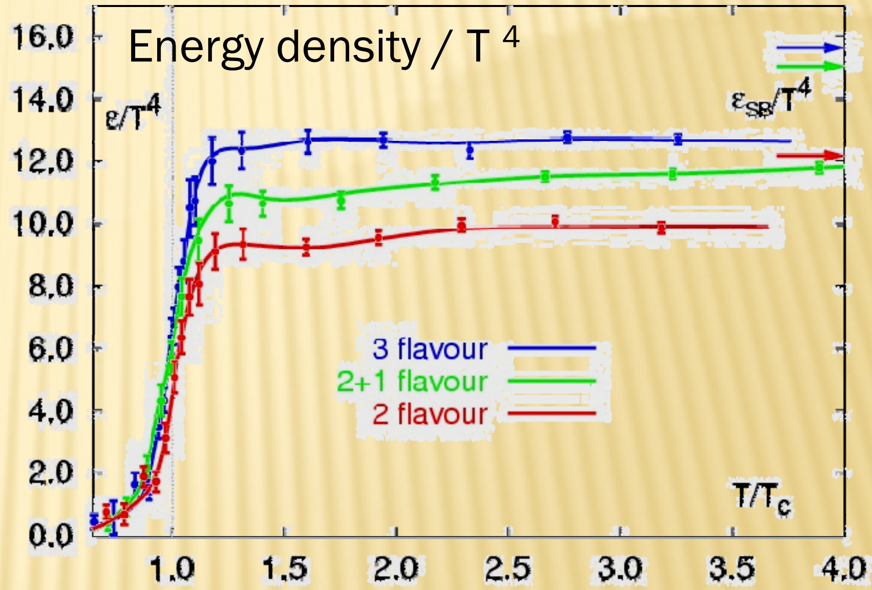
Elastic and diffractive scattering, CERN, July 2nd 2009

Raphaël Granier de Cassagnac
Laboratoire Leprince-Ringuet
PHENIX and CMS experiments

QCD AND HEAVY IONS
RHIC OVERVIEW

WHAT TELLS QCD? (ON THE LATTICE)

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

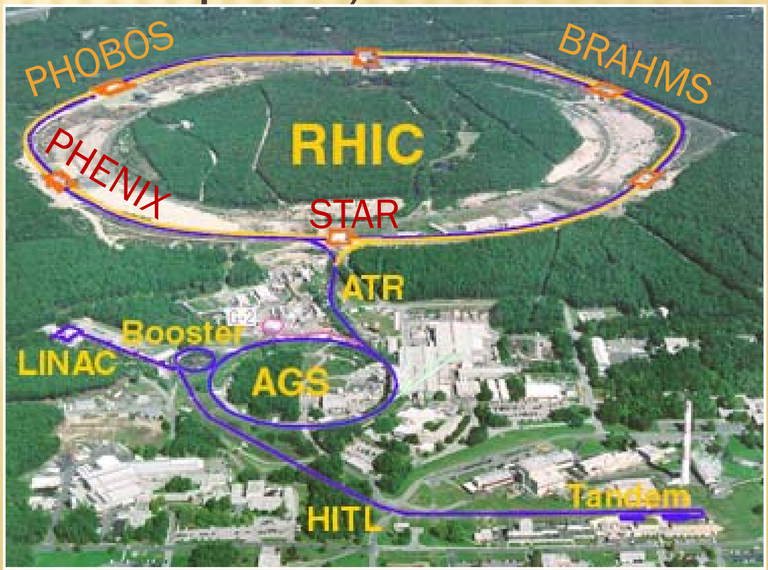


Karsch et al, hep-lat/0106019
Lect. Notes Phys.583 (2002) 209

→ But doesn't tell us everything about the matter's observable and dynamical properties

WHAT'S RHIC?

- Relativistic Heavy Ion Collider @ Brookhaven National Lab.
- First collisions in 2000, running…
- 2 large (STAR & PHENIX) >2x600 + 2 smaller (PHOBOS & BRAHMS) experiments
- Can collide anything from p+p (up to 500GeV, in 2009) to Au+Au (up to 200GeV per nucleon pairs)



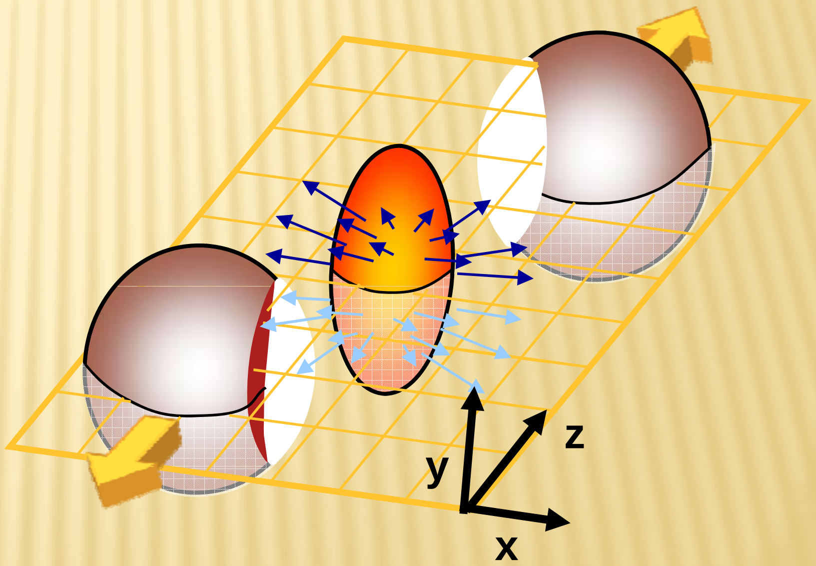
WHAT IS THE STRATEGY? (AND JARGON)

- Predict a QGP signature
- Look at it versus A+A collision <u>centrality</u> →
- Compare to p+p
  - Nuclear modification factor

$$R_{AA} = \frac{dN^{AuAu}}{dN^{PP} \times \langle N_{coll} \rangle}$$

- Without QGP, hard probes should have $R_{AA} \approx 1$
- 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…)

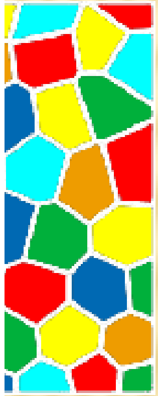
WHICH SIGNATURES?

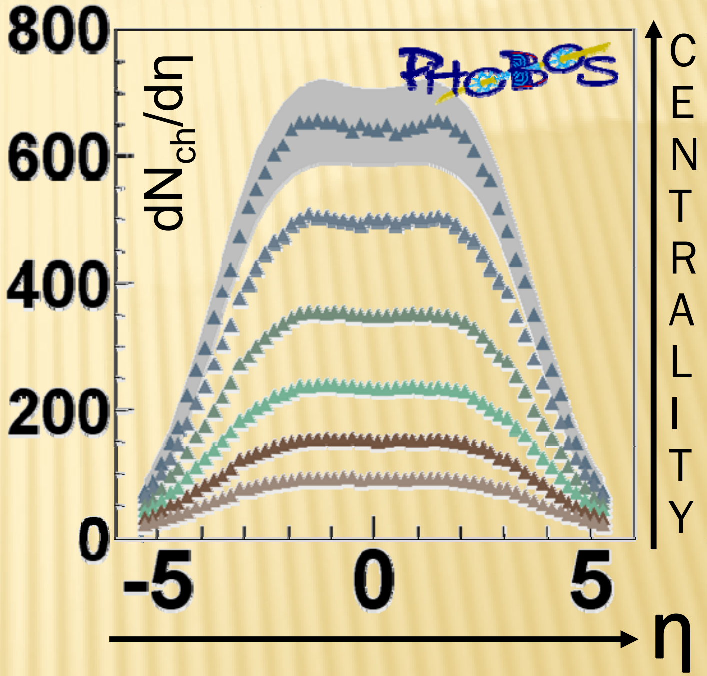
1. Total multiplicity — ≈ *"Color Glass Condensate"*
2. High p_T suppression — ≈ *"Jet quenching"*
3. Back to back jets — ≈ *"Jet quenching"*
4. Elliptic flow — ≈ *"Perfect fluid"*
5. Baryon/meson
6. Heavy flavour
7. J/ψ suppression
8. Thermal radiation
9. …

→ Not the only ones! Impossible to give an overview in 20 mn… Restrict to selected underlined topics

1. TOTAL MULTIPLICITY (AND E_T)

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





PRL 91 (2003) 052303

→ The (initial) matter saturates

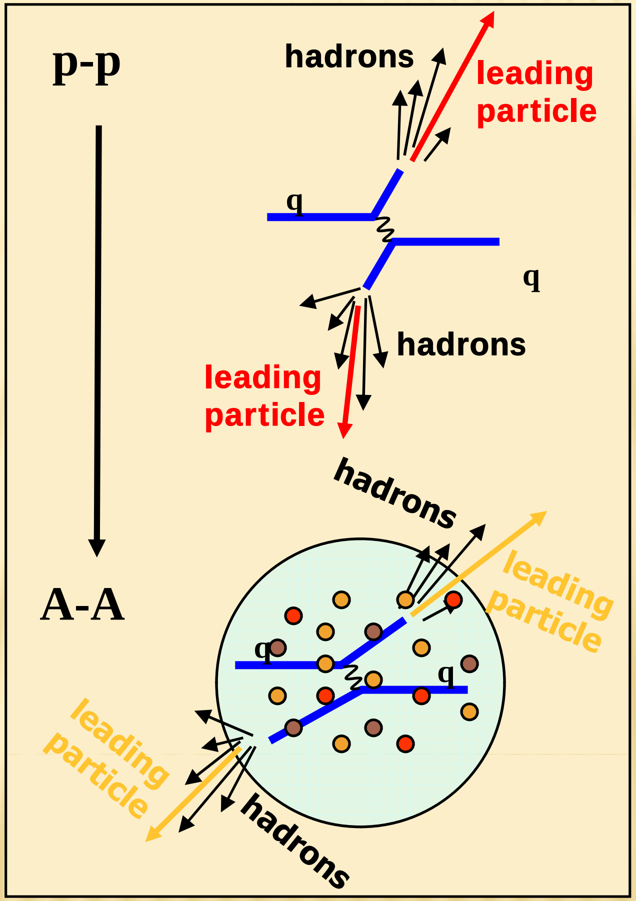
- $dE_T/d\eta|_{\eta=0}$ related to energy density
- $\varepsilon > 6$ GeV/fm$^3 > \varepsilon_c$!

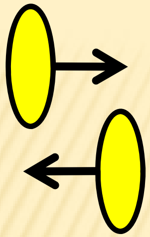
The smoking gun...

JET QUENCHING

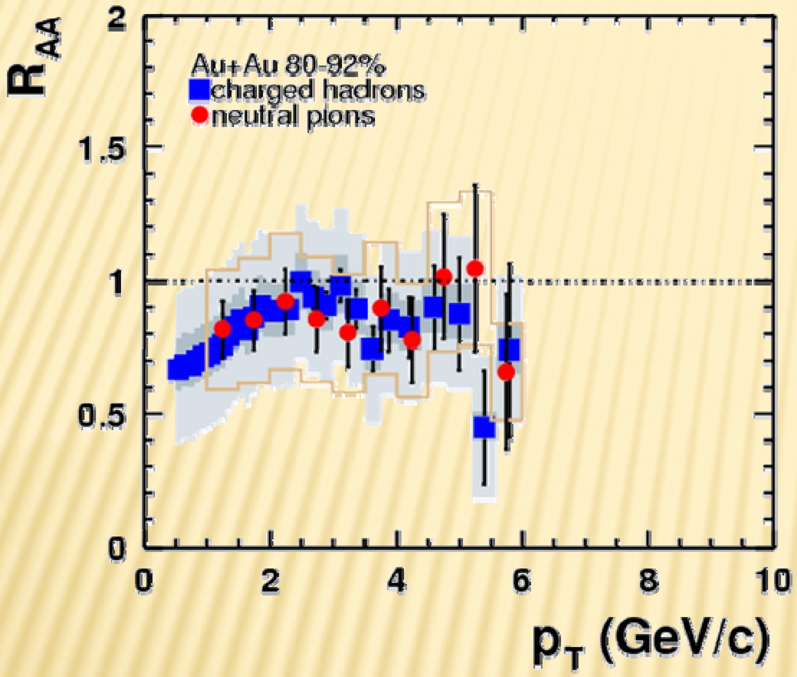
2. HIGH P_T SUPPRESSION

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

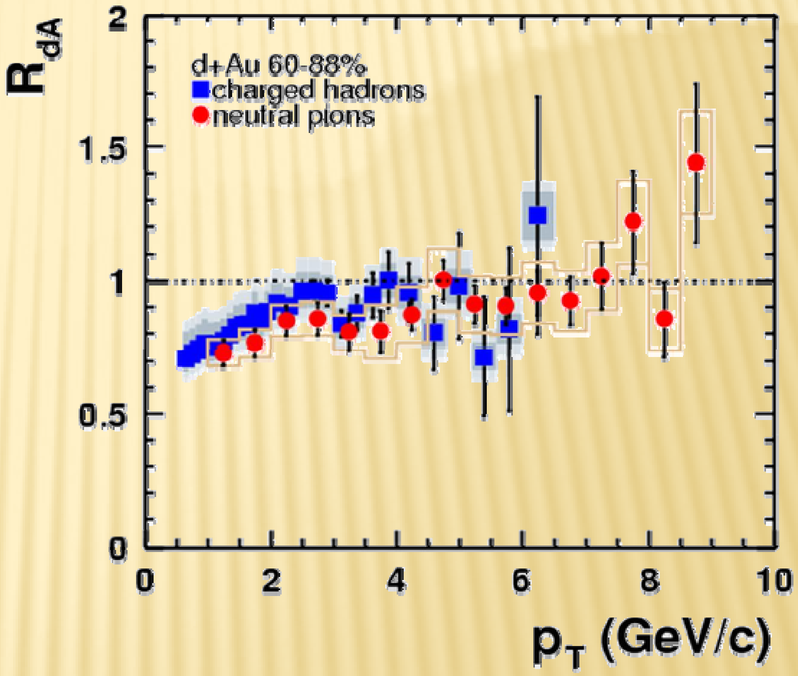




Au-Au (80-92%)



d+Au (60-88%)



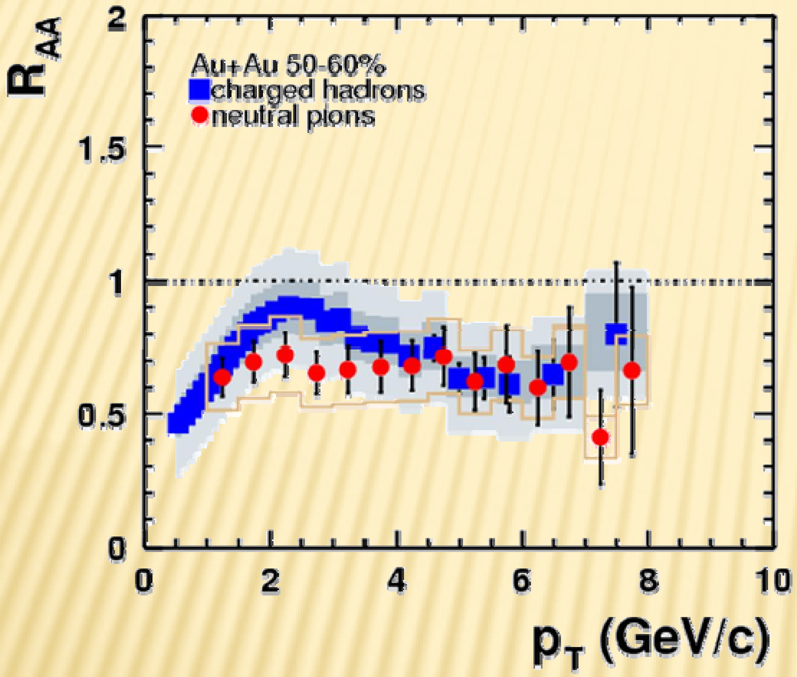
MOST PERIPHERAL COLLISIONS…

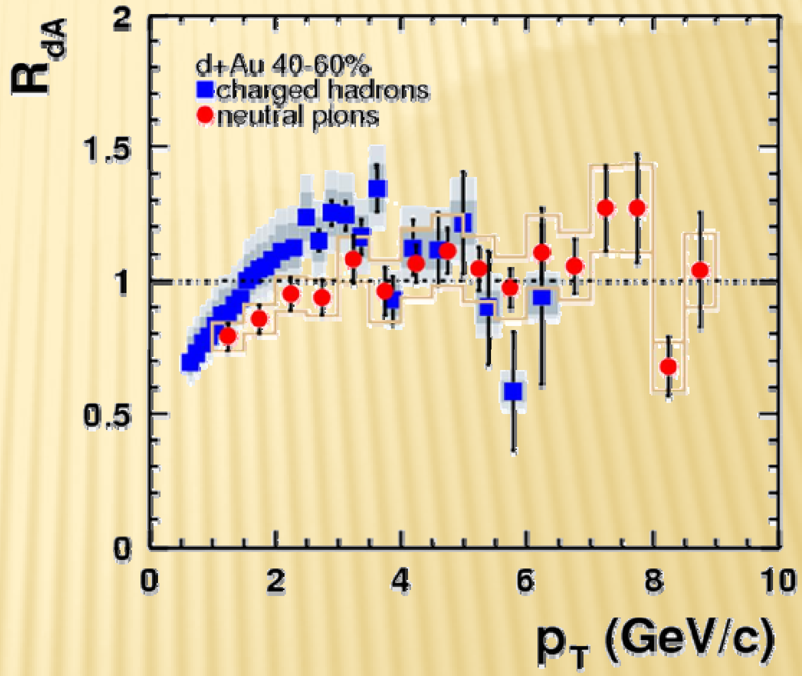
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (50-60%)

d+Au (40-60%)



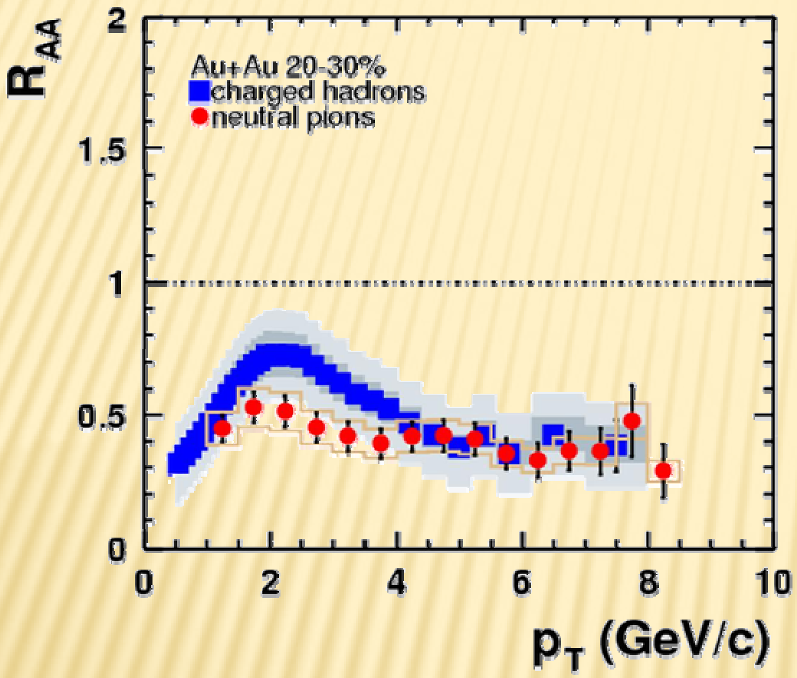


LESS PERIPHERAL COLLISIONS…

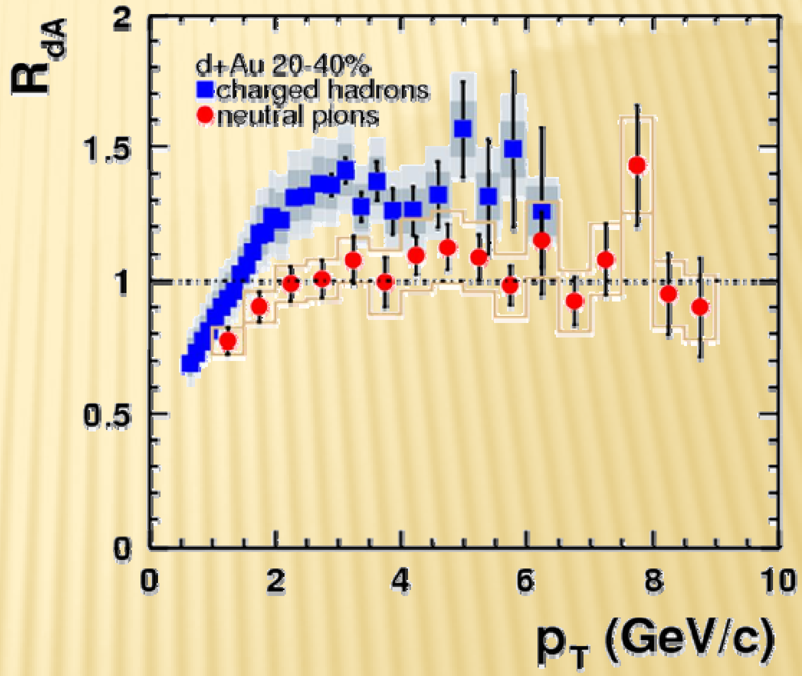
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (20-30%)



d+Au (20-40%)

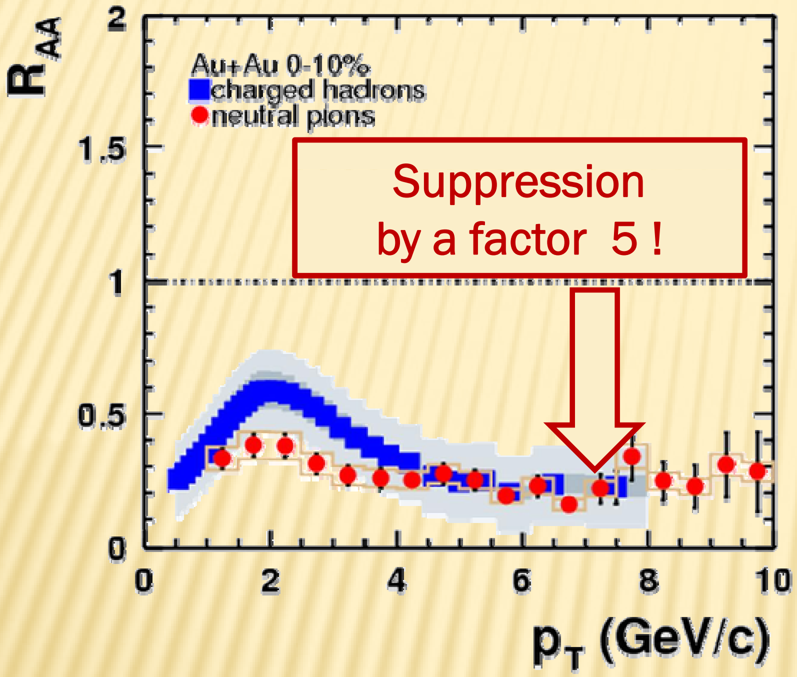


MORE CENTRAL COLLISIONS…

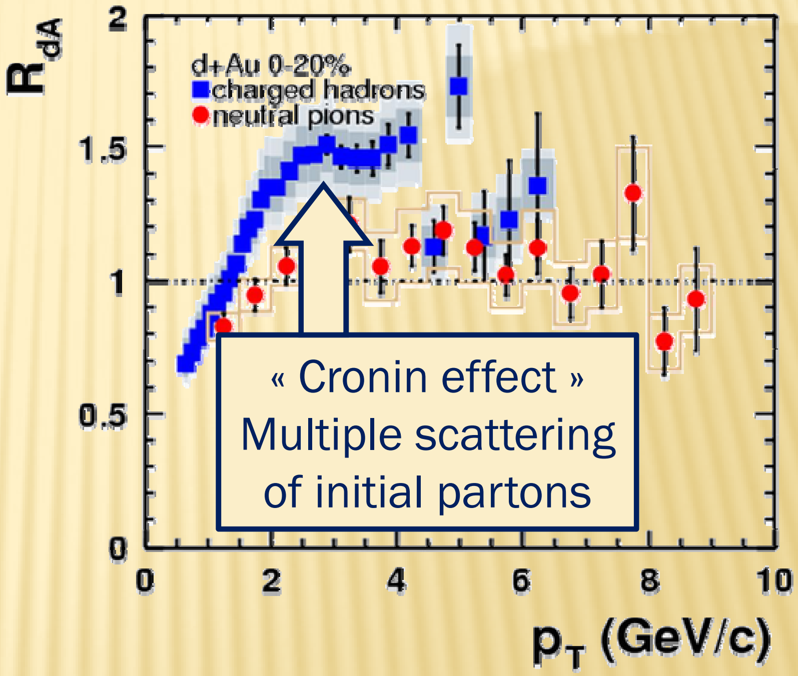
(slightly old, but pedagogical, data)

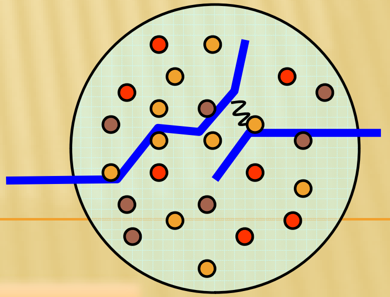
PHENIX, PRL 91 (2003) 072303

Au-Au (0-10%)



d+Au (0-20%)





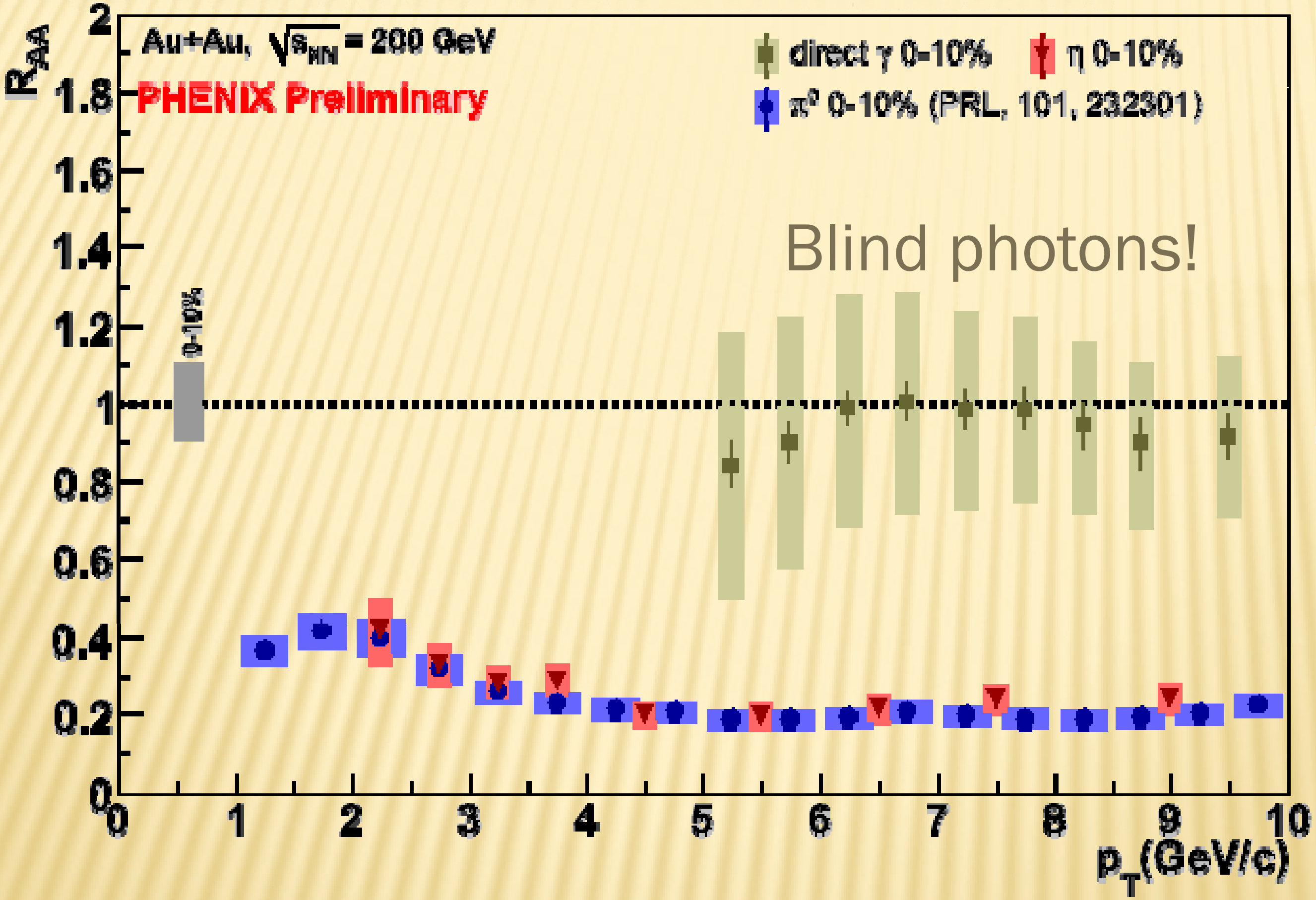
MOST CENTRAL COLLISIONS!

(slightly old, but pedagogical, data)

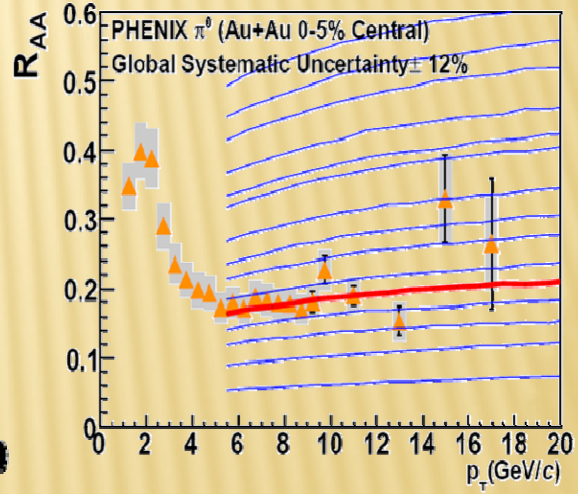
PHENIX, PRL 91 (2003) 072303

2. HIGH P_T SUPPRESSION

PHENIX, PRC77 (2008) 064907

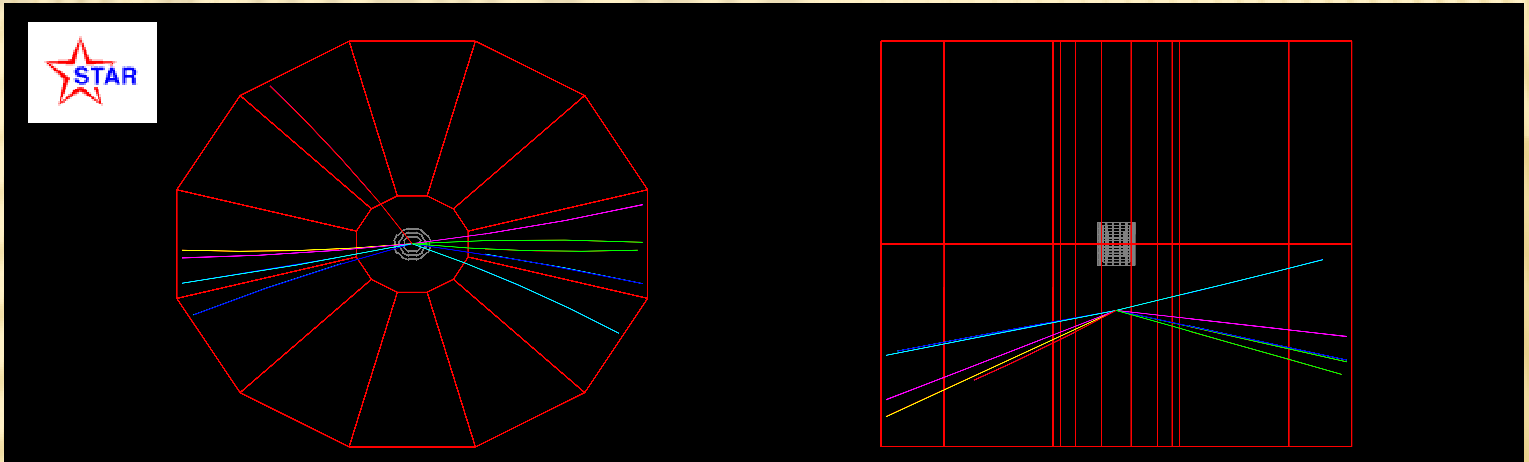


→ Comparisons to models, including experimental errors provide physical properties, e.g. $dN_{gluons}/dy = 1400 ^{+200}_{-375}$

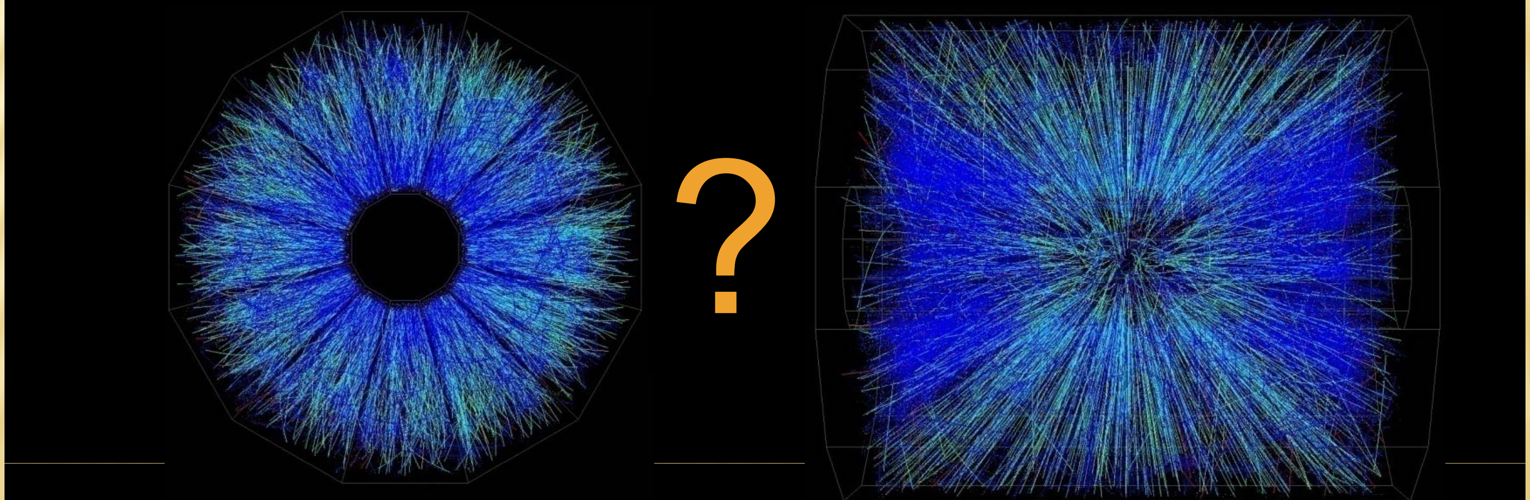


→ The matter is dense ! >1000 gluons per Δy

3. BACK TO BACK JETS



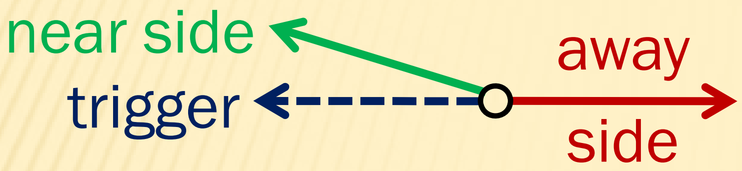
Easy in 200 GeV proton+proton collisions

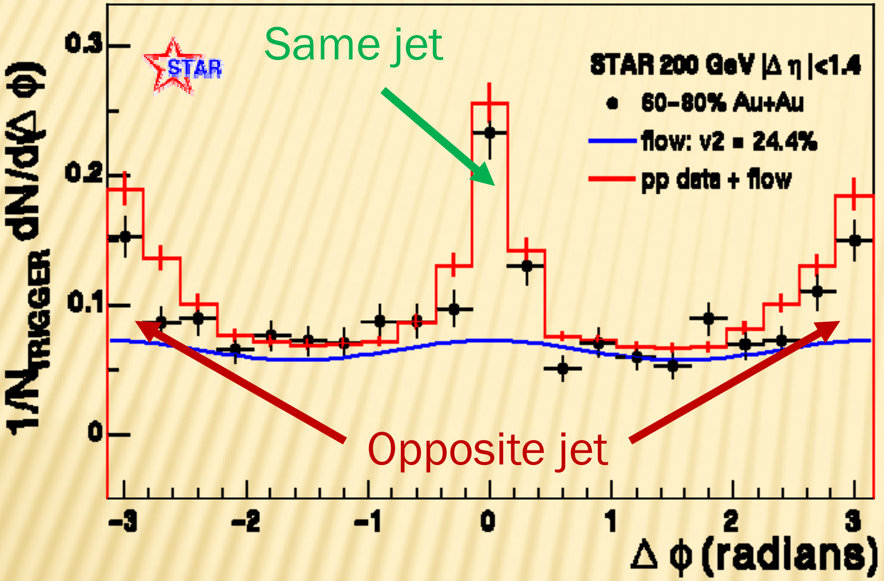


Quite difficult in Au+Au central collisions @ 200 GeV

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

Peripheral collisions (60-80%)

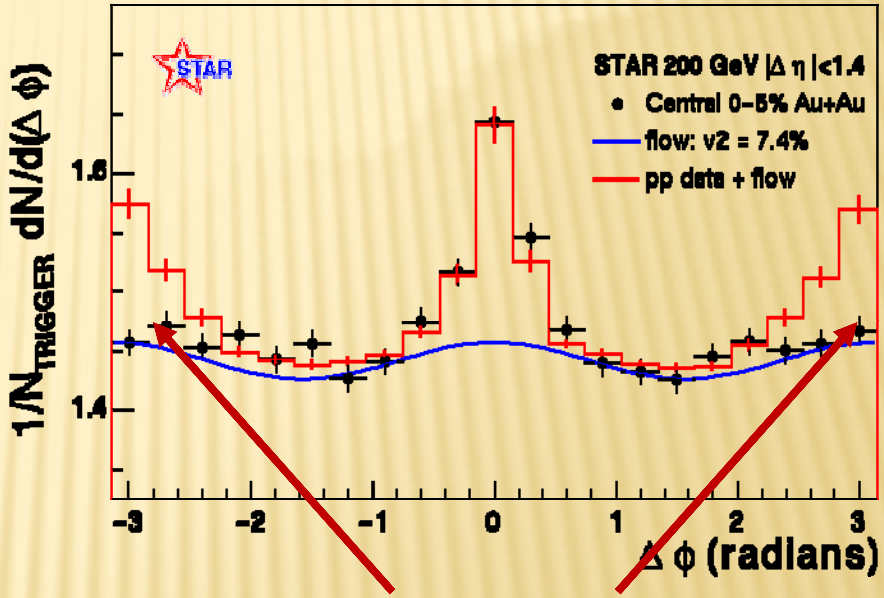




Take a “trigger” particle (p_T>4GeV/c) and look at the others (p_T>2GeV/c) azimuth

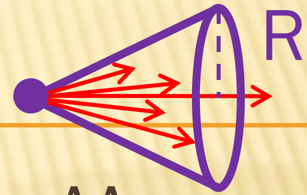
Central collisions (0-5%)

→ The matter is opaque!

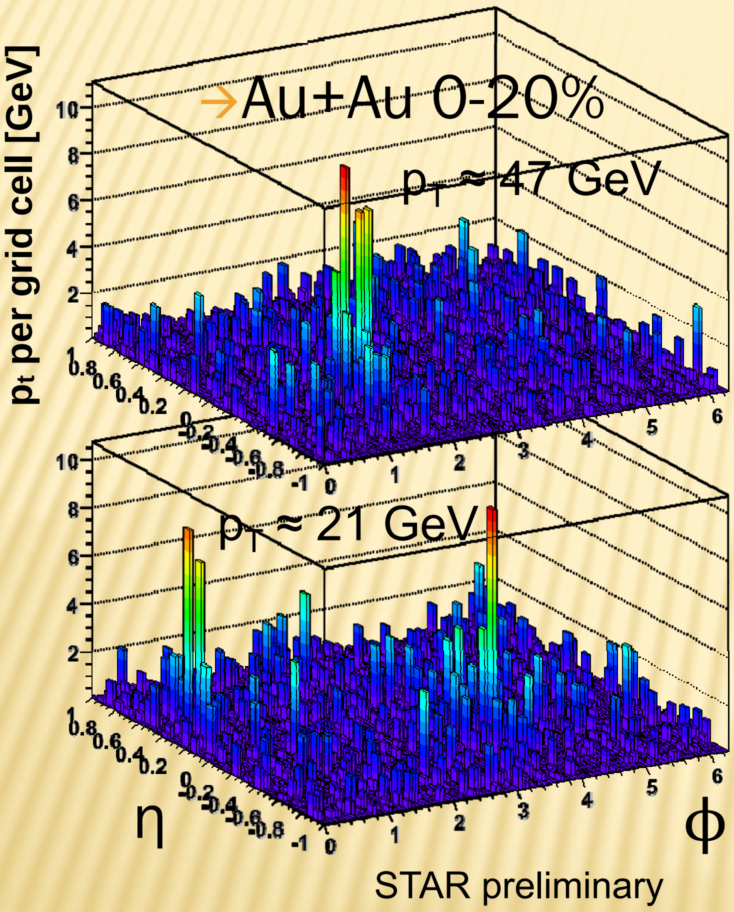


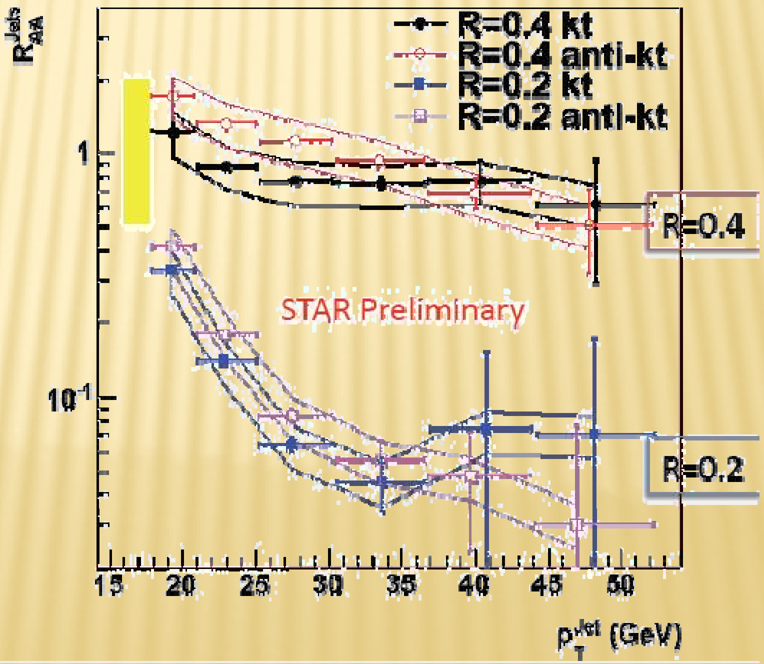
In central collision, opposite jets disappear because of jet quenching

NEW TOOL: JET RECONSTRUCTION?



- First reconstructed jets in AA
- Use of fastjet algorithms
- R_{AA}≈1 for large cone R=0.4
- Jet broadening R_{AA}<<1 for R=0.2
- Promising preliminary data



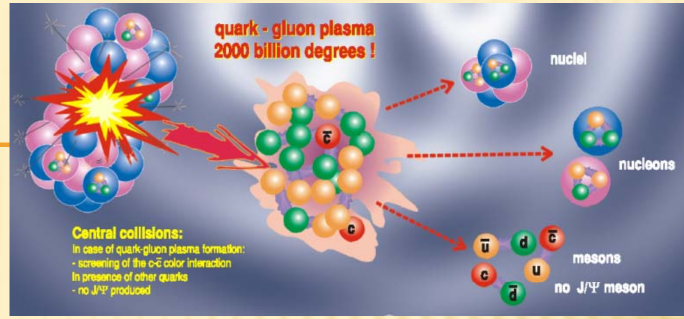


M. Polskon, Quark Matter 09
http://www.lpthe.jussieu.fr/~salam/fastjet

The originally thought "unambiguous signature"

QUARKONIA SUPPRESSION

7. J/Ψ SUPPRESSION



- J/ψ ($c\bar{c}$) can melt in QGP

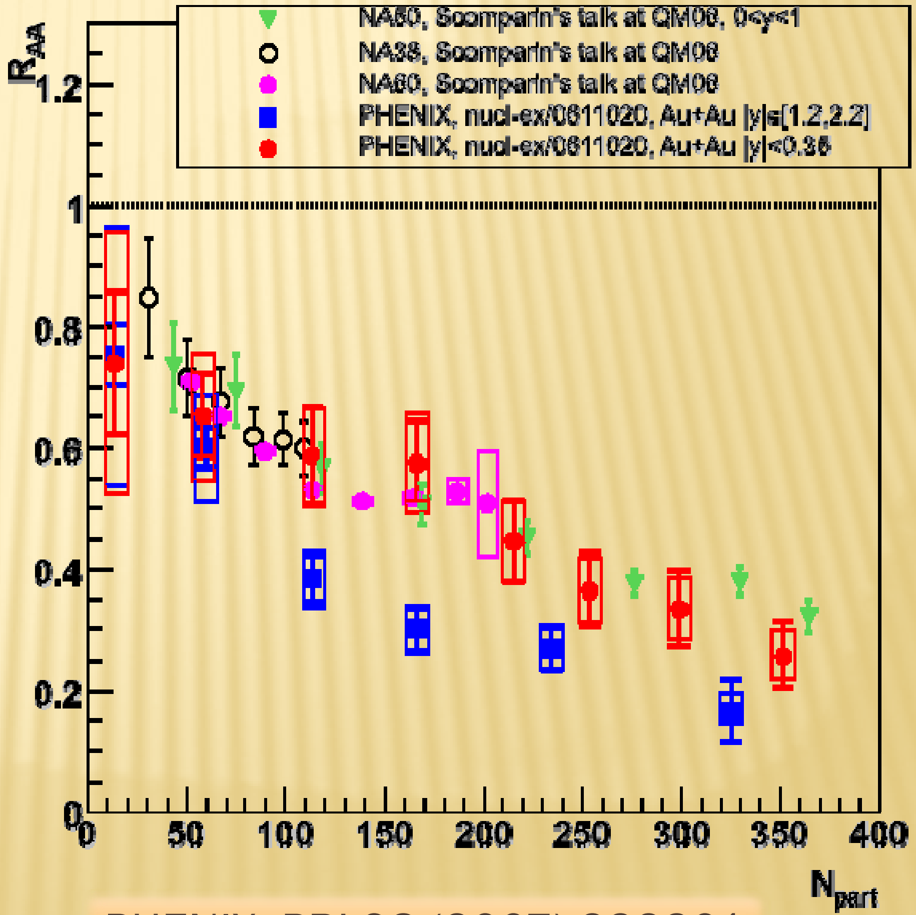
  Matsui & Satz, PLB178 (1986) 416

- Golden signature @ SPS

  (@ CERN √s ≈ 20 GeV)

  → QGP discovery claim!

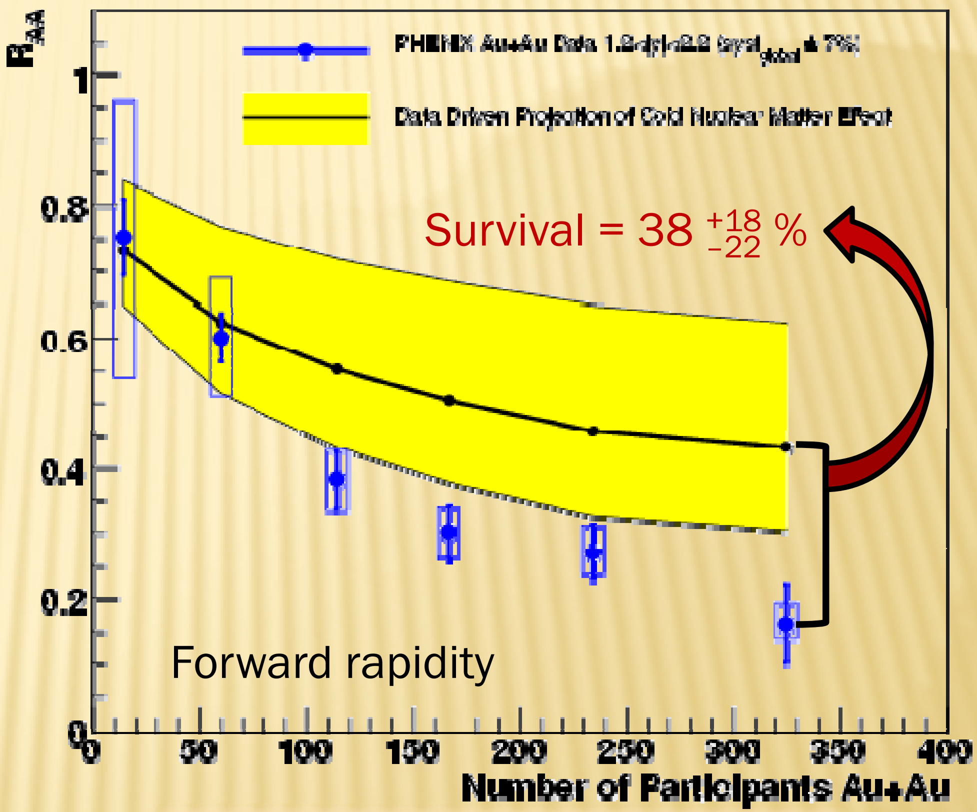
- @RHIC, same rapidity, suppression looks surprisingly similar
  - While density is higher
- Stronger @ forward
  - While density is lower
- But beware of nuclear matter!



PHENIX, PRL98 (2007) 232301

7. J/Ψ SUPPRESSION (FROM D+AU)

- Cold nuclear matter can also suppress J/ψ
  - pdf shadowing, saturation
  - absorption by incoming nucleons?
  - …
- Extrapolation from d+Au
  - Data driven, mostly model independent
  - Large uncertainty
- At least forward J/ψ are suppressed beyond cold matter effects



RGdC, J.Phys.G34 (2007) S955
PHENIX, PRC 77 (2008) 024912

→ The matter is deconfining

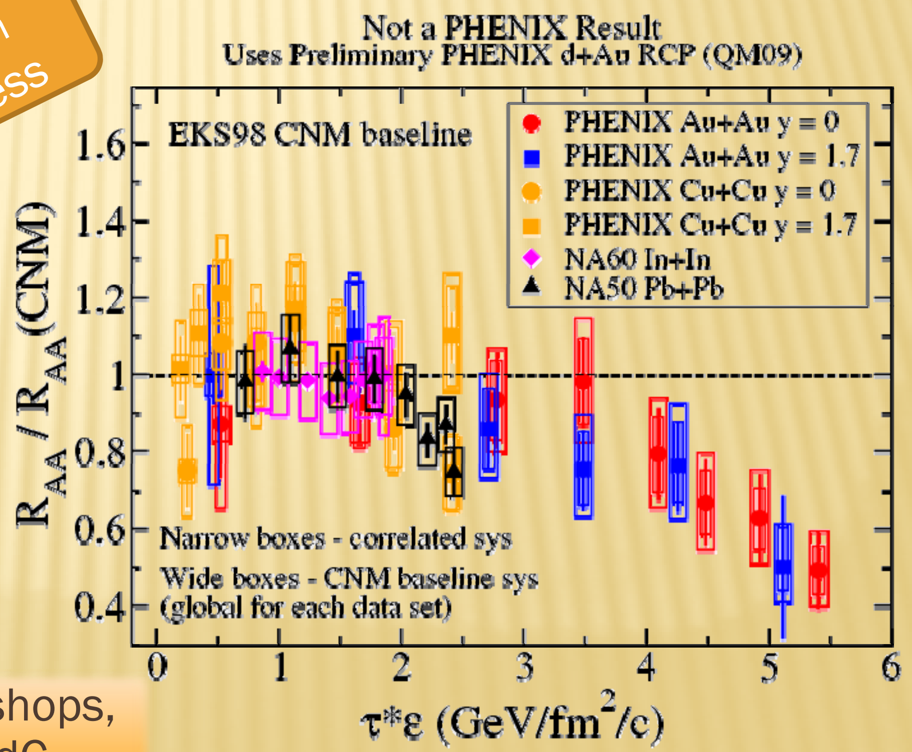
7. NEW D+AU PRELIMINARY REFERENCES

- Run 8 ≈ 30 times more d+Au data
- Preliminary, central to peripheral d+Au ratio (R_{CP}) released @ QM09
  - First extrapolation assuming EKS98 shadowing and effective absorption xsection, varying with rapidity (© T. Frawley)

→ Similar <u>anomalous</u> suppression wrt rapidity

work in progress

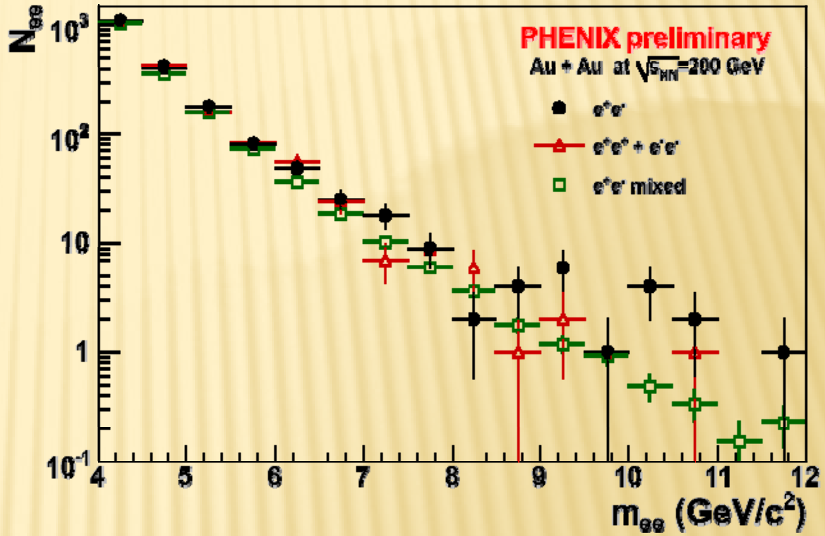
- In addition, lines up with SPS when plotted as
  - Energy density x formation times

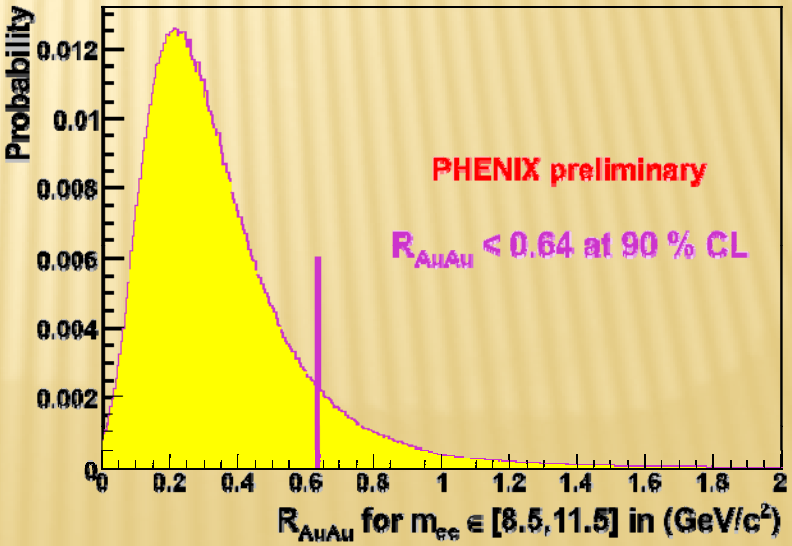


Outcome of Trento and Seattle summer workshops, R. Arnaldi, T. Frawley, M. Leitch, R. Vogt, RGdC…

FIRST LOOK AT BOTTOMONIA…

- R_{dAu} = 0.98 ± 0.32 ± 0.28 (from STAR)
- R_{AuAu} < 0.64 @ 90% CL (from PHENIX →)
  - Could be cold effects
  - No continuum subtraction
    - (but < 15% from pp)
  - Feeddown of χ_b important
    - 50% for p_T > 8 GeV/c at CDF
- Promising preliminary data
- Stay tuned…





E.T. Atomssa, C.S. da Silva, H. Liu, Z. Conesa del Valle @ QM09

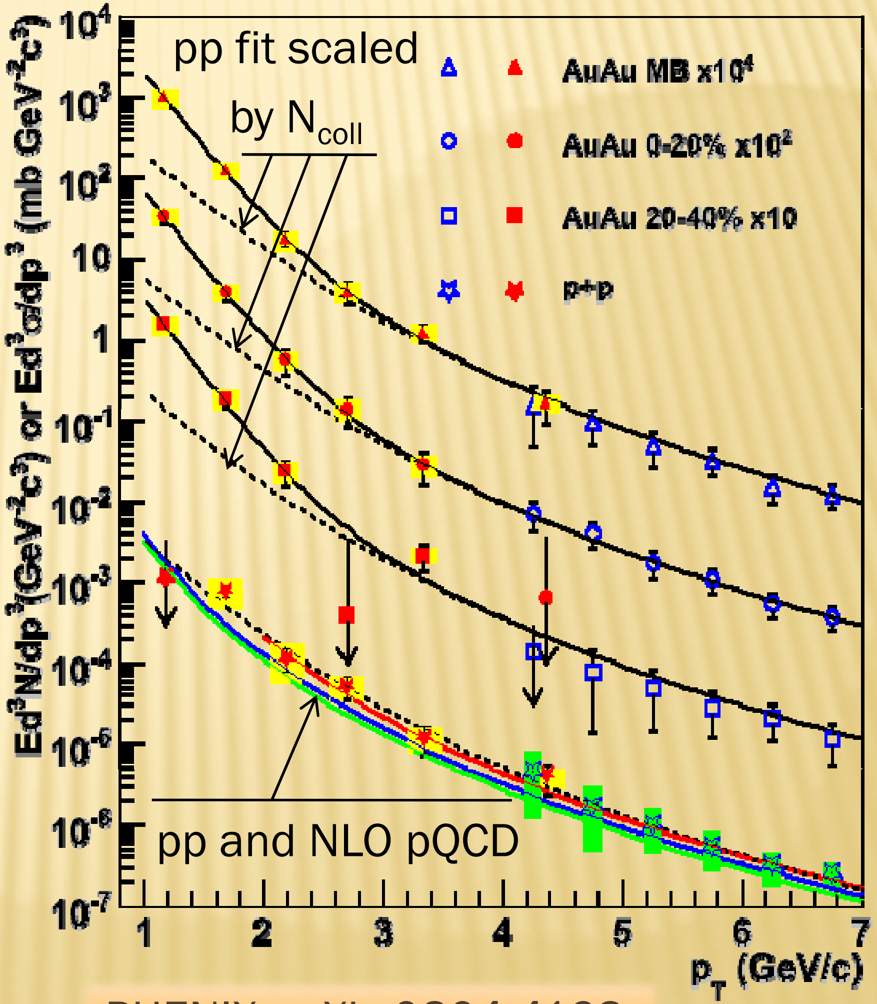
Still one or two slide to go…

THERMAL RADIATION

8. THERMAL RADIATION

→ The matter is hot !

- Direct photon from
  - Real (p_T > 4 GeV/c)
  - Virtual (m_{ee} < 300 MeV/c^2)
- In p+p pQCD works well down to p_T=1 GeV/c →
- In Au+Au, excess below p_T=2.5 GeV/c
- Simple fit:
  - <Temperature> ≈ 220 MeV
- Hydrodynamical fits:
  - Initial temp. 300 to 600 MeV
  - Time 0.15 to 0.6 fm/c



PHENIX, arXiv:0804.4168

IN SUMMARY…

- Even if we have
  - Neither seen an order parameter of the phase transition
  - Nor counted its degrees of freedom
- The RHIC Au+Au 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
- LHC Pb+Pb matter to come (see next talk)

- Bibliography:
  - Experimental "white papers":
  - Quark matter 2009 conference (Knoxville, March 30, April 4th)
  - Interesting reviews, for instance:

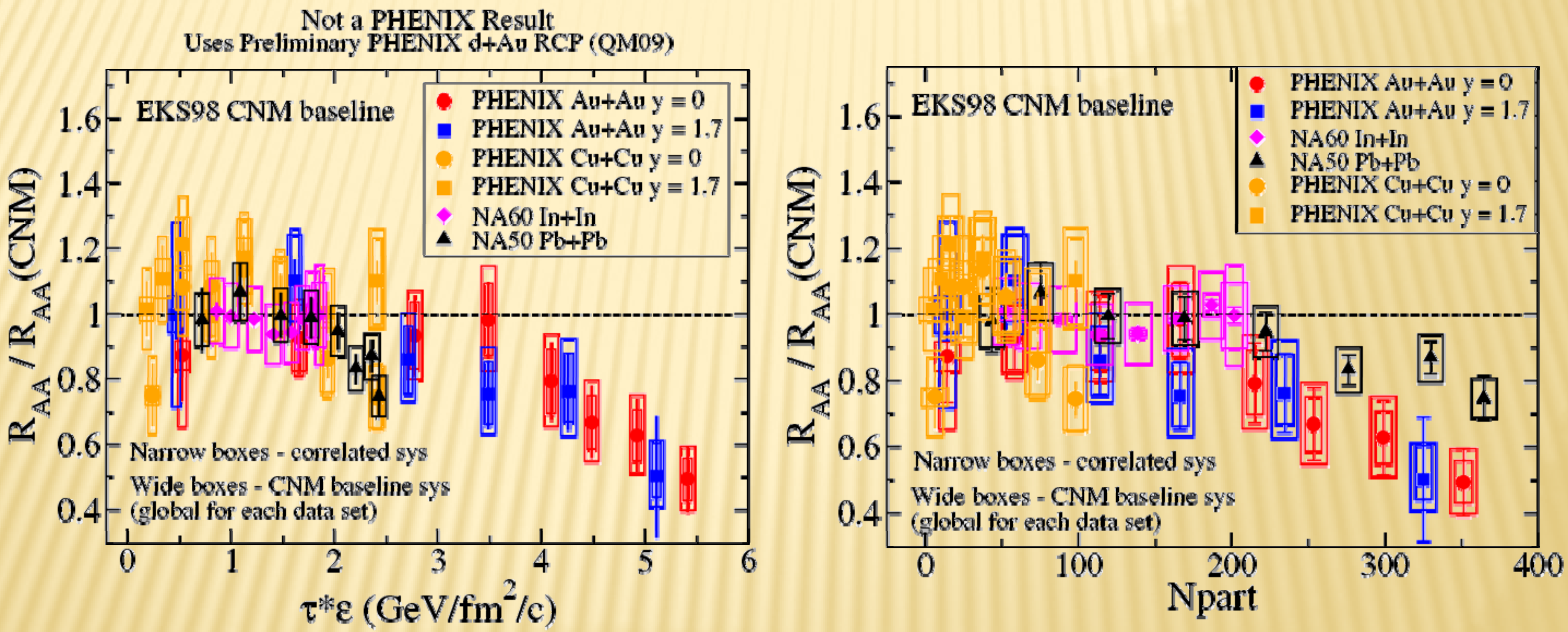
NPA757 (2005), PHENIX: nucl-ex/0410003

http://www.phy.ornl.gov/QM09/

RGdC, arXiv:0707.0328 IJMP A22(2008)6043

BACK UP SLIDES…

SPS VS RHIC, NPART VS E.DENSITY X TIME



3. BACK TO BACK (D+AU)

STAR, PRL 91 (2003) 072304

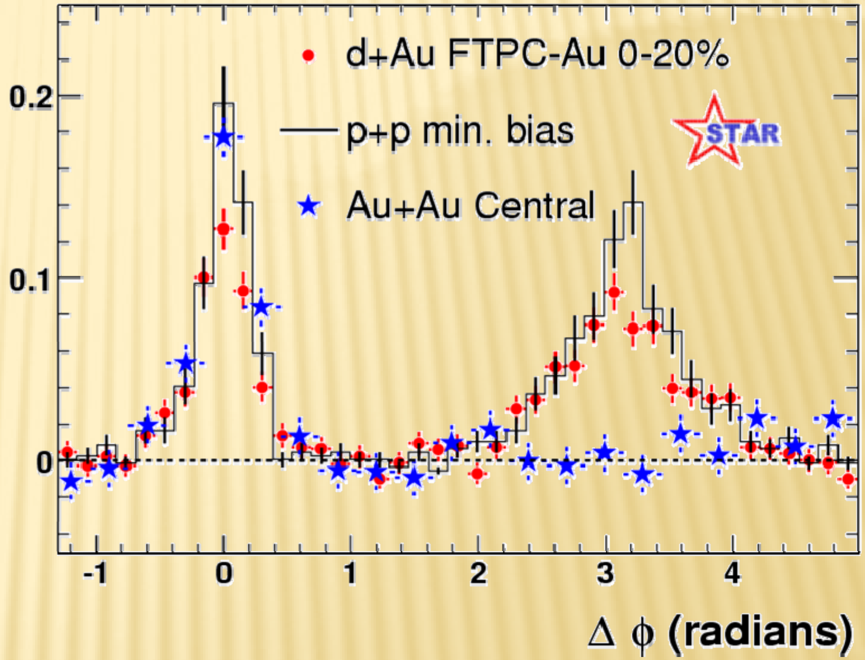
- As always, it is very important to check for d+Au


PHYSICAL REVIEW LETTERS

Articles published week ending 15 AUGUST 2003

Volume 91, Number 7

Published by The American Physical Society

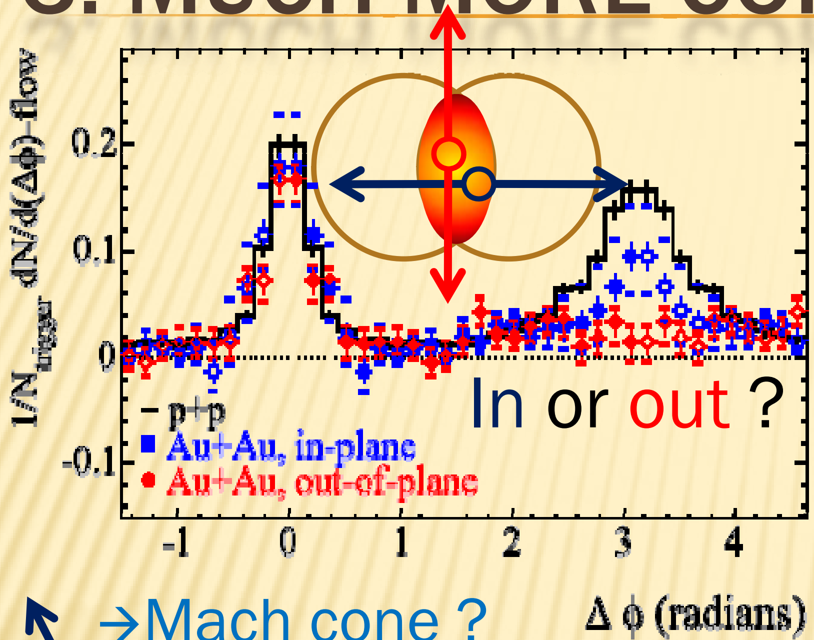


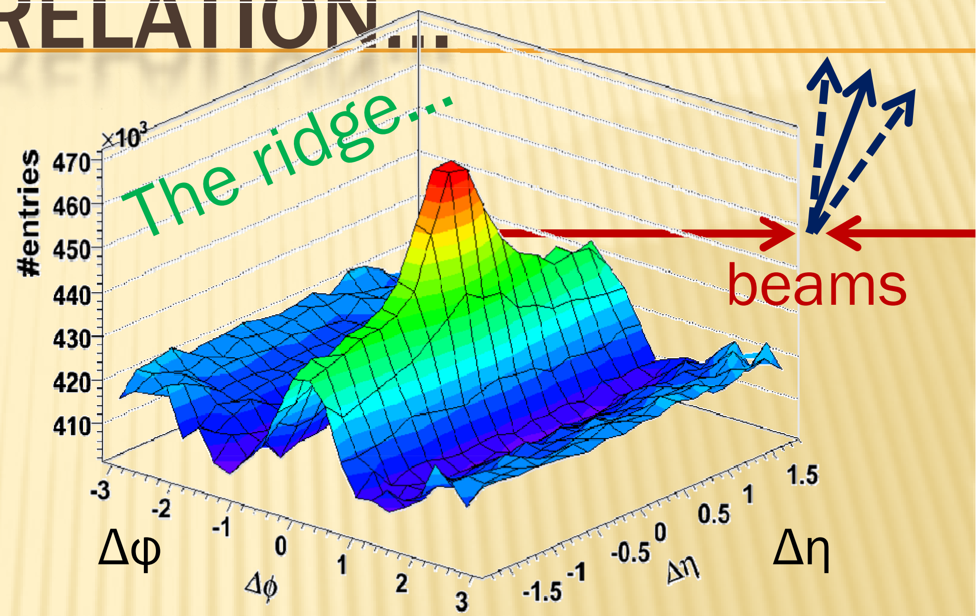
→ The matter is opaque!

@ LHC, full jet reconstruction...

Here, all plots from STAR, see also PHENIX: PRC78 (2008) 014901

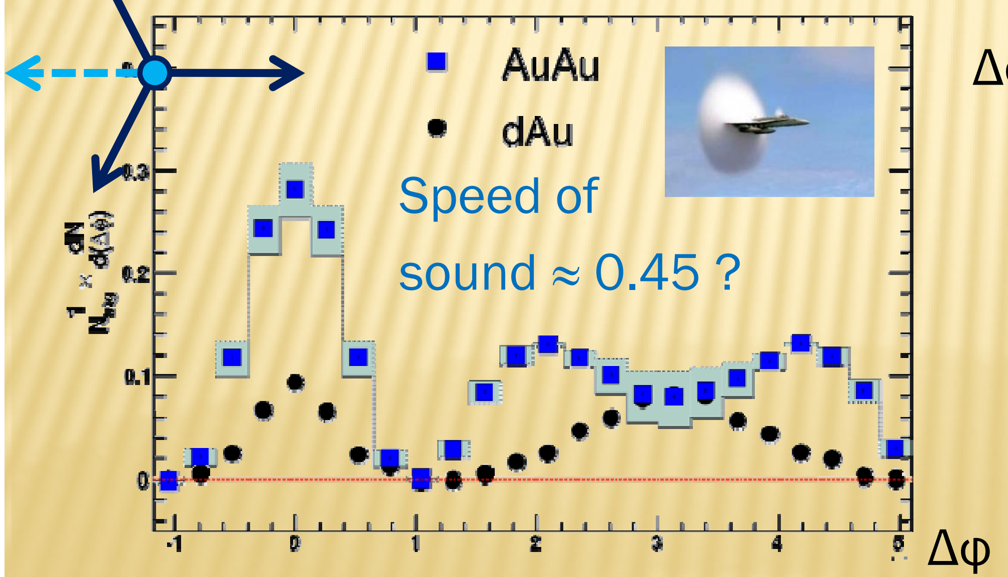
3. MUCH MORE CORRELATION…

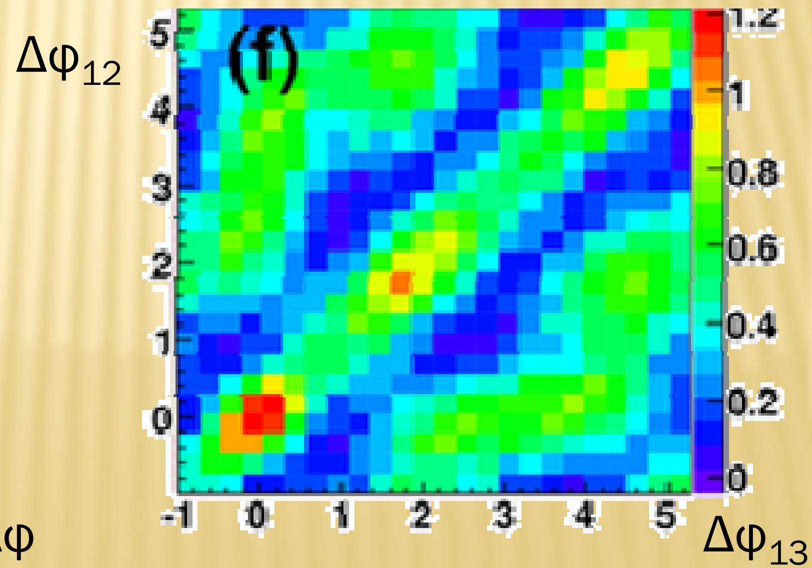




→Mach cone ?

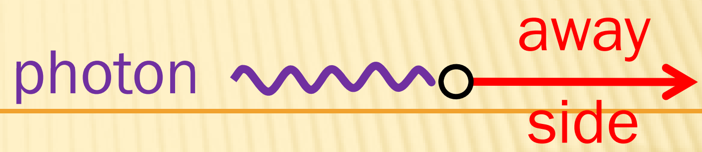
→Three particles (central Au+Au)



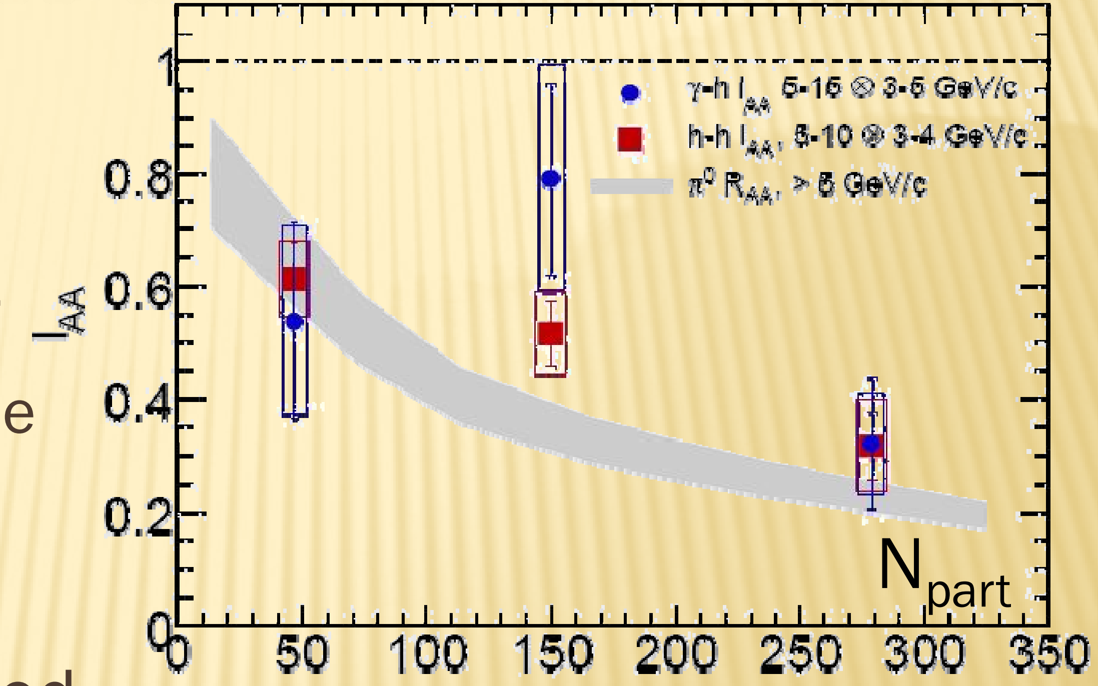


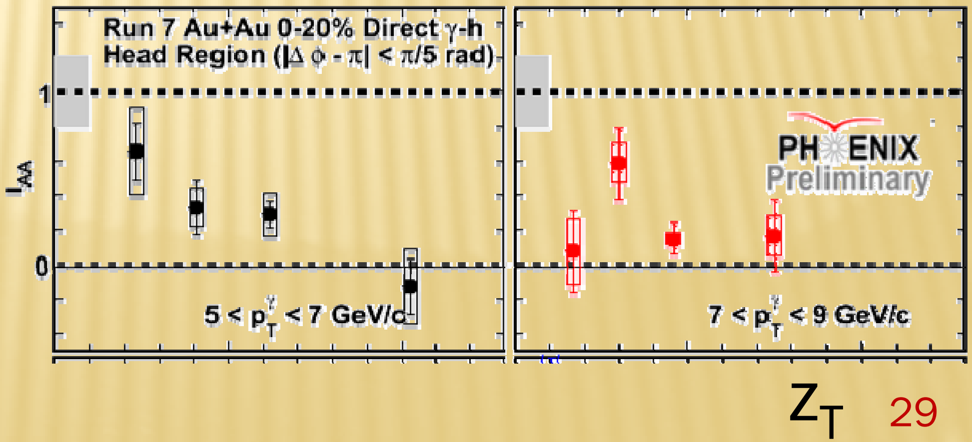
STAR: PRL102 (2009) 052302

NEW TOOL: GAMMA-JET



- Photon ≈ unmodified “reconstructed” jet
- Suppression is similar
  - Yield per trigger particle
  - Normalized to p+p
- Can start addressing the question of modified fragmentation function
  - $z_T = p_{hadron} / p_{photon}$ →

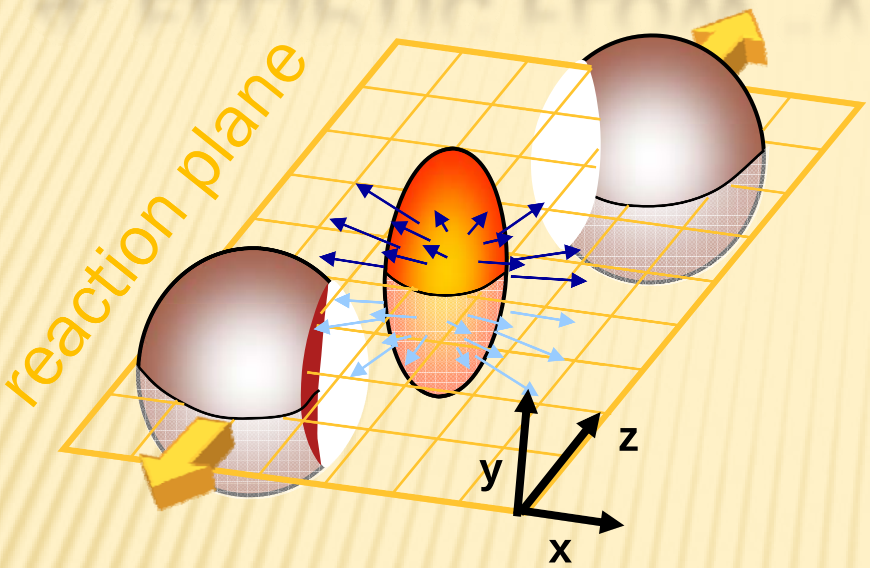




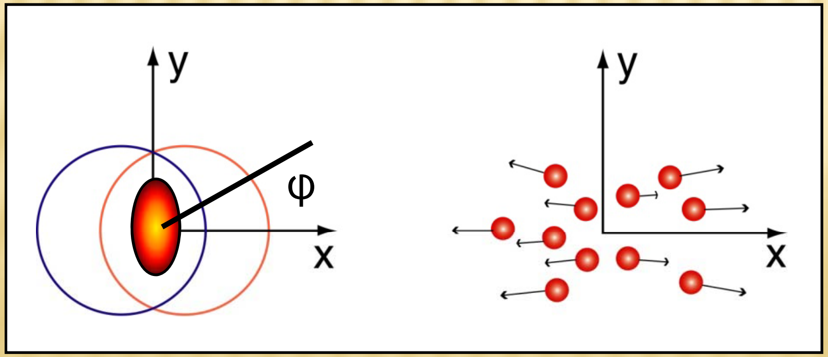
PHENIX: arXiv/0903.3399
M. Connors, QuarkMatter09

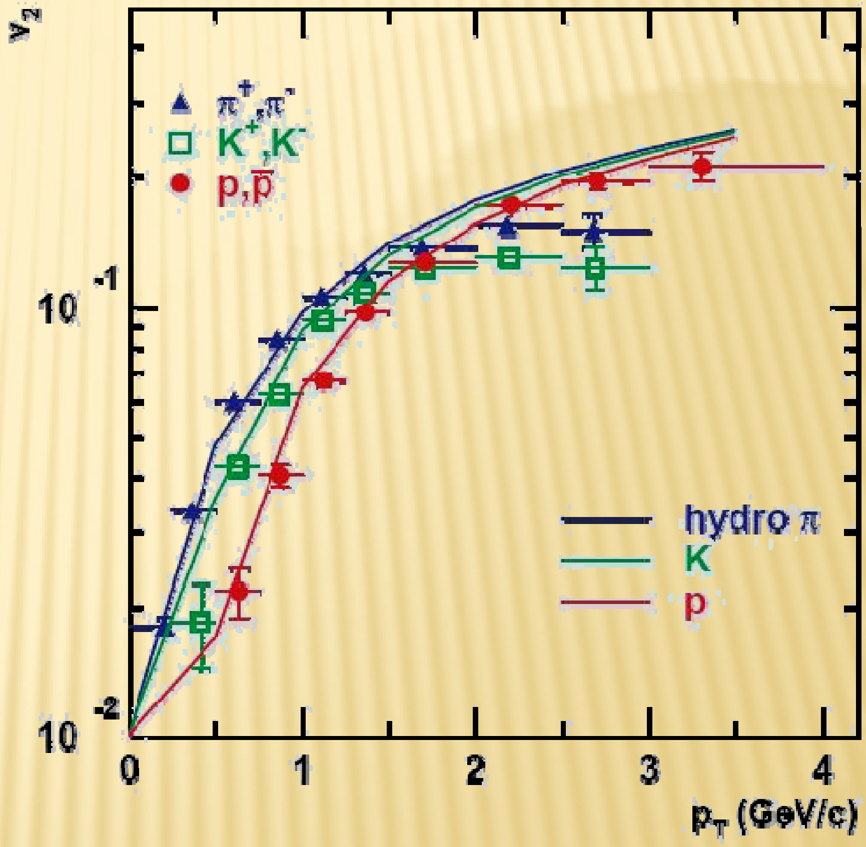
4. ELLIPTIC FLOW "V_2"

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 equation of state,
  - Early thermalization
    - (0.6 fm/c)
  - High density
    - (≈30 GeV/fm^3)
- Little need for viscosity!
  - First estimations are
    - approaching the quantum limit $\eta/s = \hbar/4\pi$
    - lower than Helium at T_c

… reproduces fairly well

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

- Not the foreseen ideal partonic gas!

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

→ *"Perfect fluid"*

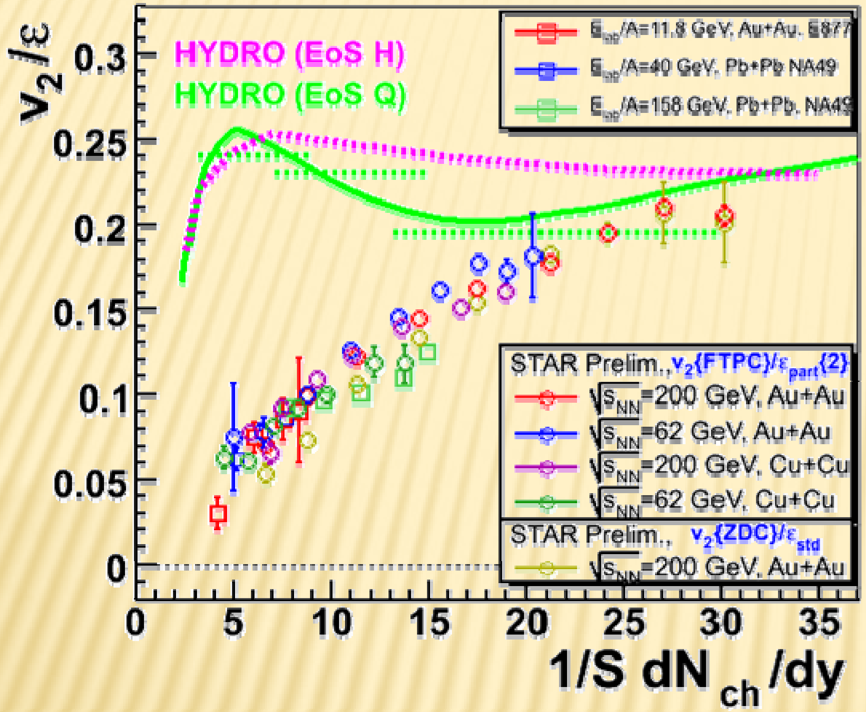
→ The matter is strongly interacting and liquid like

@ LHC, could it approach a quark gluon gas?

4. ELLIPTIC FLOW (SCALINGS)

With eccentricity vs N_{ch} density

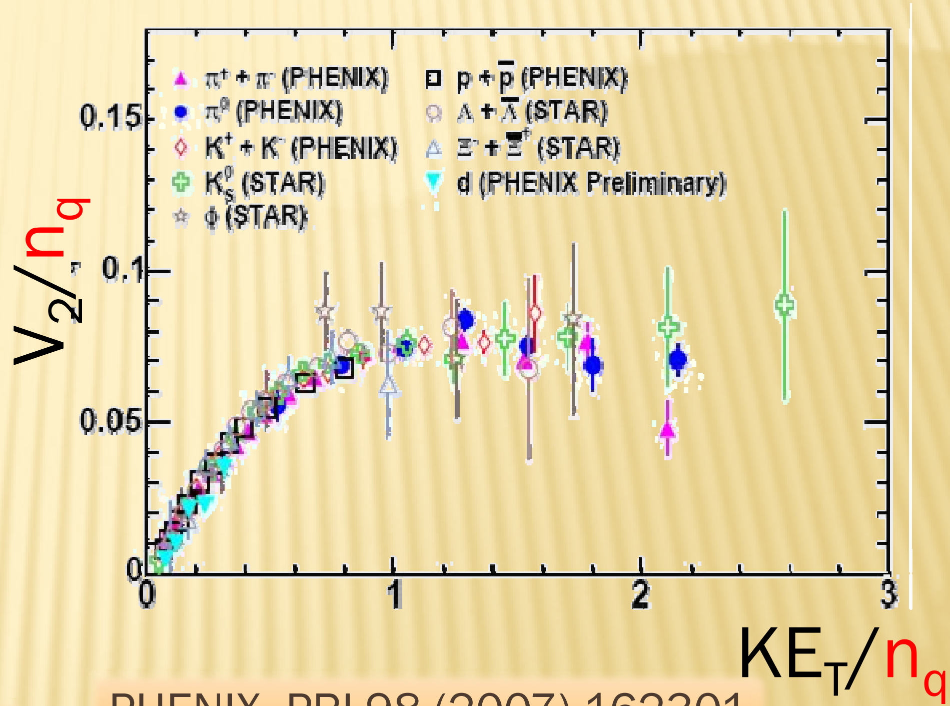
$\varepsilon = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$



Voloshin & Pokskanzer, PLB 474 (2000) 27

With the kinetic energy

per <u>constituent quarks</u>

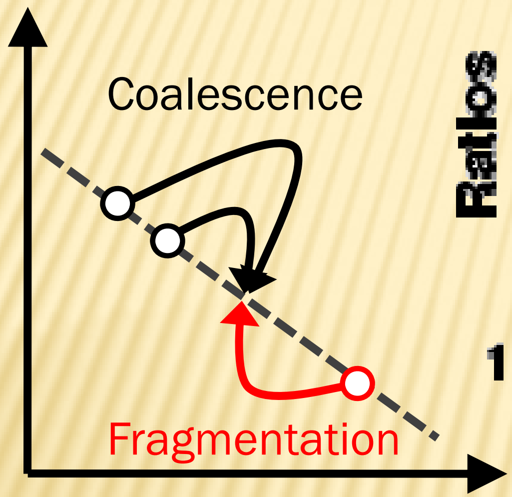


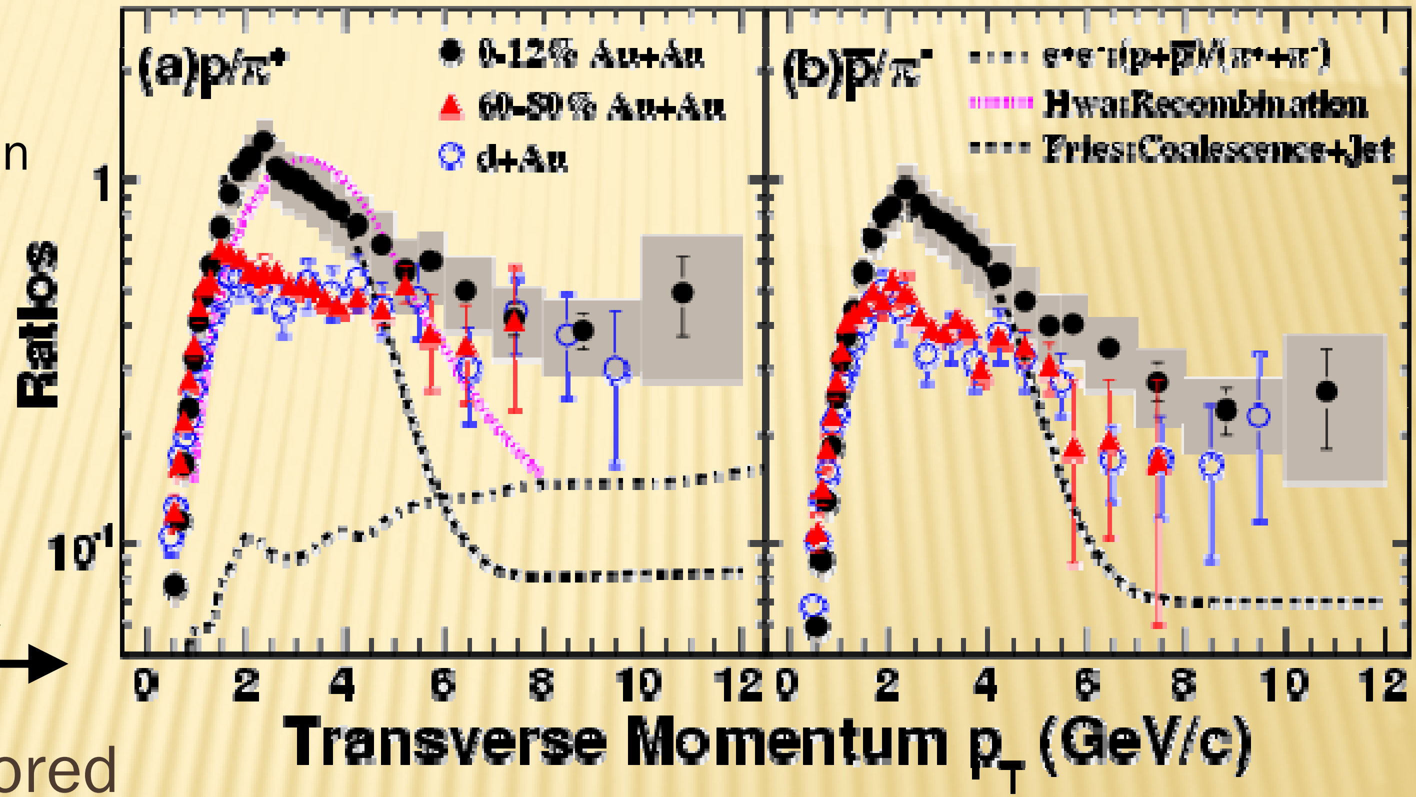
PHENIX, PRL98 (2007) 162301
(and other particles)

5. BARYONS/MESONS

STAR, PRL 97 (2006) 152301

→ Spectrum cartoon





- Baryon favored
- Not fragmentation!
- Coalescence or recombination

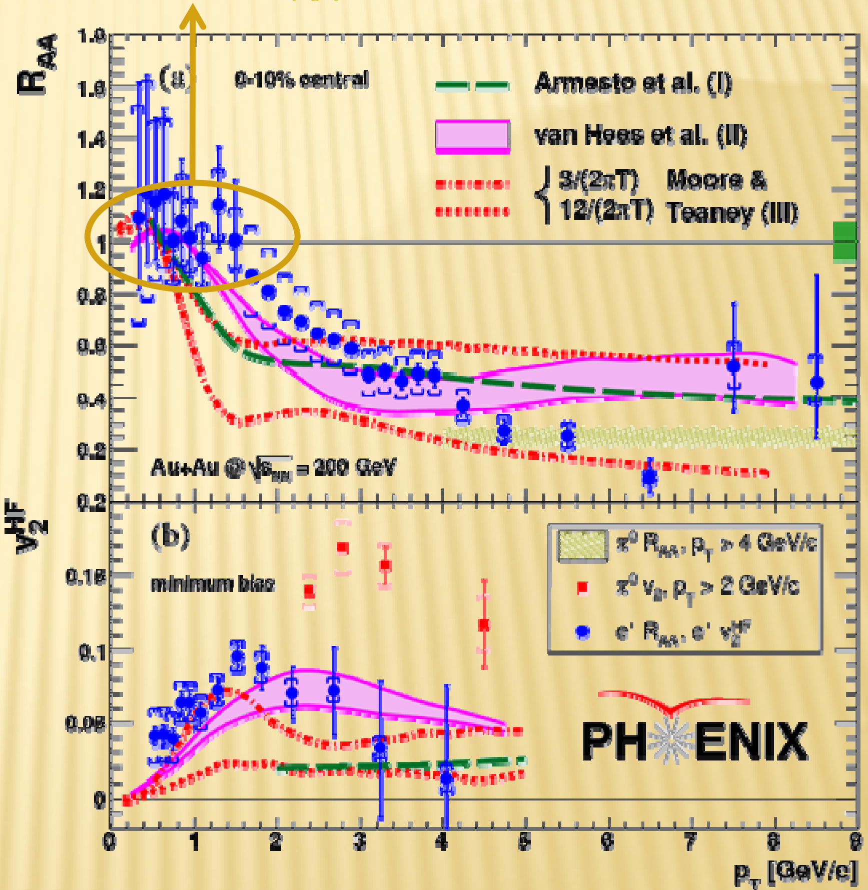
→ The matter is partonic
(constituent scaling, coalescence…)

6. HEAVY QUARKS?

PHENIX, PRC76 (2007) 034904

Note that R_{AA}=1 for most of charm

- Electrons from heavy flavour's decay (D,B → e…) 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…

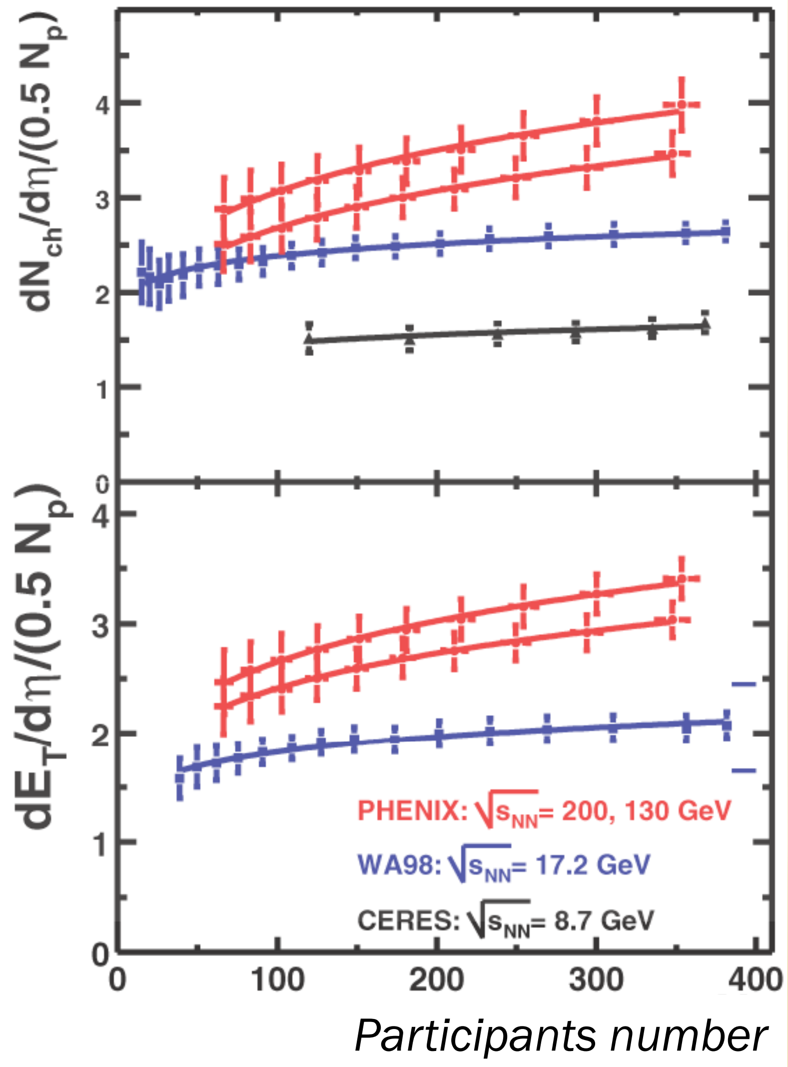
@ LHC, more thermalization?

HISTORHIC

[1] PRC69 (2004) 014901
[2] PRL92 (2004) 051802
[3] PRL96 (2006) 012304
[4] PRL98 (2007) 232301
[5] PRL98 (2007) 232002
[6] PRL101 (2008) 122301

Année	Ions	$\sqrt{s_{NN}}$	Luminosité	Statut (J/ψ)	J/ψ (ee + μμ)
2000	Au-Au	130 GeV	1 μb^{-1}	Central (elec.)	0
2001/02	Au-Au	200 GeV	24 μb^{-1}	Central (elec.) + 1 muon arm	13 + 0 [1]
	p-p	200 GeV	0,15 pb^{-1}		46 + 66 [2]
2002/03	d-Au	200 GeV	2,74 nb^{-1}	Central + 2 muon arms	360 + 1660 [3]
	p-p	200 GeV	0,35 pb^{-1}		130 + 450 [3]
2003/04	Au-Au	200 GeV	241 μb^{-1}	Published	≈ 1000 + 4500 [4]
	Au-Au	63 GeV	9 μb^{-1}	Preliminary	≈ 13
2004/05	p-p	200 GeV	3.8 pb^{-1}	Published	≈ 1500 + 10000 [5]
	Cu-Cu	63 GeV	190 mb^{-1}	(unlooked)	≈ 10 + 200
	Cu-Cu	200 GeV	3 nb^{-1}	Published	≈ 1000 + 10000 [6]
2006	p-p	200 GeV	10,7 pb^{-1}	Preliminary	> 2000 + 27000
2007	Au-Au	200 GeV	813 μb^{-1}	Preliminary (v_2)	> 3400 + 15000
2008	d-Au	200 GeV	80 nb^{-1}	QM 2009 ?	≈ 10000 + 40000

ENERGY DENSITY ESTIMATION



Transverse energy @ y=0

Bjorken formula

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

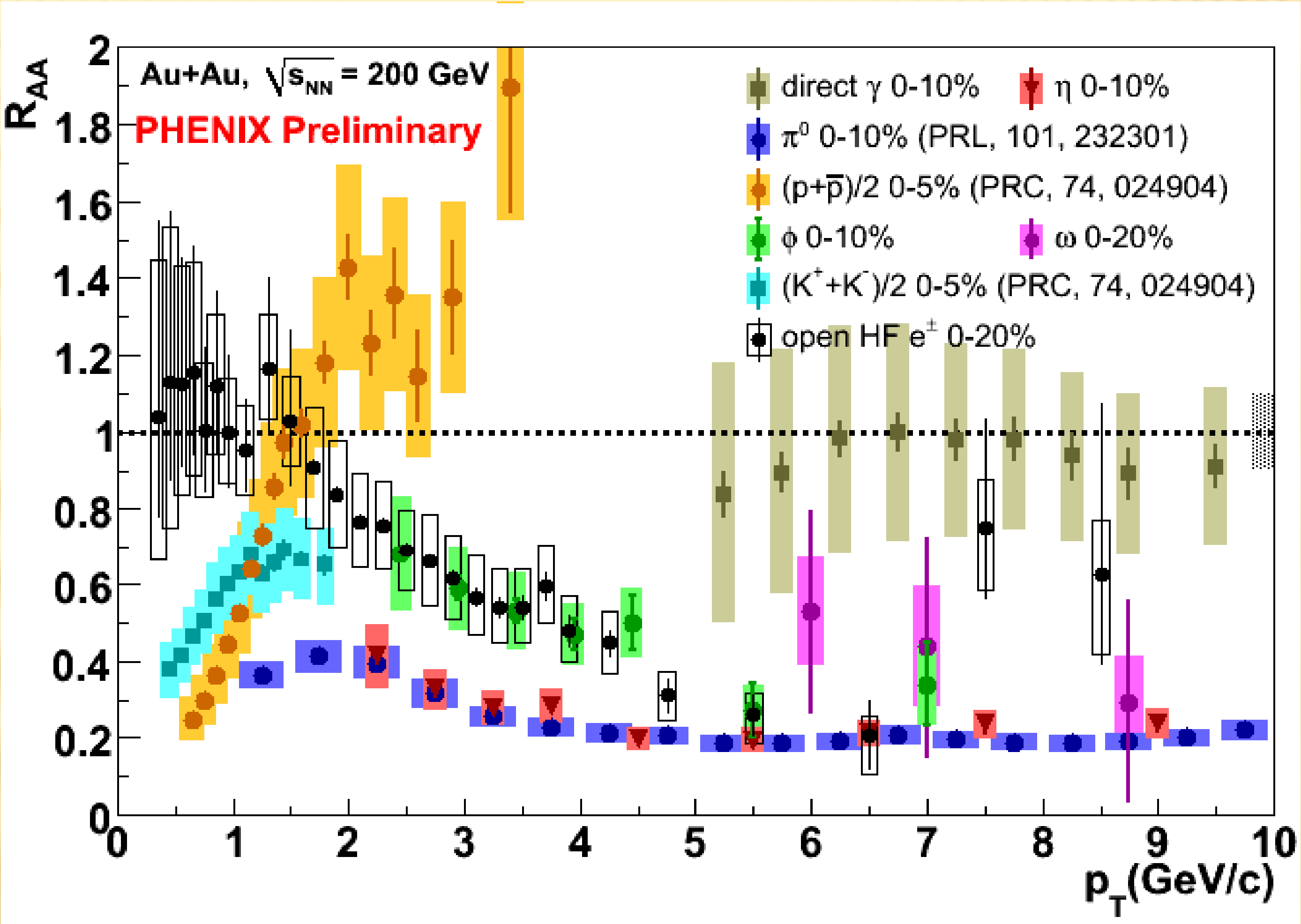
τ_0 formation time
0,35 à 1 fm/c

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

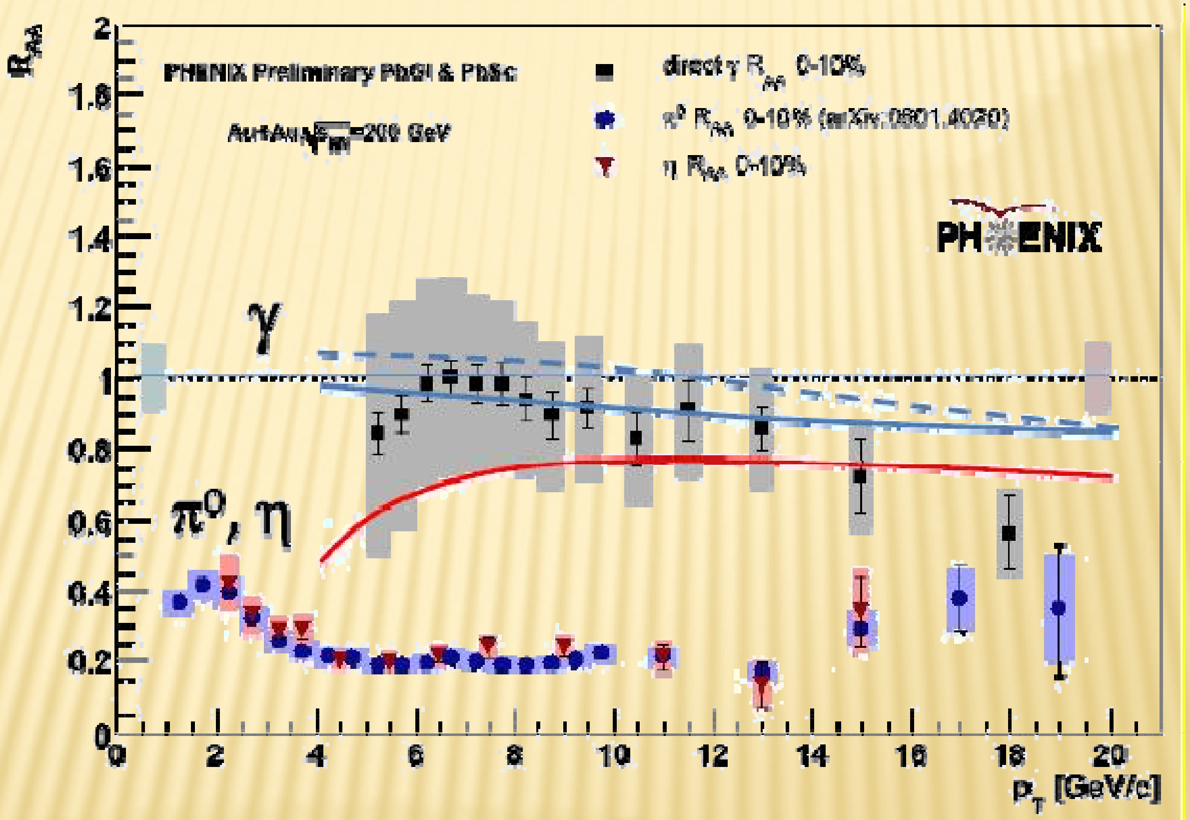
$\varepsilon > 6\ \mathrm{GeV/fm}^3$

Bjorken, PRD27 (1983) 140

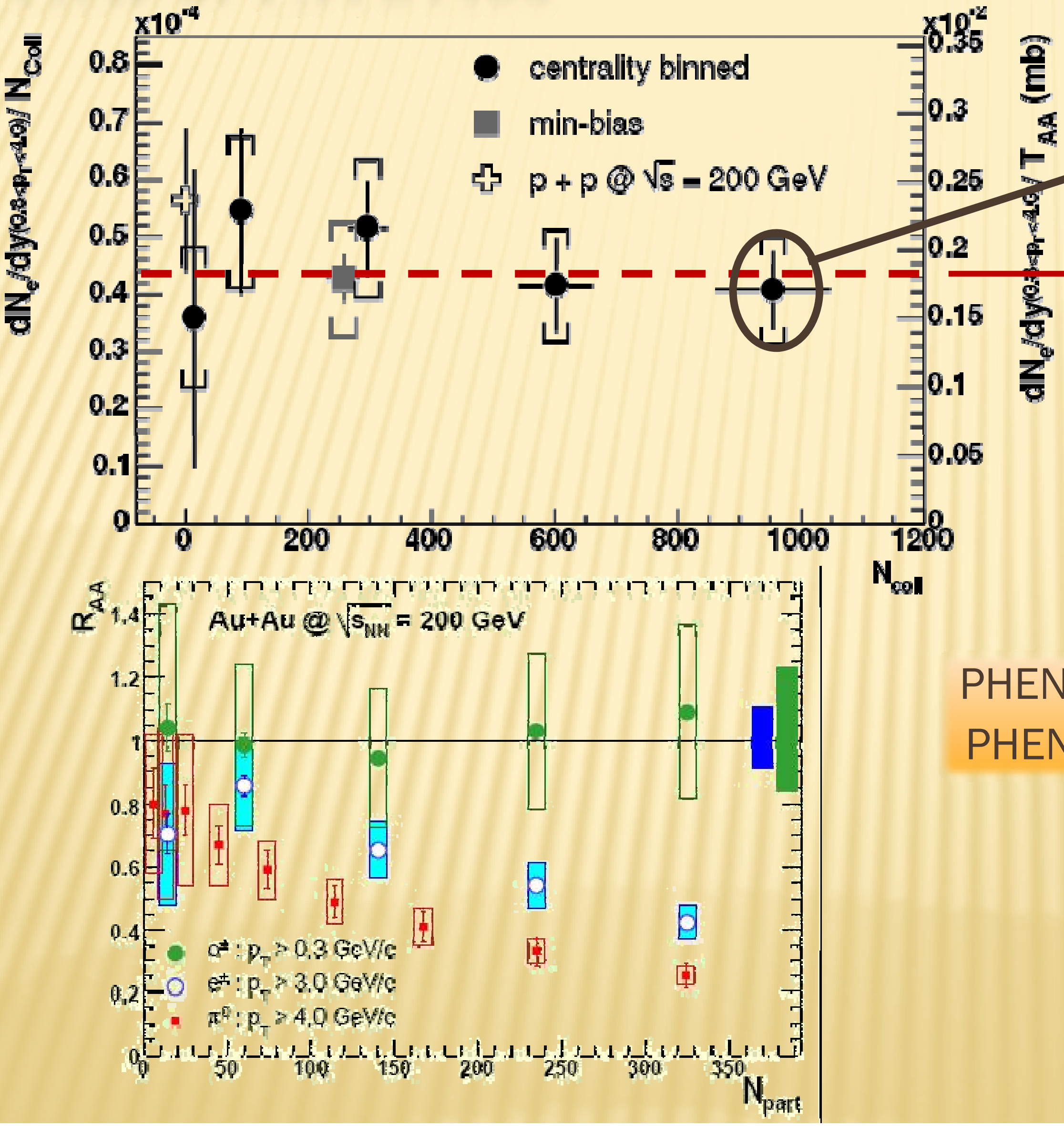
MORE NUCLEAR MODIFICATIONS…



HIGHER PT


PHENIX Preliminary PbGl & PbSc
Au+Au $\sqrt{s_{NN}}$=200 GeV
direct γ R_{AA} 0-10%
π^0 R_{AA} 0-10% (arXiv:0801.4020)
η R_{AA} 0-10%
PHENIX
γ
π^0, η
R_{AA}
p_T [GeV/c]

OPEN CHARM



10 to 20 $c\bar{c}$ pairs

N_{coll} scaling

25% systematics
(need for a vertex detector)

PHENIX, PRL 94 (2005) 082301
PHENIX, PRC76 (2007) 034904

A LINK TO STRING THEORY?

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 ...)