For Physics In Collision, Perugia, June 27th 2008

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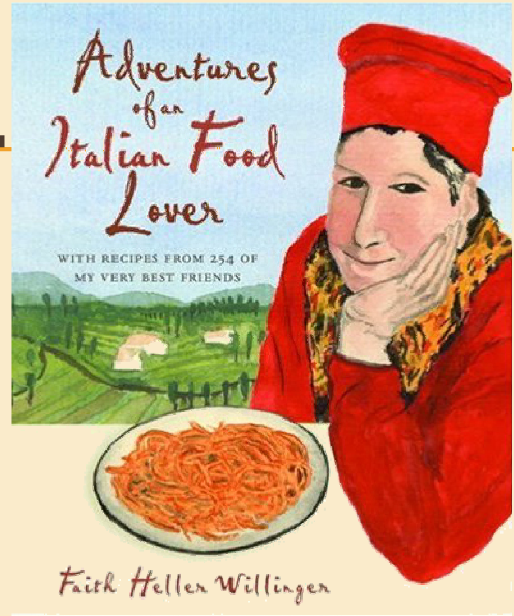
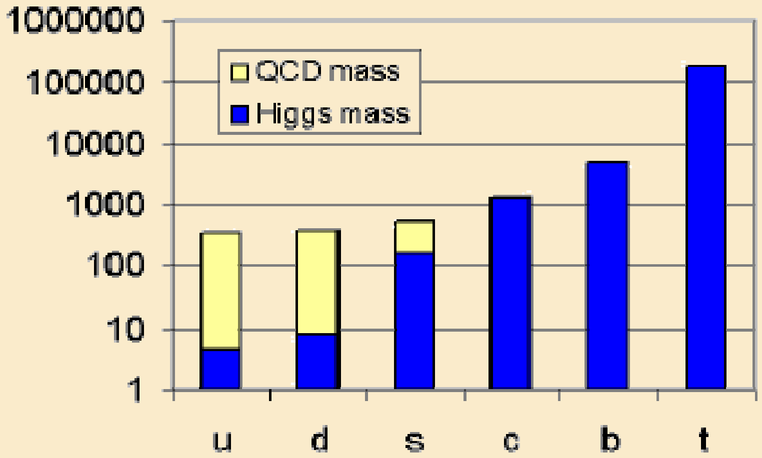
…HEAVY ION COLLISIONS?

(WHAT IS THE MATTER CREATED IN…)

☺ THE ORIGIN OF (MY) MASS…



≈ 98% from QCD + 02% from Higgs!



≈ 98% poorly understood + 02% still unseen…

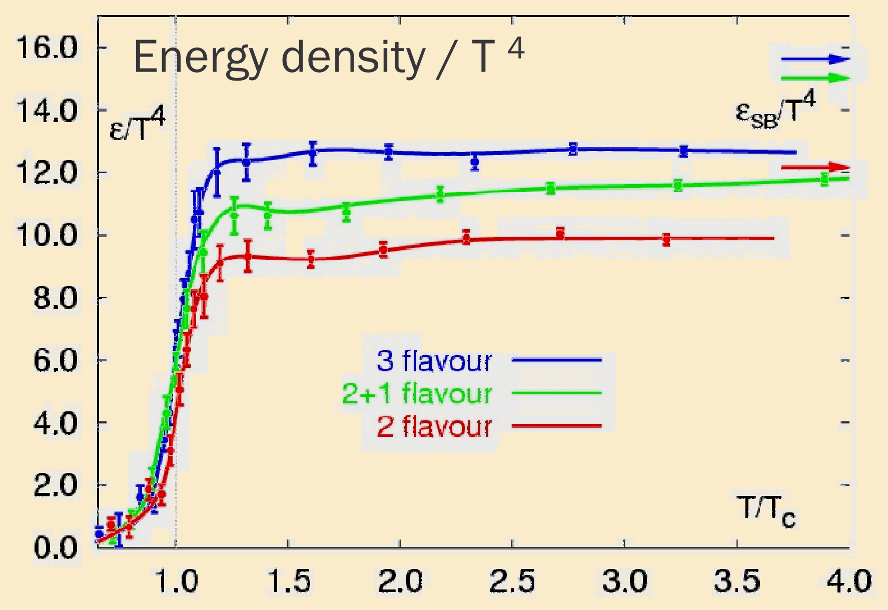
(and ok, this is only ≈ 4% of the universe ☹)

We are mostly made of confinement…

So let's look at deconfinement…

WHAT TELLS QCD? (ON THE LATTICE)

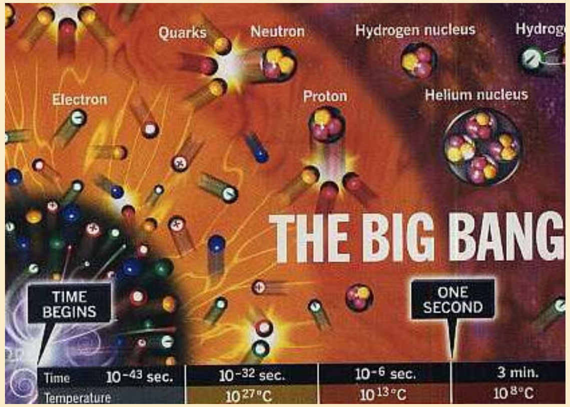
- Strong interaction is weak at high energies
  - Asymptotic freedom
- Lattice QCD predicts a phase transition from a Hadron Gas to a Quark Gluon Plasma (QGP)
  - $T_c \approx 190$ MeV (2×10^{12} K)
  - $\varepsilon_c \approx 1$ GeV/fm^3



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

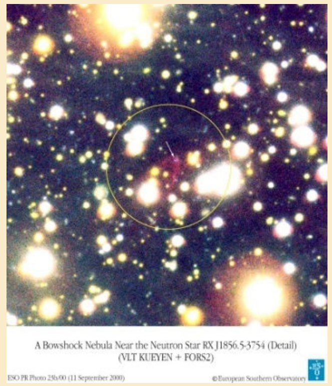
→ Does not tell us much about the matter's properties (equation of state, order of phase transition...)

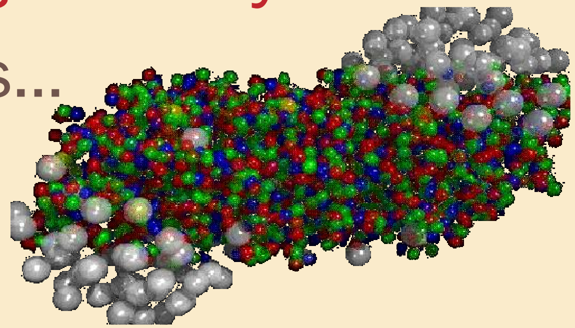
WHERE/WHEN CAN WE FIND THE QGP?



D. Schwarz, astro-ph/0303574
Annalen Phys. 12 (2003) 220

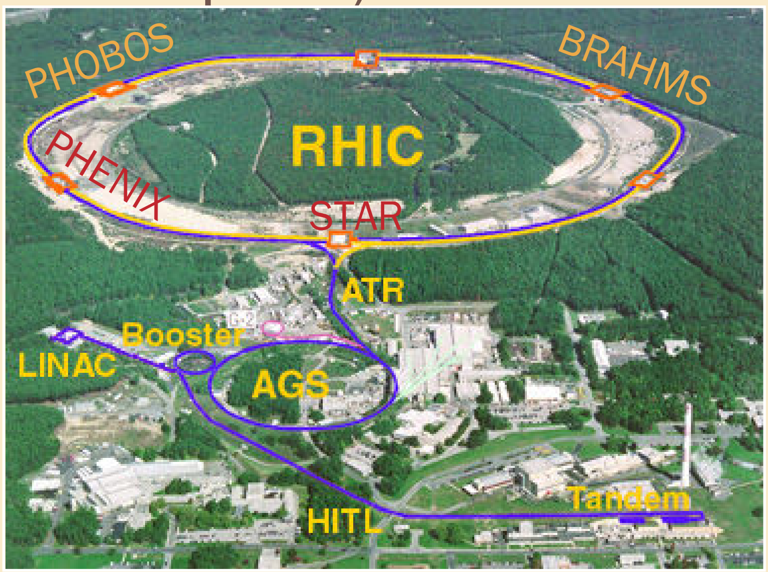
1. Early in the universe (t < 10 μs)
   - But very little chance to leave relics
     - Cold dark matter clumps?
     - Inhomogeneous nucleosynthesis?
     - Baryonic CDM (strange nuggets)?
2. Core of a compact star
   - No smoking gun candidate so far
3. In the lab, by colliding… heavy ions!
   - Freedom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





THE CURRENT LABORATORY

- Relativistic Heavy Ion Collider @ Brookhaven National Lab.
- First collisions in 2000, running
- 2 large (STAR & PHENIX) >2 x 600 + 2 small (PHOBOS & BRAHMS) experiments
- Can collide anything from (polarized) p+p (up to 500 GeV) to Au+Au (up to 200 GeV per nucleon pairs)



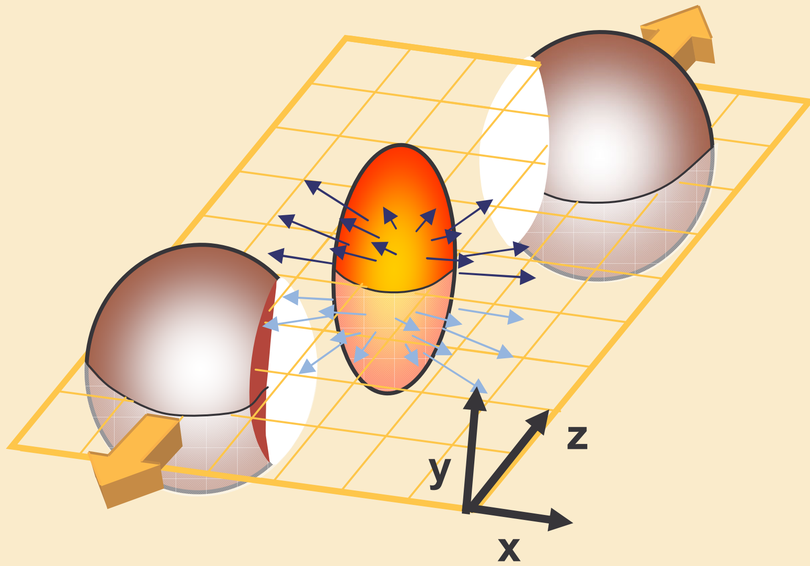
WHAT IS THE STRATEGY? (AND JARGON)

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

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

- 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…)

A COMPLETE REVIEW?

→ Impossible task in a single 30' talk

Focus on hard probes!

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 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"

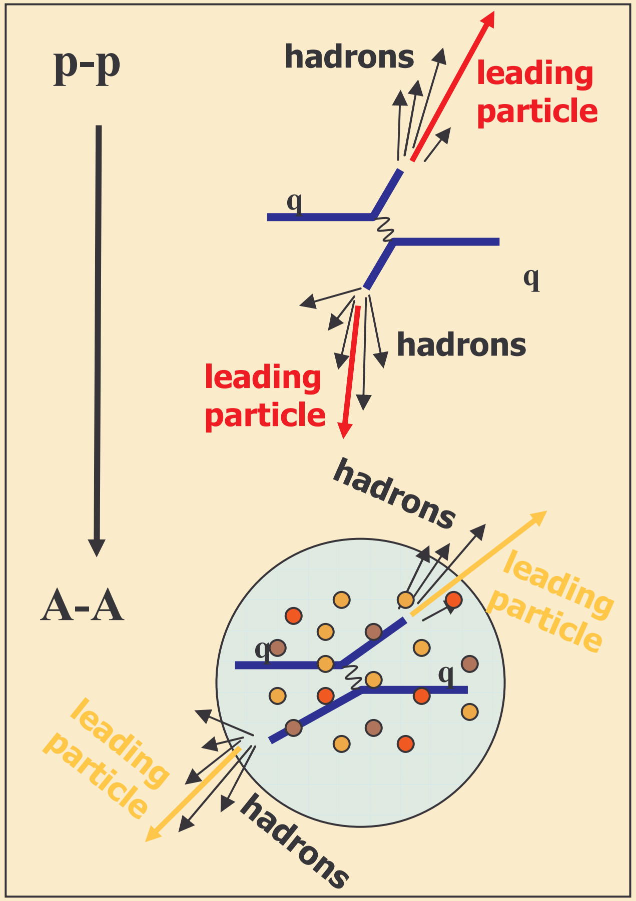
H. Satz @ Lattice 2000 hep-ph/0009099

The smoking gun...

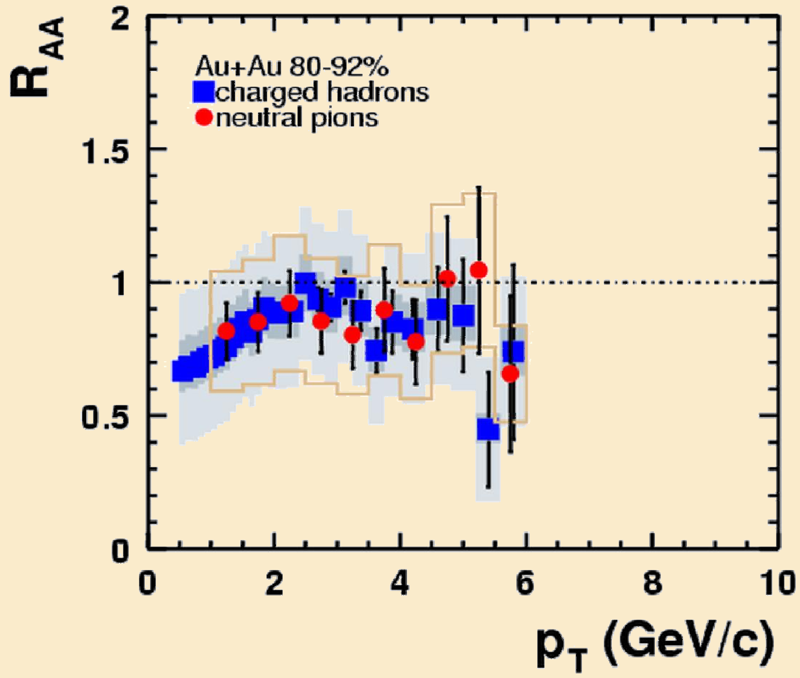
JET QUENCHING

2. HIGH P_T SUPPRESSION

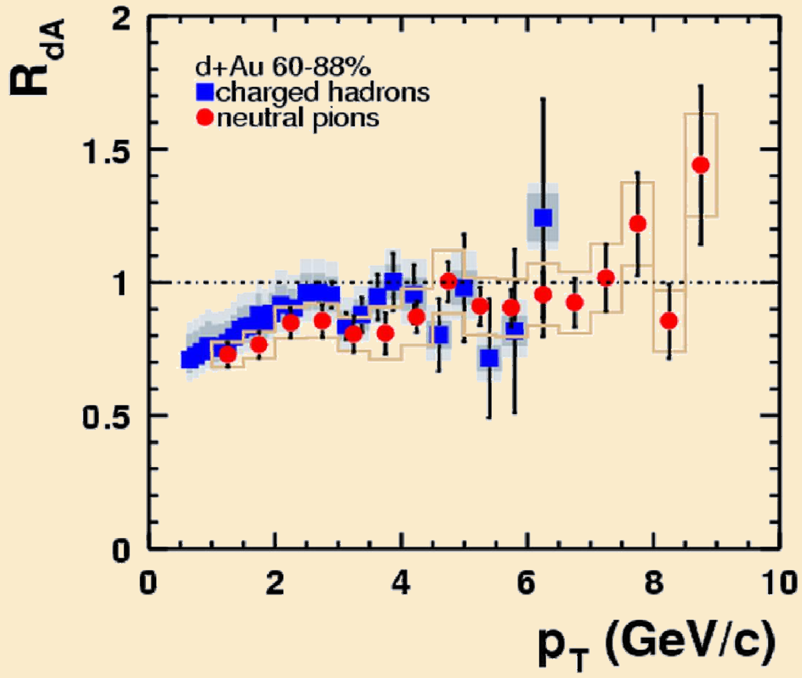
- RHIC smoking gun signature!
  - Two PRL covers
- Looking at high p_T (>2GeV)
  - Mostly from jet fragmentation
- Energy loss in the matter
- "Jet quenching"



Au-Au (80-92%)



d+Au (60-88%)

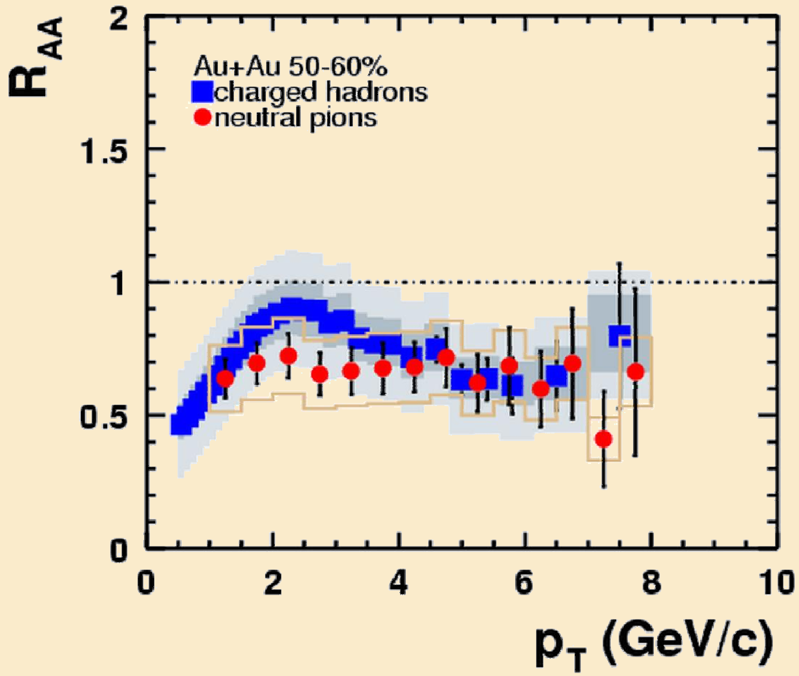


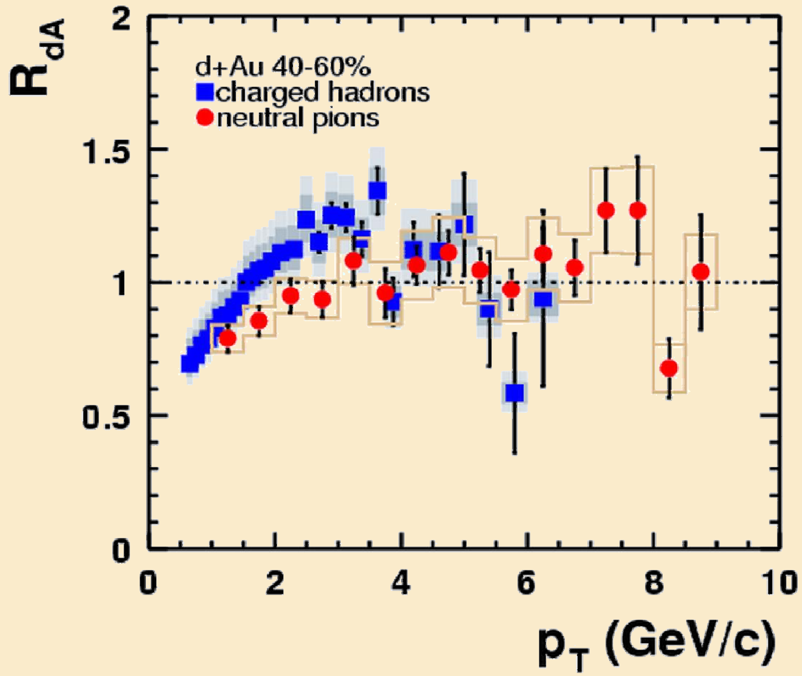
MOST PERIPHERAL COLLISIONS...

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

Au-Au (50-60%)

d+Au (40-60%)



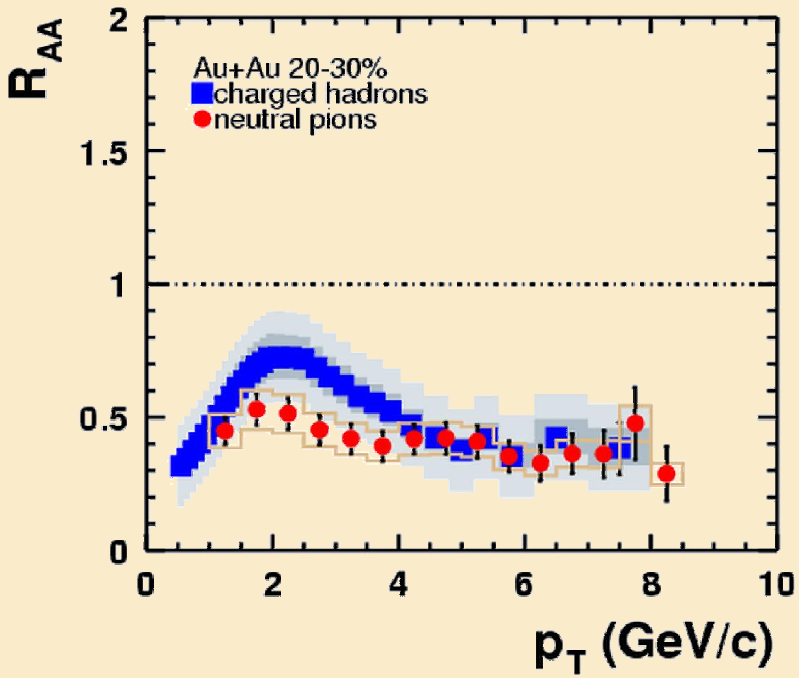


LESS PERIPHERAL COLLISIONS…

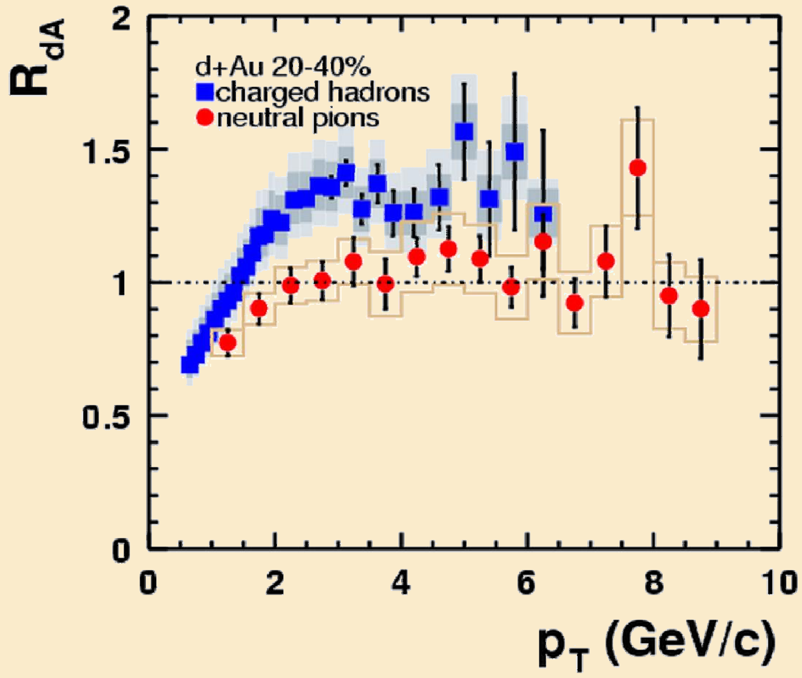
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

Au-Au (20-30%)



d+Au (20-40%)

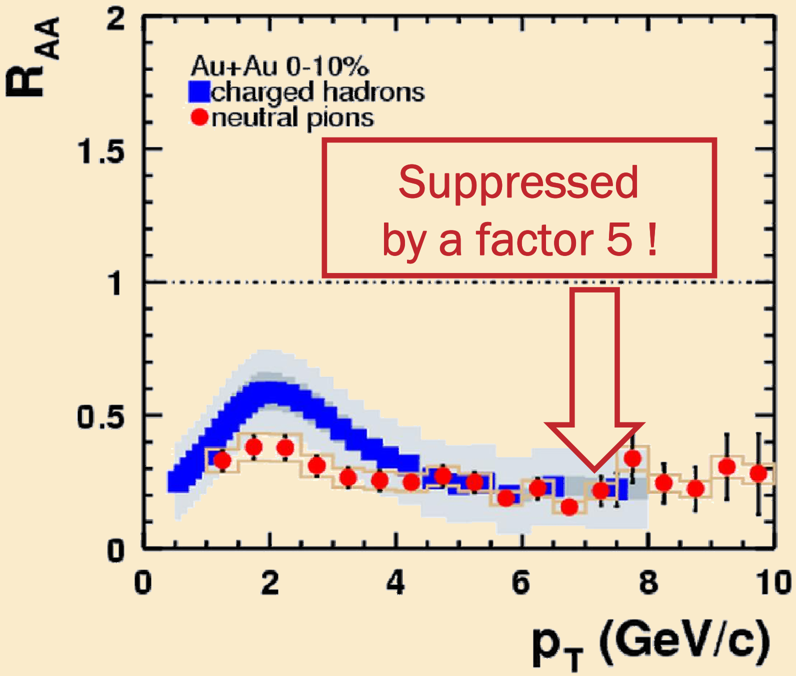


MORE CENTRAL COLLISIONS…

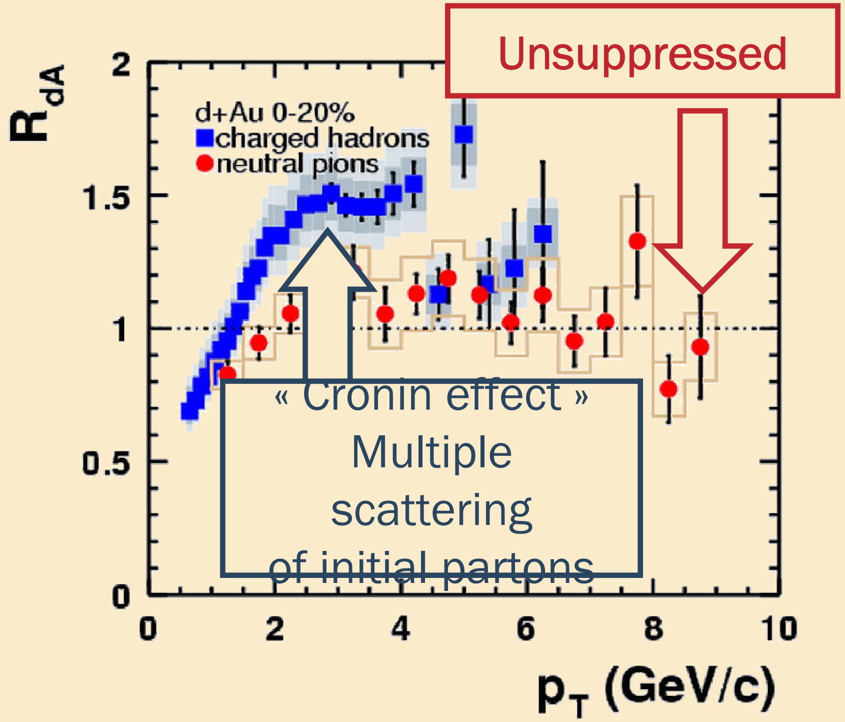
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

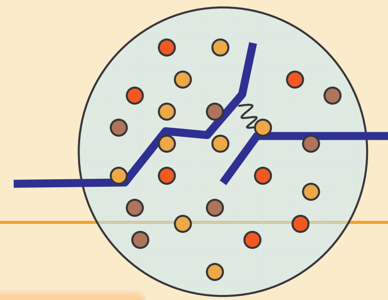
Au-Au (0-10%)



d+Au (0-20%)



MOST CENTRAL COLLISIONS!

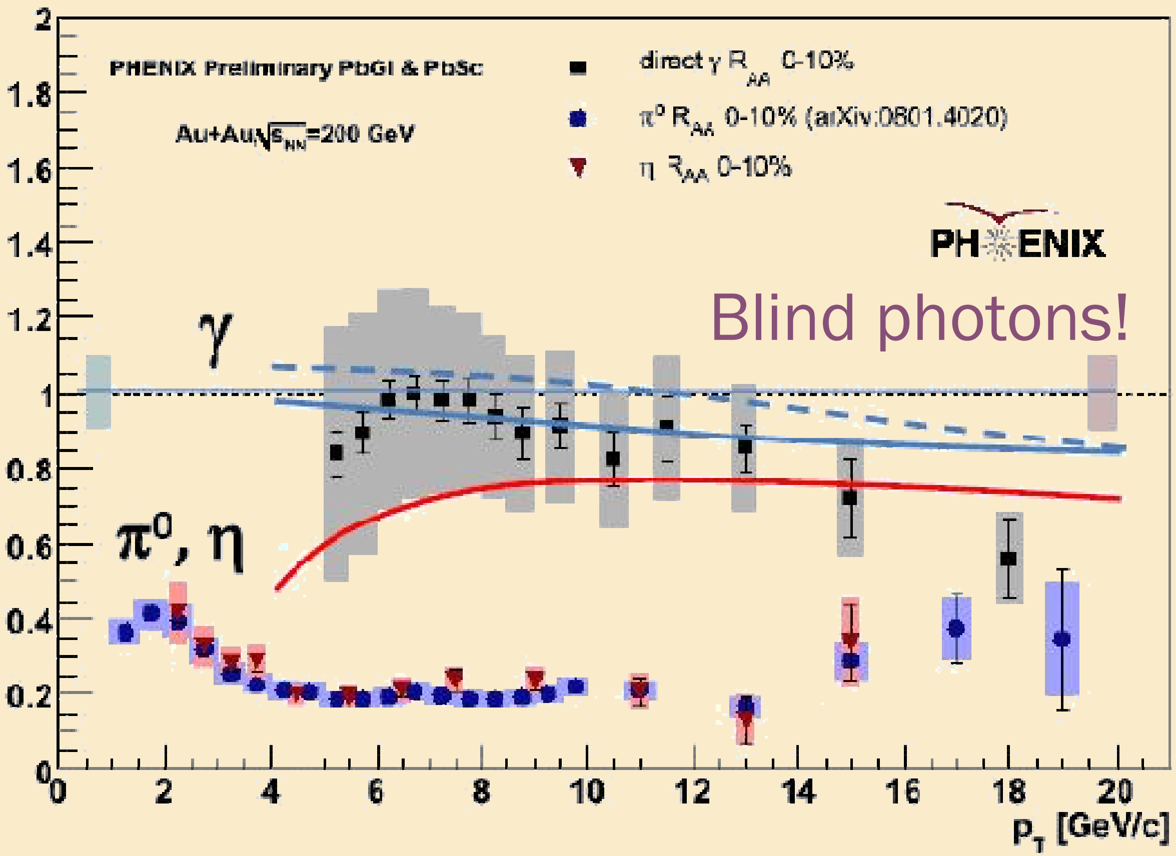


(slightly old, but pedagogical, data)

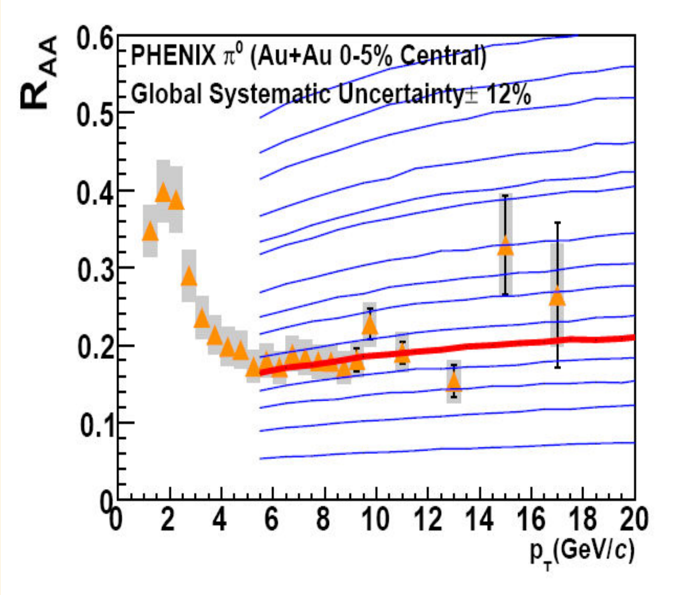
PHENIX, PRL 91 (2003) 072303

2. HIGH P_T SUPPRESSION

NEW



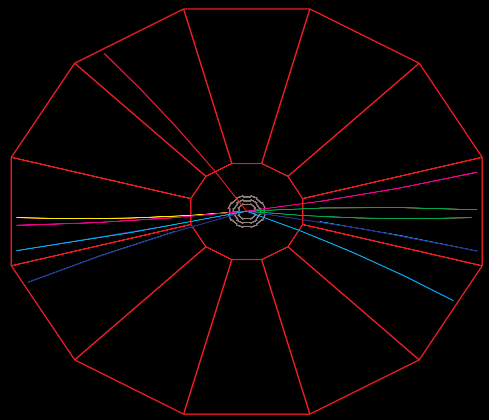
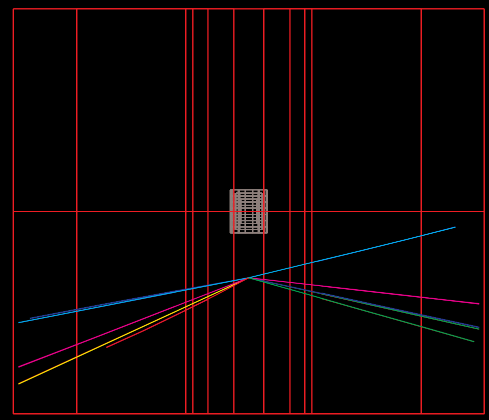
PHENIX, PRC77(2008)064907
(accepted this week)



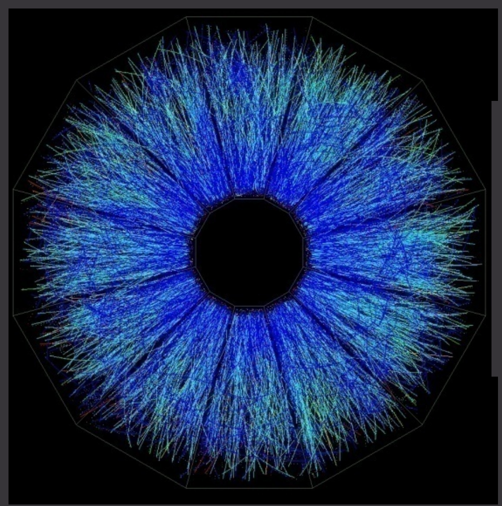
→ Comparisons to models, including experimental errors provide physical properties, e.g. $dN_{gluons}/dy = 1400^{+200}_{-375}$

→ The matter is dense !

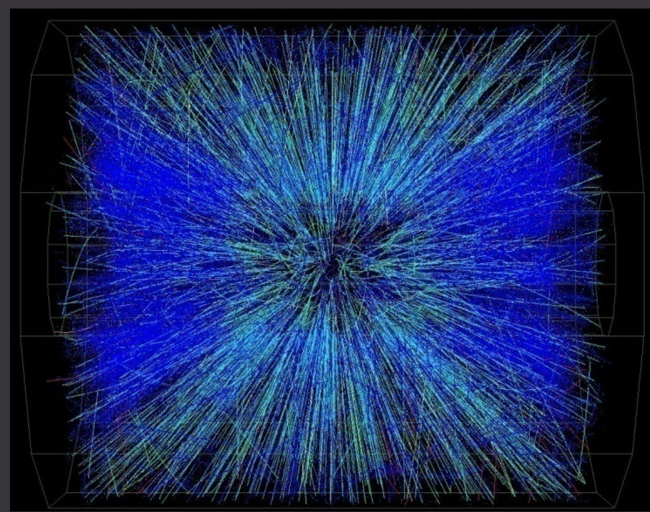
3. BACK TO BACK JETS

Easy in 200 GeV proton+proton collisions



?

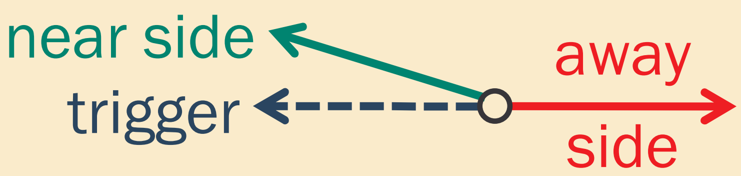


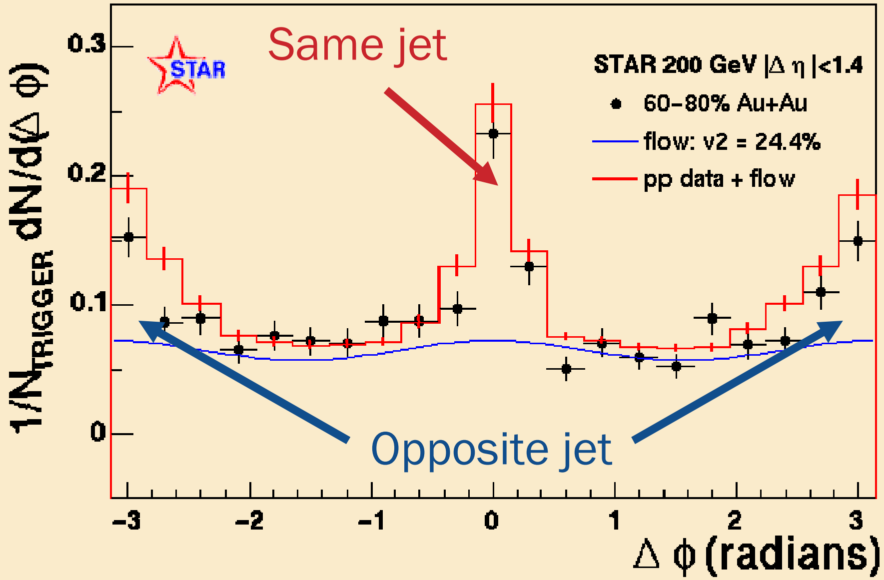
Quite difficult in Au+Au central collisions @ 200 GeV

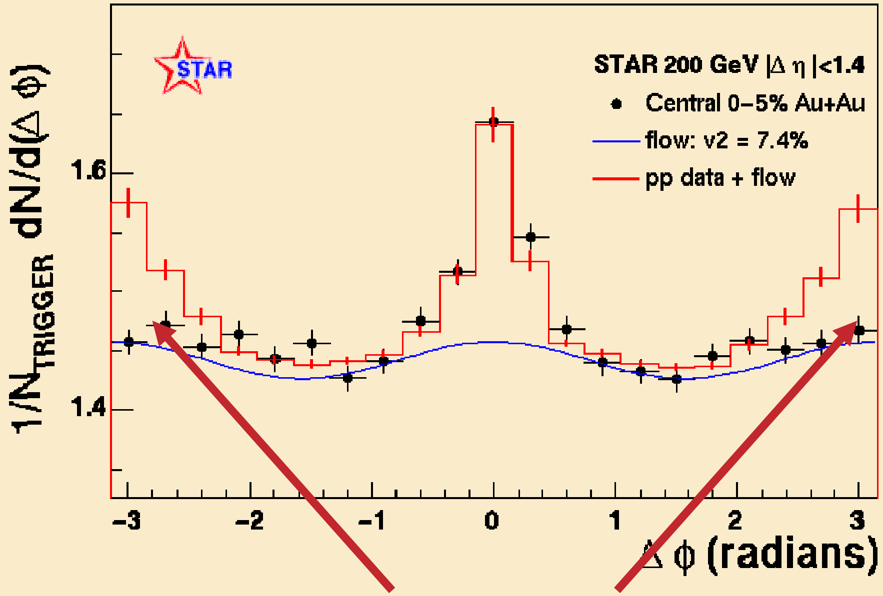
→ $N_{coll} \approx 1000$ in a single Au+Au central collision!

Peripheral collisions (60-80%)

Central collisions (0-5%)







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

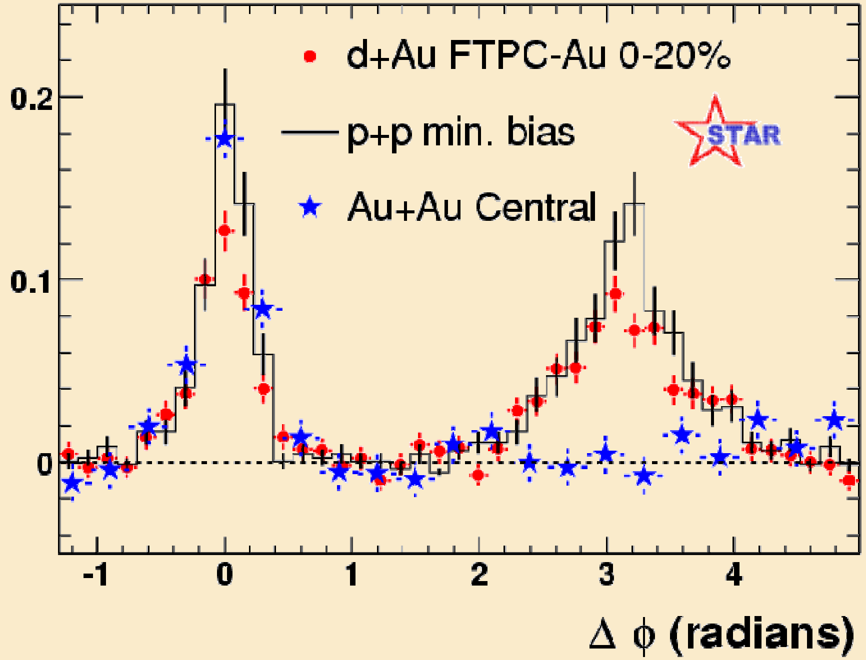
In central collision, opposite jets disappear because of jet quenching

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

3. BACK TO BACK (D+AU)

STAR, PRL 91 (2003) 072304

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



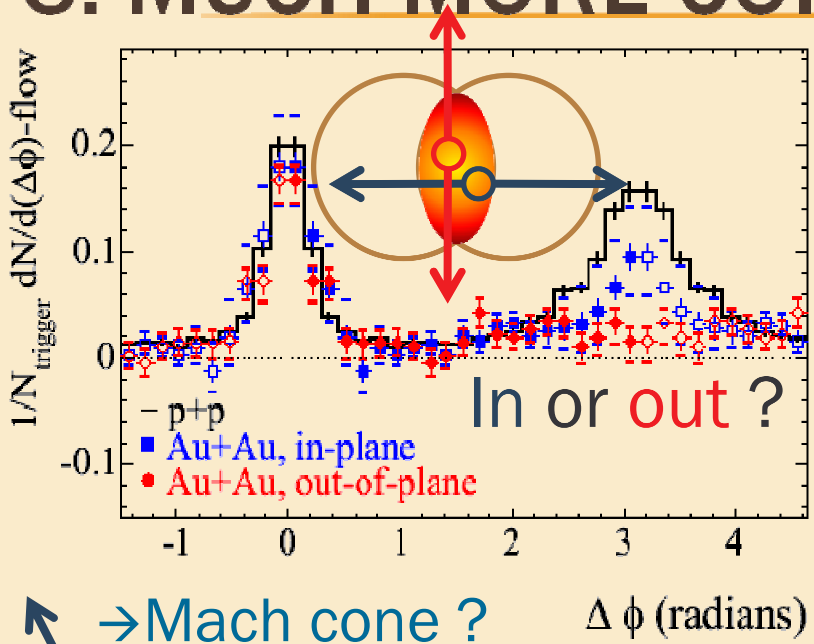
→ The matter is opaque!

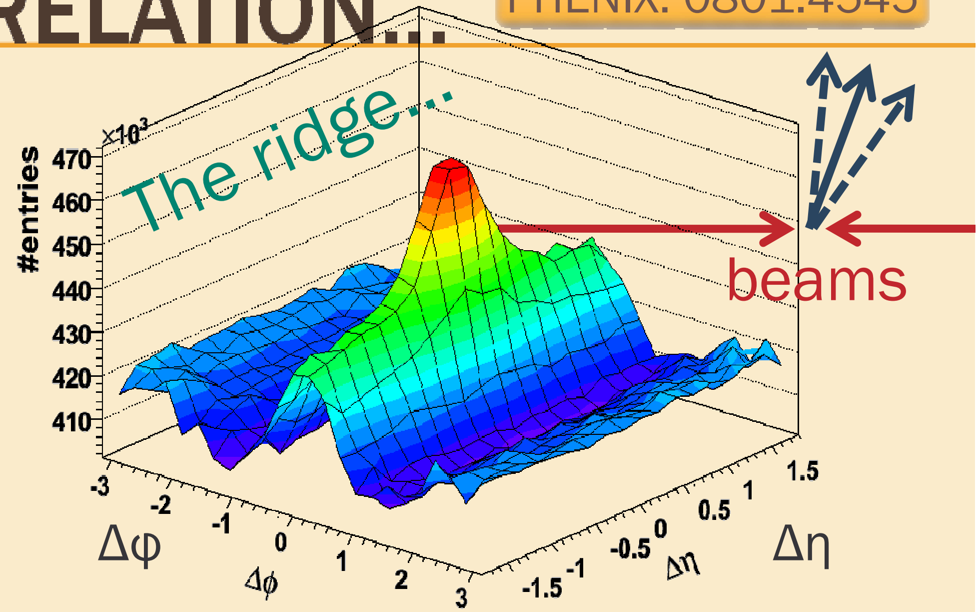
From these seminal observations,
a lot more jet-related observables…
And new tools are showing up….

OTHER JETS OBSERVABLES AND TOOLS

All plots from STAR
PHENIX: 0801.4545

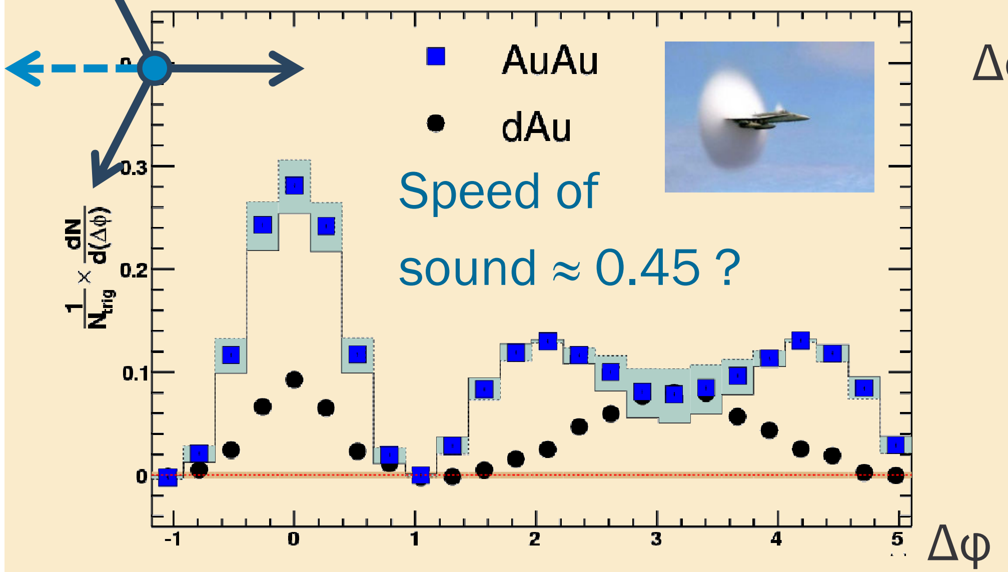
3. MUCH MORE CORRELATION...

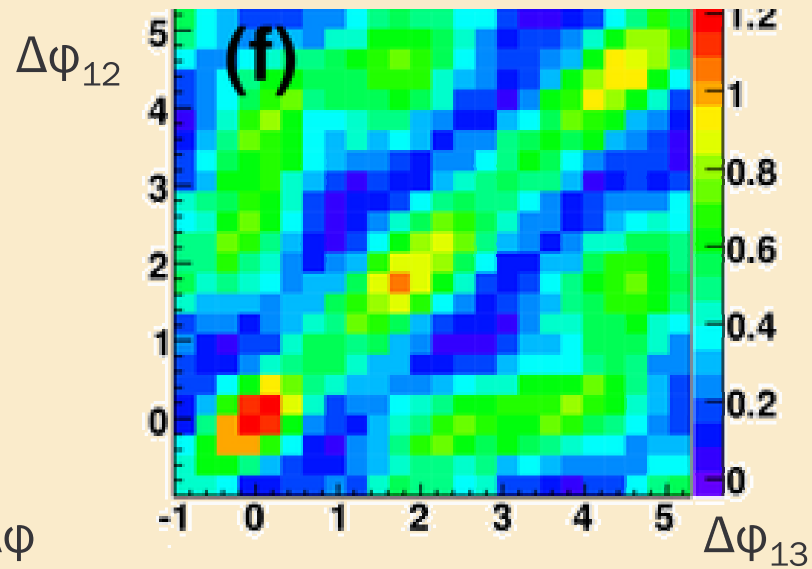




→Mach cone ?

→Three particles (central Au+Au)





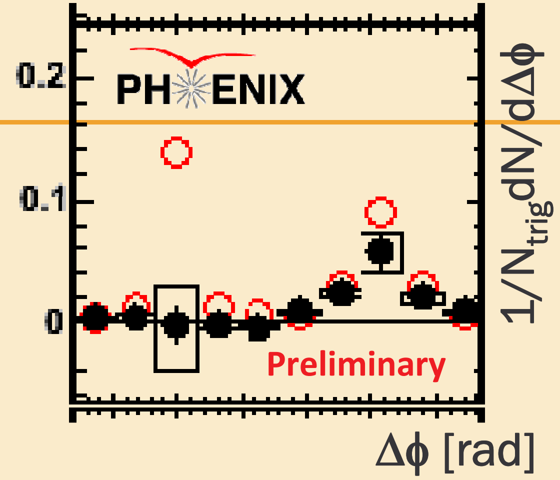
arXiv:0805.0622

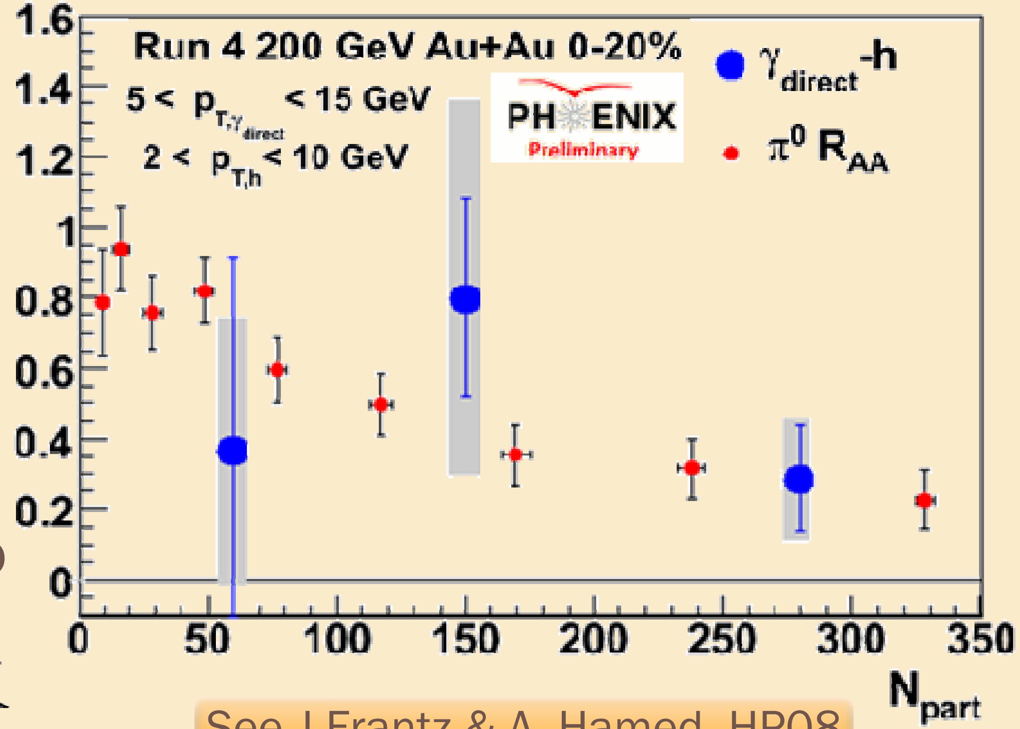
A NEW TOOL: GAMMA-JET

- Gamma ≈ unmodified "reconstructed" jet
- Away side jet is seen
  - STAR and PHENIX
- Preliminary AuAu analyses
  - Yield per trigger particle
  - Normalized to p+p
- Find back R_{AA}
  - Double pt dependence to come…

NEW

Example: p+p
Trigger 7-9 GeV
Assoc 2-3 GeV
○ π° trigger
● γ trigger



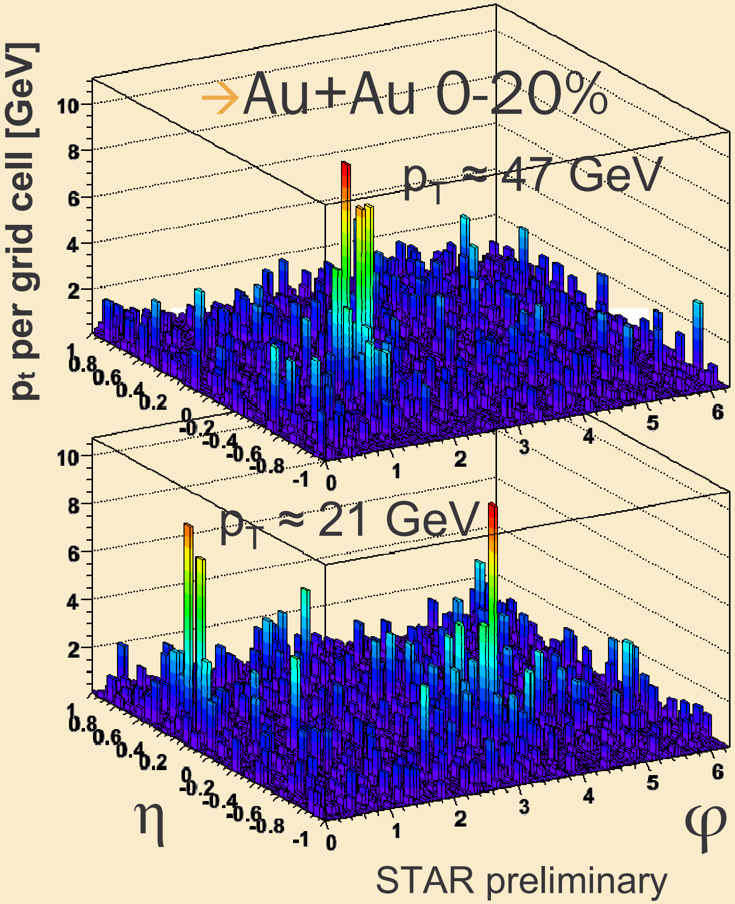


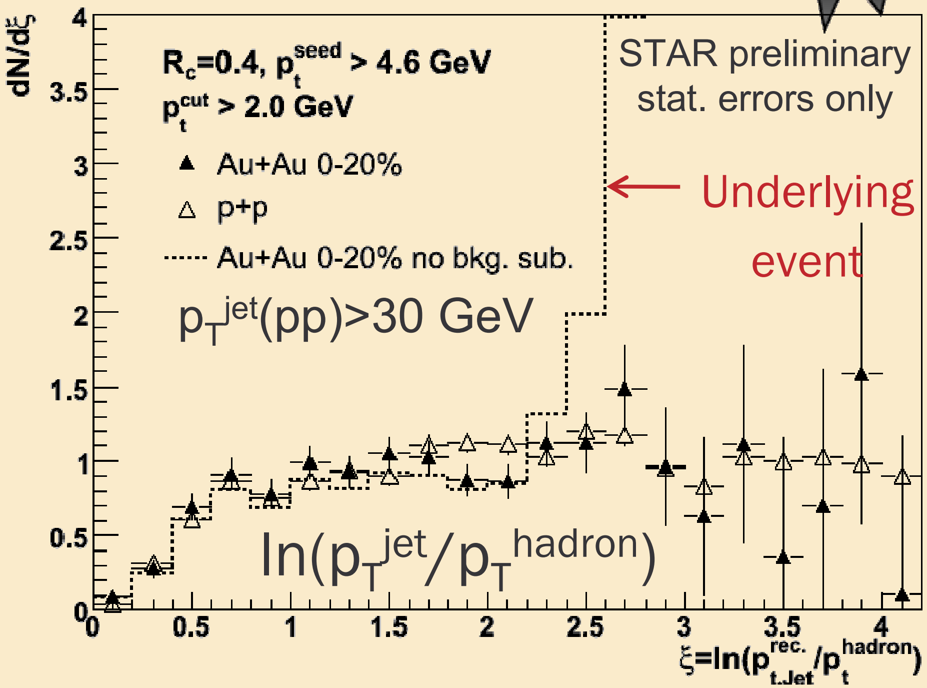
See J Frantz & A. Hamed, HP08

NEW TOOL: JET RECONSTRUCTION?

NEW

J. Putschke, Hard Probes 08
A+A reconstructed jets shown for the first time 2 weeks ago



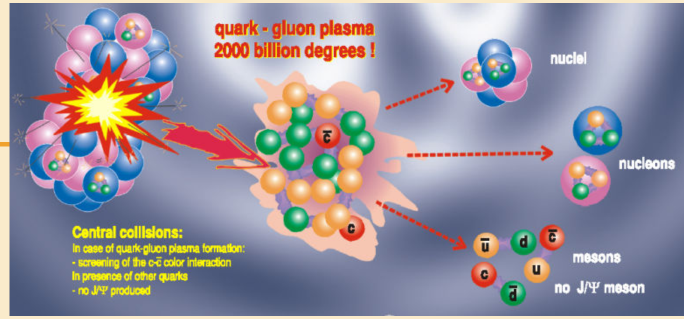


- No sizeable modification visible in fragmentation function
  - Au+Au jet energy bias?
  - Surviving jets unchanged?
- Stay tuned...

That's all for jets…

J/Ψ SUPPRESSION

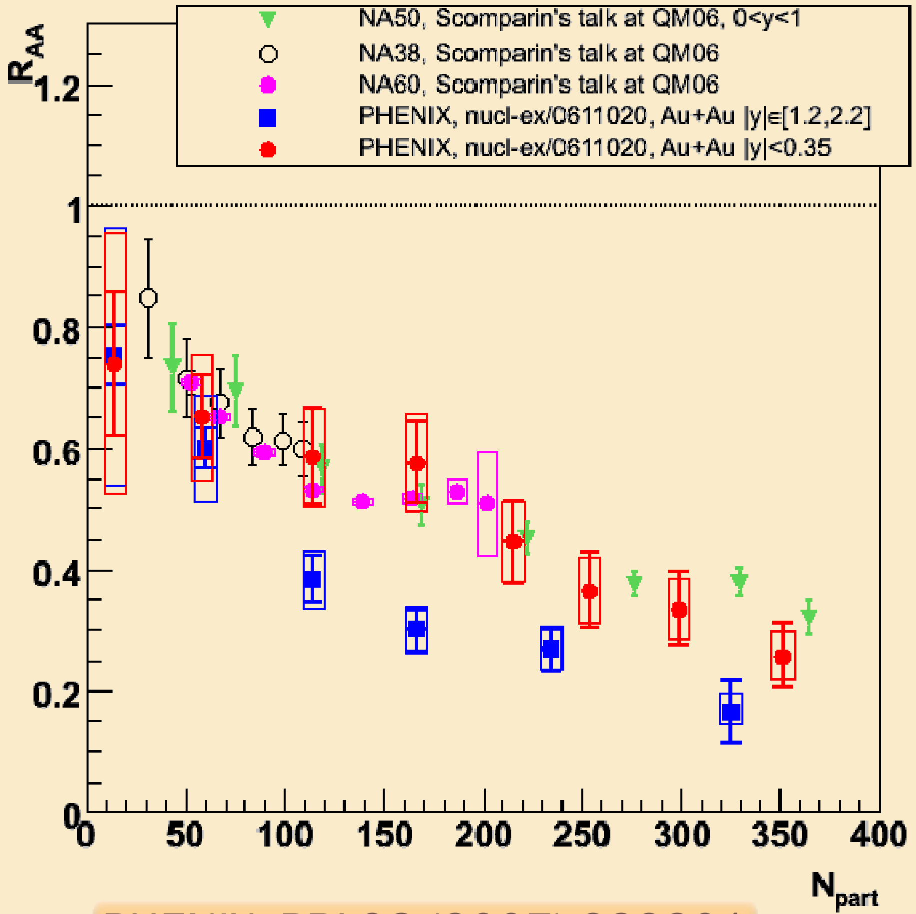
7. J/Ψ SUPPRESSION



- J/ψ ($c\bar{c}$) can melt in QGP
- 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
- But beware of nuclear matter!

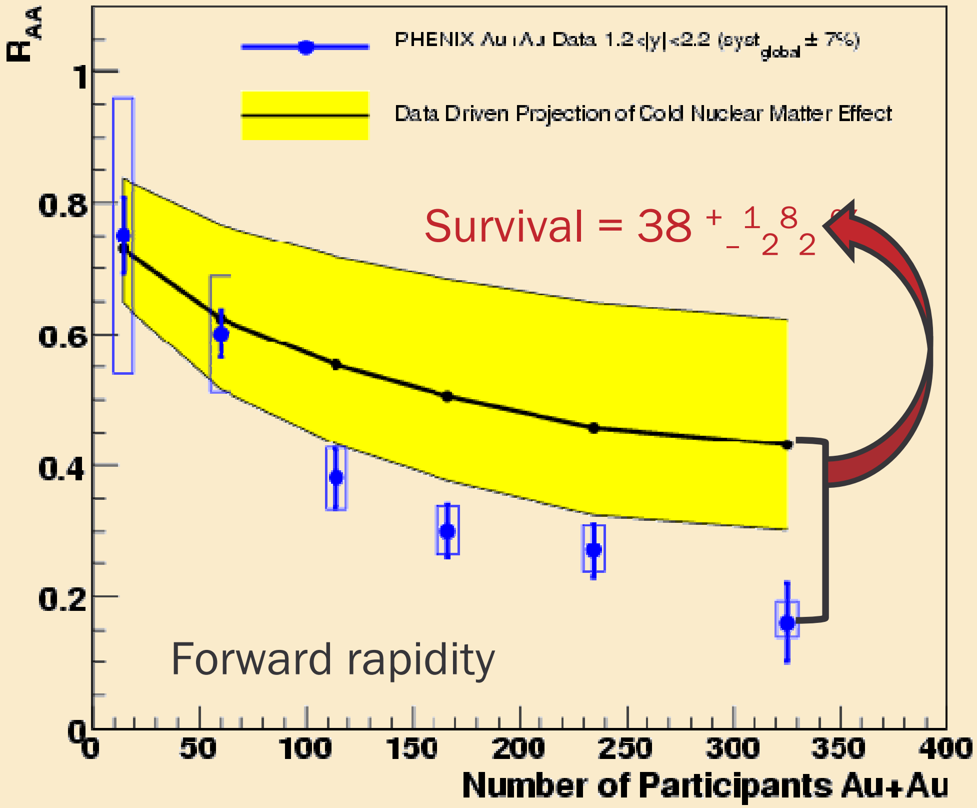


PHENIX, PRL98 (2007) 232301

7. J/Ψ SUPPRESSION (FROM D+AU)

NEW

- 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)

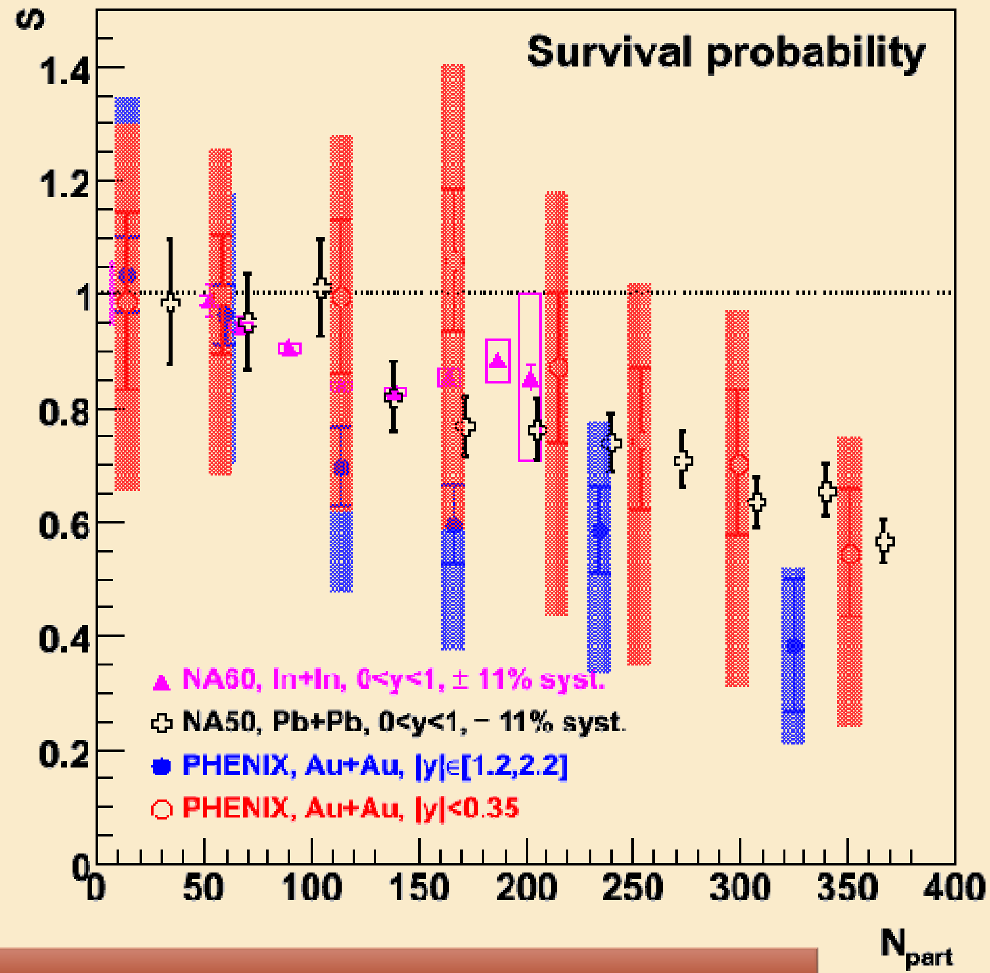


RGdC, J.Phys.G34 (2007) S955
PHENIX, PRC 77 (2008) 024912

7. J/Ψ "ANOMALOUS" SUPPRESSION

NEW

- 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, arxiv:0711.3917
(data driven method)

→ The matter is deconfining

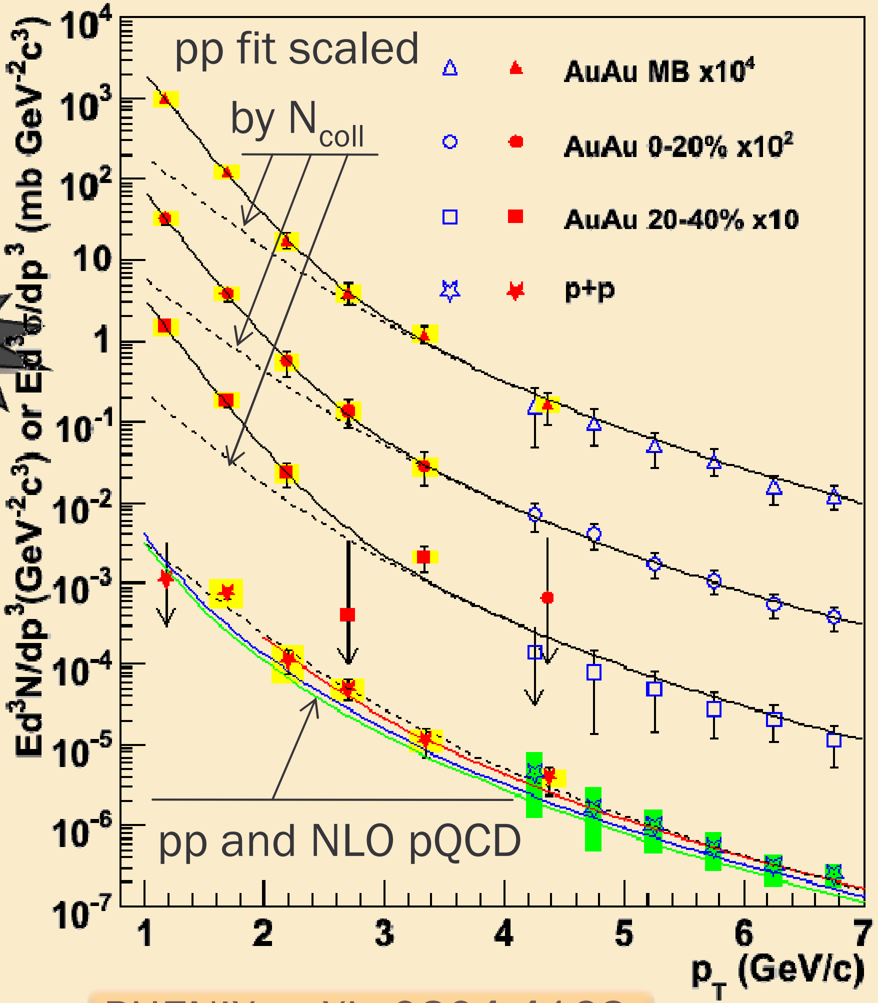
One last signature…

DIRECT PHOTONS

8. THERMAL RADIATION

→ The matter is hot! $T>T_c$

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



PHENIX, arXiv:0804.4168

AS A CLEAR 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 2008 (Jaipur)
  - Hard probes 2008 (Galicia)
  - Experimental "white papers"
  - Reviews, for instance:

http://www-fp.usc.es/hp2008/
http://www.veccal.ernet.in/qm2008.html

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

RGdC, Int.J.Mod.Phys.A22 (2008) 6043, arXiv:0707.0328