For the CTP symposium, Cairo, 11-14 March 2007

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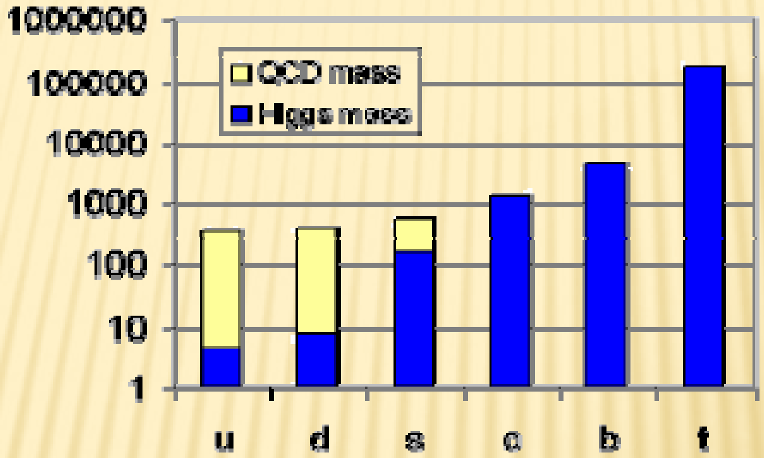
PHENIX experiment

WHAT'S THE MATTER AT RHIC ?

☺ THE ORIGIN OF (MY) MASS…

~ 98% from QCD + 02% from Higgs !



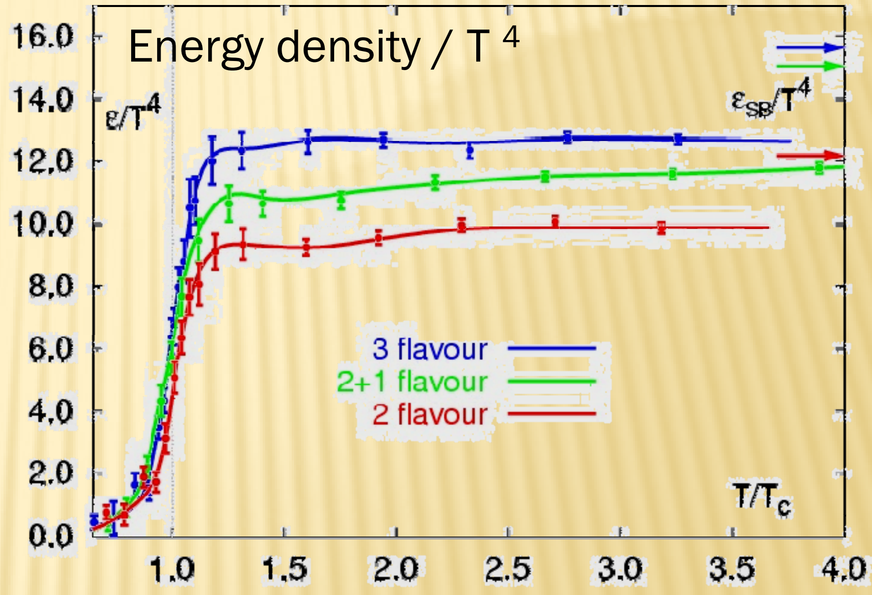
~ 98% poorly understood + 02% not yet seen…

- We are mostly made of confinement…
  - Thus, let's look at deconfinement…

(ok, this is only ~5% of the universe ☹)

WHAT TELLS QCD? (ON THE LATTICE)

- Strong interaction is weak at high energies
  - Asymptotic freedom
- Lattice QCD predicts a phase transition from a Hadron Gas to a Quark Gluon Plasma (QGP)
  - $T_c \sim 190$ MeV (2×10^{12} K)
  - $\varepsilon_c \sim 1$ GeV/fm^3



Karsch et al, hep-lat/0106019
Lect. Notes Phys.583 (2002) 209

→ Doesn't tell us much about the matter's properties (equation of state, order of phase transition…)

A LINK TO OUR MAIN TOPIC?

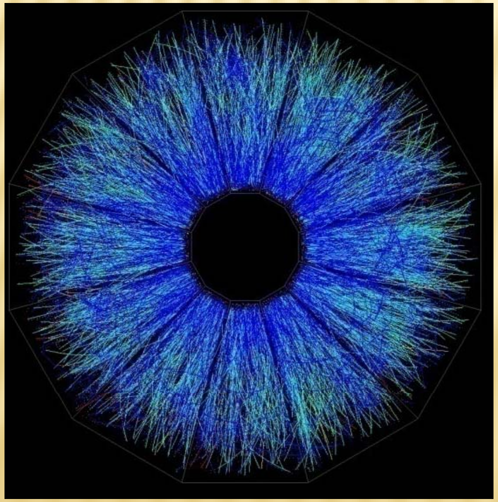
Juan Maldacena, ATMP 38 (1999) 1113 (>4500 citations)

Anti de Sitter/Conformal Field Theory correspondence

- Strongly coupled N=4 super Yang Mills theory
  - Super QCD
  - Super QGP

↔

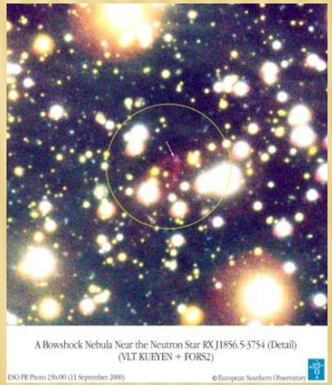
- Weakly coupled type IIB string theory on AdS_5xS^5
  - Dual gravity
  - Black hole

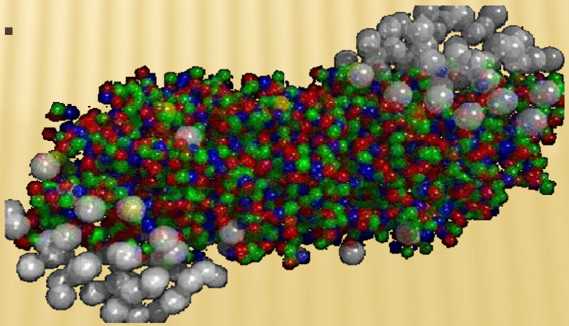


→ Can predict some properties (viscosity/entropy, quenching ...)

WHERE/WHEN CAN WE FIND THE QGP?

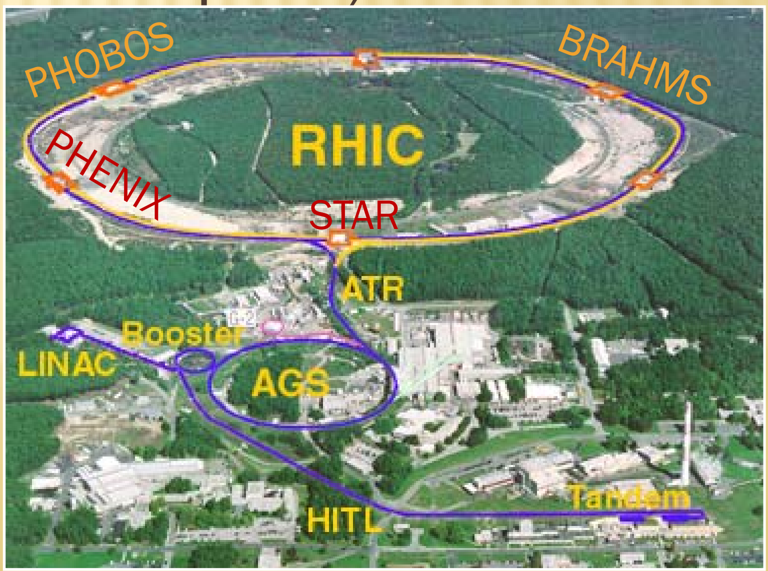
1. Early in the universe (t < 10µs)
   - But very little chance to leave relics
     - Cold dark matter clumps ?
     - Inhomogeneous nucleosynthesis ?
     - Baryonic CDM (strange nuggets) ?
2. Core of a compact star
   - No smoking gun candidate so far
3. In the lab, by colliding heavy ions
   - Freedom for the quarks…
   - … for some 10^{-23} s





WHAT'S RHIC?

- Relativistic Heavy Ion Collider
@ Brookhaven National Lab.
- First collisions in 2000, running
- 2 large (STAR & PHENIX)
+ 2 small (PHOBOS & BRAHMS) experiments
- Can collide anything from p+p (up to 500GeV)
to Au+Au (up to 200GeV per nucleon pairs)



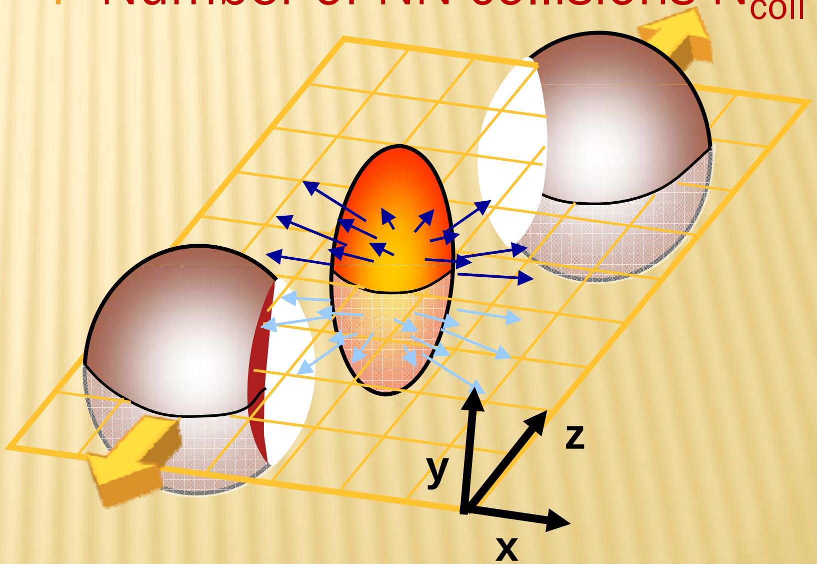
WHAT IS THE STRATEGY?

- Predict a QGP signature
- Look at it versus A+A collision centrality →
- Compare to p+p

$$R_{AA} = \frac{d^2N^{AuAu}/dydp_T}{d^2N^{PP}/dydp_T \times \langle N_{coll} \rangle}$$

- Hard probes should behave $R_{AA} = 1$
- Compare to p+A (or d+A)
  - Check that normal nuclear matter cannot account for deviations...

- Non zero impact parameter
  - Number of spectators
  - Number of participants N_{part}
  - Number of NN collisions N_{coll}



→ Derive a QGP property (temperature, density...)

WHICH SIGNATURES?

1. Total multiplicity ~ *"Color Glass Condensate"*
2. High p_T suppression
3. Back to back jets

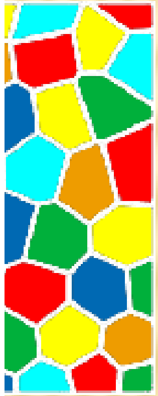
(2–3) ~ *"Jet quenching"*

4. Elliptic flow ~ *"Perfect fluid"*
5. Baryon/meson
6. Heavy flavor
7. J/ψ suppression
8. Thermal radiation

But they are not the only ones!
"There was a general feeling that if the quark-gluon plasma was indeed produced, it would manifest itself in a variety of unknown but dramatic ways, including… the end of the world"
H. Satz @ Lattice 2000 hep-ph/0009099

1. TOTAL MULTIPLICITY (AND E_T)

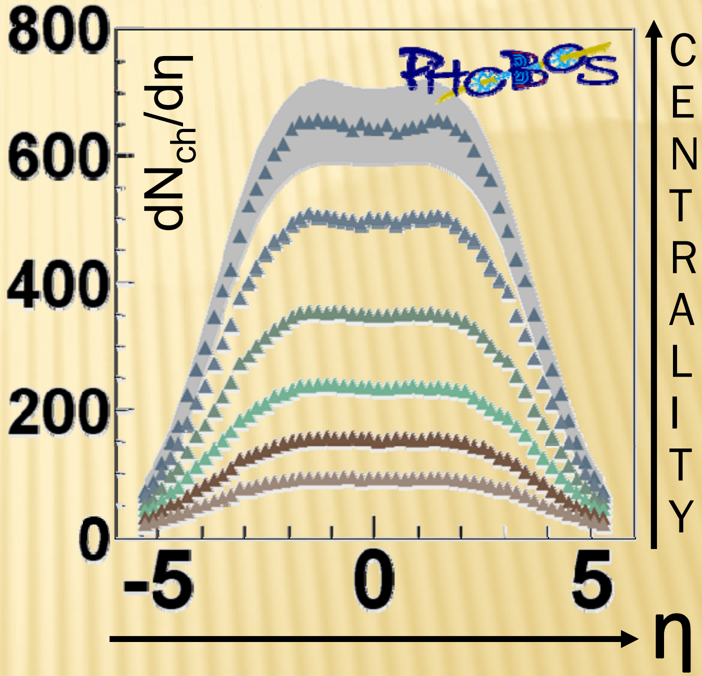
- $dN_{ch}/d\eta|_{\eta=0} \sim 670$
- (6000 particles total)
- Less than expected!
  - 1000 from p+p fragmentation
  - Low x_{Bj} gluon start to overlap, recombine, saturate…
  - (even more at forward rapidity)
  - "Color Glass Condensate"



→The (initial) matter saturates

@ LHC, even worse ! $x_{Bj} < 10^{-3}$

$dN_{ch}/d\eta|_{\eta=0} \sim 1600 - 2100$

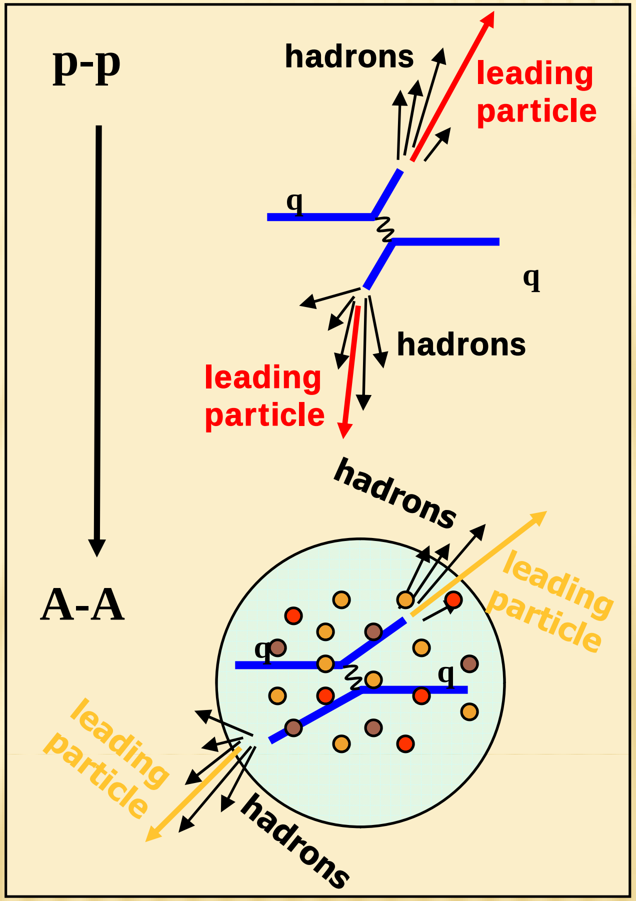


PRL 91 (2003) 052303

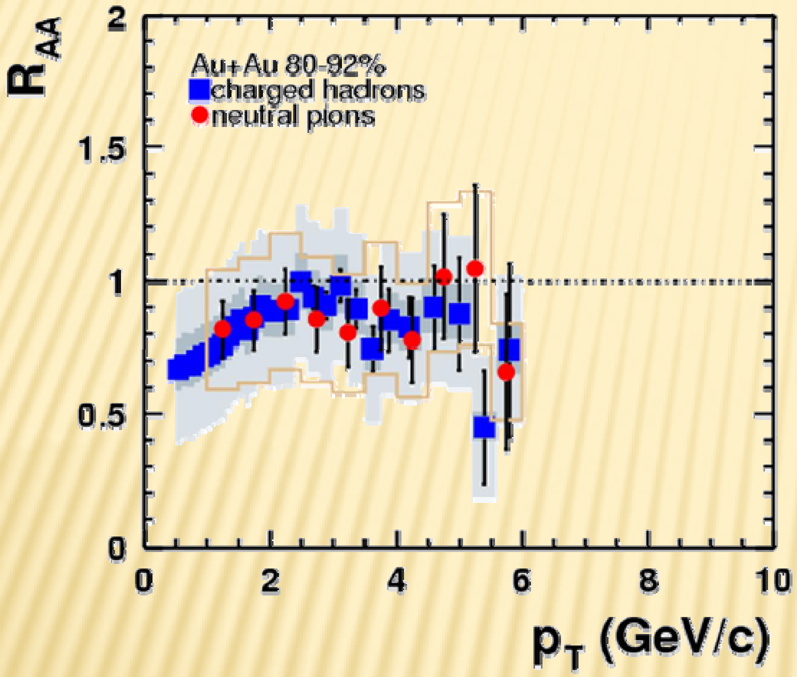
- $dE_T/d\eta|_{\eta=0}$ related to energy density
- $\varepsilon > 6$ GeV/fm$^3 > \varepsilon_c$!

2. HIGH P_T SUPPRESSION

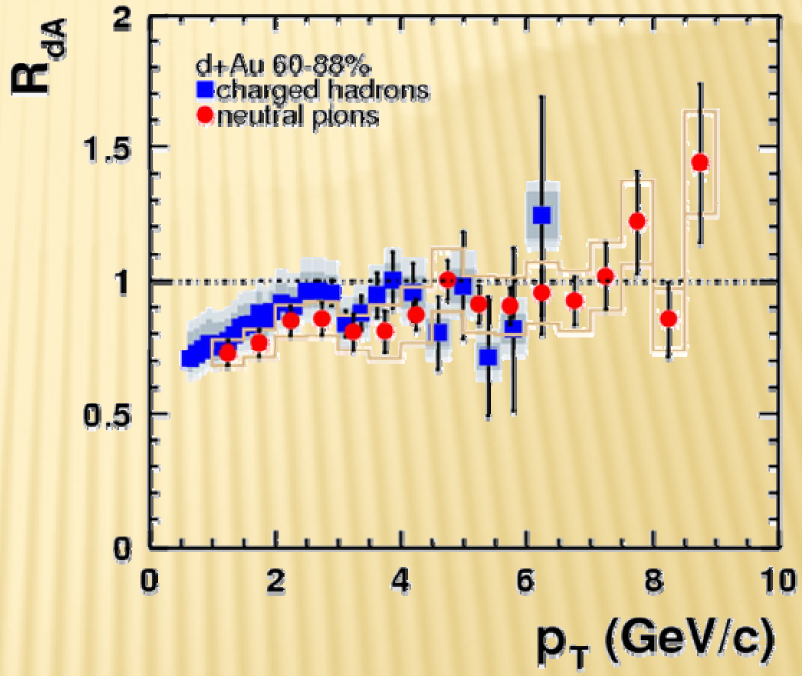
- RHIC smoking gun signature !
  - Two PRL covers
- Energy loss in the matter, looking at high p_T (>2GeV)
  - Mostly from jet fragmentation
- "Jet quenching"



Au-Au (80-92%)



d+Au (60-88%)

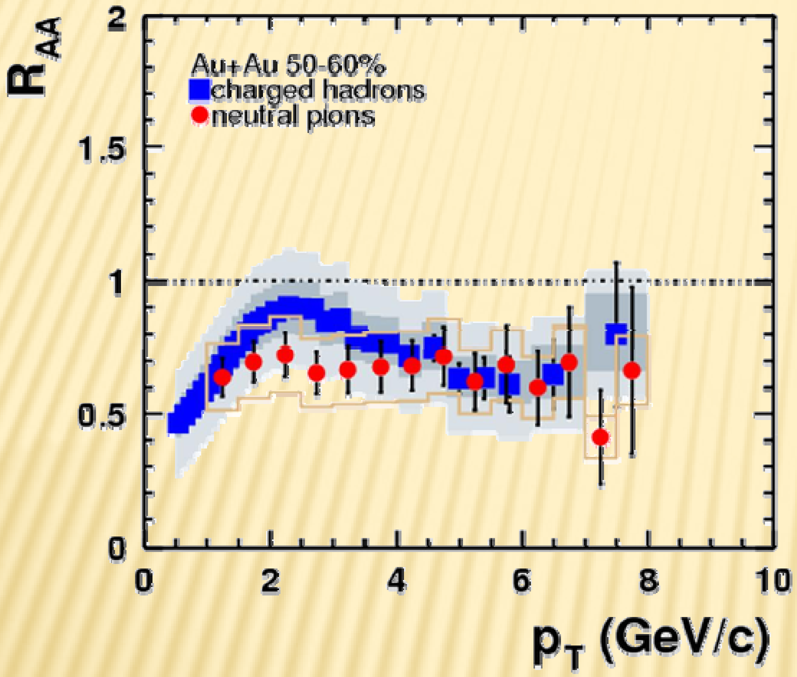


MOST PERIPHERAL COLLISIONS…

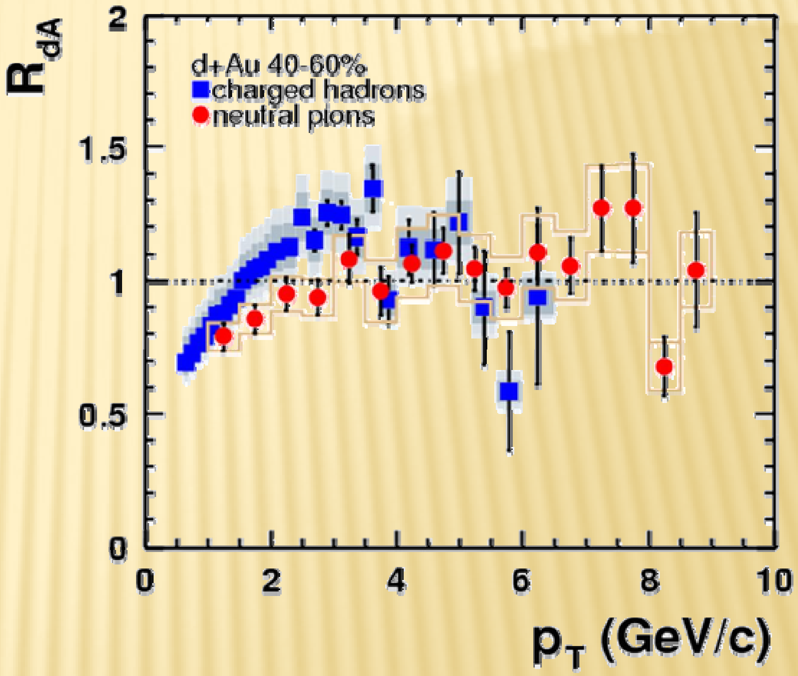
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (50-60%)



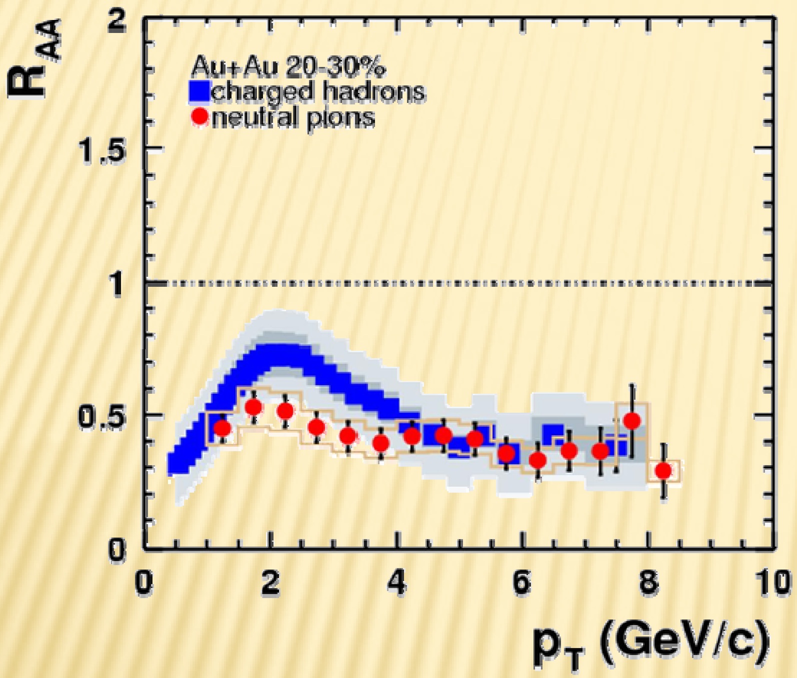
d+Au (40-60%)



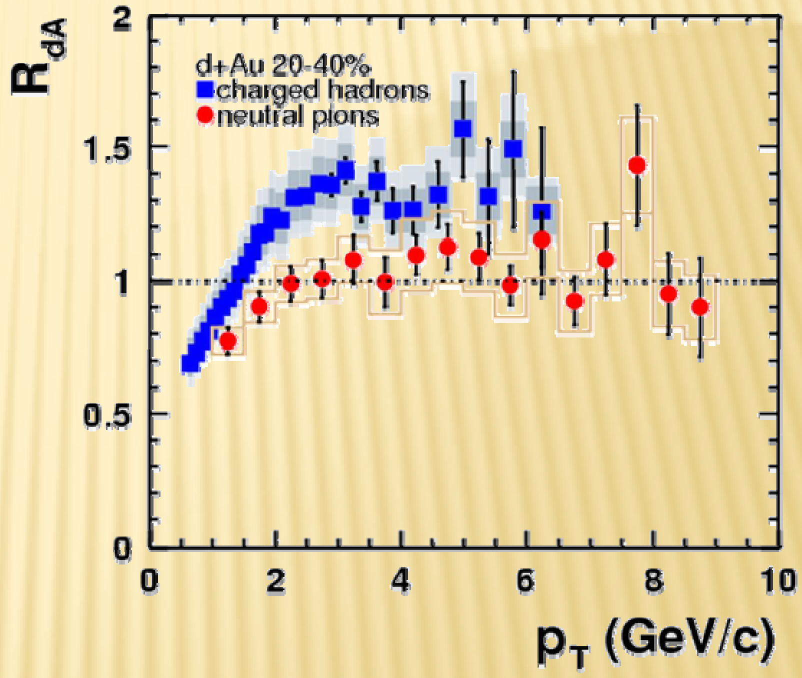
LESS PERIPHERAL COLLISIONS…

(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303

Au-Au (20-30%)



d+Au (20-40%)

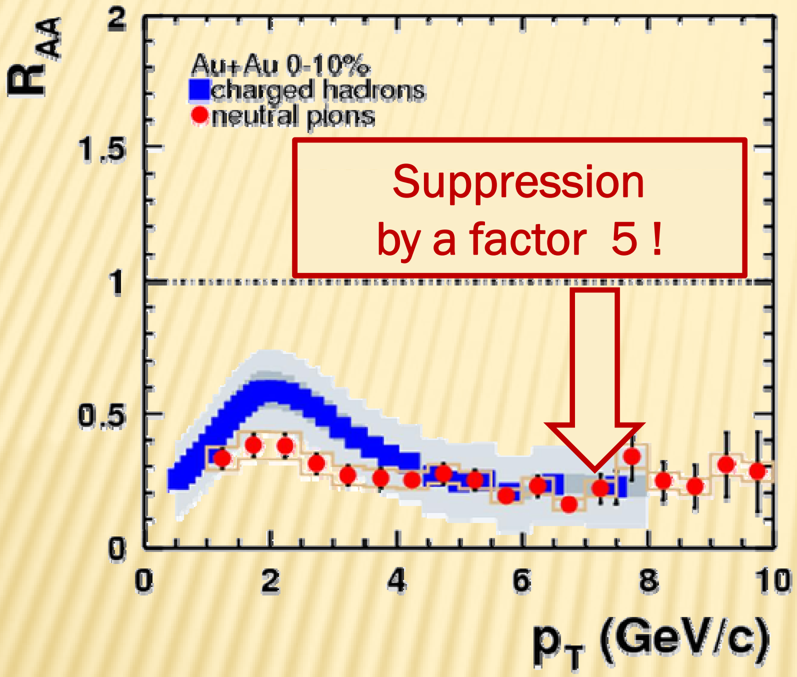


MORE CENTRAL COLLISIONS…

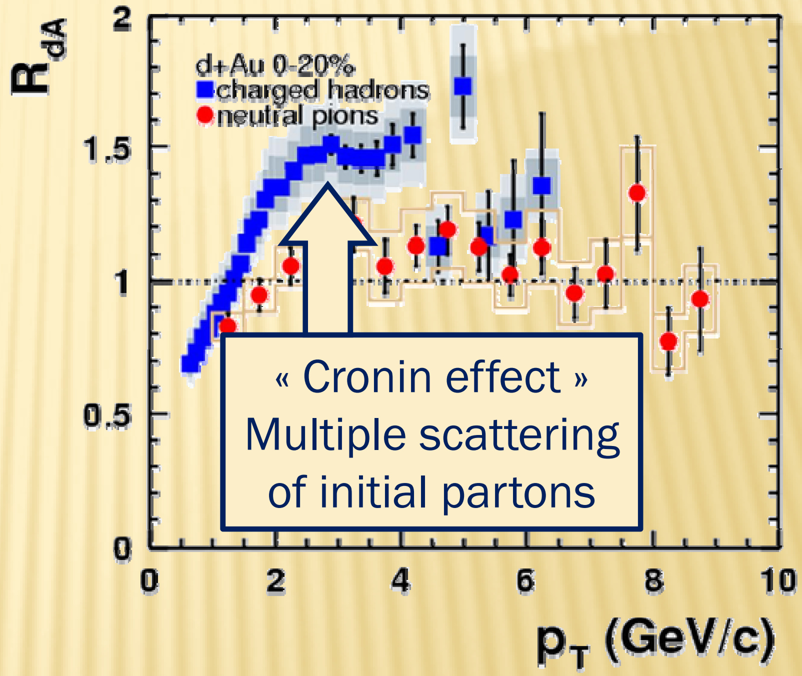
(slightly old, but pedagogical, data)

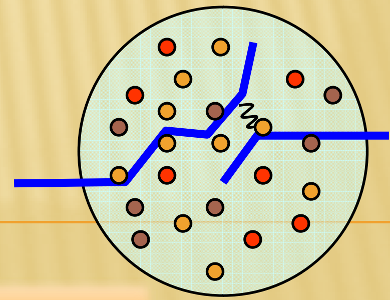
PHENIX, PRL 91 (2003) 072303

Au-Au (0-10%)



d+Au (0-20%)



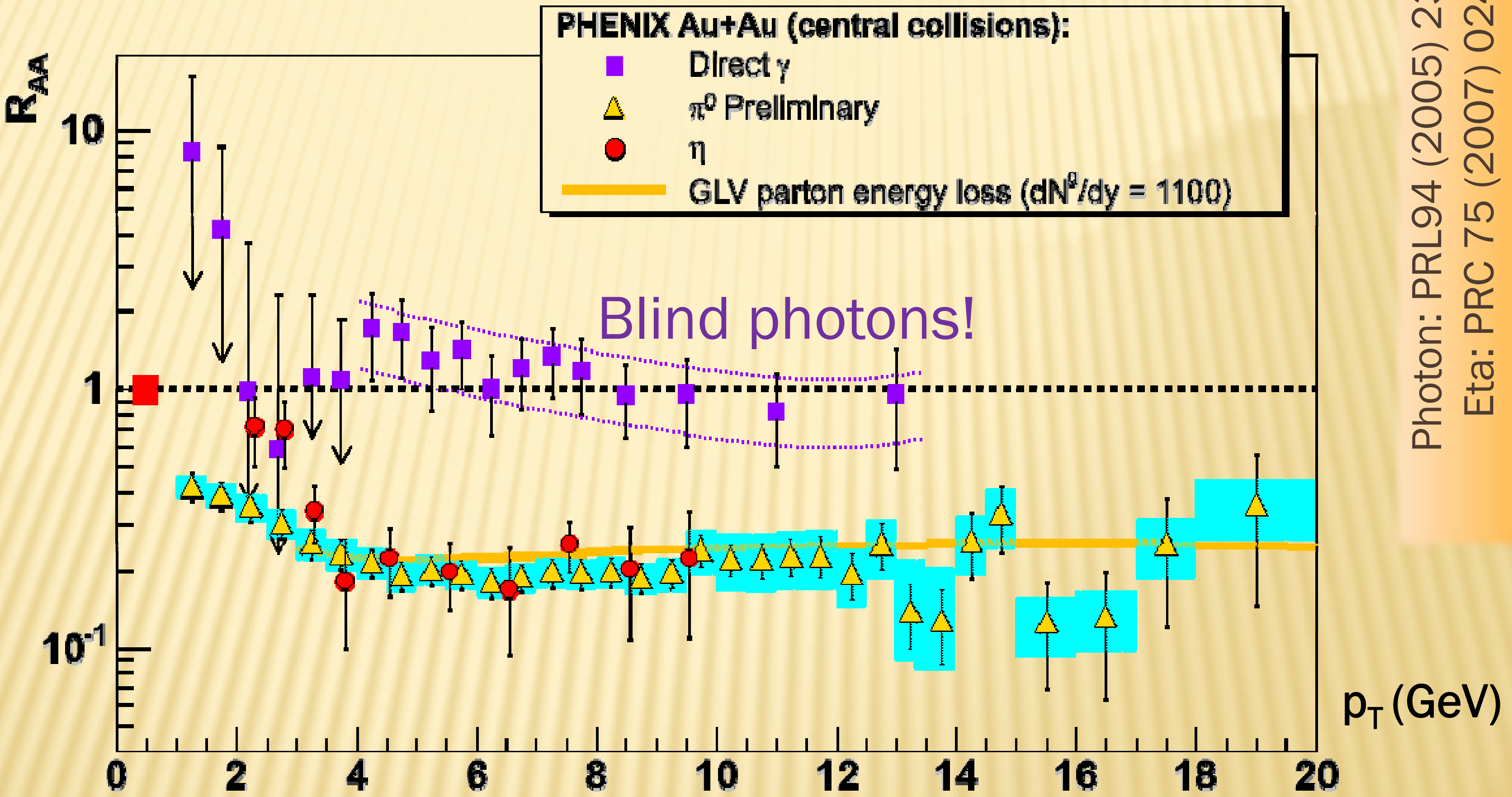


MOST CENTRAL COLLISIONS!

(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

2. HIGH P_T SUPPRESSION

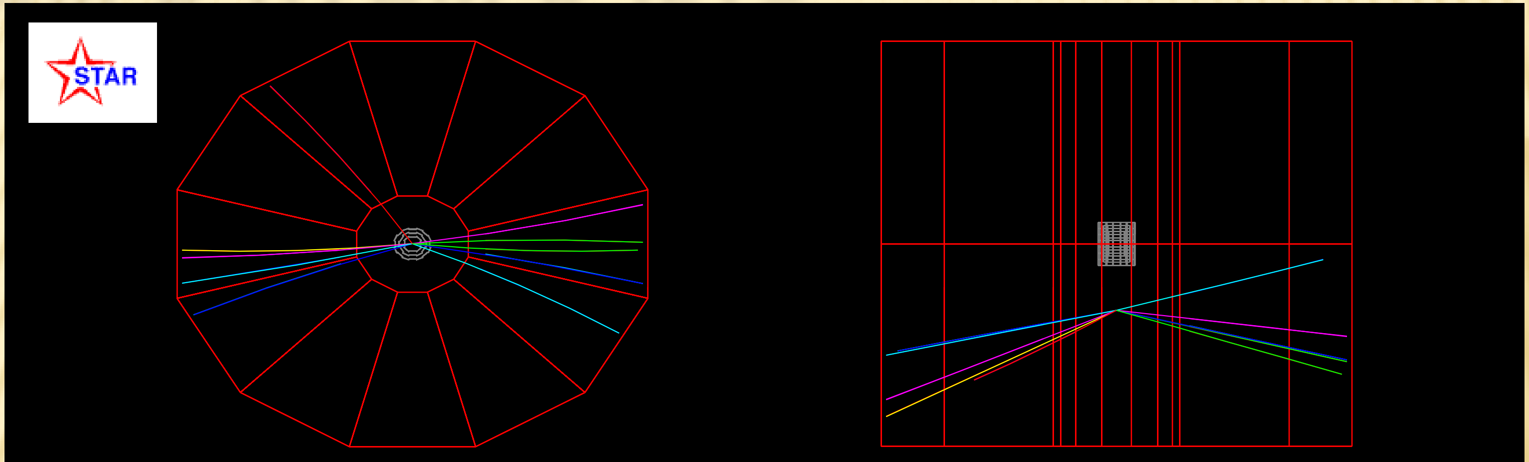


Photon: PRL94 (2005) 232301
Eta: PRC 75 (2007) 024909
Vitev & Gyulassy PRL82 (2002) 252301

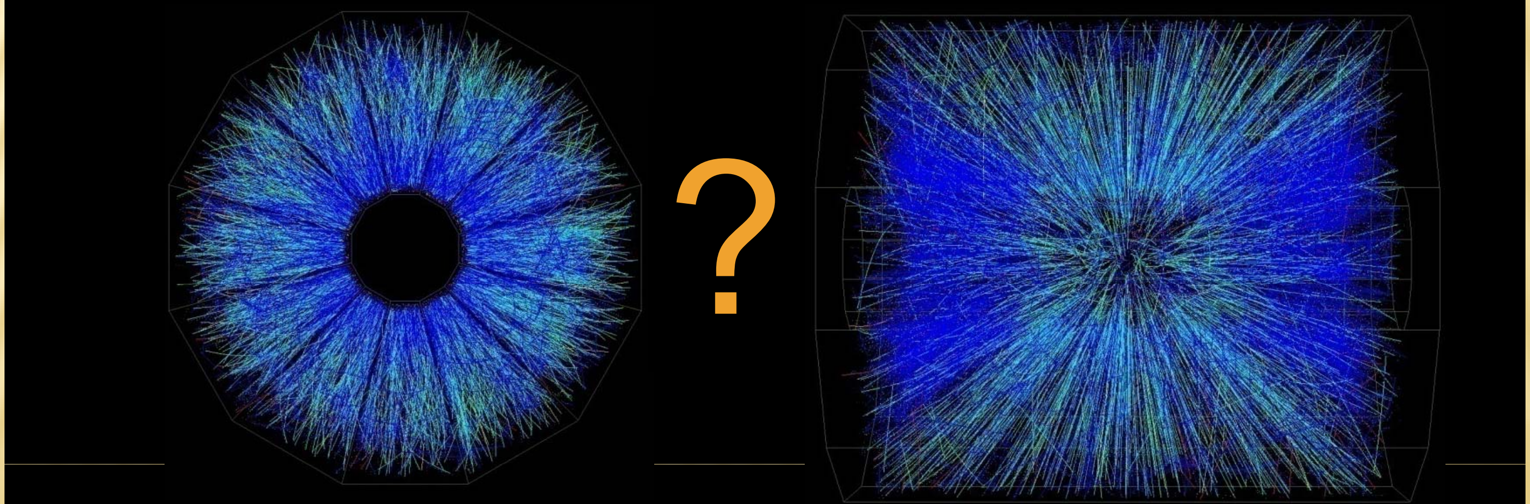
→ The matter is dense ! >1000 gluons per Δy

@ LHC, gamma-jet studies will tell us more…

3. BACK TO BACK JETS

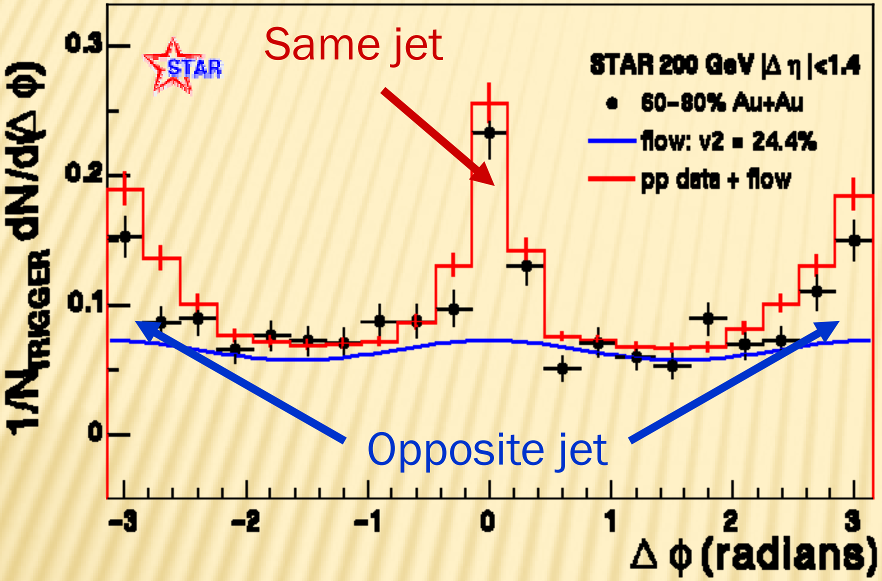


Easy in 200 GeV proton+proton collisions

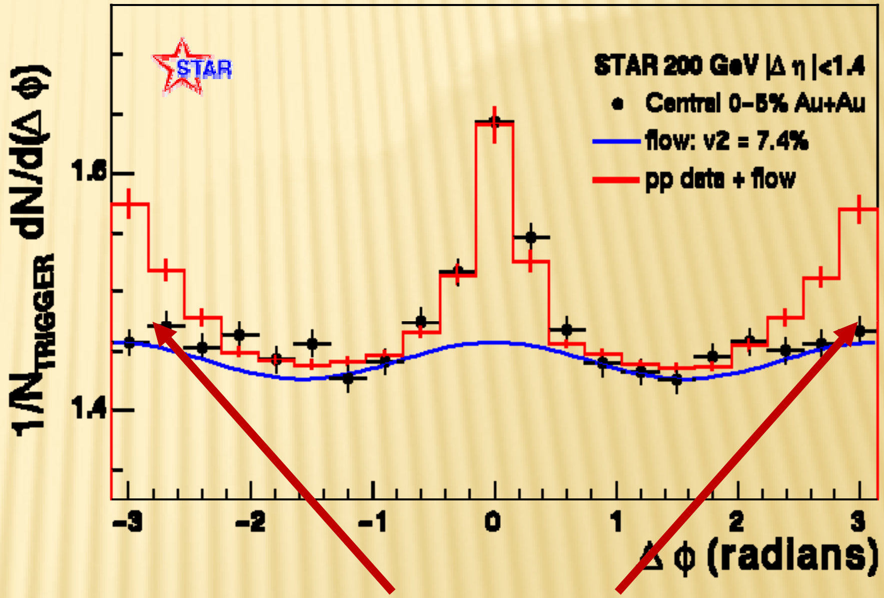


Quite difficult in Au+Au central collisions @ 200 GeV

Peripheral collisions (60-80%)



Central collisions (0-5%)



Take a "trigger" particle (p_T>4GeV) and look at the others (p_T>2GeV) azimuth

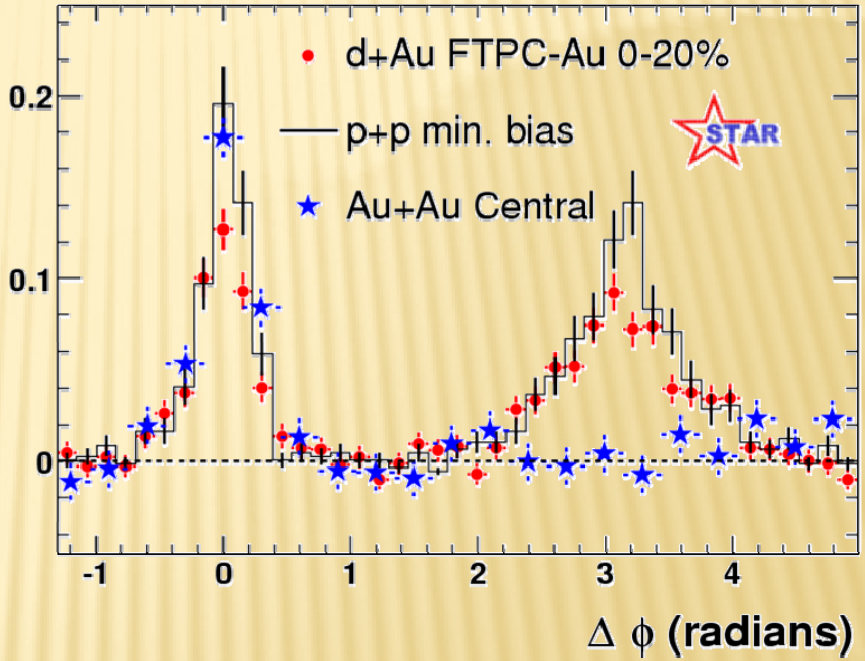
In central collision, opposite jets disappear because of jet quenching

3. BACK TO BACK JETS ANOTHER LOOK TO JET QUENCHING…

3. BACK TO BACK (D+AU)

STAR, PRL 91 (2003) 072304

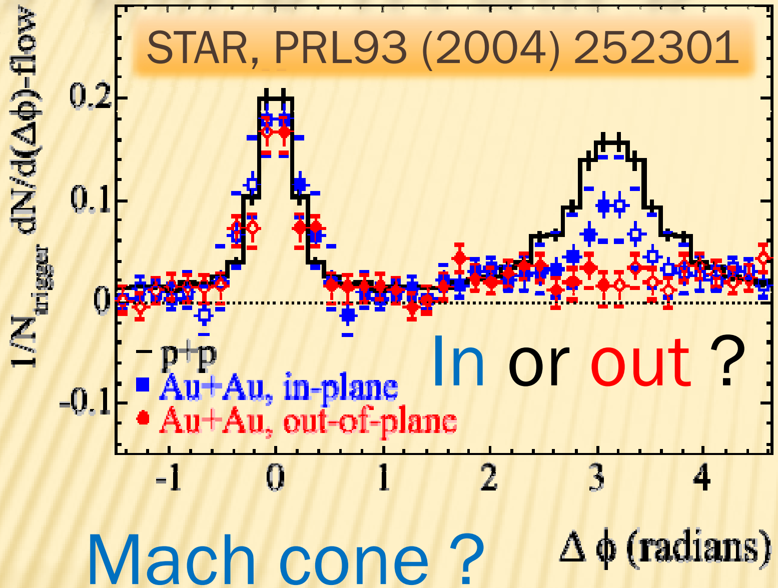
- As always, it is very important to check for d+Au

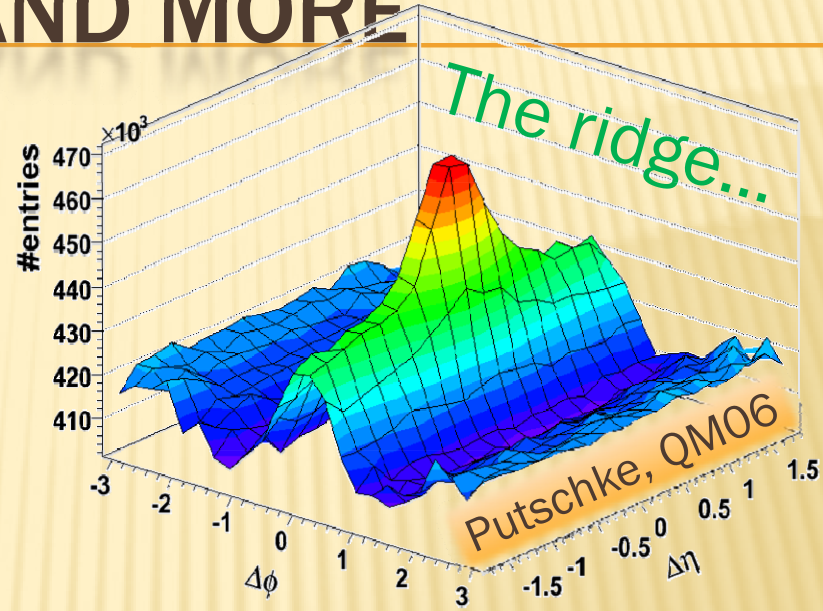


→ The matter is opaque!

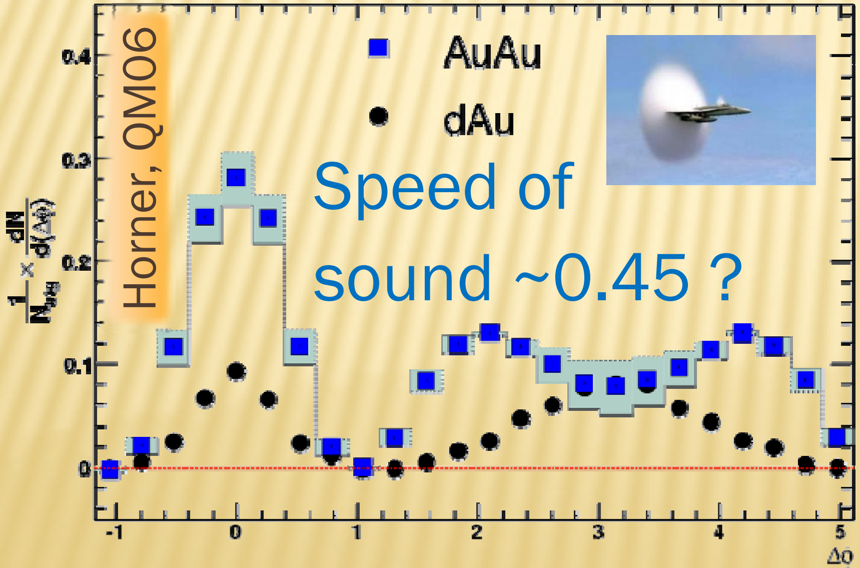
@ LHC, full jet reconstruction…

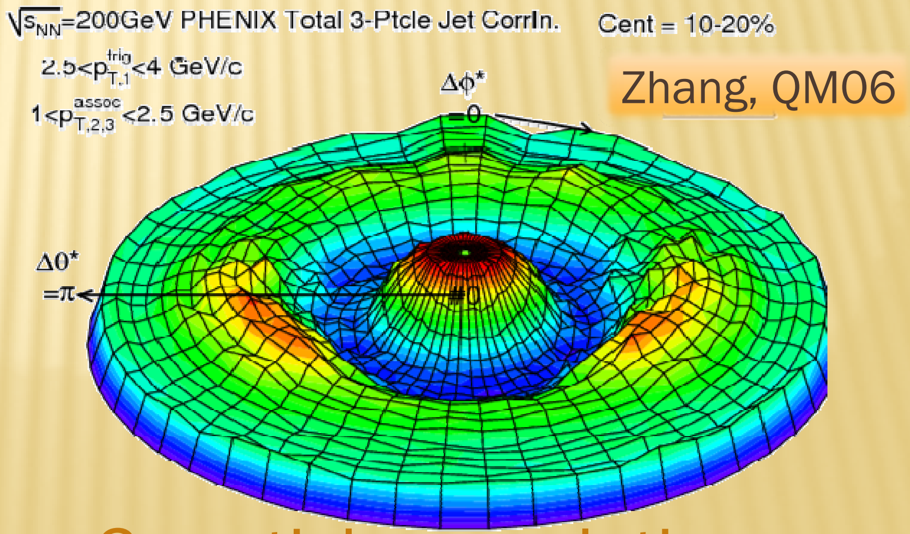
3. BACK TO BACK… AND MORE





Mach cone ?

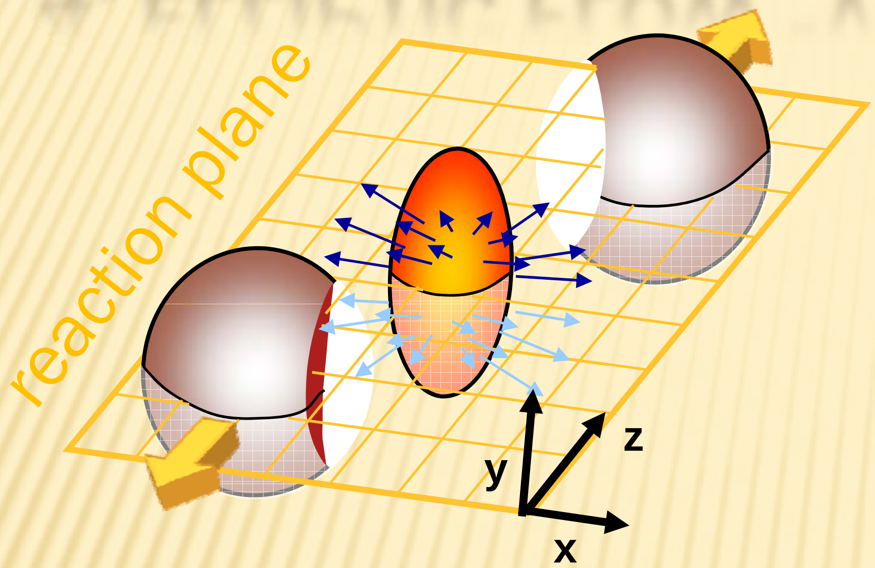




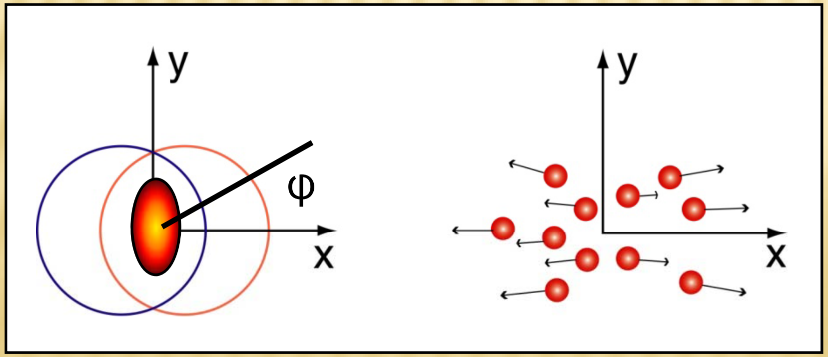
3 particle correlation

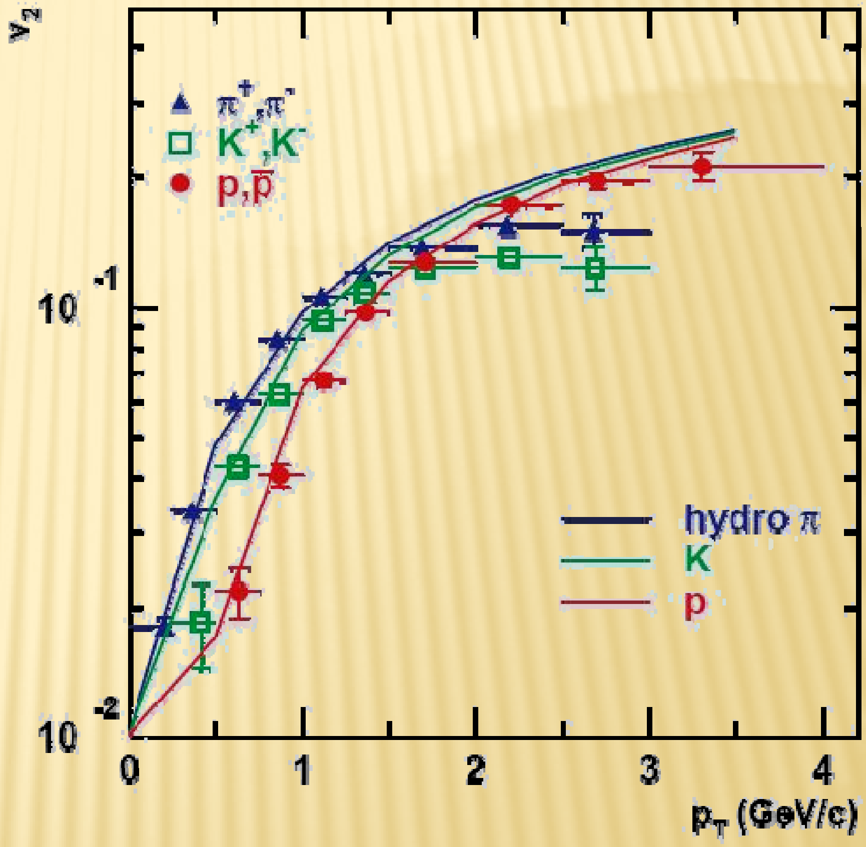
4. ELLIPTIC FLOW "V_2"

PHENIX, PRL 91 (2003) 182301
Huovinen & al, PLB 503 (2001) 58



- Pressure gradient
  - $v_2 = \langle \cos 2\varphi \rangle$





→ Strong collective behavior

4. IDEAL HYDRODYNAMICS

- Ideal hydrodynamics…
  - QGP EoS,
  - Early thermalization
    - (0.6 fm/c)
  - High density
    - (~30 GeV/fm^3)
- Little need for viscosity!
  - (first estimations approach the AdS/CFT estimates $\eta/s = \hbar/4\pi$)

… reproduces fairly well

1. Single hadron p_T spectra
   - (mass dependence)
   - $<\beta_T> \sim 0.6$
2. Elliptic flow

- Not the foreseen ideal partonic gas!

→ *"sQGP"* (s stands for strong, not super ☺)

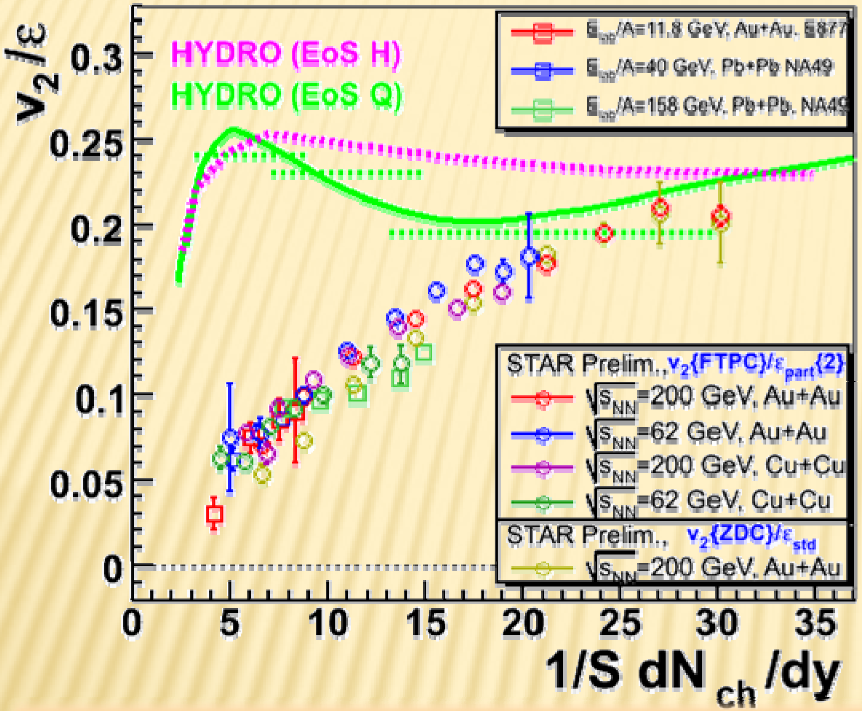
→ *"Perfect fluid"*

→ The matter is strongly interacting and liquid like @LHC, could it approach a quark gluon gas ?

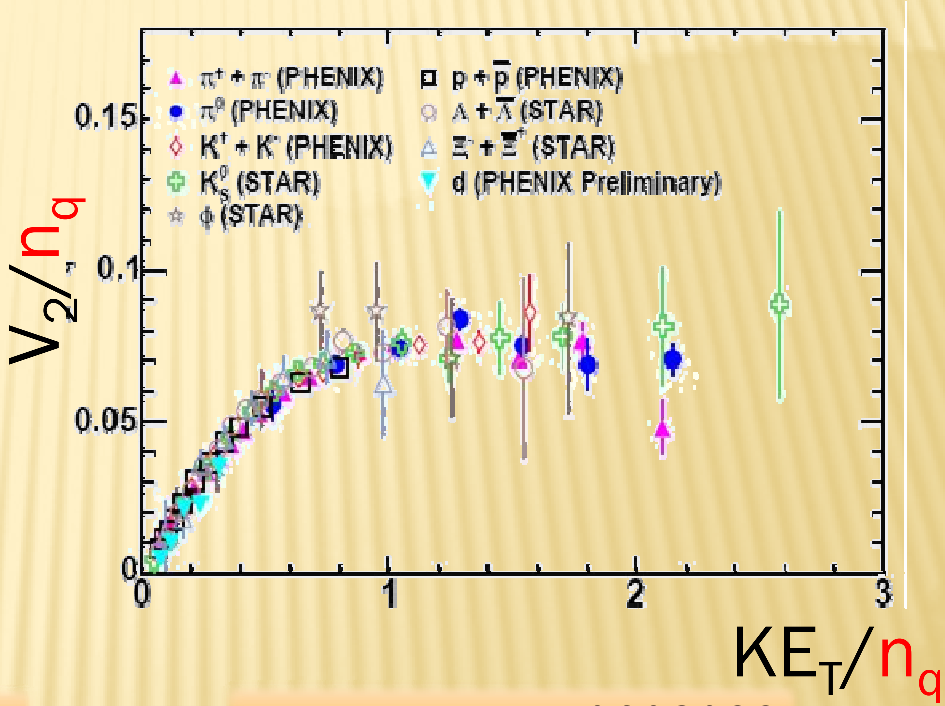
With eccentricity vs N_{ch} density

$\varepsilon = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$

With the kinetic energy per constituent quarks



Voloshin & Pokskanzer, PLB 474 (2000) 27

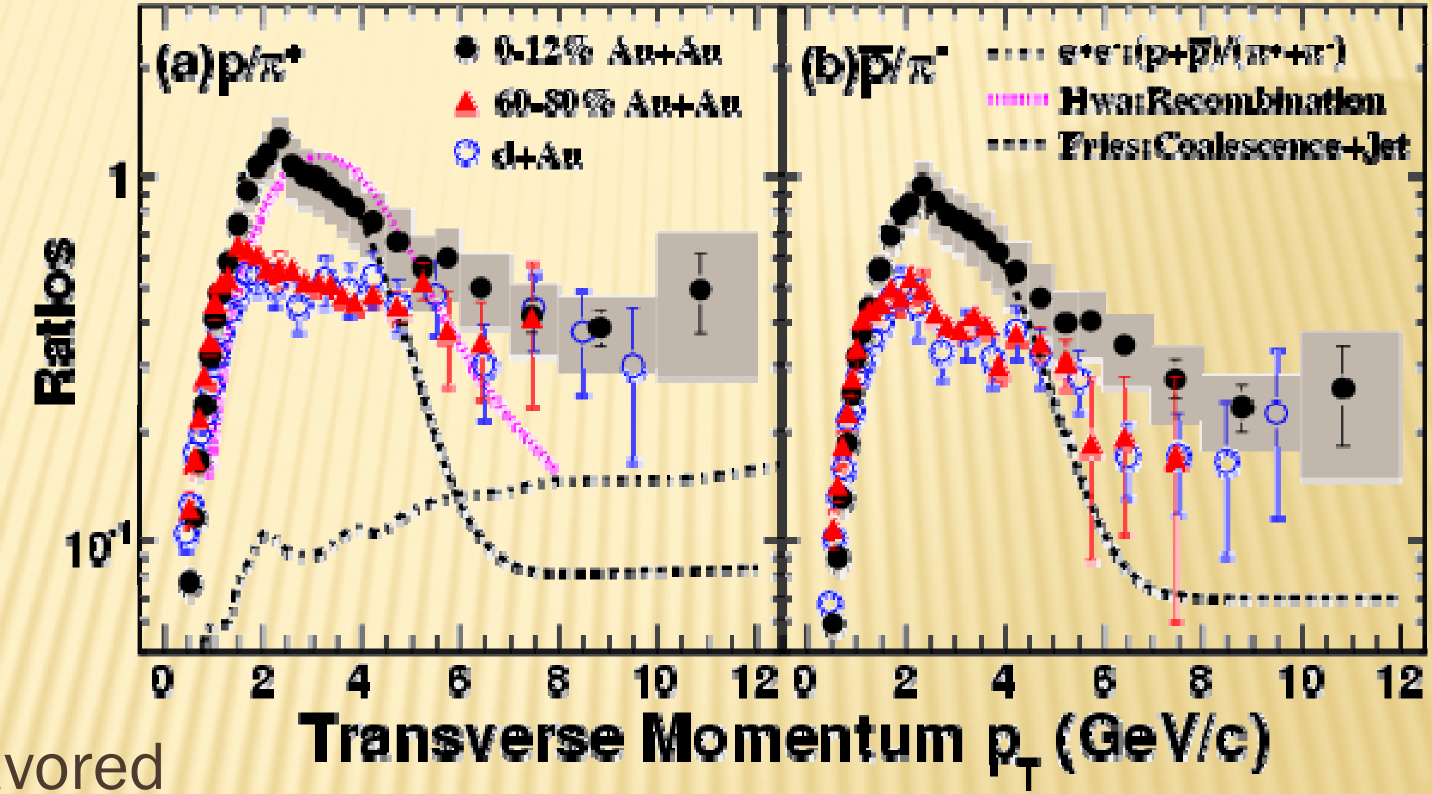


PHENIX, nucl-ex/0608033

4. ELLIPTIC FLOW (SCALINGS)

5. BARYONS/MESONS

STAR, PRL 97 (152301) 2006



- Baryon favored
- Not fragmentation!
- Coalescence or recombination

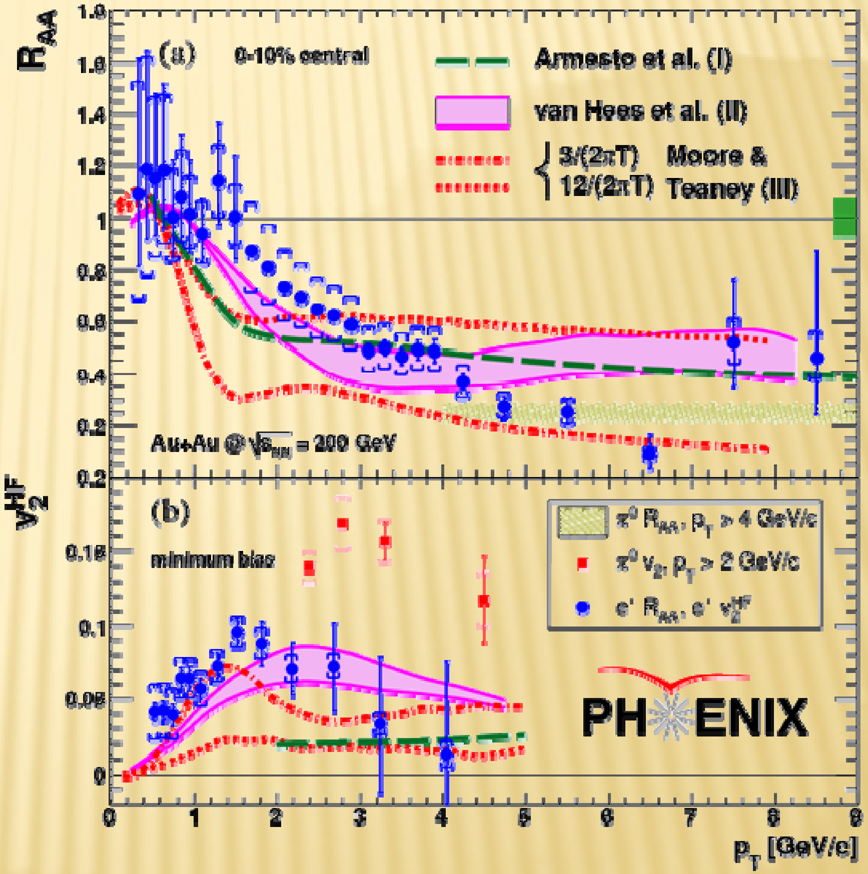
→ The matter is partonic

@LHC, even more thermalized

6. HEAVY QUARKS ?

PHENIX, nucl-ex/0611018

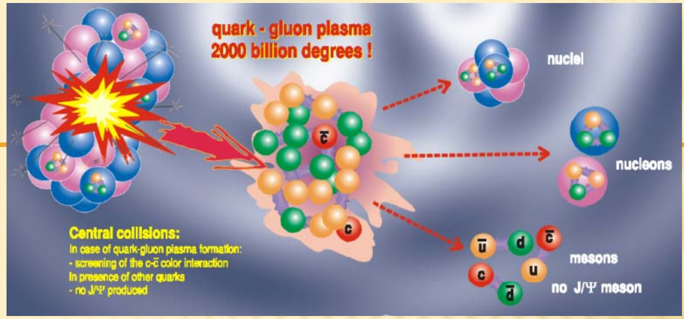
D,B → e + …



- Electrons from heavy flavor's decay suffer (large) quenching and flow! Was a surprise!
  - Thermalization?
- What makes the charm quench ?
  - Gluon density is to low!
  - Beauty contribution?
  - Elastic energy loss?
- Not well understood yet

→ The matter is tough…

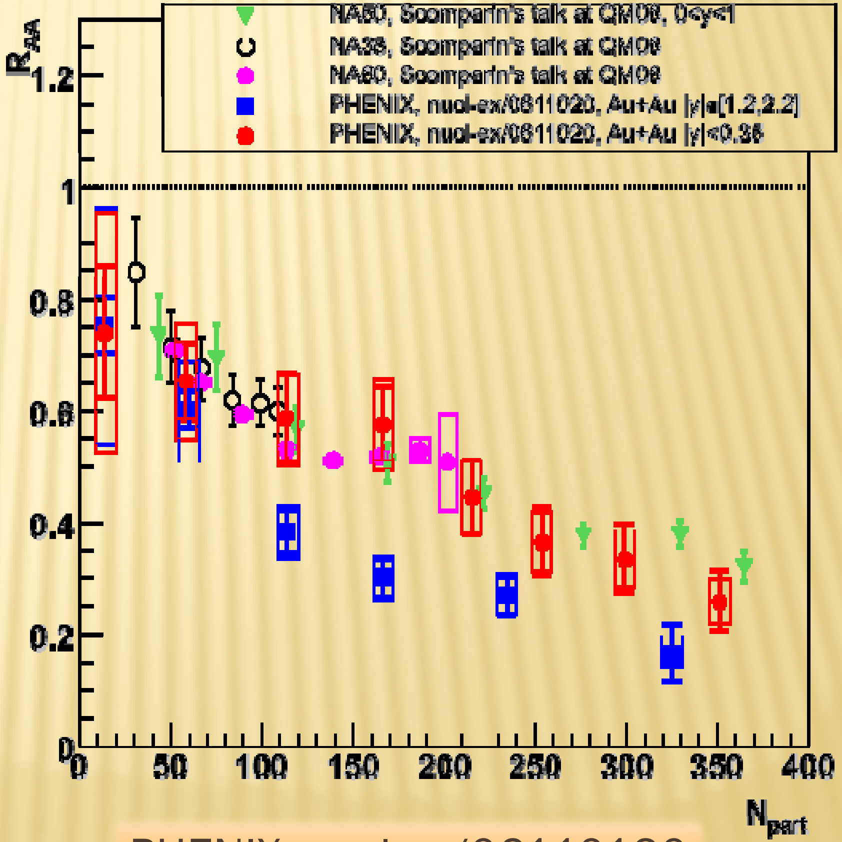
7. J/Ψ SUPPRESSION



- J/ψ ($c\bar{c}$) can melt in QGP
- Golden signature @ SPS (@ CERN √s ~ 20 GeV)

→ QGP discovery claim

- @RHIC, same rapidity, suppression look surprisingly similar
  - While density is higher
- Stronger @ forward
  - While density is lower
- But beware of cold matter!

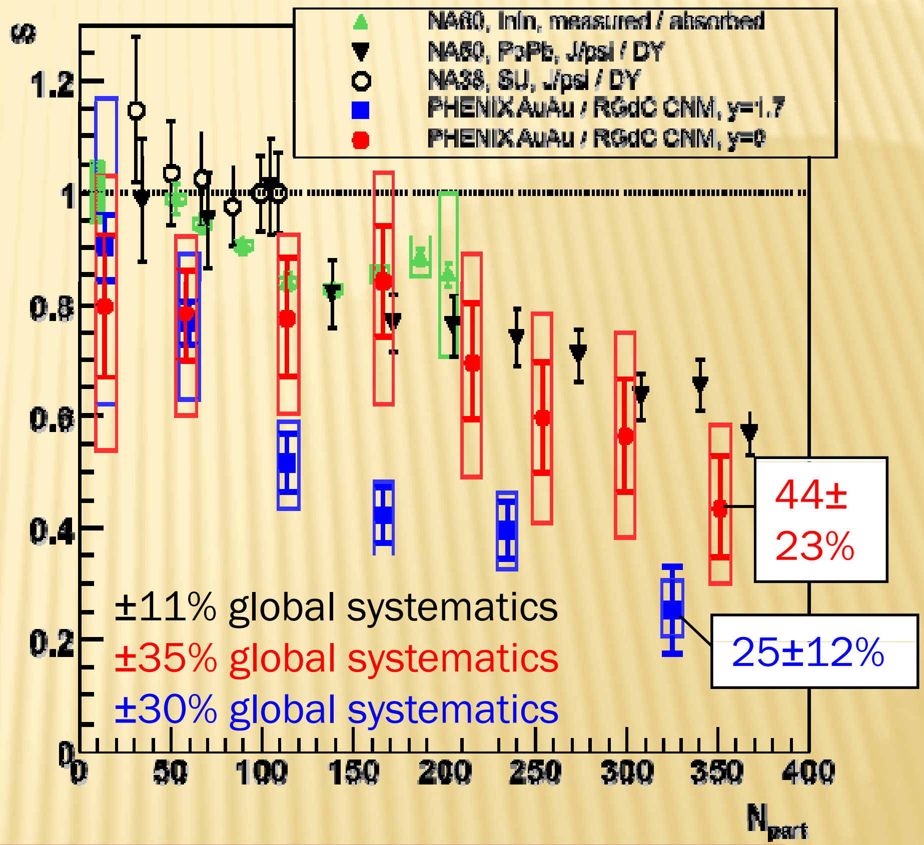


PHENIX, nucl-ex/06110120

RGdC, hep-ph/0701022

7. J/Ψ SUPPRESSION

- Cold nuclear matter effects extrapolated from d+Au collisions
- Still, more suppression at forward than mid rapidity…
- Could be a sign of recombination ?
- However J/ψ do melt !



→ The matter is deconfining

@ LHC recombination R_{AA} >1?

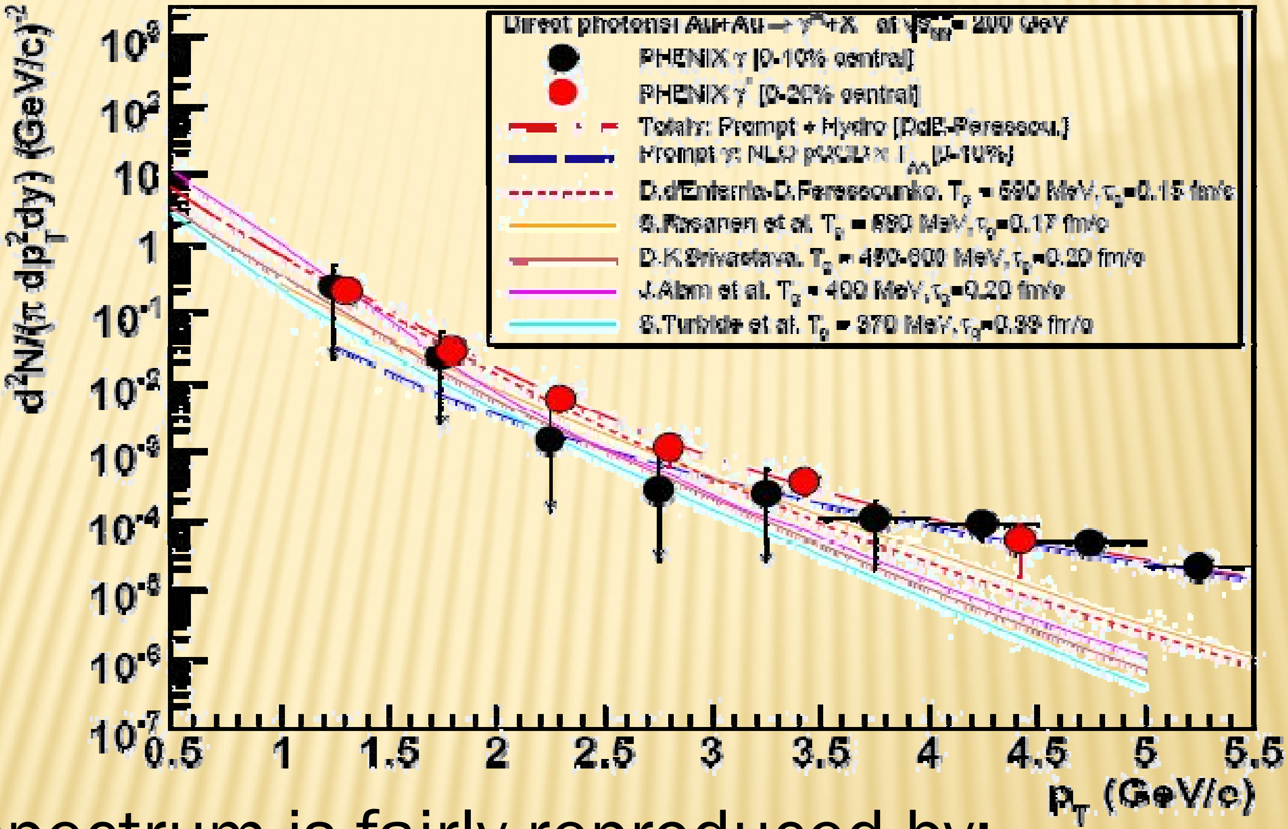
@ LHC Upsilon studies !

8. THERMAL RADIATION

The matter is hot !

@LHC, T ~ 1 GeV ?

PHENIX, PRL94 (2005) 232301
Virtual photon are preliminary
+ various theory papers



Photon spectrum is fairly reproduced by:

@ high p_T prompt photon (pQCD)

@ low p_T thermal photons (T~400 – 600 MeV >> T_c)

IN SUMMARY…

- Even if we have
  - Neither seen an order parameter of the phase transition
  - Nor counted its degrees of freedom
- The matter is:
  - Gluon saturated, dense and opaque, strongly interacting and liquid-like, partonic and deconfining, tough and hot…

  … thus likely to be a quark-gluon plasma

- Bibliography :
  - Quark matter 2006 conference (Shanghai)

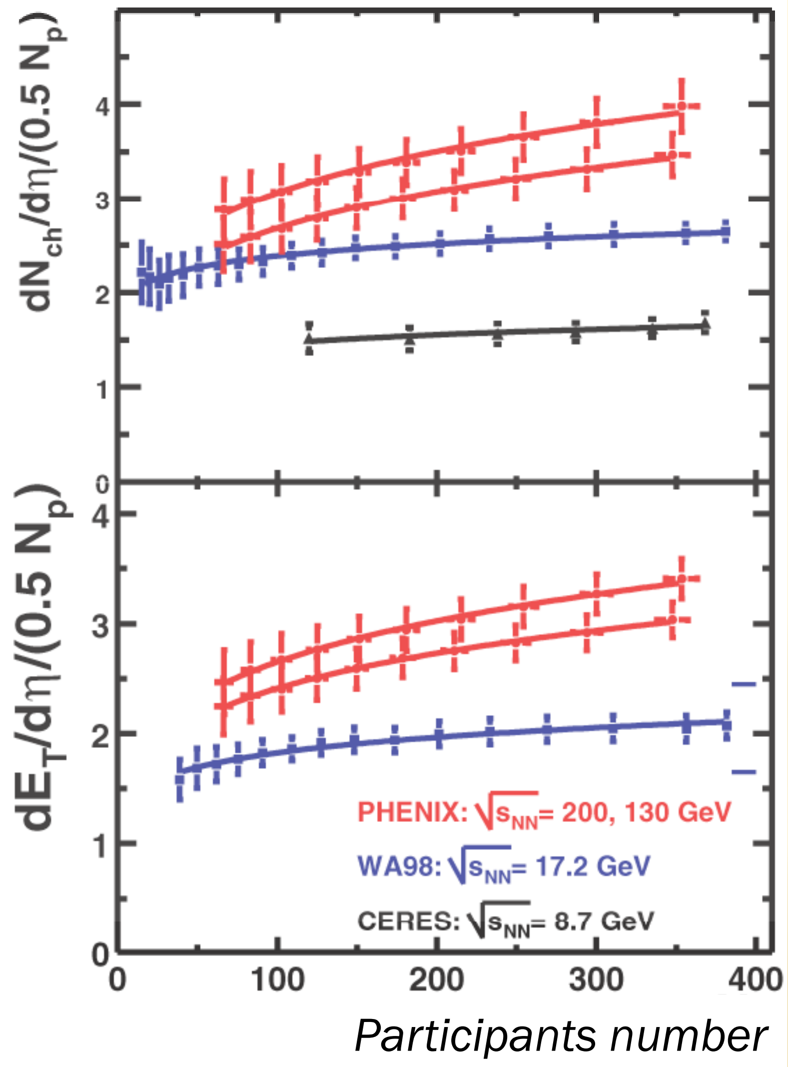
    http://www.sinap.ac.cn/qm2006/
  - Experimental "white papers" :

    NPA757 (2005), PHENIX : nucl-ex/0410003
  - Interesting reviews showing up, for instance:

    D d'Enterria, nucl-ex/0611012

BACK UP SLIDES…

ENERGY DENSITY ESTIMATION



~ Transverse energy @ y=0

Bjorken formula

$$\varepsilon = \frac{1}{\pi R^2 \tau_0} \times \left. \frac{dE_T}{dy} \right|_{y=0}$$

τ_0 formation time
0,35 à 1 fm/c

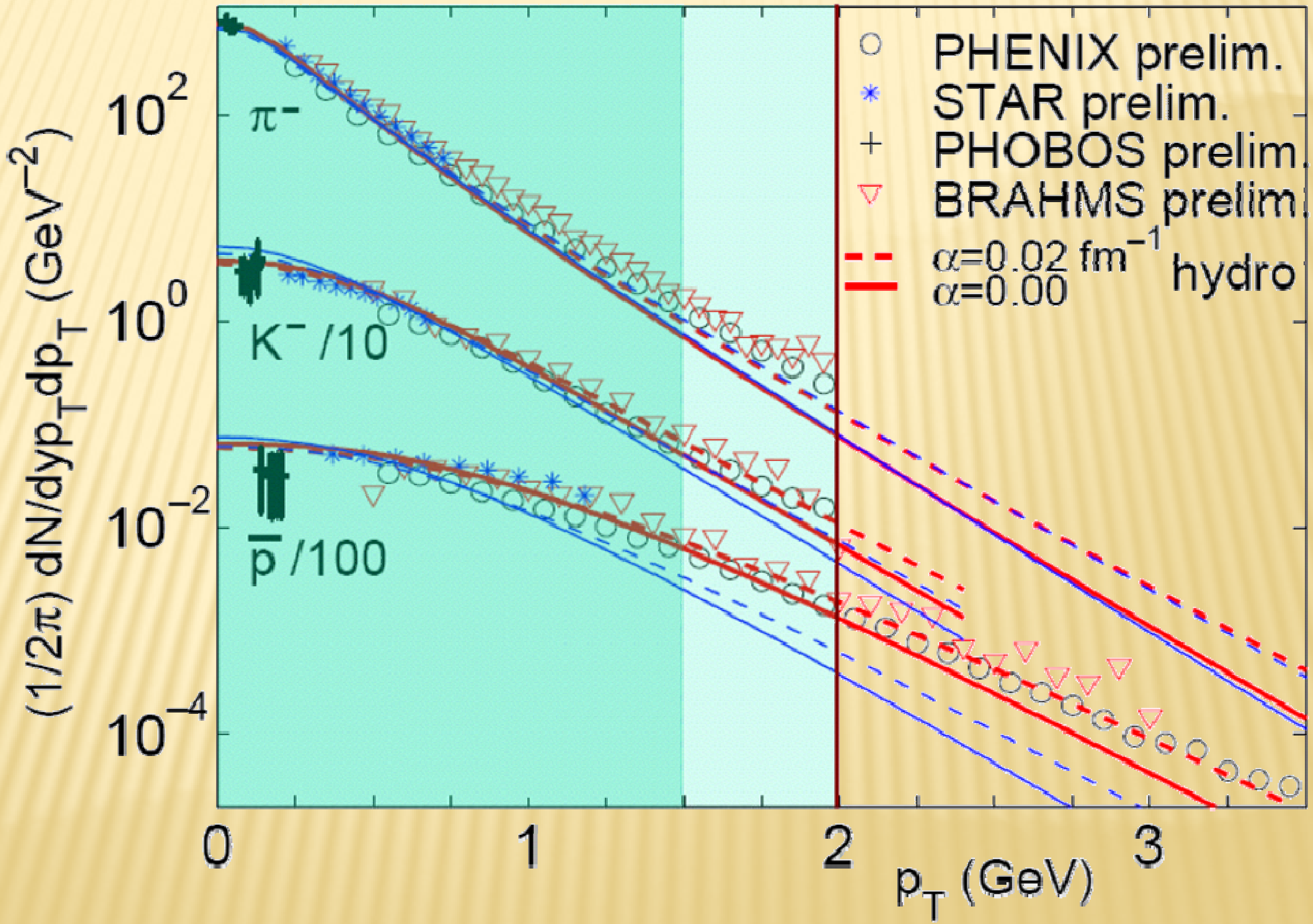
R = nuclear radius
1.18 $A^{1/3}$ fm

ε > 6 GeV/fm^3

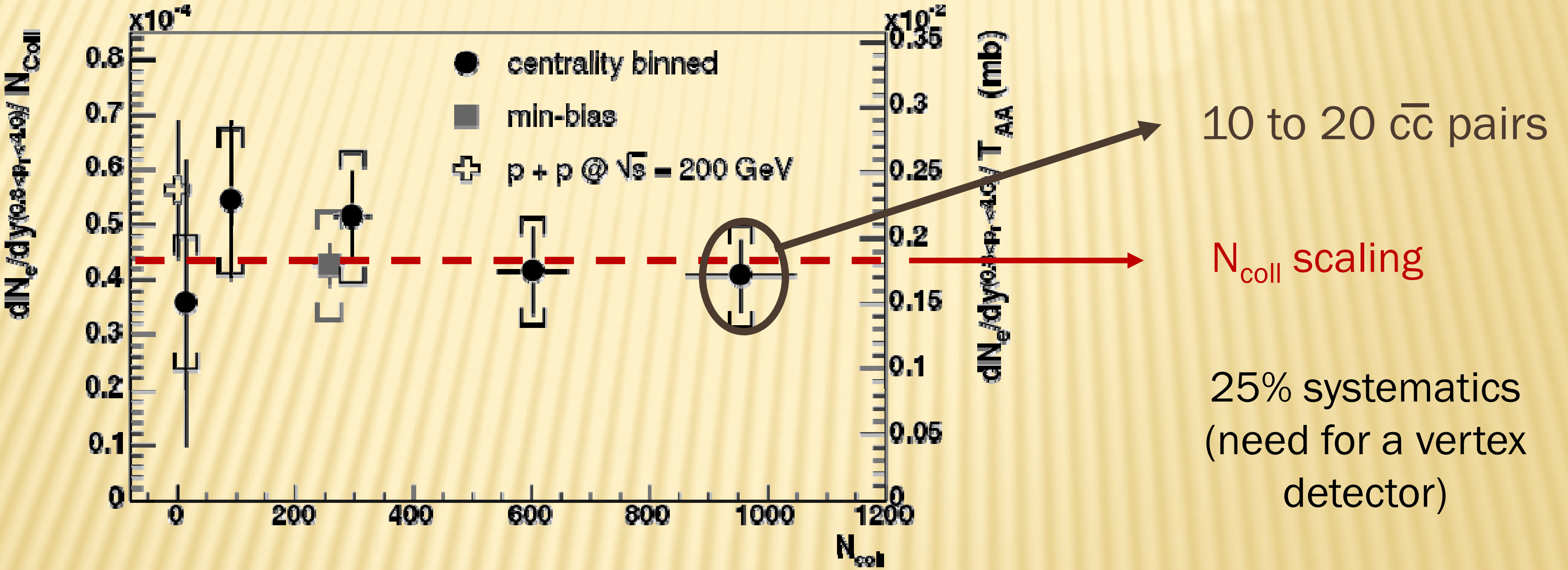
Bjorken, PRD27 (1983) 140

HYDRO FIT OF SPECTRA

P. Kolb and R. Rapp, PRC 67 044903 (2003)



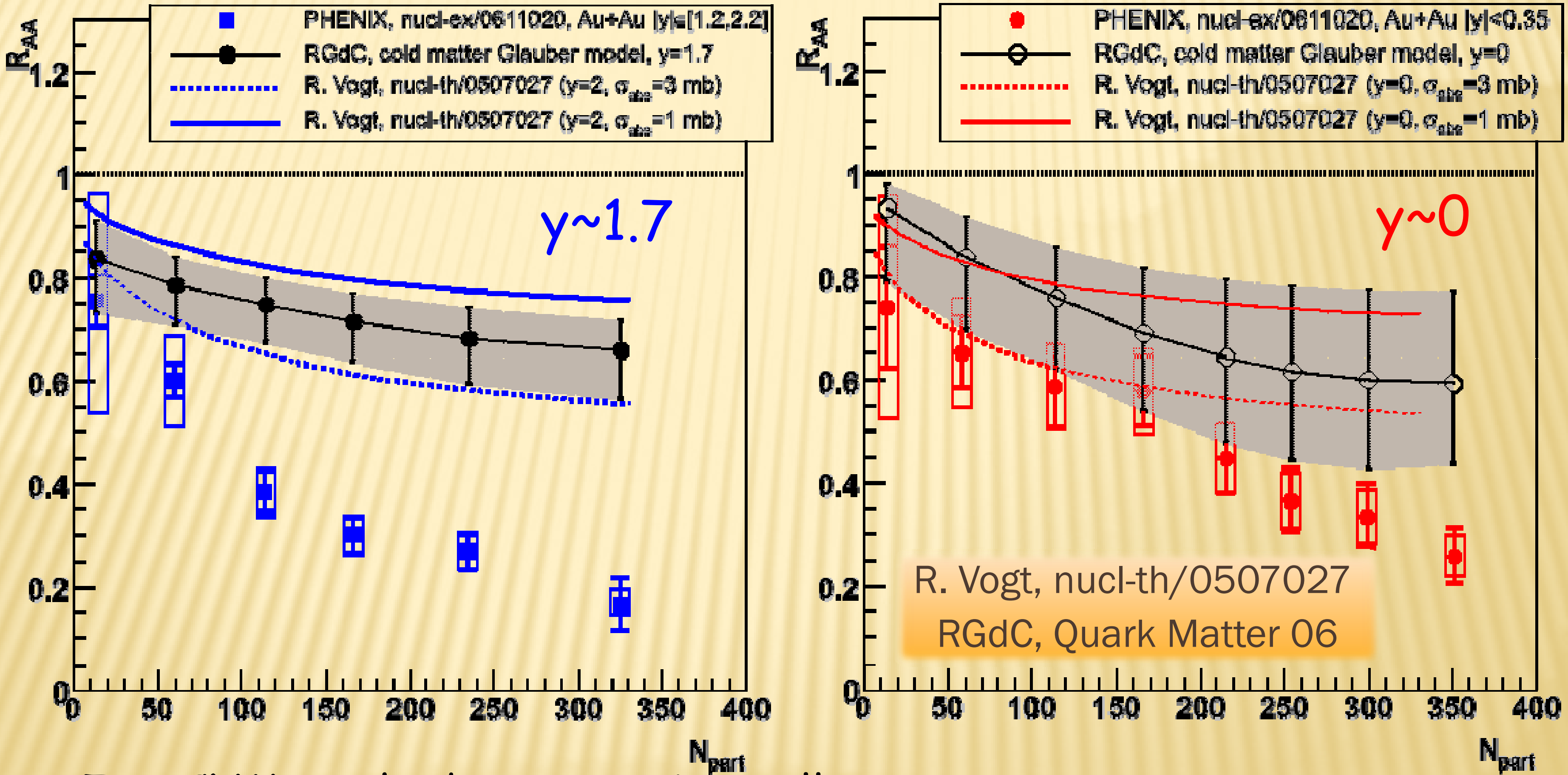
OPEN CHARM



PHENIX, PRL 94 (2005) 082301

25% systematics (need for a vertex detector)

J/Ψ AND COLD NUCLEAR MATTER

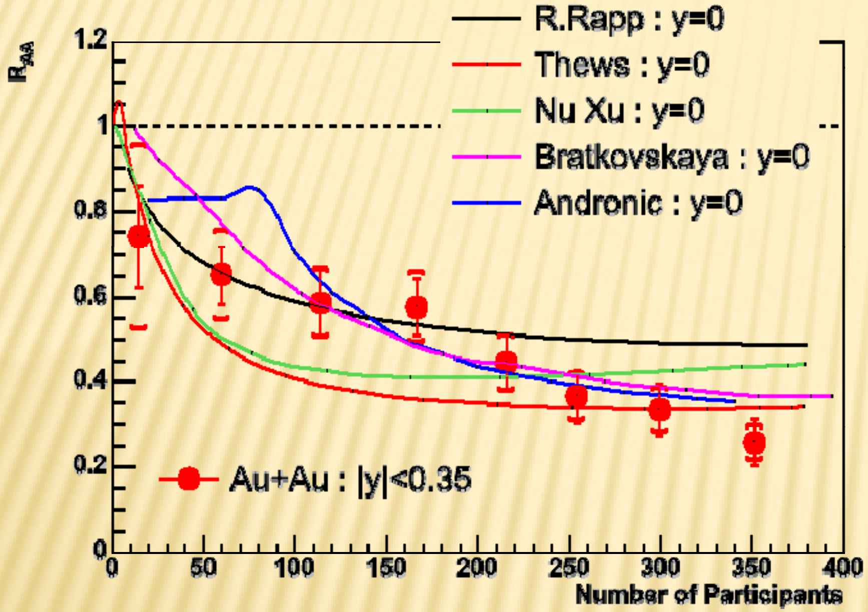


- Two CNM methods agree quite well
  - (shadowing+absorption by Vogt and dA-driven Glauber by RGdC)
- Clear anomalous suppression (stronger @ y~1.7)

J/Ψ VERSUS MODELS…

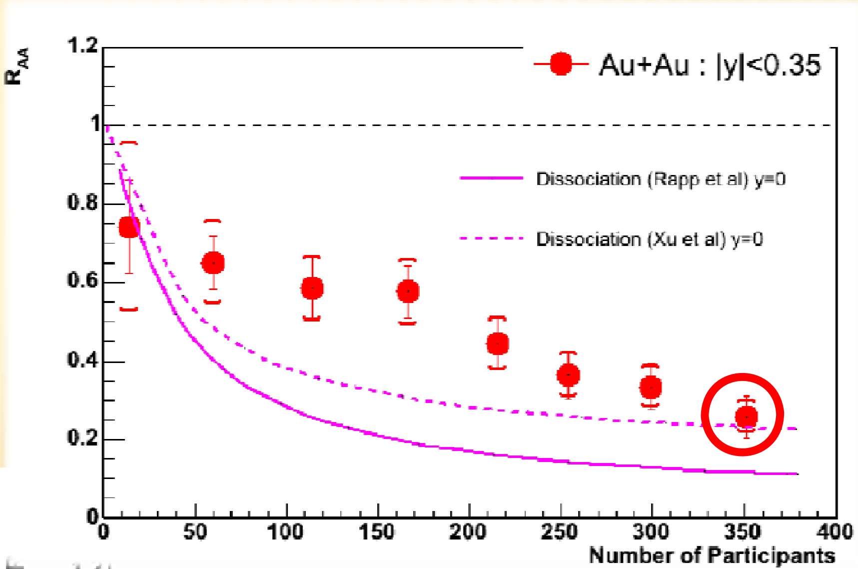
R. Rapp & al., nucl-th/0608033
Yan, Zhuang, Xu, nucl-th/0608010

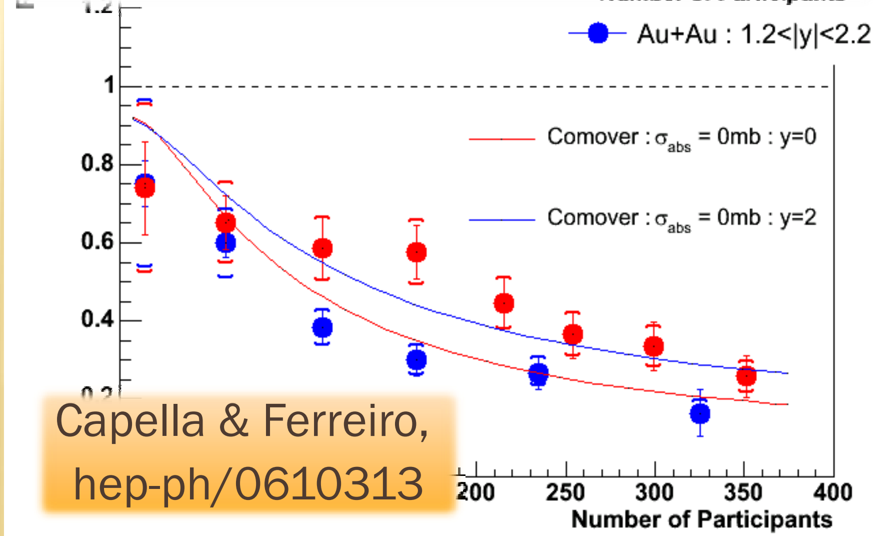
- Recombination…



R. Rapp et al.PRL 92, 212301 (2004)
R. Thews et al, Eur. Phys. J C43, 97 (2005)
Yan, Zhuang, Xu, nucl-th/0608010
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al., nucl-th/0611023

- SPS like…





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