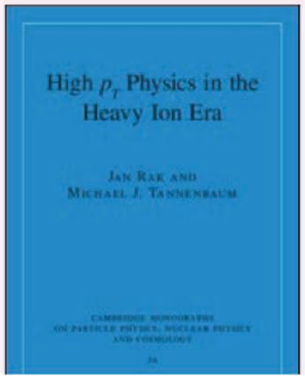
Highlights from BNL and RHIC 2014

For previous years and more details see:

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

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



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

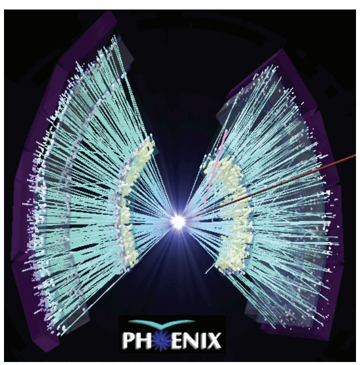
Hardback

Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology(No. 34)

ISBN:9780521190299

396pages
202 b/w illus.
Dimensions: 247 x 174 mm
Weight: 0.87kg
Availablity: In Stock

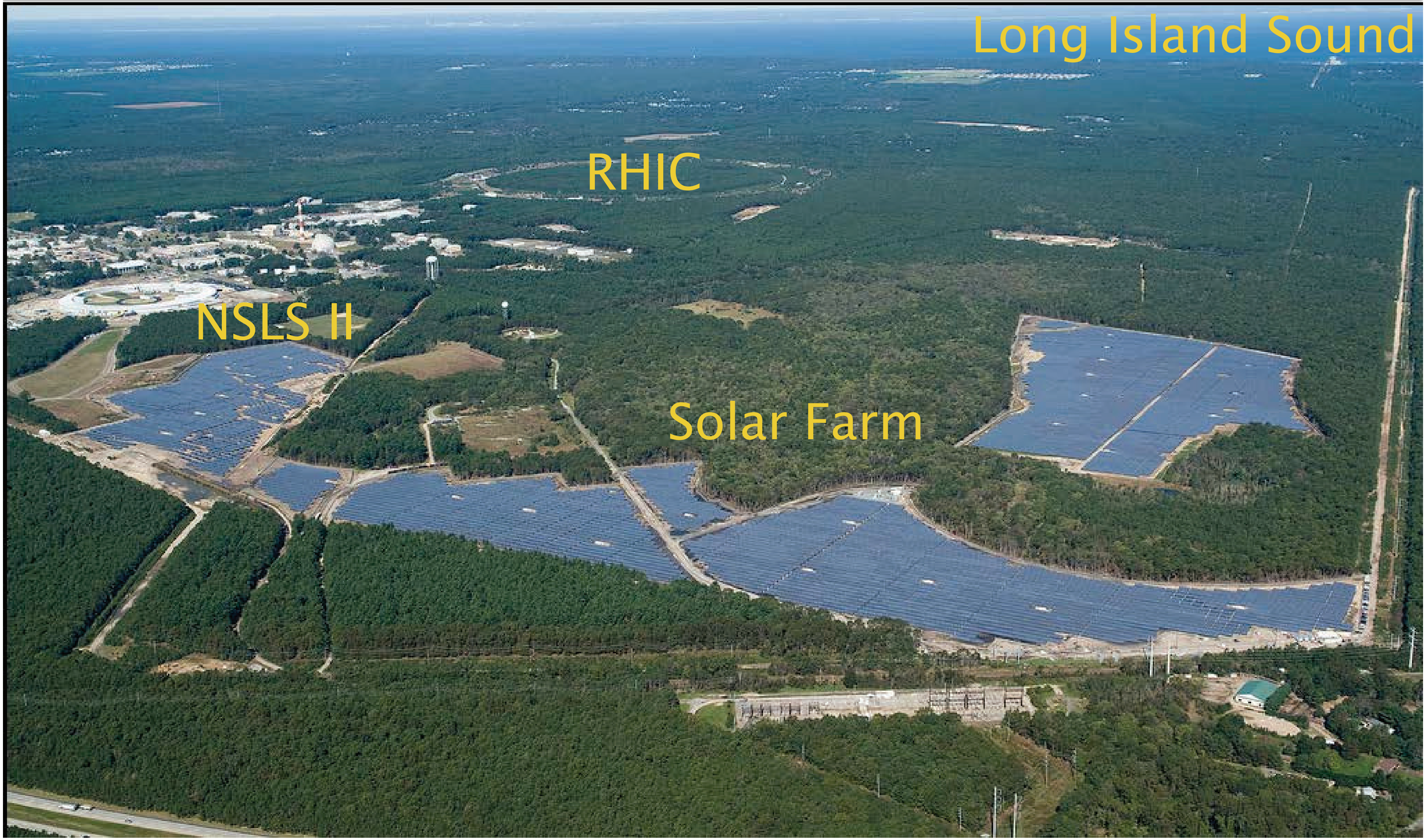
M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



International School of Subnuclear Physics,
"Status of Theoretical Understanding and of
Experimental Power for LHC Physics and Beyond"
51st Course-Erice, Sicily, Italy June 24- July 3, 2014

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)



Major Research Facilities

National Synchrotron Light Source

National Synchrotron Light Source

- Industrial and academic users
- Researching battery storage, Alzheimer's disease, breast cancer, HIV/AIDS, environmental cleanup technology, and more

National Synchrotron Light Source II

National Synchrotron Light Source II

- Soon to be world's most advanced x-ray source
- $960 million project - hundreds of local jobs
- Will deliver research advancements in energy, nanotechnology, medicine and other fields

Center for Functional Nanomaterials

Center for Functional Nanomaterials

- Exploring energy science at the nanoscale
- Building new materials atom-by-atom to achieve desired properties and functions

Major Research Facilities

Relativistic Heavy Ion Collider (RHIC)

RHIC

- 2.4 mile circumference
- Studying the origins of the universe through particle collisions revealing make up of matter
- Discovery of the 'perfect liquid'

New York Blue Supercomputer

New York Center for Computational Science

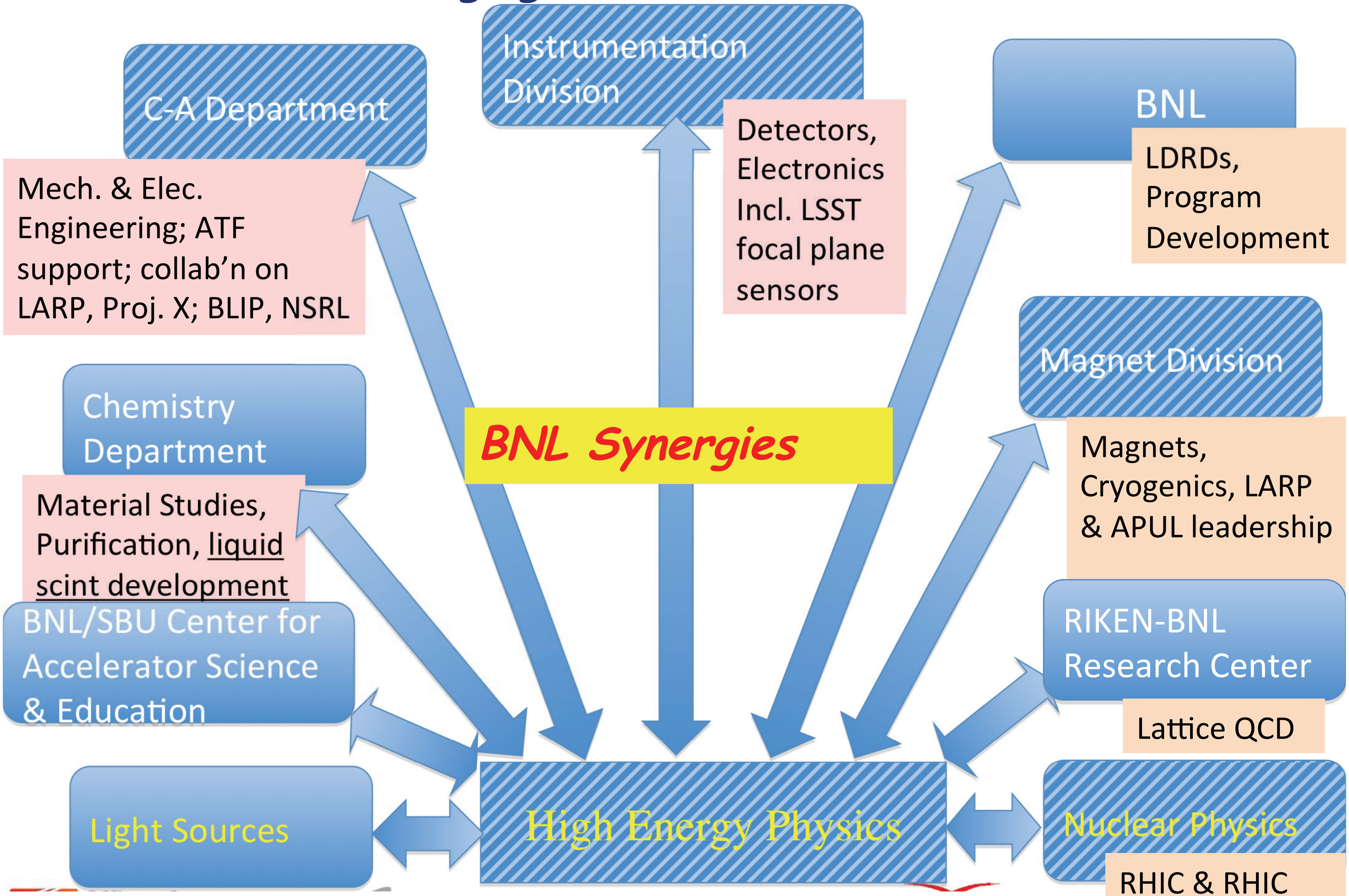
- Partnership between BNL & Stony Brook University
- Two IBM supercomputers
- Supports broad range of research

Long Island Solar Farm

Long Island Solar Farm

- Partnership between BNL, LIPA and BPSolar
- 32MW Peak to power 4500 L.I. homes
- Unique opportunity to study renewables in the Northeast and test new Grid technologies

Broad Leveraging for Overall HEP/NP Efforts



Cross-hatched boxes reside in Nuclear and Particle Physics Directorate

Fiscal year 2014 began on October 1, 2013 with the U.S. Federal Government shut down due to lack of a budget

From: Rob Pisarski <rob.pisarski@gmail.com>
Subject: Physics seminars for October and November: cancelled
Date: October 4, 2013 10:38:03 AM EDT
To: Marcy Chaloupka <marcy@bnl.gov>, Pam Esposito <pesposit@bnl.gov>, "Colleen Michael, RBRC" <cmichael@bnl.gov>, Sam Aronson <samaronson@bnl.gov>, "Mabuchi, Kazunori" <kmabuchi@bnl.gov>, bern@physics.ucla.edu, Harald Fritzsch <fritzsch@mppmu.mpg.de>, Tannenbaum Michael <mjt@bnl.gov>, Gerald Guralnik <gerry@het.brown.edu>, mrigol@phys.psu.edu, capasso <capasso@bnl.gov>, Abhay Deshpande <abhay.deshpande@stonybrook.edu>, akiba@bnl.gov, izubuchi taku <izubuchi@quark.phy.bnl.gov>

Dear Profs. Fritzsch, Guralnik, Bern, and Rigol:

Because of [redacted] I have to disinvite you to the colloquia previously scheduled.

I apologize for any inconvenience. As far as I know, however, you have not spent any funds on your travel to BNL.

I have no idea when things will change.

[redacted]

Yours, Rob.

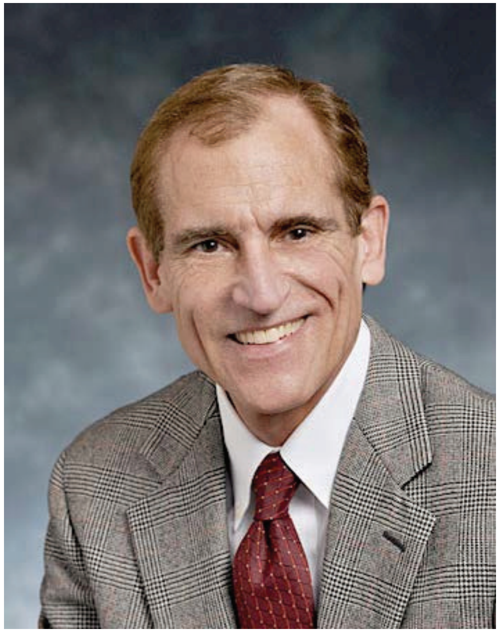
After the budget was passed and the government reopened on Oct. 17, 2013 things went surprisingly well for the rest of FY2014 at RHIC

Bob Tribble from the eponymous reports now works at BNL

Robert Tribble Named Brookhaven Lab's Deputy Director for Science and Technology

February 18, 2014

UPTON, NY – Robert Tribble, a widely respected physicist who has played a key role in charting the future direction of nuclear science in the U.S., has been named Deputy Director for Science & Technology at the U.S. Department of Energy's Brookhaven National Laboratory, effective February 24, 2014. Tribble is currently a Distinguished Professor of Physics & Astronomy at Texas A&M University (TAMU) and Director of the Cyclotron Institute and the Nuclear Solutions Institute there.



Robert Tribble

+ ENLARGE

An experimental physicist whose work spans a broad range of topics, Tribble has conducted groundbreaking research exploring fundamental symmetries, the Standard Model, nuclear structure and reactions, nuclear astrophysics, and proton spin. He is widely credited with developing new tools and techniques that have advanced the field, and has also served as a member or chair of numerous long-range planning committees for the American Physical Society (APS) and the Nuclear Science Advisory Committee (NSAC, an advisory committee for the Department of Energy and National Science Foundation).

Tribble ran DOE panels in 2005 and 2012-13 on recommendations for the future of U.S. nuclear physics in a constrained budget environment, i.e. The money in the Long Range Plans of 2002 and 2007 didn't materialize. Recommendation in both cases was that a small increment (~2% real increase per year above present budget) would save RHIC, JLAB, FRIB, although Tribble 1 delayed RIA which was then descoped to FRIB.

A new NP Long Range Plan exercise has begun

U.S. Department of Energy
and the
National Science Foundation

April 23, 2014

Dr. Donald Geesaman
Chair
DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue
Argonne, Illinois 60439

Deadline October 2014

Dear Dr. Geesaman:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade. This exercise should exclude the DOE Isotope Program managed by the DOE Office of Science's Office of Nuclear Physics, for which a dedicated strategic planning exercise will be convened.

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national

DOE RFP for M&O of BNL

Department of Energy
Office of Science

Brookhaven National Laboratory

Executive Summary

Solicitation No. DE-SOL-0006266

March 20, 2014

TO: Prospective Offerors

SUBJECT: REQUEST FOR PROPOSALS (RFP) NO. DE-SOL-0006266 FOR THE SELECTION OF A MANAGEMENT AND OPERATING CONTRACTOR FOR THE BROOKHAVEN NATIONAL LABORATORY (BNL)

This letter is a summary of the salient elements of the acquisition, but is not an integral part of the attached RFP. Should there be any conflict between this Executive Summary Letter and the RFP, the data and information in the RFP shall prevail.

The Department of Energy (DOE) is releasing the RFP for award of a contract for the management and operation of BNL. DOE is seeking proposals from offerors interested in competing for this contract.

Specific details of the contract performance requirements are described in the RFP. The RFP can be found on the BNL Competition website at URL http://bnlcompetition.science.energy.gov/. All questions must be directed to BNLcompetition@ch.doe.gov or as specified in the RFP. Responses to questions and any amendments to the RFP will be posted on the BNL Competition website.

Deadline for proposals June 19, 2014 15:00

Proposal Due Date. Proposals, and any modifications or revisions, are due on June 19, 2014, by 3:00 p.m., Eastern Standard Time. (Refer to Section L.15 entitled "Date, Time, and Place Offers/Proposals are Due".) Proposals are to be submitted in writing and on CD-ROM. Instructions for submission of proposals are located in Section L. Late proposals, modifications, and withdrawals will be treated in accordance with Section L.16 entitled "FAR 52.215-1 – Instructions to Offerors – Competitive Acquisition".

Oral Presentations. All Offerors are required to make oral presentations to the SEB approximately three weeks after receipt of proposals. The SEB will schedule the oral presentations via lottery and will notify each Offeror, within ten (10) working days after the date for receipt of proposals, of the date and time of its oral presentation. The oral presentation will be held at a location in the vicinity of the Brookhaven National Laboratory, Upton, NY. The Government reserves the right to reschedule the oral presentation at its discretion, and the Government shall not consider requests to reschedule the oral presentation except in extenuating circumstances. Evaluation of proposals will be based on both the written information and the oral presentation.

U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

- **June 23, 2014**
  - The home page has been updated to reflect the expiration of the submission date. No additional proposals will be considered.

This means that they got more than one proposal

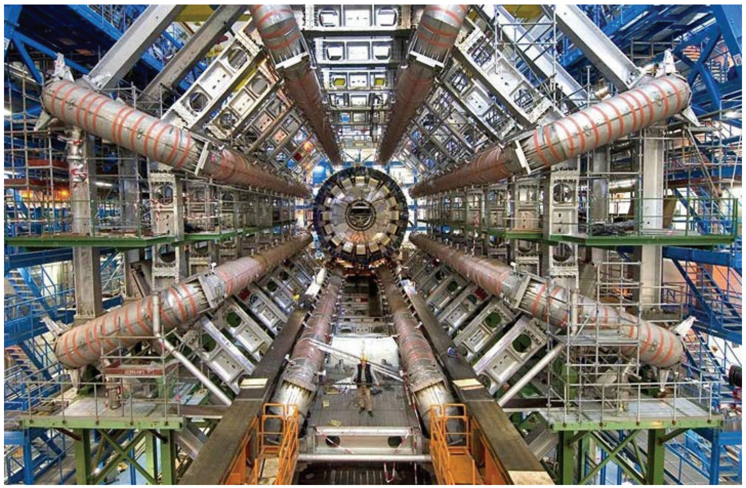
Oral presentations may be going on right now!

P5 Panel Reports-IMHO recommends U.S move to 4th place in HEP-hijacked by astrophysics/cosmology-May 21,2104

MJT opinion only; not BNL

http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/DRAFT2_P5_ExecutiveSummary_052114.pdf

Particle PhysicsProject Prioritization Panel (P5) Report to the High Energy Physics Advisory Panel (HEPAP)



The report emphasizes the important opportunities for the field, which include:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

The report also identifies the need to support enabling technologies in accelerator, detector, and computing sciences.

- Redirect muon collider R&D and consult with international partners on the early termination of the MICE muon cooling R&D facility.
- LBNE→ LBNFacility to start in ~2029!!

The recommendations for the unconstrained budget Scenario focus on three additional high-priority activities:

- Develop a greatly expanded accelerator R&D program that would emphasize the ability to build very high-energy accelerators beyond the HL-LHC and ILC at dramatically lower cost.
- Play a world-leading role in the ILC experimental program and provide critical expertise and components to the accelerator, should this exciting scientific opportunity be realized in Japan.
- Host a large water Cherenkov neutrino detector to complement the LBNF large liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam at Fermilab.

NSLS-II Stores Beam

By Mona S. Rowe | April 16, 2014 PRINT

NSLS-II Storage Ring Begins Commissioning

Stored Beam Achieved on April 5

+ ENLARGE

Quick kudos came in from around the world at the news of first stored beam at the National Synchrotron Light Source II (NSLS-II) on April 5, 2014. NSLS-II is under construction at Brookhaven National Laboratory.

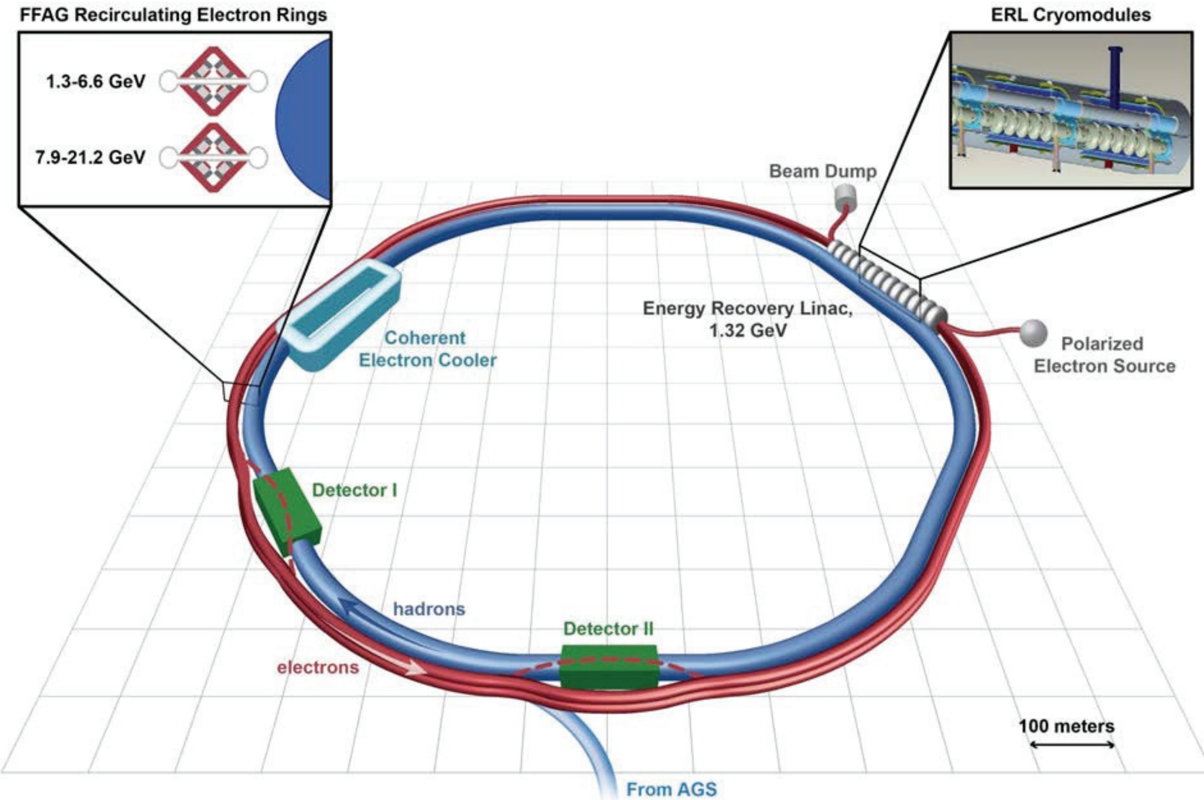
PHENIX Data and Measurements to the present

RHIC Run	Year	Species	Energy	Ldt
Run-1	2000	Au+Au	130 GeV	1 μb-1
Run-2	2001-2	Au+Au	200 GeV	24 μb-1
Run-2		Au+Au	19 GeV	0.4 μb-1
		p+p	200 Gev	150 nb-1
Run-3	2002/3	d+Au	200 GeV	2.74 nb-1
		p+p	200 GeV	0.35 nb-1
Run-4	2003/4	Au+Au	200 GeV	241 μb-1
		Au+Au	62.4 GeV	9 μb-1
Run-5	2005	Cu+Cu	200 GeV	3 nb-1
		Cu+Cu	62.4 GeV	0.19 nb-1
		Cu+Cu	22.4 GeV	2.7 μb-1
Run-6	2006	p+p	200 GeV	10.7 pb-1
		p+p	62.4 GeV	100 nb-1
Run-7	2007	Au+Au	200 GeV	813 μb-1
Run-8	2007/2008	d+Au	200 GeV	80 nb-1
		p+p	200 GeV	5.2 pb-1
		Au+Au	9.2 GeV	
Run-9	2009	p+p	200 GeV	16 pb-1
		p+p	500 GeV	14 pb-1
Run-10	2010	Au+Au	200 GeV	1.3 nb-1
		Au+Au	62.4 GeV	100 μb-1
		Au+Au	39 GeV	40 μb-1
		Au+Au	7.7 GeV	260 mb-1
Run-11	2011	p+p	500 GeV	27 pb-1
		Au+Au	200 GeV	915 μb-1
		Au+Au	27 GeV	5.2 μb-1
		Au+Au	19.6 GeV	13.7 M events
Run-12	2012	p+p	200 GeV	9.2 pb-1
		p+p	510 GeV	30 pb-1
		U+U	193 GeV	171 μb-1
		Cu+Au	200 GeV	4.96 nb-1
Run-13	2013	p+p	510 GeV	156 pb-1
Run-14	2014	Au+Au	15 GeV	44.2 μb-1
		Au+Au	200 GeV	2.56 nb-1

RHIC run Schedule 2014-2024: the future

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

eRHIC: Highly Innovative and Cost-Effective Design



- 80% polarized e
  - E = 6.6 - 21.2 GeV
- 70% polarized protons
  - E = 25 - 275 GeV
- Ions (d … U)
  - 10 - 110 GeV/u
- $\sqrt{s}$ = 30 – 145 GeV
- L ≈ 1-3×10^{33} cm^{-2} s^{-1}

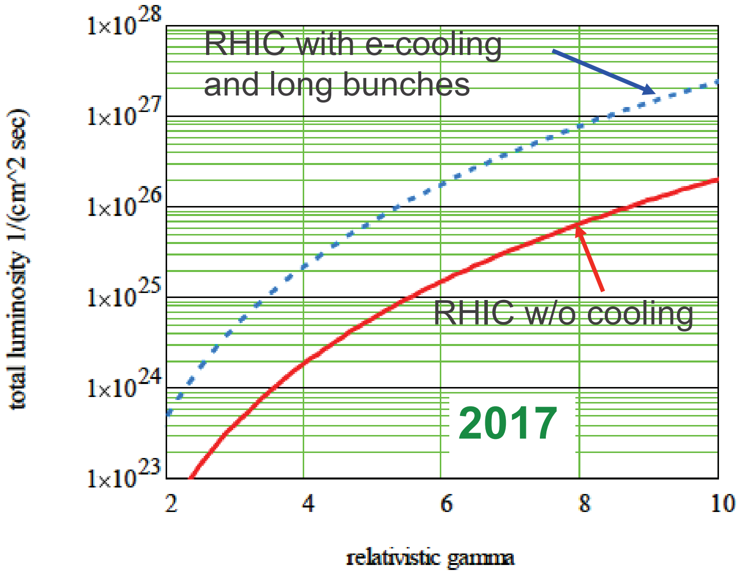
- Full use of existing RHIC complex including tunnel & cryo
- 1.32 GeV Energy Recovery Linac with 99.5% recovery efficiency
- Novel FFAG lattice allows 16 beam re-circulations using only two beam transport rings
- Permanent magnet technology is used for the FFAG beamline
- Initial cost estimate: FY14$: 750M (not including detectors)

Planned RHIC Upgrades

Machine upgrade:

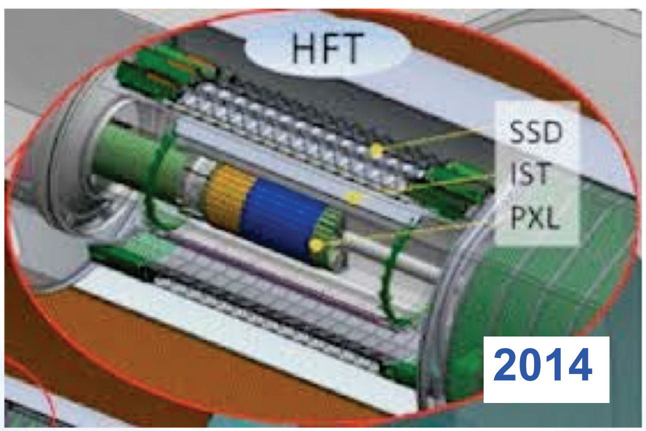
Bunched beam electron cooling for low-E beams

~10x luminosity

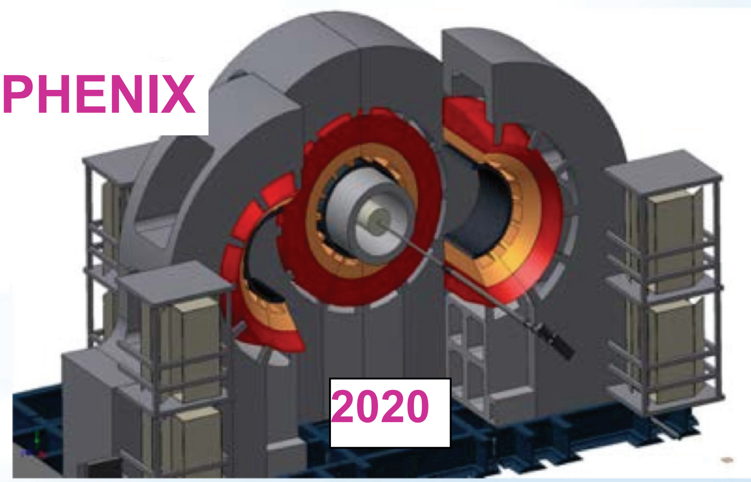


Detector upgrades:

- STAR HFT
- PHENIX MPC-EX
- STAR TPC pad rows
- sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC



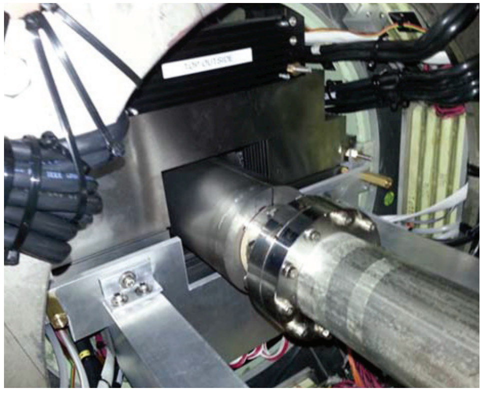
STAR Heavy Flavor Tracker



PHENIX Upgrades-for 2015 & beyond

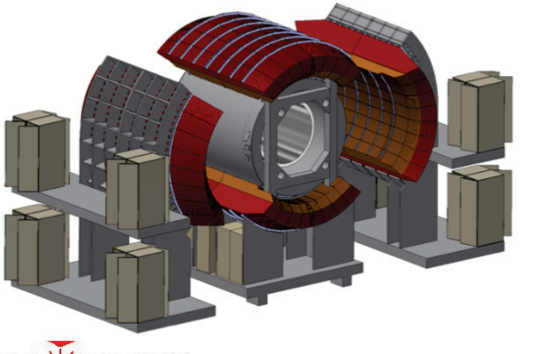
Muon Piston Calorimeter – Extension (MPC-EX)

- All sensors in production at ETRI in Korea
- Micromodule production underway
- All tungsten absorber plates at BNL
- MPC-EX on schedule for installation in PHENIX during the summer of 2014
- Purpose is forward spin asymmetry in $\vec{p} + p, A$

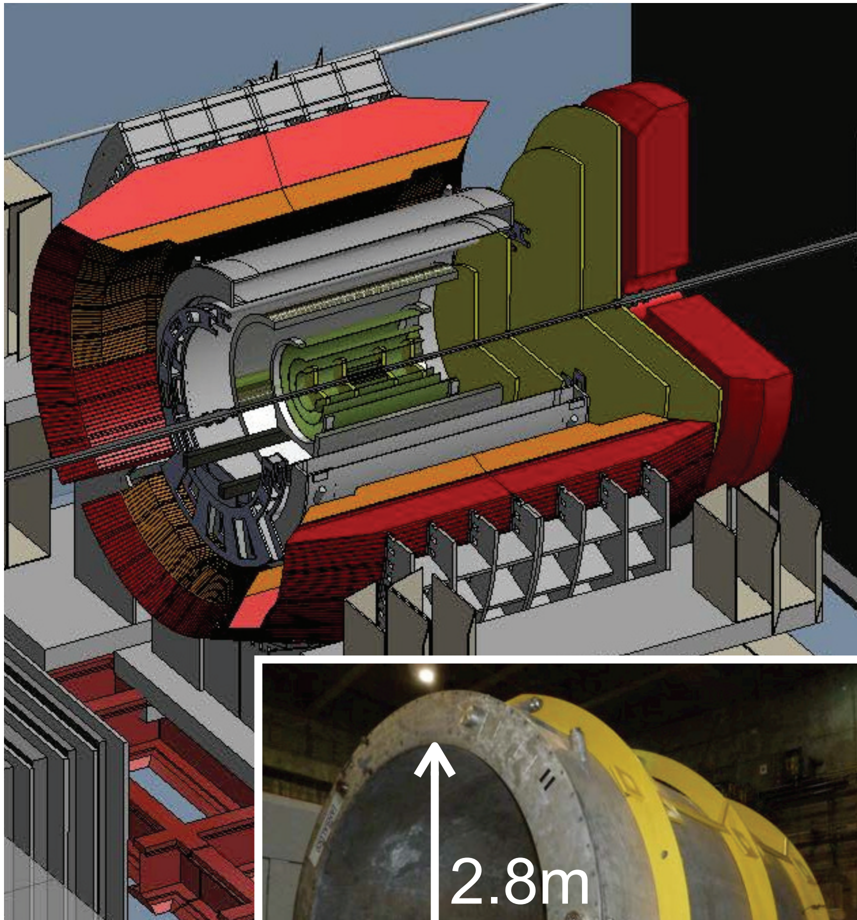


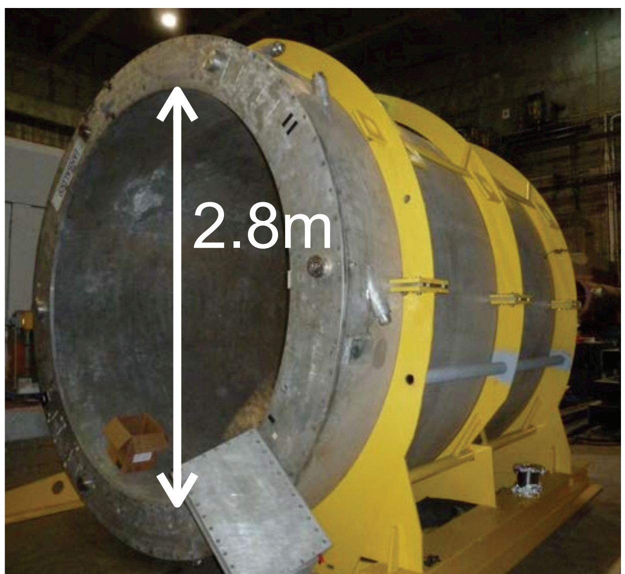
sPHENIX

- Plans underway for moving the BaBar solenoid to BNL and setting up a magnet test station on the AGS floor
- sPHENIX science review scheduled for the Jun 30-Jul 2
- Good progress on engineering design

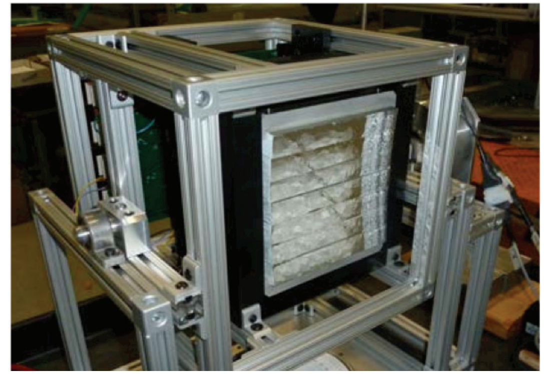


sPHENIX: Technology and Design

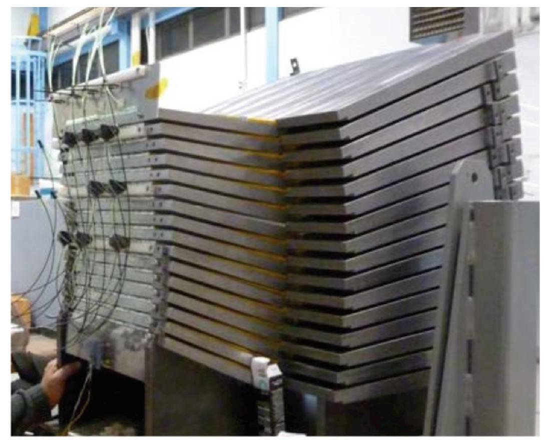




Recently acquired BaBar solenoid – shipping this summer to BNL



Prototype tungsten/scintillator EMCal with SiPMs and fully digital readout electronics



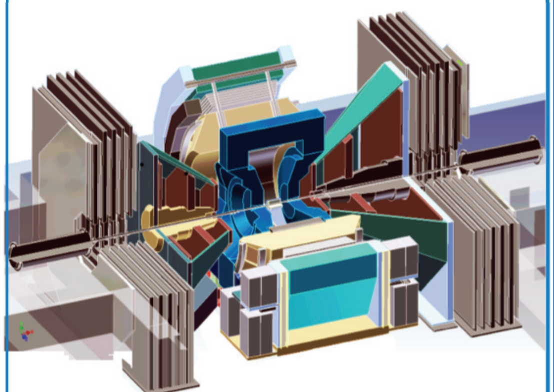
Prototype of steel/scintillator HCal with novel geometry – same RO electronics as EMCal

Evolution PHENIX->f/sPHENIX->eIC detector

Documented: http://www.phenix.bnl.gov/plans.html

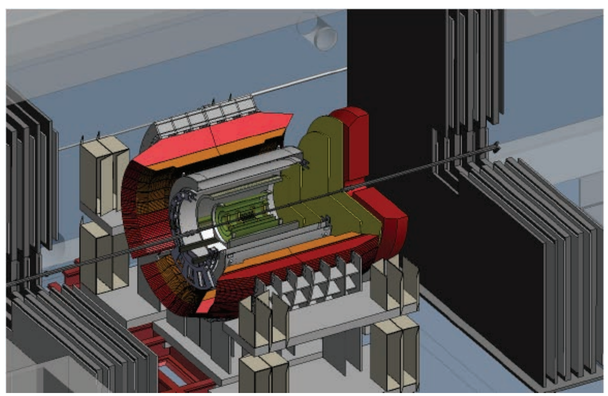
Current PHENIX

- Current PHENIX as discussed in many previous talks
- 14y+ work
  100+M$ investment
- 130+ published papers to date
- Last run 2016



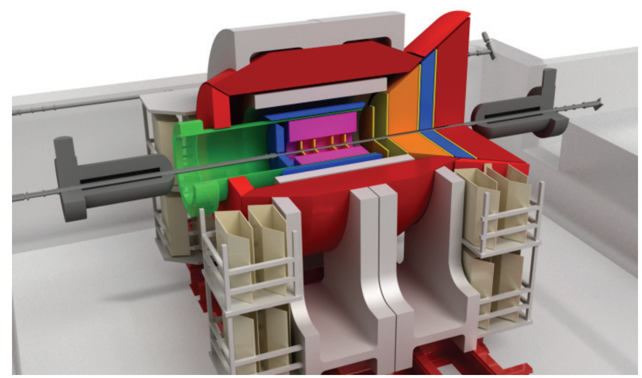
*f/s*PHENIX

- Comprehensive central upgrade based on BaBar magnet
- Detailed study of QGP using jets and heavy quarks at RHIC energies
- fsPHENIX : forward tracking, Hcal and muon ID coverage
- Key tests of theoretical frameworks for transverse spin



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- Open for new collaboration/ new ideas



~2000 | 2017→2020 | ~2025 | Time

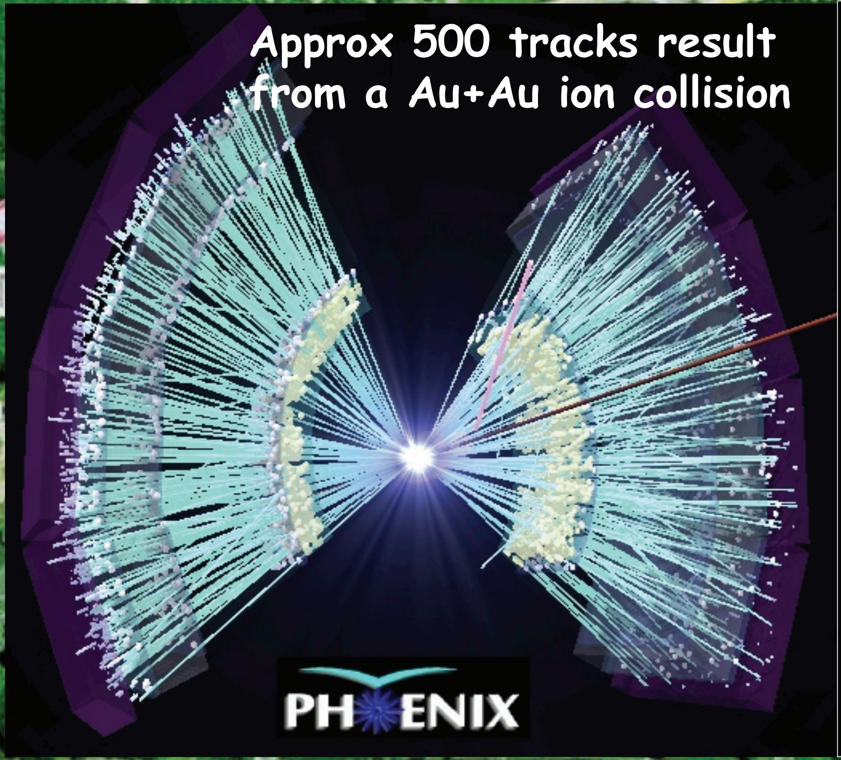
RHIC: A+A, spin-polarized p+p, spin-polarized p+A

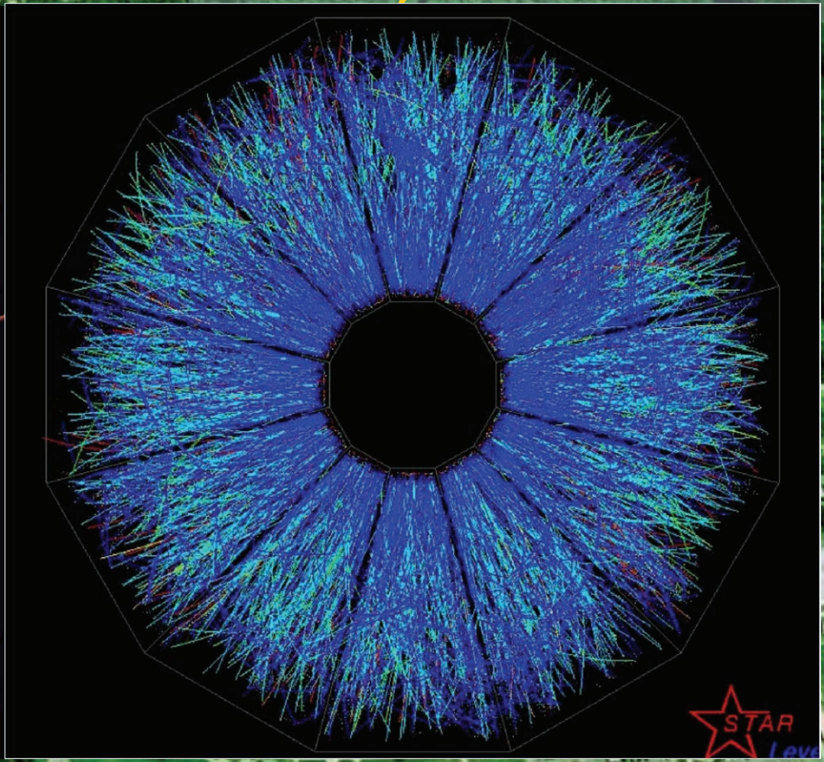
eRHIC: e+p, e+A

Back to the Present PHENIX and STAR detectors for Run 14

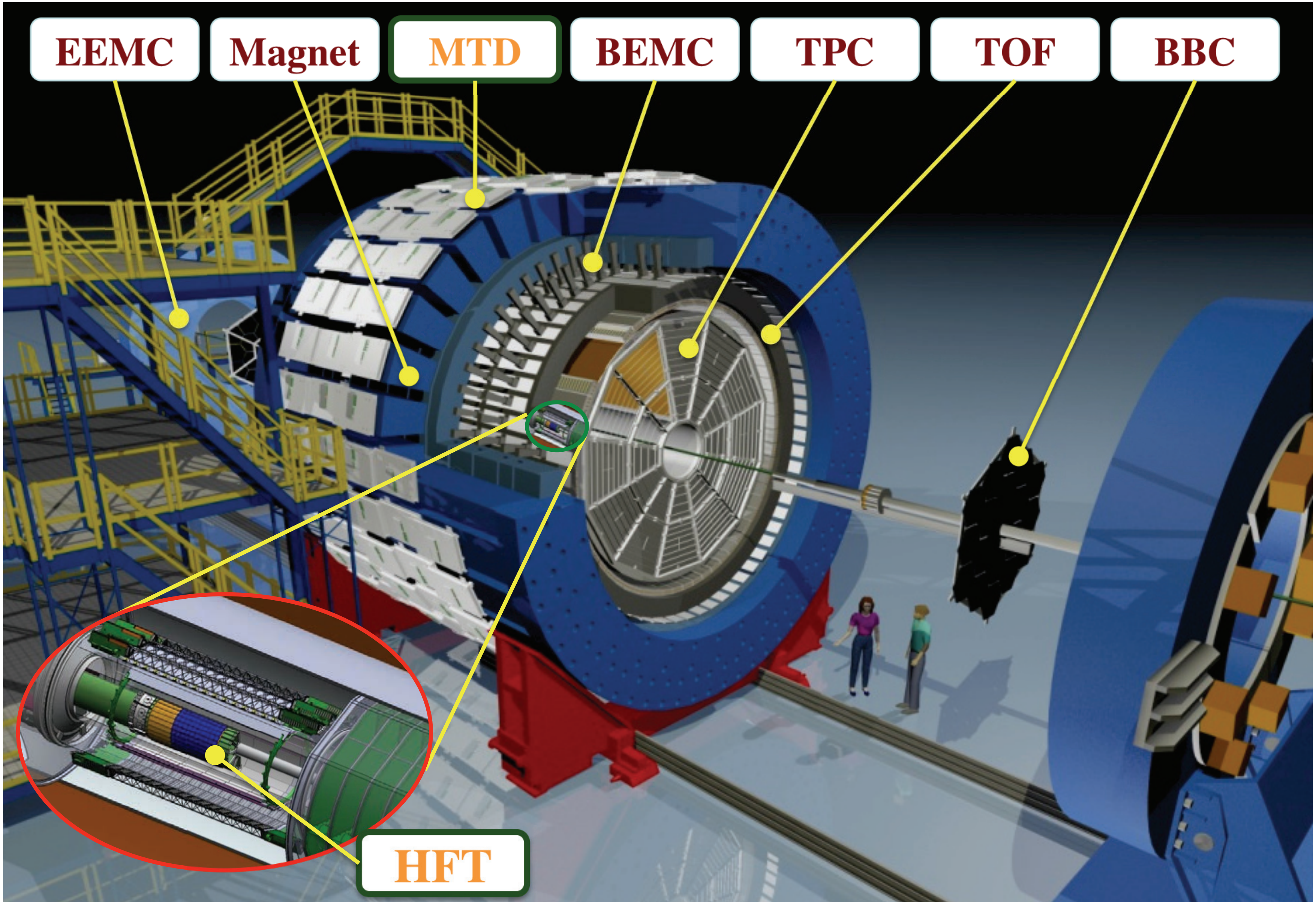
RHIC at BNL

p+p at $\sqrt{s}$=510 GeV max
Au+Au at $\sqrt{s}$=200 GeV max
Started at Year 2000
collided various beams
pp, dAu, CuCu, CuAu
AuAu, UU will do He^3+Au

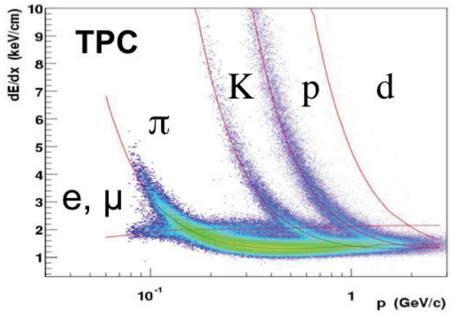


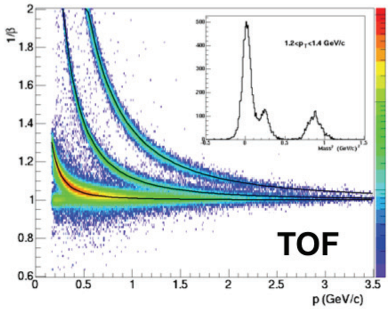


STAR Detector System

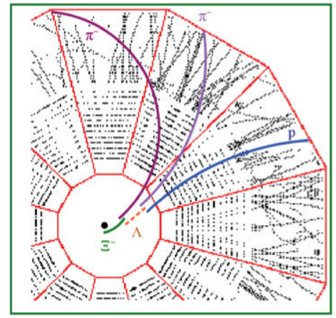


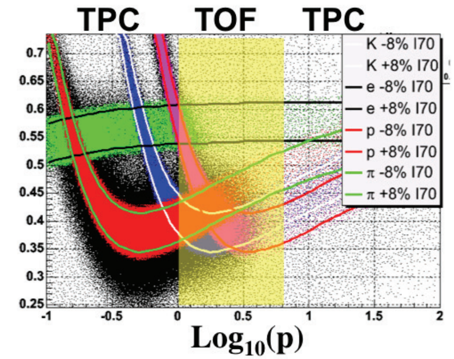
Particle Identification at STAR



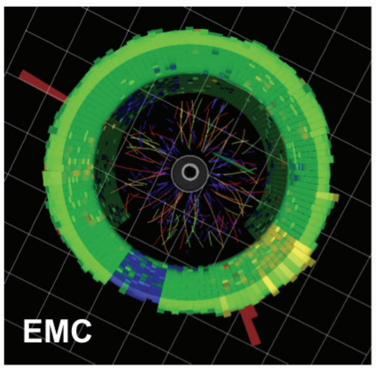


Charged hadrons

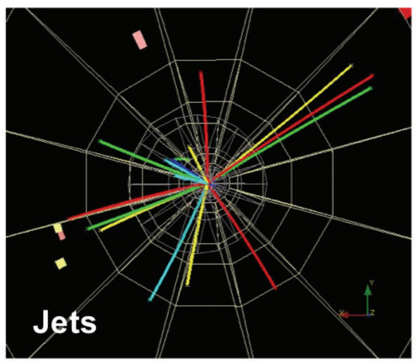




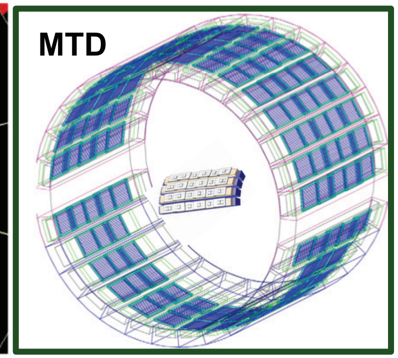
Hyperons & Hyper-nuclei



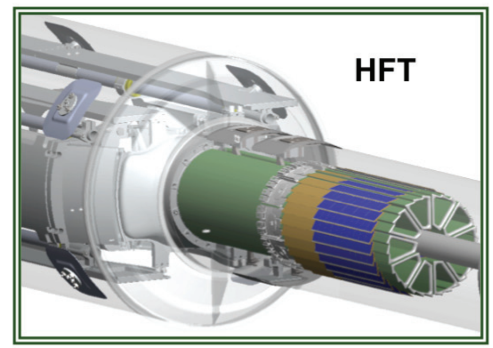
Neutral particles



Jets & Correlations



High p_T muons

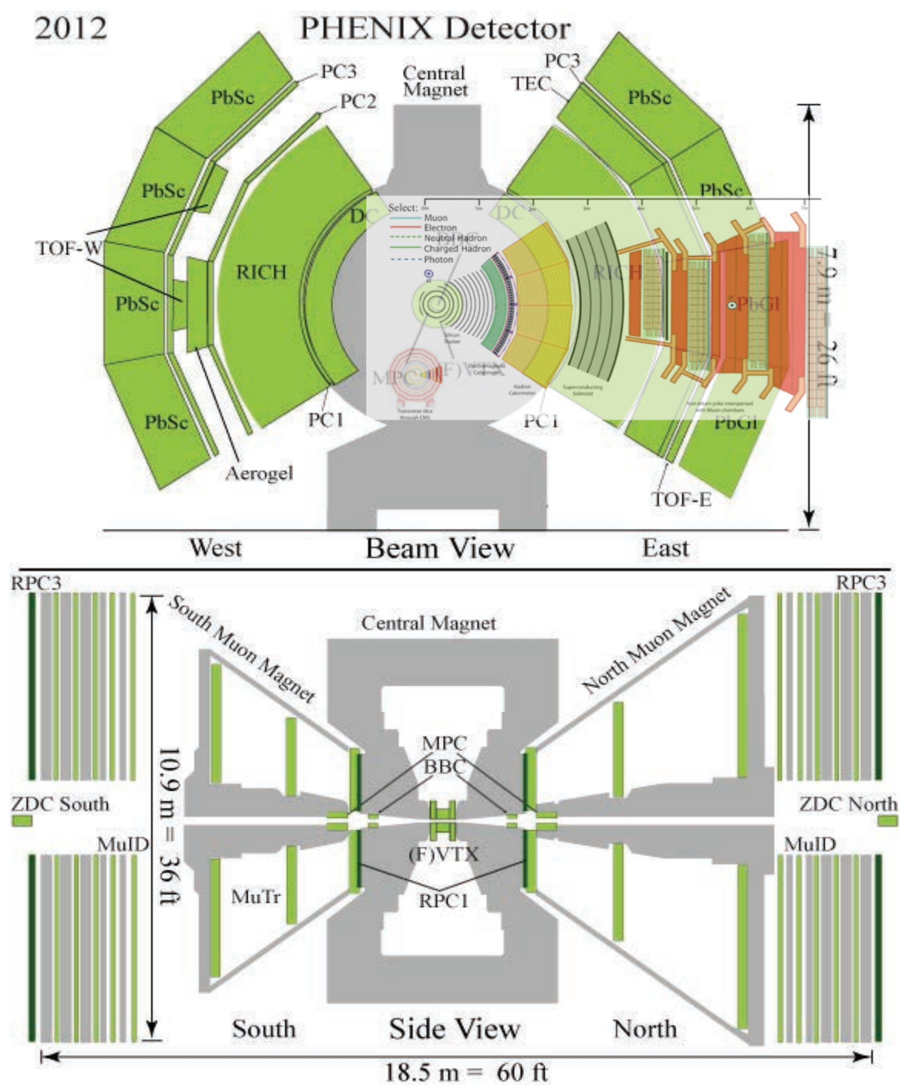


Heavy-flavor hadrons

Wide acceptance plus excellent particle identification

Multi-fold correlations for identified particles!

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



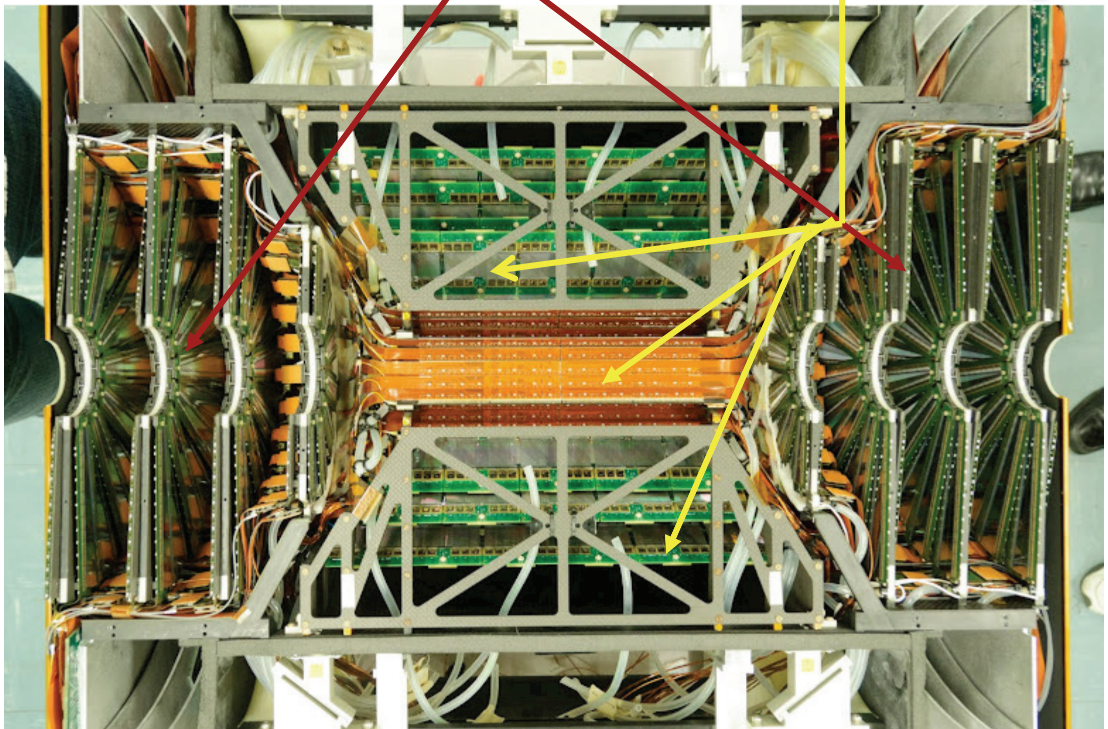
- **PHENIX is a special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**

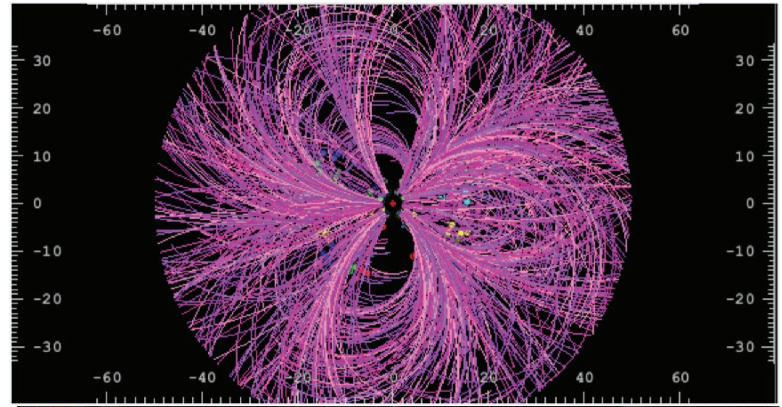
✓ *possibility of zero magnetic field on axis*
✓ *minimum of material in aperture 0.4% X_o*
✓ *EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger*

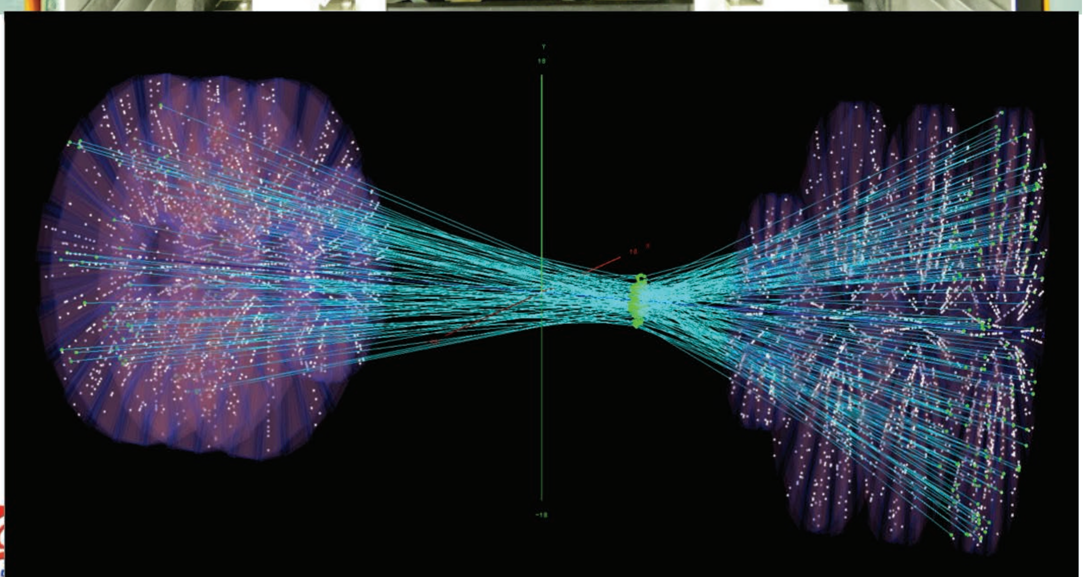
- *γ π^0 separation up to $p_T \sim 25$ GeV/c*
- *EMCAL and precision TOF for $h^{\pm}$ pid*
- *Main Central detector $|\eta|<0.35$*
- *Muon arms $1.1<|\eta|<2.3$*
- *BBC, MPC $3.1<|\eta|<3.9$*

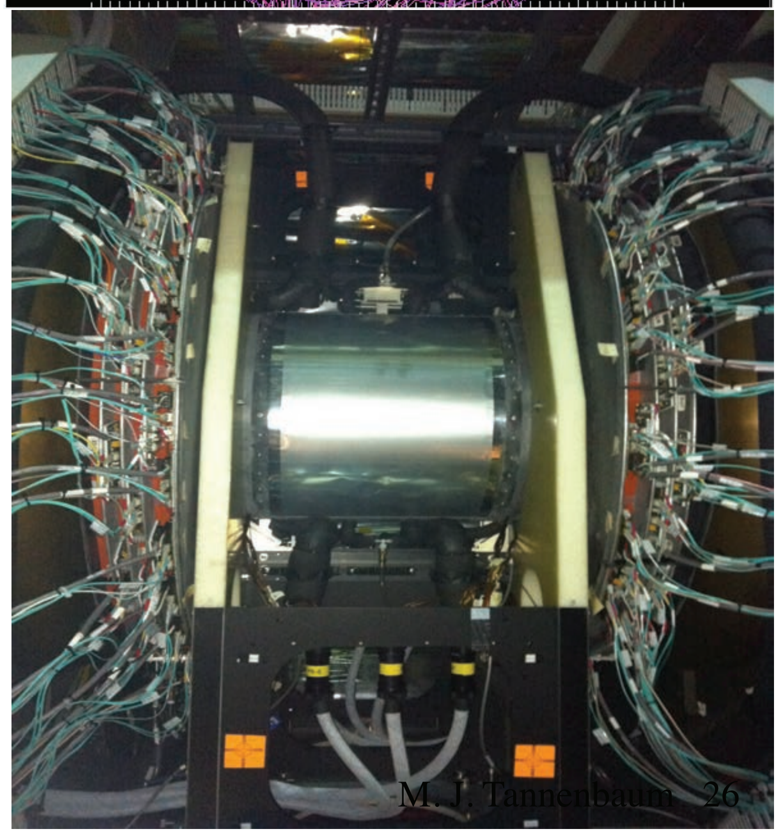
Comparison to scale with a wedge of CMS

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



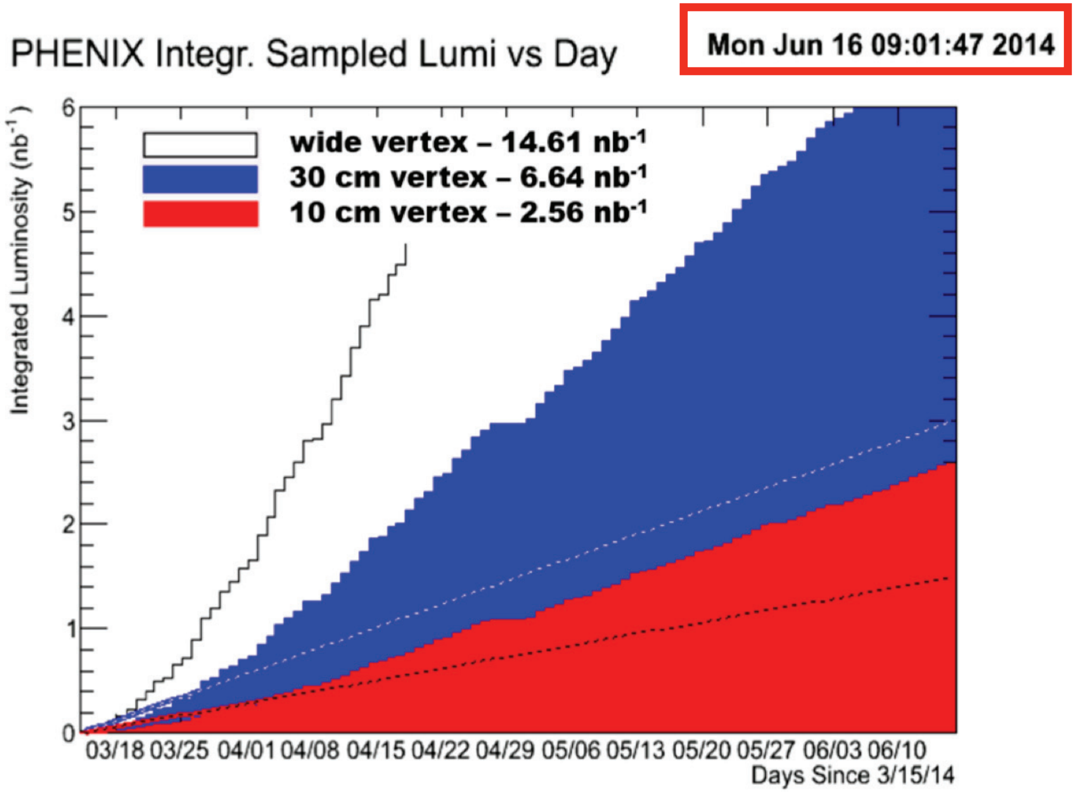






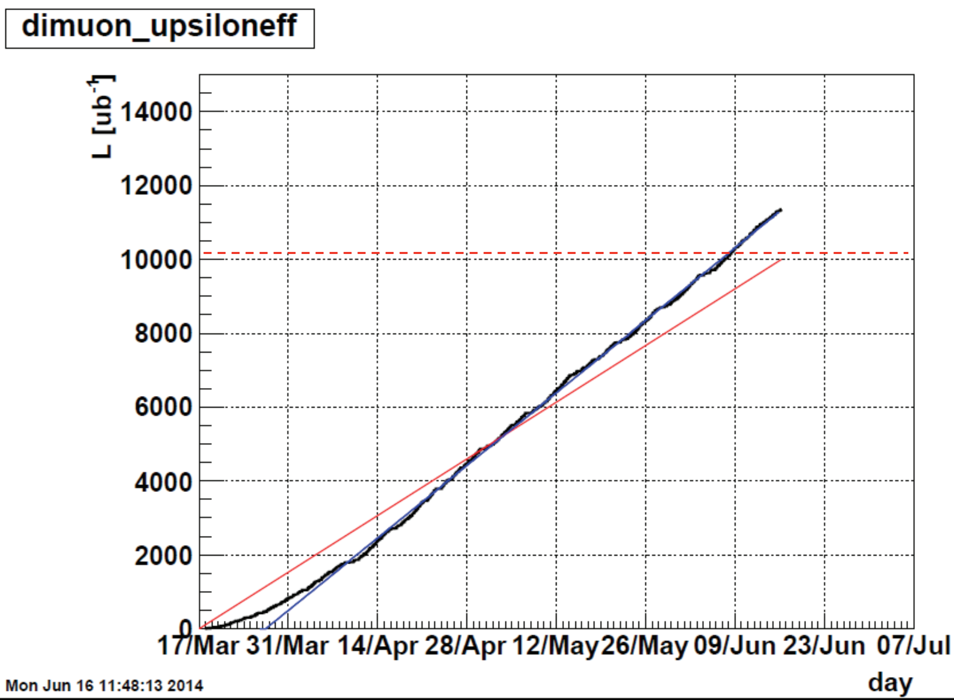
Run-14 Is Going Extremely Well

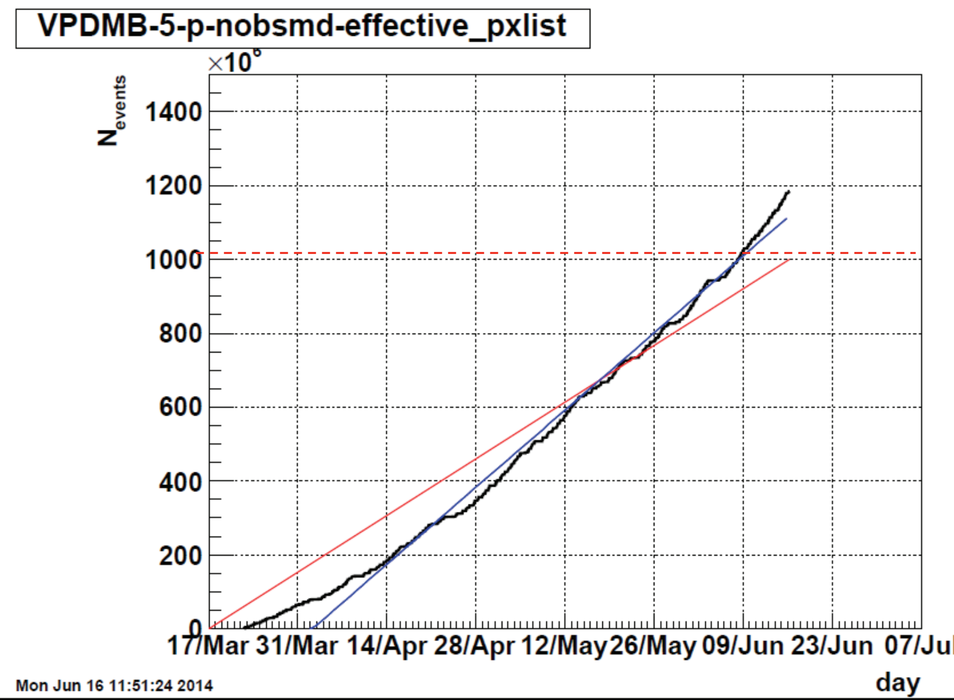
- Collected
  - 19.3B events in [+/- 10 cm]
  - 48.8B events in [+/- 30 cm]
  - 92.0B events in [+/- 144 cm]



- **PHENIX has exceeded its goal of Au+Au 200 GeV 1.5 nb-1 recorded data. Au+Au 200 GeV run ended June 16 with 2.56nb^{-1}. On June 16-17 changed to He^{3} +Au for 3 weeks—Run-14 is extended to July 7**
- **RHIC has consistently exceeded its pre-Run-14 max luminosity projections, sometimes more than doubling it.**
- **PHENIX has a high average live time and good data taking efficiency**
- **same for STAR**

Completion of the 200 GeV Run

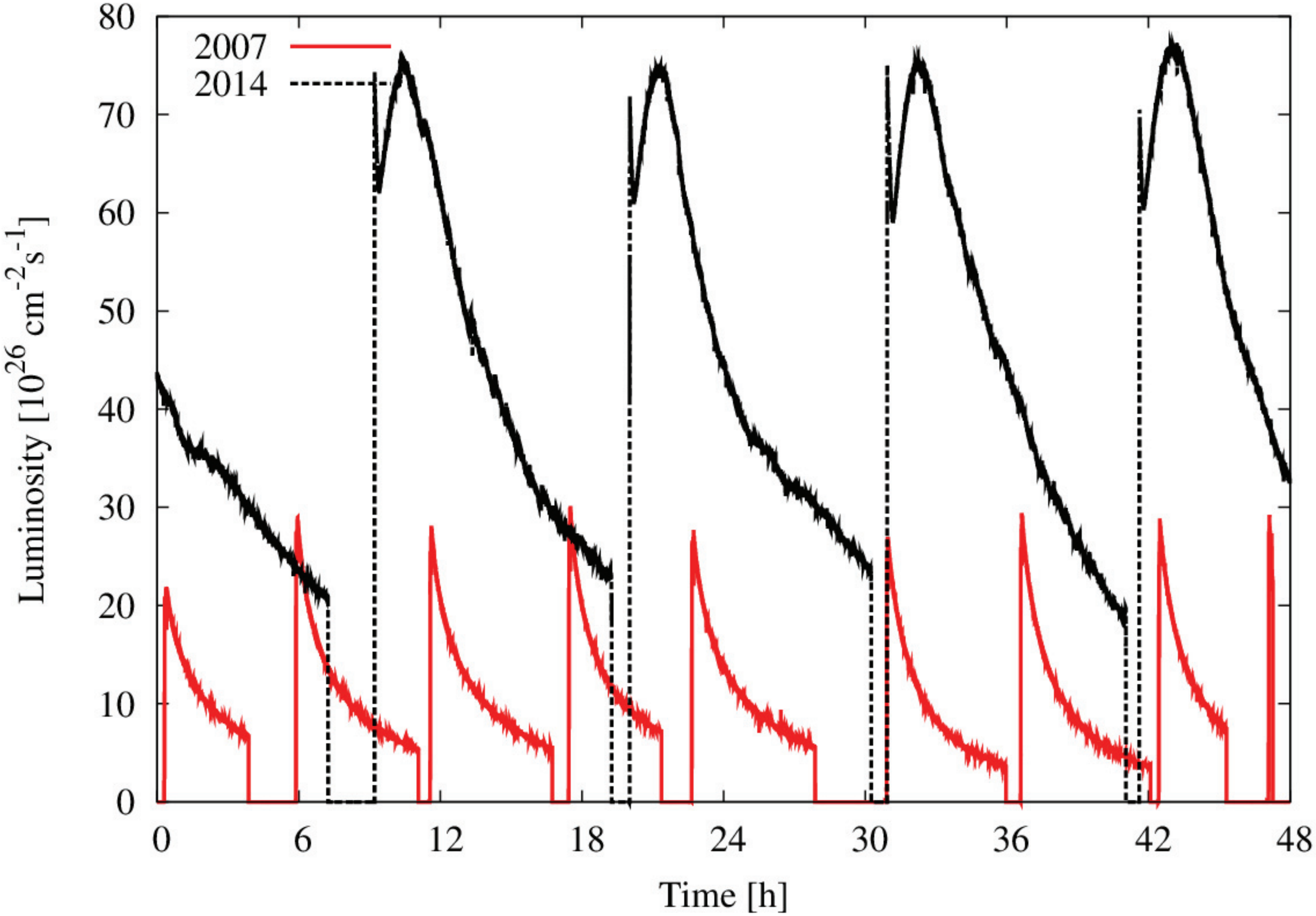




- *Both physics goals (di-muon and HF) are reached and exceeded*
- *Exceptional CAD performance, many thanks for the whole team!*

Machine Performance achieves RHIC-II specs

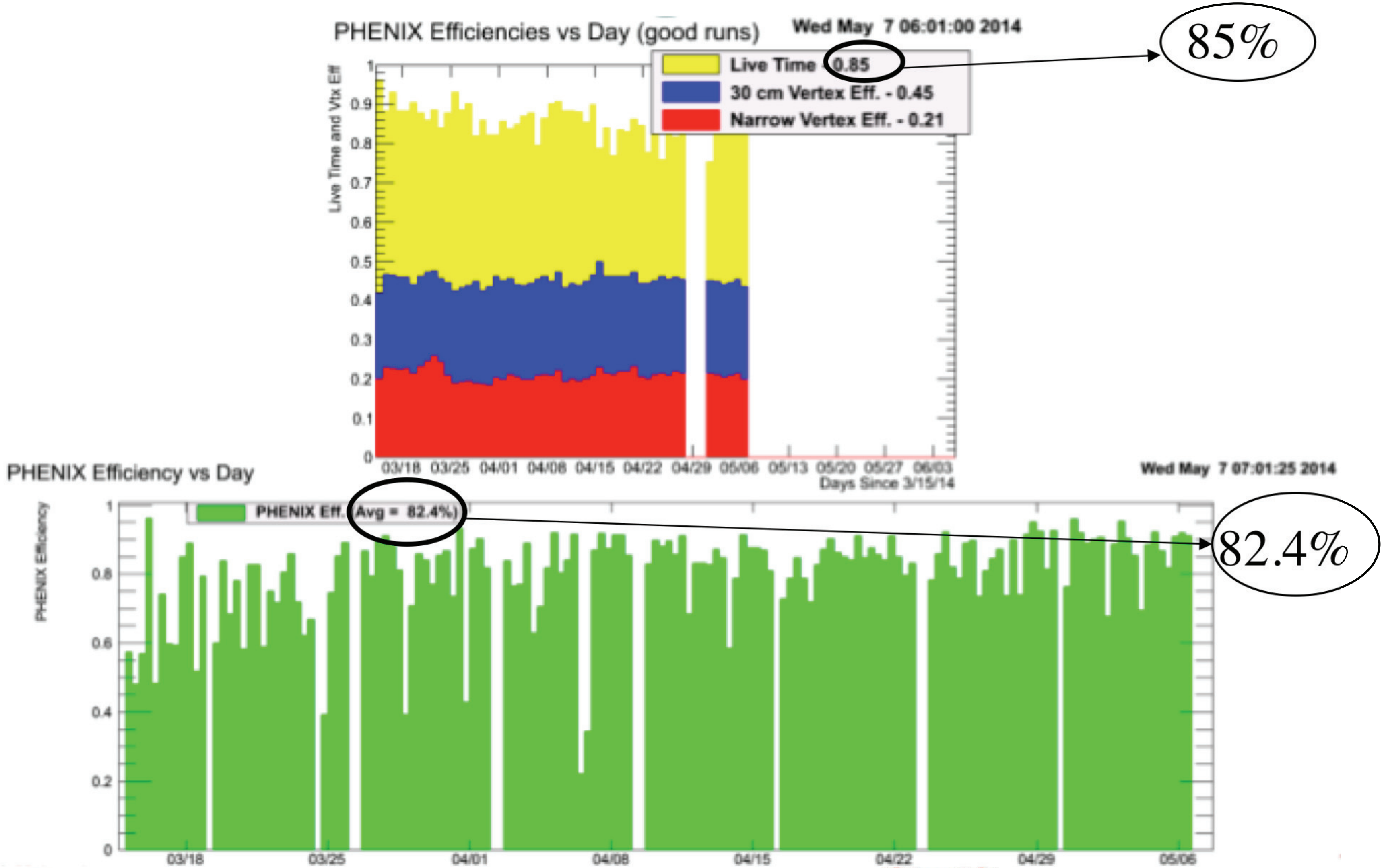
From Wolfram Fischer, 5/6/2014



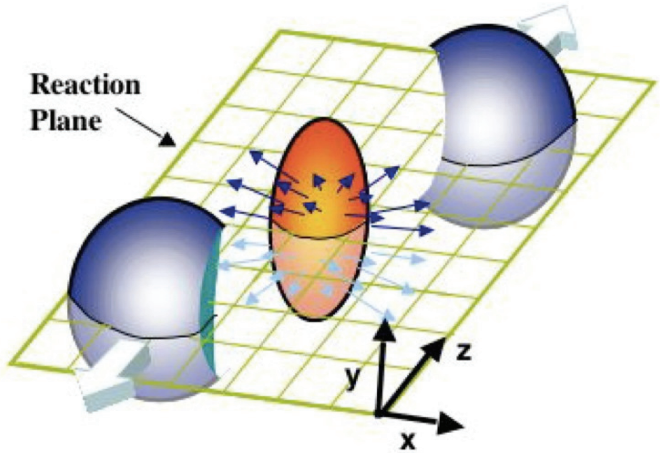
Much longer lifetime, more level load due to 3d stochastic cooling

PHENIX Livetime and Efficiency

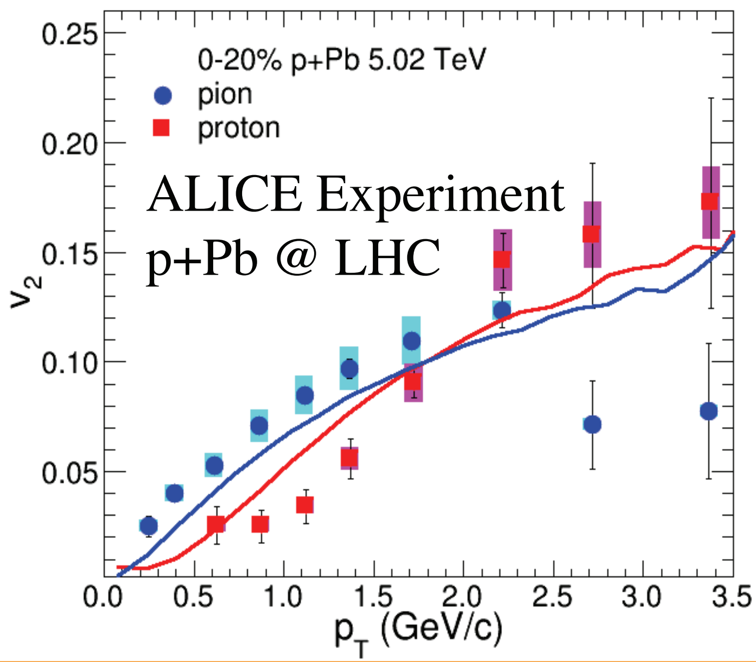
Both DAQ live time and data-taking efficiency have remained high throughout Run-14

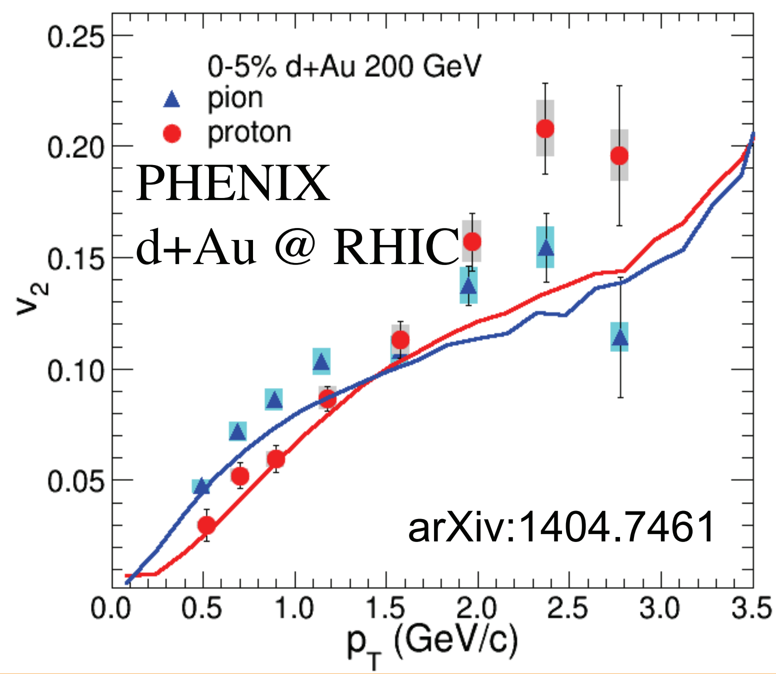


Latest big discovery, π and p flow in dAu



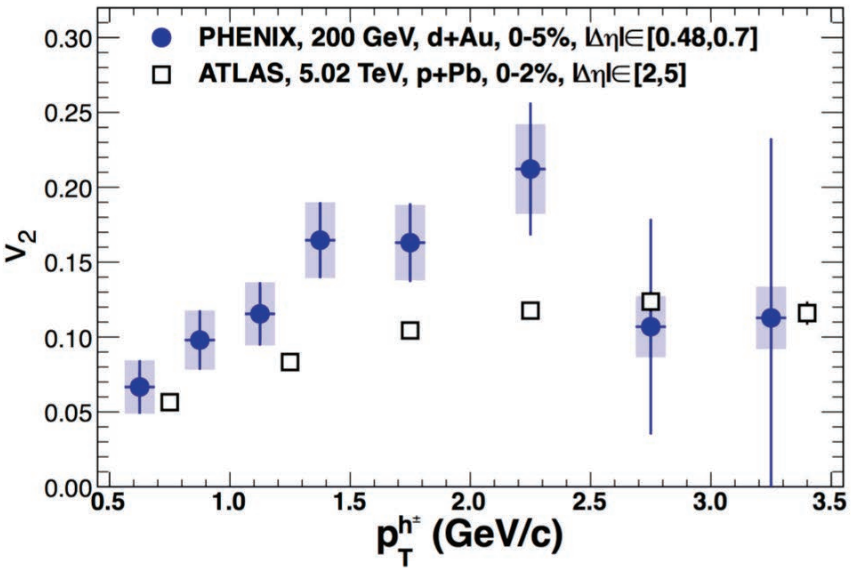
$v_2 \sim \langle\cos 2\Phi\rangle$ asymmetry around reaction plane due to ellipsoidal shape is a collective effect. In hydrodynamics, for a given expansion velocity β, protons have larger $p_T = \gamma\beta m$ than π as clearly shown by the d+Au data, as in Au+Au

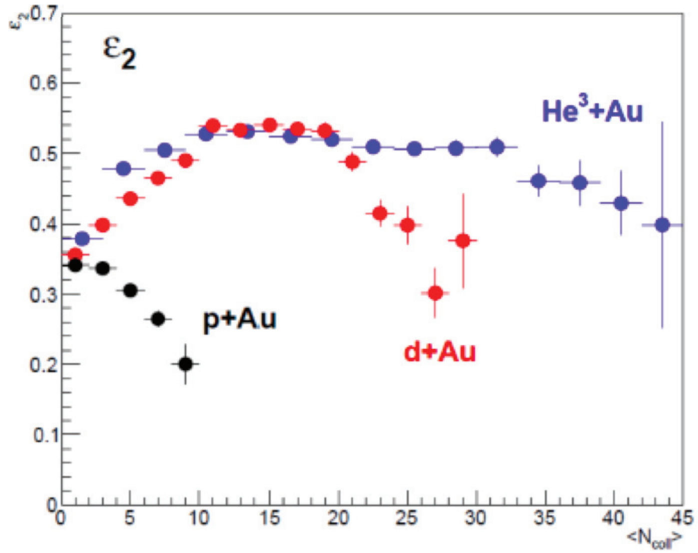




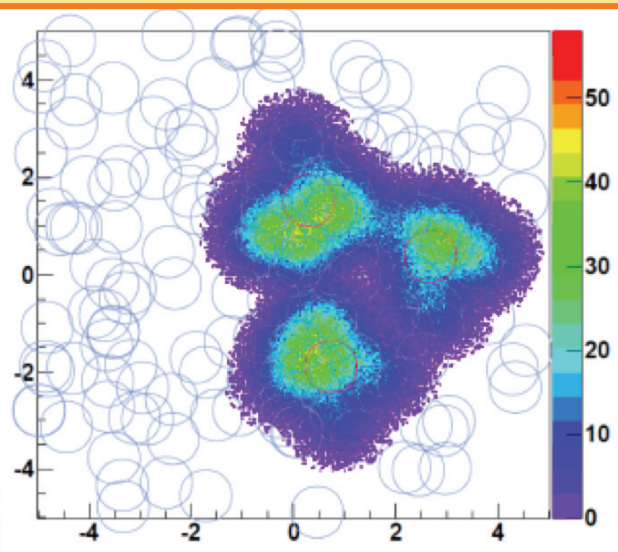
$v_2(p_T)$ seems larger at in d+Au at RHIC. We are now measuring He^3+Au to see if v_3 appears due to 3 nucleons

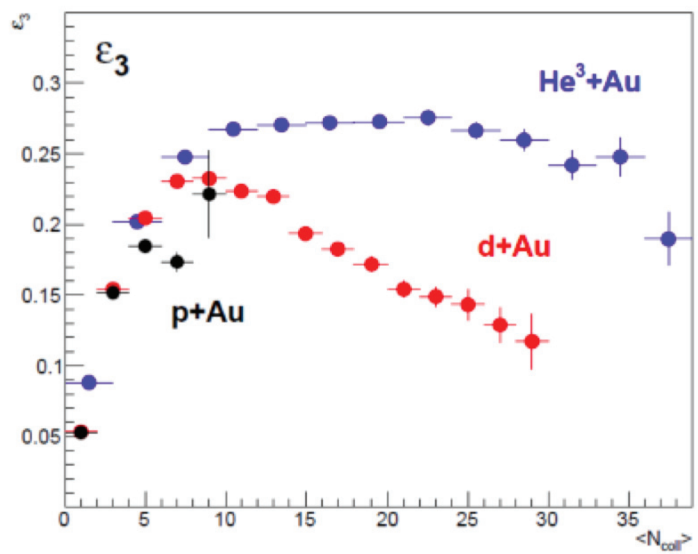
Why study He^3+Au?





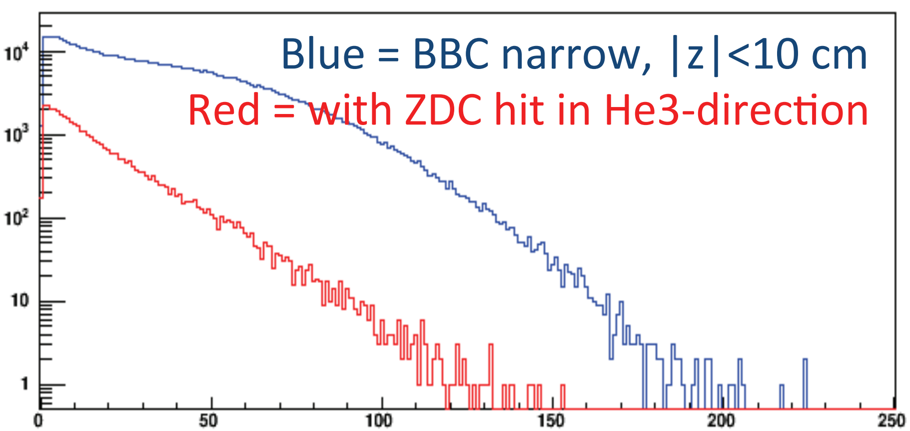
Significantly larger v_2 at RHIC (dAu) than LHC (pPb) at similar centrality likely due to natural eccentricity ε_2 in deuteron with 2 nucleons. Increase the triangularity of the initial state with He^3 to get natural ε_3. Will we now see large v_3 in He^3. Shows the versatility of RHIC to do He^3 so fast



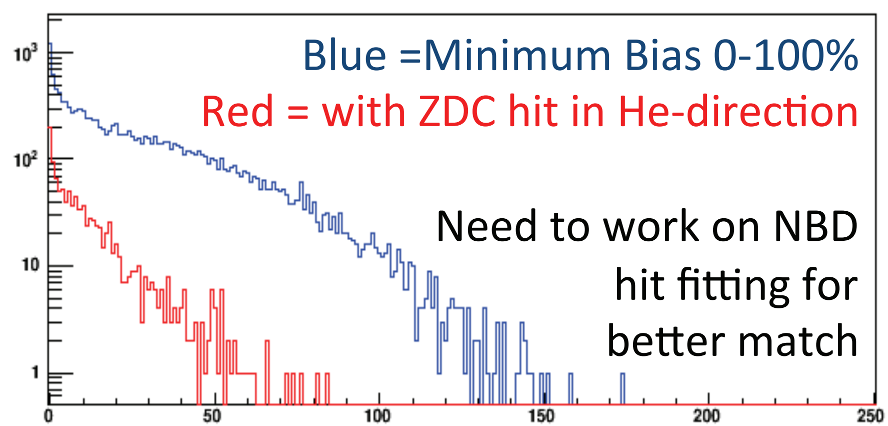


Real He3+Au Data

Glauber MC



BBC Charge Au-going Direction



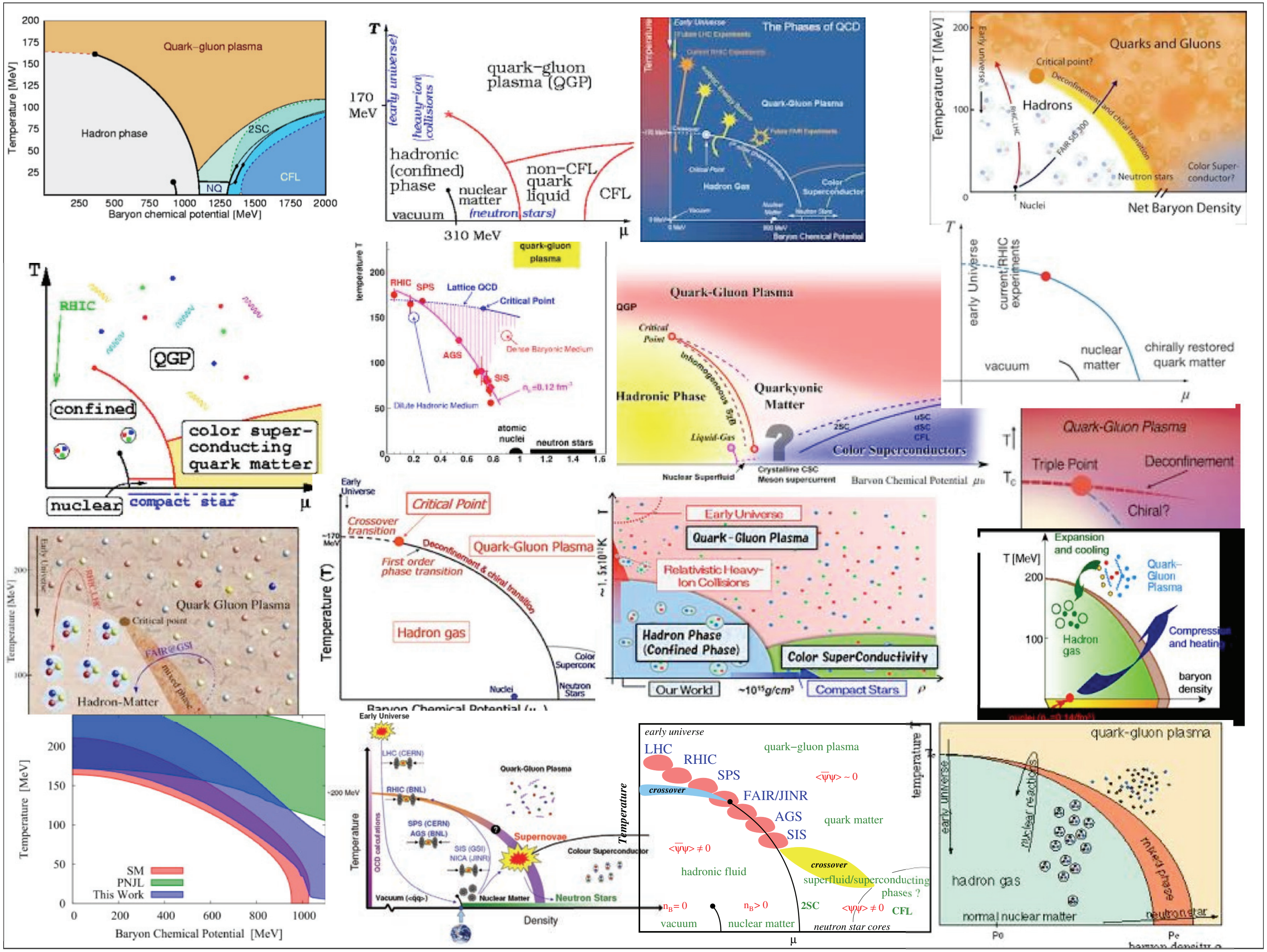
BBC Charge Au-going Direction

Glauber MC corresponds to 0-100% of the cross section not condition of data plotted

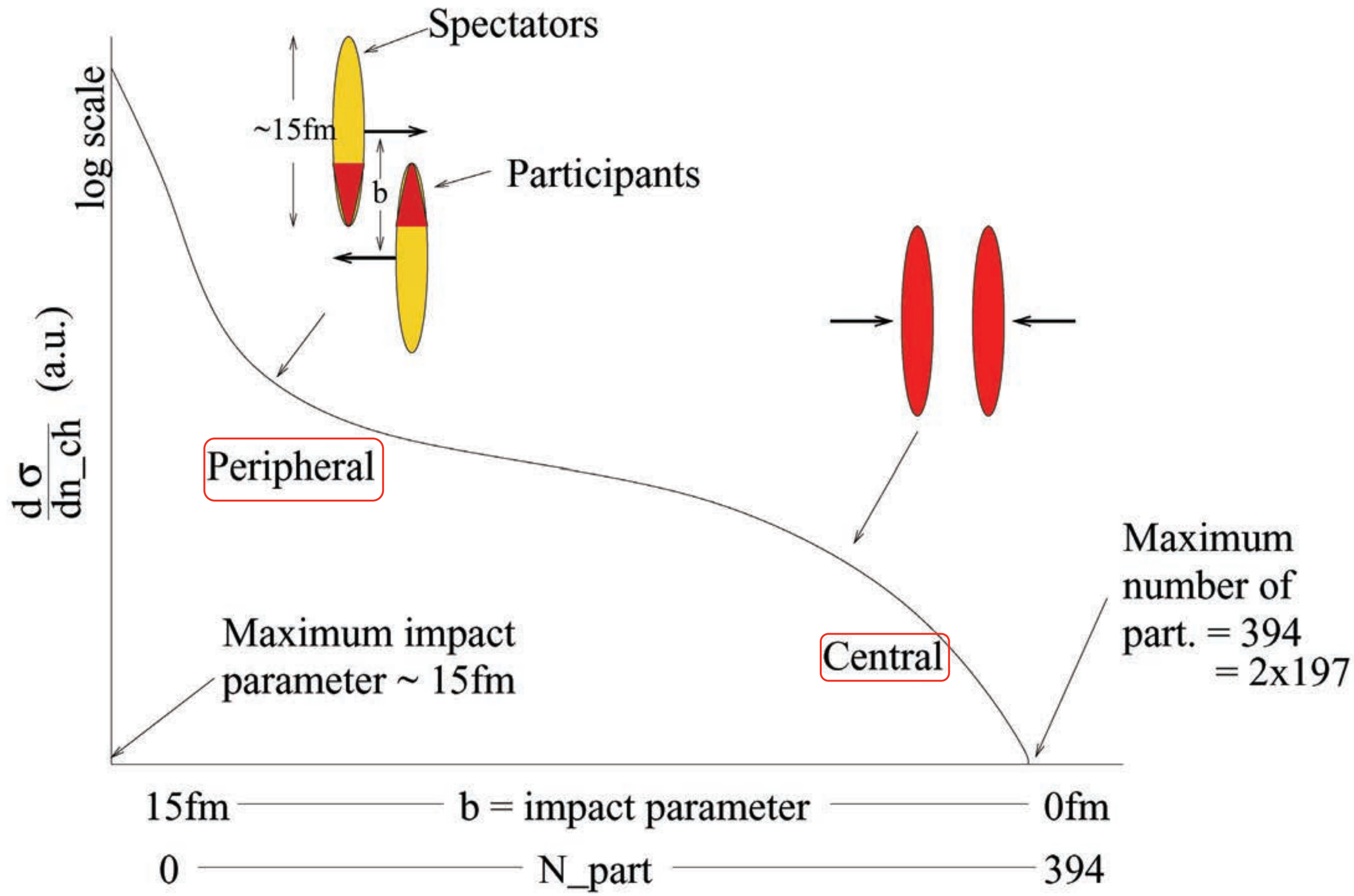
How to find the Quark Gluon Plasma (QGP) in A+A collisions c.1990:--a medium of quarks and gluons deconfined from their original nucleons covering a volume that is many units of the confinement length scale (~1fm) in which the q and g with their color charge fully exposed freely traverse the medium composed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

Proposed Phase diagrams Nuclear matter

Pawlowski-QM2014

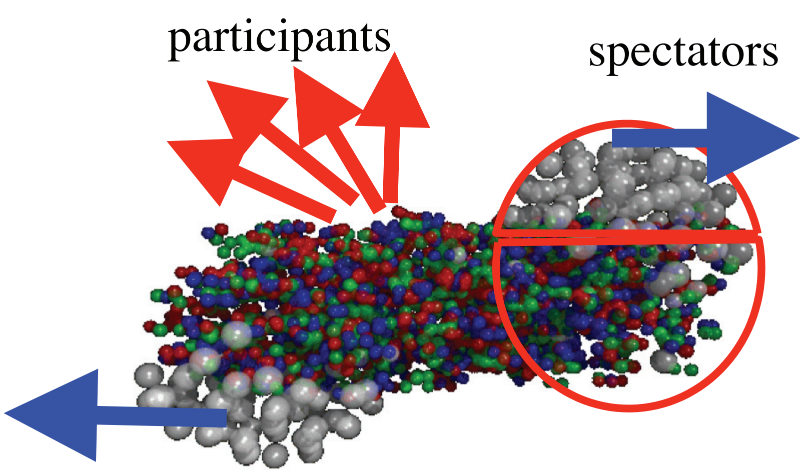


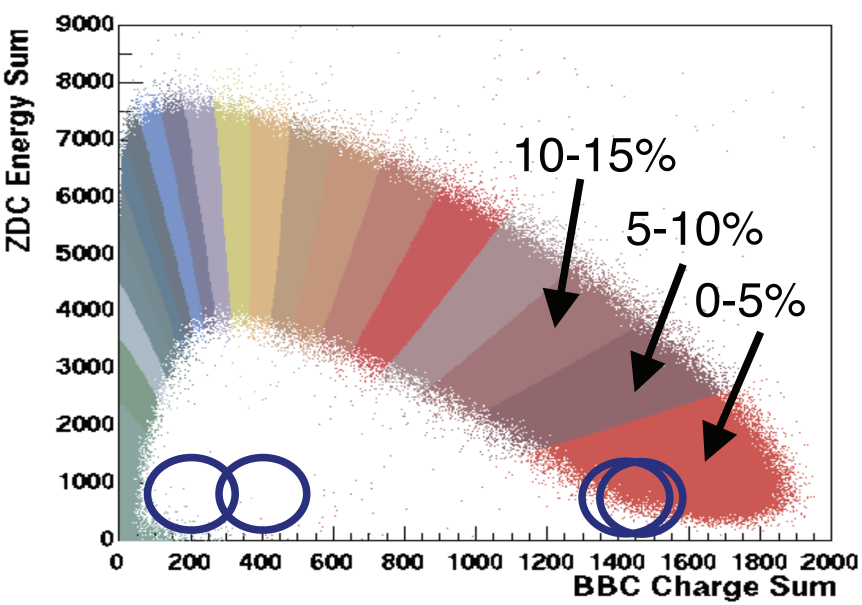
Some special Issues for A+A collisions



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

E_T distributions

η= pseudorapidity

- E_T is an event-by-event variable defined as:

$$E_T = \sum_i E_i \sin\vartheta_i \quad \text{and} \quad dE_T(\eta)/d\eta = \sin\theta(\eta) dE(\eta)/d\eta$$

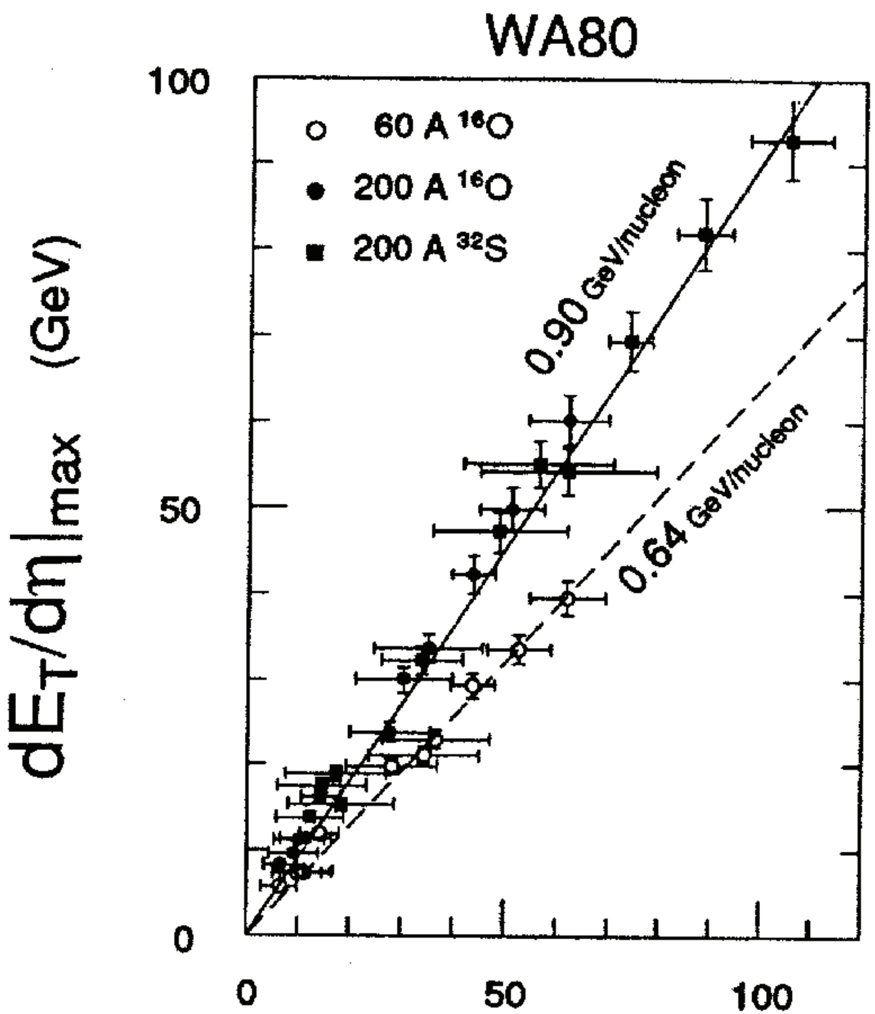
- The sum is over all particles emitted on an event into a fixed but large solid angle (which is different in every experiment)

- Measured in hadronic and electromagnetic calorimeters and even as the sum of charged particles $\Sigma_i \, |p_{Ti}|$

- Introduced by High Energy Physicists as an "improved" method to detect and study the Jets of hard-scattering. It didn't work as expected, E_T distributions are dominated by soft particles near $\langle p_T \rangle$.

- The importance of E_T distributions in relativistic heavy ion (RHI) collisions is that they are largely dominated by the *nuclear geometry* of the reaction and so provide a measure of the overall character or *centrality* of individual RHI interactions.

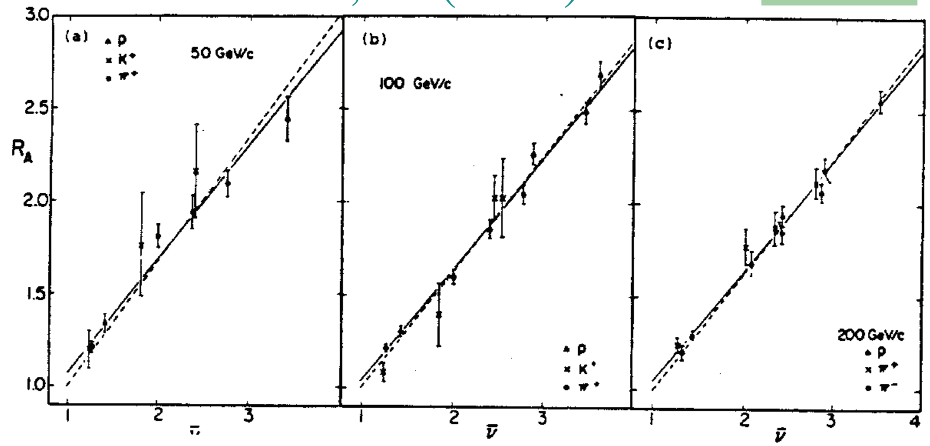
In 60, 200 A GeV fixed target p+A and A+A collisions N_{ch} and E_T scale with N_{part} not N_{coll}



PRC **44**, 2736 (1991) $\overline{W}$ = <Npart> from ZDC

Original Discovery by W. Busza, et al at FNAL $\langle n\rangle_{pA}$ vs $\langle\nu\rangle = (N_{coll})$ PRD **22**, 13 (1980)

$$\bar{\nu} = \frac{A\sigma_{pp}}{\sigma_{pA}}$$



$$R_A = \langle n\rangle_{pA} / \langle n\rangle_{pp} = (1+\langle\nu\rangle) / 2$$

$\langle Npart\rangle_{pA}$

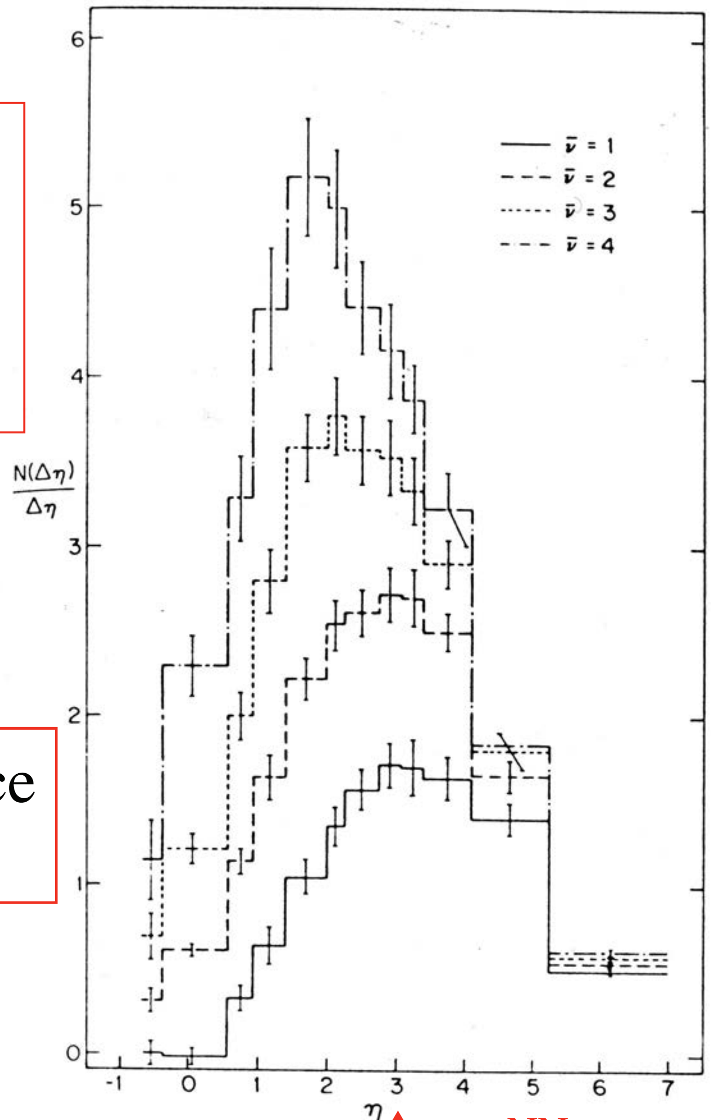
$\langle Npart\rangle_{pp}$

FNAL p+A data inspire Wounded Nucleon N_{part} Model

p+A where A is represented by average number of collisions $\bar{\nu}$

$$\bar{\nu} = \frac{A\sigma_{pp}}{\sigma_{pA}}$$

Strong dependence on rapidity



PRL **39**, 1499 (1977)

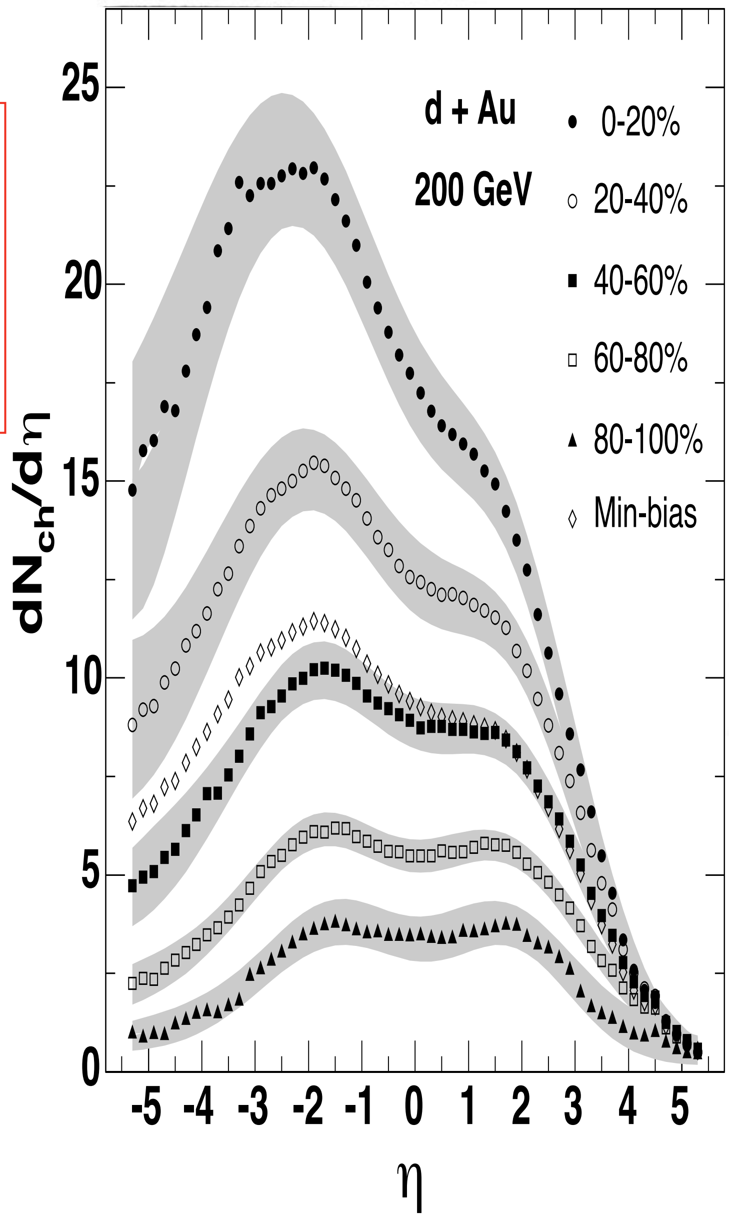
- NO CHANGE (η>5) Forward fragmentation proton passes through!!
- Tremendous Activity Target region (η<0.5)
- ★ Mid rapidity: dn/dη increases with A with small shift backwards with increasing A

200 GeV fixed target

$y^{NN}_{cm}=3.0$ $\sqrt{s_{NN}}=19.4$ GeV

FNAL p+A data inspire Wounded Nucleon N_{part} Model

d+Au at RHIC looks the same vs **centrality** PHOBOS

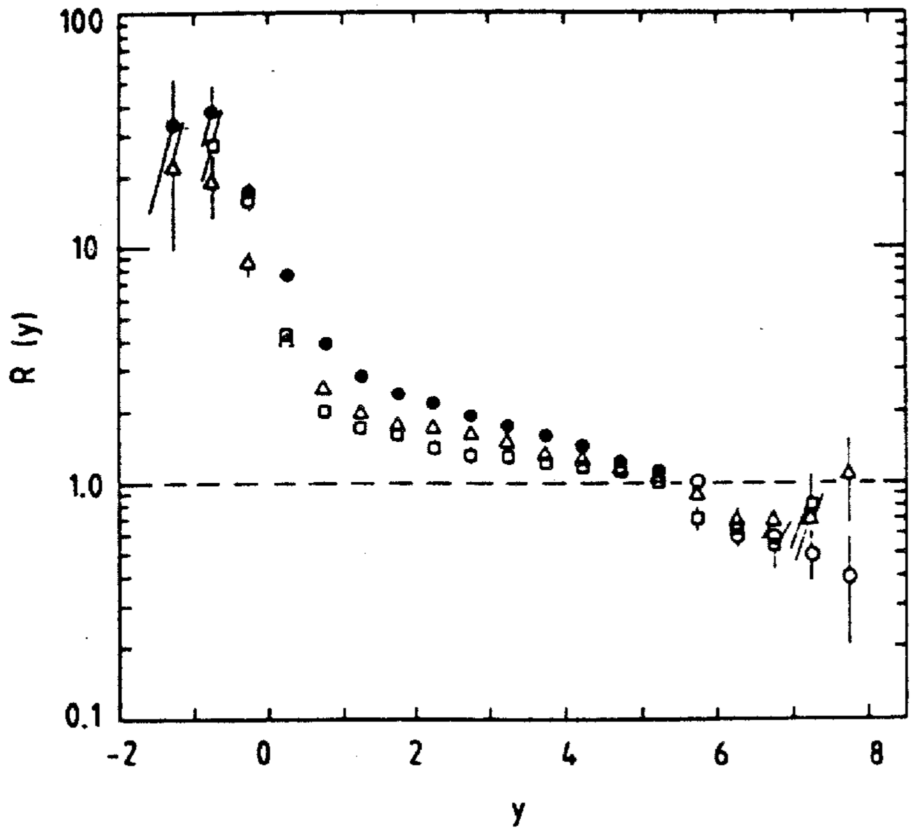


PRC**72**,031901(2005)

- NO CHANGE (η>5) Forward fragmentation proton passes through!!
- Tremendous Activity Target region (η<0.5)
- ★ Mid rapidity: $dn/d\eta$ increases with A with small shift backwards with increasing A

$\sqrt{s_{NN}}$=200 GeV

Same Features from CERN streamer Chamber



PRD **29** (1984) 2476

★ The beauty of mid-rapidity

The charged particle multiplication ratio $R(y)=(dn^{pA}/dy)/(dn^{pp}/dy)$ for fixed target 200 GeV/c protons on Ne(squares) , Ar(ν=2.4,triangles), Xe(ν=3.3,circles). The 3 distinct regions are clear here, Target ($y<0.5$), Fragmentation ($y>5$); mid-rapidity ($1<y<5$).
Although the distributions are not symmetric about $y^{NN}_{cm}=3.0$, integrals in the region up to $\Delta y\sim\pm 2$ around mid-rapidity, y_{cm}, give the same <dn/dy> as at y^{NN}_{cm}.

Physics of A+A collisions c. 1980. Quantum Mechanics and Relativity Very Important

- Immediately after a nucleon interacts with another nucleon in a nucleus the only thing consistent with relativity and quantum mechanics is for the nucleon to become an excited nucleon with roughly the same energy but reduced longitudinal momentum (rapidity), i.e. $m \longrightarrow m^*$, $E^*=E$, $p^*<p$

- The nucleus is transparent, incident protons pass through, make many successive collisions and come out the other side

- Uncertainty principle and time dilation prevent cascading of produced particles in relativistic collisions $\gamma\ h/m_\pi c > 10\text{fm}$ even at AGS energies: particle production takes place outside the Nucleus in a p+A reaction.

With 2 additional assumptions:

- An excited nucleon interacts with the same cross section as an unexcited nucleon.

- Successive collisions of the excited nucleon do not affect the excited state or its eventual fragmentation products

The conclusion is that the elementary process for particle production in nuclear collisions is the excited nucleon and that the multiplicity is proportional to the number of excited nucleons **=Wounded Nucleon Model (Npart)**

Extreme Independent Models

- **Extreme-Independent models:** separate nuclear geometry and fundamental elements of particle production.
- Nuclear Geometry represented by the weights, the relative probability w_n per B+A interaction for a given number n of fundamental elements, which are assumed to emit particles independently.
- I will discuss models with 3 different fundamental elements:
  - ✓**Wounded Nucleon Model (WNM)** - number of participants N_{part}
  - ✓**Quark Part. Model (NQP),** -number of constituent-quark participants N_{qp}
  - ✓**Additive Quark Model (AQM),** color-strings between quark participants in projectile & target: constraint: one string per qp → **projectile quark participants**.
- AQM & NQP cannot be distinguished for symmetric collisions, since projectile and target have the same number of struck quarks. Need asymmetric collisions, *e.g*, d+Au,

See A. Bialas pp139-165 in Proc. Bielefeld Workshop 1982, Eds Jacob, Satz, World Scientific.

Probability theory-sums⇔convolutions

- From the theory of mathematical statistics, the probability distribution of a random variable $S_{(n)}$ which is itself the sum of n independent random variables with a common distribution function $f(x)$:

$$S_{(n)} = x_1 + x_2 + \cdots + x_n$$

is given by $f_n(x)$, the n-fold convolution of the distribution $f(x)$:

$$f_n(x) = \int_0^x dy\, f(y) f_{n-1}(x-y)$$

The mean, $\mu_n = \langle S_{(n)} \rangle$ and standard deviation, σ_n , of the n-fold convolution obey the familiar rule

$$\mu_n = n\mu \qquad \sigma_n = \sigma\sqrt{n}$$

where μ and σ
are the mean and standard deviation of the distribution $f(x)$.

Implementation

- The dynamics of the fundamental elementary process is taken from the data: e.g. the measured E_T distribution for a p-p collision represents: 2 participants (WNM); a predictable convolution of constituent-quark-participants (Nqp); or projectile quark participants (AQM).

- The above bullet is why I like these models: a Glauber calculation of the weights, w_n, and a p-p measurement provide a prediction for B+A in the same detector.

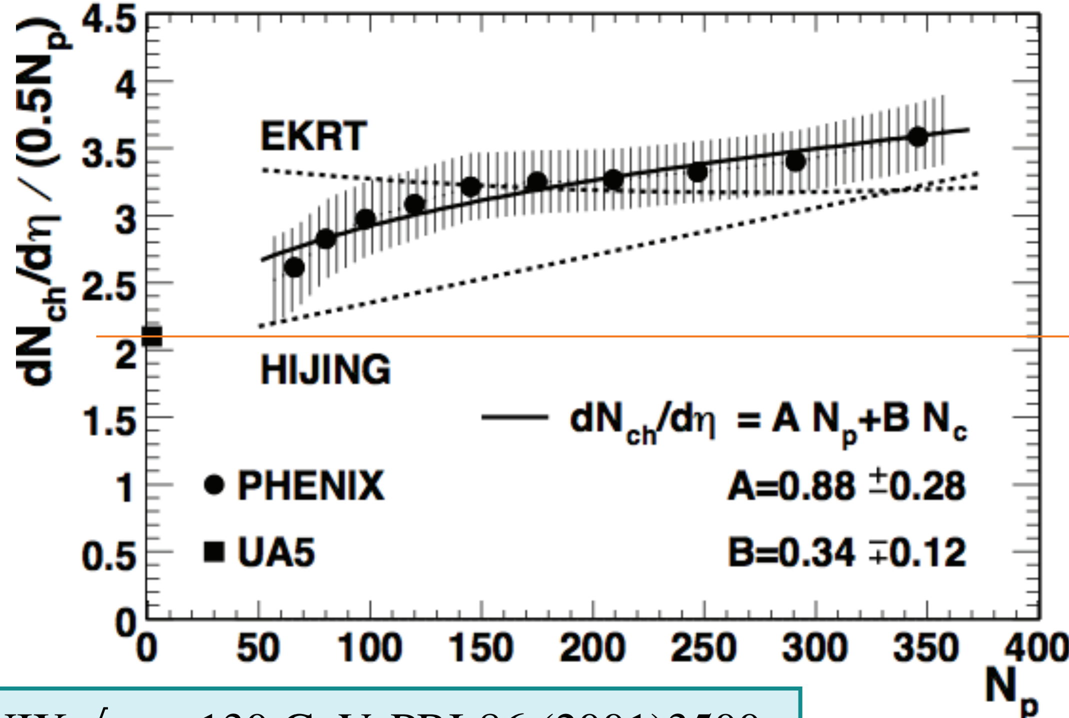
- Use a Gamma distribution as the pdf for a fundamental element

$$f(x) = f_\Gamma(x,p,b) = \frac{b}{\Gamma(p)}(bx)^{p-1}e^{-bx}$$

  - If E_T adds independently for n elements, i.e. participants, etc, the pdf is the n-fold convolution of $f(x)$: $p \rightarrow np \quad b \rightarrow b$

$$f_n(x) = \frac{b}{\Gamma(np)}(bx)^{np-1}e^{-bx} = f_\Gamma(x,np,b)$$

But first, evolution of mid-rapidity $dN_{ch}/d\eta/(0.5N_{part})$ with centrality, N_{part}



If WNM works, $dN_{ch}/d\eta/(0.5\ N_{part})$ should be constant at the p-p value, i.e. WNM fails!

PHENIX $\sqrt{s_{NN}}$=130 GeV, PRL86 (2001)3500

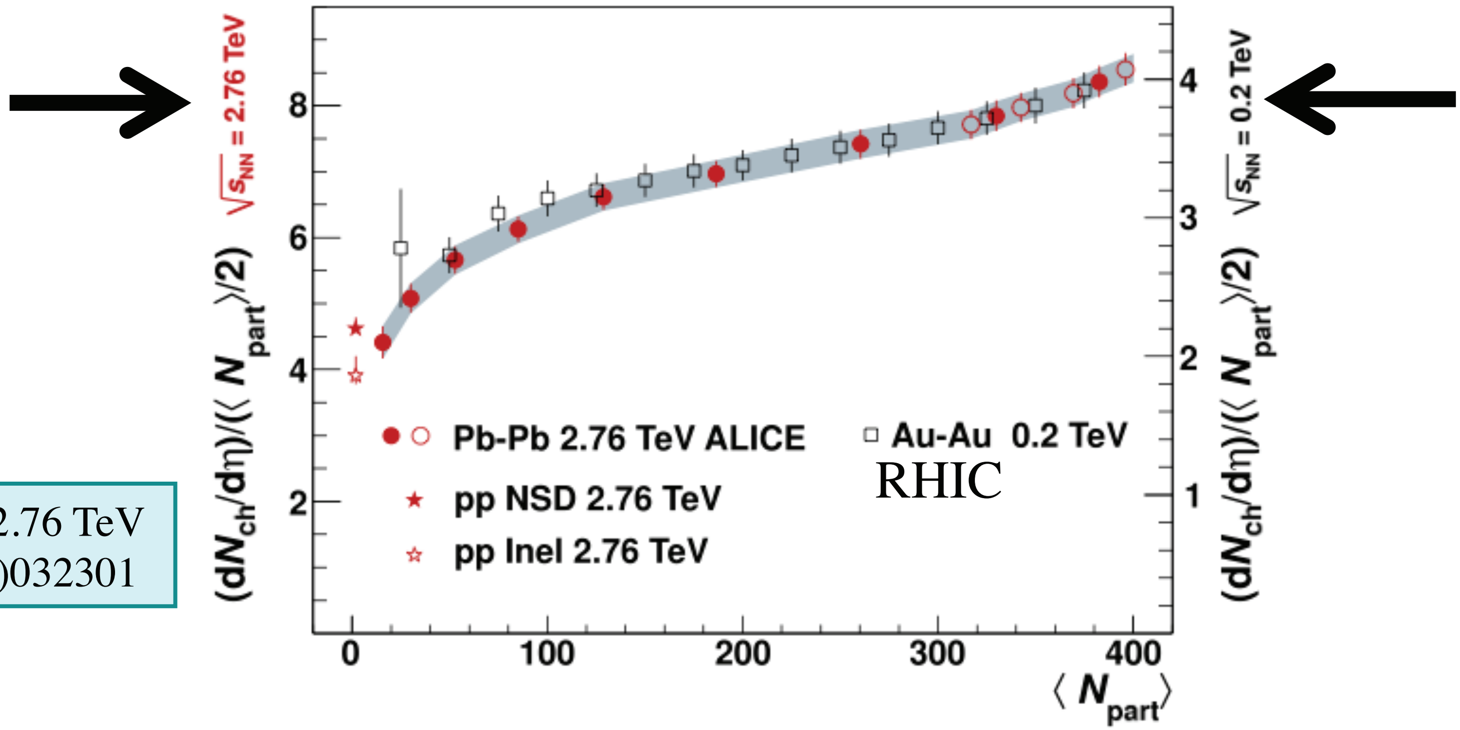
Inspired by article in same issue [PRL86, 3496], PHENIX included the following fit:

$$dE_T{}^{AA}/d\eta = [(1-x)\ \langle N_{\rm part}\rangle\ dE_T{}^{pp}/d\eta/2 + x\ \langle N_{\rm coll}\rangle\ dE_T{}^{pp}/d\eta]$$

The N_{coll} term implied a hard-scattering component for E_T, known to be absent in p-p

Important Observation 2.76TeV cf. 200 GeV

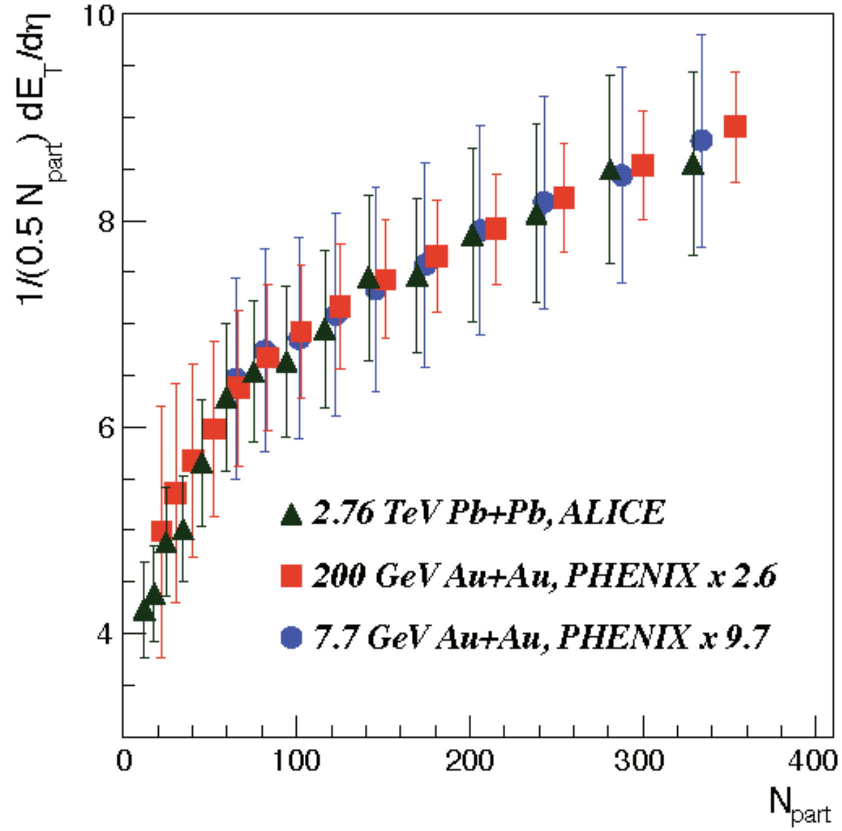
ALICE $\sqrt{s_{NN}}$=2.76 TeV
PRL 106(2011)032301



- **Exactly the same shape vs. N_{part}** although $\langle N_{coll}\rangle$ is a factor of 1.6 larger and the hard-scattering cross section is considerably larger.
  - ✓ PHENIX (2001) $dN_{ch}/d\eta \sim N_{part}^{\alpha}$ with $\alpha=1.16\pm0.04$ at $\sqrt{s_{NN}}=130$ GeV
  - ✓ ALICE (2013) $dN_{ch}/d\eta \sim N_{part}^{\alpha}$ with $\alpha=1.19\pm0.02$ at $\sqrt{s_{NN}}=2760$ GeV
- Strongly argues against a hard-scattering component and for a Nuclear Geometrical Effect.

Identical shape of distributions indicates a nuclear-geometrical effect

New RHIC data for Au+Au at $\sqrt{s_{NN}}$ =0.0077 TeV show the same evolution with centrality

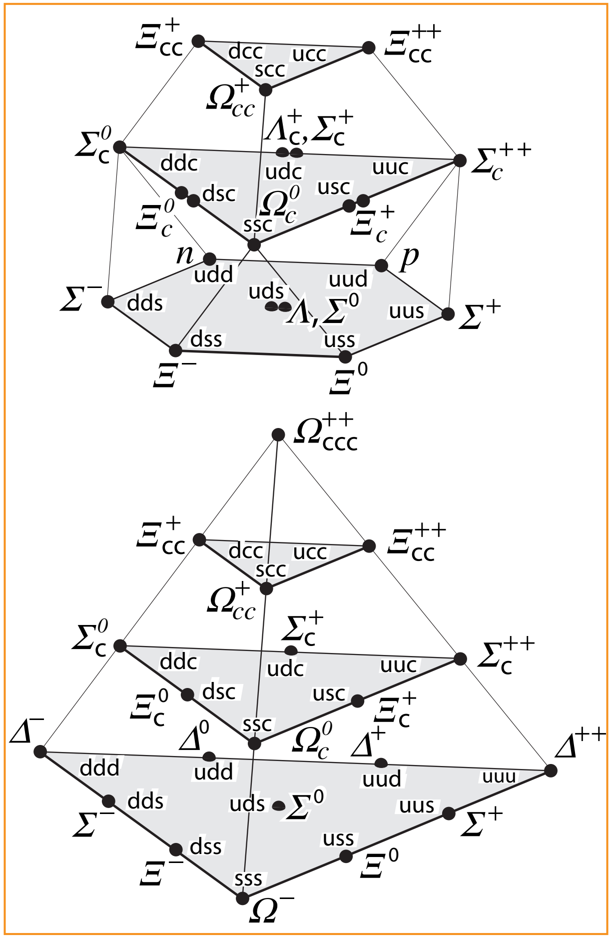


The geometry is the number of constituent quark participants/nucleon participant

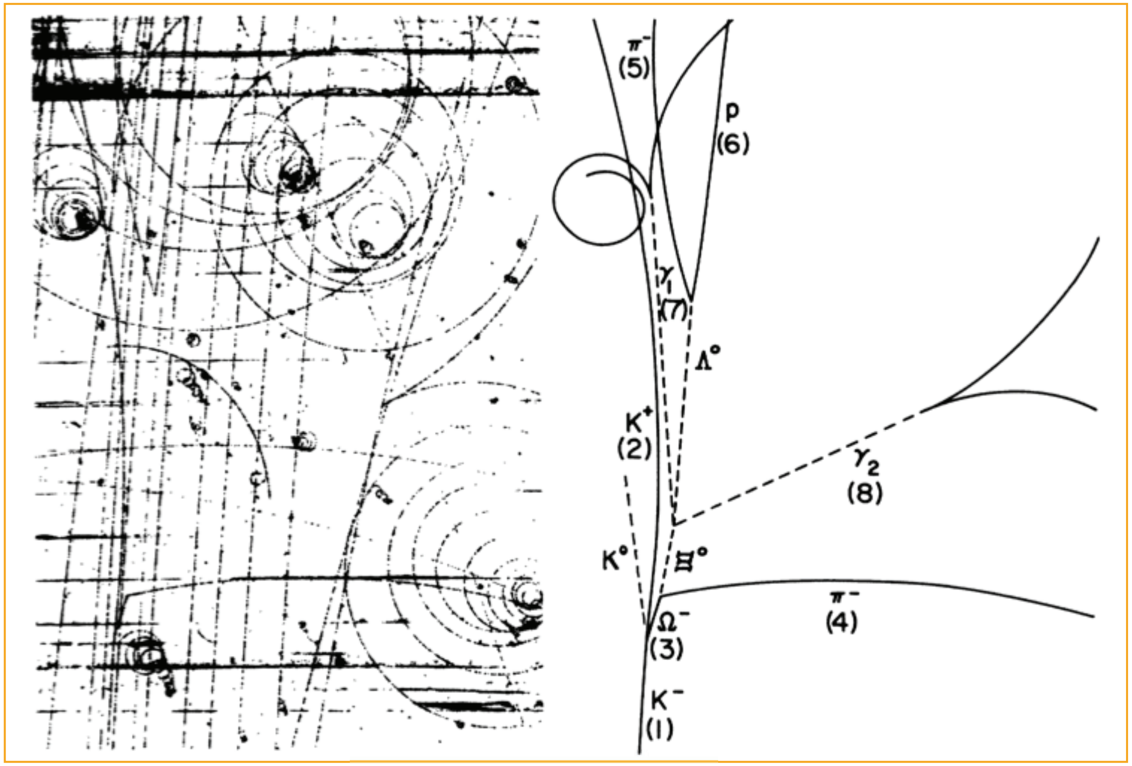
Eremin&Voloshin, PRC 67, 064905(2003) ; De&Bhattacharyya PRC 71; Nouicer EPJC 49, 281 (2007)

Remember, constituent quarks also gave universal scaling for v_2/n_q vs KE_T/n_q

Constituent quarks are Gell-Mann's quarks from Phys. Lett. **8** (1964)214, Zweig's Aces



Constituent quark model of Baryons



Ω^- (sss)

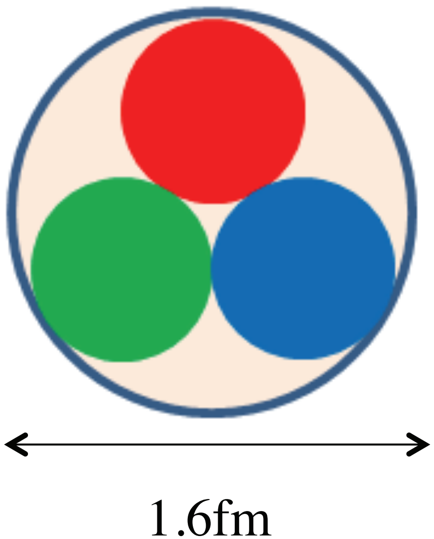
BNL-Barnes, Samios *et al*., PRL**12**, 204 (1964)

For more on Constituent quarks in QCD see E. V. Shuryak, Nucl. Phys. B 203, 116 (1982).

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

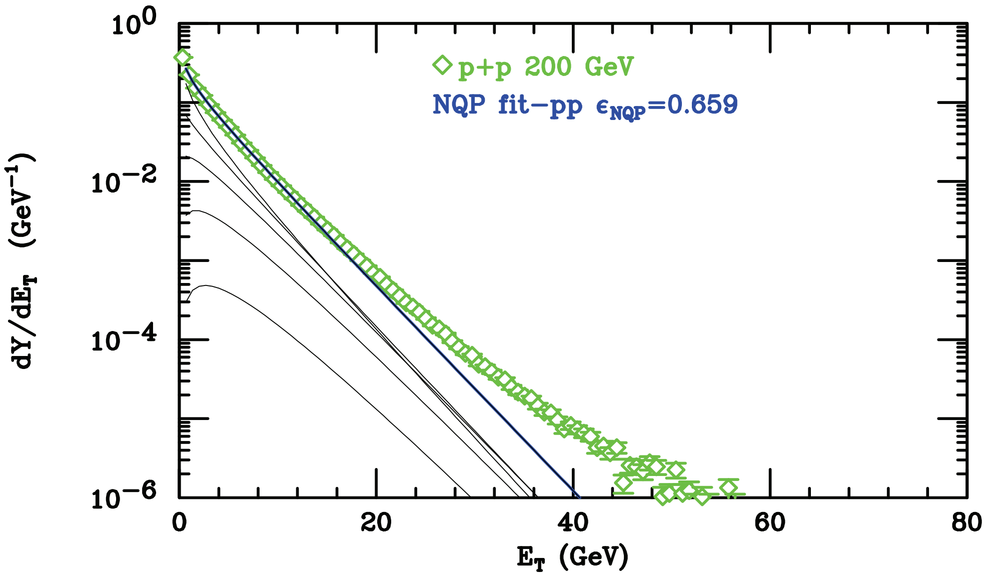


Resolution ~0.5fm

Resolution ~0.1fm

Resolution <0.07fm

PHENIX NQP model: Data driven pp→ dAu, AuAu

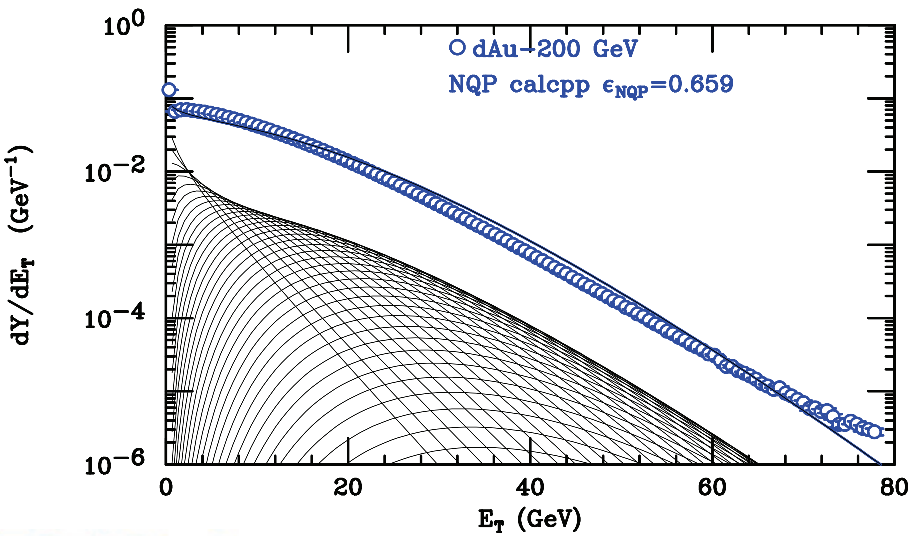


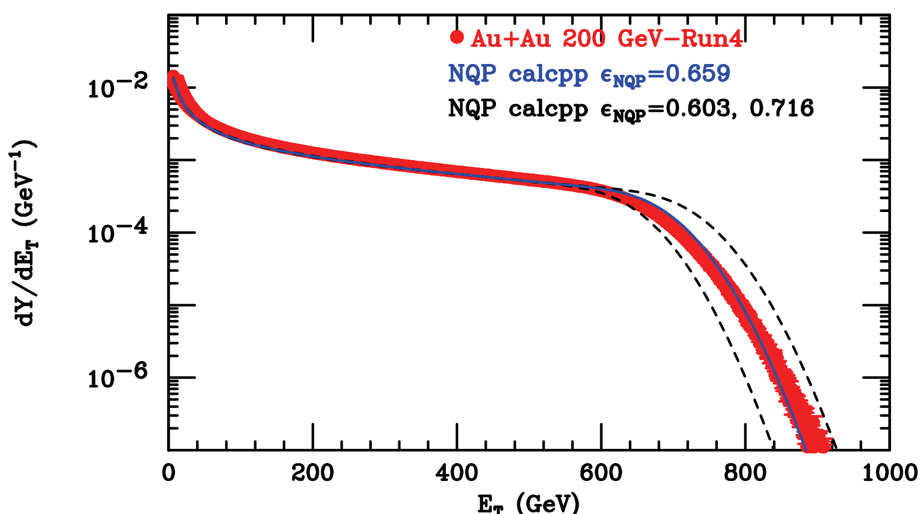
PHENIX PRC**89** (2014) 044905

1) Generate 3 constituent quarks around nucleon position, distributed according to proton charge distribution for pp, dA, AA

2) Deconvolute p-p E_T distribution to the sum of 2—6 quark participant (QP) E_T distributions taken as Γ distributions

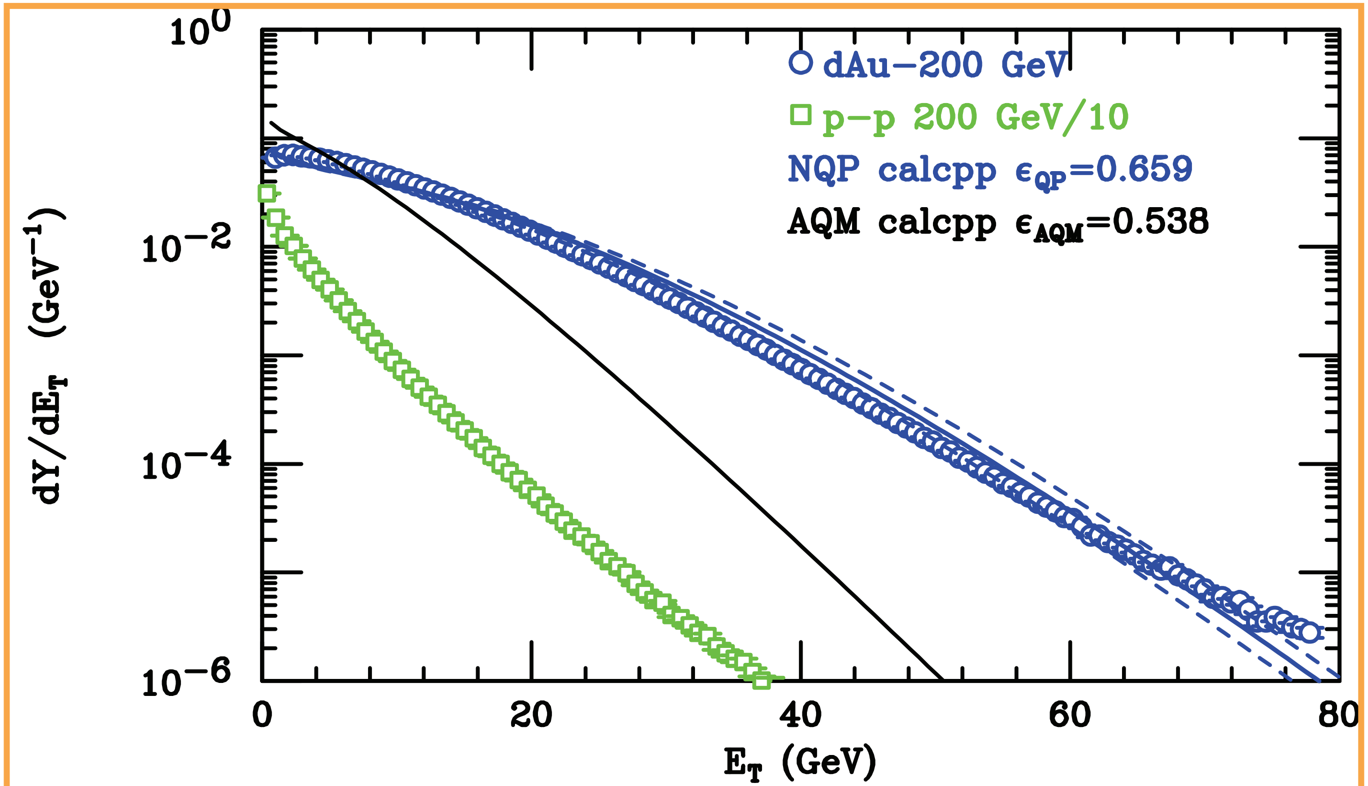
3) Calculate dAu and AuAu E_T distributions as weighted sum of QP E_T distributions





N_{qp} or AQM?

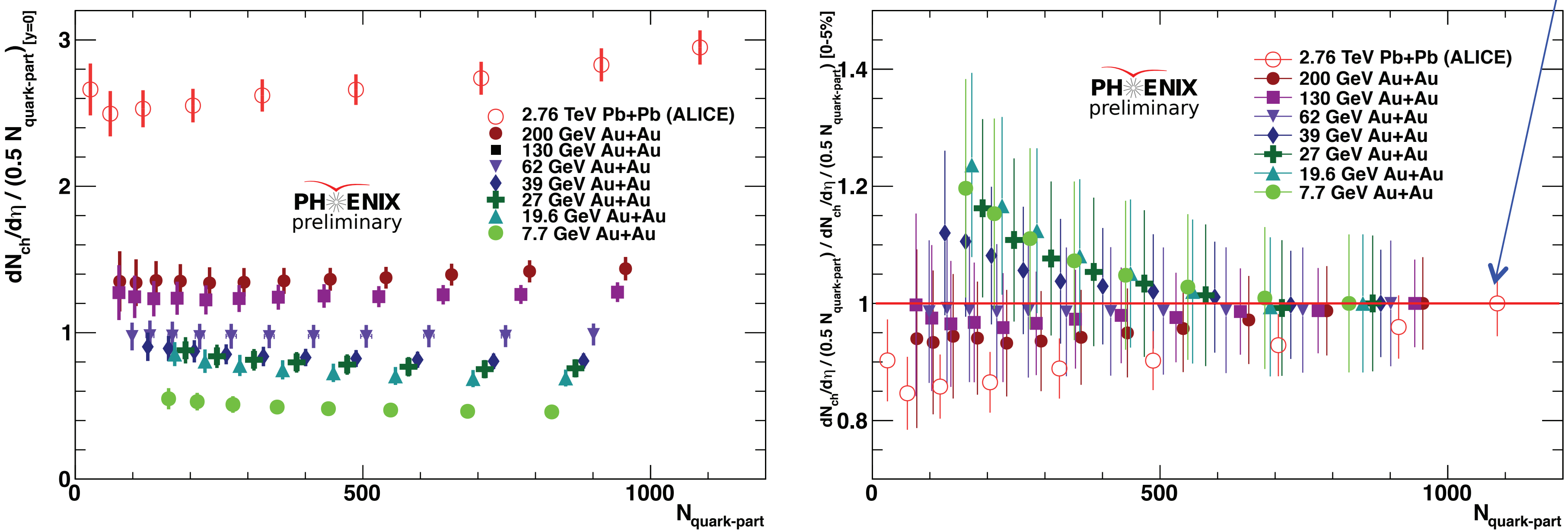
- Additive Quark Model (AQM) & Nqp Identical for symmetric collision systems
- PHENIX asymmetric d+Au data resolves the degeneracy! It is Nqp



The Additive Quark Model (AQM), Bialas and Bialas PRD20(1979)2854 and Bialas, Czyz and Lesniak PRD25(1982)2328,→ color string model. In the AQM model only one color string can be attached to a wounded quark. However for asymmetric systems such as d+Au it is a ``wounded projectile quark'' model since in this model, a maximum of 6 color strings are allowed from d to Au although the Au has many more quark participants. PHENIX data shows that all the quark participants are needed to reproduce d+Au data.

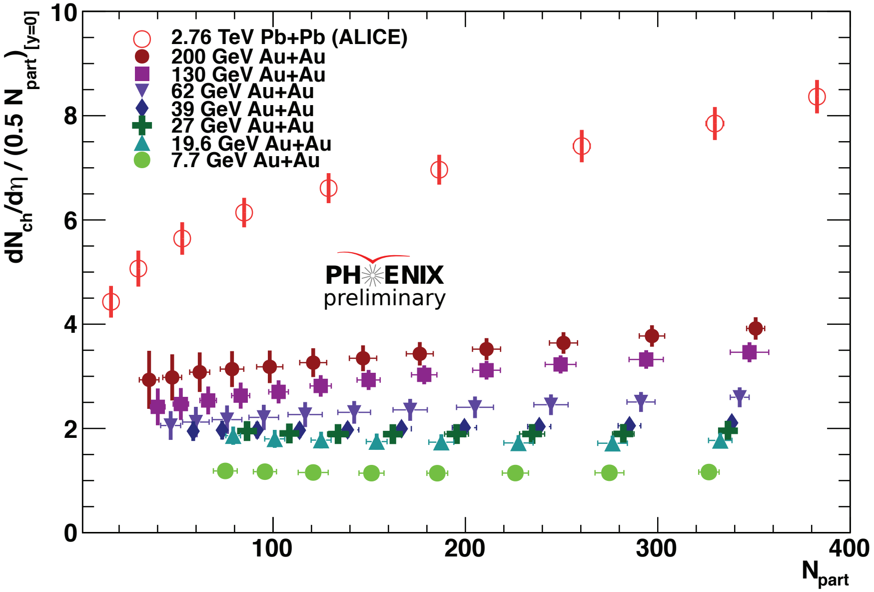
Au+Au Multiplicity--$dN_{ch}/d\eta/(0.5N_{qp})$ vs Constituent Quark Participants (N_{qp})

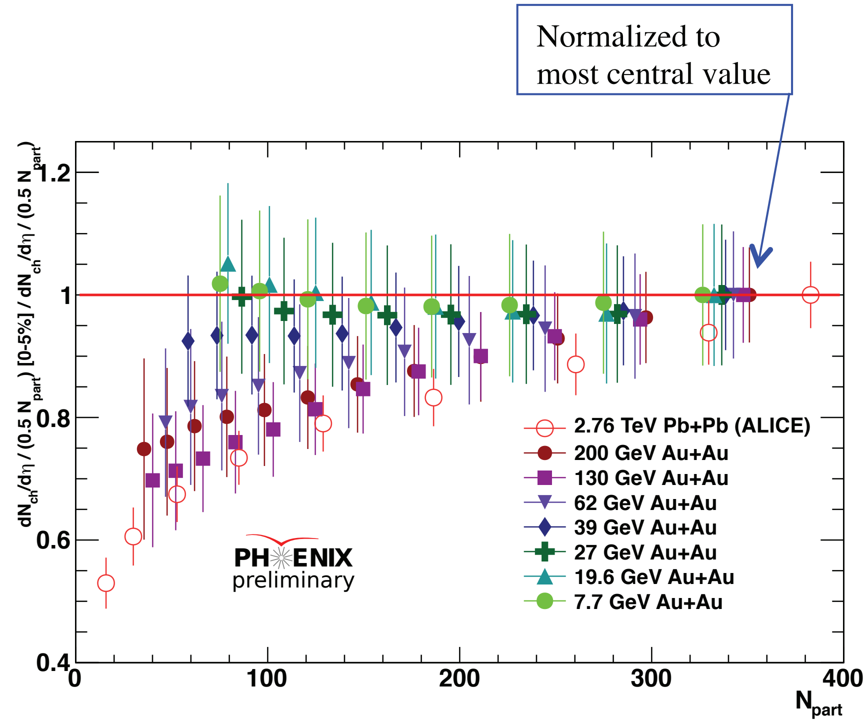
Normalized to most central value



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

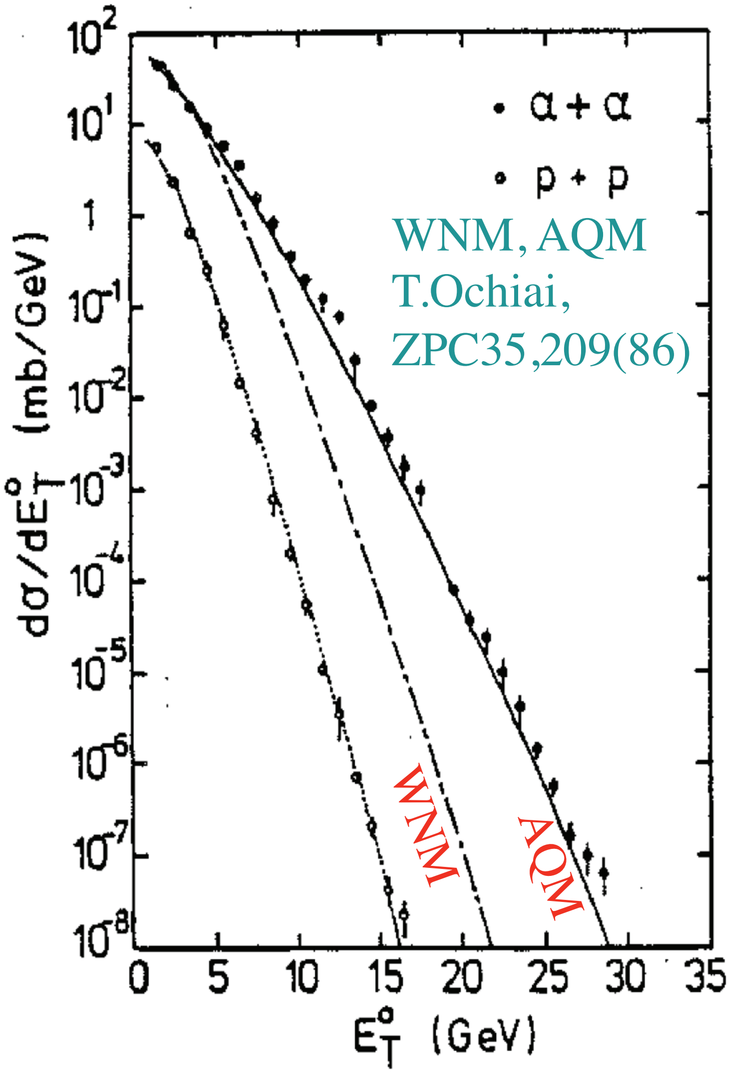
Au+Au Multiplicity $dN_{ch}/d\eta/(0.5N_{part})$ vs *Nucleon Participants* N_{part}





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

From My First Quark Matter Talk 1984
ISR-BCMOR-αα $\sqrt{s_{NN}}$=31GeV: WNM FAILS! AQM works

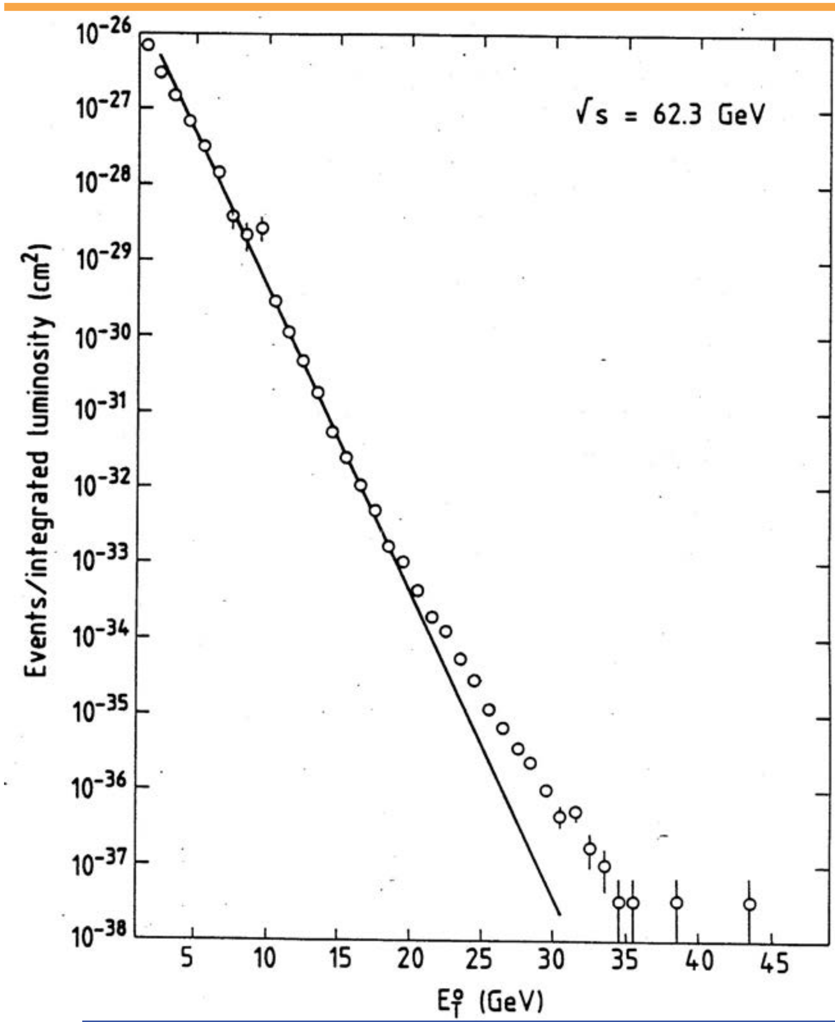


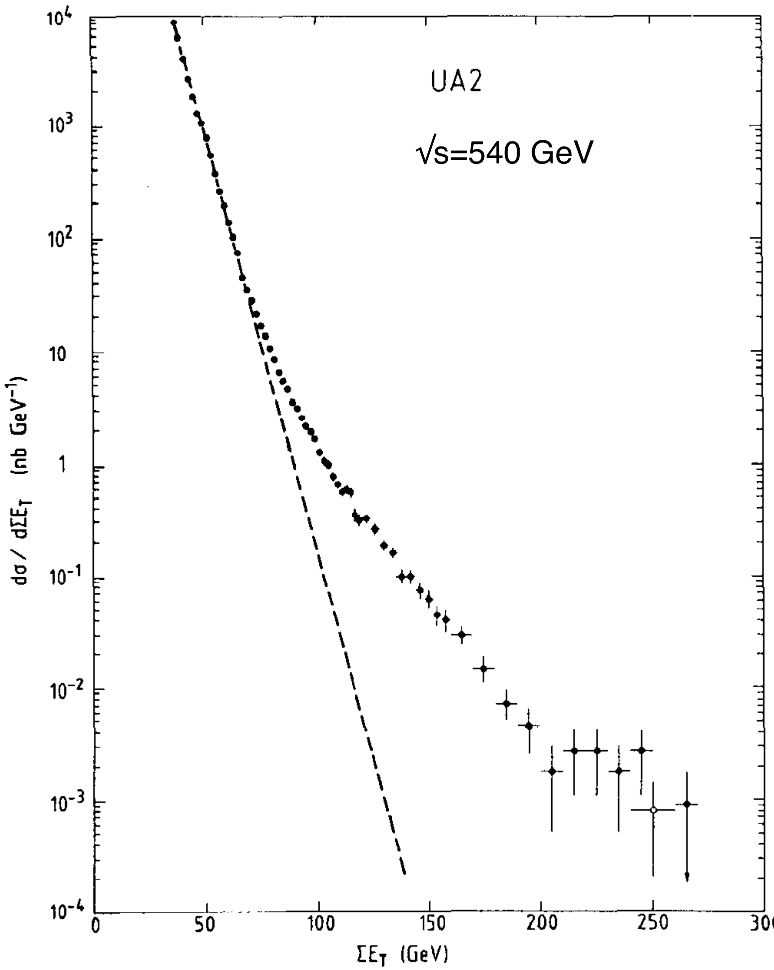
BCMOR PLB**168**(1986)158

WNM agrees with αα data for 1 order of magnitude but disagrees for the other 10 orders of magnitude. AQM (Nqp) is in excellent agreement over the entire distribution. WNM Fails! AQM=Nqp works at 31 GeV

A youngster, Bill Zajc, and other Penn collaborators claimed that failure of WNM was due to jets. BUT, in pp collisions E^o_T is dominated by soft physics, jet effects are not visible until four orders of magnitude down in cross section. For α-α no jet effect in whole measured region [see CMOR Nucl.Phys B**244**(1984)1]

Jets are a <<10^{-3} effect in p-p E_T distributions





COR PLB**126**(1983)132 E_T in $\Delta\Phi=2\pi$, $|\eta|<0.8$ EMCal. Break above 20 GeV is due to jets. Also see NuclPhys B**244**(1984)1

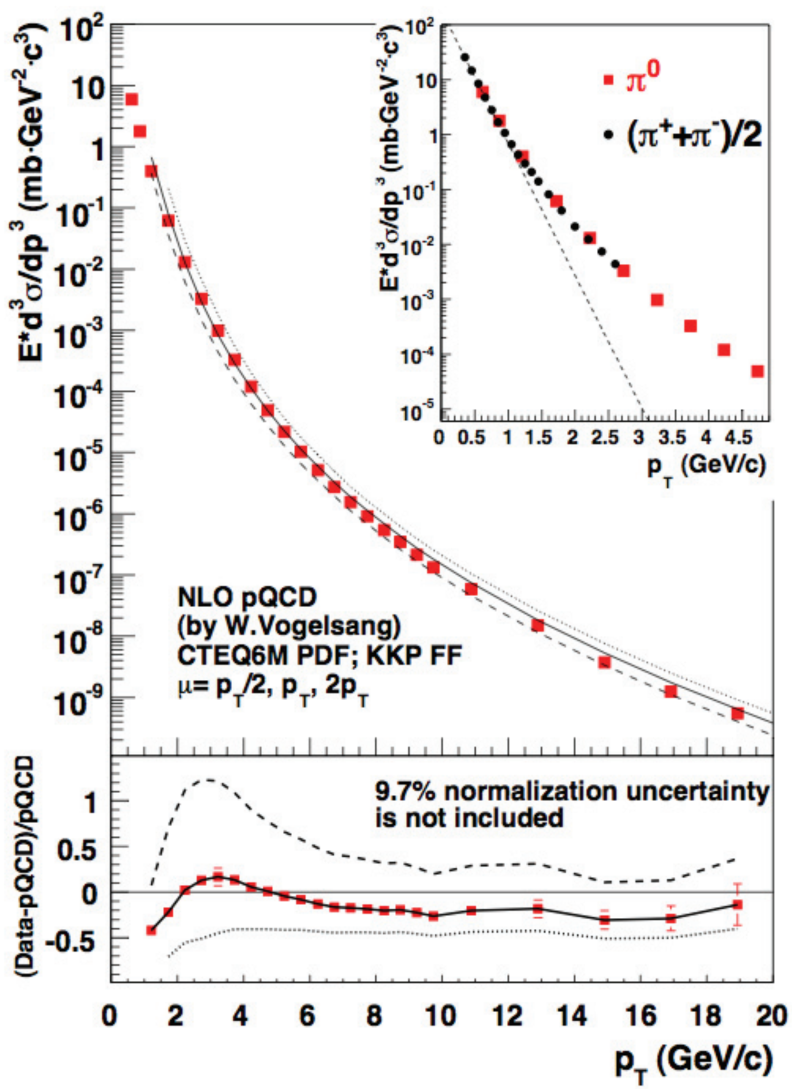
UA2 PLB**138**(1984)430 (from DiLella) Break from jets ~5-6 orders of magnitude down for E_T in $\Delta\Phi=2\pi$, $|\eta|<1.0$

π^0's in p+p $\sqrt{s}$=200 GeV: Data vs. pQCD

- All hadron spectra are exponential for p_T<2 GeV/c in both p-p and A+A collisons. Exponential does not mean thermal unless you think pp is thermal.
- Result from run2-a classic PRL91 (2003) 241803. Better result shown is PRD76 (2007) 051006(R)

NLO-pQCD describes data down even to $p_T \sim 1.5$ GeV/c

Inclusive invariant π^0 spectrum is a pure power law for $p_T \geq 3$ GeV/c, n=8.1±0.1, indicating hard scattering which is visible by the break from an exponential ~3 orders of magnitude down in cross section. Hard scattering more prominent in single particle p_T spectrum than E_T



How I learned to love the Ansatz-Autumn 2013

$$dE_T{}^{AA}/d\eta = [(1-x)\ \langle N_{\rm part}\rangle\ dE_T{}^{pp}/d\eta/2 + x\ \langle N_{\rm coll}\rangle\ dE_T{}^{pp}/d\eta]$$

The N_{coll} term implied a hard-scattering component for E_T, known to be absent in p-p!

However, both ATLAS [PLB707(2012)330] and ALICE [PRC 88 (2013)044909] computed this ansatz in an event-by-event MC Glauber Calculation which fit their forward E_T measurements used to define centrality in 2.76 TeV Pb+Pb collisions. ALICE realized that this combination represented the number of emitting sources of particles, which they named “ancestors”.

But if the ansatz works as a nuclear geometry element and a constituent quark also works THEN said Bill Zajc [now very senior] “the success of the two component model is not because there are some contributions proportional to N_{part} and some going as N_{coll}, but because a particular linear combination of N_{part} and N_{coll} turns out to be an empirical proxy for the number of constituent quarks”. We checked and it worked so we are very happy!

PHENIX Calculation vs Centrality Au+Au

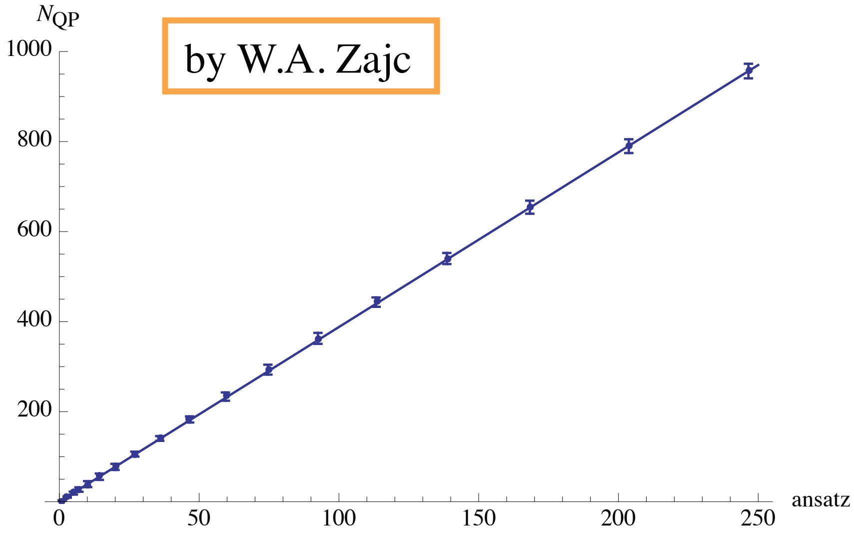
Et voilà, we checked and it worked: the ratio of $N_{qp}/[(1-x)N_{part}/2+x\ N_{coll}]=3.38$ on the average and varies by less than 1% over the entire centrality range in 1% bins, except for the most peripheral bin where it is 5% low and for p-p collisions where it is 2.99

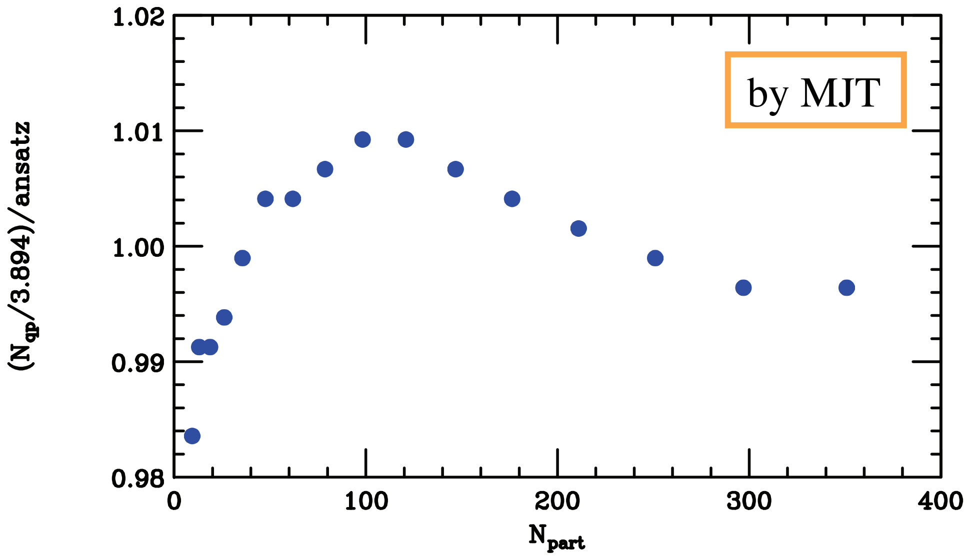
Centrality	$\langle N_{part}\rangle$	$\langle N_{qp}\rangle$	$\langle N_{\rm coll}\rangle$	ansatz	$\langle N_{\rm qp}\rangle$/ansatz
0-5%	350.9 ± 4.7	956.6 ± 16.2	1064.1 ± 110.0	246.5	3.88
5-10%	297.0 ± 6.6	789.8 ± 15.3	838.0 ± 87.2	203.7	3.88
10-15%	251.0 ± 7.3	654.2 ± 14.5	661.1 ± 68.5	168.3	3.89
15-20%	211.0 ± 7.3	540.2 ± 12.3	519.1 ± 53.7	138.6	3.90
20-25%	176.3 ± 7.0	443.3 ± 10.4	402.6 ± 39.5	113.3	3.91
25-30%	146.8 ± 7.1	362.8 ± 12.2	311.9 ± 31.8	92.5	3.92
30-35%	120.9 ± 7.0	293.3 ± 11.0	237.8 ± 24.2	74.6	3.93
35-40%	98.3 ± 6.8	233.5 ± 9.2	177.3 ± 18.3	59.4	3.93
40-45%	78.7 ± 6.1	182.7 ± 6.8	129.6 ± 12.6	46.6	3.92
45-50%	61.9 ± 5.2	140.5 ± 5.3	92.7 ± 9.0	35.9	3.91
50-55%	47.6 ± 4.9	105.7 ± 5.5	64.4 ± 8.1	27.0	3.91
55-60%	35.6 ± 5.1	77.3 ± 6.8	43.7 ± 7.6	19.9	3.89
60-65%	26.1 ± 4.7	55.5 ± 7.1	29.0 ± 6.5	14.3	3.87
65-70%	18.7 ± 4.0	39.0 ± 6.7	18.8 ± 5.3	10.1	3.86
70-75%	13.1 ± 3.2	27.0 ± 4.9	12.0 ± 3.6	7.0	3.86
75-80%	9.4 ± 2.1	19.0 ± 3.2	7.9 ± 2.2	5.0	3.83
80-92%	5.4 ± 1.2	10.3 ± 1.5	4.0 ± 1.0	2.8	3.67
p+p	2	2.99 ± 0.05	1	1	2.99

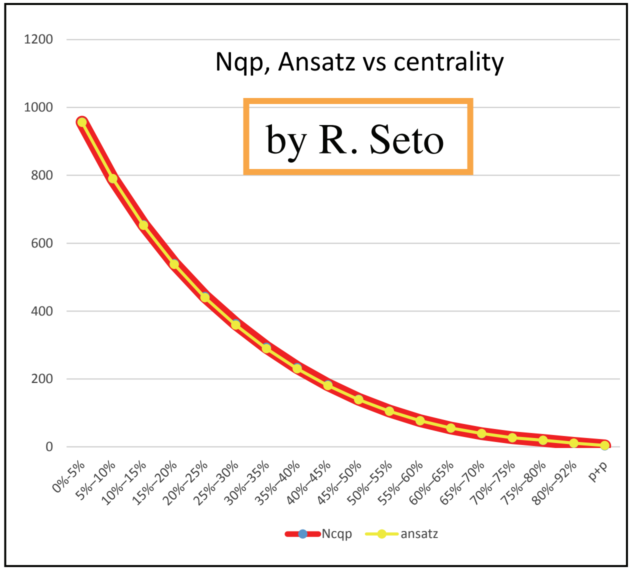
x=0.08

PHENIX Collab. S. S. Adler, *et al*., PRC 89, 044905 (2014)

People who prefer plots are also happy







Conclusions

- The Constituent Quark Participant Model (N_{qp}) works at mid-rapidity for A+B collisions in the range (~30 GeV) 62.4 GeV< $\sqrt{s_{NN}}$< 2.76 TeV.
- The two component ansatz [$(1-x)N_{part}/2+x\,N_{coll}$] also works but does not imply a hard-scattering component in N_{ch} and E_T distributions. It is instead a proxy for N_{qp} as a function of centrality.
- Thus, ALICE's "ancestors" are constituent-quarks.
- Everybody's happy. (OK probably not everybody).

Edward Shuryak is Happy, (CGC types less so)

Collective interaction of QCD strings and early stages of high multiplicity pA collisions

arXiv:1404.1888

Tigran Kalaydzhyan and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Dated: April 8, 2014)

We study early stages of "central" pA and peripheral AA collisions. Several observables indicate that at the sufficiently large number of participant nucleons the system undergoes transition into a new "explosive" regime. By defining a string-string interaction and performing molecular dynamics simulation, we argue that one should expect a strong collective implosion of the multi-string "spaghetti" state, creating significant compression of the system in the transverse plane. Another consequence is collectivization of the "sigma clouds" of all strings into collective chorally symmetric fireball. We find that those effects happen provided the number of strings $N_s > 30$ or so, as only such number compensates small sigma-string coupling. Those finding should help to understand subsequent explosive behavior, observed for particle multiplicities roughly corresponding to this number of strings.

I. INTRODUCTION

A. The evolving views on the high energy collisions

Before we got into discussion of high multiplicity pA collisions, let us start by briefly reviewing the current views on the two extremes: the AA and the minimum bias pp collisions.

The "not-too-peripheral" AA we will define as those which have the number of participant nucleons $N_p > 40$, and the corresponding multiplicity of the order of few hundreds. (*Peripheral* AA, complementary to this definition, we will discuss in this paper, below in section IV B.) Central AA collisions produce many thousands of secondaries: the corresponding fireball has the

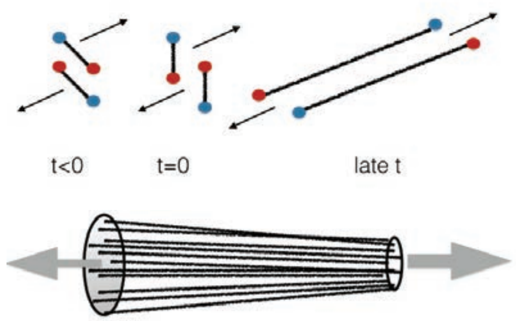
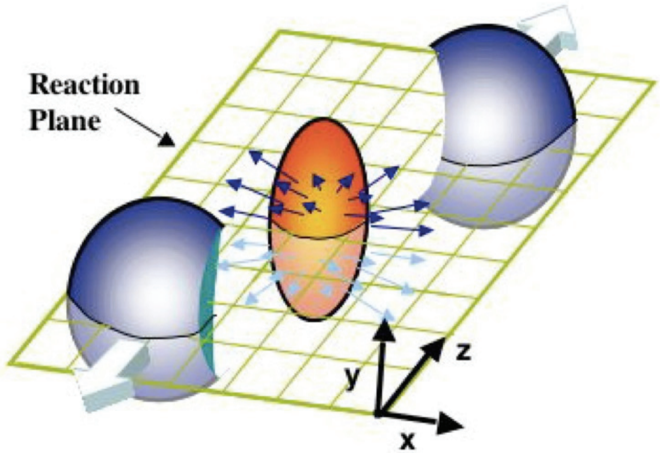
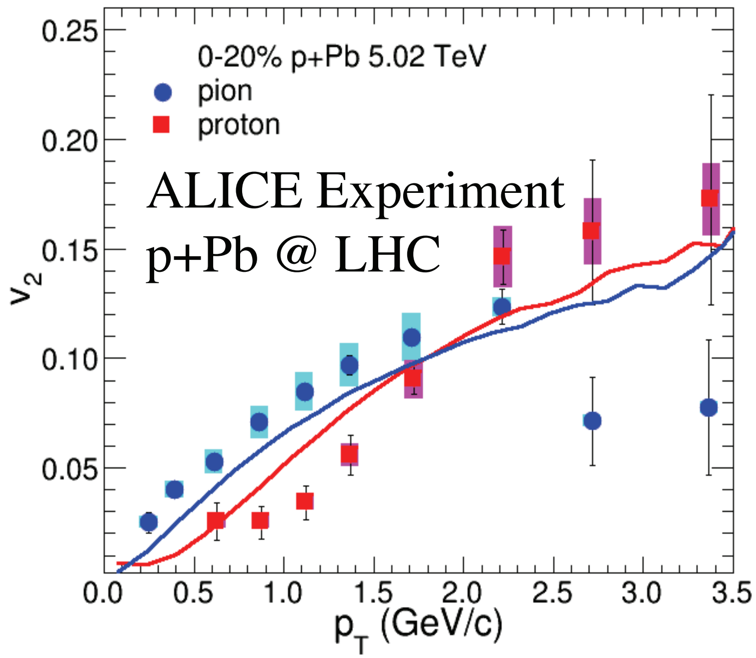


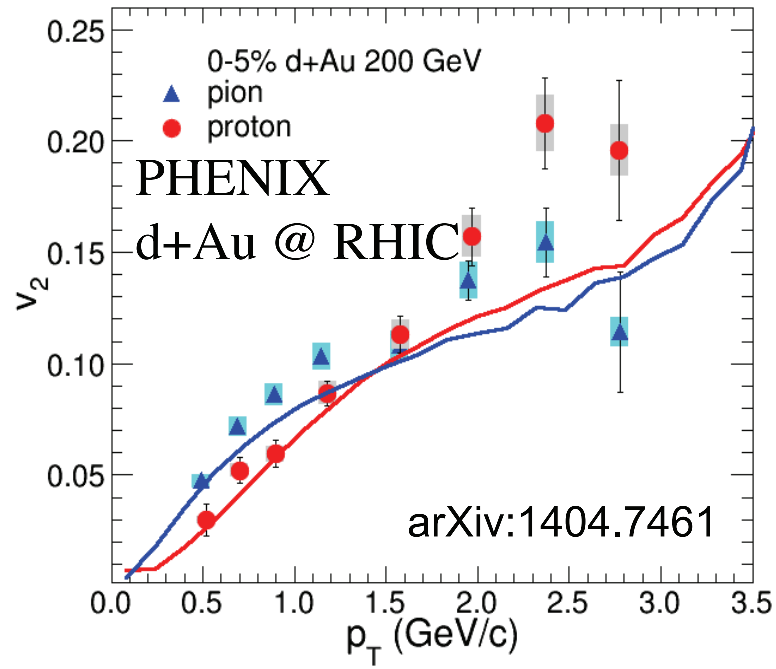
FIG. 1: The upper plot reminds the basic mechanism of two string production, resulting from color reconnection. The lower plot is a sketch of the simplest multi-string state, produced in pA collisions or very peripheral AA collisions, known as "spaghetti".

PHENIX is happy, 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 $p_T=\gamma\beta m$ 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 are now measuring He^3+Au to see if v_3 appears due to 3 nucleons

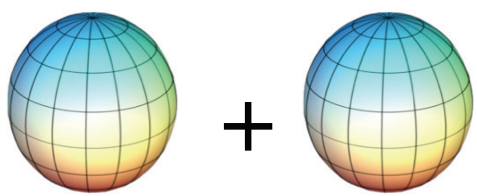
Hui Wang, BNL-STAR

U+U Collisions-STAR Motivation

Allows us to manipulate the initial geometry and study:

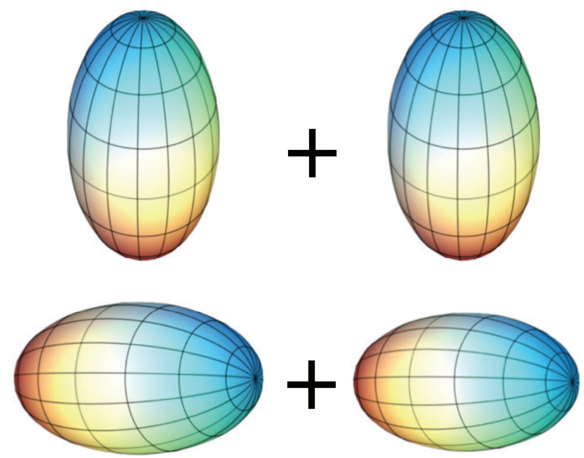
- How multiplicity depends on N_{part} and N_{coll} They won't be happy
- Path-length dependence of jet quenching
- Particle production in heavy-ion collisions
- Other effects most importantly v_2 in central collisions

Au+Au Collisions



Oblate

U+U Collisions

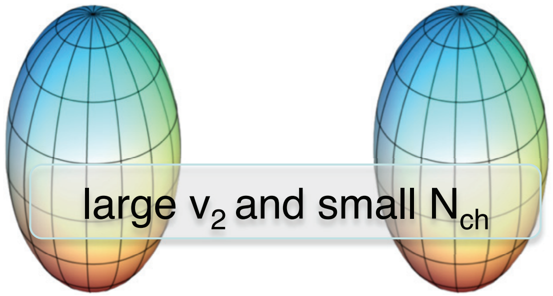


Prolate

Can we see a difference between Au+Au and U+U and preferentially select body-body or tip-tip U+U collisions?

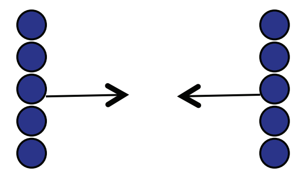
Selecting Body-body or Tip-tip

In two-component model, multiplicity depends on the N_{part} and N_{coll} and since v_2 is propotional to initial eccentricity



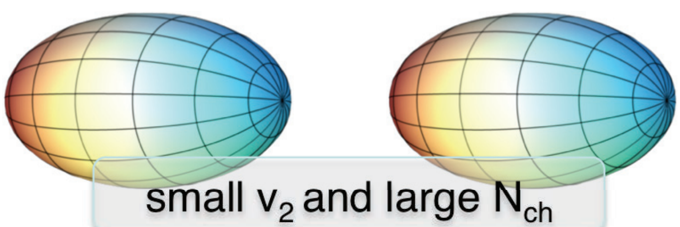
fully overlapping

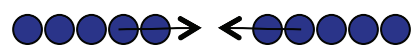
$$n_{AA} \propto n_{pp}[(1-x_{hard})\frac{N_{part}}{2} + x_{hard}N_{coll}]$$



N_{part}=10
N_{coll}= **5**

**idealizations*





N_{part}= 10
N_{coll}= **25**

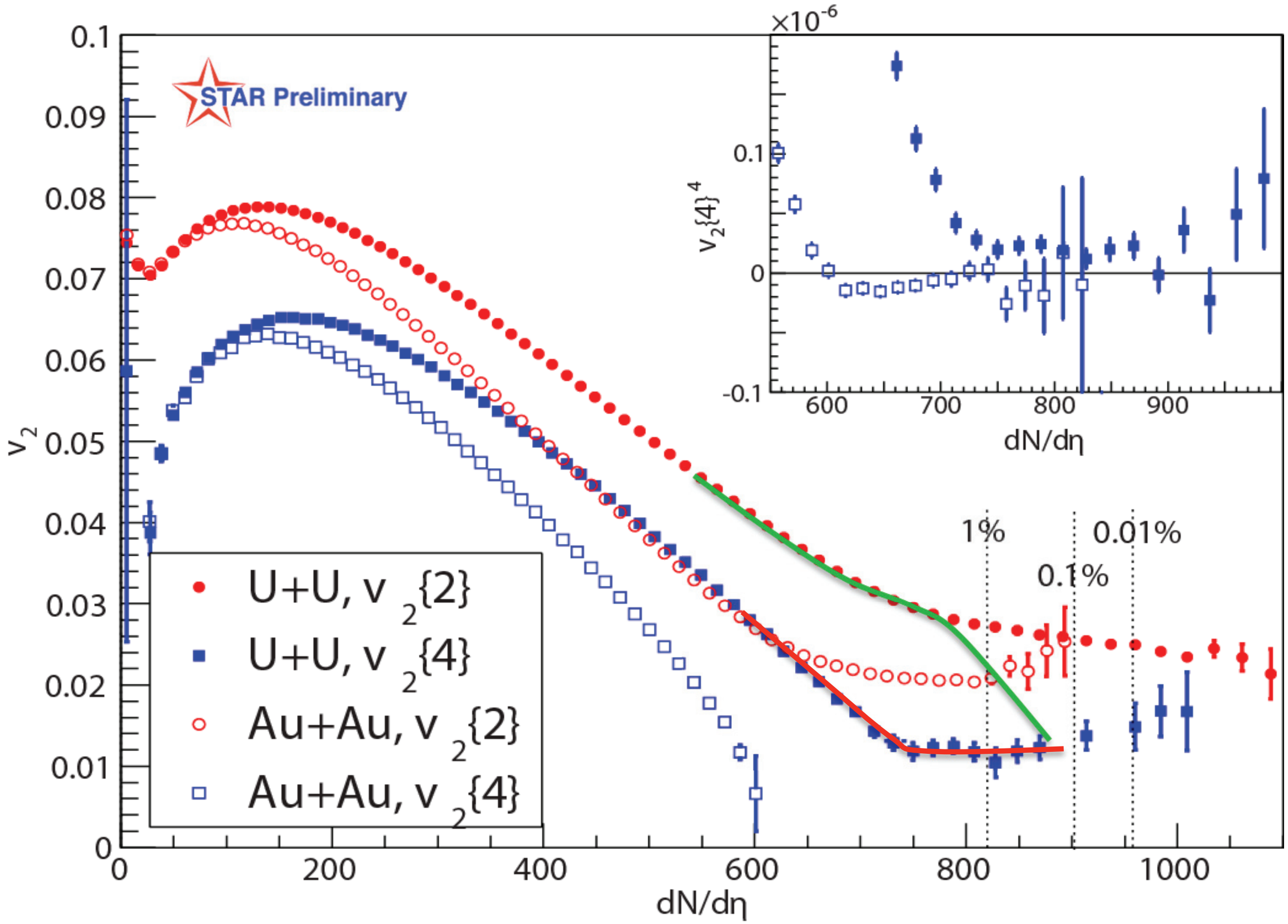
This is wrong they will be disappointed

If dN/dη depends on N_{coll}, large dN/dη should correlate with small v_2.

➪ *Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs. multiplicity: **how strong is the correlation?**

Minimum-bias U+U and Au+Au



No evidence of knee structure for central U+U

- ✓Glauber plus 2-component model suggests knee structure at ~2% centrality
- ✓Knee washed out by additional multiplicity fluctuations?1
- ✓Other interpretations? Yes,Nqp!!!

[1]Maciej Rybczyński, et. al. Phys.Rev. C87 (2013) 044908

The U+U $v_2\{4\}$ results are non-zero in central

✓Result of intrinsic prolate shape of the Uranium nucleus
✓Au $v_2\{4\}$4 becomes consistent with zero

Dashed lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

$v_2\{4\}$ data: we see the prolate shape of the Uranium nucleus ✓

The lack of a knee indicates a weakness in Ncoll multiplicity models

Lecture II
BEAM Energy Scan
Search for Critical Endpoint
I was sandbagged at ISSP2011

STAR's opinion of phase diagram c. 2011

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493 arXiv: 1007.2613

The QCD Phase Diagram

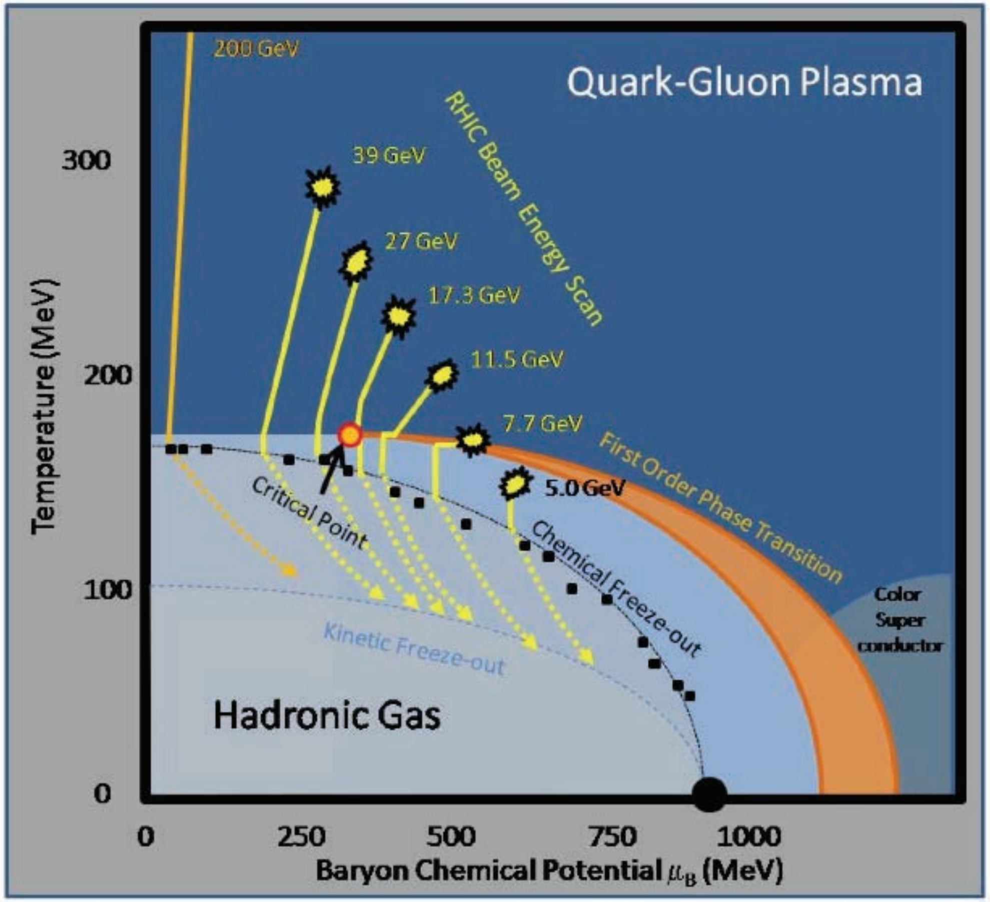
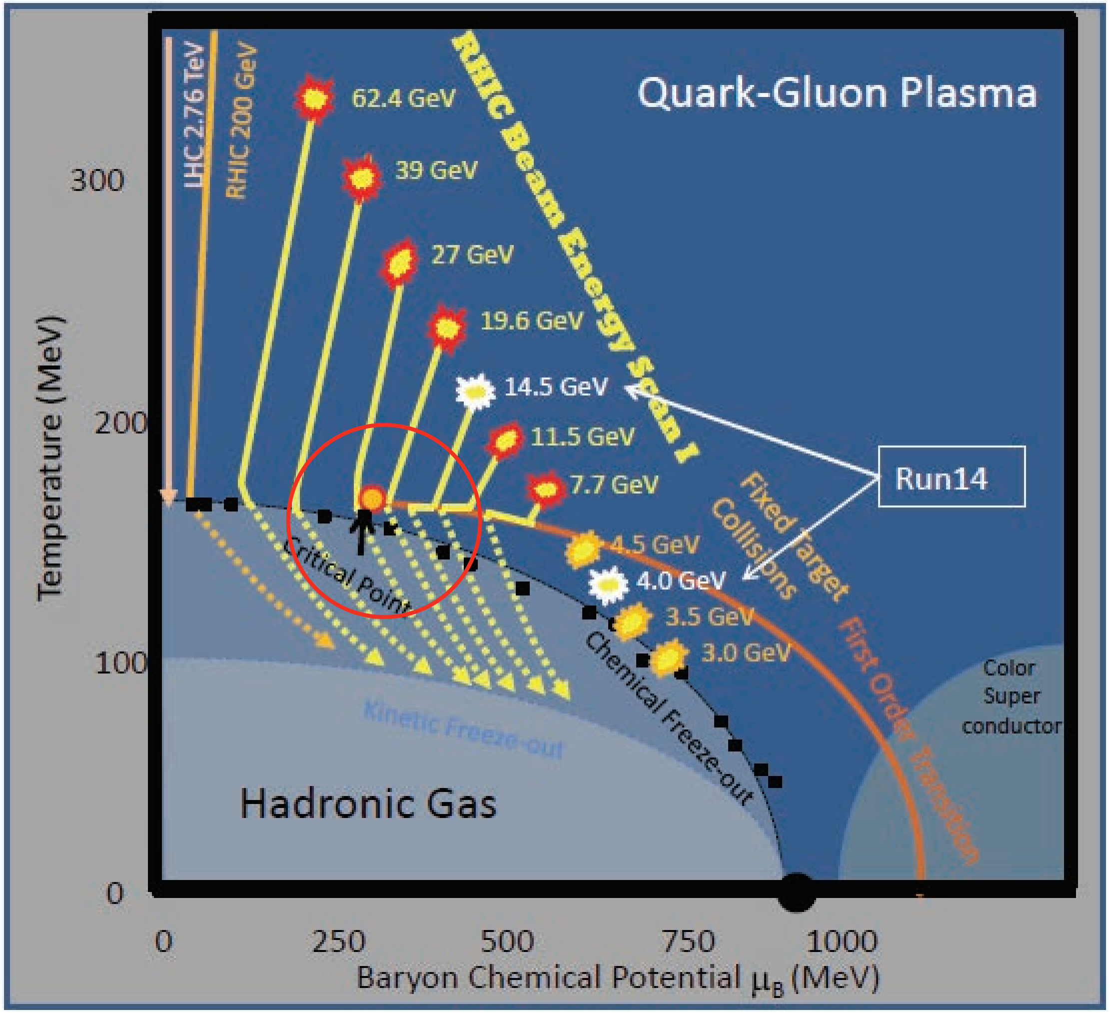


Fig. 1: A schematic representation of the QCD Phase Diagram. The location of the critical point, the separation between the 1st-order transition and chemical freeze-out, and the focusing of the event trajectories towards the critical point, are not based on specific quantitative predictions, but are all chosen to illustrate plausible possibilities.

STAR's opinion of PHASE diagram 2014



Warning

T=160 MeV
μ_B=300 MeV
$\sqrt{s_{NN}}$~30 GeV

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

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

Hot off the presses-LBL Press release June 24, 2011

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

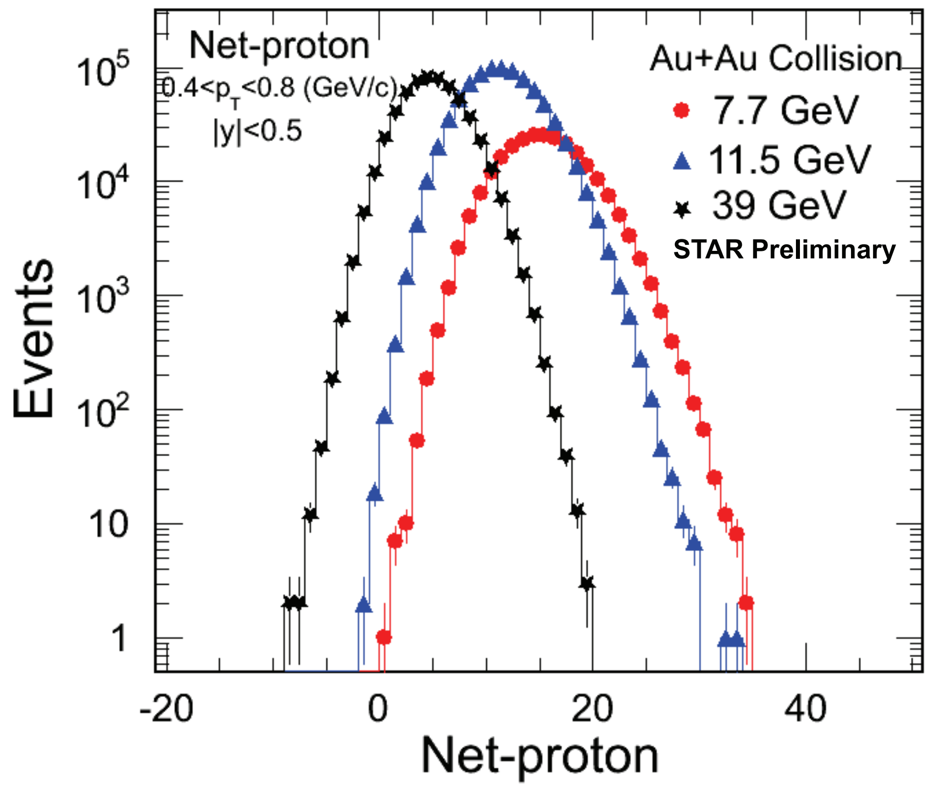
When Matter Melts

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

June 23, 2011

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

- 1^{st} moment: mean = $\mu = \langle x \rangle$
- 2^{nd} cumulant: variance $\kappa_2 = \sigma^2 = \langle (x-\mu)^2 \rangle$
- 3^{rd} cumulant: $\kappa_3 = \sigma^3 = \langle (x-\mu)^3 \rangle$
- 3^{rd} standardized cumulant: skewness = $S = \kappa_3/\kappa_2^{3/2} = \langle (x-\mu)^3 \rangle/\sigma^3$
- 4^{th} cumulant: $\kappa_4 = \langle (x-\mu)^4 \rangle - 3\kappa_2^2$
- 4^{th} standardized cumulant: kurtosis = $\kappa = \kappa_4/\kappa_2^2 = \{\langle (x-\mu)^4 \rangle/\sigma^4\} - 3$
- 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 Gauge 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 χ

- The only connection of this method to mathematical statistics is that the Cumulant generating function is also a Taylor expansion of the ln of an exponential:

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

Lattice and Experiment Compared-a first?

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

- Calculate QGP-QCD on Lattice. Find P/T^4 as a function of T/T_c and μ_B/T, (Tc is critical temp) (μ_B Baryon chemical potential). Take derivatives to find cumulants, B^n (just terms in the series expansion). V is volume.

$$T^{n-4}\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right) = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_B/T)^n}P\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)\Bigg|_{T/T_c}$$

$$[B^n] = VT^3T^{n-4}\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)$$

- Higher moments of net-proton distribution can be related to thermodynamic susceptibilities, B^n, but take ratios so that Volume and other factors cancel:
  $(\kappa\sigma^2)_B = \langle(x-\langle x\rangle)^4\rangle/\sigma^2 - 3\sigma^2 = B^4/B^2 = T^2\, \chi_B^{(4)}/\chi_B^{(2)}$
  $(\kappa\sigma/S)_B = \{\langle(x-\langle x\rangle)^4\rangle/\sigma^3 - 3\sigma\}/\langle(x-\langle x\rangle)^3\rangle/\sigma^3 = B^4/B^3 = T\,\chi_B^{(4)}/\chi_B^{(3)}$
- Hadron Resonance Gas Calculations: M.Cheng et al, Phys. Rev. D 79, 074505 (2009), F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011))\
- Predictions that critical fluctuations contribute to higher moments and are strongly dependent on correlation length (ζ) of the system:
  4th order moments go as ζ^7. (M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009))
- For net-charge, change index from B to Q. For net-kaons, change B to S.

Following T. Tarnowsky QM2011

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

Table 1: 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	$\sigma^2(1-6p+6p^2)$	$\sigma^2(1+6\mu/k+6\mu^2/k^2)$
$S \equiv \kappa_3/\sigma^3$	$1/\sqrt{\mu}$	$(1-2p)/\sigma$	$(1+2\mu/k)/\sigma$
$\kappa \equiv \kappa_4/\kappa_2^2$	$1/\mu$	$(1-6p+6p^2)/\sigma^2$	$(1+6\mu/k+6\mu^2/k^2)/\sigma^2$
$S\sigma$	1	$(1-2p)$	$(1+2\mu/k)$
$\kappa\sigma^2$	1	$(1-6p+6p^2)$	$(1+6\mu/k+6\mu^2/k^2)$

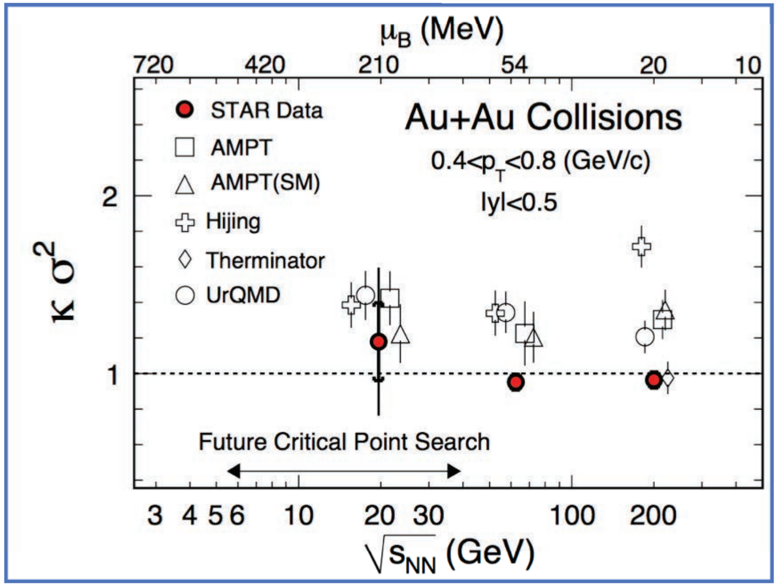
Thanks to Gary Westfall of STAR in a paper presented at Erice-International School of Nuclear Physics 2012, I found out that the cumulants of the difference of samples from two such distributions P(n-m) where $P^+(n)$ and $P^-(m)$ are both Poisson, Binomial or NBD with Cumulants κ_j^+ and κ_j^- respectively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

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

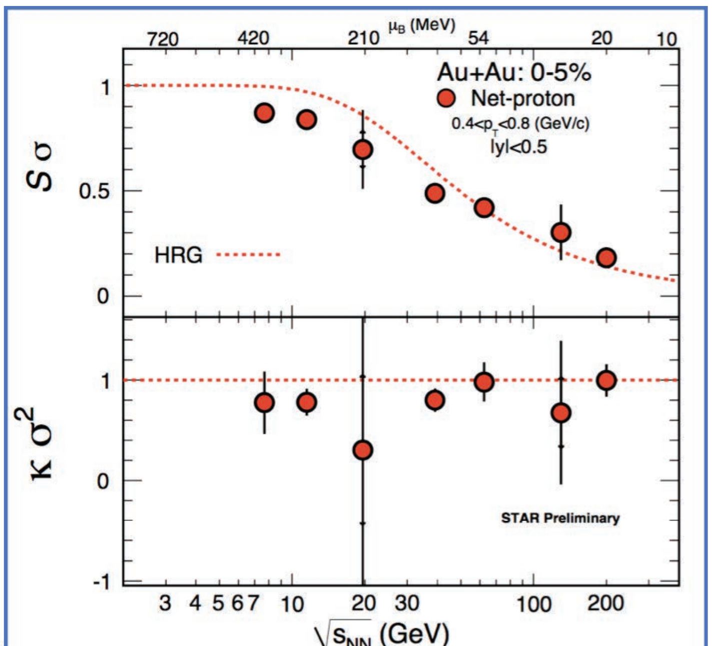
Results from 2011

STAR Plots

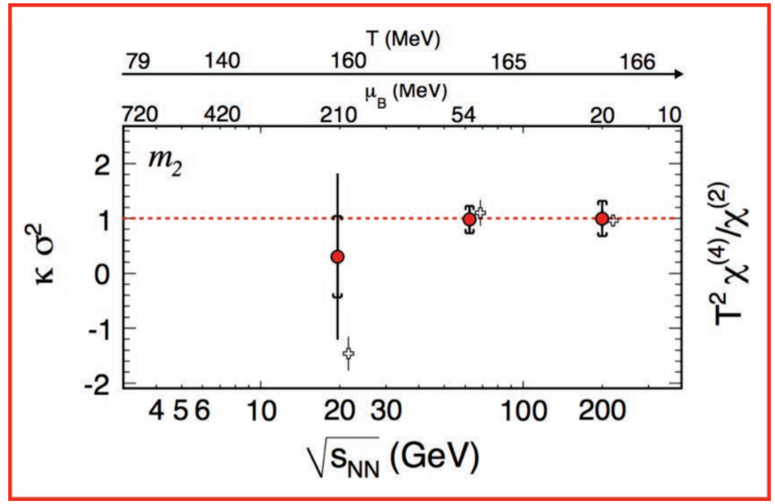
PRL105(2010) 022302



JPG38(2011) 124054



Theorists Plot
Science 332 (2011) 1525



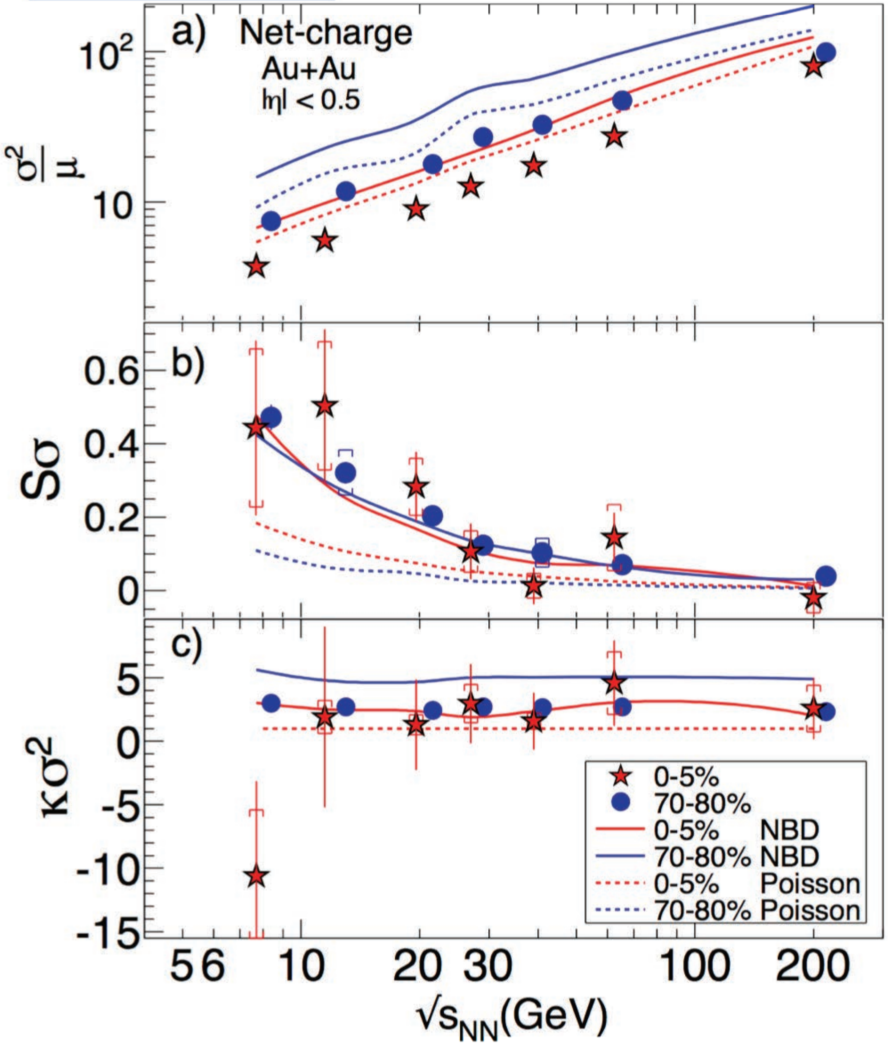
Lattice shows huge deviation of $T^2\,\chi^{(4)}/\,\chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa\sigma^2$ suggests not; but with big errors. Need more data. Above plot is different from PRL105

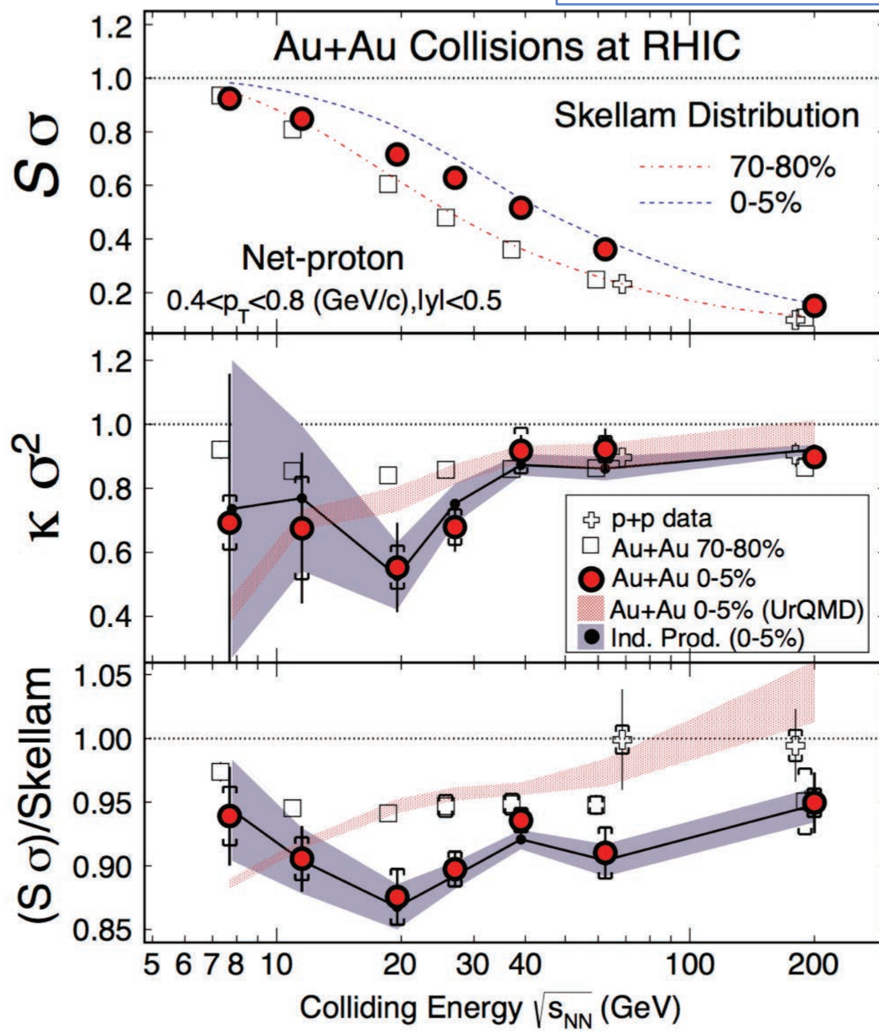
Is JPG38 plot Evidence for phase transition from resonance gas to QGP at T_c=175 MeV ???!!!!!!!

New STAR publications 2014

arXiv: 1402.1558

PRL 112(2014) 032302



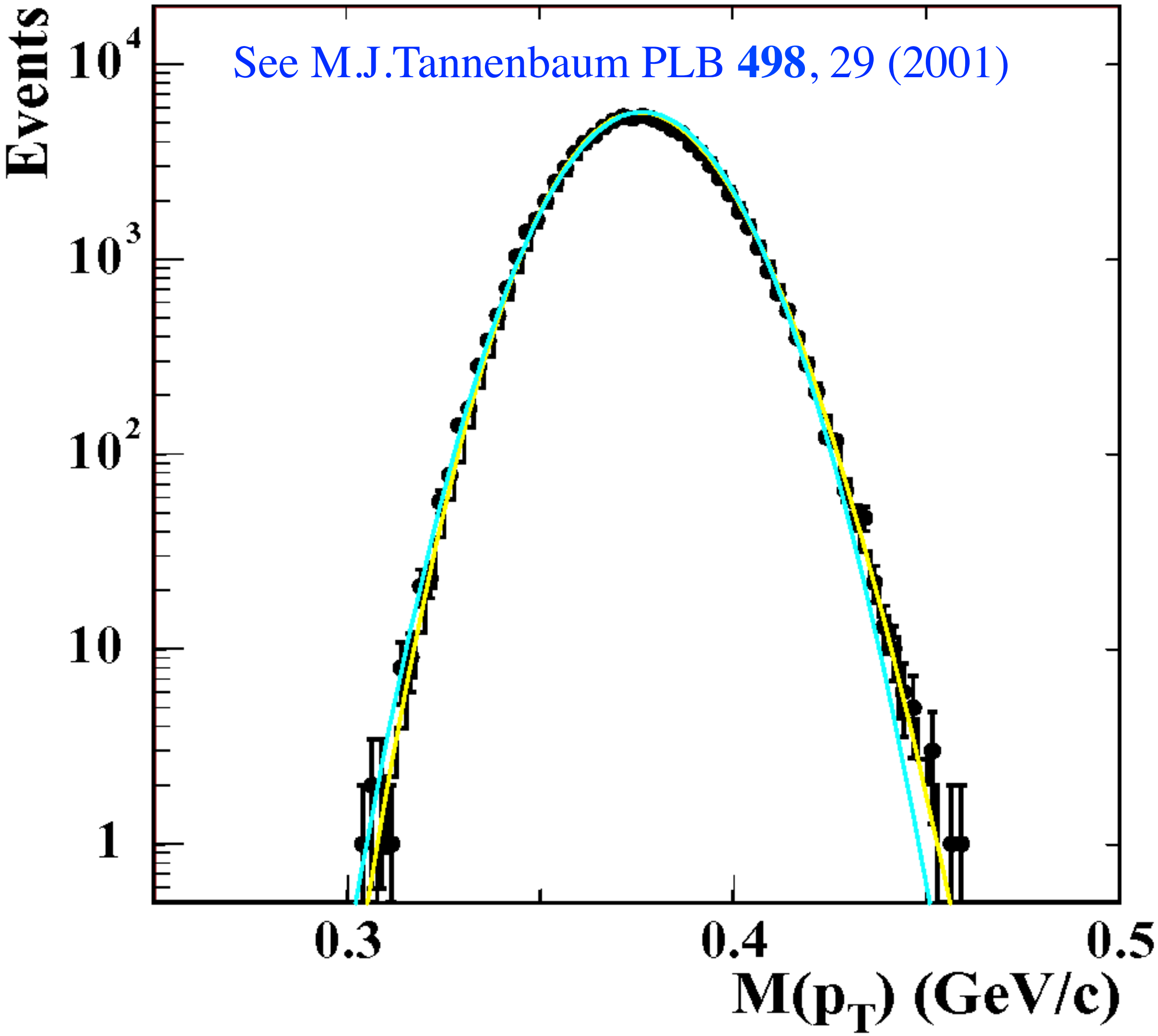


Sσ clearly favors NBD, not Poisson (!).
No non- monotonic behavior in Sσ or $\kappa\sigma^2$
but $\kappa\sigma^2$=-1.5 at $\sqrt{s_{NN}}$ =20 can't be ruled out

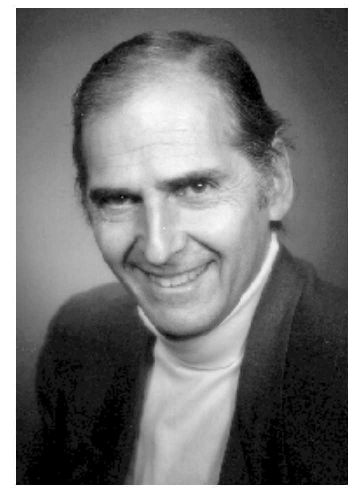
$\kappa\sigma^2$=-1.5 at $\sqrt{s_{NN}}$ =20 **can** be ruled out
$\kappa\sigma^2$ changes for $\sqrt{s_{NN}} \leq$ 30 GeV but
antiprotons become negligible ≤0.02 p

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

NA49 Pb+Pb central PLB **459**, 679 (1999)

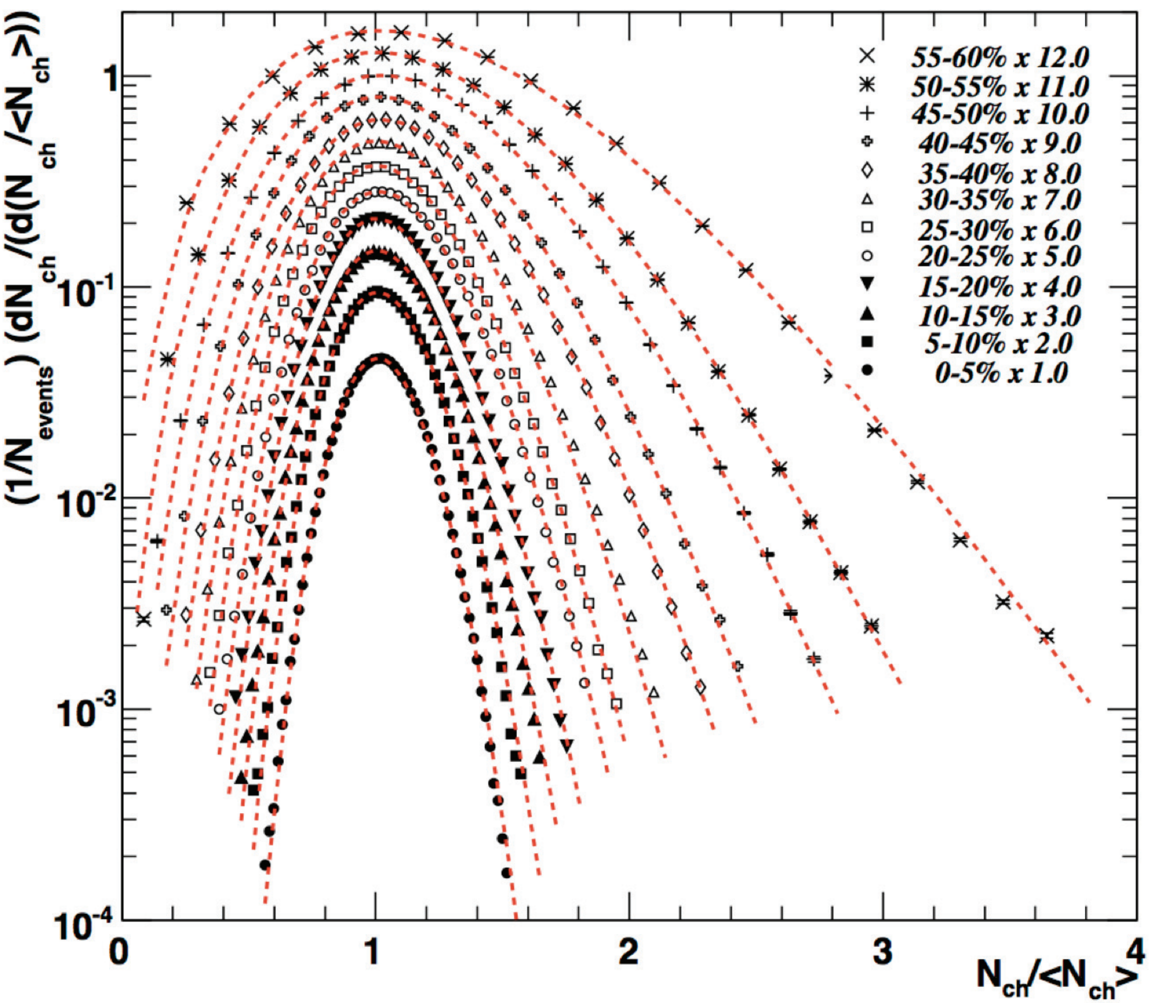


It's not a Gaussian… it's a Gamma distribution!



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

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



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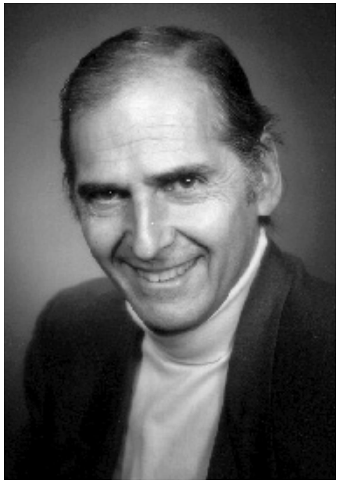


Also: It's not Poisson, it's negative binomial

Why I am so Adamant about NOT POISSON:

CORRELATIONS

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 $\rightarrow$ Poisson as $k \rightarrow \infty$, $1/k \rightarrow 0$

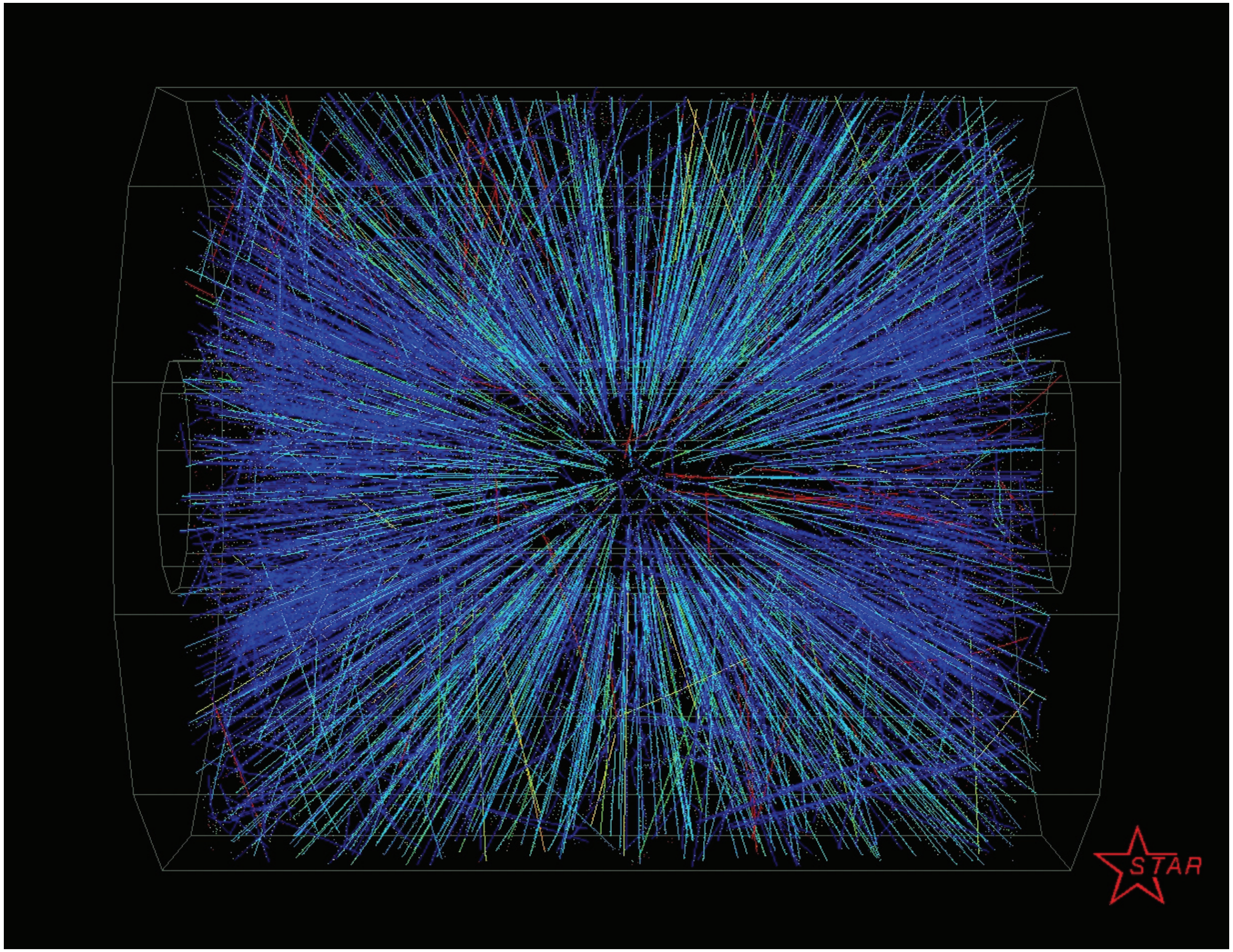
$$P(m)|_\mu = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\frac{\mu}{k}\right)^m}{\left(1+\frac{\mu}{k}\right)^{m+k}}$$

- Moments: $\langle m \rangle = \mu \qquad \dfrac{\sigma^2}{\mu^2} = \dfrac{1}{\mu} + \dfrac{1}{k} \qquad \dfrac{\sigma^2}{\mu} = 1 + \dfrac{\mu}{k}$

- The n-th convolution of NBD is an NBD with $k \rightarrow nk$, $\mu \rightarrow n\mu$ 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.

STAR first event 2001
Long Range Rapidity correlations



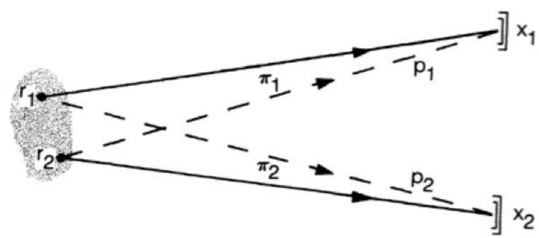
Large multiplicity on left side $\eta<0$ also has large multiplicity $\eta>0$

Do Short range multiplicity correlations 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 $\xi \sim 1$ unit of rapidity

- In A+A collisions the chance of getting two particles from the same ρ meson is reduced by $\sim 1/N_{part}$ 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.

for NBD: k vs δη:

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

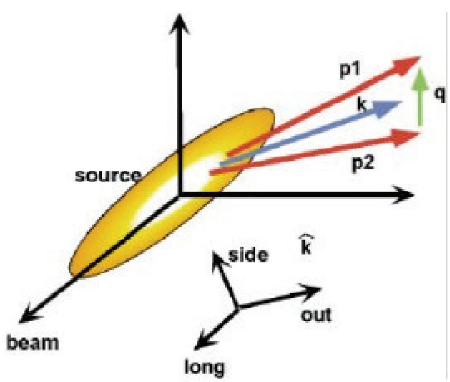
The rapidity correlation length $\xi = 0.2$ for Si+Au E802, PRC56(1977) 1544 is from HBT.

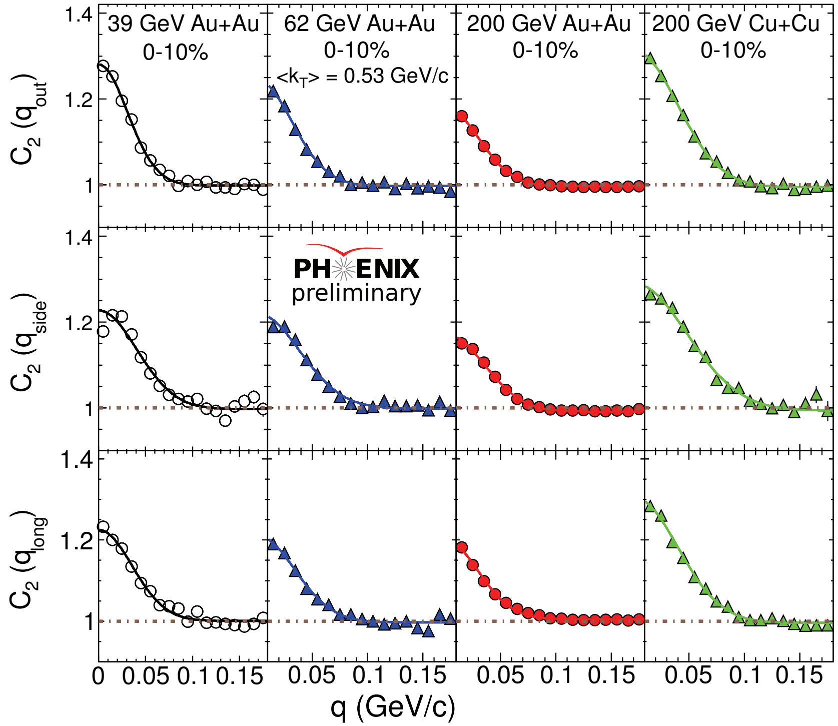
- For HBT analyses of two particles with $\mathbf{p}_1$ and $\mathbf{p}_2$, $C^{HBT}{}_2(\mathbf{q})=R_2(\mathbf{p}_1 - \mathbf{p}_2)+1$ and the random (un-correlated) distribution is taken from particles with $\mathbf{p}_1$ and $\mathbf{p}_2$ on different events. The HBT correlation function is taken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

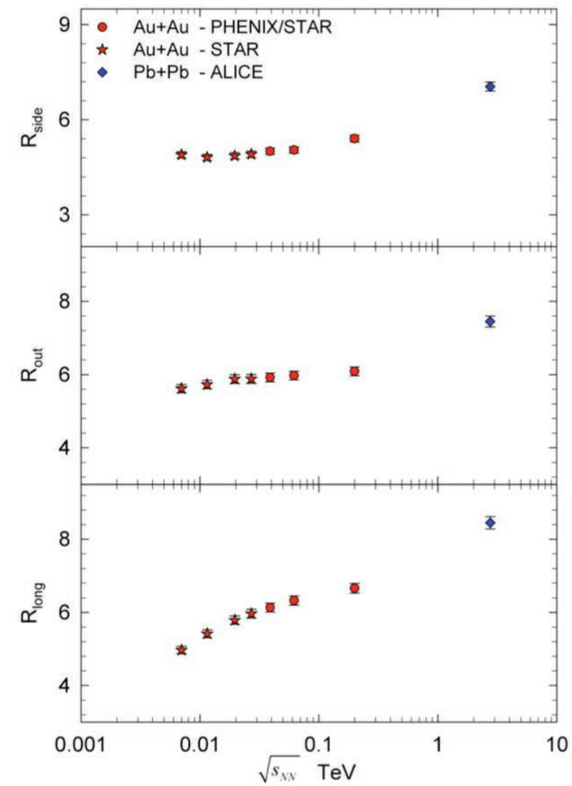
$$\boxed{C_2^{HBT} = 1 + \lambda \exp-(R^2_{side}q^2_{side} + R^2_{out}q^2_{out} + R^2_{long}q^2_{long})}$$

PHENIX HBT BES Results

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





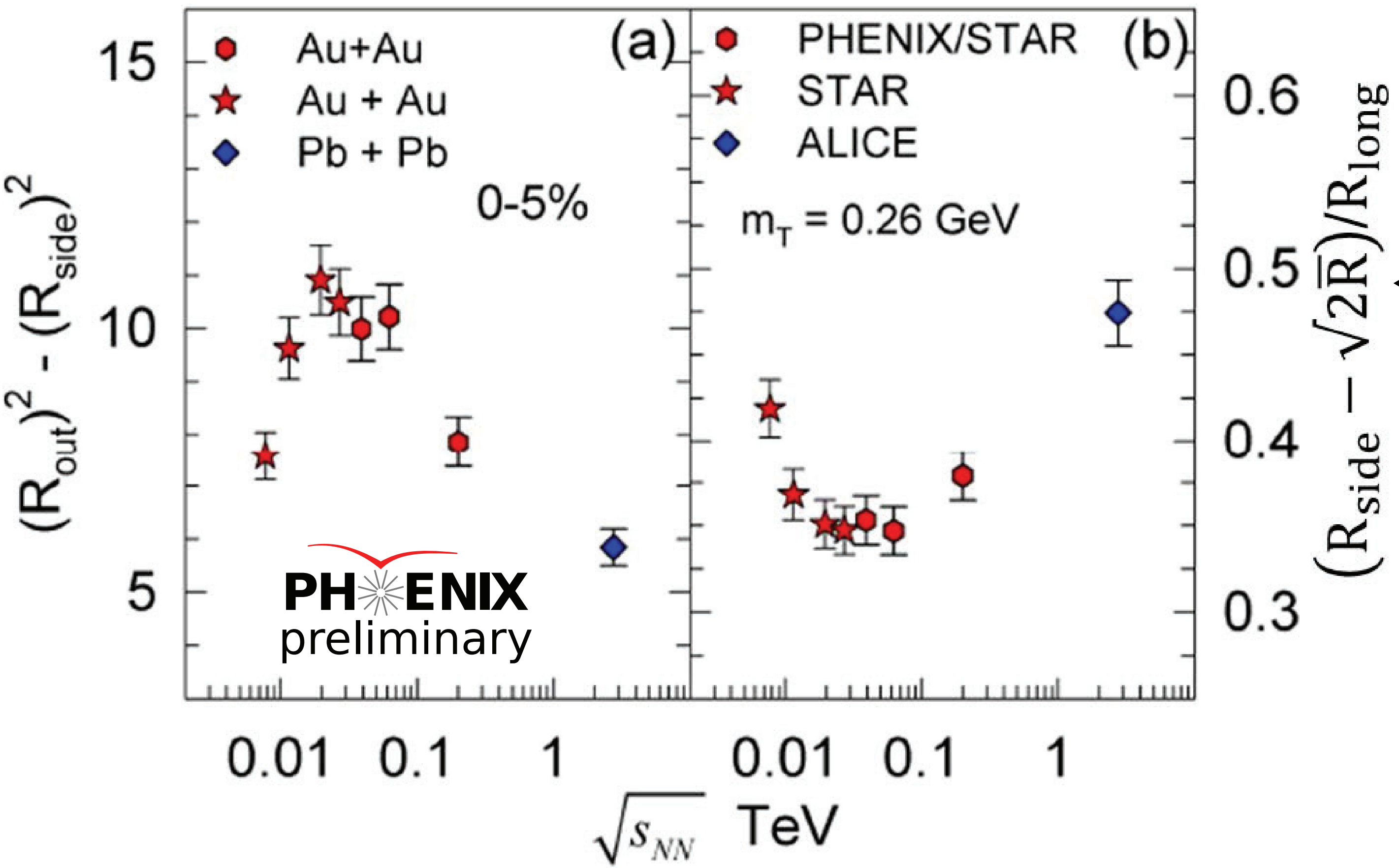


$C_2^{HBT}(q)$

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

J/Ψ Suppression: some new, some unfinished business since/from ISSP2013

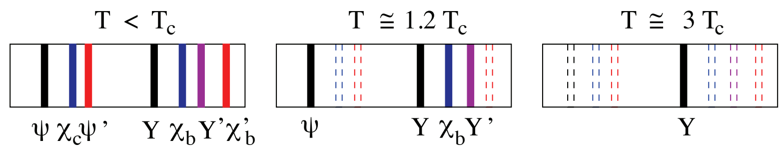
The gold-plated signature for the QGP: J/ψ Suppression

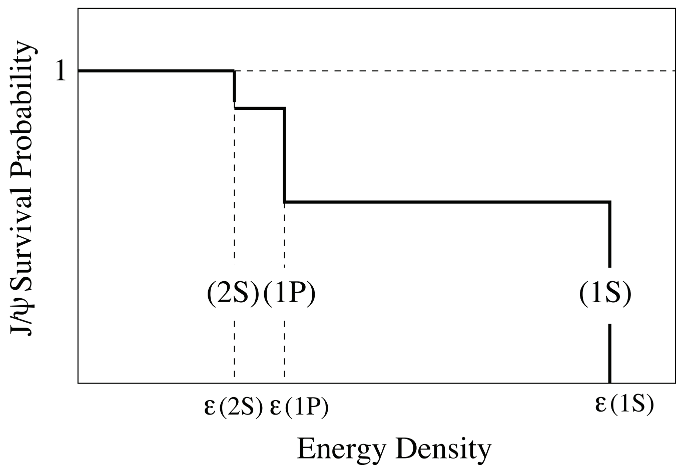
• 1986, T. Matsui & H. Satz PL **B178**, 416 (1987) propose that the Debye screening of the color potential in a QGP, will suppress charmonium production because the cc-bar couldn't bind.

Binding Energy, radius: J/Ψ:600 MeV, 0.2fm; Υ:1.2 GeV, 0.1fm, T_c~400MeV

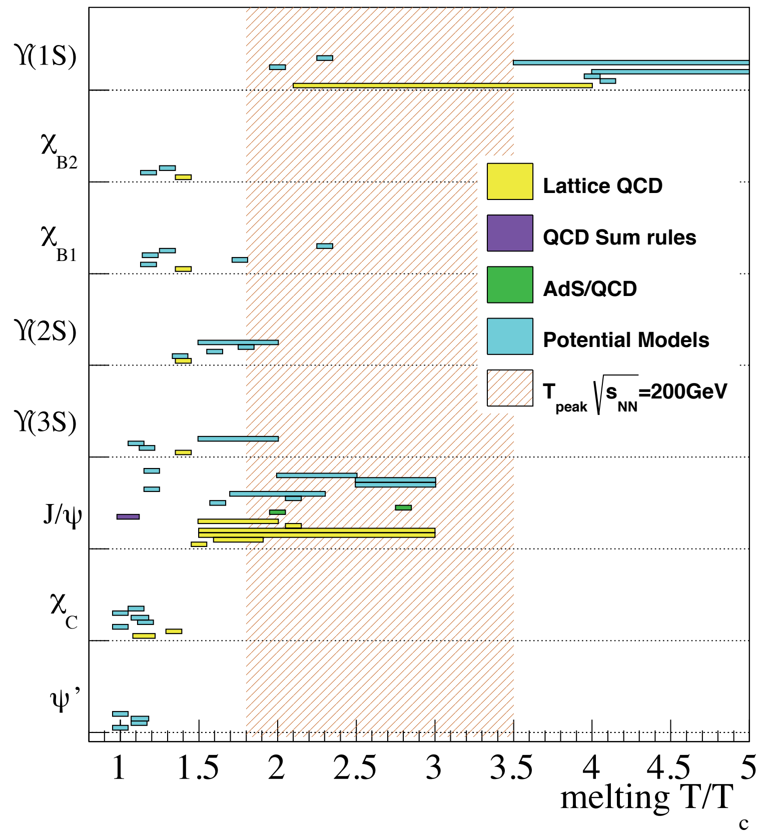
Latest review H.Satz, arXiv:1310.1209: Sequential Screening with Increasing temperature and smaller radius

LQCD results (still debated) ...⟶





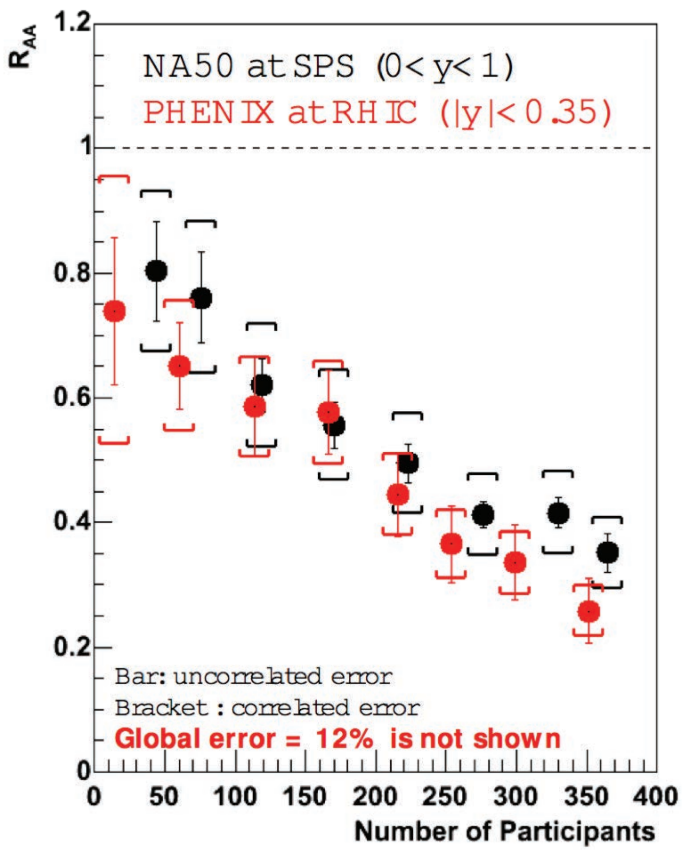
quarkonium as thermometer

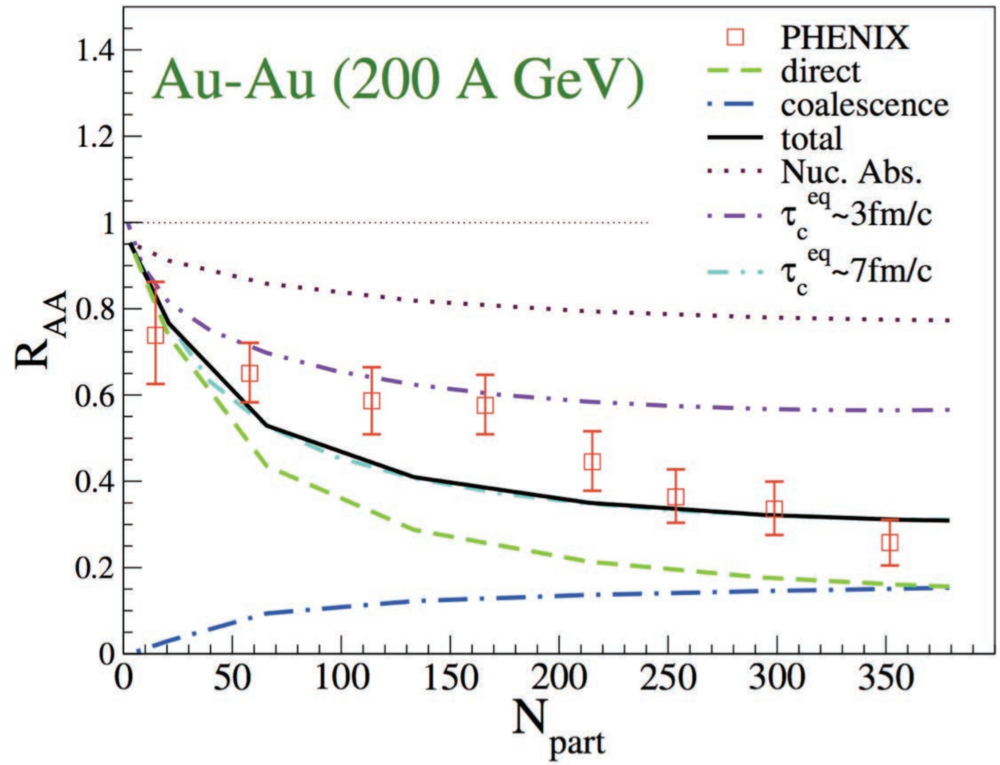


PHENIX, arXiv:1404.2246

PHENIX was designed to see J/Ψ at p_T=0

J/ψ Suppression same at $\sqrt{s_{NN}}$ 17 and 200 GeV





PHENIX PRL **98**, 232301 (2007)

- One possible explanation: Grandchamp, Rapp, Brown; PRL 92, 212301 (2003)
  - ✓ In-media dissolution from deconfinement
  - ✓ Plus regeneration from coalescence of "off-diagonal" c-cbar pairs:

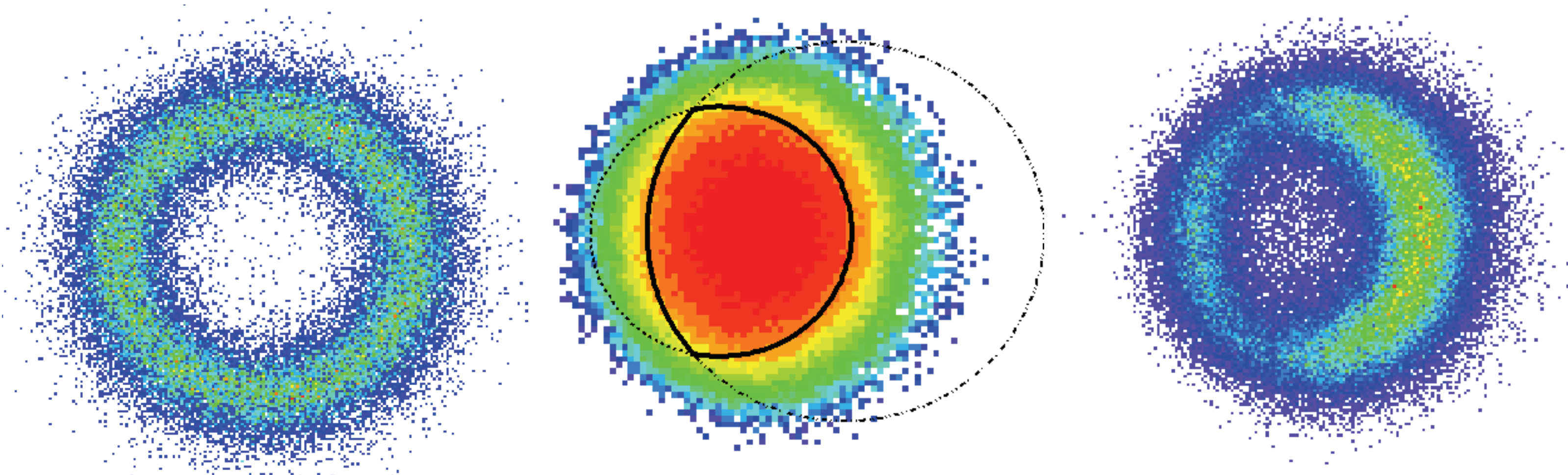
My Nightmare Scenario: I thought that nobody would believe this. Must see J/ψ enhancement to believe⇒Wait for LHC result

Satz-Corona Effect?

Helmut suggested that the reason $R_{AA}(J/\psi)$ is the same at SpS and RHIC is that only the J/ψ in the corona at the edges of the overlap region are seen in both places. Total absorption takes place in the center. We ran Cu+Au to test this---Also shows the versatility of RHIC.

- Completely swallowed Cu-nucleus in central collisions
  - Cu-going corona vanishes
- Naturally odd harmonics
  - Possibility to investigate a “true v3”
- Large “corona” on Au-side
  - Investigation of it's size
  - “v_1-like” azimuthal dependence

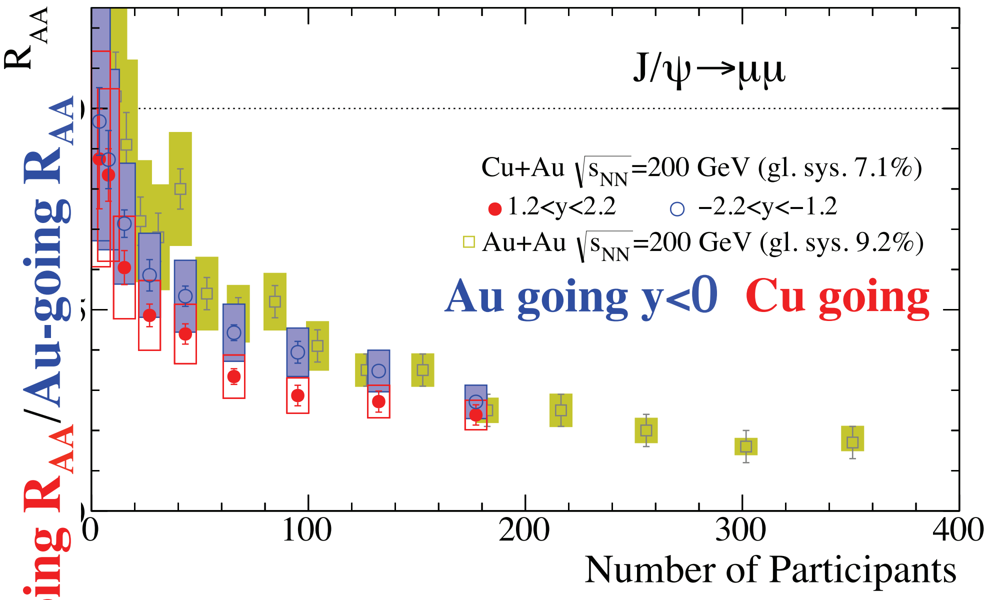
Glauber model CuAu

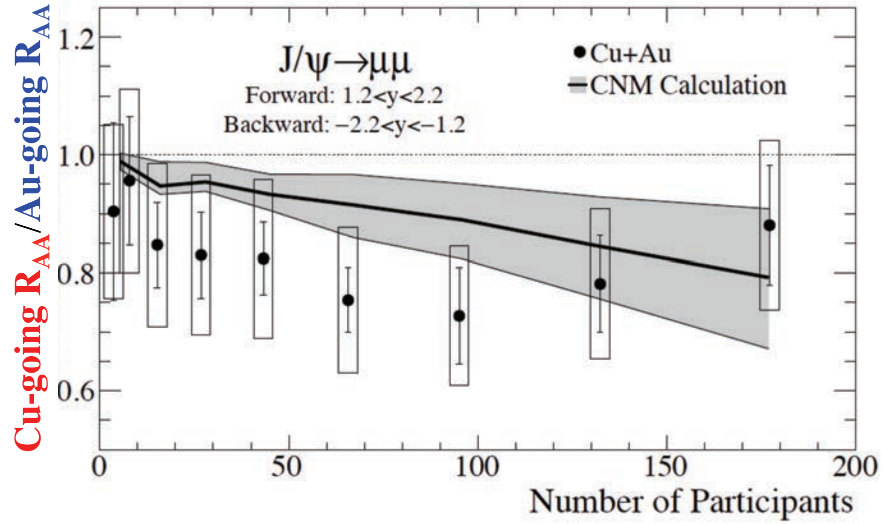


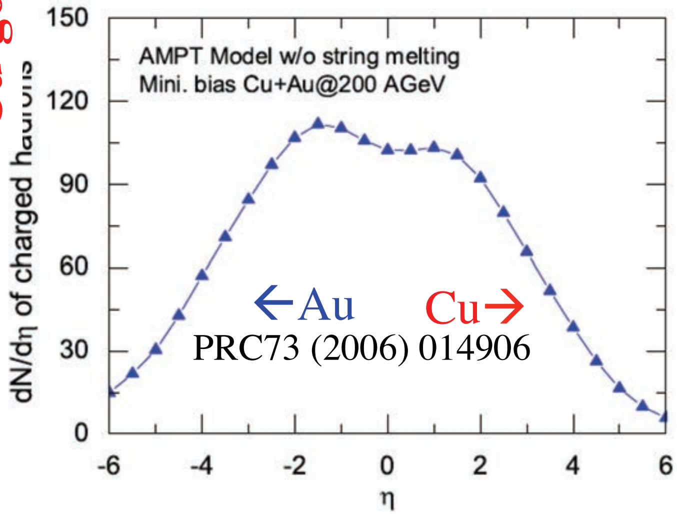
Spectators | Participants | Corona

Cu+Au (Corona Effect is not the Explanation)

PHENIXarXiv:1404.1873





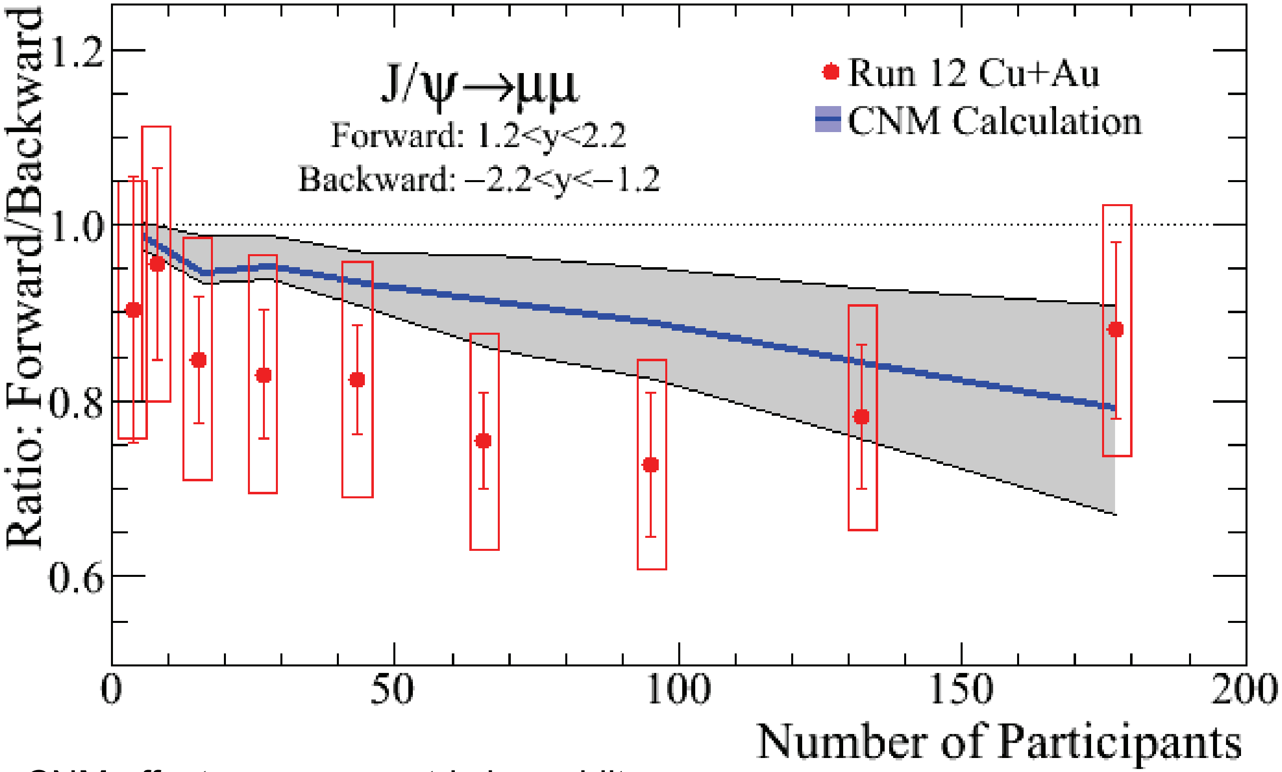


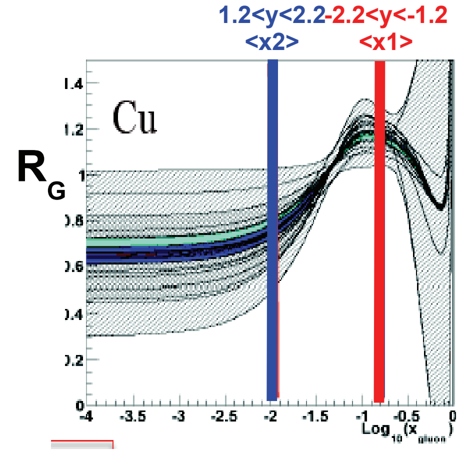
Asymmetric nuclear effects

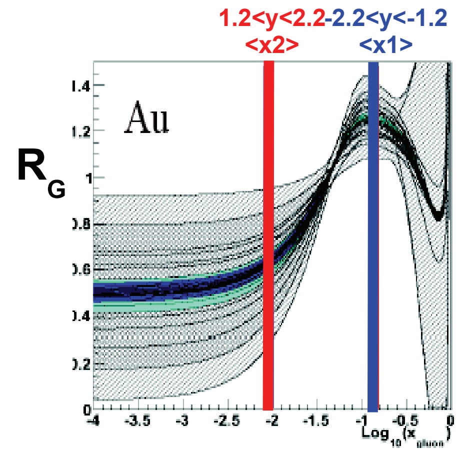
- Higher suppression in region of lower nucleon density. Fewer J/ψ at rapidity with fewer nucleons. Similar to d+Au collisions.
- Hot nuclear matter effect would have affected it the other way.
- Forward/Backward ratio consistent with Cold Nuclear Matter Effect; not lack of forward corona.

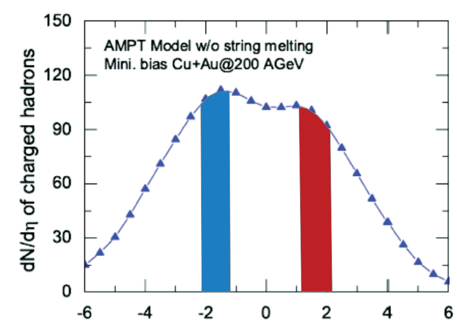
Probing Cold and Hot-Details

arXiv:1404.1873









CNM effects → asymmetric in rapidity

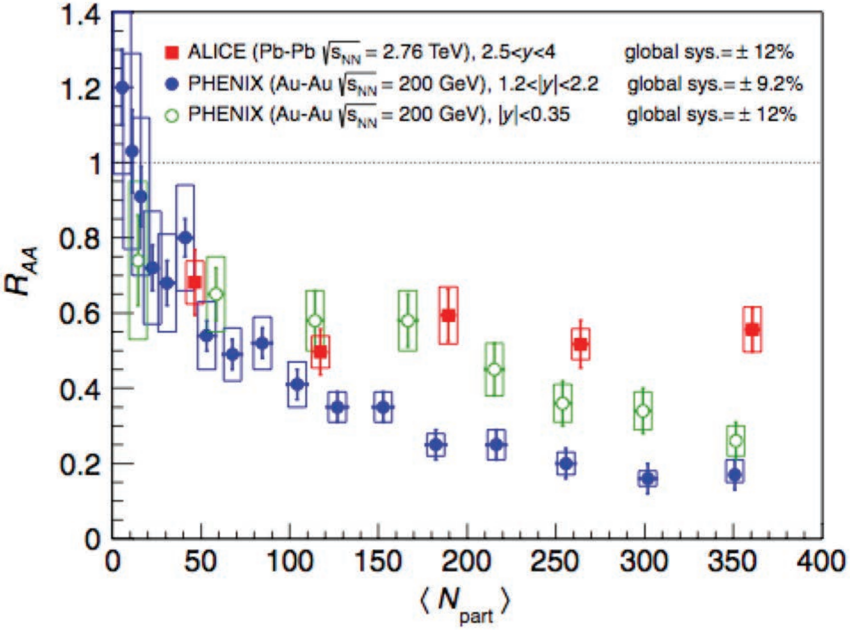
Forward CNM effects (Cu-going)

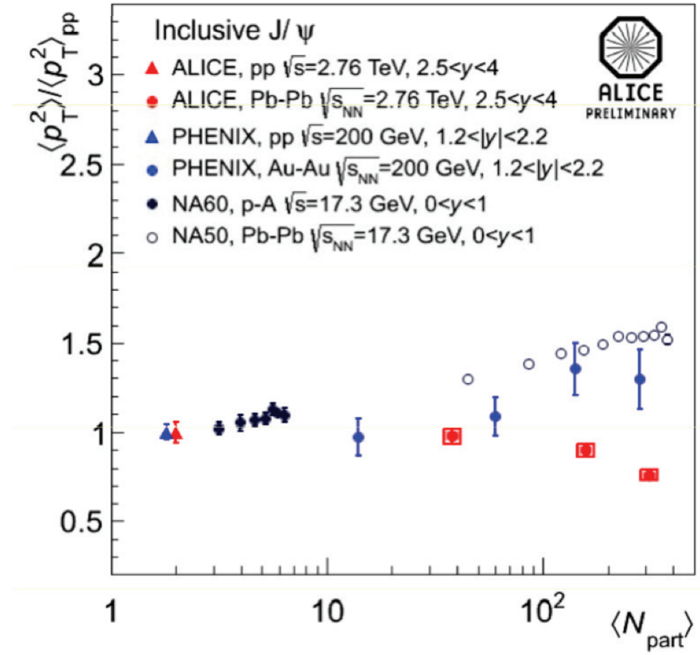
- gluon modification – J/ψ probes gluons at high-x in Cu, low -x in Au
- dynamical processes
  - Eloss, J/ψ short crossing proper time in Au
  - $c\bar{c}$ breakup by nucleon collisions, long crossing proper time in Cu

Backward (Au-going)

- Reversed CNM effects

J/ψ issues---Left over from ISSP2013



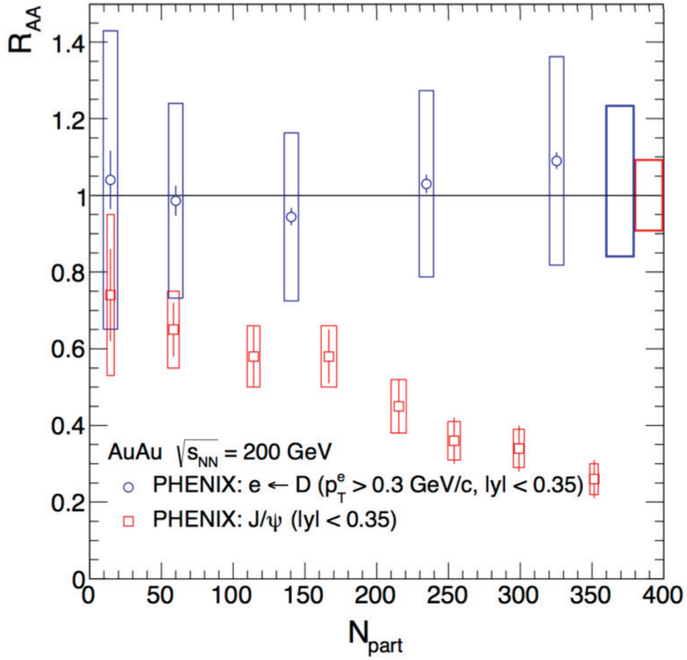


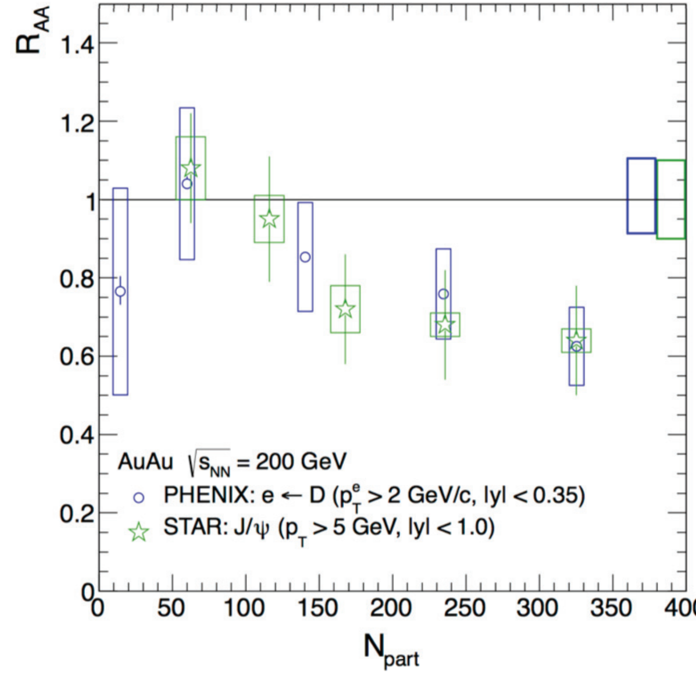
- In 2012, ALICE published a convincing measurement of reduced J/Ψ suppression at forward rapidity at $\sqrt{s_{NN}}$=2.76 TeV, compared to $\sqrt{s_{NN}}$=200 GeV, which in my opinion was clear proof of the regeneration prediction.
- At ISSP2013, Paolo Giubellino presented ALICE preliminary results for the ratio of $\langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$ as a function of centrality in Pb+Pb at 2.76 TeV, which show a decrease from 1 in p-p and mid-peripheral collisons to ≈ 0.7 for central collisions while both the SpS and PHENIX data continue rising to values ≈1.2-1.5. Paolo claimed that this proved deonfinement in central collisions.
- In the following discussion I disagreed and claimed that the reduction of $\langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{p}$ proves regeneration which is more probable at low p_T. Deconfinement would remove particles at low p_T in central collisions which would increase $\langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$ as shown by the PHENIX and NA50 data

This is good news for CERN because it proves the existence of the QGP at LHC

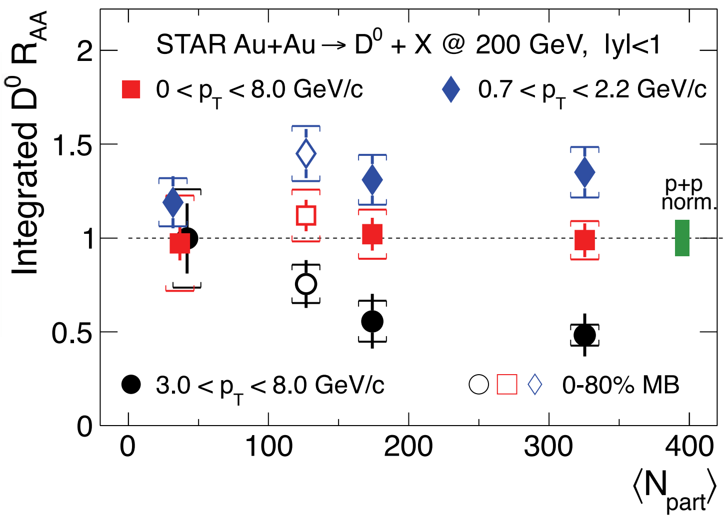
- The clear observation of regeneration proves directly the existence of the QGP at LHC, since it is evidence that the c and c-bar quarks (with their color charges fully exposed) freely traverse the medium (with a large density of similarly exposed color charges) to find each other and form a J/ψ.
- Prof. Zichichi uncharacteristically cut off the discussion of deconfinement, due to time pressure, and said that he agreed with Paolo.
- After the discussion, Prof. Tawfik pointed out that Satz had recently presented a way to distinguish deconfinement in the presence of regeneration. The crucial issue is whether the medium modifies the fraction of produced c-cbar pairs which form J/ψ. Dissociation of J/ψ in the medium would reduce the observed J/ψ/(c-cbar) ratio in A+A compared to p-p collisions, i.e. $R^{J/\Psi}_{AA}/ R^{(c\text{-}cbar)}_{AA} \ll 1$.

Satz's test for deconfinement vs. regeneration





arXiv:1404.6185

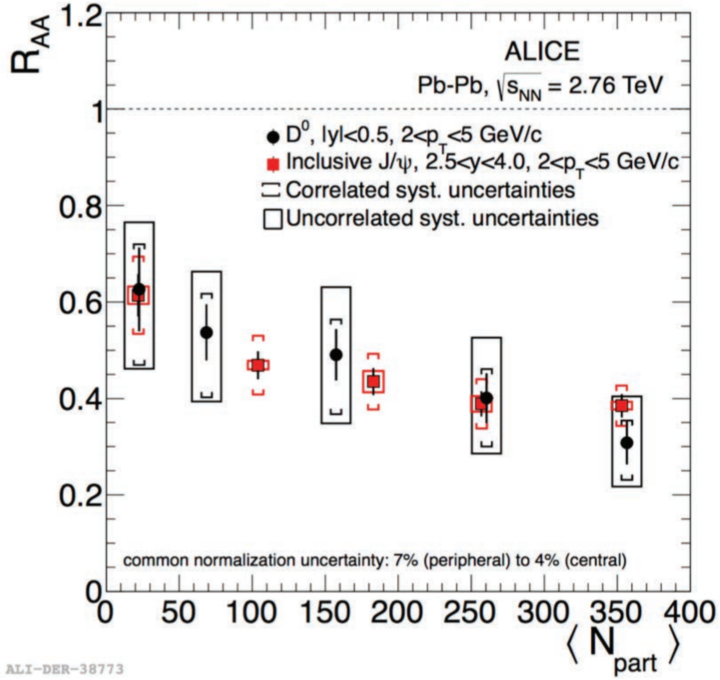


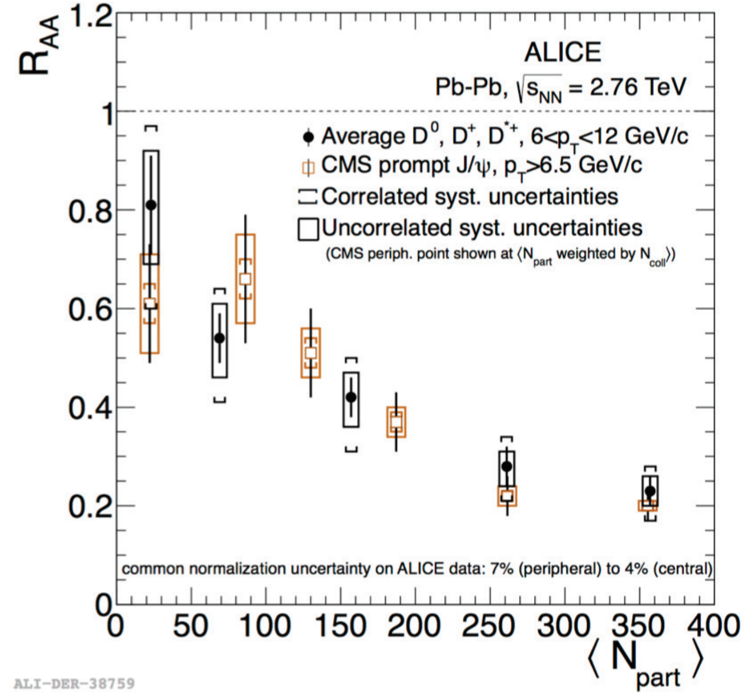
Satz arXiv:1303.3493 says:
R_{AA} (J/Ψ)/R_{AA}(charm)<<1 indicates deconfinement via Debye Screening

Deconfinement seen at RHIC. R_{AA}(charm) at low p_T or p_T integrated measured by prompt e± PHENIX and this year directly measured D° by STAR

Thanks to A. Tawfik for pointing out Satz' paper

Satz view of LHC Results



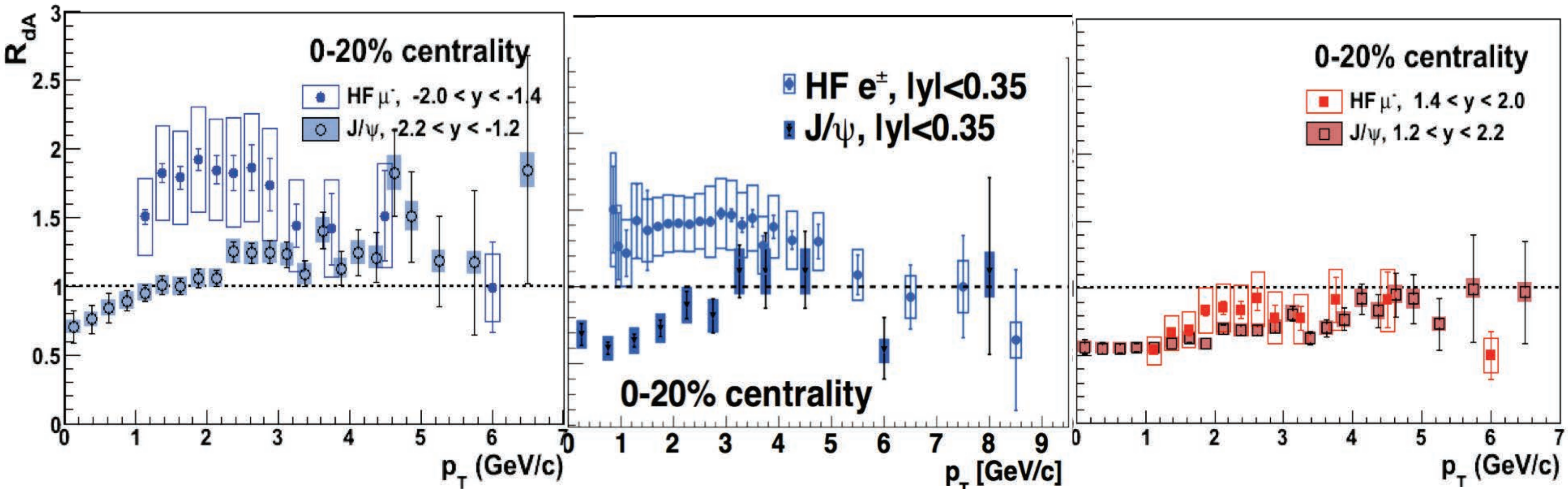


R_{AA} of J/ψ and D track with increasing centrality both for pT>2 GeV/c and 6 GeV/c No measurement at pT=0. Hence inconclusive on deconfinement.

Paolo Giubellino suggests that one should also make this comparison down to $\sqrt{s_{NN}}$ =17 GeV. Good job for RHIC BES, but life is complicated in charm vs J/Ψ

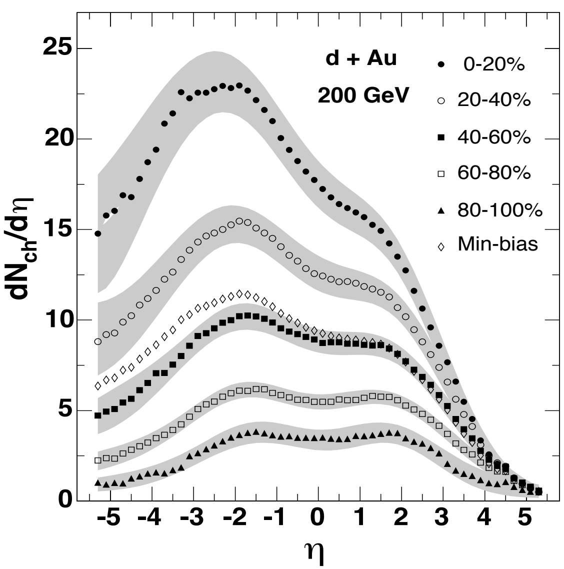
R_{dA} Open vs closed charm

arXiv:1310.1005, Phys.Rev.Lett. 109 (2012) 24, 242301, Phys.Rev. C87 (2013) 3, 034904



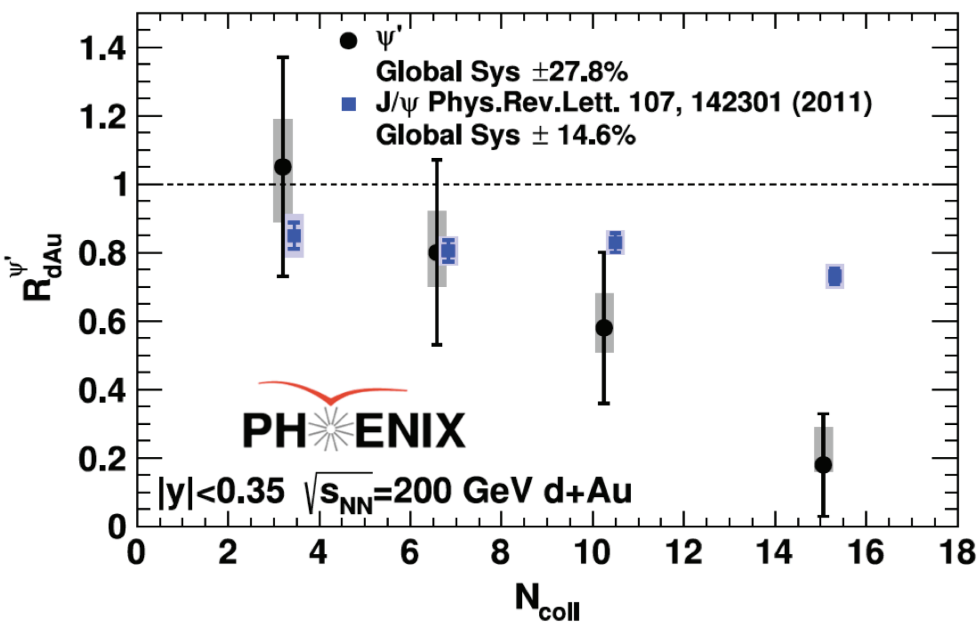
Higher final particle density

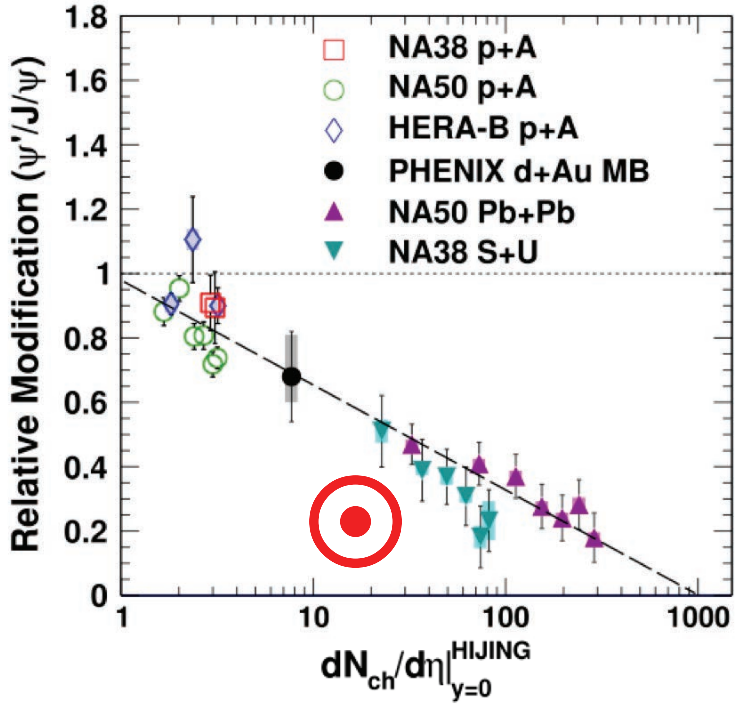
Probing lower-x gluons in Au



Both J/Ψ and charm follow the multiplicity y dependence; BUT fewer J/Ψ relative to charm as nucleon density increases likely indicates a significant breakup effect in cold nuclear matter for quarkonium production.

ψ' R_{dAu}





$$R_{dAu}{}^{\psi'} = \frac{[\psi'/(J/\psi)]^{dAu}}{[\psi'/(J/\psi)]^{pp}} R_{dAu}{}^{J/\psi}.$$

PHENIX PRL **111** (2013) 202301

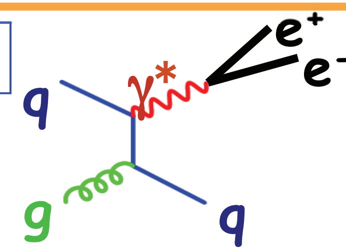
Strong suppression of ψ′ with increasing N_{coll} at the mid-rapidity.
Very unexpected results!!

Lepton Pairs

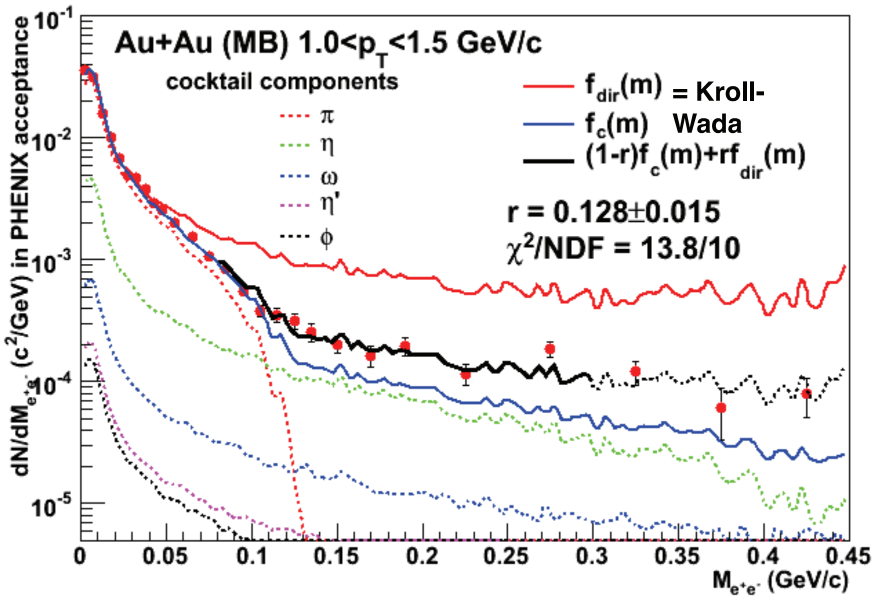
QM2005-direct γ in AuAu via internal conversion

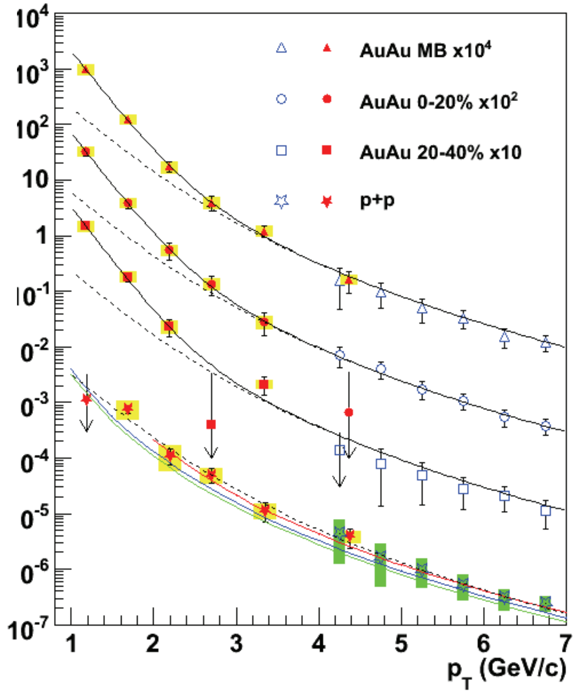
Kroll Wada PR**98**(1955) 1355

PHENIX PRL 104(2010)132301



$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\left(1-\frac{m_{ee}^2}{M^2}\right)^3 \mid F(m_{ee}^2)\mid^2 \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)$$





centrality	T(MeV)
0-20%	$221 \pm 23 \pm 18$
20-40%	$215 \pm 20 \pm 15$
MB	$224 \pm 16 \pm 19$

T independent of centrality!?

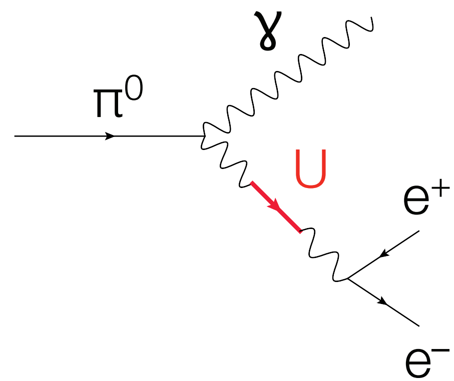
Eliminating the π^0 background by going to $0.2<m_{ee}<0.3$ GeV enables direct γ signal to be measured for $1<p_T<3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal? Yes because in p-p, direct γ it is NOT exponential like π^0, it turns over as $p_T \rightarrow 0$ as in Drell-Yan, Fit exponential to difference between AuAu and scaled p-p, A exp $(-p_T/T)$

Gauge theory of Dark Matter suggests Dark Photons

Muon g-2 experiment has 3.6σ result beyond the Standard Model calculation.

One option is dark photon – low mass, very weak coupling.

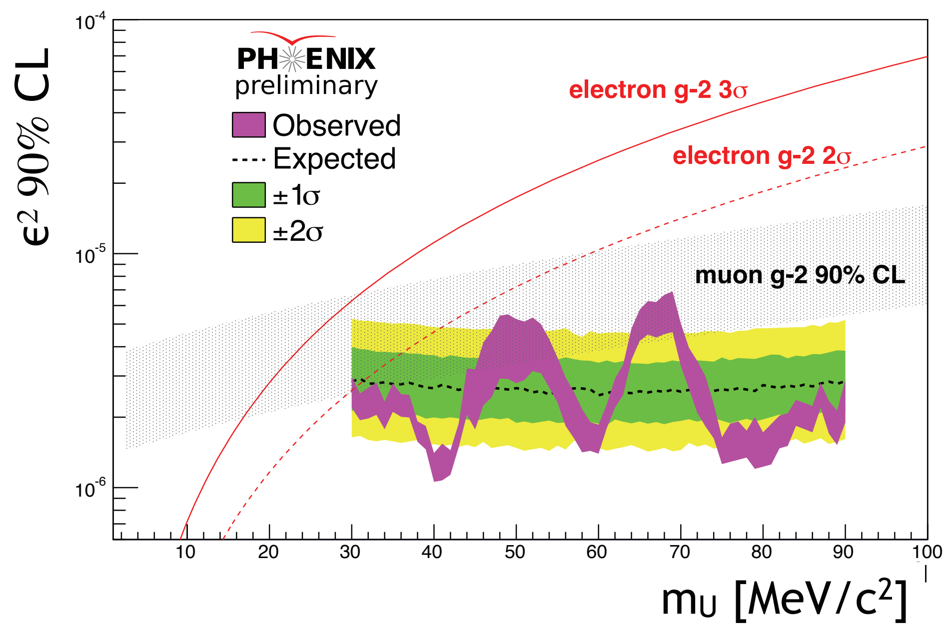
Many searches via fluctuation of virtual to dark photon



PHENIX has excellent capabilities to look for dark photons

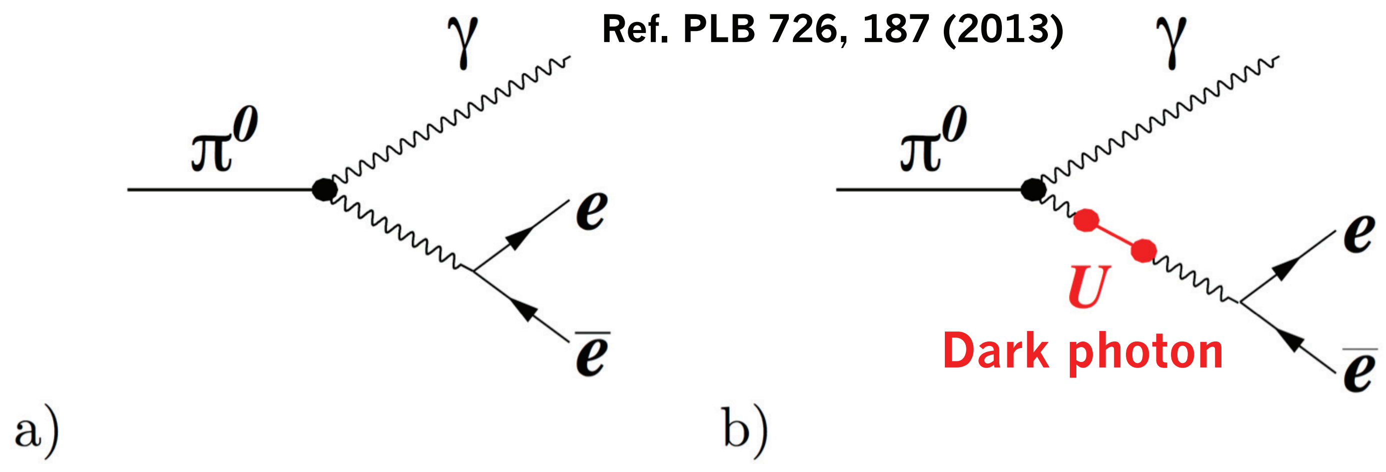
No dark photon signal is seen.

Our upper limit, plus others (including recent HADES result) nearly rules out dark photons



Search in π^0/η Dalitz decays

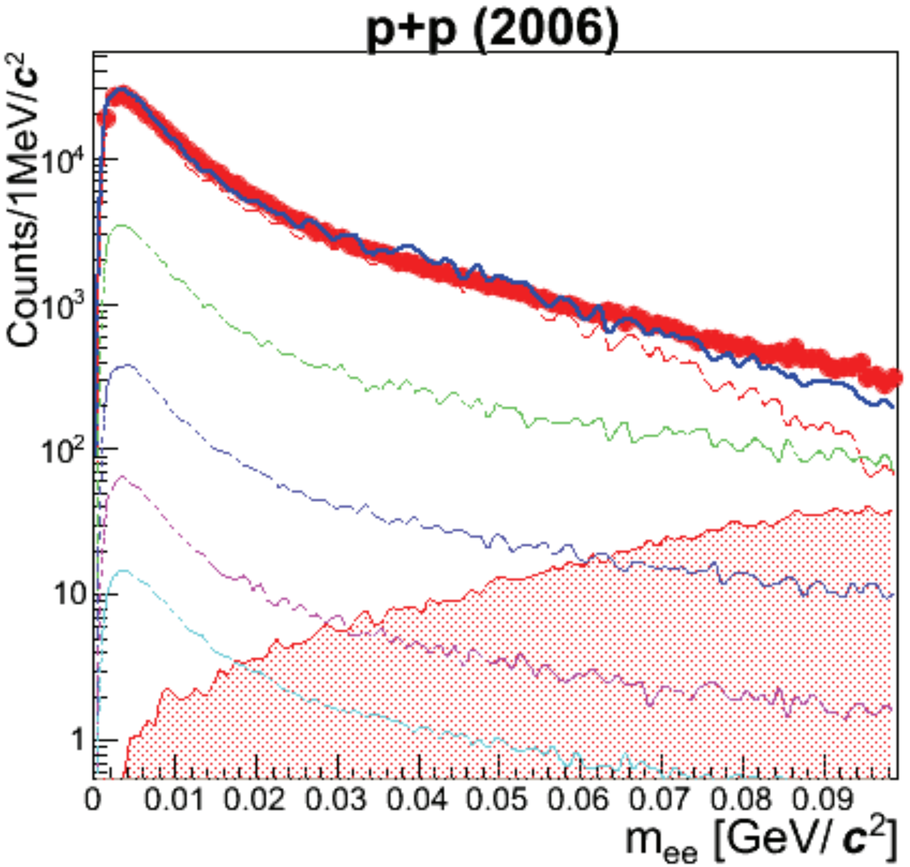
Ref. PLB 726, 187 (2013)

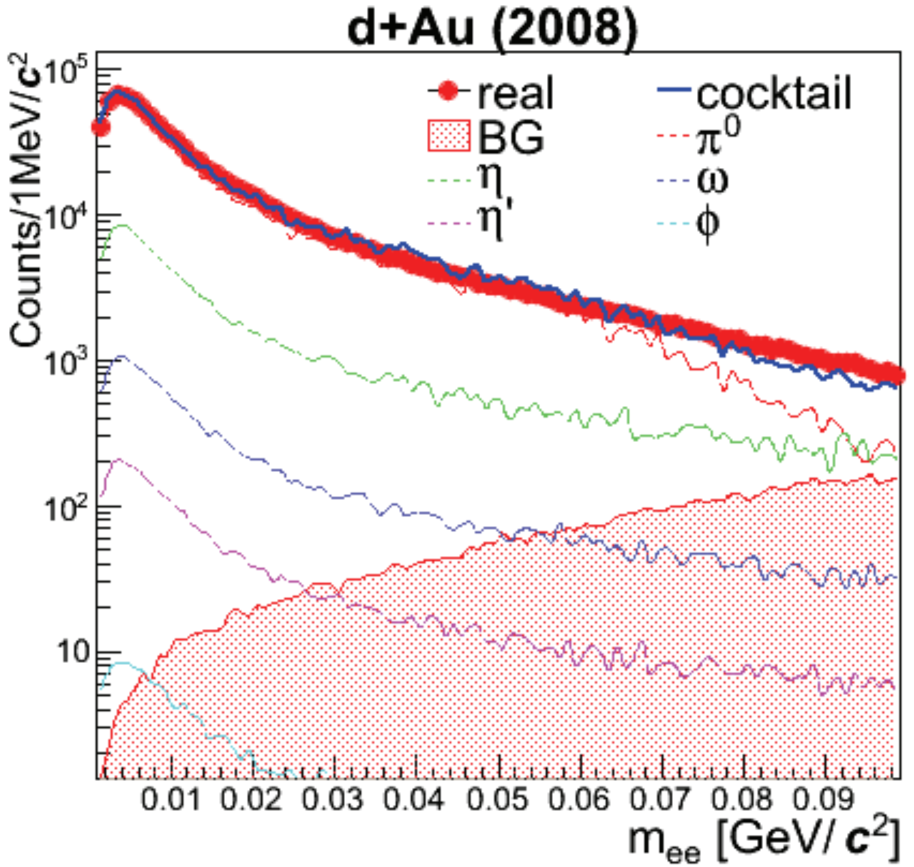


Measurement of $\pi^0/\eta \rightarrow \gamma U \rightarrow \gamma e^+e^-$ in Dalitz decays

- Aim to detect possible e^+e^- pairs from the dark photons in the π^0/η Dalitz decayed e^+e^- pairs
  - ✓ The dark photon exclusively decays into e^+e^- pair.
  - ✓ Its natural width is very narrow.
    - Expected peak width = detector mass resolution
  - ✓ Same approach with COSY-WASA & HADES

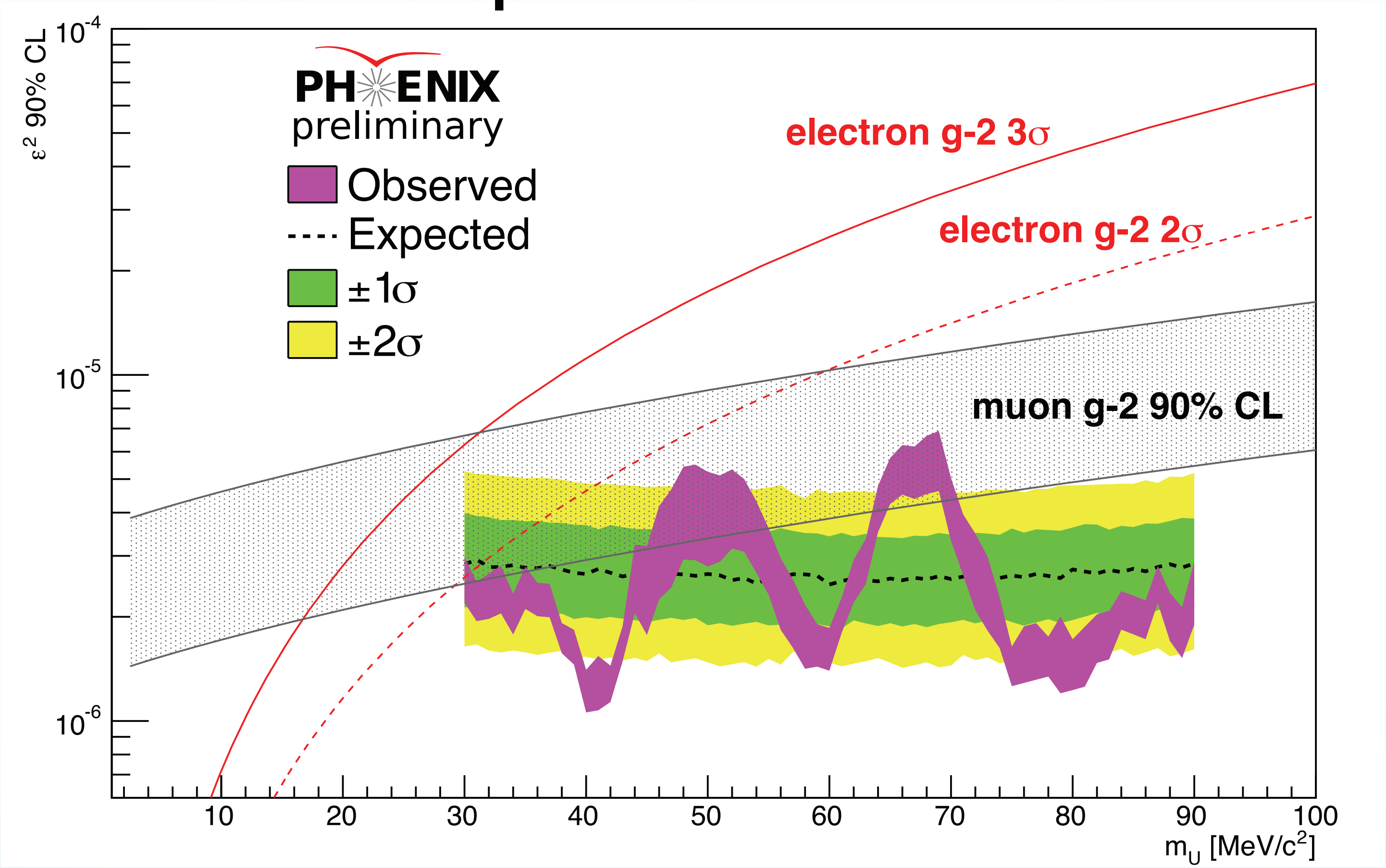
e+e- Mass spectra





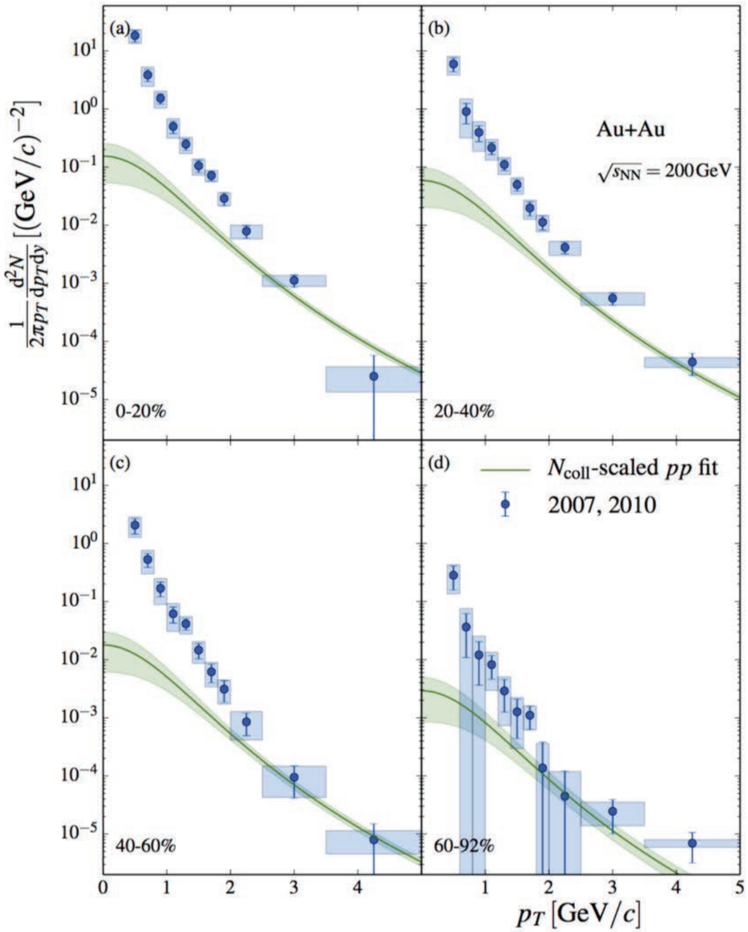
- ✧ Measured e^+e^- spectra can be well described by a "cocktail" of hadron decays + BG.
  - ✓ 400k (p+p) + 1.0M (d+Au) = total 1.4M e^+e^- Dalitz pairs
  - ✓ No significant dark photon signal

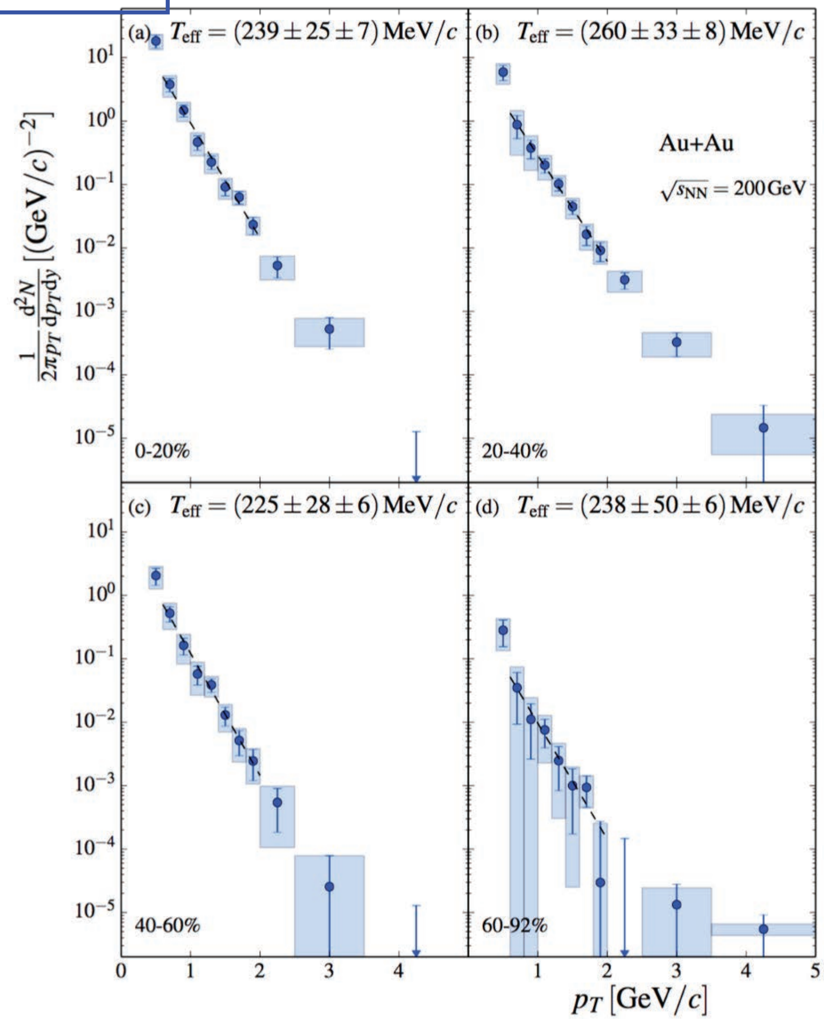
Dark photon limit



Thermal photons using external conversion

PHENIX arXiv:1405.3940



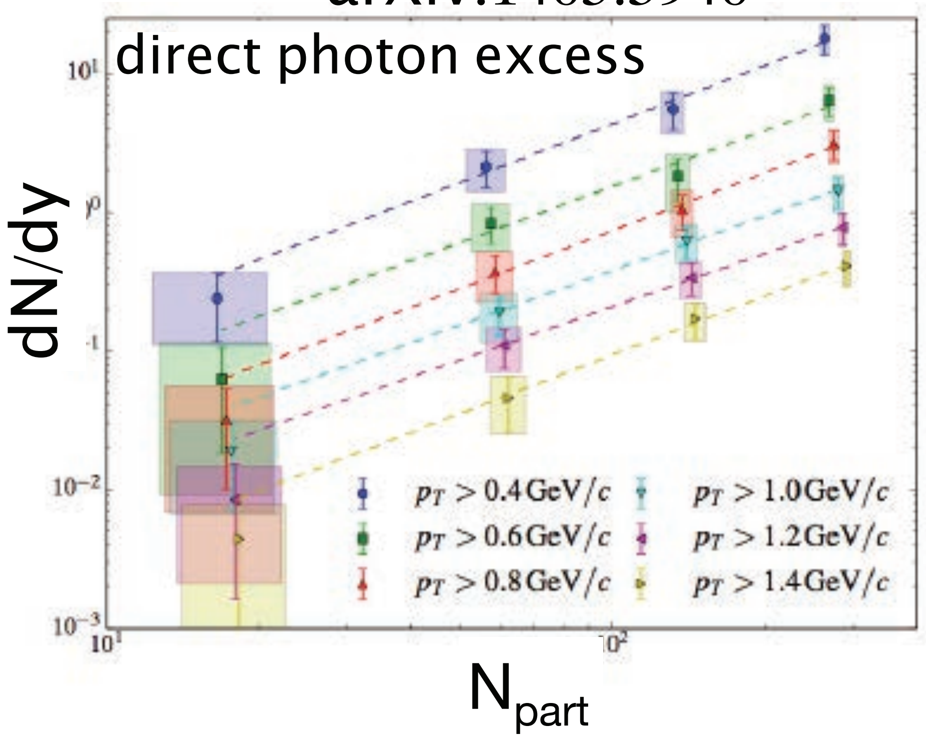


AuAu direct γ spectra vs centrality compared to scaled p-p spectrum

Subtract scaled p-p spectrum to get AuAu direct γ spectra vs centrality which are exponential with T parameter independent of centrality

Au+Au @ 200 GeV: Real Photons

arXiv:1405.3940



Integrated excess photon yields scale as

$$\mathbf{Yield = A\, N_{part}^{\alpha}}$$

$\alpha = 1.48 \pm 0.08$ (stat) $\pm\ 0.04$ (sys)

Exponential slopes of photon excess are centrality independent within uncertainties

$$\mathbf{Yield = B\, exp(-p_T/T)}$$

T (0-20%) = 239 ± 25 ± 7 MeV
T (20-40%) = 260 ± 33 ± 8 MeV
T (40-60%) = 225 ± 28 ± 6 MeV
T (60-92%) = 238 ± 50 ± 6 MeV

Strong new constraint on hydrodynamic time evolution and modeling of radiation emission

Hard Scattering

RHIC's main claim to fame— Jet suppression in AA collisions via inclusive high p_T single particles QM2001

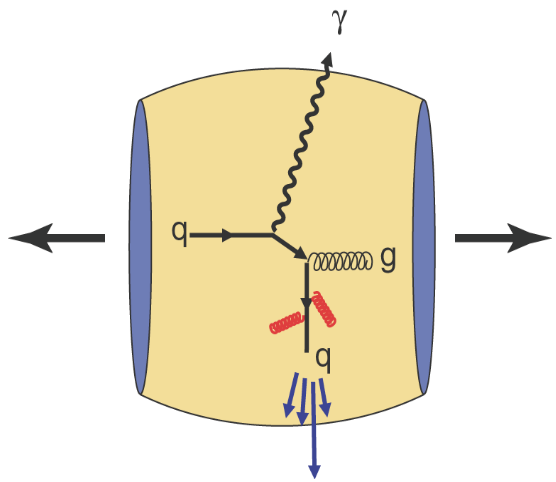
PHENIX PRL88 (Jan**2002**) 022301-**787 cites**

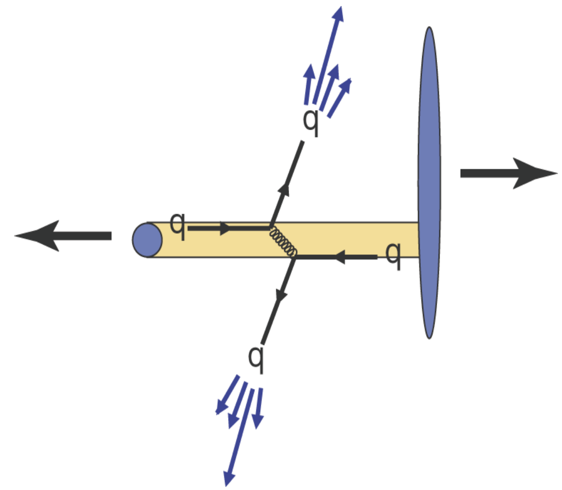
STAR PRL89 (Oct**2002**) 202301-**527 cites**

First Jet publication: p-p STAR PRL 97 (Dec2006), 252001-for spin

First Jet suppression: AuAu STAR NOT YET

Hard scattering as a probe of the medium: Hot (AA) vs Cold pA Nuclear Matter Effects





Hard scattering of partons in the initial collision is in-situ internal probe of medium. Do quarks and gluons lose energy in the medium? If so exactly how?

In p+A or d+A, medium is small, (1 nucleon wide) or non-existent. This is baseline for any cold nuclear matter effect in initial collision

- RHIC is versatile
  - ✓ Can collide any nuclear species on any other

Jets vs single high p_T particles--RHIC

- In 1998 at the QCD workshop in Paris, Rolf Baier asked me whether jets could be measured in Au+Au collisions because he had a prediction of a QCD medium-effect on colored partons in a hot-dense-medium with lots of unscreened color charge.

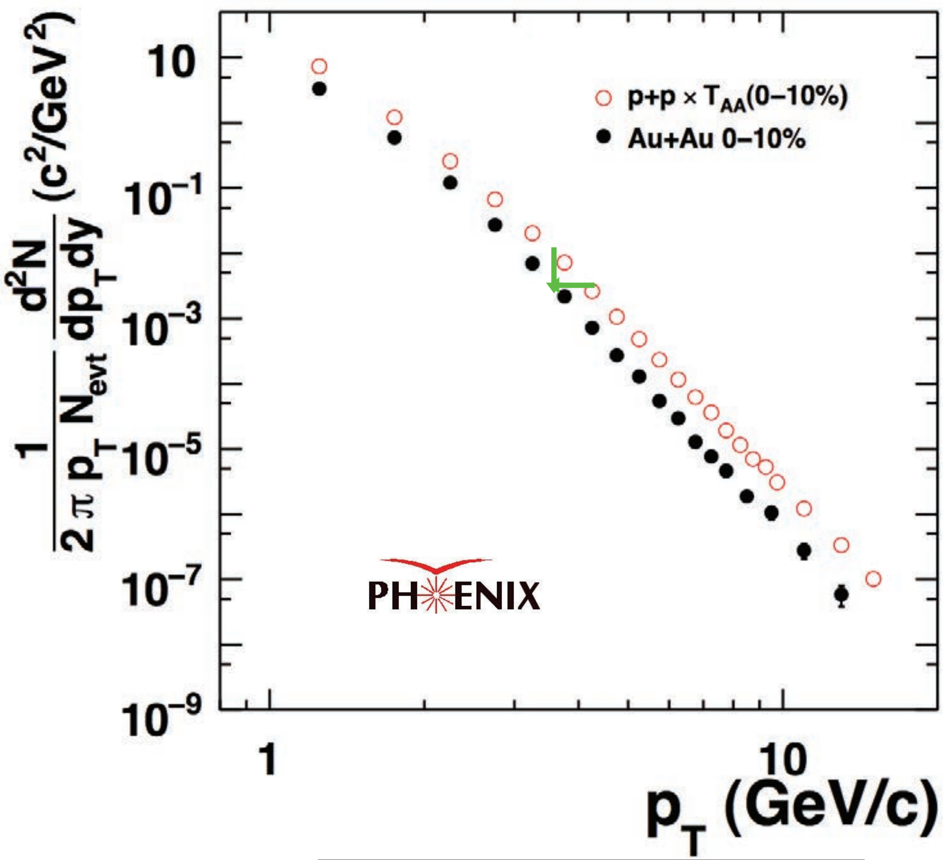
- As the expected energy in a typical jet cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is $\pi R^2 \times 1/2\pi \times dE_T/d\eta = R^2/2 \times dE_T/d\eta \sim$ 350 GeV for R=1 at $\sqrt{s_{NN}}$=200 GeV where the maximum Jet energy is 100 GeV, I said that Jets can not be reconstructed in Au+Au central collisions at RHIC—still correct after 16 years.

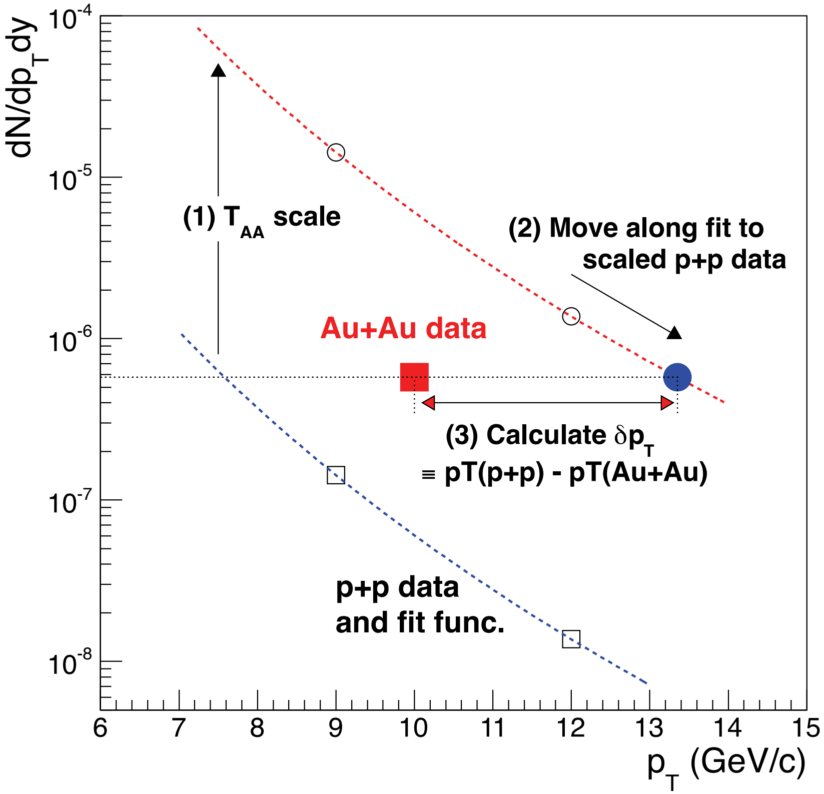
- Hard scattering was discovered in p-p at the CERN-ISR 1972 with single particle and few particle correlations, while jets had a long learning curve from 1977-1982, with false claims! So use single and few particles---which we did and it WORKED!

- The solution (LHC 2010 and) RHIC c.2014 is to take smaller cones: 60 GeV in R=0.4, 34 GeV in R=0.3, 15 GeV in R=0.2.

RHIC π^0 pp vs AuAu

π^0 are suppressed in Au+Au eg 200 GeV



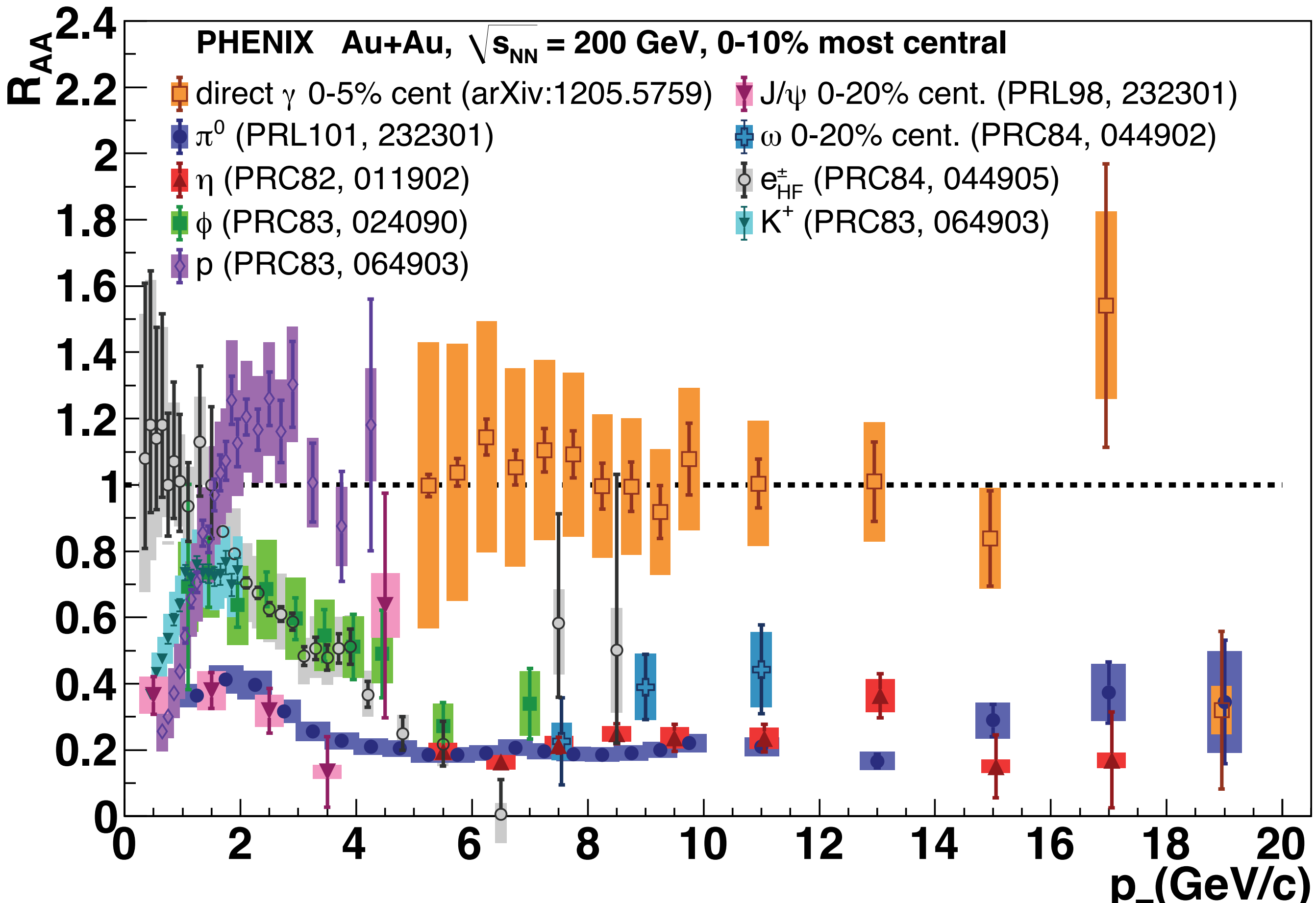


Nuclear Modification Factor

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

After a decade of the ratio R_{AA} we are now paying more attention to δp_T the shift in the p_T spectrum as an indicator of energy loss in the QGP

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

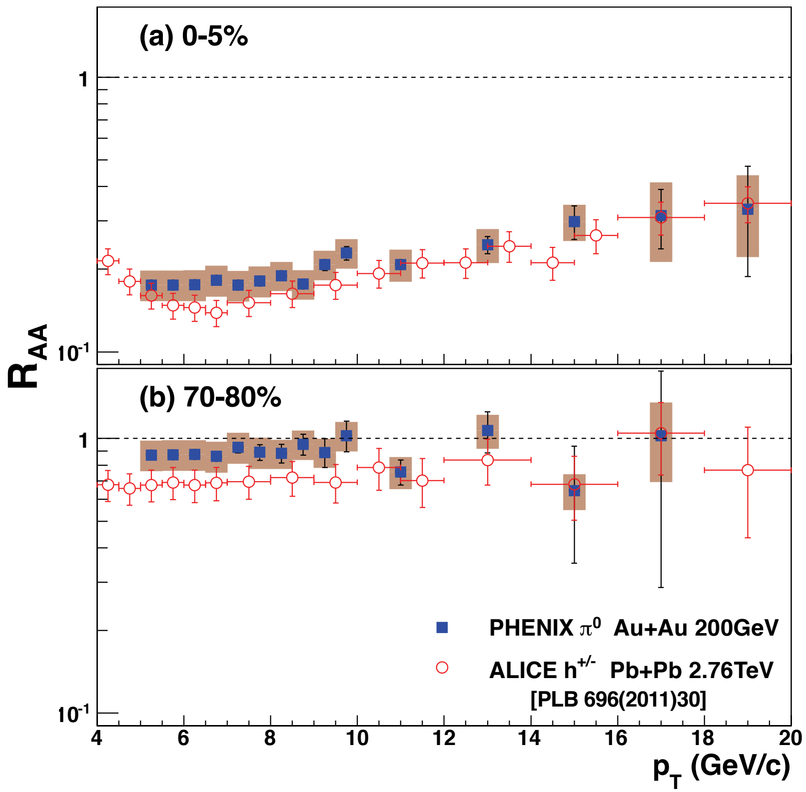


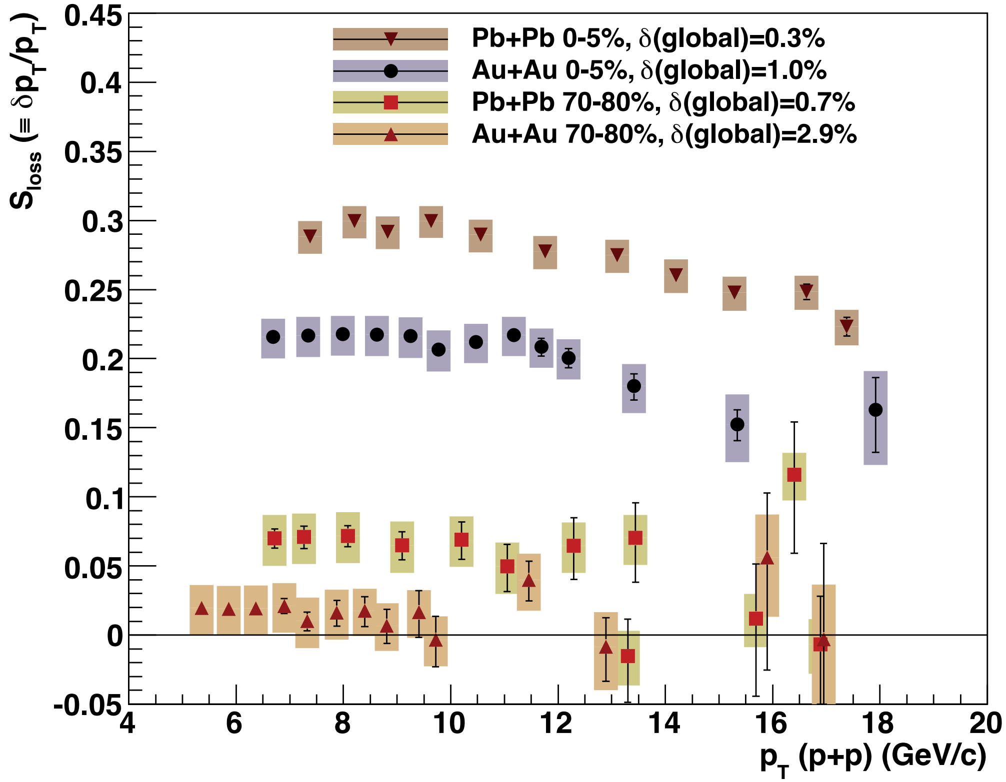
particle ID is crucial: different particles behave differently

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)

RHIC $\sqrt{s_{NN}}$=200 GeV cf. LHC $\sqrt{s_{NN}}$=2.76 TeV

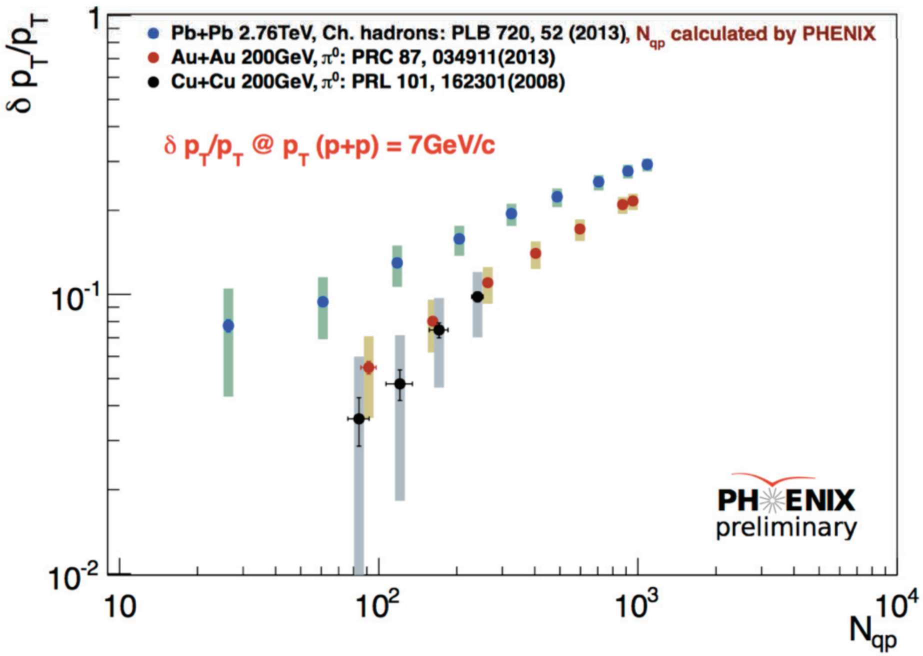
PHENIX PRC **87** (2013) 034911

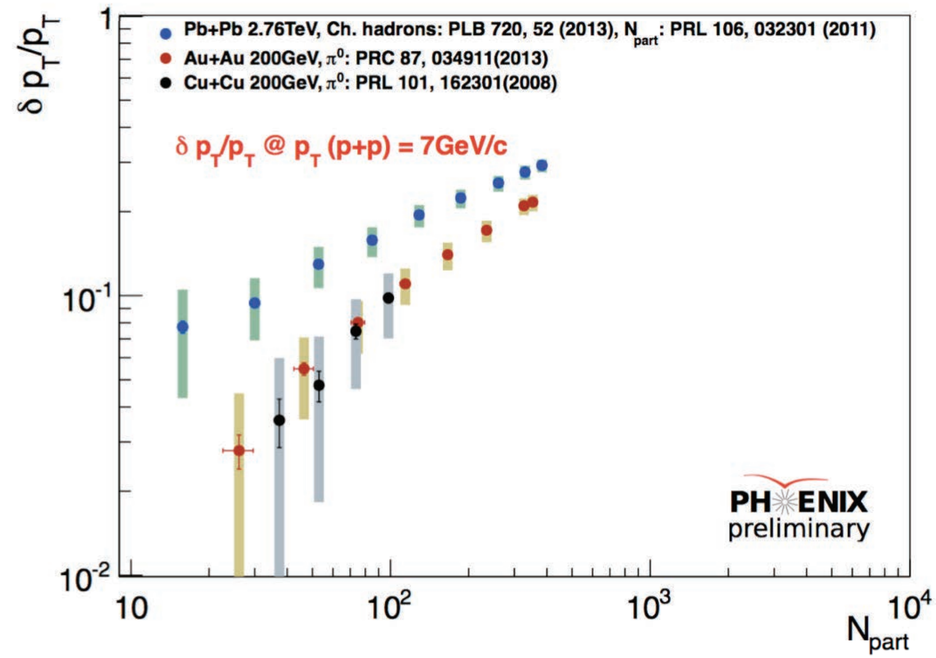


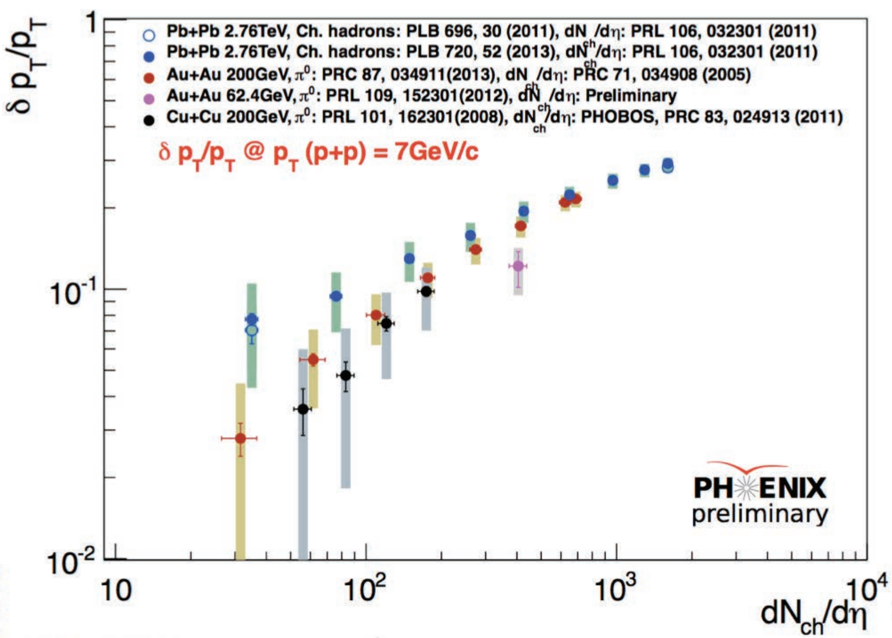


Agreement of ALICE $h^{\pm}$ R_{AA} with PHENIX π^0 in the overlap region $5<p_T<20$ GeV/c is incredible; BUT because invariant p_T spectrum at LHC is flatter than at RHIC, spectrum shift δp_T is 40% larger at LHC than at RHIC presumably due to the hotter and possibly denser medium.

What determines energy loss δp_T?





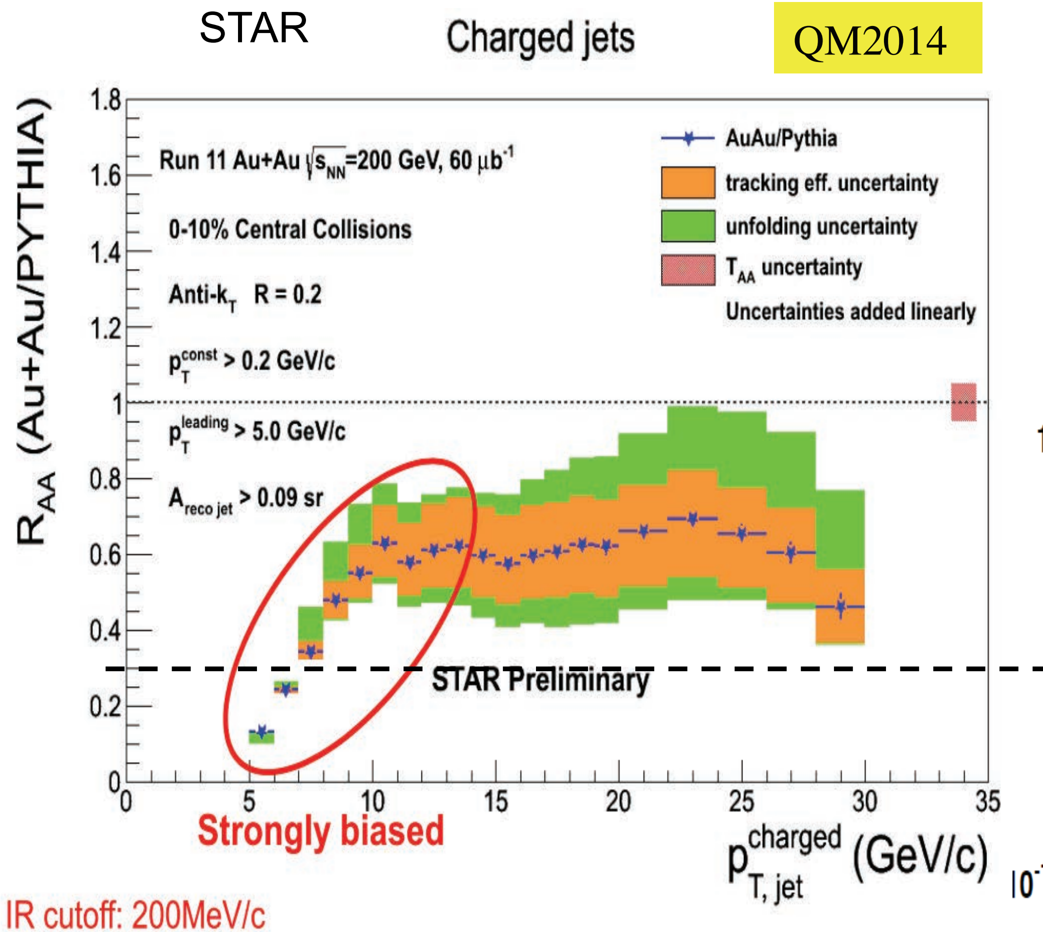


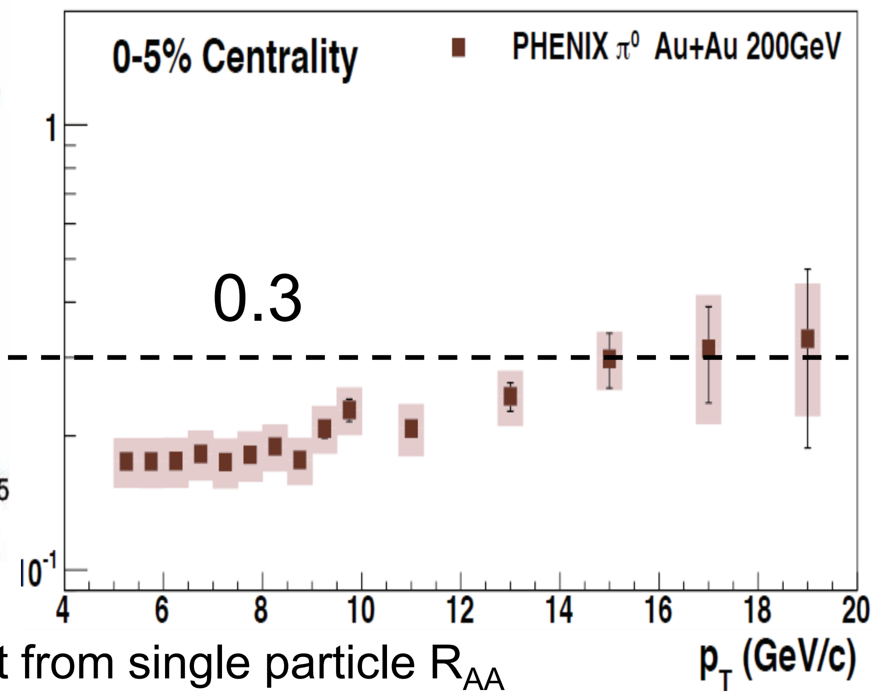
Not quite universal
$\delta p_T/p_T \approx (dN_{ch}/d\eta)^{\alpha}$,
$\alpha \approx 0.35$ @ 2.76 TeV,
$\alpha \approx 0.55$ @200 GeV

200 GeV and 2.76 TeV curves may merge $(dN_{ch}/d\eta) \geq 300$

STAR Charged jets R_{AA}>>single particle

QM2014



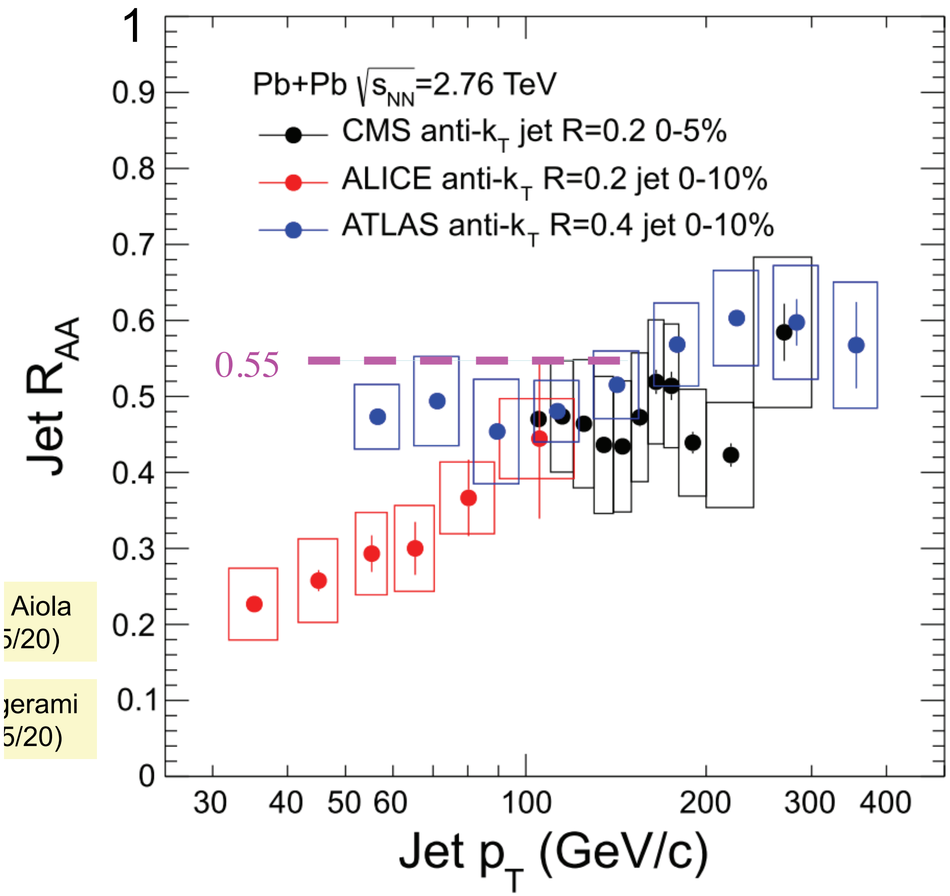


Charged jet R_{AA} results: different from single particle R_{AA}

Gets worse with increasing cone size

At LHC Jet and single particle R_{AA} ~ equal for p_T>40 GeV/c

LHC Jets have comparable or lower R_{AA} than single particles



Aiola
5/20)

jerami
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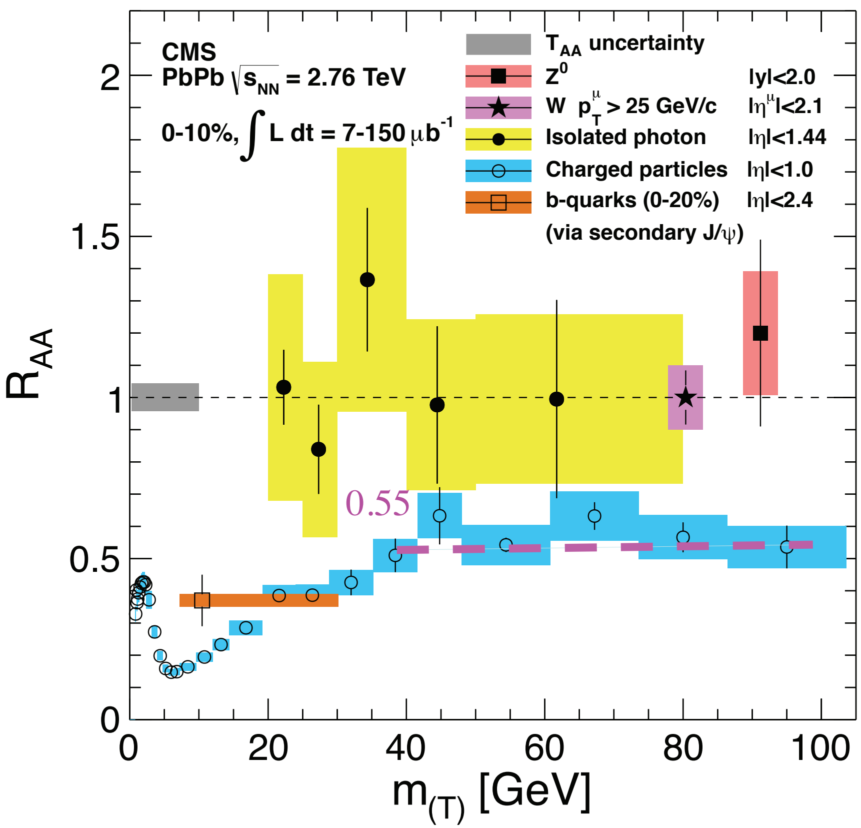
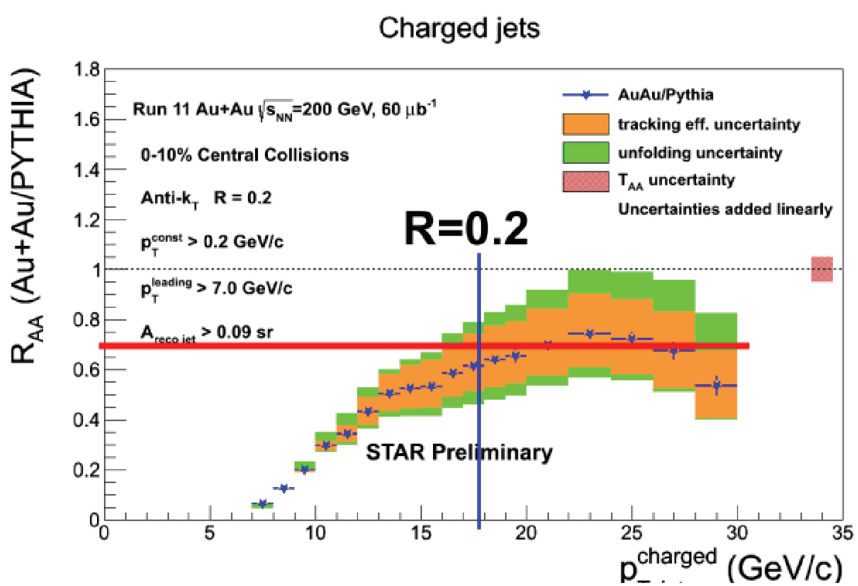
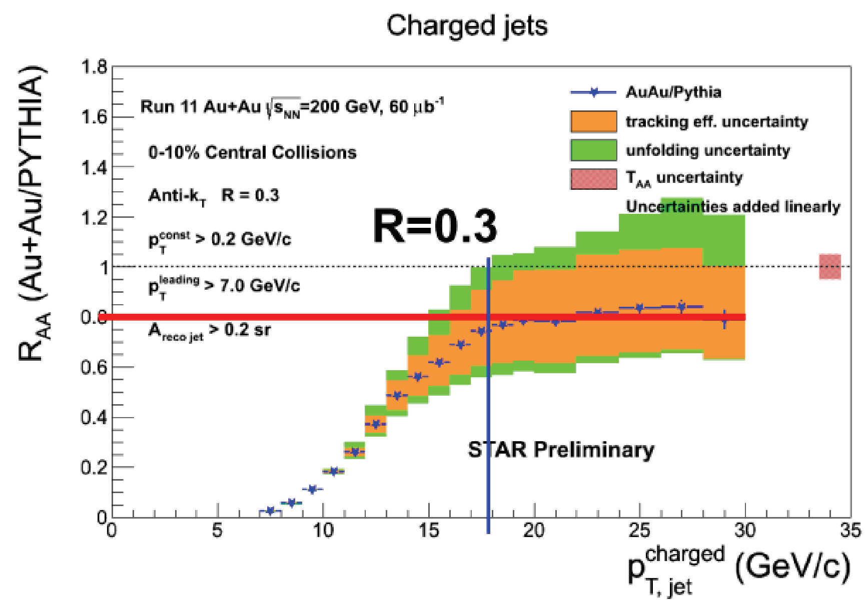
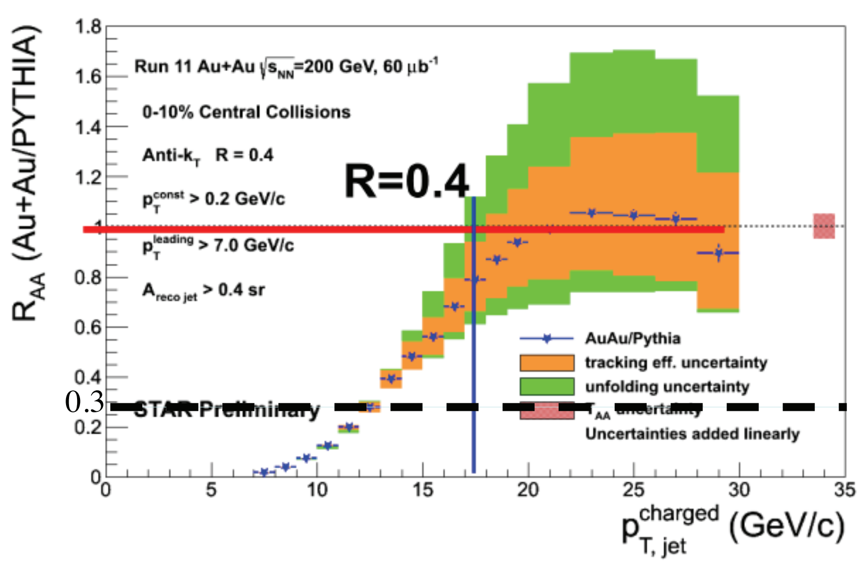


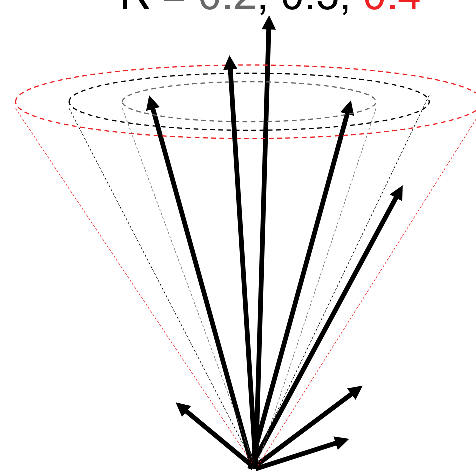
STAR R_{AA} v.s. R



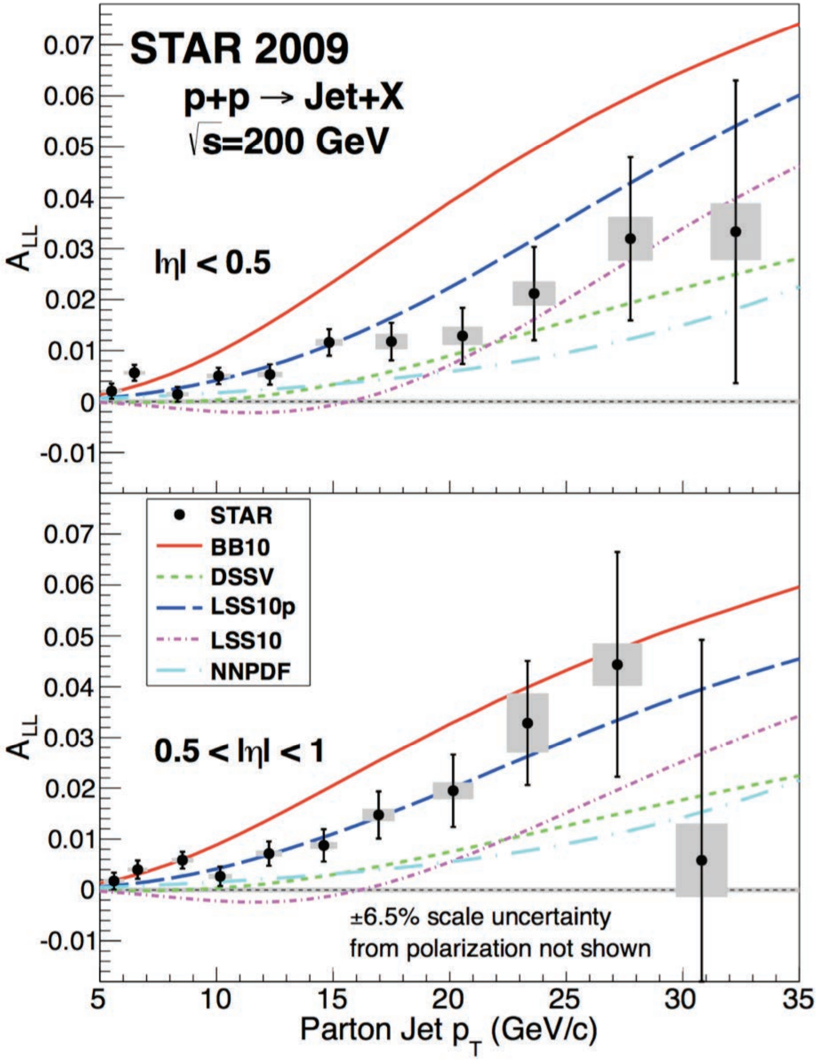




Anti-k_T jets with
R = 0.2, 0.3, 0.4

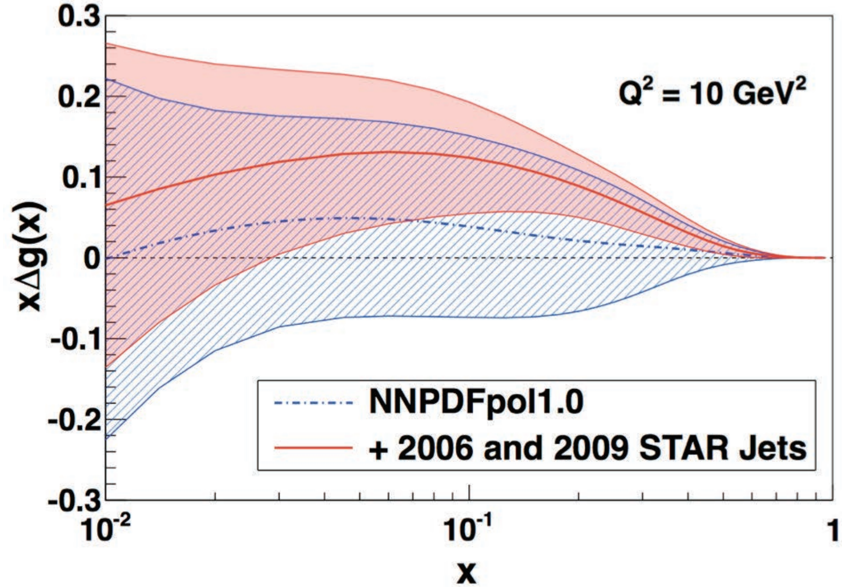


New Star Jet Measurement in polarized p-p



$$A_{LL} = \frac{1}{P_1 P_2}\,\frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

STAR PRC **87** (2013) 034911



This results indicates positive gluon polarization $x\Delta g(x)$ for $0.03<x<0.3$ deFlorian, Sassot, Stratmann, Vogelsang arXiv:1404.4293

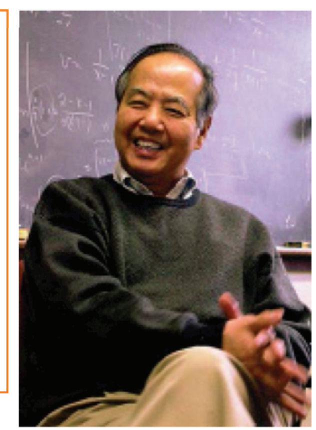
2^{nd} Lecture Stopped Here
Some more information and results from Polarized Proton collisions at RHIC follow

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^+.

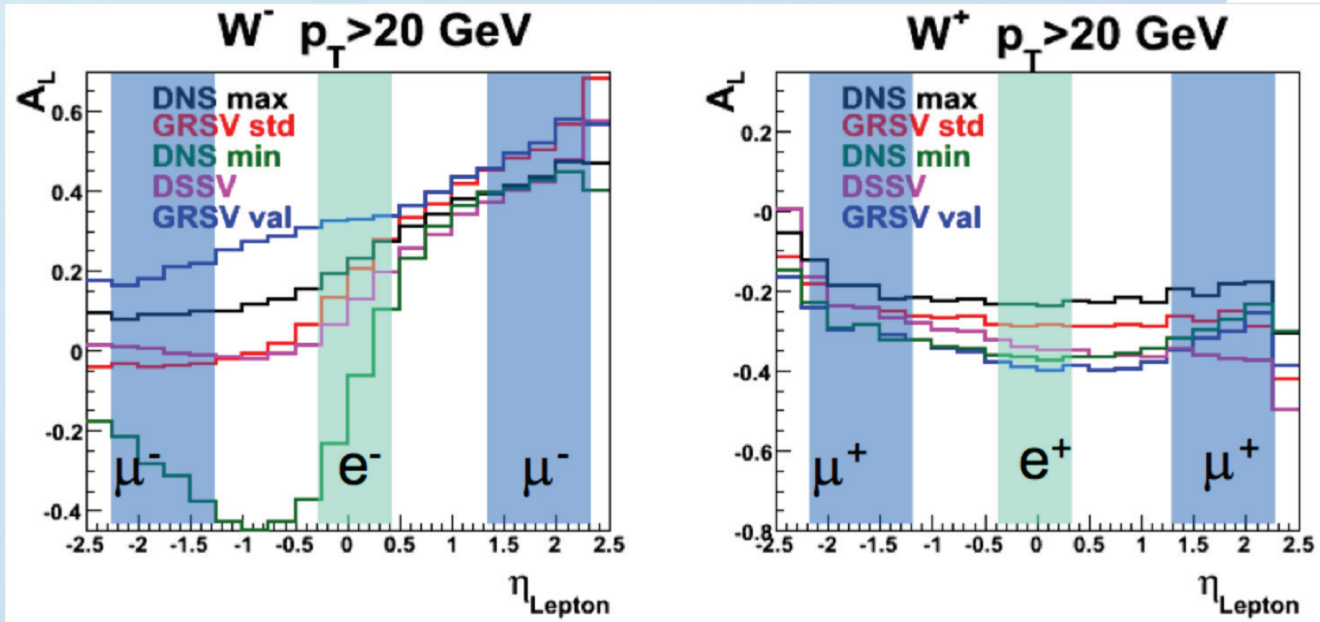
1997: To exploit spin physics and lattice gauge theory, RIKEN (Japan) provided one muon arm in PHENIX and money to support the snakes and spin rotators in RHIC. Also: the RIKEN BNL Research Center (RBRC) was established at BNL with T.D. Lee as founding Director.



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



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

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

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

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

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

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

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

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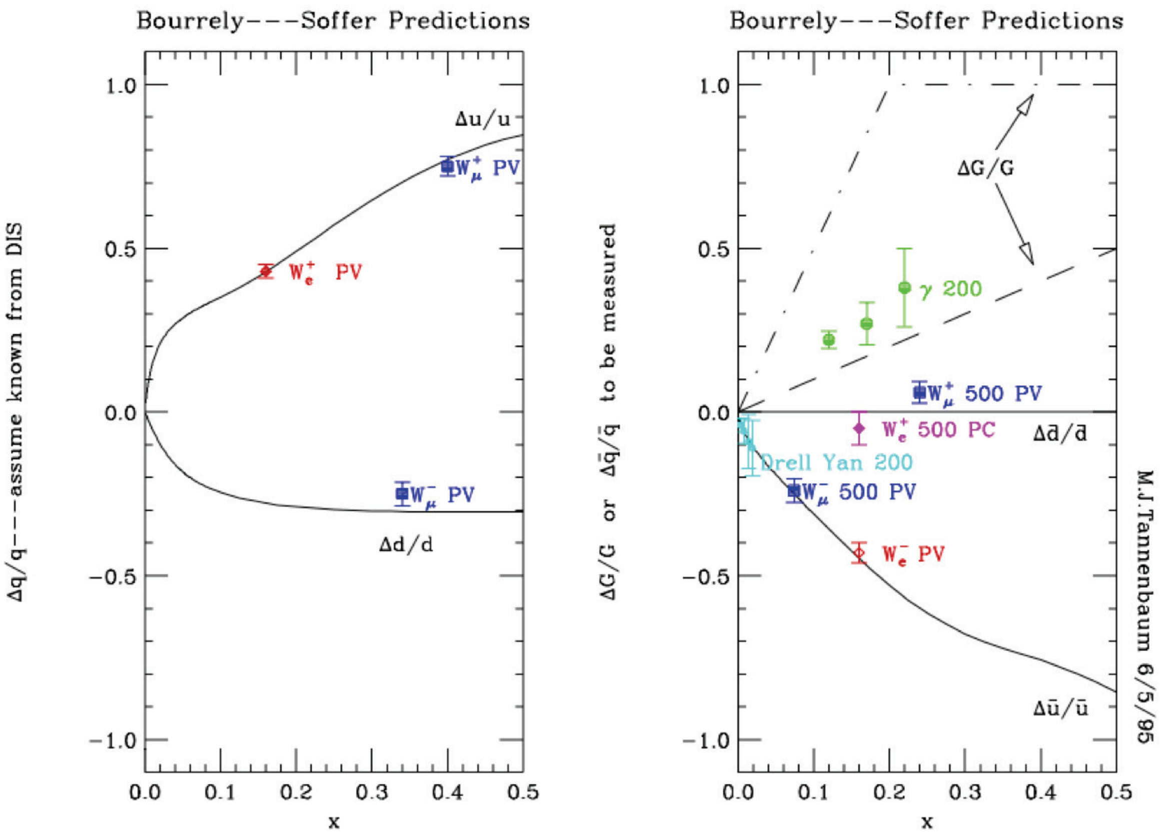
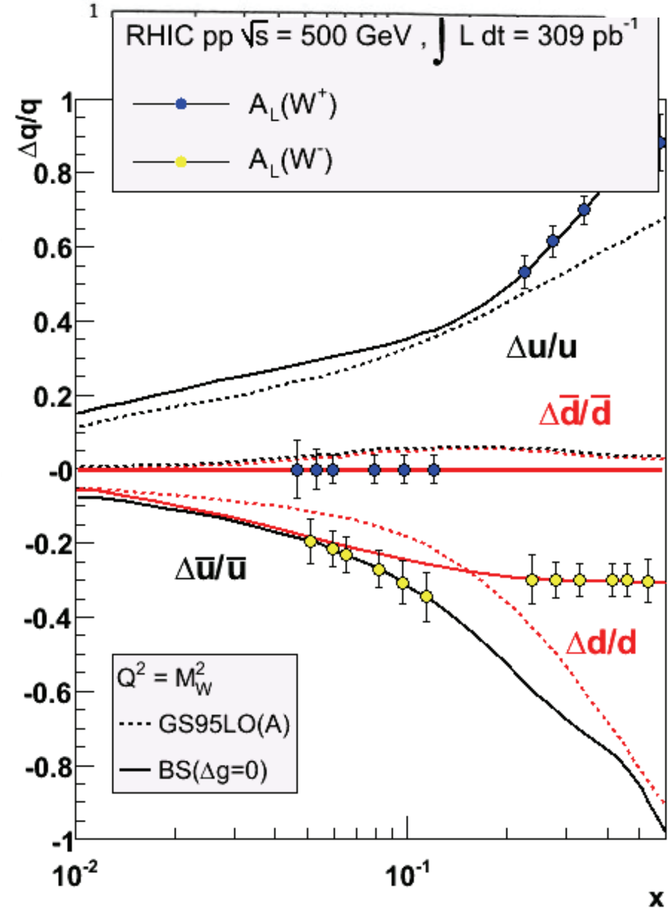
Results Expected with 800 pb^{-1} at 500 GeV c.1995





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$^\pm$ ⇢ μ$^\pm$ +ν.
Works well for μ p_T but more complicated than we thought-kinematic ambiguity.

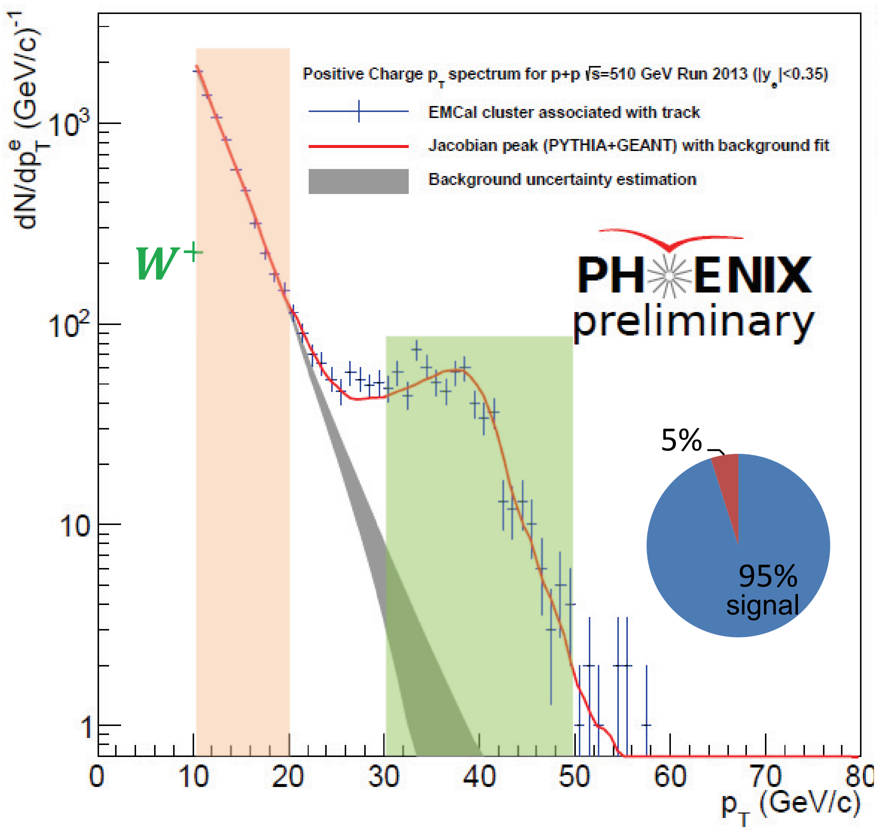
PHENIX prelim $W^{\pm} \dashrightarrow e^{\pm} + \nu$ 2013 run

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

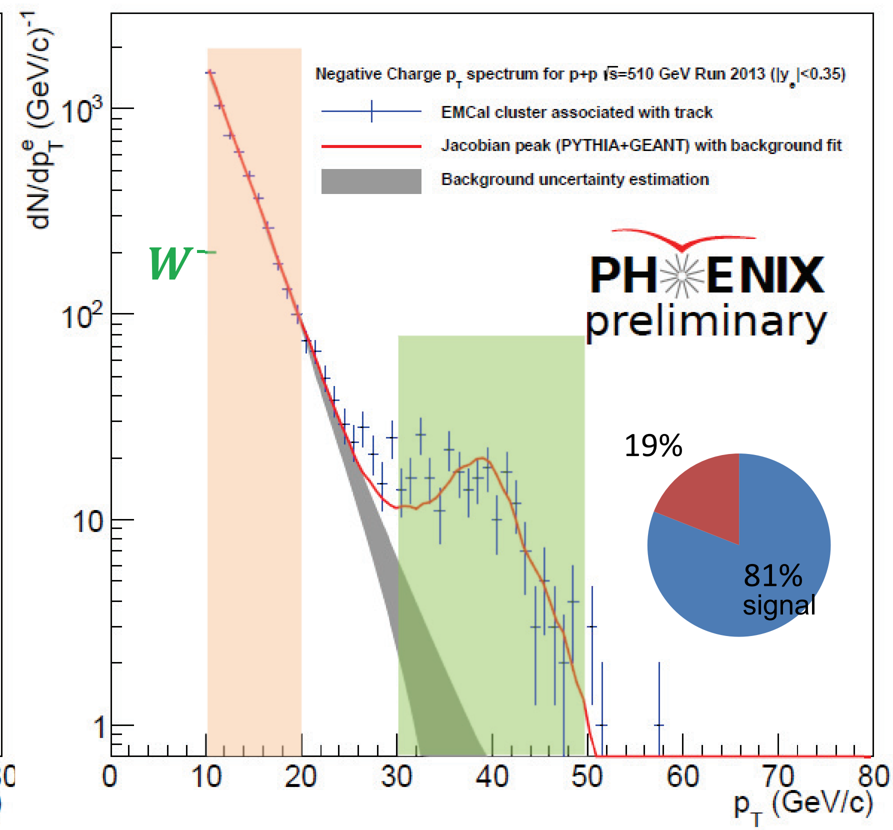
Background estimation using two independent methods:

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

fit simultaneously with simulated jacobian peak shape



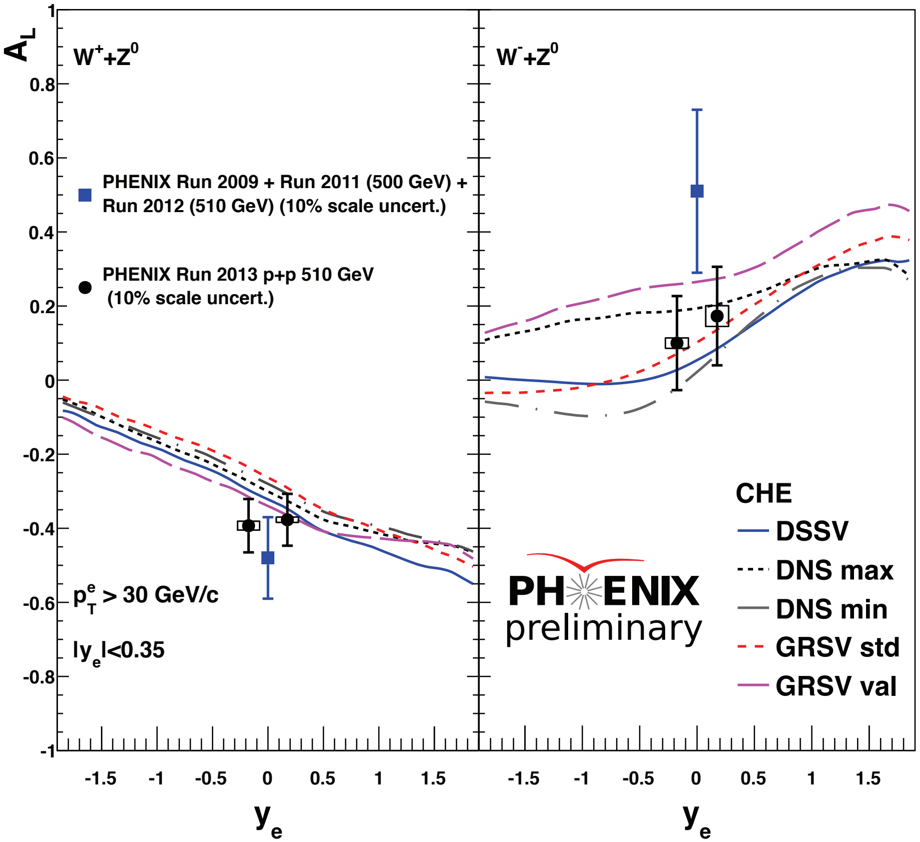
W^+ signal ~ 95%



W^- signal ~ 81%

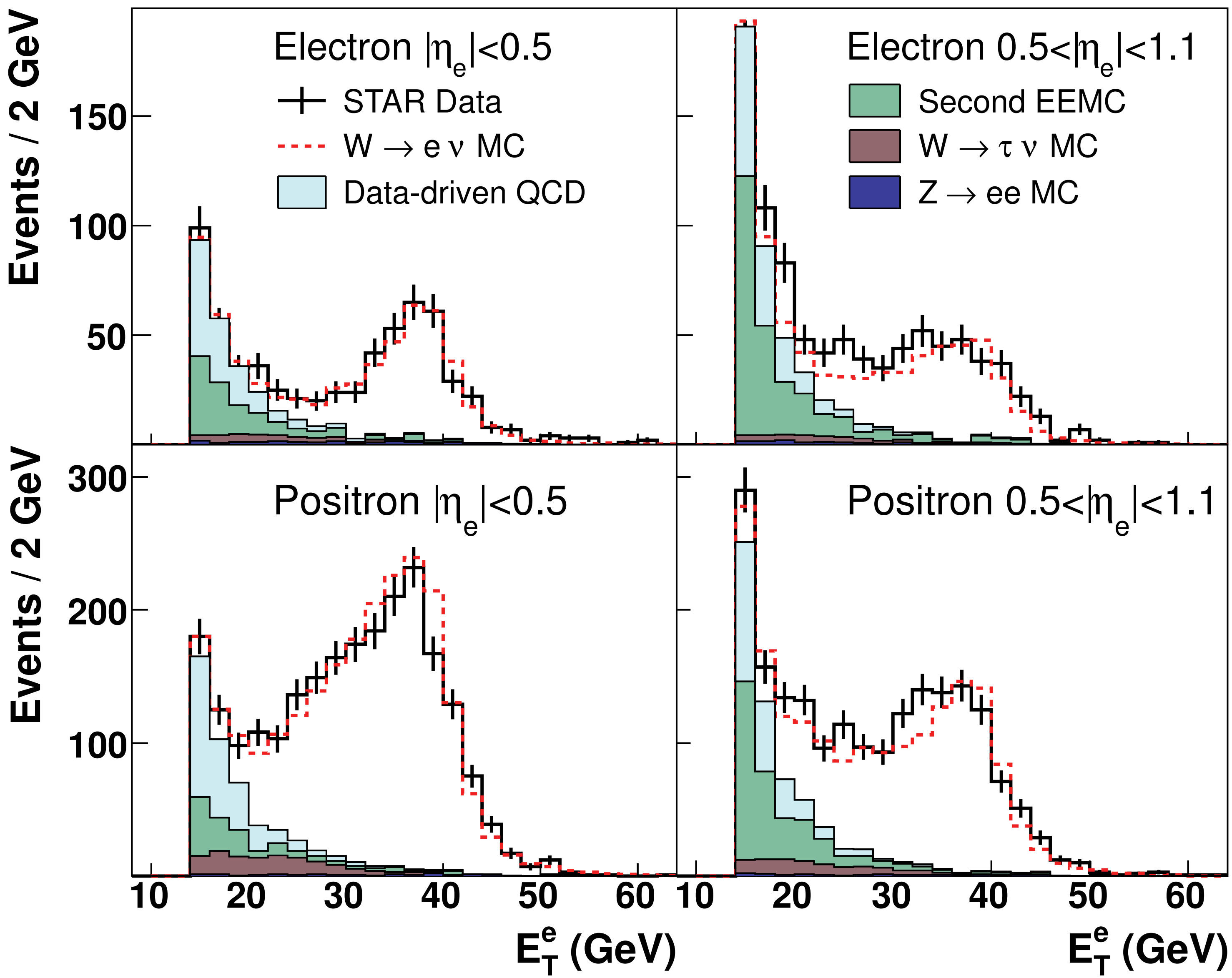
PHENIX single-spin PV asymmetry A_L

Year	√s (GeV)	∫Ldt (pb^{-1})	Pol. (%)	P^2L (pb^{-1})
2009	500	8.6	39	1.3
2011	500	16	48	3.7
2012	510	23.7	55	7.2
2013	510	114.9	55	34.8



- Run 2009 results have been published (with $W^{\pm}$ production cross section measurement).
- Run 2011, 2012 and 2013 have preliminary results, nearing completion.
- A_L measurements are overall consistent with theoretical predictions.

STAR arXiv1404.6880



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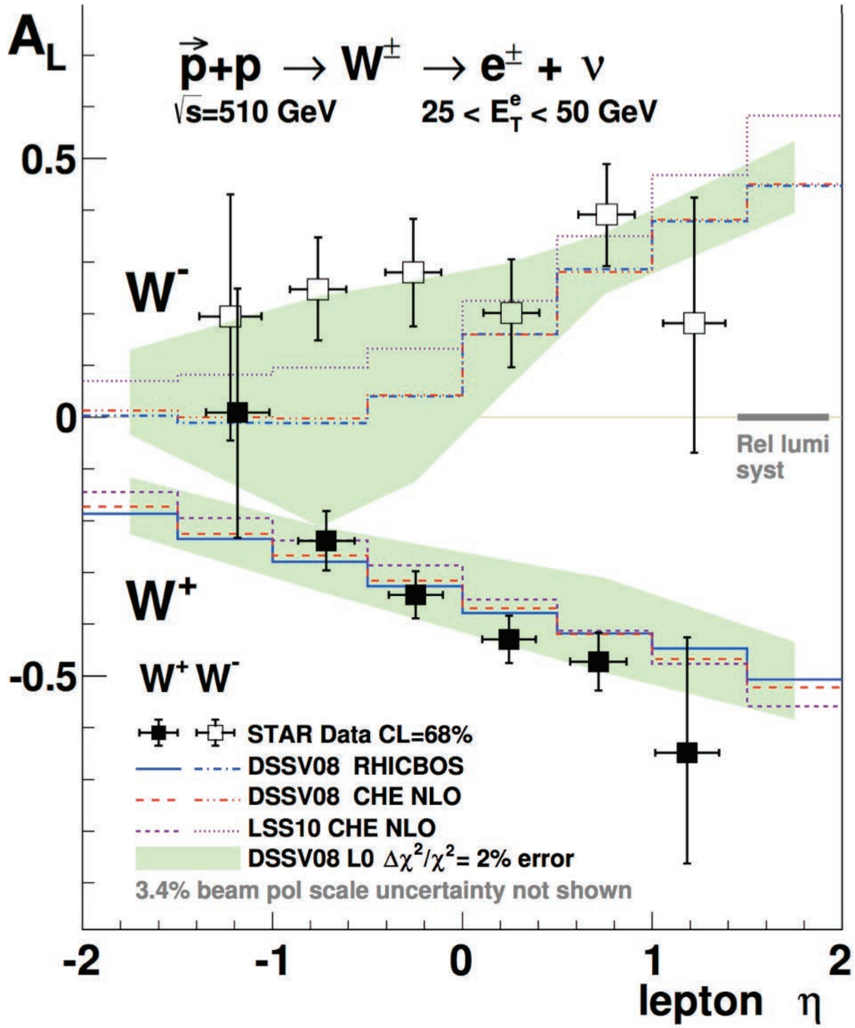
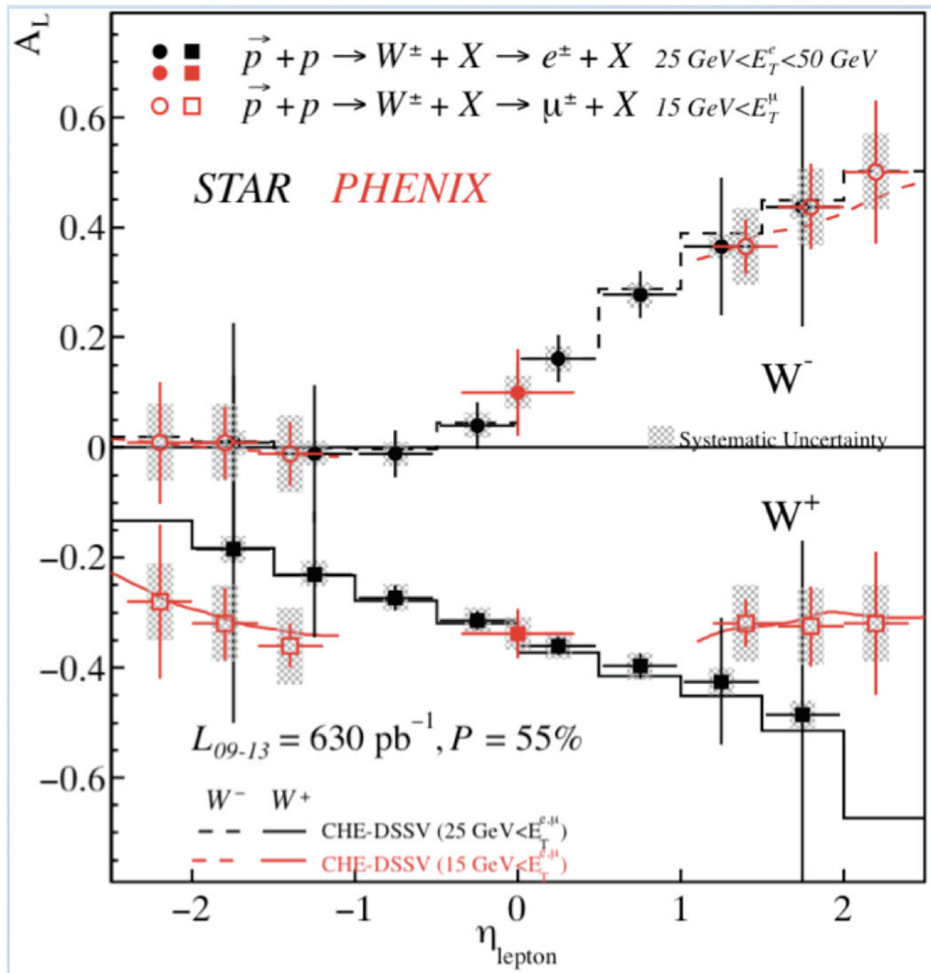
STAR A_L and projections for all 2013 data





STAR arXiv:1404.6880

projected STAR+PHENIX

The End (of this talk)

But there are still much to be understood, and our progress is more like Brownian Motion, than a racing car. Many times when we have looked at something new, we found out that what we thought was the established common knowledge was incorrect.

BACKUP

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:

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

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

- Example: distributing a total number of particles N onto a limited acceptance. Note that if $p \to 0$ 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: $\langle m\rangle = \mu \qquad \sigma_m^2 = \mu$

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

- 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.