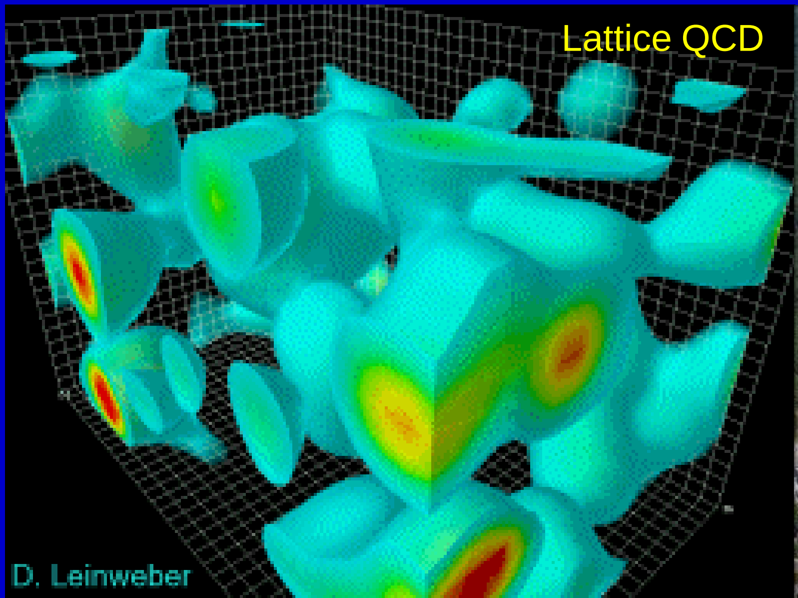
BROOKHAVEN NATIONAL LABORATORY

The 12th International Conference
on Nucleus-Nucleus Collisions
June 21-26 2015, Catania, Italy

Experimental Highlights on QCD Medium Properties at RHIC

Rachid Nouicer

Brookhaven National Laboratory, NY



Outline

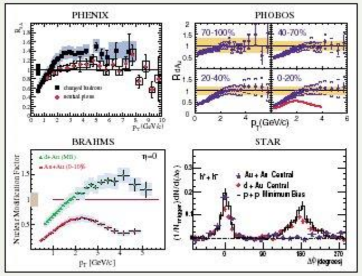
- Introduction
  - 10 years anniversary of perfect fluid in heavy ion collisions (2005-2015)
- The RHIC **B**eam **E**nergy **S**can: Mapping QCD PHASE Diagram
  - Determine the energy at which key QGP signatures turn off
  - Search for the critical end point (CEP)
- Surprise: QGP-like behavior in Small Colliding Systems
  - **BES**: Near energy independence of the $v_n(p_T)$ in A+A collisions
  - Non-zero p,d, ^{3}He + A $v_n(p_T)$ moments comparable to the A+A ones
- Quarkonia as Probe for Hot and Cold Nuclear Matter
  - J/ψ and Υ measurements: centrality, system size and energy Dependence
- RHIC from now to NN2017

RHIC Discoveries in the Press

The Collaboration of the four experiments: PHENIX, BRAHMS, PHOBOS and STAR at RHIC

CONCLUDED strongly-interacting matter

PHYSICAL REVIEW LETTERS
Articles published week ending 15 AUGUST 2003
Volume 91, Number 7



APS Published by The American Physical Society

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

Secretary of Energy Samuel Bodman

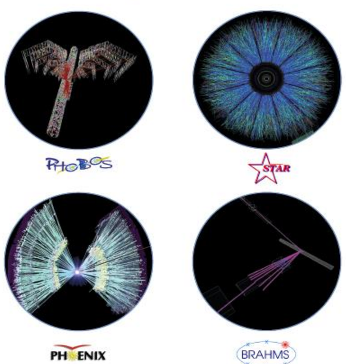
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005



Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

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RHIC Scientists Serve Up 'Perfect' Liquid: New State Remarkable Than Predicted

Apr. 25, 2005 — TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had

These images co and collective mo the predicted gas (Figure A, see mp that has been obs RHIC (Figure B, s "force lines" and animated version degree of interact what is now being liquid. (Courtesy Laboratory)

International Journal of High-Energy Physics

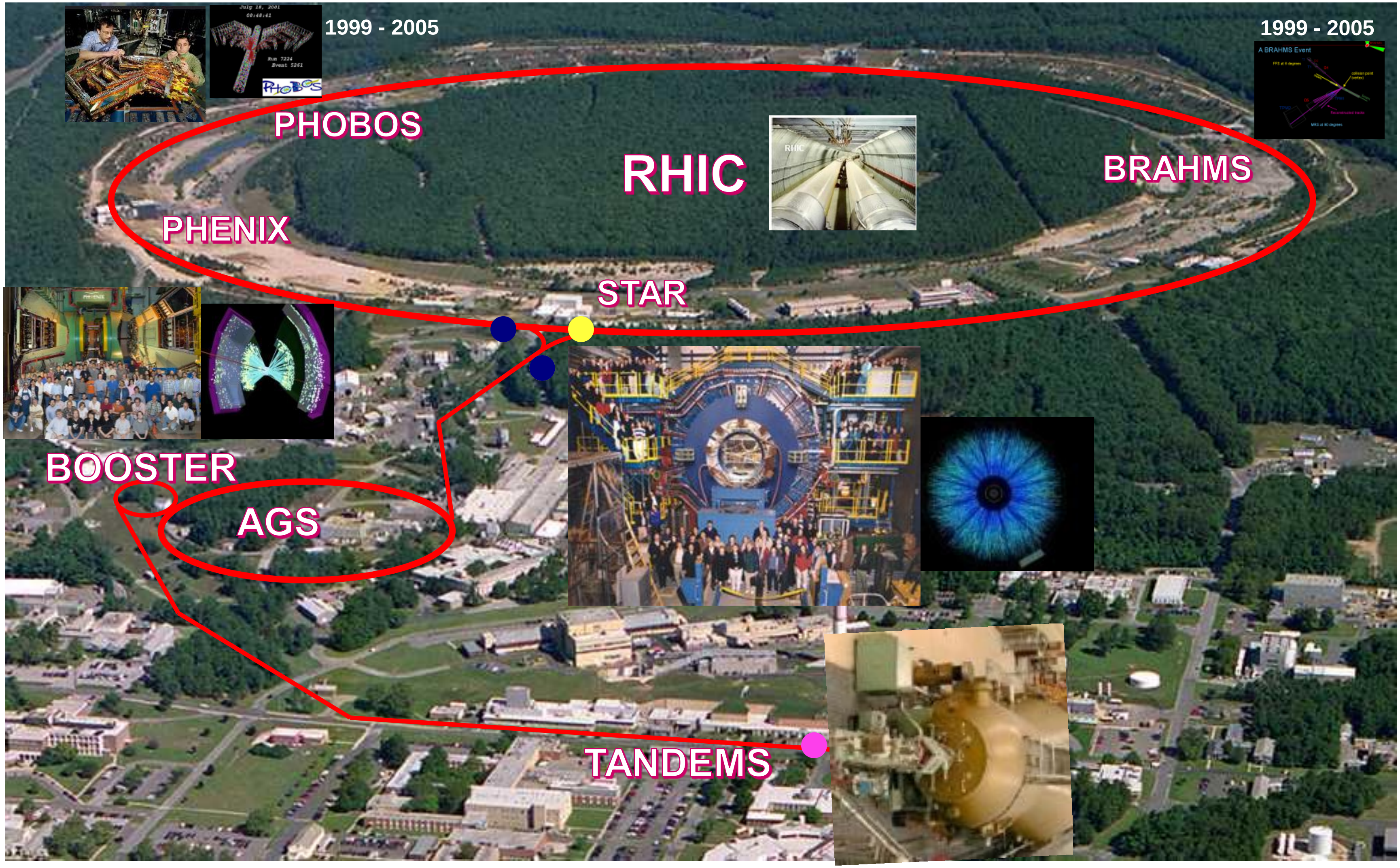
CERN COURIER

May 6, 2005

RHIC groups serve up 'perfect' liquid

The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory have announced results indicating that they have observed a state of hot, dense matter that is more remarkable than had been predicted. In papers summarizing the first three years of RHIC findings, to be published simultaneously by the journal *Nuclear Physics A*, the four collaborations (BRAHMS, PHENIX, PHOBOS and STAR) say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter

Relativistic Heavy Ion Collider (RHIC)



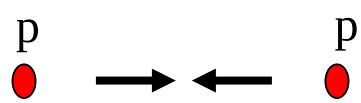
Beam-Beam Collisions at RHIC: 2000 to 2015 (NON-STOP)

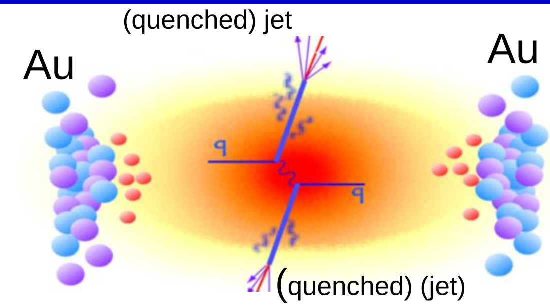
Run	Faisceaux	Énergie centre-de-masse [GeV]	Luminosité totale [mb^{-1}]
I (2000)	Au+Au Au+Au	56 130	< 0.001 20
II (2001/2002)	Au+Au Au+Au p+p	200 19.6 200	25.8 0.4 1.4×10^{-6}
III (2003)	d+Au p+p	200 200	73×10^{-3} 5.5×10^{-6}
IV(2004)	Au+Au Au+Au p+p	200 62.4 200	3.53×10^{-3} 67 7.1×10^{-6}
V (2005)	Cu+Cu Cu+Cu Cu+Cu p+p p+p	200 62.4 22.4 200 410	42.1×10^{-3} 1.5×10^{-3} 0.02×10^{-3} 29.5×10^{-6} 0.1×10^{-6}
VI (2006)	p+p p+p	200 62.4	88.6×10^{-6} 1.05×10^{-6}
VII (2007)	Au+Au Au+Au	200 9.2	7.25×10^{-3} Small

Run	Faisceaux	Énergie centre-de-masse [GeV]	Luminosité totale [mb^{-1}]
VIII(2008)	d+Au p+p Au+Au	200 200 9.6	437×10^{-3} 38.4×10^{-6} Small
IX (2009)	p+p P+p	500 200	110×10^{-6} 114×10^{-6}
X(2010)	Au+Au Au+Au Au+Au Au+Au Au+Au	200 62.4 39 7.7 11.5	10.3×10^{-3} 544 206 4.23 7.8
XI(2011)	p+p Au+Au Au+Au Au+Au	500 19.6 200 27	166×10^{-6} 33.2 9.79×10^{-3} 63.1
XII(2012)	p+p p+p U+U Cu+Au	200 510 193 200	74×10^{-6} 283×10^{-6} 736 27×10^{-3}
XIII(2013)	p+p	510	1.04×10^{-9}
XIV (2014)	Au+Au Au+Au ^{3}He+Au	14.6 200 200	44.2 43.9×10^{-3} 134×10^{-3}
XV(2015)	p+p p+Au p+Al	200 200 200	382×10^{-9} done In progress

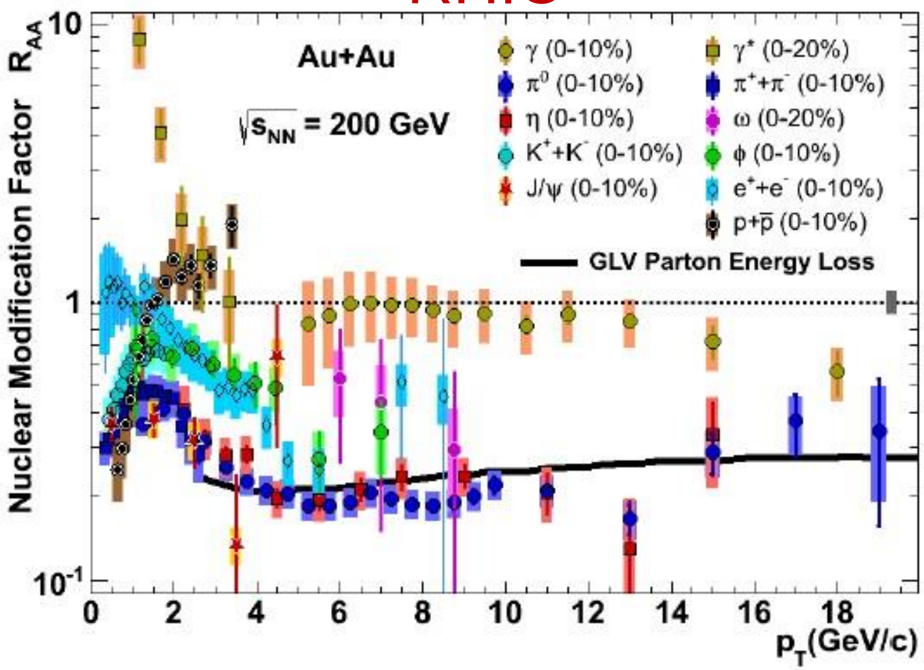
Motivation: Jet Quenching "Major Discovery"

$$R_{AA}(p_T, y, b) = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}(b) \rangle \, d^2\sigma^{pp}/dp_T d\eta}$$

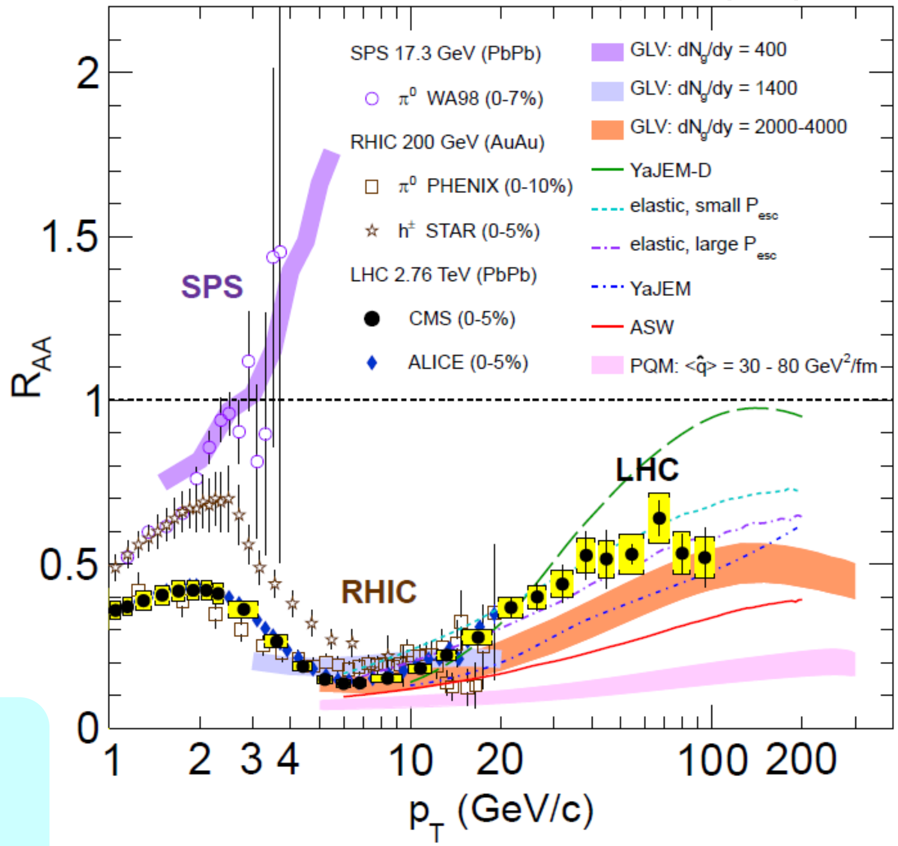




RHIC



SPS - RHIC - LHC **Eur. Phys. J. C (2012) 72:1945**

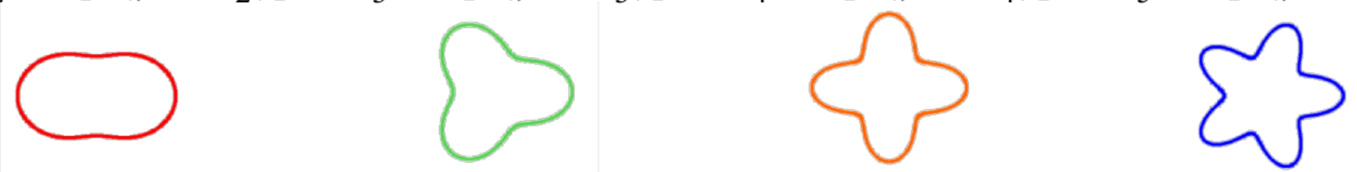


Suppression of π^0 is the major discovery at RHIC as well at LHC

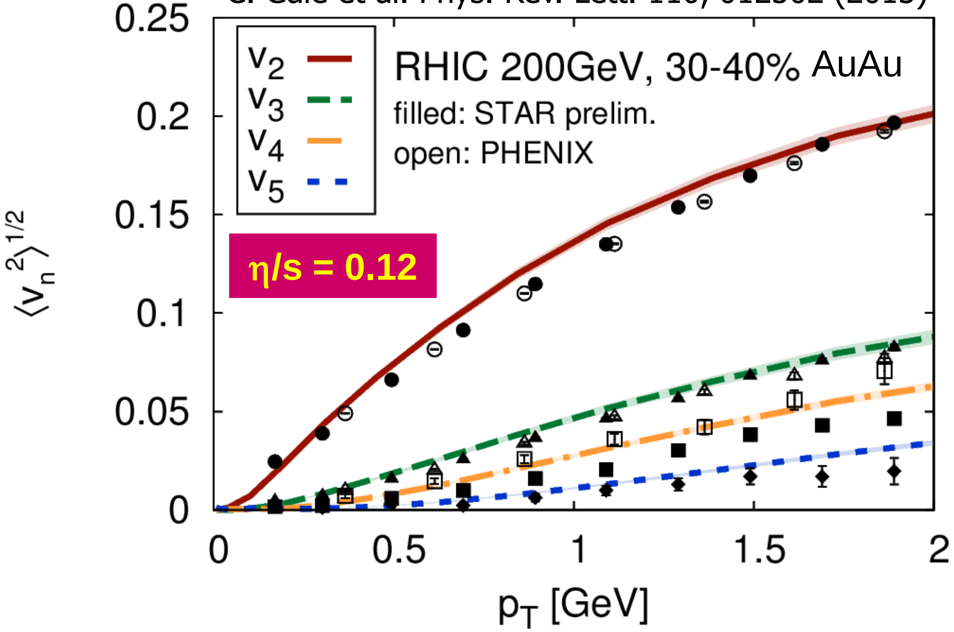
Motivation: Perfect Liquid "Major Discovery"

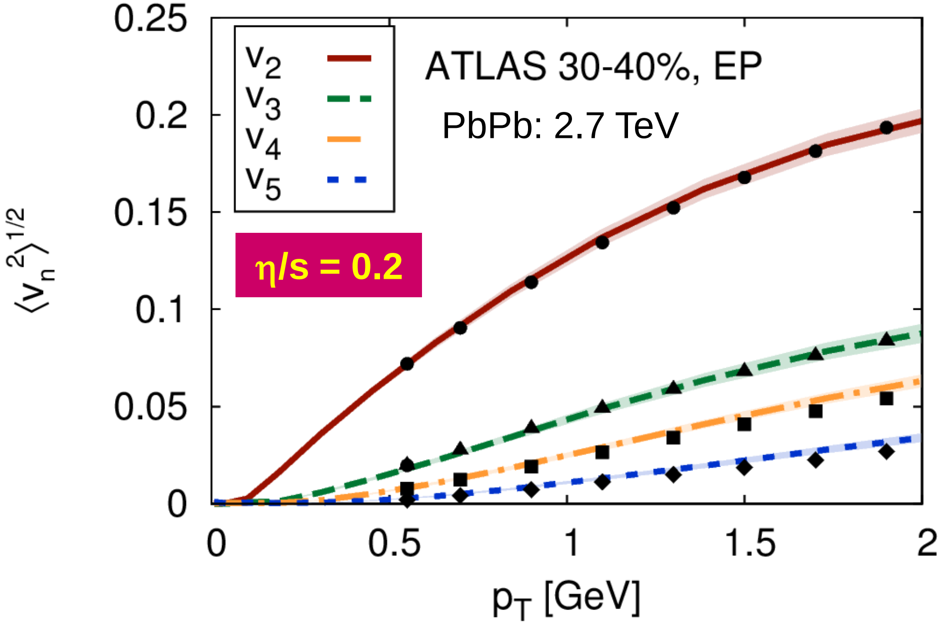
RHIC and LHC precision measures of higher moments

$$\frac{dN}{d\phi} = 1 + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + 2v_4 \cos[4(\phi - \Psi_4)] + 2v_5 \cos[5(\phi - \Psi_5)] + \ldots$$



C. Gale et al. Phys. Rev. Lett. 110, 012302 (2013)



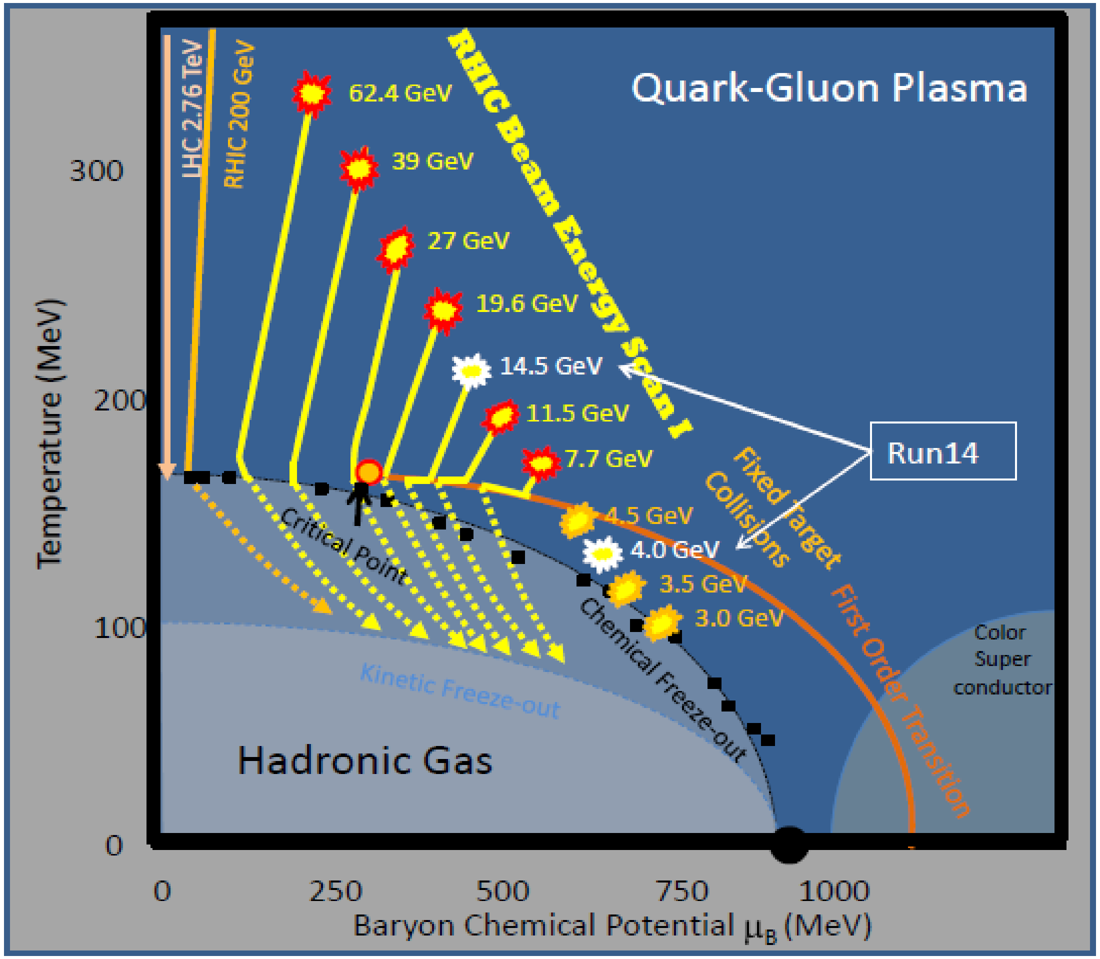


- **Medium is strongly interactive (the large amplitude of v_2)**
- Comparisons models hydrodynamic viscous with RHIC and LHC data seem to support very small values for η/s. This implies that the nuclear matter created **is almost perfect fluid**. The properties of this fluid remains to be determined.

The RHIC Beam Energy Scan (BES)

Phases of QCD matter

- How do we map the QCD phase diagram?

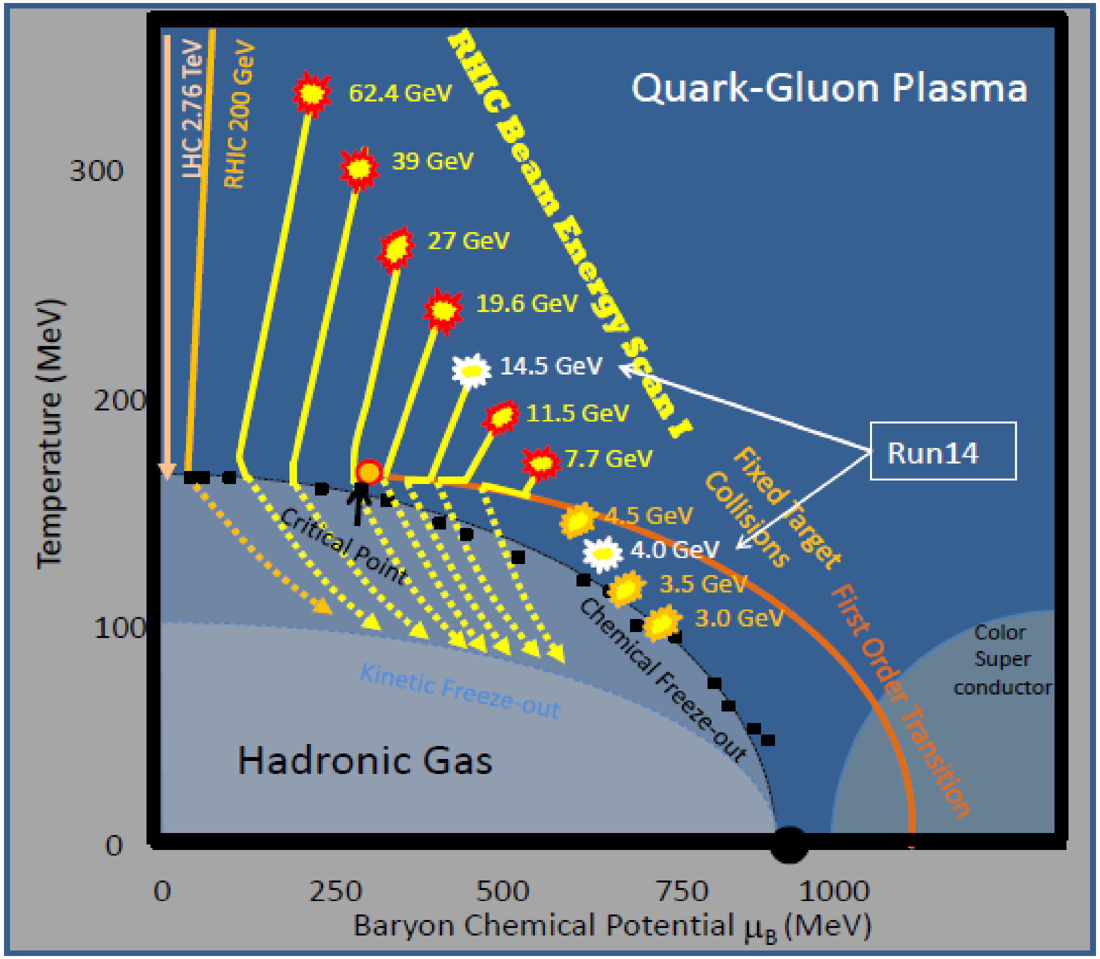


The RHIC Beam Energy Scan (BES)

Phases of QCD matter

- How do we map the QCD phase diagram?

- Vary the collision energy over the full range accessible at RHIC



The RHIC Beam Energy Scan (BES)

Phases of QCD matter

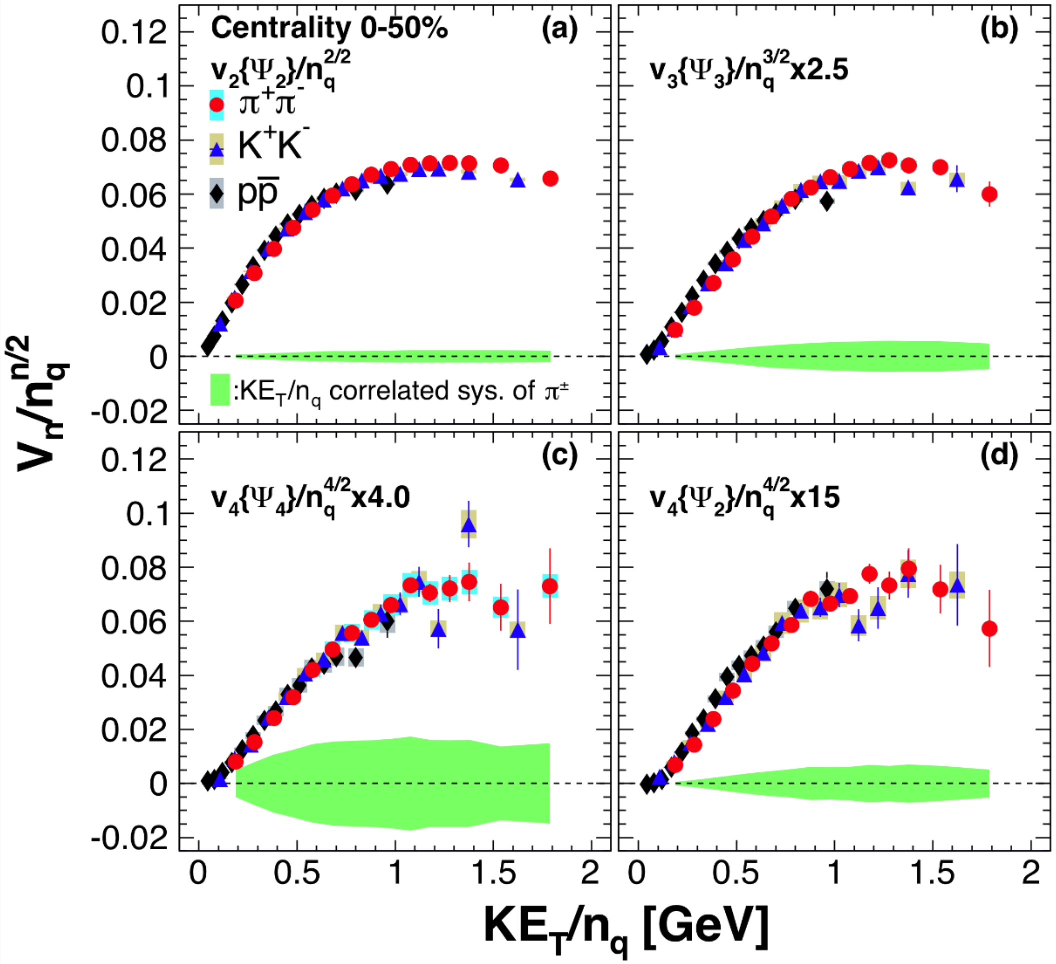
- How do we map the QCD phase diagram?
- Vary the collision energy over the full range accessible at RHIC
- Do we observe turn off of the new phenomena that have been observed in full-energy RHIC collisions?
  - Constituent quark number scaling of higher moments v_n (p_T)
  - Jet quenching in central collisions
- Do we observe signatures of a phase transition and/or critical end point?
  - Elliptic and directed flow: indicators of the “softest point” in momentum space
  - Azimuthally-sensitive HBT: indicator of the “softest point” in coordinate space

The RHIC Beam Energy Scan (BES)

Constituent quark number scaling of higher moments v_n (p_T)

Au+Au at 200 GeV

PHENIX: arXiv:1412.1038



the transverse kinetic energy

$$KE_T \equiv m_T - m_0 = \sqrt{p_T^2 - m_0^2} - m_0$$

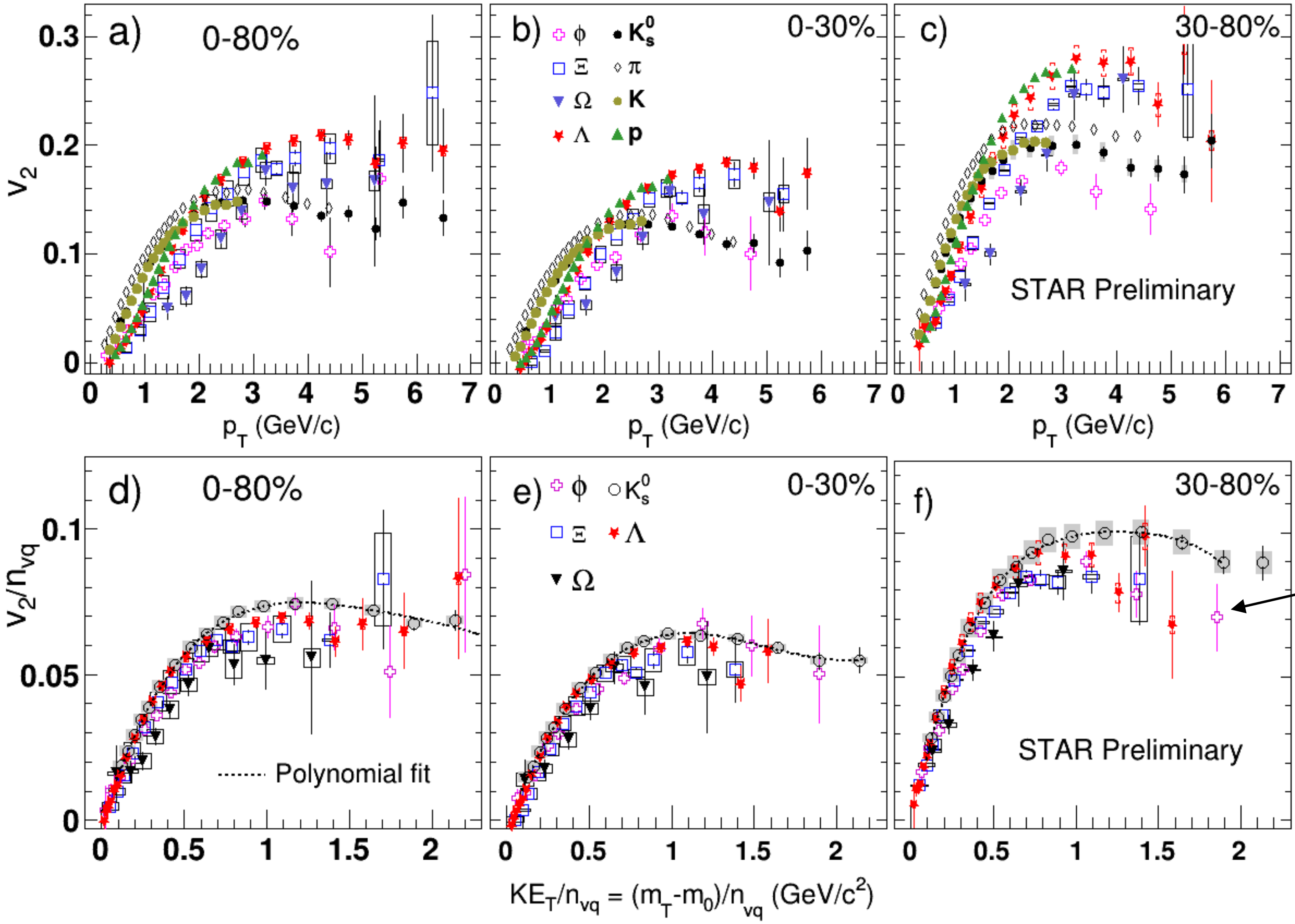
where m_0 is the particle's mass

Constituent quark scaling is seen as an indication of partonic behavior

The RHIC Beam Energy Scan (BES)

Constituent quark number scaling of v_2 (p_T)

Au+Au at 200 GeV



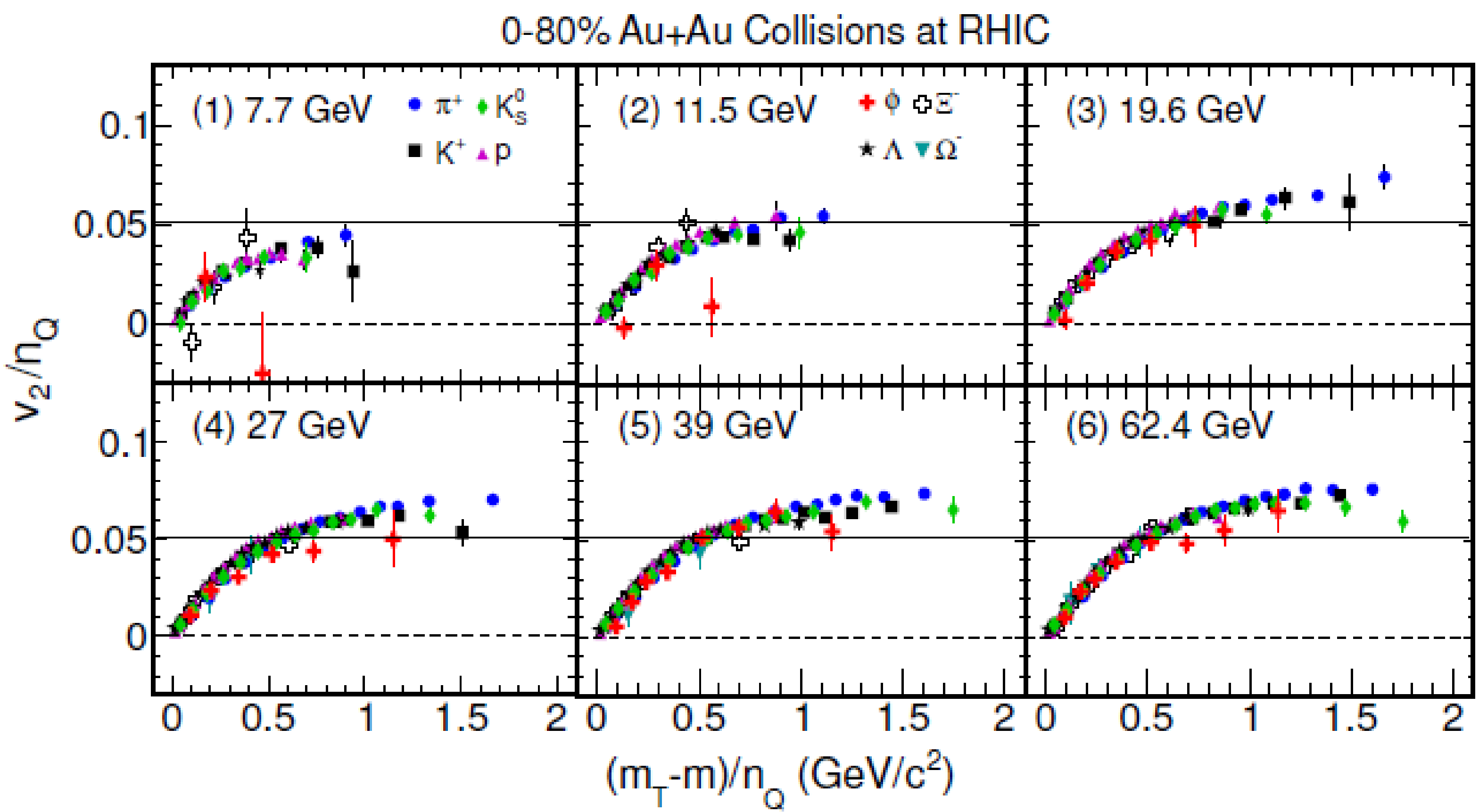
It is known that the Φ meson does not participate as strongly as others do in hadronic interactions

Constituent quark scaling is seen as an indication of partonic behavior

The RHIC Beam Energy Scan (BES)

Disappearance of QGP Signatures

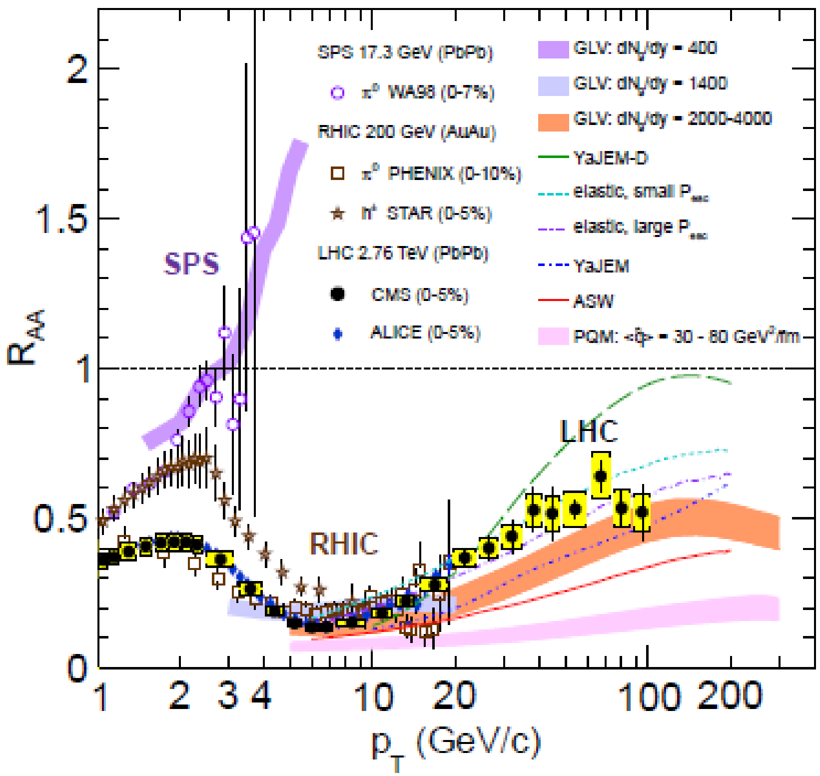
Constituent quark number scaling of $v_2(p_T)$
Au+Au versus energy

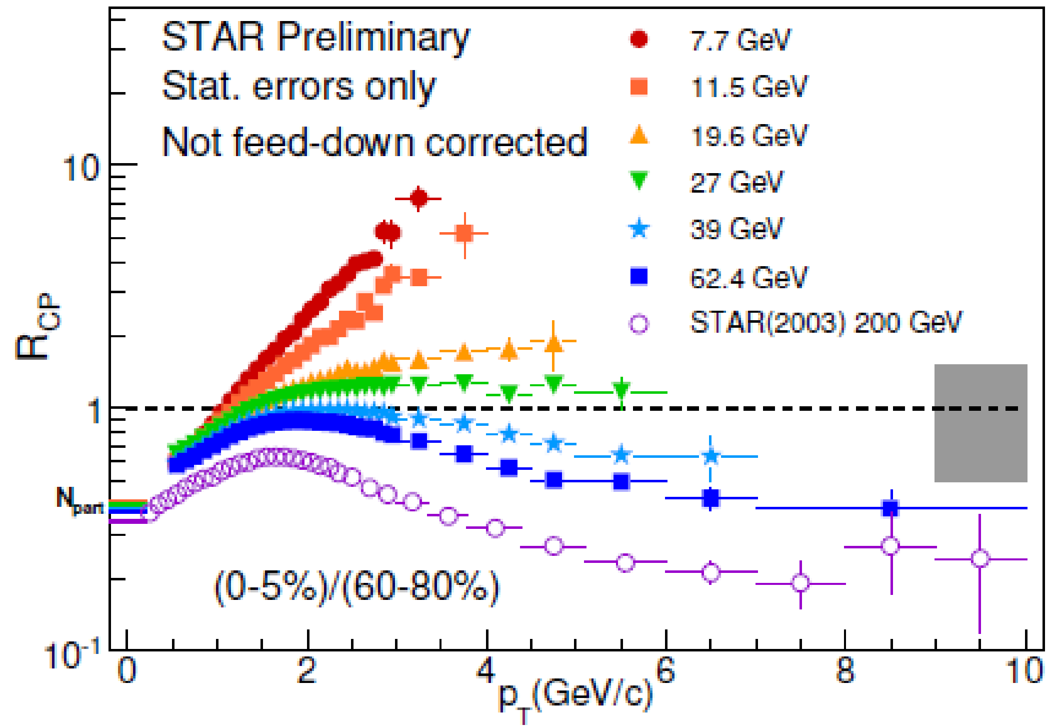


The magnitude of v_2 doesn't change with energy > 19.6 GeV
The ϕ meson no longer follows the trends below 19.6 GeV

Jet quenching

R_{CP} for hadrons can provide a measure of partonic energy loss in the medium



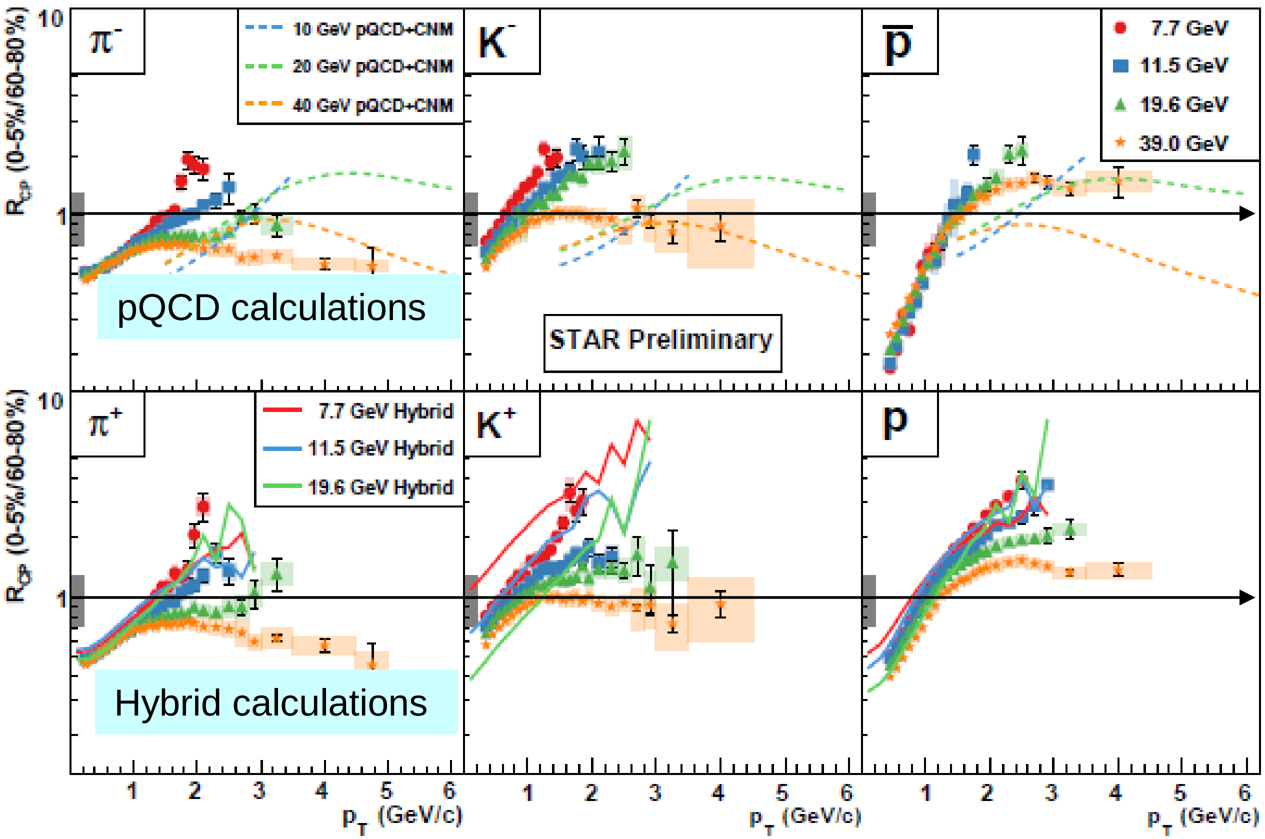


Insufficient reach to search for evidence of high p_T suppression below 19.6 GeV

Jet quenching

R_{CP} for identified particles can provide a measure of partonic energy loss in the medium

- Stopped Baryons shows complicated inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior

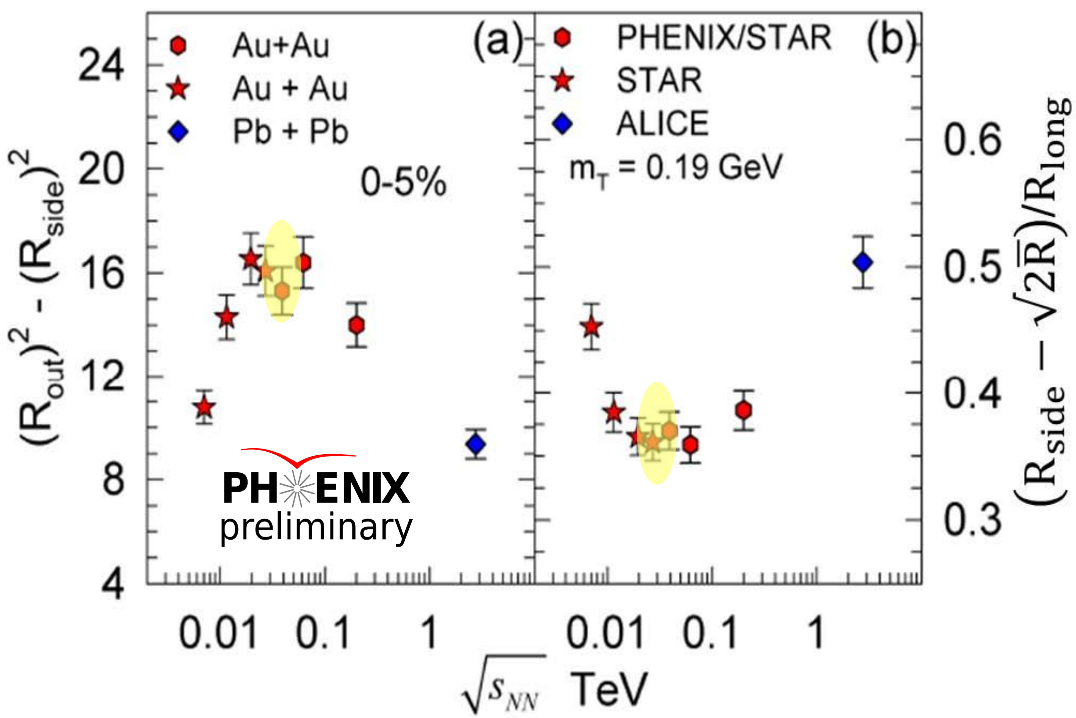


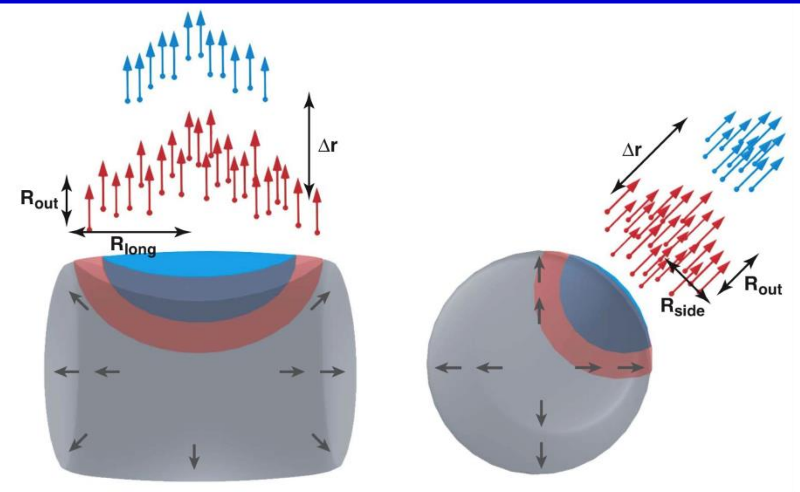
Insufficient reach to search for evidence of high p_T suppression below 19.6 GeV

The RHIC Beam Energy Scan (BES)

Interferometry probe:
energy dependence of HBT signals

HBT radii are sensitive to the expansion dynamics





Roy Lacy: BNL seminar

$$R^2_{side} = \frac{R^2_{geo}}{1 + \frac{m_T}{T} b_T^2}$$

$$R^2_{out} = \frac{R^2_{geo}}{1 + \frac{m_T}{T} b_T^2} + b_T^2 (\Delta t)^2$$

$$R^2_{long} \approx \frac{T}{m_T} t^2$$

(R^2_{out} - R^2_{side}) sensitive to emission duration

These non-monotonic patterns signal an important change in the reaction dynamics; CEP?

QGP-like behavior in Small Colliding Systems

Significant v_2

and

striking similarity of v_3

for p+Pb

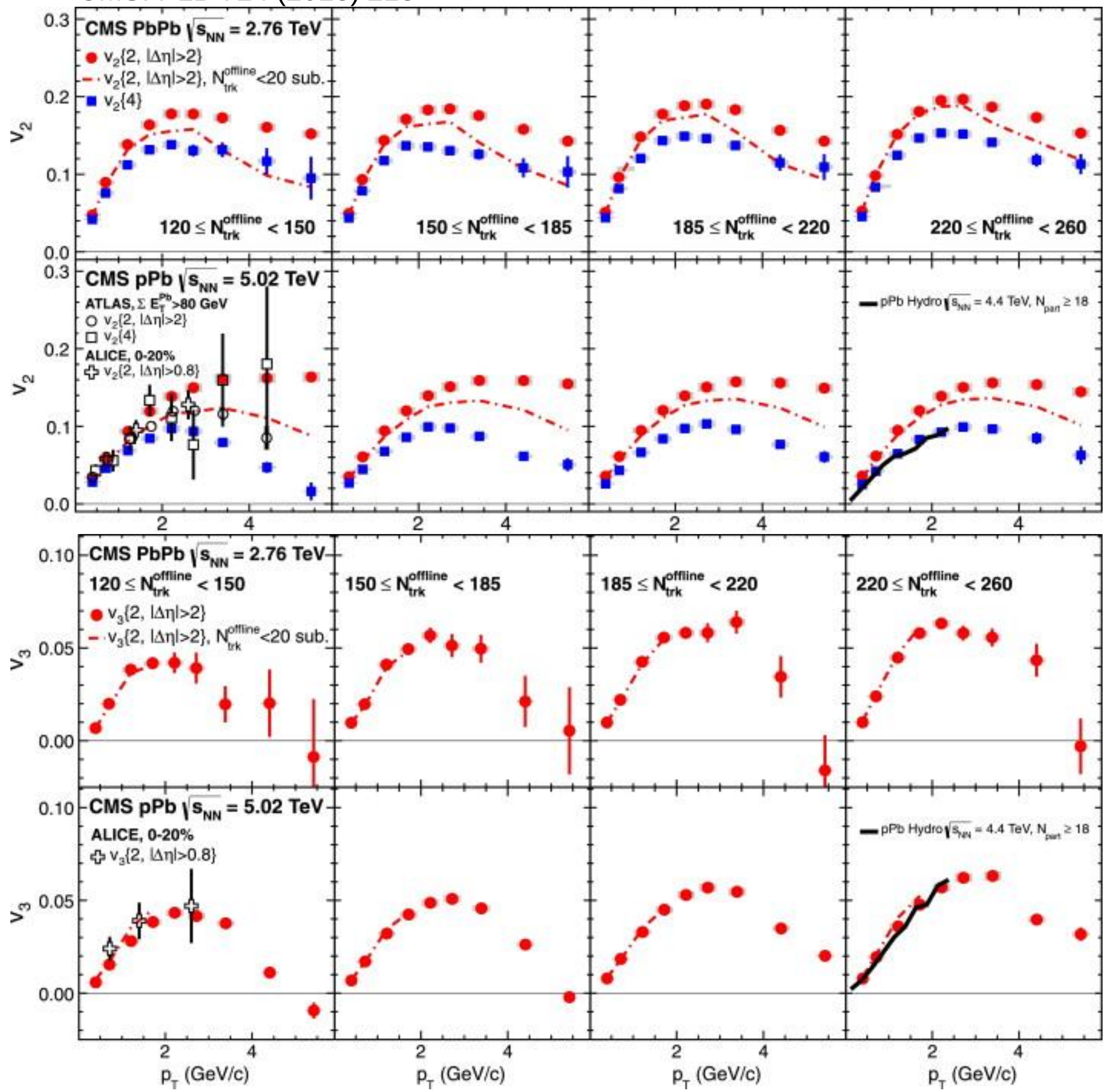
and Pb+Pb systems

with drastically

different collision

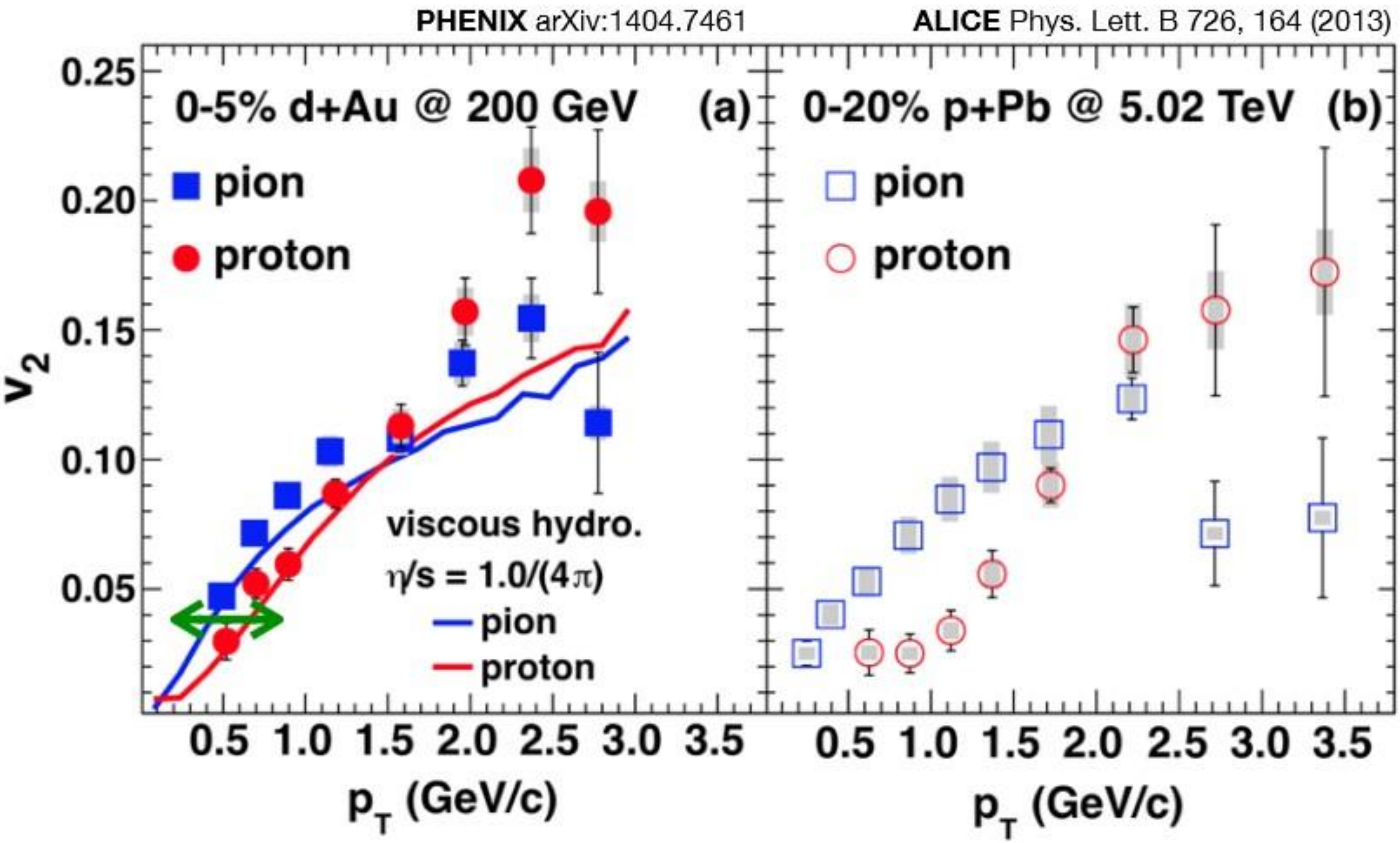
geometry

CMS: PLB 724 (2013) 213



QGP-like behavior in Small Colliding Systems

Mass Ordering



Consistent with expectation given a fluid velocity field

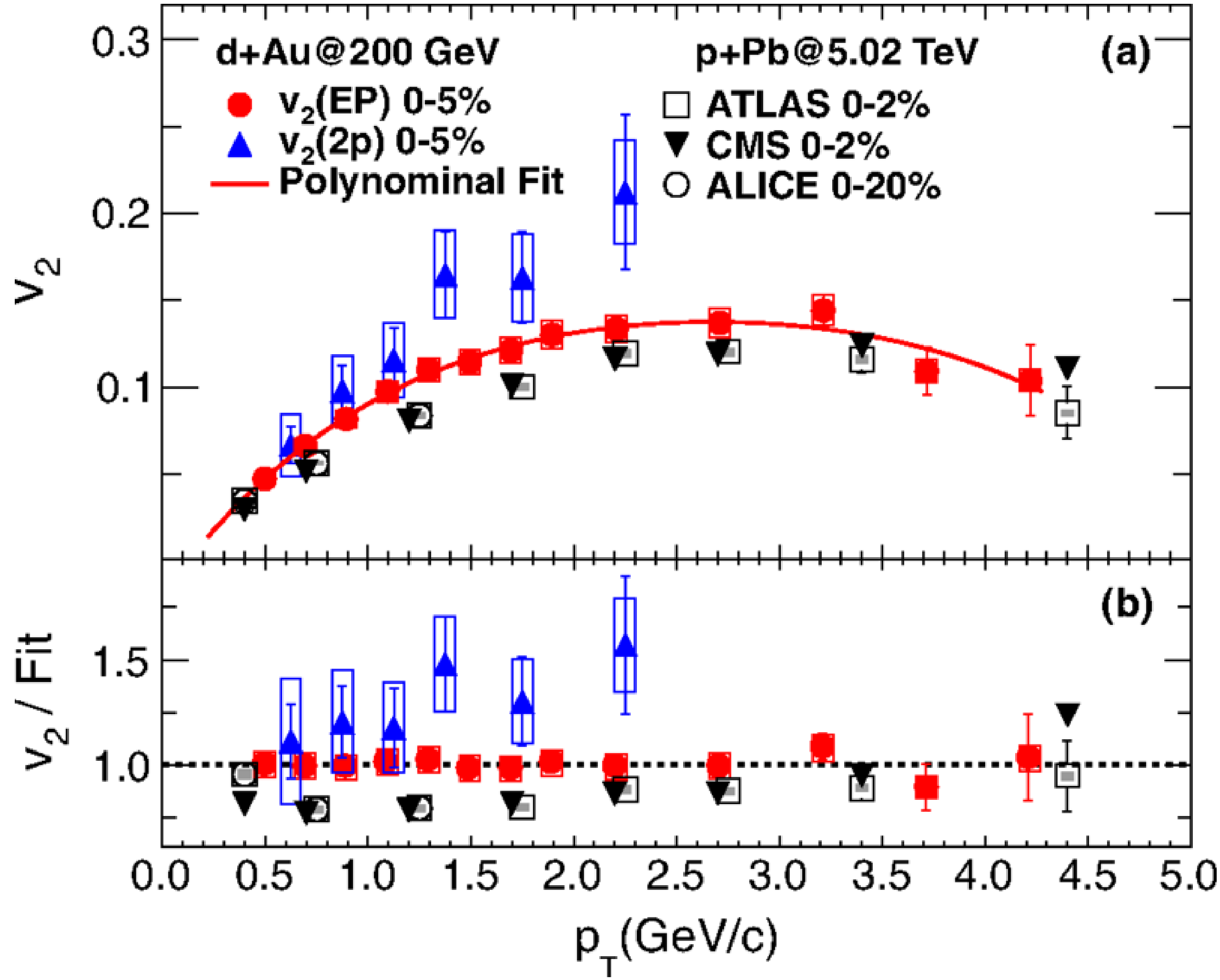
v_2(EP) of charged hadron in 0-5% d+Au

Phys. Rev. Lett. **114**, 192301 (2015)

Hydro-like

shape

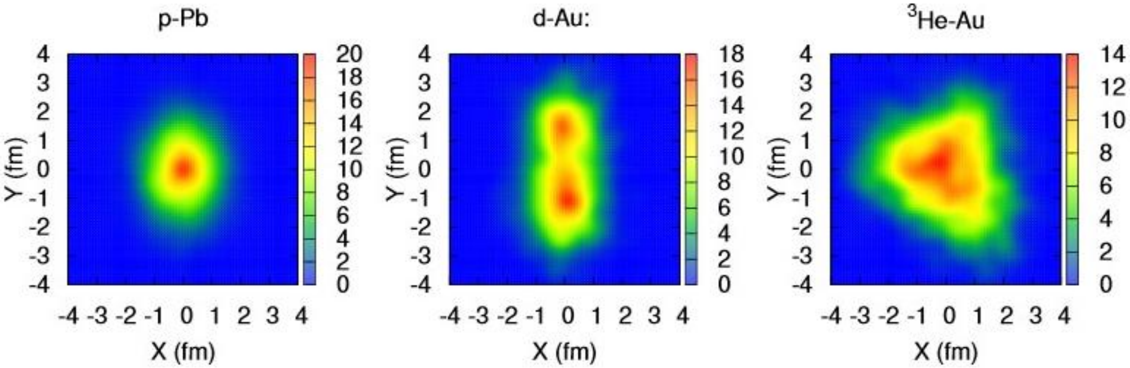
in $v_2(p_T)$?



QGP-like behavior in Small Colliding Systems

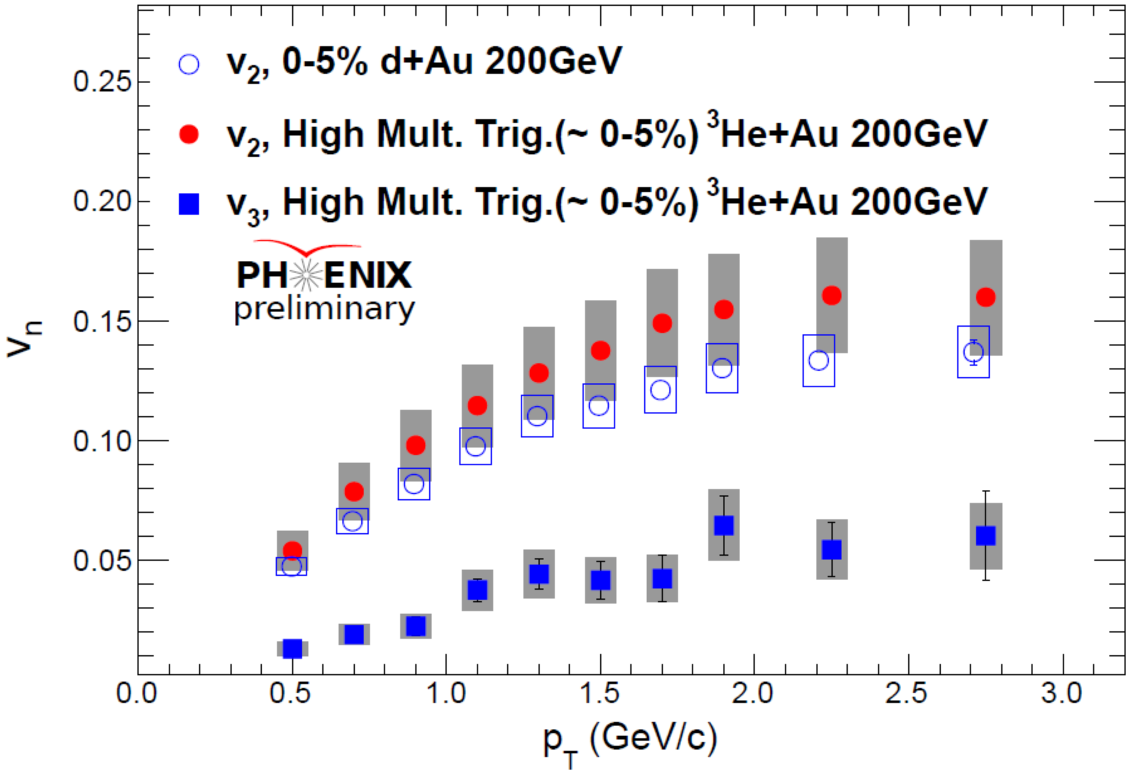
Central collision events of p-Pb, d-Au, ^{3}He-Au

Averaged density profile of central events: (PHOBOS Monte Carlo Glauber)



Li Yan, RBRC workshop

Azimuthal flow,
v_n (n=2,3) in ^{3}He+Au



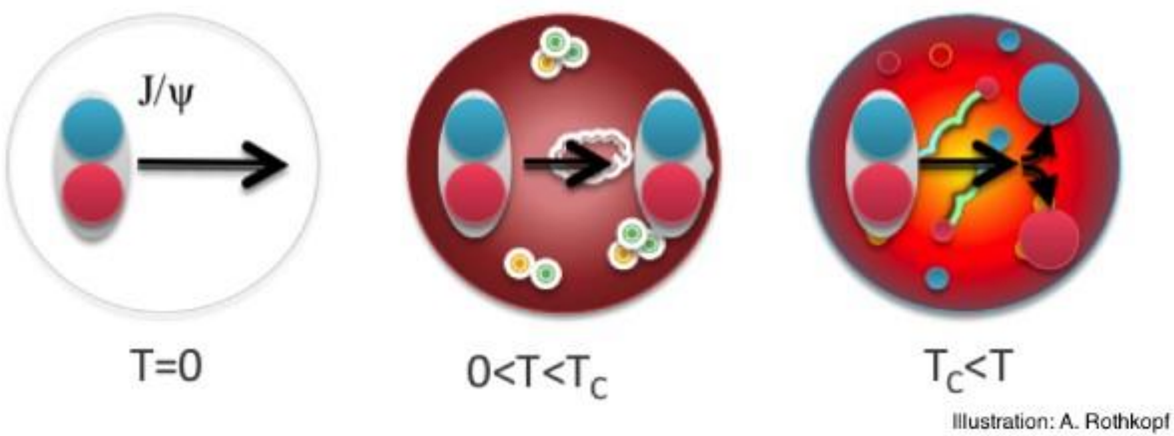
Hydro-like

shape

in $v_2(p_T)$?

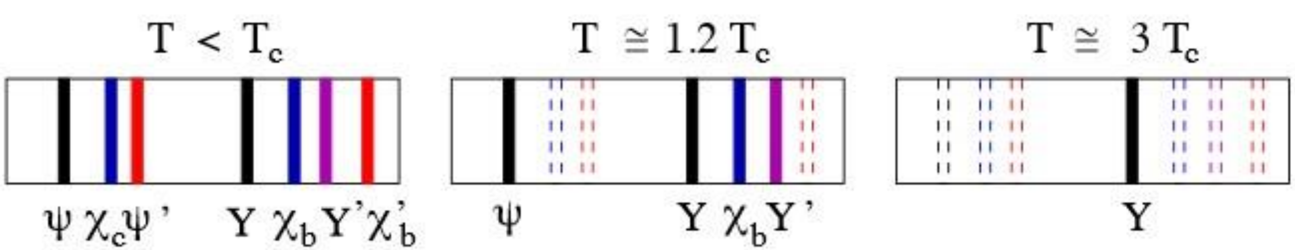
Why study Quarkonia?

- To learn about thermal properties of QGP medium
  - ✓ Quarkonia are expected to dissociate due to Debye screening of heavy quark potential (r_D α 1/T) Phys. Lett. B178, 416



Charmonia ($c\bar{c}$):
J/Ψ, Ψ', χ_c

Bottomonia ($b\bar{b}$):
ϒ(1S), ϒ(2S), ϒ(3S), χ_B



Phys. Rev. D77, 014501

Quarkonia as Probe for Hot and Cold Nuclear Matter

System Size/ Collision Asymmetry

Change the relative contributions
of **Cold** and **Hot** nuclear matter effects

Centrality

Suppression vs path length

Collision Energy

Change system energy density

Momentum

Hard collision dynamics

Rapidity

Probes different gluon
(anti)shadowing

Heavy/Light

Mass ordering of suppression

Particle Species

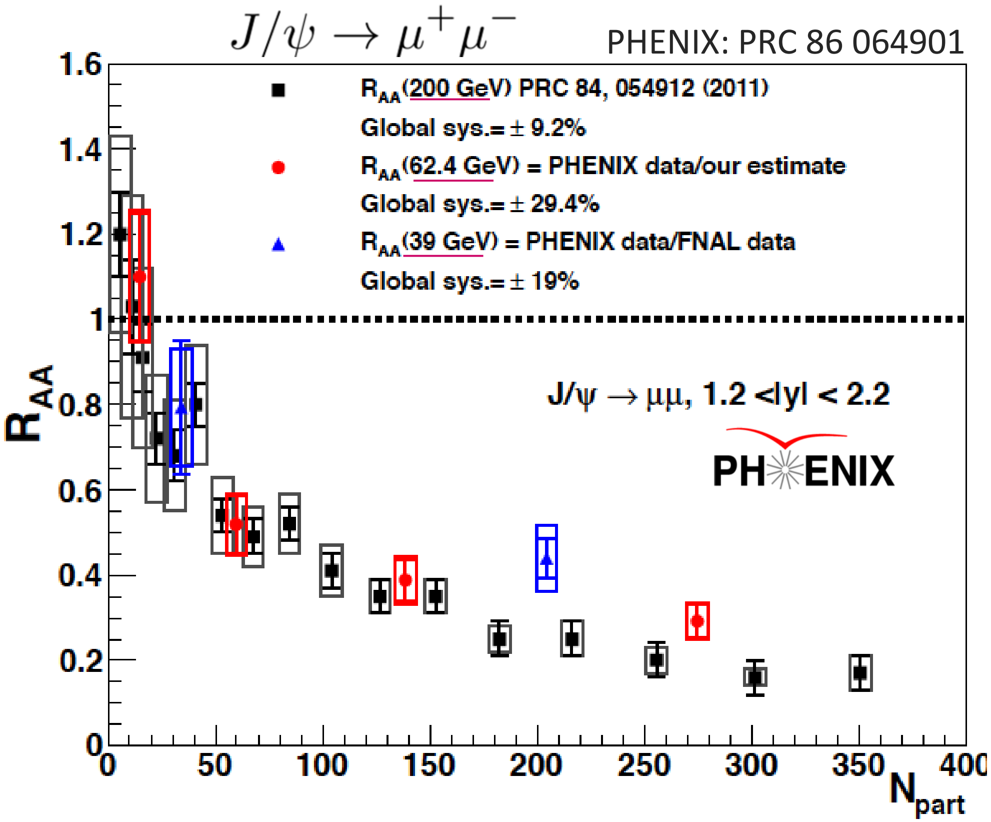
Break-up, Temperature?

Each parameter probes different admixtures of nuclear modification

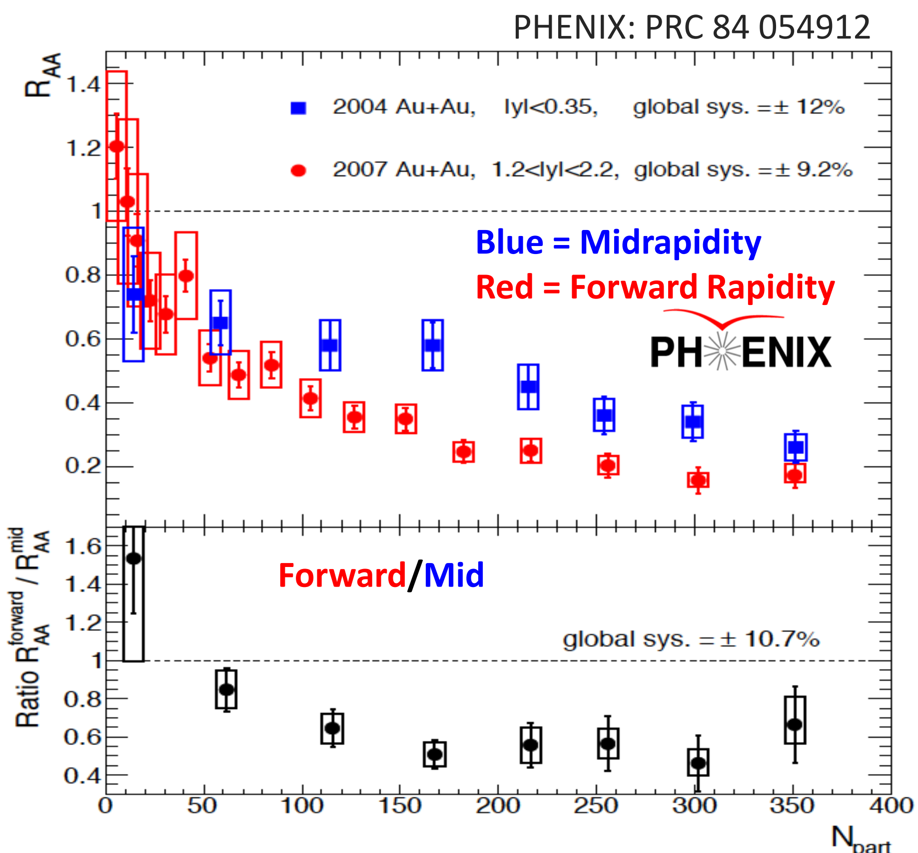
Quarkonia as Probe for Hot and Cold Nuclear Matter

Bound Heavy Flavor: J/ψ R_{AA}

Au+Au at different energies



Au+Au at 200 GeV
mid- vs. forward rapidities



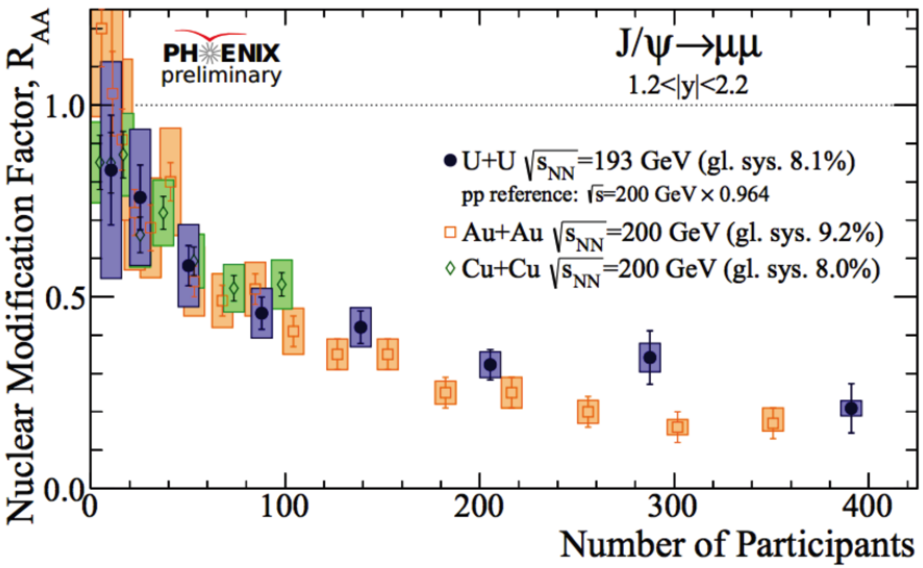
In Au+Au and at forward rapidity:
R_{AA} show similar suppression at different collision energies:
200, 62.4 and 39 GeV

Significant J/ψ suppression at mid- and forward rapditiy regions is observed in central Au + Au collisions
R_{AA} decreases with increasing N_{part}

Quarkonia as Probe for Hot and Cold Nuclear Matter

Bound Heavy Flavor: J/ψ R_{AA}

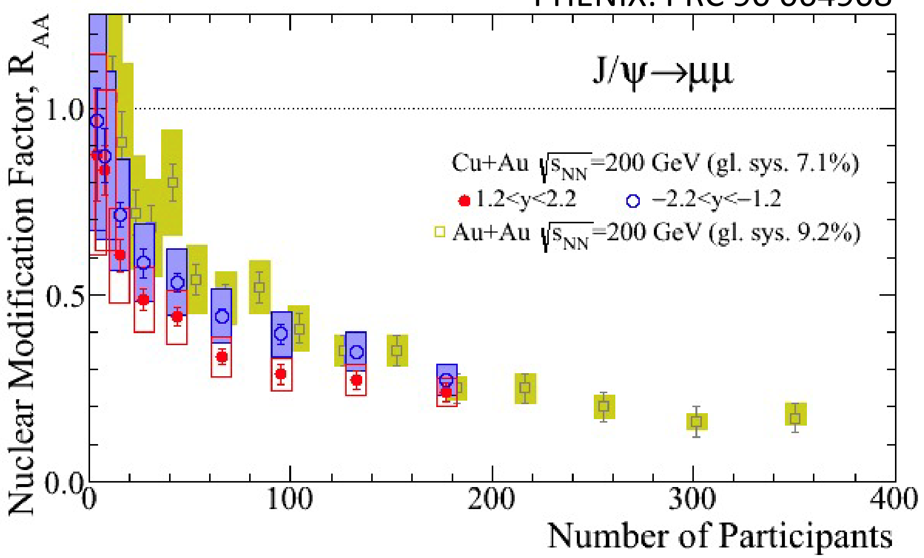
System Size study:
Cu+Cu, Au+Au and U +U ≈ 200 GeV
J/ψ → $\mu^+ \mu^-$ at forward rapidity
$1.2 < |y| < 2.2$



Not much net effect on R_{AA} at forward rapidity from increasing system size of colliding nuclei!
Is this what we expected?

System Size study:
Cu+Au vs Au+Au at 200 GeV
J/ψ → $\mu^+ \mu^-$

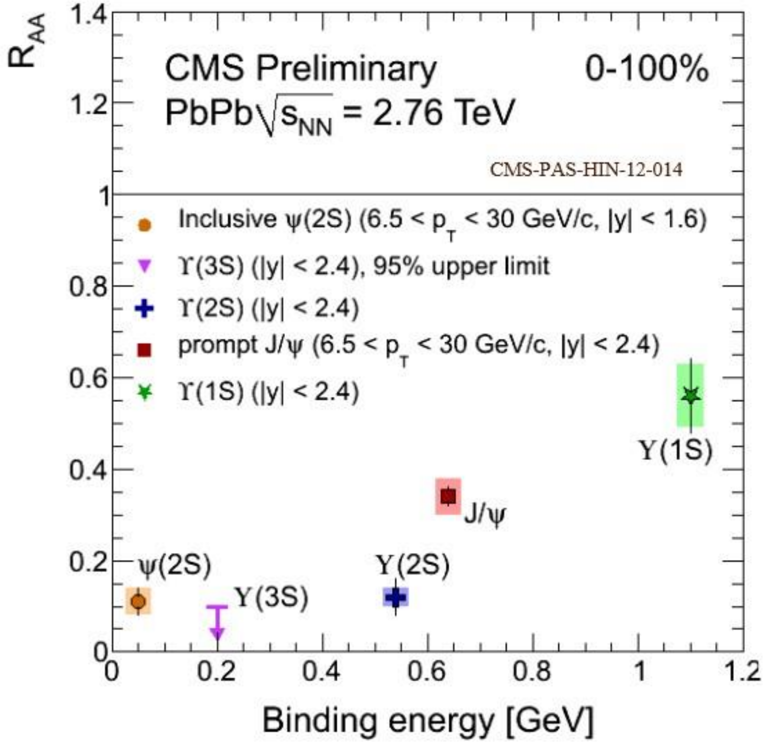
PHENIX: PRC 90 064908

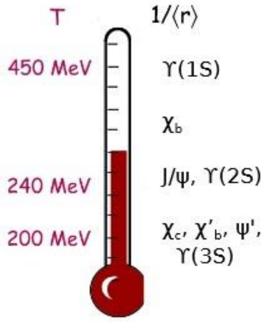


- Similar suppression in Cu+Au compared to Au+Au
- Forward (Cu-going) more suppressed than Backward → CNM effects?

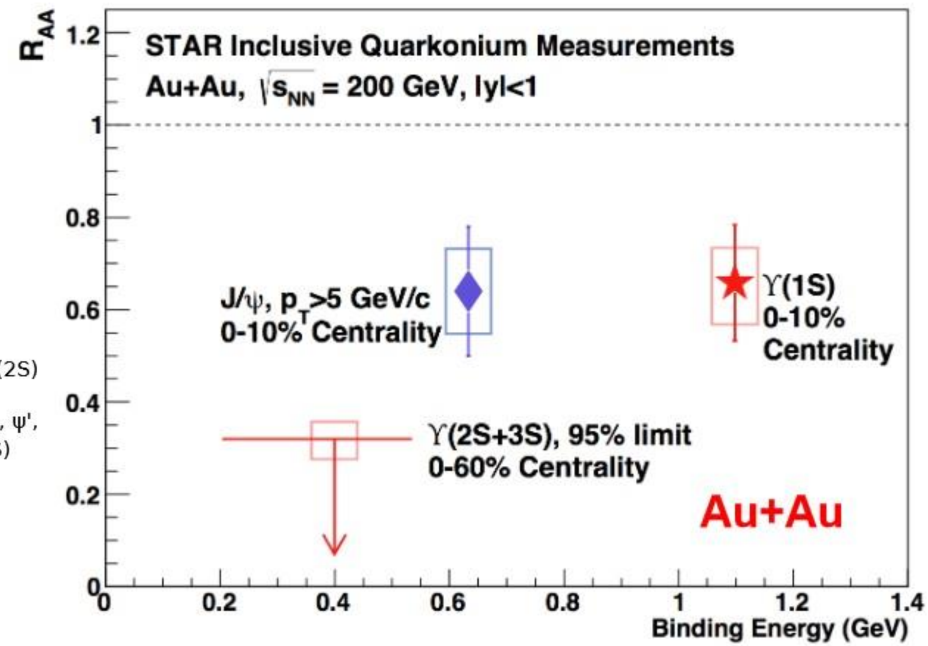
Quarkonia as Probe for Hot and Cold Nuclear Matter

LHC



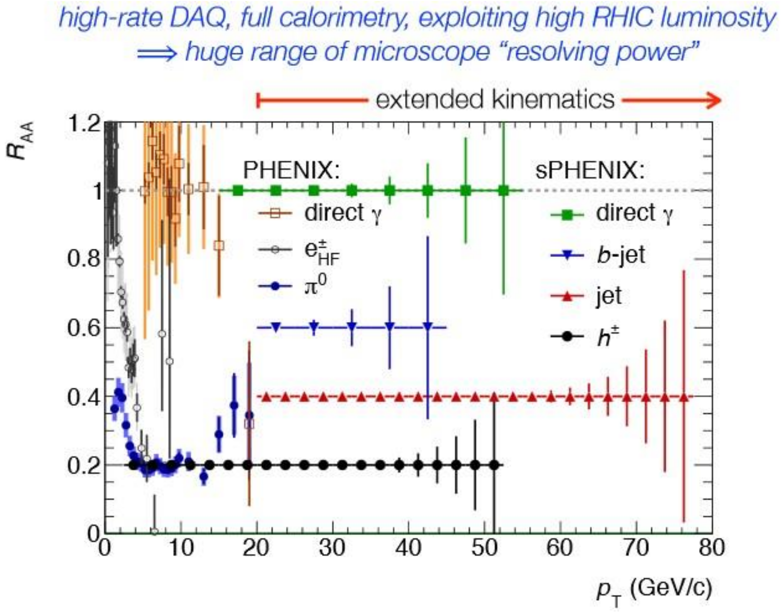


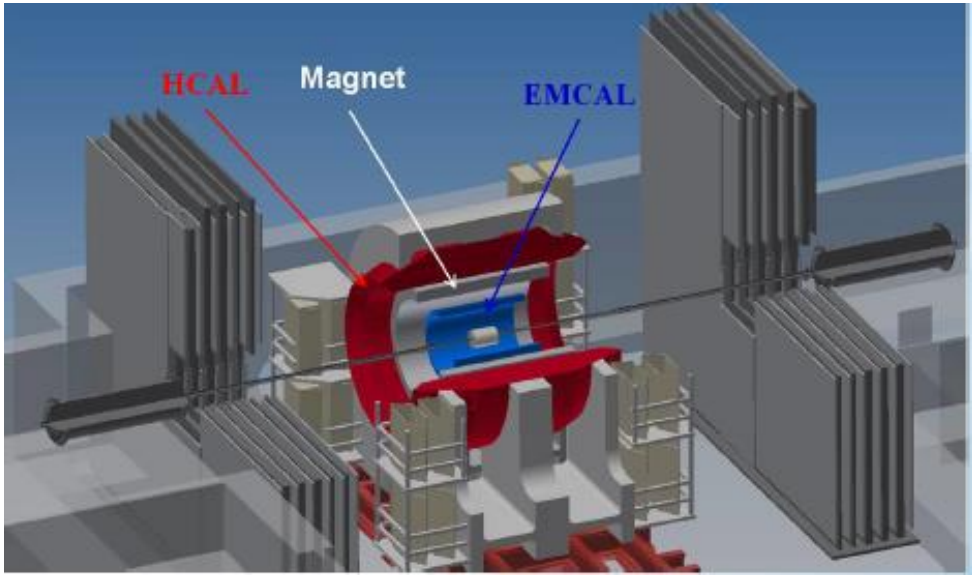
RHIC

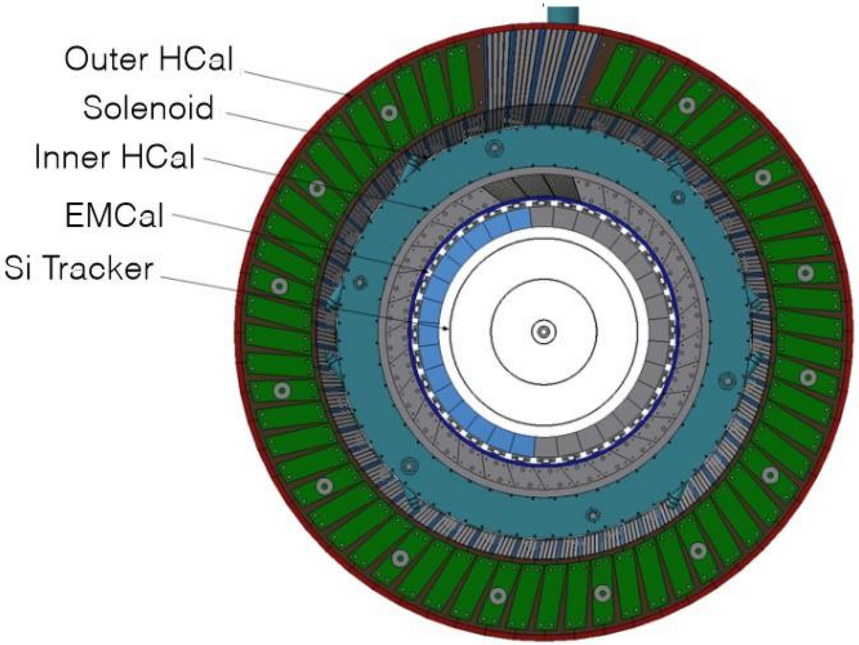


- Results of A+A support the idea of quarkonia dissocitation in hot QGP medium
- Y suppression pattern supports sequential melting
- but what about p+A?
- Why the dissociation pattern of J/ψ and Y(1S) is different in RHIC and LHC?.

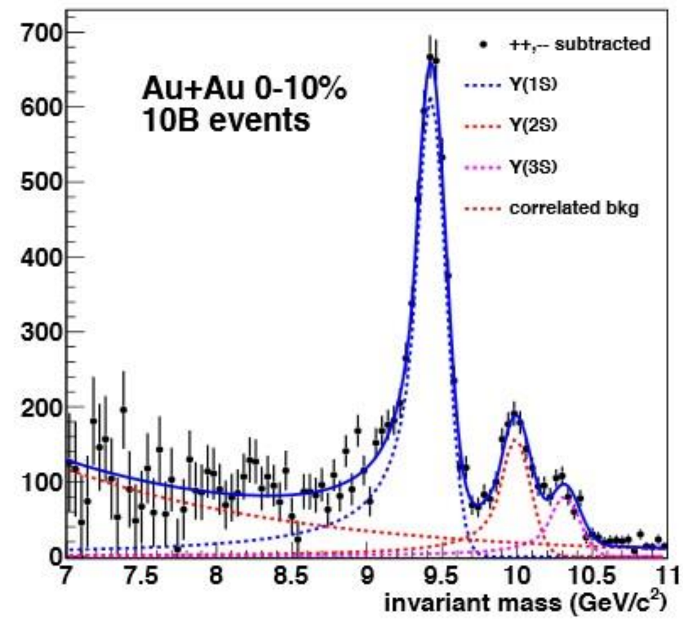
Upgrades: PHENIX → sPHENIX





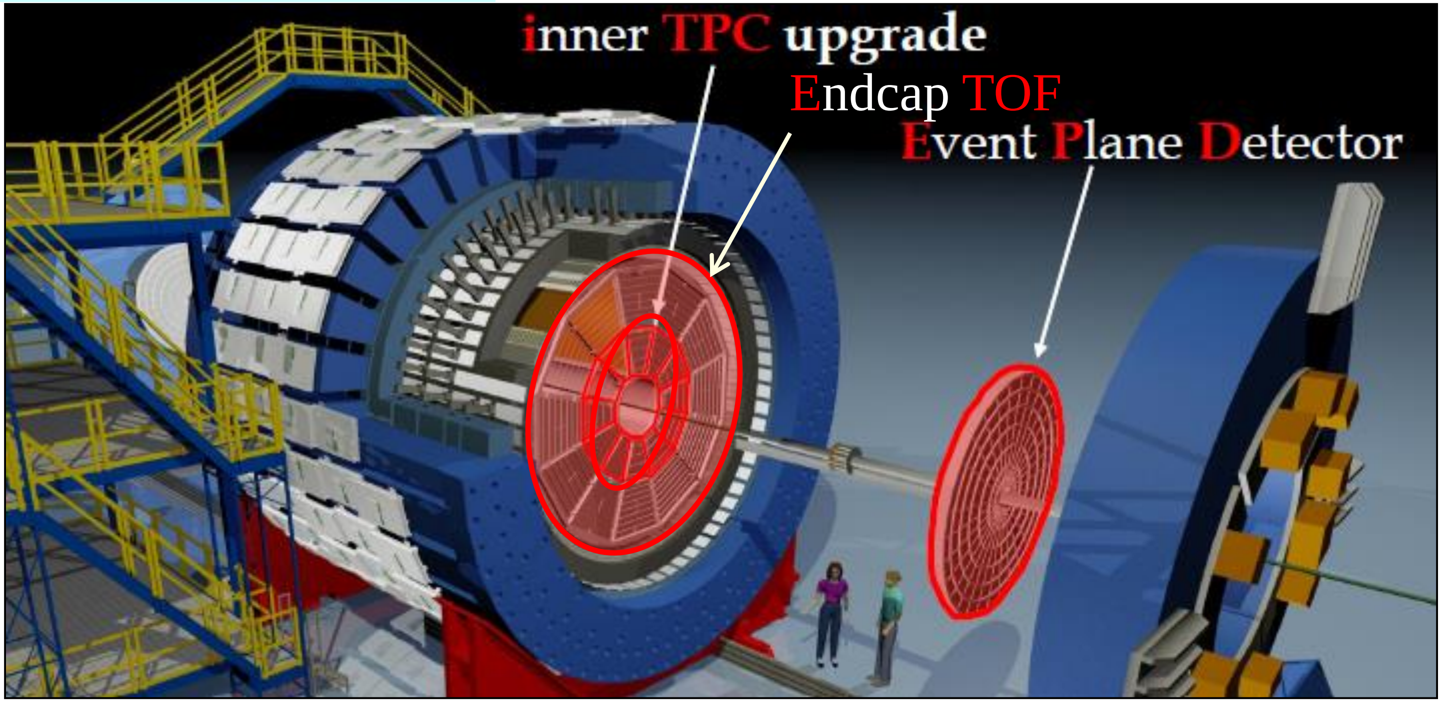


Fully resolved Upsilon mass states



The STAR Upgrades and BES Phase II

Major improvements for BES-II



iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Full (azimuth) coverage Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Conclusions

- RHIC is a remarkable QCD Machine and versatile facility!
  - Au+Au at 7.7, 11.5, 14.5 ,19.6, 27, 39, 62.4, and 200 GeV
  - d+Au at 200 GeV, p+p (polarized!) at 200, 500, and 510 GeV
  - U+U at 193 GeV
  - Cu+Au at 62.4 and 200 GeV
  - 2015: p+Au and p+Al at 200 GeV

- The RHIC Beam Energy Scan is mapping out the QCD phase diagram
  - Don't yet have a smoking gun for the critical end point but the search window is narrowed
  - Beam Energy Scan Phase-II (2019) will shed light on the critical end point

- Recent results from RHIC and LHC in small p, d, ^{3}He+A collisions provide brand new insight into the role of initial and final state effects. These have proven to be interesting and more surprising than originally anticipated; and could conceivably shed new light in our understanding of collective behavior in heavy-ion physics

- Quarkonia is an excellent probe to learn about thermal properties of QGP medium

- Upgrades to the accelerator, PHENIX, and STAR will usher in the RHIC heavy flavor and jets eras

- Watch for many more new results at NN2017