Studies of Hot Dense Matter with the PHENIX Detector at RHIC

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A bit of history and a few personal remarks

James Vary and I first came to Iowa State University in 1975 as part of an effort to strengthen the low-energy program in nuclear structure.

In the early 1990’s our experimental nuclear program was at a crossroads and Fred Wohn and I decided to evolve to relativistic heavy ion physics with the ultimate goal of searching for the quark-gluon plasma (QGP).

Naively thinking that J/psi suppression would be the golden signal indicating the formation of the quark-gluon plasma we joined the Dimuon Detector proposal with Glenn Young of ORNL.

That proposal was declined but was joined with two other proposals to eventually become PHENIX.

In 1998 our group expanded from two to four faculty (Hill, Lajoie, Ogilvie, Rosati).

LAS College Award for Outstanding Career Achievement in Research

RHIC and LHC Landmarks

June 2000 The first collisions at RHIC of 130 GeV/A (Au+Au), flow observed.

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

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

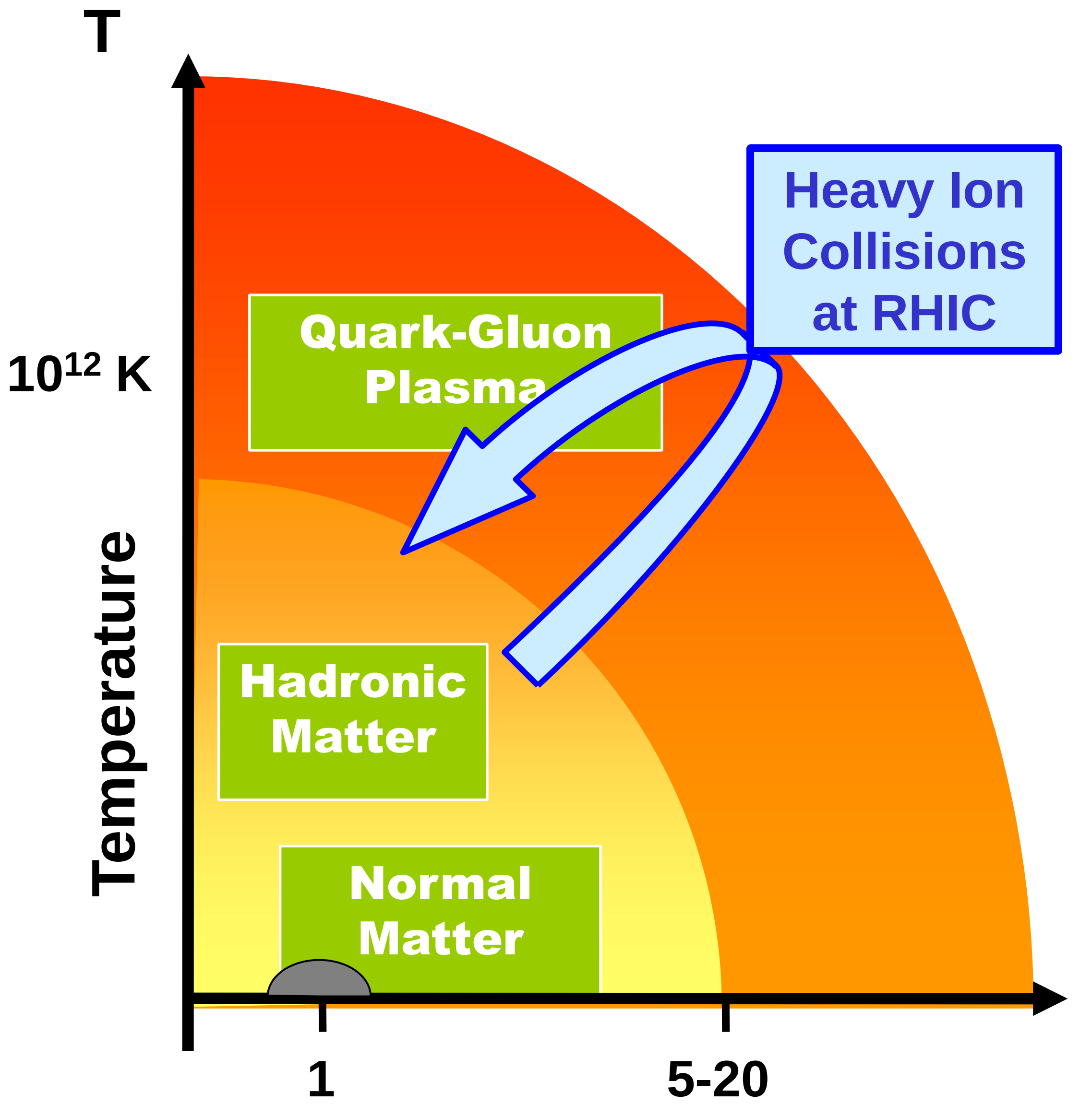
2010 First Pb+Pb collisions at LHC.

Scope of Talk

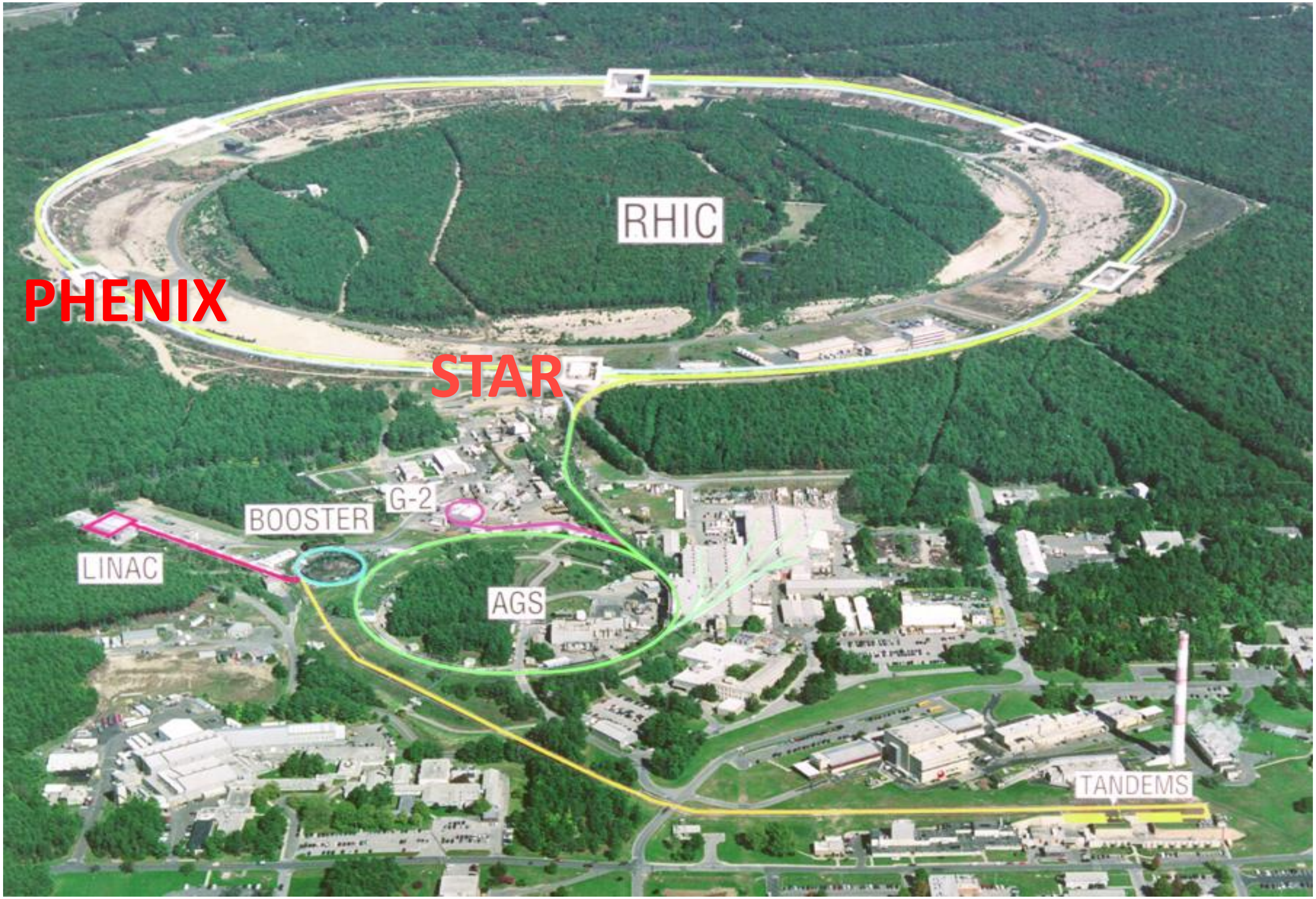
Iowa State is involved in both the RHIC heavy ion and spin programs. Can't cover both so chose to discuss just three features of the heavy ion program that have led us to our present picture of the Quark-Gluon Plasma.

A. Suppression of particles in hot dense medium.
B. Flow
C. Temperature of QGP

Phases of Nuclear Matter



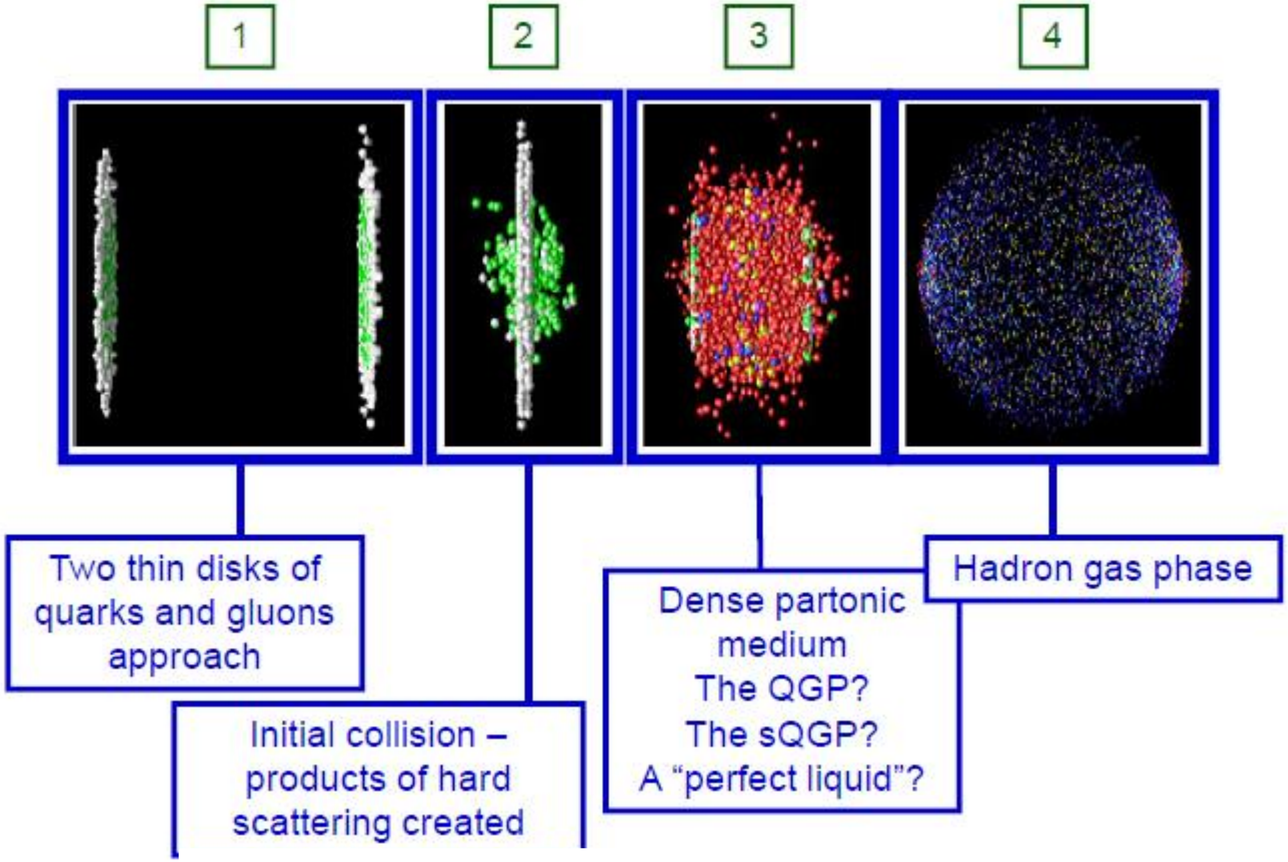
RHIC Birdview



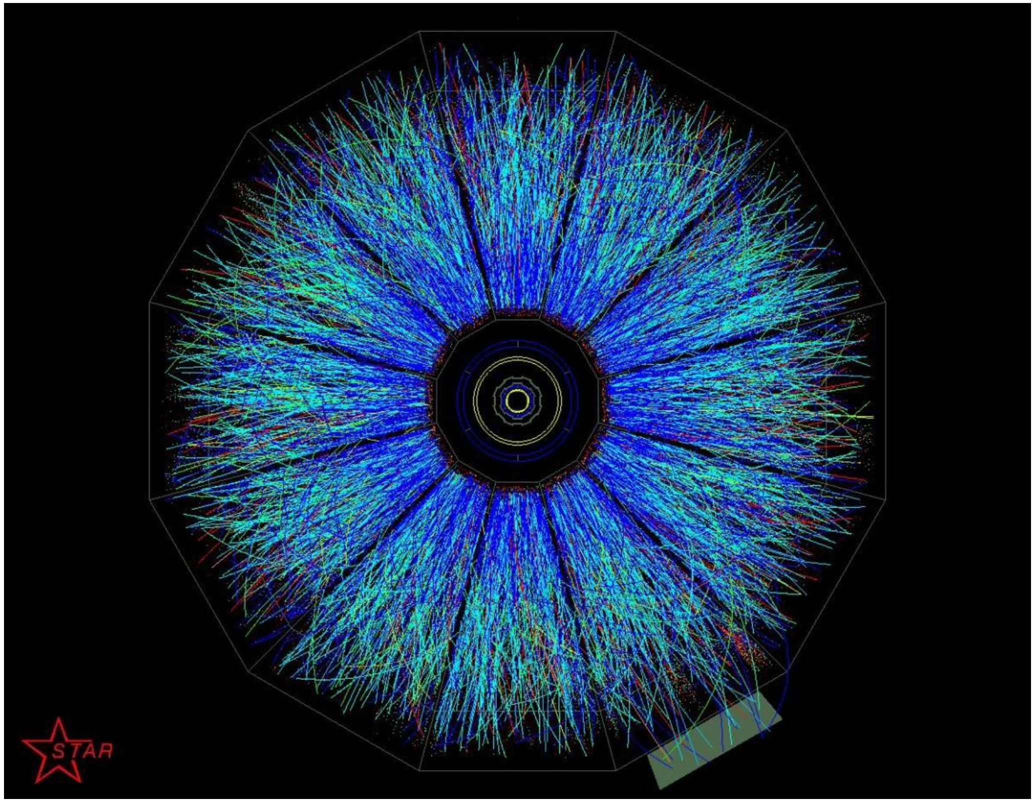

PHENIX
ILLINOIS

Stages in a Relativistic Heavy Ion Collision

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



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



What is the nature of this medium we created?

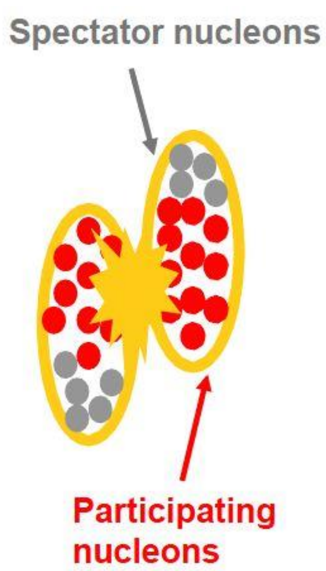
Can use particles created in the medium as a probe of the properties of the medium.

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

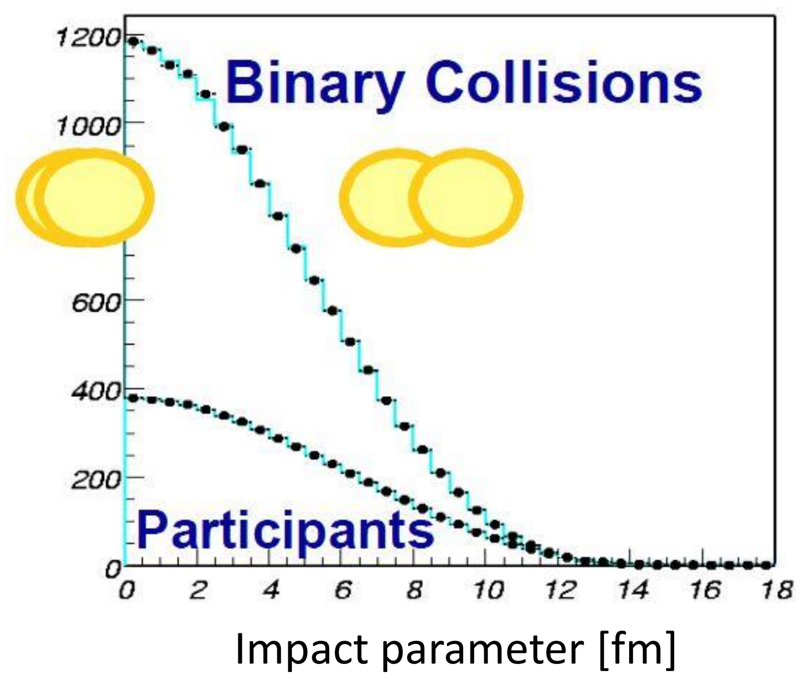
Nuclear Modification Factor R_{AA}

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

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.

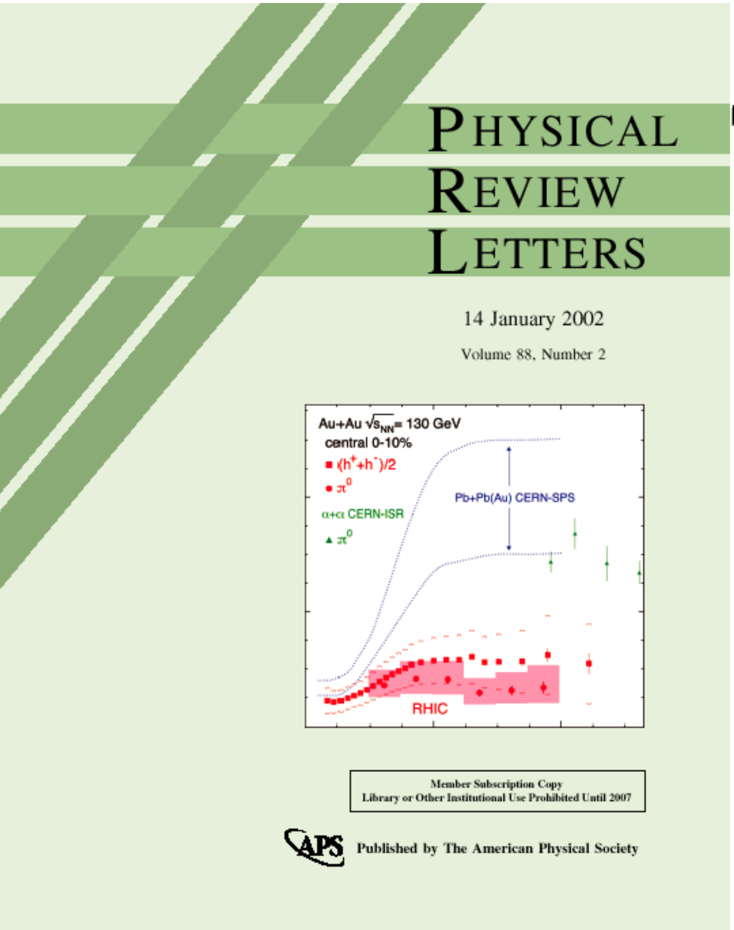


Centrality of collision is described by number of participant nucleons N_{PART}

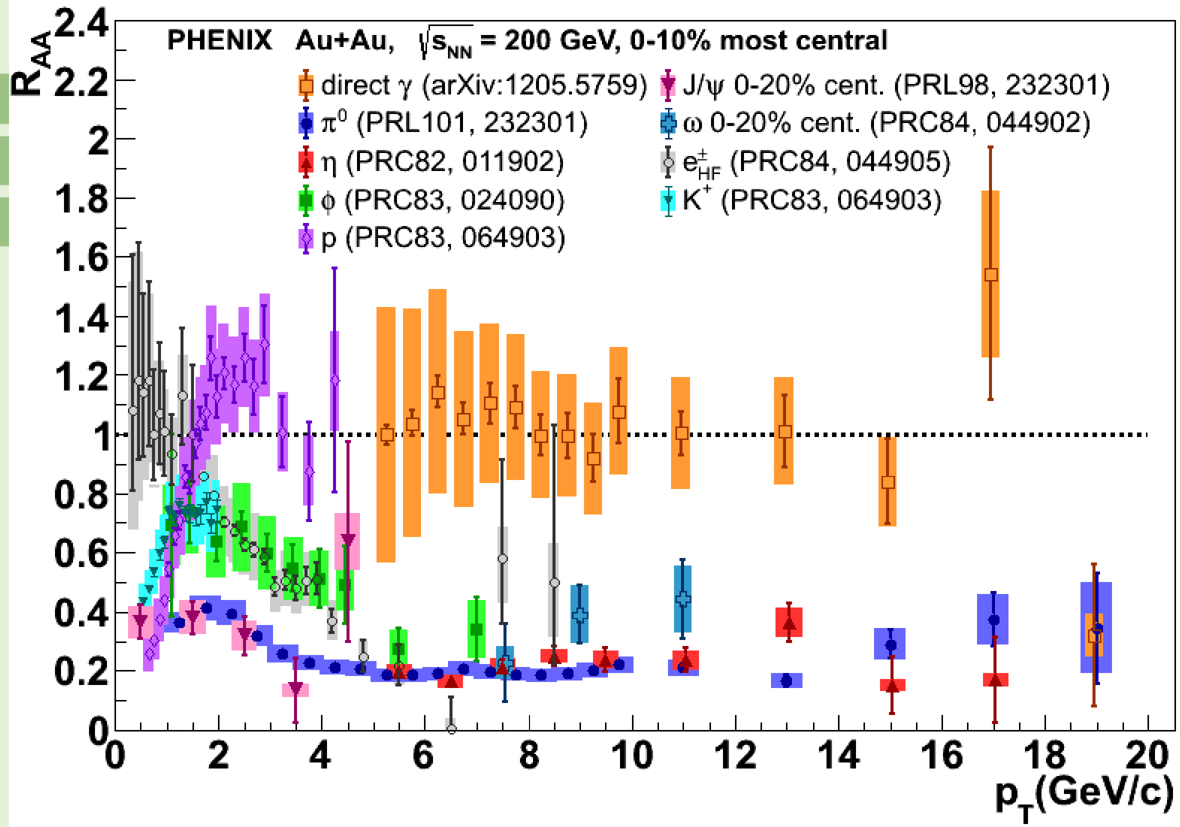


If particles not modified by medium expect RAA = 1

Are particles suppressed in the hot dense medium created?



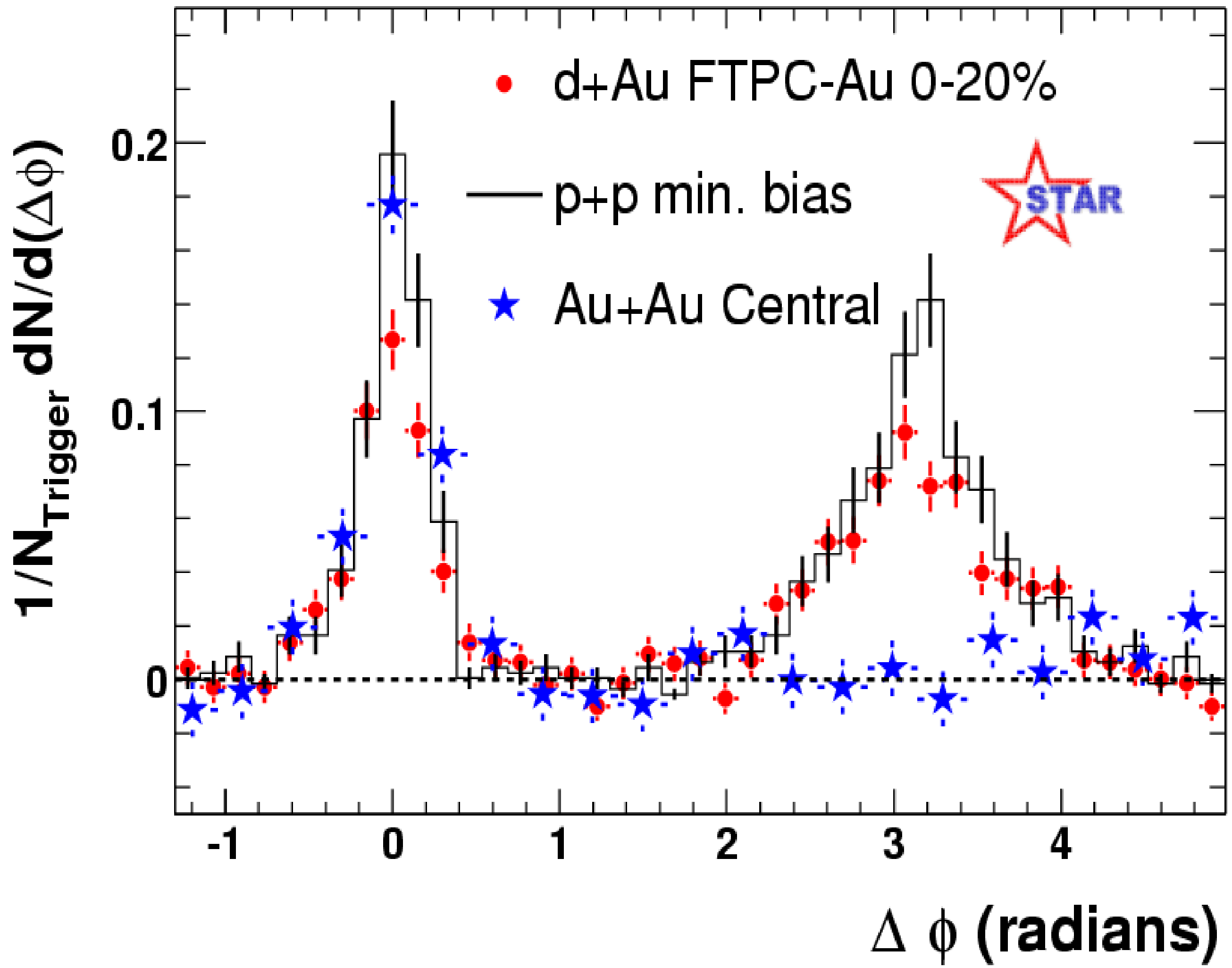
The most quoted single result RHIC paper



Hadrons suppressed.

Photons not suppressed.

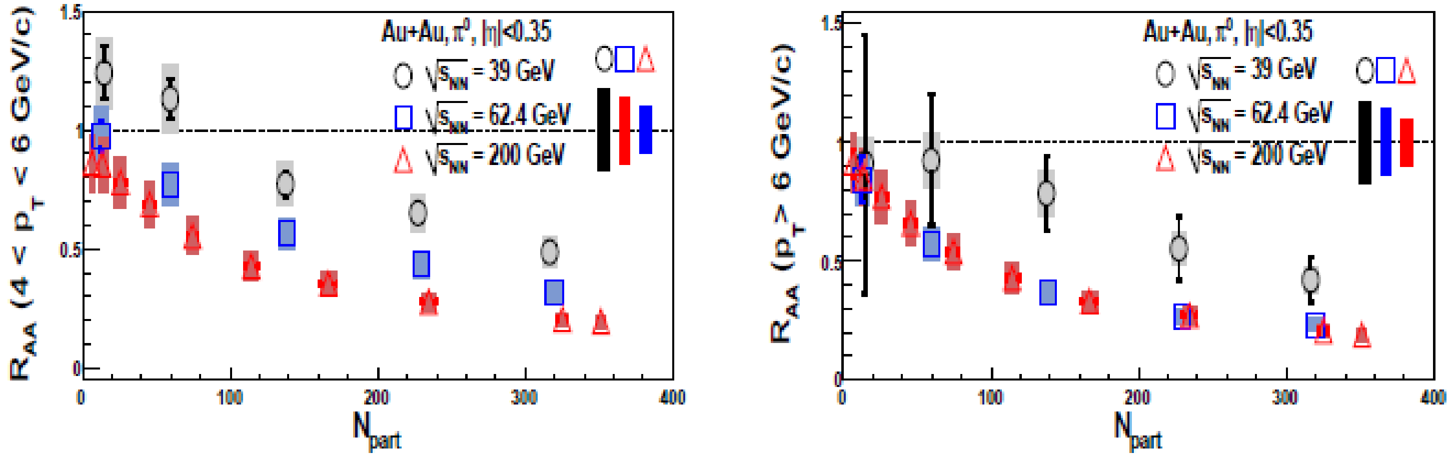
Can we see quenching at the jet level?



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?

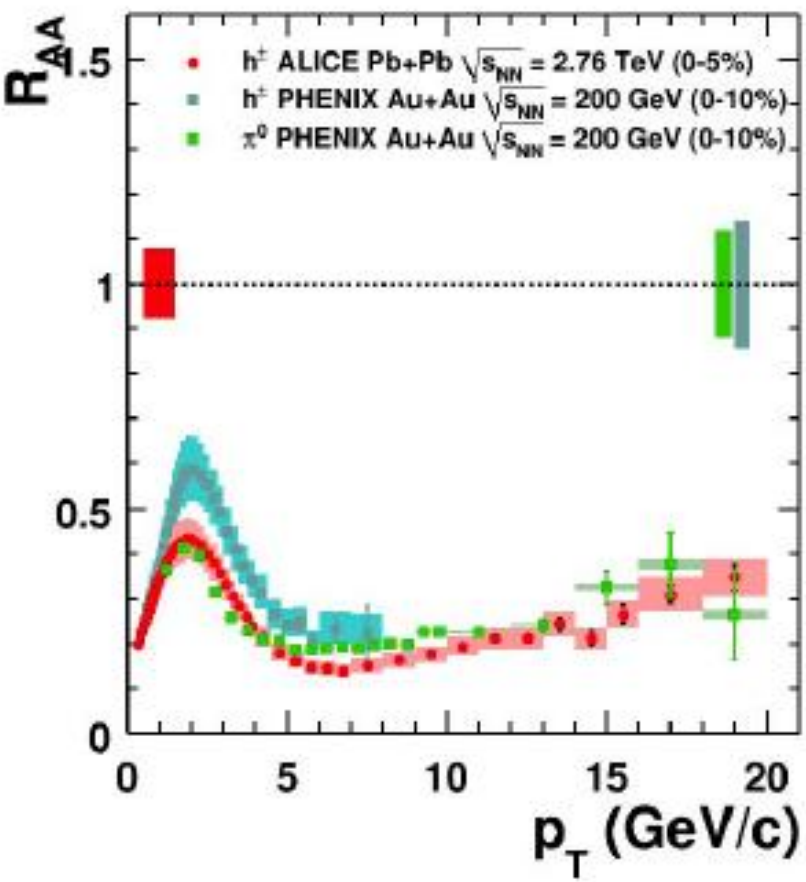
[arXiv:1204.1526]

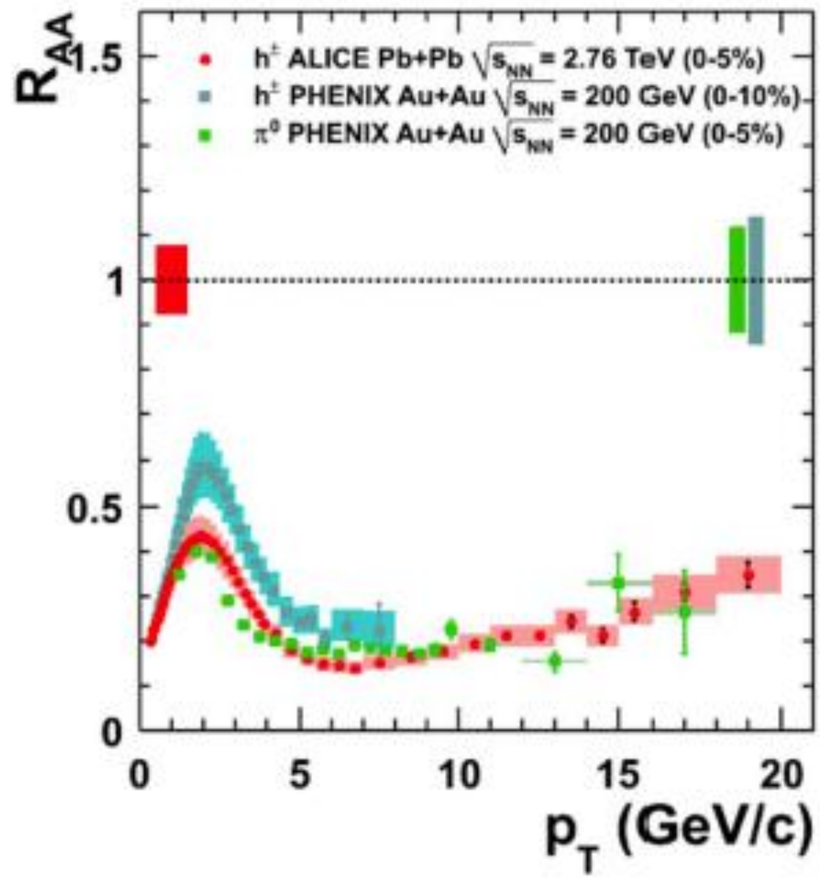


- 62.4 and 200 GeV data shows strong suppresion even in more peripheral collisions
- 39 GeV is only suppressed at higher centralities
- No significant difference between 62.4 and 200 GeV data points if $p_T > 6\ \mathrm{GeV}/c$

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?

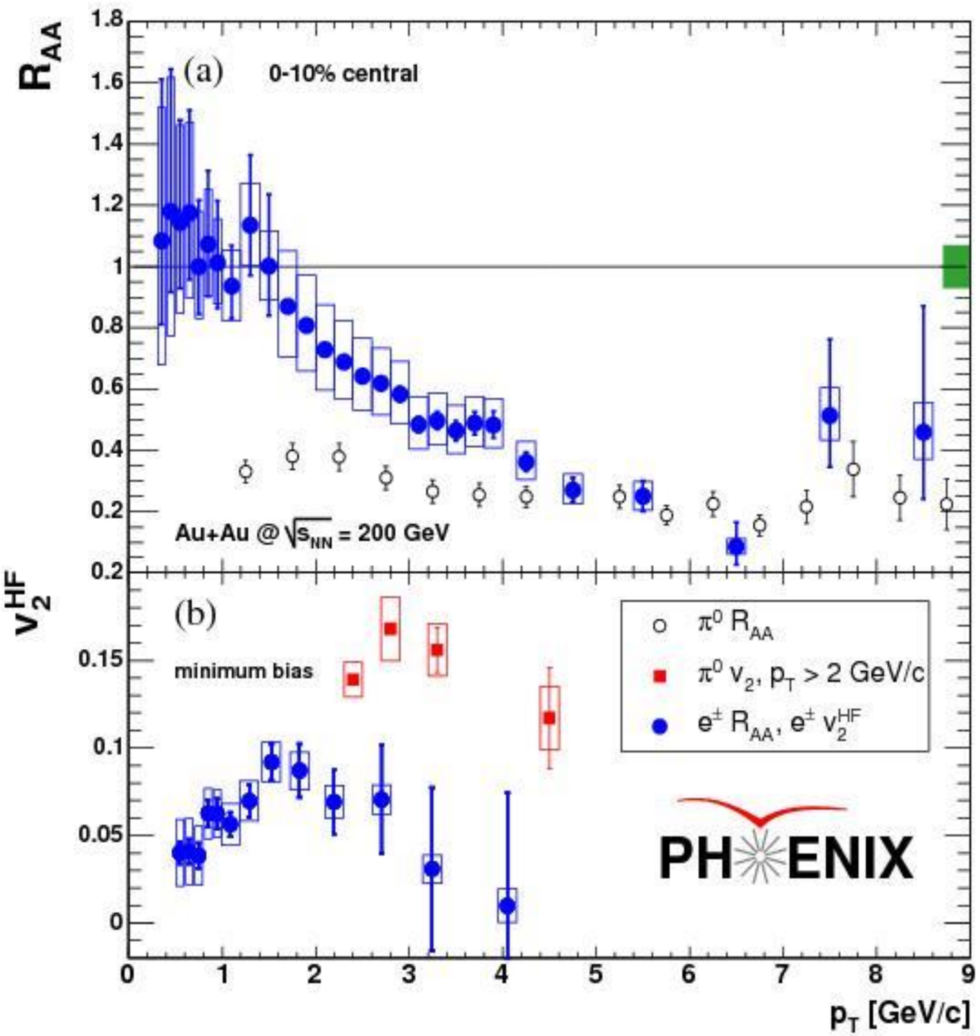




Suppression very similar for RHIC and the LHC.

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

Please look at RAA plot.



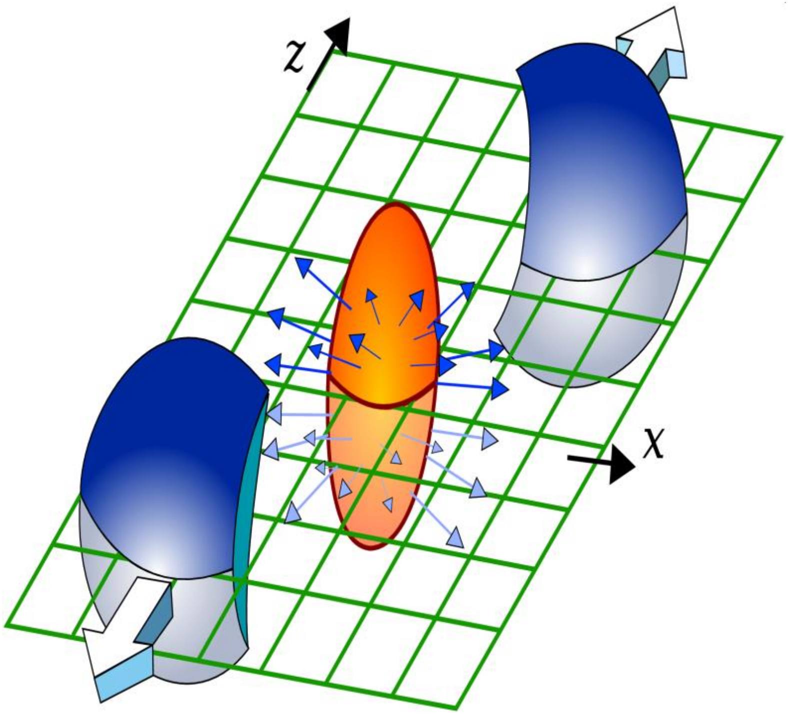
c and b quarks also stopped in QGP.

Note measured electrons from decay of open charm and beauty

Conclusions

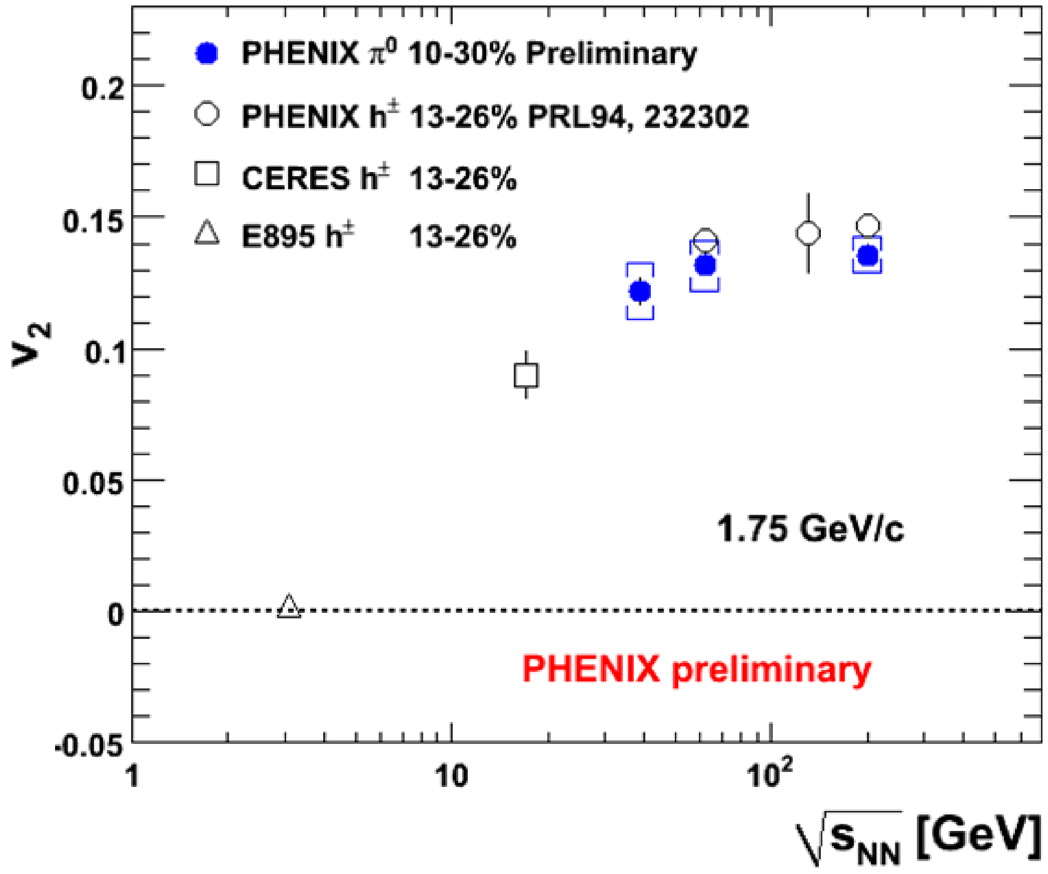
A. In heavy ion collisions we have created a color-opaque medium.
B. Suppression of particles by the medium is prominent for collision energies down to 39 GeV/A.
C. The level of suppression at the much higher energy densities of the LHC is very similar to that at RHIC.
D. The level of suppression is still very significant for the heavy c and b quarks.

Particle Anisotropy and Flow



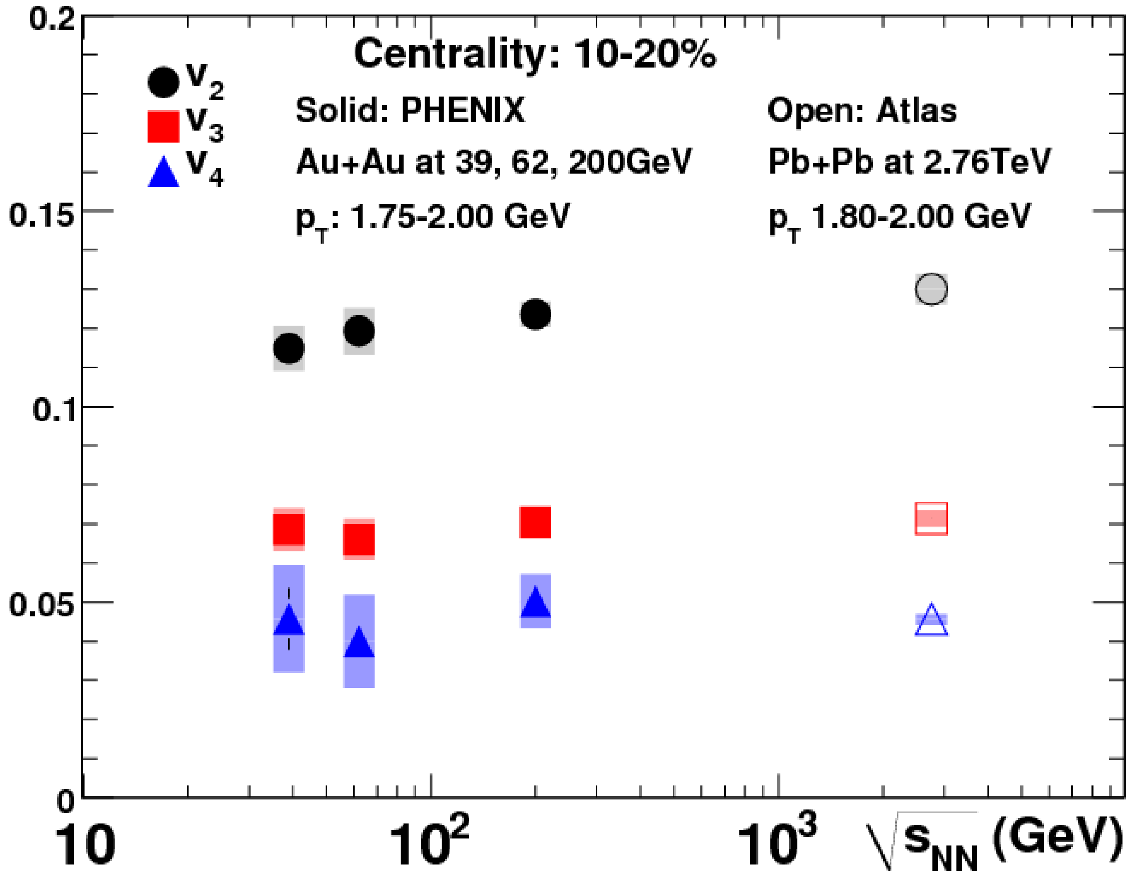
A. It was observed that when two heavy ions collided the hot matter flowed.
B. The colliding region is almond shaped due to the overlap of the colliding nuclei.
C. The regions of high density in the center exert a greater pressure resulting in the expansion of an elliptically shaped region (elliptic flow).
D. The particle angular distribution can be described as:
$dN/d(\phi) \sim 1+2v_2\cos(2\phi)$
E. For a spherically symmetric distribution v_2 is 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 reaches 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.

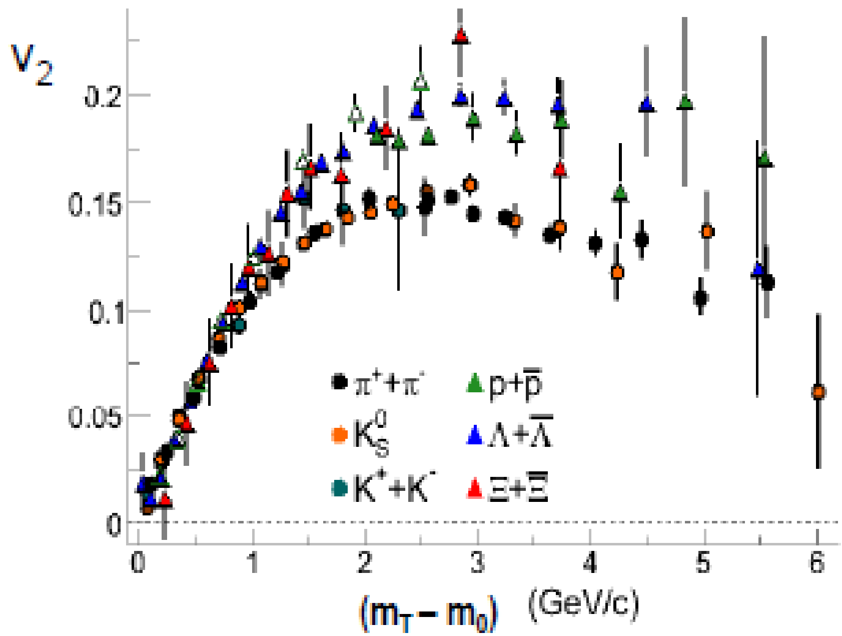
Does v_2 still saturate at high energy densities at LHC?

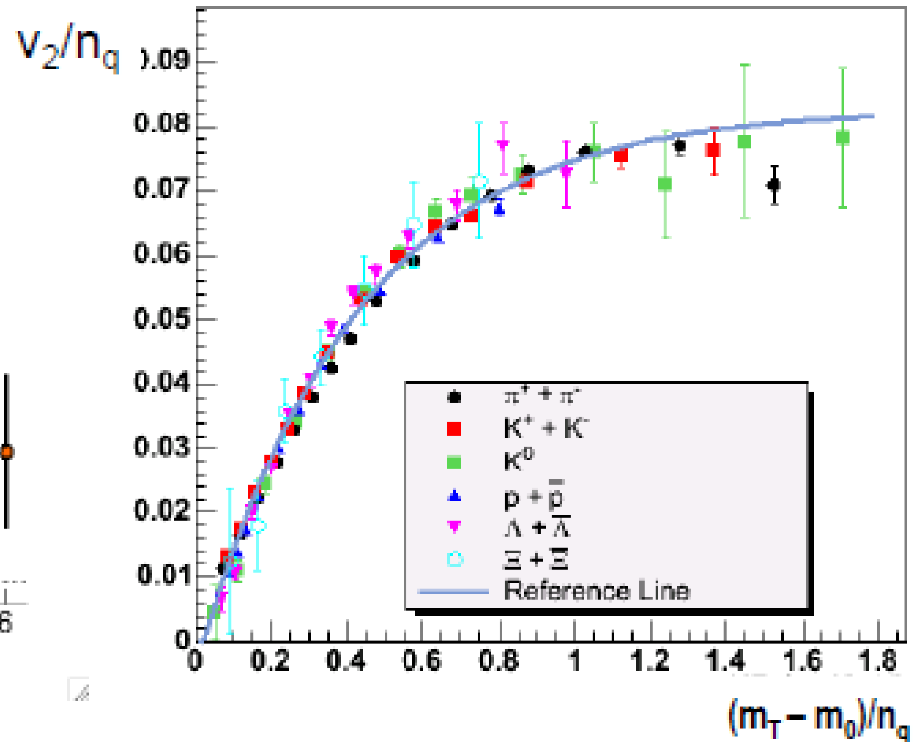


Seems fluid at LHC very similar to that at RHIC.

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

How does elliptic flow scale?



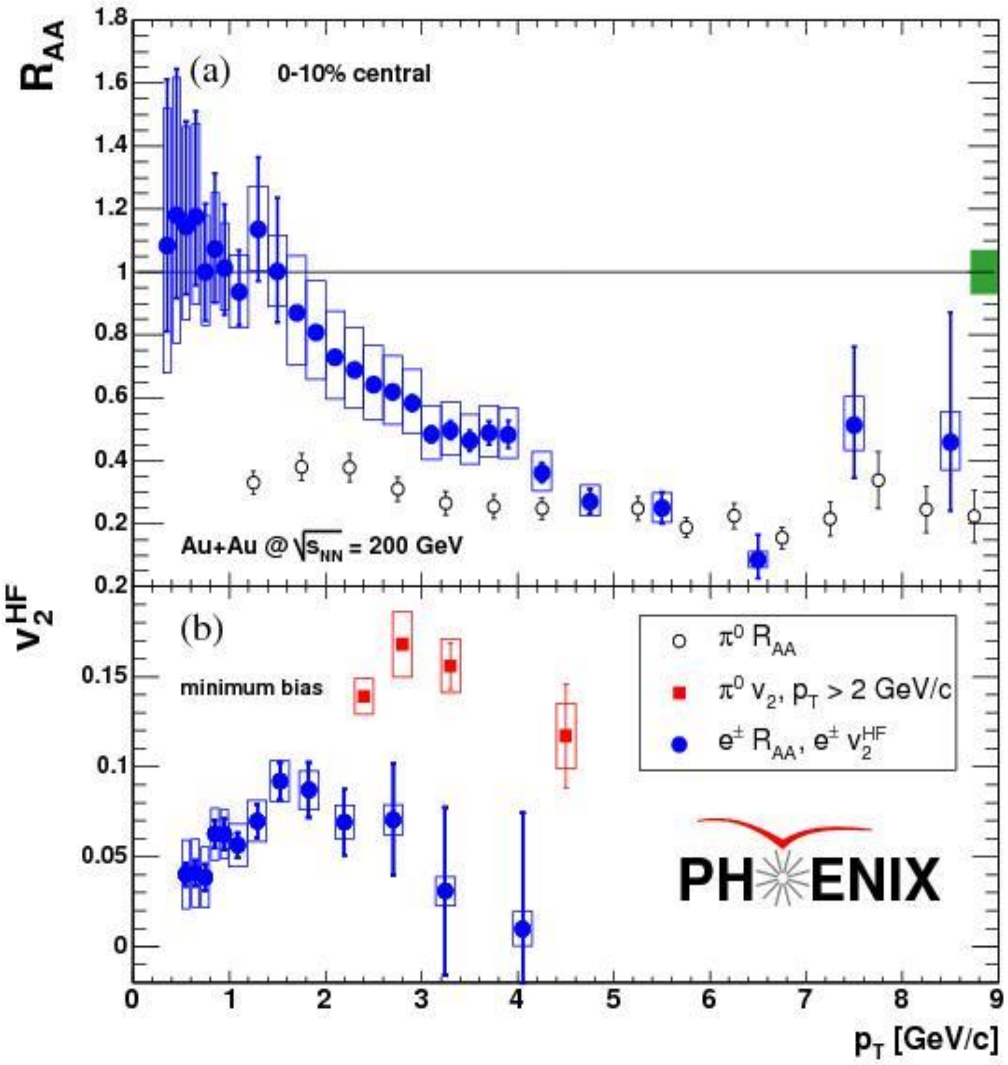


Fluid→QuasiParticles→Hadrons

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.

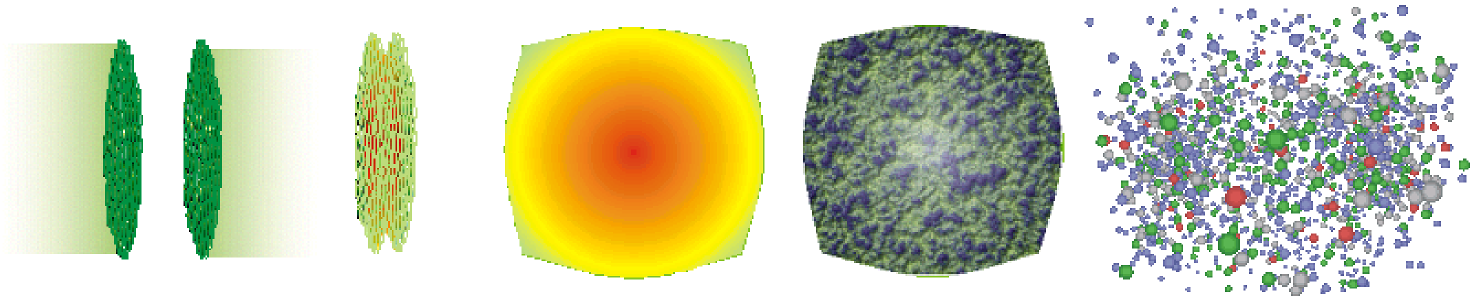
Do heavy c and b quarks also flow?

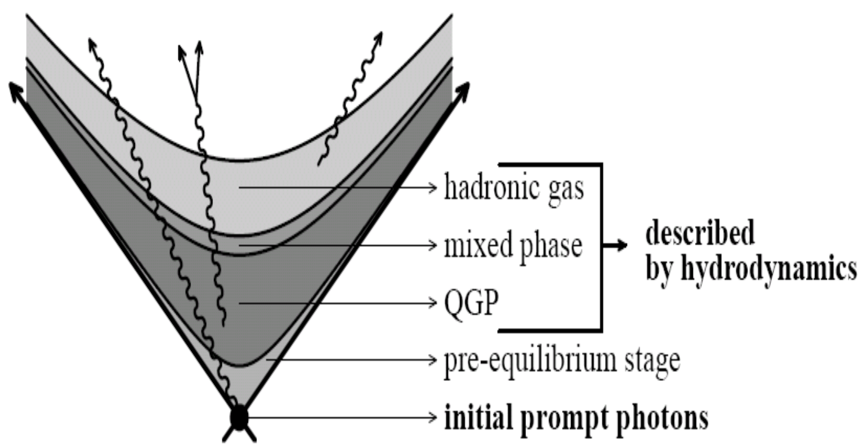
Please look at v(2) plot.



Heavy quarks flow but less strongly than light quarks.

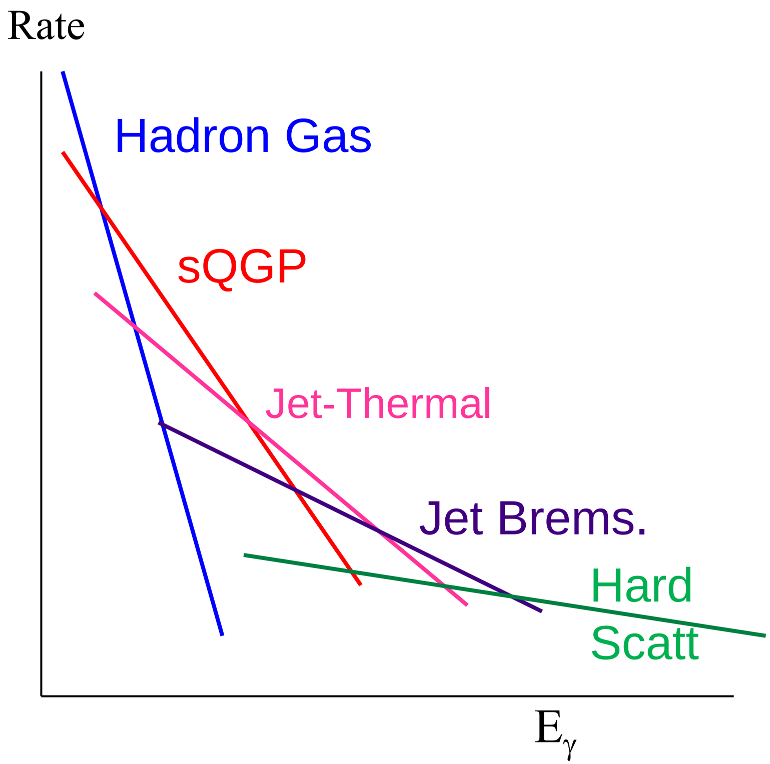
What is the Temperature of the Quark Gluon Plasma?

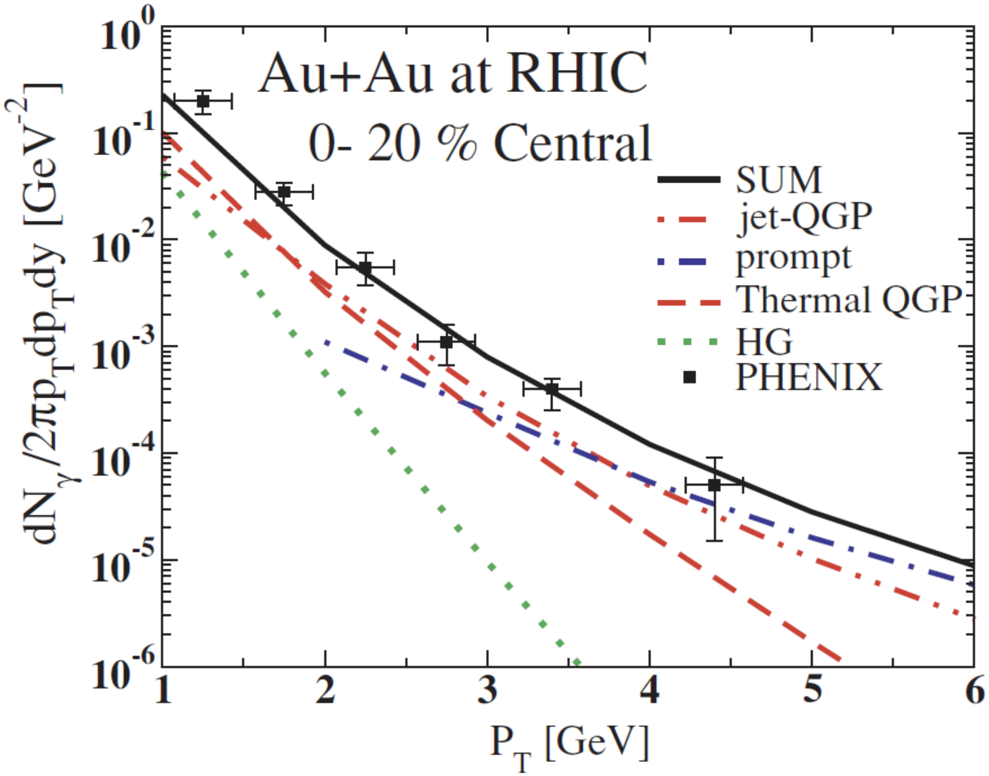




Schematically

Calculated

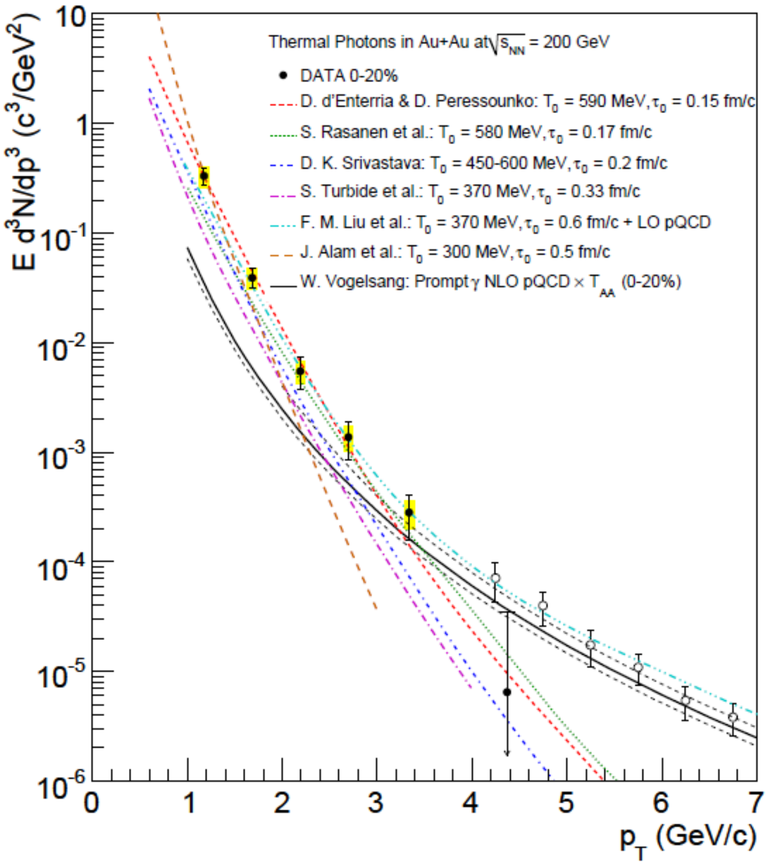




van Hees, Gale, Rapp, PRC84, 054906 (2011)

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

PHENIX Phys. Rev. C 81 (2010) 034911



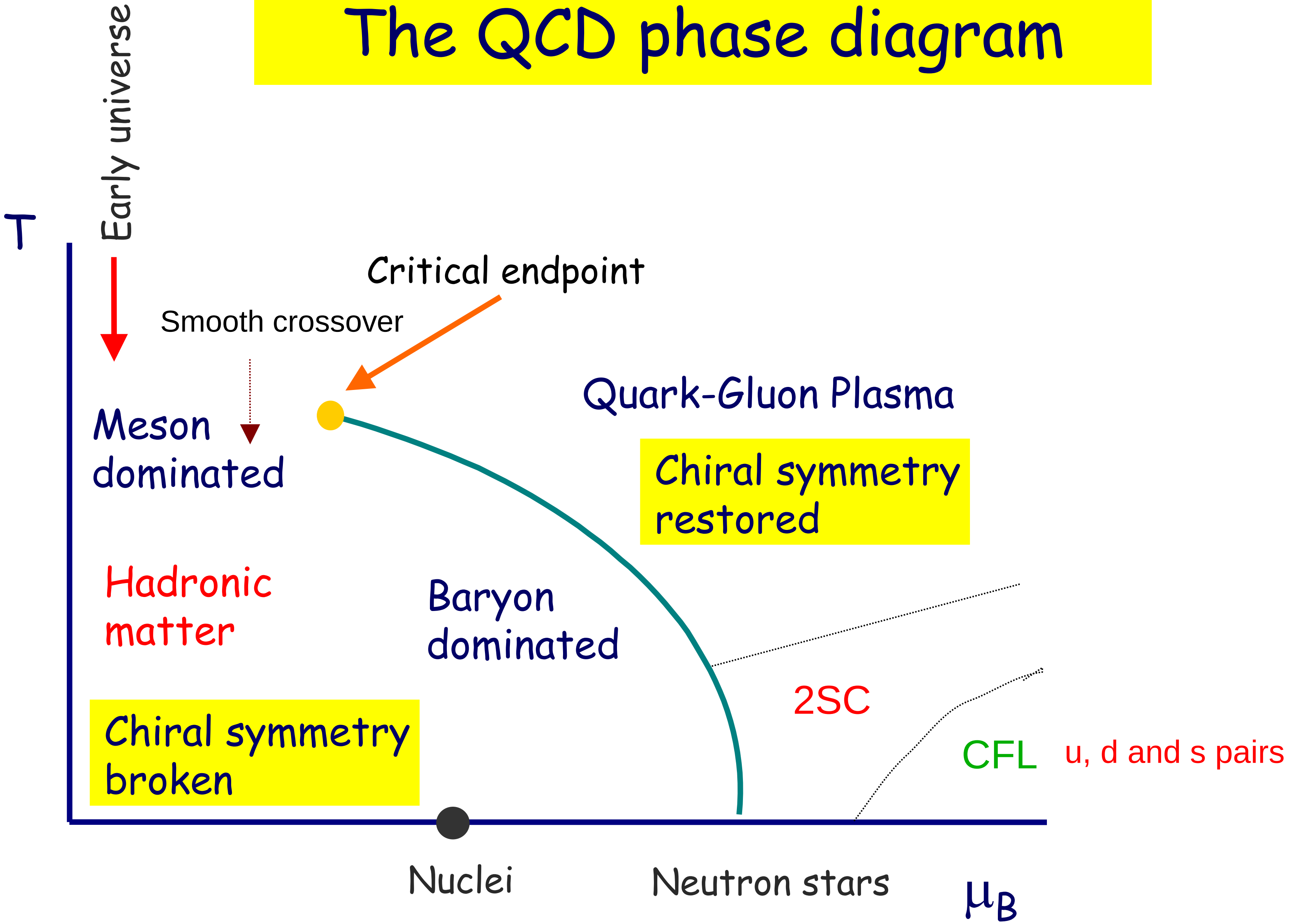
PHENIX measured dilepton production for 200 GeV/A Au and p.

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.

The QCD phase diagram



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

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.

Does the QGP contain quasiparticles or does the strong coupling eliminate long-lived collective excitations?

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?

Summary and Conclusions

A. Using 200 GeV/A Au beams at RHIC and 2.76 TeV/A Pb beams at LHC a new state of matter called the Quark-Gluon Plasma (QGP) was created.
B. The result was a very strongly interacting low viscosity liquid that was designated sQGP.
C. Even the very heavy c and b quarks were stopped in the sQGP.
D. At RHIC the temperature of the sQGP was induced to be in the range of 300-600 Mev well above the supposed limit of 170 Mev for plasma formation.
E. At RHIC and LHC energies the transition from sQGP to hot hadronic matter is continuous rather that through an abrupt phase transition.
F. The sQGP produced at the LHC has a much higher energy density but its properties are very similar to the plasma produced at RHIC.

For James Vary

So its been almost 40 years since you and I both came to Iowa State in 1975.

Over these many years I have valued you both as a colleague and especially as a friend.

Happy 70^{th} birthday!!!

John