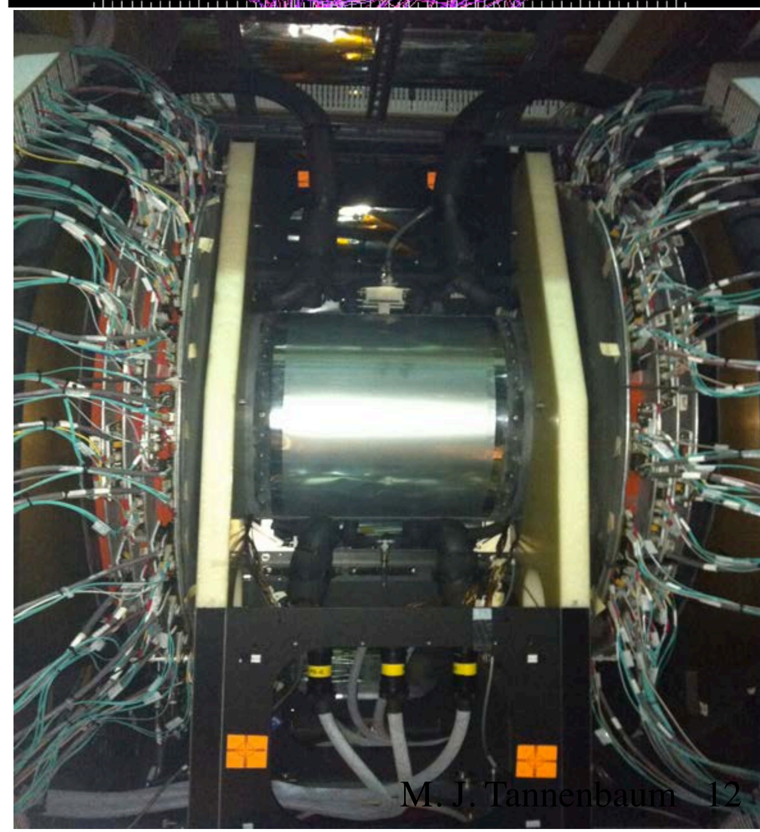
Comparison to scale with a wedge of CMS

PHENIX FVTX and VTX in place-displaced e^{HF}, μ^{HF}

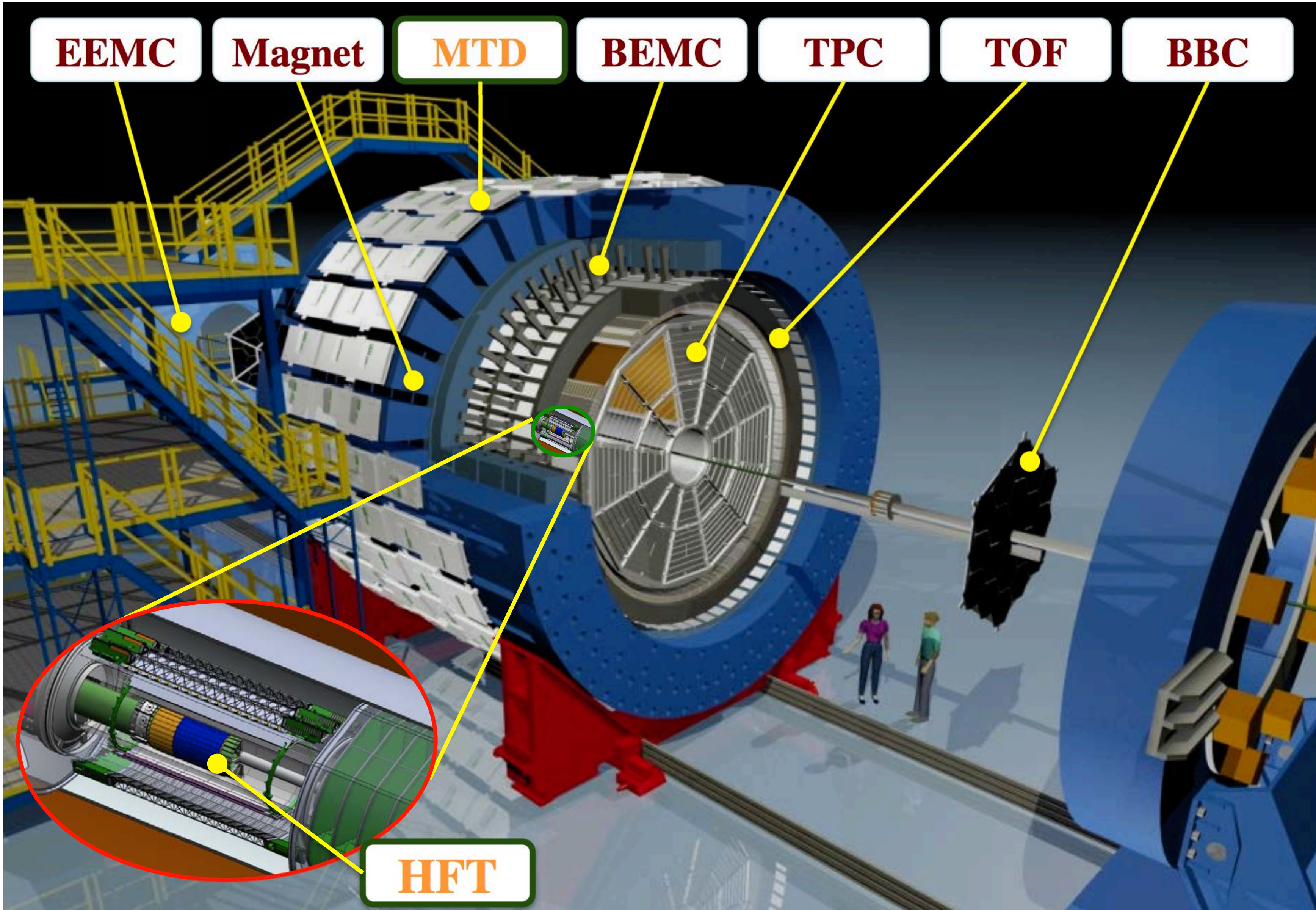






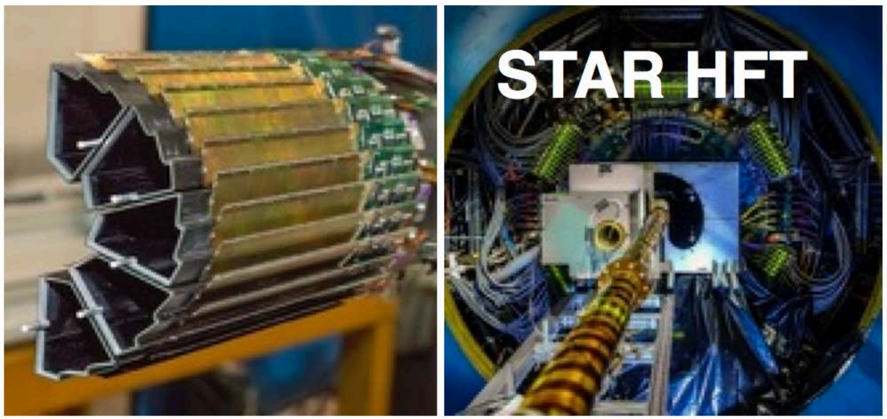


STAR Detector System

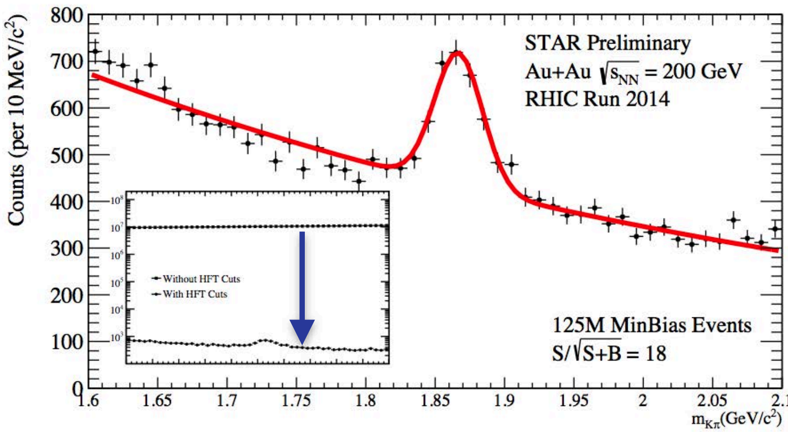


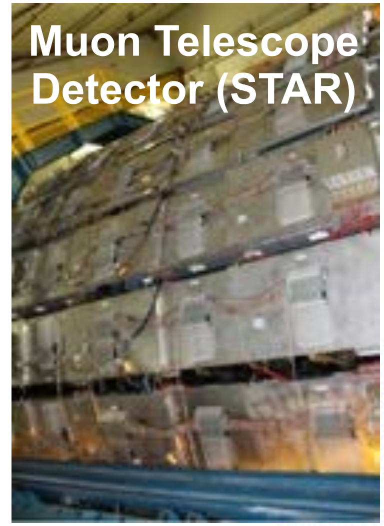
RHIC: Recent Detector Upgrades

Fully reconstruct open charm/beauty hadrons with displaced vertex

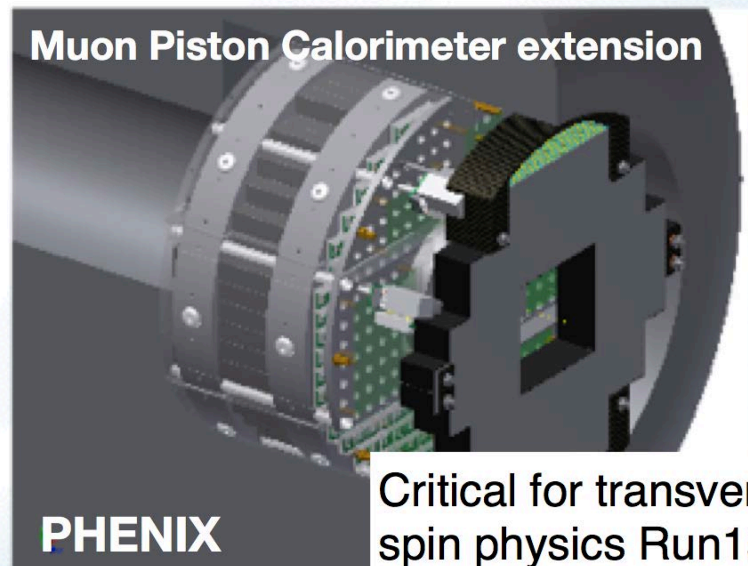


Completed on schedule and below cost



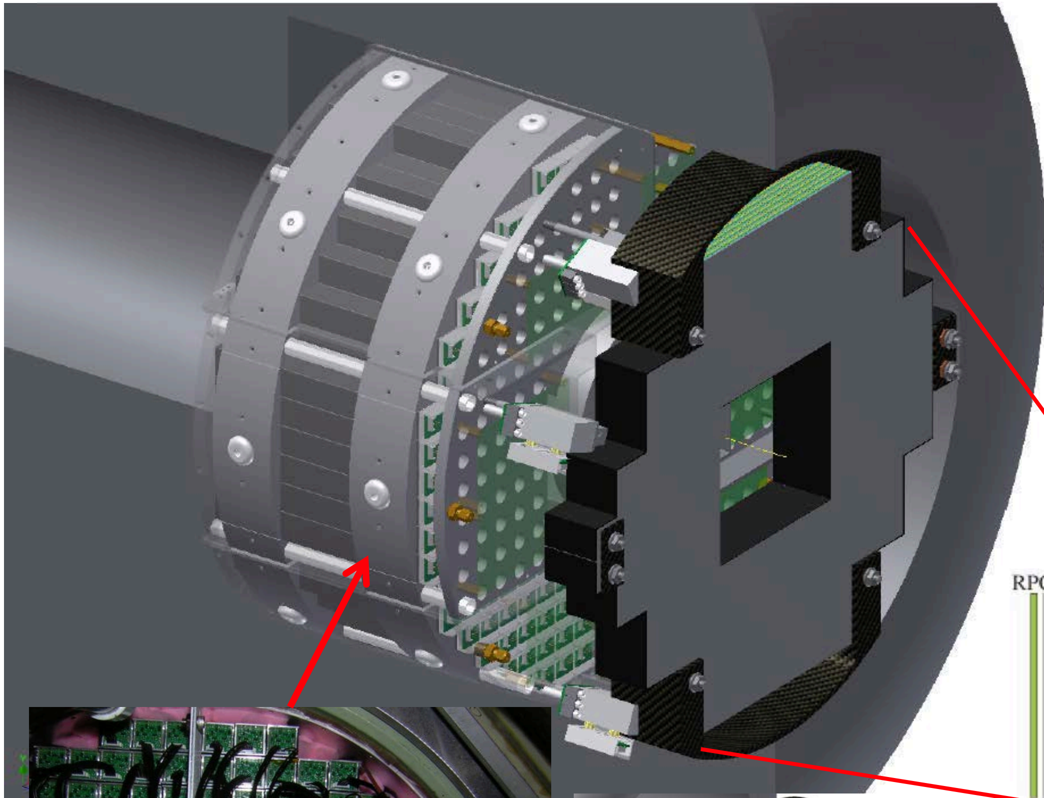


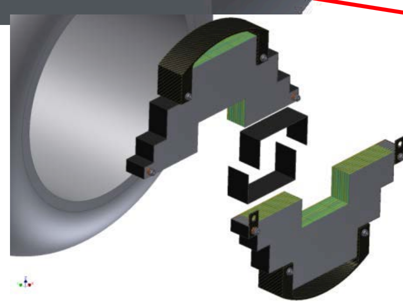
Enhances triggering capabilities for heavy quarkonia



Critical for transverse spin physics Run15

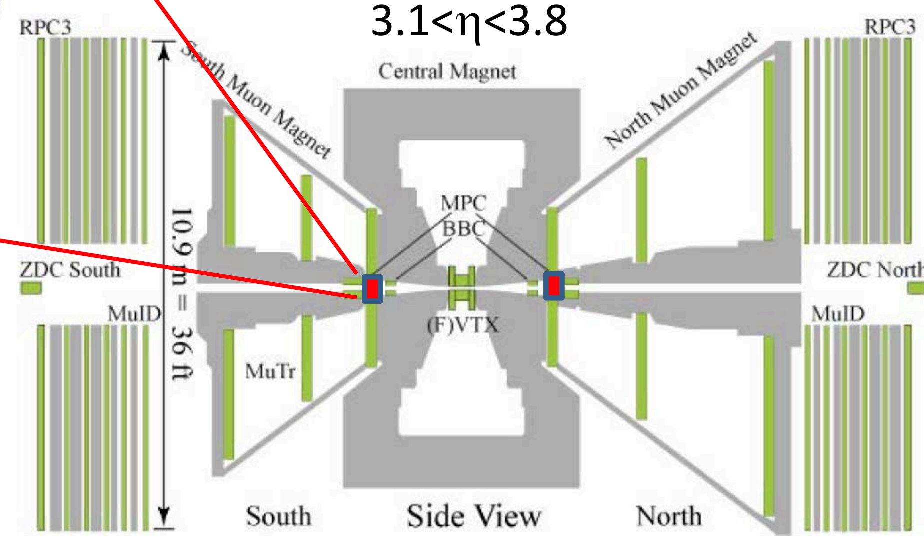
The MPC-EX Detector





A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

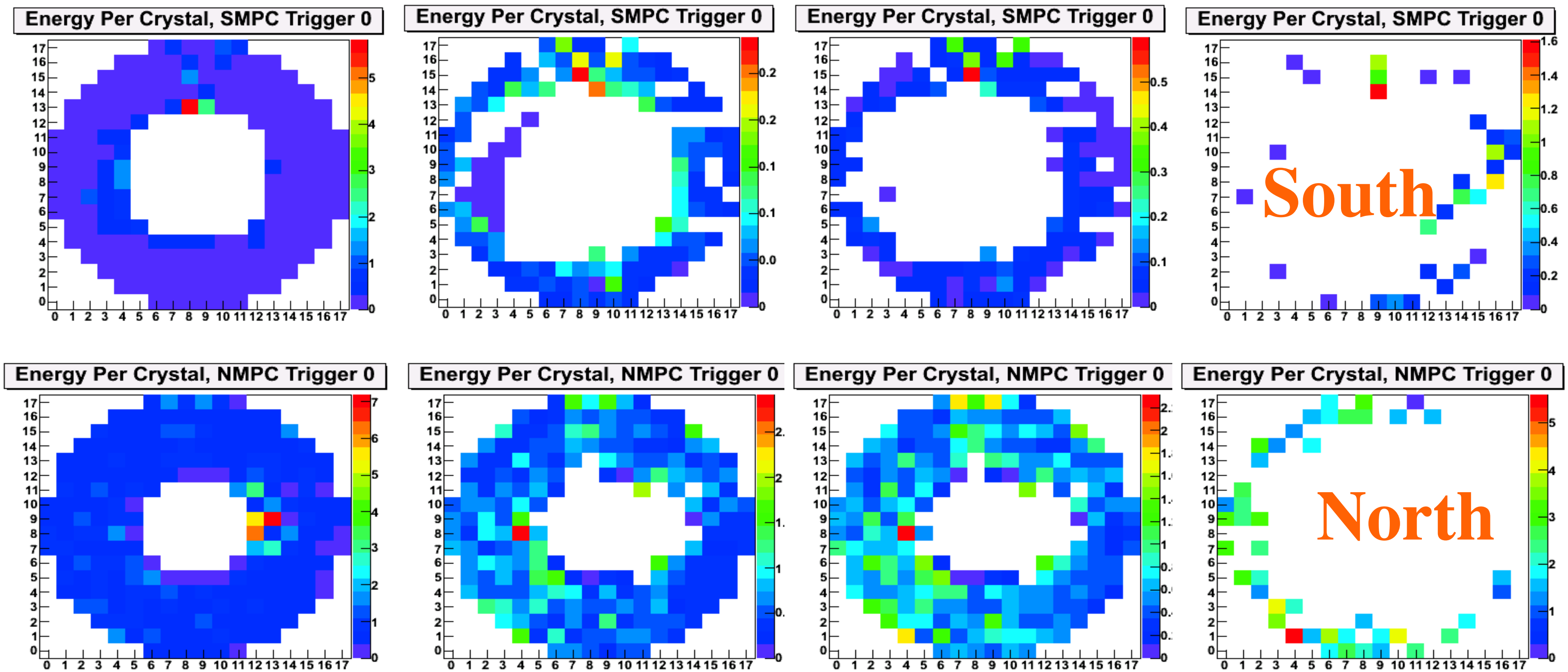
- π^0 rejection (direct photons)
- π^0 reconstruction out to >80GeV
- Charged track identification



PHENIX

MPC Damage-Yellow Abort Kicker Prefires

Store	19050	19116/18	19134
	May 11	May 28	June 1
	Damaged South Impacted North	We got lucky No addt'l damage	The end of the MPC in Run 15



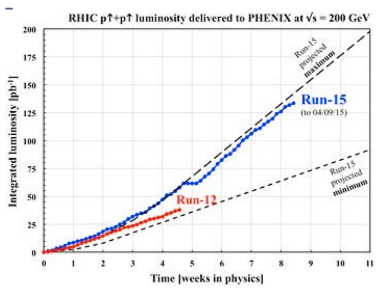
Relativistic Heavy Ion Collider Smashes Record for Polarized Proton Luminosity at 200 GeV Collision Energy

Electron lenses and other accelerator improvements keep beams focused and compact to maximize collision rates and scientific productivity

April 14, 2015

An aerial view of the Relativistic Heavy Ion Collider, the only machine in the world capable of colliding beams of polarized protons—protons whose individual spins are aligned in a particular direction—to tease out how the protons' inner building blocks, quarks and gluons, contribute to proton spin.

UPTON, NY—The Relativistic Heavy Ion Collider (RHIC), a powerful particle accelerator for nuclear physics research at the U.S. Department of Energy's Brookhaven National Laboratory, just shattered its own record for producing polarized proton collisions at 200-giga-electron-volt (GeV) collision energy. In the experimental run currently underway at this two-ringed, 2.4-mile-circumference particle collider, accelerator physicists are now delivering 1200 billion of these subatomic smashups per week—more than double the number routinely achieved in 2012, the last run dedicated to polarized proton experiments at this collision energy.

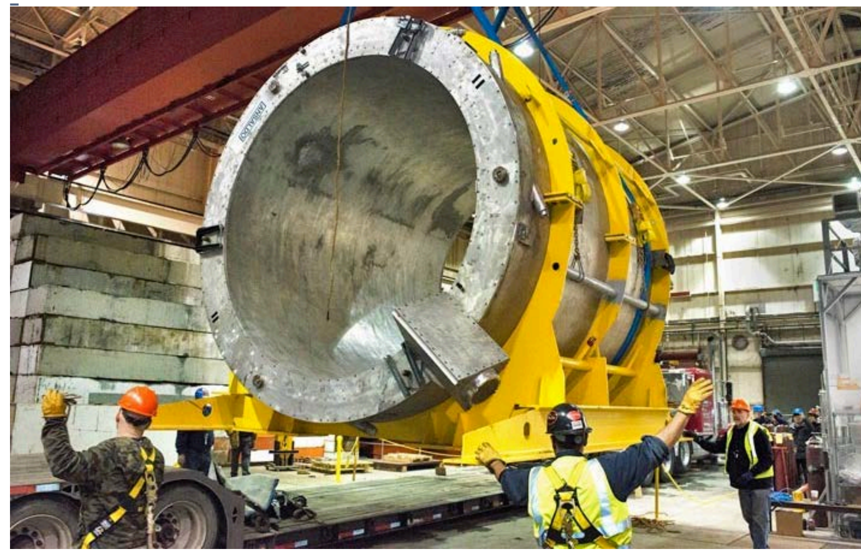


RHIC is producing more than twice as many proton-proton collisions per week during the current run as it did in 2012, the last run dedicated to polarized proton collisions. + ENLARGE

By Justin Eure | May 1, 2015 PRINT

Giant Electromagnet Arrives at Brookhaven Lab to Map Melted Matter

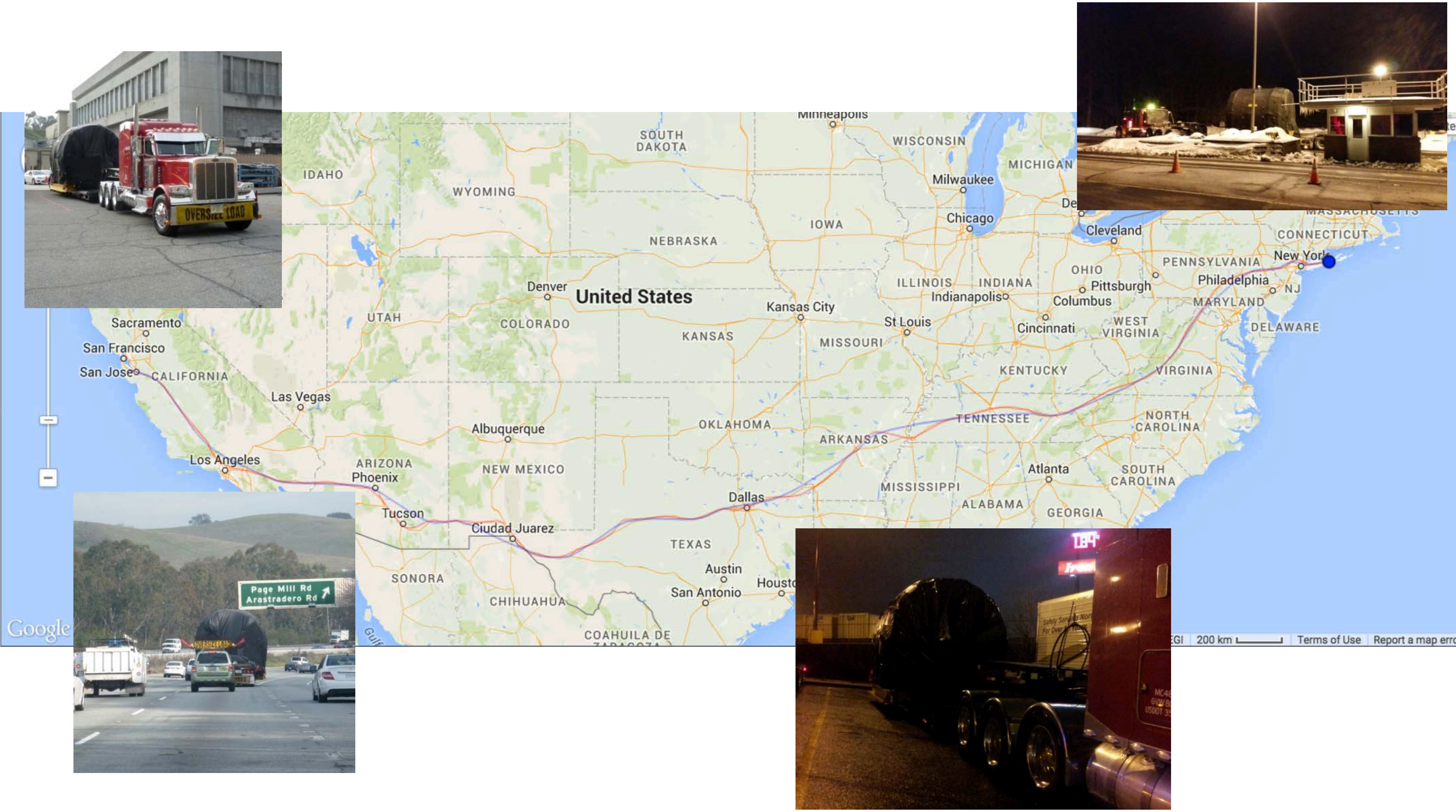
A 20-ton superconducting magnet traveled from California's SLAC Lab to New York's Brookhaven Lab as part of a proposed upgrade to the Relativistic Heavy Ion Collider's PHENIX detector



The massive, just-delivered magnet leaves the truck inside Brookhaven's Superconducting Magnet Division. + ENLARGE

Why did the 40,000-pound superconducting magnet cross the country? The full answer to this twist on the old joke is complicated, but here's the short version: to unlock the secrets

SC-Magnet From SLAC to BNL



Former BaBar Solenoid on the AGS Floor

SC-Magnet Warm Acceptance Test

- **SC-Magnet Acceptance Test Complete in 912. All is OK**

Tests Performed by Mike Aneralla and SMD crew with C-AD help
- **Hypot test**
- **Impulse tests**
- **He Leak check**
- **Inductance measurement**

Superconducting Magnet Division

sPhenix Solenoid Incoming Inspection & Acceptance

MDC No. sPhenix-010 Rev: A
Page 1 of 10
Rev Date: 04/03/2015
Author: M. Anerella
Approved: 04/06/2015

Head, Project Mechanical Engineering	M. Anerella	04/03/2015
Head, Technical Support	R. Ceruti	04/03/2015
ES&H Coordinator	W. Czekaj	04/03/2015
Quality Assurance	H. Hocker	04/06/2015
Electrical Systems	P. Joshi	04/03/2015
Design Engineering	P. Kovach	04/06/2015

Serial No	Part No	Part	P/L	ECN	Rev	P/L	ECN	Rev	P/L
SE01									

Work Order #: ____________ Deviation & Waiver: ____________

OP	Description	Name/Life #	Date	DR
5	Reference Documents: 25-2043020 Revision A			
10	This traveler covers only the work described herein. Moving, lifting, or reorienting the magnet is not a part of the work described here.	R Ceruti 15846	4/6/15	
20	The technicians shall be instructed by their cognizant technical supervisor in the operation of the required electrical test equipment and the electrical testing procedures.	[illegible] 15371	4/16/15	
30	Hipot ("Hypot") and impulse testing pose an electrical hazard. At least two properly trained technicians must be present to perform this testing. When testing, a trained technician shall be stationed at any point where the item under test is accessible to unauthorized people, and barriers shall be set up. Signs shall be posted reading "DANGER HIGH VOLTAGE" and warning lights shall be turned on.	[illegible]	4/16/15	
40	The technician is responsible for notifying the technical supervisor and/or the cognizant engineer of any discrepancies occurring during the performance of this procedure. All discrepancies shall be identified and reported in accordance with SMD-MAG-1003.	[illegible]	4/16/15	

Measuring and test equipment used for this procedure shall contain a valid calibration label in accordance with the SBMS Subject Area 'Calibration', where applicable.

SE01

SC-Magnet Warm Acceptance Test

- 13 page traveler

Superconducting Magnet Division — **sPhenix Solenoid Incoming Inspection & Acceptance**

MDC No. sPhenix-010 Rev: A
Page 2 of 10
Rev Date: 04/03/2015
Author: M. Anerella
Approved: 04/06/2015

OP	Description	Name/Life #	Date	DR
50	Technicians performing Pressure Testing shall be instructed in the procedures prescribed by the SBMS Subject Areas by the Cognizant Engineer or Technical Supervisor: * Compressed Gas Cylinders and Related Systems * Pressure Safety * Cryogenics Safety All relief devices and gauges used for pressure tests shall meet the requirements of the SBMS Subject Area. Examine all pressure test equipment before pressure is applied to ensure it is tightly connected. Suitable precautions shall be taken during pressure testing to eliminate hazards to personnel in the proximity of the test in the event of a rupture. The area shall be roped off.	R Cerutti 15846	4-6-15	
60	All work performed herein shall be done in a manner compliant with the document "Work Plan for S-Phenix Magnet". All work which has not been categorized as 'worker planned work' shall require an approved work permit.	RC	4/6	
110	Inspect, tag, and inventory all voltage tap, strain gauge and other instrumentation wires. Record lead ID's on Table 2.	A. Dietz 15371	4/6/15	
120	Remove and inspect heat shield shipping restraints. There are 3 restraints at each end of the magnet. Photograph and record damage, if any, on a discrepancy report. Tag and store the shipping restraints for future use.	RC	4/6	
130	Perform visual inspection of the magnet. Photograph and record damage, if any, on a discrepancy report.	RC	4/6	
140	Set power supply to 25 VDC maximum and apply 1 amp to coil. Measure and record voltage drops and record in Table 1	A. Dietz	4/6/15	

SE01

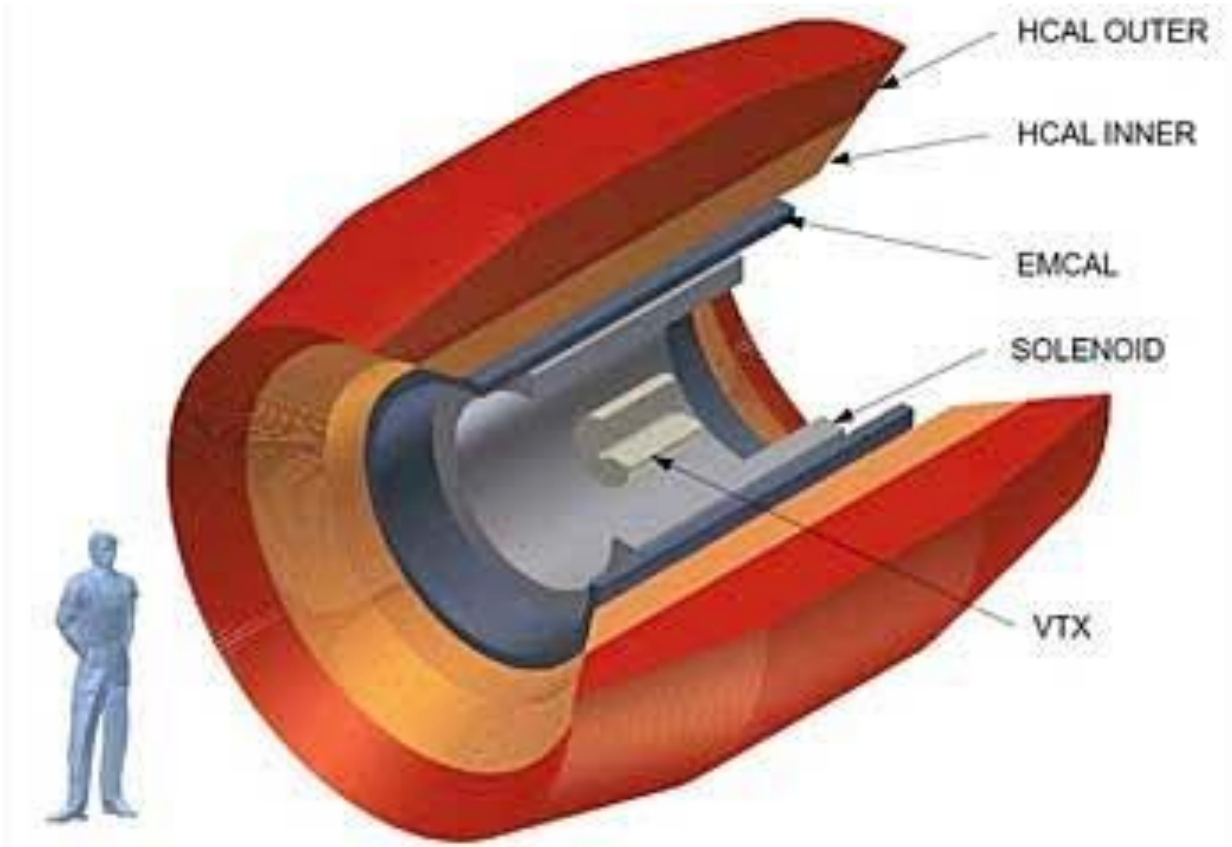
Superconducting Magnet Division — **sPhenix Solenoid Incoming Inspection & Acceptance**

MDC No. sPhenix-010 Rev: A
Page 3 of 10
Rev Date: 04/03/2015
Author: M. Anerella
Approved: 04/06/2015

OP	Description	Name/Life #	Date	DR
150	Measure overall resistance, coil inductance and quality factor. Perform tests at three frequencies, 20Hz, 60Hz and 1KHz. Record data below: Temp: 22°C R: 2.5303Ω, 2.5303Ω, 2.5303 L: 74.7228mH, 60.0337mH, 21.332 mH Q: 1.17, 1.61, 1.78 DC inductance 2.3H	A. Dietz	4/6/15	
160	Prepare coil for hypot & impulse testing: 1. Verify (3) blank-off flanges at LE & (3) blank-off flanges at NLE are installed ___ 2. Locate magnet lead feedthrough assembly along with O-Ring to the chimney. Attach single magnet lead to feedthrough ✓ 3. Dress all other leads and taps /instrumentation into the chimney in preparation for bolting of the feedthrough ✓ 4. Bolt the feedthrough in place ✓ 5. Install lead box covers ✓ 6. Connect mechanical vacuum pump to the feedthrough ✓ 7. Start pump. Continue pumping down until an absolute pressure of <50 millitorr is reached in the vacuum space ✗	R Cerutti 15846 A. Dietz 15371	4/6/15 4/6/15	

SE01

Looking Forward: Advanced Instrumentation to Help Complete the Mission



A rendering of the proposed upgrade showing the inner silicon tracker (VTX), the solenoid, and the calorimeters. The solenoid has a ~~diameter~~ radius of 1.4 m

Homepage | Registration | Agenda | Contact Us | Workshop Information

A Large-Acceptance Jet and Upsilon Detector for RHIC

General Workshop Registration (Deadline: June 12, 2015 12:00 AM)
Please note, this workshop is open to the public.

Begin Workshop Registration

Workshop Announcement

In April 2015, the Office of Nuclear Physics in the Department of Energy conducted a review of the science program enabled by a new detector, sPHENIX, that focuses on large acceptance, ultra-high rate measurements of fully reconstructed jets and high resolution spectroscopy of Upsilon states at RHIC. The outcome of that review was very positive and,

Workshop Date
June 16, 2015

Workshop Location
Brookhaven National Laboratory
Upton, NY 11973 USA

Physics Department (Bldg 510)
Large Seminar Room

Directions and Maps
To Event | To BNL

Workshop Coordinator

Following up on the afternoon discussion, which concluded that we should move expeditiously to form a new detector collaboration to take advantage of the physics opportunities offered by a large acceptance detector for jets and heavy quarkonia built around the BaBar magnet, we are inviting all interested scientists and institutions who are considering joining this effort to declare their interest in joining this new collaboration. **We request that they do so by sending an electronic message to Peter Yamin yamin@bnl.gov including their name, institution, and email address no later than July 16, 2015. If there is more than one interested scientist at the same institution, we ask them to identify the person who will serve on the provisional Institutional Board (IB) for the new detector collaboration.**

Leaked report on NSAC Long Range Plan

nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Ar

Archive > Volume 521 > Issue 7552 > News > Article

NATURE | NEWS

Billion-dollar particle collider gets thumbs up

Proposed US electron–ion smasher wins endorsement from influential nuclear-science panel.

Edwin Cartlidge

19 May 2015

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Brookhaven National Laboratory/CC BY-NC-ND 2.0

Brookhaven National Laboratory in New York is a potential host for the Electron-Ion Collider.

http://www.nature.com/news/billion-dollar-particle-collider-gets-thumbs-up-1.17579[6/21/15, 4:27:5

Excerpts

The machine should also solve a puzzle about the proton that has baffled physicists for nearly 30 years. The proton has a quantum-mechanical property called spin, but, strangely, the spins of its three constituent quarks add up to only about one-third of its own spin. The EIC would determine what makes up the difference: options include the spin of the proton's gluons, the angular momentum of its quarks or of the gluons from their orbital motion, or a mixture of all three.

Robert McKeown, deputy director for science at the Jefferson lab, thinks that limited funds might delay the start up of the EIC until at least 2030. And Michael Lubell, director of public affairs at the American Physical Society, questions whether it is feasible for the EIC to be built by the United States alone. He notes that the $1.5-billion Long-Baseline Neutrino Experiment became an international project after a slimmed-down $600-million version failed to pass scientific muster. "It is hard to see how to do this unless you get international buy-in," he says.

Proton Spin Structure

Manohar-Jaffe sum rule:

Know very little

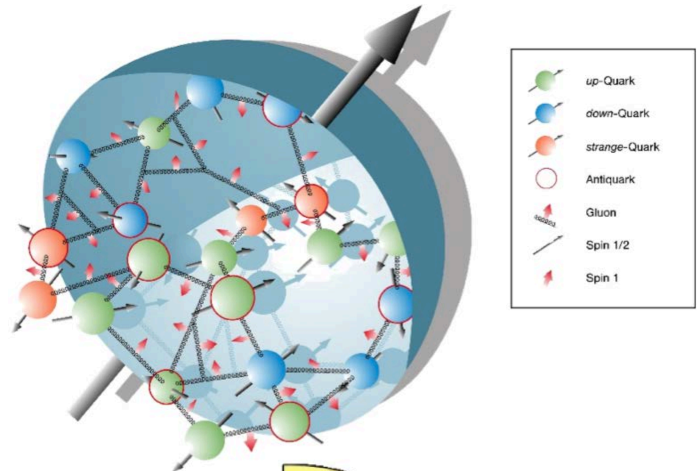
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \boxed{\Delta L_q + \Delta L_g}$$

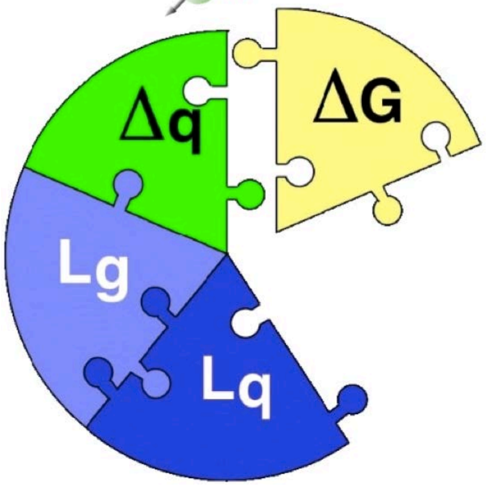
~0.33 (small)

Poorly constrained

$$\Delta\Sigma = \Delta u + \Delta d + \boxed{\Delta\bar{u} + \Delta\bar{d} + \ldots}$$

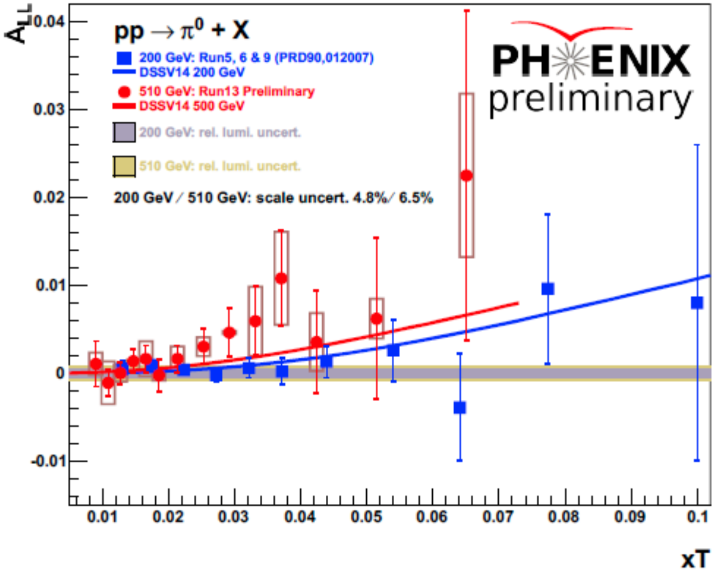
Poorly constrained

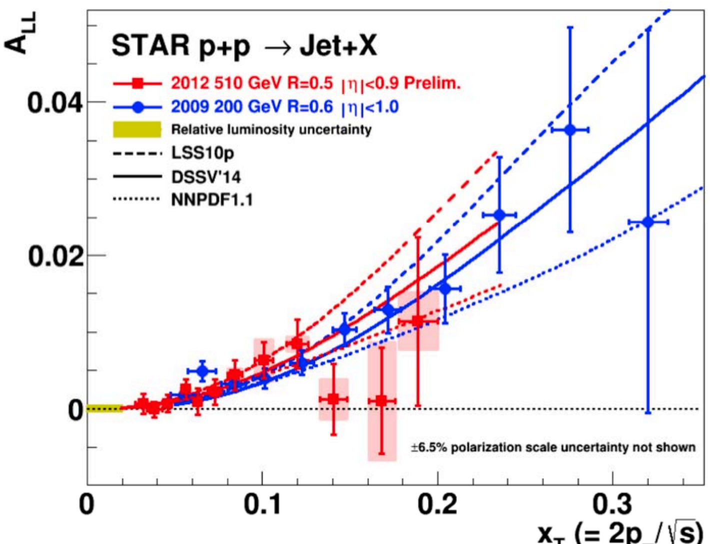


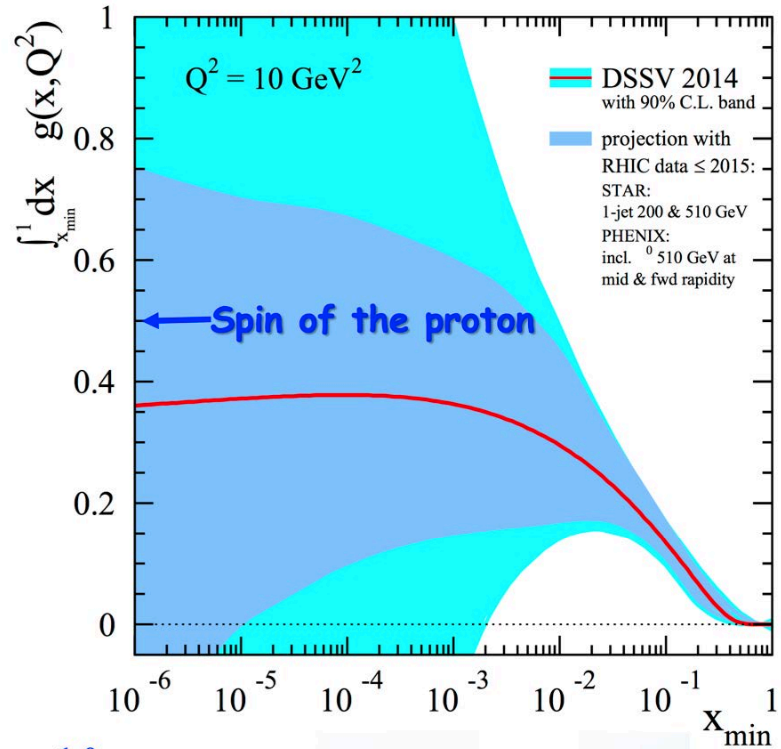


Xiaorong Wang, RHIC/AGS AUM 2015

NATURE didn't know about the latest RHIC results







$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ \mathrm{GeV}^2$$

First time a significant non-zero $\Delta g(x)$

Elke Aschenauer says a factor of 2 reduced uncertainty at $x=10^{-3}$

$$\int_{10^{-6}}^{1.0} dx\Delta g \sim 0.36 @\ 10\ \mathrm{GeV}^2$$

NSAC Sub-Committee Review of the EIC (Electron Ion Collider) Cost Estimates

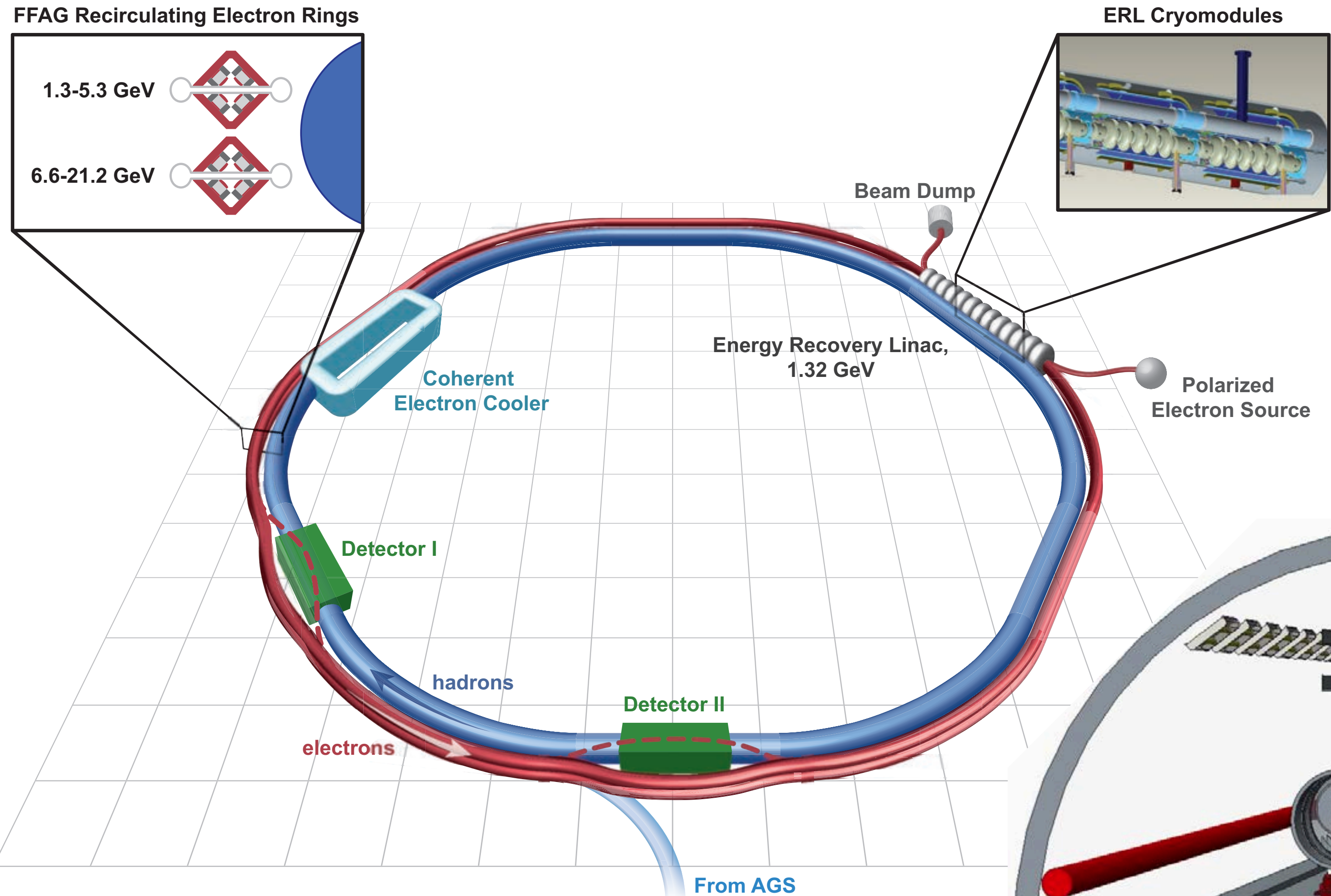
L Edward Temple, Jr. Chairman Review Conducted 1/26-28/2015 Report Given to NSAC 4/3/2015

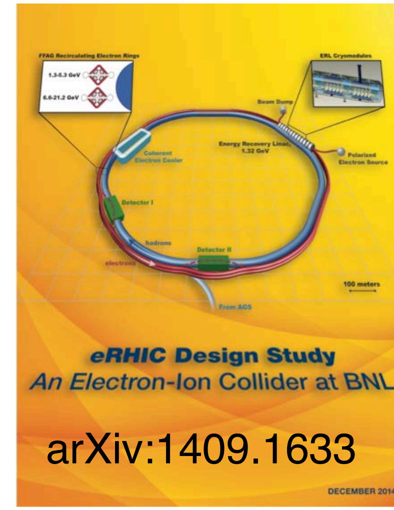
Overall Review Committee Summary

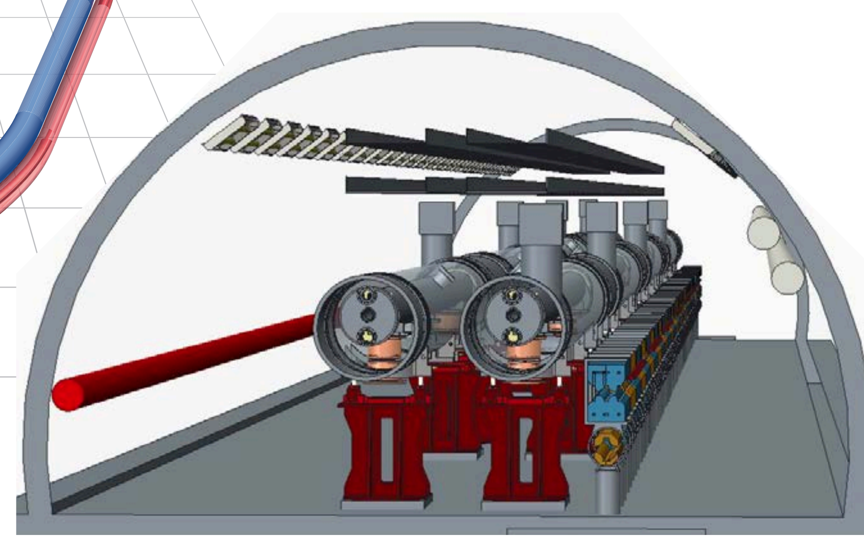
- The accelerator total project cost was presented to be $755.9M in FY15$ including 31% contingency.
- eRHIC incorporates certain technical advances which are beyond the state of the art; the 31% contingency is, in the opinion of the subcommittee insufficient.
- MEIC is based on largely conventional technology with fewer technical risks; the proposed 35% contingency is marginally sufficient.
- An EIC could be built for about $1.5B in FY15$.
  - This is equal to the MEIC TPC and $0.5B higher than the eRHIC TPC to account for the higher technical risk.

eRHIC design

Highly advanced and energy efficient accelerator







- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑ on 250 GeV p↑)

LHeC Workshop

24-26 June 2015
CERN (24 June) and Chavannes-de-Bogis (25-26 June)
Europe/Zurich timezone

Search

There is a live webcast for this event.

- Overview
- Committees and Convenors
- Timetable
- Registration
- Participants List
- Transport & Accommodation (incl. shuttle service and CERN access)
- Internet access
- Video Conference Rooms
- LHeC website

Support

lhec.ws@cern.ch

Wed 24/06 | Thu 25/06 | Fri 26/06 | **All days**

Print | PDF | Full screen | Detailed view | Filter

Session legend

Accelerator and ER... | Coordination Grou... | IAC closed session | IAC open session

see more...

Wed 24/6

15:00	**Welcome** *Main Auditorium, CERN*	*Herwig SCHOPPER* 15:00 - 15:10
	The Development of the LHeC *Main Auditorium, CERN*	*Sergio BERTOLUCCI* 15:10 - 15:30
	Accelerator Design *Main Auditorium, CERN*	*Oliver BRUNING* 15:30 - 15:50
16:00	**Concept of a High Intensity Energy Recovery Linac Facility** *Main Auditorium, CERN*	*Erk JENSEN* 15:50 - 16:10

BROOKHAVEN NATIONAL LABORATORY **Monday Memo**

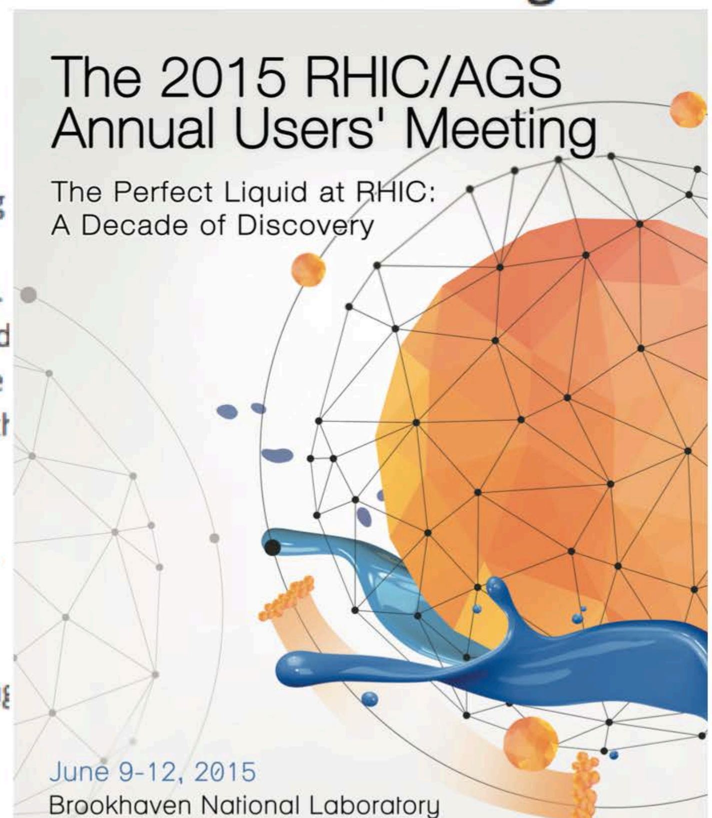
Monday Memo Home | Archives

Monday, June 1, 2015

The Perfect Liquid 10th Anniversary Celebration and 2015 RHIC & AGS Annual Users' Meeting

By Justin Frantz

Please join us for the 2015 Relativistic Heavy Ion Collider (RHIC) & Alternating Gradient Synchrotron (AGS) Users' Meeting, June 9-12 at Brookhaven Lab. This year's theme is "The Perfect Liquid at RHIC: 10 Years of Discovery" and we will celebrate the 10th anniversary of th 2005 announcement that marked the discovery of the "Perfect Liquid," also known as the strongly-coupled Quark-Gluon-Plasma (QGP).



The Perfect Liquid is made by smashin together nuclei at ultra-relativistic energies. As a kind of QGP, it is composed of quarks and gluons that

From Erice ISSP2011, see arXiv:1406.1100

The QGP was discovered at RHIC, announced on April 19, 2005 as 'the perfect fluid' (10th anniversary celebrated this year), published NPA750,757(2005)1-171,1-283 with properties quite different from the 'new state of matter claimed' by the CERN fixed target heavy ion program on February 10, 2000 ("unpublished")

Mortadella-NYTimes 2/10/2000


"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, THURSDAY, FEBRUARY 10, 2000

Spread of Attacks on Web Sites Is Slowing Traffic on the Internet

Attorney General Says There Are No Solid Leads

Paige and Louise's Big Interview

CLINTON IS RAISING MILLIONS TO PUSH EARLY 'ISSUE ADS'

EFFORT TO HELP NOMINEE

DIALLO TESTIMONY: A MAN CRIED 'GUN'

Democrats Drawn to McCain Are Unsettling Republicans

Mayor Unfairly Using Religion, First Lady Says

More Hostages Freed

Lobbyists for McCain

A Trade Truce, Over Lunch

Particle Physicists Getting Closer To the Bang That Started It All

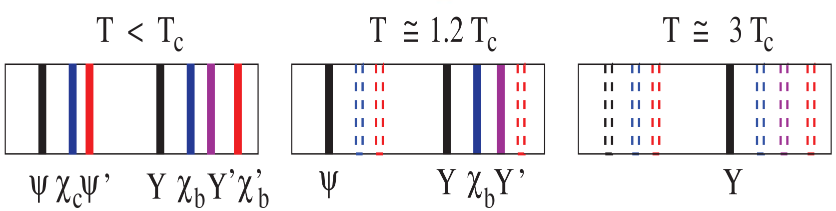
In Britain's Health Service, Sick Itself, Cancer Care Is Dismal

INSIDE

How to find the Quark Gluon Plasma (QGP) in A+A collisions c.1990:--a medium of quarks and gluons deconfined from their original nucleons covering a volume that is many units of the confinement length scale (~1fm) in which the q and g with their color charge fully exposed freely traverse the medium composed of a large density of similarly exposed color charges.

The gold-plated signature for the QGP J/ψ Suppression-1986

• In 1986, T. Matsui & H. Satz PL **B178**, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar couldn't bind. QGP thermometer



J/Ψ PHENIX design goal 1990-1991
ϒ sPHENIX design goal 2015

Jet Quenching: Parton energy loss by coherent LPM radiative energy loss in the QGP-1997

• In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS **50**, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would "result in an attenuation of the jet energy and a broadening of the jets"

The energy loss, -dE/dx, of an outgoing parton per unit length (x) of a medium with total length L, due to coherent gluon bremsstrahlung is proportional to the q^2 and takes the form:

$$\boxed{\frac{-dE}{dx} \approx \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s \mu^2 L / \lambda_{mfp} \equiv \alpha_s \hat{q} L}$$

where μ, is the mean momentum transfer per collision (~the Debye screening mass). Thus, the total energy loss in the medium goes like L^2.

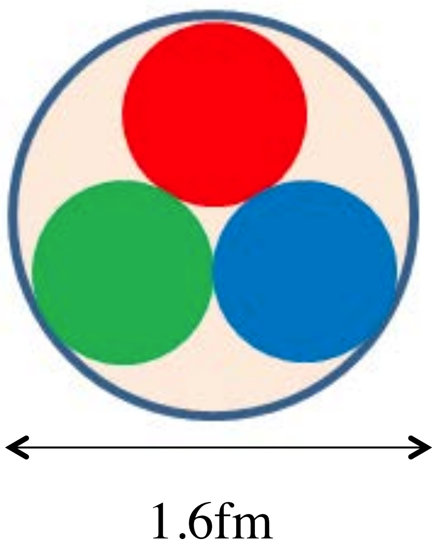
QGP Discoveries at RHIC

- Suppression of high p_T hadrons from hard-scattering of initial state partons; also modification of the away-side jet
- Elliptic Flow at the Hydrodynamic limit as a near ideal fluid with shear viscosity/entropy density at or near the quantum lower bound $\eta/s \approx 1/(4\pi)$
- Elliptic flow of particles proportional to the number of the valence (constituent) quark count.
- Charged particle multiplicity proportional to the number of constituent quark participants
- Higher order flow moments proportional to density fluctuations of the initial colliding nuclei
- Suppression and flow of heavy quarks roughly the same as that of light quarks; QCD hard direct photons not suppressed, don't flow.
- Production and flow of thermal soft photons.

Constituent Quarks cf. Partons

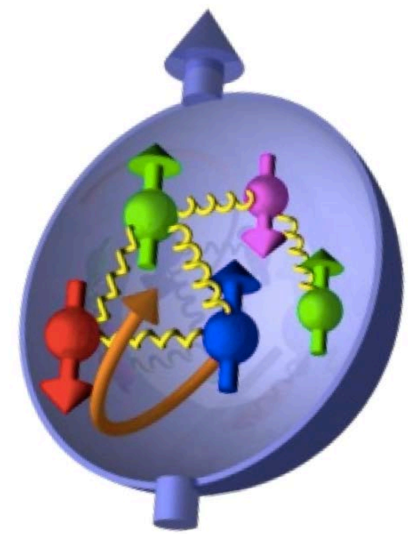
Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig's Aces].These are relevant for static properties and soft physics, low $Q^2<2$ GeV^2 ; resolution> 0.14fm

For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible



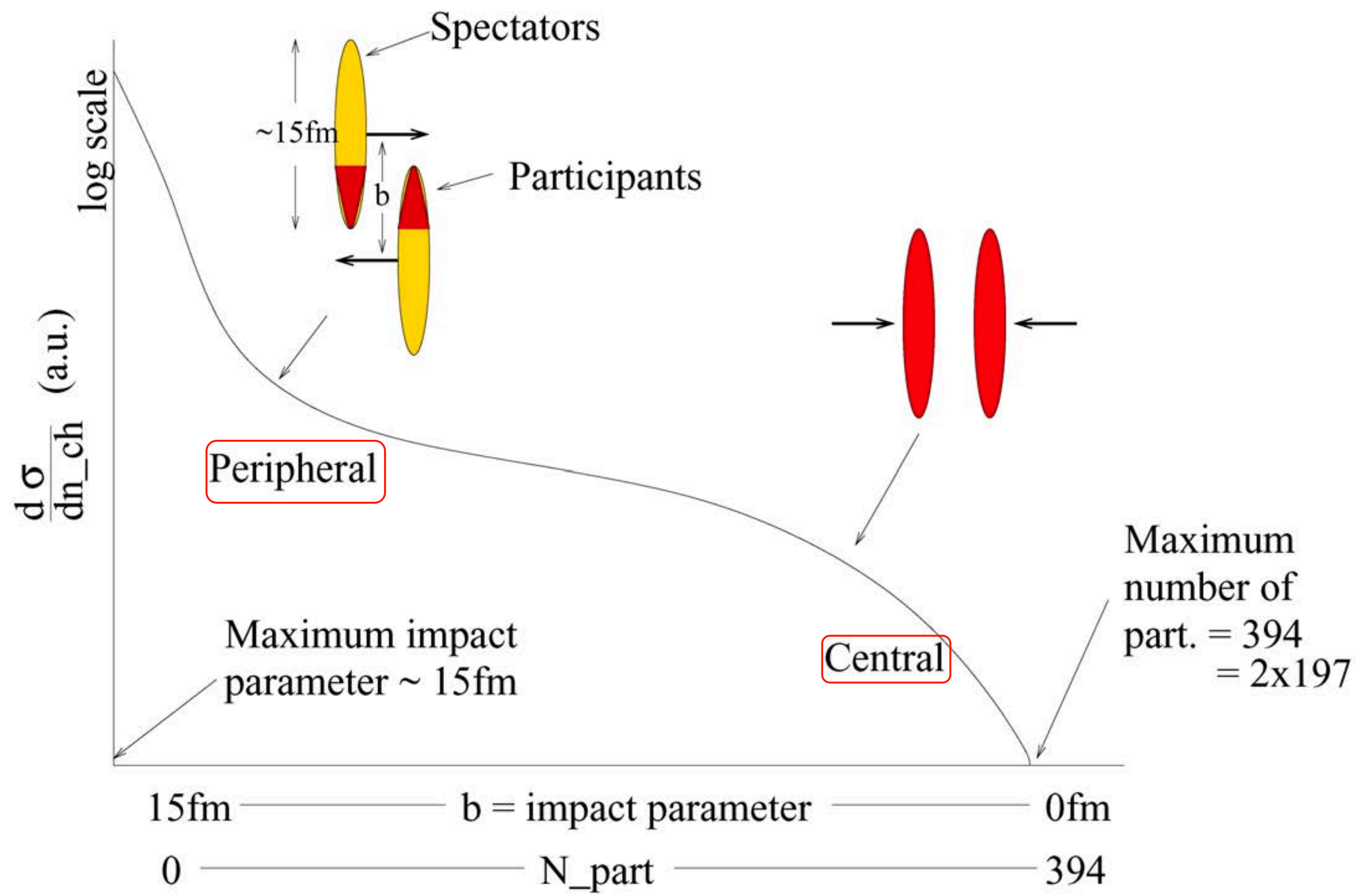
Resolution ~0.5fm

Resolution ~0.1fm



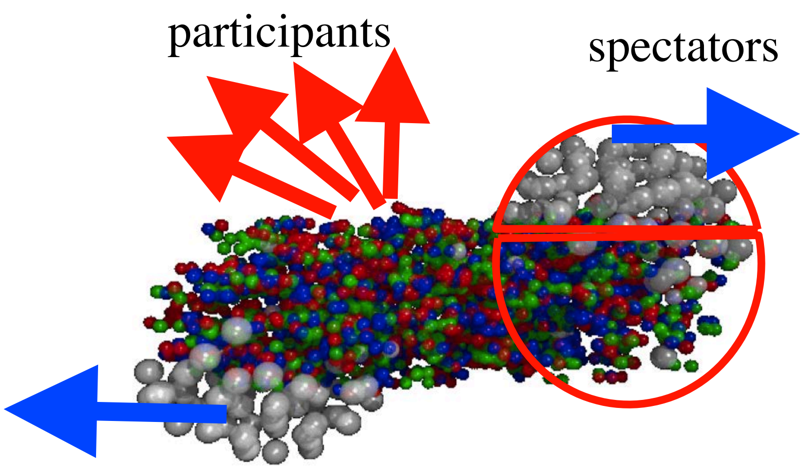
Resolution <0.07fm

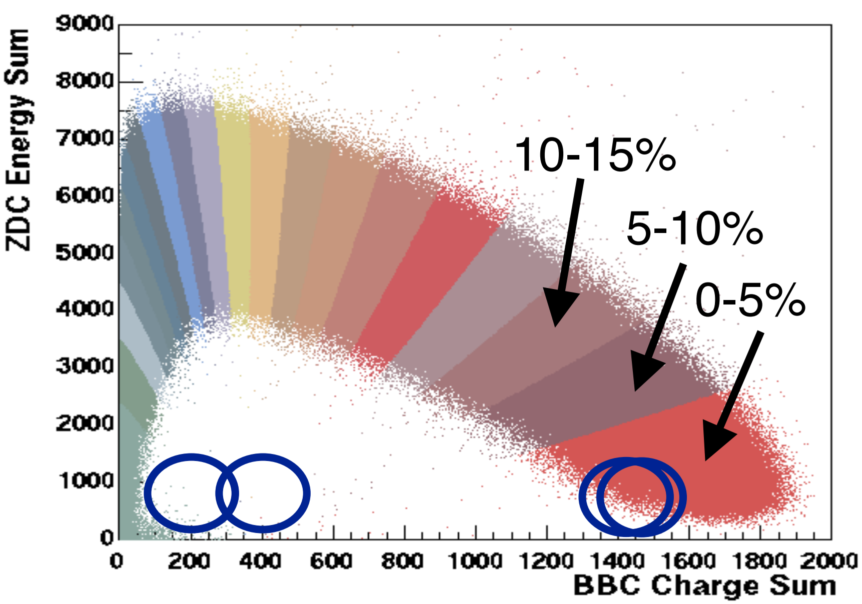
Some special Issues for A+A collisions



Schematic of collision in N-N c.m. system of two Lorentz contracted nuclei with radius *R* and impact parameter *b*. The curve with ordinate $d\sigma/dn_{ch}$ represents the relative probability of charged particle multiplicity n_{ch} which is proportional to the number of participating nucleons N_{part}. The degree of overlap of the two nuclei is called the centrality. More central means smaller *b*.

Collision Centrality defined by the number of participating nucleons N_{part} can be measured from spectators in Zero Degree Calorimeter for fixed target but not at a collider

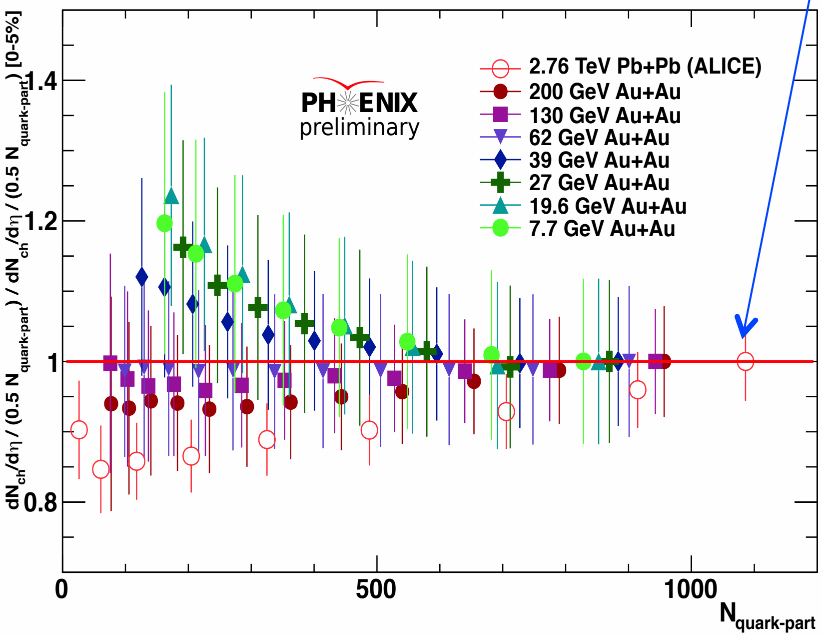




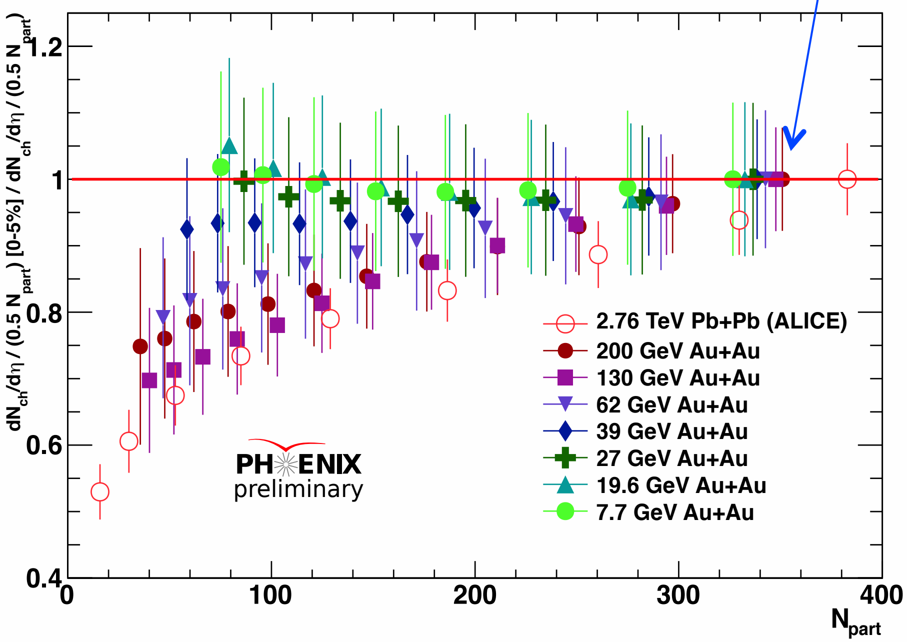
- Number of Spectators (i.e. non-participants) N_s can be measured directly in Zero Degree Calorimeters in fixed target experiments.
- Enables unambiguous measurement of (projectile) participants = A_p -N_s
- For symmetric A+A collision N_{part}=2 $N_{projpart}$
- At a collider can not measure the spectators which may be free neutrons, protons or clusters. If Z/A of cluster is same as the beam, it stays in the beam; but the neutrons can be detected at zero degrees. The distribution of Energy in Beam Beam Counters can be measured and the centrality defined by upper percentile of the distributions, but N_{part} is model dependent and may have biases

Au+Au Multiplicity--$dN_{ch}/d\eta/(0.5N_{qp})$ vs Constituent Quark Participants (N_{qp})

Normalized to most central value



Normalized to most central value

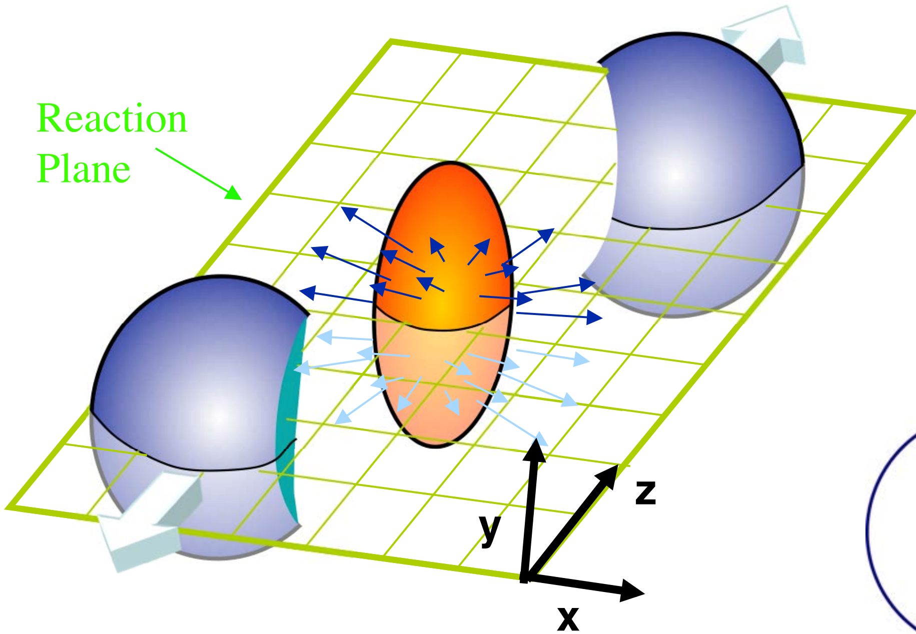


N_{qp}=Quark participant scaling works well $\sqrt{s_{NN}}$= 62-200 GeV

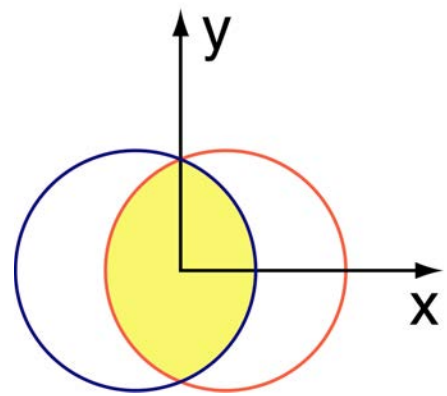
WNM=Participant nucleon scaling works well $\sqrt{s_{NN}}$ <= 27 GeV

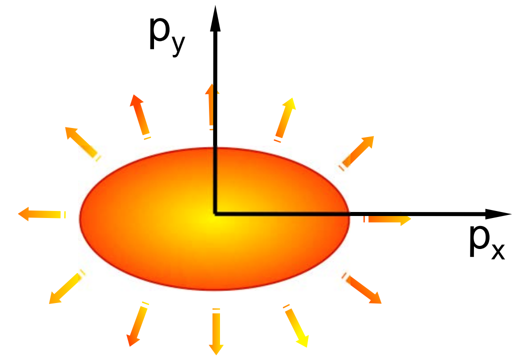
Charged Multiplicity is proportional to the Number of Constituent Quark Participants at RHIC &LHC $\sqrt{s_{NN}}$

Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions



• spatial anisotropy⇒ momentum anisotropy





$$\phi = \text{atan}\frac{p_y}{p_x}$$

$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi\, p_T dp_T dy}[1+2v_1\cos(\phi-\Phi_R)+2v_2\cos 2(\phi-\Phi_R)+\cdots]$$

$$v_1 = \langle\cos\phi\rangle \qquad v_2 = \langle\cos 2\phi\rangle$$

•Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane

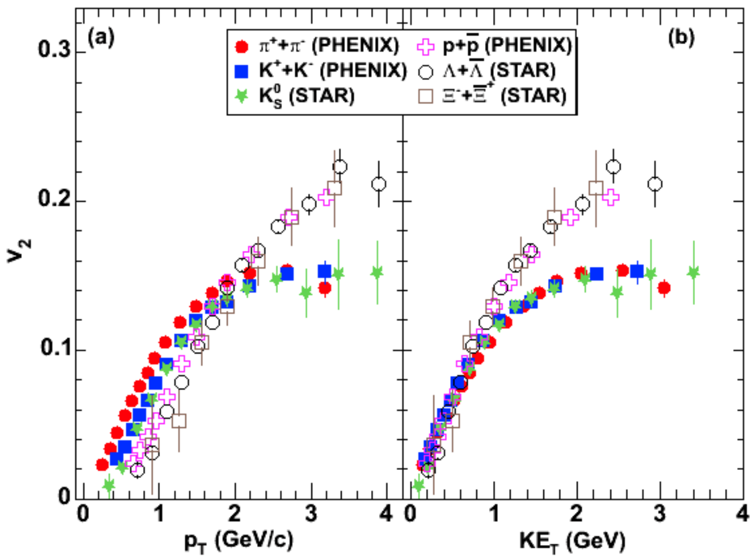
✓ v_2 is the 2nd harmonic Fourier coefficient

Directed flow zero at midrapidity

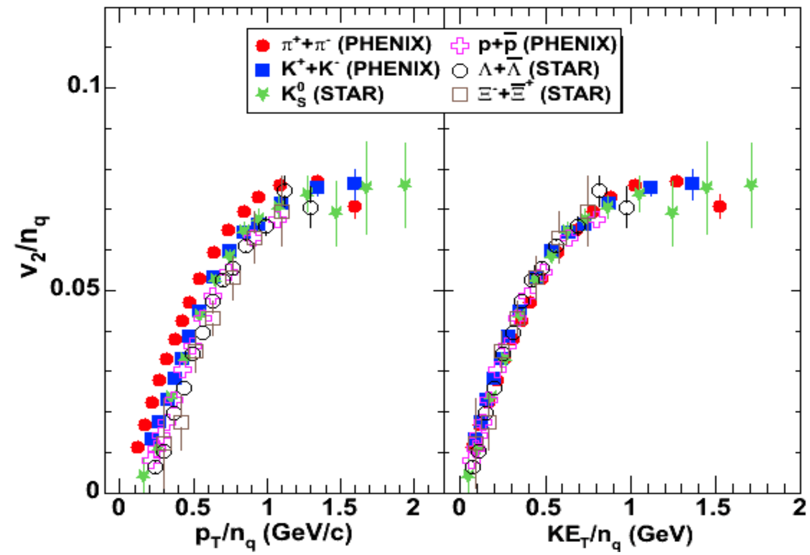
Elliptical flow dominant at midrapidity

Elliptic Flow v_2 in AuAu Central 200 GeV Universal in constituent quark Kinetic Energy

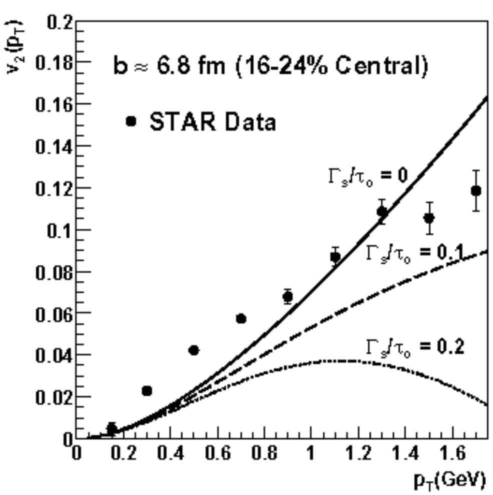
STAR-PRC**72** (2005) 014904



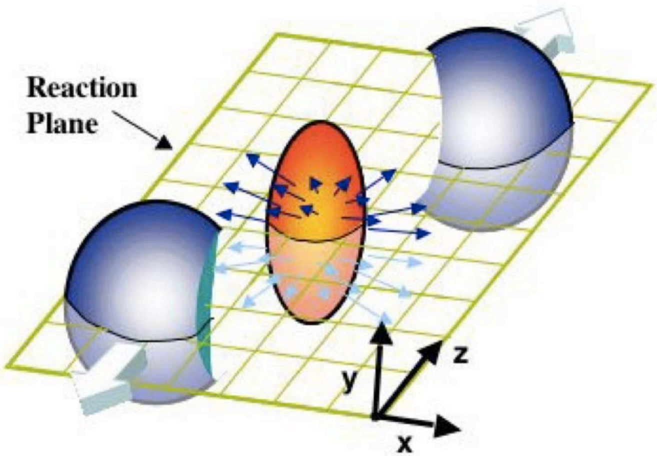
PHENIX PRL**98** (2007) 162301



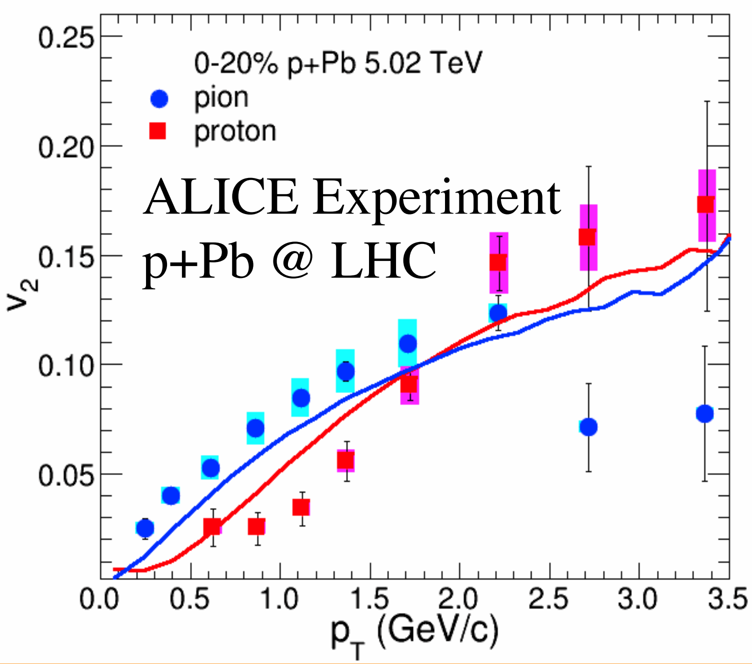
- large v_2 for high and low p_T, plateaus for p_T>2 GeV/c for mesons, scales in KE/constituent quark
- ϕ-meson (not shown) follows same scaling: further implies flow is partonic not hadronic
- KE scaling suggests Hydrodynamic origin.
- v_2 for p_T> 1 GeV/c suggests low viscosity, D.Teaney, PRC**68** (2003) 034913, ``the perfect fluid'' ??
- Quantum Viscosity Bound from string theory reinforces this idea, Kotvun, Son, Starinets, PRL **94** (2005) 111601

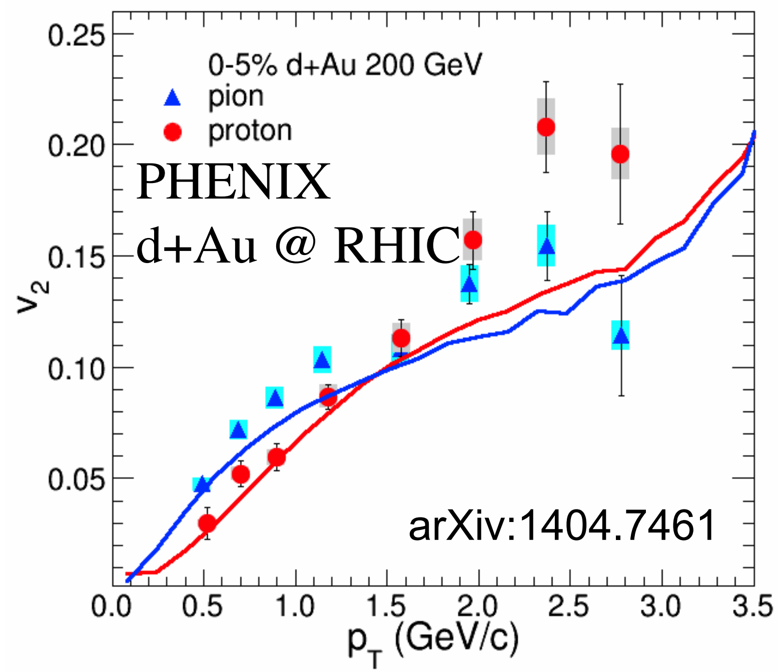


Latest big discovery, π and p flow in dAu



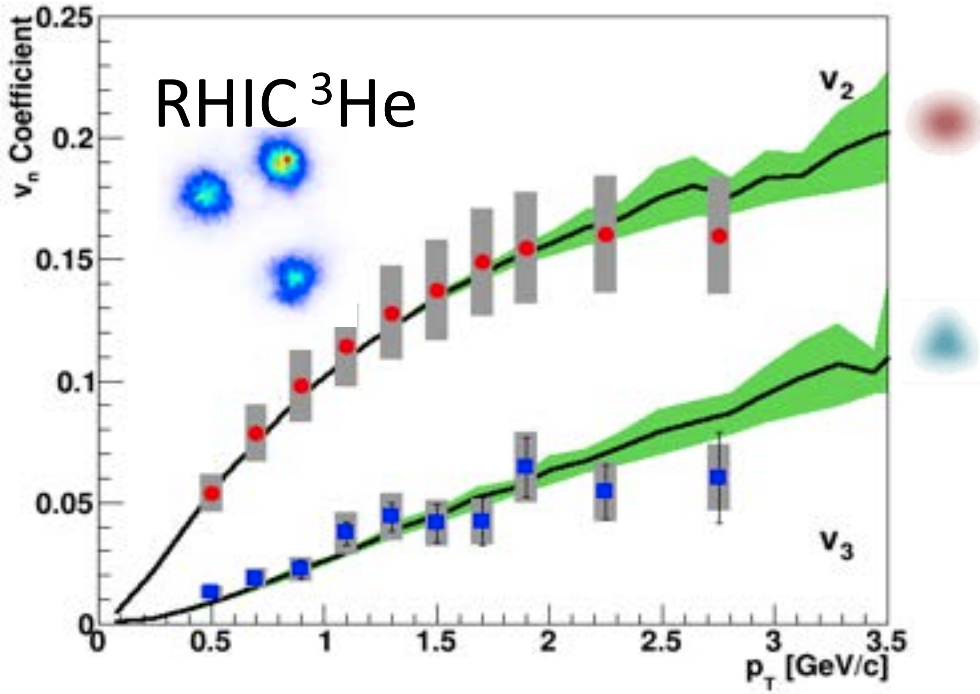
v_2~<cos2Φ> asymmetry around reaction plane due to ellipsoidal shape is a collective effect. In hydrodynamics, for a given expansion velocity β, protons have larger p_T=γβm than π as clearly shown by the d+Au data, as in Au+Au



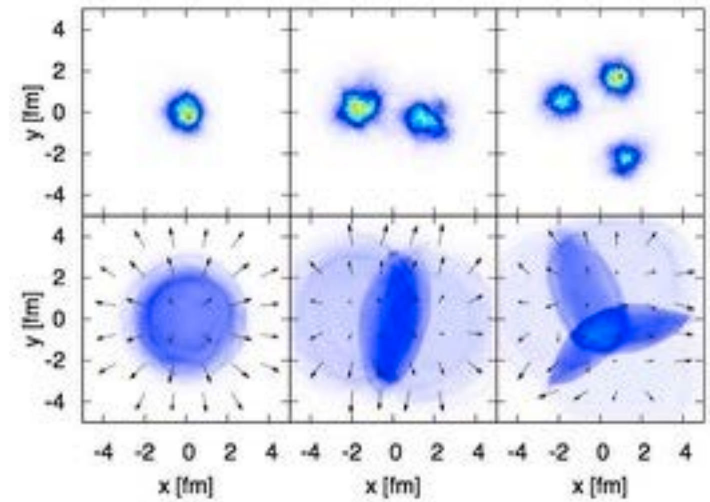


$v_2(p_T)$ seems larger at in d+Au at RHIC. We measured He^3+Au in 2014 to see if v_3 appears due to 3 nucleons

How small can a QGP droplet be?

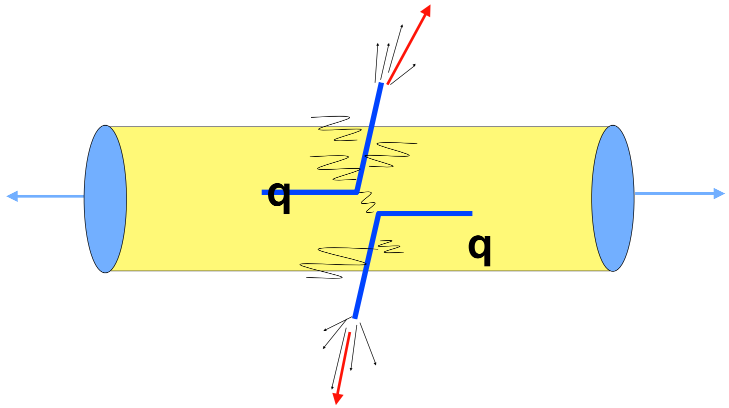


Very successful 3-week run resulted in 2.2 **billion** recorded minimum bias ^{3}He+Au collisions (PHENIX)



Strong v_3/v_2 in ^{3}He+Au!
p+Au run just completed will be the crucial test

Jet quenching: a parton-medium Effect



Toward quantitative measurement of basic medium properties: *q-hat*

$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L \qquad \frac{dE}{dx} = -C_2 \hat{e}$$

Radiative Collisional

JET Collaboration

Phys. Rev. C 90 (2014) 014909

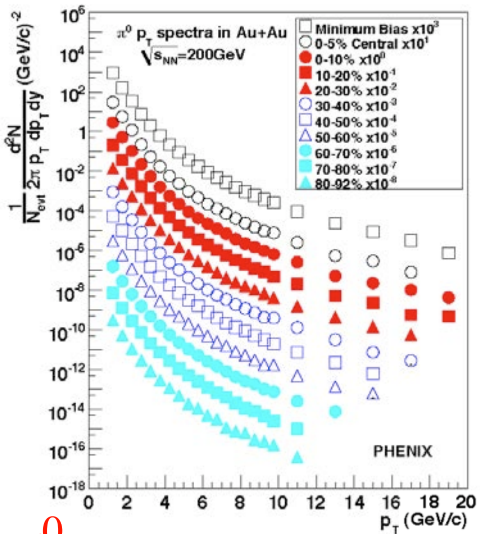
$$\frac{\hat{q}}{T^3} = \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC} \end{cases}$$

QGP @ RHIC is more strongly coupled than QGP@ LHC.

Partons lose energy going through the medium so that there are fewer partons or jet fragments at a given p_T. The ratio of measured AA to scaled pp cross section for no effect is:

$$R_{AA}(p_T) = \frac{d^2N_{AA}^{\pi} / dp_T dy N_{AA}^{inel}}{\langle T_{AA} \rangle d^2\sigma_{pp}^{\pi} / dp_T dy}$$

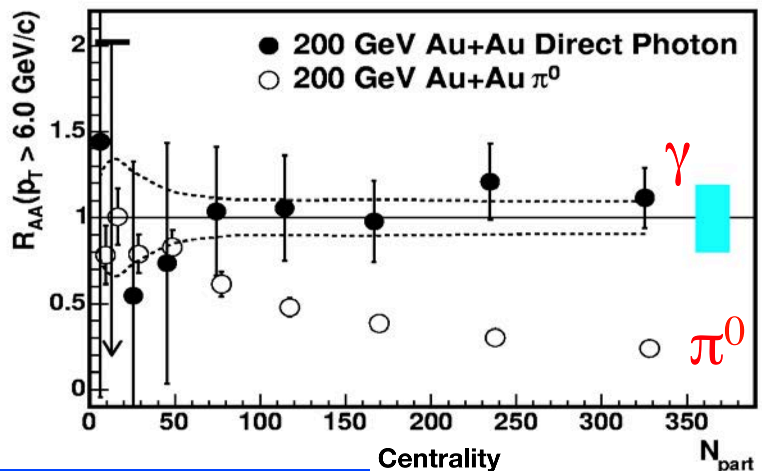
RHI physics is based on Precision Msmts + QCD

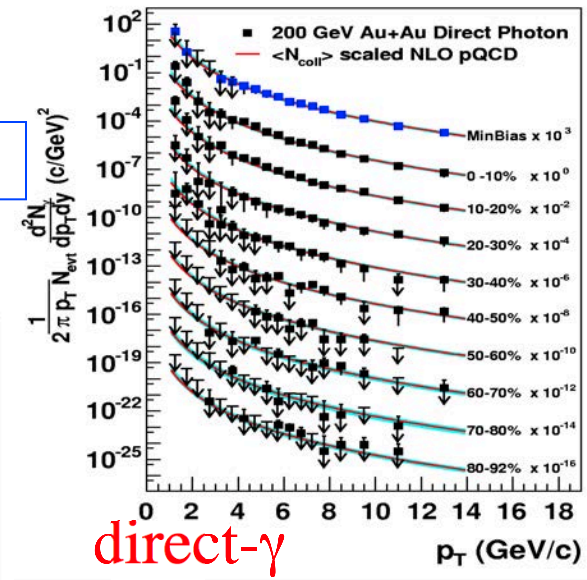


- This one figure encodes rigorous control of systematics

PRL**94** (2005) 232301

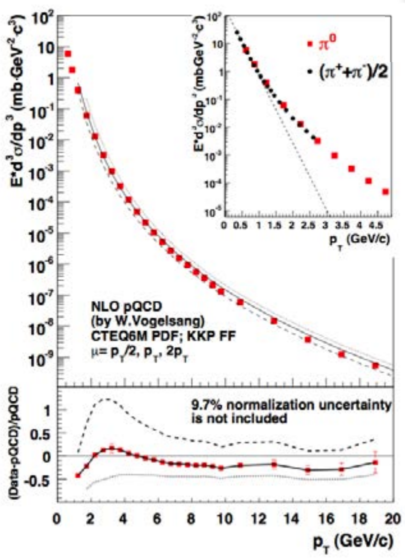
PRL**101** (2008) 232301





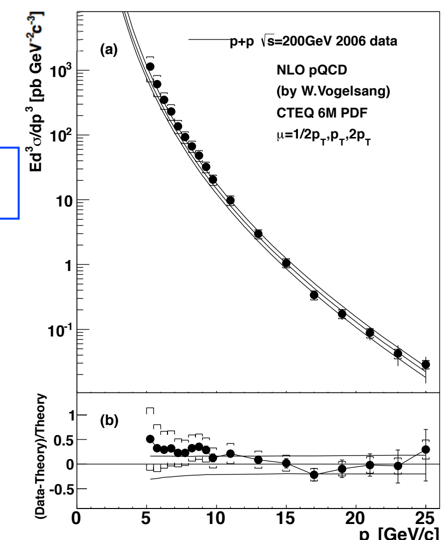
π^0

direct-γ



PRD**76** (2007) 051106(R)

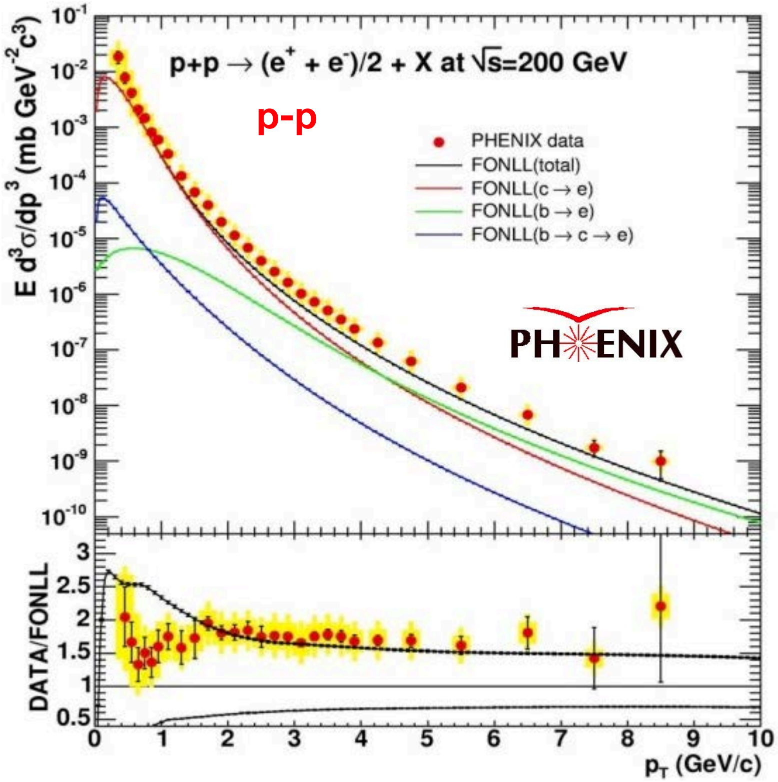
PRD **86** (2012) 072008

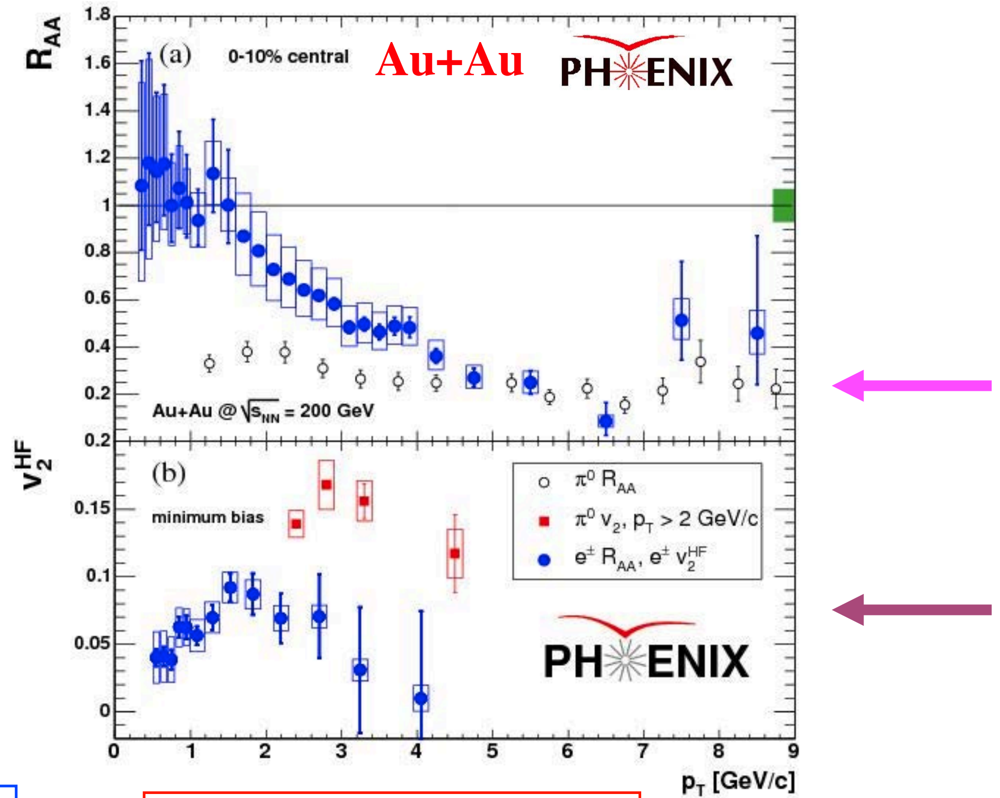


- in four different measurements over many orders of magnitude

Direct photons unaffected by QGP medium in Au+Au →
π^0 suppression is medium effect

QM2006-Direct e± in Au+Au indicate a theoretical crisis



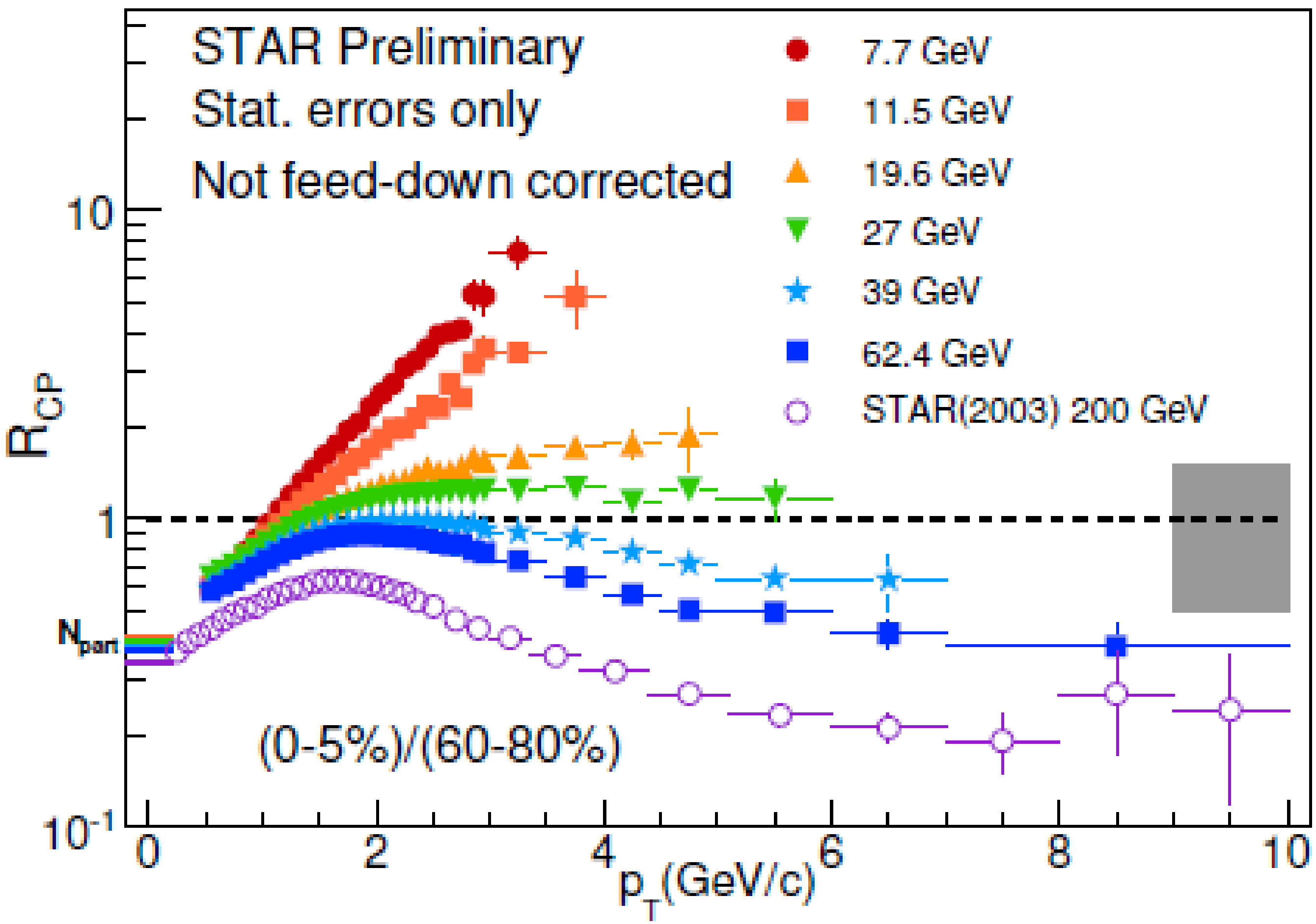


p-p beautiful agreement of e± with *c b* production PHENIX PRL**97**(2006)252002

Au+Au PHENIX PRL **98** (2007)172301

• heavy quarks suppressed the same as light quarks, and they flow, but less. • This disfavors the hypothesis of energy loss by gluon bremsstrahlung in medium • but brings string theorists into the game, see references in PRL 98 (2007) 172301.

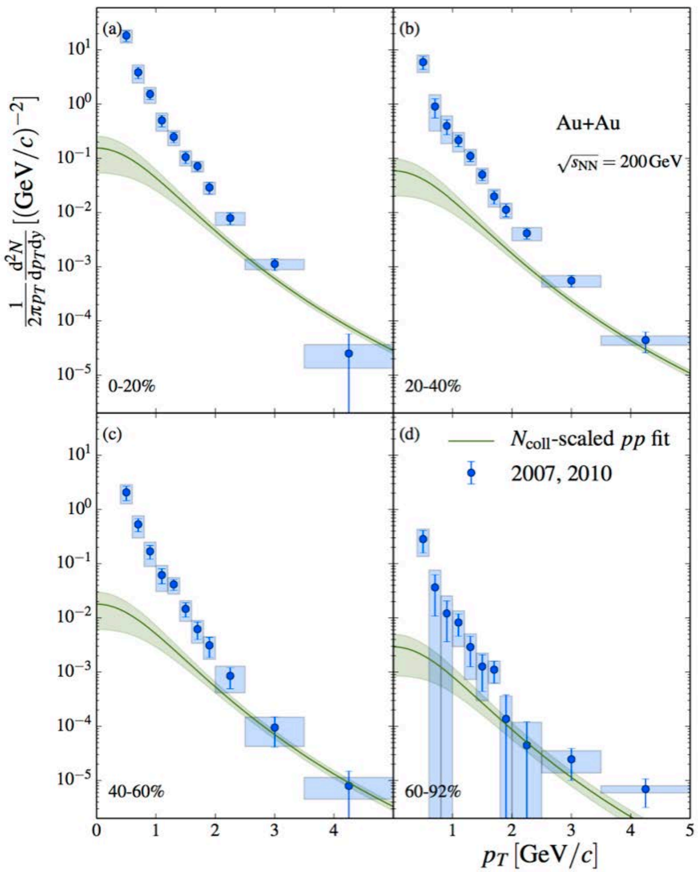
Jet Quenching vanishes for $\sqrt{s_{NN}} \leq 30$ GeV

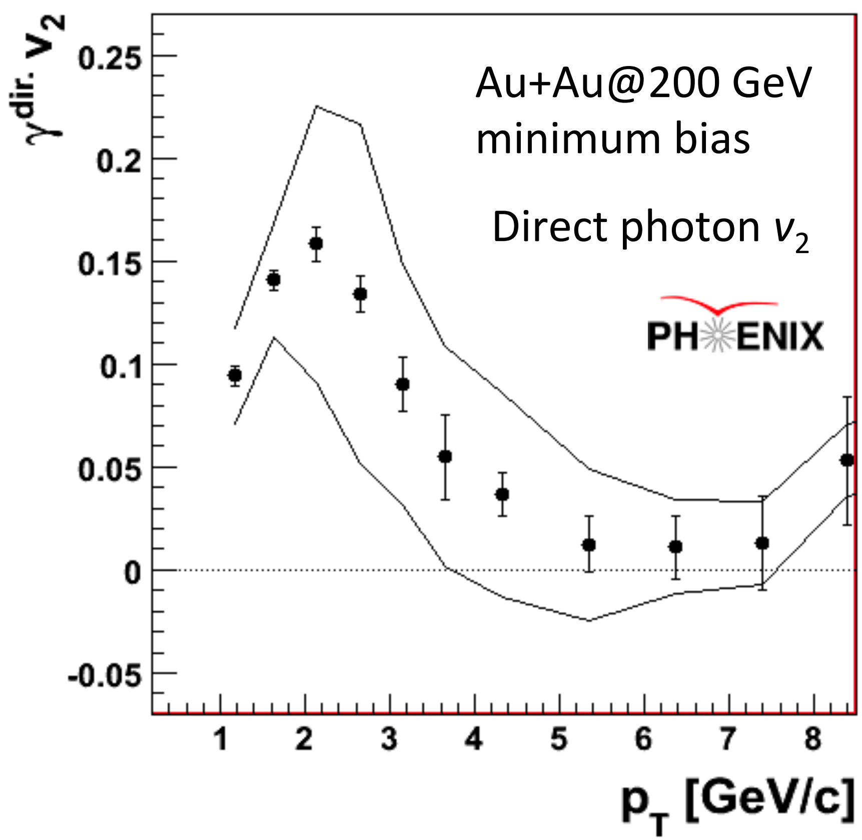


Non identified charged particles central/peripheral

Low p_T photons in AuAu: thermal, flow

PHENIX PRC91 (2015) 064904





PHENIX PRL109 (2012) 122302

AuAu direct γ spectra vs centrality compared to scaled pp spectrum- Note exponential distribution of γ in AuAu which is lacking in pp

- direct-γ v_2 large (~15 %) at p_T <3 GeV thermal region-- γ's from the medium.
- $v_2 \rightarrow 0$ where qcd hard direct-γ dominate no effect of the medium

The Future: RHIC run Schedule 2014--≥2023

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

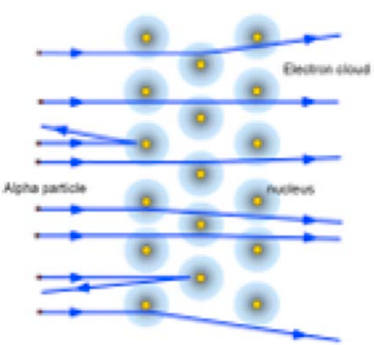
Key questions to be answered by RHIC before completion of its "mission" from the RHI community white paper

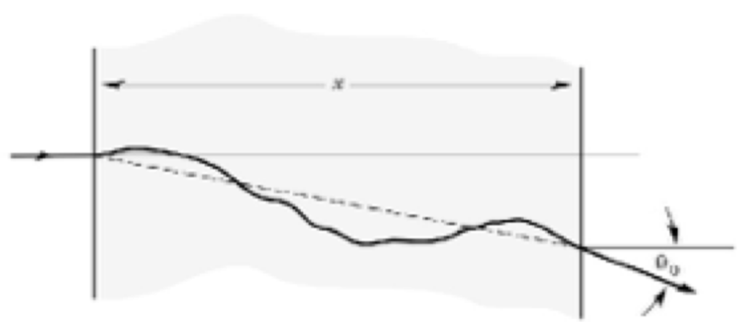
- a beam-energy scan program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependence of the shear-viscosity to entropy-density ratio η/s (including an assessment of whether the conjectured lower bound has been reached to within a precision of 10%), and that of the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.
- a jet physics program to study the nature of parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium, as well as quarkonia measurements that will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.
- a systematic forward physics program to study the nature of gluon saturation at low x.

This last bullet leads naturally to the physics program of an Electron Ion collider

If the "medium is the message", then what exactly is the medium?

- The QCD Plasma is strongly coupled, but at what scales?
- Does it contain quasiparticles or does the strong coupling completely wipe out long-lived collective excitations?
- What impact does the coupling have on color screening? Is there a characteristic screening length? If so,what is it?
- What is the mechanism for parton QGP interactions and how does the QGP respond to energy deposited in it?
- At what scale do discrete scattering centers "dissolve" into a collectively acting, continuous, flowing medium?





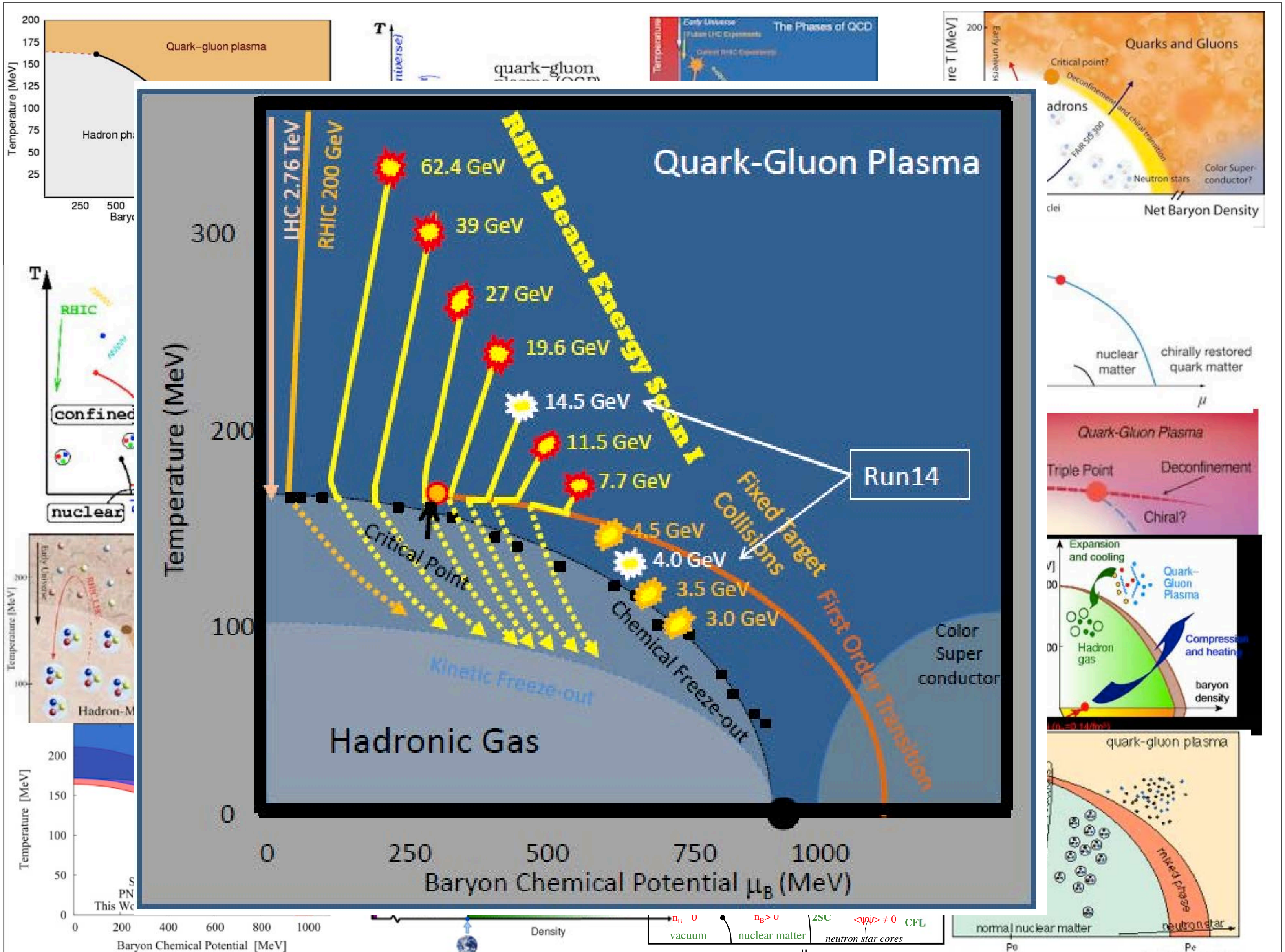
Point-like scattering centers: $1/q^4$ tail

Quasi-continuous medium: Gaussian

BEAM Energy Scan Search for Critical Endpoint Helped by Lattice QCD

Proposed Phase diagrams Nuclear matter

Pawlowski-QM2014



3

Hot off the presses-LBL Press release June 24, 2011
Lattice and Experiment Compared-a first?

Sourendu Gupta, et al., Science 332,1525 (2011)-LBL press release

When Matter Melts « Berkeley Lab News Center http://newscenter.lbl.gov/news-releases/2011/06/23/when-matter-melts/

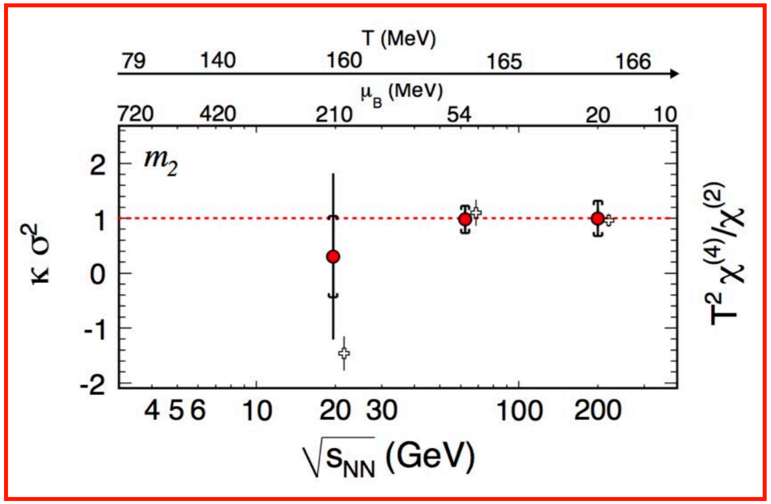
BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY
A-Z INDEX | PHONE BOOK | JOBS | SEARCH

When Matter Melts

By comparing theory with data from STAR, Berkeley Lab scientists and their colleagues map phase changes in the quark-gluon plasma

June 23, 2011

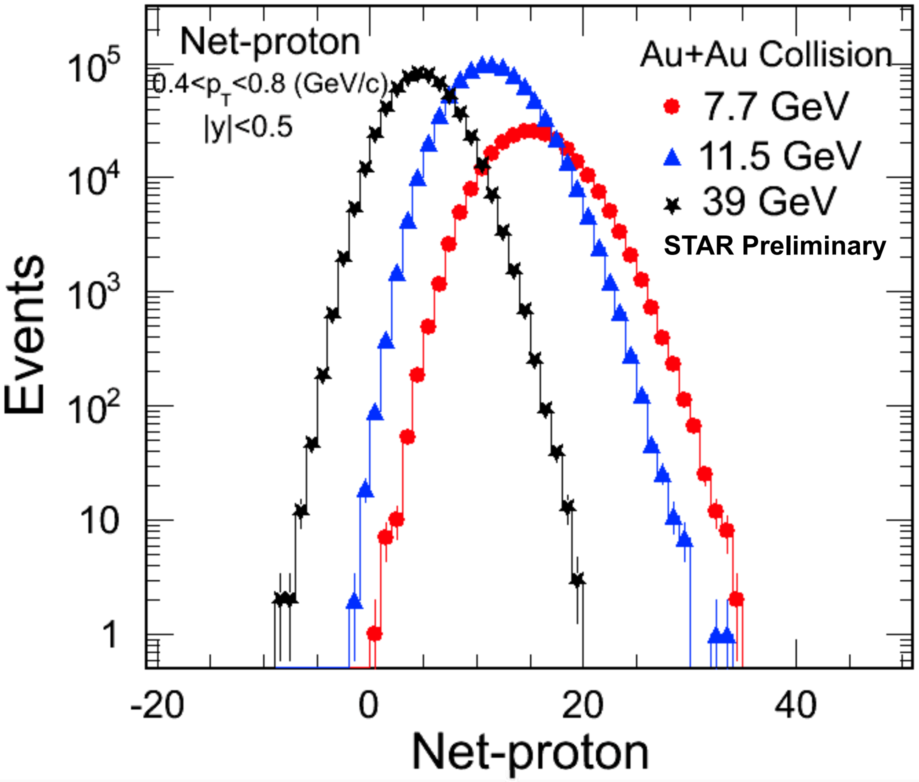
Theory:Lattice shows huge deviation of $T^2 \chi^{(4)}/\chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa\sigma^2$: maybe but with big errors.



I had to do lots of work to address this issue in my second in 2011lecture to understand if this physics by press-release (not published in PRL) made sense.

Hot off the presses-LBL Press release June 24,2011
Higher Moments of Net-Proton Distributions

- 1^{st} moment: mean = $\mu = <x>$
- 2^{nd} cumulant: variance $\kappa_2 = \sigma^2 = <(x-\mu)^2>$
- 3^{rd} cumulant: $\kappa_3 = \mu_3 = <(x-\mu)^3>$
- 3^{rd} standardized cumulant: skewness = $S = \kappa_3/\kappa_2^{3/2} = <(x-\mu)^3>/\sigma^3$
- 4^{th} cumulant: $\kappa_4 = <(x-\mu)^4> - 3\kappa_2^2$
- 4^{th} standardized cumulant: kurtosis = $\kappa = \kappa_4/\kappa_2^2 = \{<(x-\mu)^4>/\sigma^4\} - 3$
- Calculate moments from the event-by-event net proton distribution.
  - ✓ Have similar plots for net-charge and net-kaon distributions.



MJT-If you know the distribution, you know all the moments, but statistical mechanics and Lattice QCD use Taylor expansions, hence moments/cumulants

Statistical Mechanics uses derivatives of the free energy to find susceptibilities

- Theoretical analyses tend to be made in terms of a Taylor expansion of the free energy $F=-T \ln Z$ around the critical temperature T_c where Z is the partition function or sum over states, $Z \approx \exp -[(E-\Sigma_i \mu_i Q_i)/kT]$ and μ_i chemical potentials associated with conserved charges Q_i

- The terms of the Taylor expansion are called susceptibilities or $\chi_{(m)}$ which are proportional to the correlation length, e.g. $\chi_{(3)} \sim \xi^6$, $\chi_{(4)} \sim \xi^8$

M.A.Stephanov, PRL 102 (2009) 032301

- The connection of this method to mathematical statistics is that the Cumulant generating function is also a Taylor expansion of the ln of an exponential, so $\chi_{(m)}$ predicts measured Cumulants κ_m:

$$g_x(t) = \ln \langle e^{tx} \rangle = \sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!} \qquad \kappa_m = \left. \frac{d^m g_x(t)}{dt^m} \right|_{t=0}$$

Taylor expansion of the pressure

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V,T,\mu_B,\mu_S,\mu_Q)$$
$$= \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

generalized susceptibilities: $\chi_{ijk}^{BQS} = \left.\frac{\partial^{i+j+k} p/T^4}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\mu=0}$

conserved charge fluctuations: $\chi_n^X(T,\mu_B,\ldots) = \frac{\partial^n P/T^4}{\partial(\mu_X/T)^n}$

$X = B,\ Q,\ S$

$$\boxed{\frac{M_X}{\sigma_X^2} = \frac{\chi_1^X(T,\mu)}{\chi_2^X(T,\mu)} \ , \quad S_X\sigma_X = \frac{\chi_3^X(T,\mu)}{\chi_2^X(T,\mu)} \ , \quad \kappa_X\sigma_X^2 = \frac{\chi_4^X(T,\mu)}{\chi_2^X(T,\mu)}}$$

Moments and Distributions

- The moments of a distribution P(x) are defined as

$$\mu_k' \equiv \langle x^k \rangle \equiv \int_{-\infty}^{\infty} x^k P(x)dx \to \sum_{i=1}^{n} x_i^k P(x_i)$$

where $\mu_1' \equiv \mu = \langle x \rangle$ and $\sigma^2 = \mu_2 \equiv \langle (x-\mu)^2 \rangle$ is the variance

- Cumulants are moments with all combinations of lower order moments subtracted.

- Combinations of moments and cumulants which are sensitive to fluctuations (thus correlations) will be used. For instance, the second "normalized binomial cumulant" A. H. Mueller PRD **4**,151 (1971)

$$\boxed{K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu}}$$

vanishes for a Poisson distribution (no correlations).

- Most people use the normalized variance σ^2/μ which is 1 for a Poisson. It has its purpose, but not what everybody thinks.

Binomial Distribution

- A **Binomial** distribution is the result of repeated independent trials, each with the same two possible outcomes: success, with probability *p*, and failure, with probability $q=1-p$. The probability for *m* successes on *n* trials ($m,n \geq 0$) is:

$$P(m)|_n = \frac{n!}{m!(n-m)!} p^m (1-p)^{n-m}$$

  - The moments are:

$$\mu = \langle m \rangle = np \qquad \sigma_m^2 = np(1-p)$$

$$\boxed{K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = -\frac{1}{n}} \qquad \boxed{\frac{\sigma^2}{\mu} = 1 - p \leq 1}$$

- Example: distributing a total number of particles *n* onto a limited acceptance. Note that if $p \rightarrow 0$ with $\mu = np$=constant we get a

Poisson Distribution

- A **Poisson** distribution is the limit of the Binomial Distribution for a large number of independent trials, n, with small probability of success p such that the expectation value of the number of successes $\mu = \langle m \rangle = np$ remains constant, i.e. the probability of m counts when you expect μ.

$$P(m)|_{\mu} = \frac{\mu^m e^{-\mu}}{m!}$$

- Moments: $\langle m \rangle = \mu$ $\qquad \sigma_m^2 = \mu$

$$\boxed{K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = 0} \qquad \boxed{\frac{\sigma^2}{\mu} = 1}$$

- Example: The Poisson Distribution is intimately linked to the exponential law of Radioactive Decay of Nuclei, the time distribution of nuclear disintegration counts, giving rise to the common usage of the term "statistical fluctuations" to describe the Poisson statistics of such counts. The only assumptions are that the decay probability/time of a nucleus is constant, is the same for all nuclei and is independent of the decay of other nuclei.

Negative Binomial Distribution NBD

- For statisticians, the **Negative Binomial Distribution** represents the first departure from statistical independence of rare events, i.e. the presence of correlations. There is a second parameter $1/k$, which represents the correlation: NBD → Poisson as $k \to \infty$, $1/k \to 0$

$$P(m)|_{\mu} = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\frac{\mu}{k}\right)^m}{\left(1+\frac{\mu}{k}\right)^{m+k}}$$

- Moments: $\langle m \rangle = \mu$ $\quad \boxed{K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = \frac{1}{k}} \quad \boxed{\frac{\sigma^2}{\mu} = 1 + \frac{\mu}{k}}$

- The n-th convolution of NBD is an NBD with $k \to nk$, $\mu \to n\mu$ such that μ/k remains constant. Hence constant σ^2/μ vs N_{part} means multiplicity added by each participant is independent.

- Example: Multiplicity Distributions in p+p and A+A are NBD. There are both long-range and short-range correlations in rapidity.

K_2 in Binomial, Poisson and NBD

Binomial

$$K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = -\frac{1}{n}$$

Poisson, no correlation

$$K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = 0$$

NBD correlation= 1/k

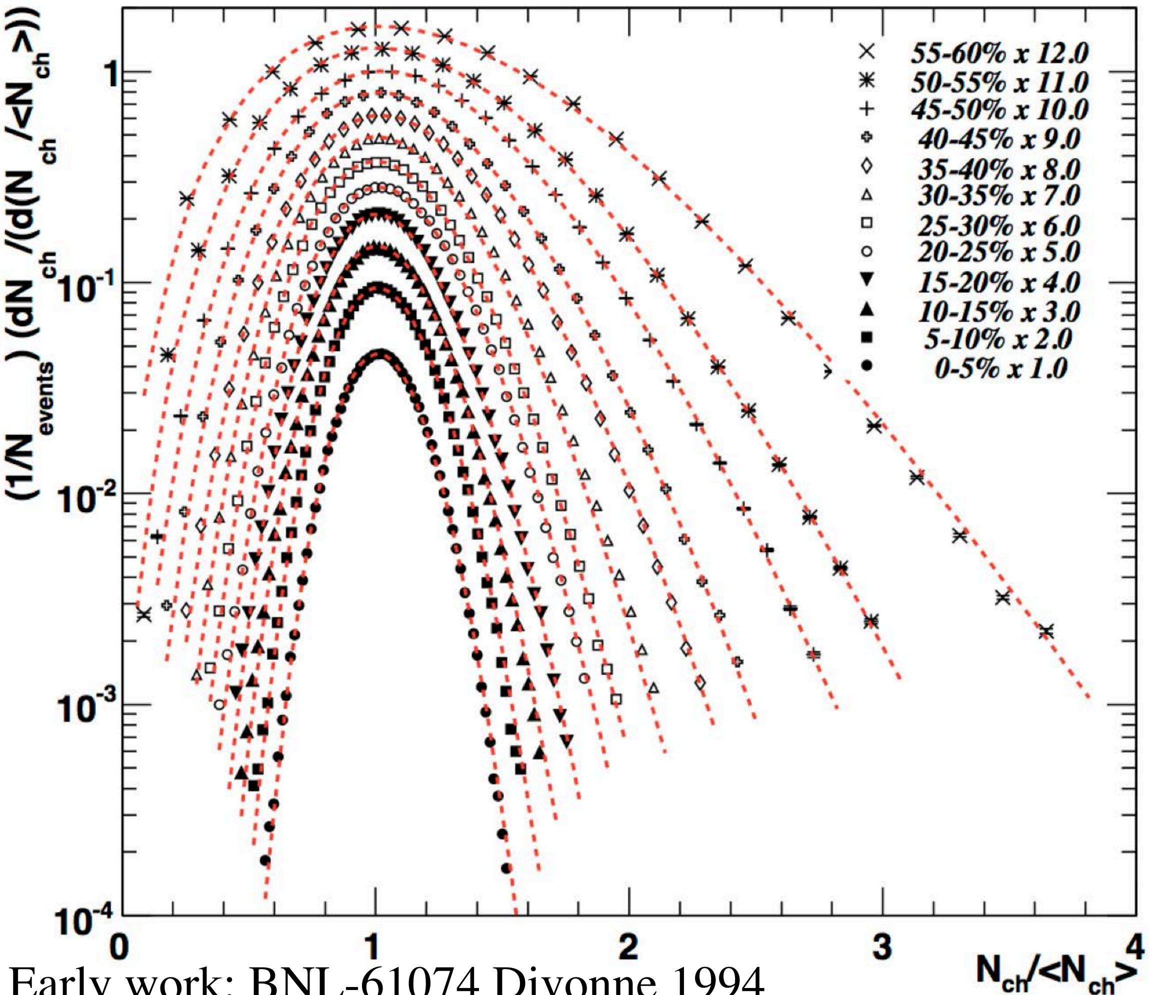
$$K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = \frac{1}{k}$$

Becomes Poisson
if $k \to \infty$, $1/k \to 0$

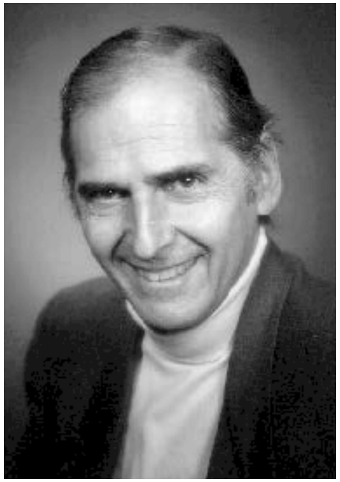
- Example: Multiplicity Distributions in p+p and A+A are NBD. There are both long-range and short-range correlations in rapidity.

From one of Jeff Mitchell's talks 2001: "Multiplicity Fluctuations"

PHENIXAuAu Multiplicity N_{ch} PRC **78**, (2008) 044902



It's not a Gaussian… it's a Gamma distribution!



Early work: BNL-61074 Divonne 1994
http://www.osti.gov/scitech/servlets/purl/10108142

Also: It's not Poisson, it's negative binomial

If you measure the distribution, then you know all the cumulants

Cumulants for Poisson, Binomial and Negative Binomial Distributions

Cumulant	Poisson	Binomial	Negative Binomial
$\kappa_1 = \mu$	μ	np	μ
$\kappa_2 = \mu_2 = \sigma^2$	μ	$\mu(1-p)$	$\mu(1+\mu/k)$
$\kappa_3 = \mu_3$	μ	$\sigma^2(1-2p)$	$\sigma^2(1+2\mu/k)$
$\kappa_4 = \mu_4 - 3\kappa_2^2$	μ	$\sigma^2(1-6p+6p^2)$	$\sigma^2(1+6\mu/k+6\mu^2/k^2)$
$S \equiv \kappa_3/\sigma^3$	$1/\sqrt{\mu}$	$(1-2p)/\sigma$	$(1+2\mu/k)/\sigma$
$\kappa \equiv \kappa_4/\kappa_2^2$	$1/\mu$	$(1-6p+6p^2)/\sigma^2$	$(1+6\mu/k+6\mu^2/k^2)/\sigma^2$
$S\sigma = \kappa_3/\kappa_2$	1	$(1-2p)$	$(1+2\mu/k)$
$\kappa\sigma^2 = \kappa_4/\kappa_2$	1	$(1-6p+6p^2)$	$(1+6\mu/k+6\mu^2/k^2)$

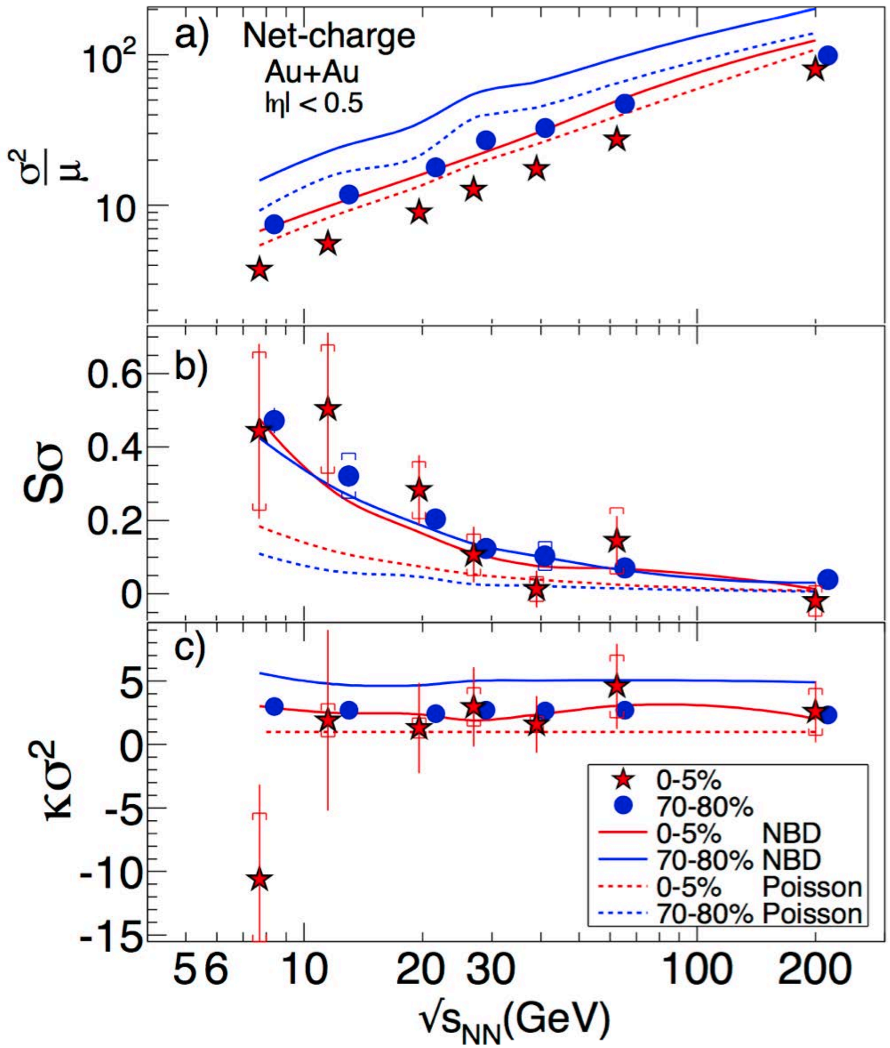
Thanks to Gary Westfall of STAR in a paper presented at Erice-International School of Nuclear Physics 2012, I found out that the cumulants of the difference of samples from two such distributions P(n-m) where $P^+(n)$ and $P^-(m)$ are both Poisson, Binomial or NBD with Cumulants κ_j^+ and κ_j^- respectively is the same as if they were statistically independent, so long as they are not 100% correlated. I call this the NBD Cumulant Theorem.

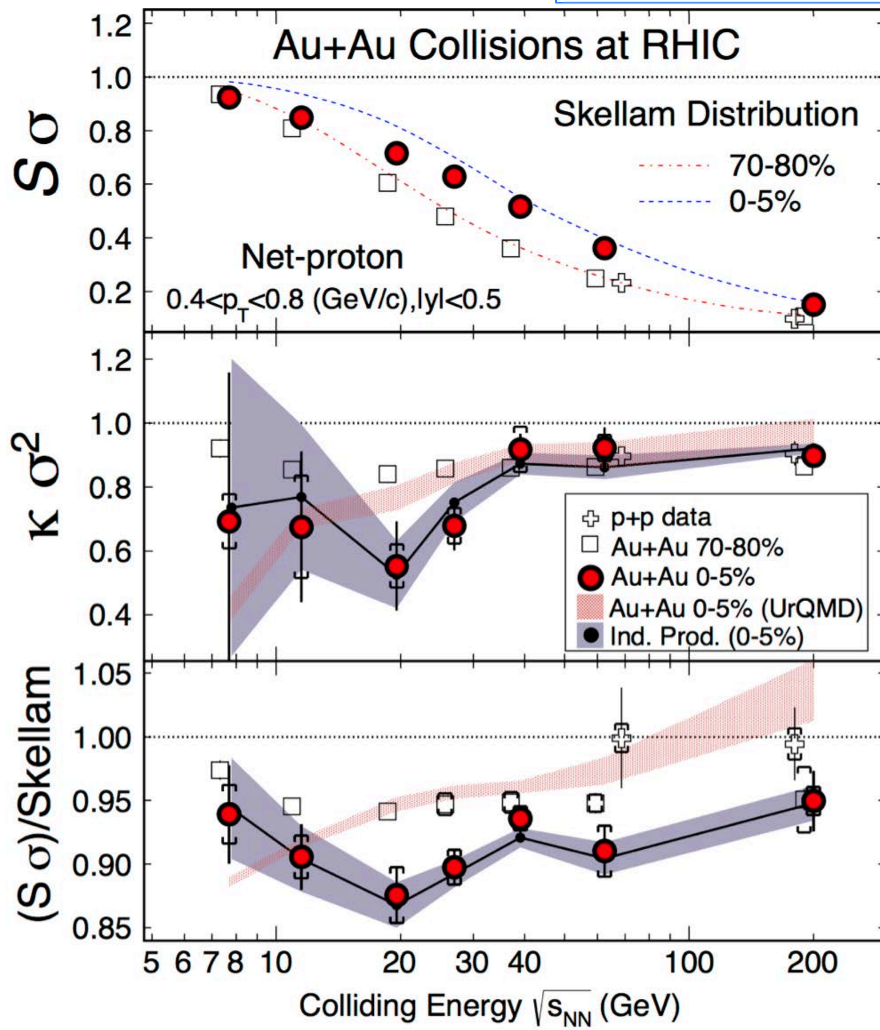
$$\boxed{\kappa_j = \kappa_j^+ + (-1)^j \kappa_j^-}$$

STAR publications 2014

arXiv: 1402.1558

PRL 112(2014) 032302

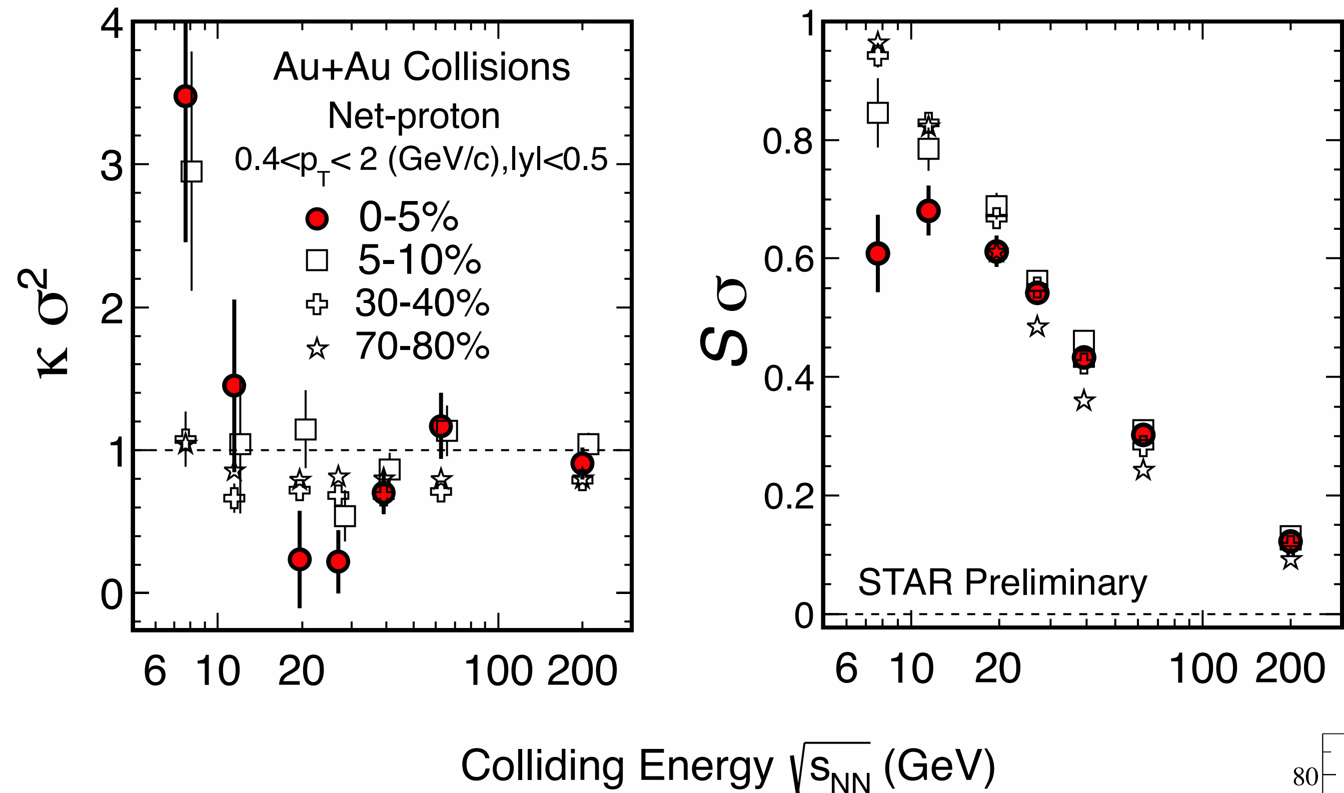




$S\sigma$ clearly favors NBD, not Poisson (!).
No non- monotonic behavior in $S\sigma$ or $\kappa\sigma^2$
but $\kappa\sigma^2$=-1.5 at $\sqrt{s_{NN}}$ =20 can't be ruled out

$\kappa\sigma^2$=-1.5 at $\sqrt{s_{NN}}$ =20 **can** be ruled out
$\kappa\sigma^2$ changes for $\sqrt{s_{NN}} \leq$ 30 GeV but
antiprotons become negligible $\leq$0.02 p

New STAR net-p Preliminary 2015

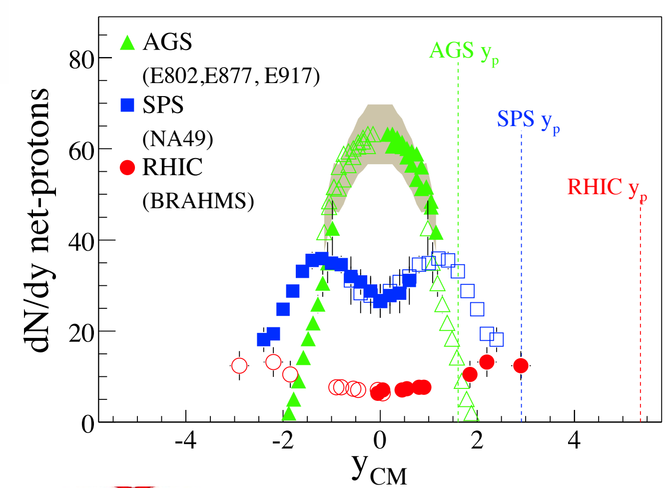


Binomial p	Sσ	κσ^2
p	1-2p	1-6p+6p^2
0.01	0.98	0.941
0.02	0.96	0.882
0.03	0.94	0.825
0.04	0.92	0.770
0.05	0.9	0.715
0.06	0.88	0.662
0.07	0.86	0.609
0.08	0.84	0.558
0.09	0.82	0.509
0.1	0.8	0.460
0.15	0.7	0.235
0.2	0.6	0.040
0.25	0.5	-0.125
0.3	0.4	-0.260
0.35	0.3	-0.365
0.4	0.2	-0.440
0.45	0.1	-0.485
0.5	0	-0.500

X.Luo, arXiv:1503.02558

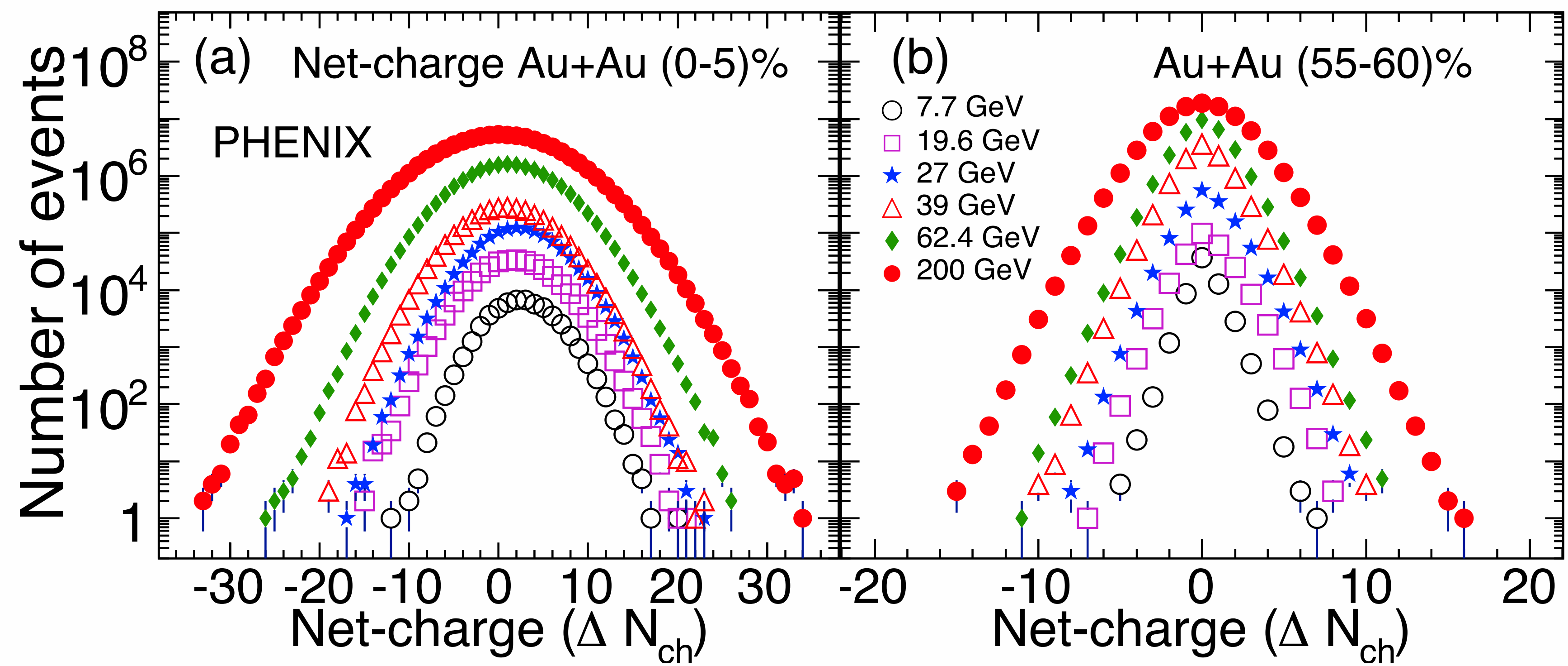
How can adding tracks >0.8 GeV/c make such changes in $\kappa\sigma^2$ but not in $S\sigma$

Show me the distributions!



NEW! PHENIX net-charge fluctuations

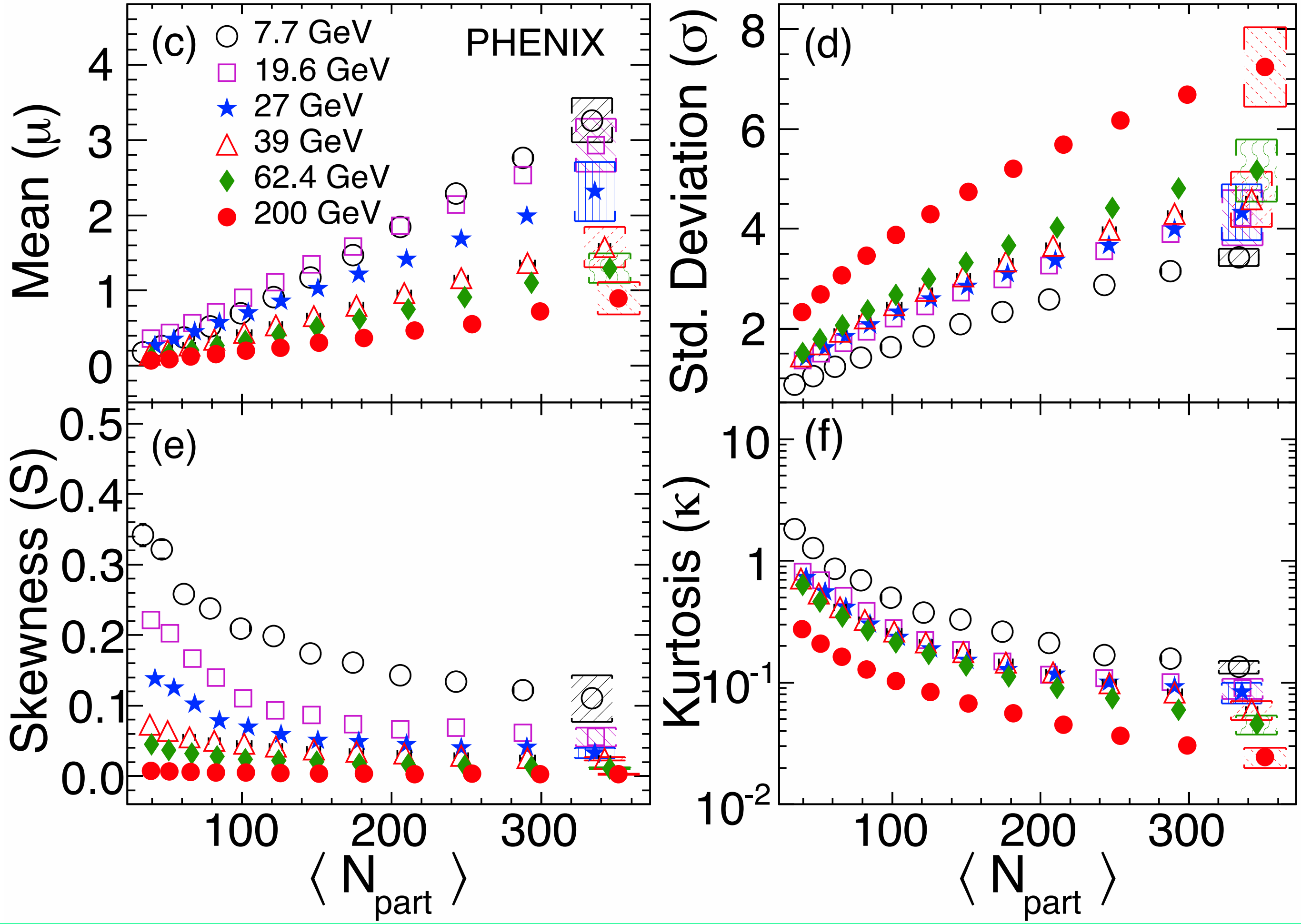
PHENIX arXiv:1506.07834



$\Delta N_{ch}=N^{+} - N^{-}$ distribution in $|\eta|<0.35$, $\delta\phi=\pi$, $0.3<p_T<2.0$ GeV/c
Not corrected for detection efficiency $\varepsilon\approx 0.70$ in acceptance

PHENIX corrected cumulants vs centrality

PHENIX arXiv:1506.07834

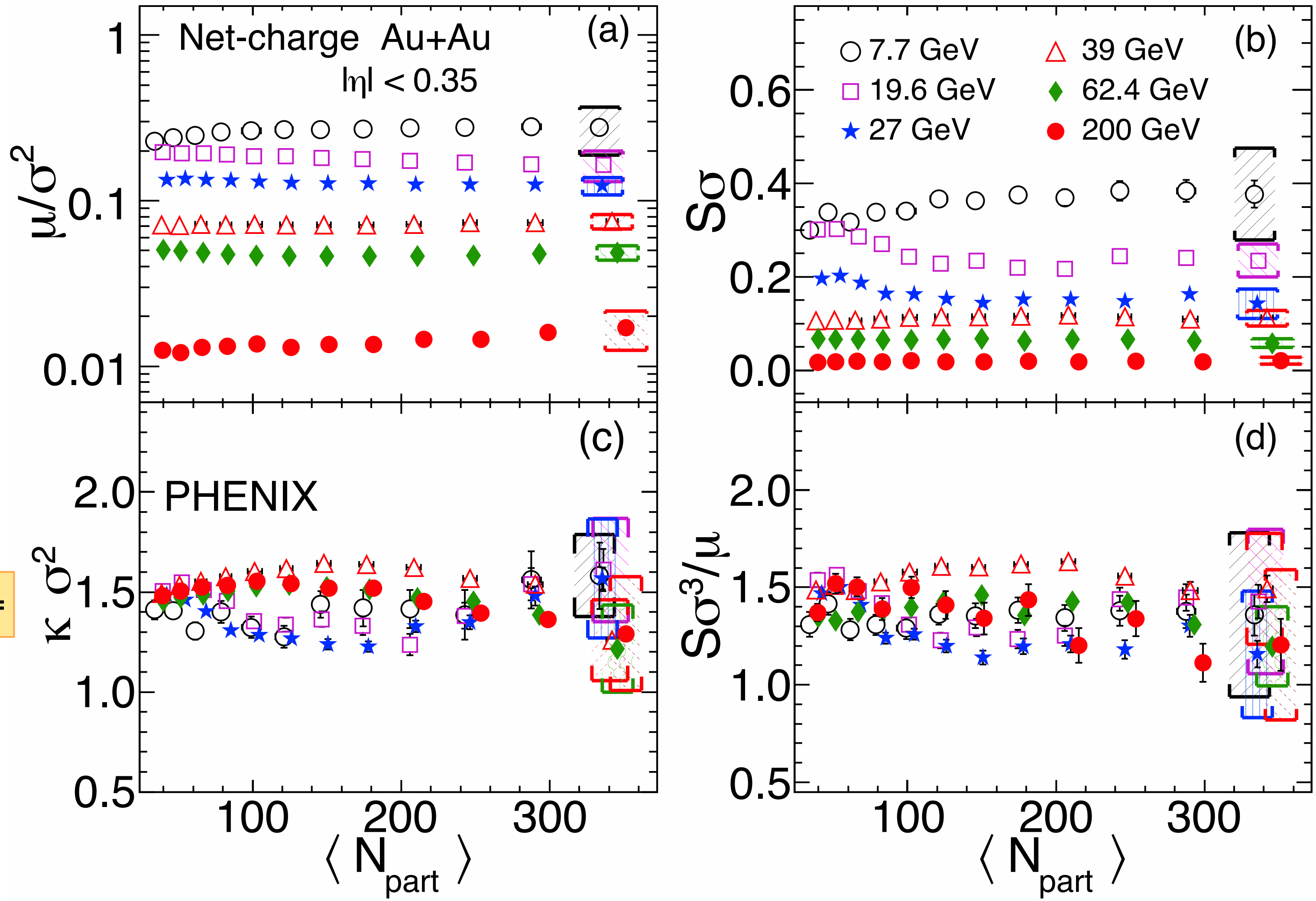


To compare with Lattice QCD theory, ratios of cumulants are used so that the dependence on volume V cancels

PHENIX Cumulant Ratios vs centrality

PHENIX arXiv:1506.07834

$\kappa_4 / \kappa_2 =$

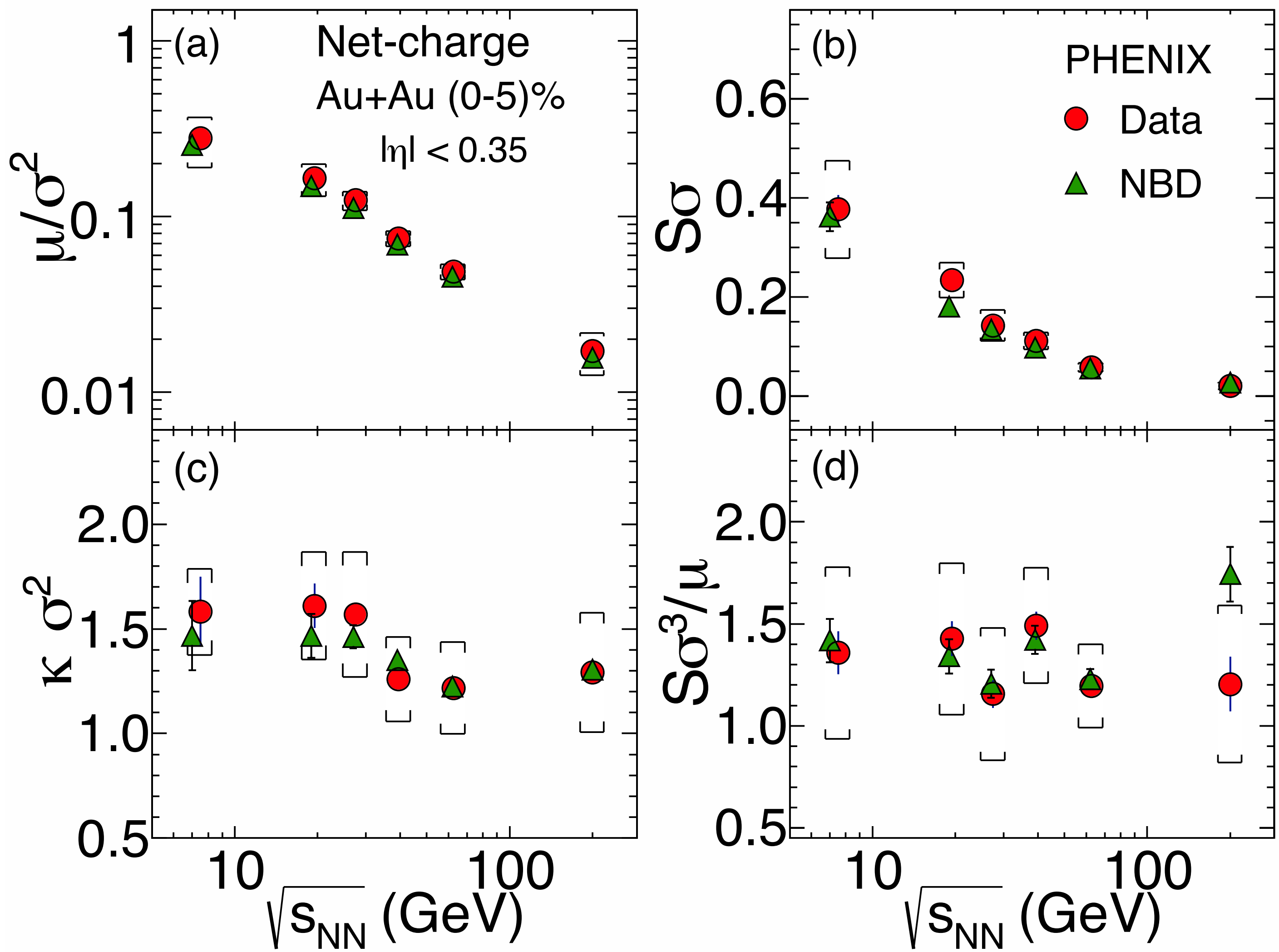


$= \kappa_3 / \kappa_1$

The centrality dependence is minimal for all ratios while the $\sqrt{s_{NN}}$ dependence is weak for κ_4 / κ_2 and κ_3 / κ_1, very strong for μ/σ^2 and strong for $S\sigma$

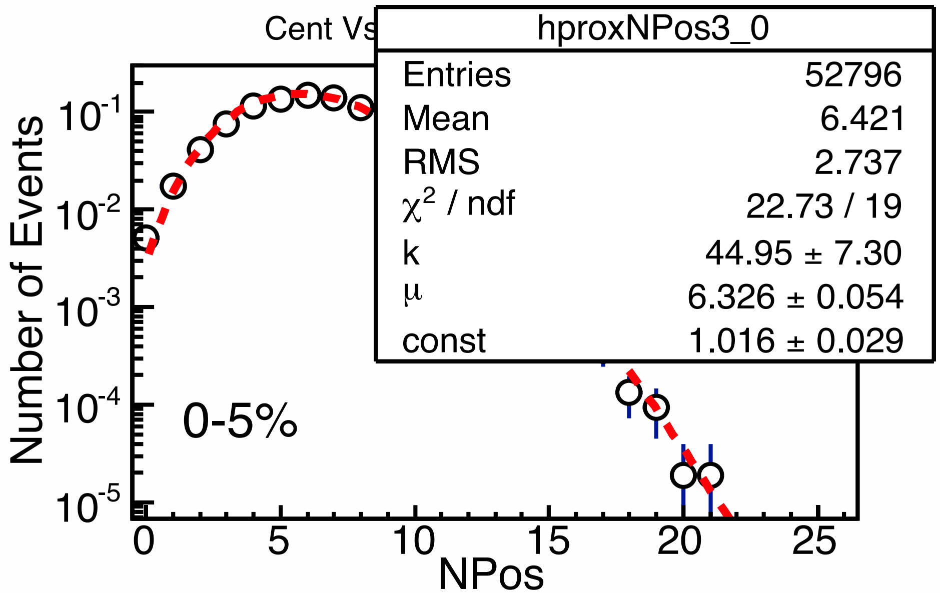
PHENIX central cumulant ratios vs $\sqrt{s_{NN}}$

PHENIX arXiv:1506.07834

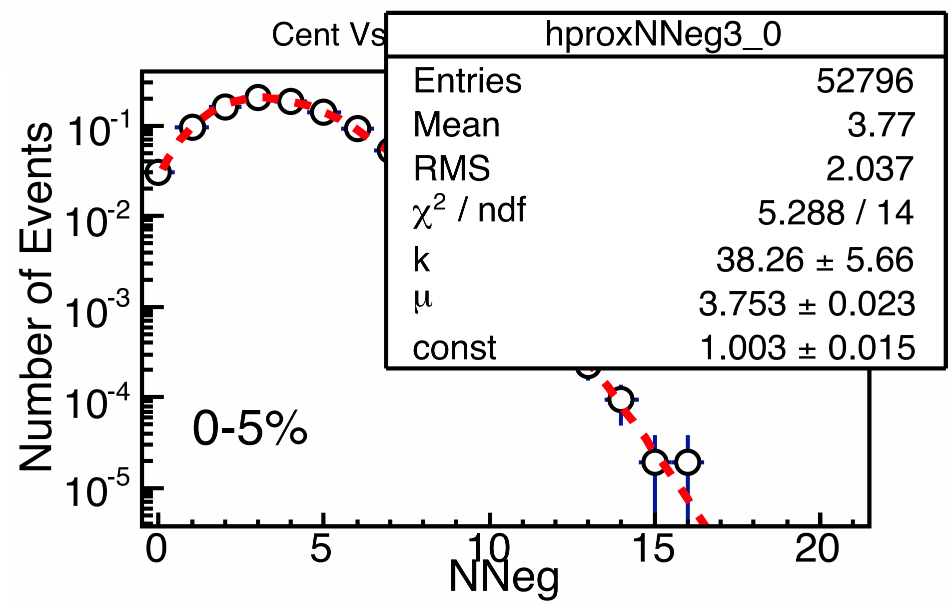


Note that the ``data'' • calculations from the $\Delta N_{ch}=N^+ - N^-$ distributions agree with the NBD fits to the N^+ and N^- distribution and the NBD Cumulant Theorem.

The N^+, N^- (and N^++N^-) distributions are NBD

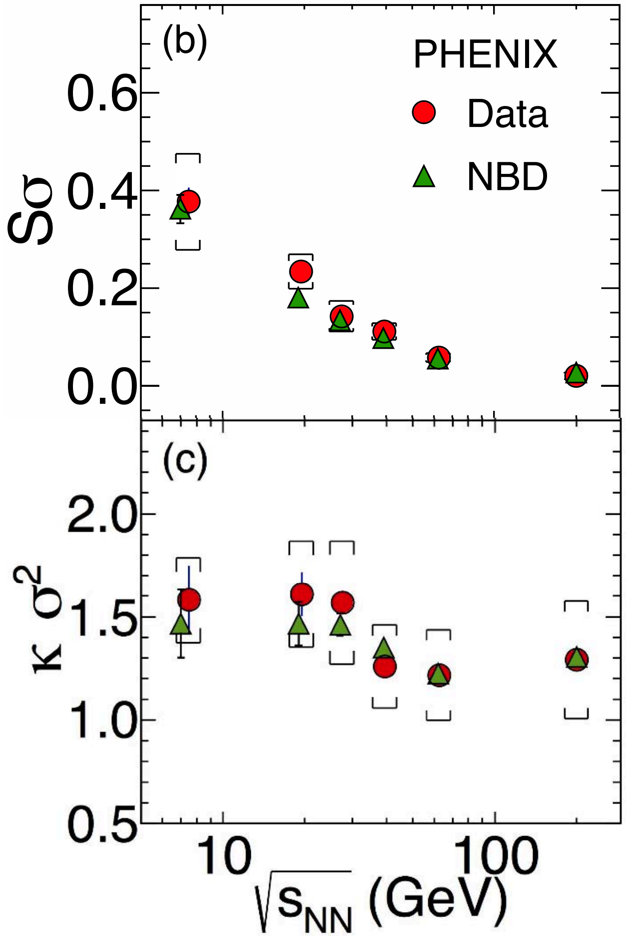


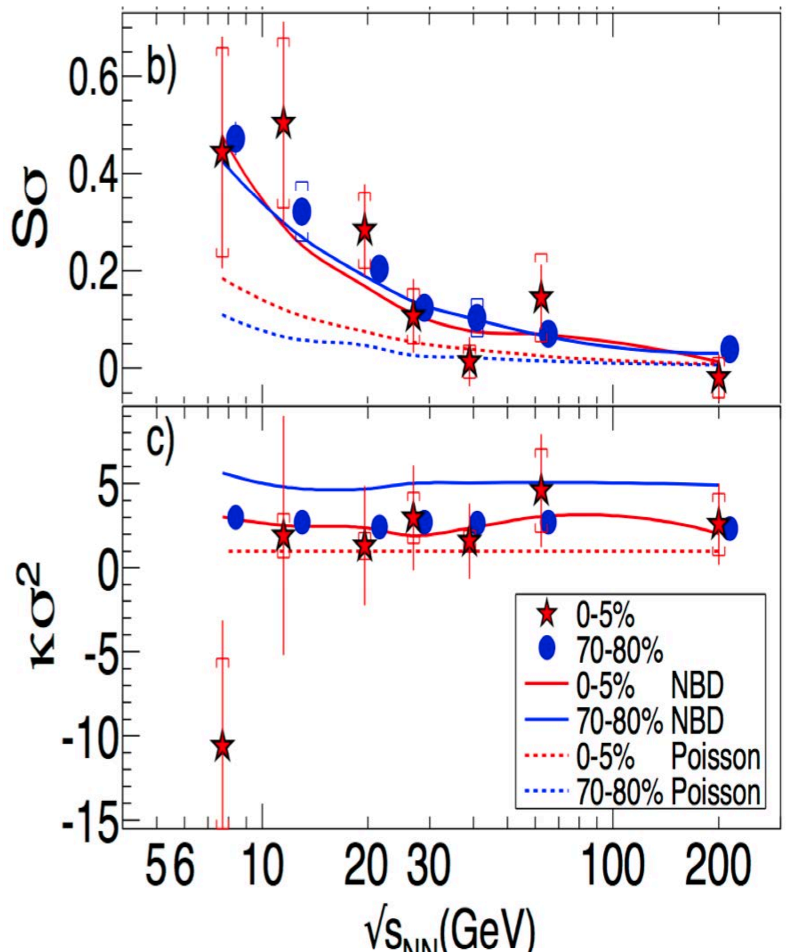
PHENIX: centrality 0-5%
$\sqrt{s_{NN}}$=7.7 GeV



PHENIX and STAR comparison!!!

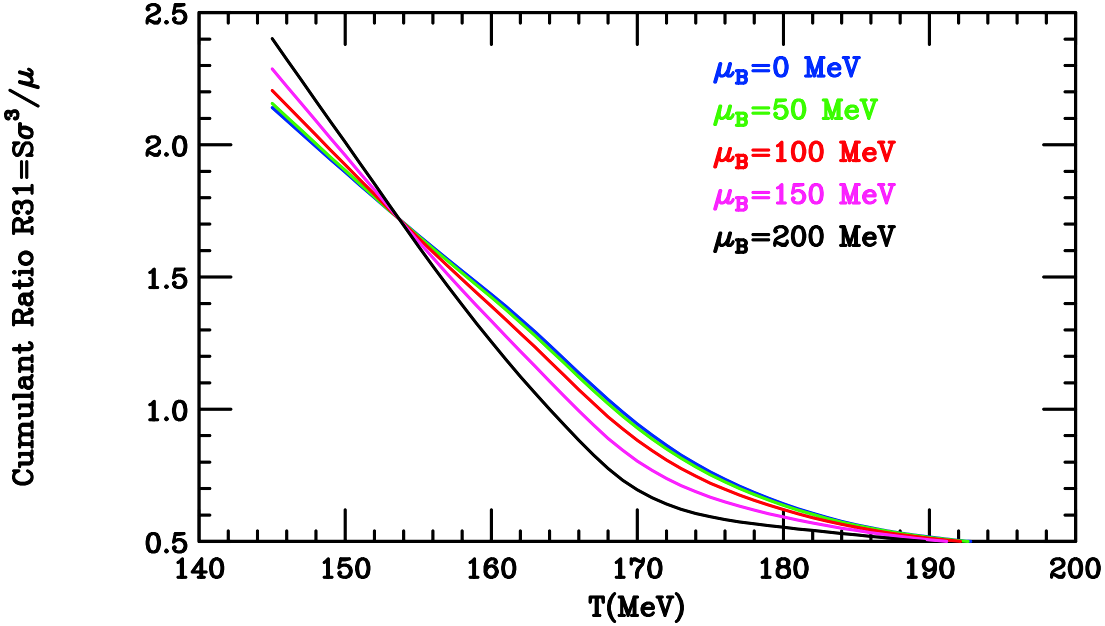
PHENIX arXiv:1506.07834



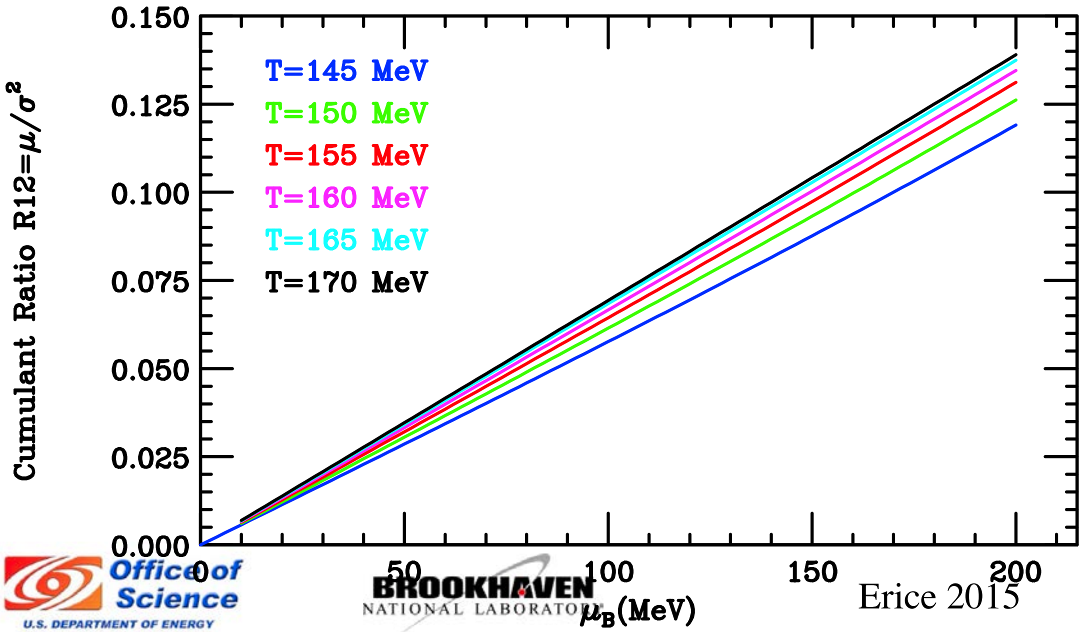


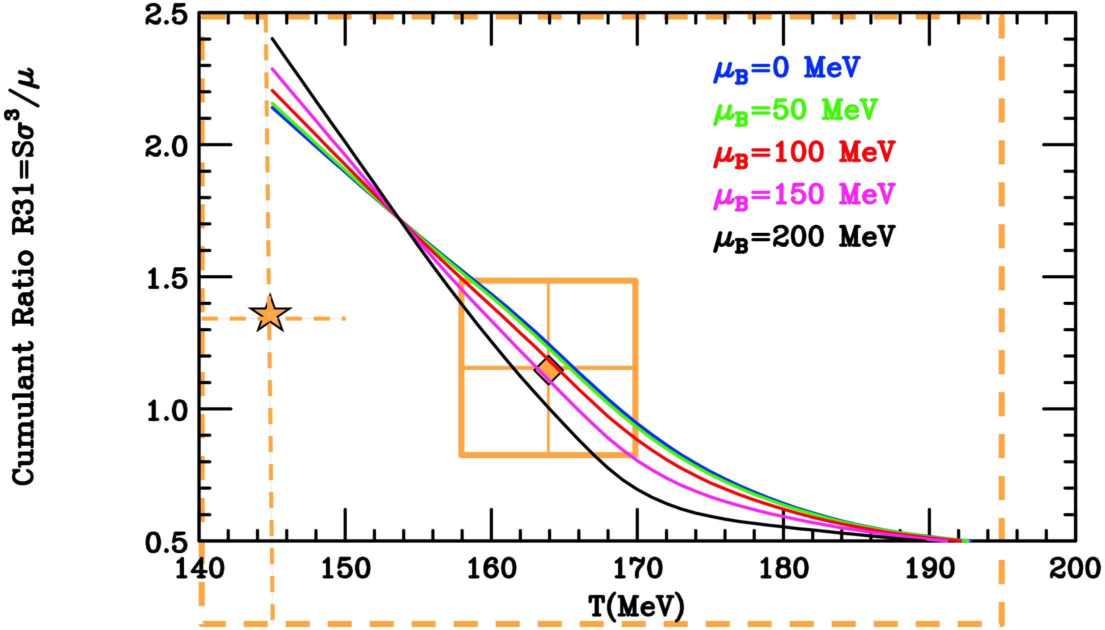
STAR arXiv: 1402.1558

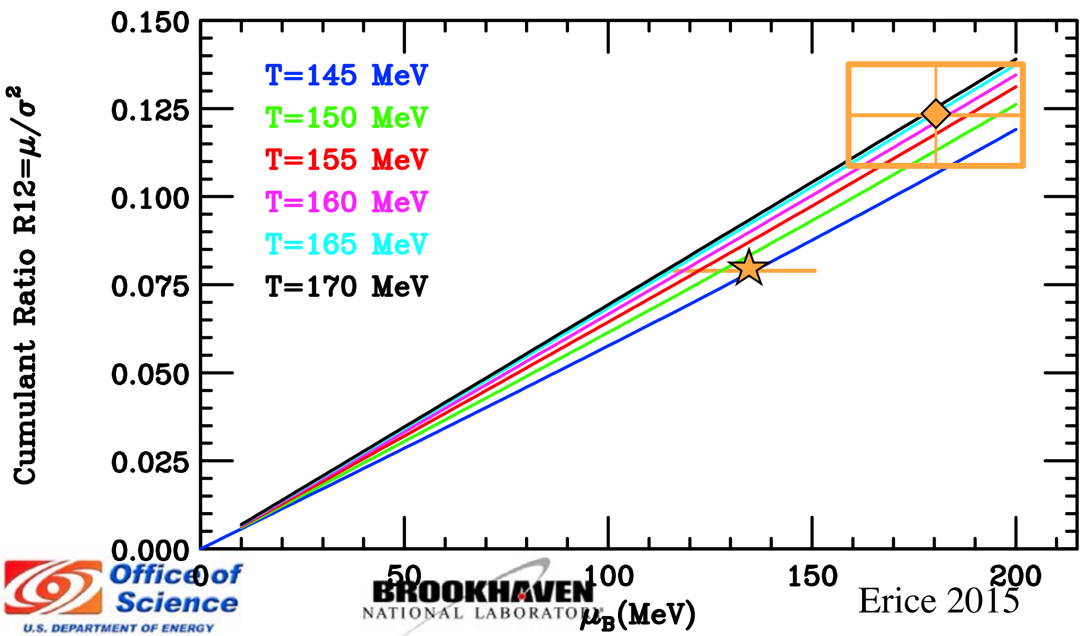
The key difference of the PHENIX and STAR results is that the error on all corrected cumulant ratios is 20-30% for PHENIX while for STAR the error on e.g. $S\sigma$ is ~ 50%, on $\kappa\sigma^2$ is >100% but <1% for σ^2/μ!!! (which turns out to be important)



BNL Lattice QCD group predictions for cumulant ratios R31 and R12 vs T_f and μ_B at freezout (when QGP hadronizes)
Pos(CPOD2014)005.
PRL **109** (2012) 192302



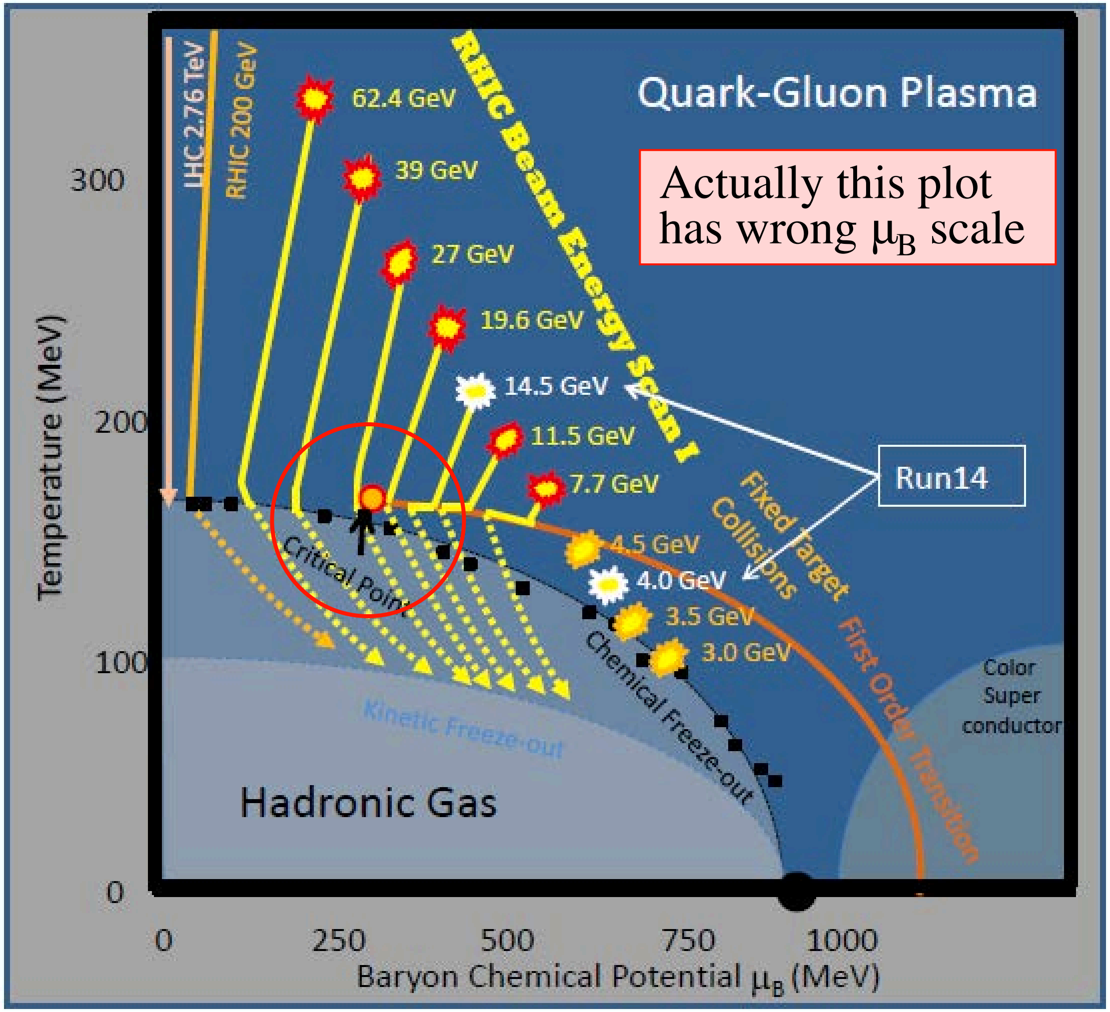




STAR☆ measurement of $R31=\kappa_3/\kappa_1$ has such a huge error that the central ☆ could go anywhere in the dashed region, while R12 has such a small error that it is constrained to the region of the horizontal line by the assumption $140<T_f<150$MeV PRL **113** (2014) 052301

PHENIX ◇ measurement with comparable errors on R31 and R12 enables both T_f and μ_B to be determined from the Lattice QCD calculations: Pos(CPOD2014)005

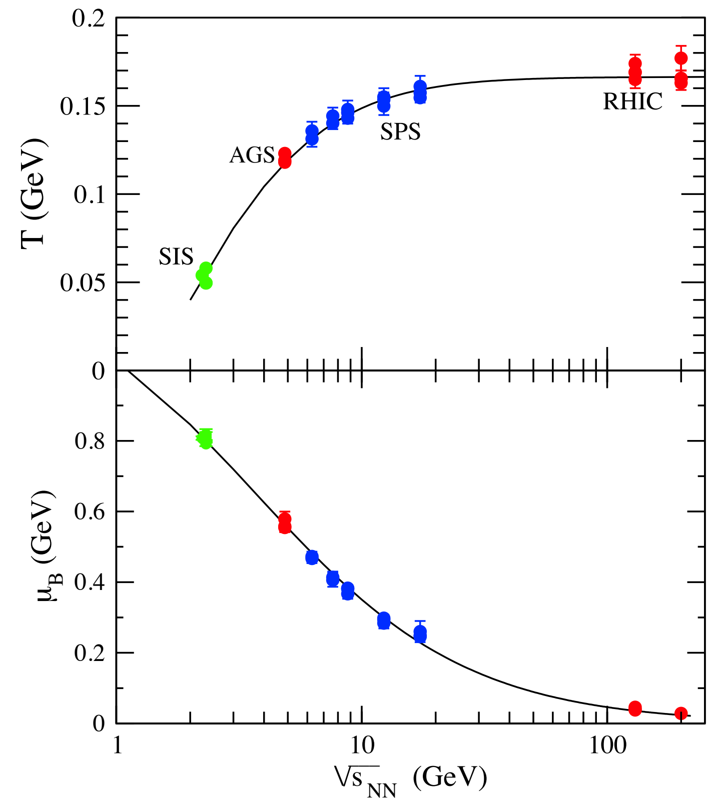
STAR's opinion of PHASE diagram 2014



Actually this plot has wrong μ_B scale

T=160 MeV
μ_B=300 MeV
$\sqrt{s_{NN}}$~27 GeV

$$\frac{\bar{p}}{p} \approx 0.02$$

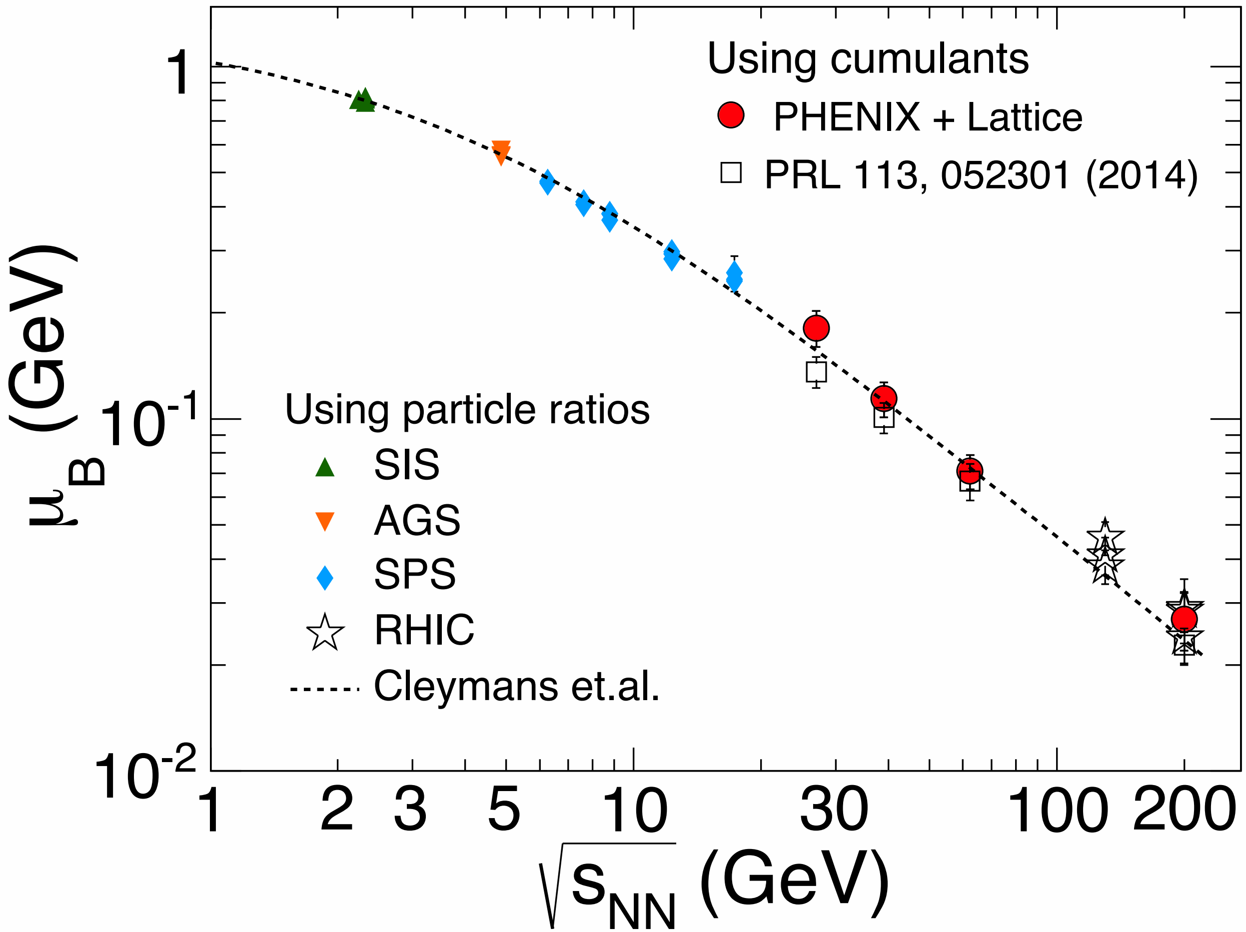


Cleymans,Oeschler *et al.*
PRC73(2006)034905

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-(2\mu_B)/T}$$

NEW: Experiment +Theory=Physical Quantity

PHENIX arXiv:1506.07834



Experimental result on net-charge cumulants + Lattice QCD calculation gives both freezeout T_f+Baryon Chemical Potential μ_B without particle identification!! I think this is a first and it also agrees with the best accepted calculations from baryon/anti-baryon ratios, PRC73(2006)034905

Why are STAR errors on R31 so large?

It must be that statistical errors and efficiency corrections are a BIG issue in these measurements even though the correction is simply Binomial; and analytical for NBD N^+ and N^- distributions (**k unchanged, $\mu_t=\mu/p$ where p is the efficiency**). So use the NBD "integer value Levy process" cumulant theorem:

Tarnowsky, Westfall PLB 724 (2013) 51

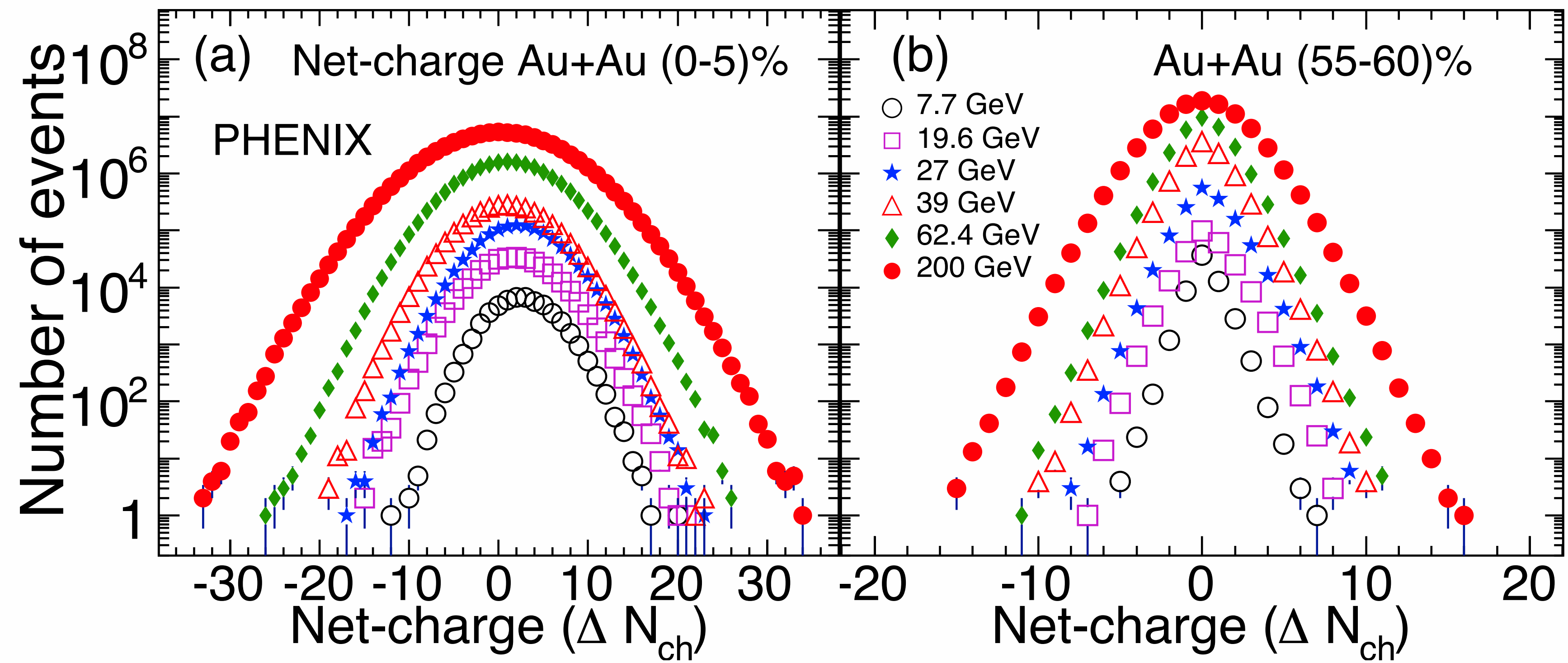
Barndorff-Nielsen,Pollard,Shephard: Quantitave Finance 12(2012)587

http://www.economics.ox.ac.uk/materials/papers/4382/paper490.pdf

$$\boxed{\kappa_j = \kappa_j^+ + (-1)^j \kappa_j^-}$$

From PHENIX net-charge fluctuations

PHENIX arXiv:1506.07834



$\Delta N_{ch}=N^+ - N^-$ distribution in $|\eta|<0.35$, $\delta\phi=\pi$, $0.3<p_T<2.0$ GeV/c
Not corrected for detection efficiency $\varepsilon\approx 0.70$ in acceptance

The raw moments of the uncorrected distributions can be easily calculated

$$\mu'_k \equiv \langle x^k \rangle \equiv \sum_{i=1}^{n} x_i^k E(x_i) / \sum_{i=1}^{n} E(x_i)$$

$\mu'_1 \equiv \mu = \langle x \rangle$ and x_i is a bin in the ΔN_{ch} plot with $E(x_i)$ events.

Statistical errors--the complications begin

$$\mu'_k \equiv \langle x^k \rangle \equiv \sum_{i=1}^{n} x_i^k E(x_i) / \sum_{i=1}^{n} E(x_i)$$

The statistical errors for every μ'_k can be calculated from the statistical errors of each data point $E(x_i) \pm \sigma_{E(x_i)}$. Even though the $\sigma_{E(x_i)}$ on each point are independent, the errors on each μ'_k are not independent because the same $\sigma_{E(x_i)}$ appears in all the moments.

Next one computes the cumulants κ_i from the raw (aka) non-central moments:

$$\begin{aligned}
\mu = \kappa_1 &= \mu'_1 \\
\sigma^2 = \mu_2 \equiv \langle (x-\mu)^2 \rangle = \kappa_2 &= \mu'_2 - \mu'^2_1 \\
\mu_3 = \kappa_3 &= \mu'_3 - 3\mu'_2\mu'_1 + 2\mu'^3_1 \\
\mu_4 - 3\mu_2^2 = \kappa_4 &= \mu'_4 - 4\mu'_3\mu'_1 - 3\mu'^2_2 + 12\mu'_2\mu'^2_1 - 6\mu'^4_1
\end{aligned}$$

Next correction---Efficiency

A certain random fraction of the tracks that fall on the acceptance are not detected because of inefficiency---a clearly random, thus binomial effect. This is further complicated if the N^+ and N^- measurements have different efficiencies.

Bzdak-Koch standard Binomial efficiency correction PRC 86 (2012) 044904

Efficiency corrected cumulants in terms of corrected double Factorial moments

$$N = \langle N_+ \rangle + \langle N_- \rangle$$

$$\kappa_1 = \langle N_+ \rangle - \langle N_- \rangle = \frac{\langle n_+ \rangle}{\epsilon_+} - \frac{\langle n_- \rangle}{\epsilon_-},$$

$$F_{ik} = \sum_{N_1=i}^{\infty} \sum_{N_2=k}^{\infty} P(N_1, N_2) \frac{N_1!}{(N_1-i)!} \frac{N_2!}{(N_2-k)!}$$

$$\kappa_2 = N - \kappa^2{}_1 + F_{02} - 2F_{11} + F_{20},$$

$$\kappa_3 = \kappa_1 + 2\,\kappa^3{}_1 - F_{03} - 3F_{02} + 3\,F_{12} + 3\,F_{20} - 3F_{21} + F_{30}$$
$$- 3\kappa_1(N + F_{02} - 2F_{11} + F_{20}),$$

$$\kappa_4 = N - 6\kappa^4{}_1 + F_{04} + 6\,F_{03} + 7\,F_{02} - 2F_{11} - 6F_{12} - 4F_{13}$$
$$+ 7F_{20} - 6F_{21} + 6F_{22} + 6F_{30} - 4F_{31} + F_{40}$$
$$+ 12\kappa^2{}_1(N + F_{02} - 2F_{11} + F_{20}) - 3(N + F_{02} - 2F_{11} + F_{20})^2$$
$$- 4\kappa_1(\kappa_1 - F_{03} - 3F_{02} + 3\,F_{12} + 3\,F_{20} - 3F_{21} + F_{30})$$

Here you can see the nice subtraction of the lower order moments; but new quantities, double Factorial Moments are introduced and very difficult to compute $P(13^+, 11^-)$=? so you need to know both N_+ and N_- distributions and their correlations. The F_{ik} can be calculated from the data by making a 3d Lego plot with base axes N_+ and N_- and height $P(N_+, N_-)$ which costs statistical error but other methods ``Bootstrap'' are used.

If you measure the distribution, then you know all the corrected cumulants

Cumulants for Poisson, Negative Binomial Distributions Measured with **efficiency** p corrected to true value, explicit in μ_t and k

Measured Cumulant	Corrected Poisson	Corrected Negative Binomial Expanded
$\kappa_1 = \mu$	$\mu_t \equiv \mu/p$	$\mu_t \equiv \mu/p$
$\kappa_2 = \mu_2 = \sigma^2$	μ_t	$\mu_t(1+\mu_t/k) \equiv \sigma_t^2$
$\kappa_3 = \mu_3$	μ_t	$\mu_t(1+3\mu_t/k+2\mu_t^2/k^2)$
$\kappa_4 = \mu_4 - 3\kappa_2^2$	μ_t	$\mu_t(1+7\mu_t/k+12\mu_t^2/k^2+6\mu_t^3/k^3)$
$S \equiv \kappa_3/\sigma^3$	$1/\sqrt{\mu_t}$	$(1+2\mu_t/k)/\sqrt{\mu_t(1+\mu_t/k)}$
$\kappa \equiv \kappa_4/\kappa_2^2$	$1/\mu_t$	$(1+6\mu_t/k+6\mu_t^2/k^2)/[\mu_t(1+\mu_t/k)]$
$S\sigma = \kappa_3/\kappa_2$	1	$(1+2\mu_t/k)$
$\kappa\sigma^2 = \kappa_4/\kappa_2$	1	$(1+6\mu_t/k+6\mu_t^2/k^2)$
$\mu/\sigma^2 = \kappa_1/\kappa_2$	1	$1/(1+\mu_t/k)$
$S\sigma^3/\mu = \kappa_3/\kappa_1$	1	$(1+3\mu_t/k+2\mu_t^2/k^2)$

Use the NBD Cumulant Theorem allowing ε=p to be different for N^+ and N^-

$$\kappa_j = \kappa_j^+ + (-1)^j \kappa_j^-$$

Efficiency-Corrected NBD Cumulant Ratios

$$\frac{\mu}{\sigma^2} = \frac{\kappa_1^+ - \kappa_1^-}{\kappa_2^+ + \kappa_2^-} = \frac{\mu_t^+ - \mu_t^-}{\mu_t^+[1 + (\frac{\mu_t^+}{k^+})] + \mu_t^-[1 + (\frac{\mu_t^-}{k^-})]}$$

$$\mu_t = \frac{\mu}{\varepsilon}$$

$$\frac{S\sigma^3}{\mu} = \frac{\kappa_3^+ - \kappa_3^-}{\kappa_1^+ - \kappa_1^-} = \frac{\mu_t^+[1 + 3(\frac{\mu_t^+}{k^+}) + 2(\frac{\mu_t^+}{k^+})^2] - \mu_t^-[1 + 3(\frac{\mu_t^-}{k^-}) + 2(\frac{\mu_t^-}{k^-})^2]}{\mu_t^+ - \mu_t^-}$$

$$S\sigma = \frac{\kappa_3^+ - \kappa_3^-}{\kappa_2^+ + \kappa_2^-} = \frac{\mu_t^+[1 + 3(\frac{\mu_t^+}{k^+}) + 2(\frac{\mu_t^+}{k^+})^2] - \mu_t^-[1 + 3(\frac{\mu_t^-}{k^-}) + 2(\frac{\mu_t^-}{k^-})^2]}{\mu_t^+[1 + \frac{\mu_t^+}{k^+}] + \mu_t^-[1 + \frac{\mu_t^-}{k^-}]}$$

$$\kappa\sigma^2 = \frac{\kappa_4^+ + \kappa_4^-}{\kappa_2^+ + \kappa_2^-} = \frac{\mu_t^+[1 + 7(\frac{\mu_t^+}{k^+}) + 12(\frac{\mu_t^+}{k^+})^2 + 6(\frac{\mu_t^+}{k^+})^3] + \mu_t^-[1 + 7(\frac{\mu_t^-}{k^-}) + 12(\frac{\mu_t^-}{k^-})^2 + 6(\frac{\mu_t^-}{k^-})^3]}{\mu_t^+[1 + \frac{\mu_t^+}{k^+}] + \mu_t^-[1 + \frac{\mu_t^-}{k^-}]}$$

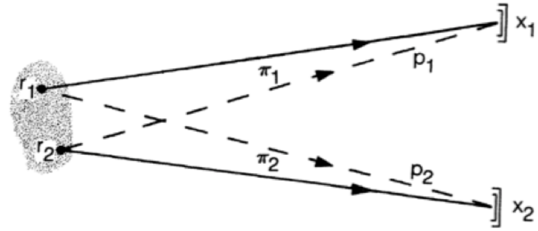
The error on μ_t <<than the error on μ_t/k so is neglected. The errors are highly correlated for the sums of powers of μ_t/k in both the numerator and denominator. These correlations are handled by varying the $(\mu_t/k)^+$ and $(\mu_t/k)^-$ by $\pm 1\sigma$ independently and adding the variations in quadrature

Short range multiplicity correlations do not vanish in A+A collisions!

- Short range multiplicity correlations in p-p collisons come largely from hadron decays such as $\rho\rightarrow\pi\,\pi$, $\Lambda\rightarrow\pi^-\,p$, etc., with correlation length ξ~1 unit of rapidity

- In A+A collisions the chance of getting two particles from the same ρ meson is reduced by~$1/N_{part}$ so that **the only remaining correlations are Bose-Einstein Correlations---**when two identical Bosons, e.g. $\pi^+\,\pi^+$, occupy nearly the same coordinates in phase space so that constructive interference occurs due to the symmetry of the wave function from Bose statistics---a quantum mechanical effect, which remains at the same strength in A+A collisions:the amplitudes from the two different points add giving a large effect also called Hanbury-Brown Twiss (HBT).

See W.A.Zajc, et al, PRC 29 (1984) 2173



HBT effects in 2-particle Correlations

- The normalized two-particle short range rapidity correlation $R_2(y_1,y_2)$ is defined as

$$R_2(y_1,y_2) \equiv \frac{C_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} \equiv \frac{\rho_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1 = R(0,0)\, e^{-|y_1-y_2|/\xi} \quad , \qquad (8)$$

where $\rho_1(y)$ and $\rho_2(y_1,y_2)$ are the inclusive densities for a single particle (at rapidity y) or 2 particles (at rapidities y_1 and y_2), $C_2(y_1,y_2) = \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2)$ is the Mueller correlation function for 2 particles (which is zero for the case of no correlation), and ξ is the two-particle short-range rapidity correlation length[3] for an exponential parameterization.

$$\boxed{K_2(\delta\eta) = 2R(0,0)\frac{(\delta\eta/\xi - 1 + e^{-\delta\eta/\xi})}{(\delta\eta/\xi)^2}}$$

for NBD: $k(\delta\eta) = 1/K_2(\delta\eta)$

The rapidity correlation length $\xi = 0.2$ for Si+Au E802, PRC56(1977) 1544 is from HBT.

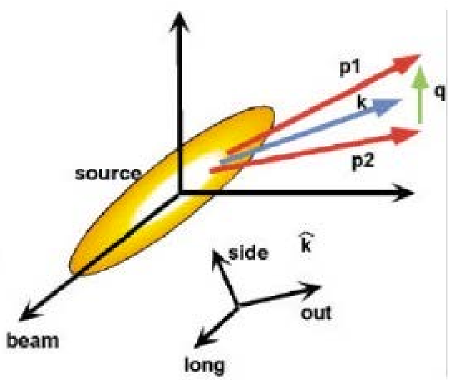
if $\delta\eta \ll \xi$, $k \rightarrow 1/R(0,0)$=constant   if $\delta\eta \gg \xi$, $k/\delta\eta \approx k/\mu \rightarrow$constant

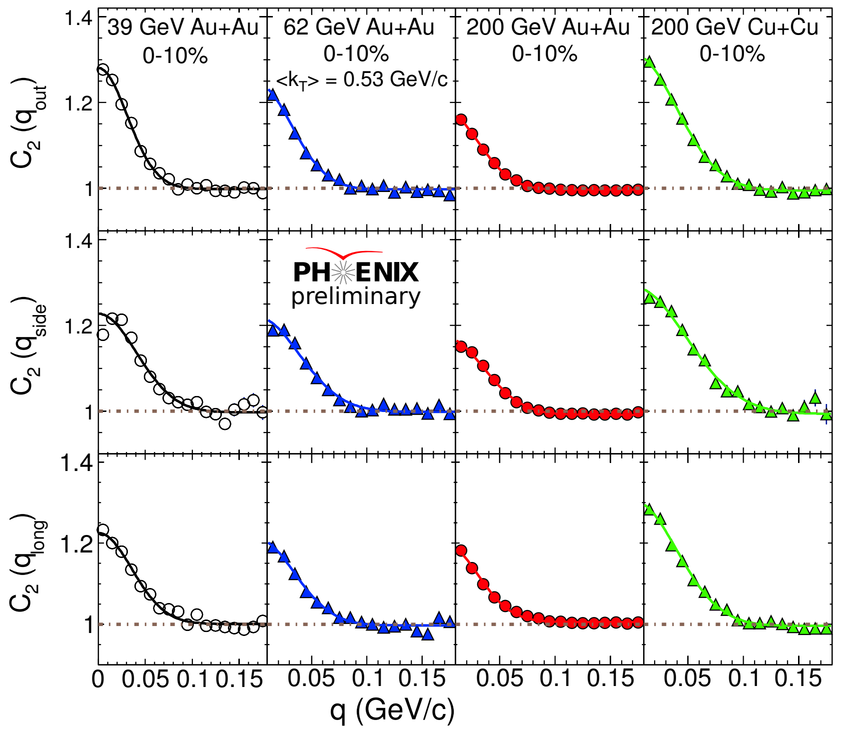
- For HBT analyses of two particles with $\mathbf{p}_1$ and $\mathbf{p}_2$, $C^{HBT}{}_2(\mathbf{q}) = R_2(\mathbf{p}_1 - \mathbf{p}_2) + 1$ and the random (un-correlated) distribution is taken from particles with $\mathbf{p}_1$ and $\mathbf{p}_2$ on different events. The HBT correlation function is taken as a Gaussian not an exponential as in (8) and is written:

$$\boxed{C_2^{HBT} = 1 + \lambda \exp-(R_{side}^2 q_{side}^2 + R_{out}^2 q_{out}^2 + R_{long}^2 q_{long}^2)}$$

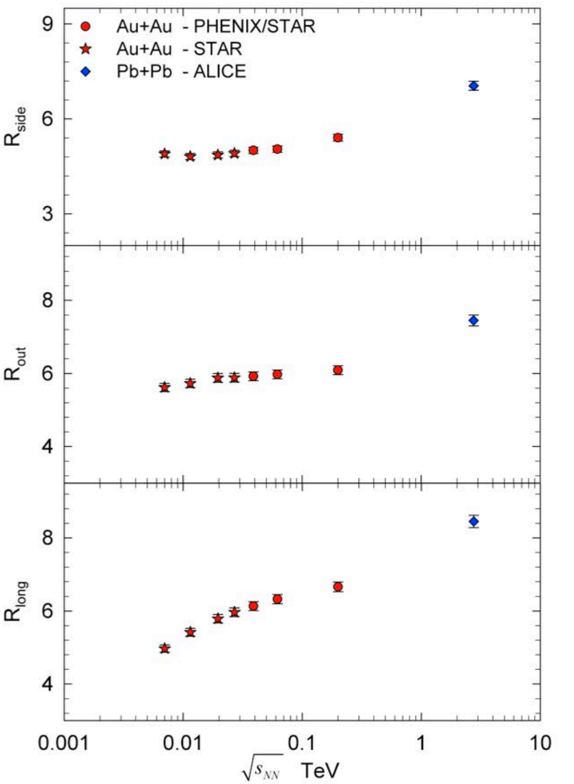
PHENIX HBT BES Results

- 3D Gaussian fits
- Bertsch-Pratt coord.
- LCMS ($p_{1z}+p_{2z}=0$)
- Coulomb Corrected





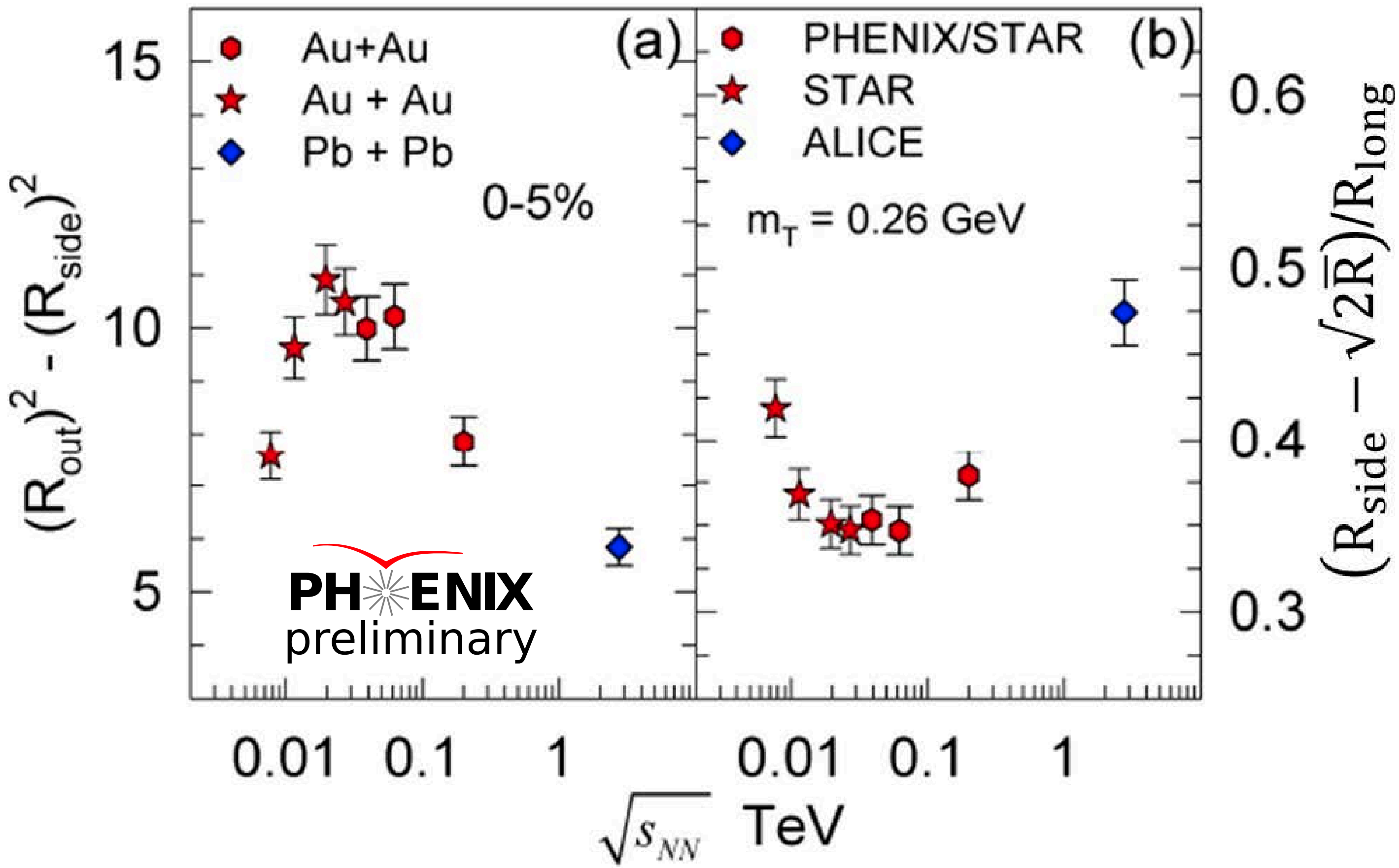
$C_2^{HBT}(q)$



R vs. $\sqrt{s_{NN}}$ fm

- R_{long} increases smoothly with $\sqrt{s_{NN}}$
- R_{side} R_{out} ~constant at RHIC, increase at LHC

Emission duration and expansion/lifetime

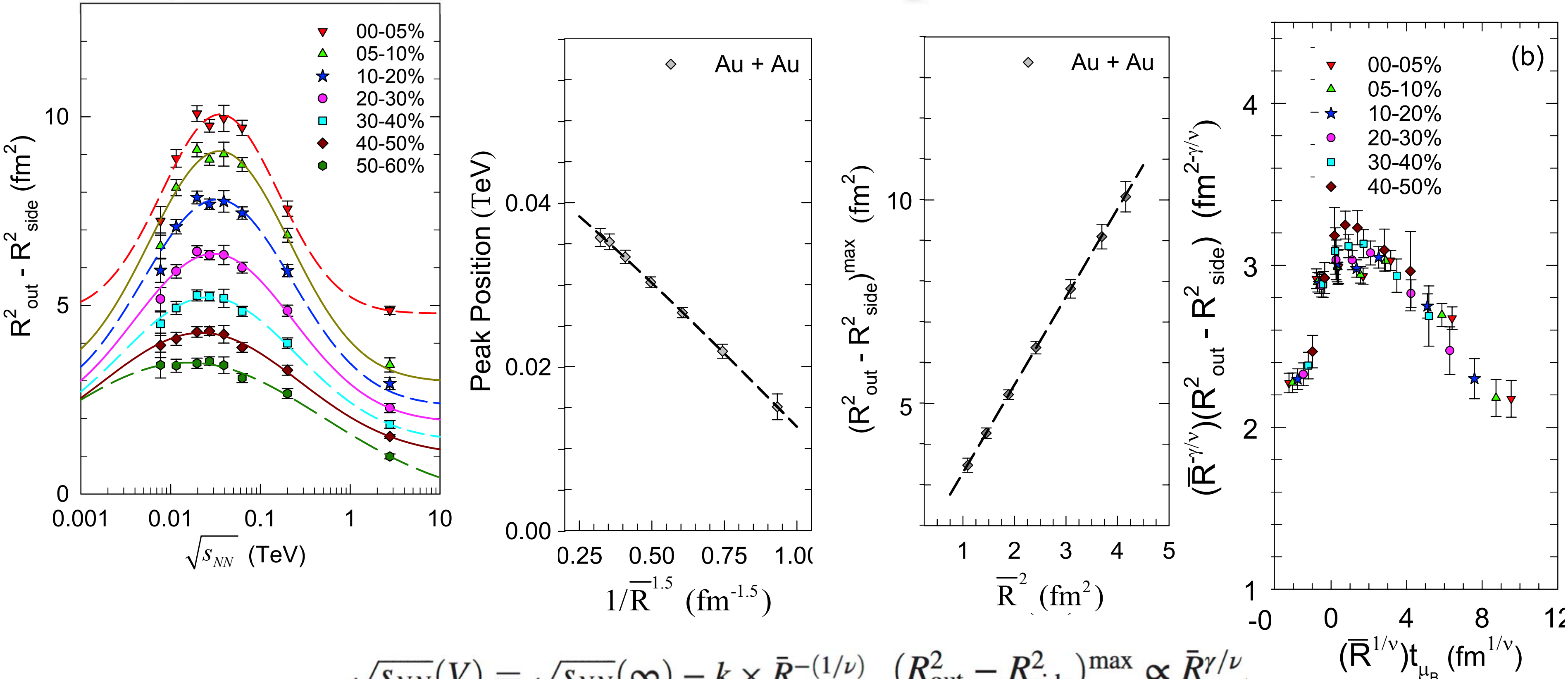


RMS radius of participants (est.)

- $(R_{out})^2 - (R_{side})^2$ measures emission duration
- R_{side} /R_{lomg} indicates expansion/lifetime
- $10 \leq \sqrt{s_{NN}} \leq 62$ GeV is the 'sweet spot' for something

Roy Lacey claims critical point

PRL114 (2015) 142301



$$\sqrt{s_{NN}}(V) = \sqrt{s_{NN}}(\infty) - k \times \bar{R}^{-(1/\nu)} \quad (R^2_{\text{out}} - R^2_{\text{side}})^{\text{max}} \propto \bar{R}^{\gamma/\nu}$$

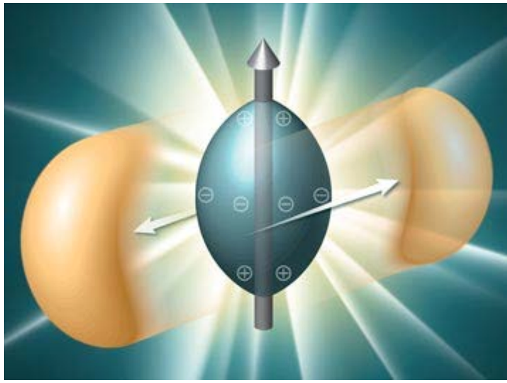
$$t_{\mu_B} = (\mu_B - \mu_B^{\text{cep}})/\mu_B^{\text{cep}}$$

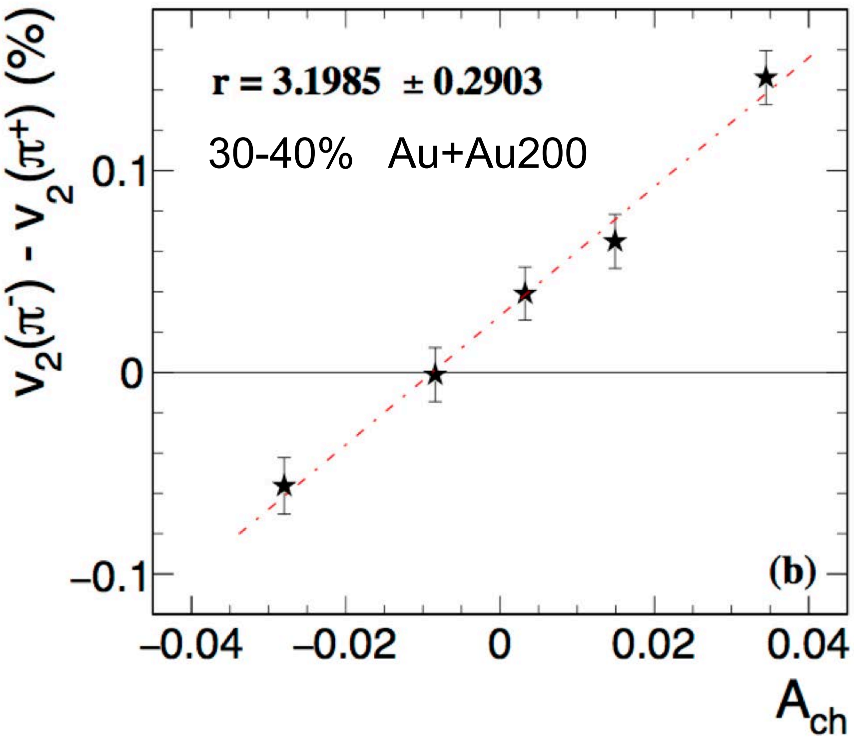
A finite-size scaling (FSS) analysis of these data suggests a second order phase transition with the estimates $T^{\text{cep}} \sim 165$ MeV and $\mu_B{}^{\text{cep}} \sim 95$ MeV for the location of the critical end point. The critical exponents ($\nu \approx 0.66$ and $\gamma \approx 1.2$) extracted via the same FSS analysis place this CEP in the 3D Ising model universality class. $\sqrt{s_{NN}}(\infty)$~47.5 GeV critical end point???

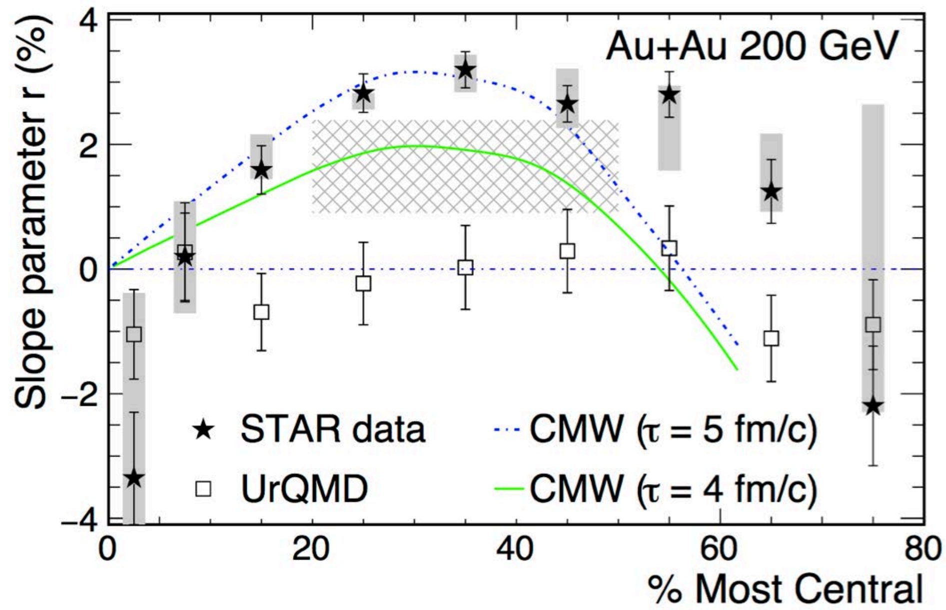
By Karen McNulty Walsh | June 8, 2015

Scientists See Ripples of a Particle-Separating Wave In Primordial Plasma

Key sign of quark-gluon plasma (QGP) and evidence for a long-debated quantum phenomenon





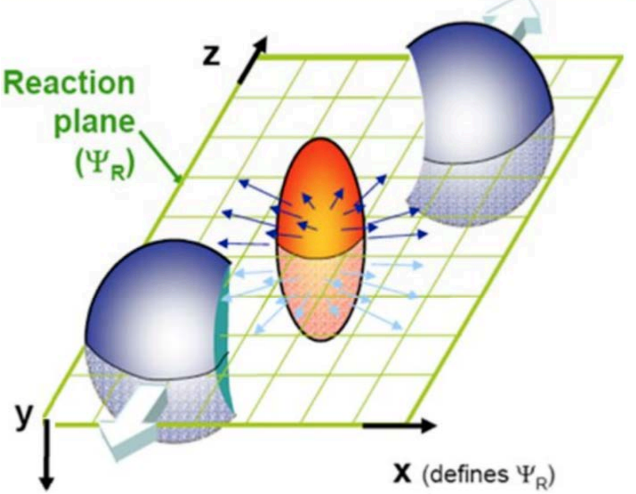


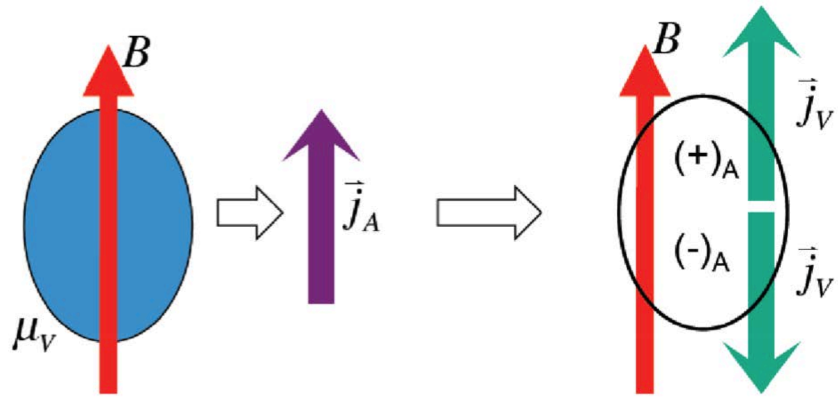
How does one prove what it is?

$$A_{\mathrm{ch}} = (N_+ - N_-)/(N_+ + N_-)$$

Chiral Magnetic Wave

Peak magnetic field ~
10^{15} Tesla !
(Kharzeev et al. NPA 803 (2008) 227)





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

Chiral Separation Effect

Chiral Magnetic Effect

CSE + CME ⟶ Chiral Magnetic Wave:

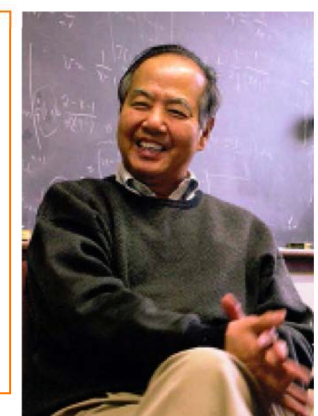
- collective excitation
- signature of chiral symmetry restoration

Polarized Proton Physics at RHIC-started at BNL Snowmass82---approved 1995

Operation of RHIC with two beams of highly polarized protons (70%, either longitudinal or transverse) at high luminosity $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} sec^{-1} for two months/year will allow high statistics studies of polarization phenomena in the perturbative region of hard scattering where both QCD and ElectroWeak theory make detailed predictions for polarization effects.

- **Spin Structure Functions** which require measurements in hadron collisions to complement DIS electron measurements:
  - $G(x)$ and $\Delta G(x)$ by inclusive γ and γ+Jet measurements.
  - $\Delta\bar{q}$ from Drell-Yan, $\Delta\bar{u}$ from W^-, $\Delta\bar{d}$ from W^+.

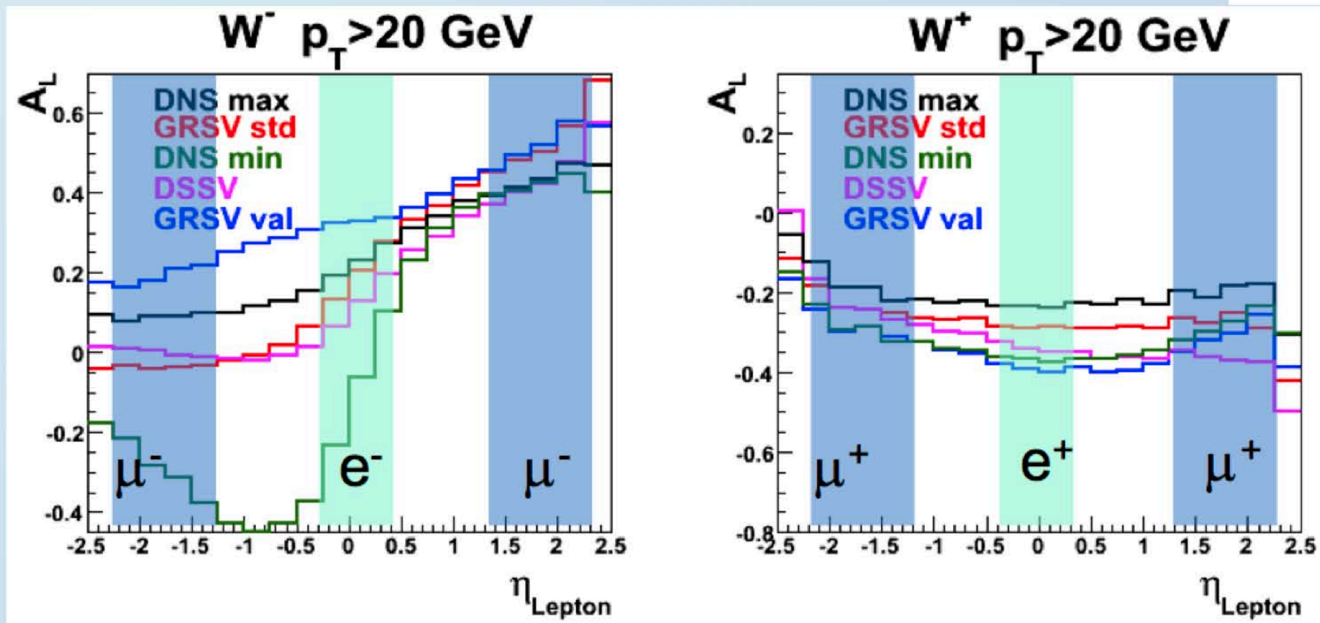
1997: To exploit spin physics and lattice gauge theory, RIKEN (Japan) provided one muon arm in PHENIX and money to support the snakes and spin rotators in RHIC. Also: the RIKEN BNL Research Center (RBRC) was established at BNL with T.D. Lee as founding Director.



Use Parity Violation of W: coupled to flavor

Sea quark polarization via W production

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



$$A_L = \frac{1}{P_1}\frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$$

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

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

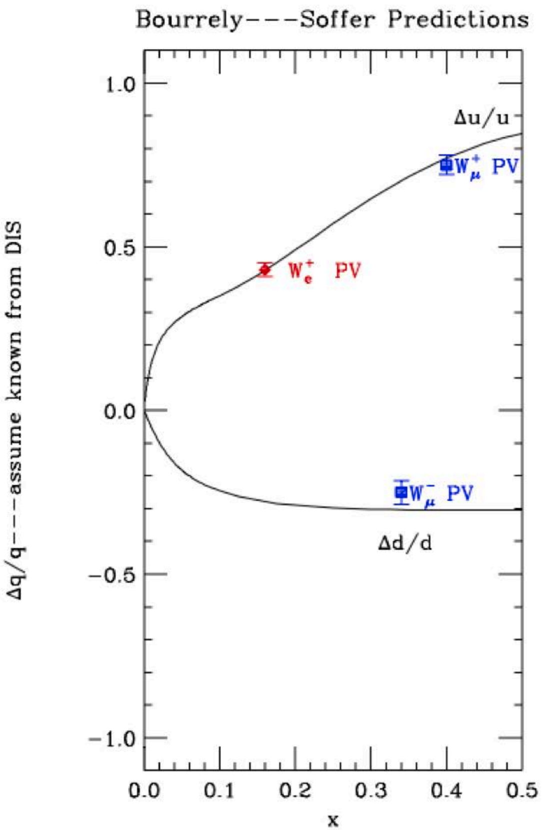
$$\langle x_1\rangle >> \langle x_2\rangle: \quad A_L^{W^-} \approx \frac{\Delta d}{d}$$

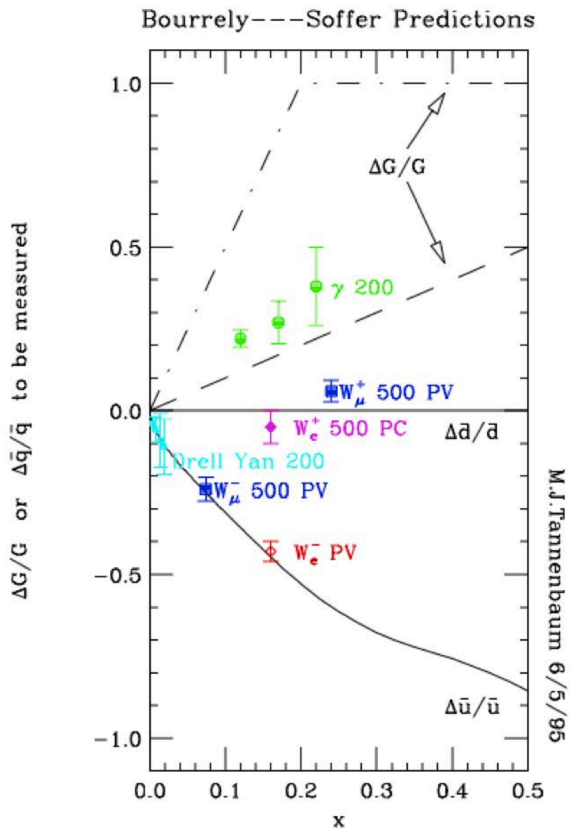
$$\langle x_1\rangle << \langle x_2\rangle: \quad A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$$

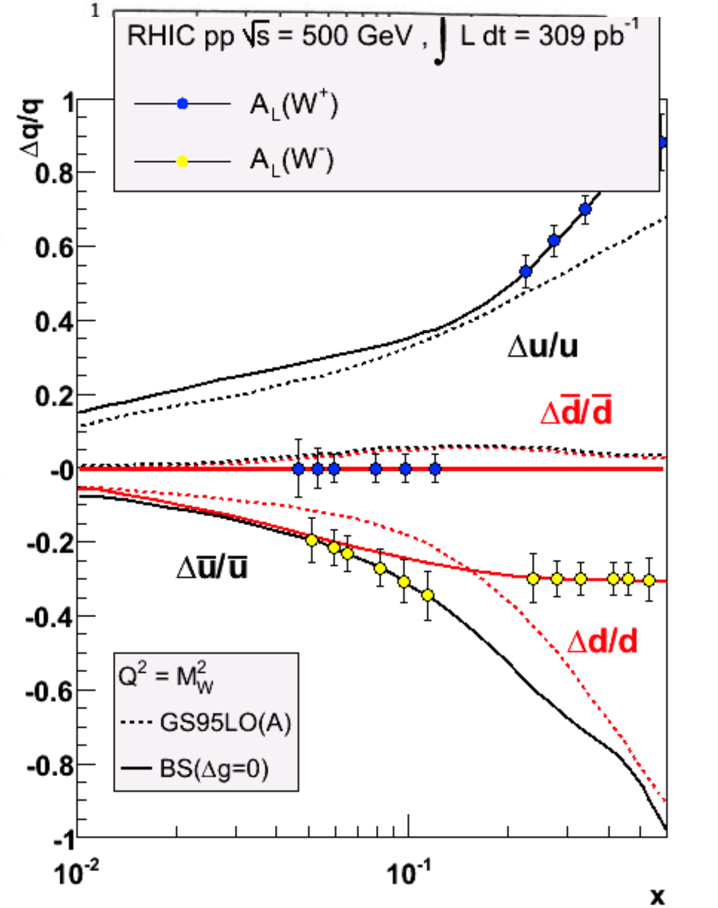
$$\langle x_1\rangle >> \langle x_2\rangle: \quad A_L^{W^+} \approx -\frac{\Delta u}{u}$$

$$\langle x_1\rangle << \langle x_2\rangle: \quad A_L^{W^+} \approx \frac{\Delta \bar{d}}{\bar{d}}$$

Results Expected with 800 pb^{-1} at 500 GeV c.1995







mid rapidity W→e+ν

forward rapidity W→ μ +ν 1.1<|y|<2.3

We thought we could calculate LO x_1 and x_2 for p+p ⇢ X+ q-qbar ⇢ W± ⇢ μ± +ν.
Works well for μ p_T but more complicated than we thought-kinematic ambiguity.

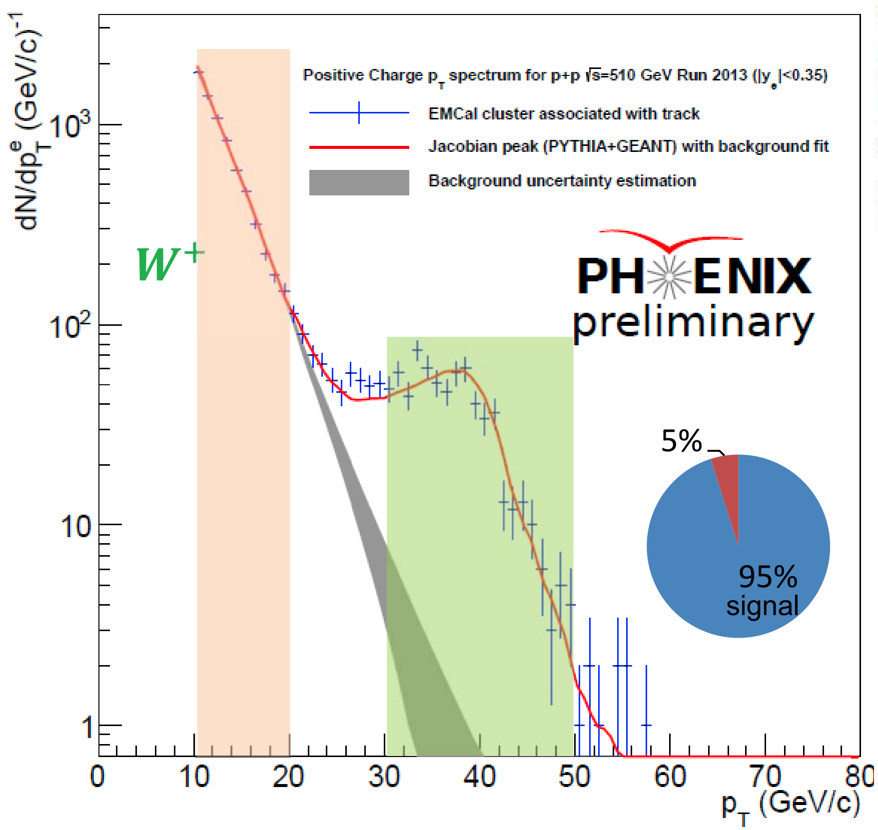
PHENIX prelim $W^{\pm} \dashrightarrow e^{\pm}+\nu$ 2013 run

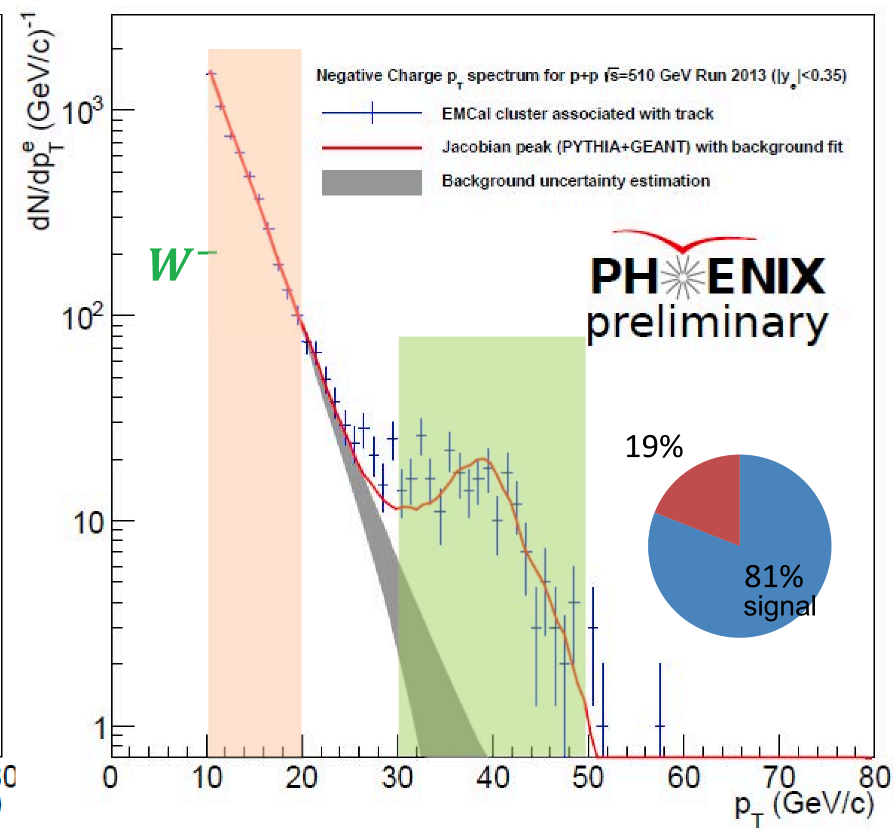
Signal region: $30 < p_T < 50$ GeV   Background region: $10 < p_T < 20$ GeV

Background estimation using two independent methods:

- Gaussian Processes for Regression (GPR)
- Modified power law $\{f(p_T) = \frac{1}{p_T^{[0]+[1]*\log(p_T)}}\}$

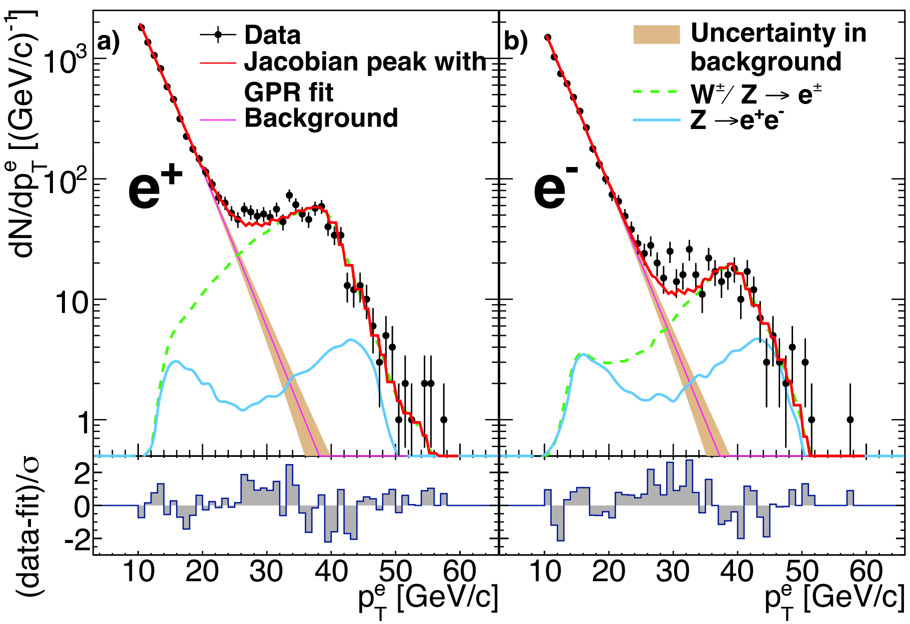
$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ fit simultaneously with simulated jacobian peak shape

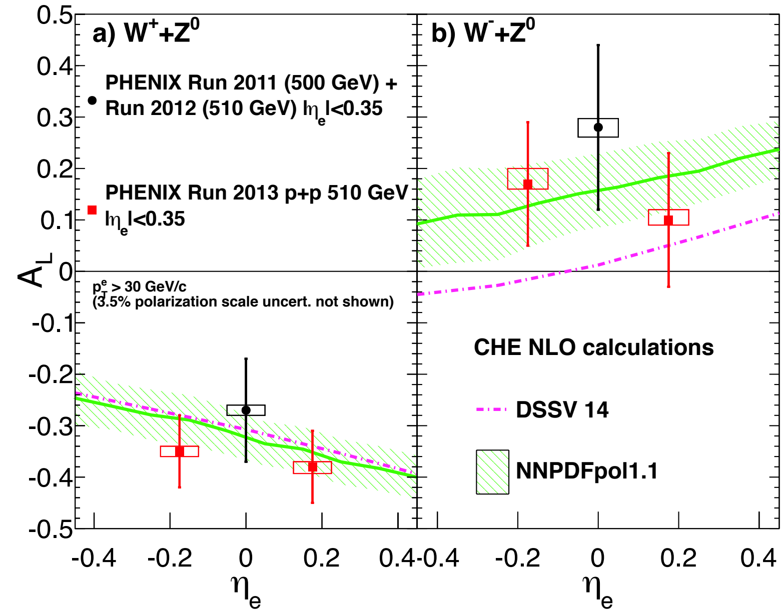




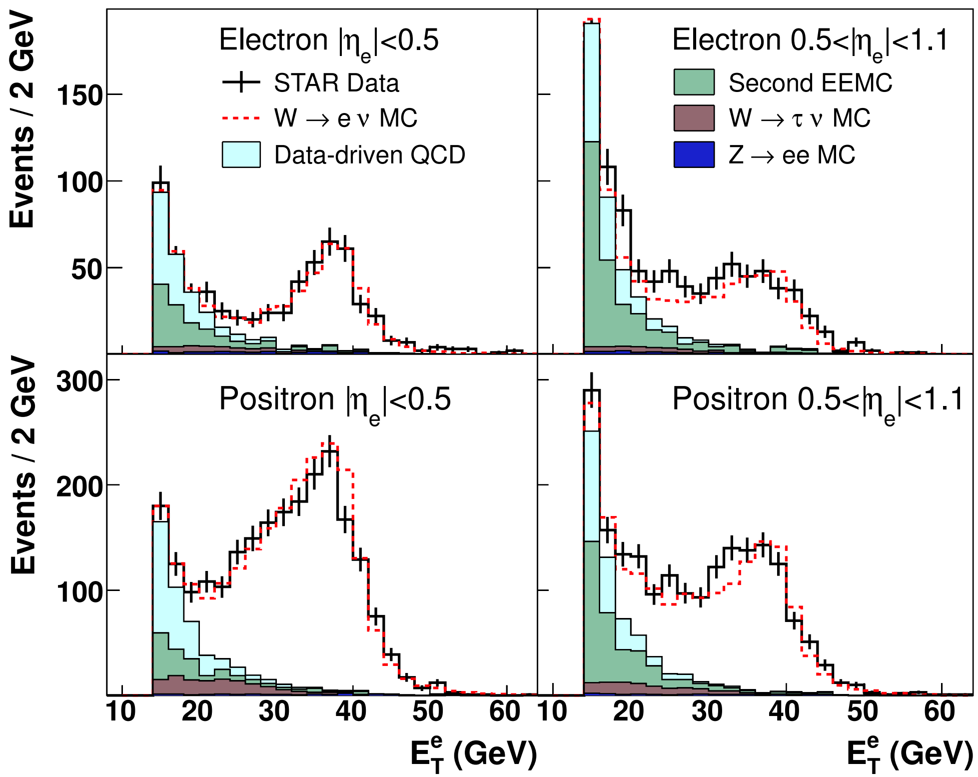
W^+ signal ~ 95% W^- signal ~ 81%

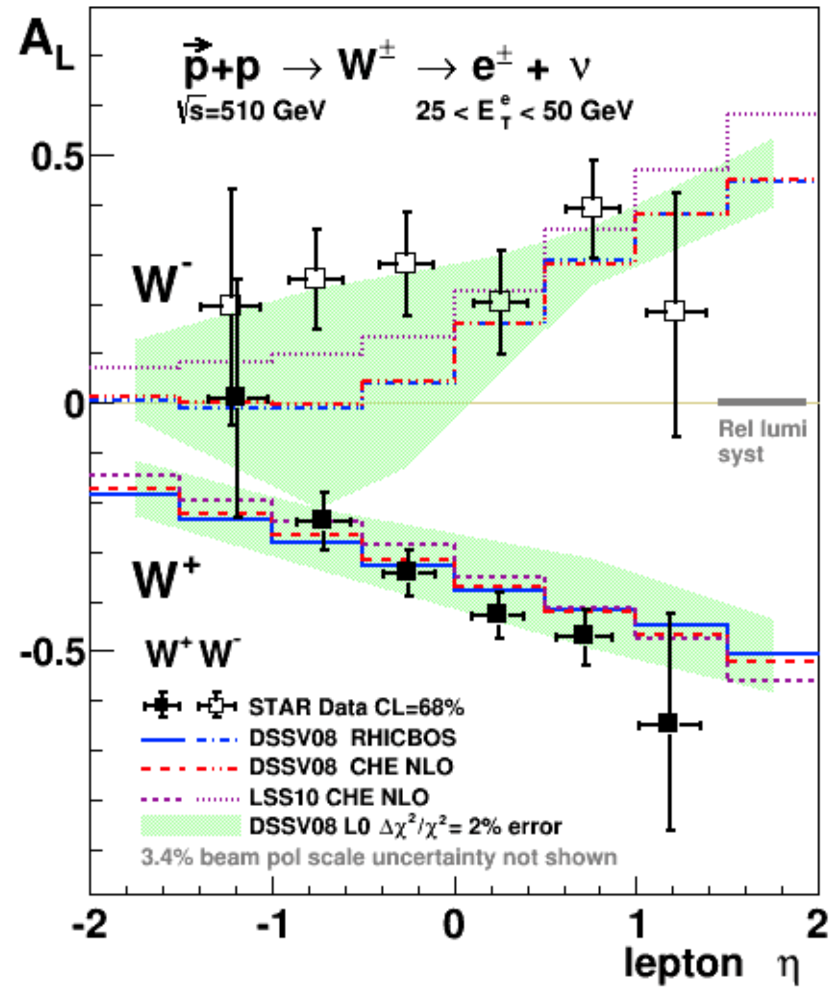
PHENIX $W^{\pm} \to e^{\pm} + \nu$ arXiv:1504.07451





STAR PRL 113(2014)072301





Neither PHENIX nor STAR quotes $\frac{\Delta\bar{u}}{\bar{u}}(x), \frac{\Delta\bar{d}}{\bar{d}}(x)$

Proton Spin Structure -- "Spin Puzzle"

- **Manohar-Jaffe sum rule:**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$$

- **PHENIX Spin Program**

Longitudinal spin program

-- Gluon polarization distribution

$$\Delta G = \int_0^1 dx \cdot \Delta g(x)$$

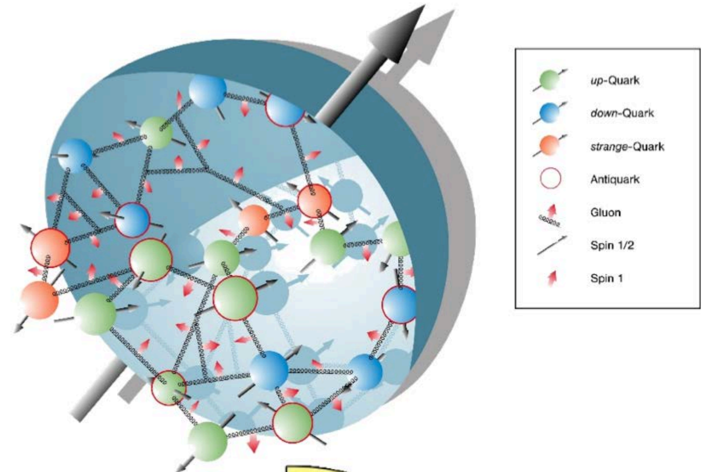
-- Anti-quark sea polarization

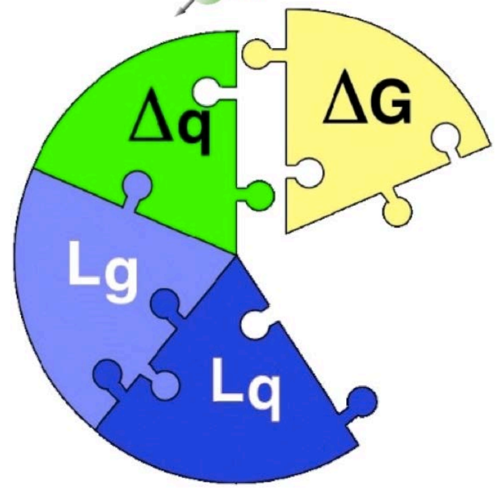
$$\mathbf{A_L(u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu_l)}$$

$$\mathbf{A_L(\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu}_l)}$$

Transverse spin program

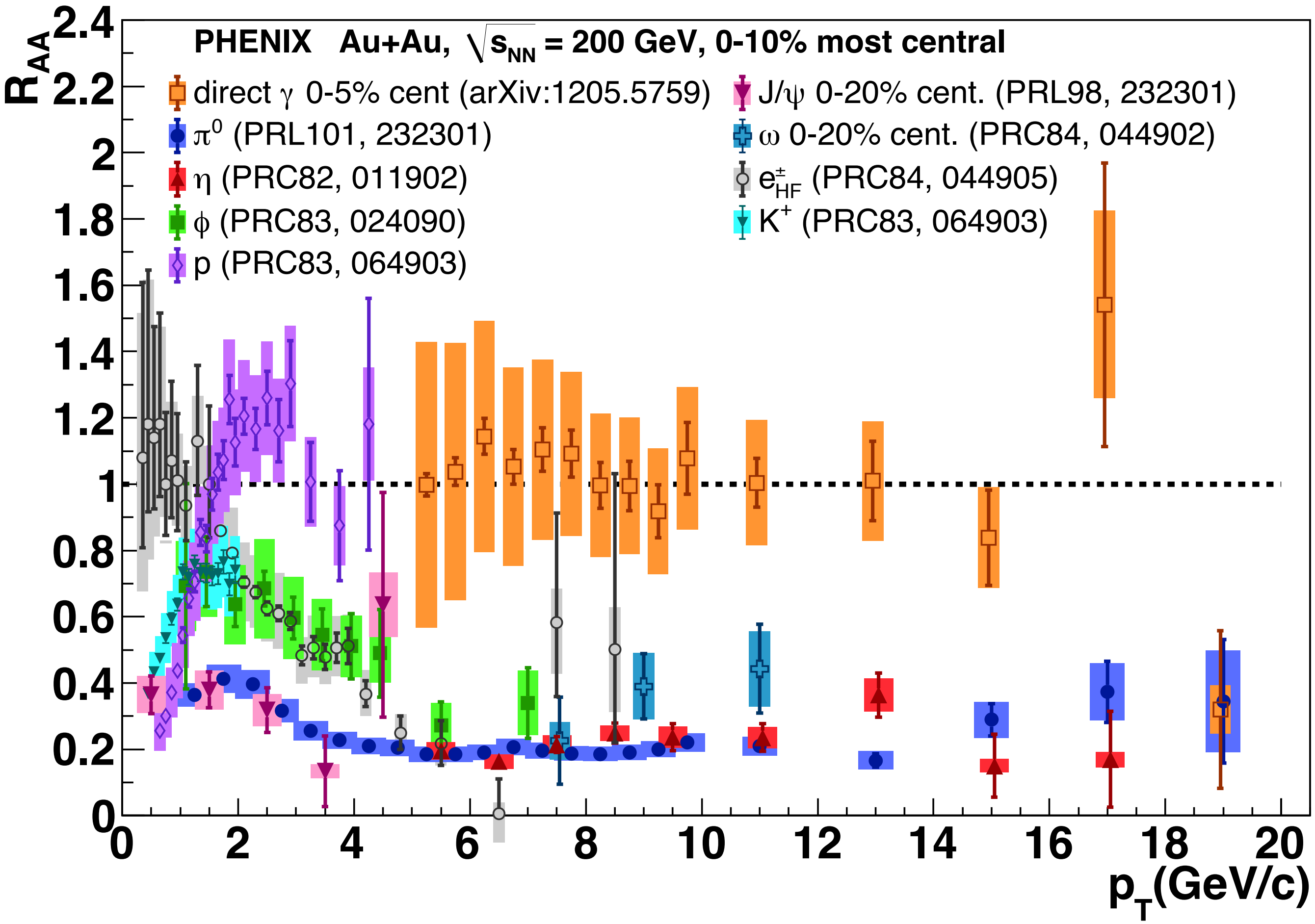
-- sensitivity to <Lz> + transversity





End

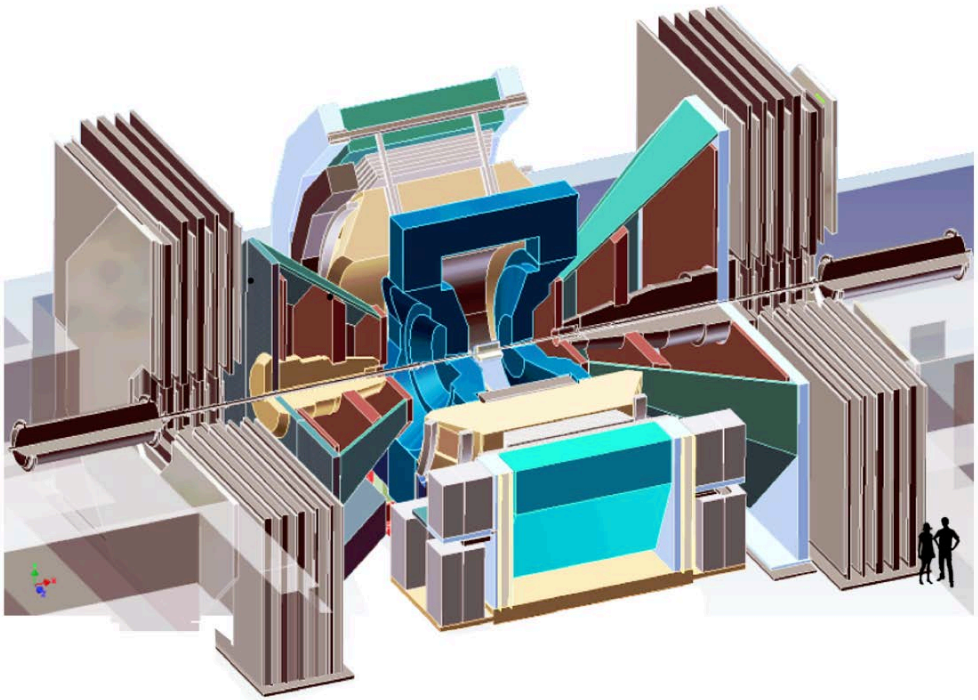
Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV 2013

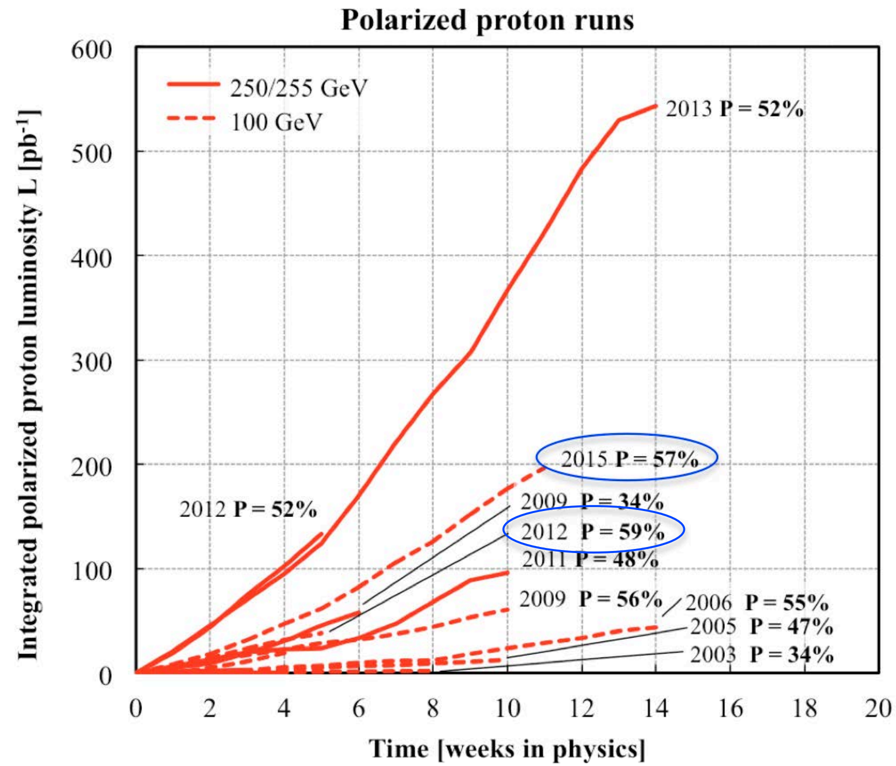


particle ID is crucial: different particles behave differently

Notable are that ALL particles are suppressed for p_T>2 GeV/c (except for direct-γ), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)

Recent PHENIX Transverse Spin Runs

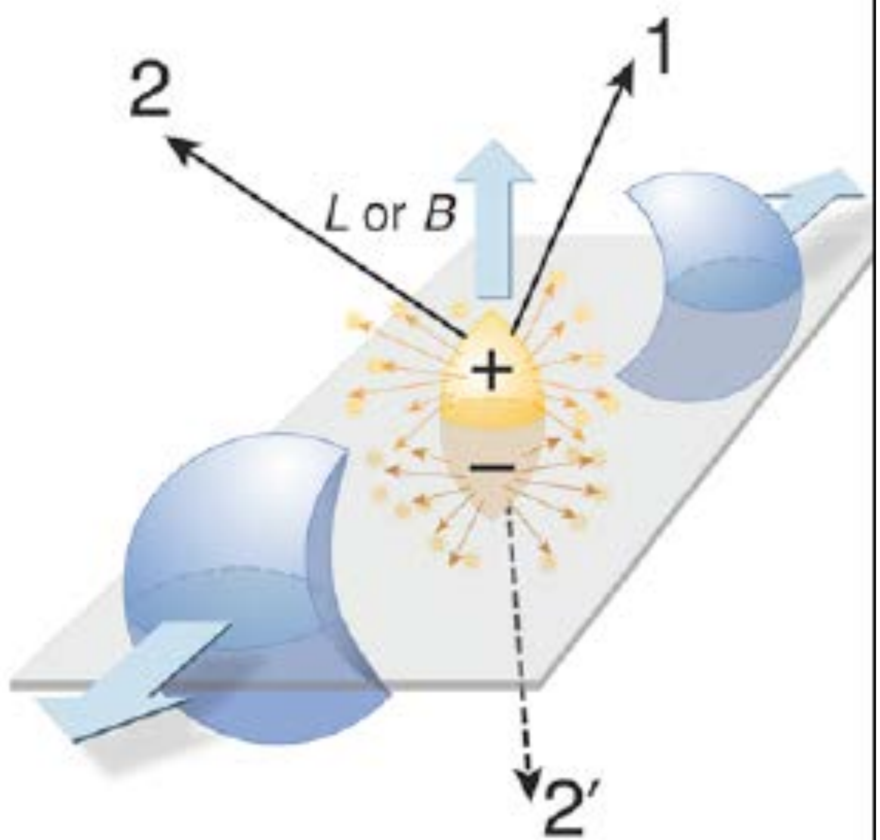




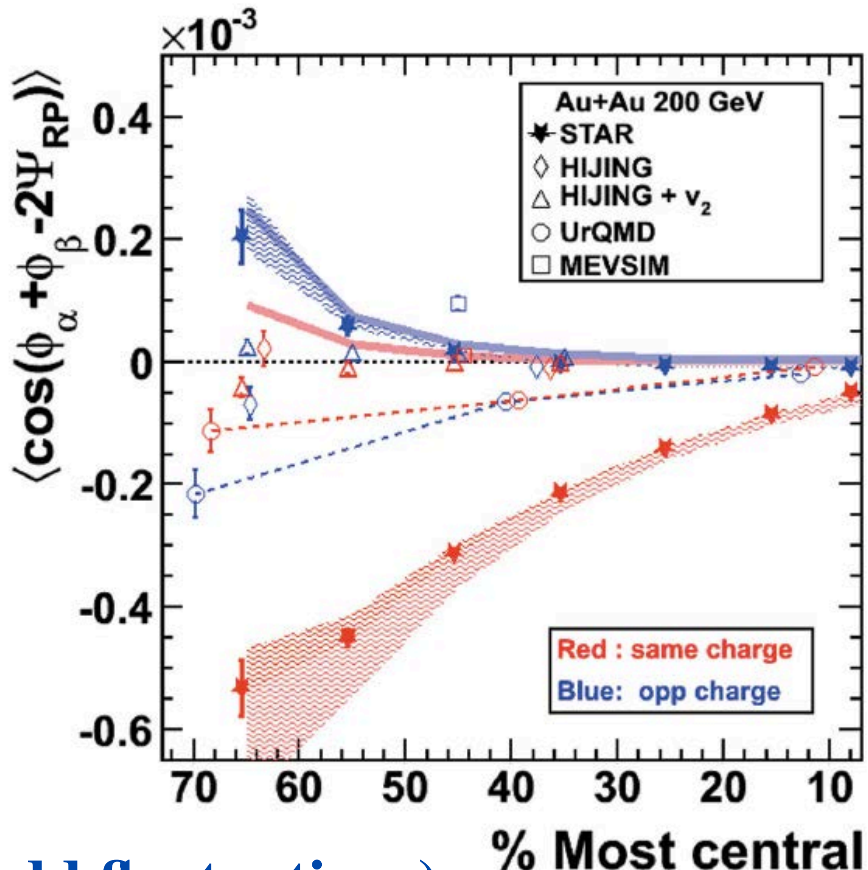
Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2015 (Run 15)	200	110 pb^{-1}	57	35 pb^{-1}
2012 (Run 12)	200	9.2 pb^{-1}	59	3.3 pb^{-1}
2008 (Run8)	200	5.2 pb^{-1}	45	1.1 pb^{-1}

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

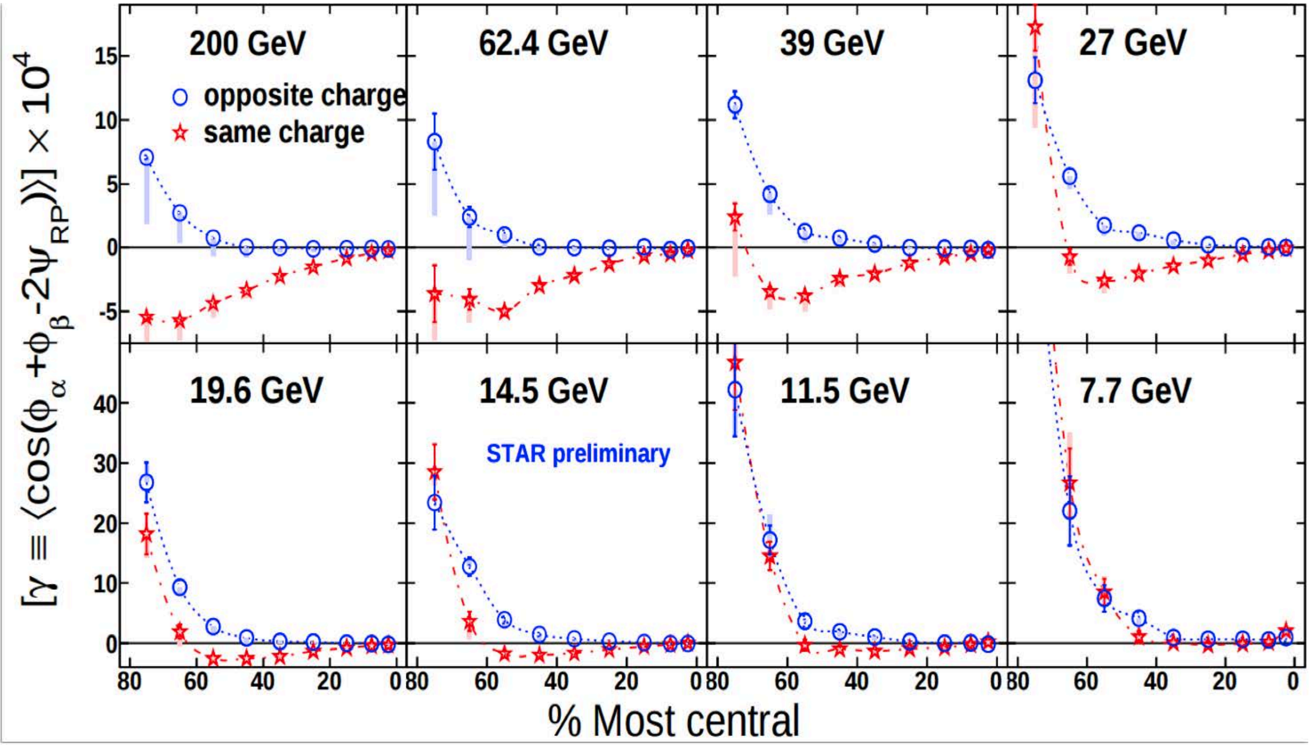


(STAR Collaboration)



NB: P-even quantity (strength of P-odd fluctuations)

CME.BES



- ▷ BES results shows charge separation starts to diminish at lower energies.

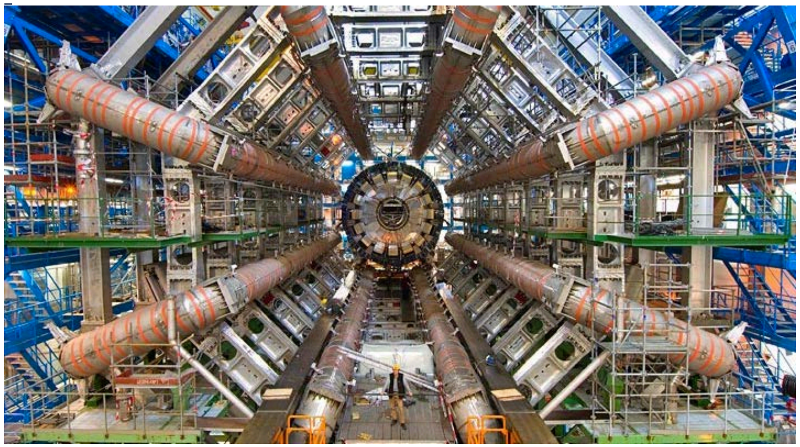
ALICE, Phys. Rev. Lett. 110 (2013)012301; STAR, Phys. Rev. Lett 113 (2014) 052302

How does one prove what it is?

U.S.-CERN Agreement Paves Way for New Era of Scientific Discovery

Department of Energy and National Science Foundation sign agreement for U.S. participation in particle physics research.

May 7, 2015



The ATLAS detector at the Large Hadron Collider, an experiment with large involvement from physicists at Brookhaven National Laboratory.

+ ENLARGE

WASHINGTON – A new agreement between the United States and the European Organization for Nuclear Research (CERN) signed today will pave the way for renewed collaboration in particle physics, promising to yield new insights into fundamental particles and the nature of matter and our universe.

The agreement, signed in a White House ceremony by the U.S. Department of Energy, U.S. National Science Foundation and CERN—the renowned European organization based in Geneva, Switzerland—will enable continued scientific discoveries in particle physics and advanced computing.

U.S. Energy Secretary Honors Brookhaven Lab Team for Building Large Hadron Collider Magnets

May 11, 2015

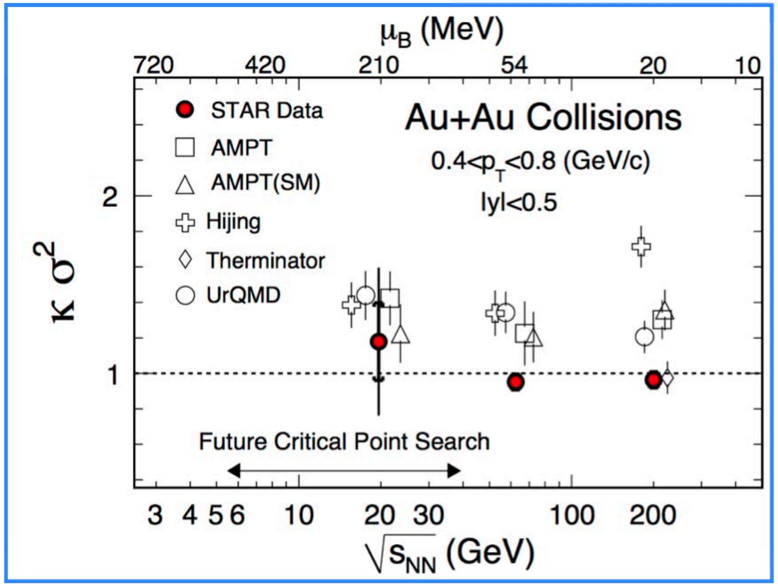
UPTON, NY — Following the much-anticipated recent restart of the Large Hadron Collider (LHC) at CERN, the European Organization for Nuclear Research, a 17-member team primarily based at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory was recognized with one of DOE's most prestigious awards for successfully completing two superconducting magnets for the 17-mile-circumference collider.

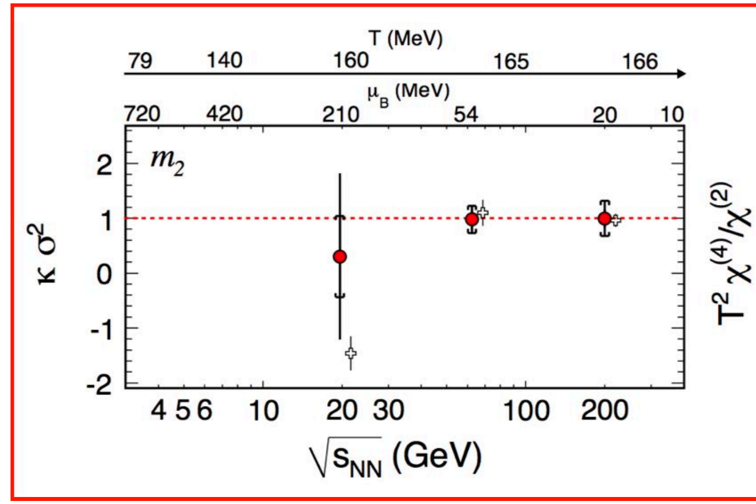
STAR Plots

Results from 2011

Theorists Plot
Science 332 (2011) 1525

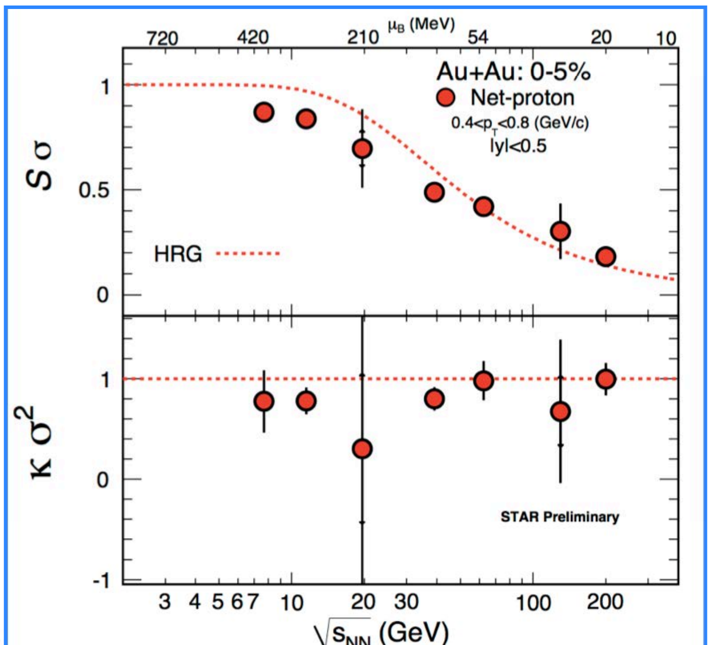
PRL105(2010) 022302





Lattice shows huge deviation of $T^2\ \chi^{(4)}/\ \chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa\sigma^2$ suggests not; but with big errors. Need more data. Above plot is different from PRL105

JPG38(2011) 124054



Is JPG38 plot Evidence for phase transition from resonance gas to QGP at T_c=175 MeV ???!!!!!!!

Bayes Rule and Conditional Probability

Bayes rule is one of the most powerful yet seemingly simple rules in probability. Let A and B be two possible outcomes with probabilities $P(A)$ and $P(B)$. Bayes Rule defines the conditional probabilities, where $P(A.and.B)$ is the probability for both outcomes to occur:

$$\boxed{P(A.and.B) = P(A) \times P(B)|_A = P(B) \times P(A)|_B} \qquad .$$

The apriori or prior probabilities $P(A)$ and $P(B)$ are very different from the conditional probabilities $P(A)|_B$, the conditional probability of A given that B has occurred, and $P(B)|_A$, the conditional probability of B given that A has occurred. However the conditional probabilities are simply related to each other:

$$\boxed{P(A)|_B = \frac{P(A) \times P(B)|_A}{P(B)} = P(B)|_A \times \frac{P(A)}{P(B)}} .$$

An interesting example of the application of Bayes rule is given in my book.

Also don't forget that if A and B are statistically independent, then

$$\begin{aligned} P(A)|_B &= P(A) \\ P(B)|_A &= P(B) \\ \text{so that} \qquad P(A.and.B) &= P(A) \times P(B) \qquad . \end{aligned}$$