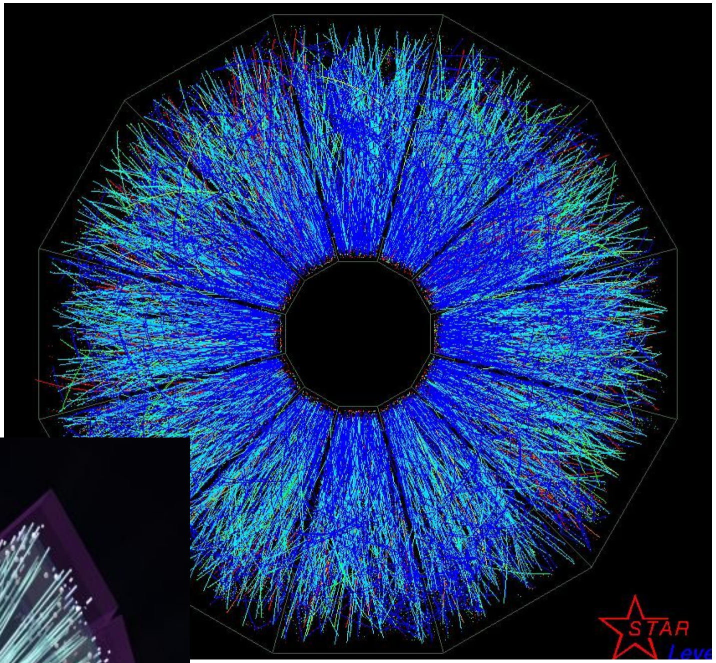
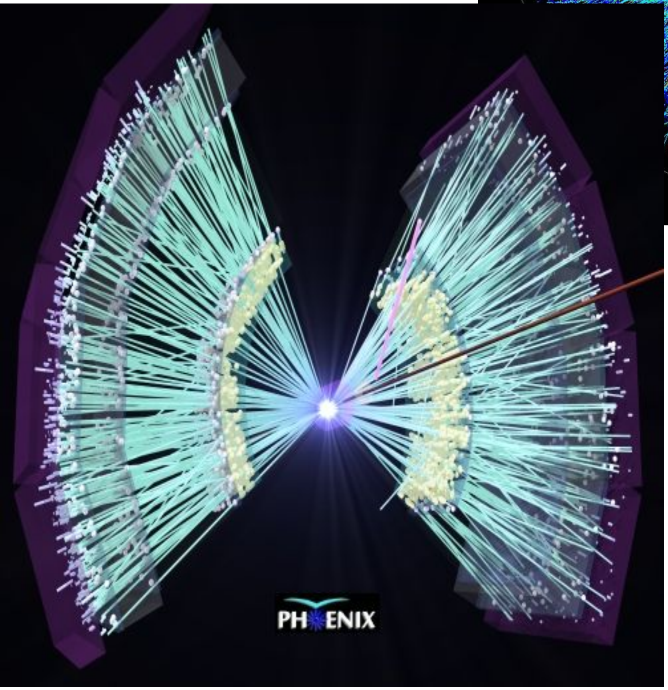
Nature's First Liquid: The Quark Gluon Plasma





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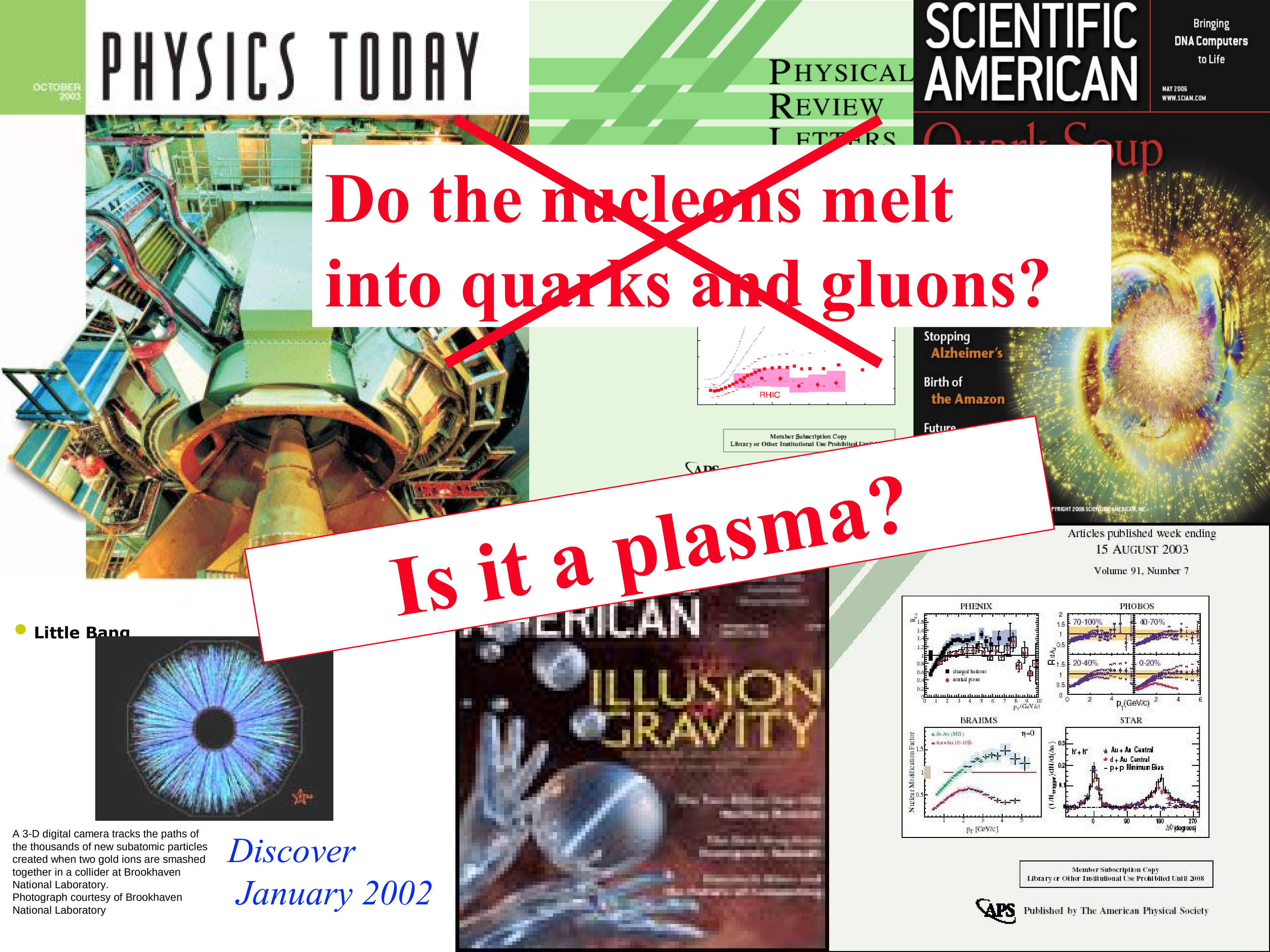
May 28, 2006



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ILLUSION OF GRAVITY
• Little Bang
A 3-D digital camera tracks the paths of the thousands of new subatomic particles created when two gold ions are smashed together in a collider at Brookhaven National Laboratory.
Photograph courtesy of Brookhaven National Laboratory
Discover
January 2002

outline

- introductory remarks
- transmission of color-charged probes by the plasma
- collective effects
  - applying hydrodynamics
- heavy quark probes
  - diffusion and viscosity
- strongly-coupled plasmas
- (color) screening
  - the ever-surprising J/ψ

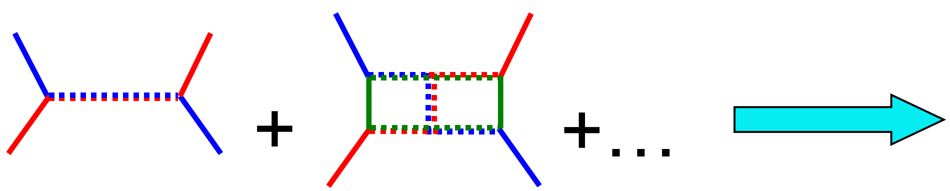
what is a plasma?

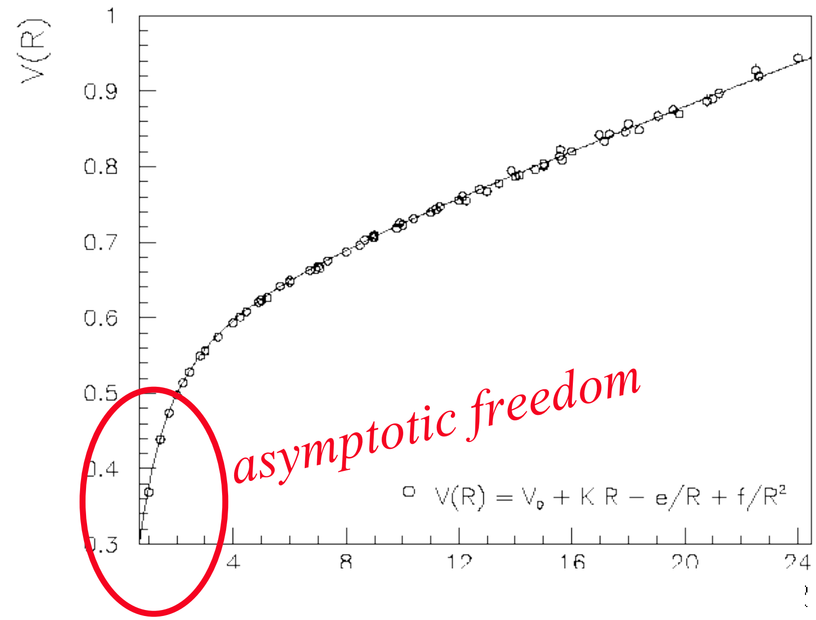
- 4^{th} state of matter (after solid, liquid and gas)
- a plasma is:
  - ionized gas which is macroscopically neutral
  - exhibits collective effects
- interactions among charges of multiple particles
  - spreads charge out into characteristic (Debye) length, λ_D
  - multiple particles inside this length
    - they screen each other
  - plasma size > λ_D
- "normal" plasmas are electromagnetic (e + ions)
  - quark-gluon plasma interacts via strong interaction
    - color forces rather than EM
    - exchanged particles: g instead of γ

QCD: expect a phase transition

gluons carry color charge ⇒ gluons interact among themselves

theory is non-abelian





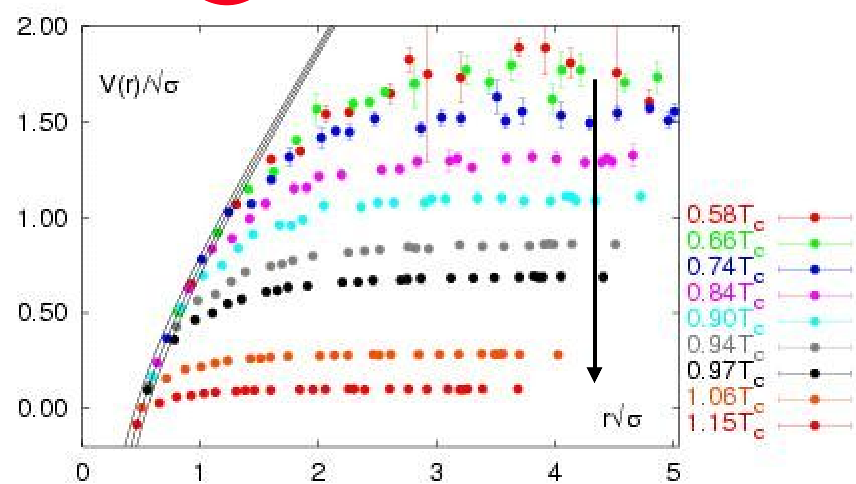
special properties at large distance:

confinement of quarks in hadrons

***At high temperature and density*:**

force is screened by produced color-charges

expect transition to ***gas of free quarks and gluons***



look at radiated & "probe" particles

- as a function of transverse momentum

  $p_T = p \sin\theta$ (with respect to beam direction)

  90° is where the action is (max T, ρ)

  midway between the two beams!

- $p_T < 1.5$ GeV/c

  "thermal" particles

  radiated from bulk of the medium

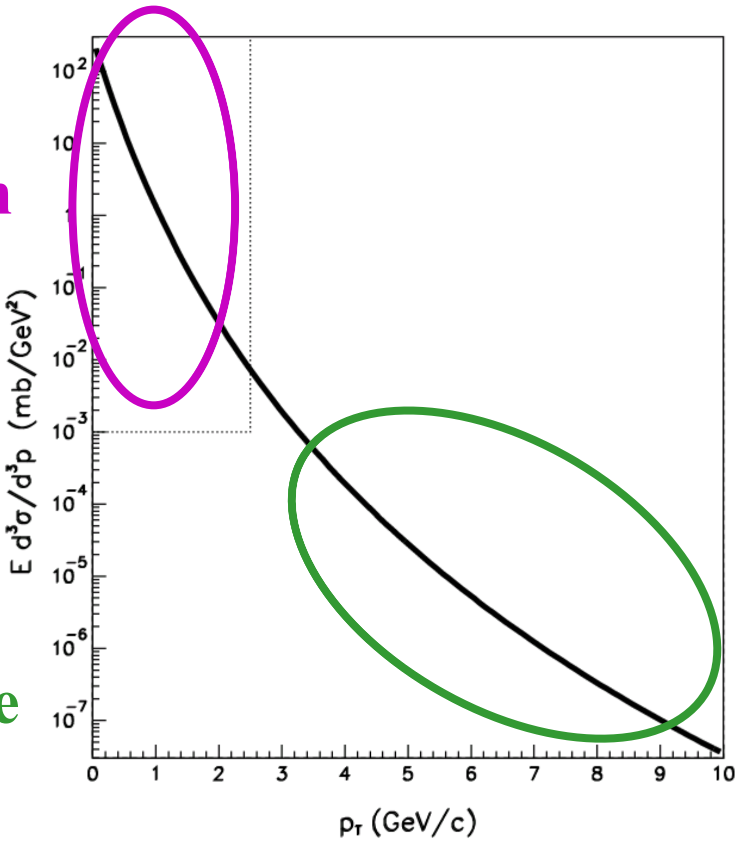
  internal plasma probes

- $p_T > 3$ GeV/c

  jets (hard scattered q or g)

  heavy quarks, direct photons

  produced early→"external" probe

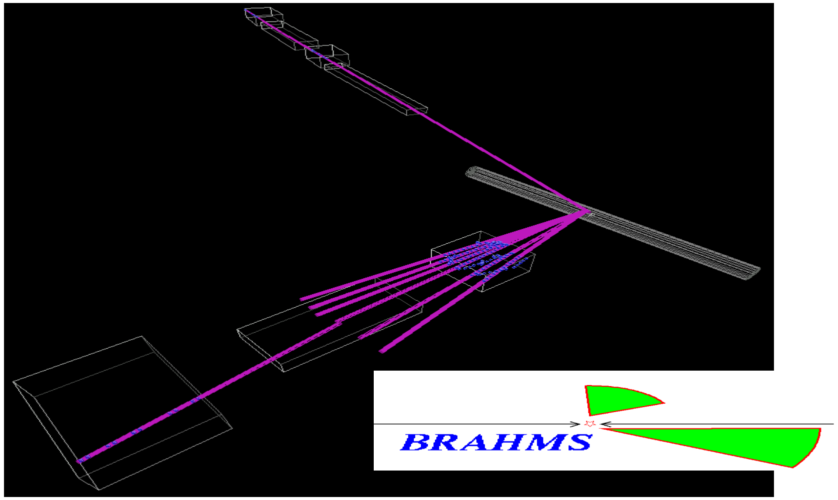


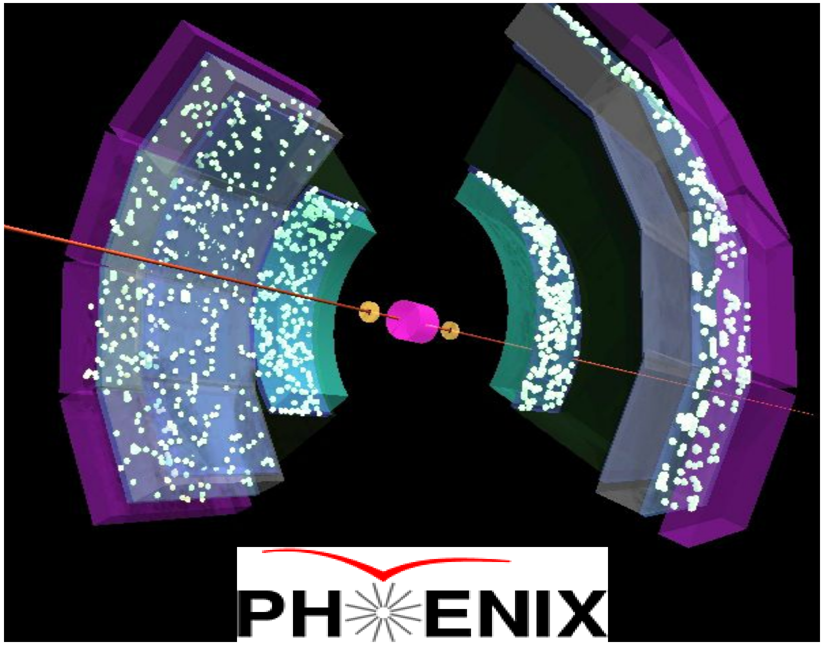
RHIC at Brookhaven National Laboratory

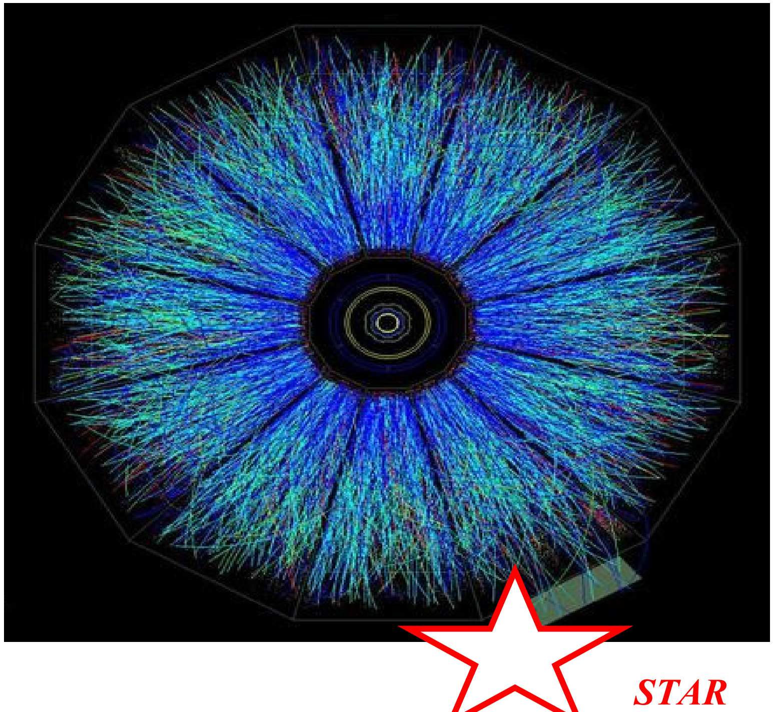
Collide Au + Au ions for maximum volume

$\sqrt{s}$ = 200 GeV/nucleon pair, p+p and d+A to compare

4 complementary experiments



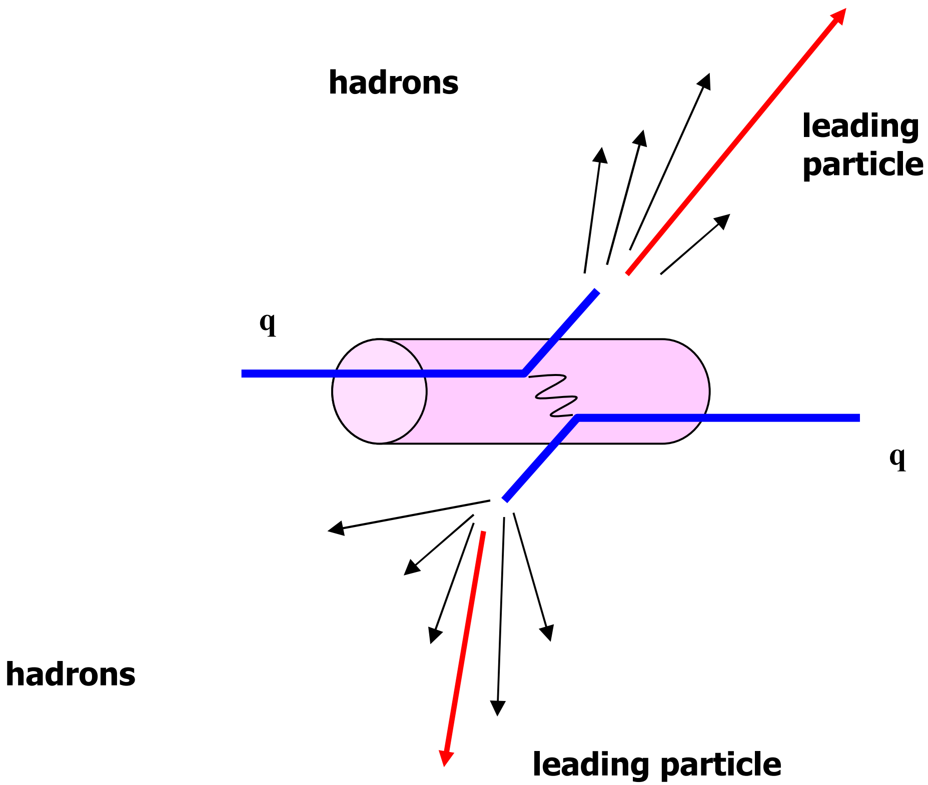




a common plasma technique

transmission of probes which interact with plasma for QGP: fast g and light quarks

schematic view of jet production

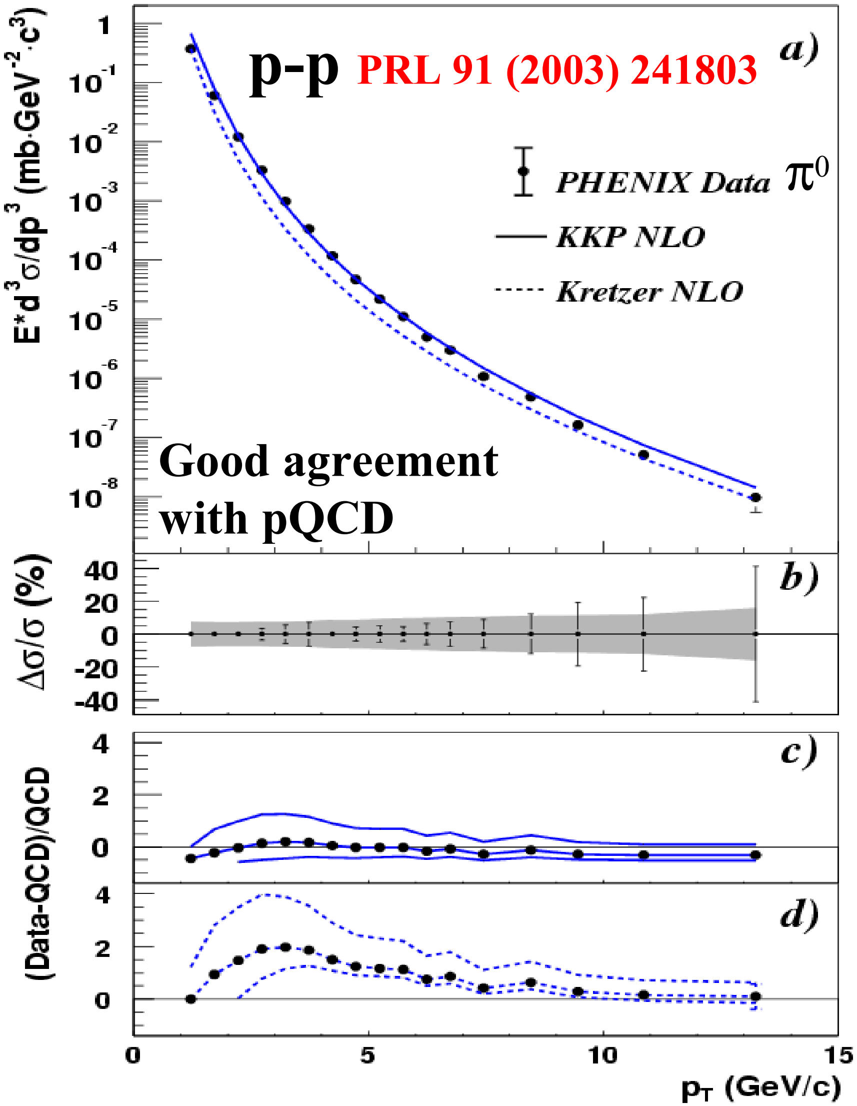


calculate probe rate & distribution with pQCD

look for modification by medium

d+Au collisions provide the control

step 1: benchmark in p+p collisions

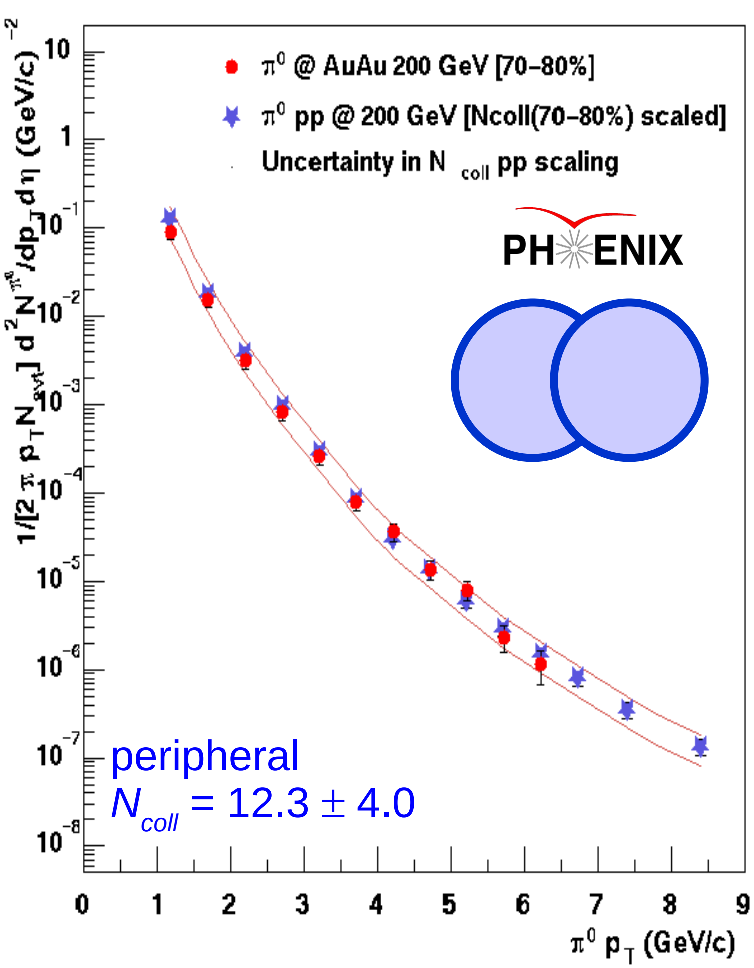


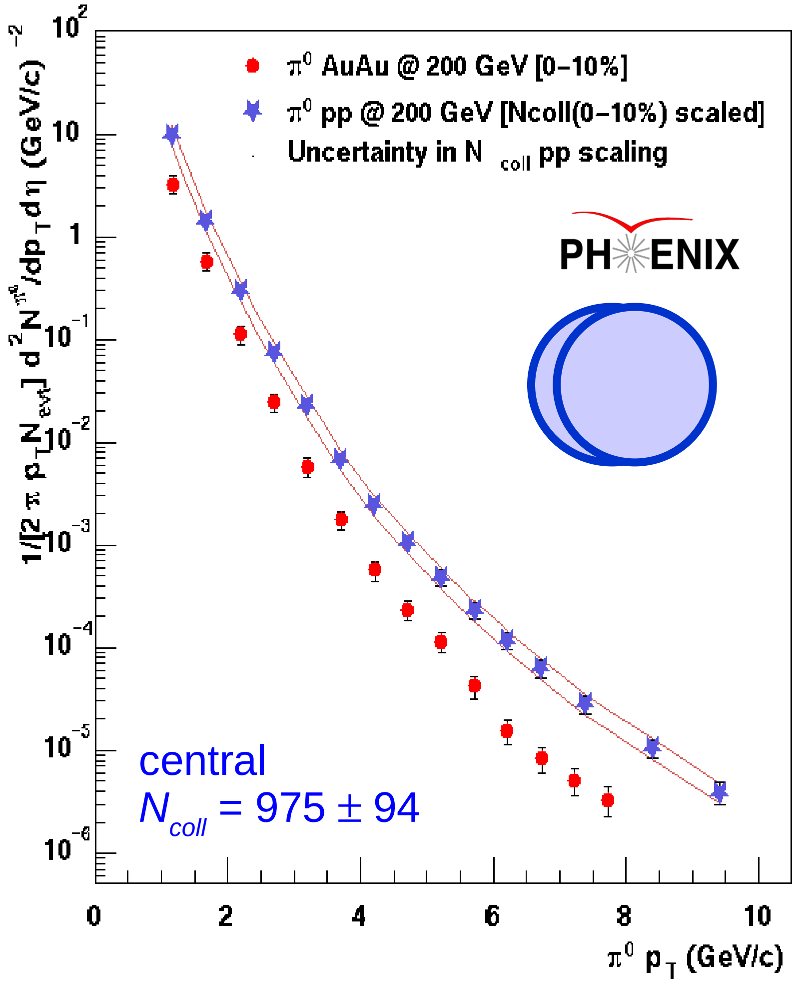
QCD works at RHIC

can use perturbation theory for high p transfer processes

understand initial hard interactions in Au+Au: scattering of q, g inside N

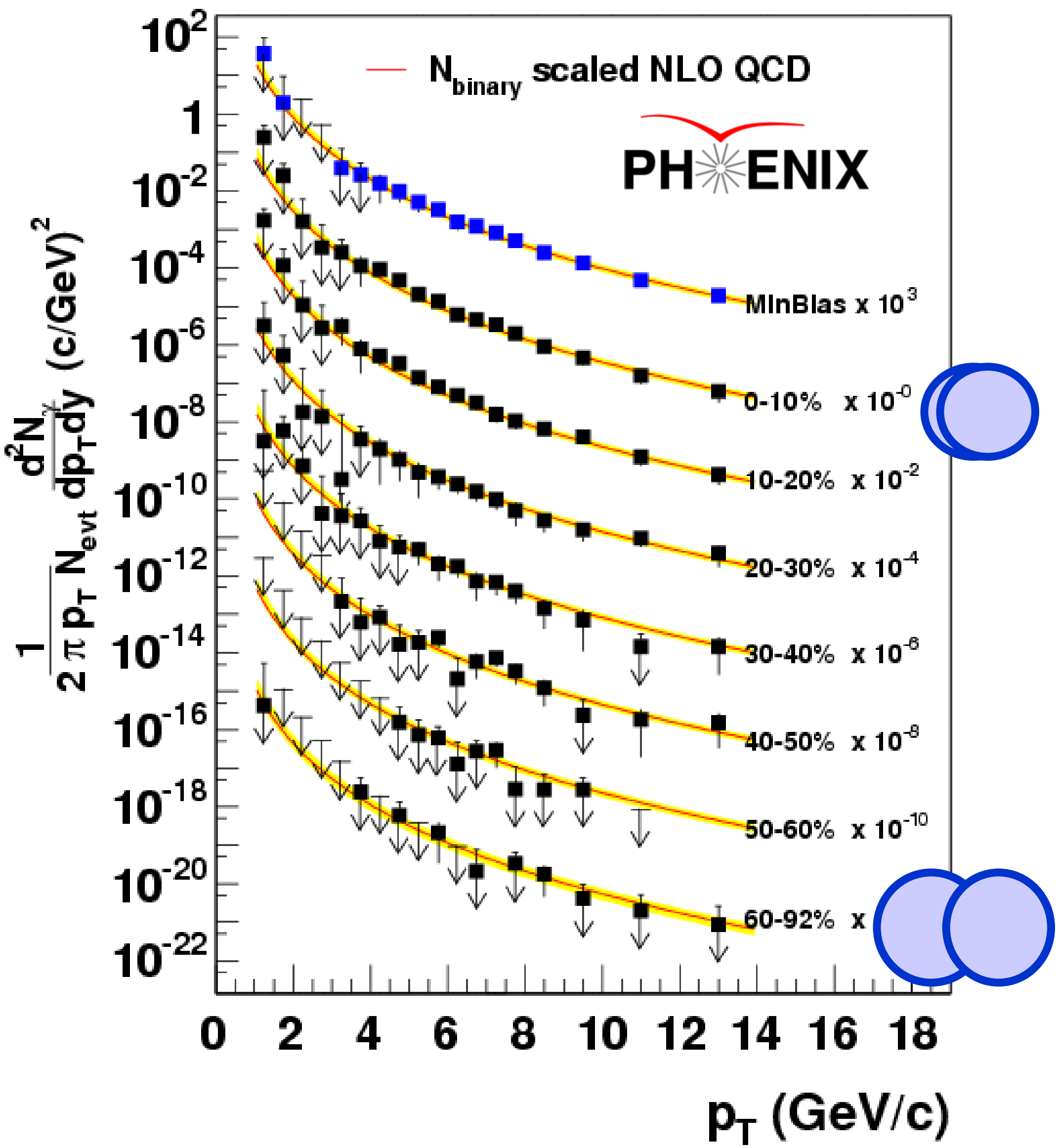
jet fragments in Au+Au vs. p+p





jets are quenched by the plasma!

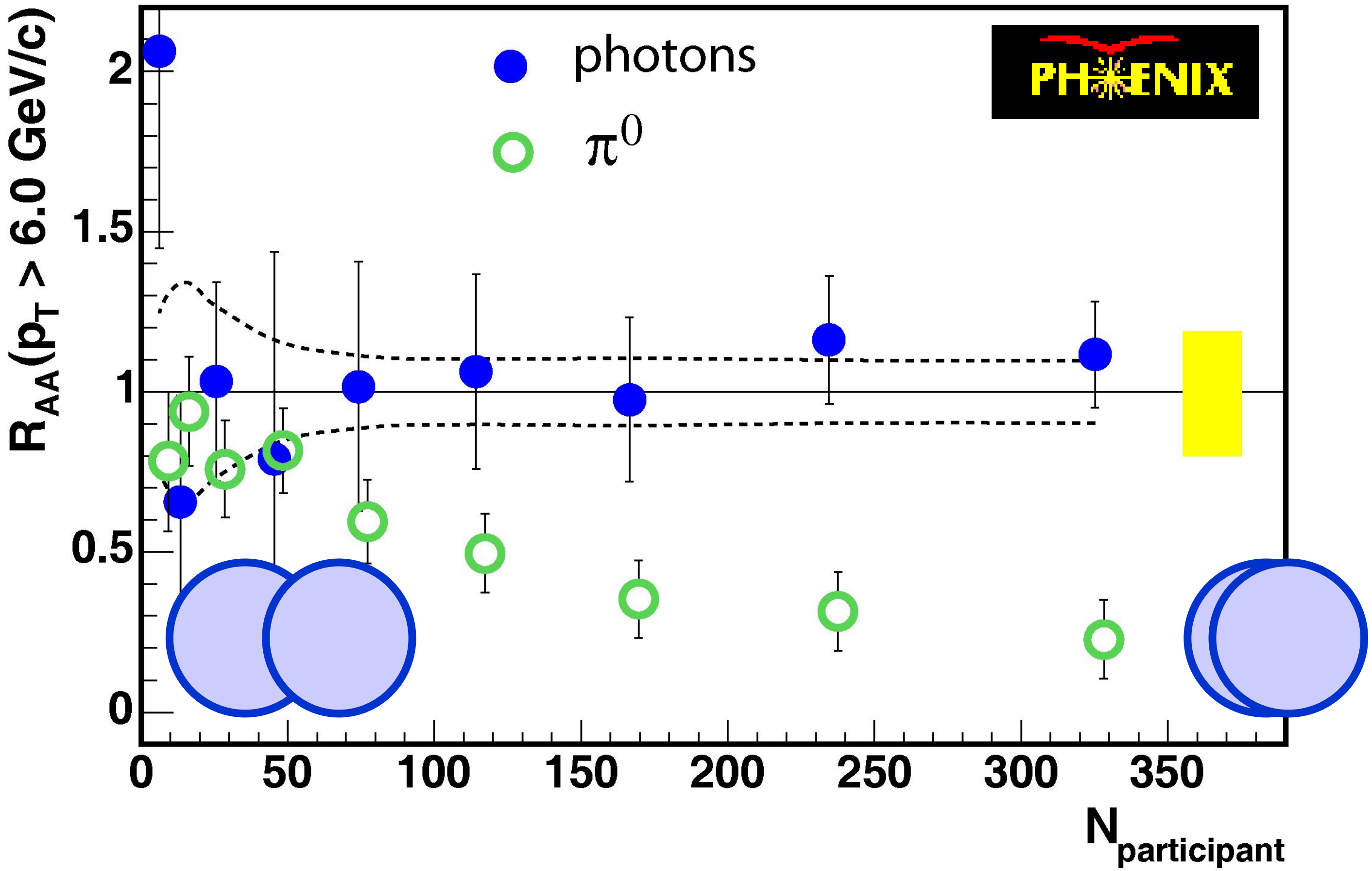
Direct Photon Spectra in Au+Au



- $q + g \rightarrow q + \gamma$
- γ should not interact with the color charges
- data agree with QCD $\rightarrow$ calibrated probes
- pQCD works in the complex environment of two nuclei (Au+Au) colliding at high energies!

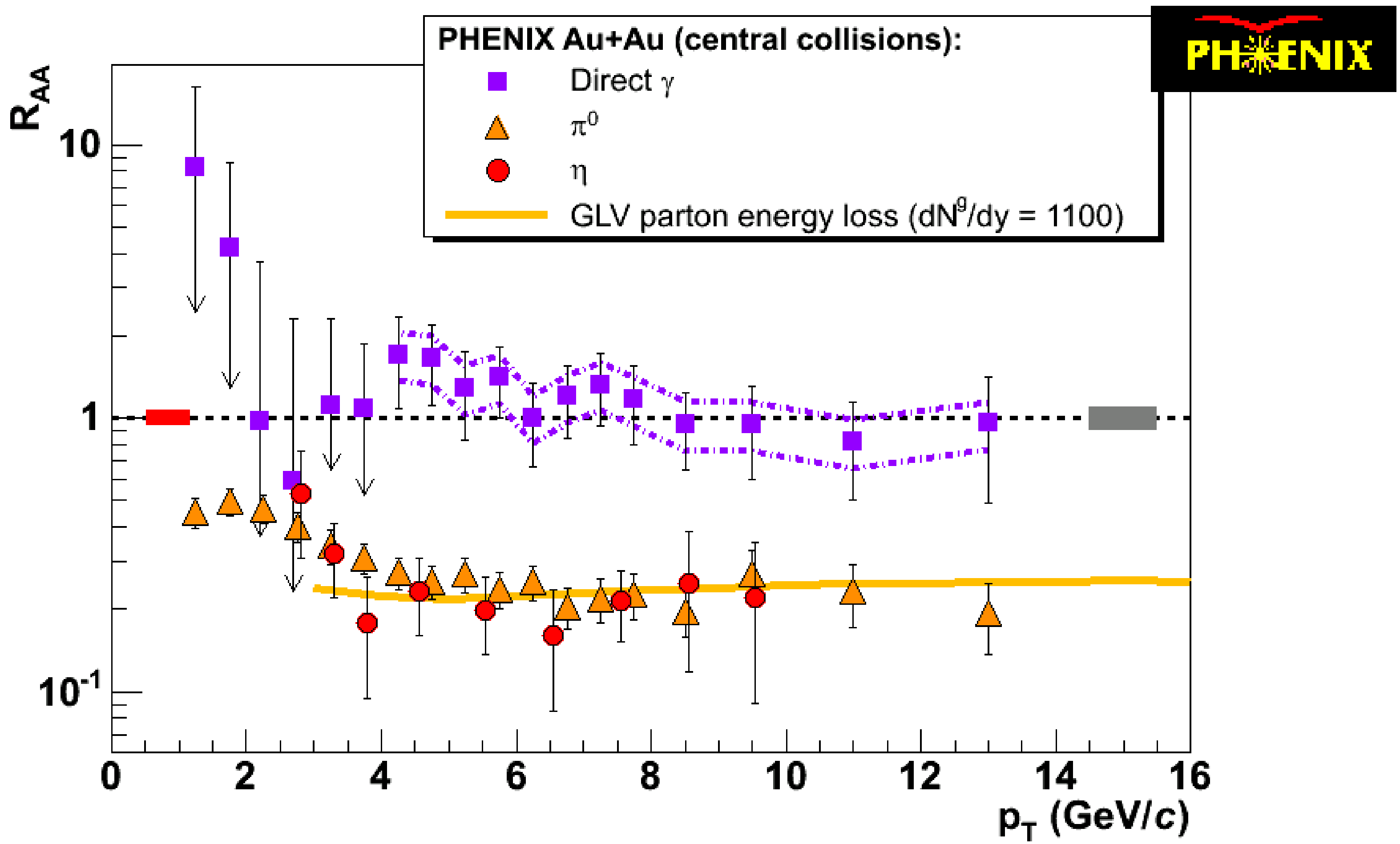
nuclear modification factor

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

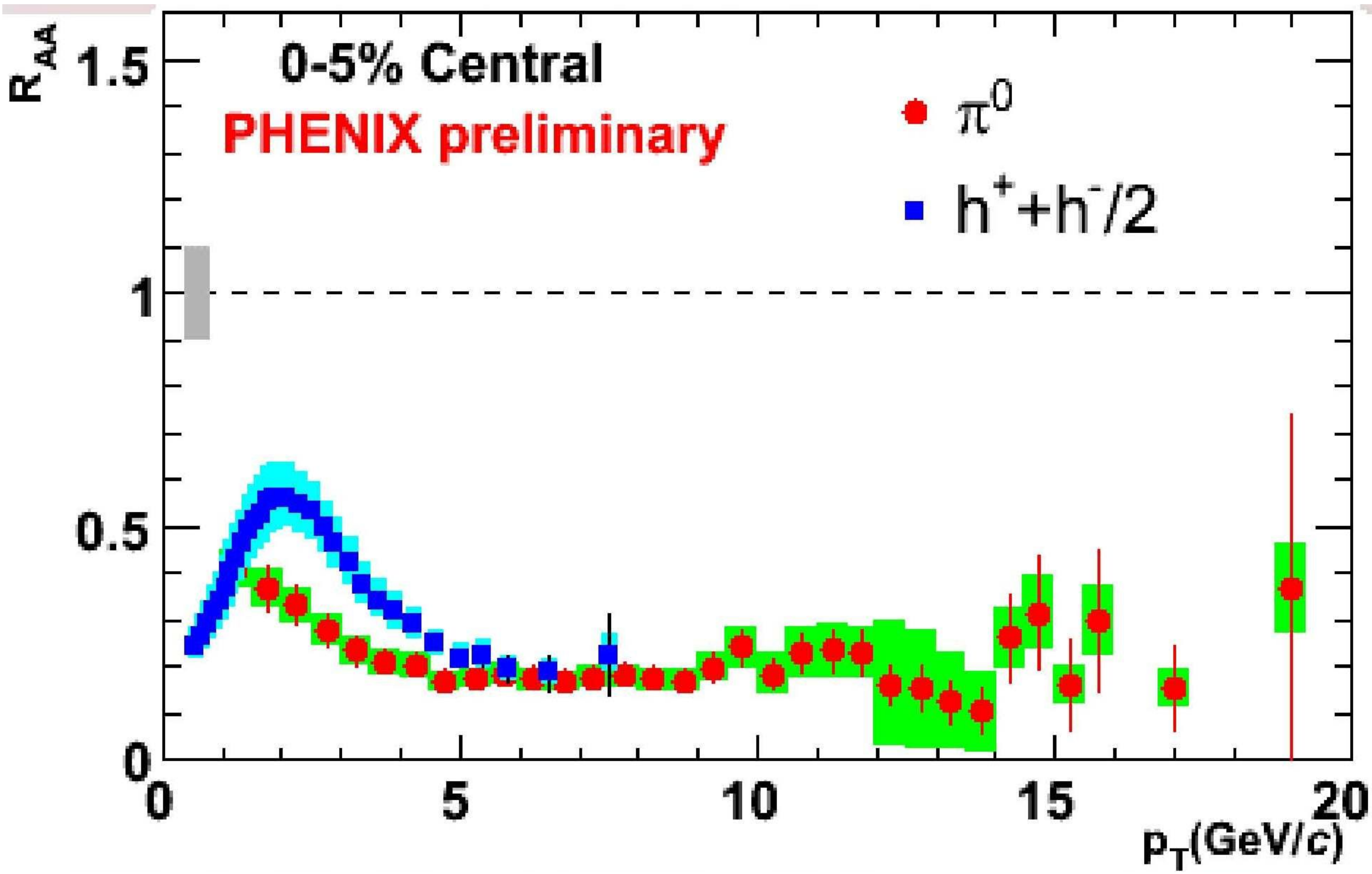


- photons escape plasma
- pions and other hadrons: strong interaction, absorbed

mesons show common p_T dependence



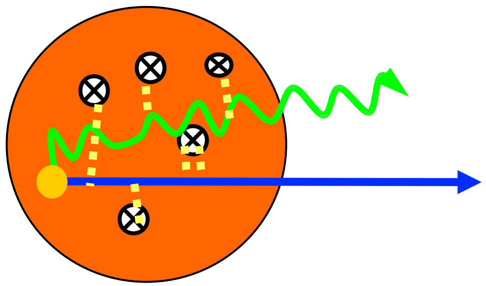
suppression persists to 20 GeV/c!

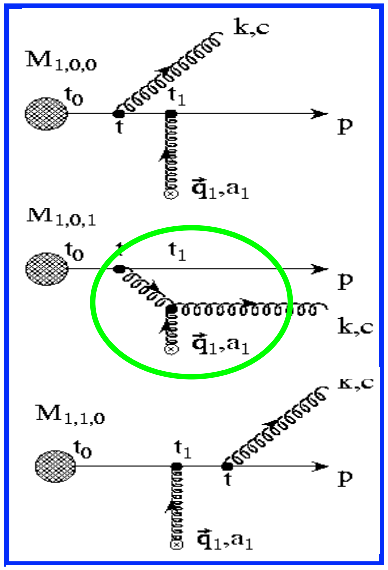


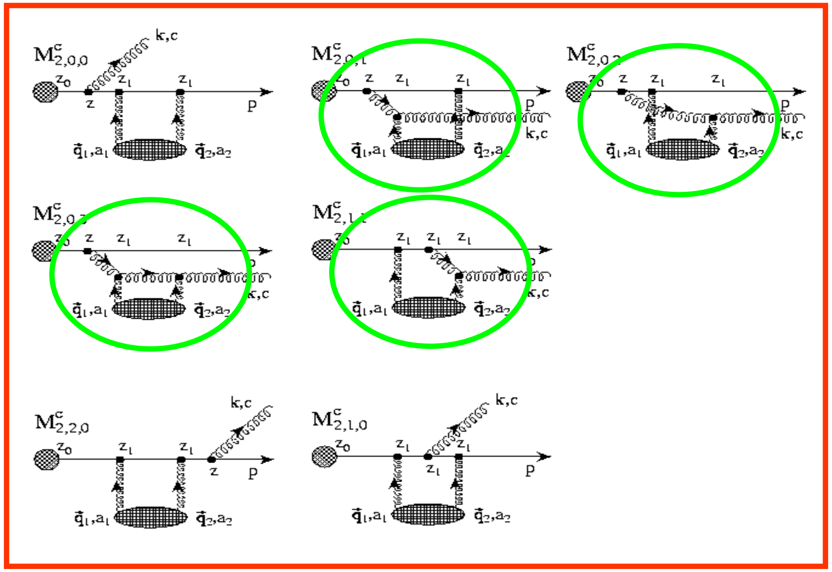
question to theory: accidental cancellations or a physics message?

flatness not expected at LHC – what will the data say?

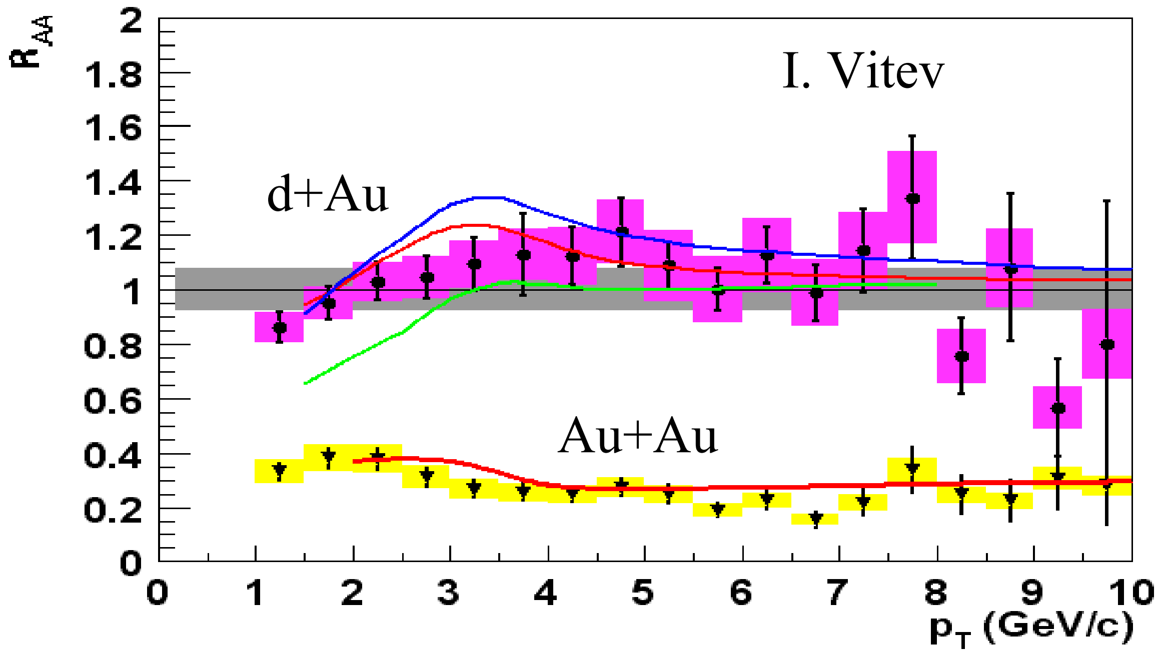
learn about QGP density from this







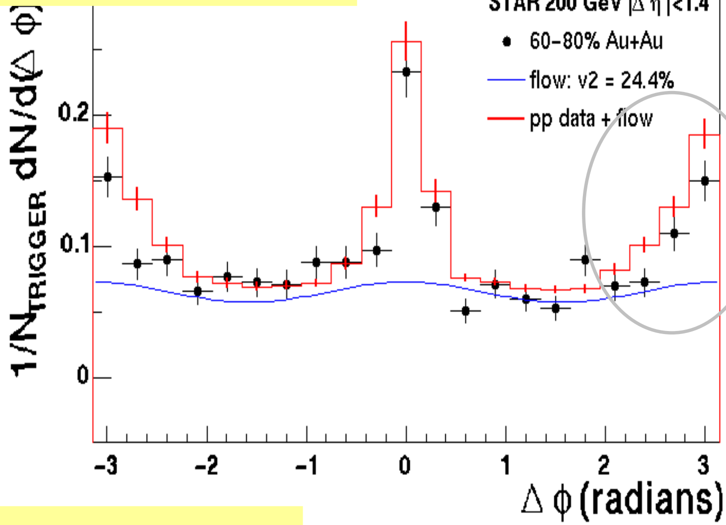
interaction of radiated gluons with gluons in the plasma greatly enhances the amount of radiation



calculate using an opacity expansion
answer: L/mfp ~ 3.5
model dependent!
$\rho \geq 1000$ gluons/dy

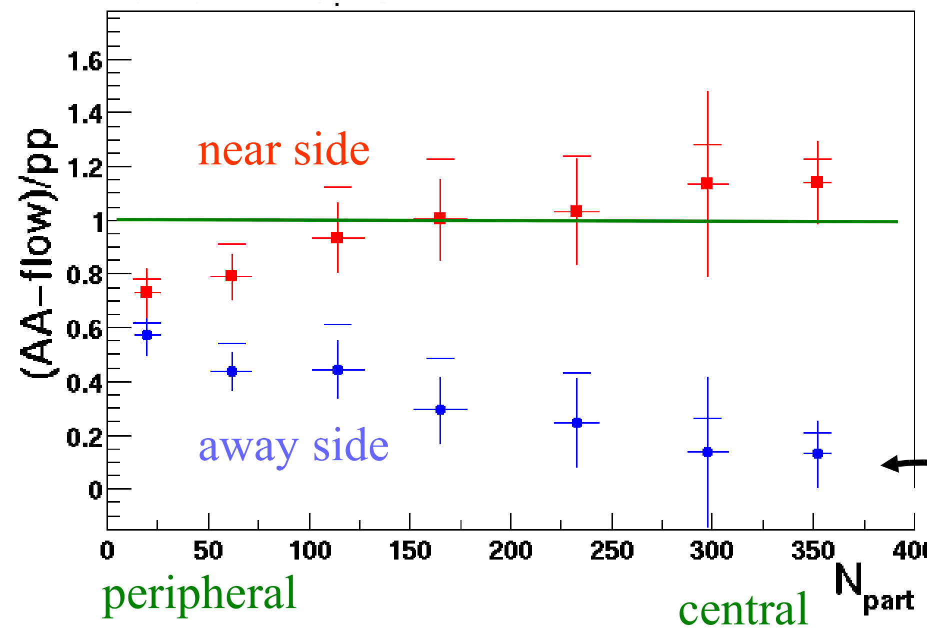
look for the jet on the other side

Peripheral Au + Au

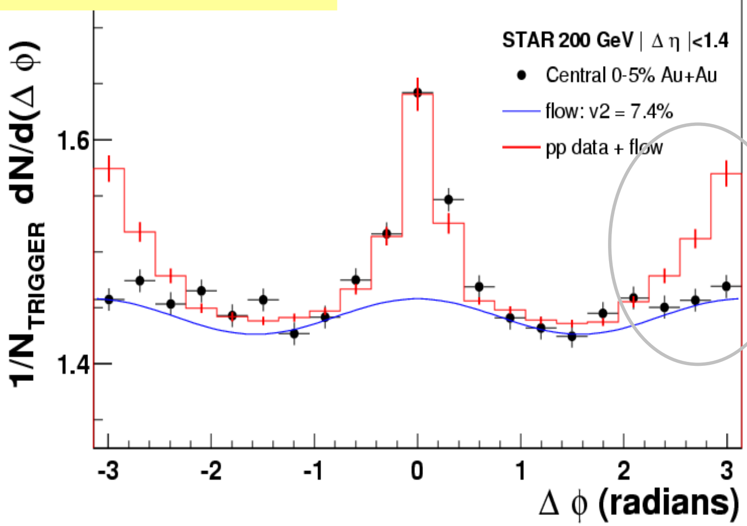


STAR PRL 90, 082302 (2003)

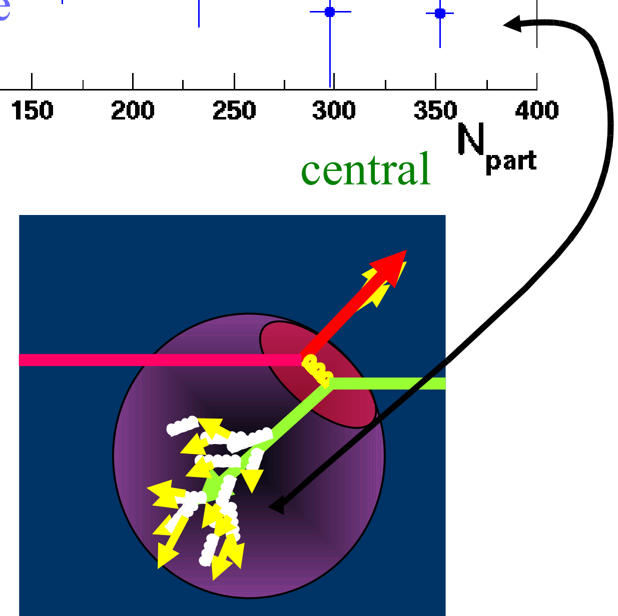
$$D_2(Au+Au) = D_2(p+p) + B(1 + v_2^2\cos(2\Delta\phi))$$



Central Au + Au



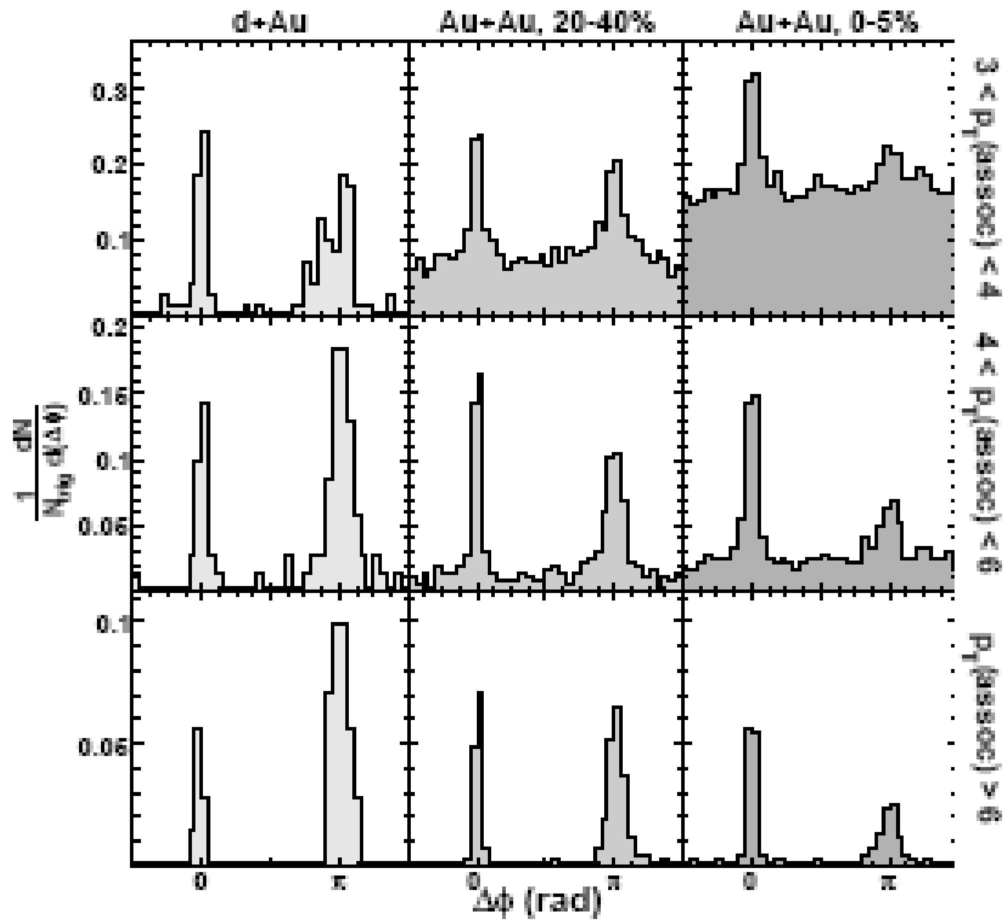
Medium is opaque!



do see some away side particles at higher p_T

STAR nucl-ex/0604018

p_T trigger > 8 GeV/c



away side yield: some jets escape, some eaten

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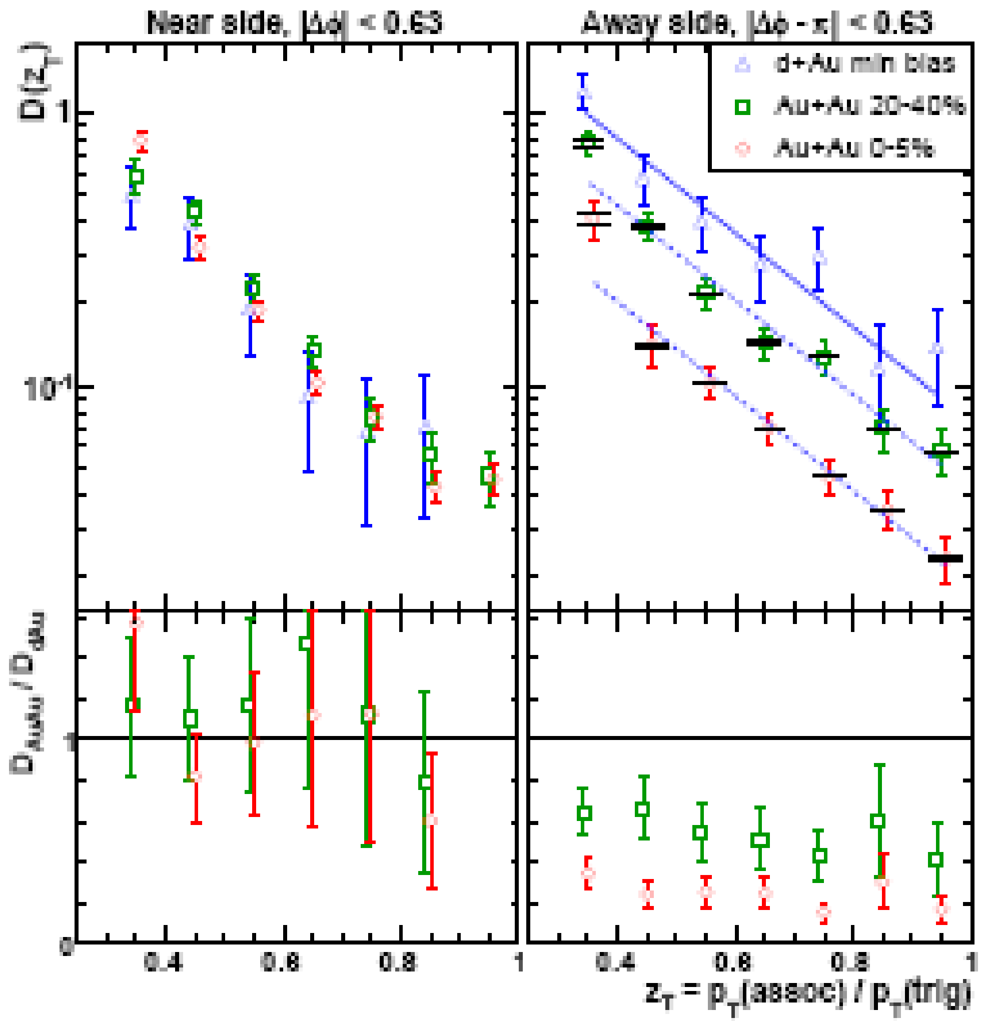
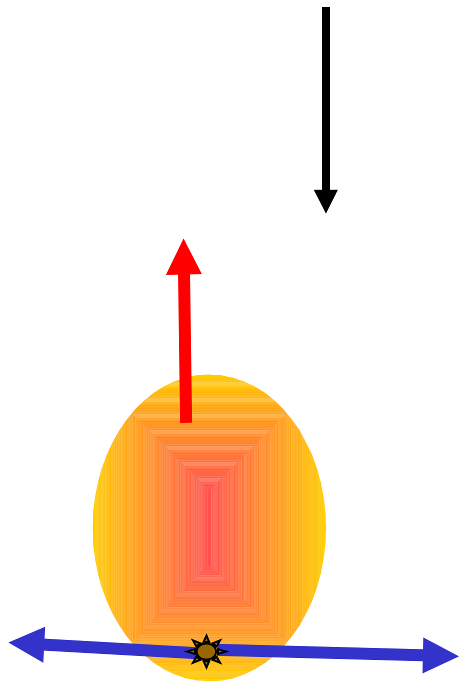


Note similarity of away side jet fragmentation. Only yield changes



summary of transmission measurements

we have seen that:

- the medium is very opaque to hard probes
  opacity (L/mfp) ~ 3.5
- medium is very dense and/or interaction cross section is very high
  perturbative calculations say $dN_g/dy \sim 1000$
- but detailed calculations of expected medium modification of fragmentation function don't quite reproduce the data quantitatively…

**Let's turn to another feature of plasmas:
collective motions**

collective effects

a basic feature distinguishing plasmas from ordinary matter

- **simultaneous interaction of each charged particle with a considerable number of others**

  due to long range of electromagnetic forces

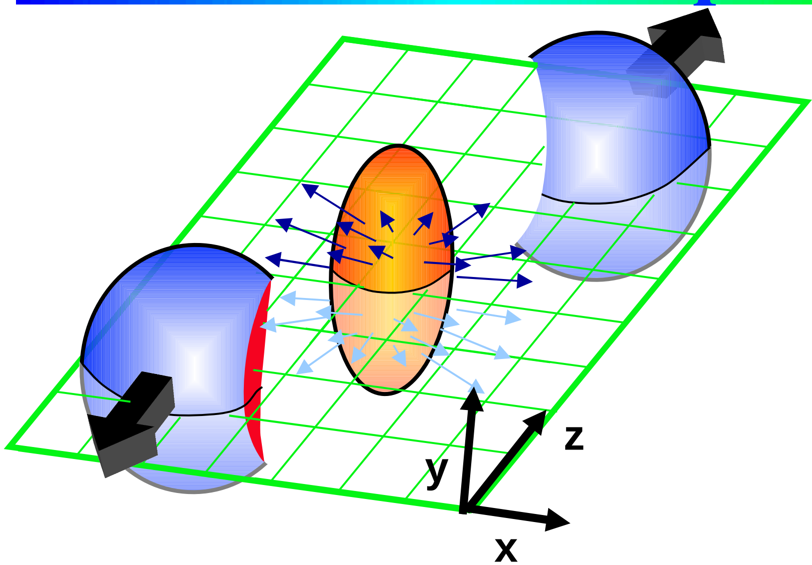
  both charge-charge and charge-neutral interactions

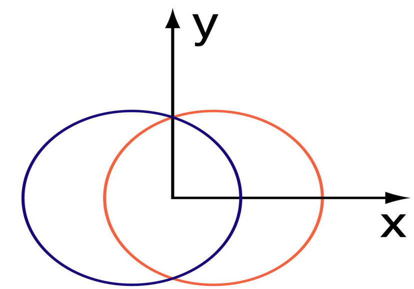
    charge-neutral dominates in weakly ionized plasmas

    neutrals interact via distortion of e cloud by charges

- **magnetic fields generated by moving charges give rise to magnetic interactions**

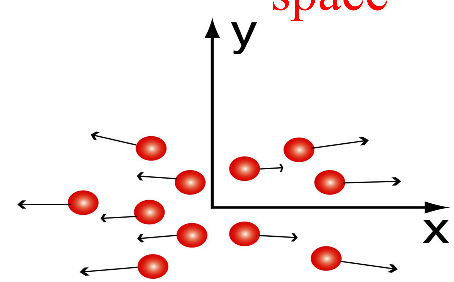
search for collectivity in QGP
use "internal" probes – emitted particles

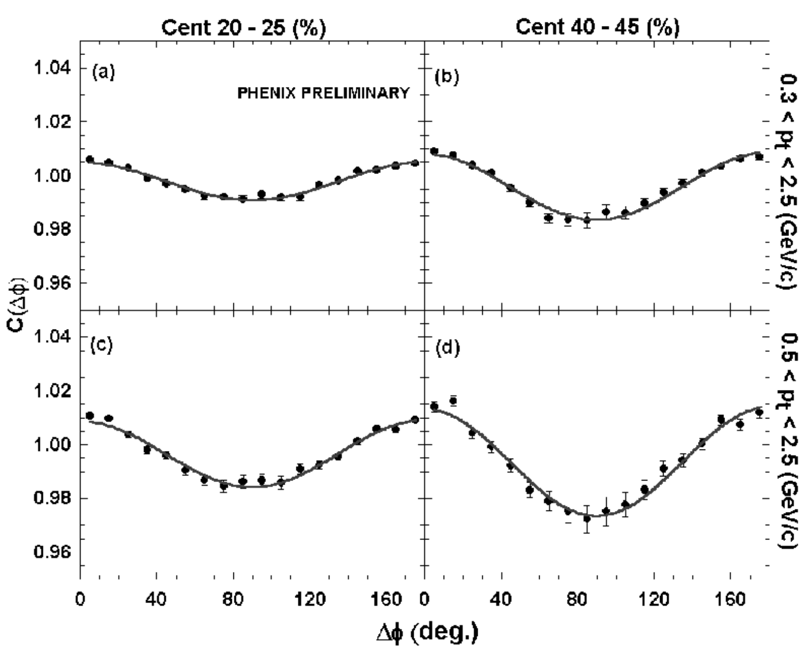




Almond shape overlap region in coordinate space

momentum space

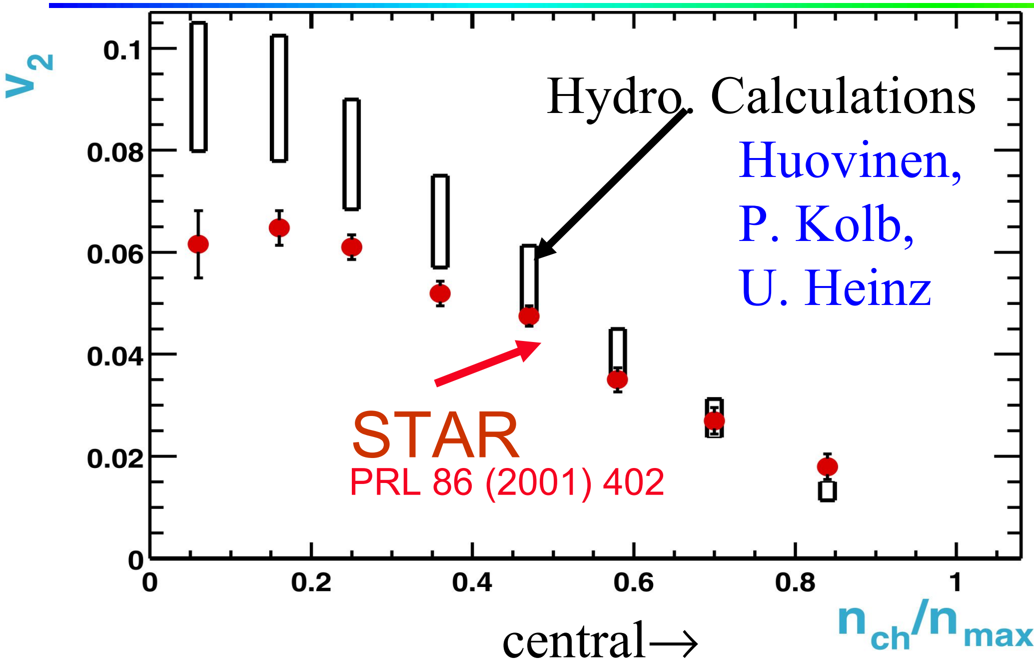




$dN/d\phi \sim 1 + 2\,v_2(p_T)\cos(2\phi) + \ldots$

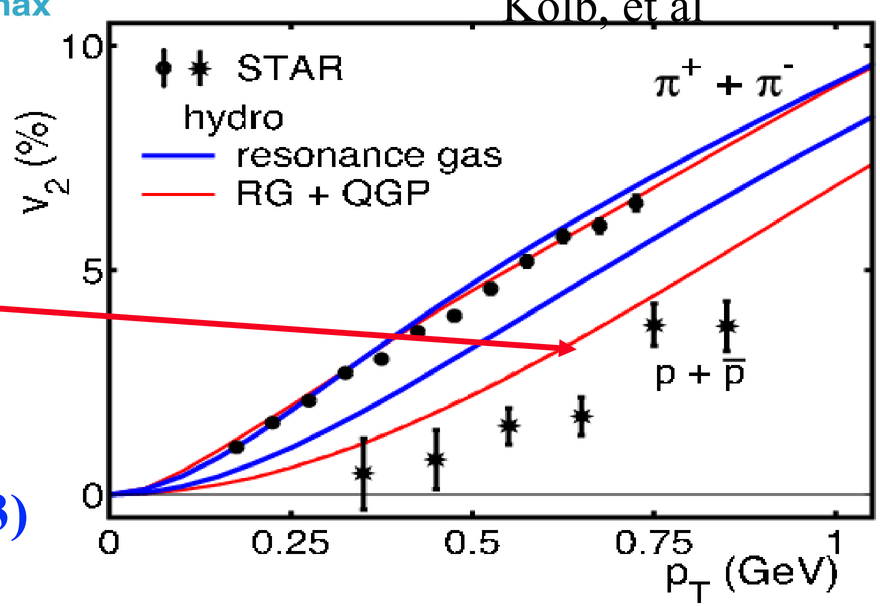
"elliptic flow"

v_2 is large & reproduced by hydrodynamics



- **large pressure buildup**
- **anisotropy → happens fast**
- **fast equilibration!**

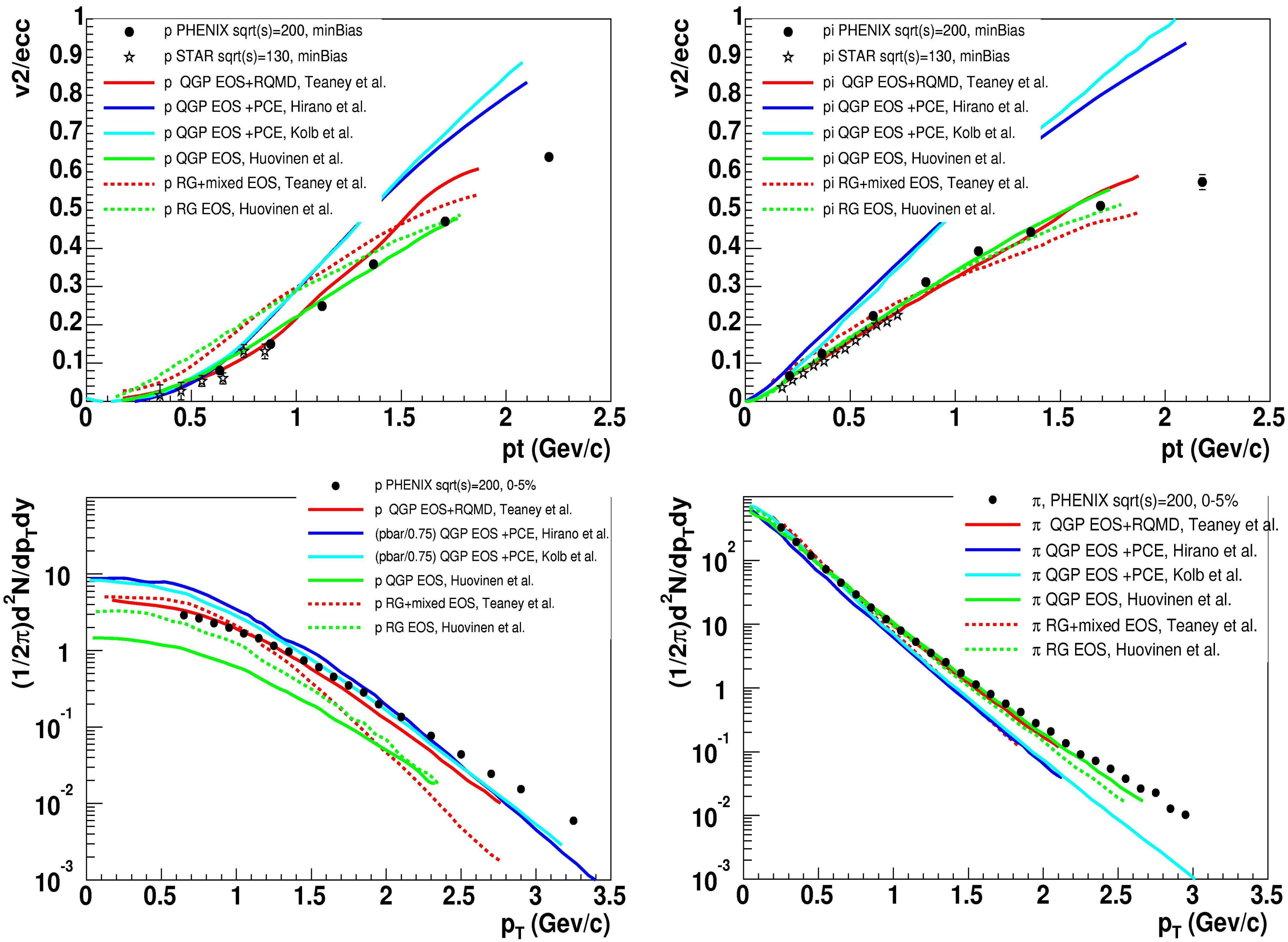
Hydrodynamics reproduces elliptic flow q-$\bar{q}$ and 3q states
Mass dependence requires *softer than hadronic EOS!!*



NB: these calculations have viscosity ~ 0
"perfect" liquid (D. Teaney, PRC68, 2003)

Truth in advertising! (details matter)

proton pion **nucl-ex/0410003**



Hydro models:

Teaney
(w/ & w/o RQMD)

Hirano
(3d)

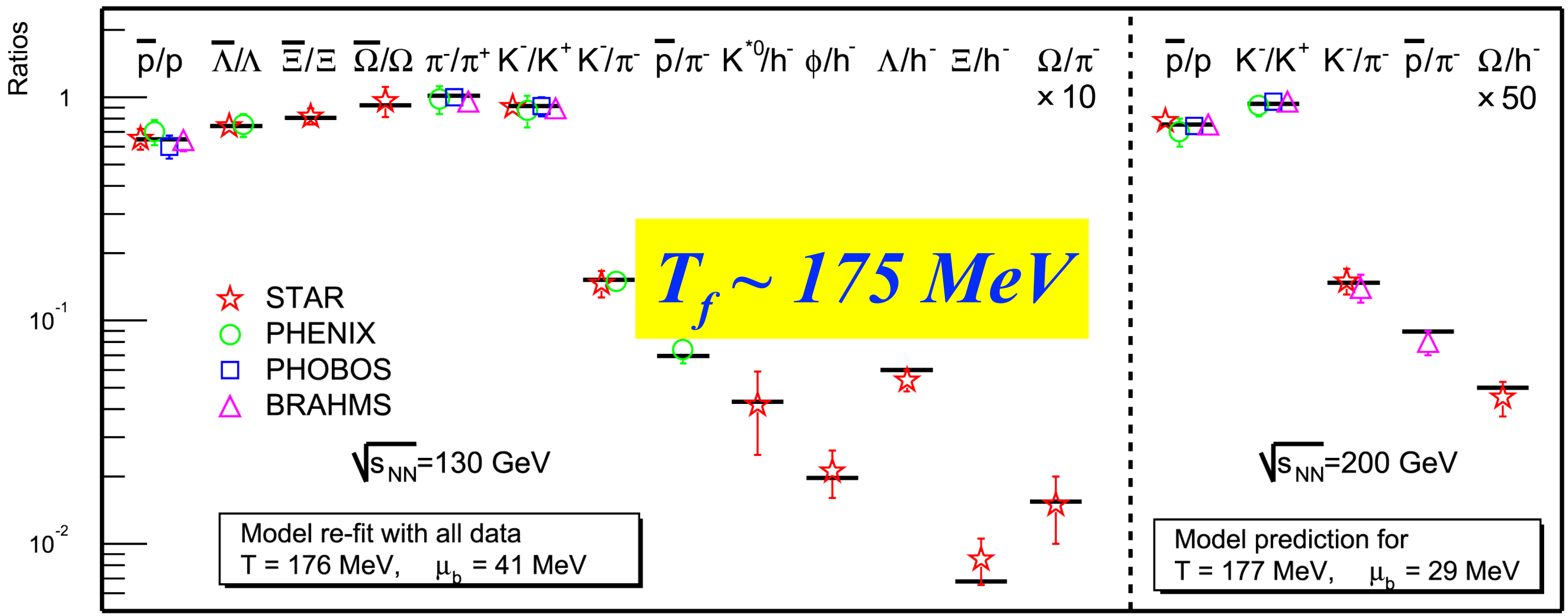
Kolb

Huovinen
(w/& w/o QGP)

hadron population arises from thermal system

Assume all distributions described by temperature T and (baryon) chemical potential μ :

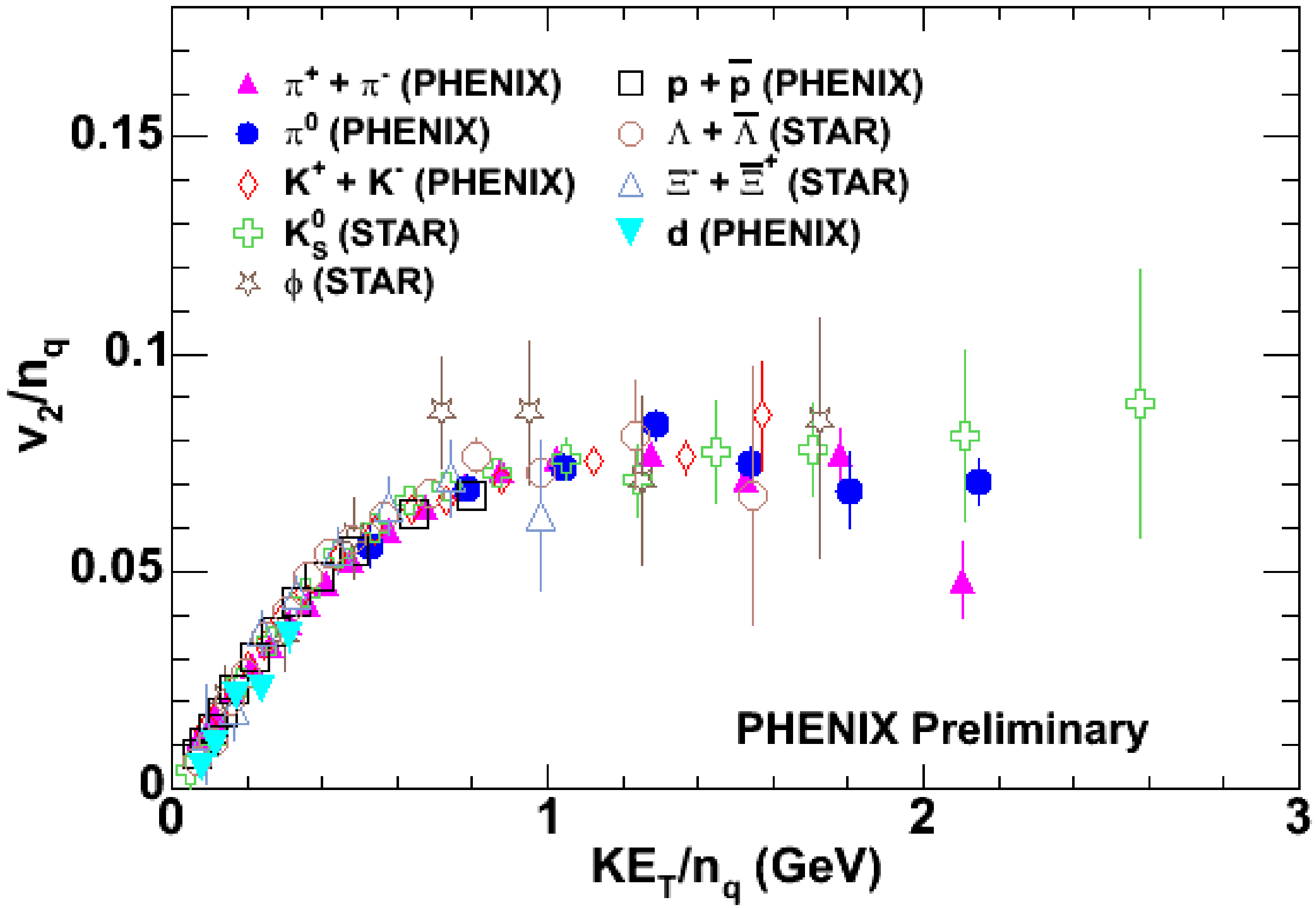
$$dn \sim e^{-(E-\mu)/T}\, d^3p$$



Braun-Munzinger et al., PLB 518 (2001) 41

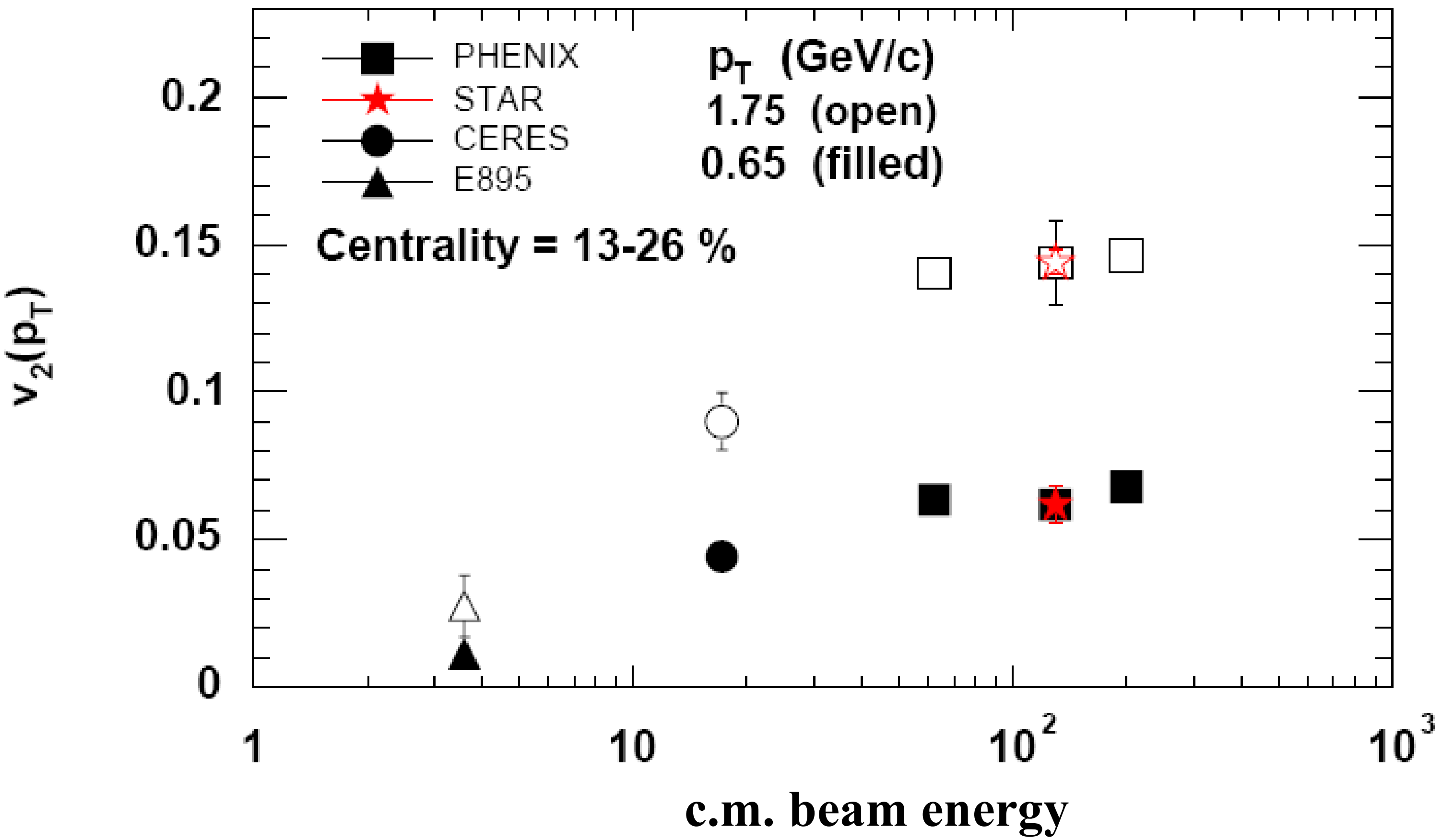
D. Magestro (updated July 22, 2002)

Elliptic flow scales with number of quarks



implication: quarks are the relevant degrees of freedom when the pressure is built up

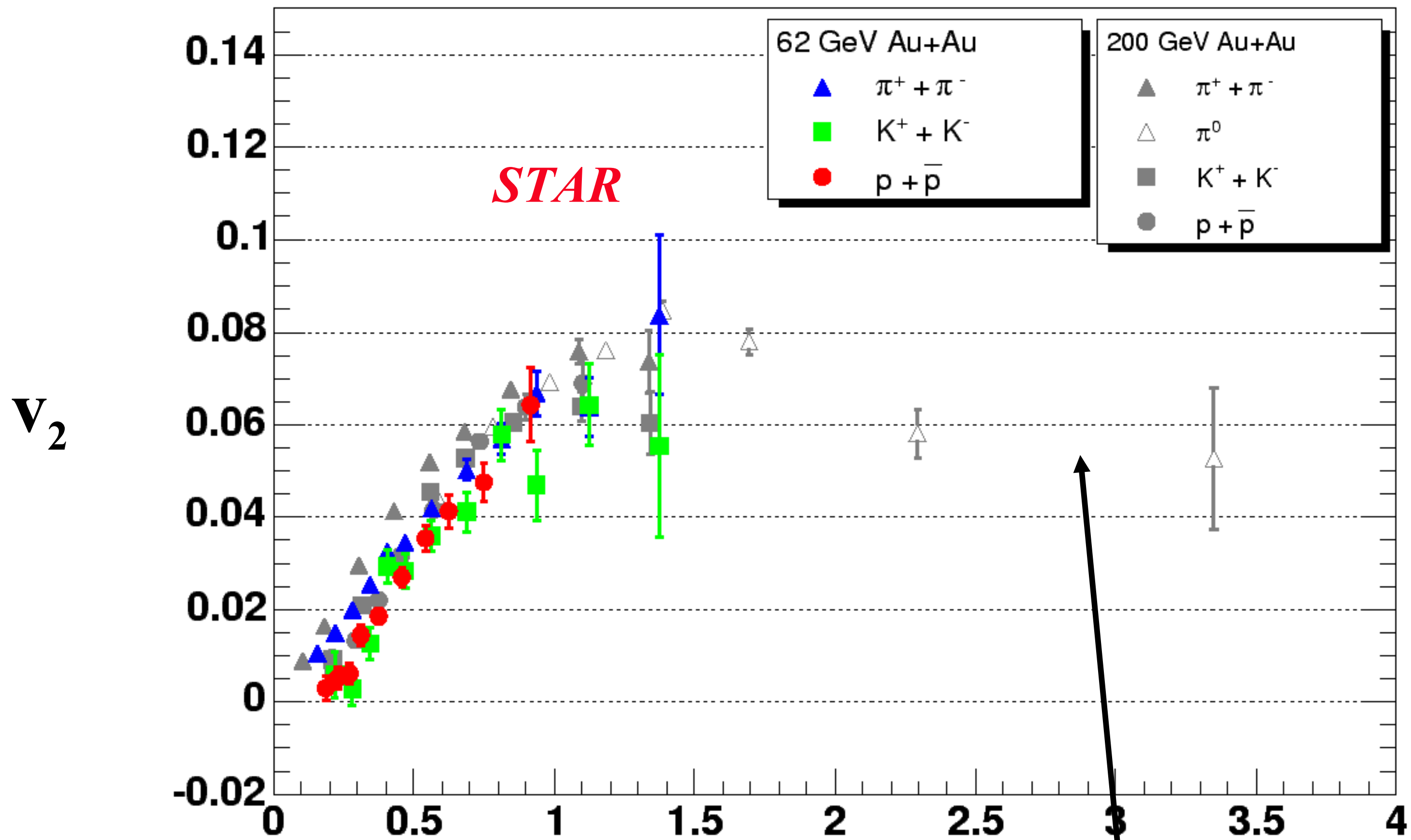
beam energy dependence



Anisotropy amplitude grows with beam energy, then flattens.

For LHC first guess – use same v_2 at same p_T

at high p_T v_2 reflects opacity of medium



approximately expected level from jet quenching

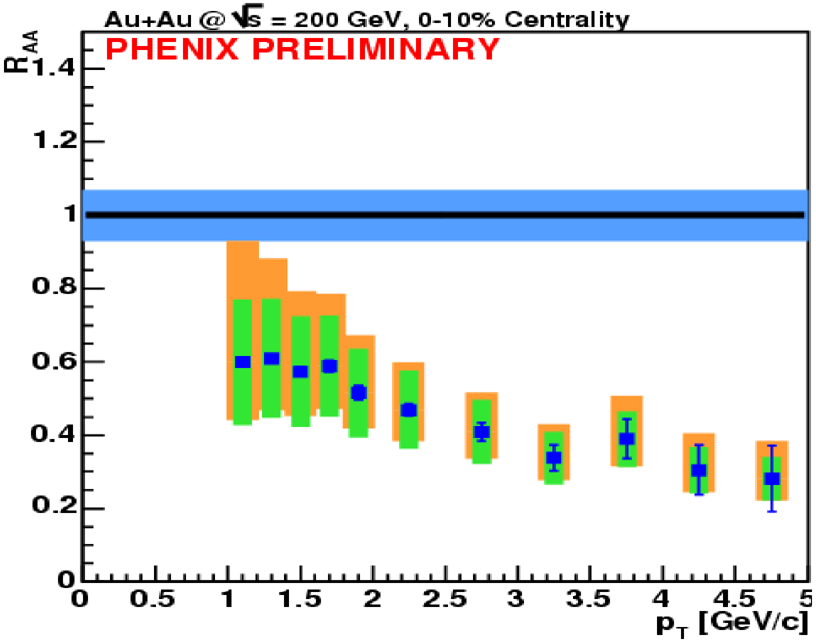
other probes? *consider leptons in matter*

- electrons vs. muons
- electrons radiate γ and stop very quickly
  - the radiation is bremsstrahlung
- muons have large range because they DON'T radiate!
  - radiation is suppressed by the large mass
  - dominant energy loss mechanism is via collisions
- suggests that we should use heavy quarks to probe
  - should we expect collisional energy loss for heavy quarks?
  - is it reasonable to expect ONLY radiative energy loss for light quarks?

EM plasmas suggest answer = no

radiation: blackbody, bremsstrahlung, collisional, recombination

further test interaction with charm quarks ($m=1.3$ GeV/c^2)

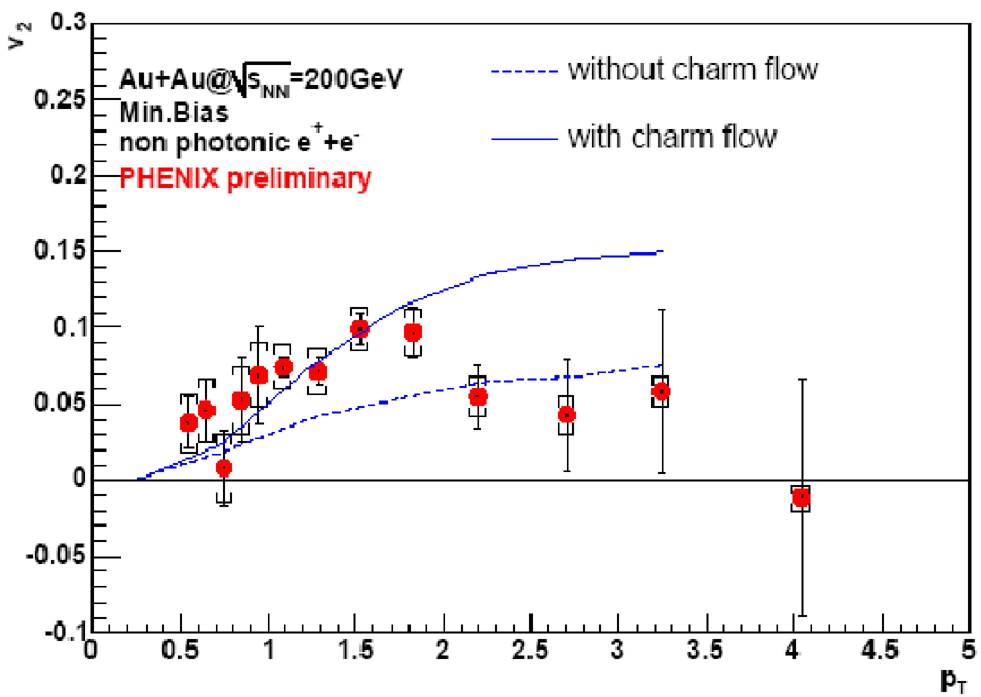


~ same E loss as u,d quarks

∴ energy loss not all radiative

need collisions!

charm also flows

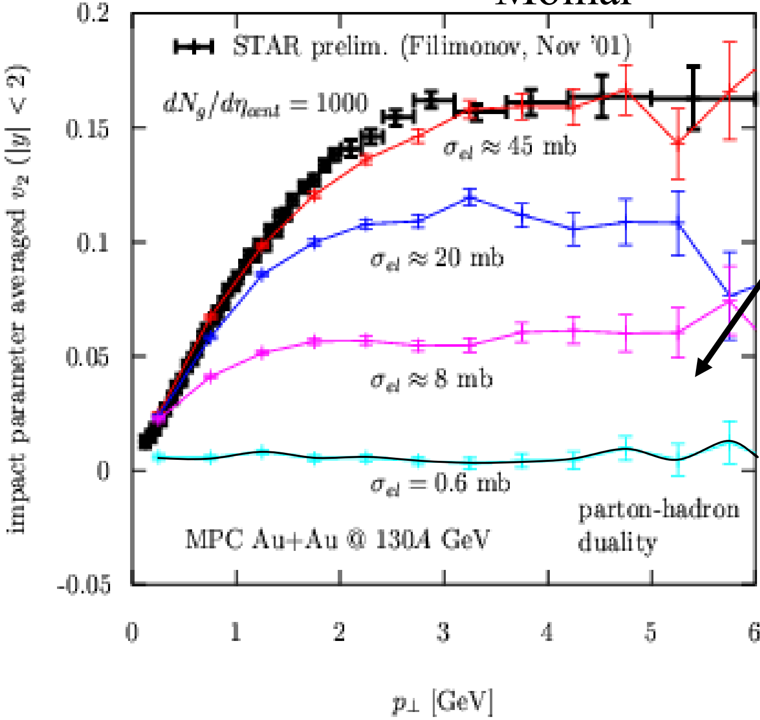


thermalization with the light quarks?

not so easy!

Fast equilibration, high opacity (even for charm): how?

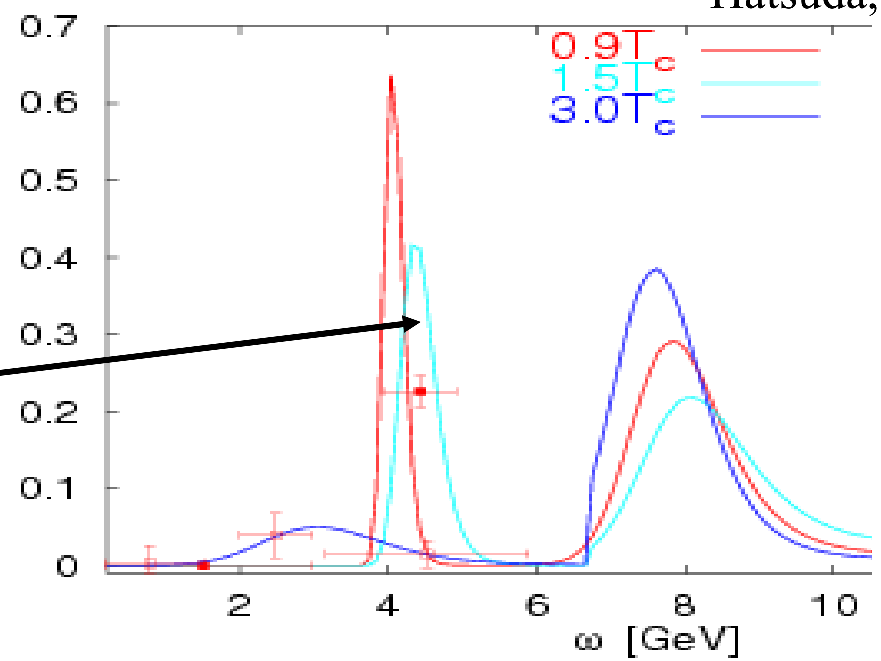
Molnar



multiple collisions using free q,g scattering cross sections ***<u>doesn't work!</u>***

need σ x50 in the medium

Hatsuda, et al.



Lattice QCD shows $q\bar{q}$ resonant states at T > Tc, also implying high interaction cross sections

What is going on?

- The objects colliding inside the plasma are not baryons and mesons
- The objects colliding also do not seem to be quarks and gluons totally free of the influence of their neighbors
- So, what kind of a plasma should we expect the QGP to be?

Plasma Coulomb coupling parameter Γ

- ratio of mean potential energy to mean kinetic energy

$$\Gamma_e = (e^2/4\pi\varepsilon_0 a)/k_B T_e$$

a = interparticle distance

e = charge

T = temperature

$$a = (4\pi n/3)^{-1/3}$$

- typically a small number in a normal, fully shielded plasma

  Γ = 1/(number particles in Debye sphere)

- when Γ > 1 have a strongly coupled, or non-Debye plasma

  many-body spatial correlations exist

  behave like liquids, or even crystals when Γ > 150

  $\lambda_D < a$

plasma basics – Debye Length

- distance over which the influence of an individual charged particle is felt by the other particles in the plasma
- charged particles arrange themselves so as to effectively shield any electrostatic fields within a distance of order λ_D
- $\lambda_D = \left(\dfrac{\varepsilon_0 kT}{n_e e^2} \right)^{1/2}$
- Debye sphere = sphere with radius λ_D
- number electrons inside Debye sphere is typically large

  $N_D = N/V_D = \rho V_D \quad V_D = 4/3\, \pi\, \lambda_D^{\,3}$

Debye screening in QCD: a tricky concept

- **in leading order QCD (O. Philipsen, hep-ph/0010327)**

$$V(r) \sim \frac{\mathrm{e}^{-\mathrm{m}_\mathrm{D}^0 \mathrm{r}}}{4\pi r}, \quad m_D^0 = \left(\frac{N}{3} + \frac{N_f}{6}\right)^{1/2} gT \,.$$

- However, at next-to-leading order the problem becomes non-perturbative. The general form of the series in g can be shown to be [2]

$$m_D = m_D^0 + \frac{N}{4\pi} g^2 T \ln \frac{m_D^0}{g^2 T} + c_N g^2 T + \mathcal{O}(g^3 T)\,, \qquad (6)$$

which is non-analytic in the coupling constant. While the coefficient of the logarithm is fixed perturbatively, c_N is entirely non-perturbative. The reason is that, starting from this order in g, the non-abelian A_0 couples to the soft magnetic gluons $A_i \sim g^2 T$, and hence becomes sensitive to the non-abelian infrared divergencies in the magnetic sector for which there is no perturbative cure [3]: $\Pi_{ii}(k_0 = 0, \mathbf{k} \to 0) \sim g^2 T \neq 0$, with contributions from all loop orders two and larger.

This raises the conceptual problem whether a perturbative definition of Debye screening in QCD is at all sensible.

give up on the concept?

Of course not!!!

- Two options proposed by Philipsen:
  1) assume a pole in the propagator and attempt to measure its value from the exponential fall-off in some fixed gauge (done with lattice QCD)
  2) seek a manifestly gauge invariant definition

- Lattice says: "interactions weak @ l =1/T, but screening function is not exponential until 1/2T"
- *idea: calculate λ_D for strongly coupled plasma & convert ε inside to particle density to get Γ*

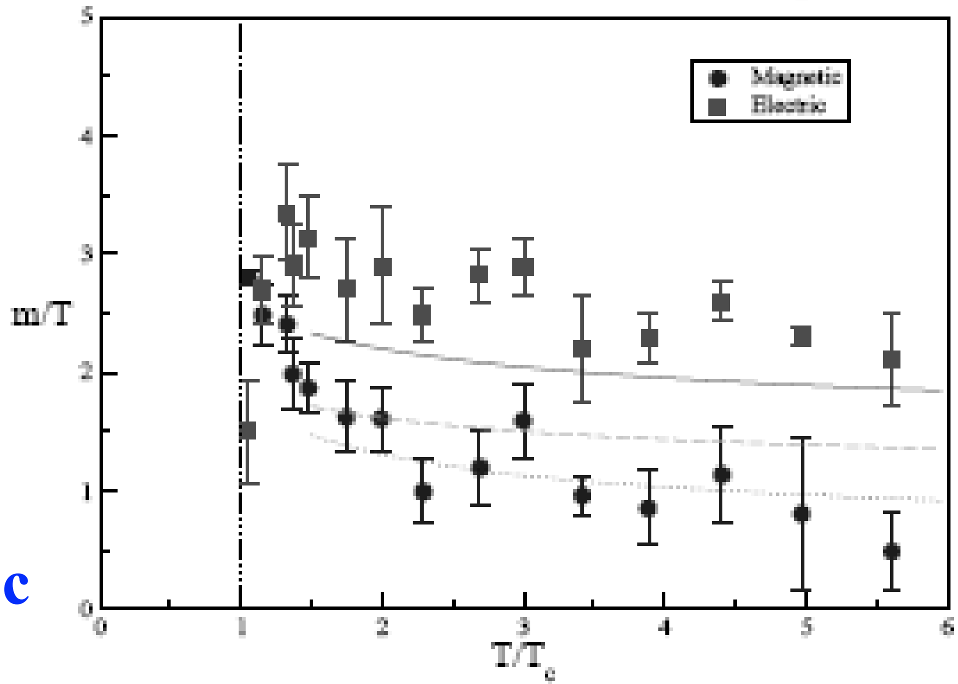
screening and thermal masses

Screening mass, m_D, defines inverse length scale

Inside this distance, an equilibrated plasma is sensitive to insertion of a static source

Outside it's not.

Nakamura, Saito & Sakai, hep-lat/0311024



T dependence of electric & magnetic screening masses

Quenched lattice study of gluon propagator

figure shows:

$m_{D,m}$= 3Tc, $m_{D,e}$= 6Tc at 2Tc

$\lambda_D \sim$ 0.4 & 0.2 fm

magnetic screening mass significant not very gauge-dependent, but DOES grow w/ lattice size (long range is important)

compare to oversimplified Γ estimate

estimate $\Gamma = \langle PE\rangle / \langle KE\rangle$

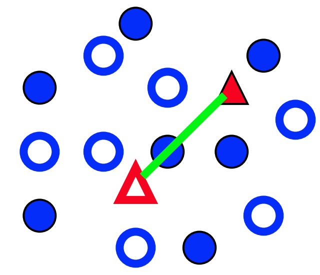
using QCD coupling strength g

$\langle PE\rangle = g^2/d \quad d \sim 1/(4^{1/3}T)$

$\langle KE\rangle \sim 3T$

$\Gamma \sim g^2\,(4^{1/3}T)\,/\,3T$

$g^2 \sim 4\text{-}6$ (value runs with T)



Γ > 1: strongly coupled, few particles inside Debye radius

for T=200 MeV plasma parameter $\Gamma \sim 3$

see M. Thoma, J.Phys. G31(2005)L7

use λ=0.2 fm and ε=15 GeV/fm^3 get 0.5 GeV inside Debye sphere

FEW particles!

∴ quark gluon plasma should be a strongly coupled plasma

As in warm, dense plasma at lower (but still high) T

dusty plasmas, cold atom systems

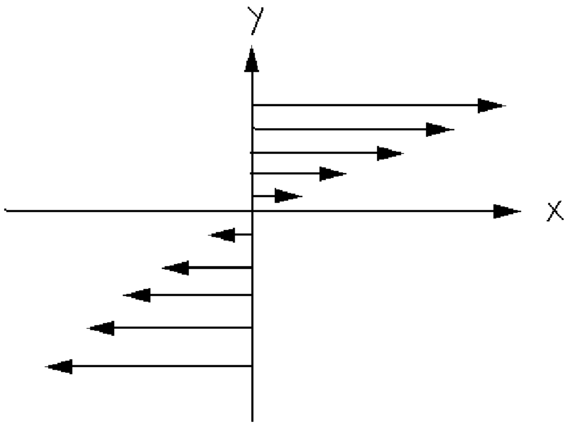
such EM plasmas are known to behave as liquids!

so, what is a "perfect fluid?"

- **one that exhibits ideal, non-dissipative hydrodynamics**

  "not-quite-ideal" = can support a shear stress

  Viscosity η is $\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$



- **$\eta \sim \langle v \rangle / \sigma \sim \sqrt{kT}/\sigma$**

  so viscosity *increases* with T

  ***decreases* with σ**

Ideal hydrodynamics ($\eta \sim 0$) reproduces data at RHIC

does this make sense to QCD?

→ $\eta \gtrsim (h/4\pi)\, S$: conjectured quantum mechanical limit

entropy density

"*A Viscosity Bound Conjecture*",

P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231

collisions → transport in the plasma

- transport of particles → diffusion
- transport of energy by particles → thermal conductivity
- transport of momentum by particles → viscosity
- transport of charge by particles → electrical conductivity
  is transport of color charge an analogous question for us?

what exactly is diffusion?

- **diffusion = brownian motion of particles**

  definition: flux density of particles $J = -D \text{ grad } n$

  particle concentration

- **integrating over forward hemisphere:**

  D = diffusivity = $1/3 \langle v \rangle l$

  l = mean free path

  so $D = \langle v \rangle / 3n\sigma$

$D \propto$ collision time

determines relaxation time for the system

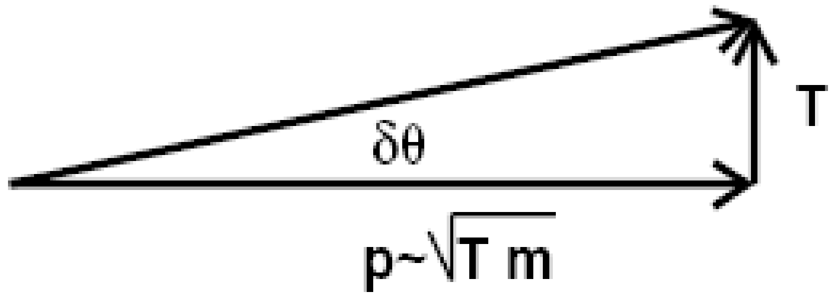
note: $\eta = 1/3 \rho \langle v \rangle l$ so $D = \eta/\rho$

nice implication: measure D get η!

ρ from T, or maybe transmission

Estimate of transport times with Heavy Quarks

- Put a heavy quark in this medium



$$\delta\theta \sim \sqrt{\frac{T}{m}}$$

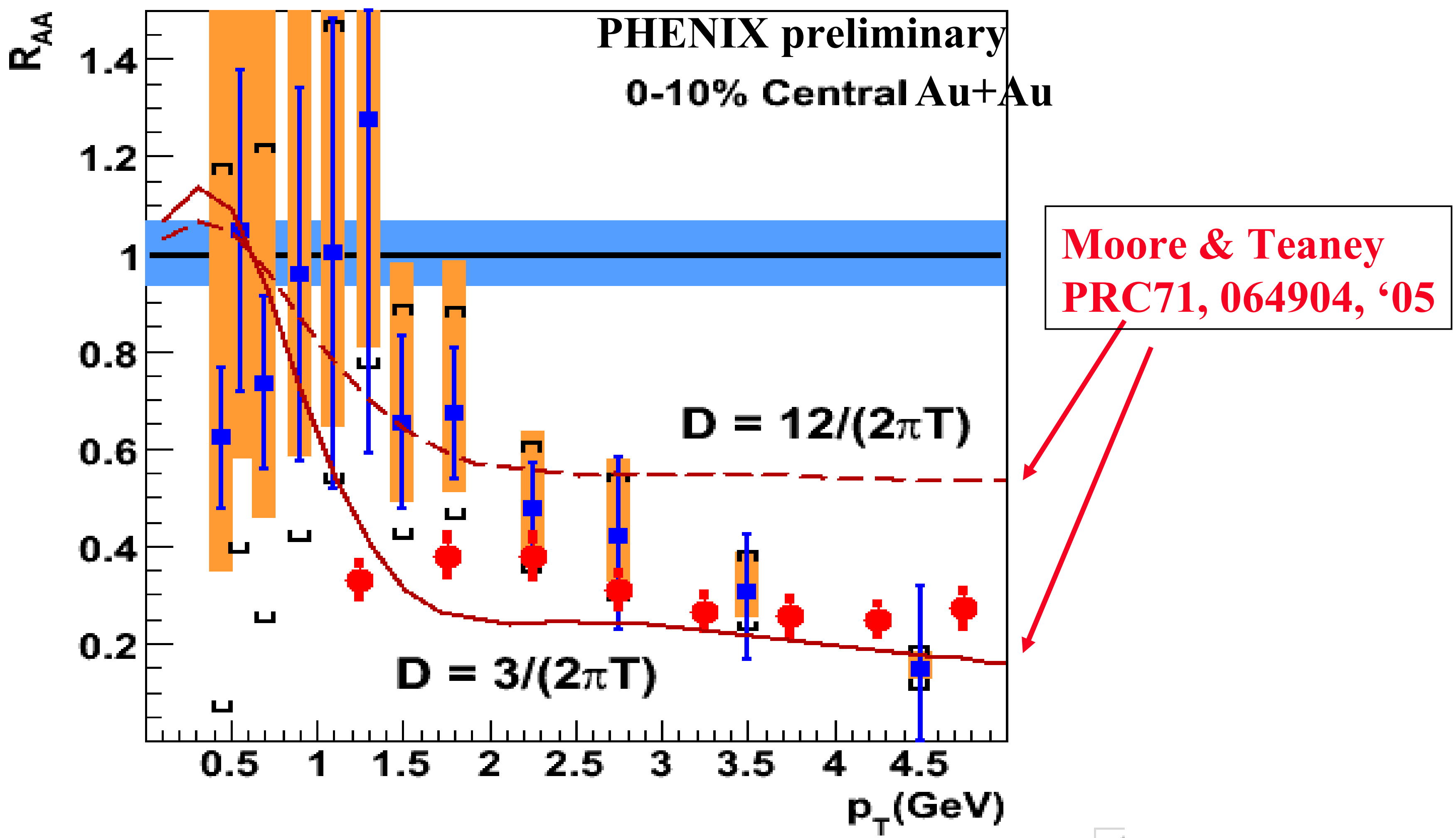
- The charm quark undergoes a random walk suffering many collisions

- The relaxation time of the heavy quark is:

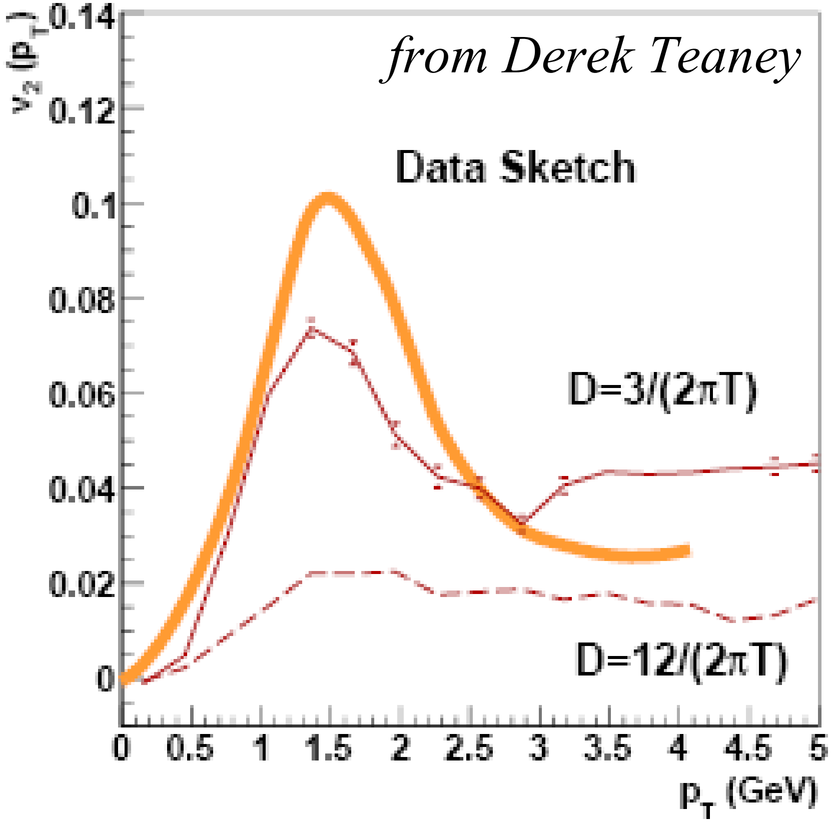
$$\tau_R^{\text{charm}} \sim \frac{M}{T}\tau_R^{\text{light}}$$

Will the heavy quark follow the flow of the underlying medium

can we measure the diffusion coefficient?



collisional energy loss also implies flow

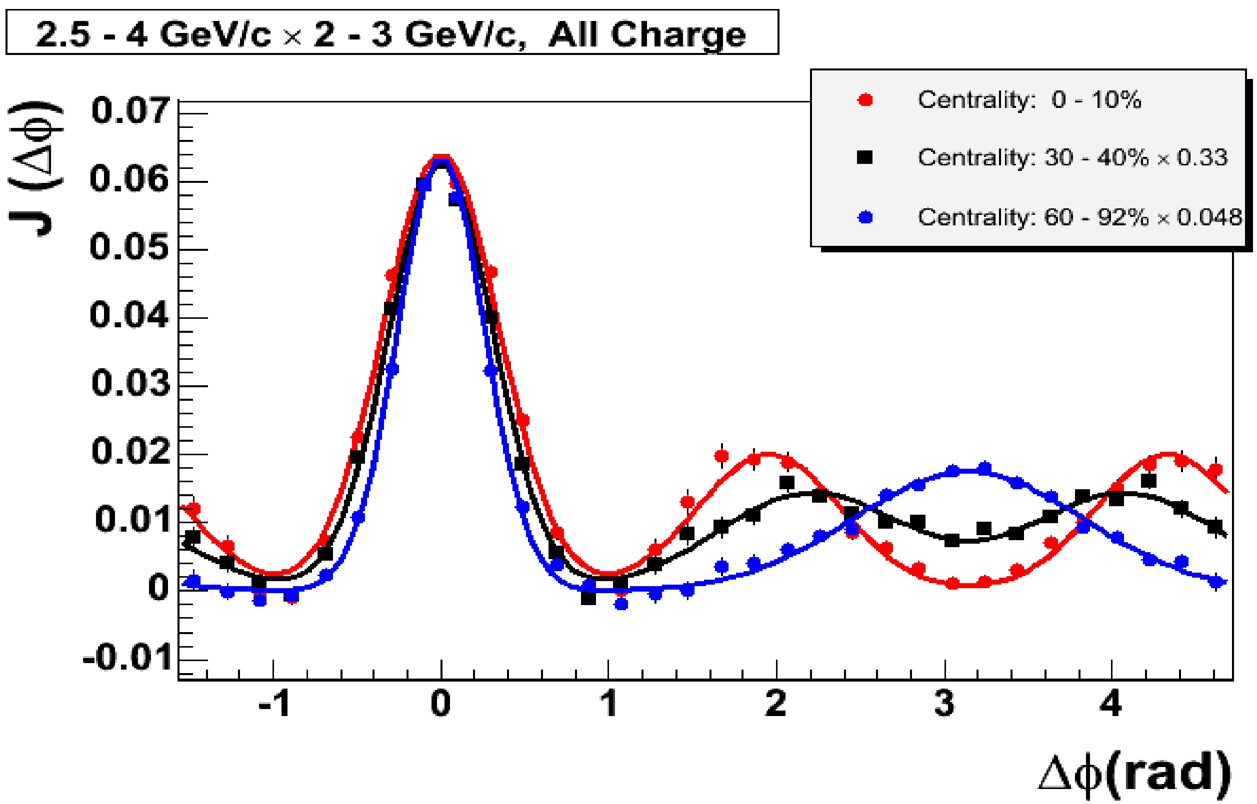


D ~ 3/(2πT)
small!
→ strong interaction of charm quarks with the plasma

larger D would mean less charm e loss fewer collisions with plasma, smaller v_2

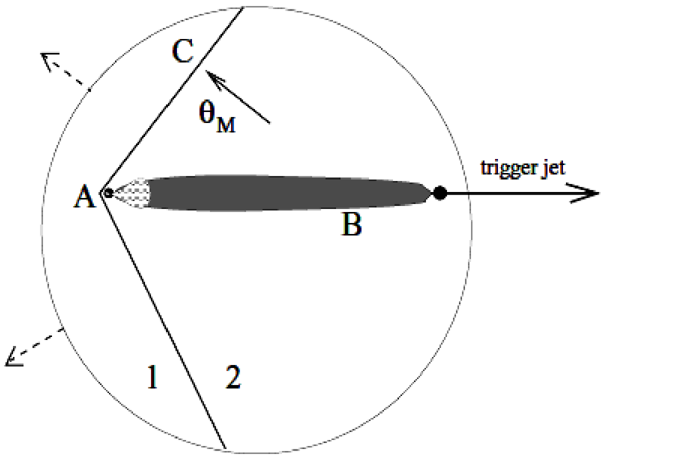
can we measure the energy transport?

- Plasma physicists do by applying a shear stress, or shock
- Jets do that when they dump energy into QGP
  where does the energy go?

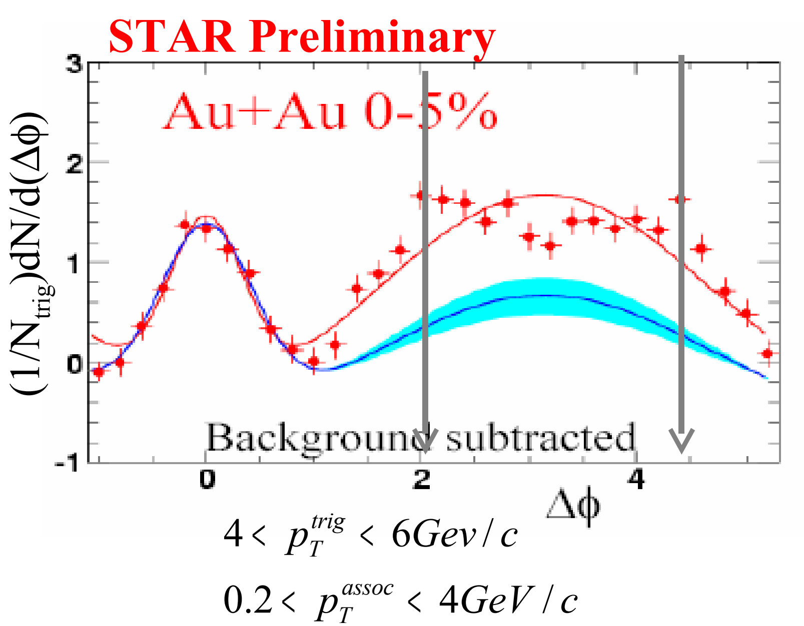


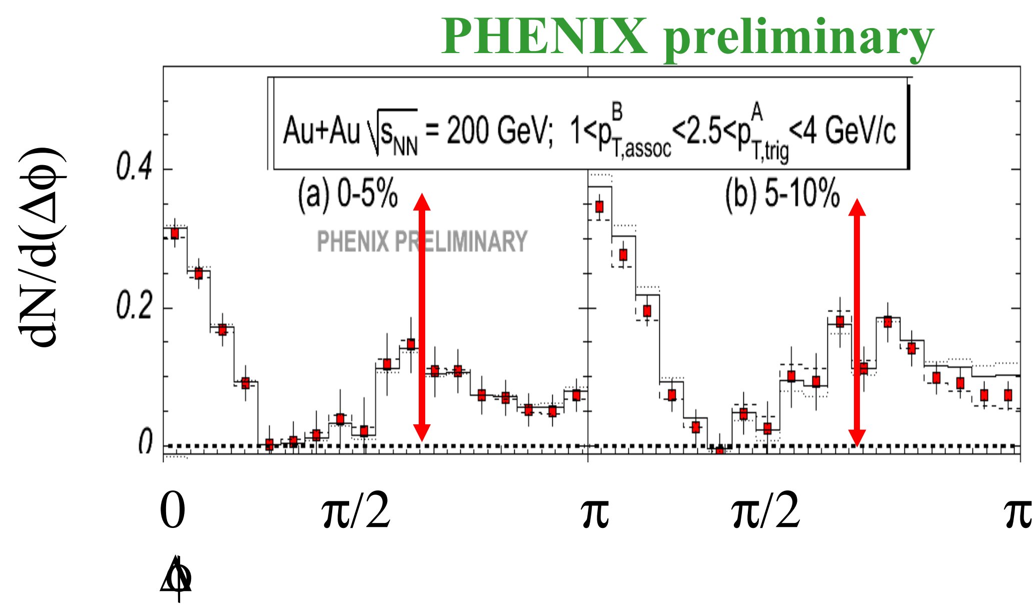
look at lower p_T particles where away side jet should be

excite a density wave in the plasma?



g radiates energy
kick particles in the plasma
accelerate them along the jet

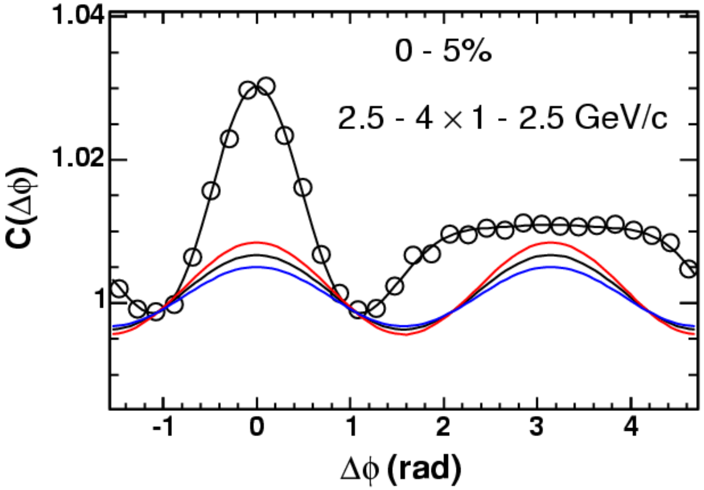


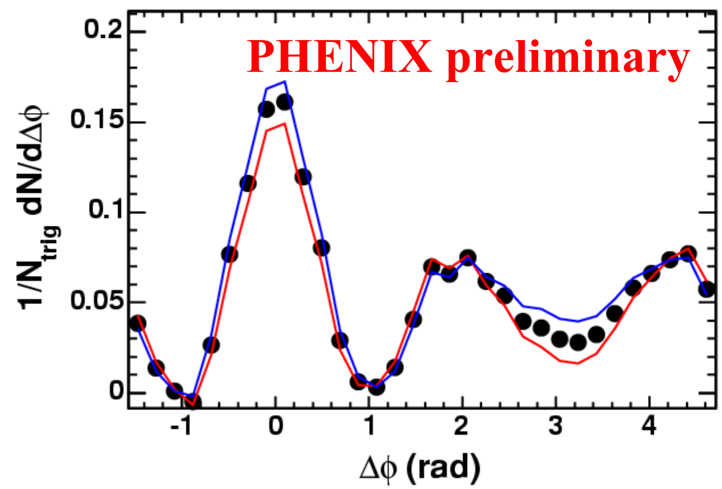


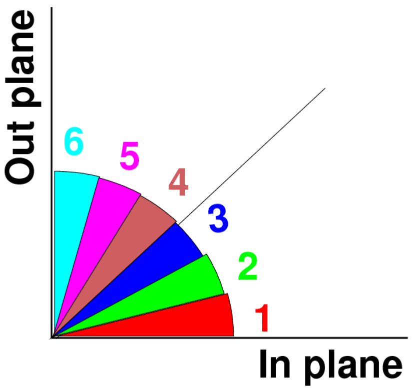
ϕ=π ⇓∝↖1.23=1.91,4.37 → c_s ~ 0.33

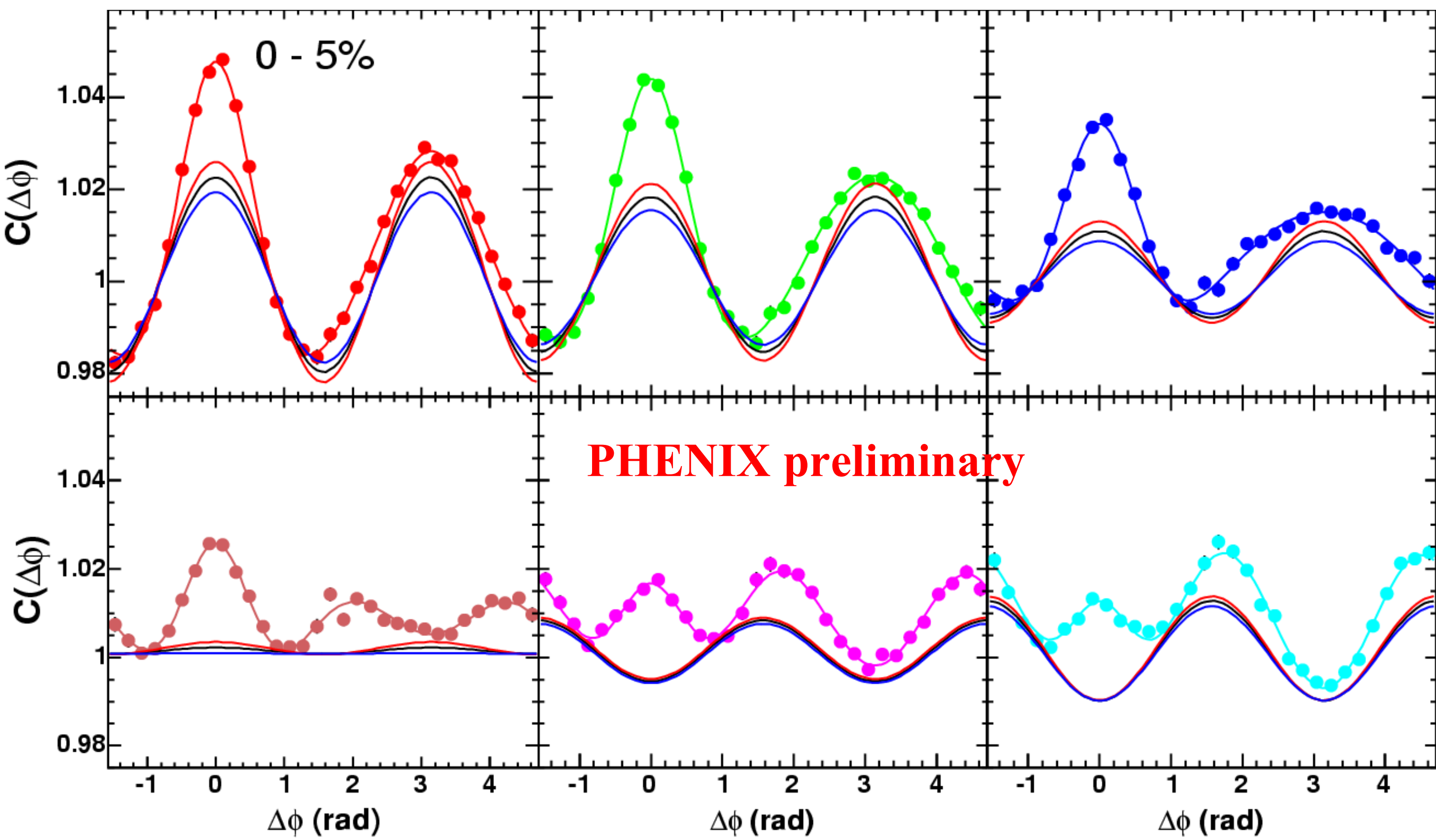
(√0.33 in QGP, 0.2 in hadron gas)

0-5%


0 - 5%
2.5 - 4 × 1 - 2.5 GeV/c
C(Δφ)
Δφ (rad)


PHENIX preliminary
1/N_trig dN/dΔφ
Δφ (rad)


Out plane
In plane
6
5
4
3
2
1


0 - 5%
PHENIX preliminary
C(Δφ)
Δφ (rad)

Compressional and shear wakes in a two-dimensional dusty plasma crystal

NOSENKO *et al.* PHYSICAL REVIEW E 68, 056409 (2003)

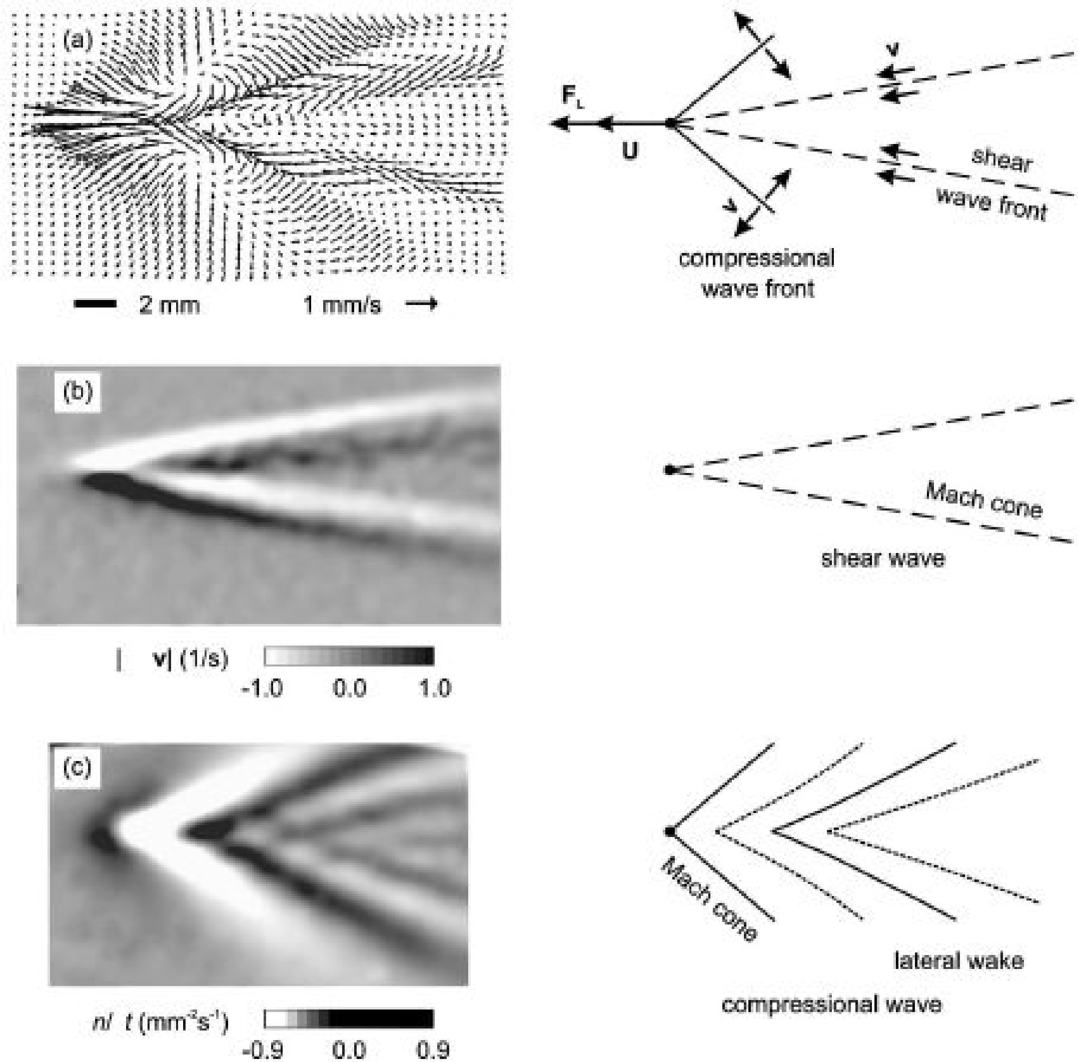
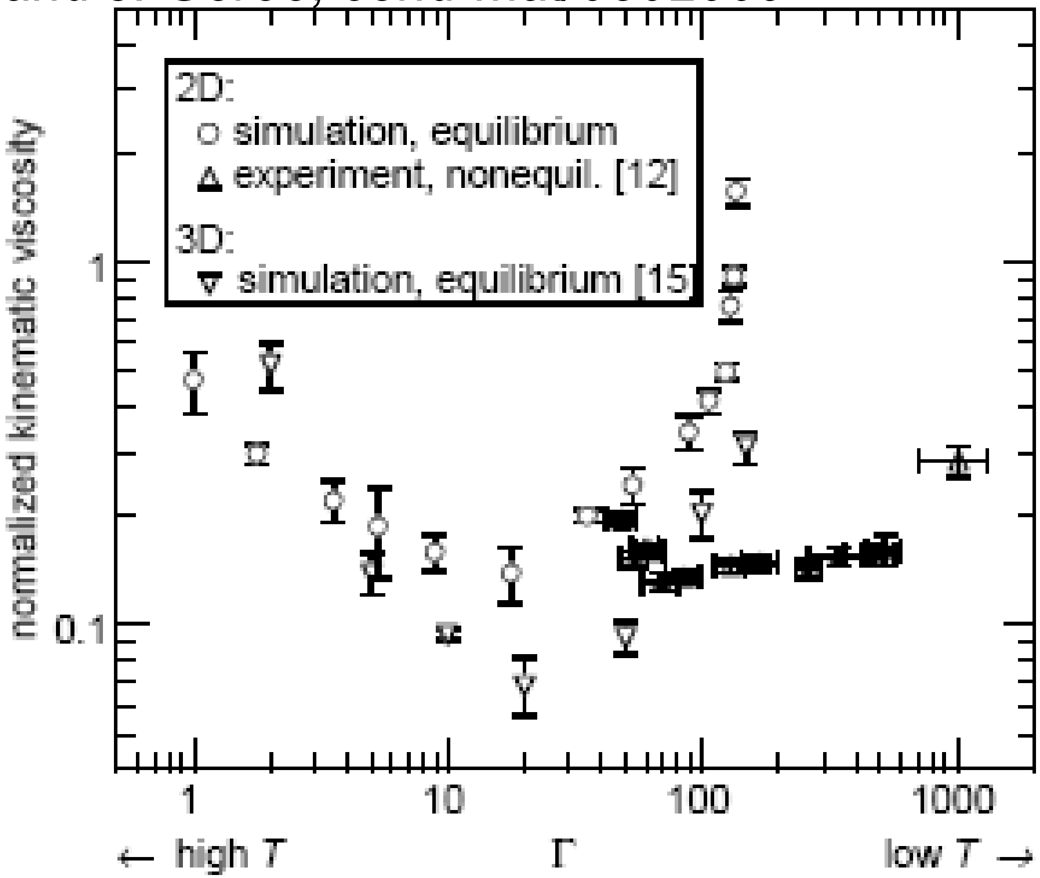


FIG. 4. The compressional- and shear-wave Mach cones, excited simultaneously. The scanning speed U is higher than the sound speed for both the compressional and shear waves. Maps are shown for (a) particle velocity $\mathbf{v}$, (b) vorticity $|\nabla \times \mathbf{v}|$, and (c) $\partial n/\partial t$, where n is the particle areal number density.

generally a phenomenon in crystals but not liquids

use to get η & compare to molecular dynamics

B. Liu and J. Goree, cond-mat/0502009



MD: solve the equations of motion for massive particles subject to (screened) interaction potential

follow evolution of particle distribution function (&correlations)

solve coupled diff.eq's over nearby space

density-density correlations → η

minimum arises because kinetic part of η decreases with Γ & potential part increases

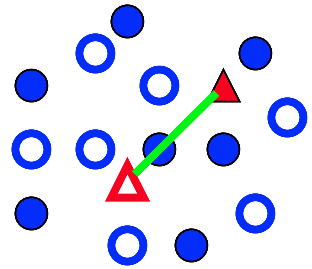
aim to measure the screening length

J/Ψ (bound state of c and cbar quarks)

Tests screening & confinement:

do bound c + c survive the medium?

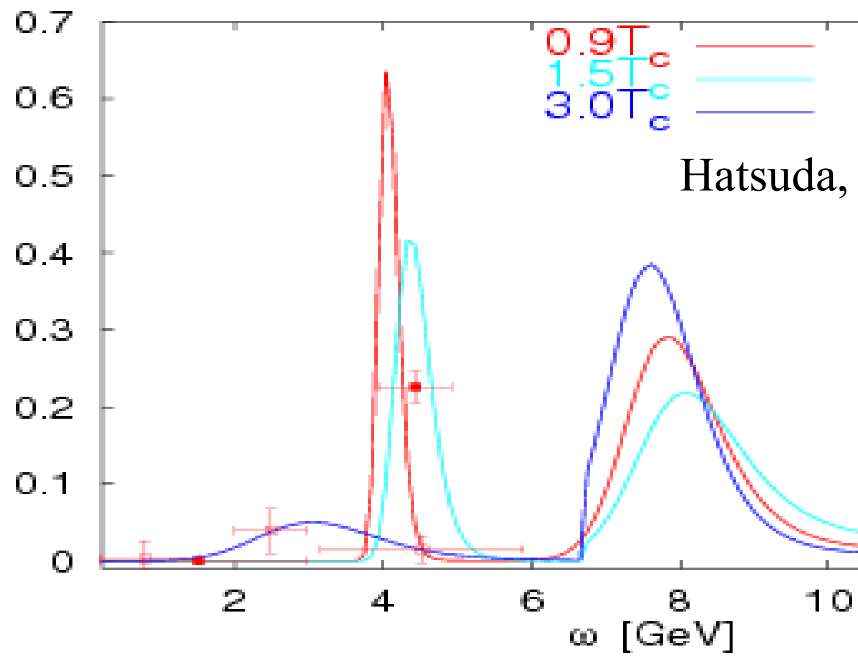
or does QGP screening kill them?



Look at R_{AA} for J/ψ

different bound states

probe different lengths



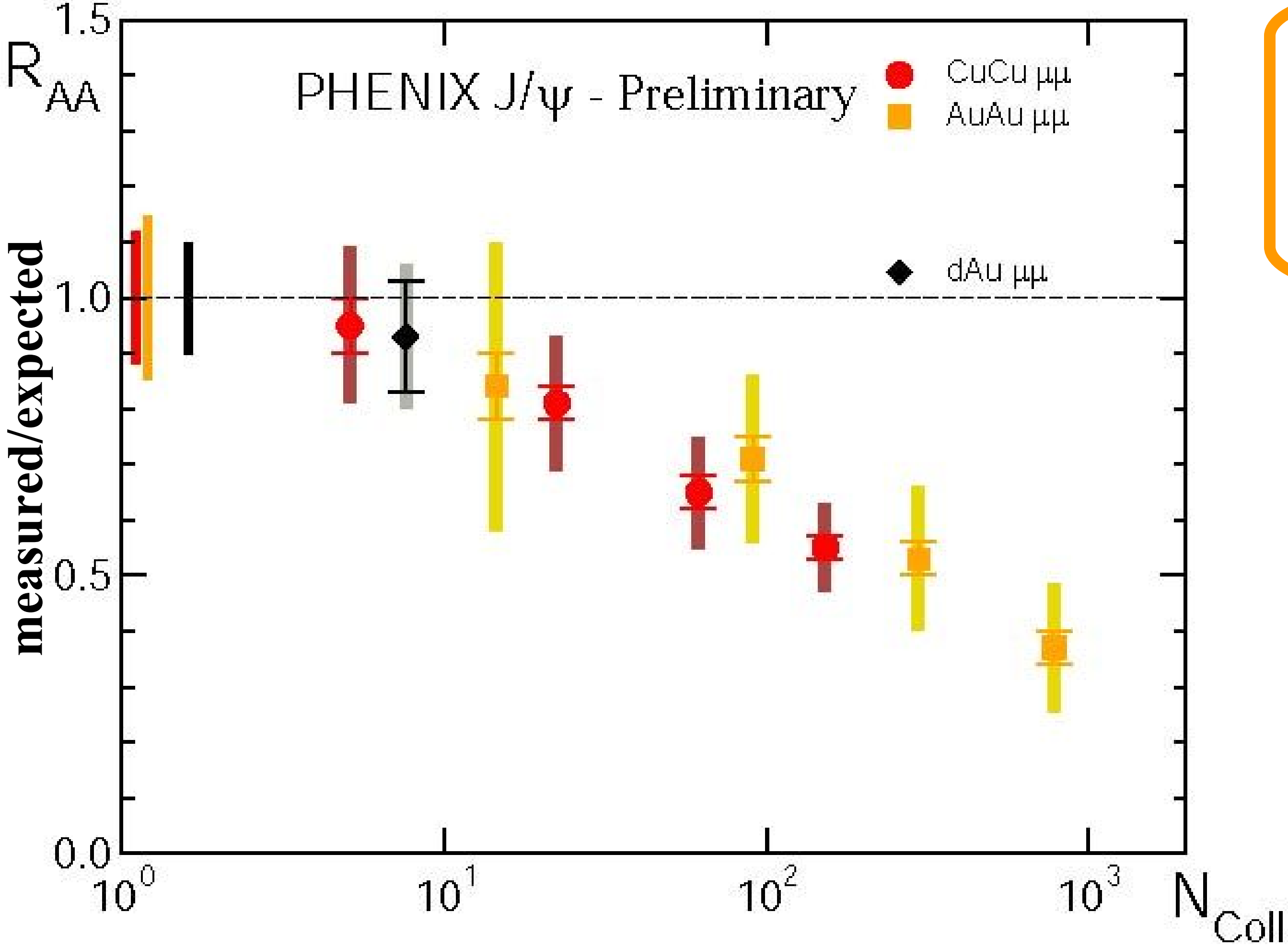
Hatsuda, et al.

note:

it's not so clear

what to expect…

At RHIC:



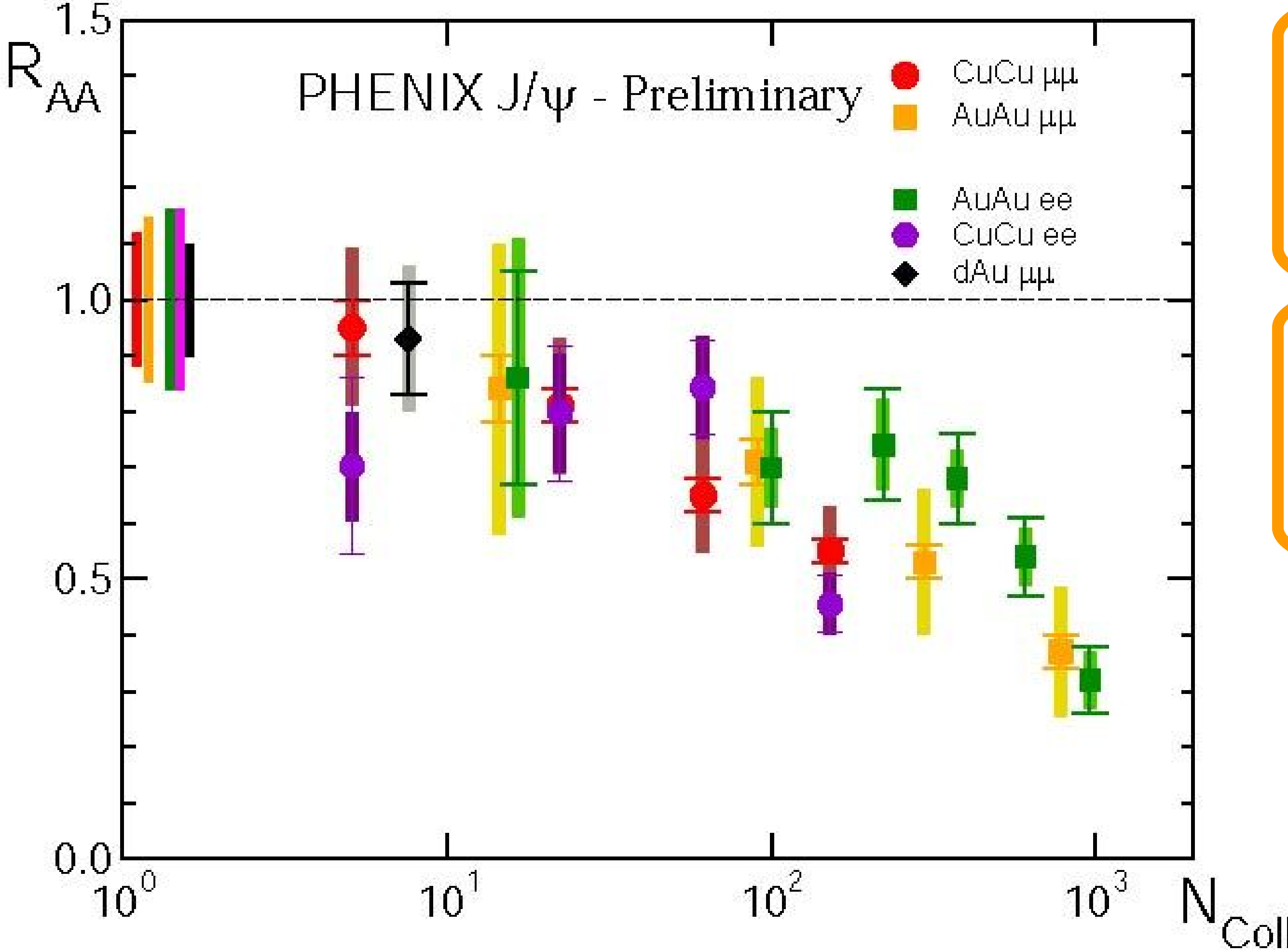
J/ψ → μμ
muon arm
1.2 < |y| < 2.2

dAu
μμ
200 GeV/c

AuAu
μμ
200 GeV/c

CuCu
μμ
200 GeV/c

At RHIC:

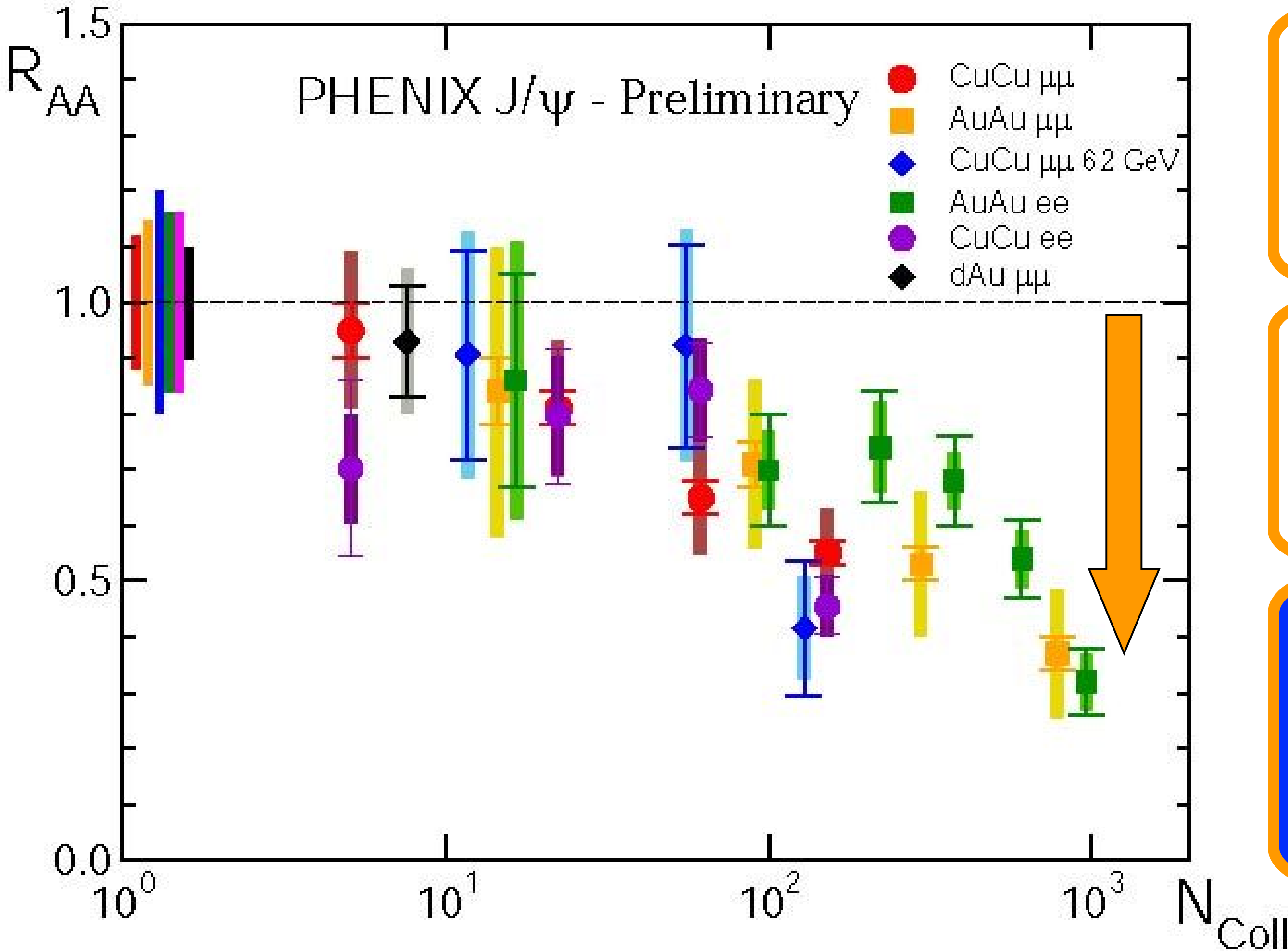


J/ψ → μμ
muon arm
1.2 < |y| < 2.2

J/ψ → ee
Central arm
-0.35 < y < 0.35

dAu **μμ** **200 GeV/c**	**AuAu** **μμ** **200 GeV/c**	**CuCu** **μμ** **200 GeV/c**	**AuAu** **ee** **200 GeV/c**	**CuCu** **ee** **200 GeV/c**

At RHIC:



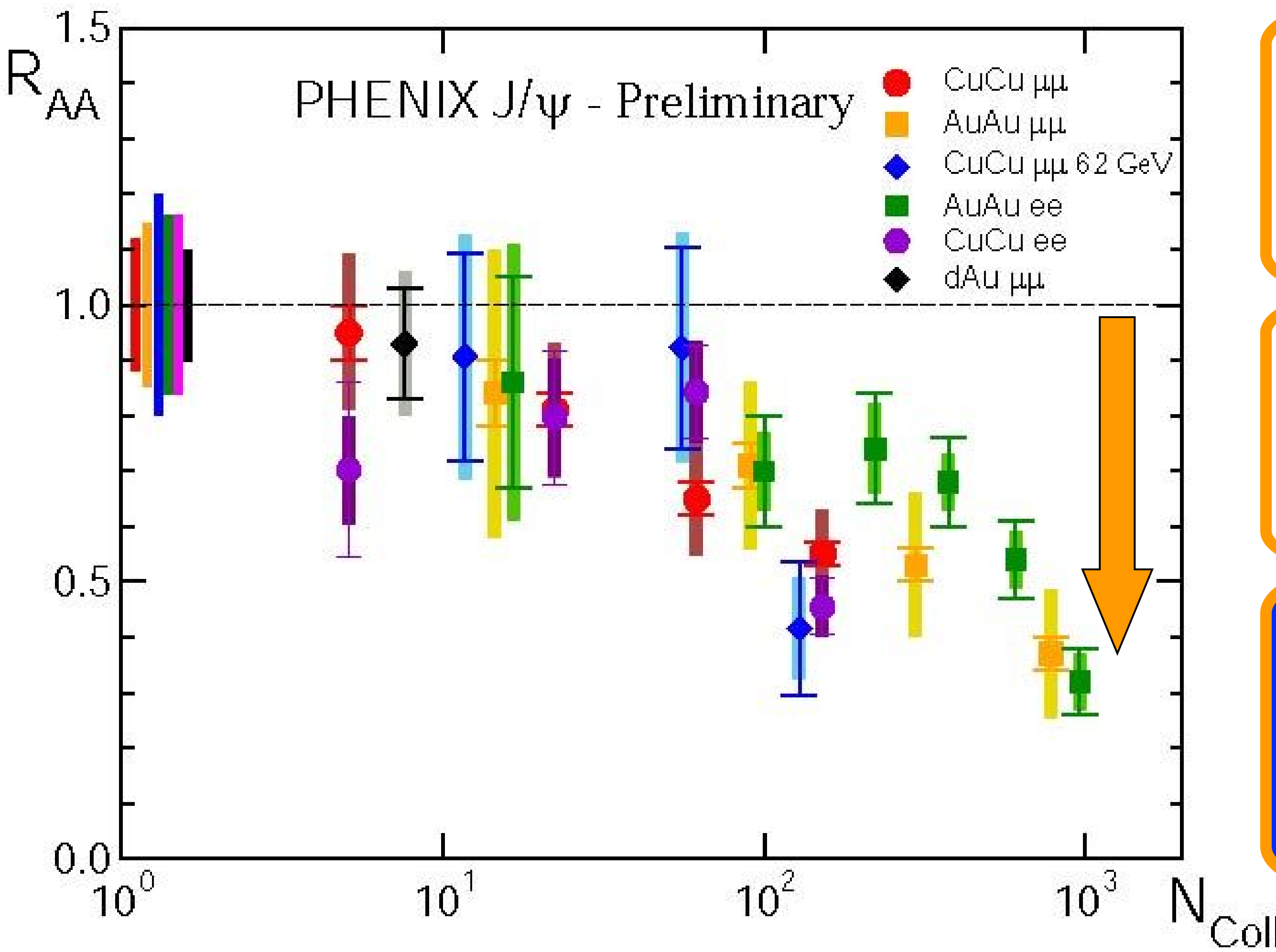
J/ψ → μμ
muon arm
1.2 < |y| < 2.2

J/ψ → ee
Central arm
-0.35 < y < 0.35

Factor ~3 suppression in central events !

dAu μμ 200 GeV/c	AuAu μμ 200 GeV/c	CuCu μμ 200 GeV/c	AuAu ee 200 GeV/c	CuCu ee 200 GeV/c	CuCu μμ 62 GeV/c

At RHIC:



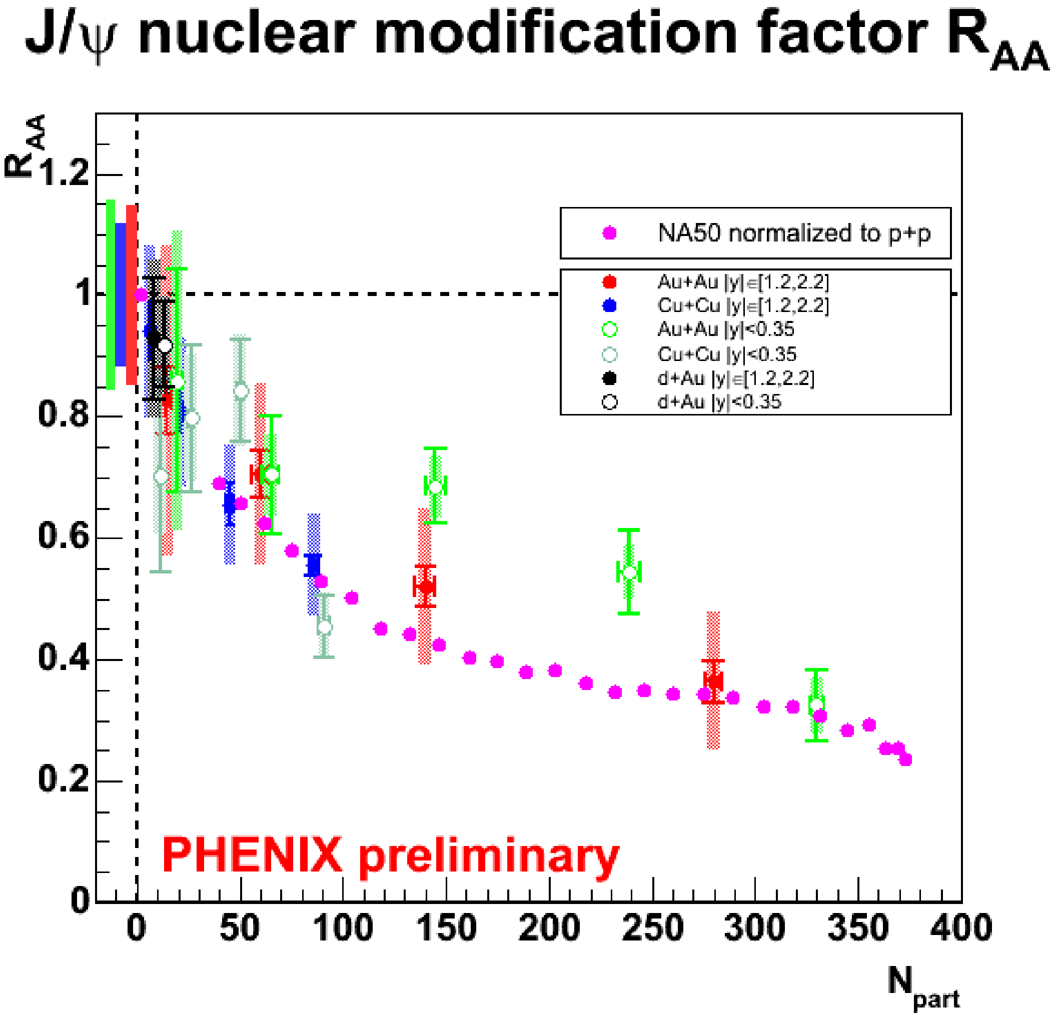
J/ψ → μμ
muon arm
1.2 < |y| < 2.2

J/ψ → ee
Central arm
-0.35 < y < 0.35

Factor ~3 suppression in central events

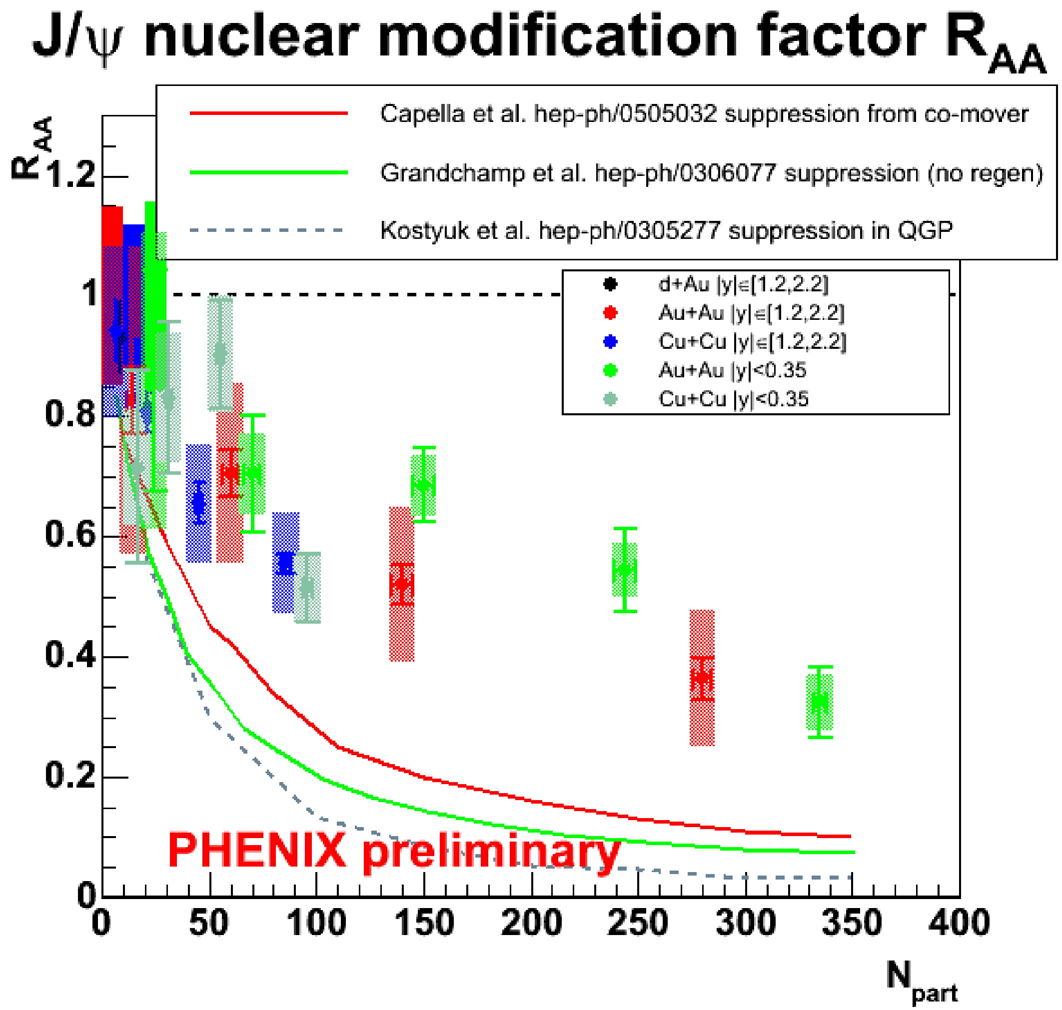
Data show the same trend within errors for all beams and even at √s=62 GeV

R_{AA} vs N_{part}: PHENIX and NA50



- ❑ NA50 data normalized at NA50 p+p point.
- ❑ Suppression similar in the two experiments, although the collision energy is 10 times higher (200GeV in PHENIX & 17GeV in NA50)

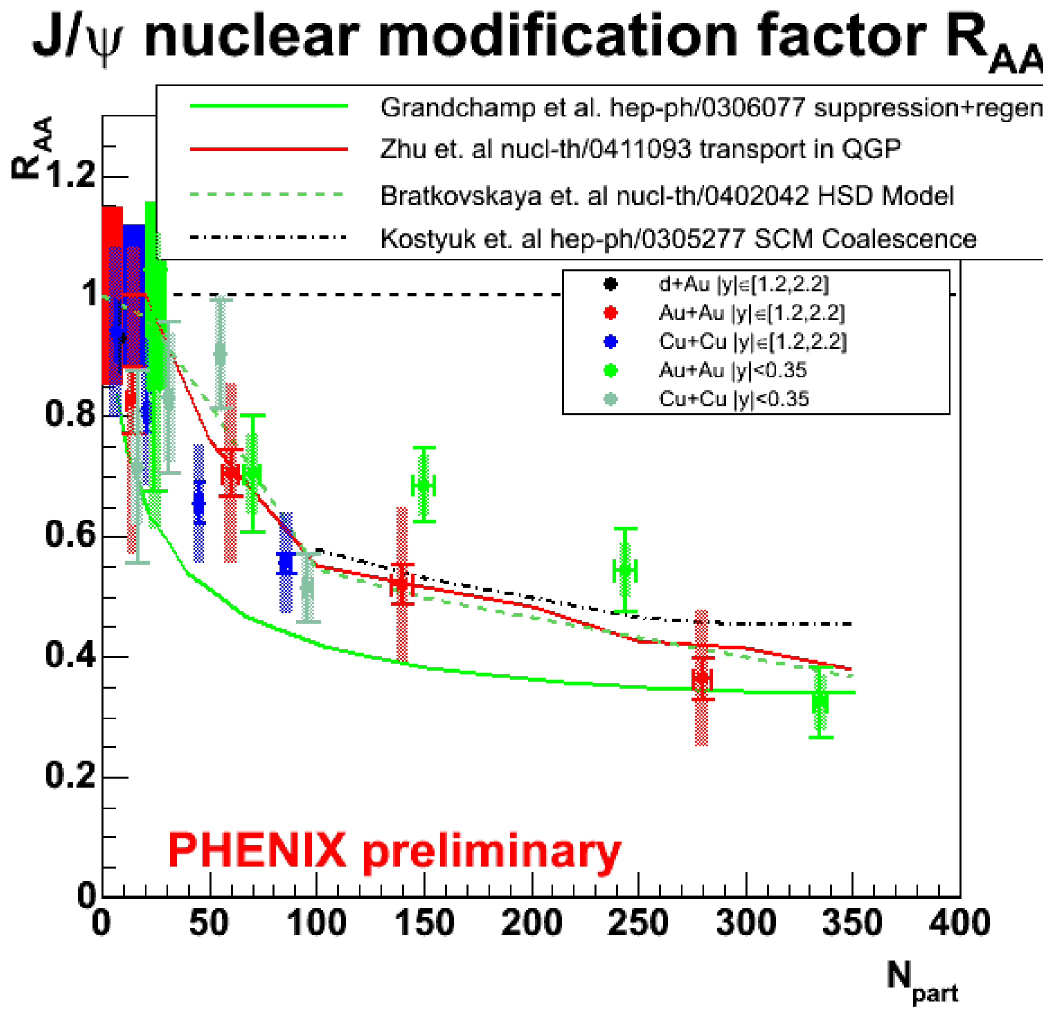
What suppression should we expect?



Models that were successful in describing SPS data fail to describe data at RHIC

- but lattice QCD says bound states until ~2T_c -

can get better agreement with data



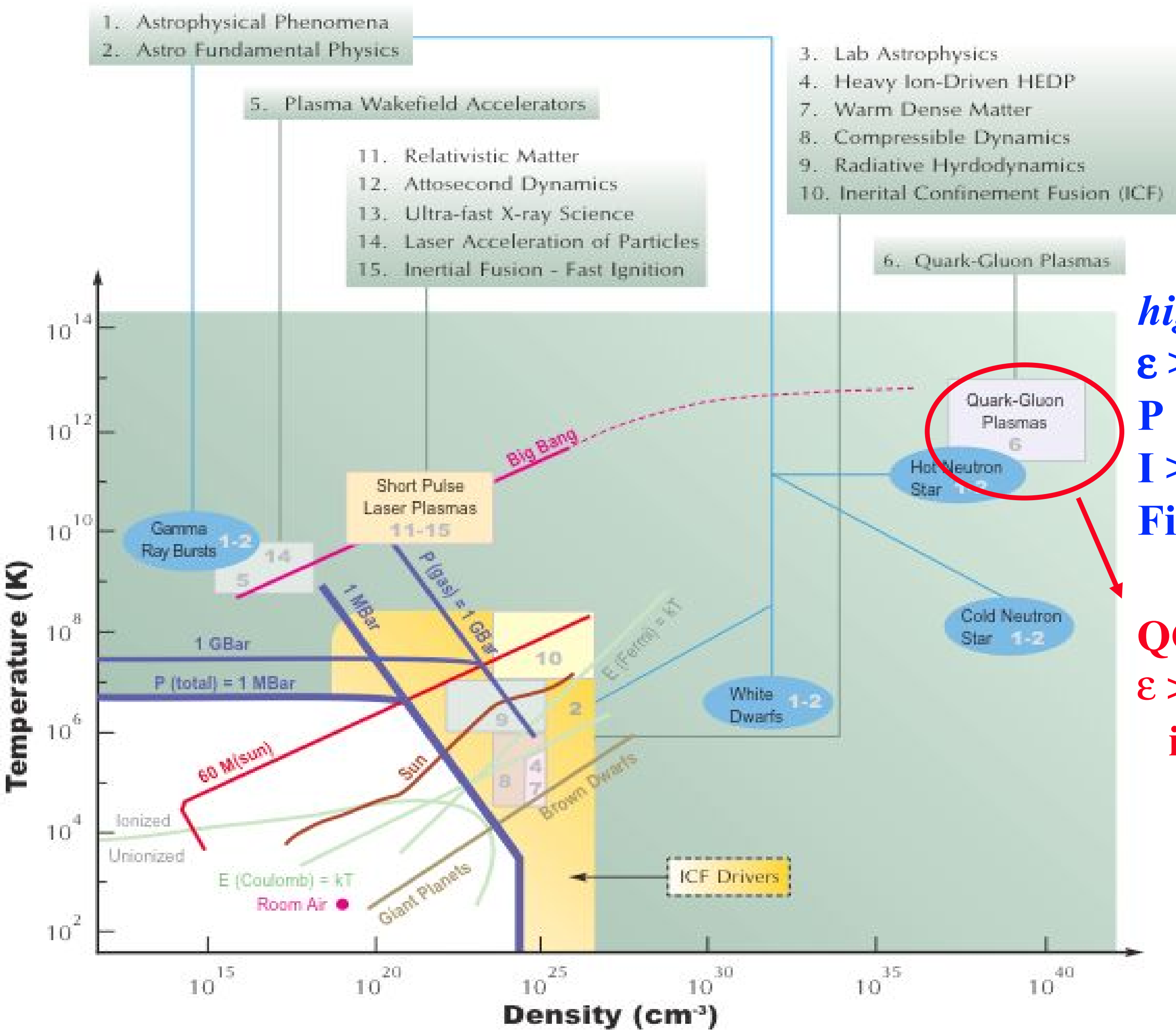
if add formation of “extra” J/ψ by coalescence of c and anti-c from the plasma
caveat: not necessarily unique or correct explanation!

conclusions

- the matter formed at RHIC is a "perfect" fluid
  shows collective flows with small viscosity
  huge interaction cross sections, very opaque
  multiple collisions affect even heavy charm quarks
- this is like other strongly coupled plasmas
  as it *should* be $\rightarrow$ it *is* a plasma!
  neutrality scale > interparticle distance

- How does this super high energy density plasma work?
  - □ map properties of the new stuff at RHIC
    how does the plasma transport the "lost" energy?
    radiation rate?
    initial temperature achieved? (theory says ~380 MeV)
  - □ collide Pb+Pb at the LHC for higher $T_{initial}$
    reach ~ 800 MeV: is coupling strong or weak?

Energy density of matter



high energy density:
$\varepsilon > 10^{11}$ J/m^3
P > 1 Mbar
I > 3 X 10^{15}W/cm^2
Fields > 500 Tesla

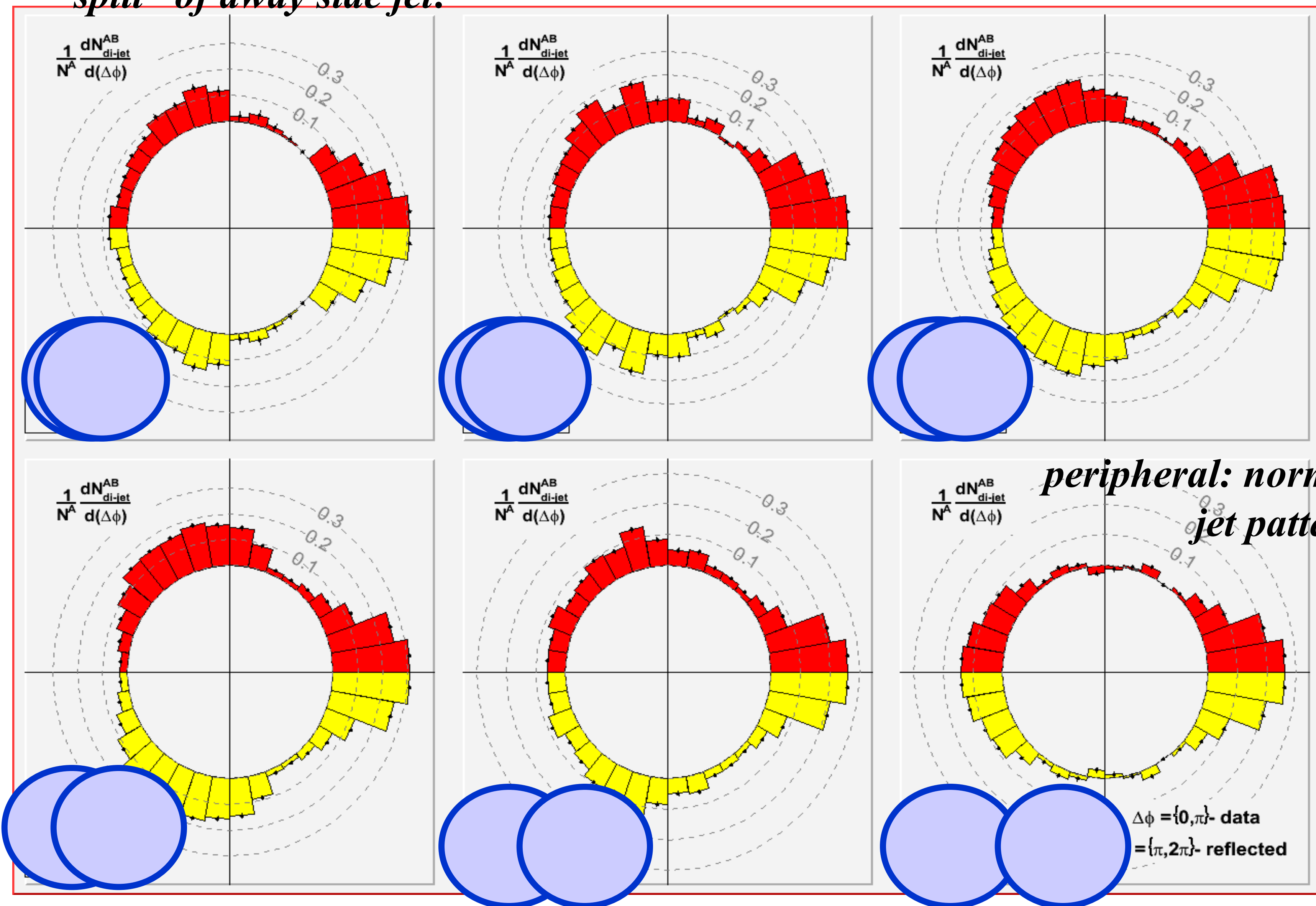
QGP energy density
$\varepsilon > 1$ GeV/fm^3
i.e. > 10^{30} J/cm^3

- **backup slides**

Angular Correlation of ~1-2 GeV/c jet fragments

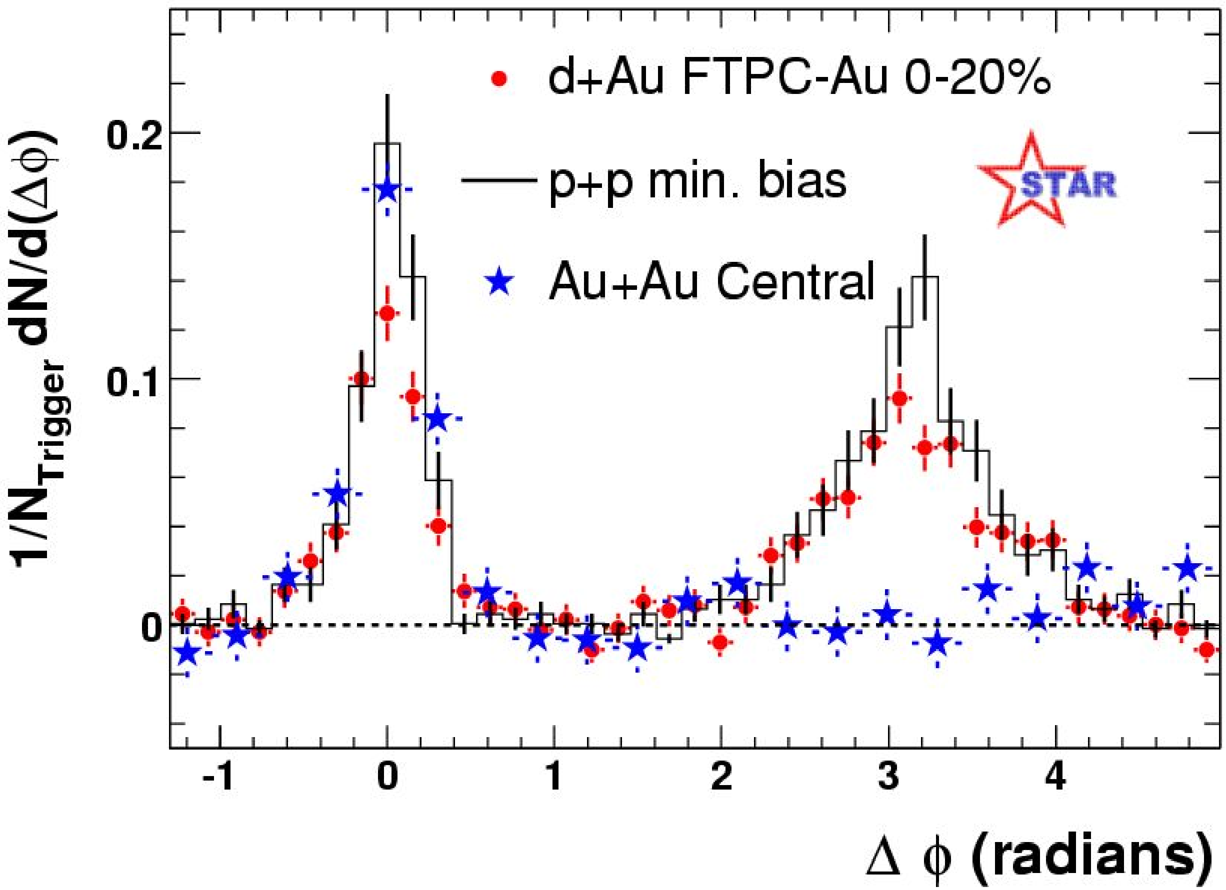
PHENIX (nucl-ex/0507004)

"split" of away side jet!



peripheral: normal jet pattern

Are back-to-back jets there in d+Au?



Yes!

no medium

↓

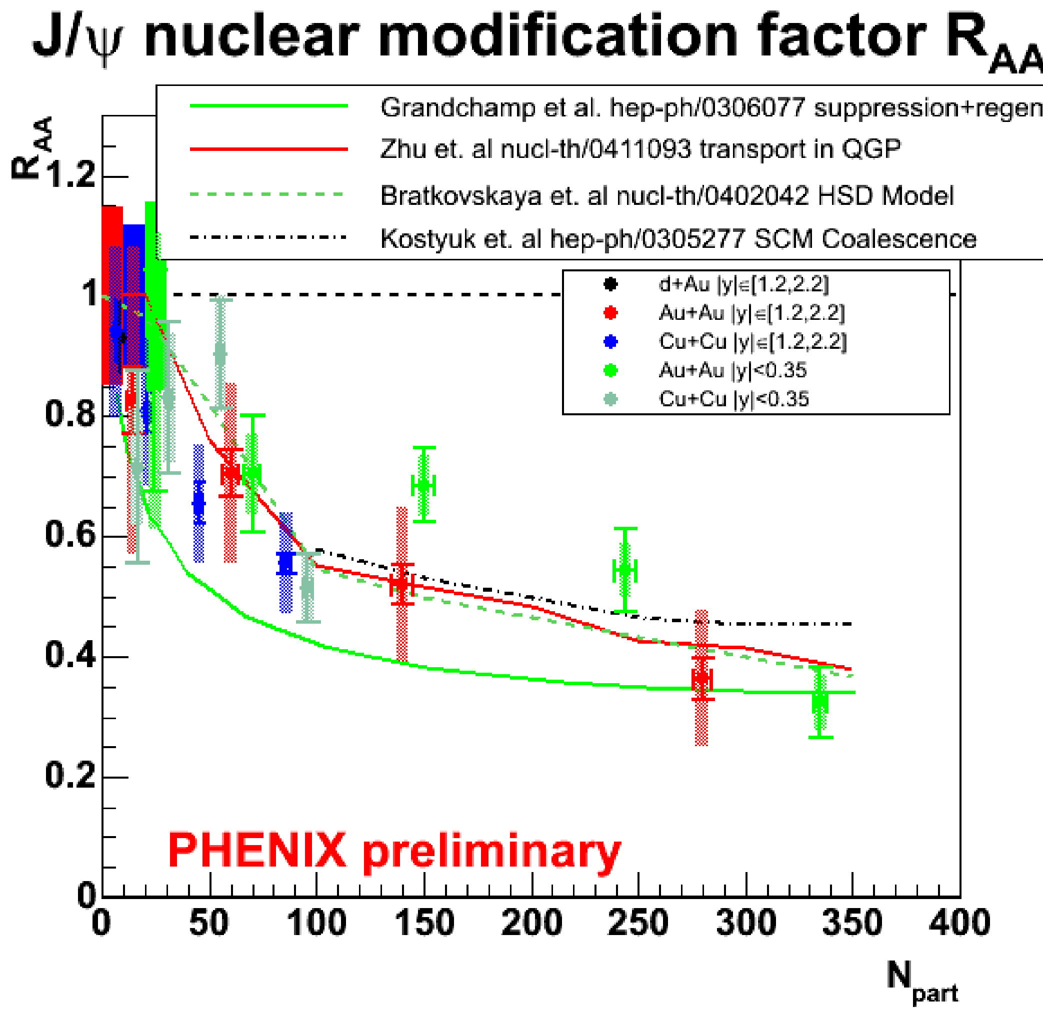
no jet quenching

plasma properties known, so far

Extract from models, constrained by data

Energy loss <dE/dz> (GeV/fm)	7-10	0.5 in cold matter
Energy density (GeV/fm^3)	14-20	>5.5 from E_T data *above hadronic E density!*
dN(gluon)/dy	~1000	From energy loss, hydro *huge!*
T (MeV)	380-400	*Experimentally unknown as yet*
Equilibration time τ_0 (fm/c)	0.6	From hydro initial condition; cascade agrees *very fast!* *NB: plasma folks have same problem & use same technique*
Opacity (L/mean free path)	3.5	Based on energy loss theory

can get better agreement with data



if add formation of “extra” J/ψ by coalescence of c and anti-c from the plasma
caveat: not necessarily unique or correct explanation!

A little more on coupling

potential $V \propto \alpha_s/r$ $<KE> \propto T$ r=interparticle distance

QCD matter: $\rho \propto 1/r^3$ $\rho \propto T^3$ and so we see that $r \propto 1/T$

- $\Gamma = <PE>/<KE> \propto (\alpha_s/r)/T \propto \alpha_s T/T \propto \alpha_s$

  T cancels, but does affect α_s

- $\lambda_D = \{T/(4\underbrace{\pi\varepsilon_0 e^2}_{\alpha_s}\rho)\}^{1/2}$ so $\lambda_D \propto \{T/(\alpha_s T^3)\}^{1/2} \propto 1/(T\alpha_s^{1/2})$
- We know $1/\Gamma \propto$ #particles inside Debye volume N_D
- $N_D = N/V_D = \rho V_D$ $V_D = 4/3\,\pi\,\lambda_D^3 \propto 1/(\alpha_s^{3/2}T^3)$

  so $N_D = \propto 1/\alpha_s^{3/2}$ T cancels again

- for α_s large, N_D is small (λ_D fairly small, but included in N_D)

  for α_s small, N_D is large (λ_D largish)

putting in some numbers

- both Γ and N_D depend on α_s

- at RHIC $dN_g/dy \sim 800$

  so $\rho = 800/(1\ \text{fm} * \pi R^2\ \text{fm}^2) = 800/100 = 8\ /\text{fm}^3$

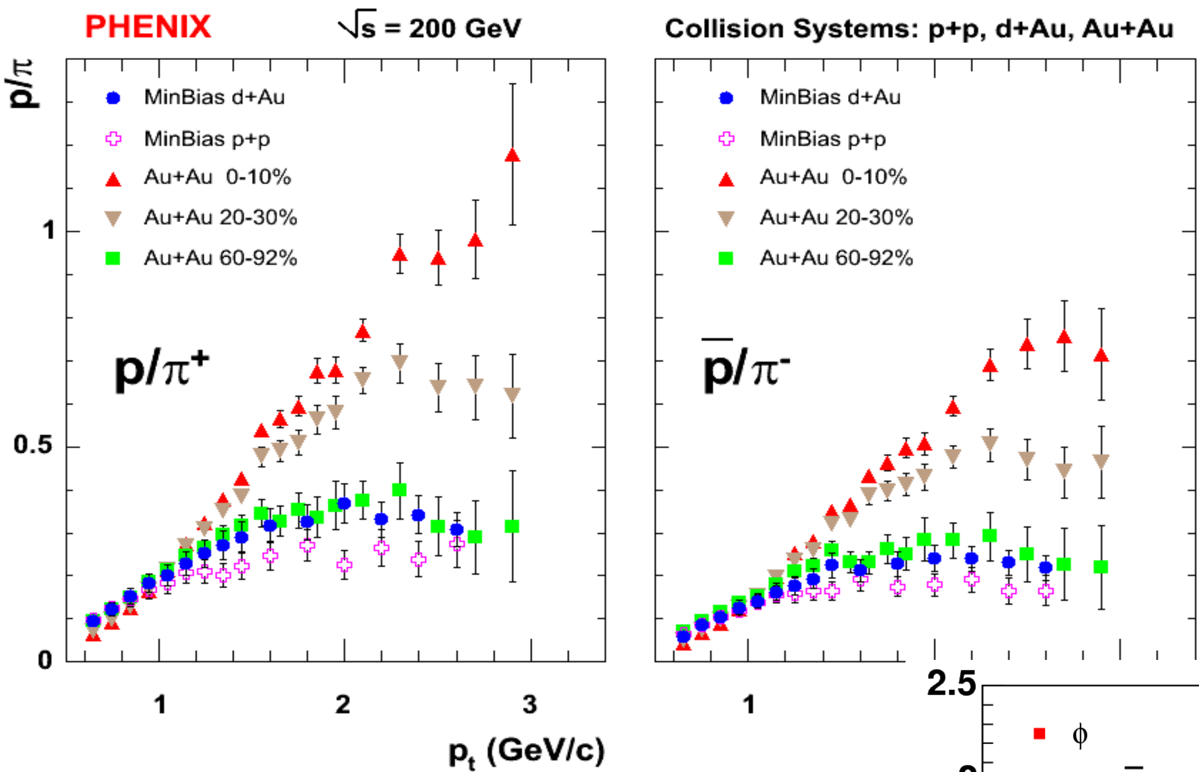
  $r = 0.5$

- from lattice at T~200 MeV $\alpha_s = 0.5\text{-}1$ for quarks

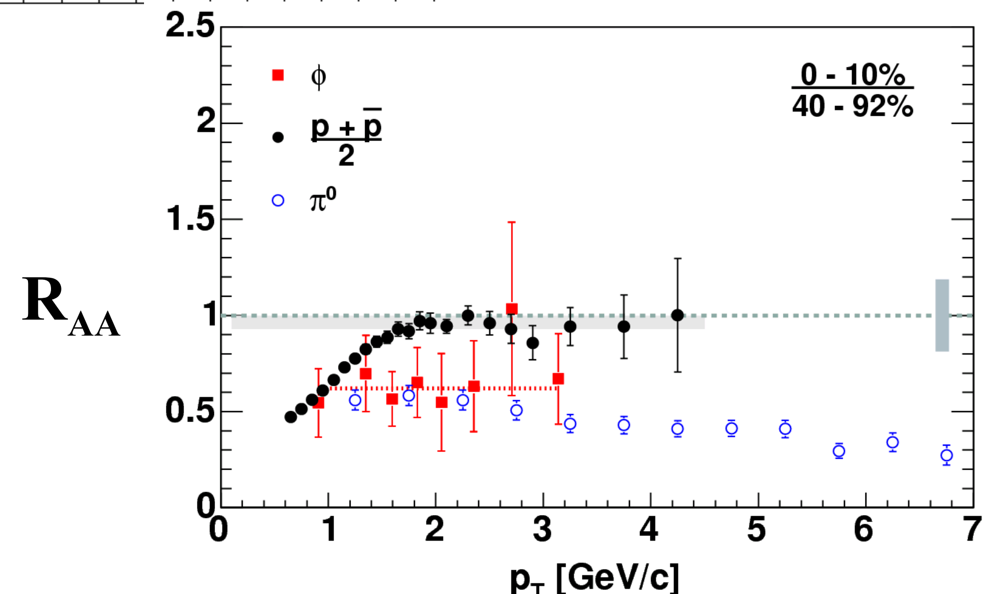
  for gluons multiply by 3/(4/3) = 9/4. It's big!

- from pQCD $\alpha_s = 0.3$ for quarks and ~0.7 for gluons

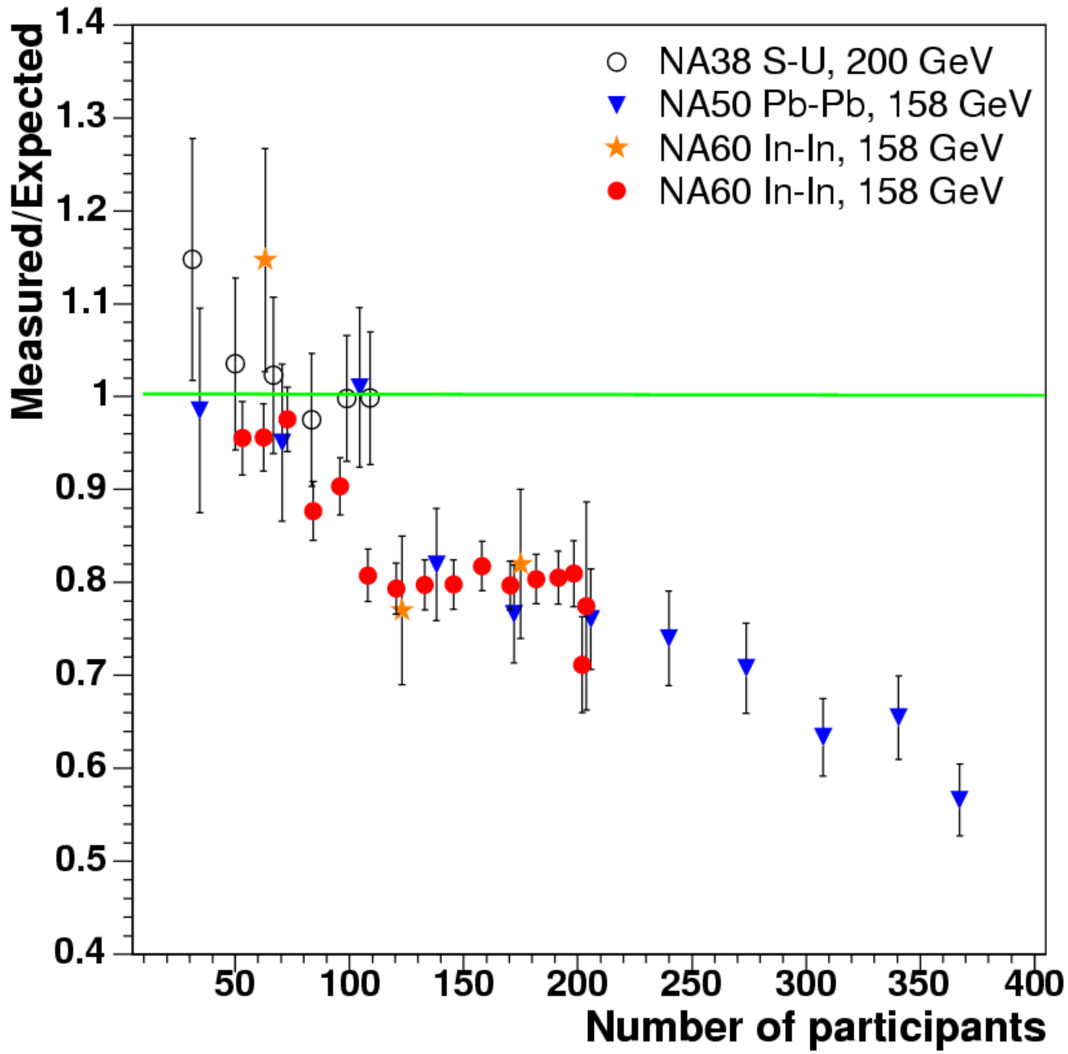
baryon puzzle…



baryons enhanced for pT < 5 GeV/c



At CERN ($\sqrt{s}$ = 17 GeV):

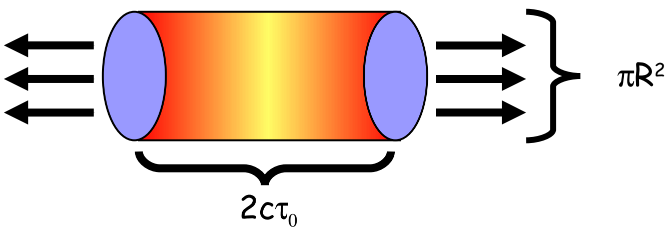


- ❑ **NA50 and NA60 show suppression in Pb+Pb & In+In**
- ❑ **suppression follows system size**
- ❑ **Normal nuclear absorption from p+A data: σ = 4.18±0.35 mb**

Is the energy density high enough?

PRL87, 052301 (2001)

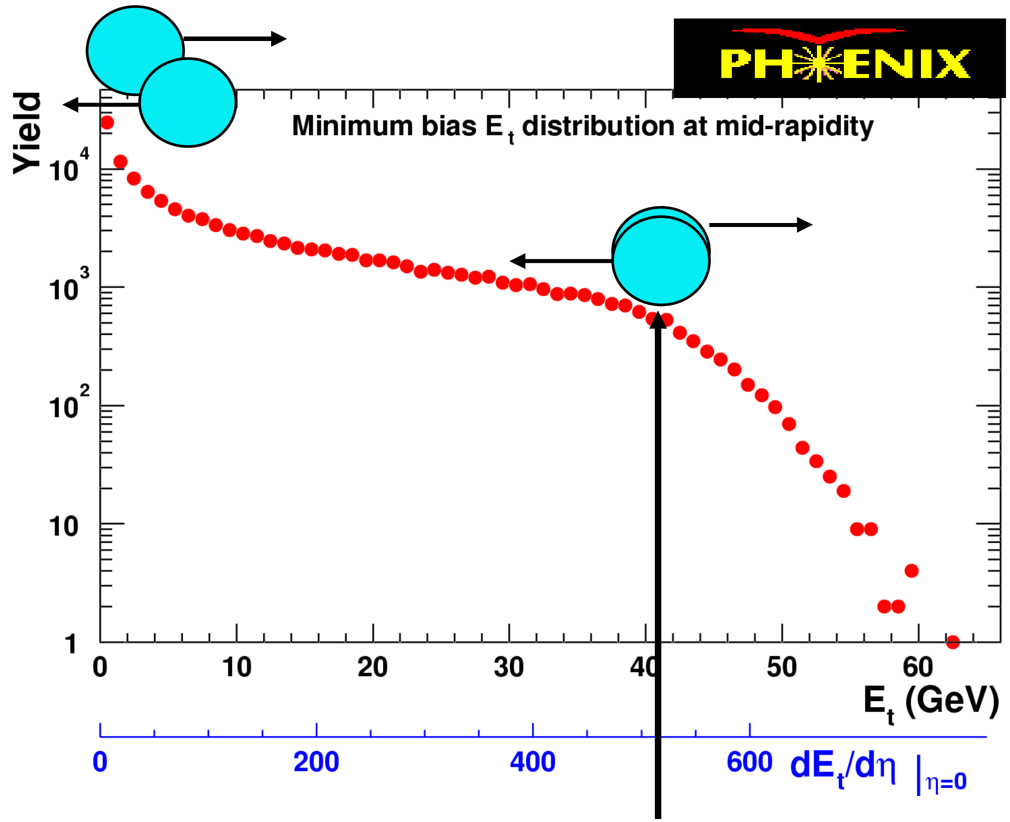
Colliding system expands:



Energy ⊥ to beam direction

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau_0}\left(2\frac{dE_T}{dy}\right)$$

per unit velocity || to beam



$\rightarrow \varepsilon \geq 5.5$ *GeV/fm³* (200 GeV Au+Au)

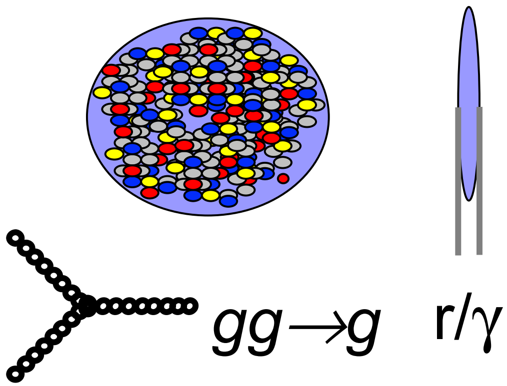
well above predicted transition!

value is lower limit:

longitudinal expansion rate, formation time overestimated

Saturation of gluons in initial state
(colored glass condensate)

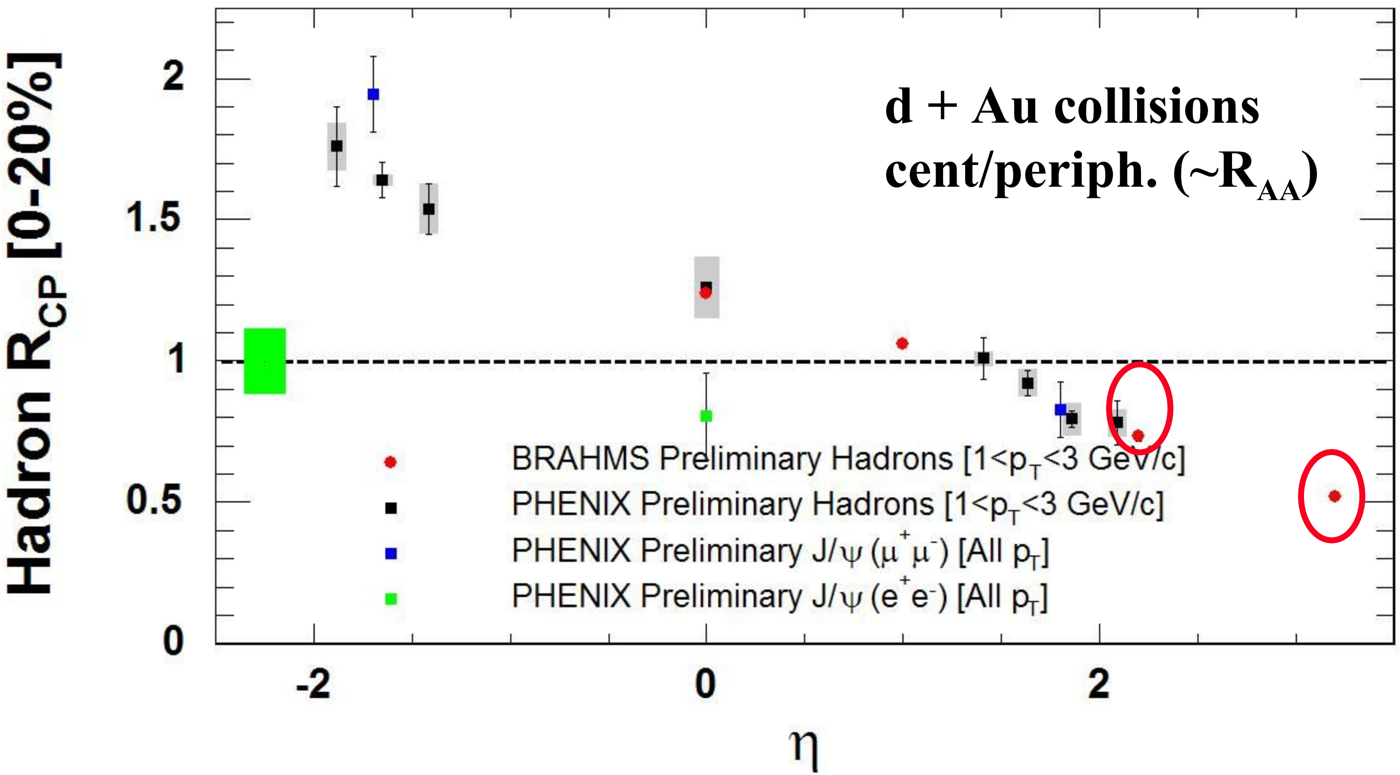
Mueller, McLerran, Kharzeev, ..



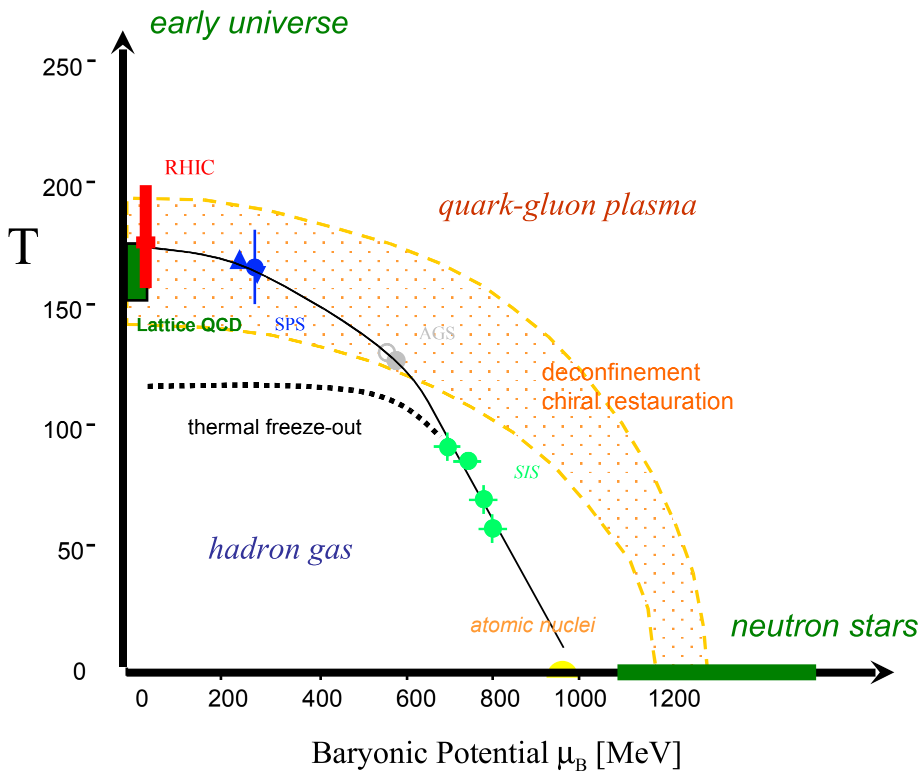
Wavefunction of low x (very soft) gluons overlap and the self-coupling gluons fuse.

Saturation at higher x at RHIC vs. HERA due to nuclear size

→ suppressed jet cross section; no back-back pairs



Locate RHIC on phase diagram



From fit of yields vs. mass (grand canonical ensemble):

T_{ch} = 176 MeV

μ_B = 41 MeV

These are the conditions *when hadrons stop interacting*

Observed particles "freeze out" at/near the deconfinement boundary!

Why no energy loss for charm quarks?

- "dead cone" predicted by Kharzeev and Dokshitzer, Phys. Lett. B519, 199 (1991)
- Gluon bremsstrahlung:

  $k_T^2 = \mu^2 \, t_{form}/\lambda$ transverse momentum of radiated gluon

  $\mu = p_T$ in single scatt. λ =mean free path

  $\theta \sim k_T / \omega$ ω = gluon energy

- But radiation is suppressed below angles $\theta_0 = M_q/E_q$

  soft gluon distribution is

  $dP = \alpha_s C_F/\pi \, d\omega/\omega \, k_T^2 \, dk_T^2/(k_T^2 + \omega^2 \theta_0^2)^2$

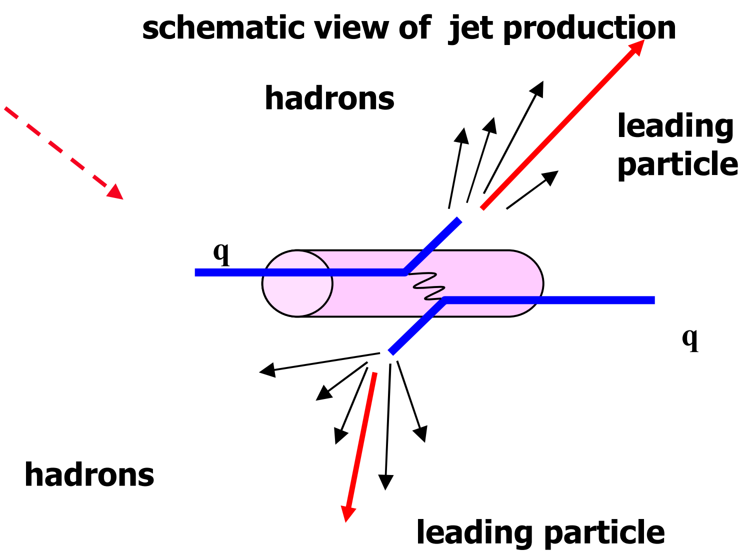
not small for
heavy quarks!
causes a dead cone

“external” probes of the medium

Hard scattering of q,g early.
Observe fast leading particles,
back-back correlations

Before creating hadron jets,
scattered quarks induced to
radiate energy (~ GeV/fm)
by the colored medium

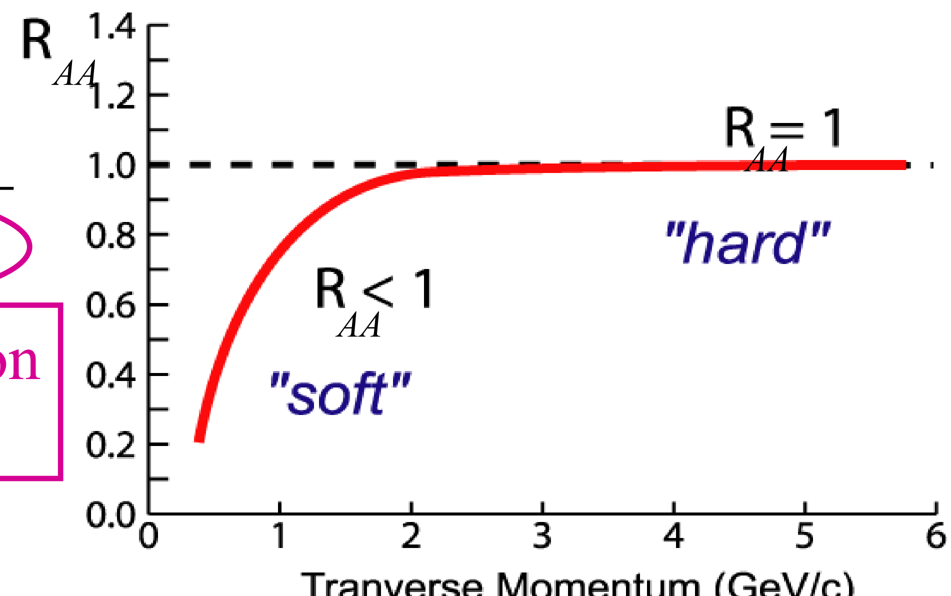
-> jet quenching



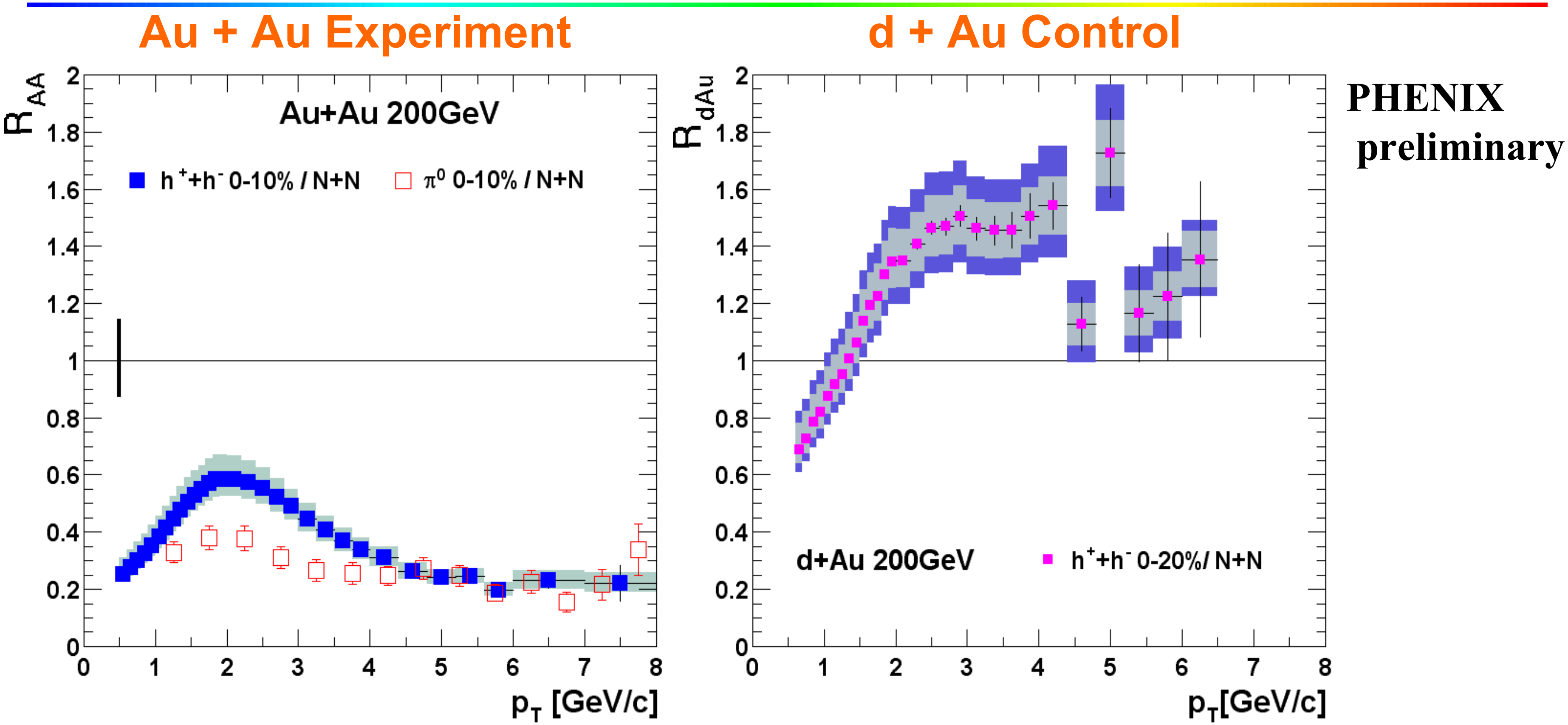
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$

nucleon-nucleon cross section

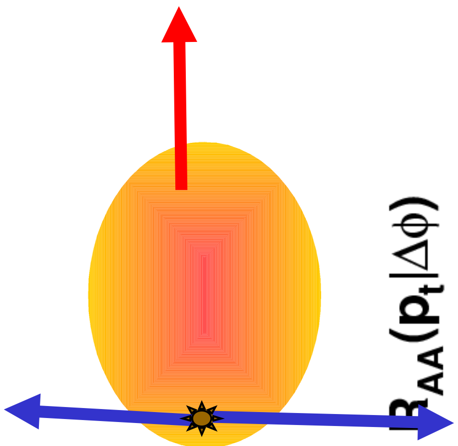


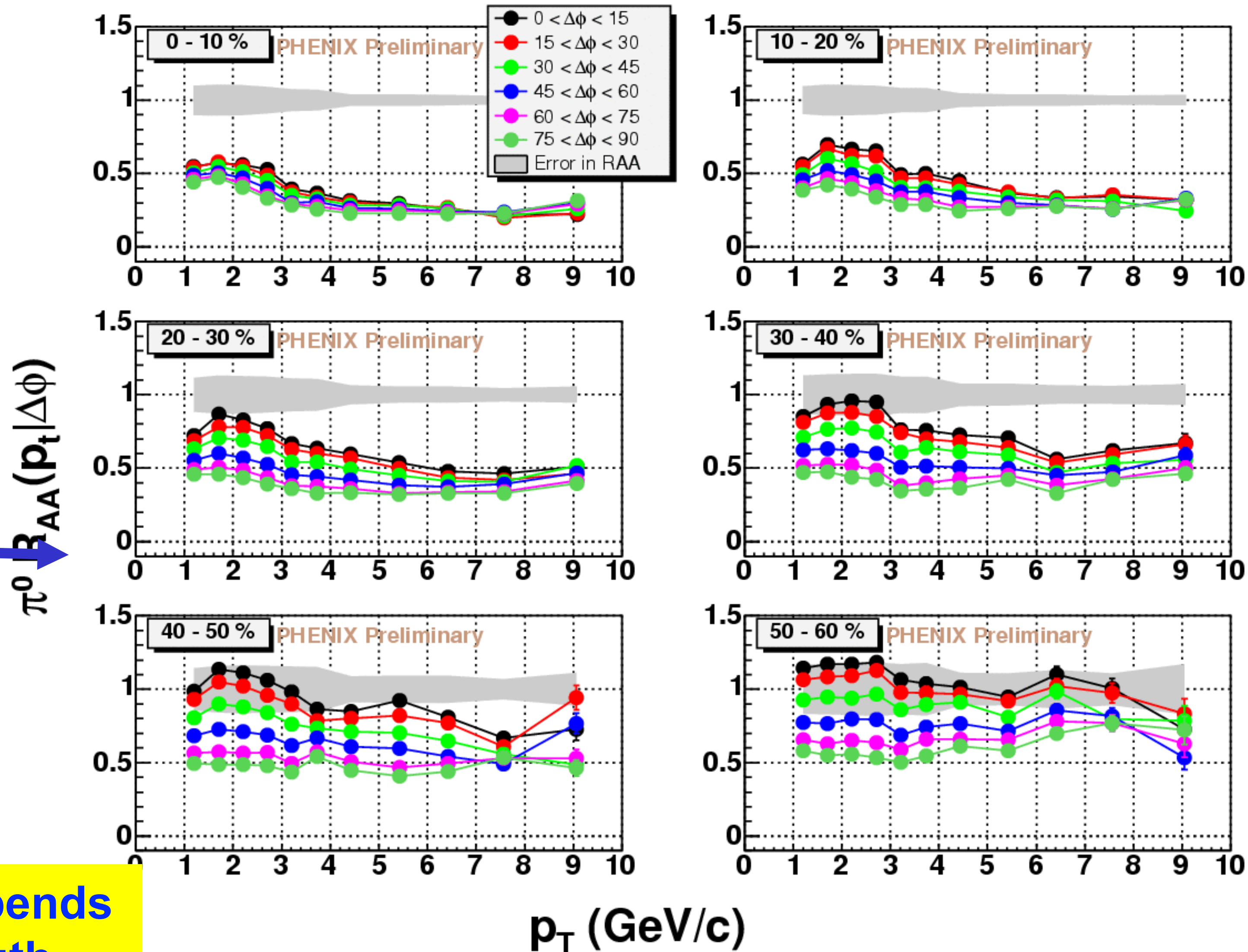
Centrality Dependence



- Dramatically different and opposite centrality evolution of AuAu experiment from dAu control.
- Jet Suppression is clearly a final state effect.

R_{AA} wrt reaction plane – more evidence





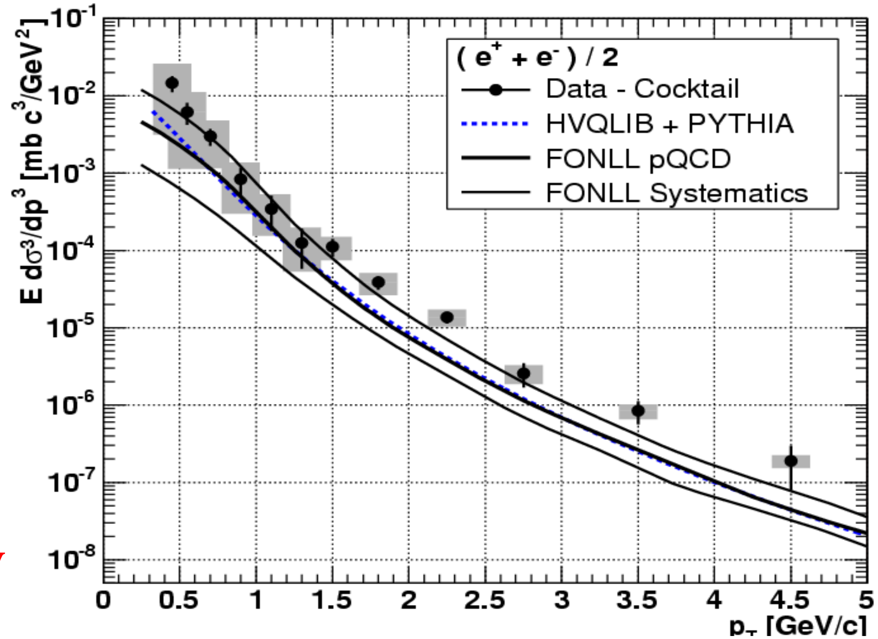
Energy loss depends on the path-length

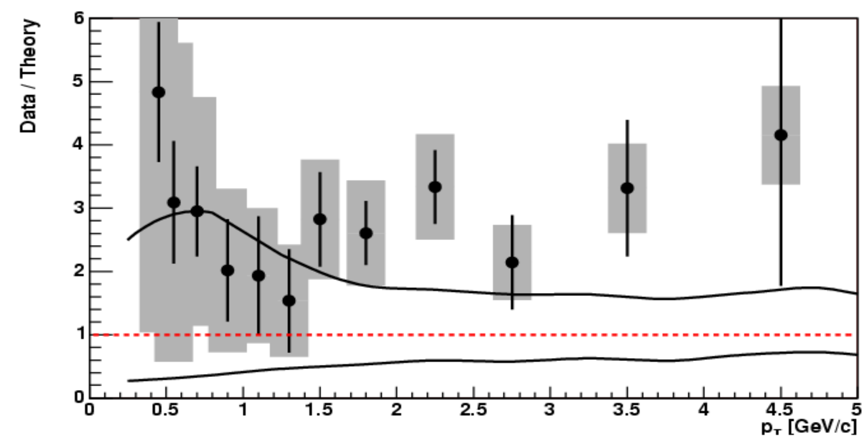
FONLL Predictions

- Mateo Cacciari provided a prediction using the Fixed Order Next Leading Logarithm pQCD approach
- His calculation agrees perfectly with our “poor man’s” HVQLIB+PYTHIA predictions
- Data exceed the central theory curve by a factor of 2-3
- Possible explanations:

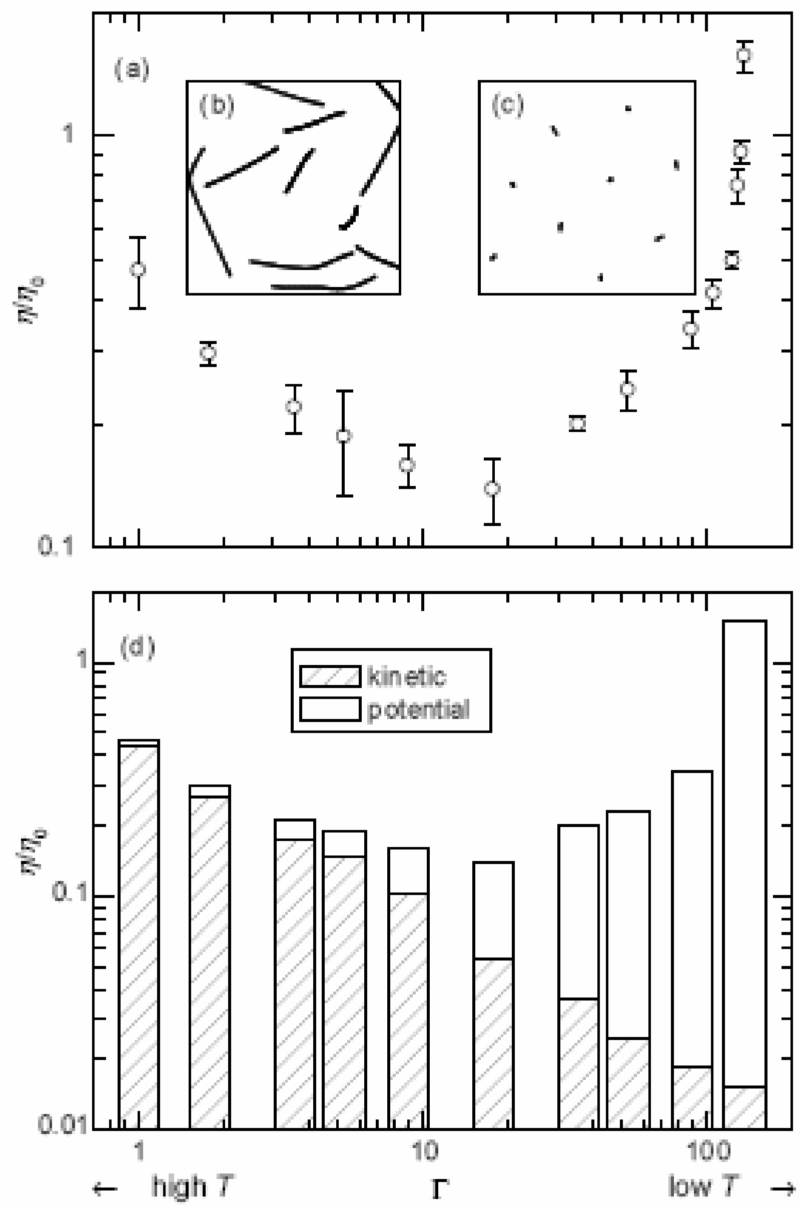
  NNLO contribution

  Fragmentation mechanisms need to be studied in more details





use this technique to measure viscosity



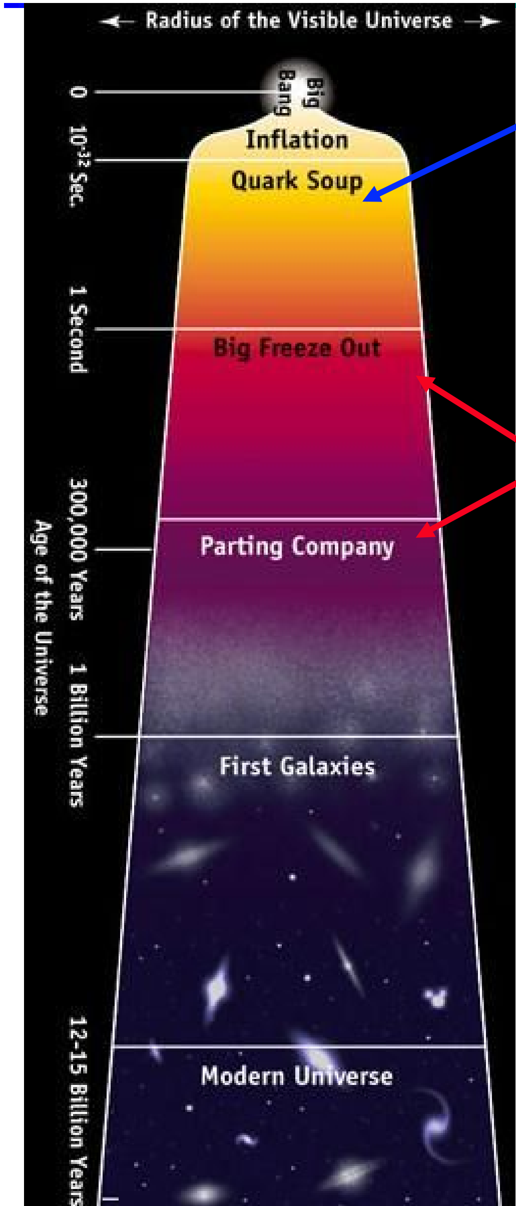
melt crystal with laser light
induce a shear flow (laminar)
image the dust to get velocity
study:
- spatial profiles $v_x(y)$
- moments, fluctuations → $T(x,y)$
- curvature of velocity profile → drag forces
- viscous transport of drag in ⊥ direction from laser

compare to viscous hydro.
- extract η/ρ
  - shear viscosity/mass density

PE vs. KE competition governs
- coupling & phase of matter

Csernai, Kapusta, McLerran nucl-th/0604032

conclusions



The stuff making up the universe ~1us after the Big Bang is NOT an ideal gas!
It's a strongly coupled, low viscosity plasma

Does (should) cosmology (ists) care??

NO!
equilibrium → we can't see back that far

YES! A first order phase transition is not the right physics

MAYBE... don't know enough about QGP behavior to know how it matters

This generation of experimenters & theorists will figure out the answer!