Highlights from the 17-Year Heavy Ion Program at the PHENIX Experiment at RHIC

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Scope of Talk

Iowa State is involved in both the RHIC heavy ion and spin programs using the PHENIX detector.

Can't cover both so will discuss just the heavy ion program that has led to our present picture of the Quark-Gluon Plasma (QGP).

If have time will discuss evolution to sPHENIX and future plans.

Our picture of the QGP and the nuclear phase diagram has grown in steps and I will present conclusions after each step with minimal conclusions at the end.

RHIC and LHC Landmarks

June 2000: First RHIC Au-Au collisions at 130 GeV/A.

Summer 2001: First full energy Au+Au collisions at 200 GeV/A.

Summer 2005: sQGP announcement at the APS meeting (liquid not gas). White paper from all RHIC experiments published.

Summer 2010: First heavy ion results from the LHC.

2013: First p+A and d+A at LHC and RHIC, respectively.

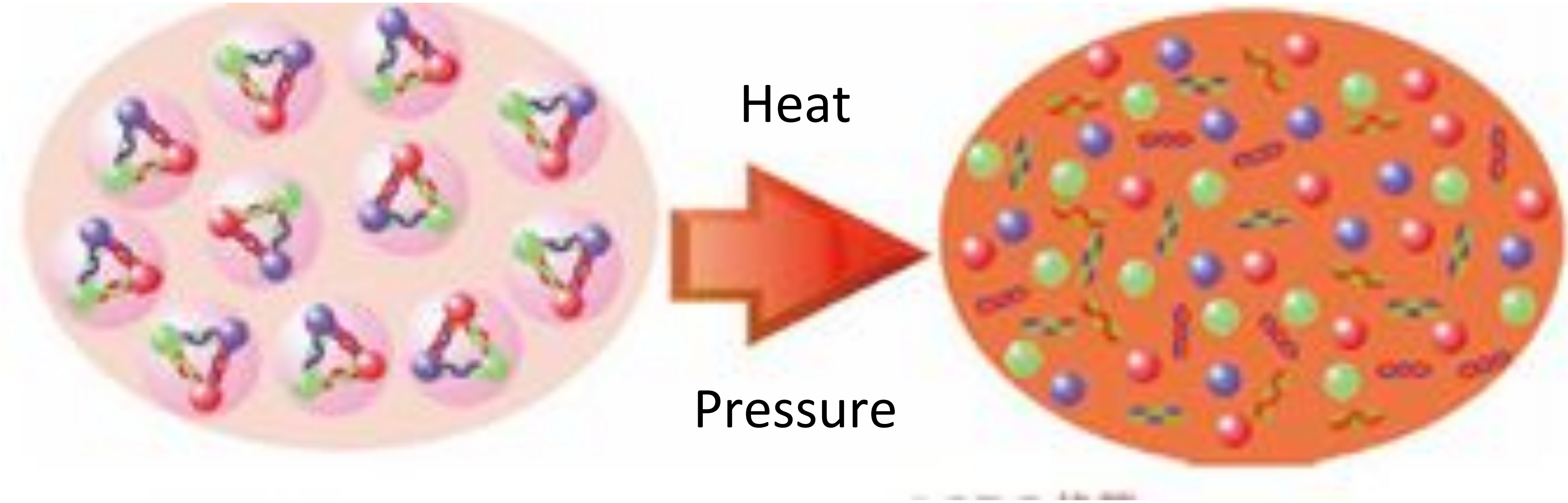
June 2016: Last data taken with PHENIX.

2022: Projected first running at RHIC with new sPHENIX detector.

Outline

A. Concept of the Quark Gluon Plasma (QGP).
B. How Make and Study the QGP (RHIC and PHENIX).
C. Properties of Hot Dense Nuclear Matter.
D. The Matter Flows.
E. The Matter is Hot.
F. Results Study of QGP with Heavy Nuclei.
G. What Happens if we Go to Smaller Mass Systems?
H. What Happens if we Study Lower Energy Systems?
I. The Future with sPHENIX.
J. Conclusions

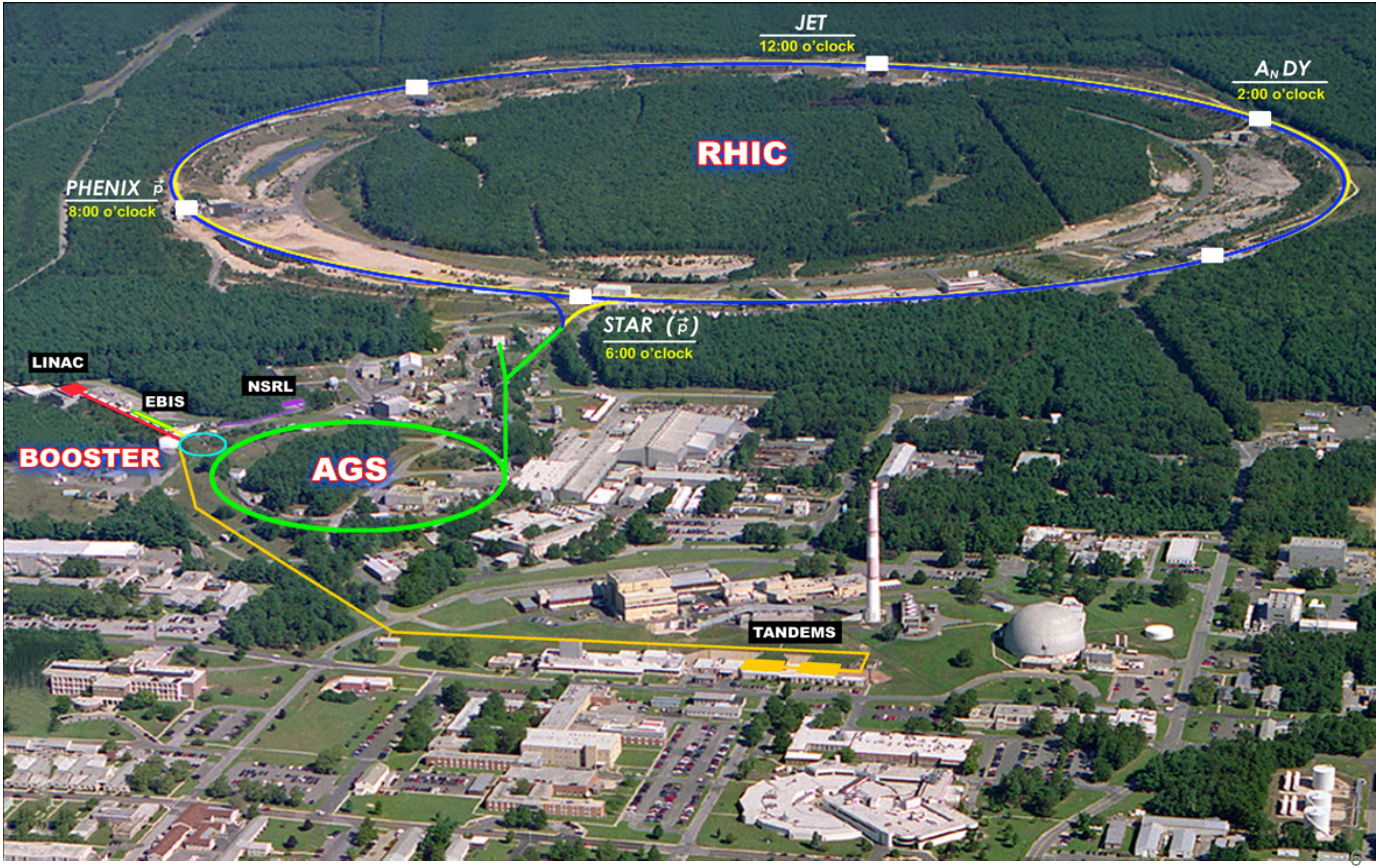
A. Concept of Quark Gluon Plasma (QGP)



Nuclear Matter

Quark Gluon Plasma

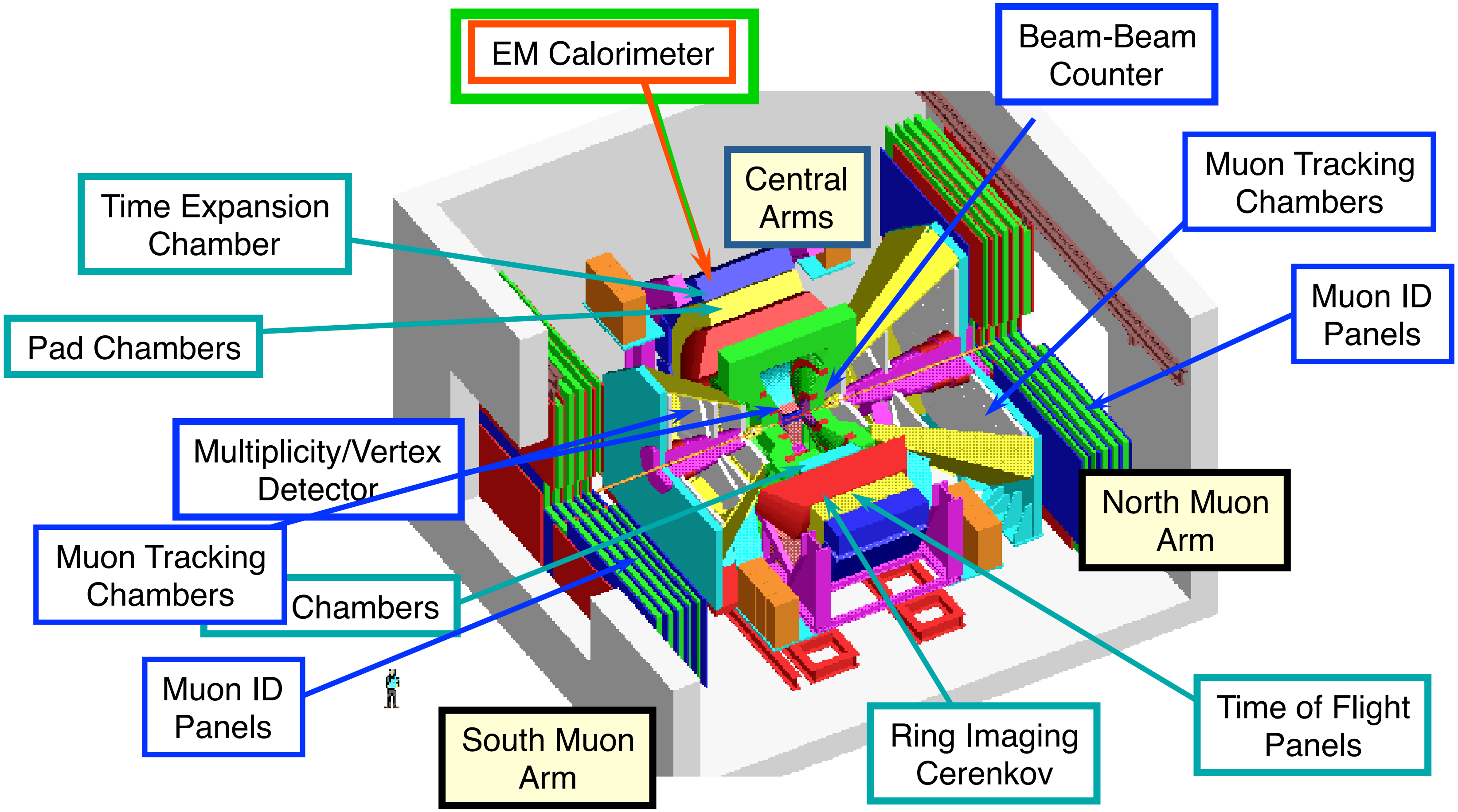
B. How Make and Study the QGP (RHIC and PHENIX)




PHENIX
ILLINOIS

The PHENIX Detector

4000 tons of detectors

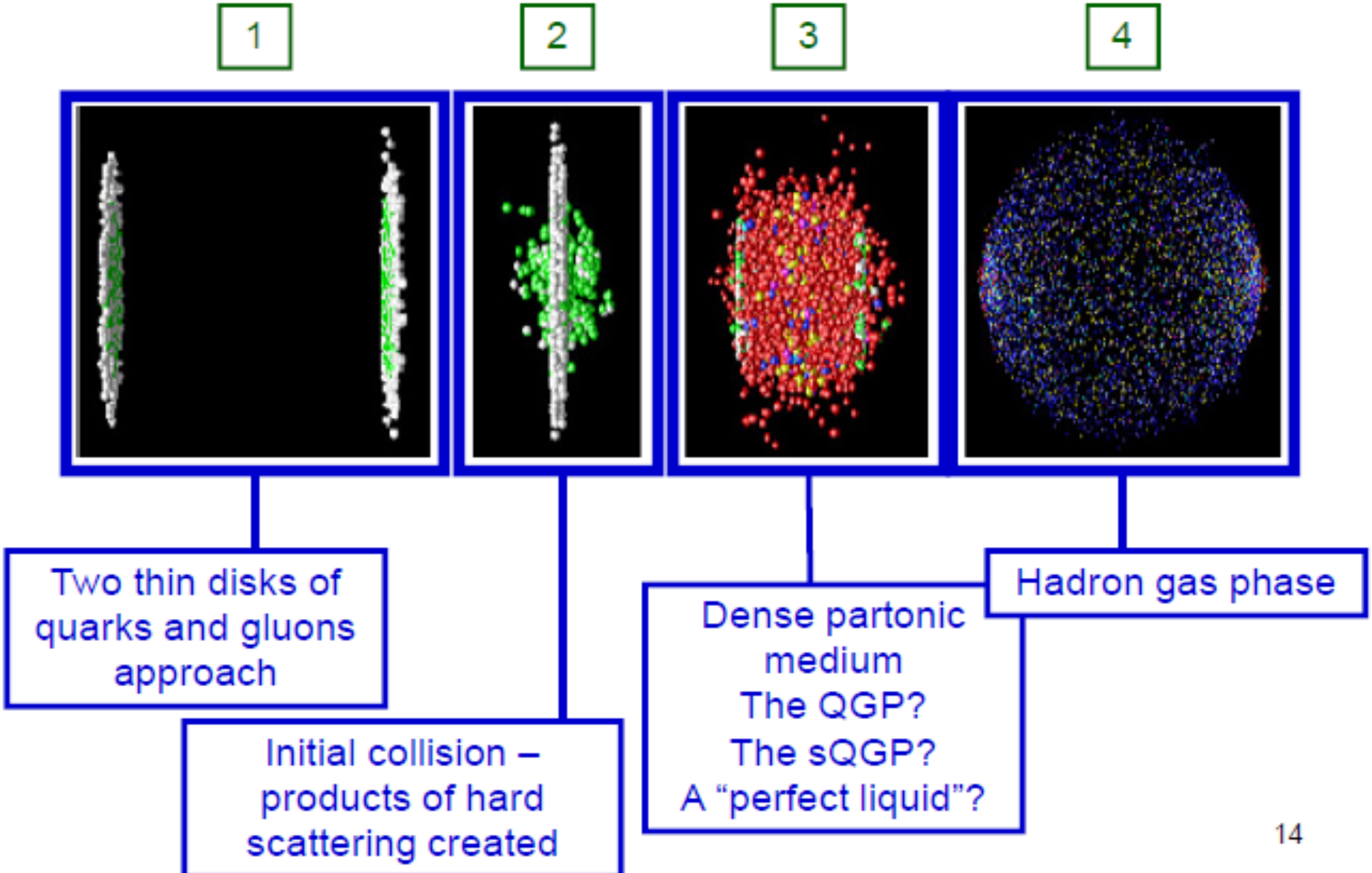


C. Properties of Hot Dense Nuclear Matter.

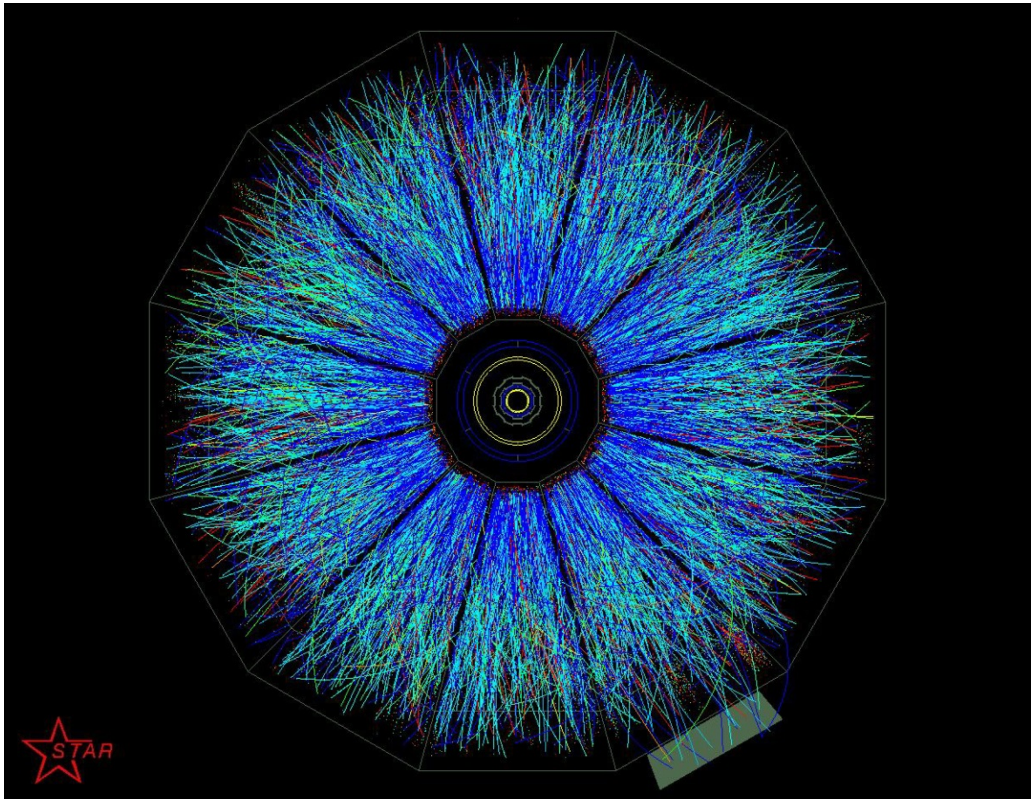
Stages in a Relativistic Heavy Ion Collision

In order to produce Quark-Gluon Plasma (**QGP**) you need not only **high energies**, but **large volumes**, to sustain high energy **densities** and **temperatures** for **a sufficiently long** time!
(Order of magnitude: 10 fm/c, 3-10 times normal nuclear density)

Stages in a Relativistic Heavy Ion Collision



In 200 GeV/A Au on Au collisions we produce a hot dense medium eventually hadronizing into thousands of particles.



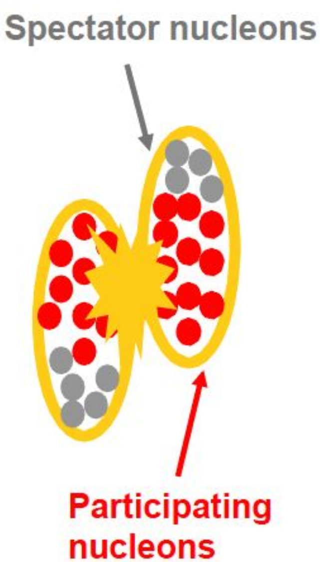
Can use particles created in the medium as a probe of the properties of the medium.

Compare with p+p collisions where no QGP is expected to form.

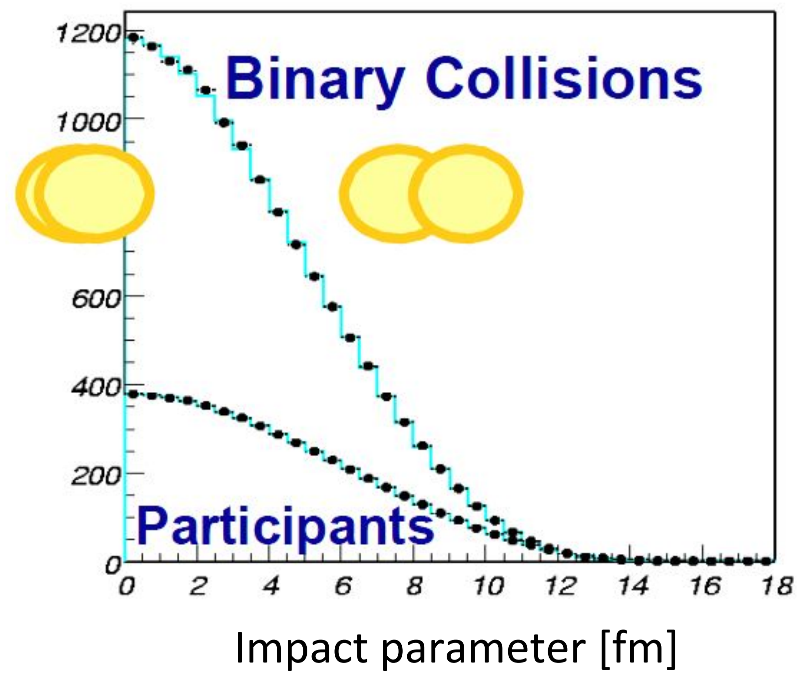
Nuclear Modification Factor R_{AA}

$$R_{AA} = \frac{dN_{AA}^{J/\psi}/dy}{N_{coll}\, dN_{pp}^{J/\psi}/dy}$$

Yield in nucleus-nucleus collisions divided by p+p yields and scaled by the appropriate number of binary collisions N_{COLL} which is calculated using Glauber model.

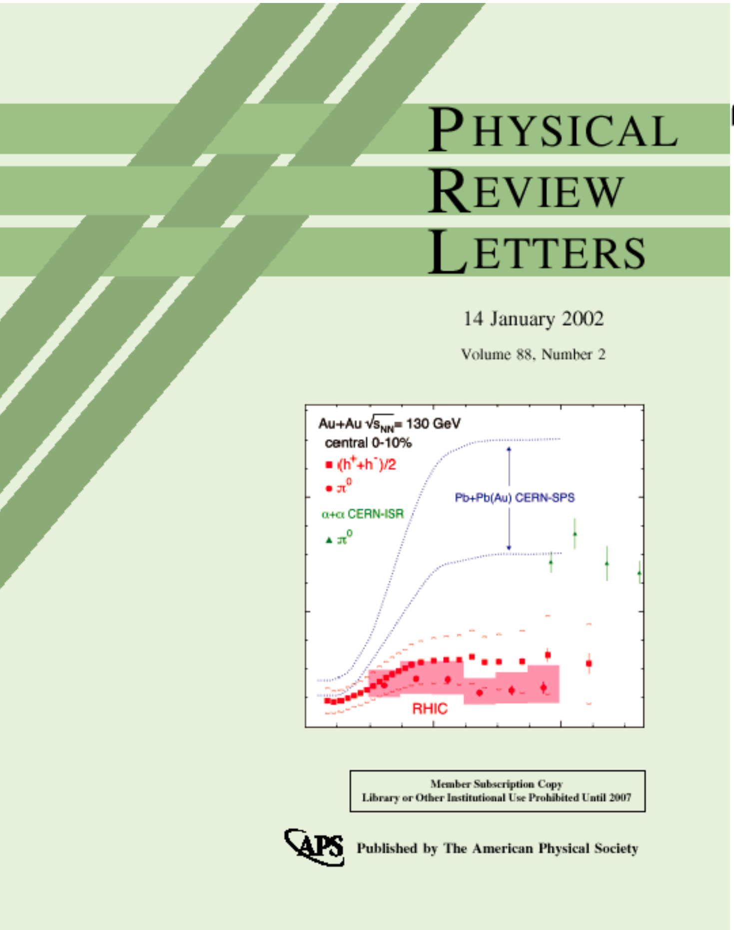


Centrality of collision is described by number of participant nucleons N_{PART}

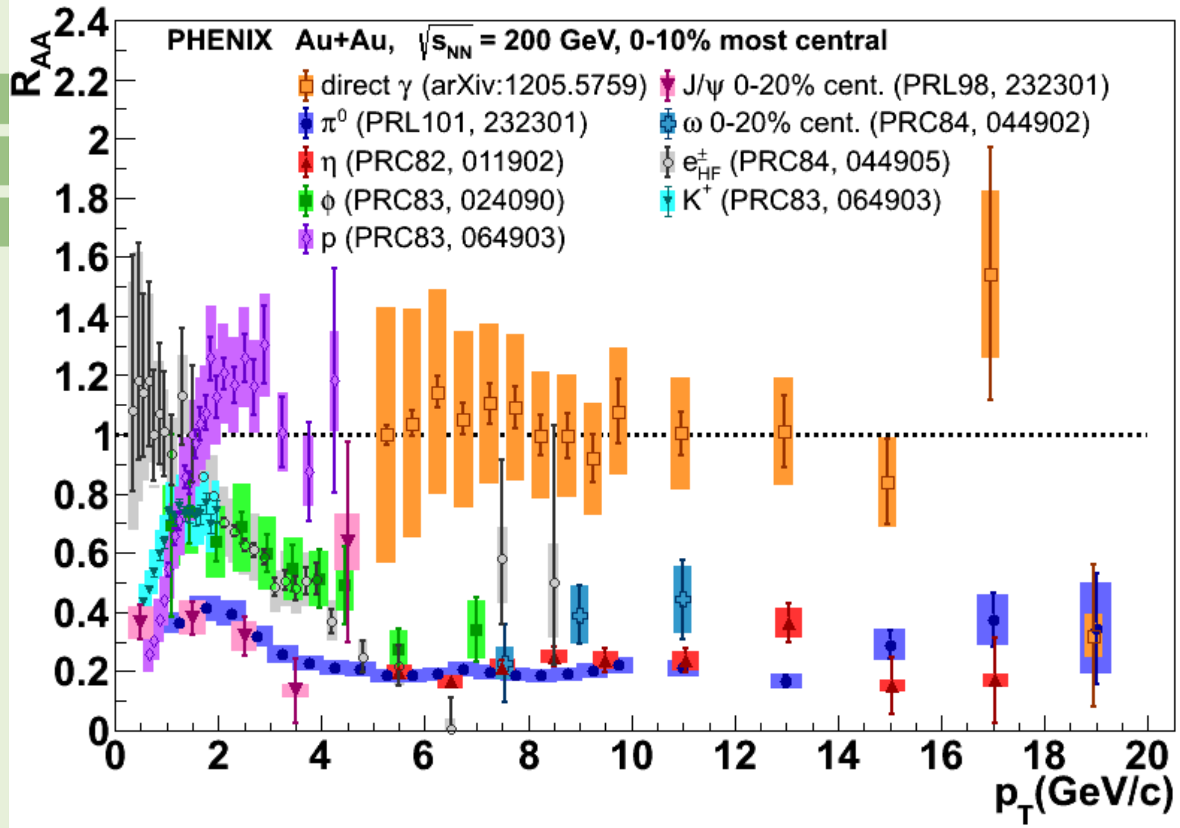


If particles not modified by medium expect R_{AA} = 1.

Are particles suppressed in the hot dense medium created?



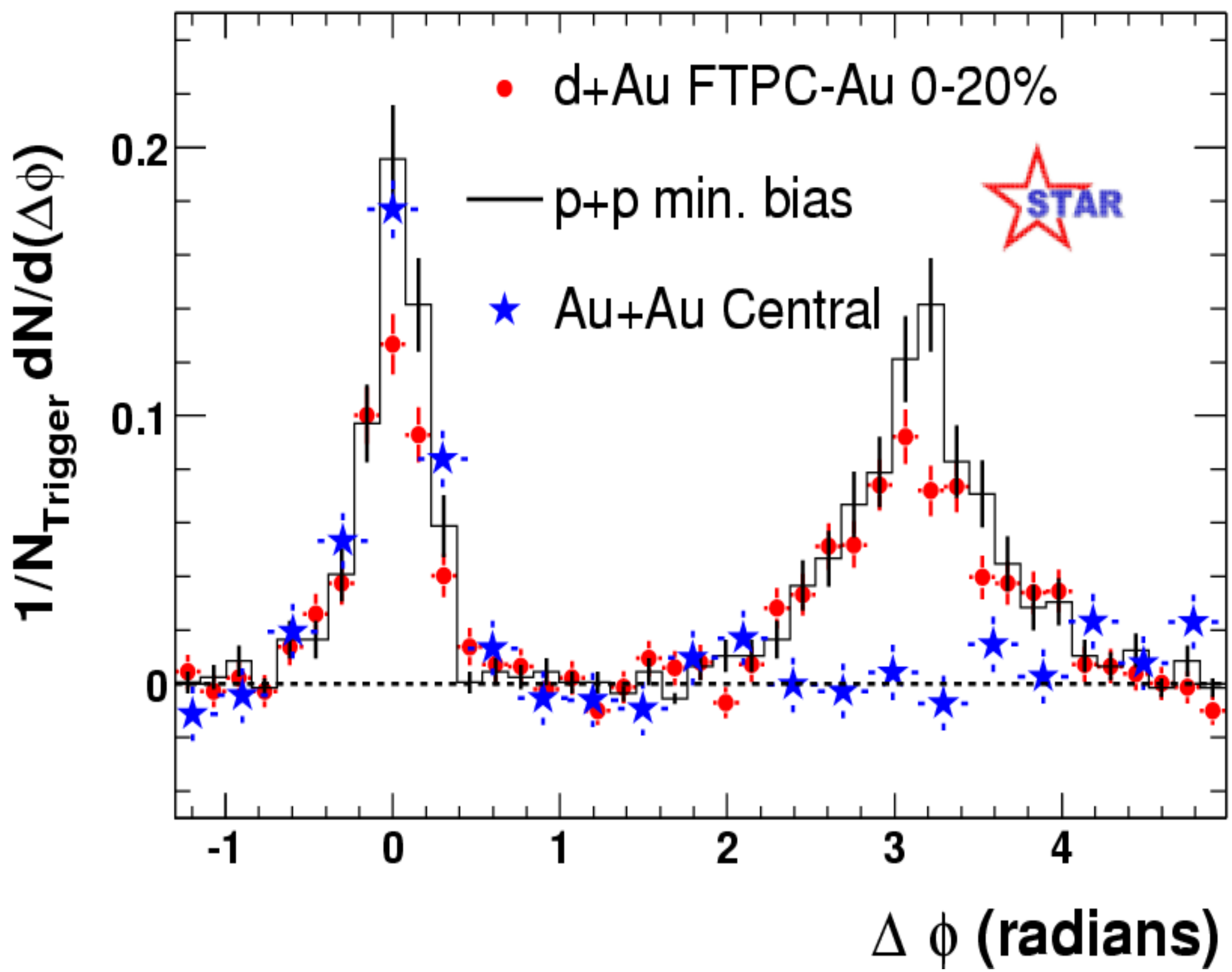
The most quoted single result RHIC paper



Hadrons suppressed.

Photons not suppressed.

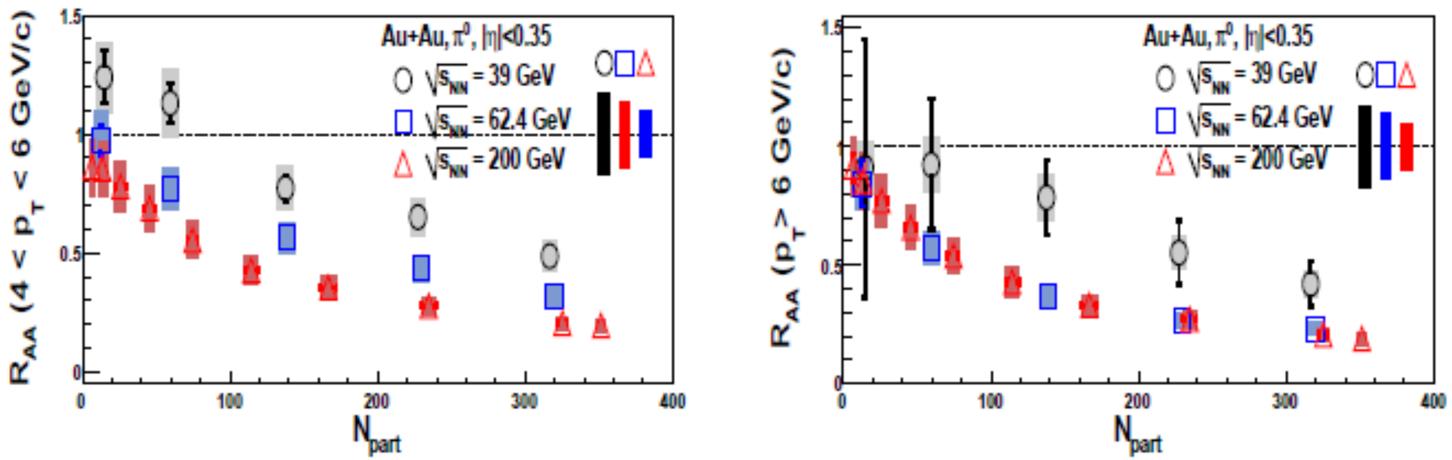
Can we see quenching at the jet level?



Back-to-back jets: both present in pp, dAu,
one disappears in AuAu: crossed the medium and lost energy

How does quenching change with centrality and collision energy?

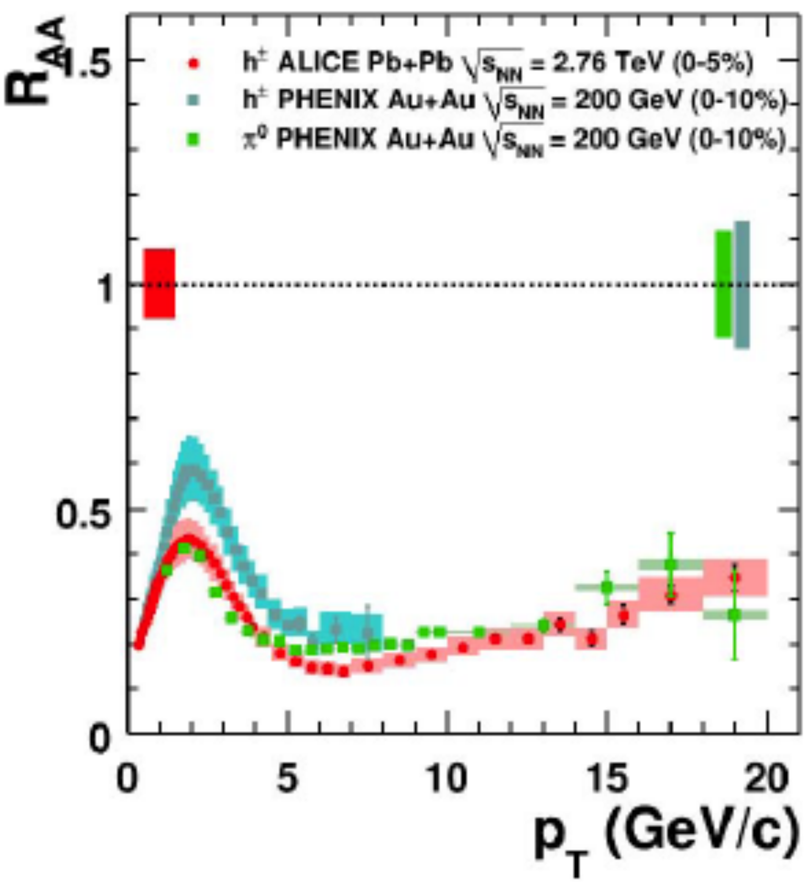
[arXiv:1204.1526]

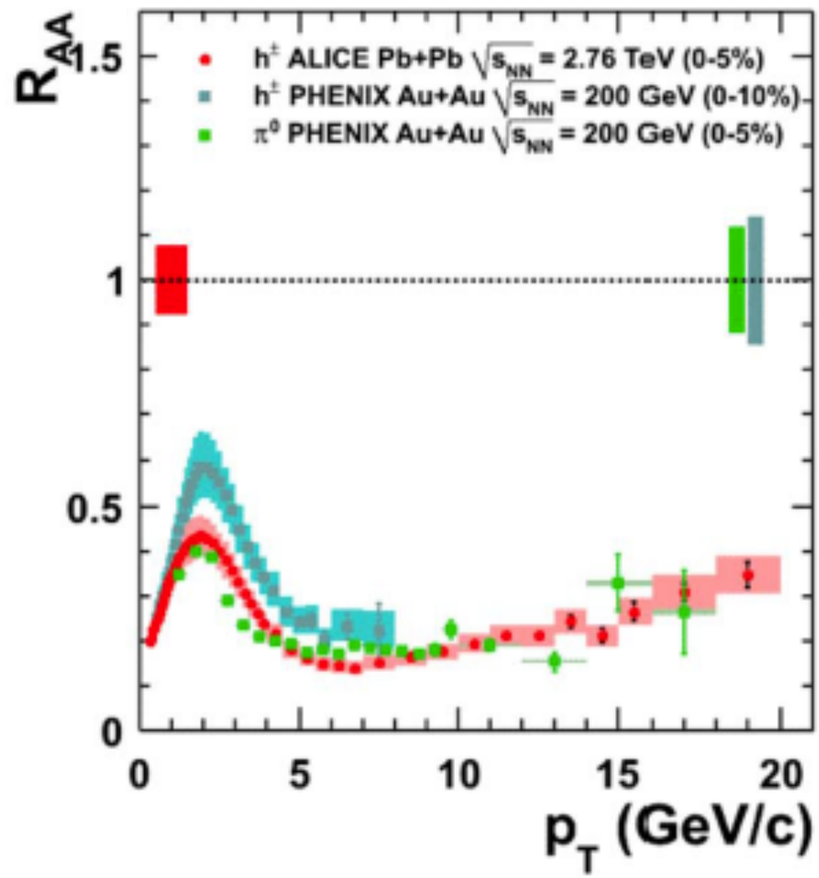


- 62.4 and 200 GeV data shows strong suppresion even in more peripheral collisions
- 39 GeV is only suppressed at higher centralities
- No significant difference between 62.4 and 200 GeV data points if $p_T > 6$ GeV/c

Suppression reduced for peripheral collisions but still significant. Suppression about same for 200 GeV and 62.4 GeV but decreasing at 39 GeV.

What happens when we go to the much higher energy densities at the LHC?

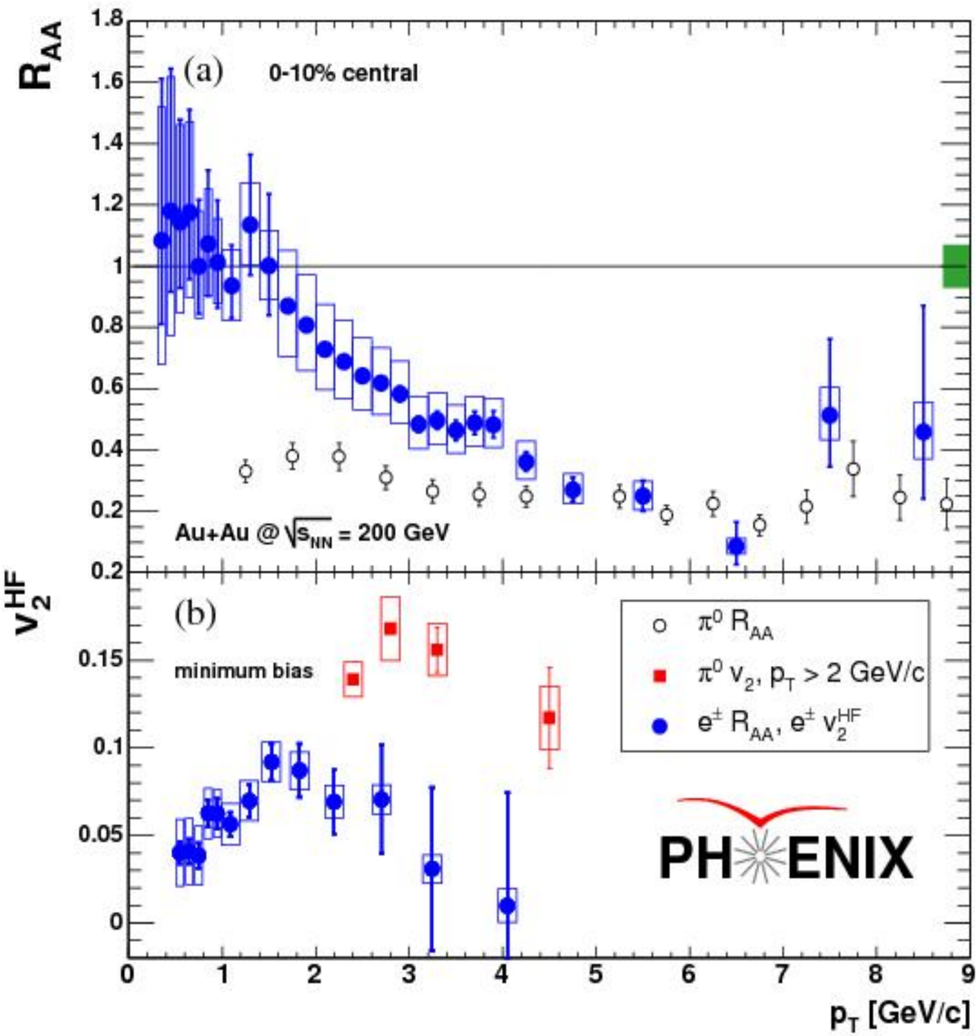




Suppression very similar for RHIC and the LHC.

Are the heavy c and b quarks also stopped in the QGP?

Please look at RAA plot.



c and b quarks (in blue) also stopped in QGP.

Note measured electrons from decay of open charm and beauty

Conclusions

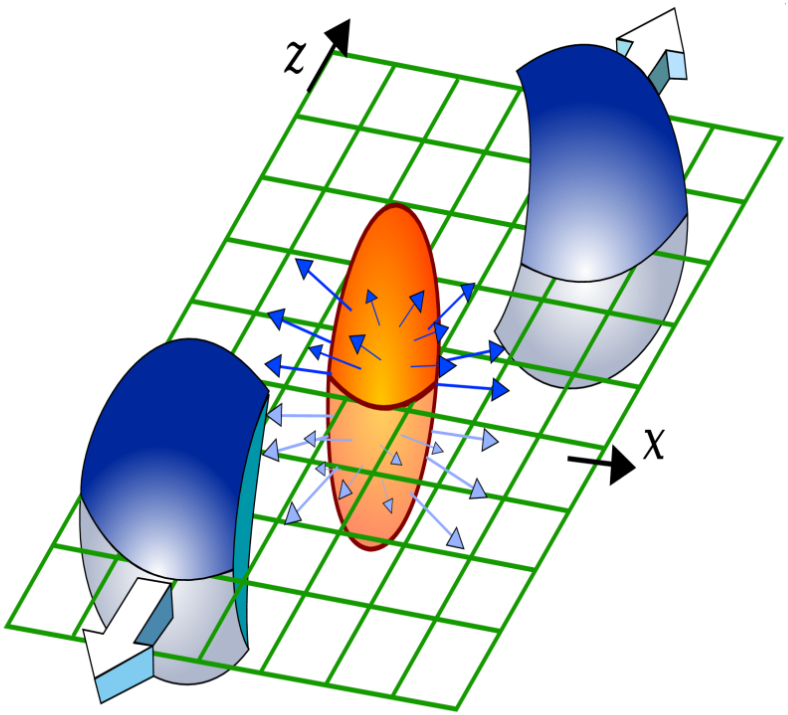
A. Suppression of particles by the medium observed for collision energies down to 39 GeV/A.

B. The level of suppression at much higher energy densities of LHC is very similar to that at RHIC.

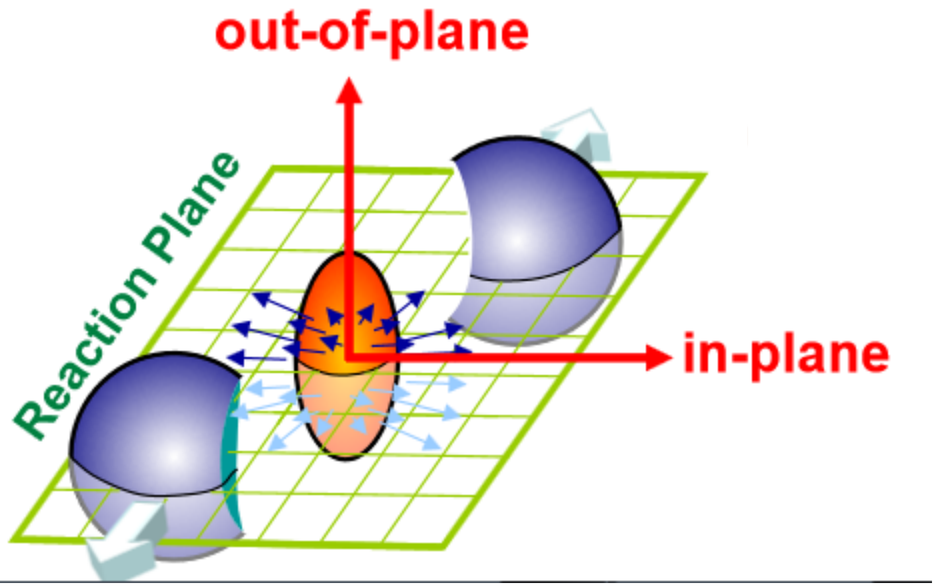
C. Suppression is still very significant for heavy c and b quarks.

D. The Matter Flows.

Particle Anisotropy and Flow



How Study Flow



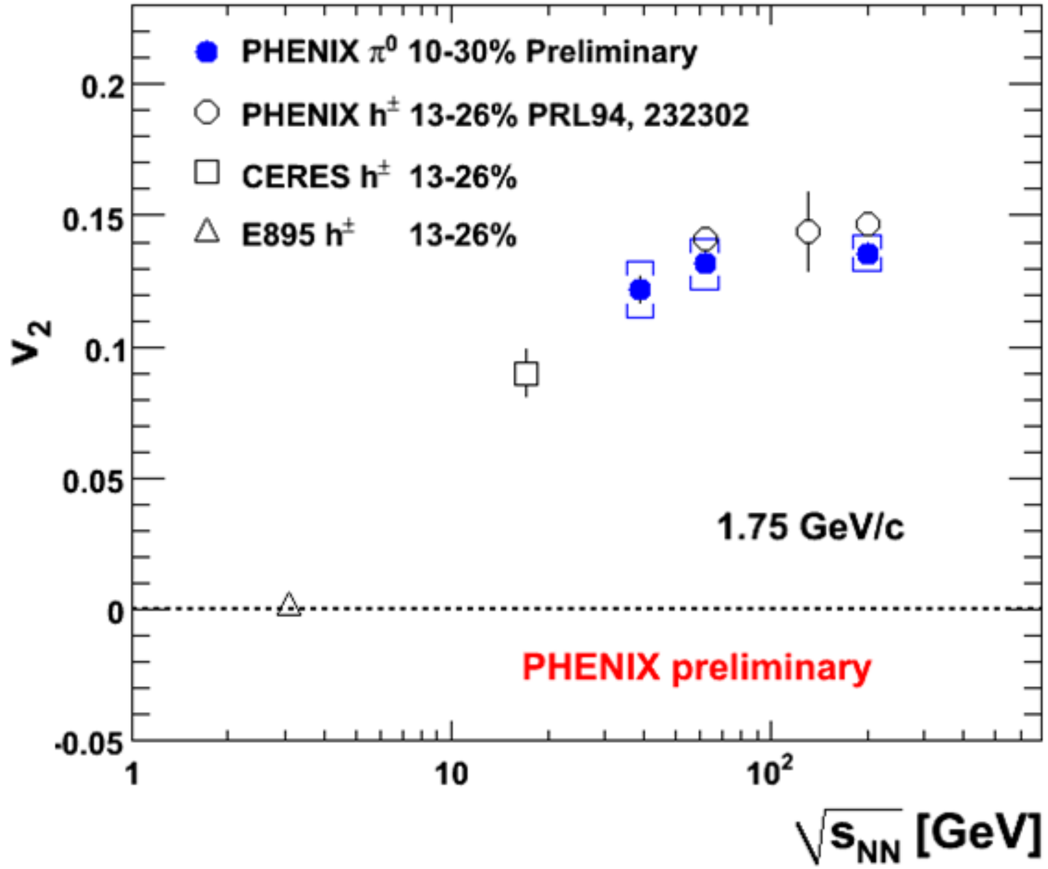
1. Reaction geometry produces almond shaped interaction region.

2. Compression of mass in center produces a higher density resulting in an anisotropic p_T distribution.

3. Resulting p_T distribution described in terms $\left[1 + \sum_{n=1}^{\infty}\left\{2v_n \cos\left[n(\phi - \Psi_R)\right]\right\}\right]$

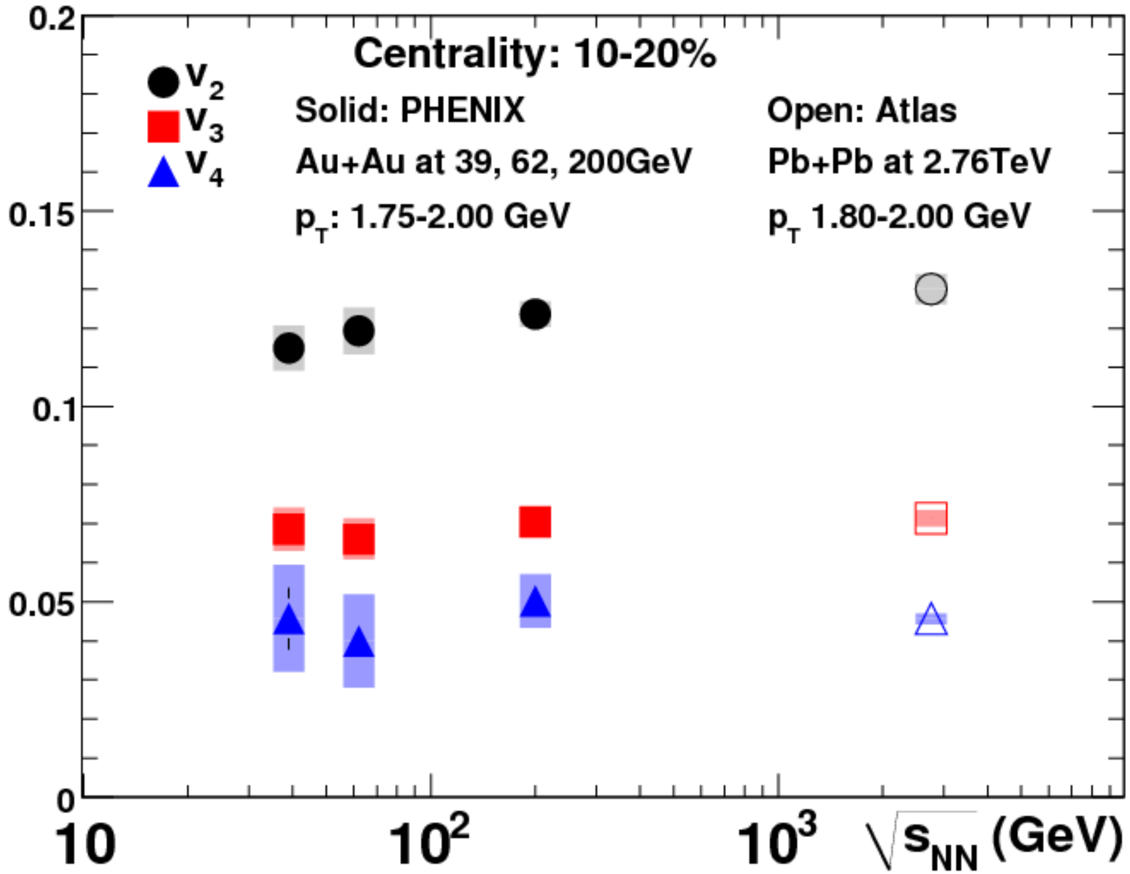
4. A finite v_2 is termed elliptic flow. Ψ_R in plane of beam and impact parameter. For spherically symmetric distribution $v_2 = 0$.

Is significant v_2 observed and how does it change with energy?



A. v(2) saturates as energy reaches the RHIC regime.
B. At saturation reach maximum achievable collective flow predicted by ideal hydrodynamics.
C. Medium behaves as a nearly perfect fluid with very low viscosity.
D. The ratio of shear viscosity to entropy density (η / s) is very near the quantum lower bound.

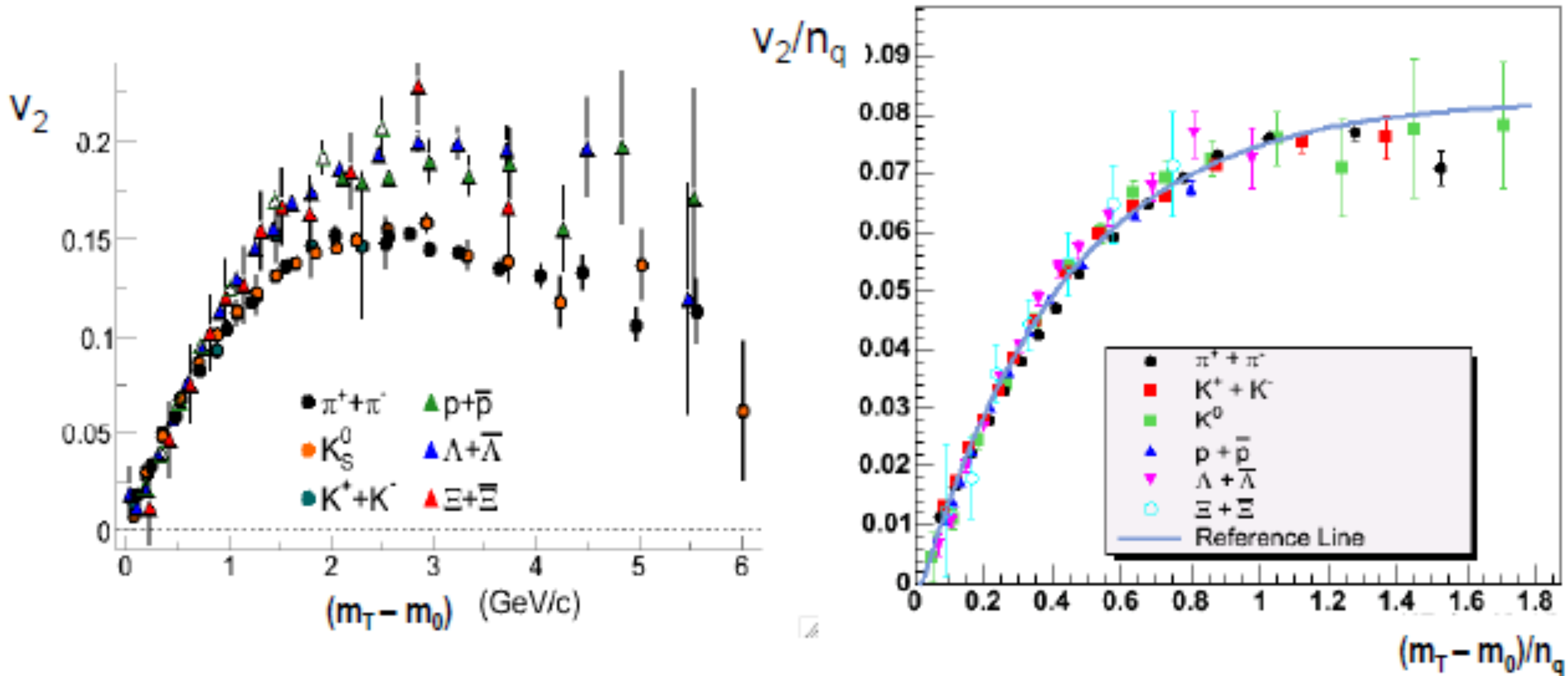
Does v_2 still saturate at high energy densities at LHC?



Seems fluid at LHC very similar to that at RHIC.

Evidently much higher energy density needed to create QGP as a gas.

How does elliptic flow scale?

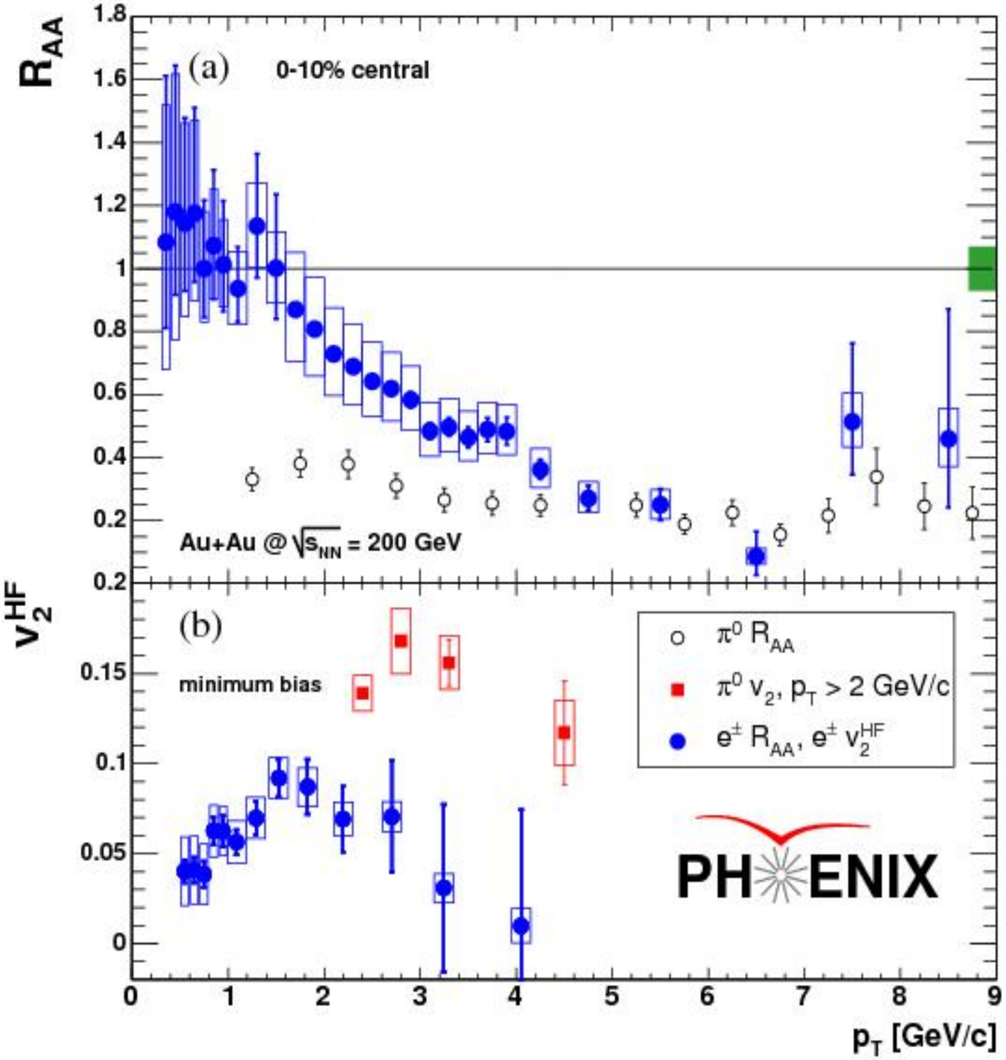


Fluid→QuasiParticles→Hadrons

A. v(2) scales according to the valence quark count.
B. Scaling identifies collective behavior as established during partonic phase of system.
C. The degrees of freedom are partonic.
D. This direct signature of deconfinement.

Do heavy c and b quarks also flow?

Please look at v(2) plot.



Heavy quarks (in blue) flow but less strongly than light quarks.

Conclusions

A. Elliptic flow observed for Au collisions.

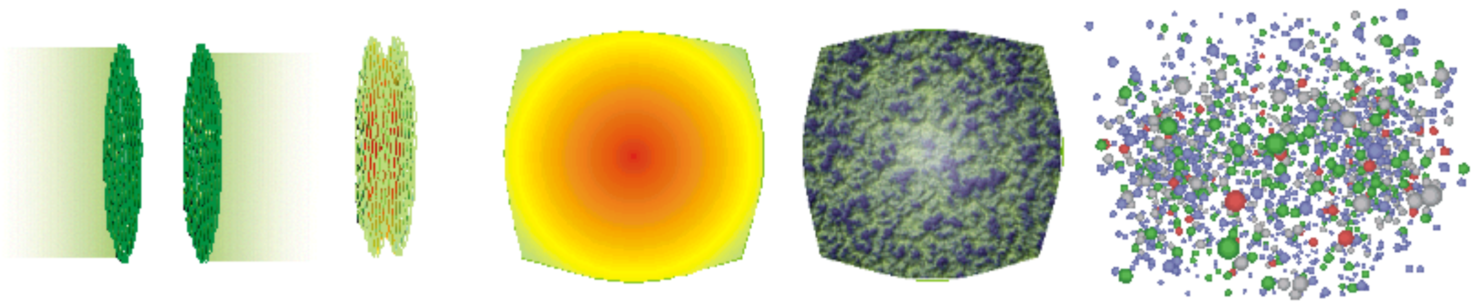
B. The flow at higher energy densities of LHC very similar to that at RHIC indicating saturation.

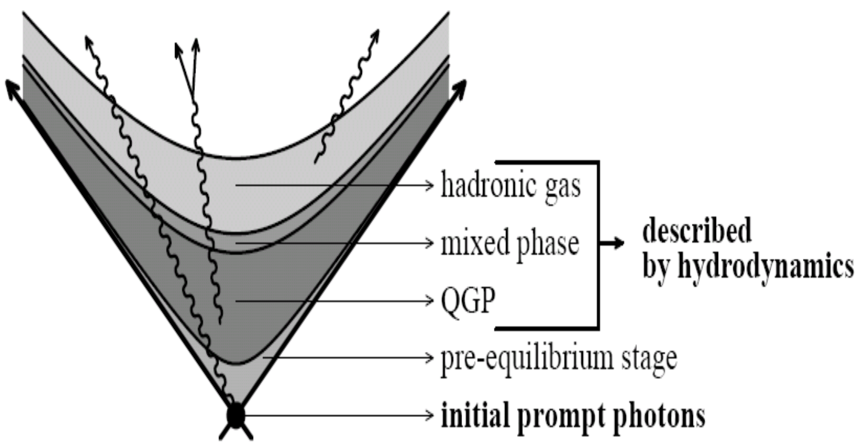
C. Flow significant for heavy quarks.

D. Quark scaling of v2 indicates formation of QGP.

E. The Matter is Hot.

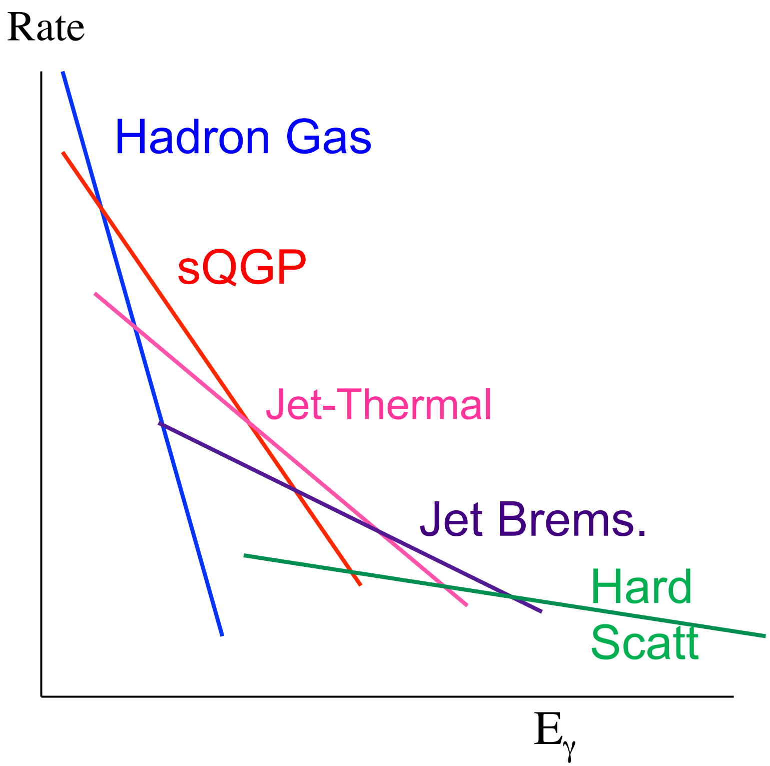
What is the Temperature of the Quark Gluon Plasma?

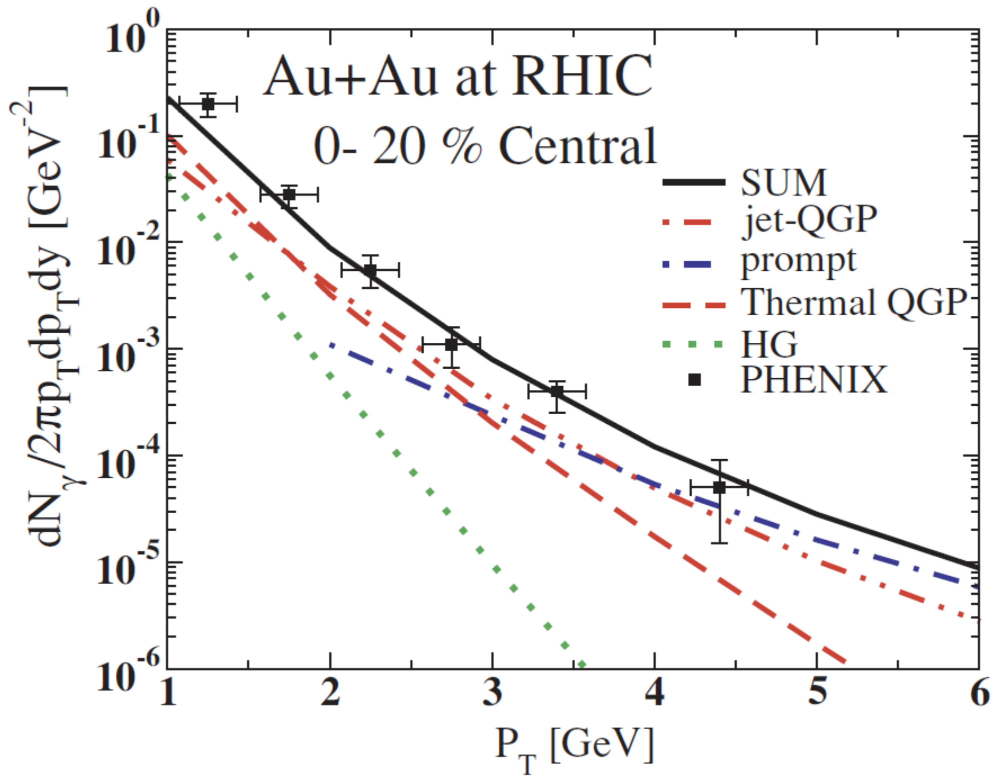




Schematically

Calculated

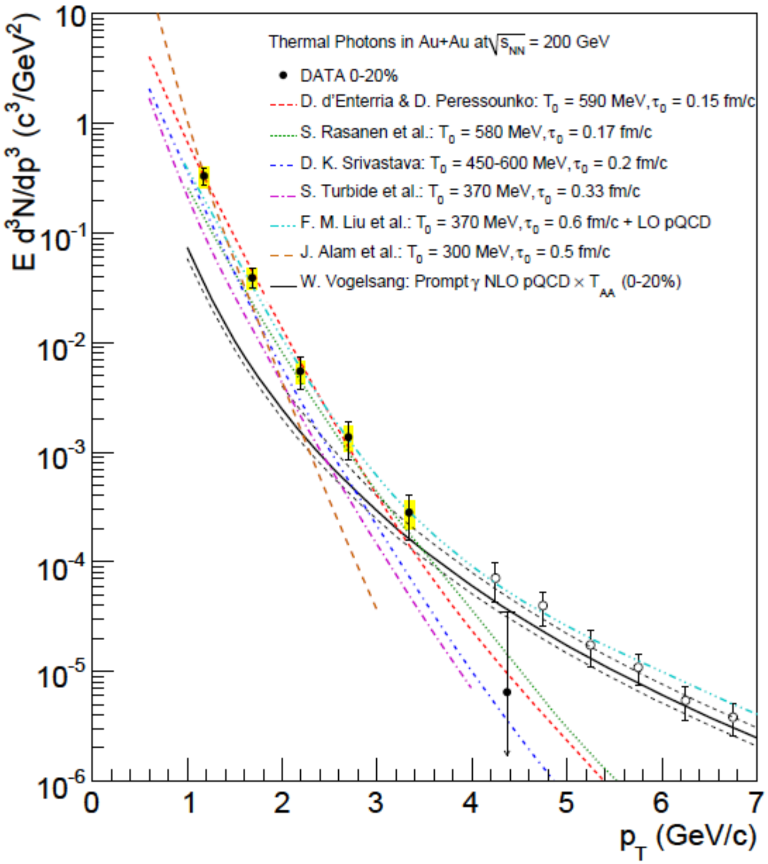




van Hees, Gale, Rapp, PRC84, 054906 (2011)

What is our estimate of the plasma temperature for 200 GeV/A Au+Au Collisions

PHENIX Phys. Rev. C 81 (2010) 034911



PHENIX measured dilepton production for 200 GeV/A Au and p.

Used to deduce direct photon spectra shown above.

Theoretical calculations assume hot system with initial temperature between 300 and 600 MeV and formation times between 0.6 and 0.15 fm/c.

Temperature well above predicted formation temperature of about 170 MeV and QGP formed rapidly.

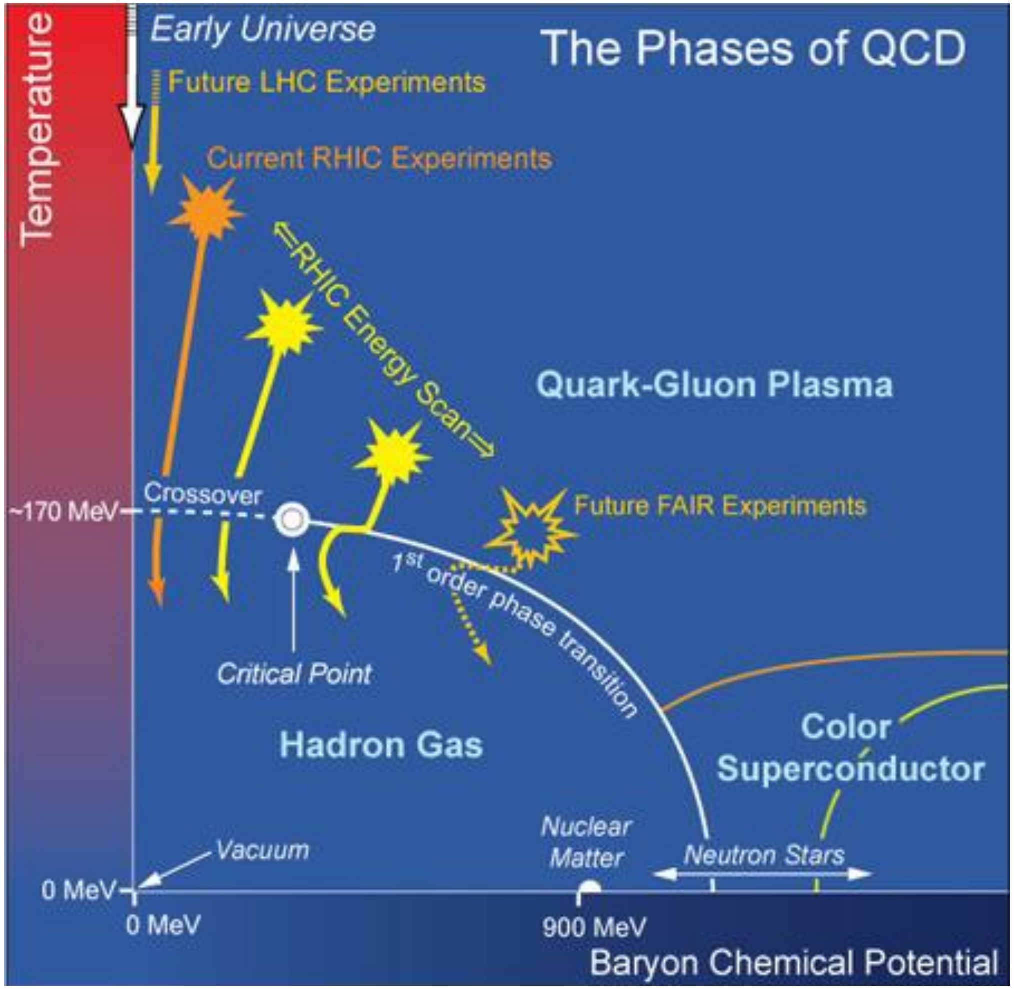
F. Results Study of QGP with Heavy Nuclei

1. Hot dense medium created in Au+Au collisions. Evidence is nuclear modification factor $R_{AA} < 1.0$.

2. The hot dense medium flows with low viscosity. Evidence is $v_2 > 0$.

3. The QGP actually created. Evidence is quark scaling of v_2 for mesons (q=2) and baryons (q=3). Also medium temperature well above needed for QGP formation.

4. No evidence for phase transition implies crossover from QGP to hadron gas.



G. What Happens if we Go to Smaller Mass Systems?

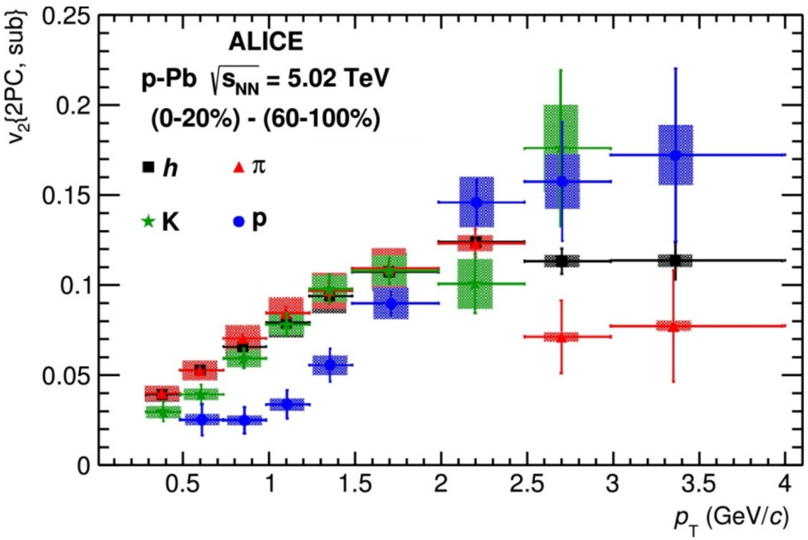
In relativistic A-A collisions a QGP medium is formed which signals its presence through long range correlations and finite flow (v_2).

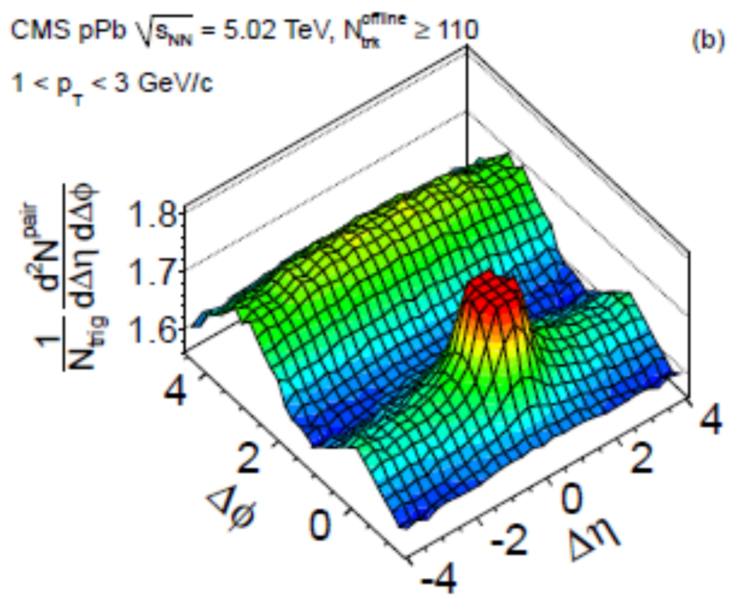
It was thought that p+p and p+A collisions could not form such a medium because of the small system size.

Recent results from p+Pb at LHC indicate presence of long range correlations.

Flow and the Ridge in p+Pb at the LHC

For p+Pb at 5.02 TeV at LHC, v_2 and a ridge observed.





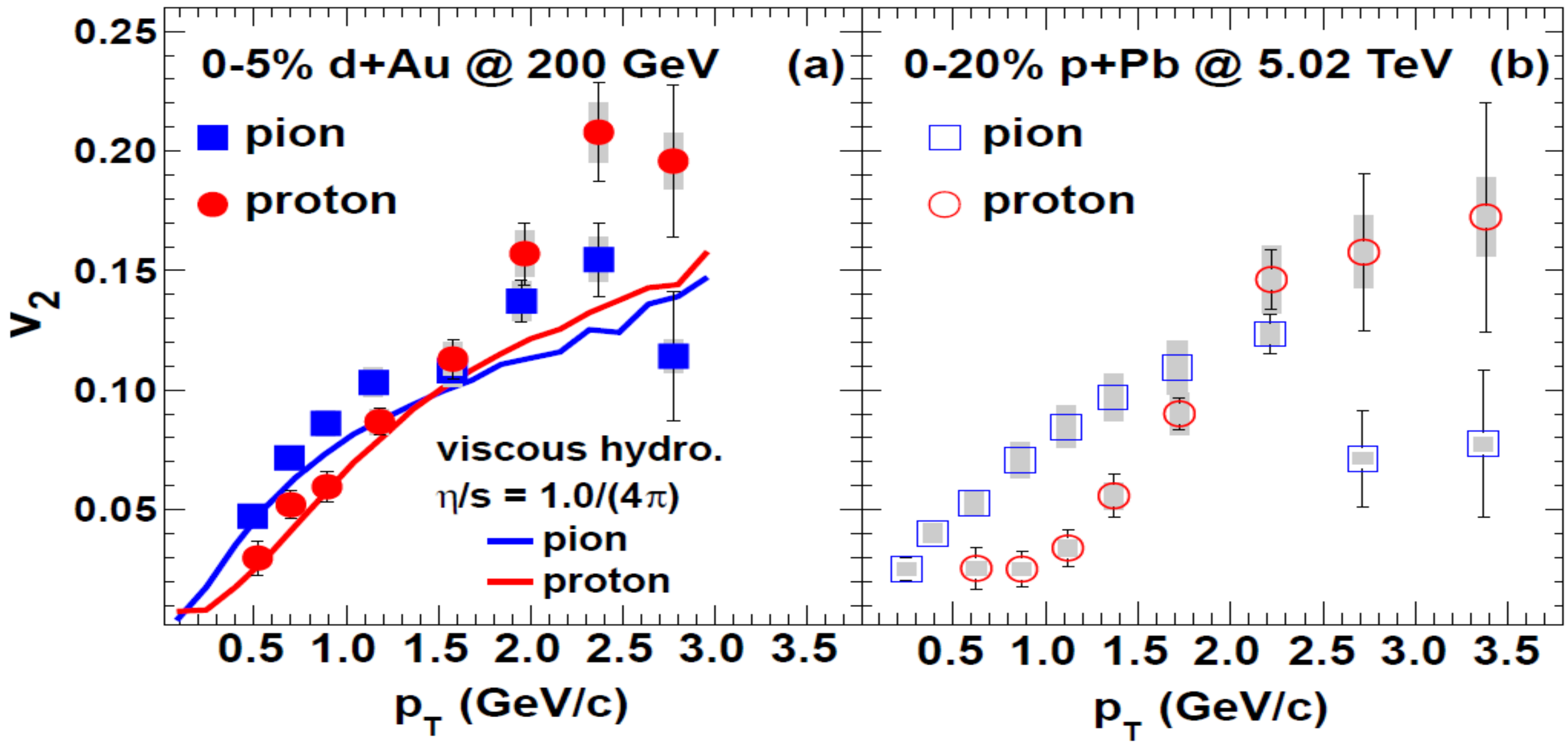
ALICE: Physics Letters B 726 (2013)
ATLAS: Phys. Rev. Lett. 110(2013)
CMS: Phys. Lett. B 7198(2013

Evidence for long range correlations and flow for p+Pb.

Do we observe v_2 and a ridge with d+Au at RHIC?

v_2 Observed for d+Au at 200 GeV

Measured v_2 of identified hadrons using event-plane method.

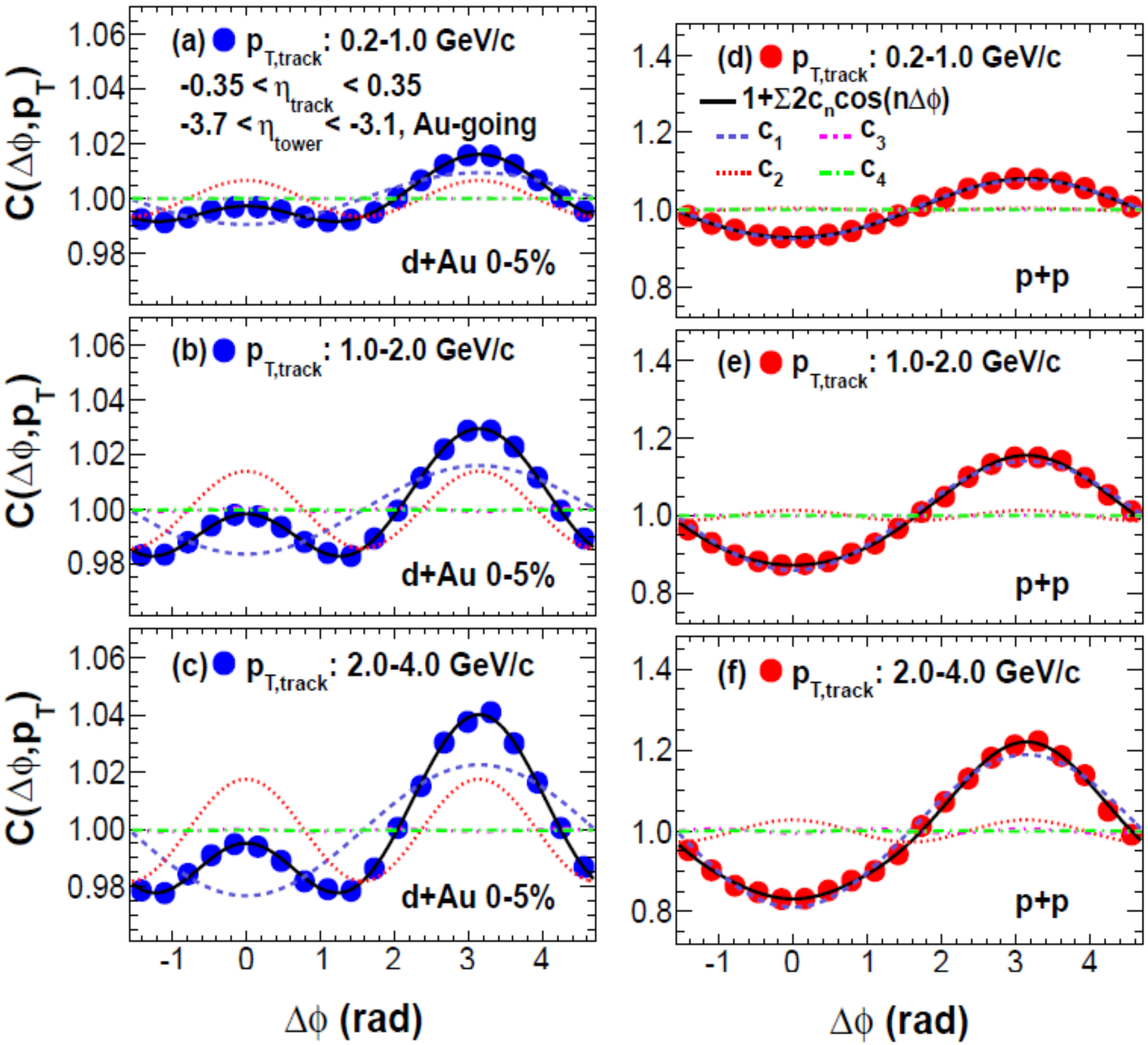


RHIC **LHC**

Do We See a Ridge with d+Au at RHIC?

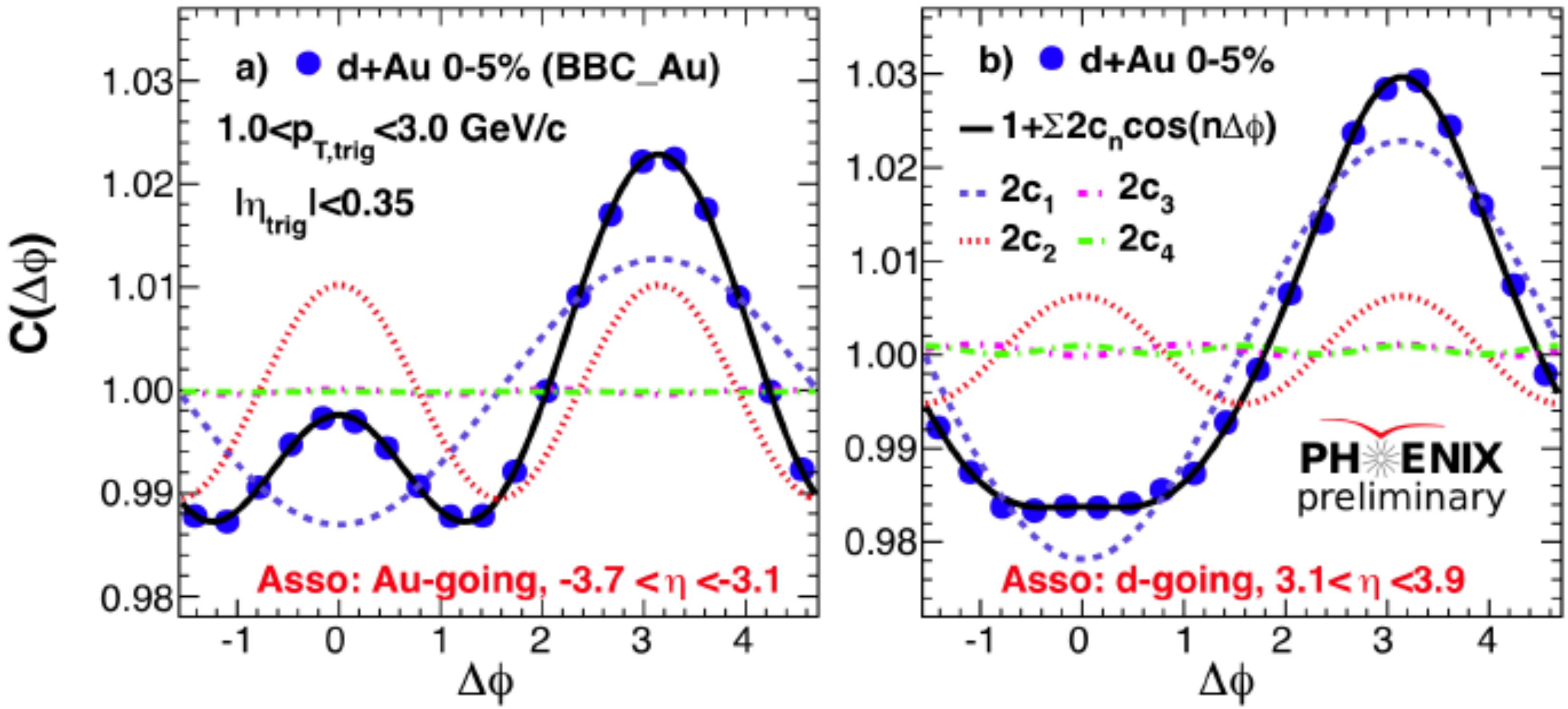
1. Construct correlation function $C(\Delta\phi, p_T)$.
2. Constructed from one track in central arm and one in the forward muon piston calorimeter (MPC).
3. Construct signal distribution $S(\Delta\phi, p_T)$ where $\Delta\phi = \phi_{track} - \phi_{tower}$.
4. Construct mixed-event distribution $M(\Delta\phi, p_T)$ from different events.
5. Construct normalized correlation function $C(\Delta\phi, p_T)$.

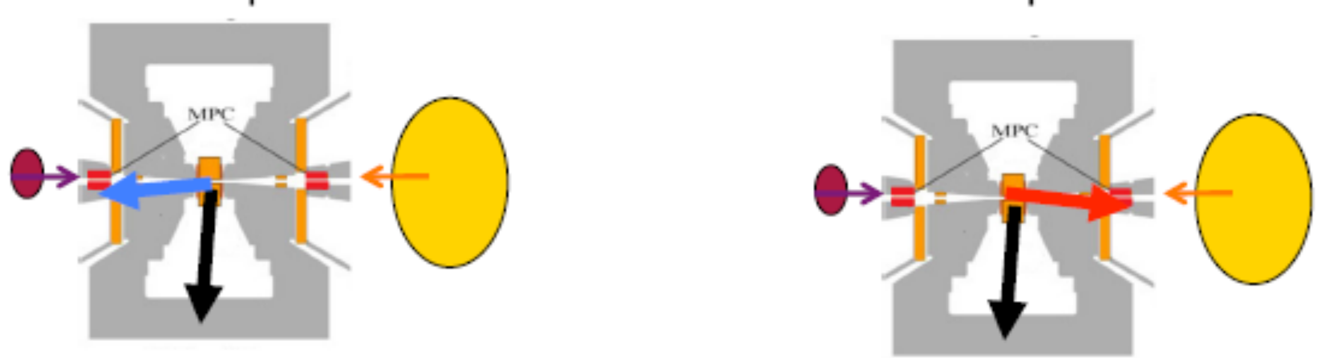
Correlation Functions for d+Au (0-5%) and p+p (MB)



1. Fits to c1 to c4 in $\cos(n\Delta\phi)$.
2. p+p dominated by dipole.
3. d+Au shows a near side peak (ridge).

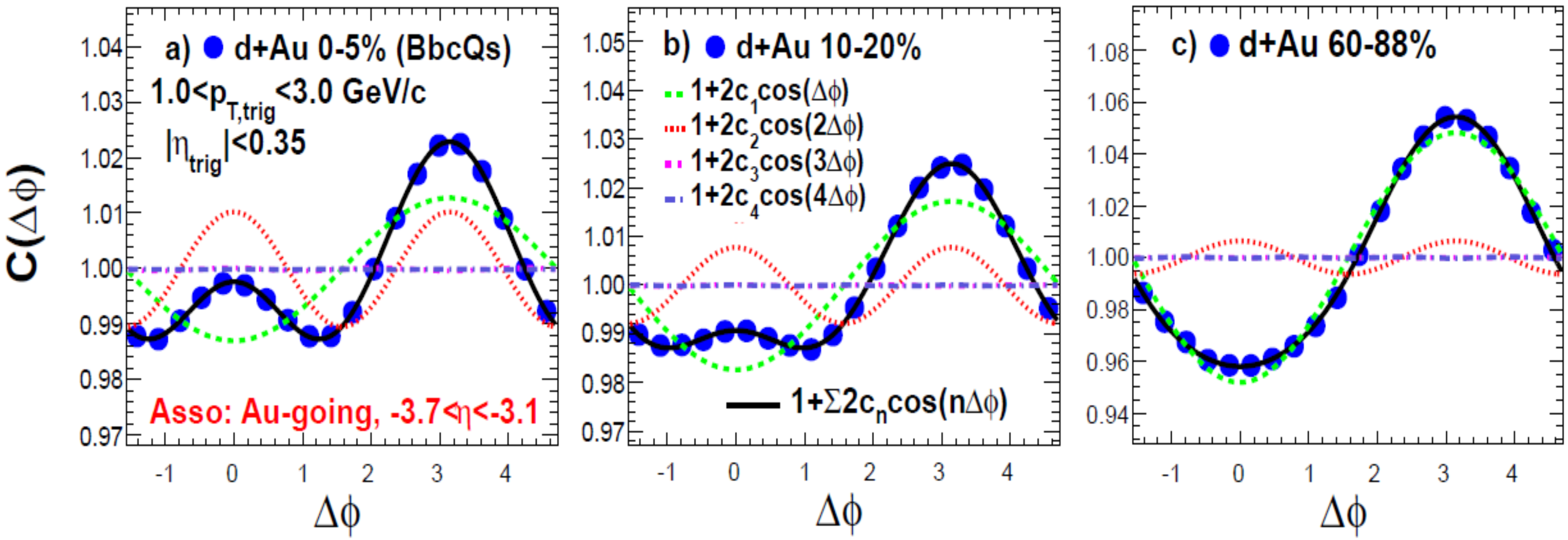
Comparison d going and Au going sides.

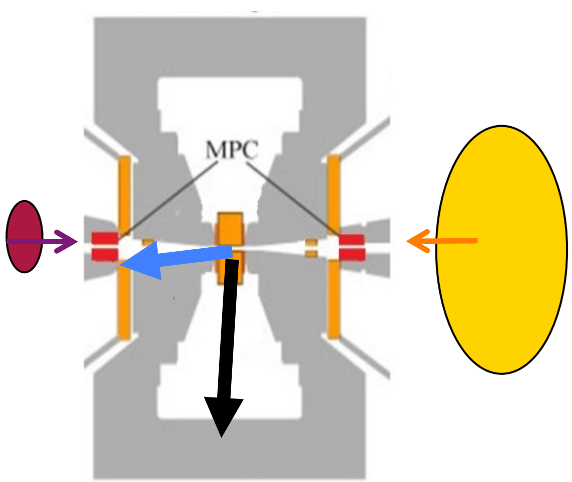




Note ridge in Au but not d going side.

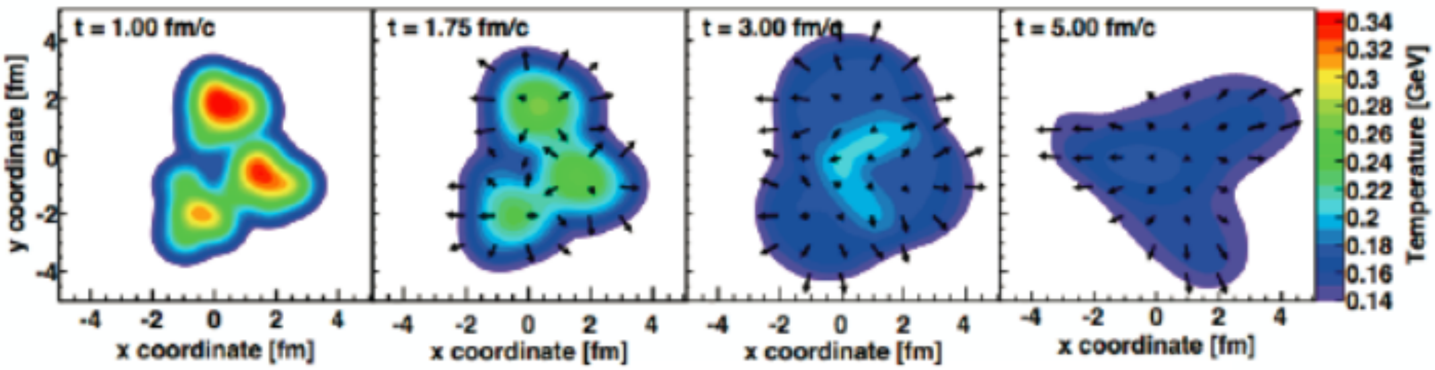
Details of Au Going Correlation





1. Clear ridge and increases with centrality.
2. Peripheral collision pattern similar for d side and Au side.

Recent ^{3}He + Au RHIC run



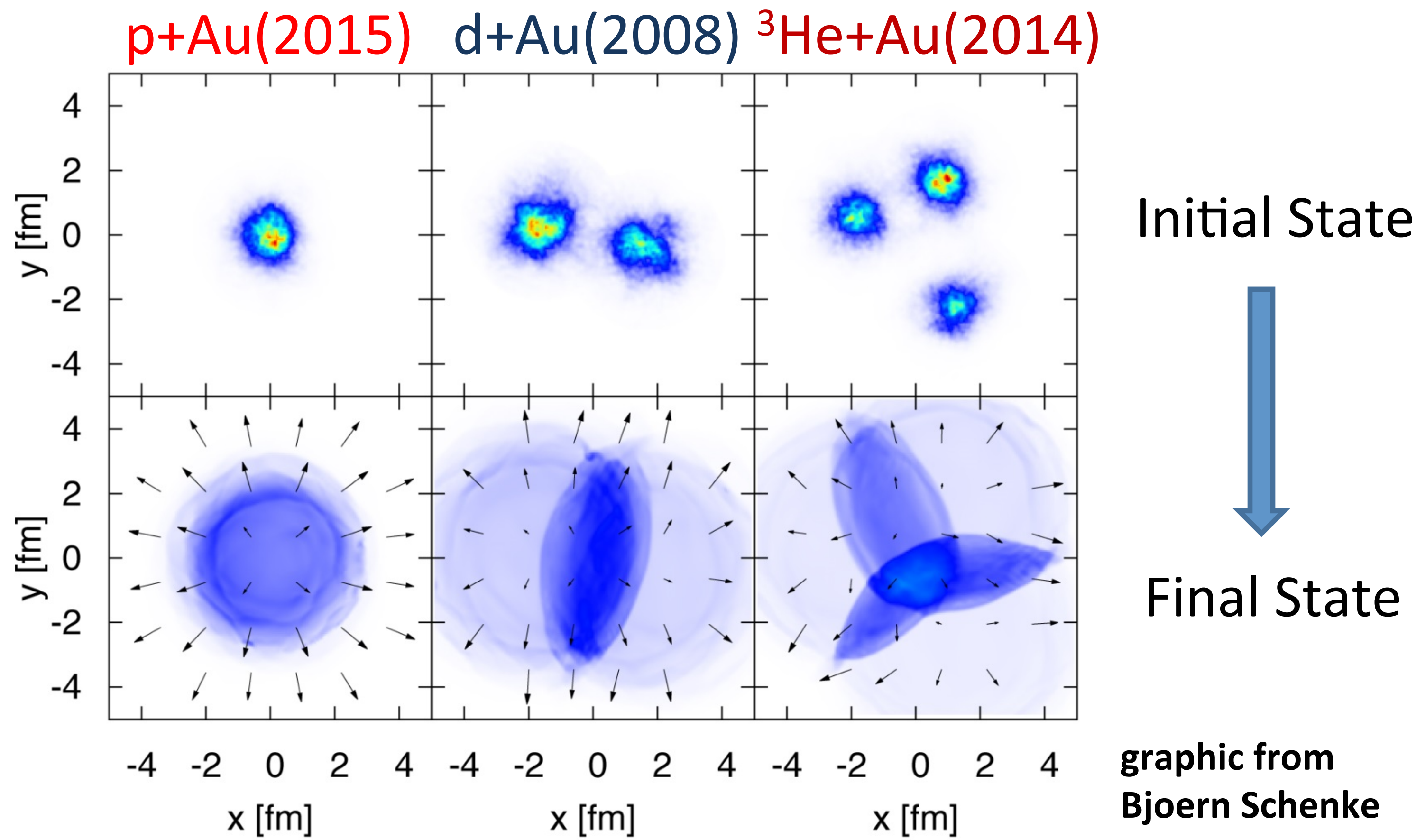
Results of hydro calculation. Note 3 hot spots.

1. We took ^{3}He + Au collision data for two weeks at RHIC.

2. We collected a data sample of 2.2B events in MB.

3. Eager to see if the odd geometry of ^{3}He gives us a significant n_3 component and more flow.

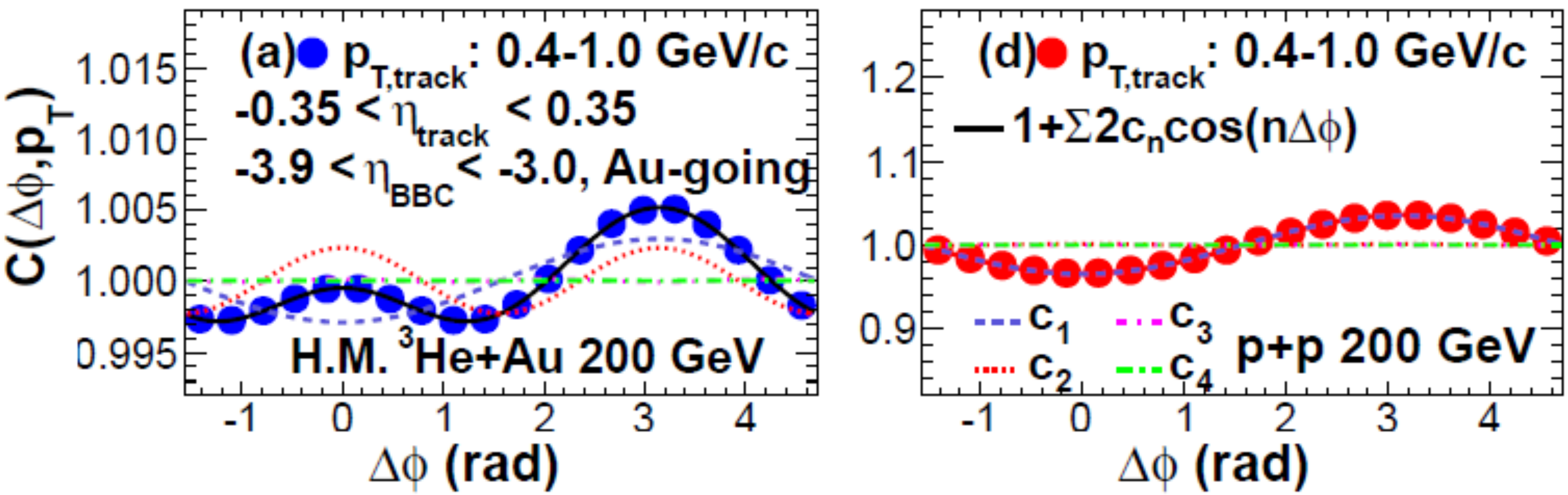
Comparison geometry for p, d and ^{3}He on Au



graphic from Bjoern Schenke

- Different initial geometry → different final state particle emission for p+Au, d+Au and ^{3}He+Au collisions

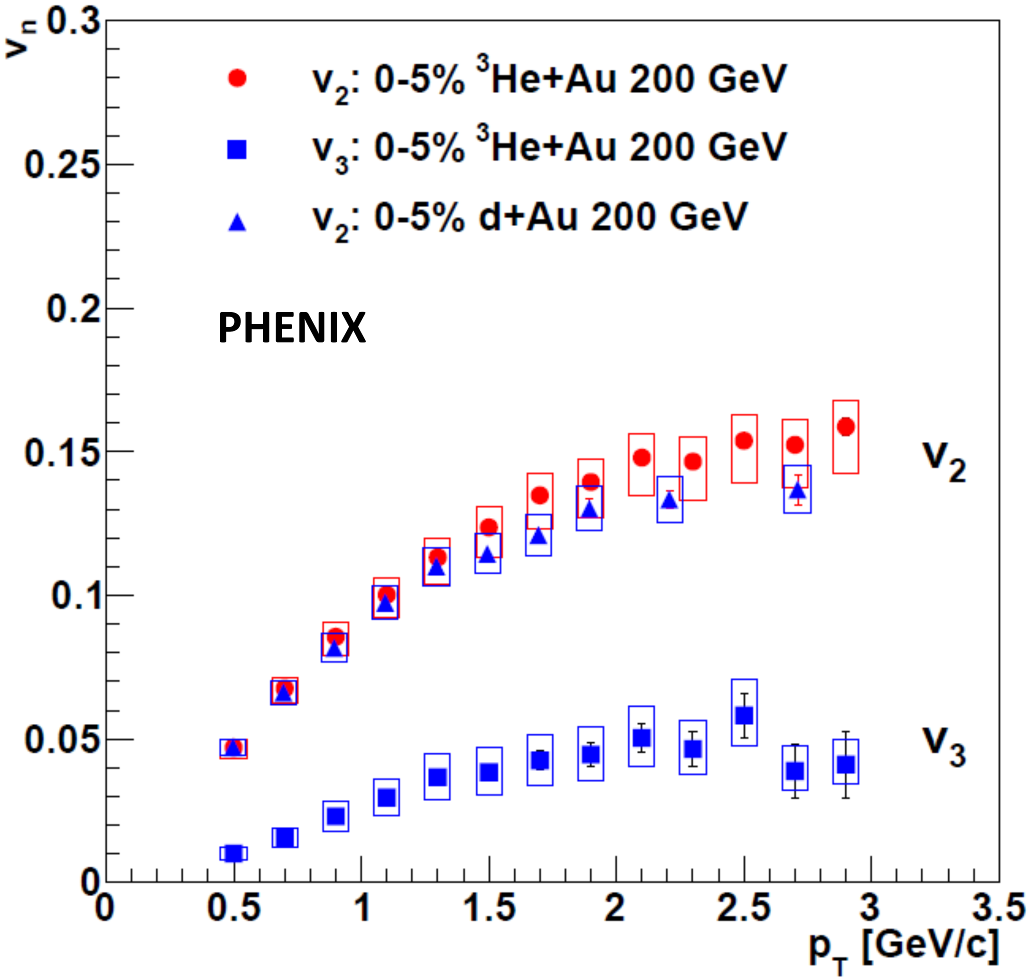
Ridge in 0-5% ^{3}He+Au 200 GeV



arXiv:1507.06273, Accepted by PRL (Editor's suggestion highlight)

- ✓ A ridge is observed in high multiplicity(0-5%) ^{3}He+Au collisions
- ✓ In the reference pp collision, the correlation is dominated by momentum conservation (including di-jets)

v_2 and v_3 in 0-5% ^{3}He+Au



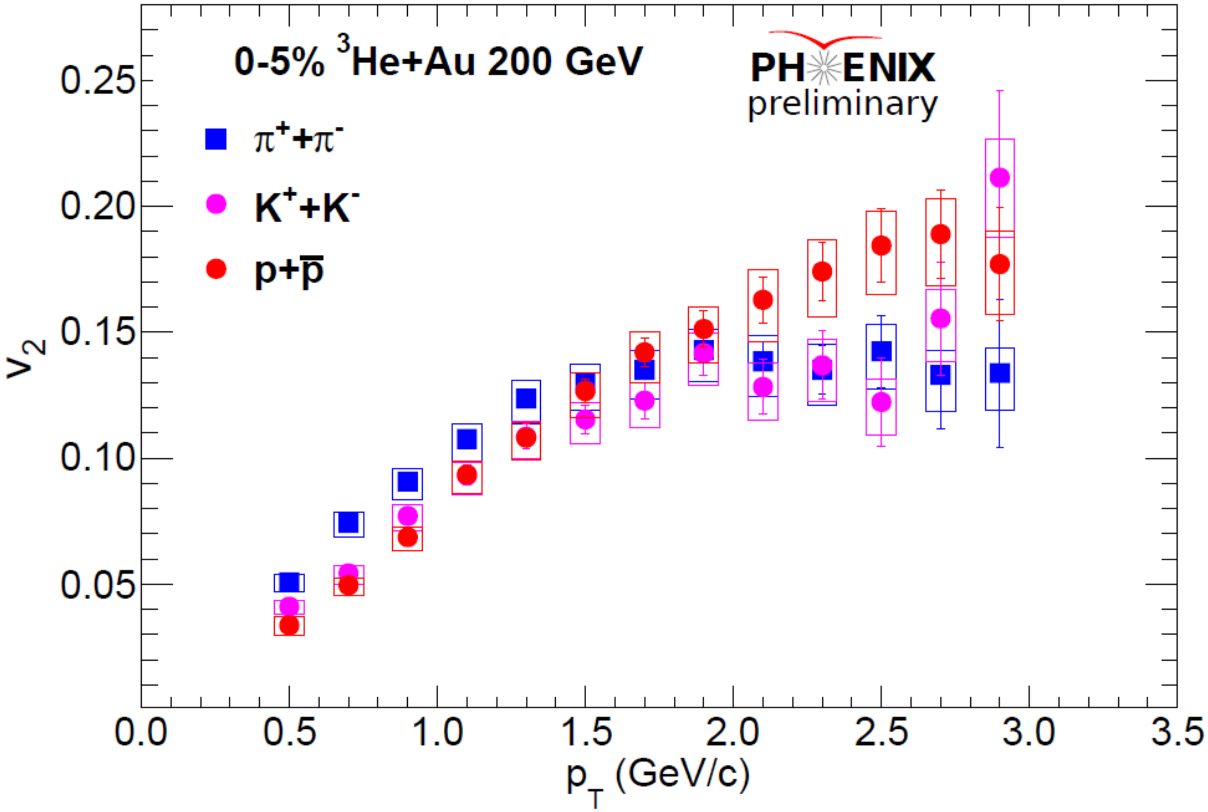
A sizeable v_2 and v_3 are observed in 0-5% ^{3}He+Au collisions, extracted by event plane method

The v_2 in 0-5% ^{3}He+Au and 0-5% d+Au collisions are very similar

^{3}He+Au: arXiv:1507.06273
d+Au: Phys. Rev. Lett. 114, 192301

} Both PRL highlights

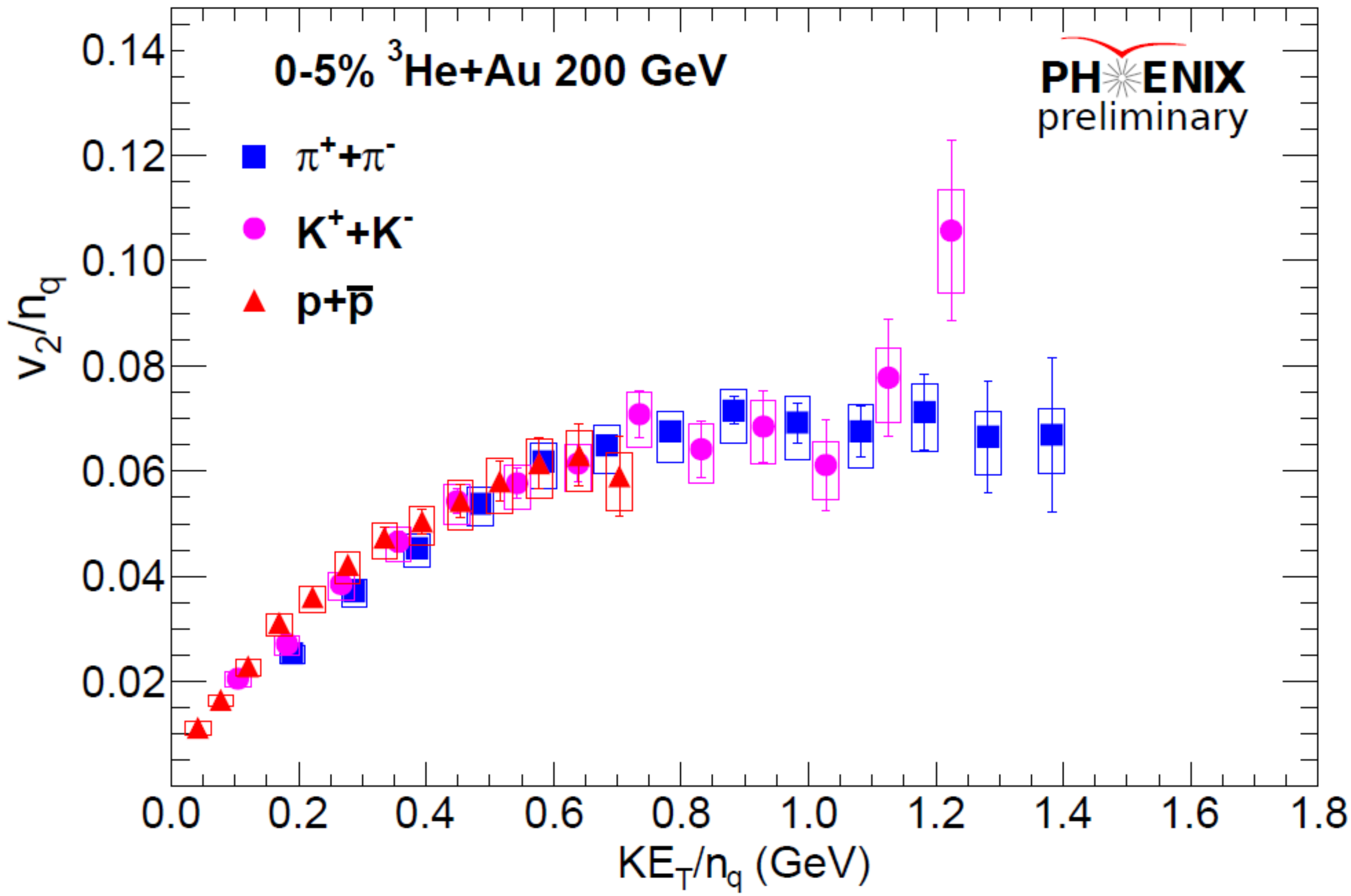
Identified particle v_2 in ^{3}He+Au



Note difference nucleons and mesons at higher p_T.

These behaviors are very similar to that in Au+Au collisions and calculations of viscous hydro.

Quark Scaling in ^{3}He+Au



Quark scaling observed in Au+Au collisions also seen in the small ^{3}He +Au system.

Conclusions

A. Flow and ridge observed for Au on p, d and ^{3}He at RHIC and p+Pb at LHC.

B. Quark scaling valid for Au+^{3}He system.

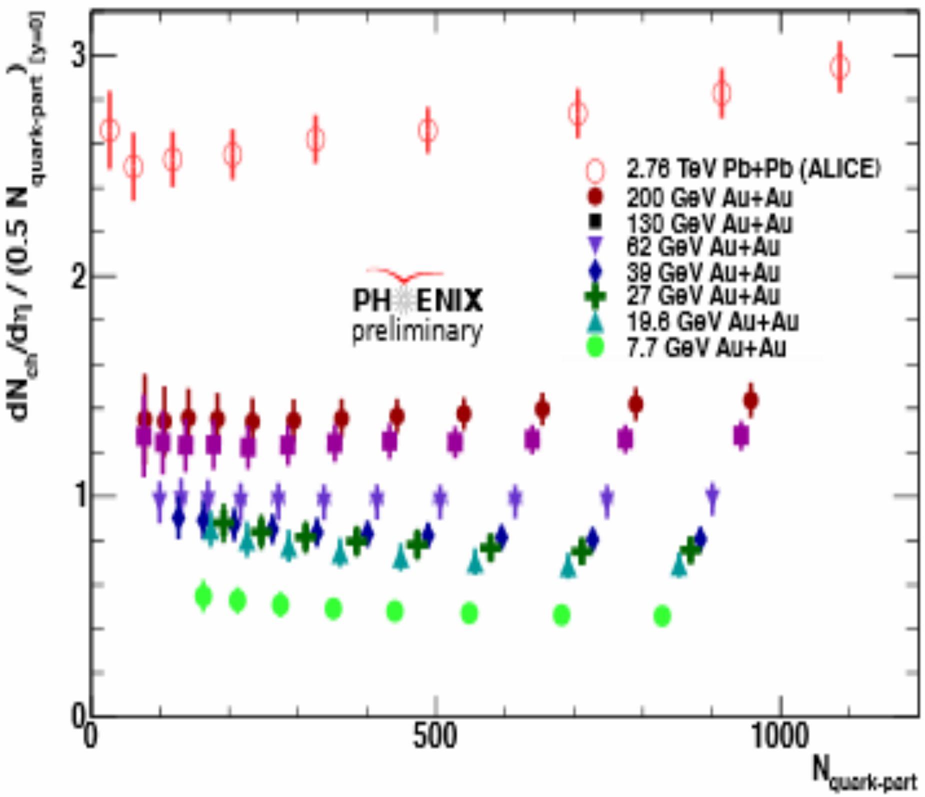
C. A. and B. suggests QGP droplets formed in collisions of large with small nuclei.

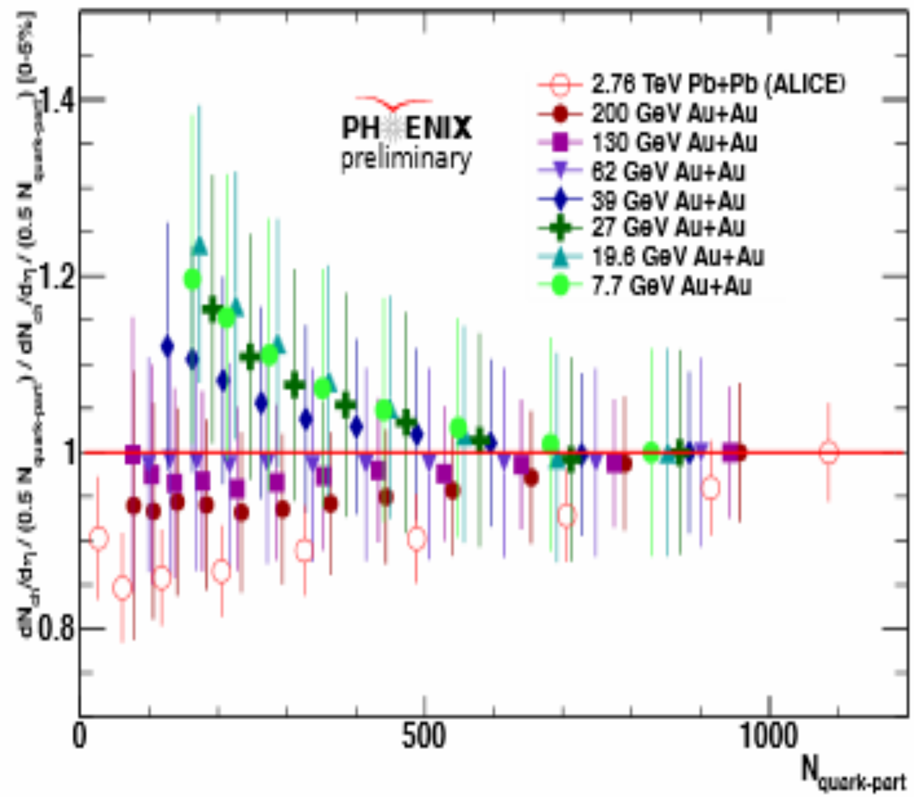
H. What Happens if we Study Lower Energy Systems?

$\sqrt{S_{NN}}$	Au + Au	Cu + Cu	Cu + Au	D + Au	^{3}He + Au
200	✔	✔	✔	✔	✔
130	✔				
62.4	✔	✔			
39	✔				
27	✔				
19.6	✔				
14.5	✔				
7.7	✔				

Summary of relevant energy particle combinations for low–energy scan measured at RHIC.

Beam Energy Scan Q Scaling Results

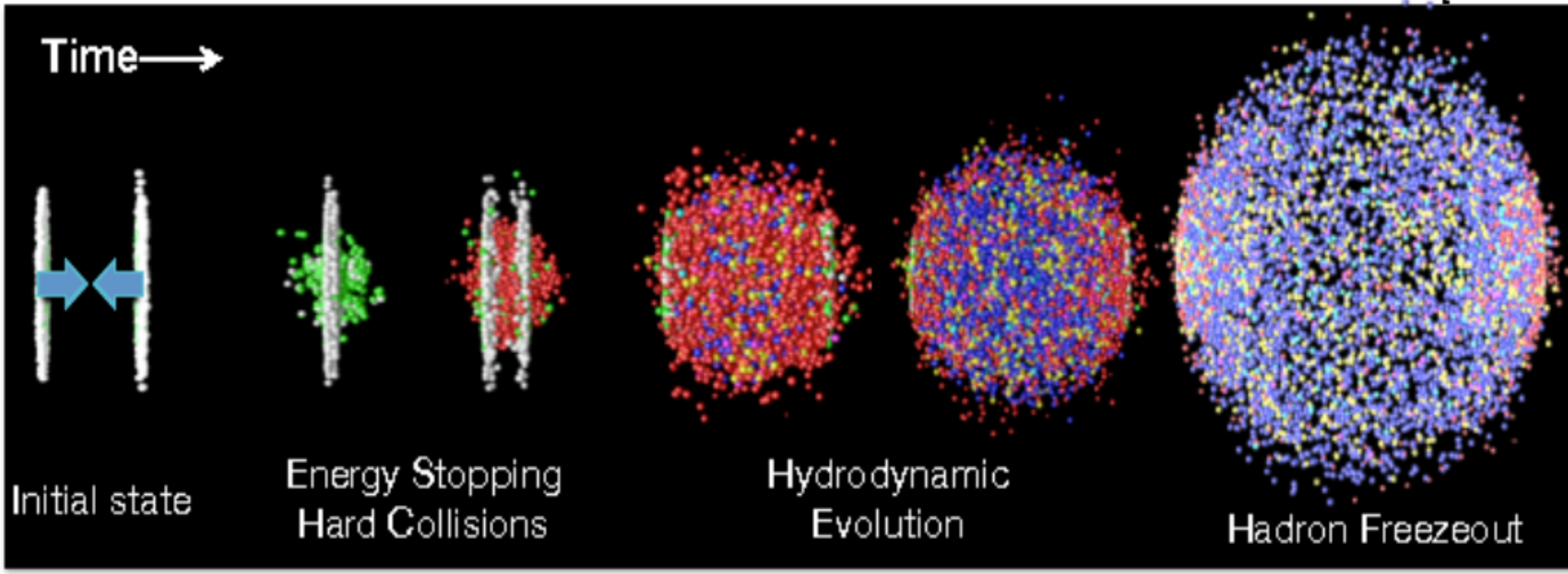




1. Plot on left shows yield of Au+Au collisions from 7.7 to 200 GeV as a function of centrality but divided by number of valence quarks.
2. Plot on right shows same data but with highest centrality points for each beam energy normalized to 1.0 to show trends.
3. Quark scaling works well from 200 to 62 GeV but breaks down at lower energies.
4. Nucleon scaling works well for energies below 40 GeV.

HBT as Tool to Study Nuclear Fireball

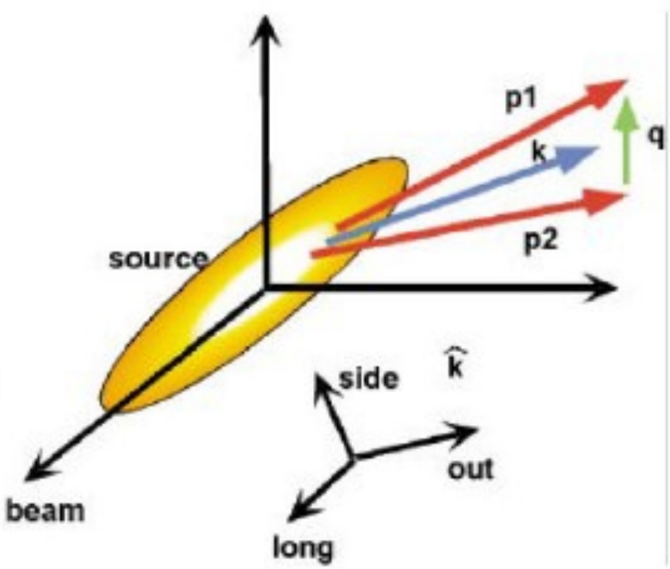
arXiv:1201.4264 [nucl-ex]



1. In 1956 Hanbury Brown and Twiss (HBT) measured angular diameter of Sirius from light.
2. In 1960 Goldhaber et al. measured correlation functions between pions in $p+p_{bar}$ reactions.
3. It is possible to use HBT to determine correlation functions for the nuclear fireball at kinetic freeze out.

Construction of 2 Pion Correlation Function

1. Determine 2 pion correlation function $C_2(q) = A(q)/B(q)$.
2. $A(q)$ is measured distribution momentum difference $q = p_2 – p_1$.
3. $B(q)$ is pair uncorrelated distribution from different events.
4. $C_2(q) = N[(\lambda(1+G(q)))F_c + (1-\lambda)]$
5. $G(q) = \exp(-R^2_{side}q^2_{side} - R^2_{out}q^2_{out} - R^2_{long}q^2_{long})$
6. Measured $C_2(q)$ can be used to determine R.



N = normalization factor

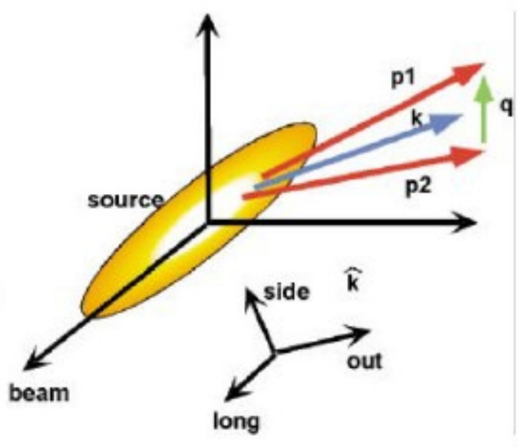
λ= correlation strength

F_c = Coulomb correction factor

R's = Gaussian HBT radii

R_{long} measured in q_{long} = 0 frame

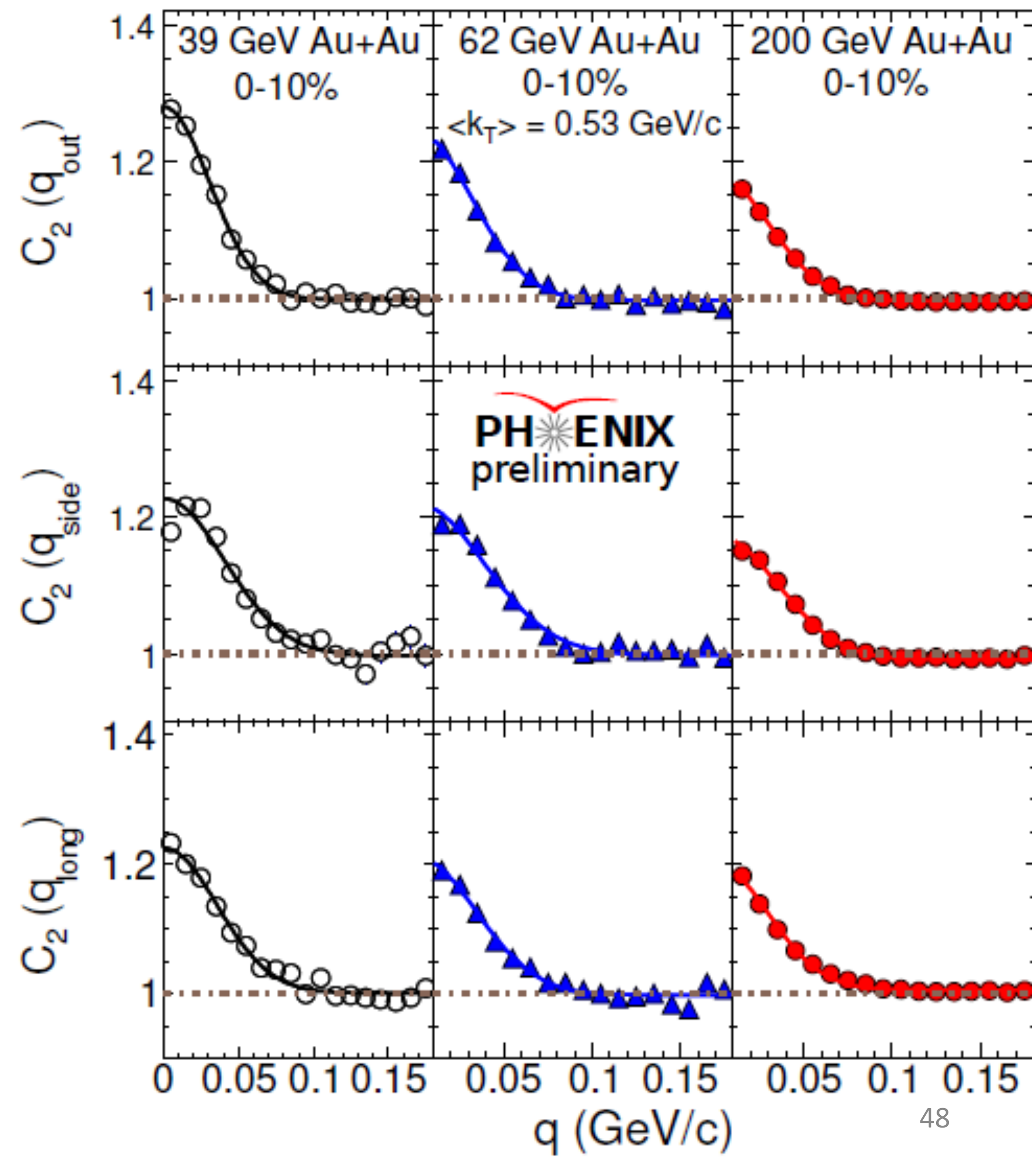
C's for 39, 62 and 200 GeV Au+Au



q_{long} along beam direction

q_{out} parallel to k_T of pair

q_{side} perpendicular to beam and k_T of pair

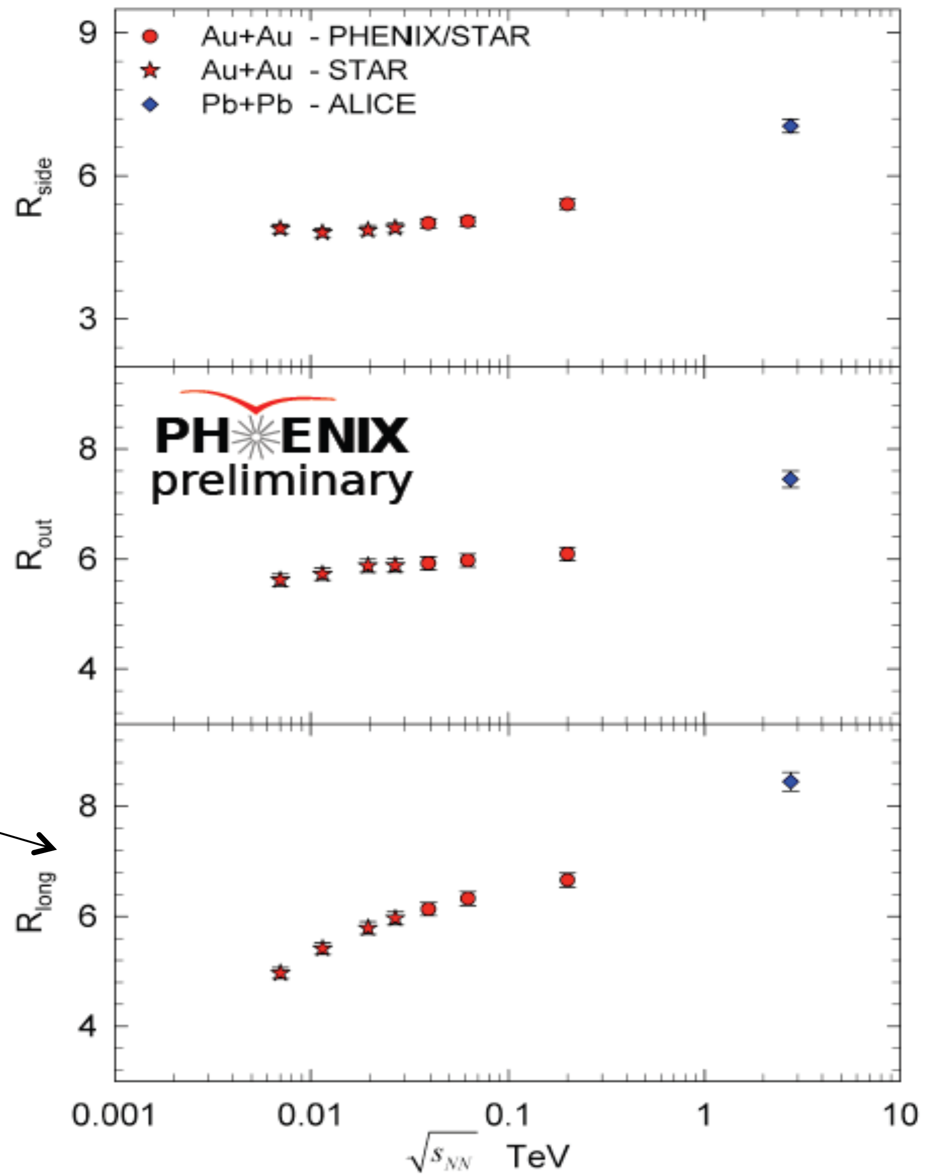


HBT Radii (fm) vs Collision Energy

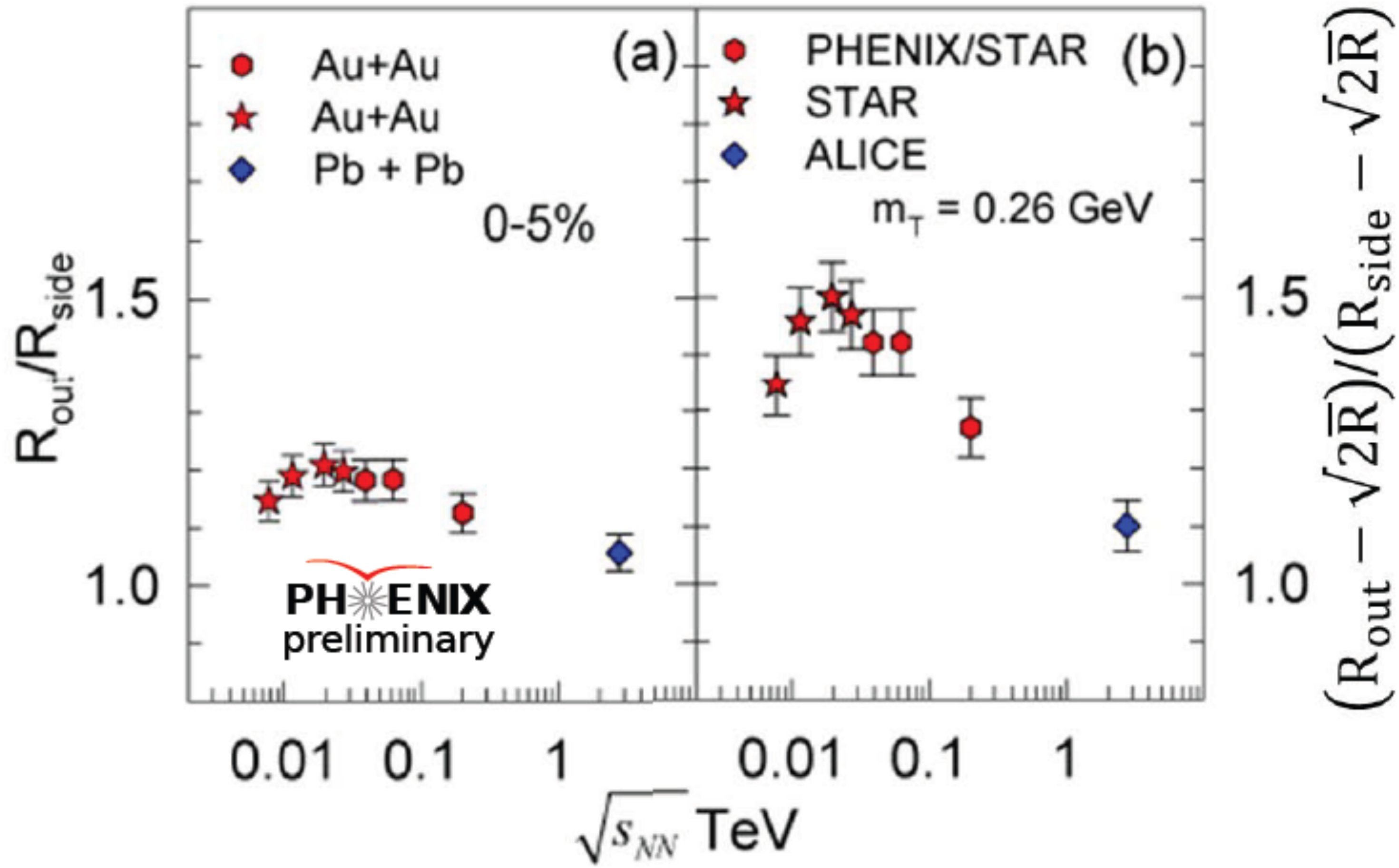
1. PHENIX, STAR and ALICE data.

2. R_{long} is a proxy for τ. Note increase with energy.

3. Construct ratios and differences.

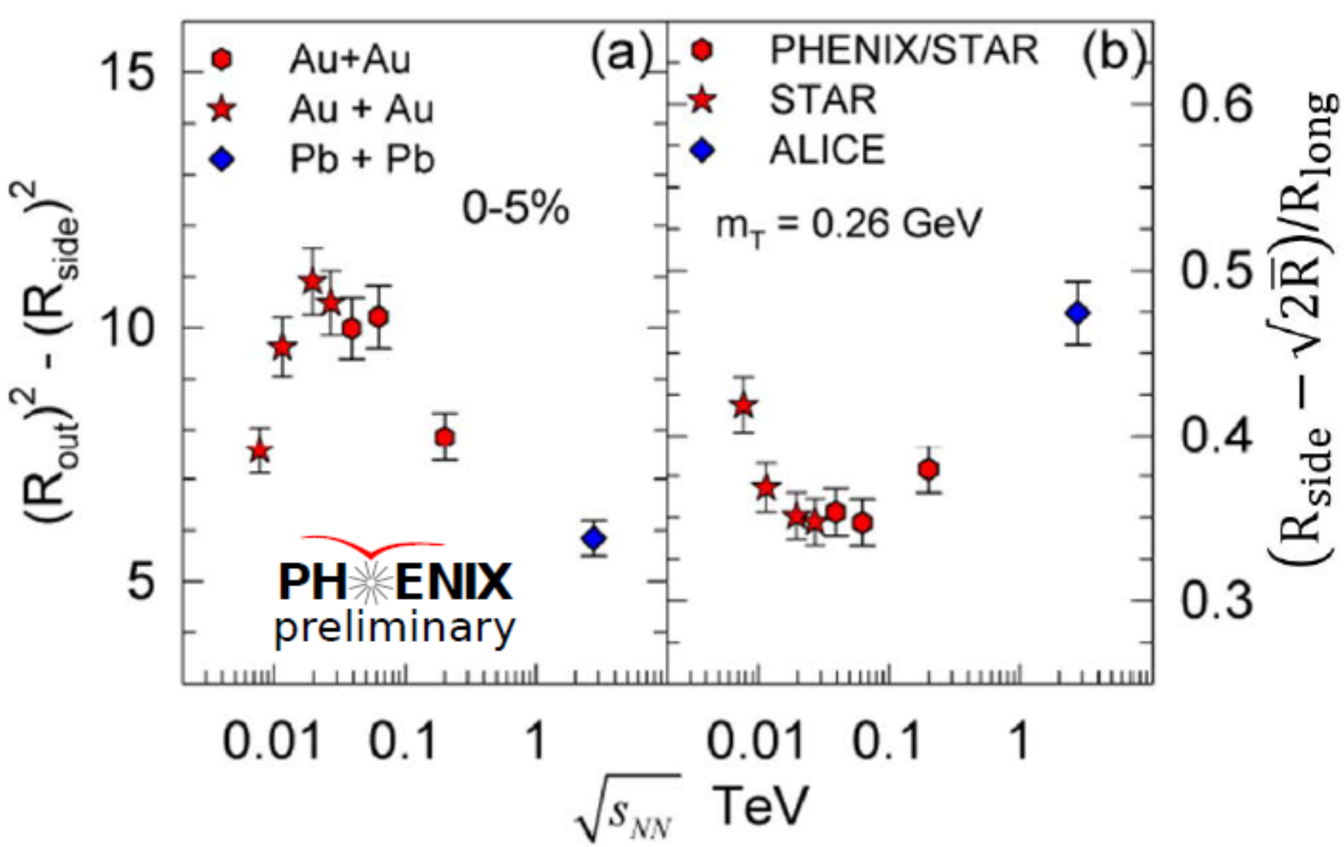


Trends of Radii Results with Energy



1. R_{out}/R_{side} shows maximum around 30 GeV.
2. R_{out}/R_{side} sensitive to emission duration $\Delta\tau$.

More Trends of Radii Results with Energy



1. $(R_{out})^2 - (R_{side})^2$ is also a proxy for emission duration $\Delta\tau$ with maximum at around 30 GeV
2. R_{side} / R_{long} is a proxy for expansion speed and the speed of sound c_s in the medium and has minimum at around 30 GeV.

Conclusions

A. Low energy scan on Au+Au suggests quark scaling breaks down below 40 GeV/A.

B. HBT measurements have determined fireball radii for Au+Au collisions at kinetic freeze out which suggests possible softening of the nuclear matter equation of state in the vicinity of 30 GeV.

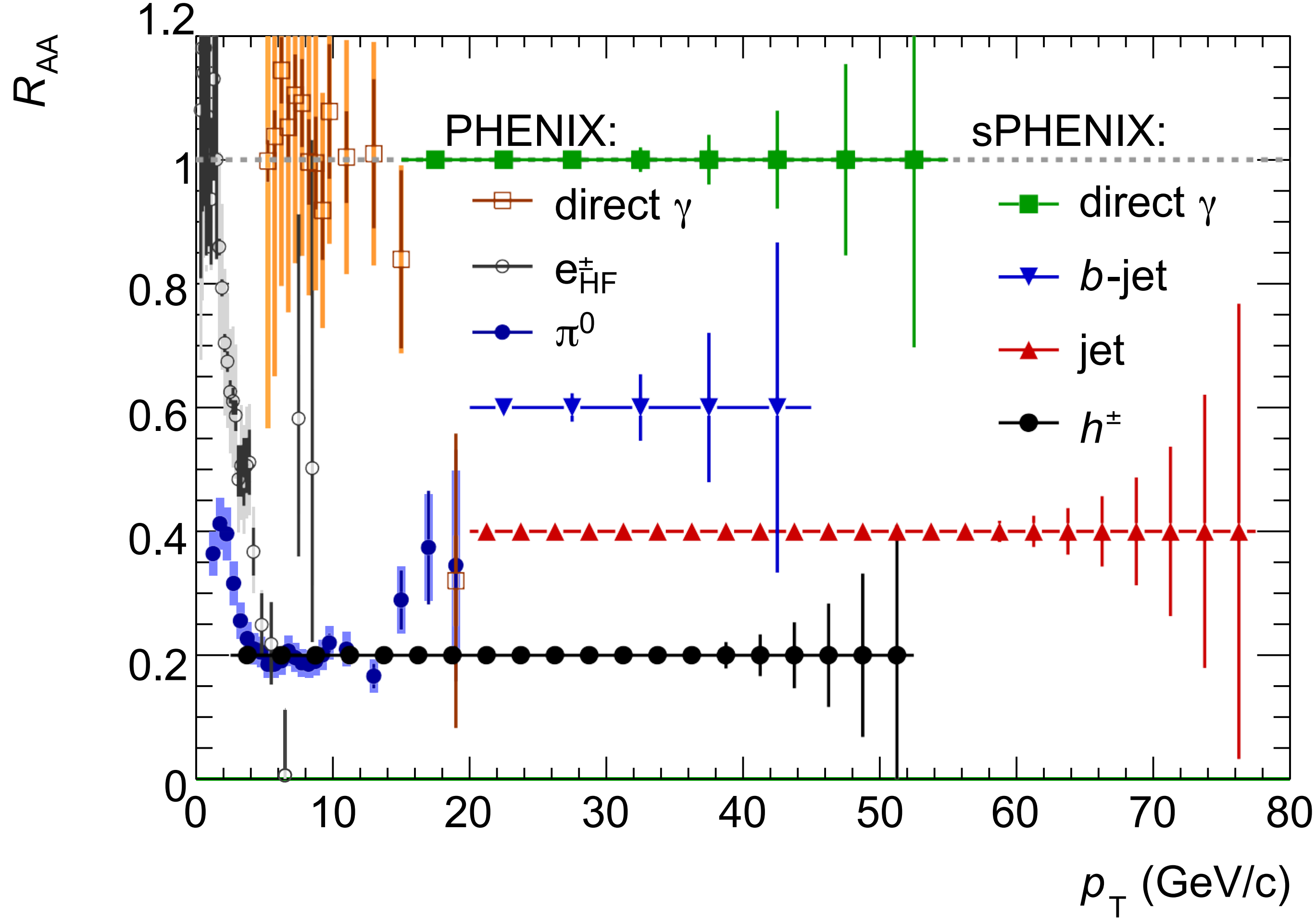
H. The Future with sPHENIX.

sPHENIX is the next generation PHENIX detector.

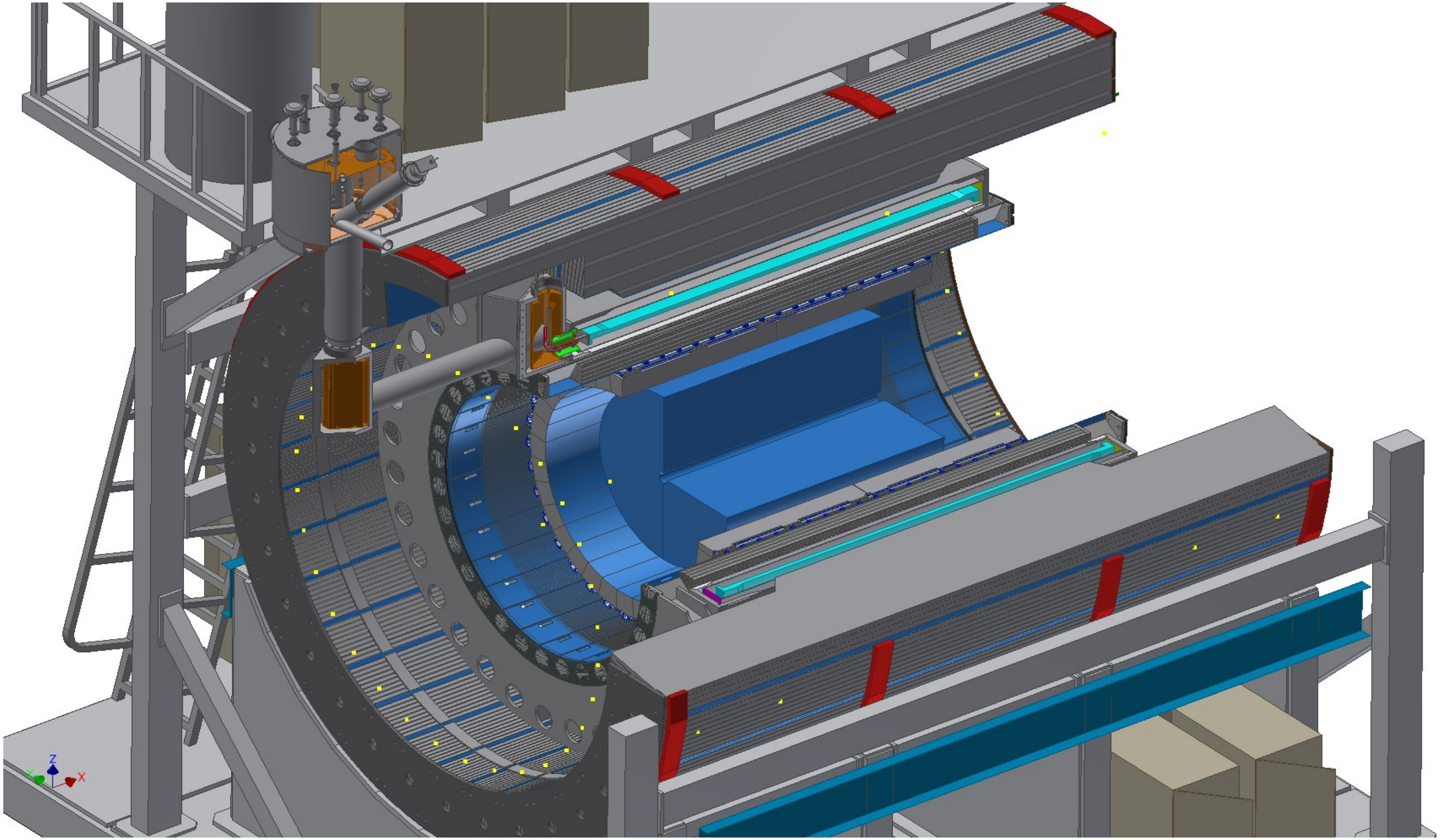
Goals for sPHENIX

- Complete the picture of evolution and coupling strength from the initial high temperature through expansion and cooling to the transition scale and below
- Fragmentation of partons measured with jets and the melting of the Upsilon states are the probes
- Direct photons and high p_T hadrons measured with high statistics due to high rates and large acceptance

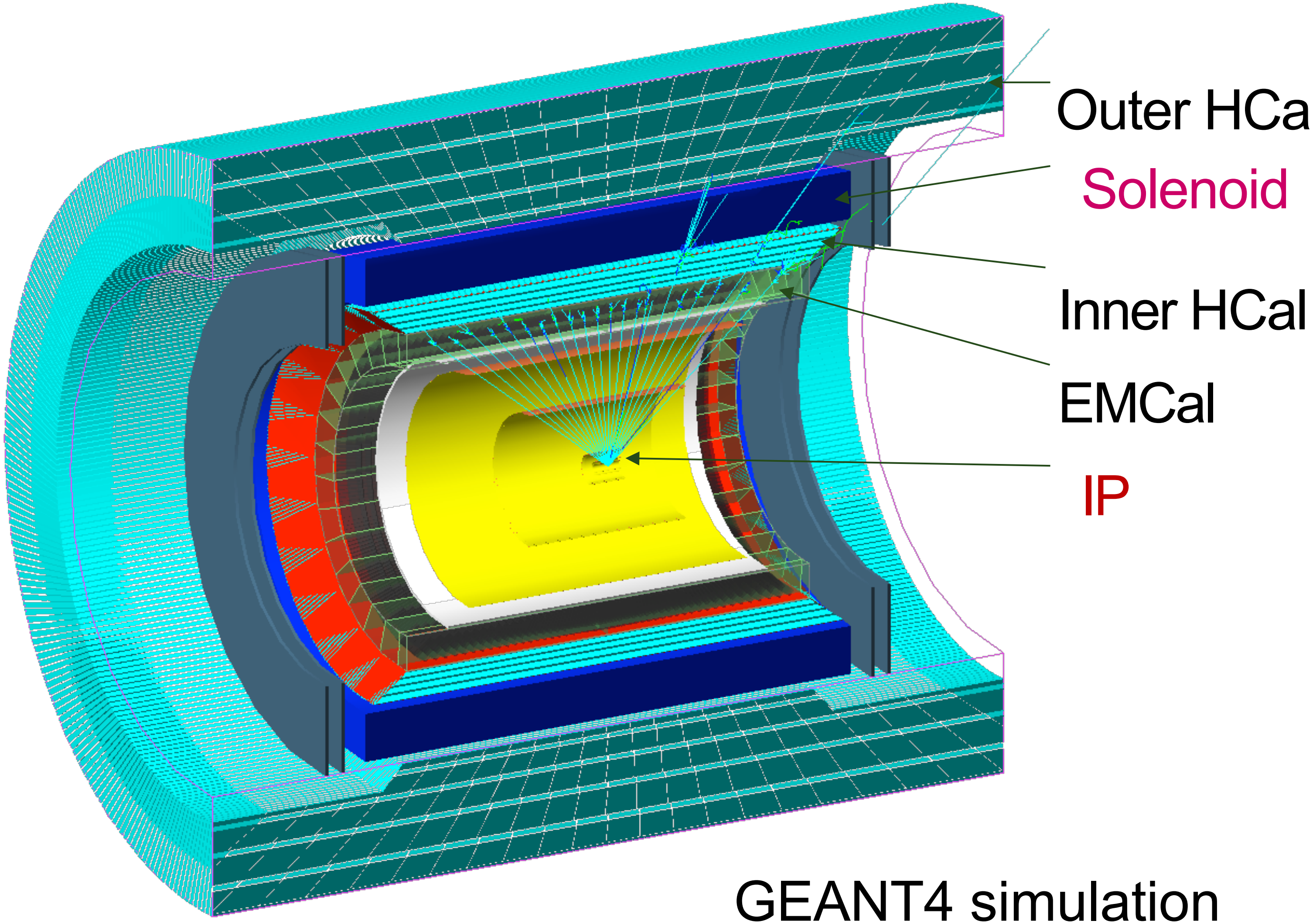
Extension of R(AA) to higher energy probes



Artist view of sPHENIX



Layout of sPHENIX subsystems

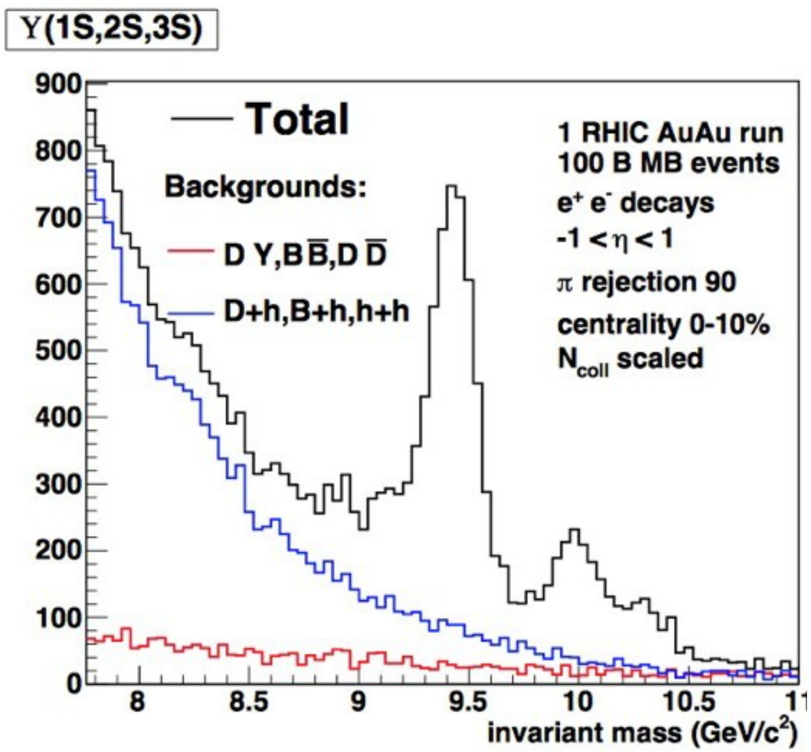


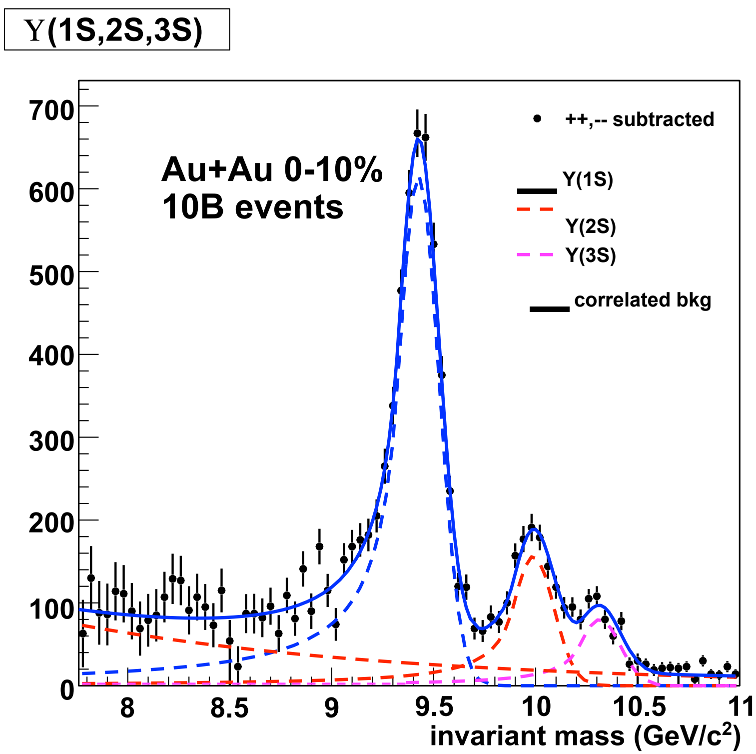
GEANT4 simulation

https://github.com/sPHENIX-Collaboration

Babar solenoid magnet in route from SLAC to BNL

Upsilon performance in Au+Au

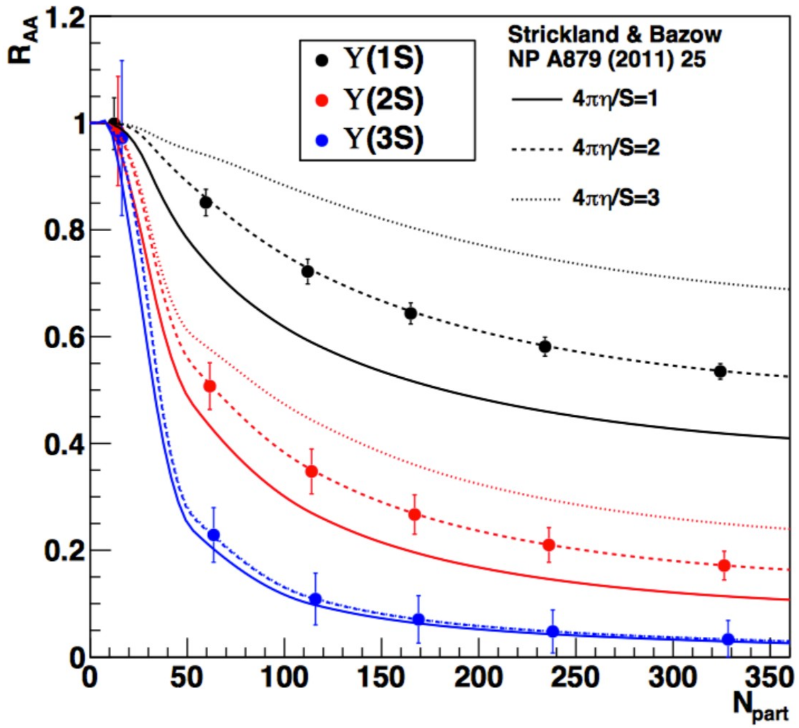




100 MeV mass resolution in reference design

Nuclear modification projections for Upsilons

- With
  - 10 weeks p+p
  - 22 weeks Au+Au
- Yield and s/b scaled to match model suppression



Status and next steps

- DOE panel accepted science case at review completed May 2015
- sPHENIX is integral part of the BNL plan after final PHENIX run in 2016
- Design, simulation, R&D, prototyping all moving forward
- BNL convened a workshop to form new collaboration in June 2015. First collaboration meeting is Dec 10-12, 2015 at Rutgers

J. Conclusions

1. QGP created in heavy ion collisions.
2. The QGP acts as a high temperature low viscosity liquid.
3. Evidence for QGP droplets observed in p, d and He-3 collisions with heavy nuclei.
4. HBT studies measured radii at freeze out and point to possible softening of nuclear EOS around 30 GeV.
5. Predicted first order phase transition and critical point yet to be observed.
6. PHENIX program ended in 2016 and now transitioning to sPHENIX.

Thank you for your attention!!

BACKUP

Open Questions for Quark-Gluon Plasma Studies

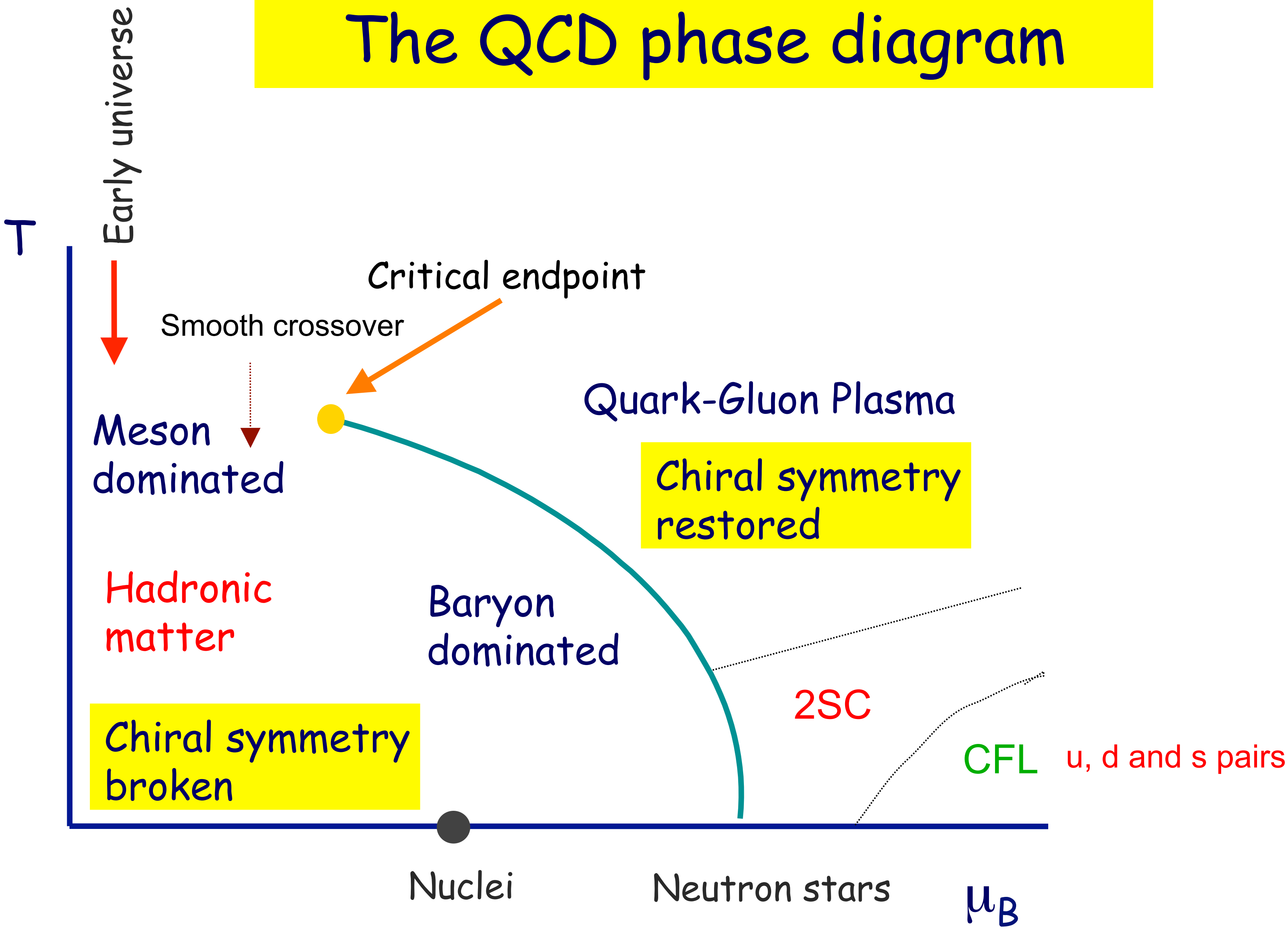
What is the nature of the phase transition at high baryon densities and where is the QCD critical point?

Where is the boundary between hadronic and deconfined matter.

Why are even the heaviest c and b quarks stopped in plasma?

What is the nature of QCD matter at low temperature but high gluon density? Is gluon saturation reached and how does this effect QGP formation?

The QCD phase diagram



$$m(s) >> m(u,d) \neq 0$$