Séminaire NPAC, Orsay, 10 novembre 2010

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PHENIX and CMS experiments
ERC grant "QuarkGluonPlasmaCMS"

QUARK GLUON PLASMA (AT RHIC AND WITH CMS)

OUTLINE: A MELTING POT OF…

- Quark gluon plasma physics and definitions
- Findings at RHIC (200 GeV)
- Capabilities of CMS (2.76 TeV)
  - Heavy-ions collisions started this week in LHC
- An intriguing result in p+p (7 TeV)

☺ THE ORIGIN OF (OUR) MASS…

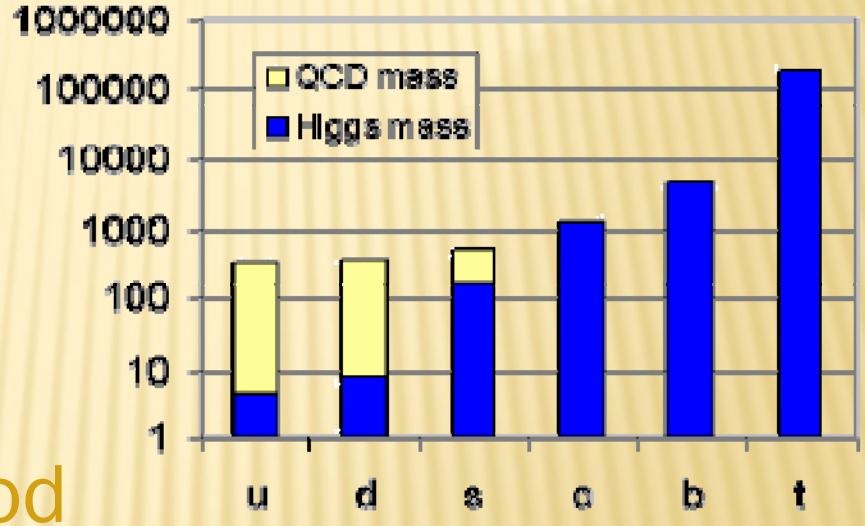
Atomic mass =

≈ 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 de-confinement…
- But remember, it's only ≈5% of the universe! ☹

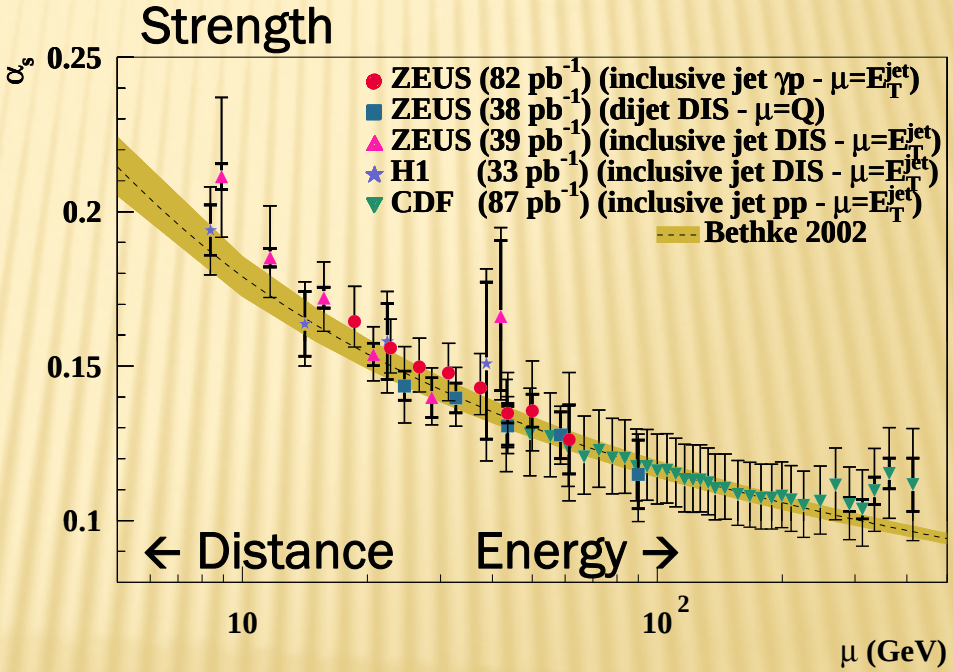
THE STRONG INTERACTION…

- … is strong at low energy, i.e. short distance (≈1fm) as seen from data (HERA…), and described by quantum chromodynamics (QCD)

→ No free quark

→ Bound hadrons

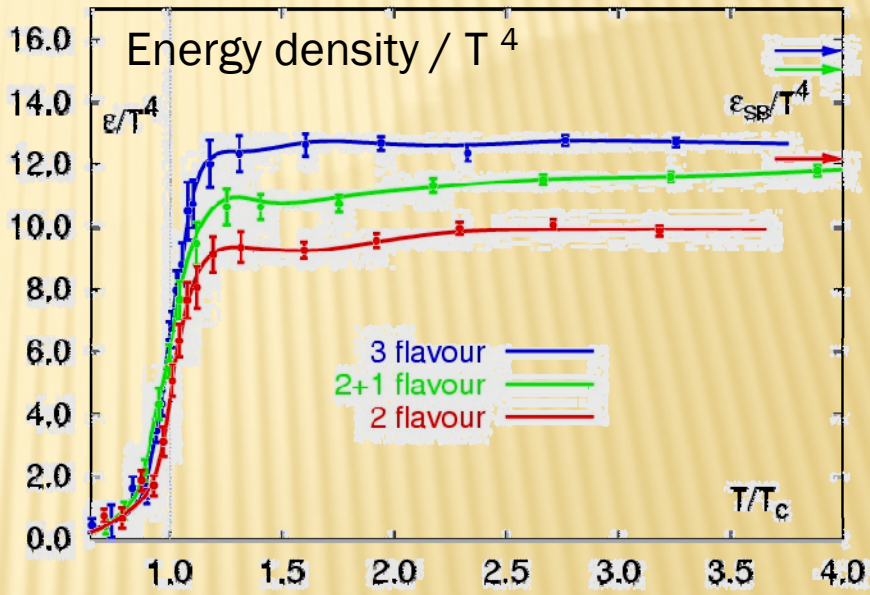
→ Confinement



- … but weak at high energy → "asymptotic freedom"

A STRONG PREDICTION (ON THE LATTICE)

- 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)
    $\approx 20\,000 \times T_{sun}$
  - $\varepsilon_c \approx 1$ GeV/fm^3
    $\approx 6 \times$ nuclear density



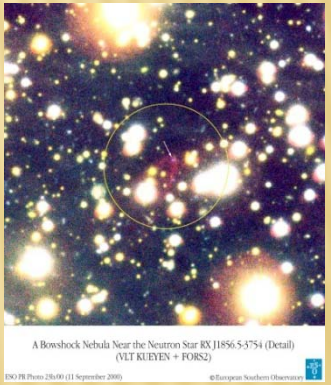
Karsch et al, hep-lat/0106019
Lect. Notes Phys.583 (2002) 209

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

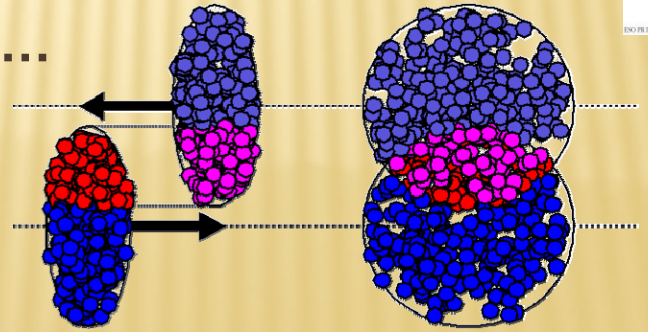
WHERE/WHEN CAN WE FIND THE QGP?

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 compact stars
   - + But no smoking gun candidate so far



3. In the lab, by colliding heavy ions
   - + Freedom for the quarks…
   - + … for some 10^{-23} s

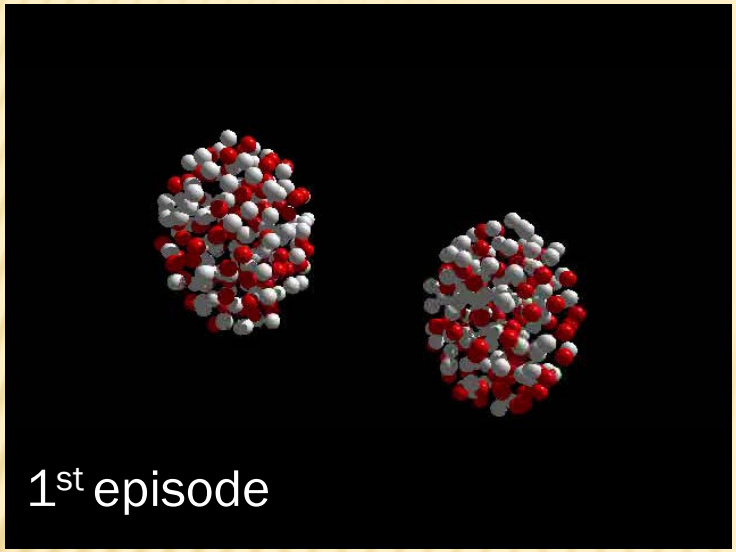


HEAVY ION COLLISIONS

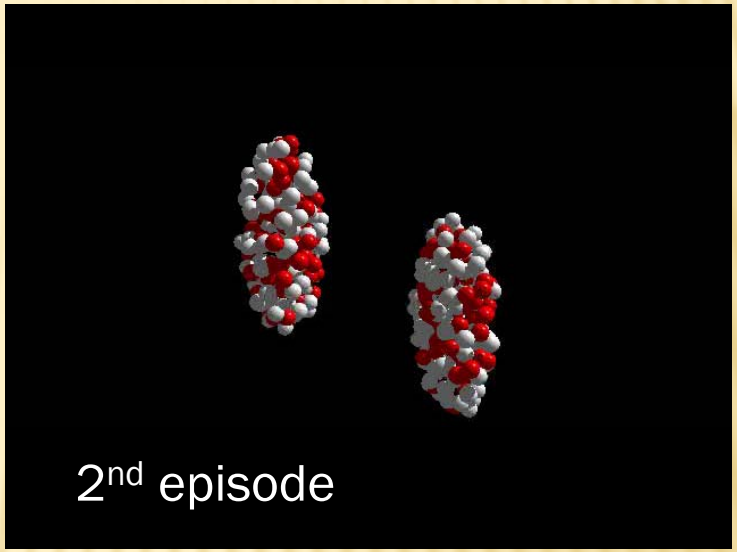
$\sqrt{s_{nn}}$

FIXED TARGET COLLISIONS

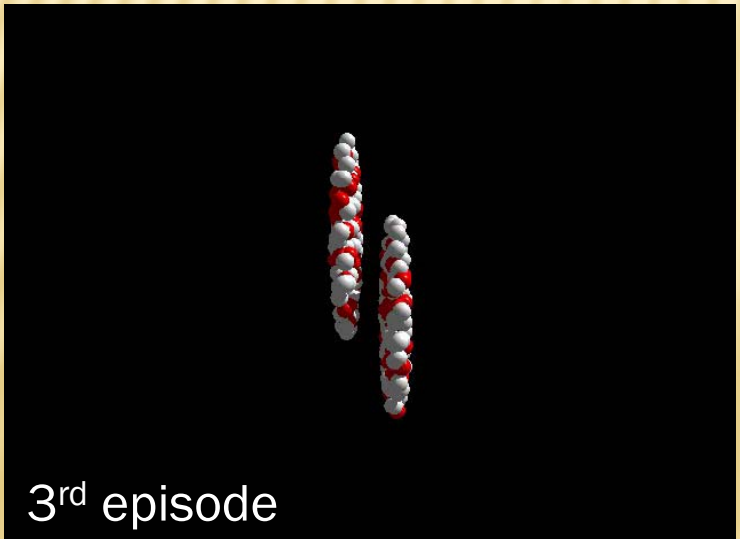
1986 BNL - AGS 4 GeV



1994 CERN - SPS 20 GeV



2000 BNL - RHIC 200 GeV



2010 CERN - LHC 5 TeV

FIXED TARGET COLLISIONS

(simulations © RQMD)

3RD EPISODE: RHIC

- Relativistic Heavy Ion Collider

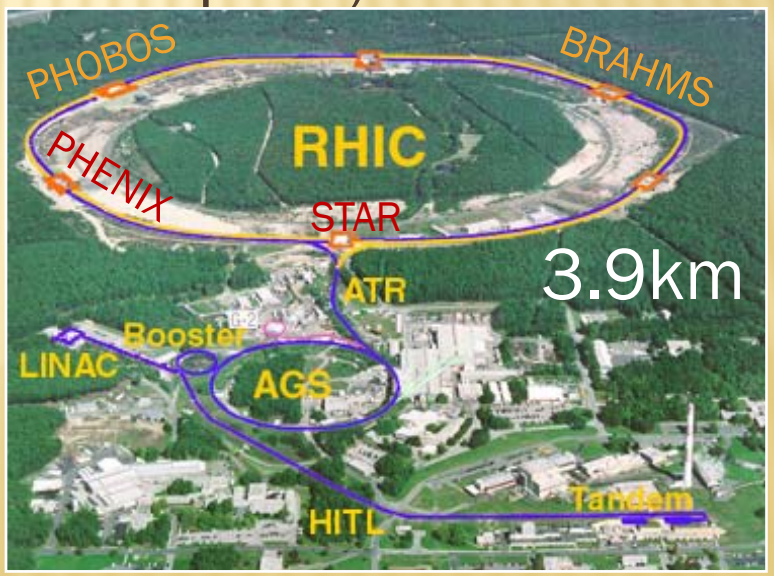
@ Brookhaven National Lab.

- First collisions in 2000, running…
- 2 large (STAR & PHENIX) >2x600

+ 2 smaller (PHOBOS & BRAHMS) experiments

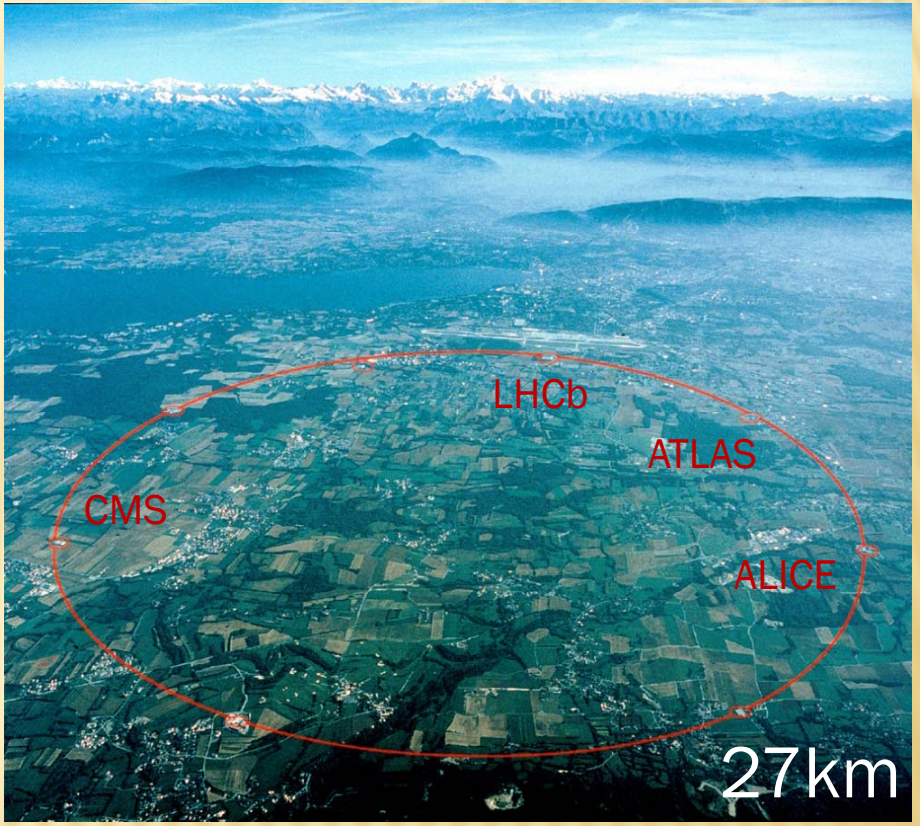
- Can collide anything from p+p (up to 500GeV, in 2009)

to Au+Au (up to 200GeV per nucleon pairs)



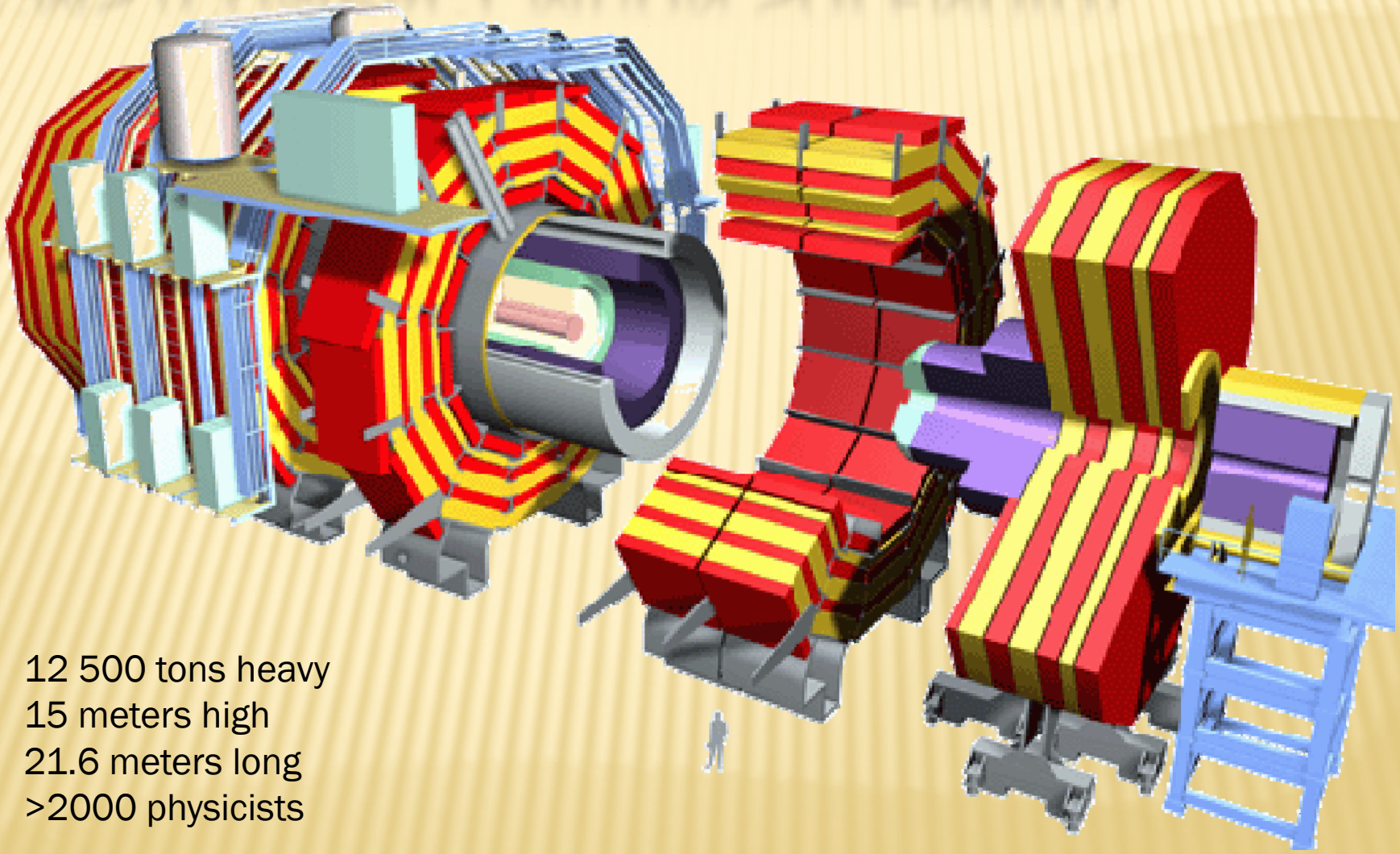
4TH EPISODE: LHC

- At CERN, always higher in energy (i.e. temperature)
  - New regime, 14xRHIC $\sqrt{s_{NN}}$
    - Nominal is x 30
  - p+p @ 7 TeV in 2010
    - Nominal is 14 TeV
  - Pb+Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV started this week!
    - Nominal is 5.5 TeV



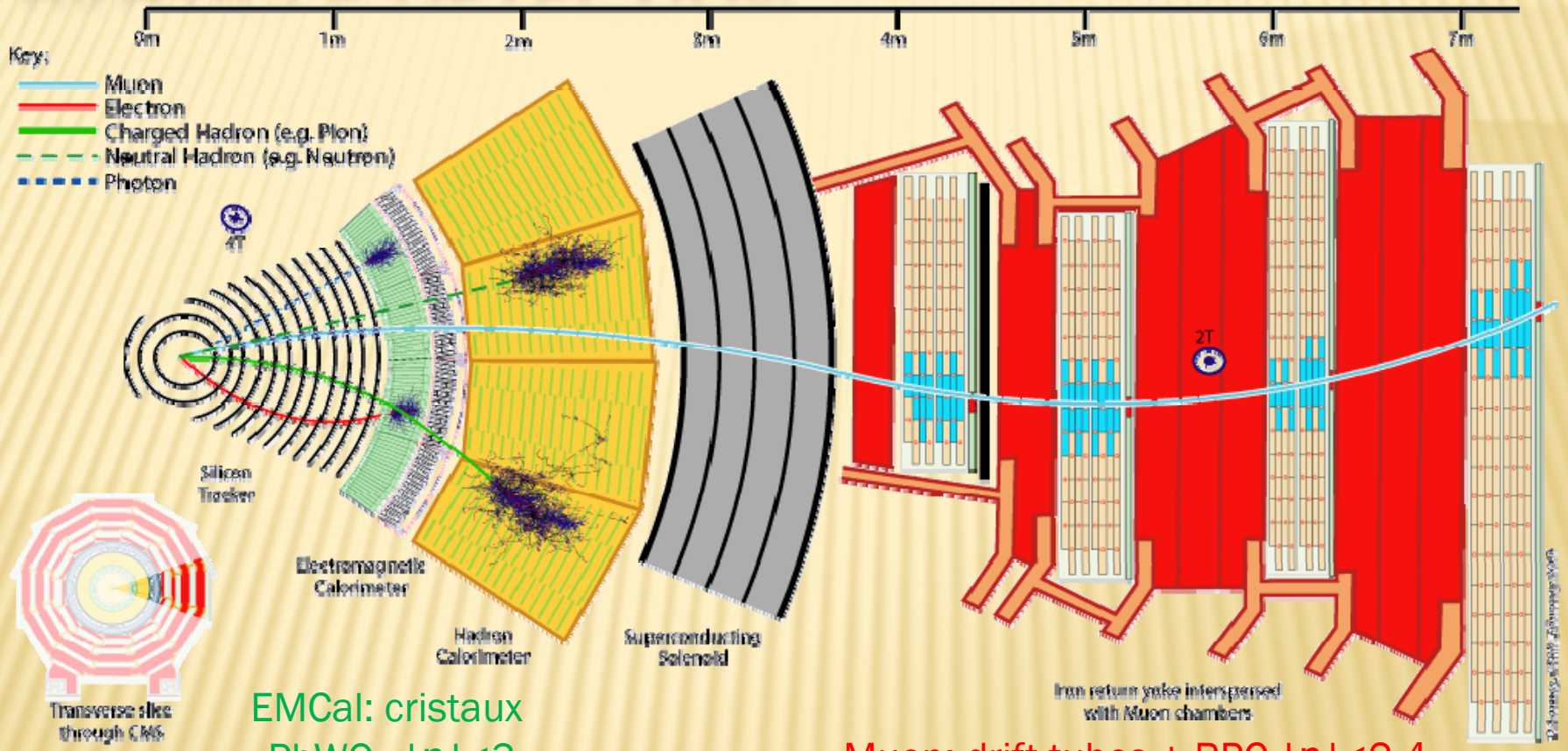
- Will look at heavy ions:
  - One experiment dedicated to heavy-ions: ALICE
  - Two multi-purpose experiments: CMS and ATLAS

CMS (COMPACT MUON SOLENOID)



12 500 tons heavy
15 meters high
21.6 meters long
>2000 physicists

PARTICLE DETECTION



EMCal: cristaux $PbWO_4$ $|\eta|<3$

Muon: drift tubes + RPC $|\eta|<2.4$

Silicium: pixels (3) and strips (10) $|\eta|<2.4$

HCal: Scintillateur $|\eta|<5$

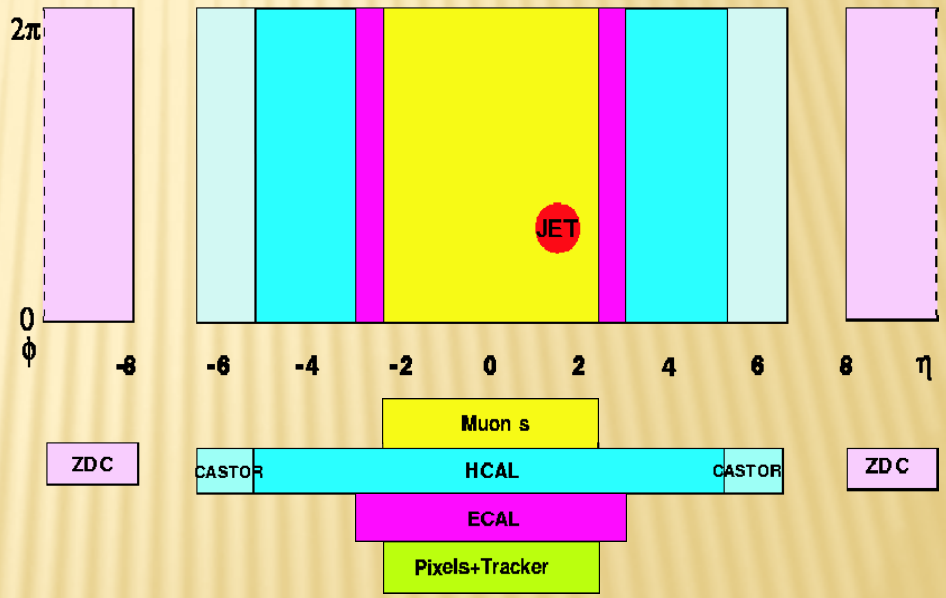
+ Large angle extension

THREE TECHNICAL ASPECTS

2. Large trigger bandwidth
   + Level 1 = All Pb-Pb collisions (≈5 kHz)
   + High Level Trigger (HLT) → 100 Hz

3. 3.8 Tesla magnetic field

1. Large angular coverage
   + More than @ RHIC



→ Very large acceptance, especially at high p_T

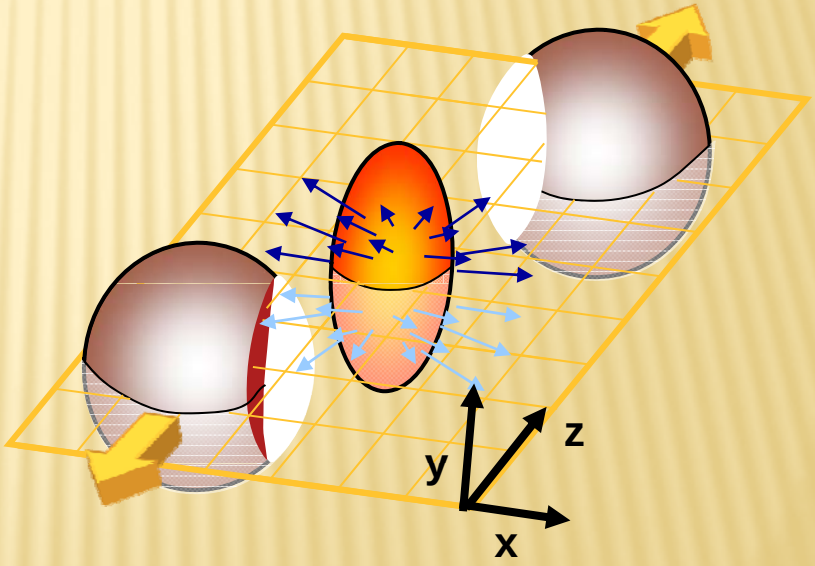
WHAT IS THE STRATEGY? (AND JARGON)

- 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. Elliptic flow ≈ *"Perfect fluid"*
3. High p_T suppression
4. Back to back jets

} ≈ *"Jet quenching"*

~~5. Baryon/meson~~

7. J/ψ suppression

~~6. Heavy flavour~~

~~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

WHICH SIGNATURES?

1. Total multiplicity
2. Elliptic flow
3. High p_T suppression
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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.

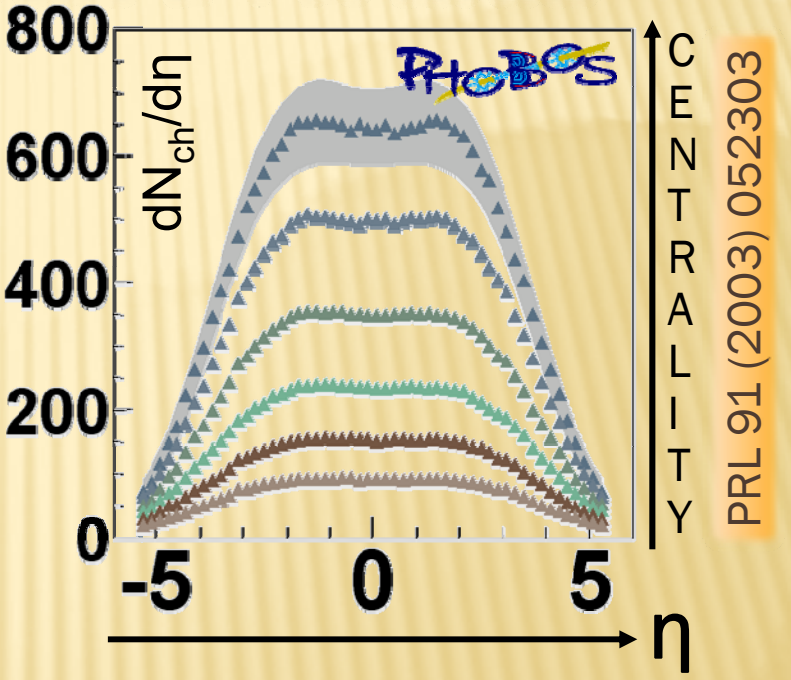
But they are not the only ones!

"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) @ RHIC

- $dN_{ch}/d\eta|_{\eta=0} \approx 670$
  - (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"



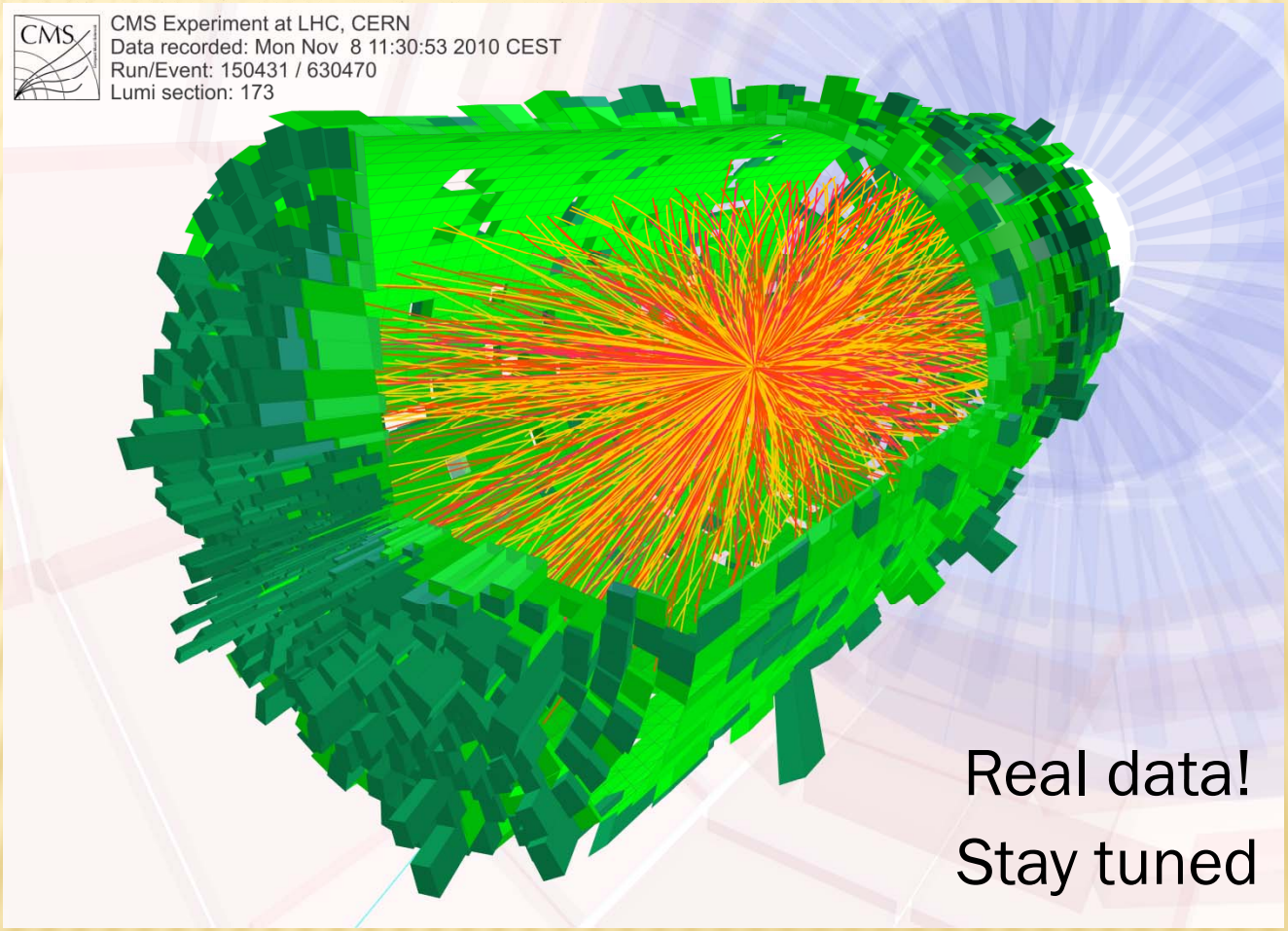
PRL 91 (2003) 052303

→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 > ε_c !

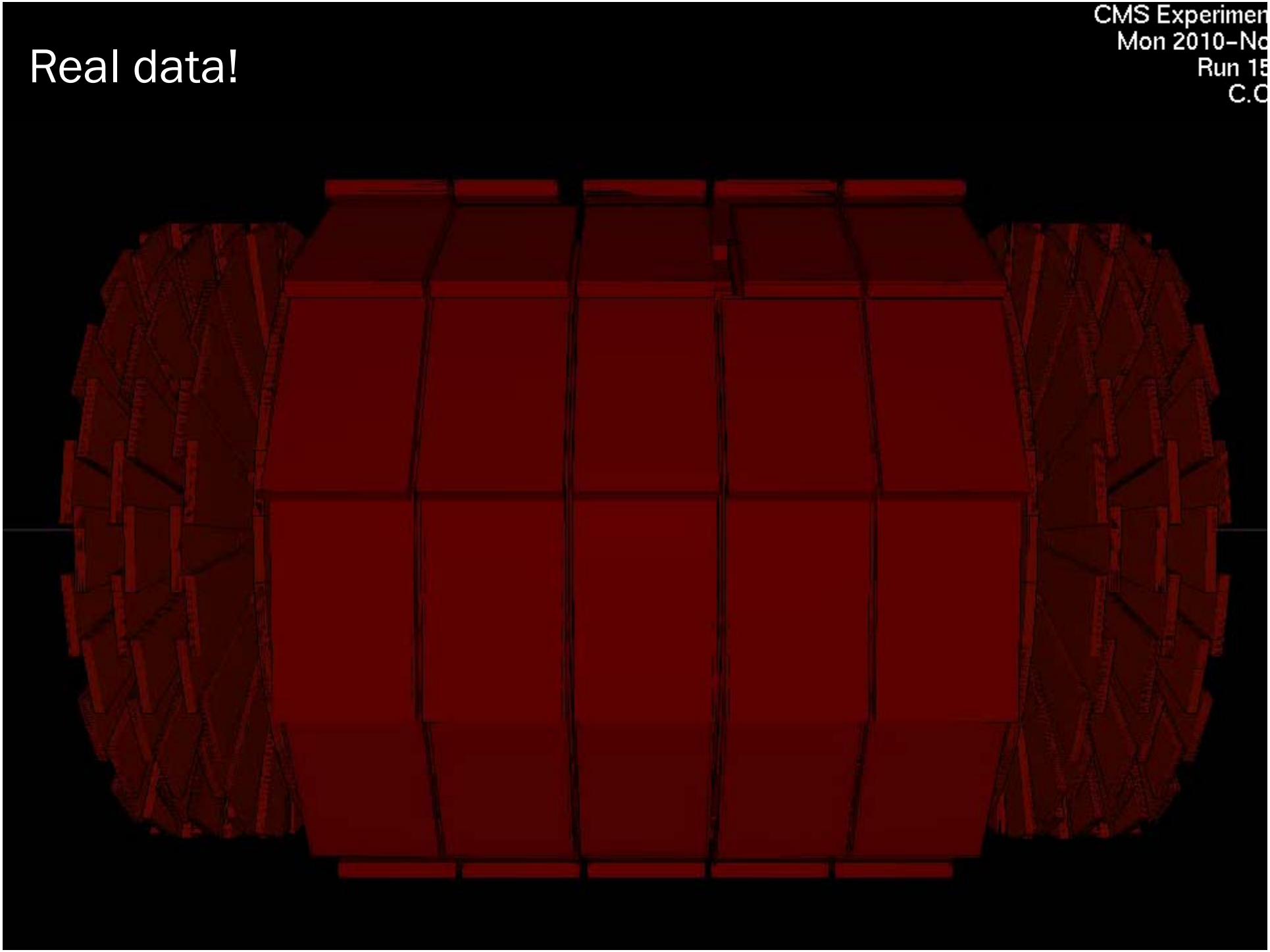
MULTIPLICITY @ LHC ? SOON…



Last Monday: First heavy ions collision in LHC (here in CMS)

http://cms.web.cern.ch/cms/News/2010/Lead-Collisions/index.html

Real data!

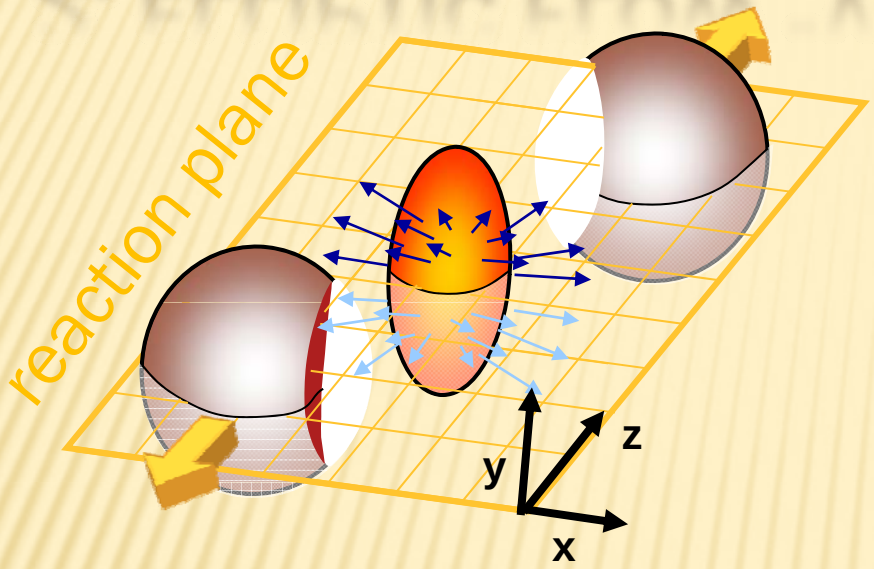


RHIC serves the perfect liquid…

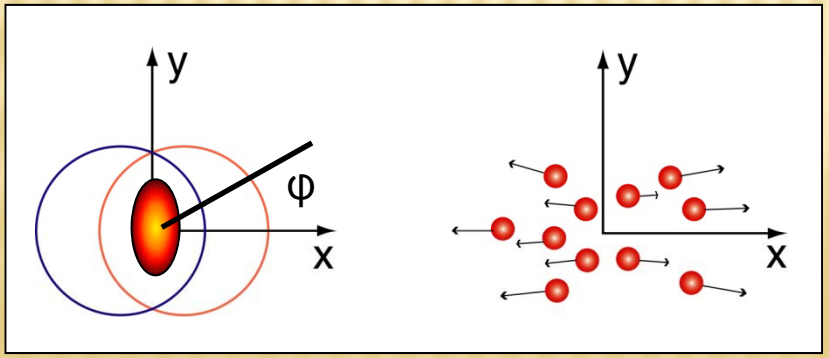
PARTONIC COLLECTIVE BEHAVIOUR

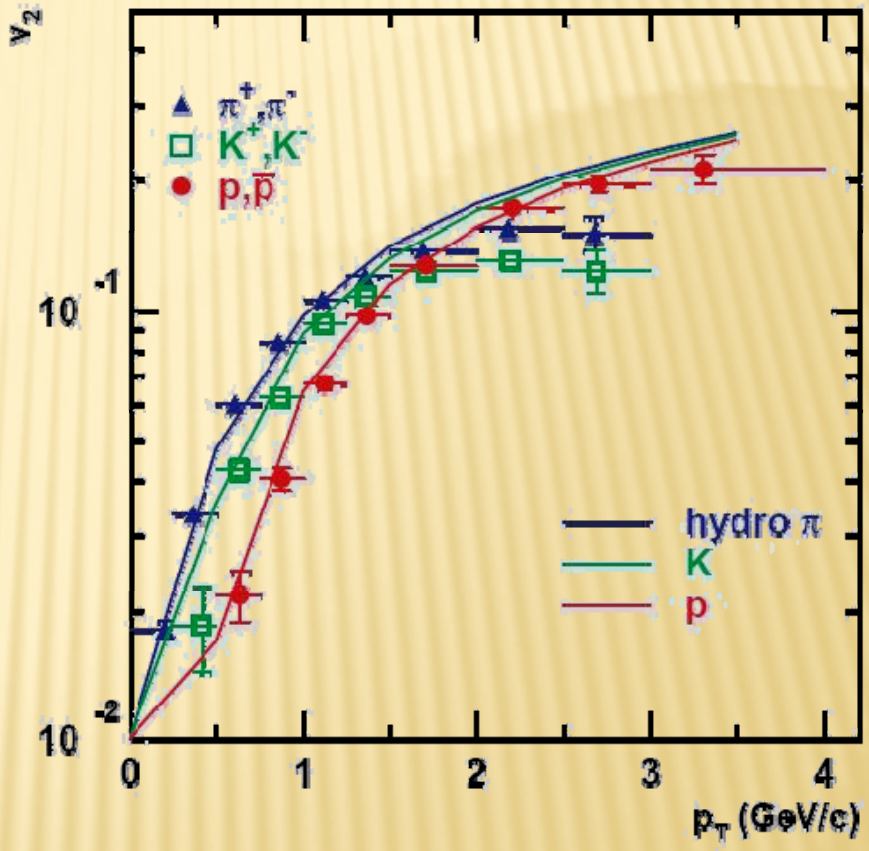
2. ELLIPTIC FLOW "V_2"

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



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





→ Strong collective behavior

2. 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 ☺)

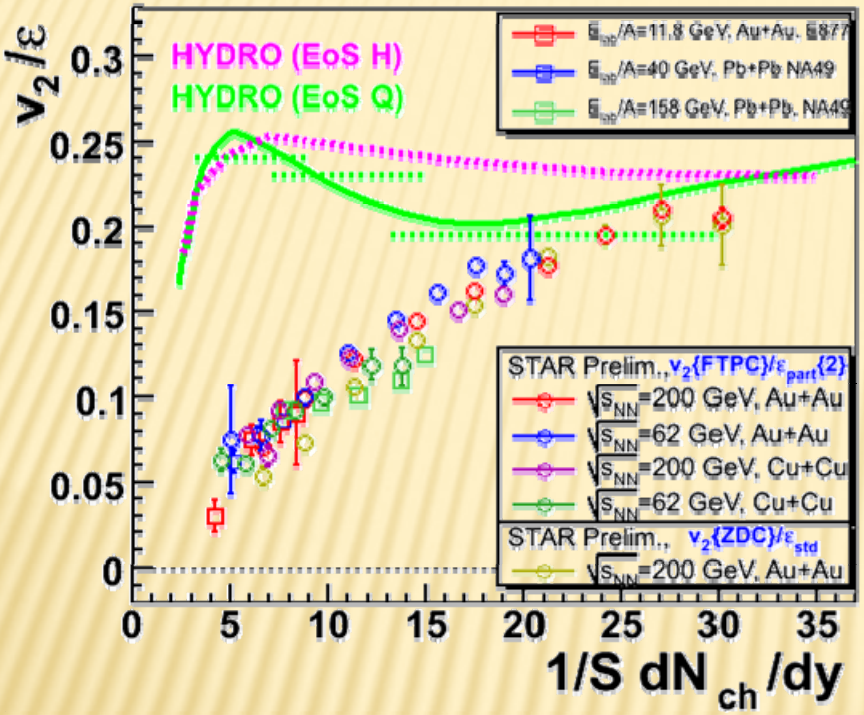
→ *"Perfect fluid"*

→ The matter is strongly interacting and liquid like

@ LHC, could it approach a quark gluon gas?

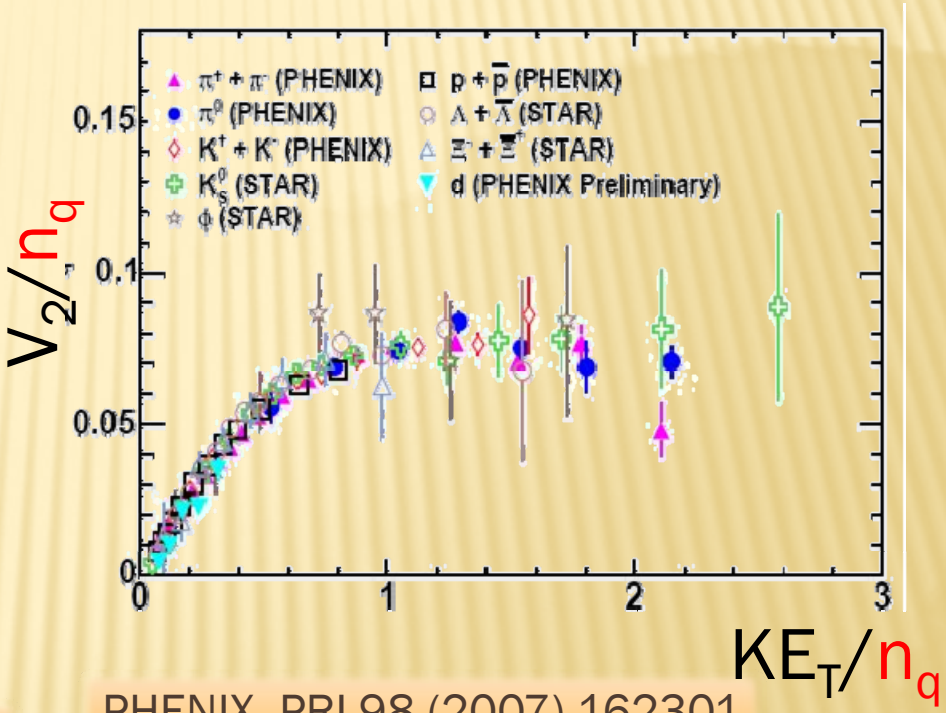
With eccentricity vs N_{ch} density

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



Voloshin & Pokskanzer, PLB 474 (2000) 27

With the kinetic energy per constituent quarks



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

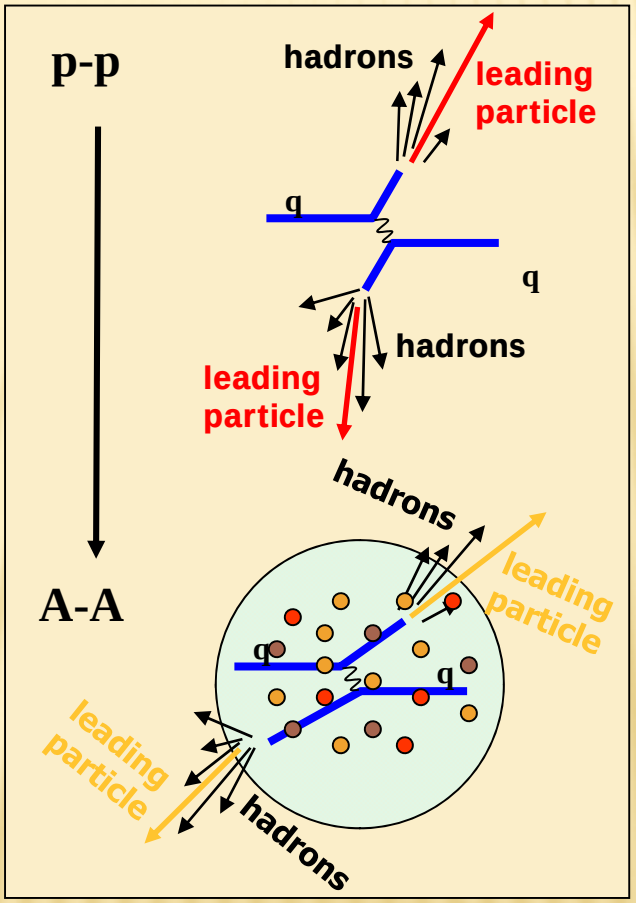
2. ELLIPTIC FLOW (SCALINGS)

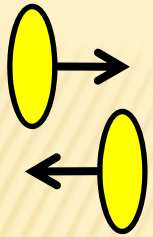
The smoking gun signature @ RHIC…

JET QUENCHING

3. HIGH P_T SUPPRESSION

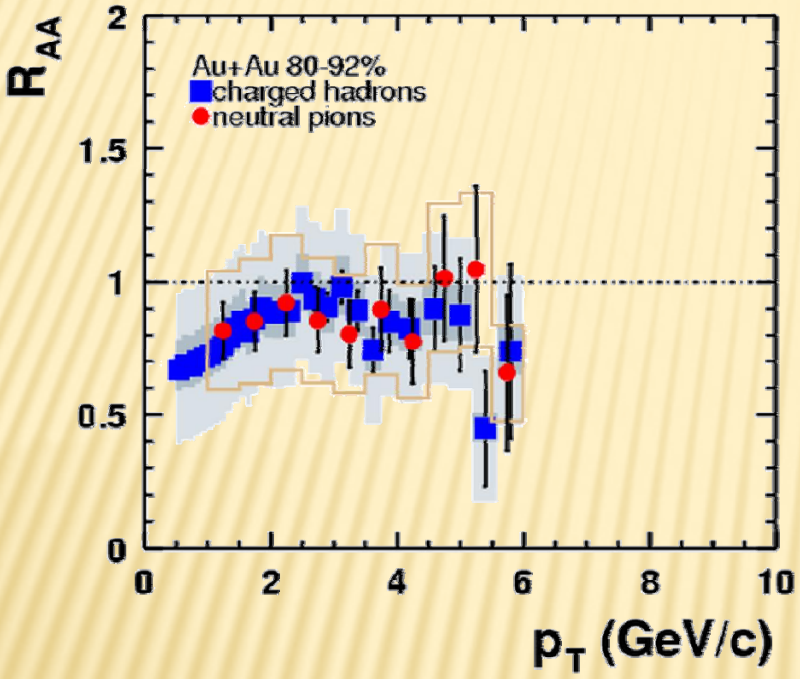
- RHIC smoking gun signature !
  - Two PRL covers
- Energy loss in the matter, looking at "high" p_T (>2GeV/c) hadrons
  - Mostly from jet fragmentation
- "Jet quenching"

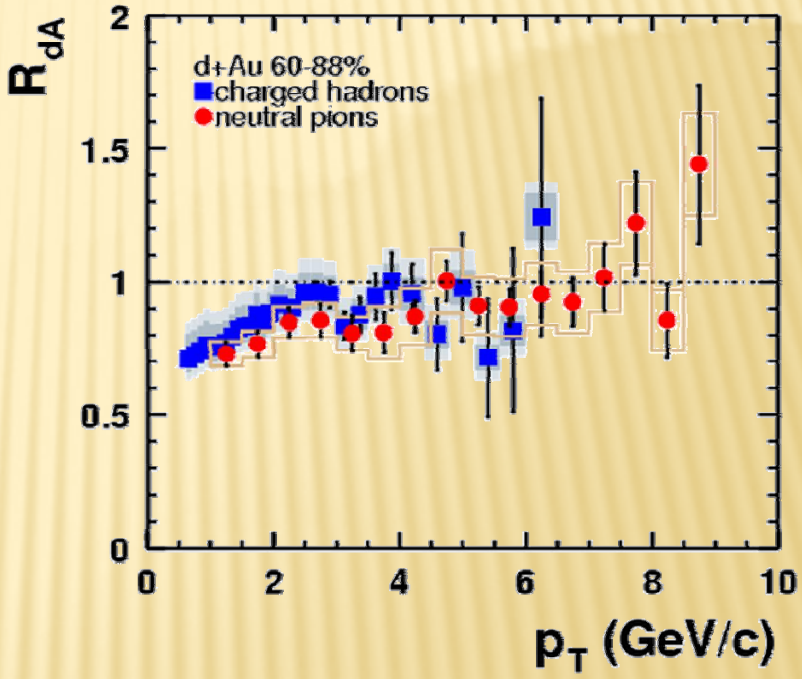




Au-Au (80-92%)

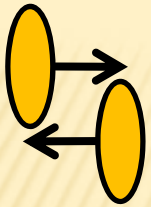
d+Au (60-88%)





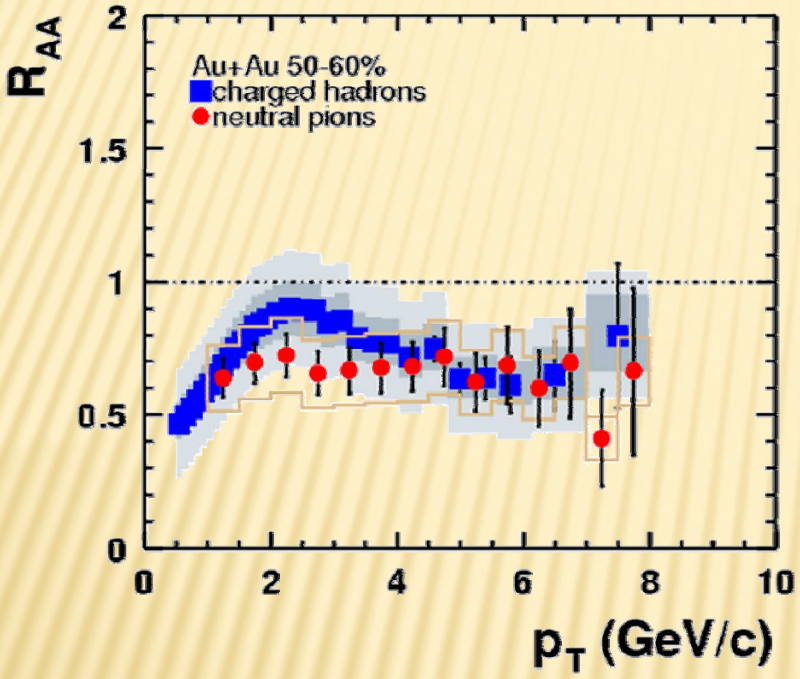
MOST PERIPHERAL COLLISIONS…

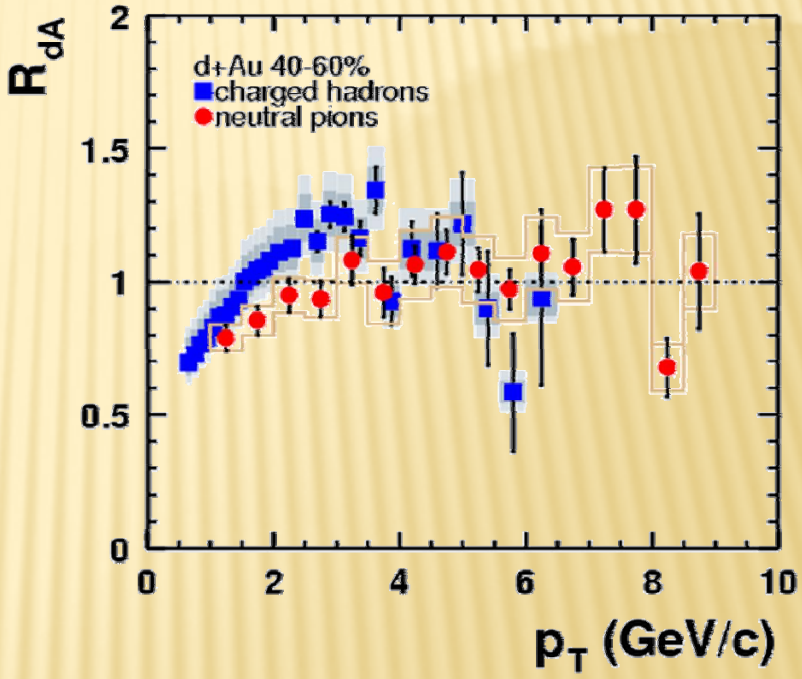
(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303



Au-Au (50-60%)

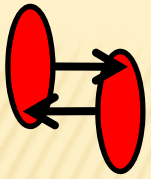
d+Au (40-60%)



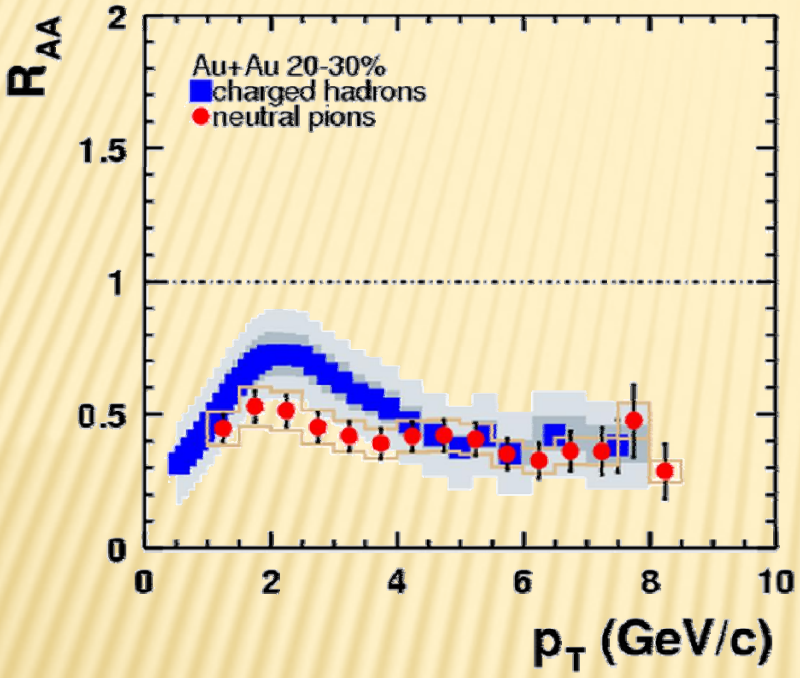


LESS PERIPHERAL COLLISIONS...

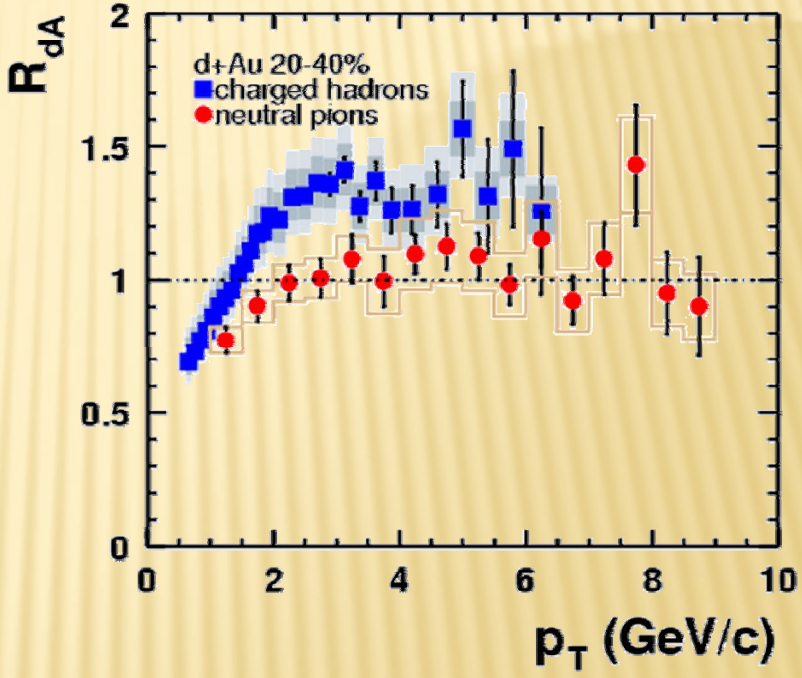
(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303



Au-Au (20-30%)

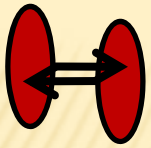


d+Au (20-40%)

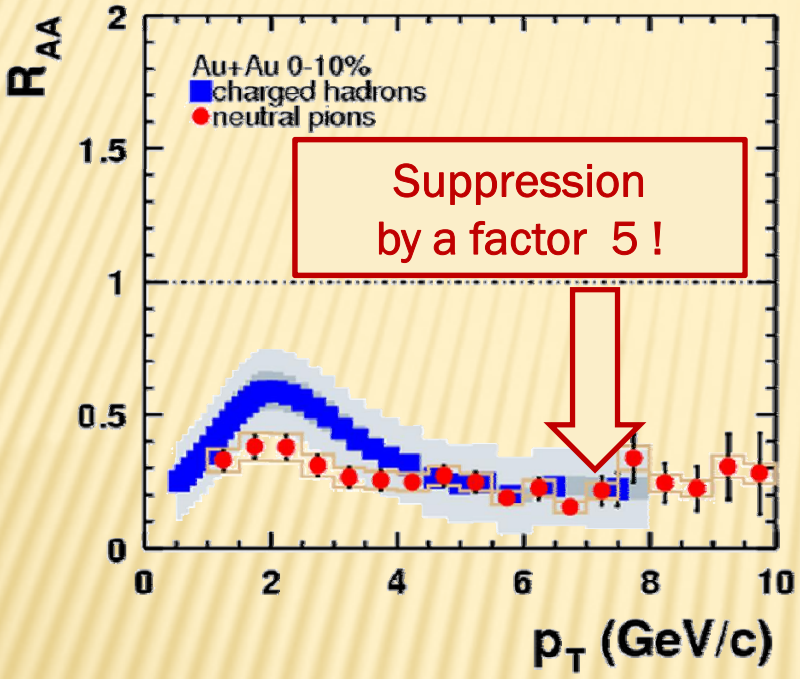


MORE CENTRAL COLLISIONS...

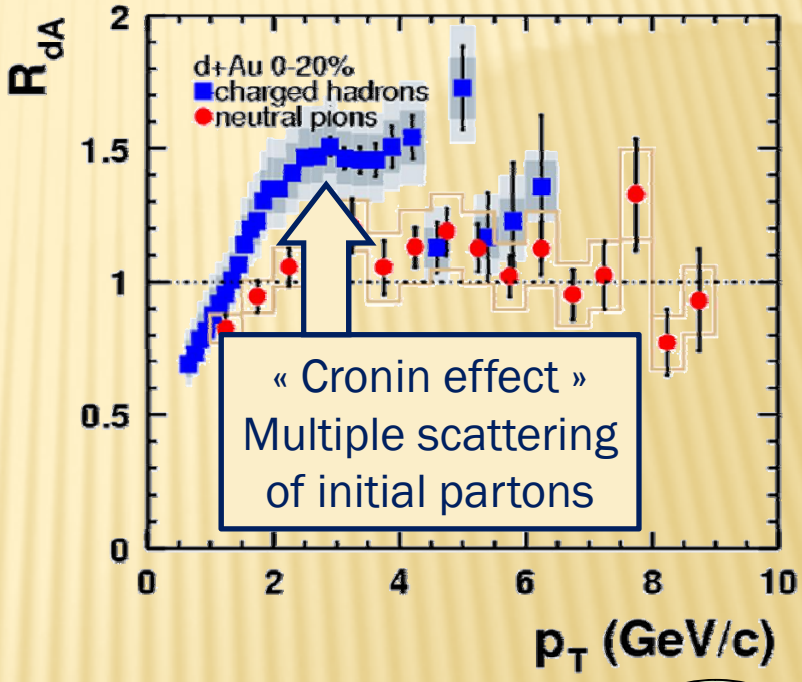
(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303

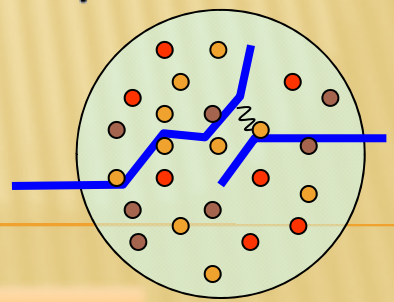


Au-Au (0-10%)



d+Au (0-20%)



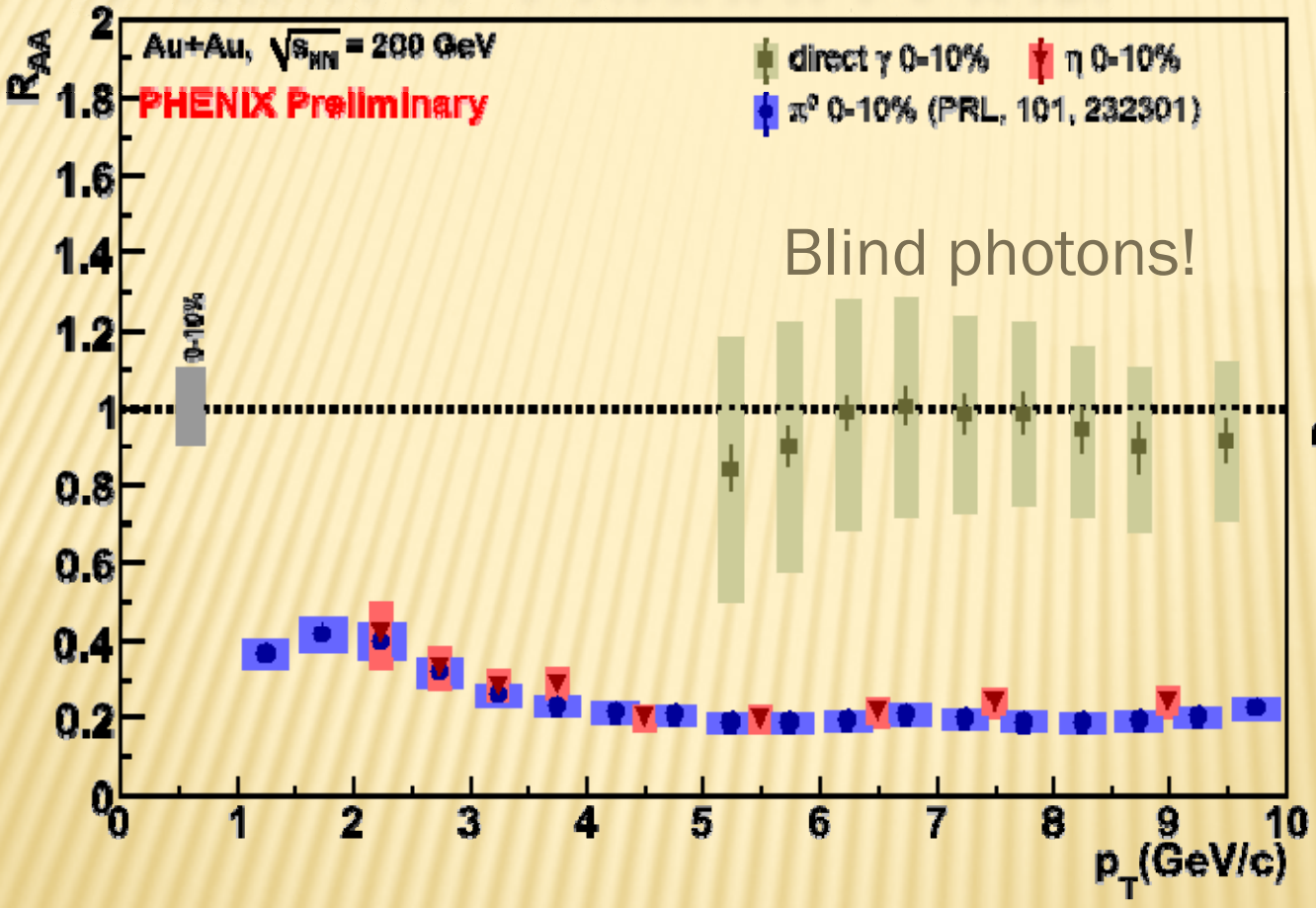


MOST CENTRAL COLLISIONS!

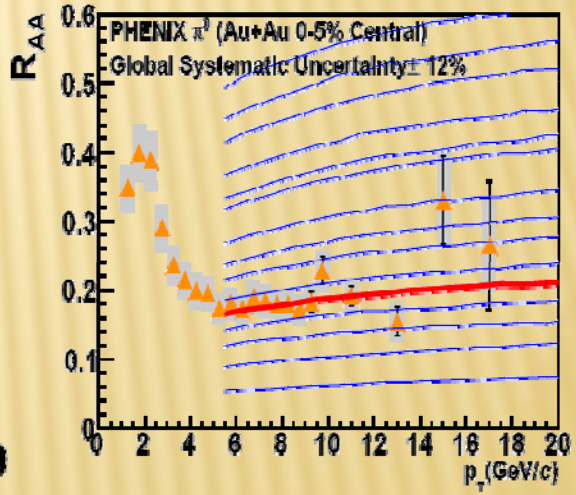
(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303

3. HIGH P_T SUPPRESSION

PHENIX, PRC77 (2008) 064907



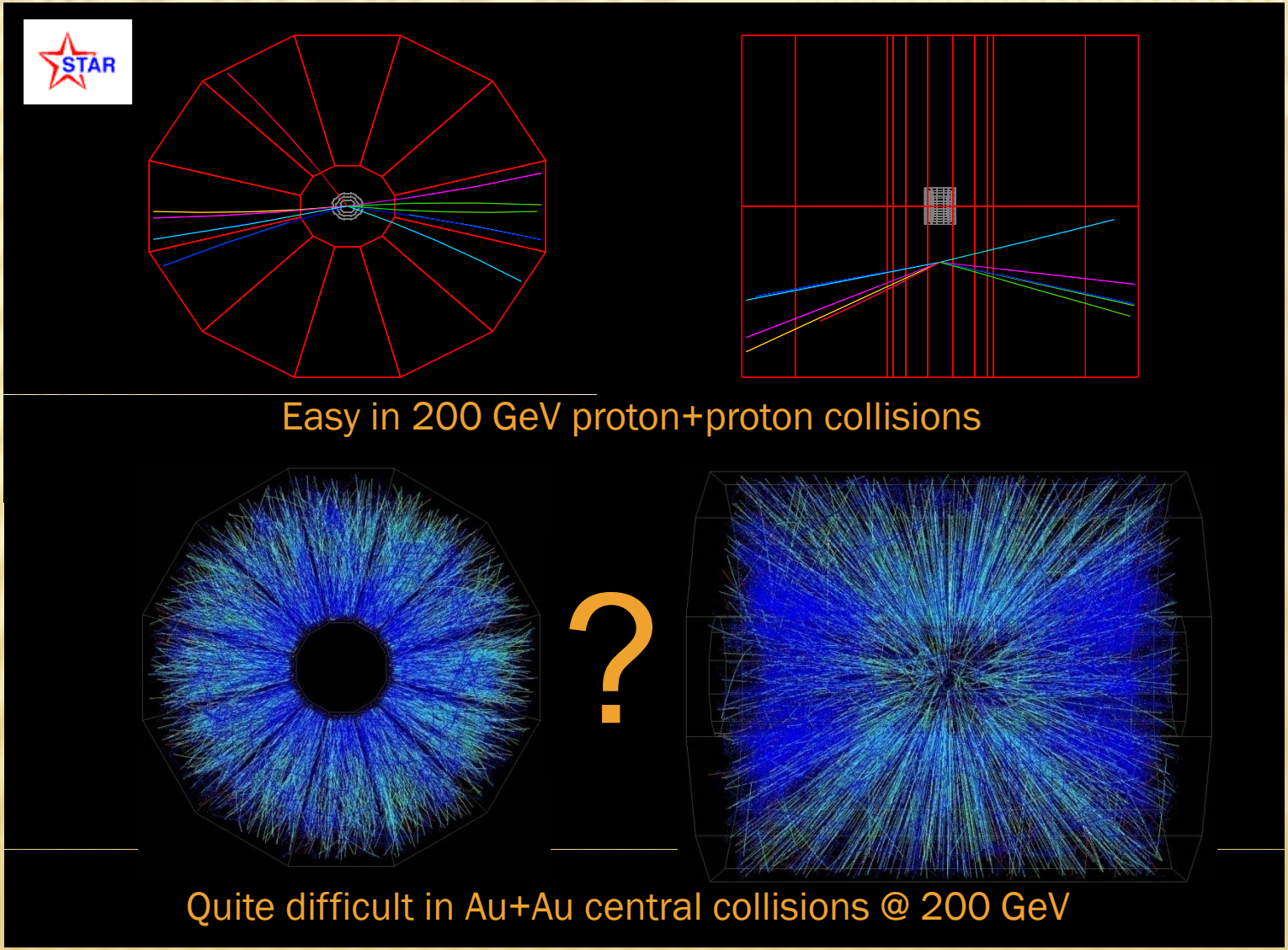
→ Comparisons to models, including experimental errors provide physical properties, e.g. $dN_{gluons}/dy = 1400\ ^{+200}_{-375}$



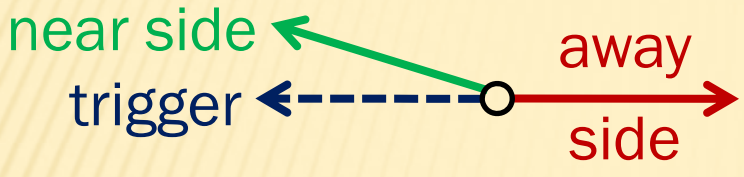
→ The matter is dense ! >1000 gluons per Δy

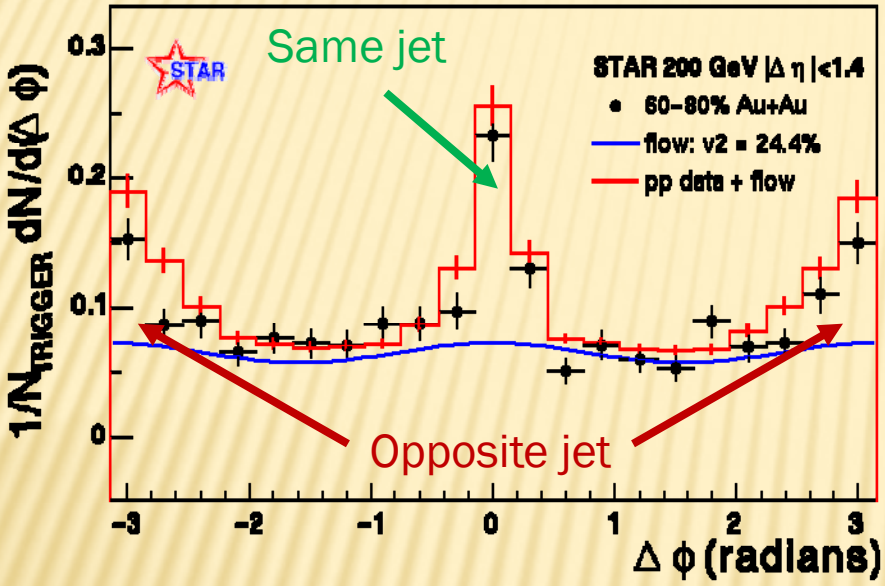
@ LHC, should be even denser…

4. BACK TO BACK JETS



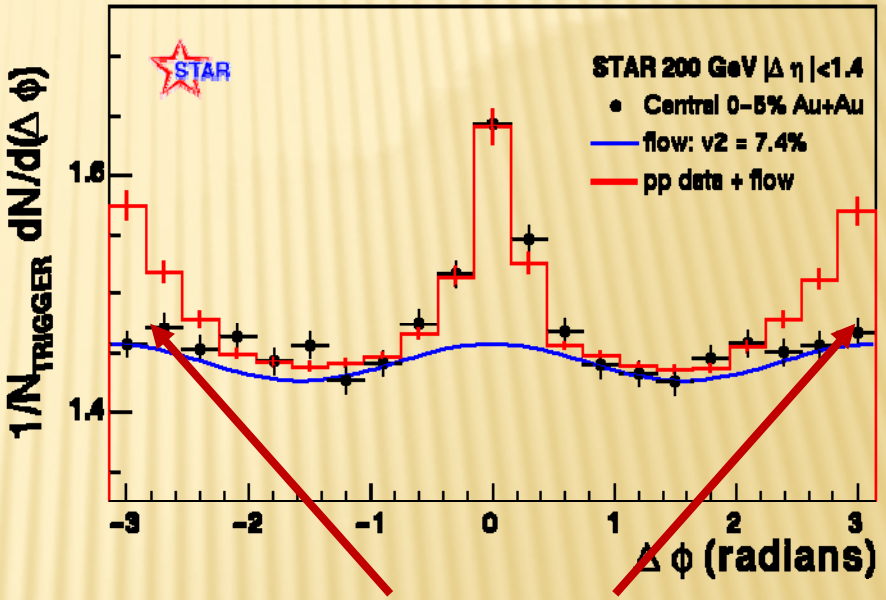
Peripheral collisions (60-80%)





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

Central collisions (0-5%)



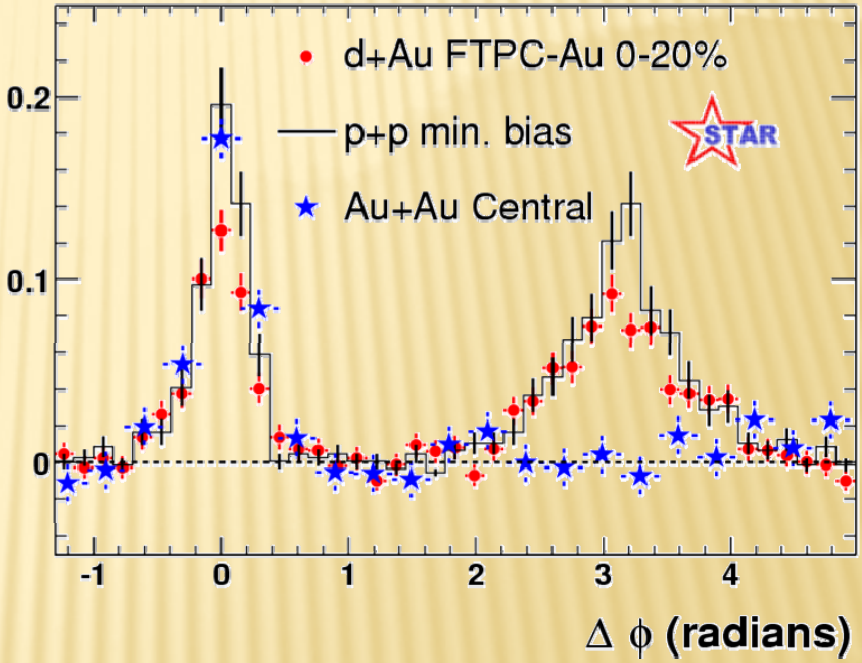
In central collision, opposite jets disappear because of jet quenching

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

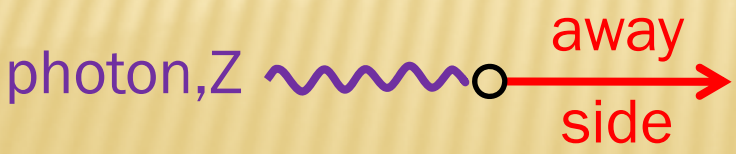


→ The matter is opaque!

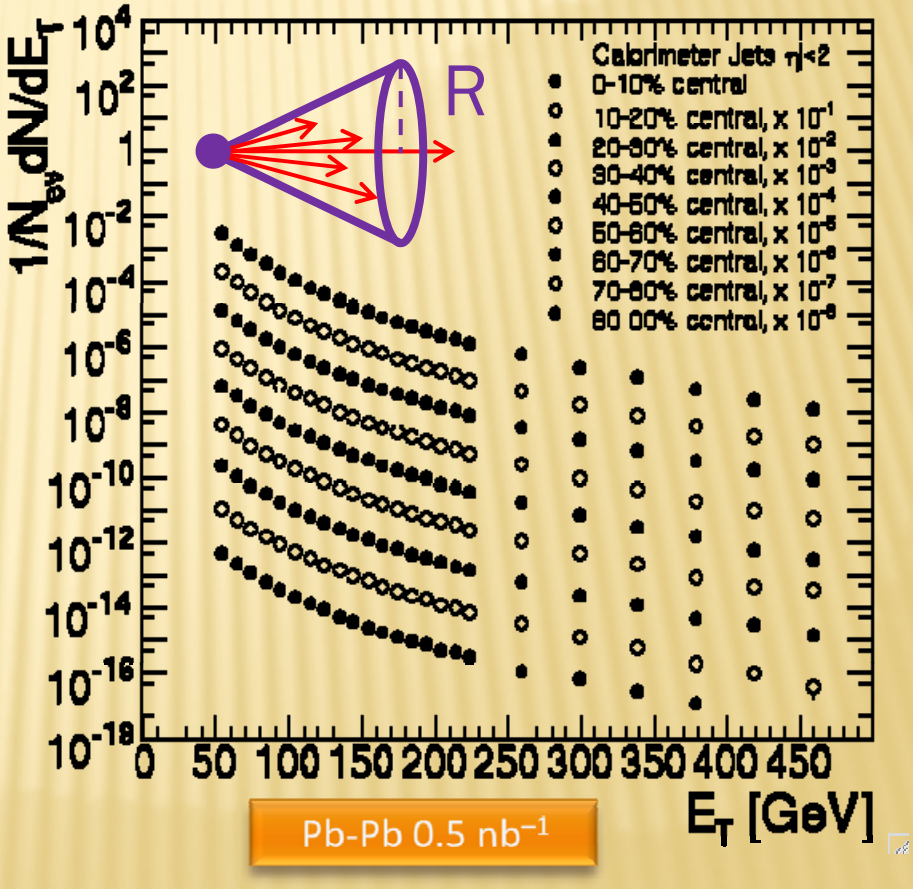
More @ LHC

JET QUENCHING @ CMS

- Further than @ RHIC
  - p_T reach → 250 GeV/c
    - 60 GeV/c first run
  - And correlations
- Better than @ RHIC
  - Fully reconstructed jet →
  - Photon-jet
- New?
  - Z-jet → quark/gluon jet

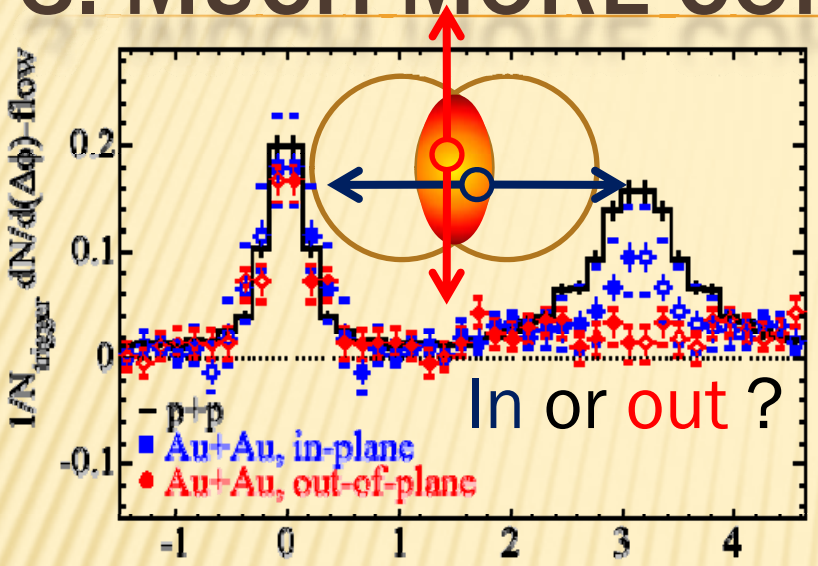


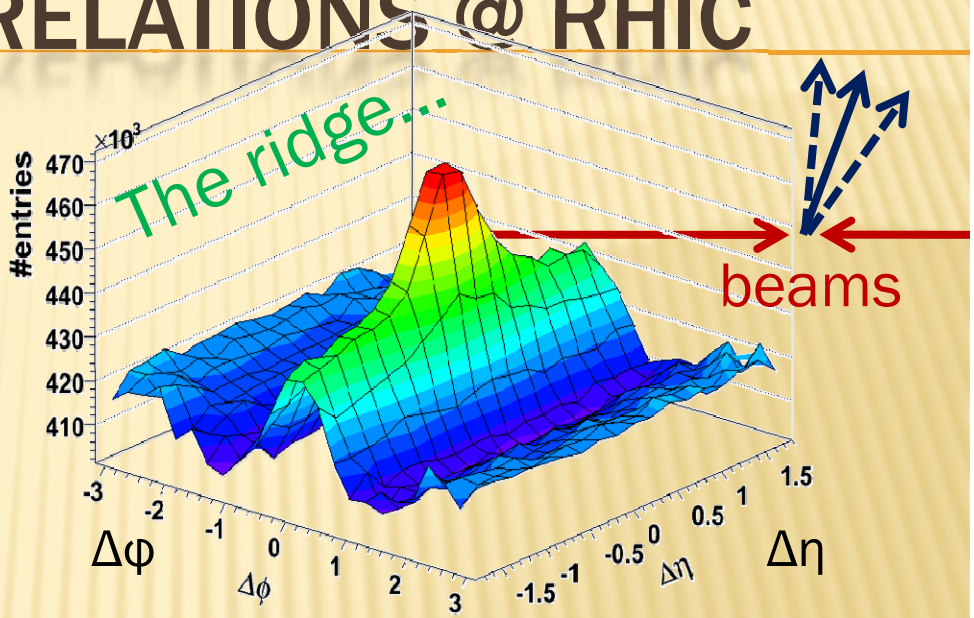
CMS TDR add, JPG34 (2007) 2307



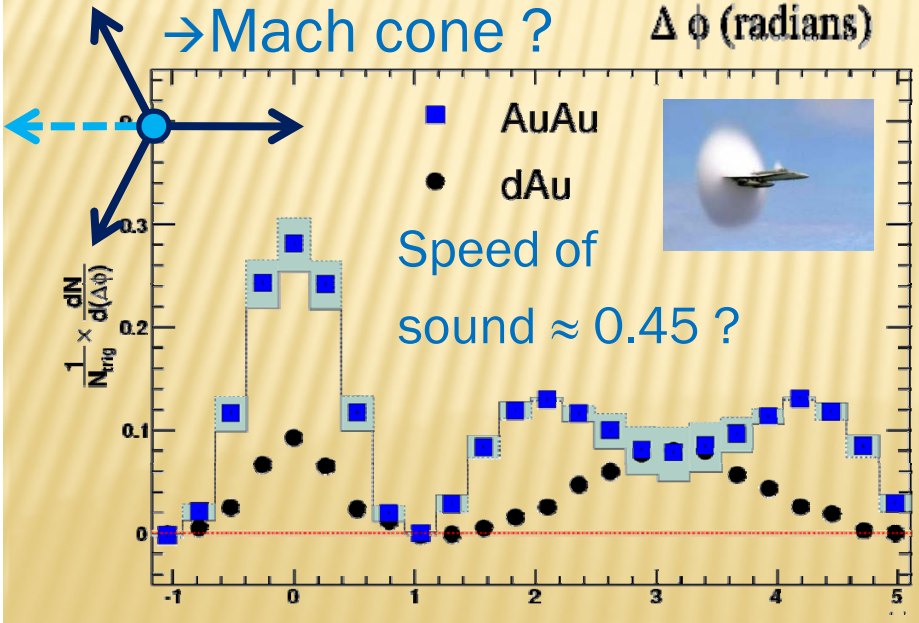
Here, all plots from STAR, see also PHENIX: PRC78 (2008) 014901

3. MUCH MORE CORRELATIONS @ RHIC

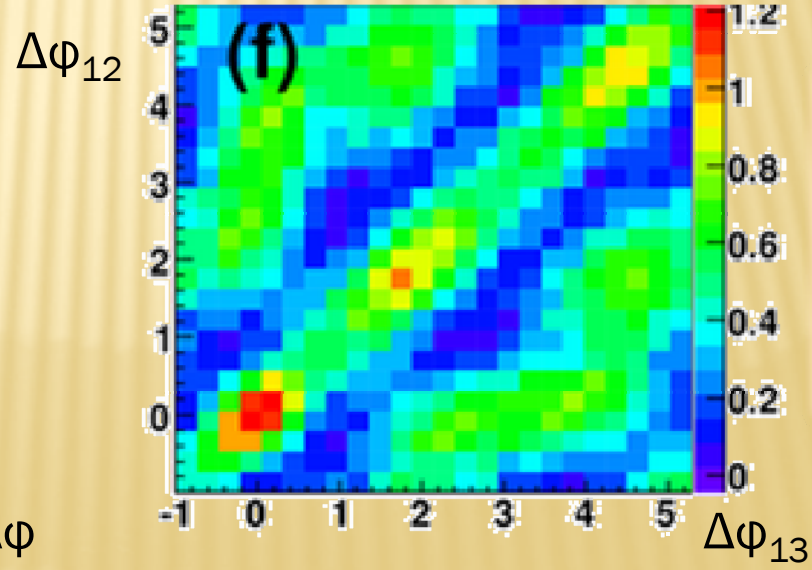




→Mach cone ?

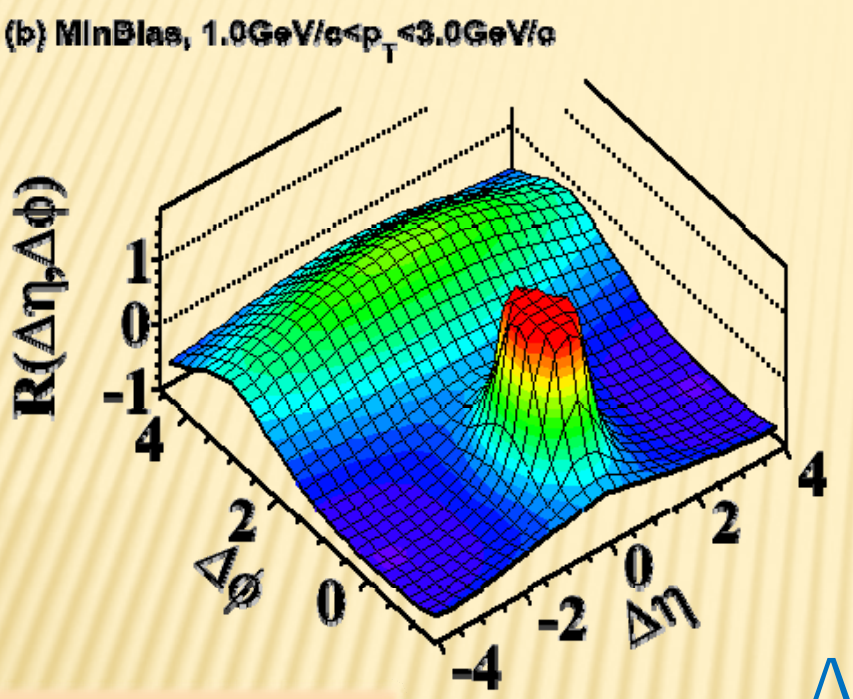


→Three particles (central Au+Au)



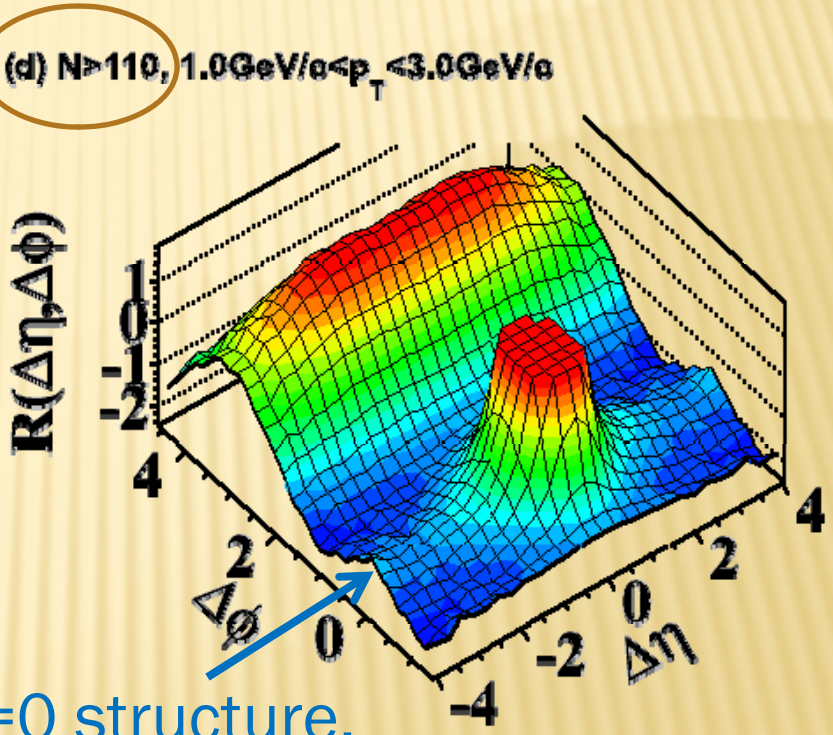
STAR: PRL102 (2009) 052302

Minimum bias p+p



JHEP 09 (2010) 091,
arxiv:1009.4122

High multplicity p+p



Δφ=0 structure,
new in p+p

CORRELATIONS @ CMS IN P+P ALREADY!

CORRELATIONS @ CMS IN P+P ALREADY!

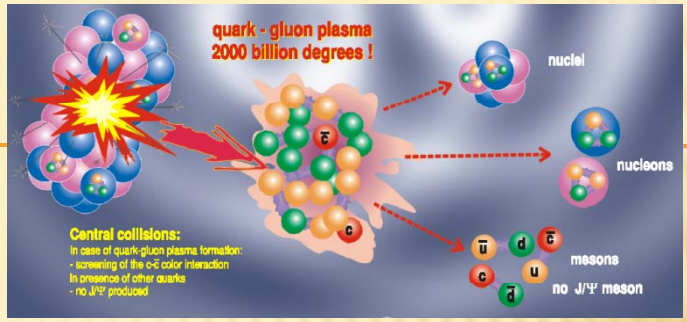
- A new phenomenon is seen in high multiplicity (N_{tracks} > 100) p+p events
  - And not in "normal" p+p events
- It was seen in A+A events at RHIC
  - Was eventually interpreted as a sign of QGP (collectivity)
  - But not only (saturation…), not a golden signature
- And it was not the key signature of QGP
  - But rather one of the weaker and one of the latest
- Moreover, much more jets at LHC, to be investigated
  - 5-6 per high multiplicity
- However, possibility of QGP in p+p are considered
  - N=100 same multiplicity as Cu+Cu
- So let's be extremely cautious and not jump on conclusions
  - Look for other signatures in p+p

JHEP 09 (2010) 091, arxiv:1009.4122

The originally thought “unambiguous signature”

QUARKONIA SUPPRESSION

7. J/Ψ SUPPRESSION

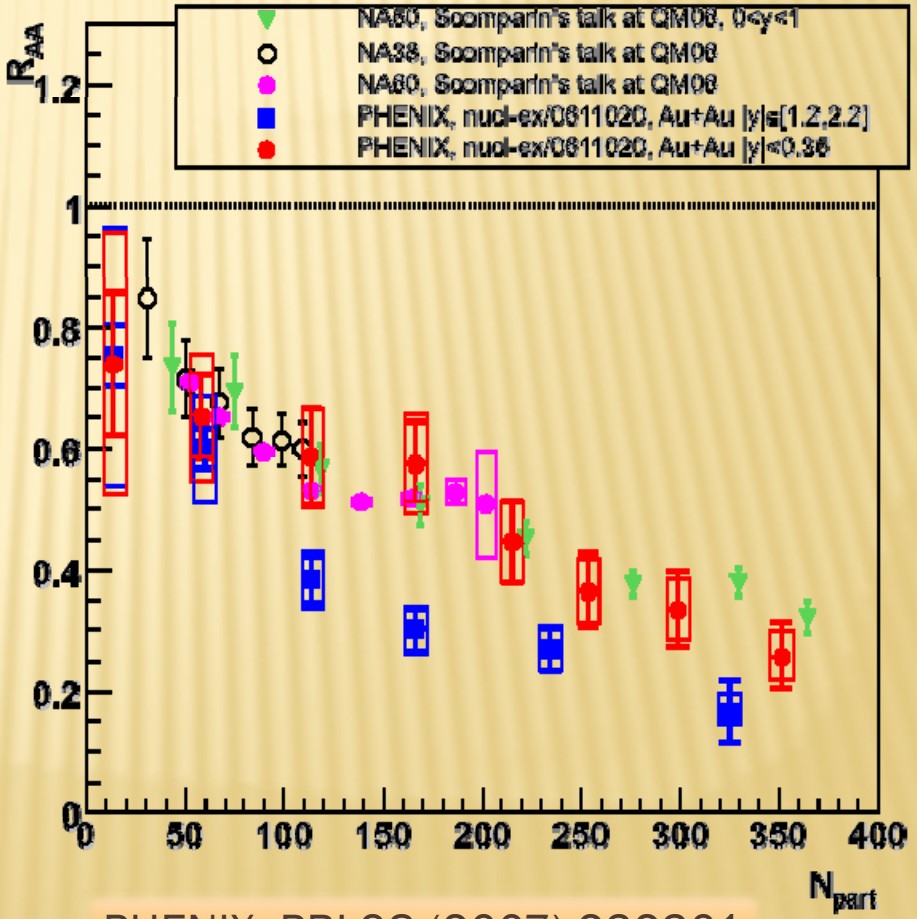


- J/ψ ($c\bar{c}$) can melt in QGP

  Matsui & Satz, PLB178 (1986) 416
- Golden signature @ SPS

  (@ CERN $\sqrt{s} \approx 20$ GeV)

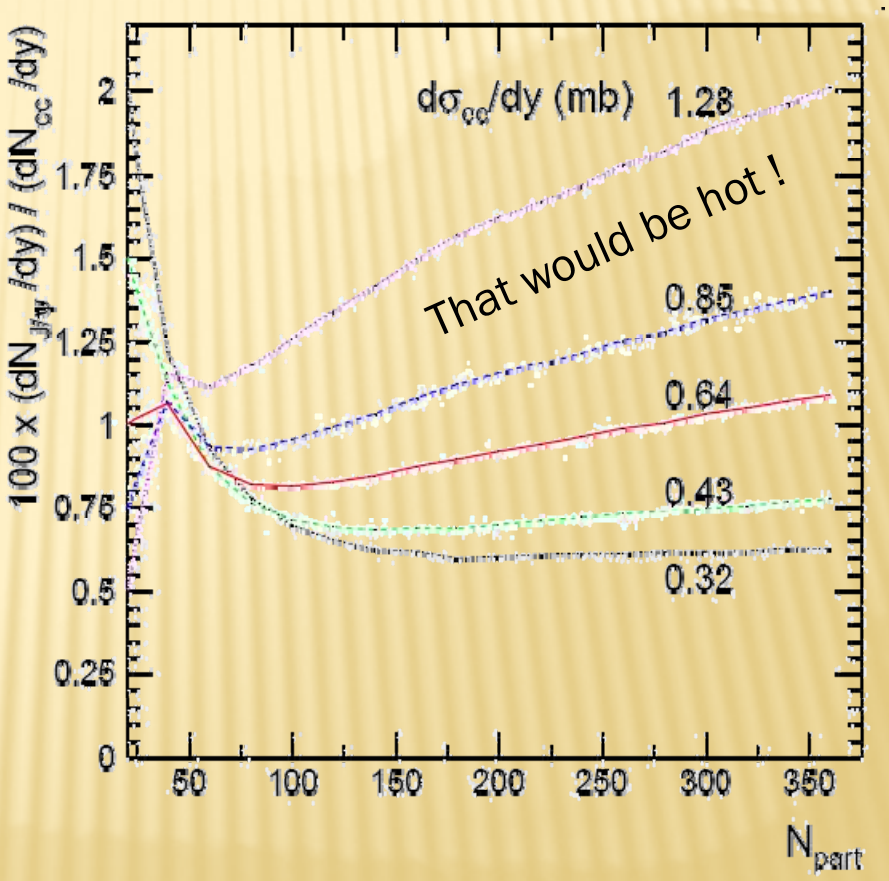
  → QGP discovery claim!
- @RHIC, same rapidity, suppression looks surprisingly similar
  - While density is higher
- Stronger @ forward
  - While density is lower
- Puzzling signature @ RHIC…



PHENIX, PRL98 (2007) 232301

7. TWO POSSIBLE EXPLANATIONS @ RHIC

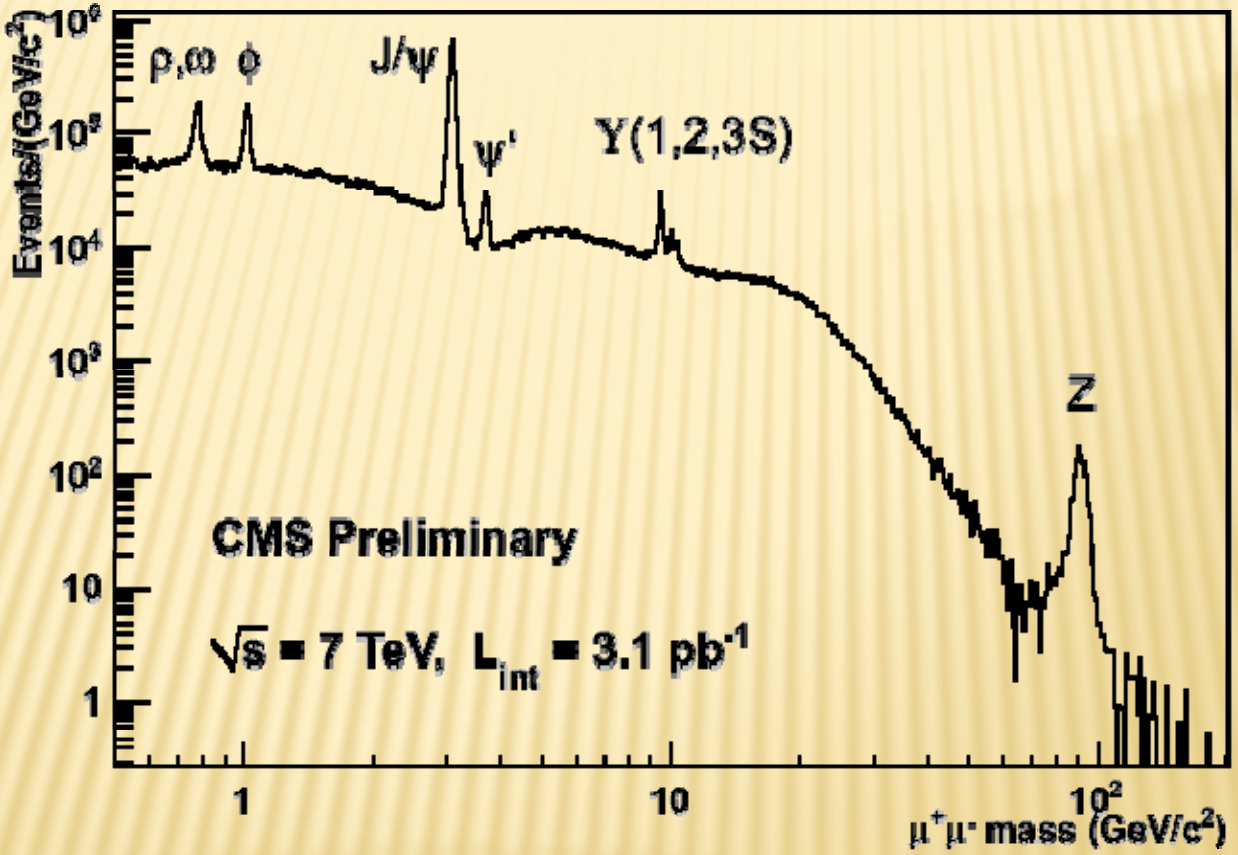
- Cold matter can further suppress J/ψ @ forward
  - pdf modifications, saturation
- QGP can regenerate J/ψ
  - Pairing of uncorrelated c and c pairs, more @ forward
- LHC could bring the answer →
  - J/ψ enhancement wrt centrality could be the smoking gun



A. Andronic et al., NPA789 (2007) 334

QUARKONIA IN CMS

proton+proton data



- Much more background in Pb+Pb but still feasible
- Also Z-bosons that were never measured in Pb+Pb

IN SUMMARY…

- 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
  - Bringing new surprises
  - And nice PhD theses ☺

- Bibliography:
  - RHIC Experimental “white papers”:
  - Interesting reviews, for instance:
  - CMS Physics TDR, add. 2

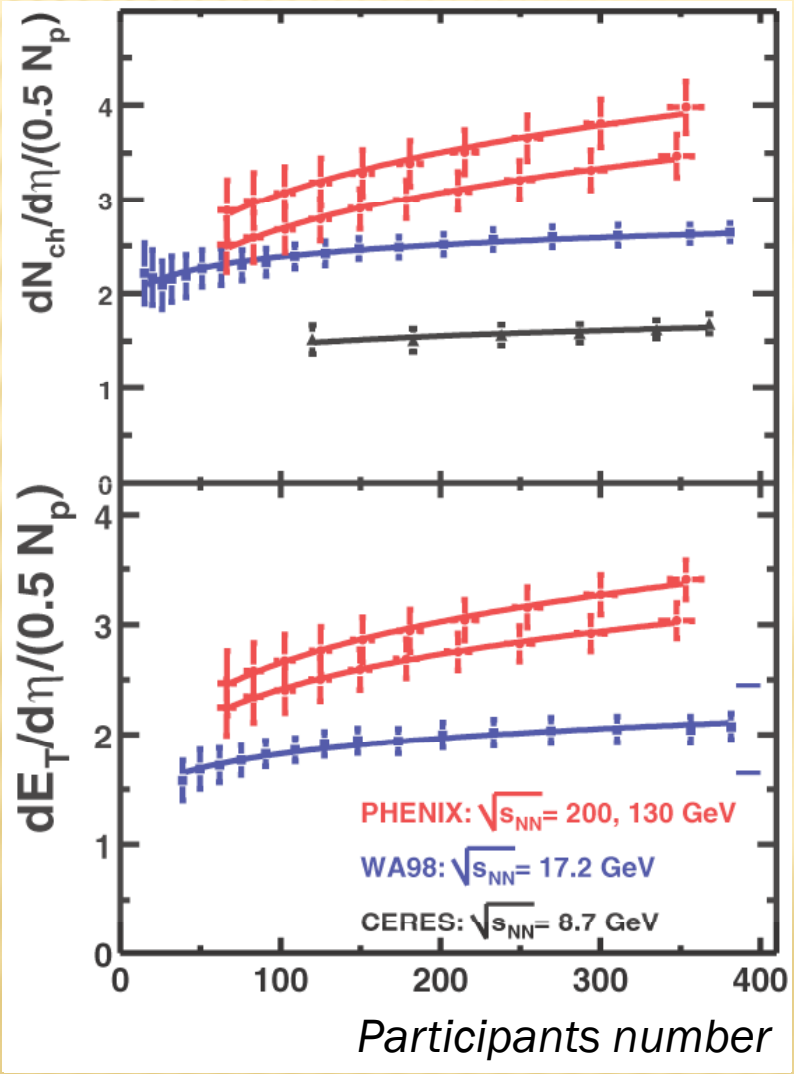
NPA757 (2005), PHENIX: nucl-ex/0410003

RGdC, arXiv:0707.0328
IJMP A22(2008)6043

CMS, JPG34 (2007) 2307

BACK UP SLIDES…

1. ENERGY DENSITY ESTIMATION



Transverse energy @ y=0

Bjorken formula

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

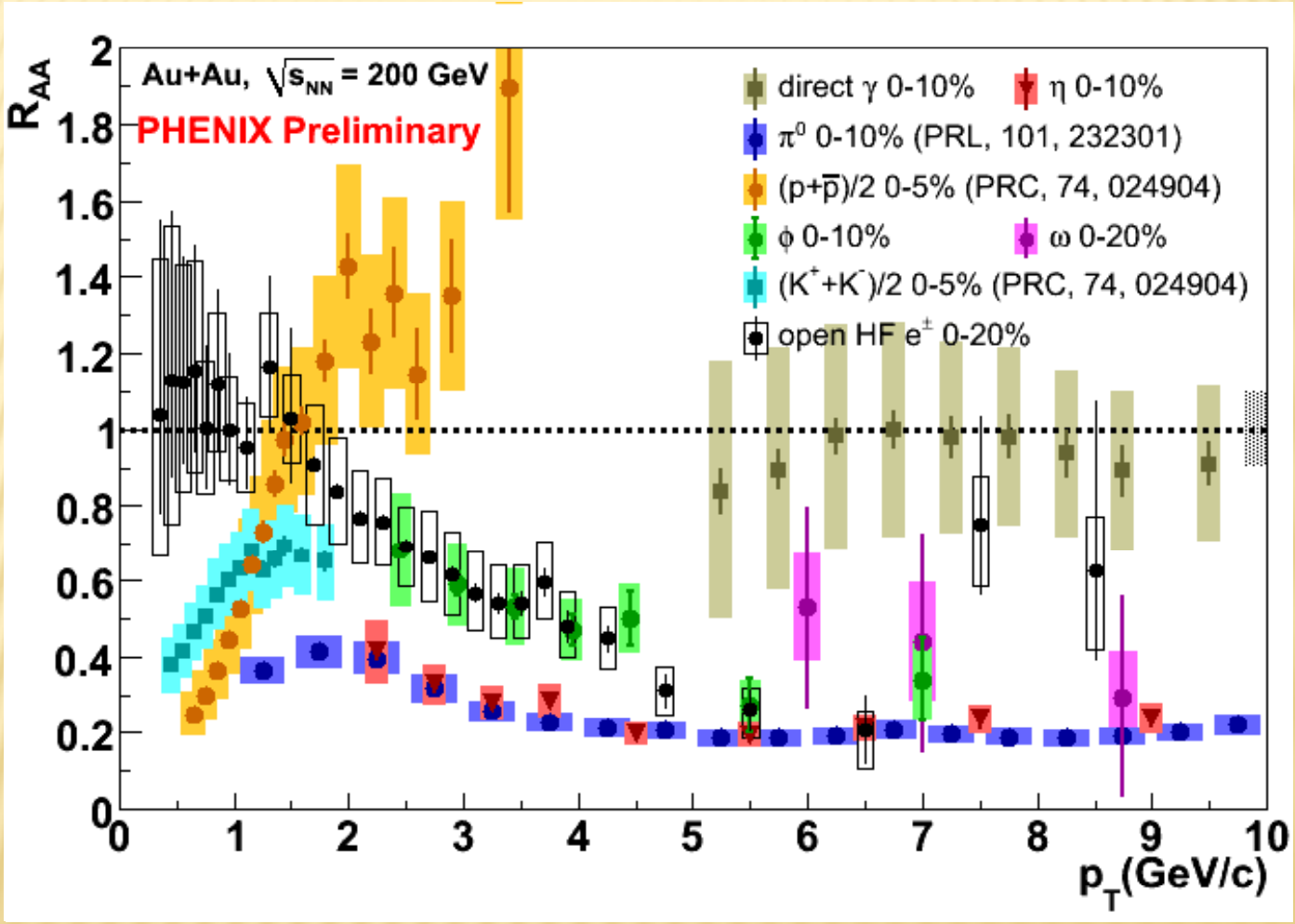
τ_0 formation time
0,35 à 1 fm/c

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

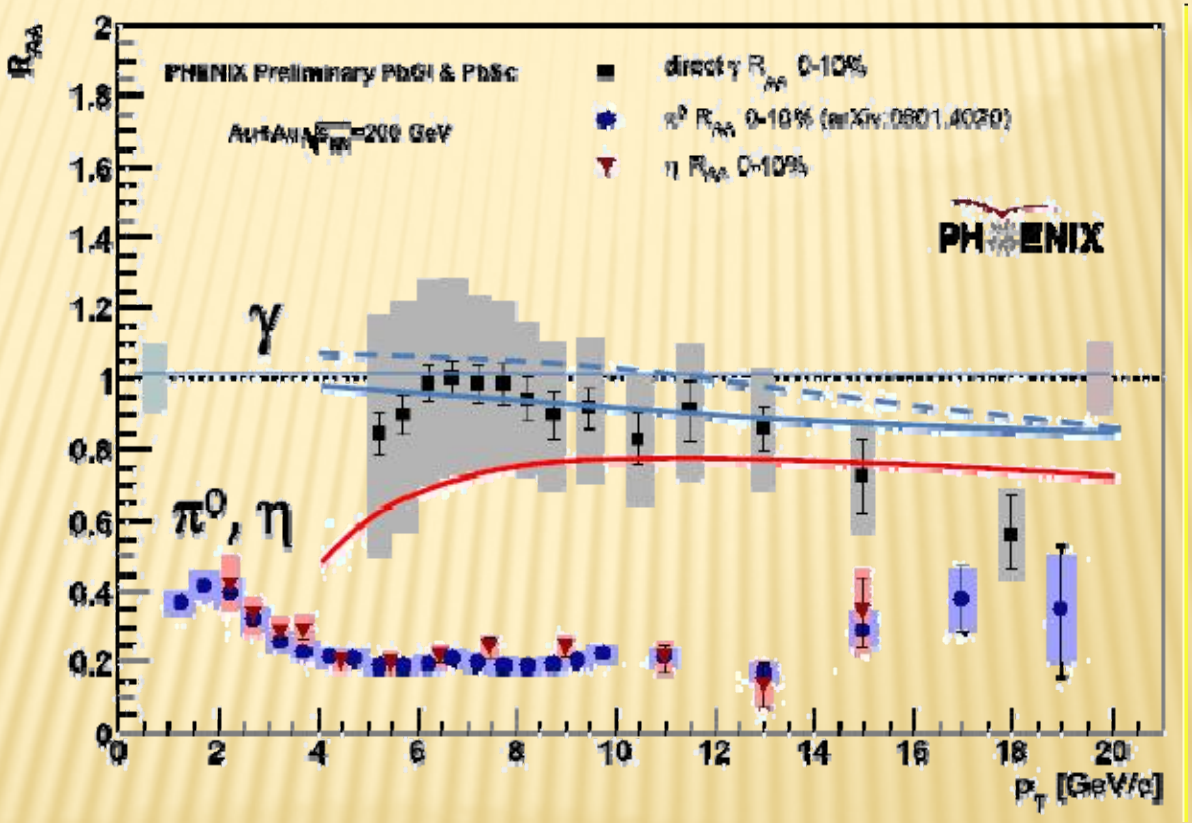
$\varepsilon > 6$ GeV/fm^3

Bjorken, PRD27 (1983) 140

2.MORE NUCLEAR MODIFICATIONS...

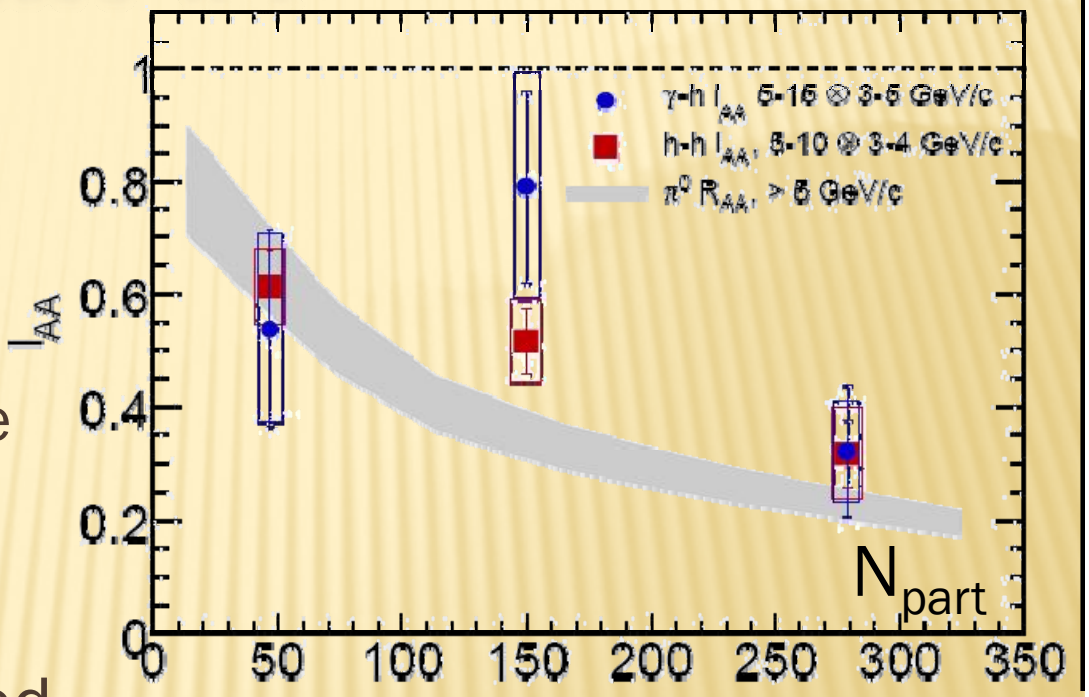


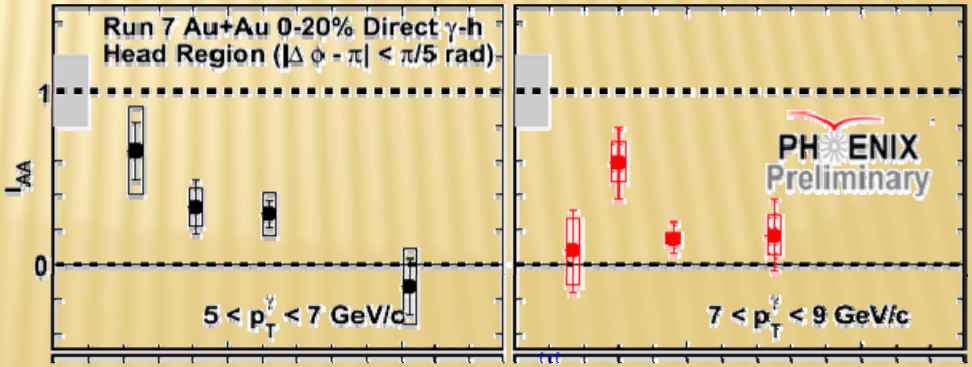
2.HIGHER PT


PHENIX Preliminary PbGl & PbSc
direct γ R_AA 0-10%
η R_AA 0-10%
PHENIX
γ
π0, η
p_T [GeV/c]

2.NEW TOOL: GAMMA-JET

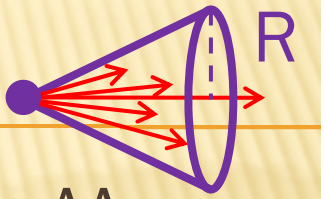
- Photon ≈ unmodified "reconstructed" jet
- Suppression is similar
  - Yield per trigger particle
  - Normalized to p+p
- Can start addressing the question of modified fragmentation function
  - $z_T = p_{hadron}/p_{photon}$ →



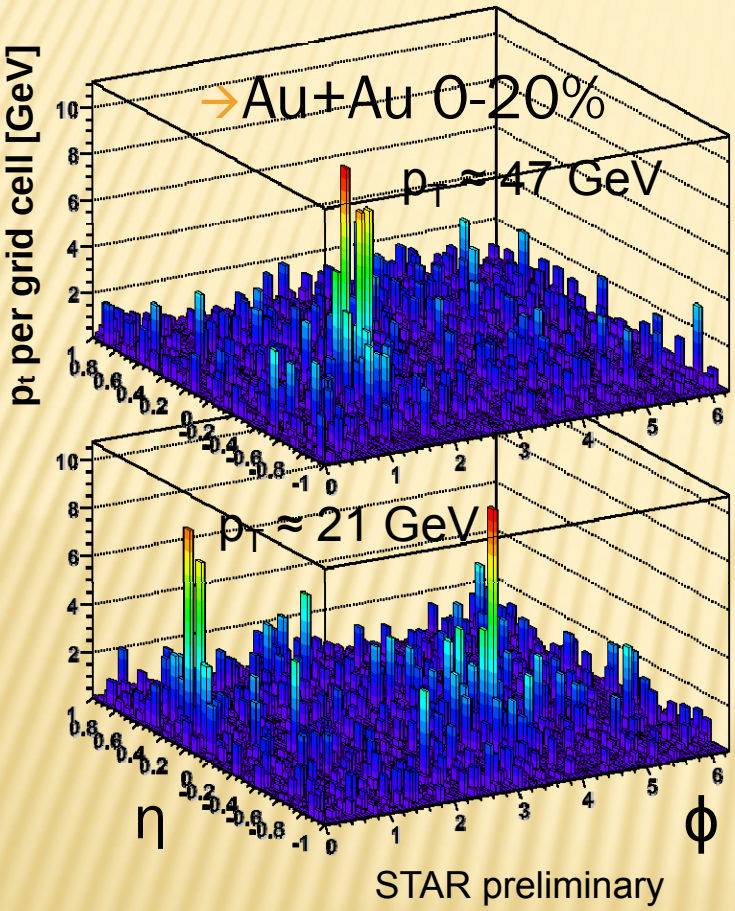


PHENIX: arXiv/0903.3399
M. Connors, QuarkMatter09

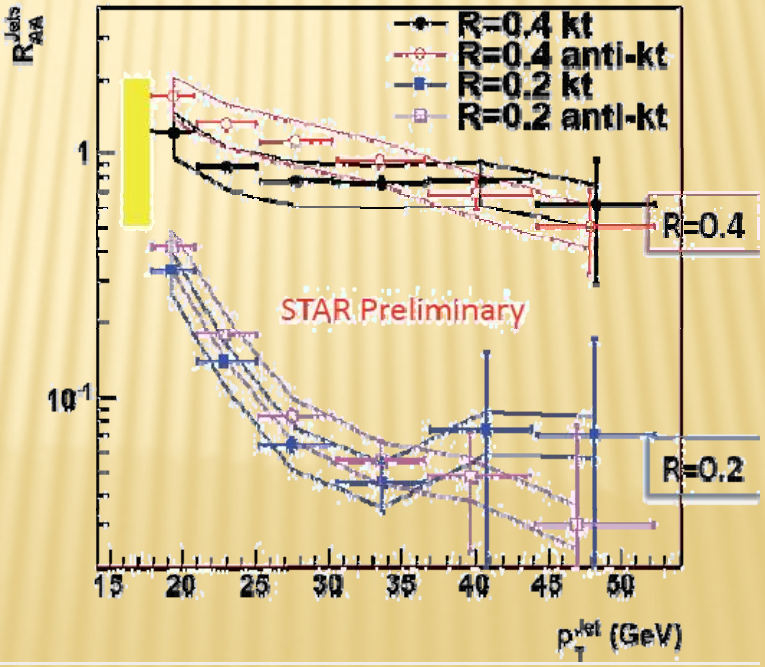
2.NEW TOOL: JET RECONSTRUCTION



- 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



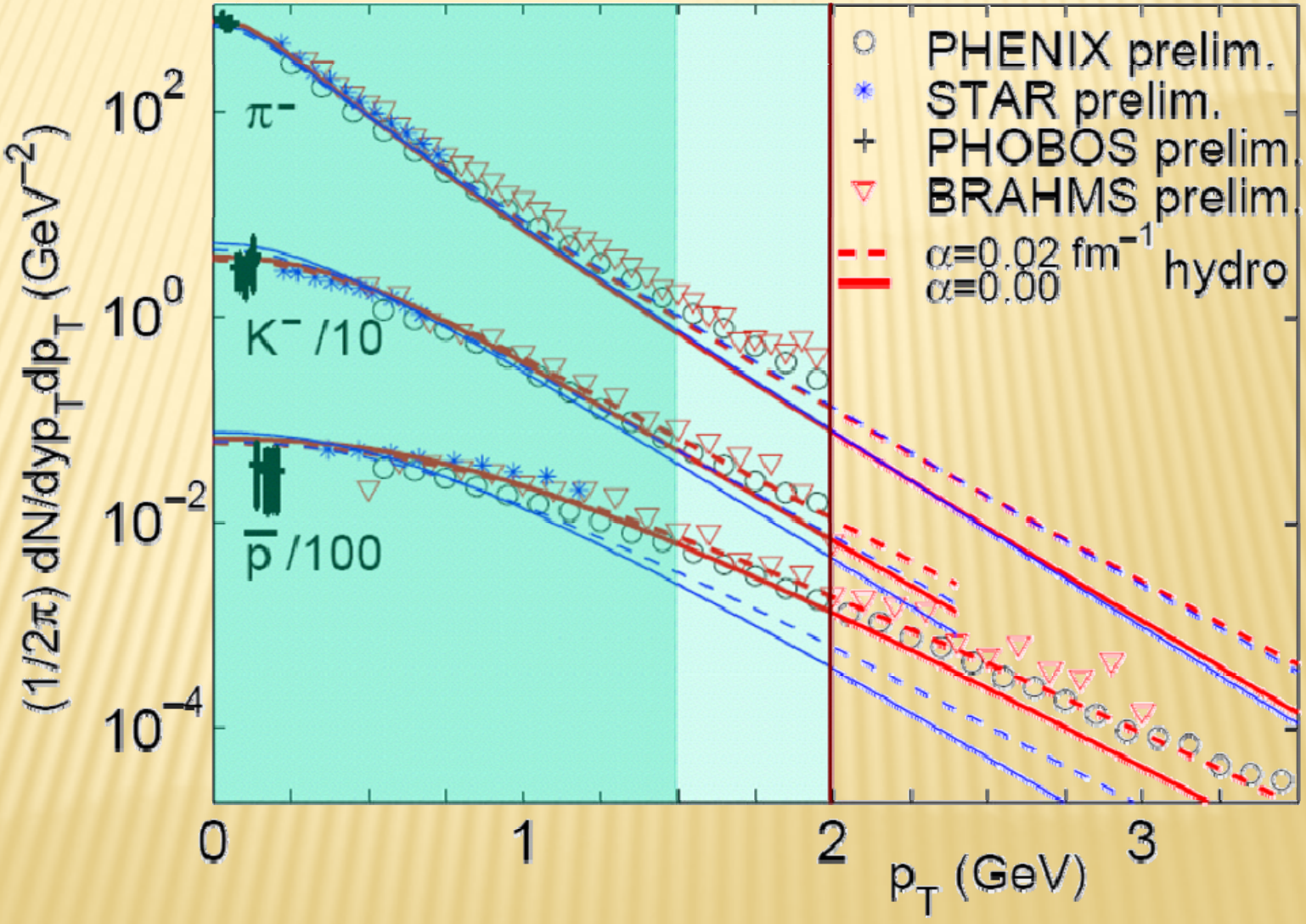
M. Polskon, Quark Matter 09
http://www.lpthe.jussieu.fr/~salam/fastjet



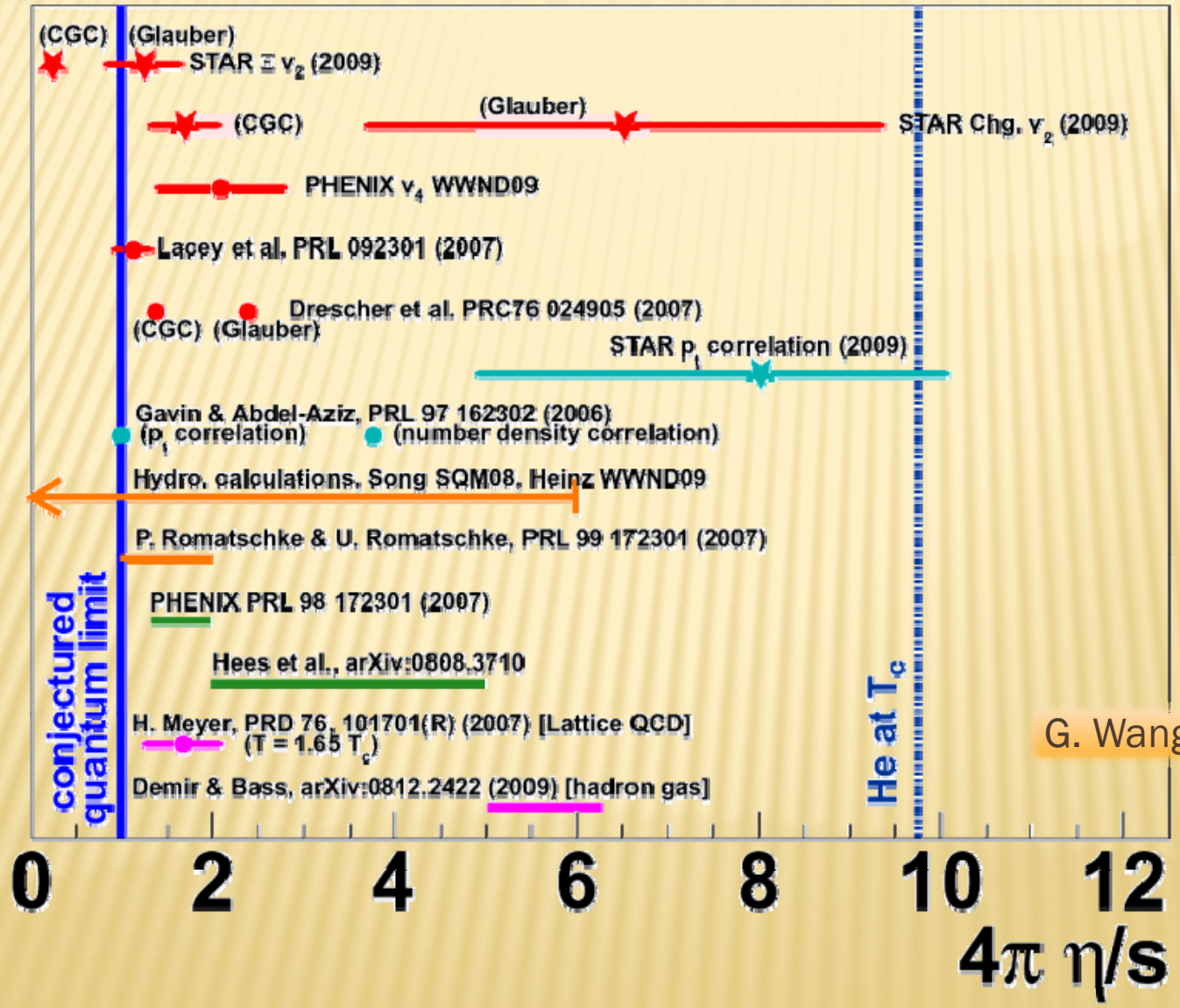
Easier @ LHC

4.HYDRO FIT OF SPECTRA

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



4.VISCOSITY/ENTROPY RATIO

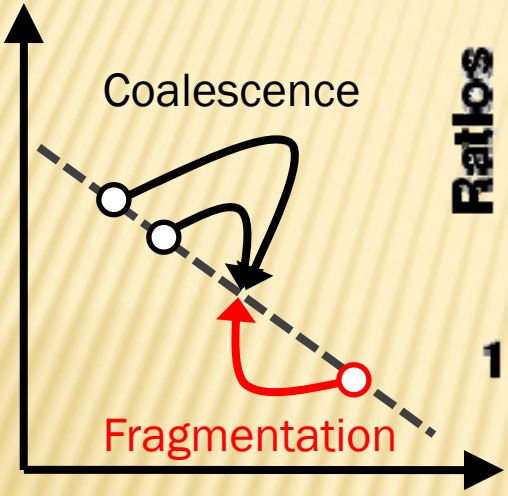


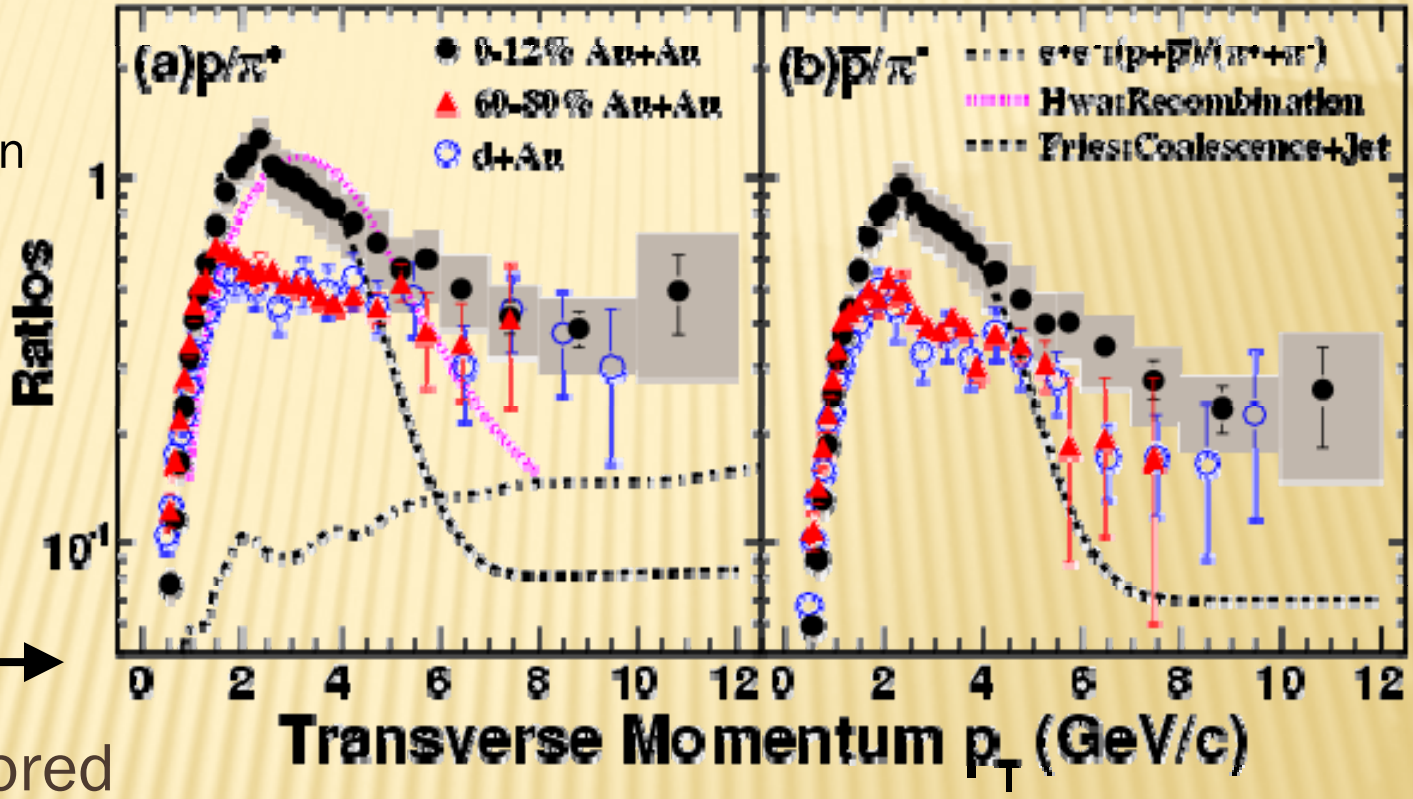
G. Wang @ QuarkMatter09

5. BARYONS/MESONS

STAR, PRL 97 (2006) 152301

→ Spectrum cartoon





- Baryon favored
- Not fragmentation!
- Coalescence or recombination

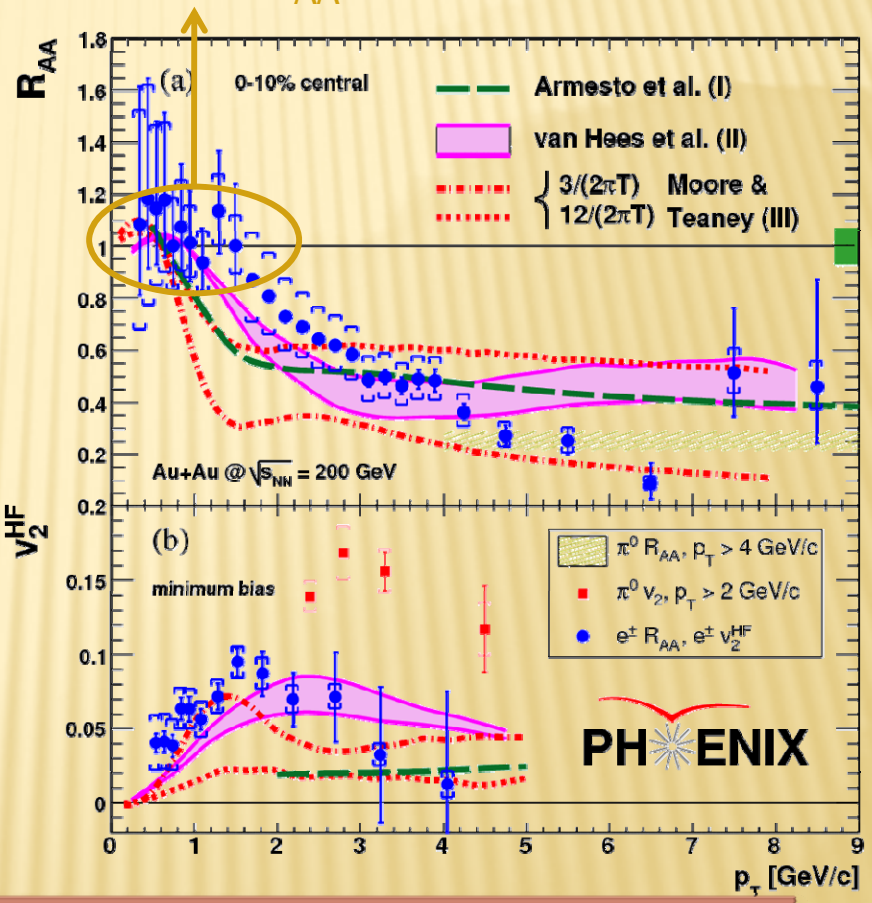
→ The matter is partonic (constituent scaling, coalescence…)

6. HEAVY QUARKS?

PHENIX, PRC76 (2007) 034904

- 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

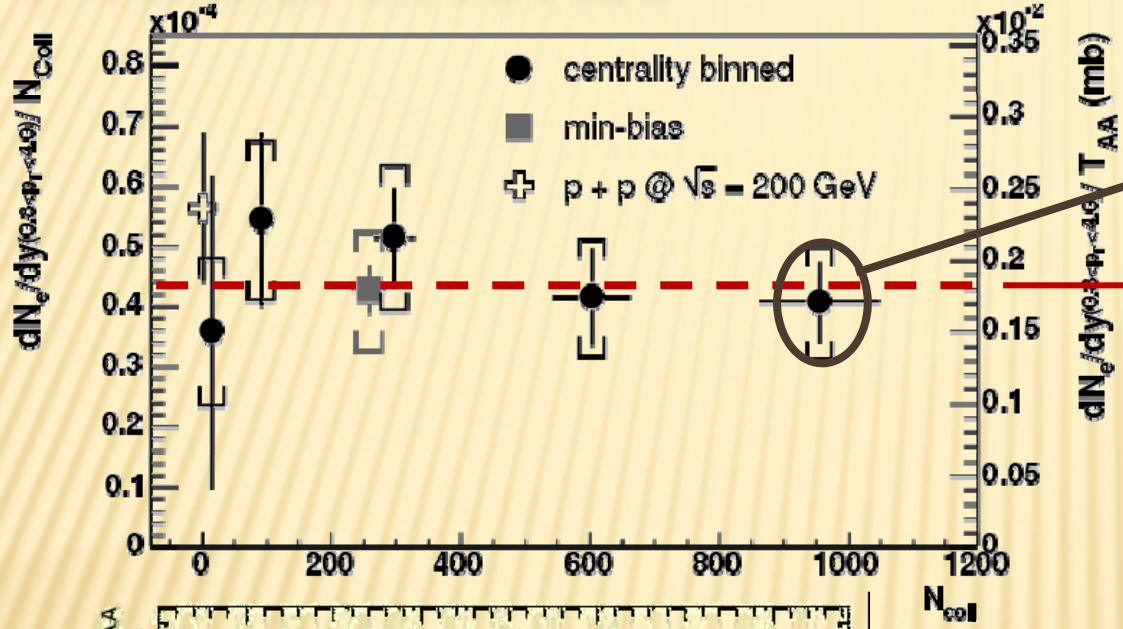
Note that R_{AA}=1 for most of charm

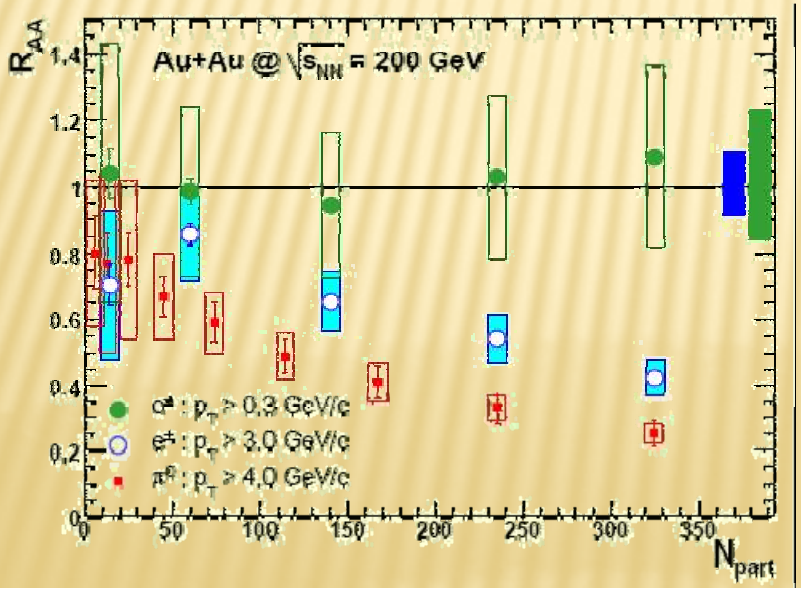


→ The matter is tough…

@ LHC, more thermalization?

6.OPEN CHARM





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

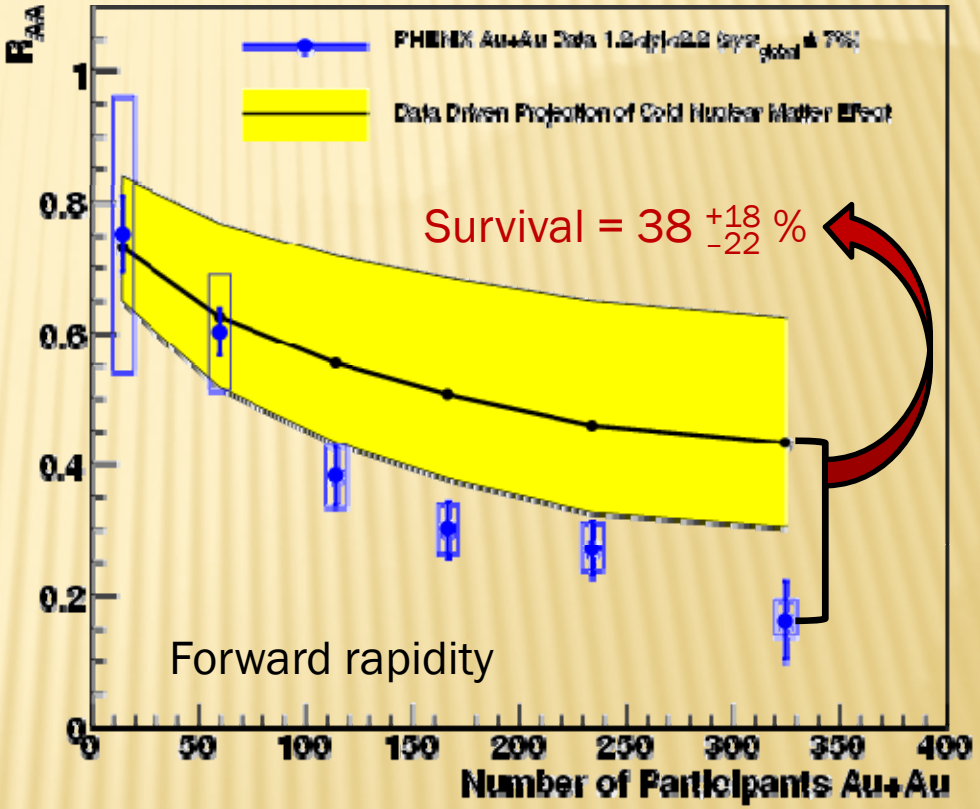
N_{coll} scaling

25% systematics (need for a vertex detector)

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

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

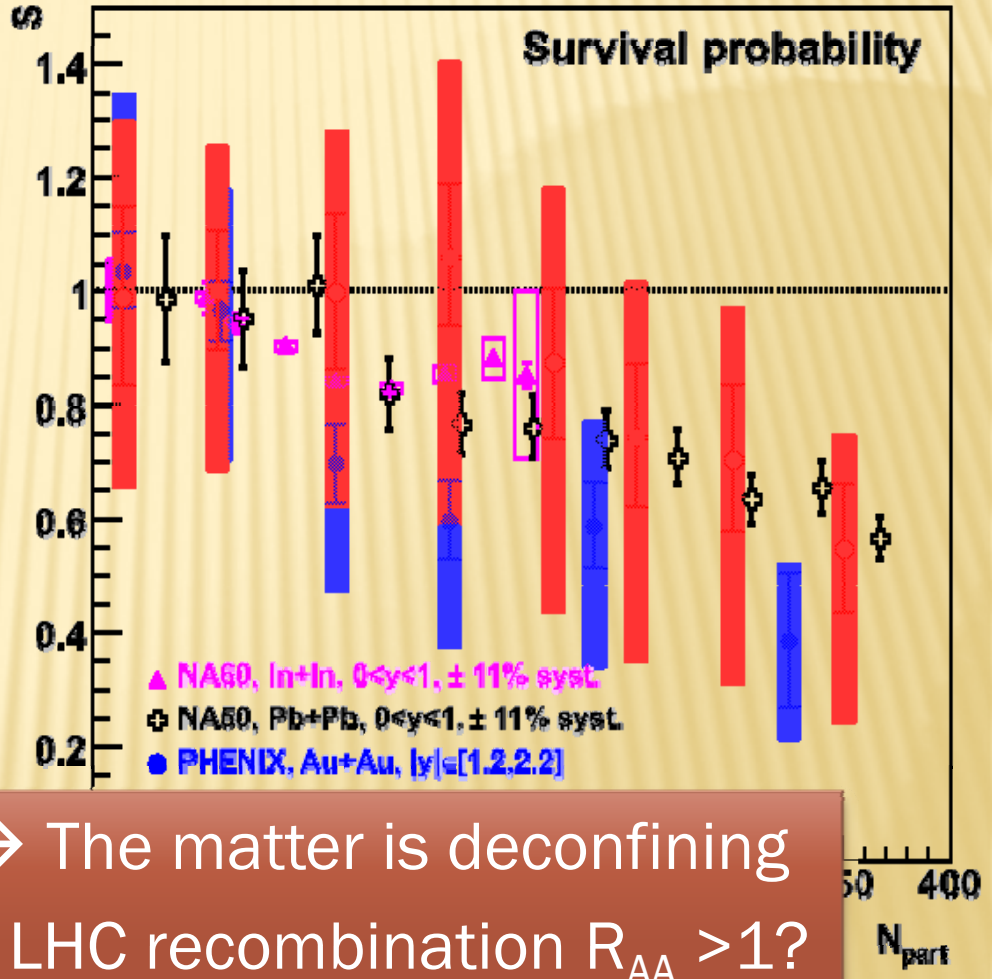


RGdC, J.Phys.G34 (2007) S955
PHENIX, PRC 77 (2008) 024912

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, J/ψ do melt!

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 !

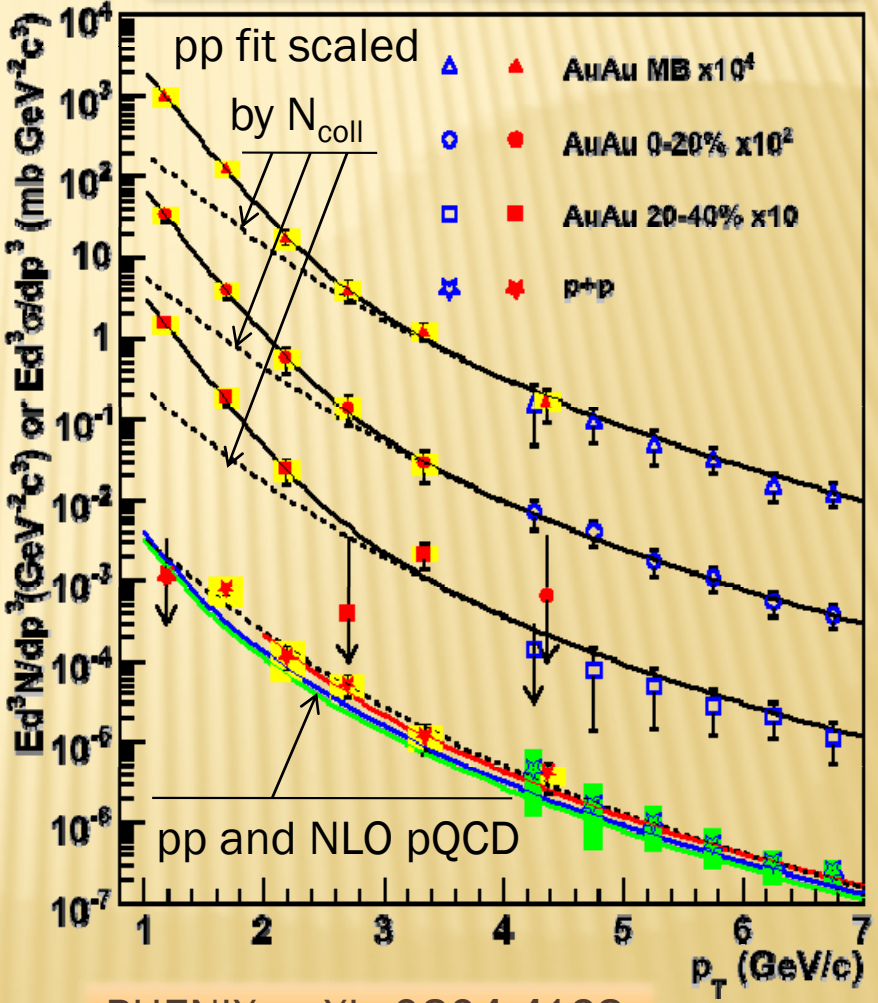
Still one or two slide to go…

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

From these seminal observations,
a lot more jet-related observables…
And new tools are showing up….

OTHER JETS OBSERVABLES AND TOOLS