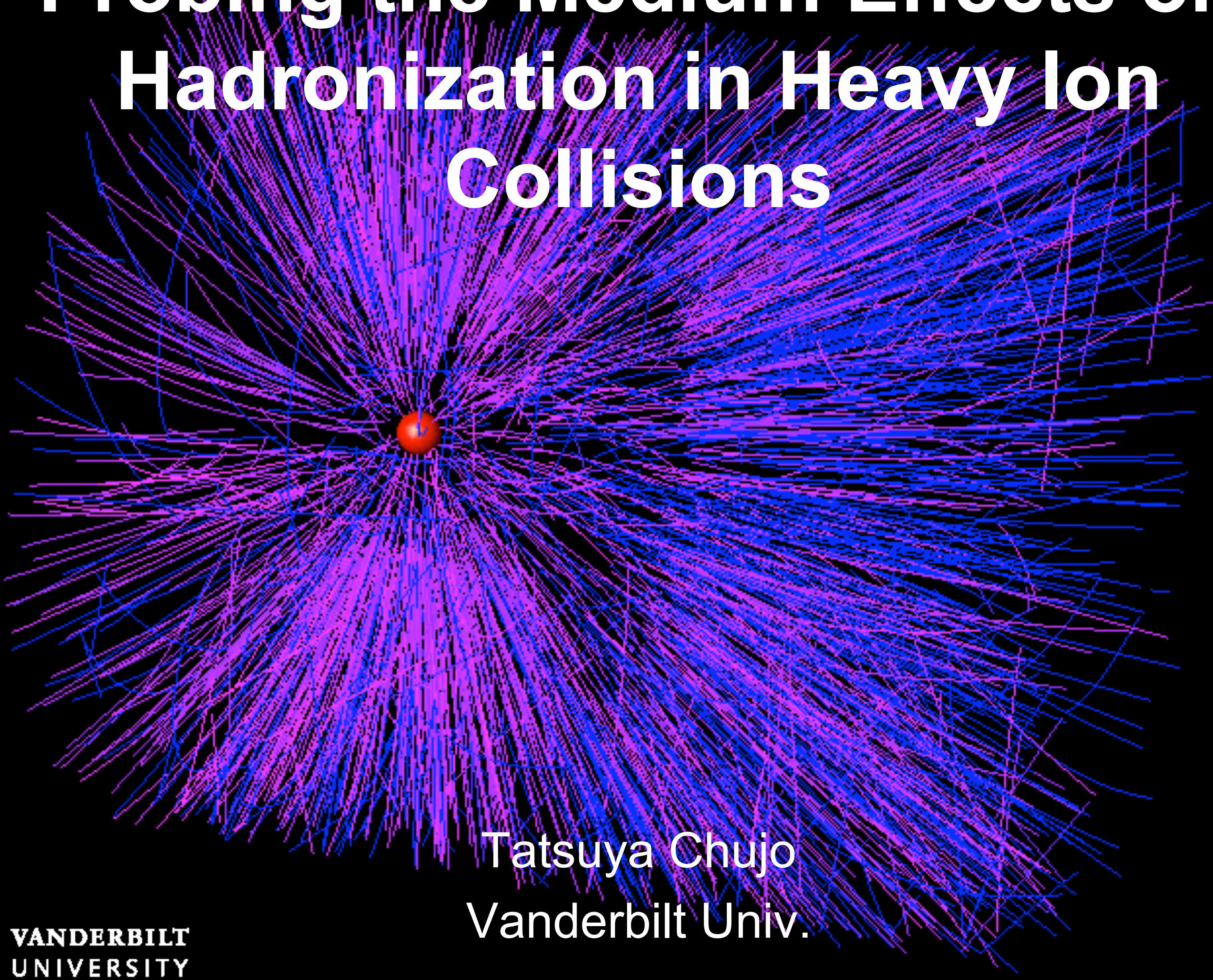
Probing the Medium Effects on Hadronization in Heavy Ion Collisions



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The Top Ten Reasons Why “RHIC” Is Important

From BNL/BSA Online Classroom
(Courtesy of Jeffery Mitchell)

10. To create and study a new state of matter called the Quark-Gluon Plasma.
9. To study the basic building blocks of matter.
8. To study the conditions of the early universe in the laboratory.
7. To study where the proton gets its spin.

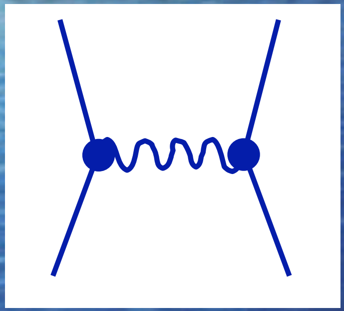
<skip> ….

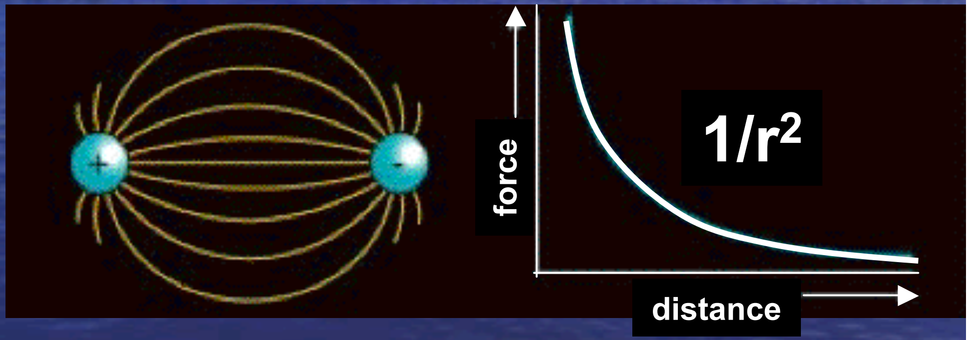
2. To expand our knowledge and open new horizons.
1. It's cool!

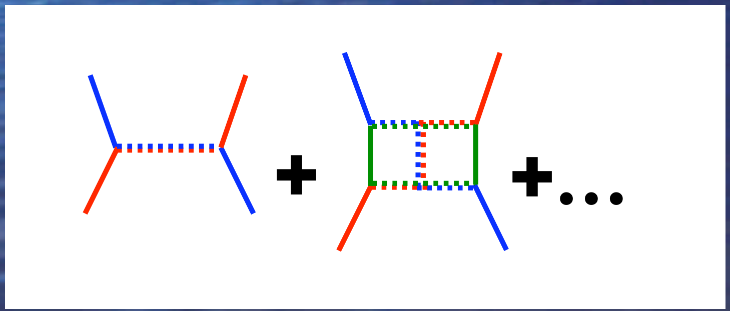
Understanding the Fundamental Nature of Quarks and Gluons
(QCD matter at high temperature and density)

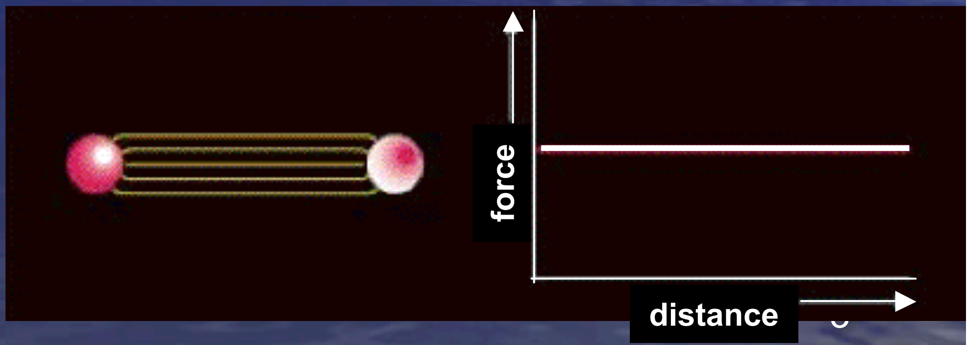
QED vs. QCD (Quantum Chromodynamics)

- QED (Abelian):
  - Photons do not carry charge
  - Flux is not confined $\Rightarrow$ 1/r potential $\Rightarrow$ $1/r^2$ force
- QCD (Non-Abelian):
  - Gluons carry charge (red, green, blue) $\otimes$ (anti-red, anti-green, anti-blue)
  - Flux tubes form $\Rightarrow$ potential ~ r $\Rightarrow$ constant force
  - confinement of quarks in hadrons



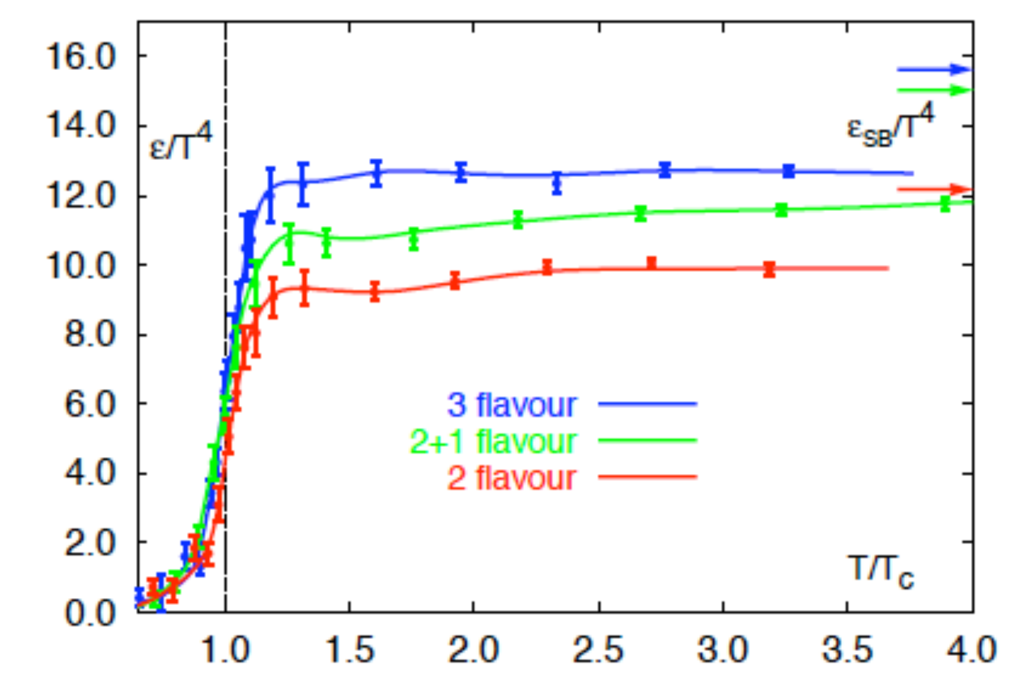






Quark Gluon Plasma (QGP)

Lattice QCD Calculations
F. Karsch, Lect. Notes Phys. 583 (2002)



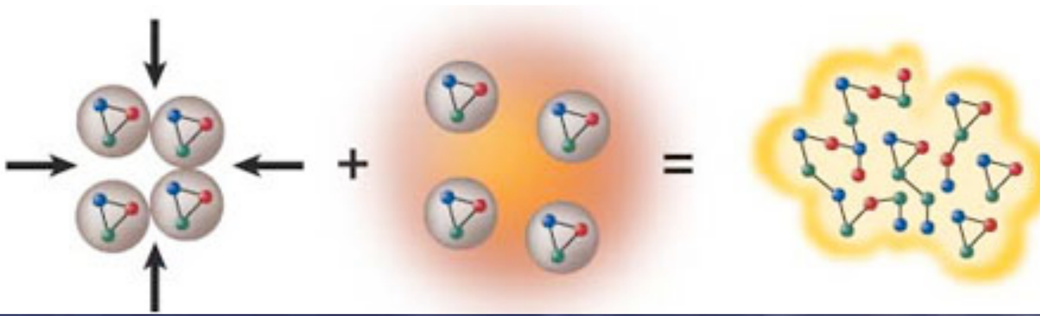
QGP phase Degrees of Freedom

8 gluons, 2 spins;
2 quark flavors, anti-quarks,
2 spins, 3 colors

g = 37! (2 flavor)

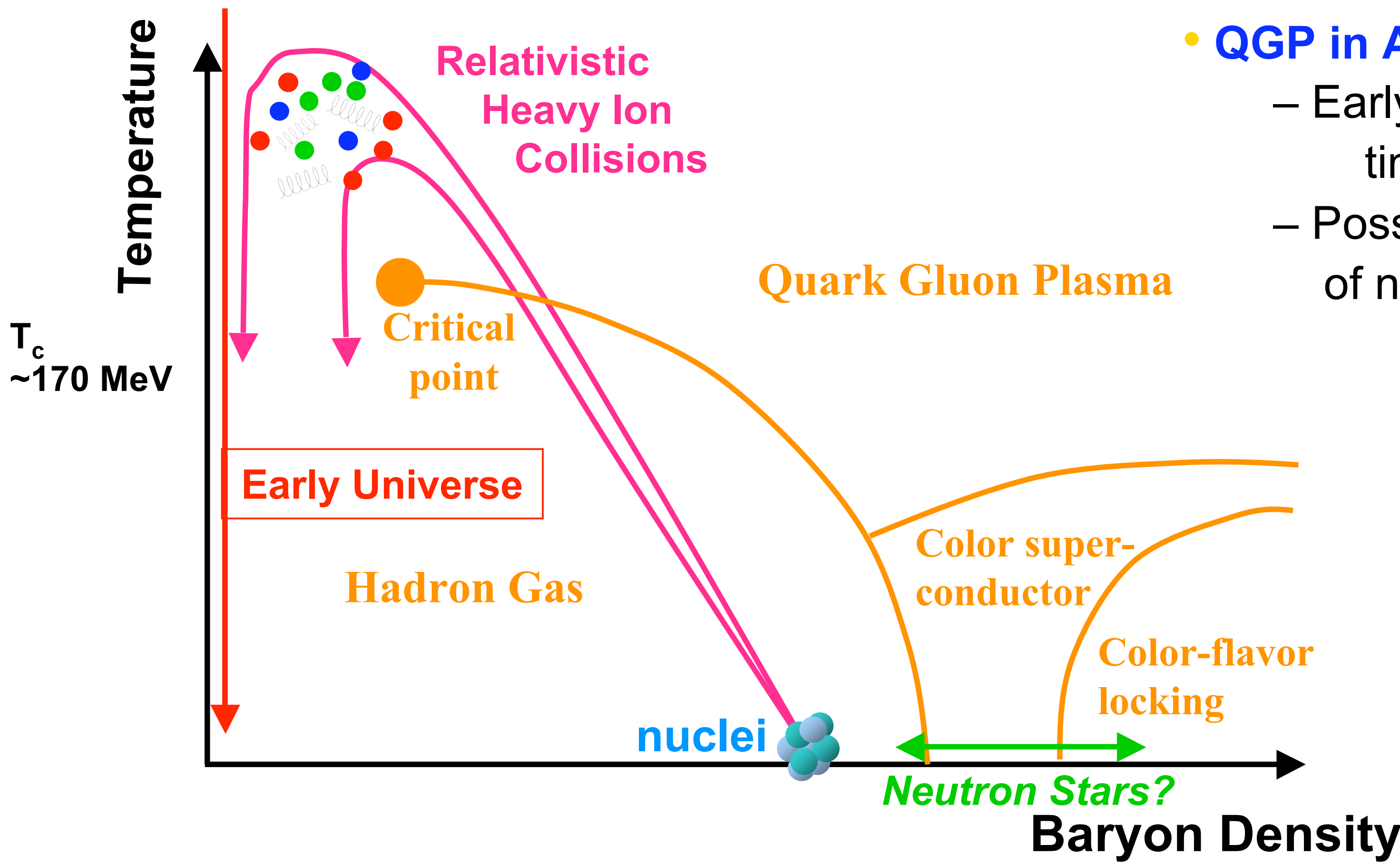
$$\varepsilon = g\frac{\pi^2}{30}T^4 = 37\cdot\frac{\pi^2}{30}T^4 \approx 12T^4$$

$$\approx 12\cdot\left(\frac{\hbar}{1\ fm}\right)^4 \approx 2.4\ \text{GeV}/\text{fm}^3$$



*** Normal Nucleus:**
$\varepsilon \sim 0.2$ GeV/fm^3, $\rho \sim 0.16$ /fm^3

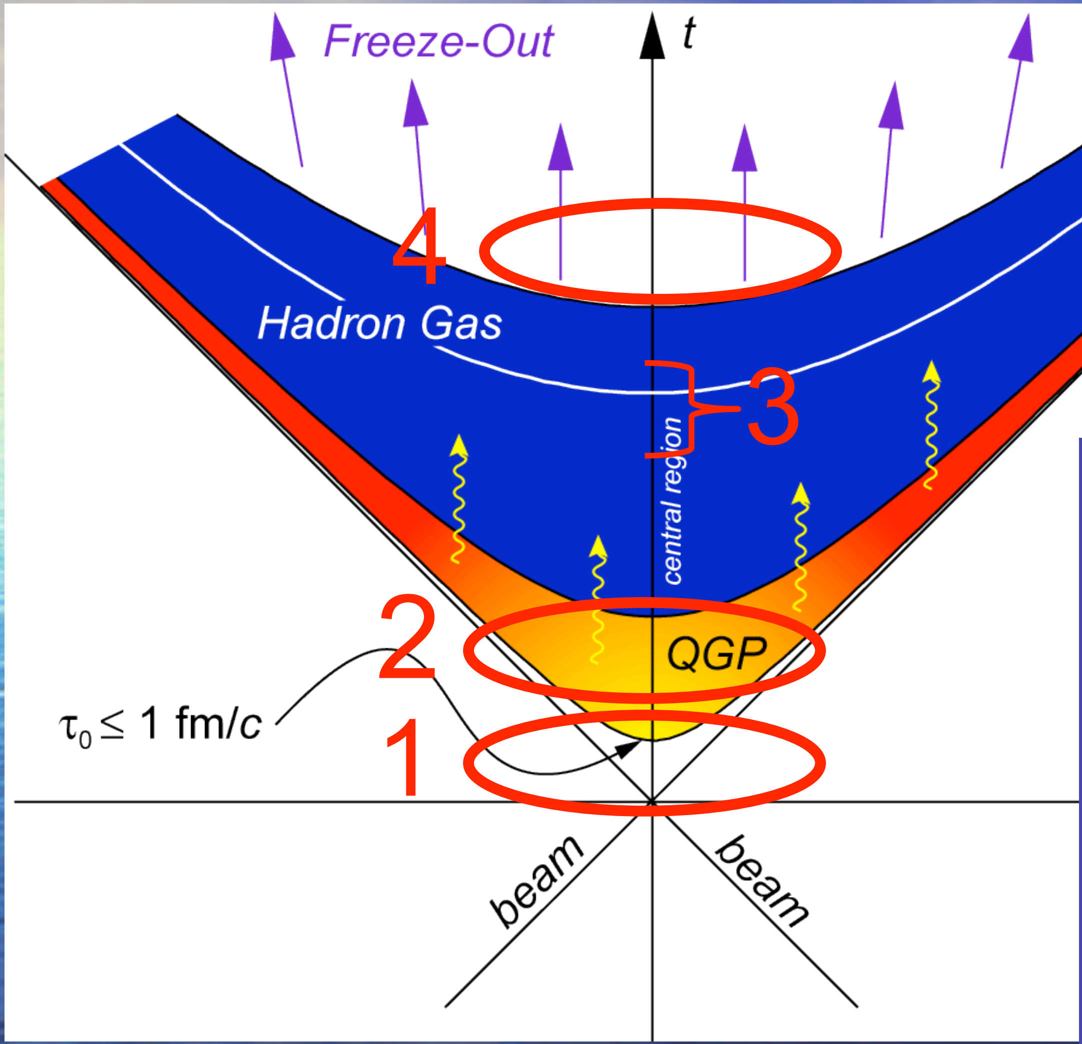
Phase Diagram of Nuclear Matter

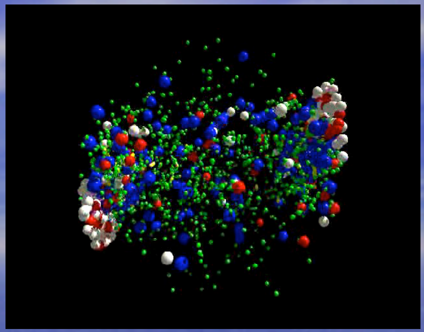


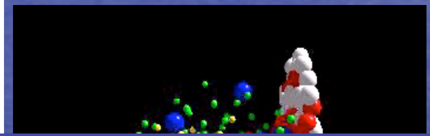
- **QGP in Astrophysics**
  - Early universe: time $< 10^{-6}$ seconds
  - Possibly in the interior of neutron stars

- **QGP in Nuclear Physics**
  - Create at the lab. by heavy ion collisions
  - Study the nature of QCD matter at the extreme temperature and energy density

Space-Time Evolution of System

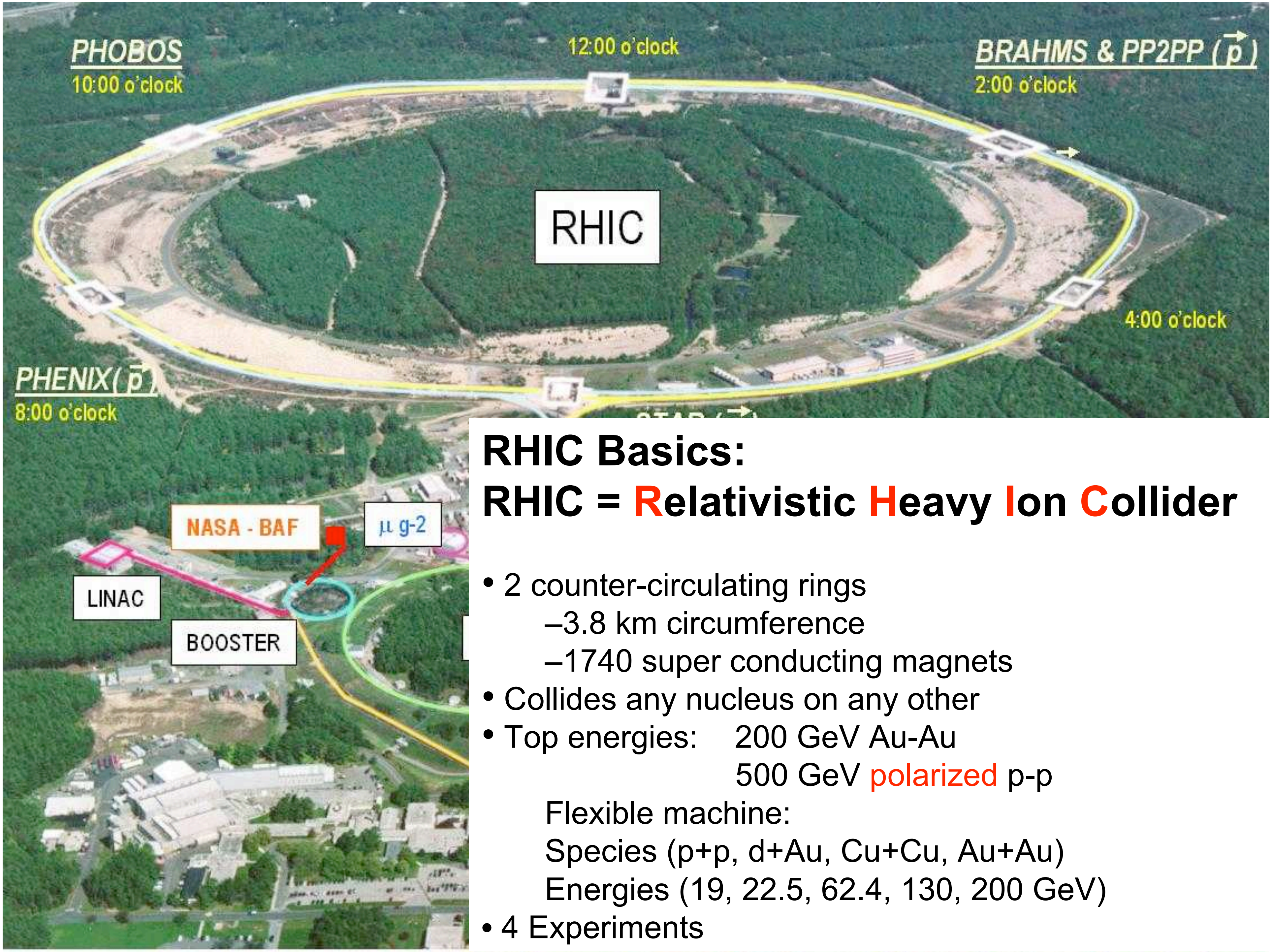






1. Hard scattering
2. Thermalization and QGP
3. Particle abundances fixed
4. Particle freeze out
   (elastic Interactions cease)

- Photon: does not interact with matter strongly (penetrating probe)
- Hadrons: interact strongly (medium effect)



RHIC Basics:
RHIC = Relativistic Heavy Ion Collider

- 2 counter-circulating rings
  - –3.8 km circumference
  - –1740 super conducting magnets
- Collides any nucleus on any other
- Top energies: 200 GeV Au-Au
  500 GeV polarized p-p
  Flexible machine:
  Species (p+p, d+Au, Cu+Cu, Au+Au)
  Energies (19, 22.5, 62.4, 130, 200 GeV)
- 4 Experiments


PHOBOS
BRAHMS
6:00 o'clock
PHENIX
STAR

Outline

- Is the energy density high enough?
  - Jets from hard scattering partons
- How is hadronization process modified by the created matter?
  - “Baryon Anomaly” at RHIC and quark recombination
- What are the bulk properties of the produced matter?
  - Elliptic flow and viscosity

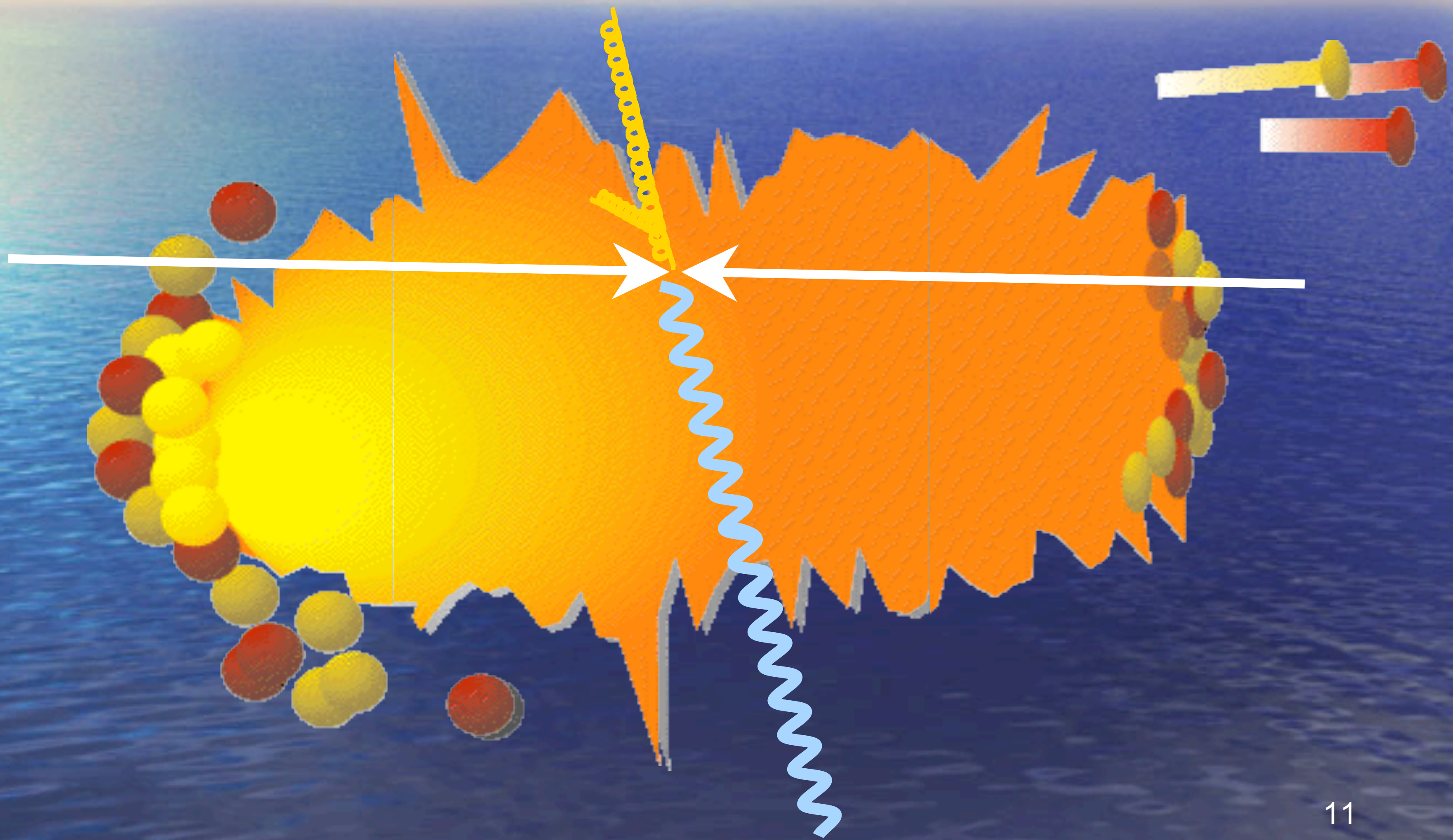
Hard processes

- Large momentum transfer at initial collision
- Can resolve partons: valence quarks, sea quarks and gluons
- Fragmentation from partons to hadrons
- Coupling is weak
  - perturbative QCD applicable
  - Theoretically “hard” is “easy”

- In Au+Au heavy ion collisions…
  - Scattered partons travel through dense matter
  - Partons loose their energy because of a large gluon density
  - Energy loss → suppression of high p_T (transverse momentum) leading particles

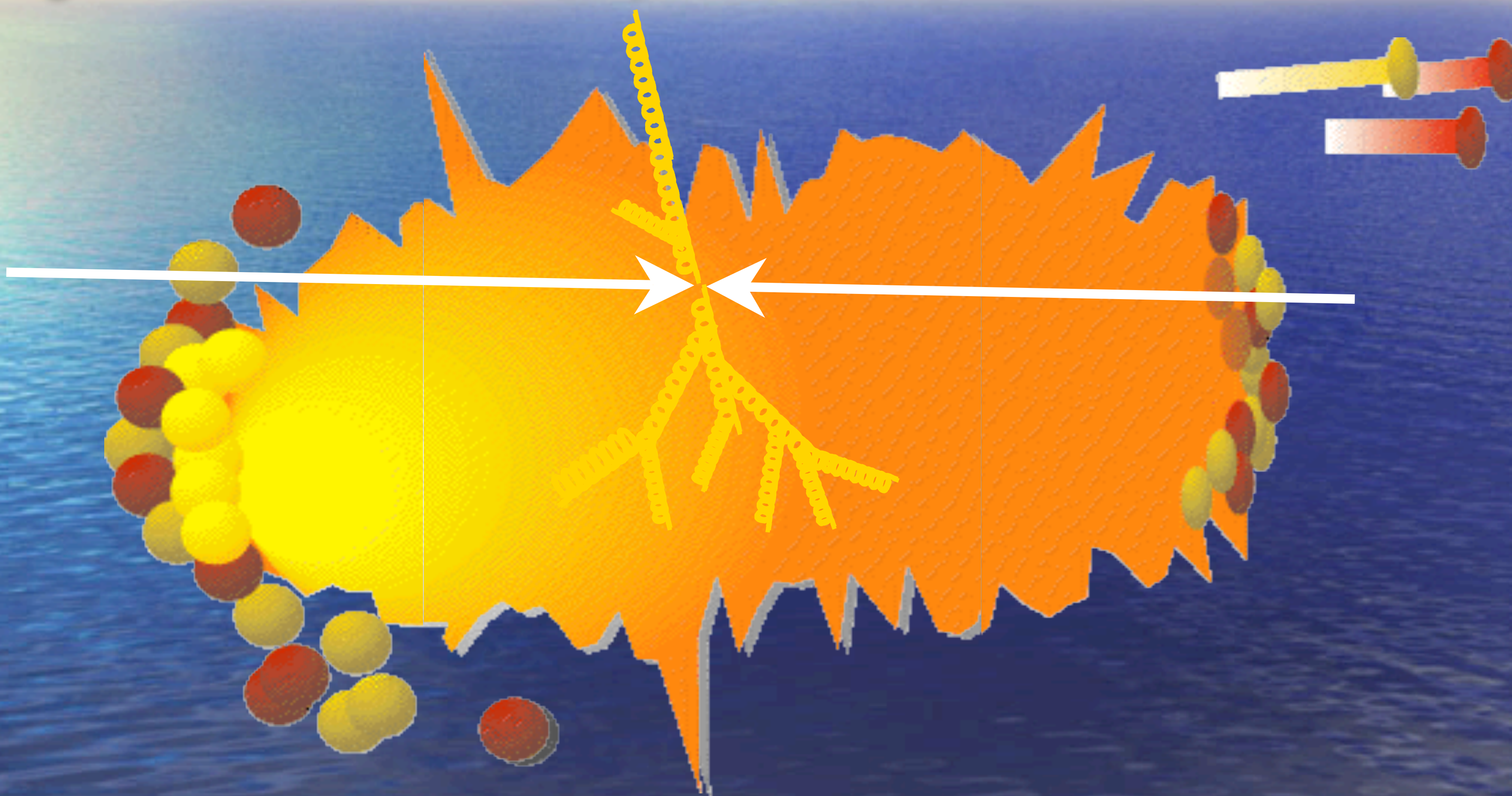
Probes of the Medium (I)

- Sometimes a high energy photon is created in the collision.
- We expect it to pass through the plasma without pause.



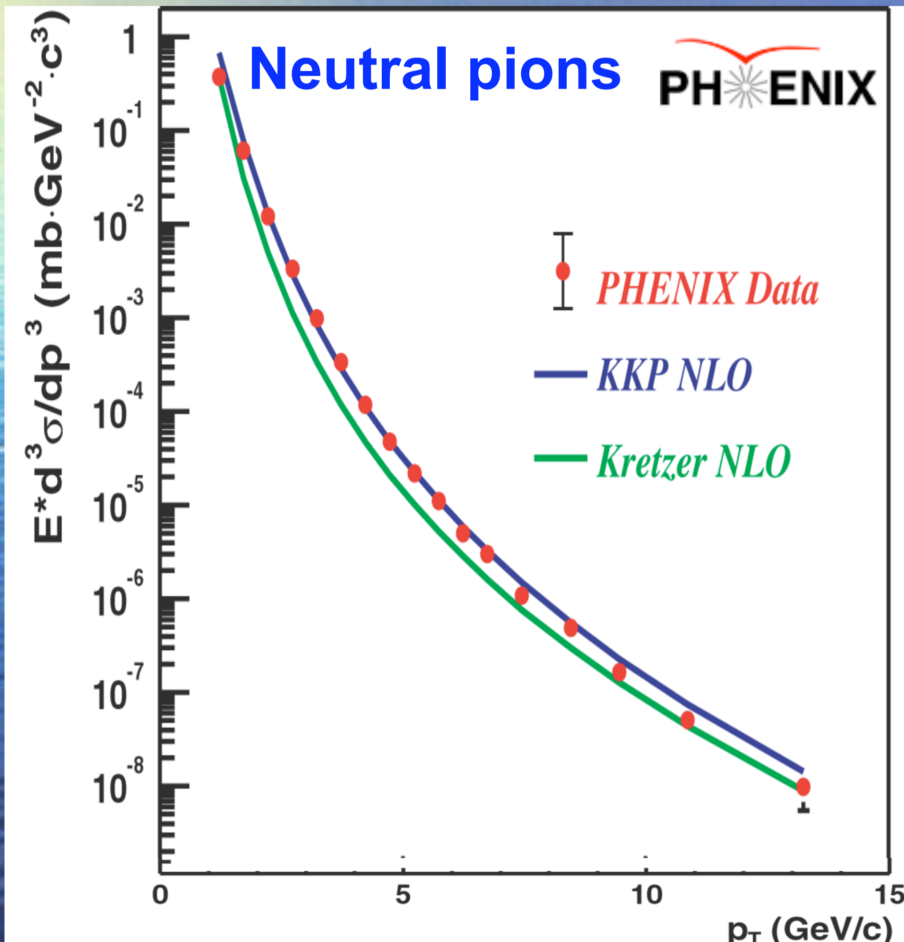
Probes of the Medium (II)

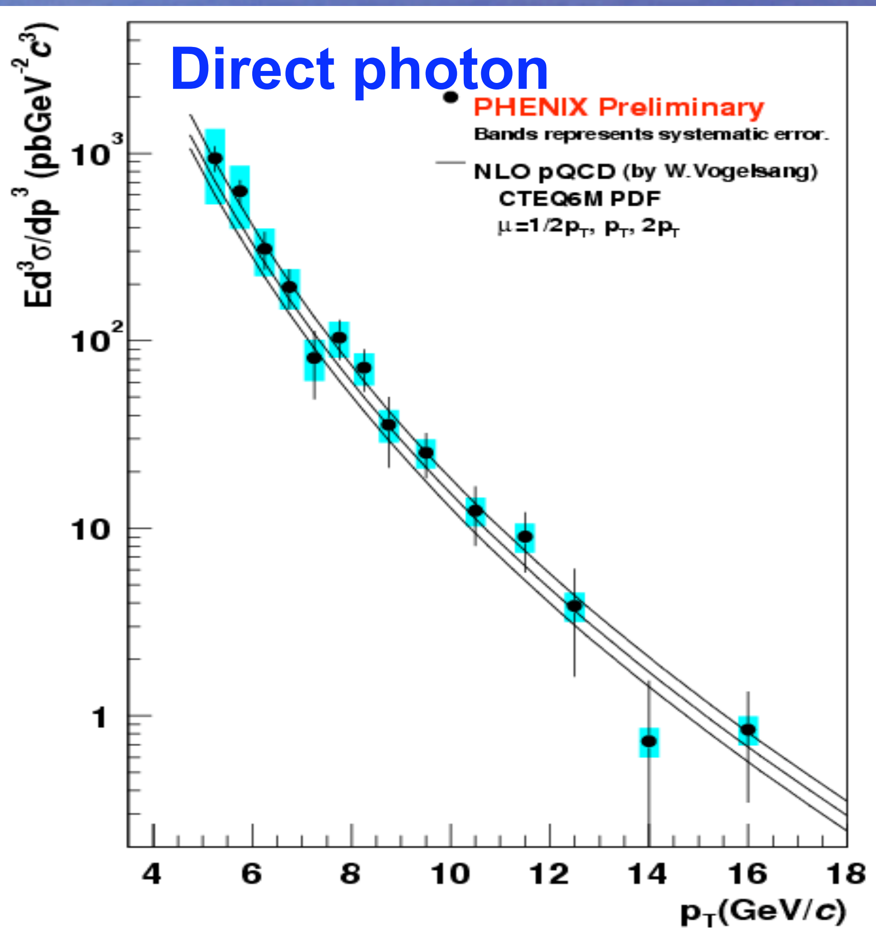
- Sometimes we produce a high energy quark or gluon.
- If the plasma is dense enough we expect the quark or gluon to be swallowed up.



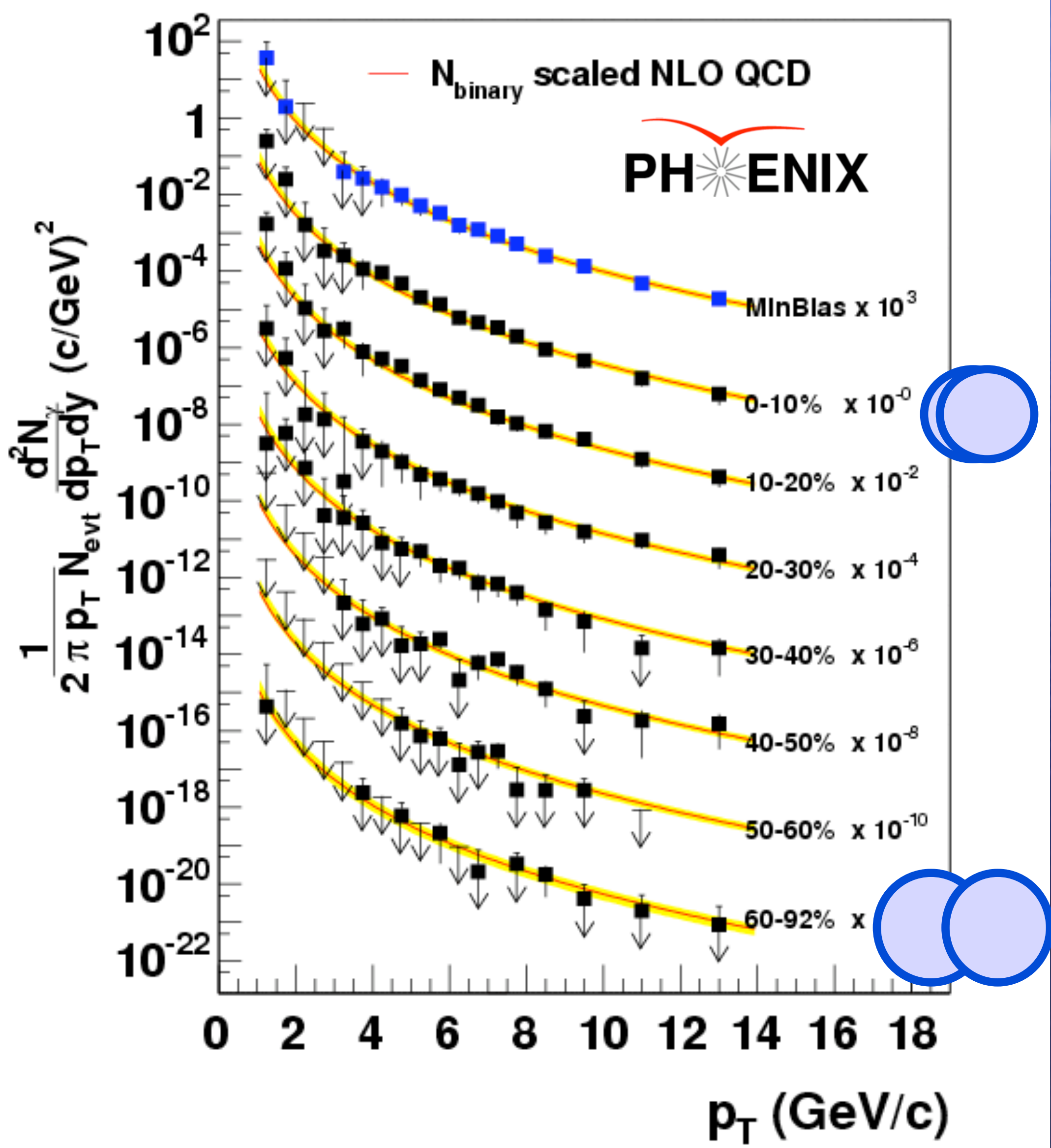
pQCD Calibrated Probes (p+p)

- Baseline measurements in p+p collisions at RHIC
  - Calibrated probes
  - Supported by well-established theory (perturbative QCD)



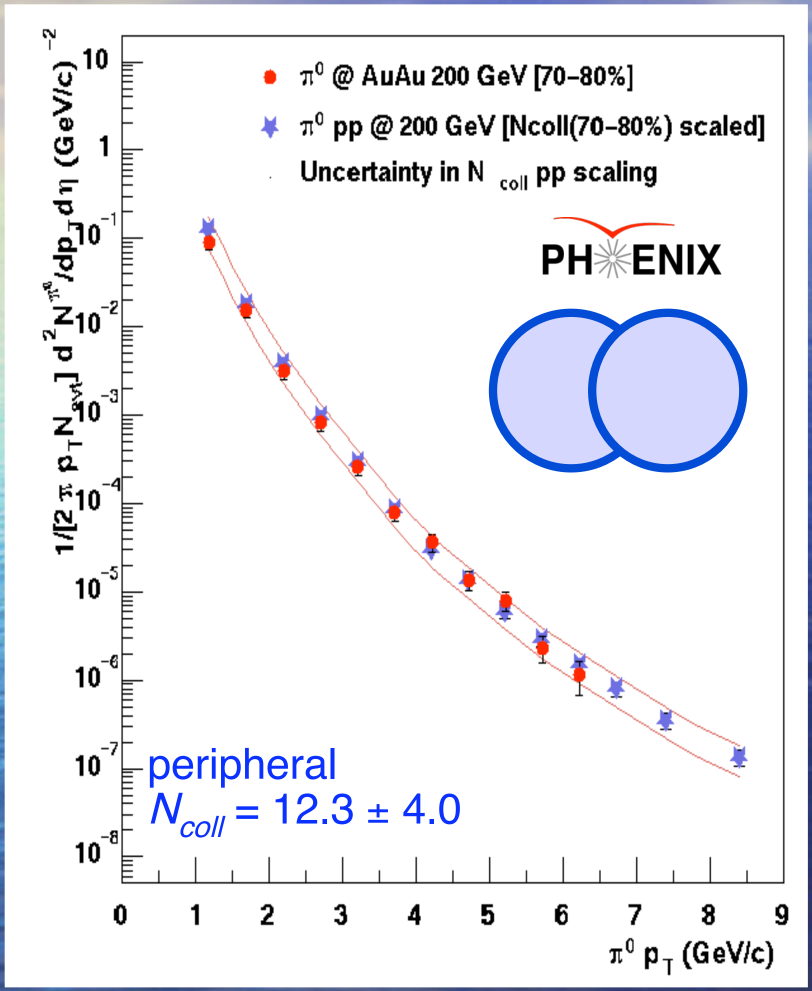


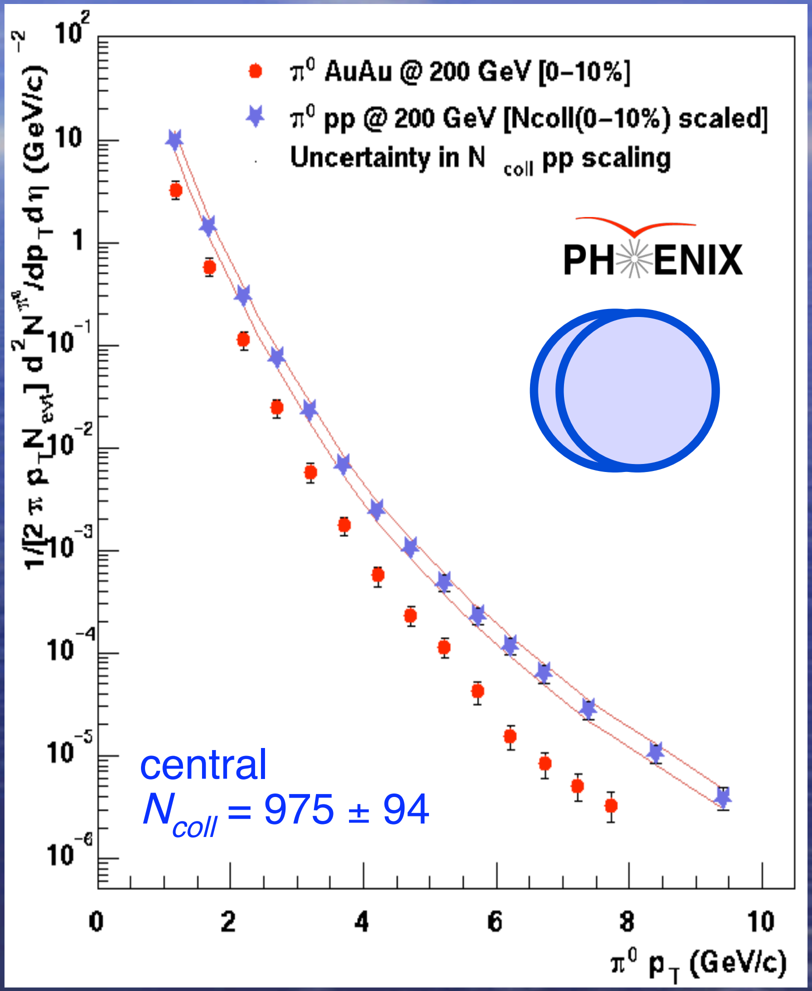
Direct Photon Spectra in Au+Au



- Now have a calibrated probe (good agreement of data and theory)
- That works in the complex environment of two nuclei (Au+Au) colliding at high energies

Discovery of Strong Suppression (Au+Au)





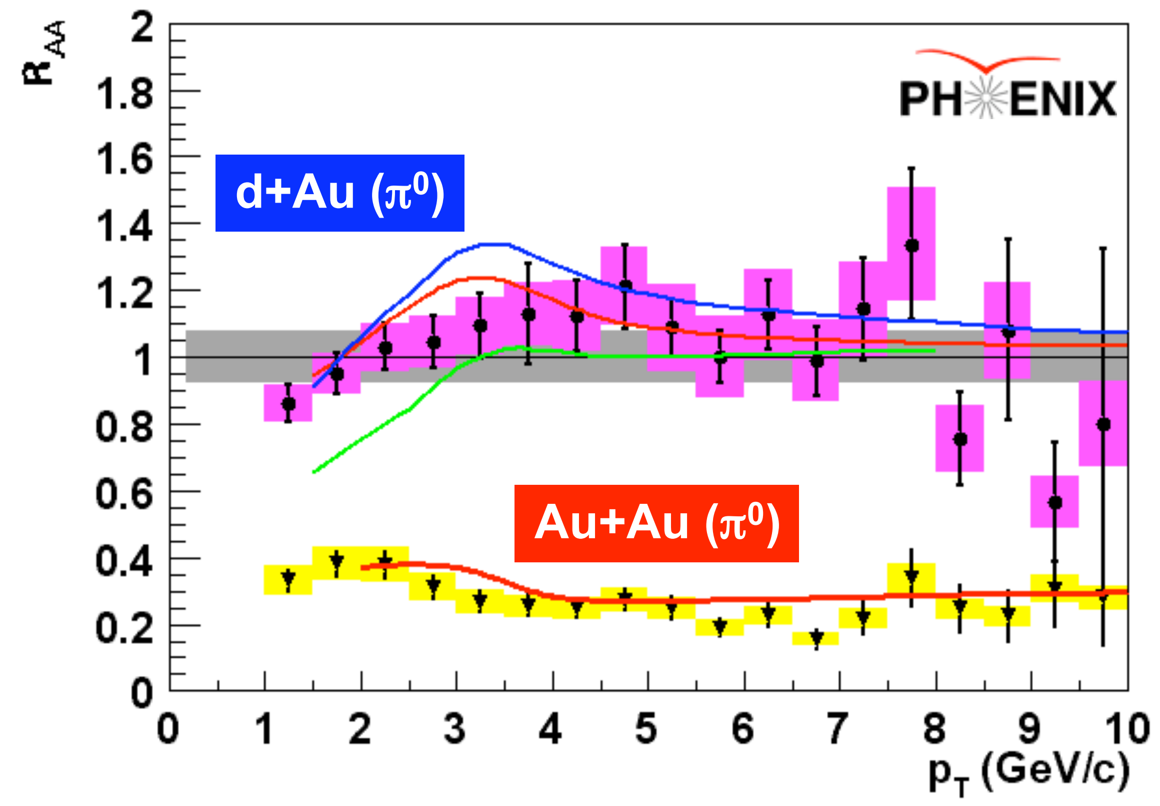
***Scaling of calibrated probe* works in peripheral Au+Au, but *strong suppression* in central Au+Au**

Determination of the Energy Density

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$

~ Survival Probability in medium



- To reproduce data by "Jet quenching" parton energy loss model:
  - Gluon density:

    $dN_g/dy \sim 1100$
  - Energy density:

    $\varepsilon > 100\ \varepsilon_0$ (!)

    ($= \varepsilon > 15$ GeV / fm^3)

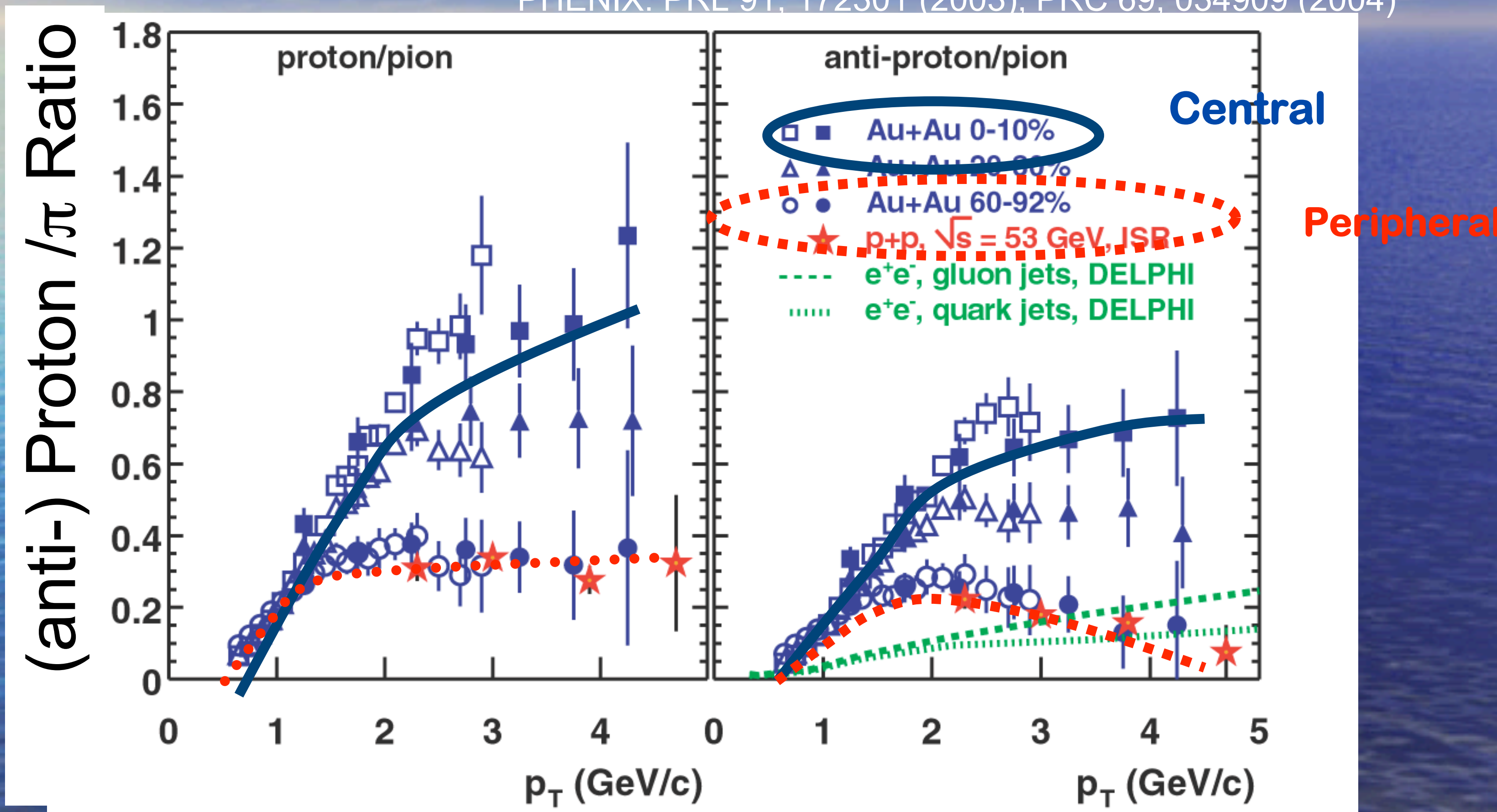
Theoretical predictions:

I.Vitev, nucl-th/0302002; I. Vitev and M. Gyulassy, hep-ph/0208108; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

Baryon Anomaly at RHIC

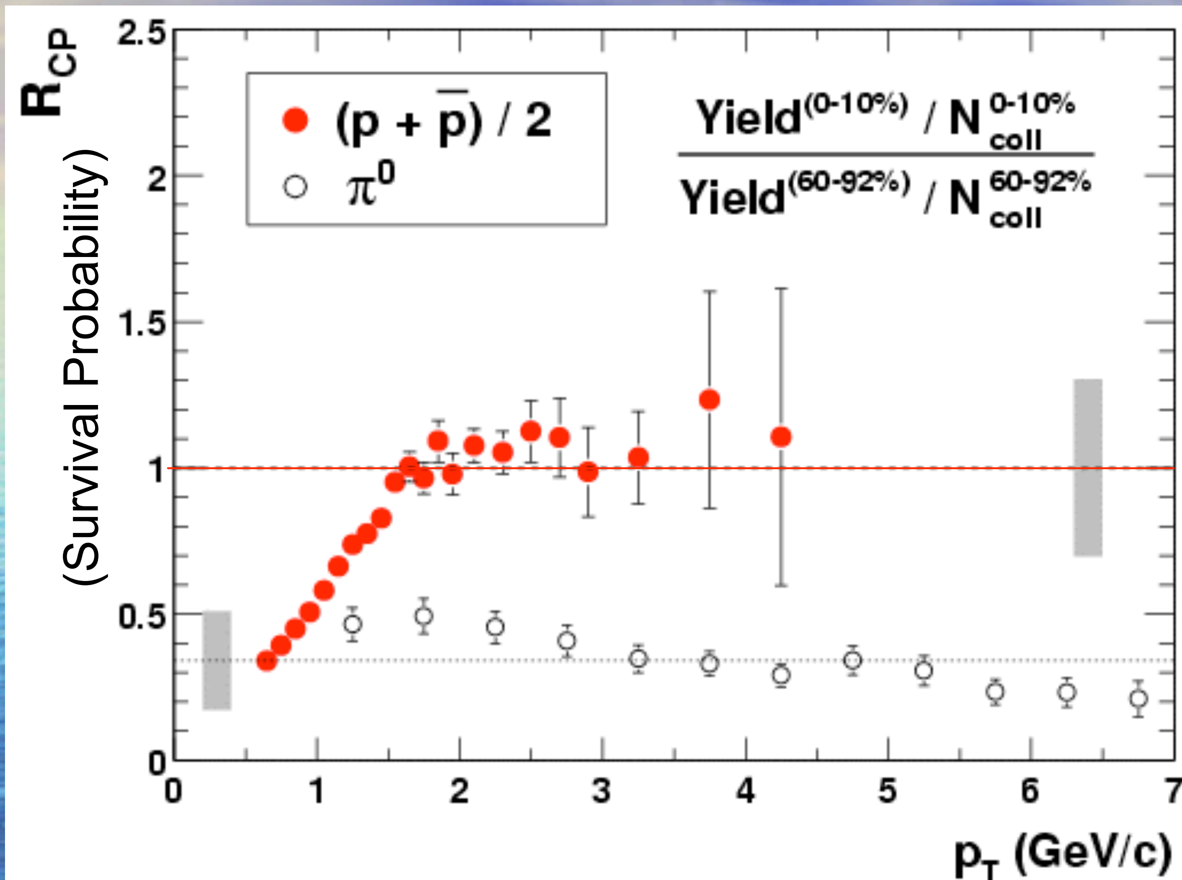
More (anti) baryons than pions at moderate p_T (2-5 GeV/c).
Does not look like vacuum jet fragmentation.

PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)



Factorization assumption of jet fragmentation completely breaks down.

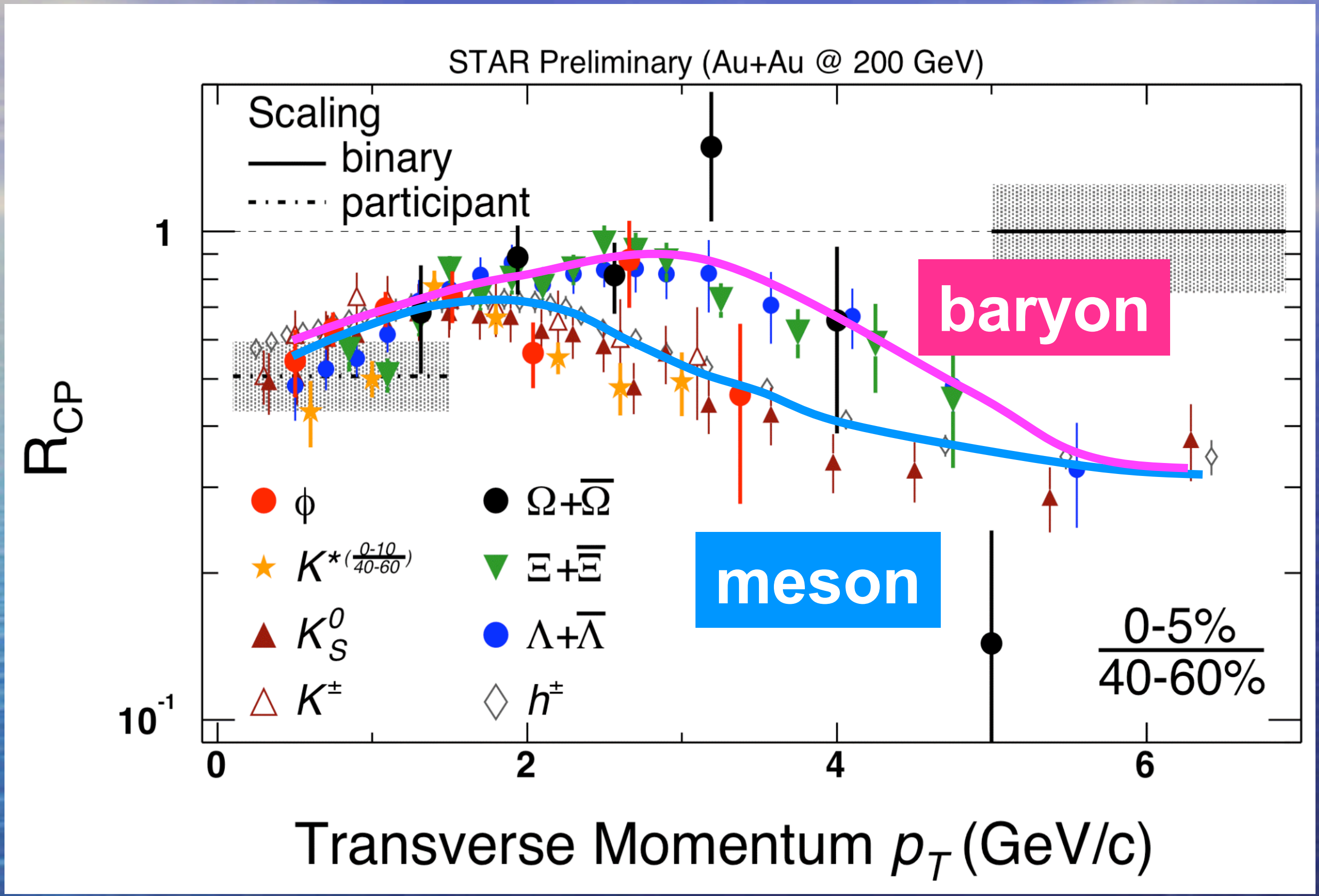
No suppression for protons



- $R_{CP} \sim R_{AA}$
- Shaded boxes : N_{part}, N_{coll} determination errors.

- p, pbar : No suppression at intermediate p_T (1.5 GeV - 4.5 GeV)
- Why. Is it due to strong radial flow or other mechanism?

Other hadrons?

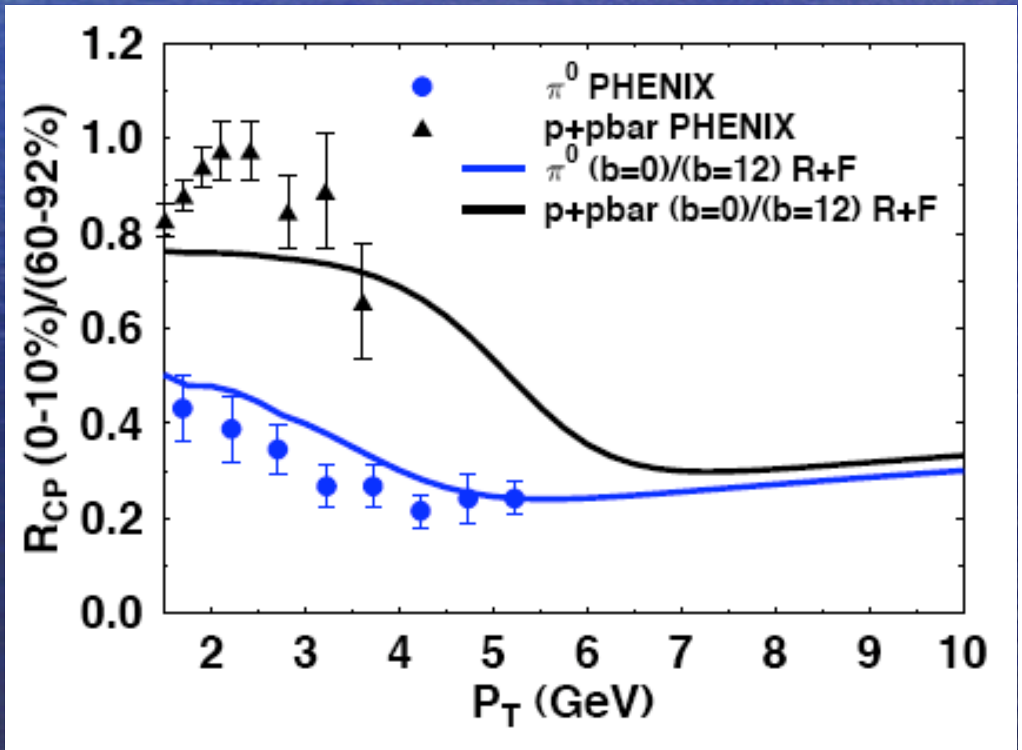


- The mesons and baryons form two distinct groups, independent of particle mass.
- Diverge at p_T ~ 2 GeV/c and come together at 5 GeV/c.
- Observed for first time at RHIC.

Quark Recombination

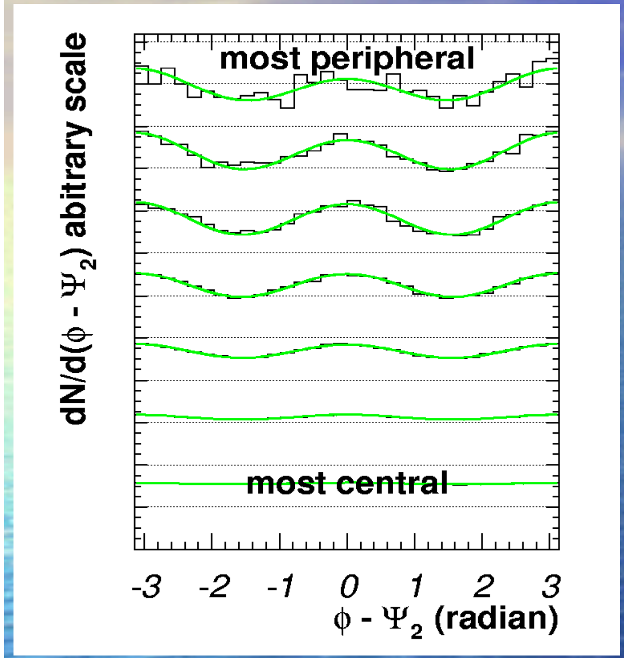
- The (normal) *in vacuum* fragmentation of a high momentum quark to produce hadrons *competes* with the *in medium* recombination of lower momentum quarks to produce hadrons

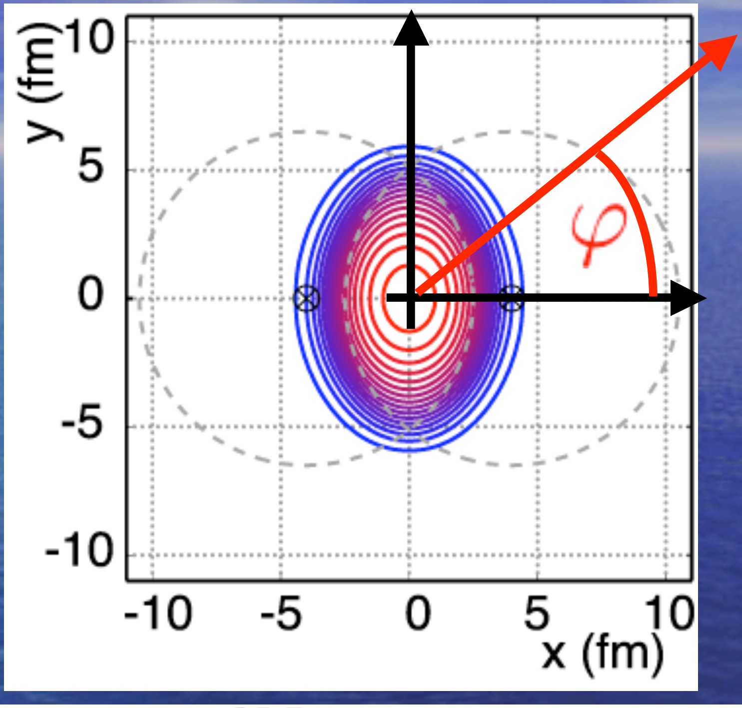
- Example:
  - Fragmentation: $D_{q \rightarrow h}(z)$
    - produces a 6 GeV/c π from a 10 GeV/c quark
  - Recombination:
    - produces a 6 GeV/c π from <u>*two*</u> 3 GeV/c quarks
    - produces a 6 GeV/c proton from <u>*three*</u> 2 GeV/c quarks



Fries, et al, nucl-th/0301087
Greco, Ko, Levai, nucl-th/0301093

Can We See Collective Behavior?



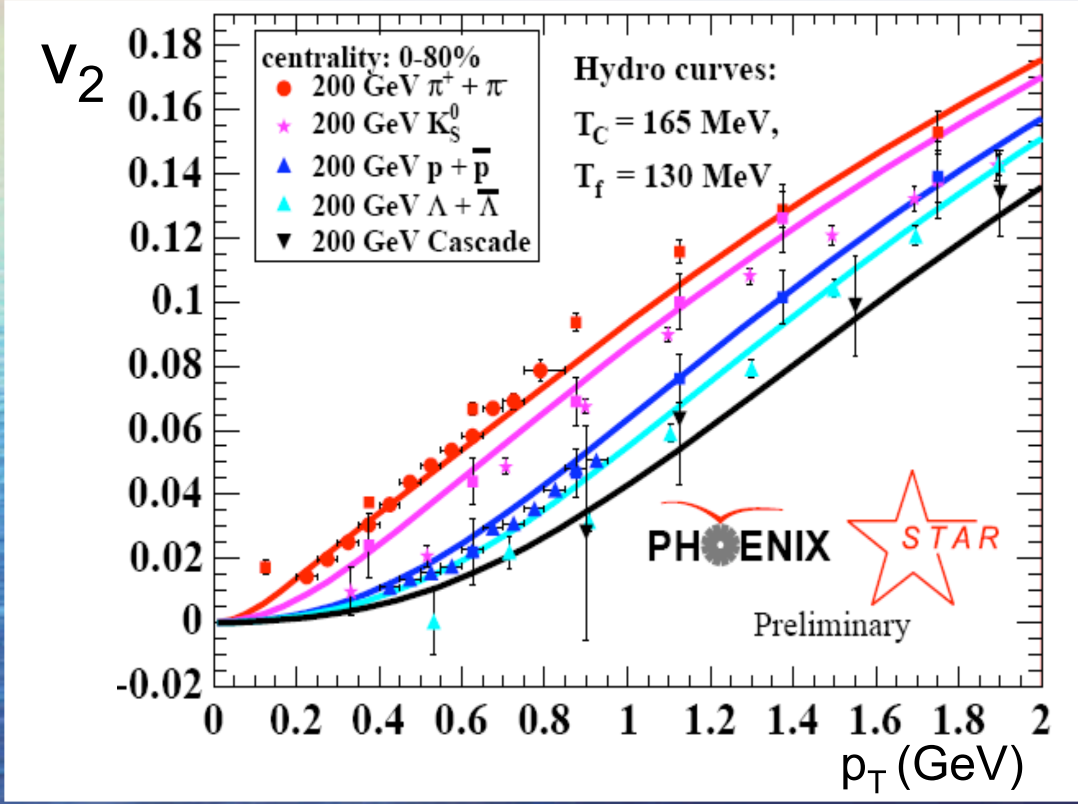


$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T; b)\cos(2\varphi) + \ldots\right)$$

- Simple answer: very high degree of collectivity is seen at RHIC.

Like a Perfect Fluid?

- First time hydrodynamics without any viscosity describes heavy ion reactions.



Lines:
Hydrodynamics calc.
with QGP type EoS.

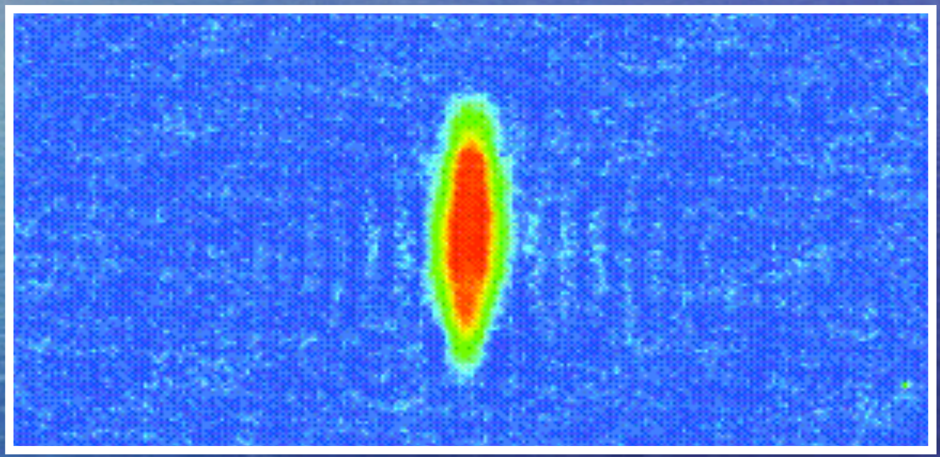
*viscosity = resistance of liquid to shear forces (and hence to flow)

Thermalization time t=0.6 fm/c and ε=20 GeV/fm^3

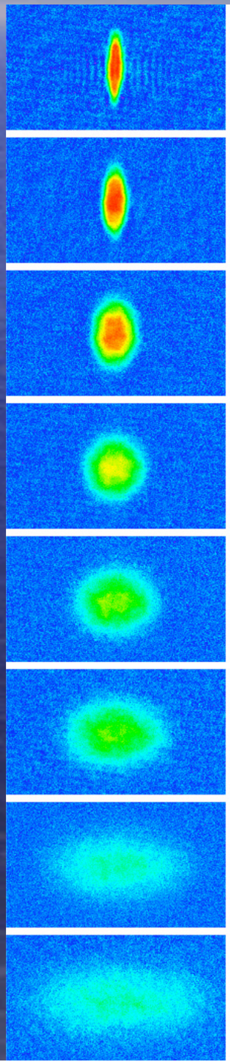
Required QGP Type EoS in Hydro model

Analogy in Atomic System

- Same phenomena observed in gases of strongly interacting atom

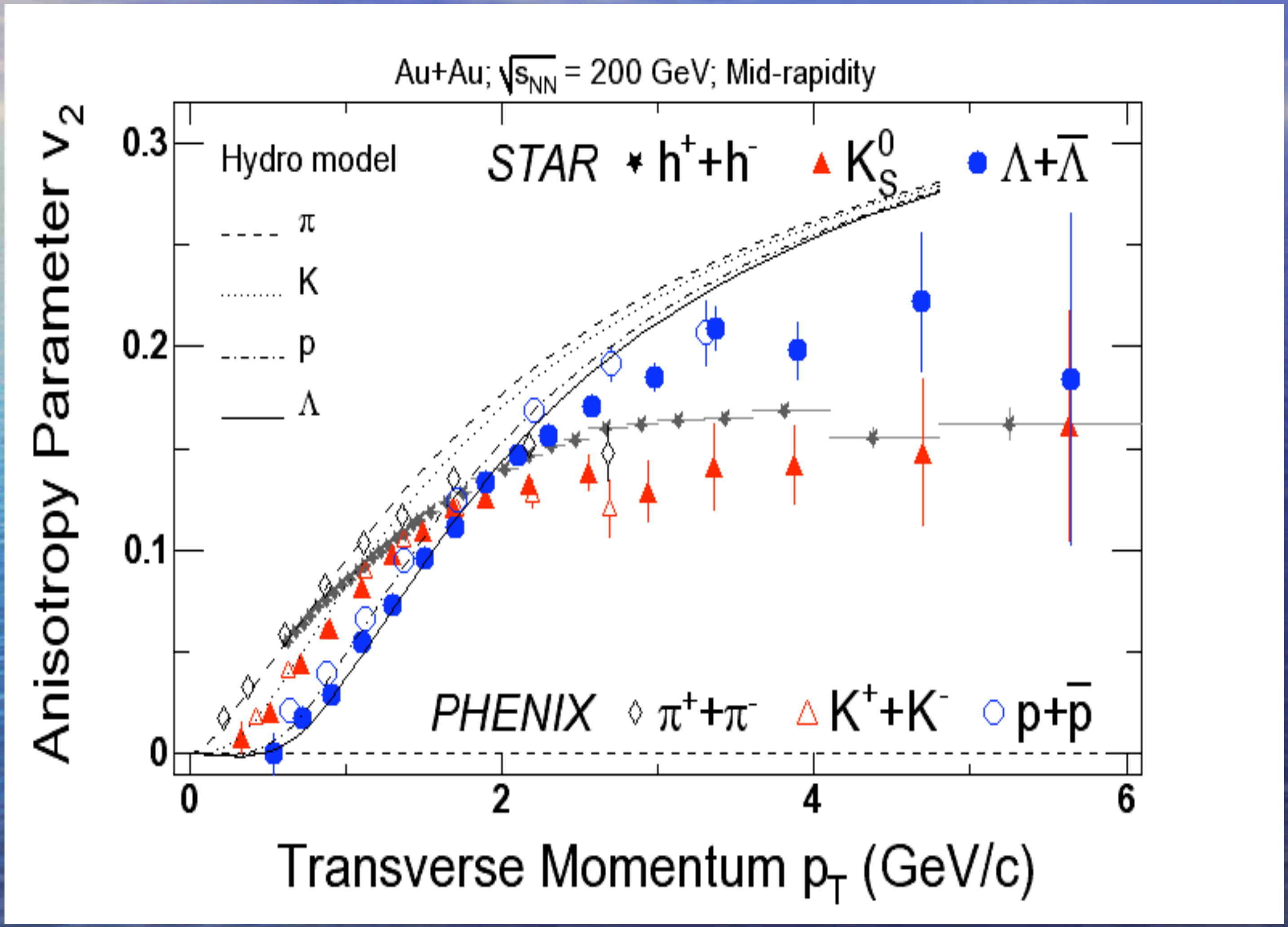


M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas
Science 298, 2179 (2002)

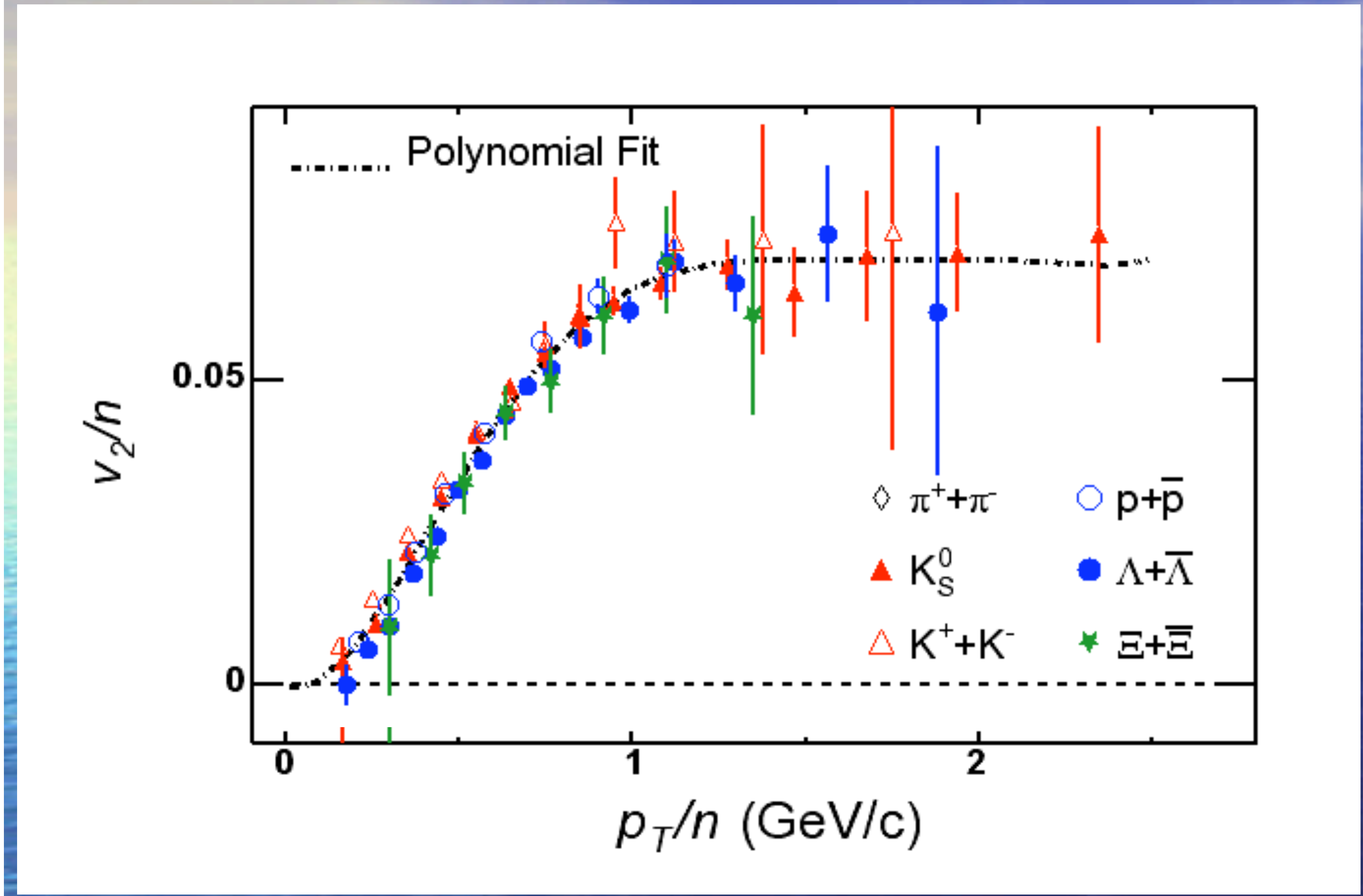


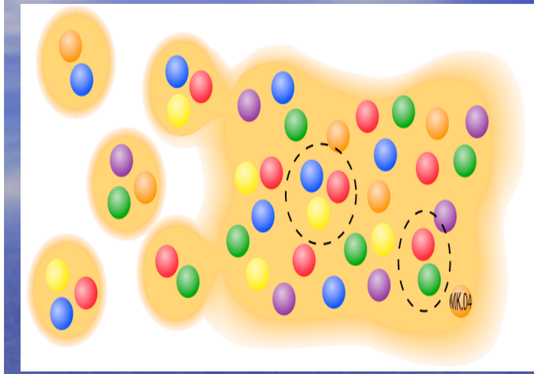
The RHIC fluid behaves like this, that is, a strongly coupled fluid.

Quark Recombination on v_2



Quark Recombination on v_2





- Number of constituent quark scaling (n =2 for mesons, n =3 for baryons) works.
- Pressure developed at quark level, not hadrons.
- Key test with multi-strangeness baryons, e.g. Ω (small hadronic cross section).

Summary

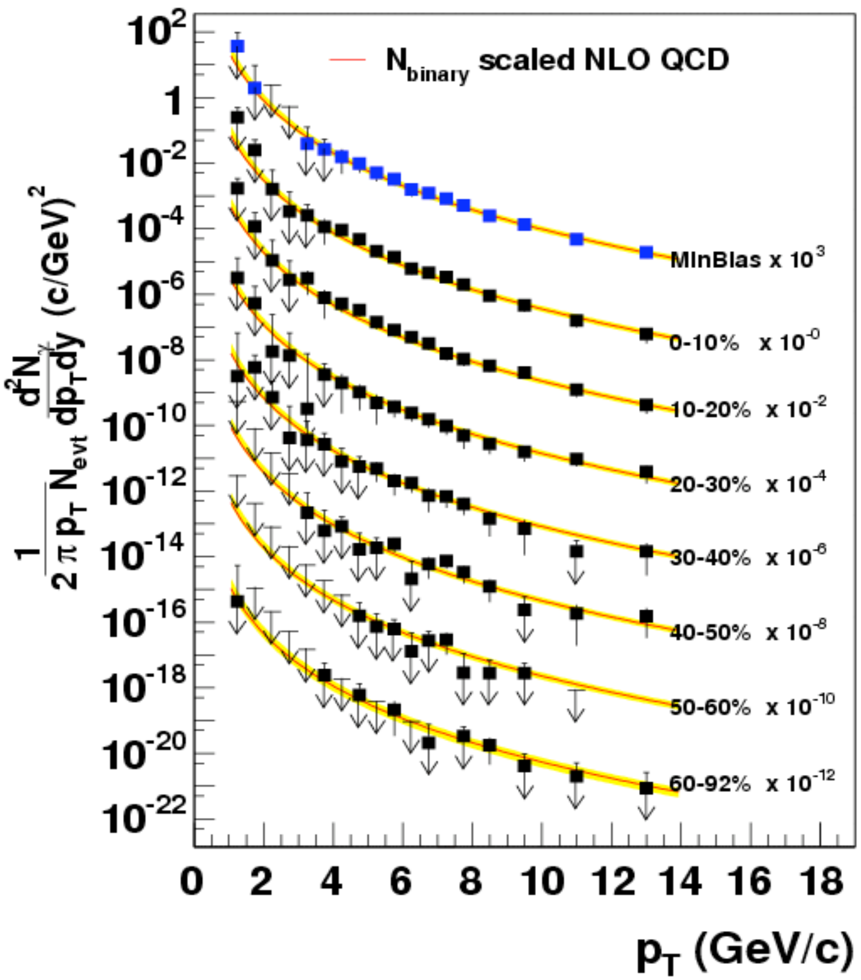
- RHIC is a proven machine to study QGP! Many (unexpected) discoveries.
- Energy density: $\varepsilon \sim 15$ GeV / fm^3 , i.e. ~100 normal nuclear density.
- Gluon density: well above lattice QCD predicted transition level.
- Suggesting importance of quark recombination for hadronization in the medium.
- Behaving as zero viscosity "perfect" liquid.
- This is not the historical idea of weakly interacting gas of quarks and gluons.
- This instead is the creation of a strongly interacting Quark-Gluon Plasma (or Quark-Gluon Liquid).

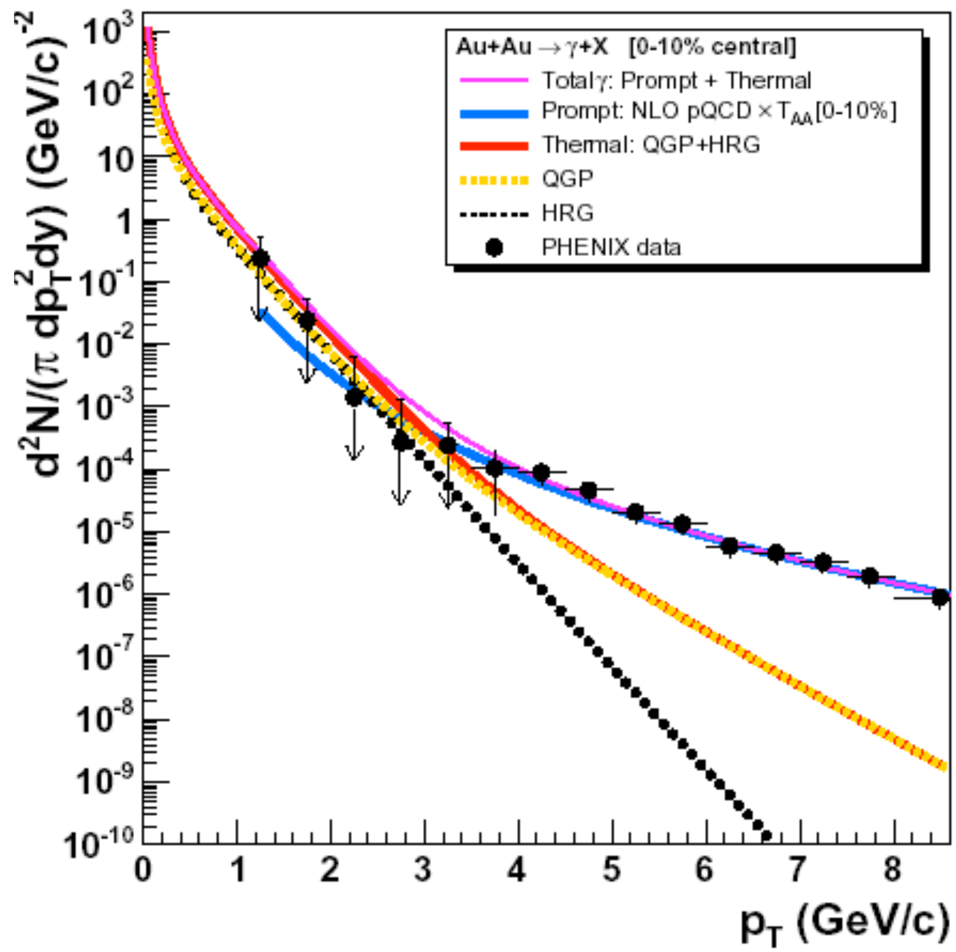
- Open Questions to be answered:
  - Heavy quarks flow (the perfect fluid behavior).
  - Thermal photon and initial temperature (constrain the degrees of freedom of QGP).
  - Charmonium production (deconfinement) & high p_T PID v_2, spectra (fragmentation).

Should be addressed in the future RHIC runs.

BACKUP SLIDES

Thermal photons and temperature



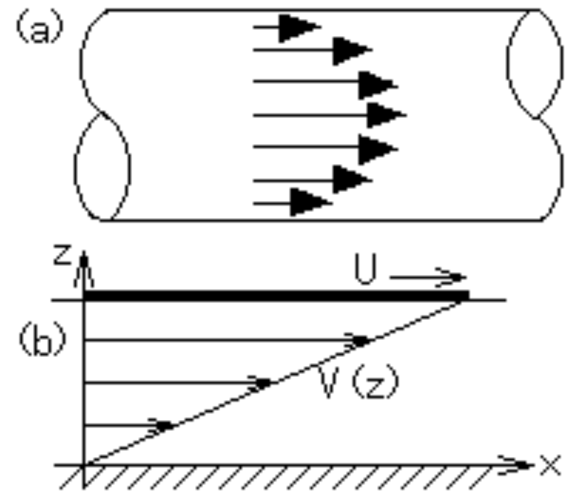


Viscosity

- Viscosity η:

$$F = -\eta\left(\frac{\partial V(z)}{\partial z}\right)$$

  - Viscosity depends on Temperature.
  - Ideal Hydro: small viscosity
    - λ (mean free path) << L (typical macroscopic scale)



$$\eta \approx \rho\langle \mathrm{v}\rangle\lambda$$

$$\langle \mathrm{v}\rangle \approx \sqrt{\frac{\mathrm{kT}}{\mathrm{m}}}, \lambda \approx \frac{1}{n\sigma}, mn = \rho$$

$$\eta \approx mn \cdot \sqrt{\frac{kT}{m}} \cdot \frac{1}{n\sigma} \propto \frac{\sqrt{kT}}{\sigma}$$

- Small viscosity ➡ **Large** cross sections, i.e. shear stress relaxes very quickly.

  = **"strong coupled liquids"**