LHC Conference, IPM, Isfahan, 20-24 April 2009

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PHENIX and CMS experiments

WHAT'S THE MATTER AT RHIC ?

☺ THE ORIGIN OF (MY) MASS…

"The world is massless" Guido, Monday

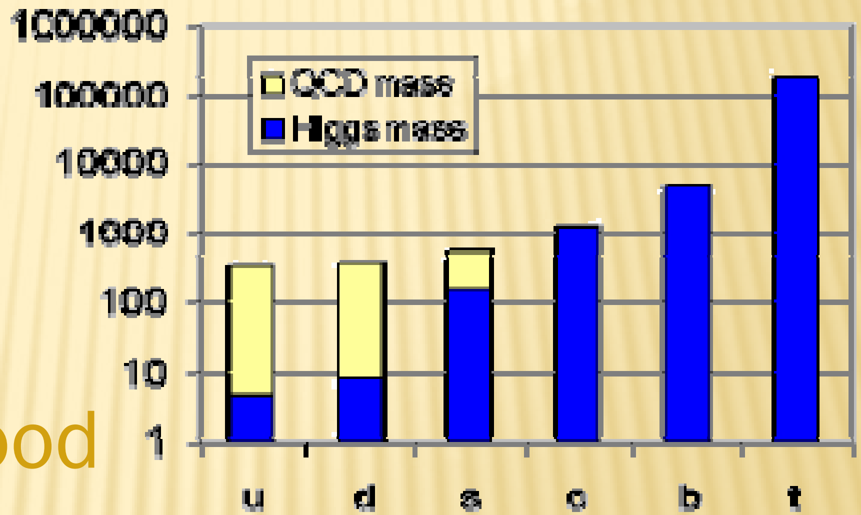
Atomic mass =

≈ 02% from Higgs

+ 98% from QCD!

≈ 02% not yet seen…

+ 98% poorly understood



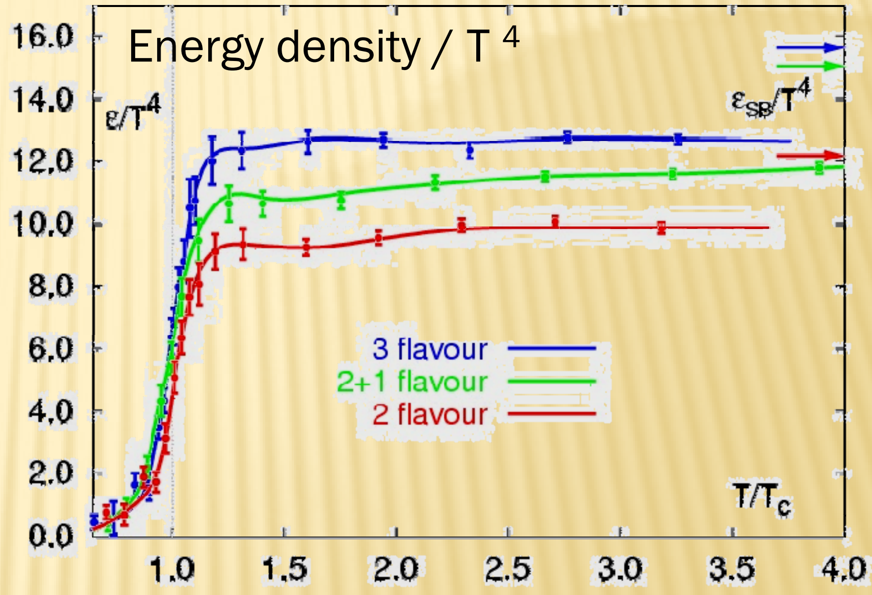
- We are then mostly made of confinement…
- This talk is all about deconfinement…

"Hey guys, it's only ≈5% of the universe!" ☹

Yannick, Tuesday

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

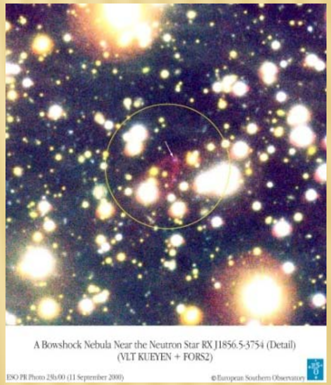


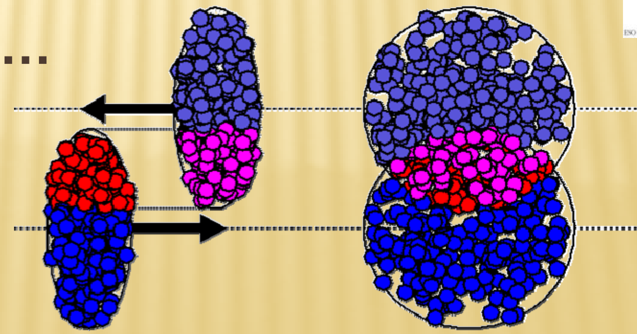
Karsch et al, hep-lat/0106019
Lect. Notes Phys.583 (2002) 209

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

WHERE/WHEN CAN WE FIND THE QGP?

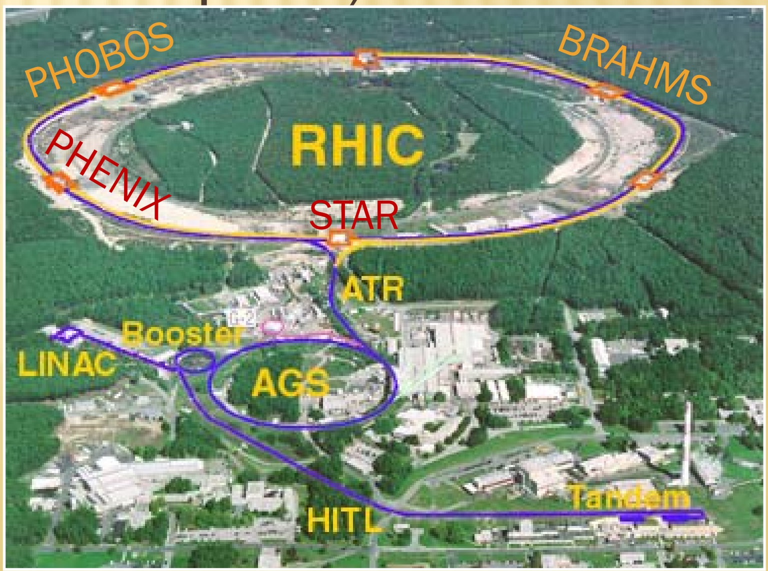
1. Early in the universe (t < 10 μs)
   - But very little chance to leave relics
     - Cold dark matter clumps?
     - Inhomogeneous nucleosynthesis?
     - Baryonic CDM (strange nuggets)?
2. Core of a compact star
   - But no smoking gun candidate so far
3. In the lab, by colliding heavy ions
   - 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) >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)



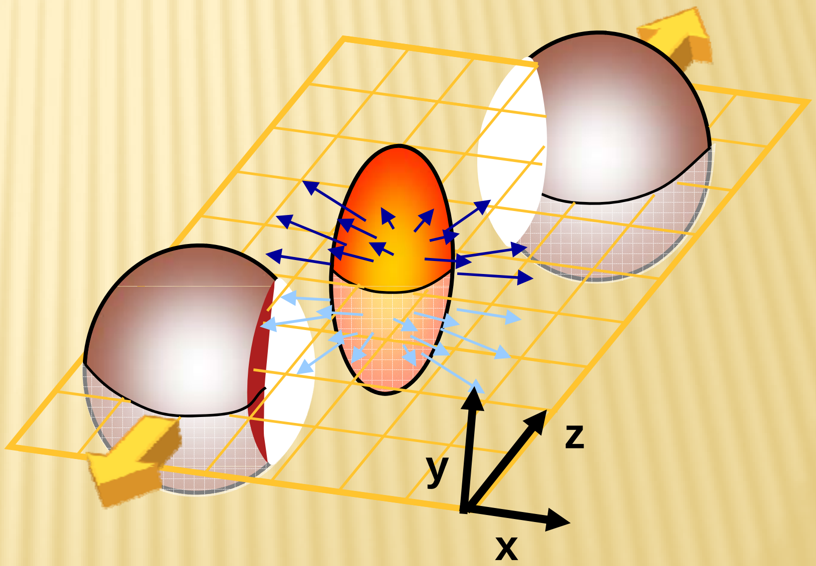
WHAT IS THE STRATEGY? (AND JARGON)

- Predict a QGP signature
- Look at it versus A+A collision centrality →
- 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 $R_{AA} = 1$
- 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

} ≈ *"Jet quenching"*

4. Elliptic flow ≈ *"Perfect fluid"*
5. Baryon/meson
6. Heavy flavour
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...

H. Satz @ Lattice 2000 hep-ph/0009099

"LHC is less dangerous than RHIC"
Albert, Wednesday, about strangelets

1. Total multiplicity
2. High p_T suppression
3. Back to back jets
4. Elliptic flow
5. Baryon/meson
6. Heavy flavour

July 18 1999 BRITAI

©

Ready for blastoff: a Brookhaven engineer puts finishing touches to the ion collider

Big Bang machine could destroy Earth

by Jonathan Leake
Science Editor

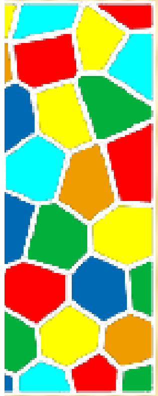
A NUCLEAR accelerator designed to replicate the Big Bang is under investigation by international physicists because of fears that it might cause "perturbations of the universe" that could destroy the Earth. One theory even suggests that it could create a black hole.

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)

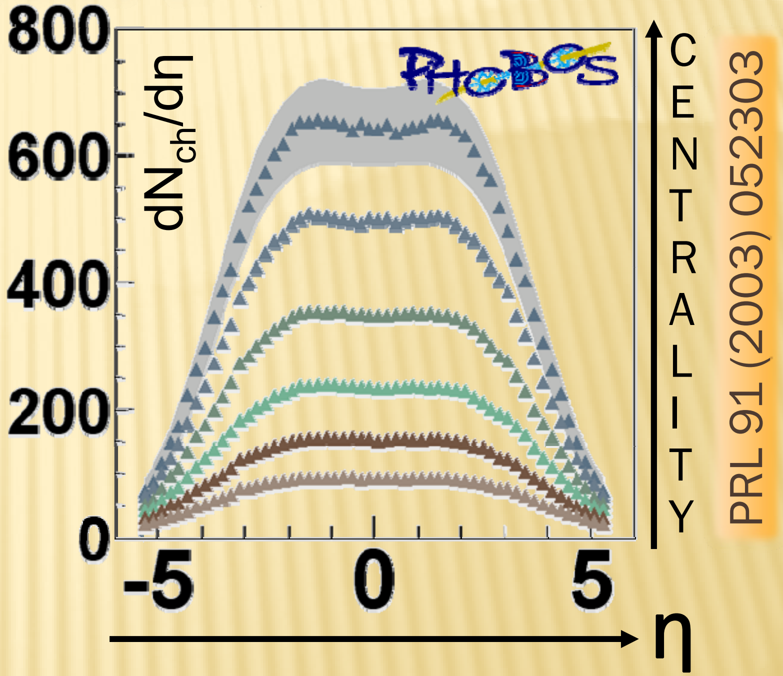
- $dN_{ch}/d\eta|_{\eta=0} \approx 670$
  - (6000 particles total)
- Less than expected!
  - 1000 from p+p fragmentation
  - Low x_{Bj} gluon start to overlap, recombine, saturate…
  - (even more at forward rapidity)
  - "Color Glass Condensate"



→The (initial) matter saturates

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

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



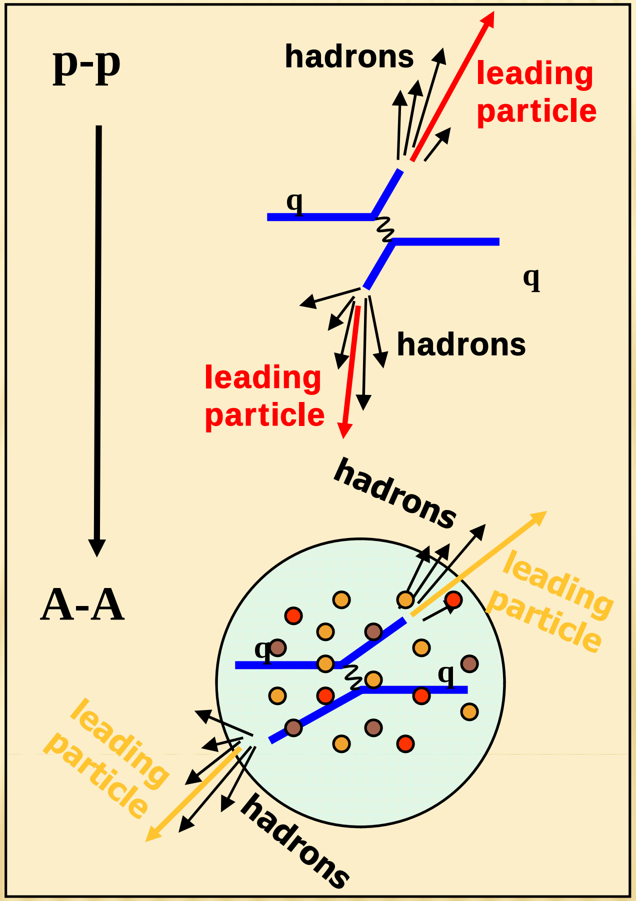
- $dE_T/d\eta|_{\eta=0}$ related to energy density
- $\varepsilon > 6$ GeV/fm$^3 > \varepsilon_c$!

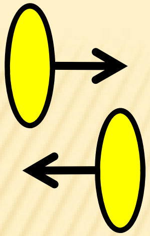
The smoking gun…

JET QUENCHING

2. HIGH P_T SUPPRESSION

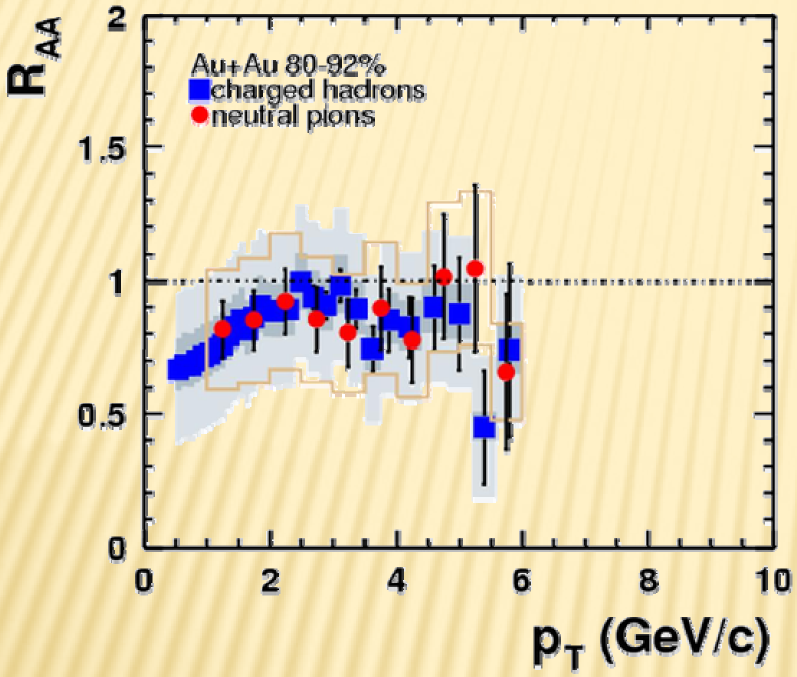
- RHIC smoking gun signature !
  - Two PRL covers
- Energy loss in the matter, looking at "high" p_T (>2GeV/c) hadrons
  - Mostly from jet fragmentation
- "Jet quenching"

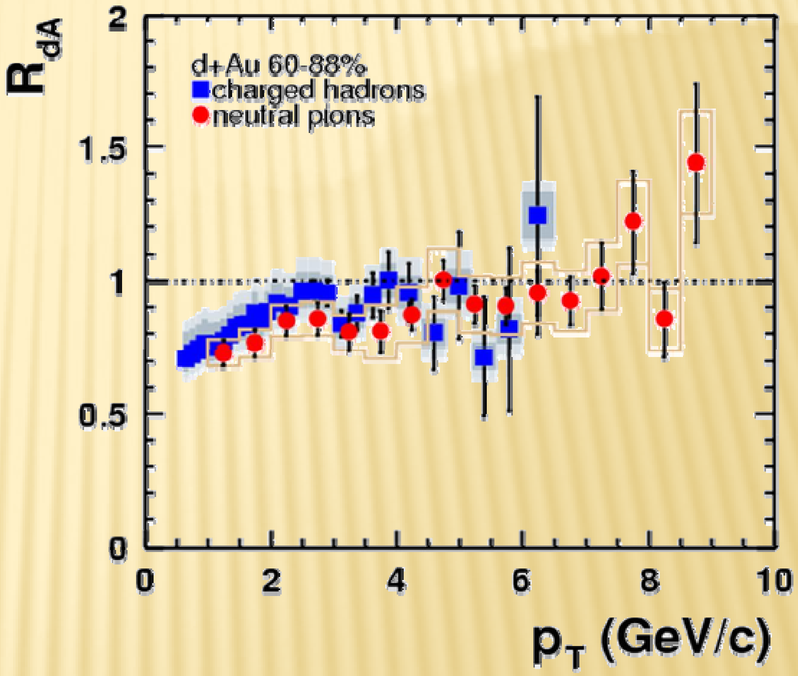




Au-Au (80-92%)

d+Au (60-88%)





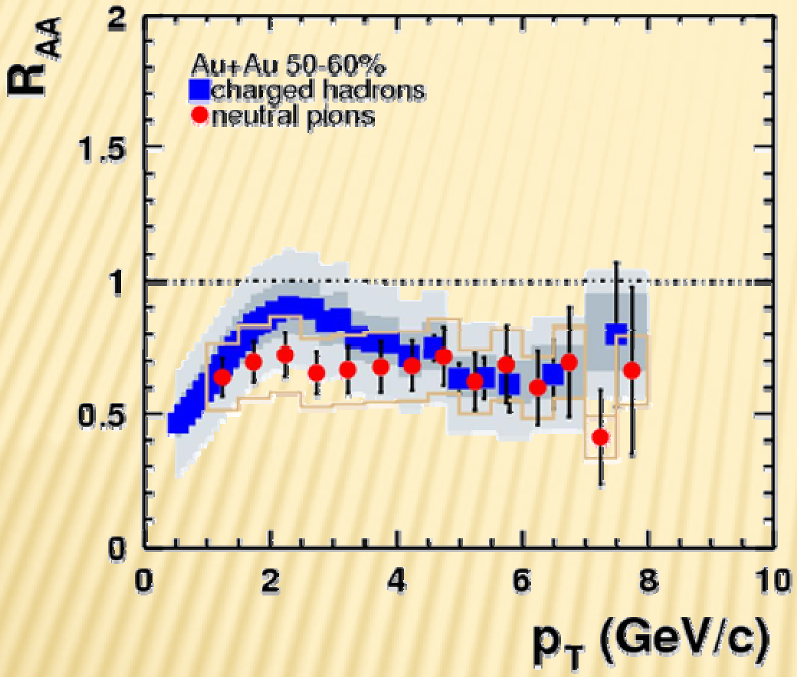
MOST PERIPHERAL COLLISIONS…

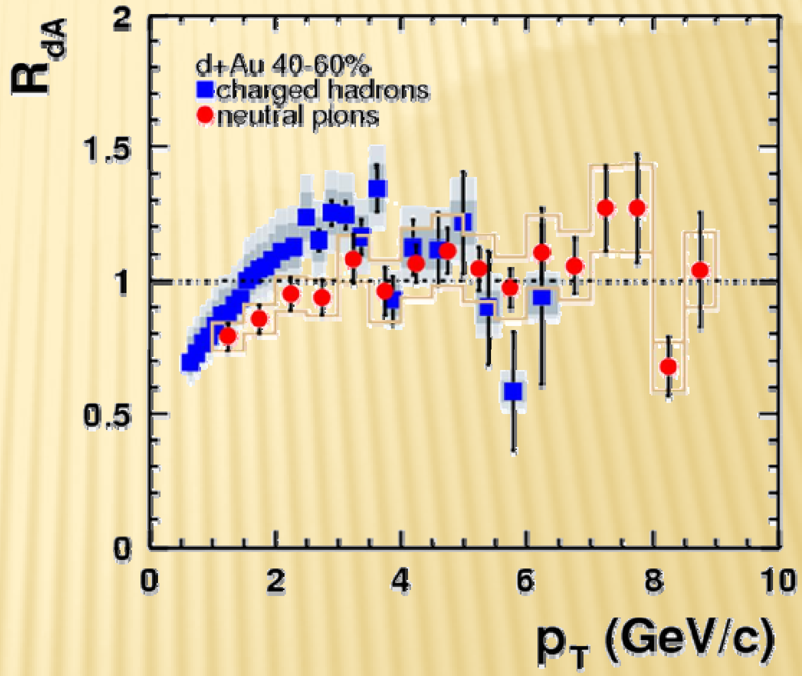
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (50-60%)

d+Au (40-60%)



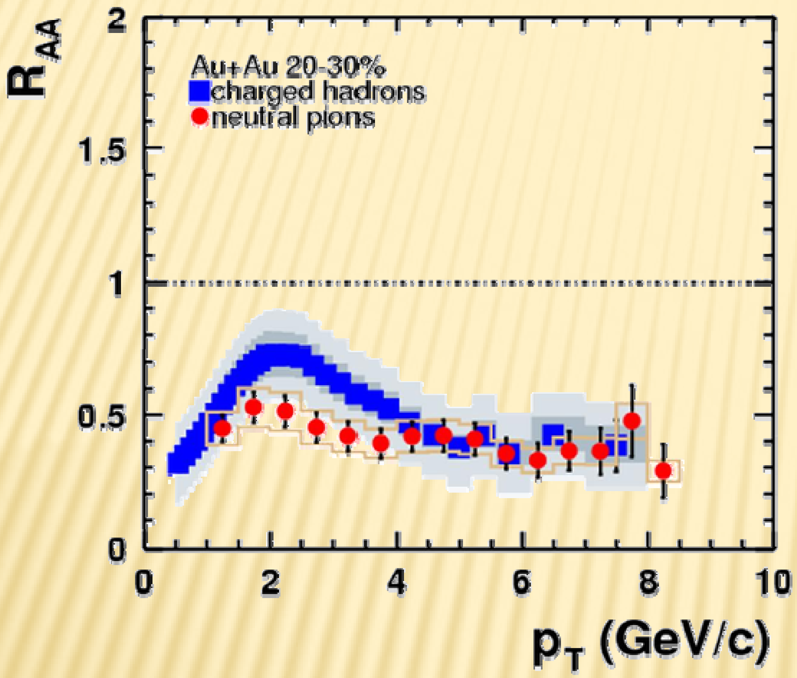


LESS PERIPHERAL COLLISIONS…

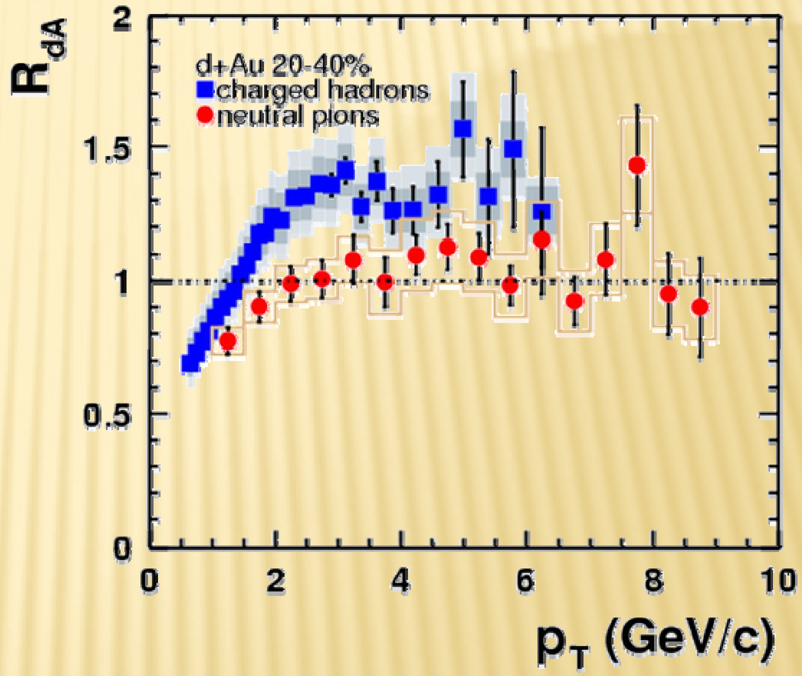
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (20-30%)



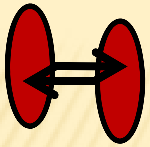
d+Au (20-40%)



MORE CENTRAL COLLISIONS…

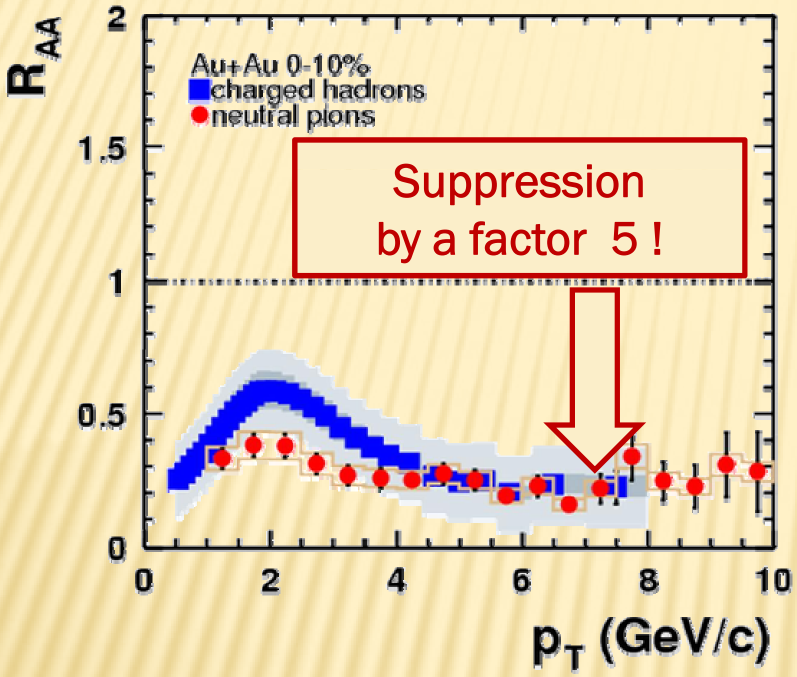
(slightly old, but pedagogical, data)

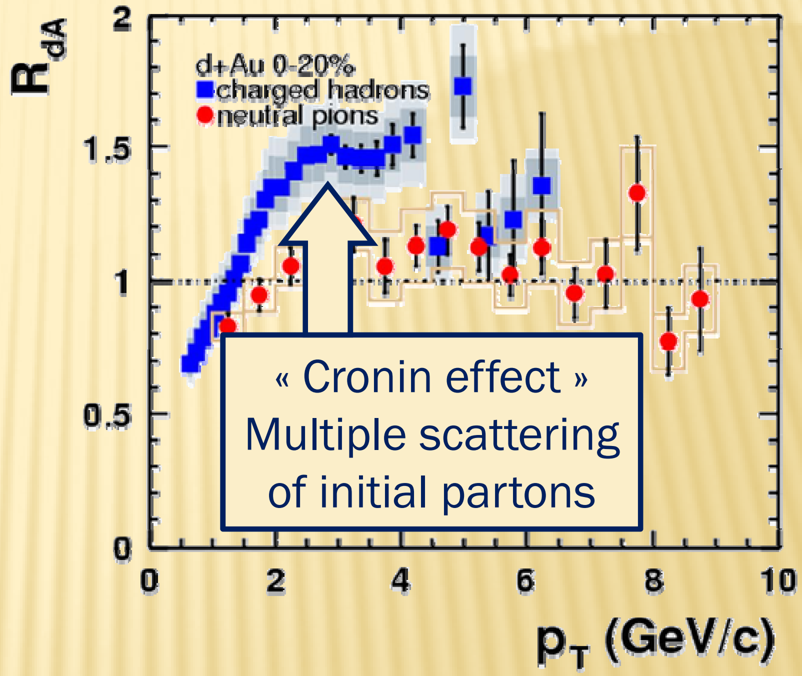
PHENIX, PRL 91 (2003) 072303

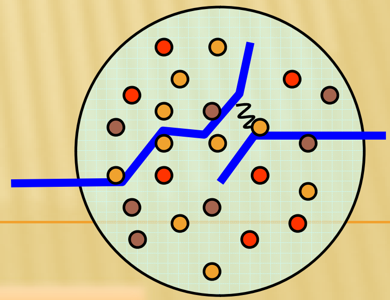


Au-Au (0-10%)

d+Au (0-20%)







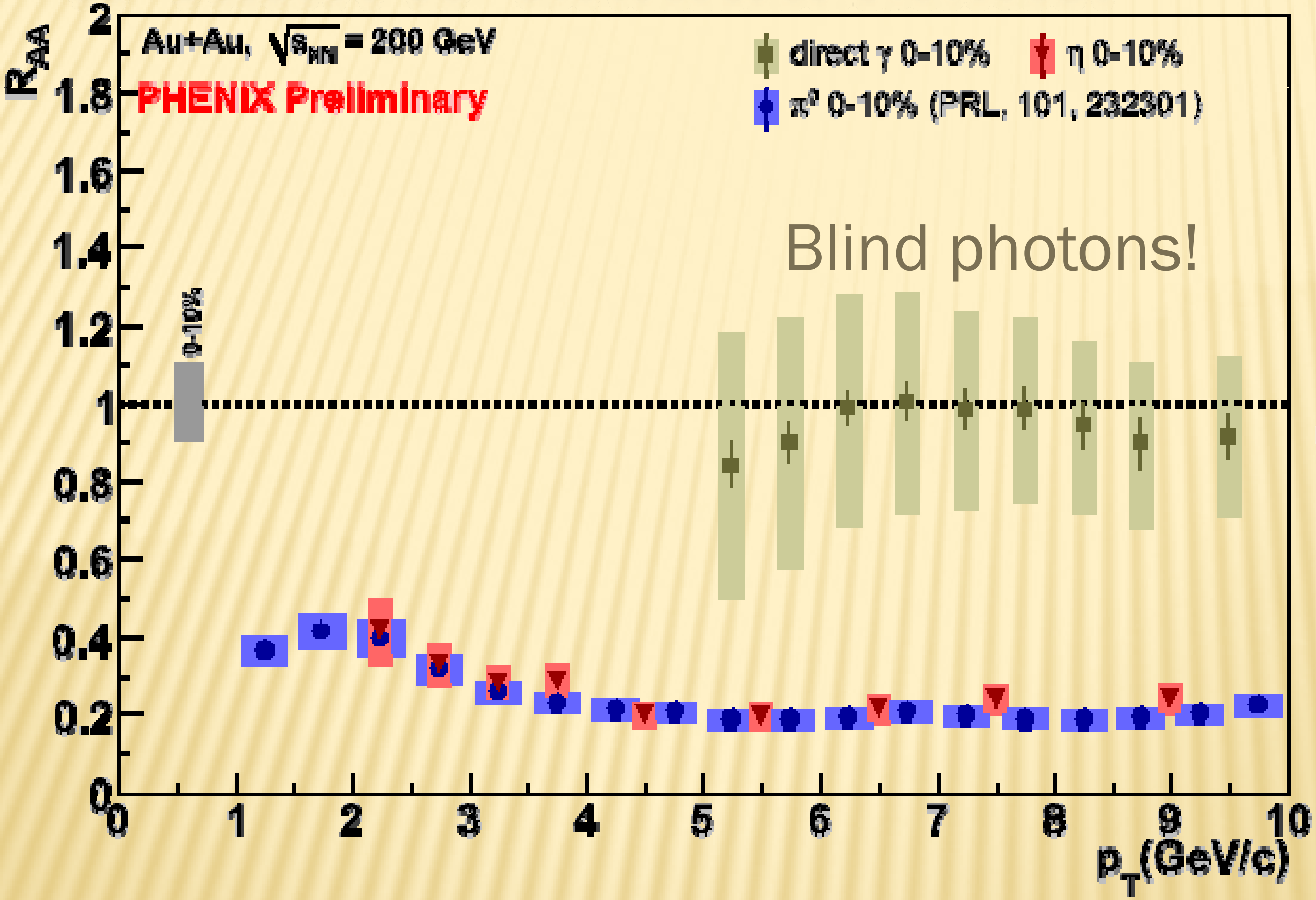
MOST CENTRAL COLLISIONS!

(slightly old, but pedagogical, data)

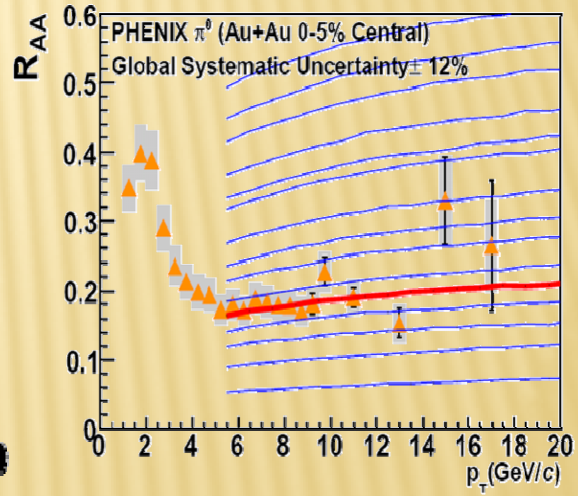
PHENIX, PRL 91 (2003) 072303

2. HIGH P_T SUPPRESSION

PHENIX, PRC77 (2008) 064907



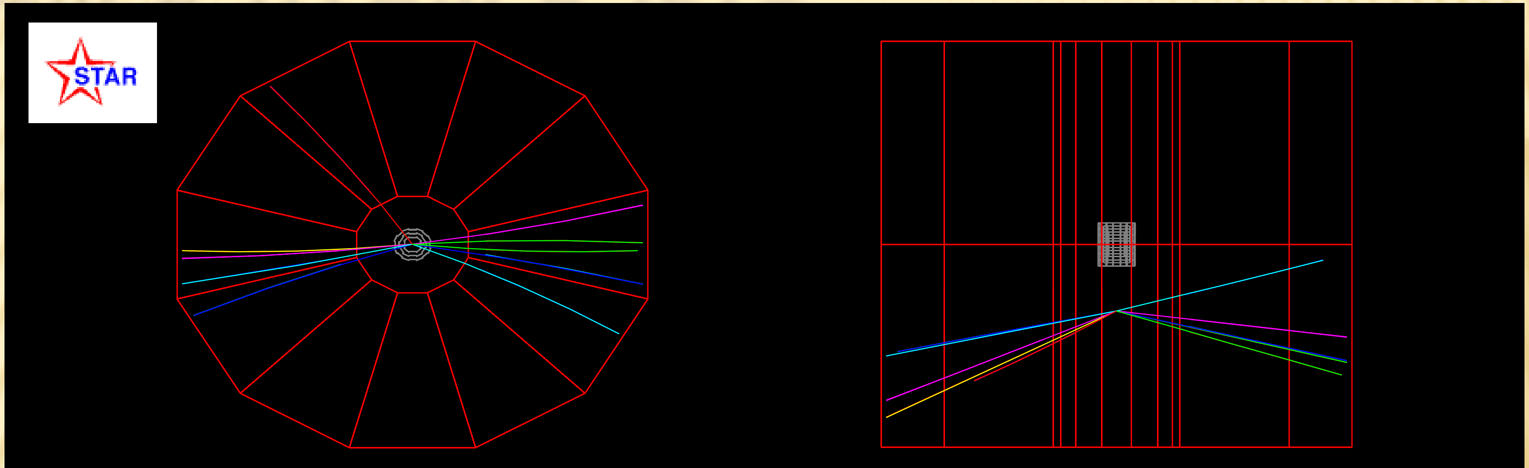
→ Comparisons to models, including experimental errors provide physical properties, e.g. $dN_{gluons}/dy = 1400 ^{+200}_{-375}$



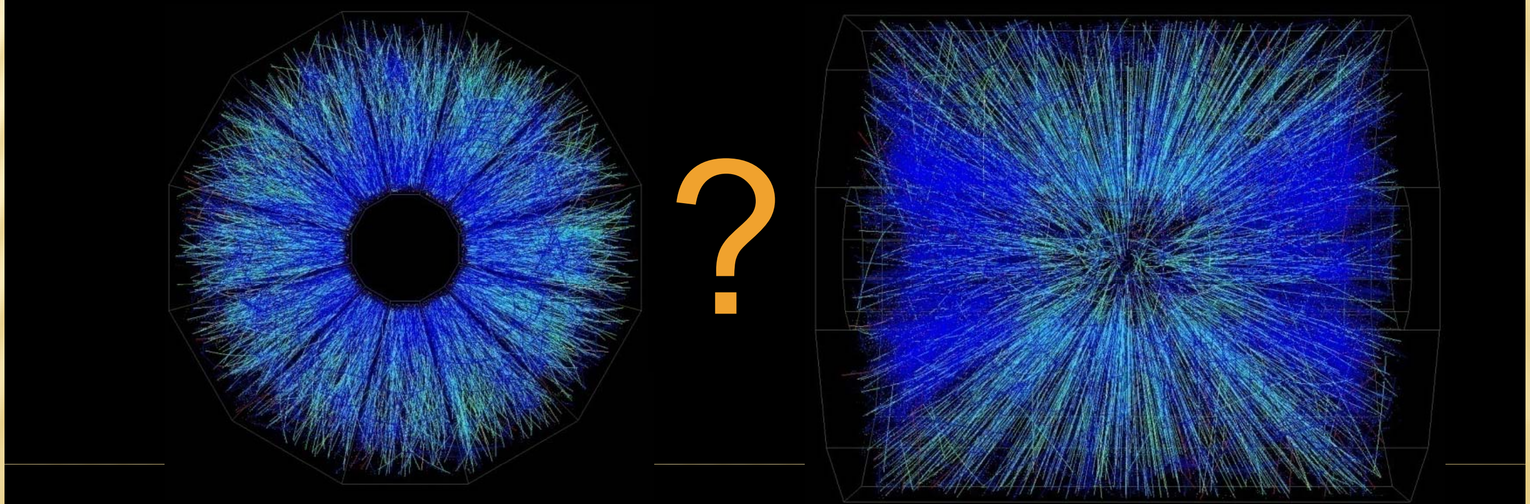
→ The matter is dense ! >1000 gluons per Δy

@ LHC, should be even denser…

3. BACK TO BACK JETS



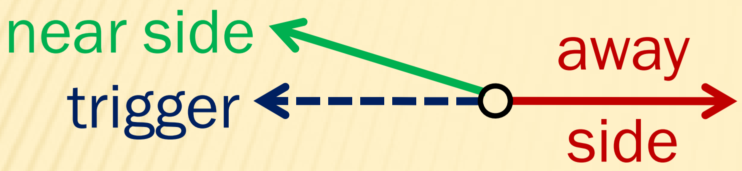
Easy in 200 GeV proton+proton collisions

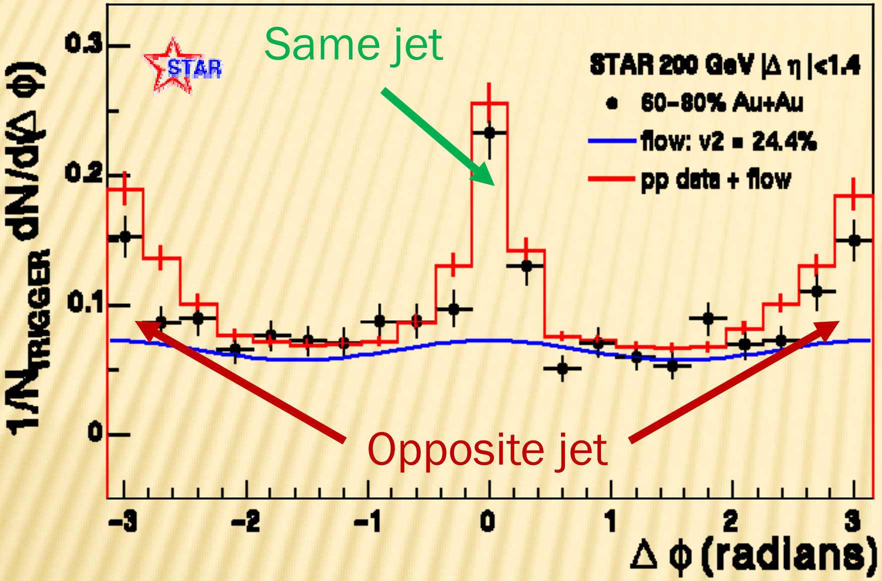


Quite difficult in Au+Au central collisions @ 200 GeV

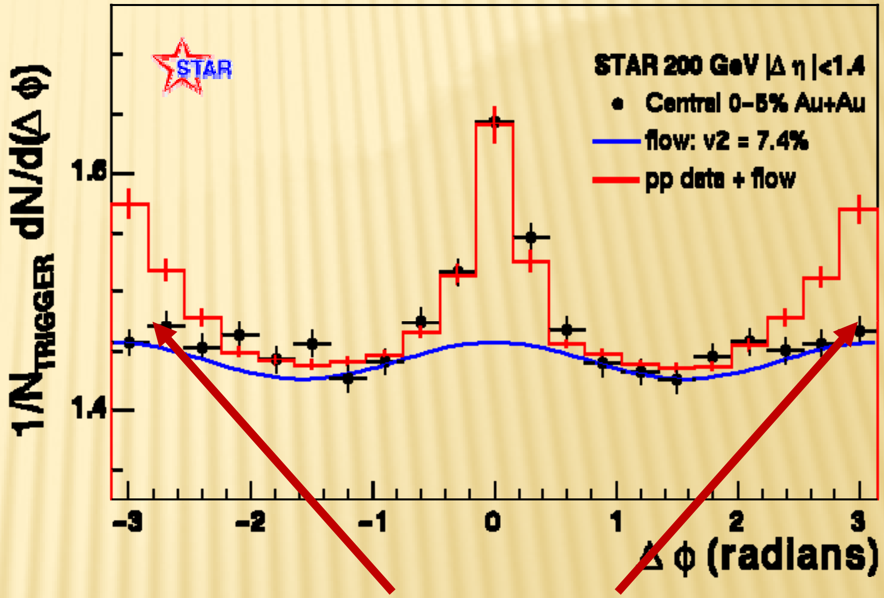
Peripheral collisions (60-80%)

Central collisions (0-5%)





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



In central collision, opposite jets disappear because of jet quenching

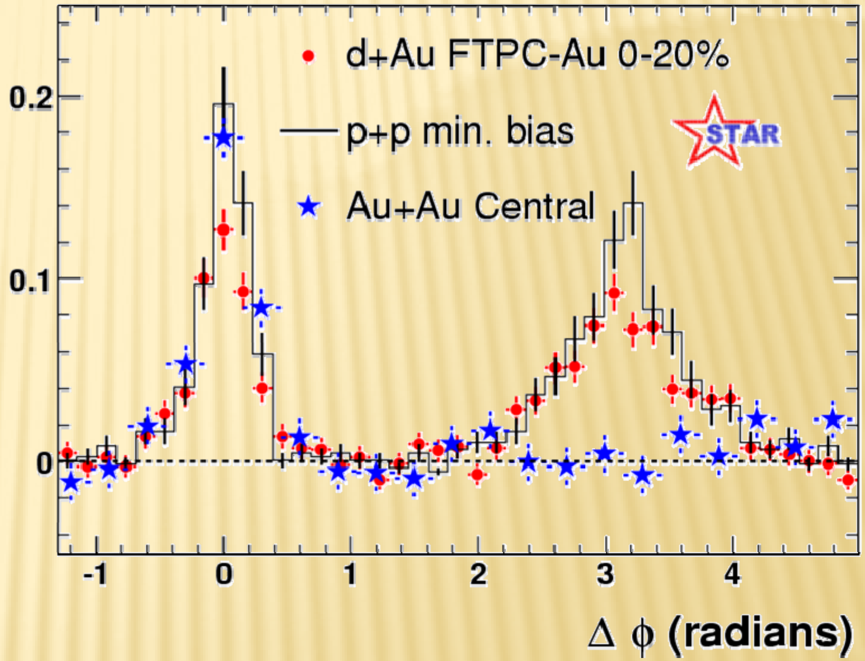
3. BACK TO BACK JETS

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...

From these seminal observations,

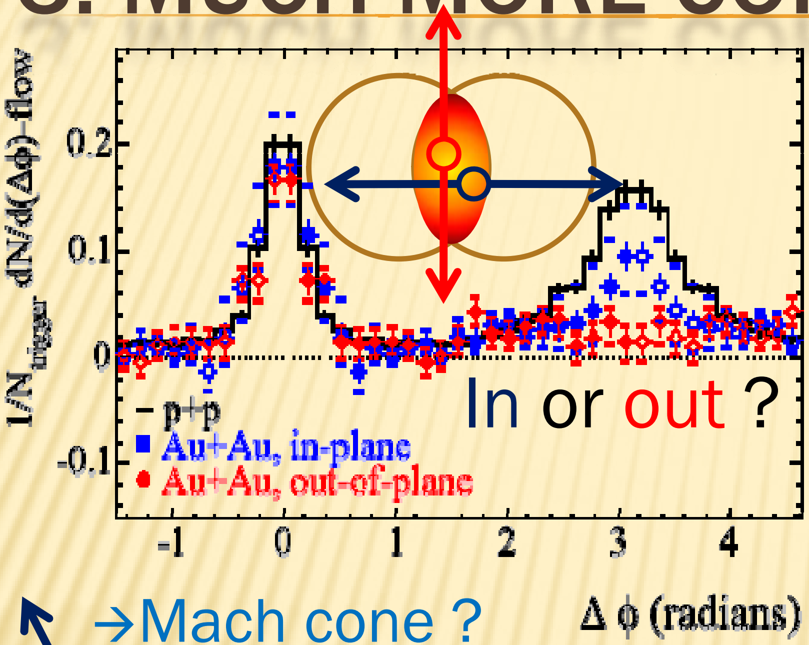
a lot more jet-related observables...

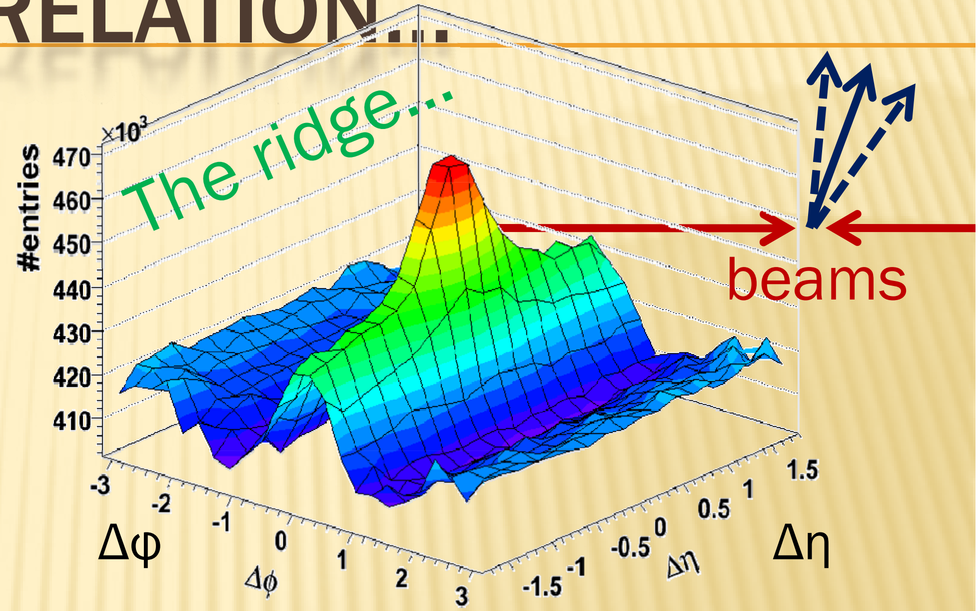
And new tools are showing up....

OTHER JETS OBSERVABLES AND TOOLS

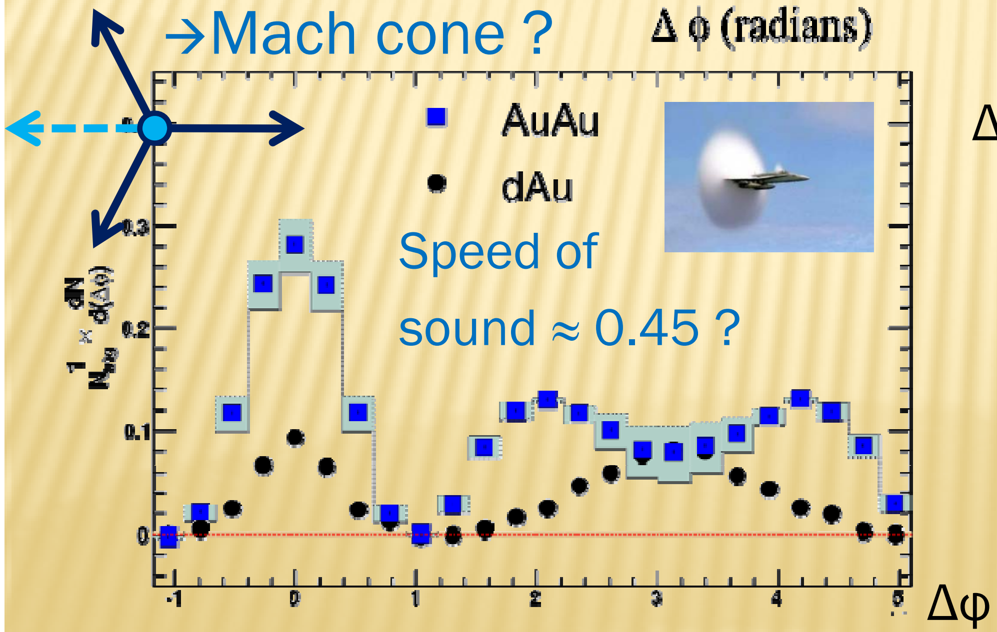
Here, all plots from STAR, see also PHENIX: PRC78 (2008) 014901

3. MUCH MORE CORRELATION…

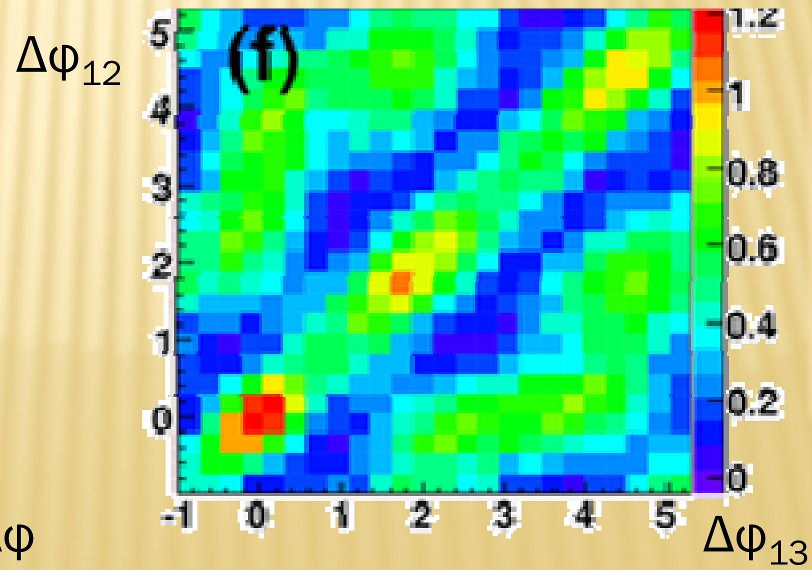




→Mach cone ?

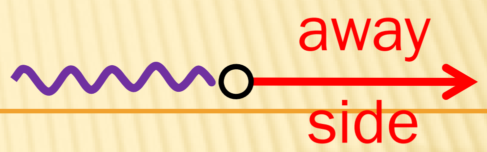


→Three particles (central Au+Au)

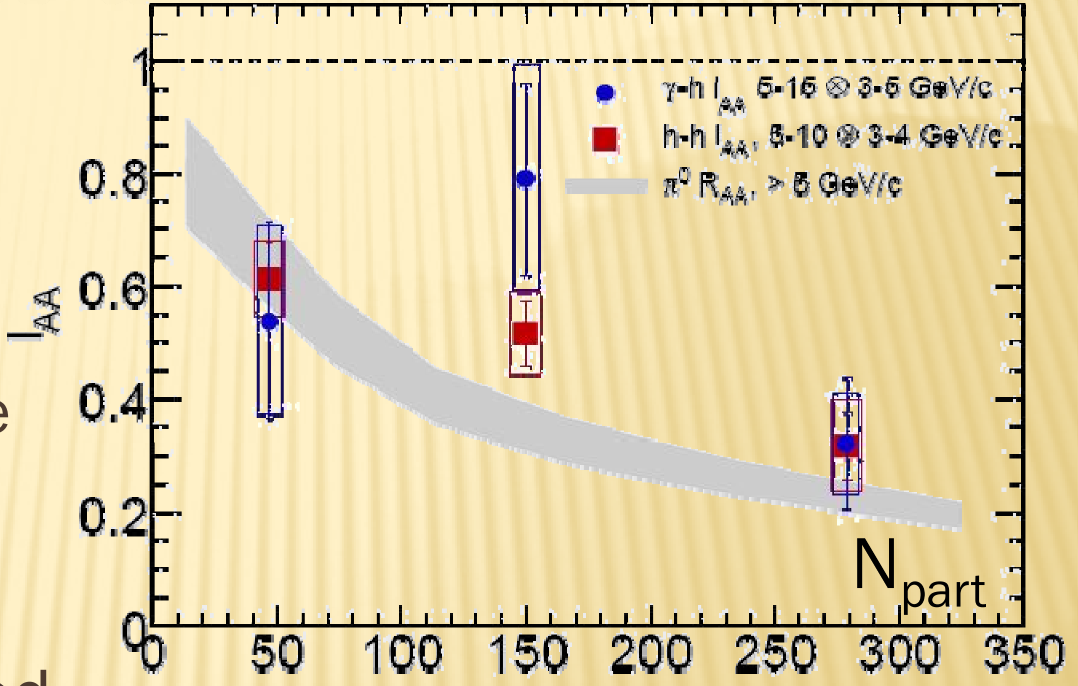


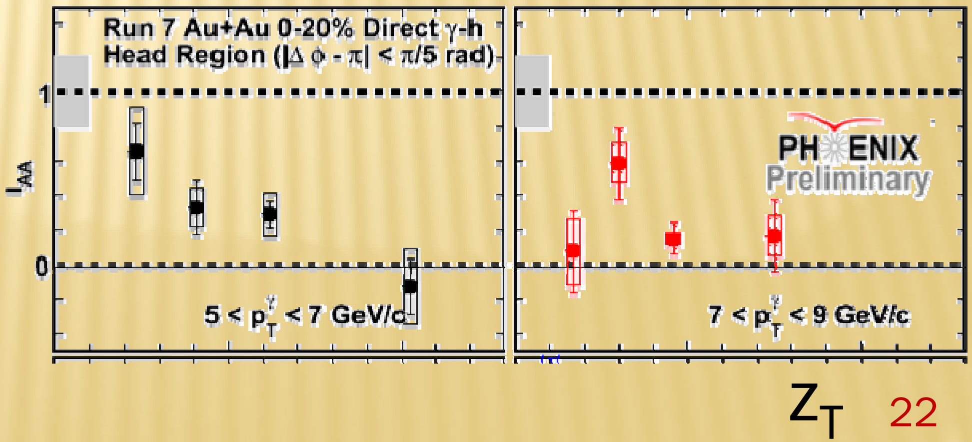
STAR: PRL102 (2009) 052302

NEW TOOL: GAMMA-JET



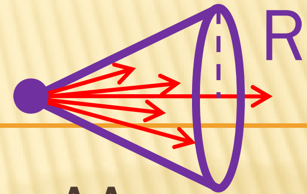
- Photon ≈ unmodified "reconstructed" jet
- Suppression is similar
  - Yield per trigger particle
  - Normalized to p+p
- Can start addressing the question of modified fragmentation function
  - $z_T = p_{hadron} / p_{photon}$ →



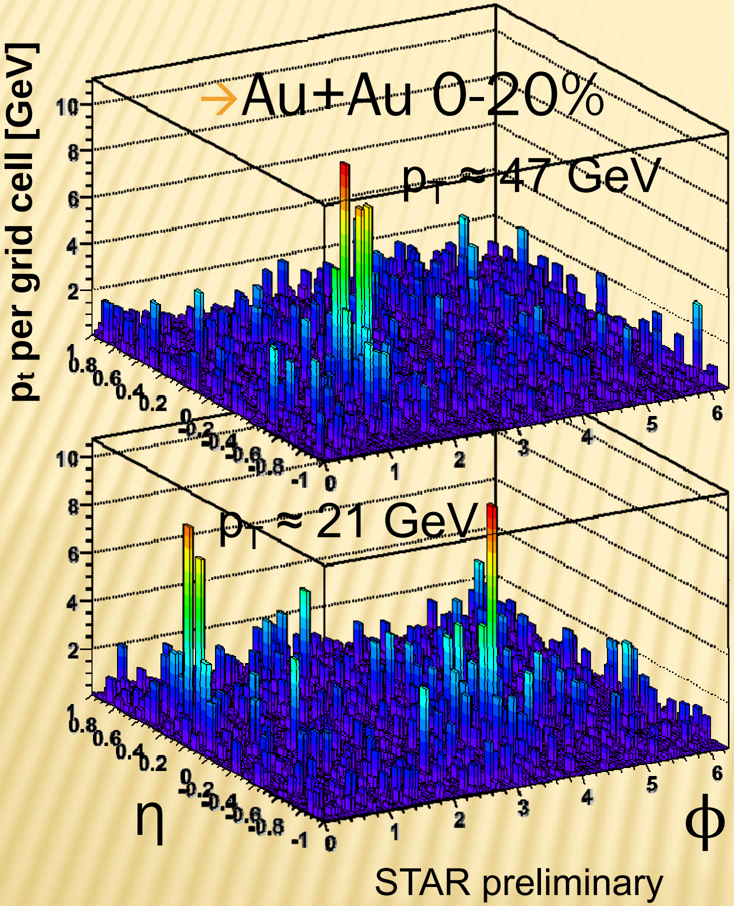


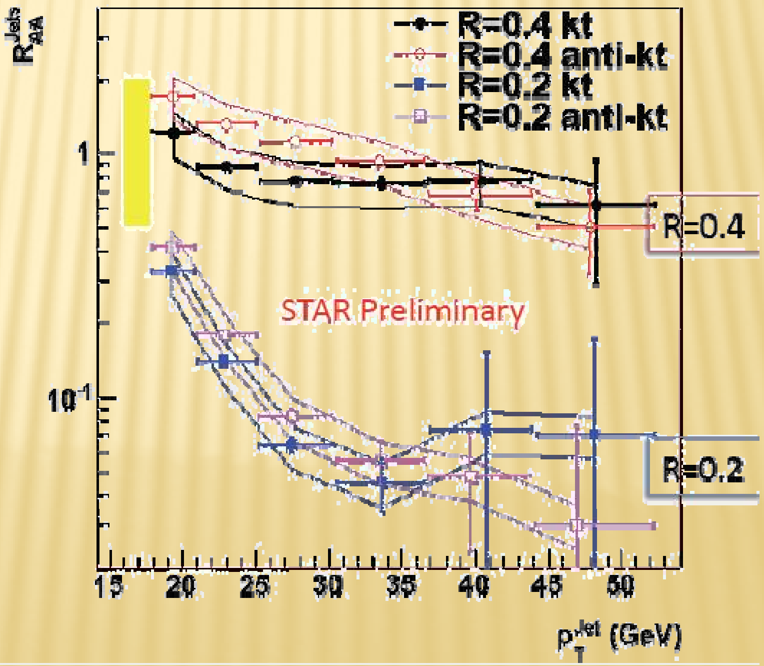
PHENIX: arXiv/0903.3399
M. Connors, QuarkMatter09

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 <u>preliminary</u> data





Easier @ LHC

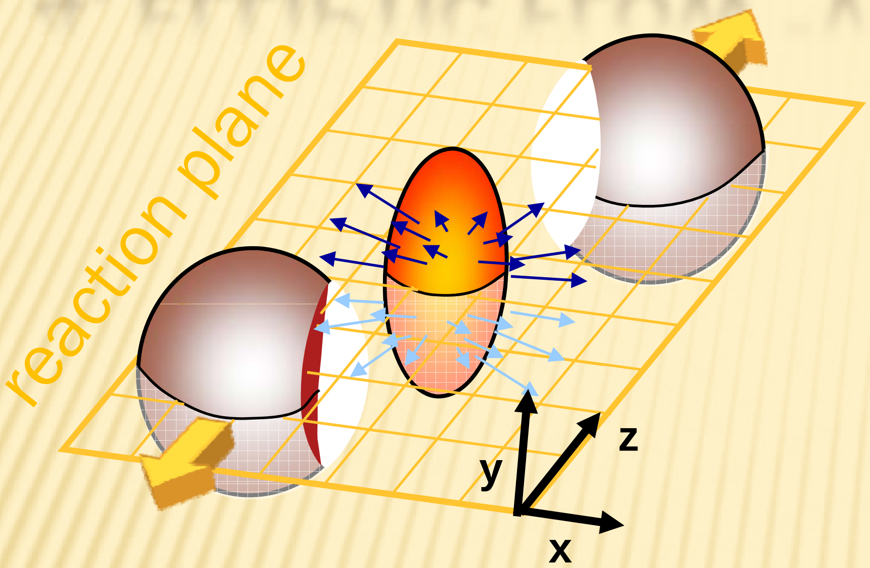
M. Polskon, Quark Matter 09
http://www.lpthe.jussieu.fr/~salam/fastjet

RHIC serves the perfect liquid…

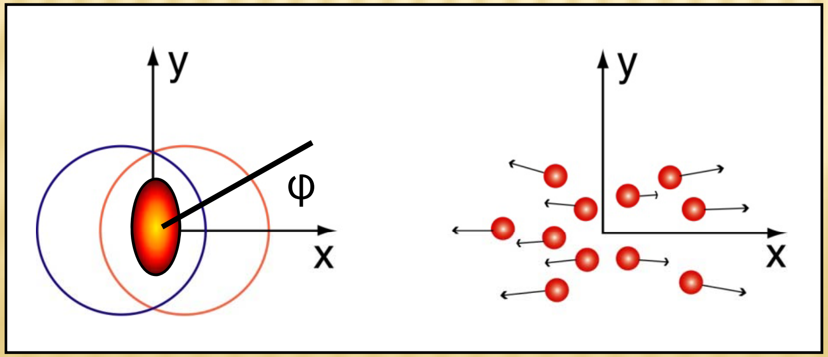
PARTONIC COLLECTIVE BEHAVIOUR

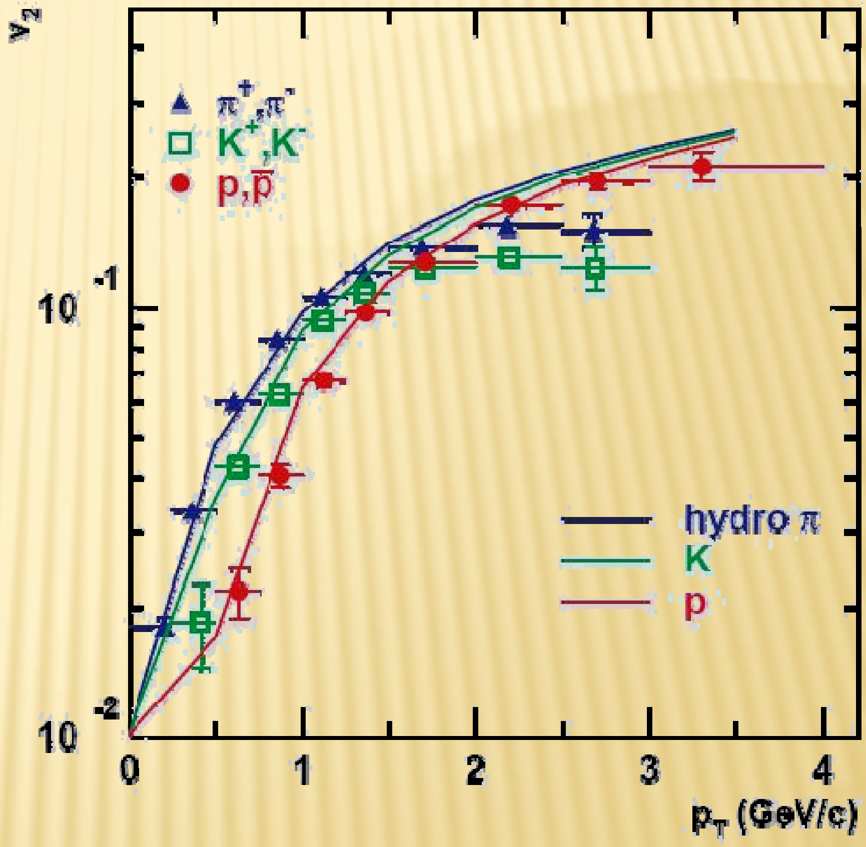
4. ELLIPTIC FLOW "V_2"

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)
   - $\langle\beta_T\rangle \approx 0.6$
2. Elliptic flow

- Not the foreseen ideal partonic gas!

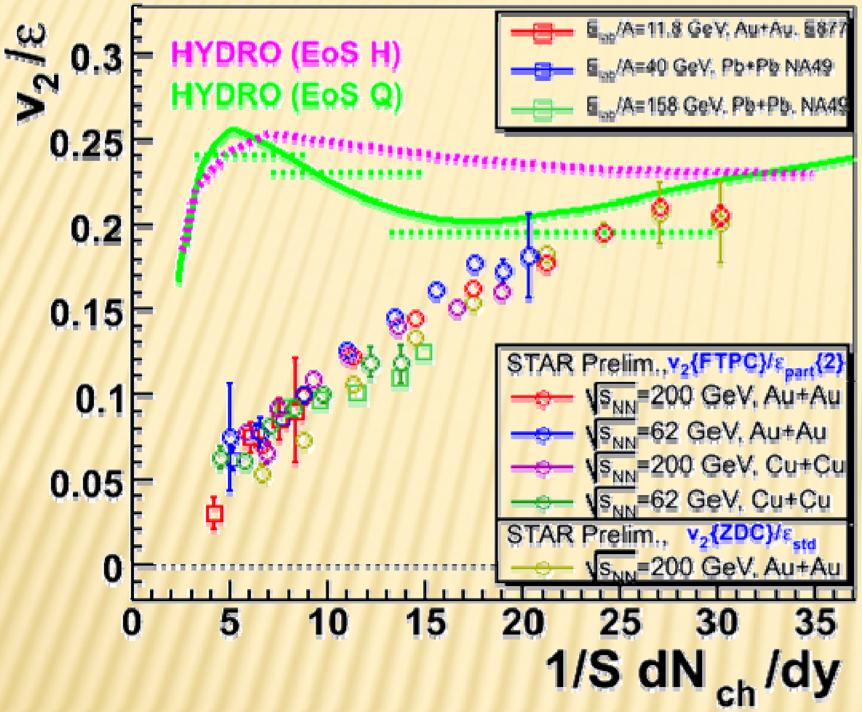
→ *"sQGP"* (s stands for strong, not super ☺)

→ *"Perfect fluid"*

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

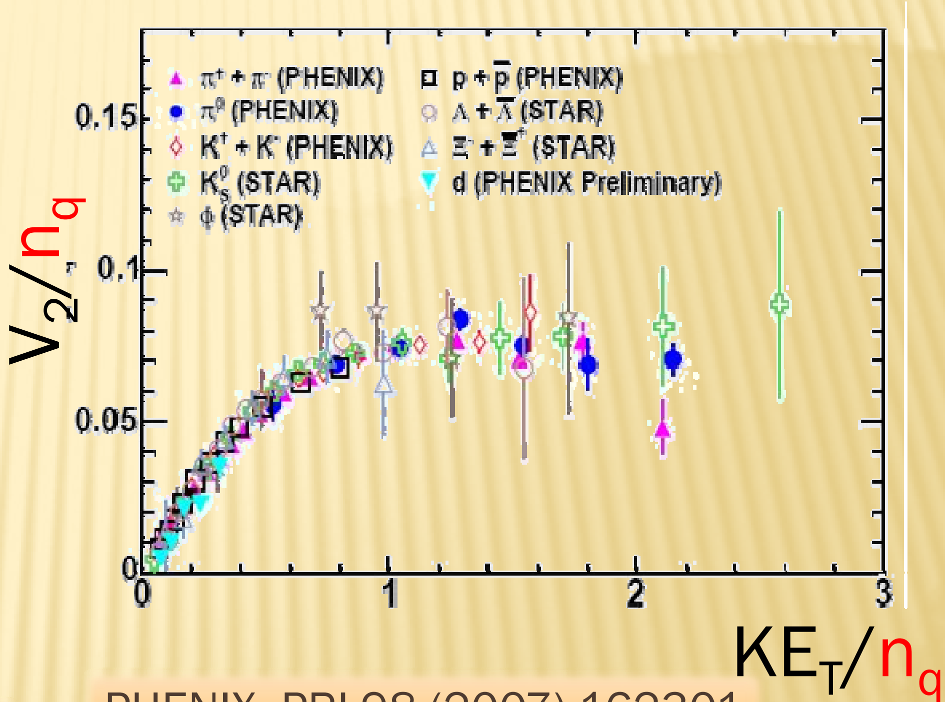
With eccentricity vs N_{ch} density

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



Voloshin & Pokskanzer, PLB 474 (2000) 27

With the kinetic energy per constituent quarks



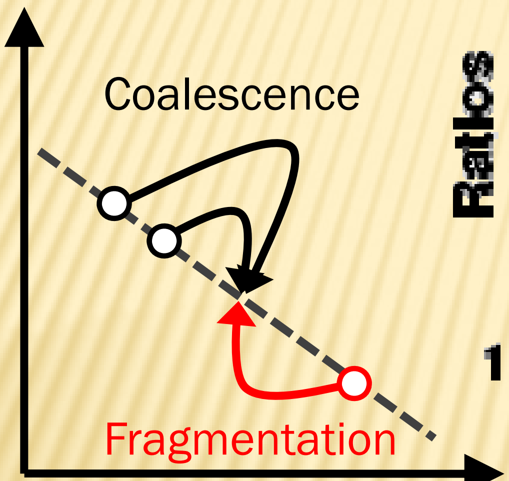
PHENIX, PRL98 (2007) 162301
(and other particles)

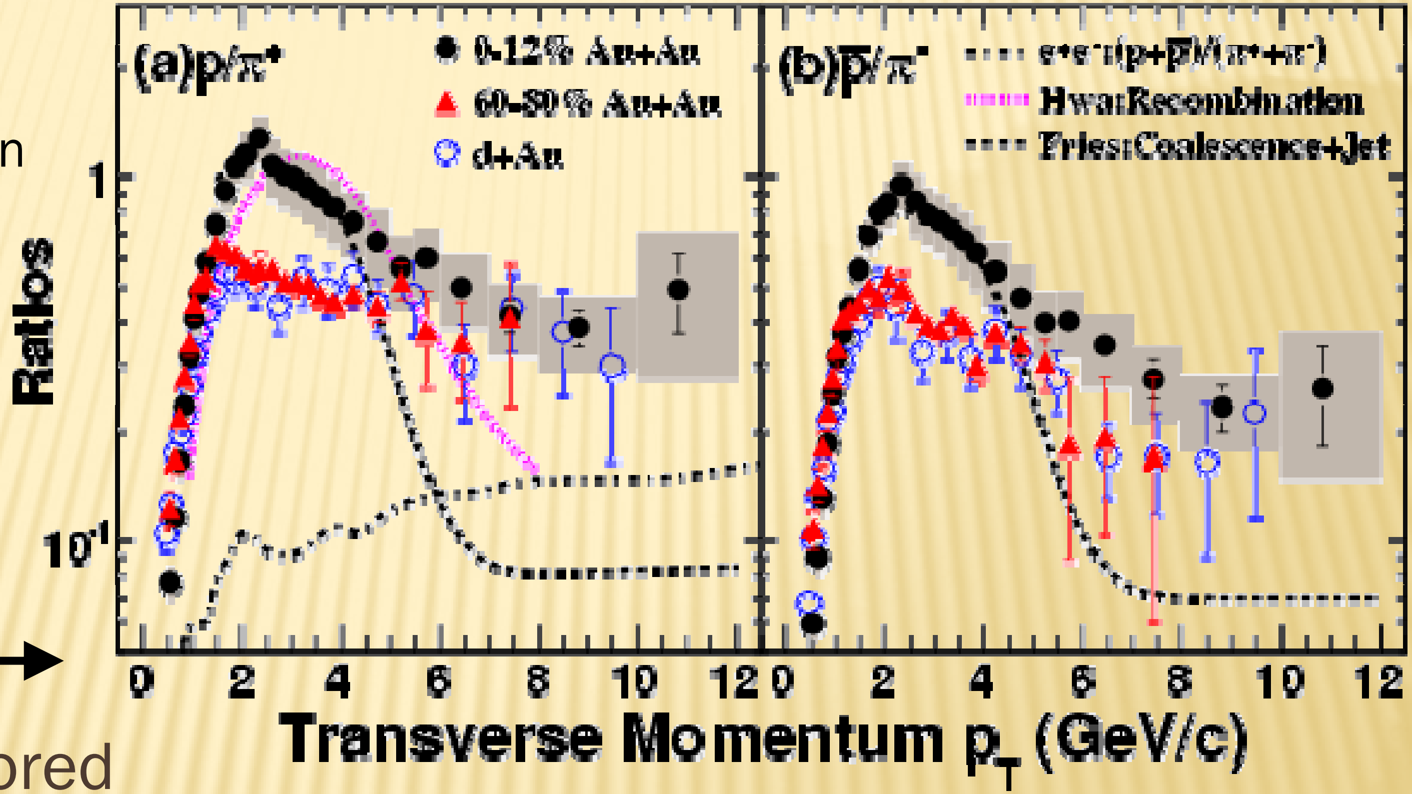
4. ELLIPTIC FLOW (SCALINGS)

5. BARYONS/MESONS

STAR, PRL 97 (2006) 152301

→ Spectrum cartoon





- Baryon favored
- Not fragmentation!
- Coalescence or recombination

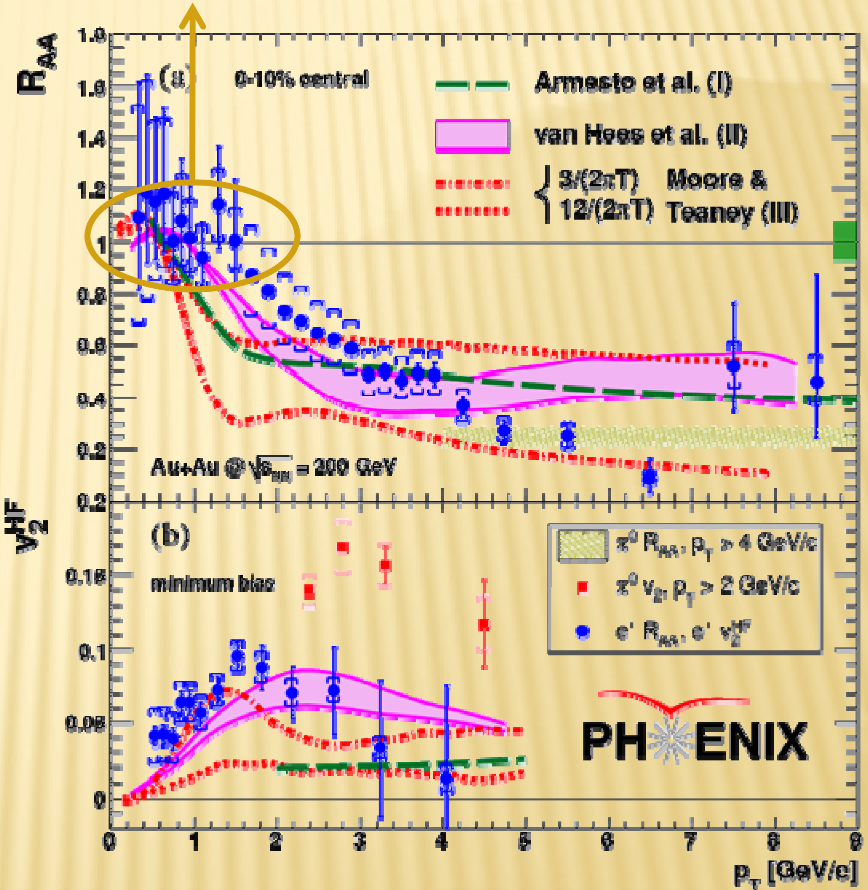
→ The matter is partonic
(constituent scaling, coalescence…)

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

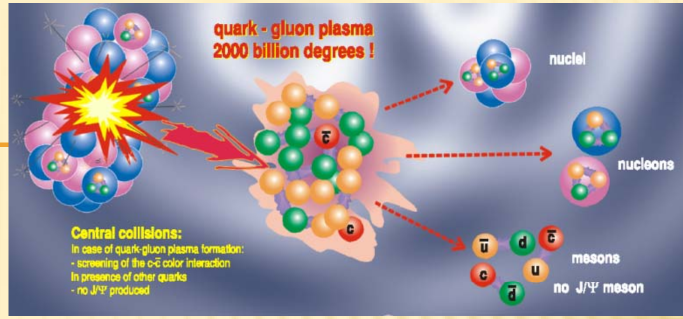


→ The matter is tough…
@ LHC, more thermalization?

The originally thought “unambiguous signature”

QUARKONIA SUPPRESSION

7. J/Ψ SUPPRESSION



- J/ψ ($c\bar{c}$) can melt in QGP

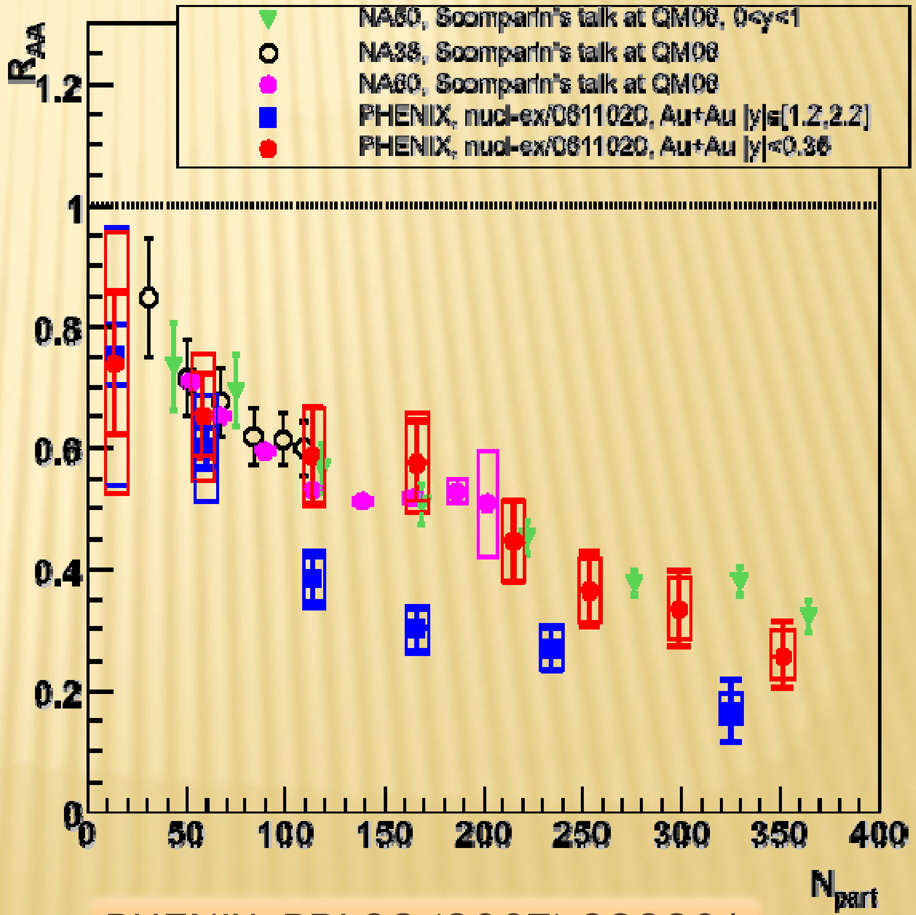
  Matsui & Satz, PLB178 (1986) 416

- Golden signature @ SPS

  (@ CERN √s ≈ 20 GeV)

  → QGP discovery claim!

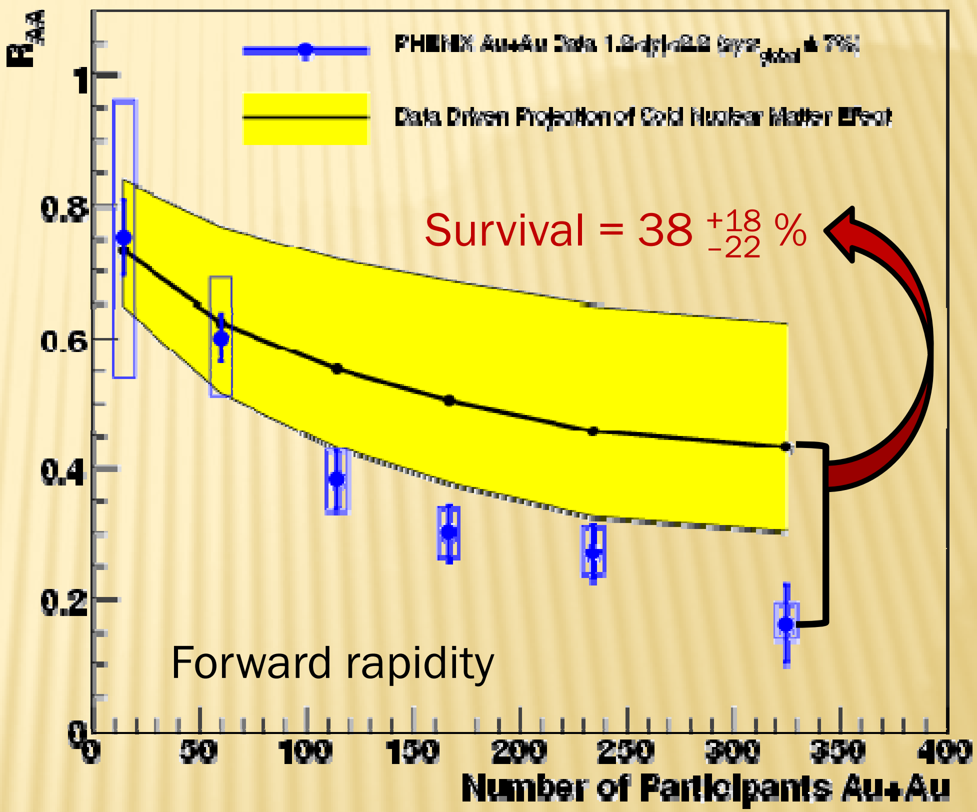
- @RHIC, same rapidity, suppression looks surprisingly similar
  - While density is higher
- Stronger @ forward
  - While density is lower
- But beware of nuclear matter!



PHENIX, PRL98 (2007) 232301

7. J/Ψ SUPPRESSION (FROM D+AU)

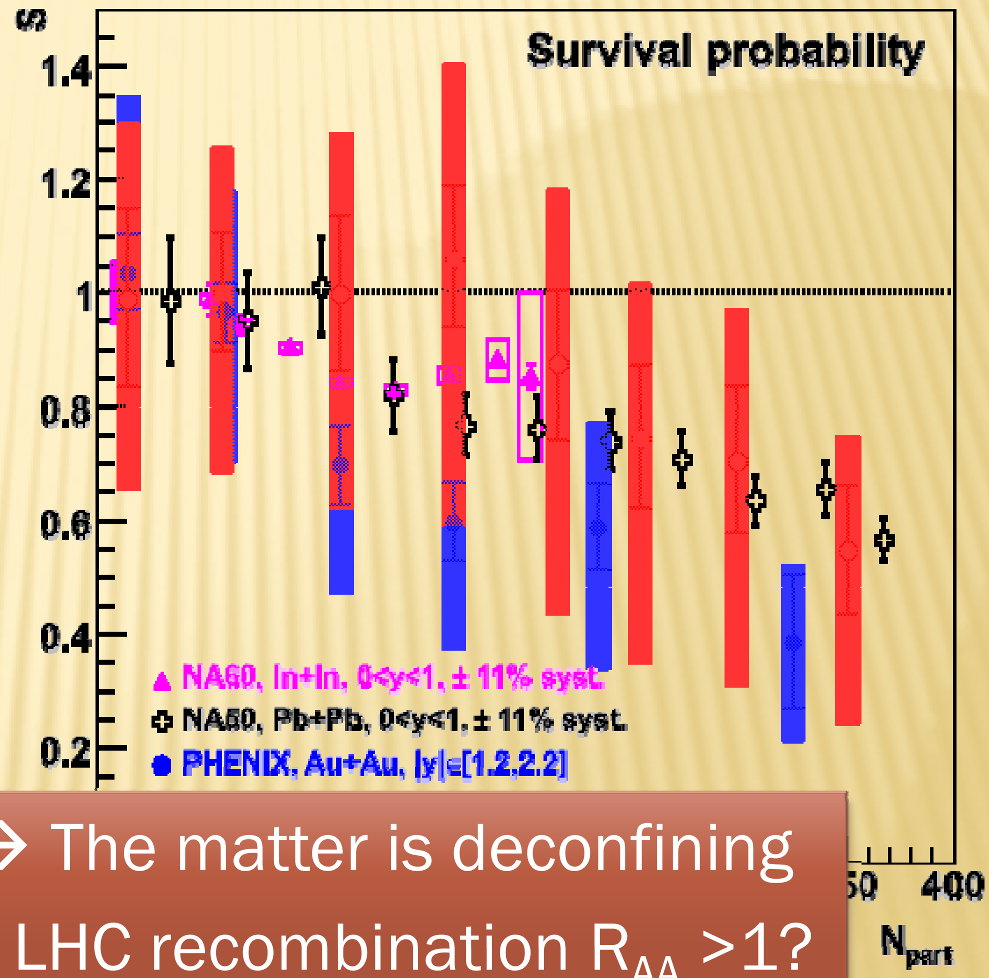
- Cold nuclear matter can also suppress J/ψ
  - pdf modifications?
  - absorption?
- Extrapolation from d+Au
  - Data driven, mostly model independent
  - Large uncertainty
- More d+Au on tape
  - (2008 = 30 x 2003)
  - Preliminary @ QM09



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

7. J/Ψ "ANOMALOUS" SUPPRESSION

- Survival beyond (safe) nuclear extrapolation:
  - Anomalous suppression could be the same at both rapidity
  - Alternate explanation: uncorrelated c+$\bar{c}$ recombination (>10 pairs in a central collision)
- However, <u>J/ψ do melt</u>!



PHENIX, PRL98 (2007) 232301
divided by
PHENIX, PRC77 (2008) 024912
(data driven method)

→ The matter is deconfining

@ LHC recombination R_{AA} >1?

@ LHC Upsilon studies !

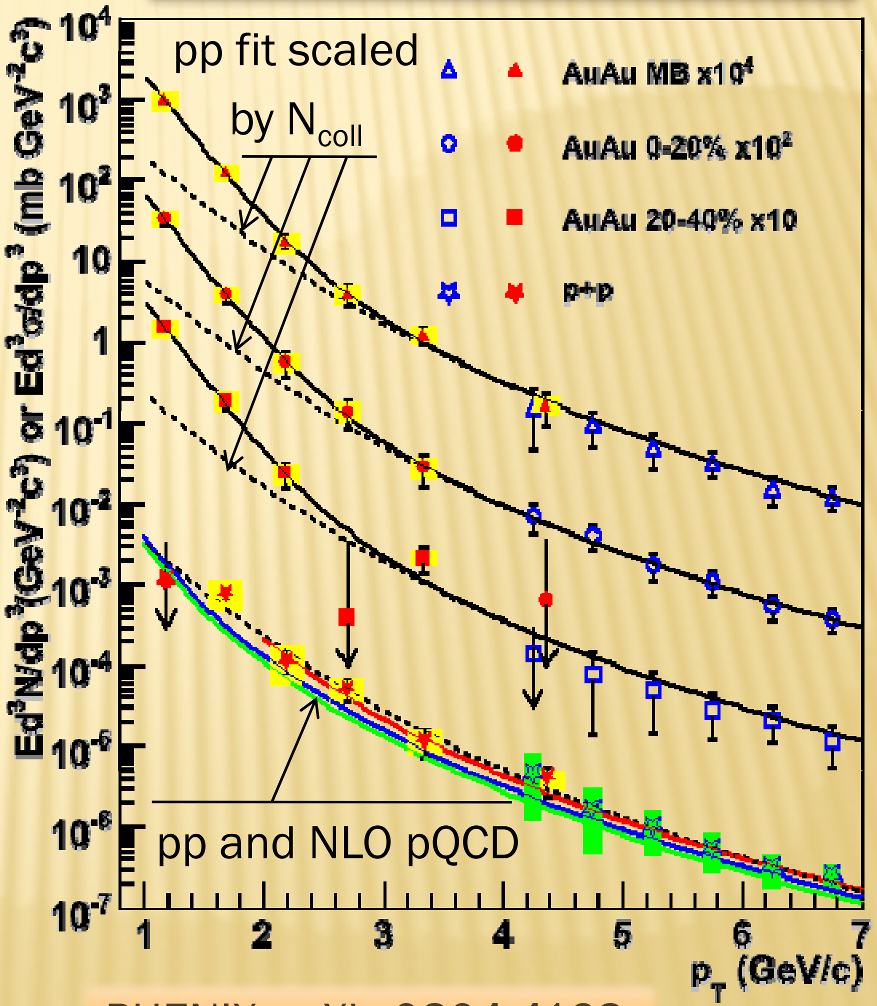
Still one or two slide to go…

THERMAL RADIATION

8. THERMAL RADIATION

The matter is hot !
@LHC, T ≈ 1 GeV ?

- 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 Olga's talk)

- Bibliography:
  - Experimental "white papers": NPA757 (2005), PHENIX: nucl-ex/0410003
  - Quark matter 2009 conference (Knoxville, March 30, April 4th) http://www.phy.ornl.gov/QM09/
  - Interesting reviews, for instance: RGdC, arXiv:0707.0328 IJMP A22(2008)6043

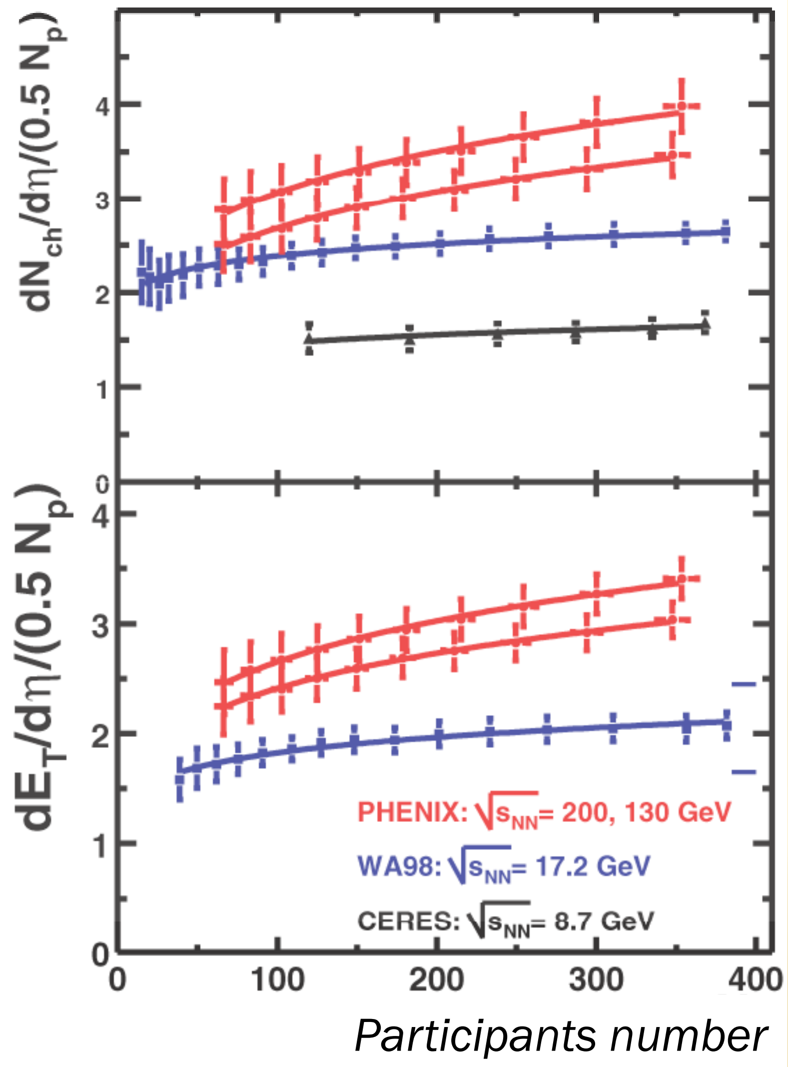
BACK UP SLIDES…

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

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

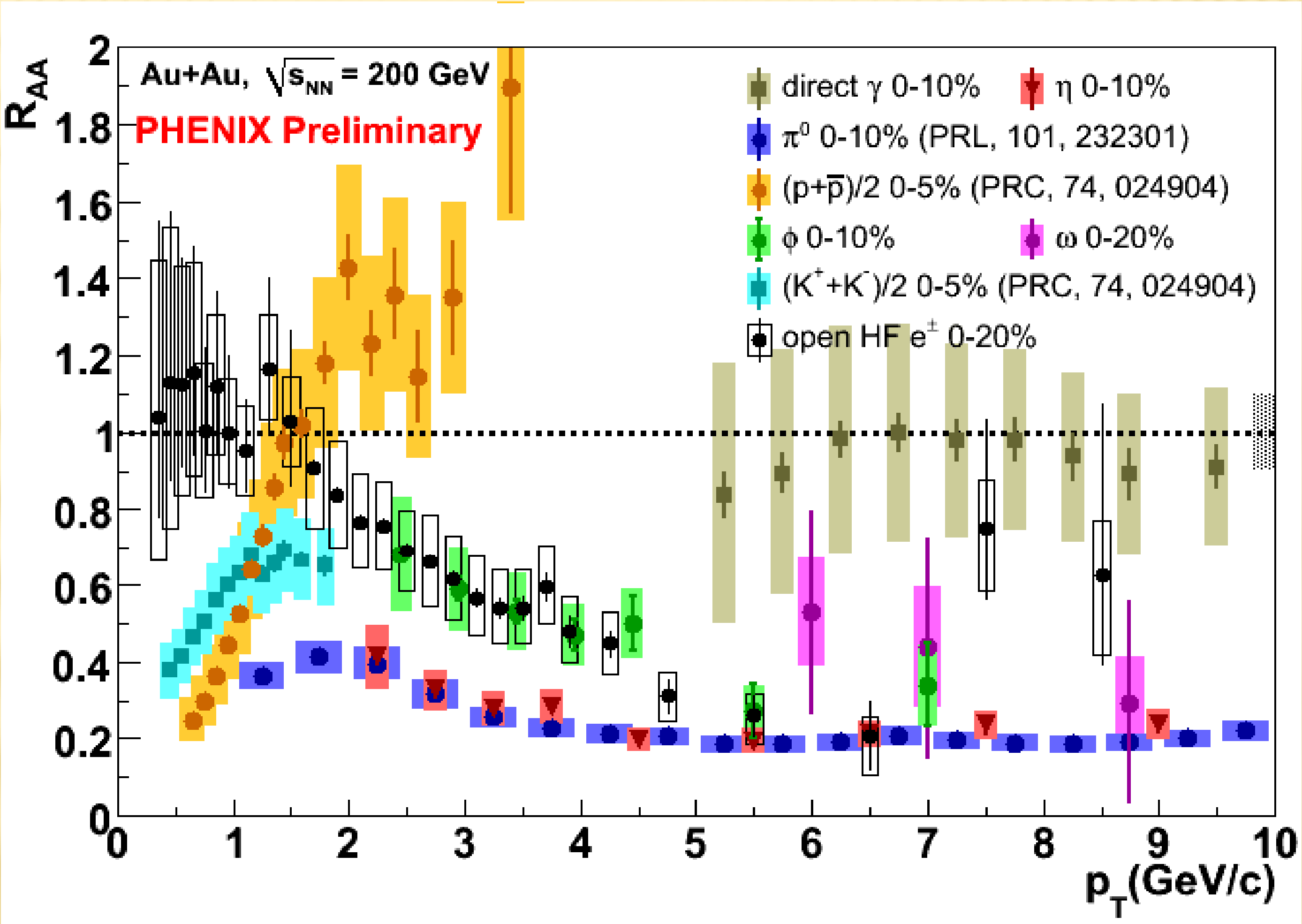
τ_0 formation time
0,35 à 1 fm/c

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

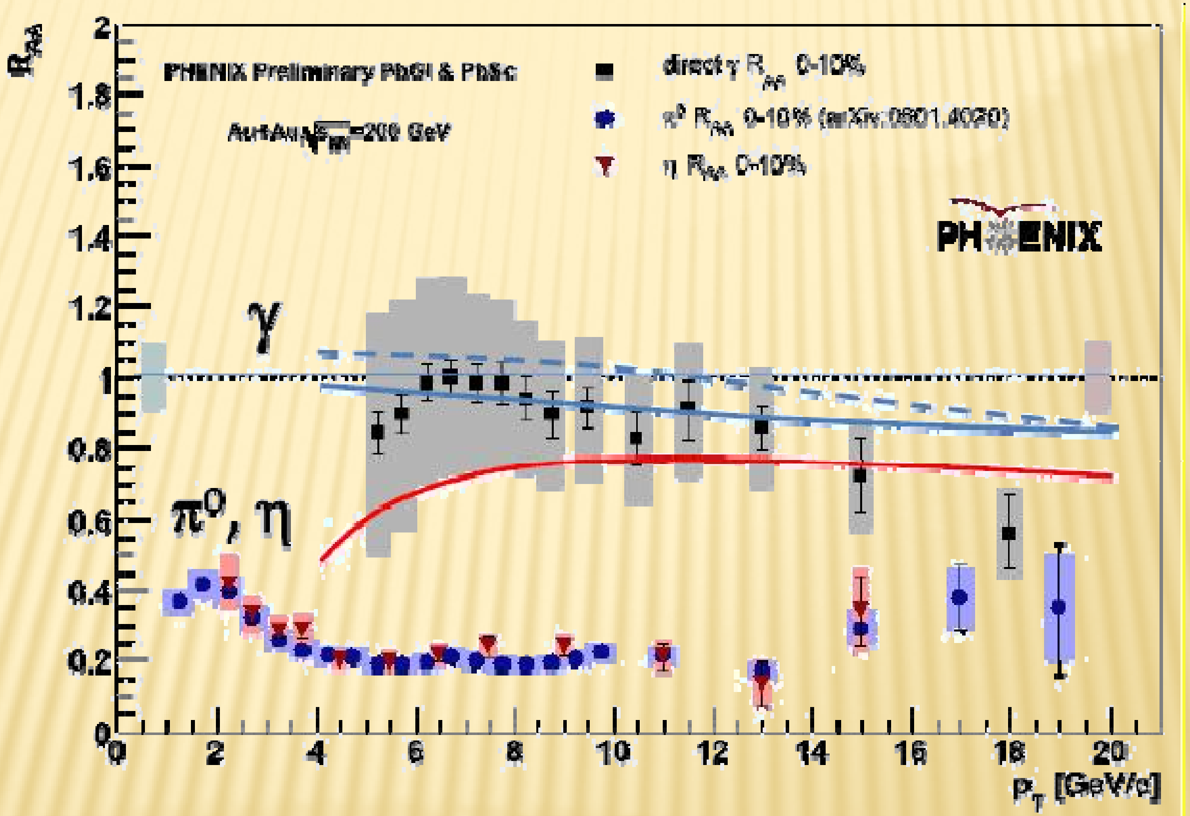
$\varepsilon > 6$ GeV/fm^3

Bjorken, PRD27 (1983) 140

MORE NUCLEAR MODIFICATIONS…



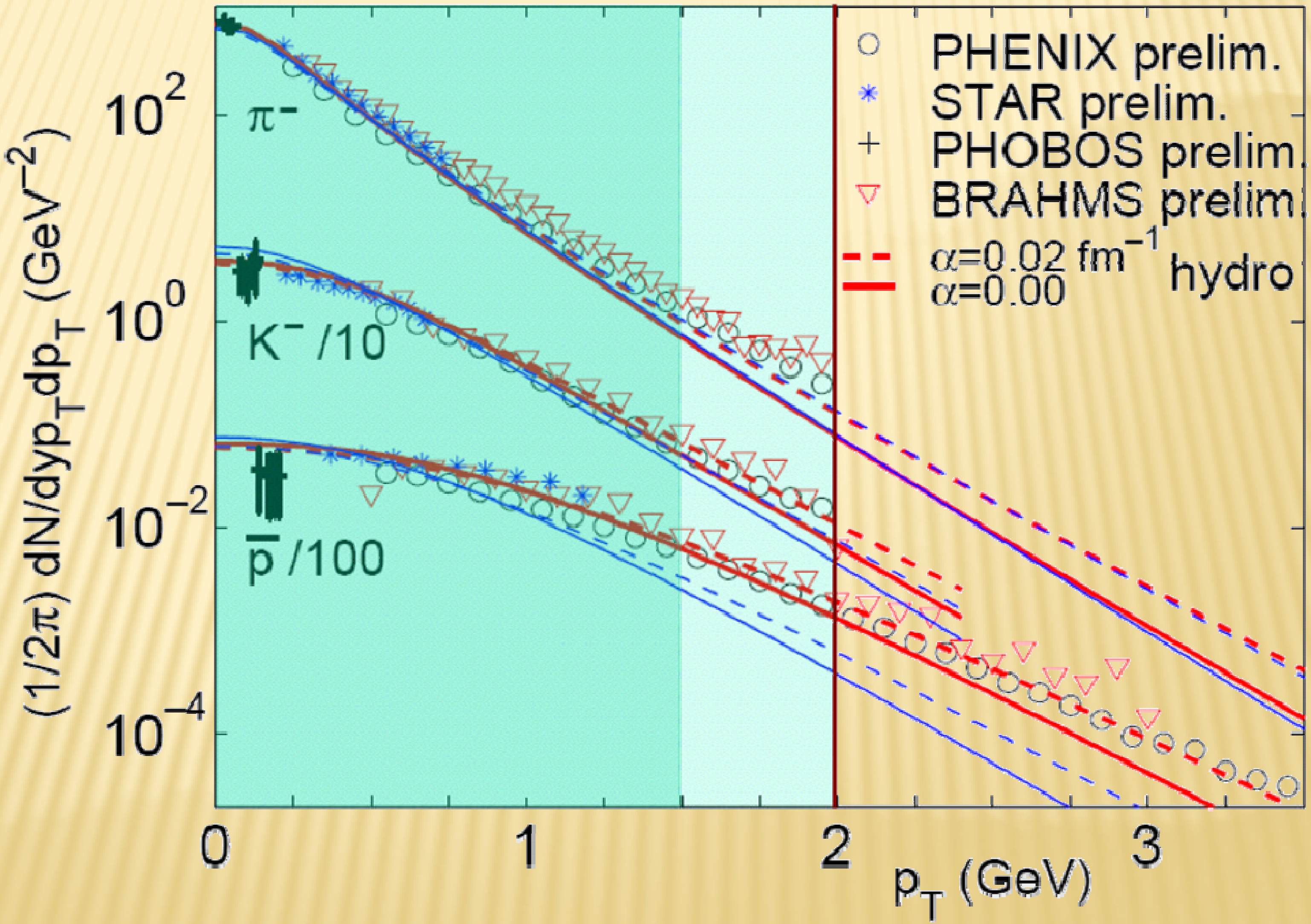
HIGHER PT



R_{AA}
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
p_T [GeV/c]

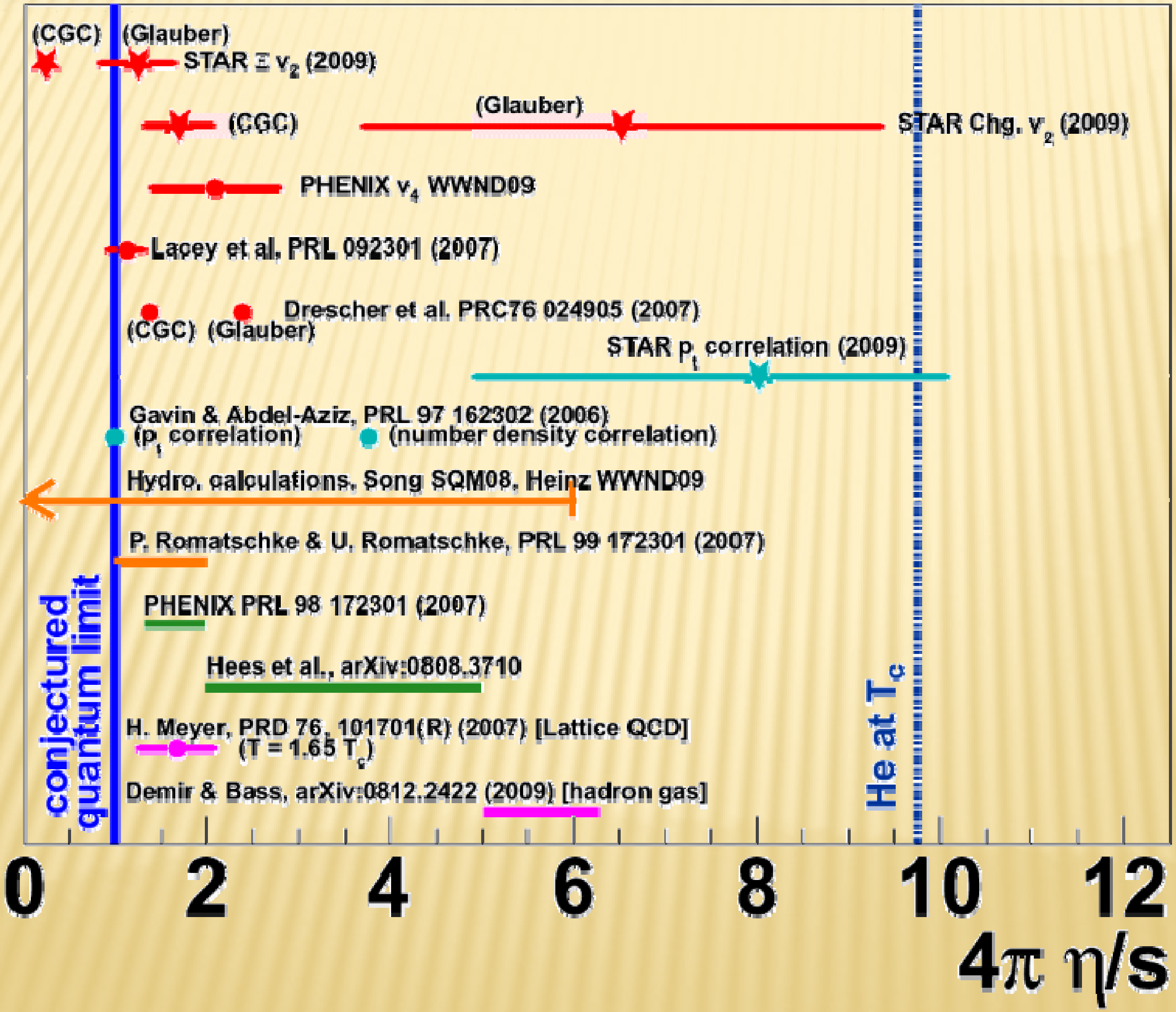
HYDRO FIT OF SPECTRA

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

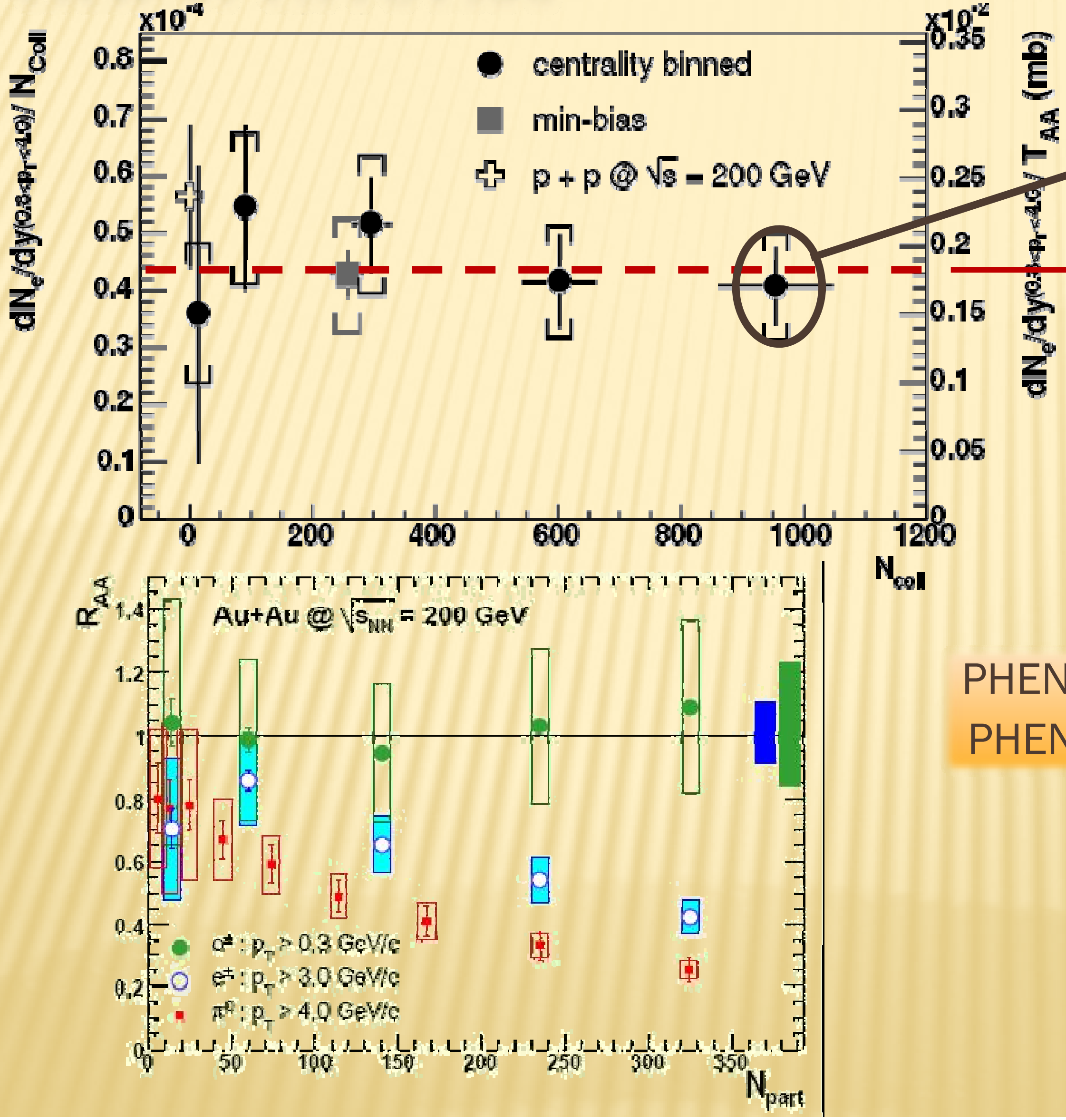


G. Wang @ QuarkMatter09

VICOSITY/ENTROPY RATIO



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?

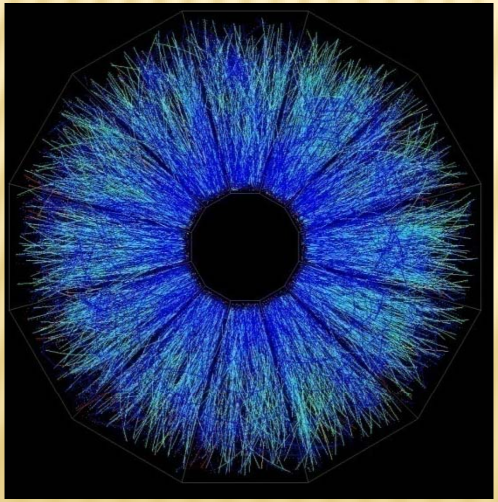
Juan Maldacena, ATMP 38 (1999) 1113 (>4500 citations)

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 ...)