Colloquium, Bielefeld, 5 November 2007

Raphaël Granier de Cassagnac
Laboratoire Leprince-Ringuet
PHENIX experiment

CHARMING CHARMONIA IN THE QUARK GLUON PLASMA

THE PROGRAM

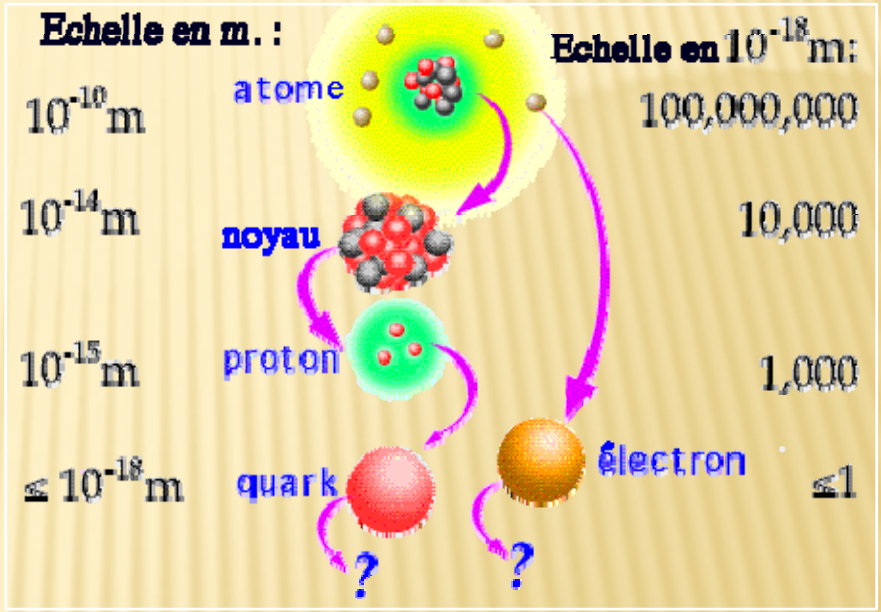
- The quark gluon plasma
  - What is it ? Where to find it ? When ?
  - How to recognize it ?
- Charming charmonia
  - Following a chronological timeline, how charm quarks and “charmonia” mysteriously appeared, disappeared, reappeared, as if by magic…
- Other charms
  - Two golden signatures of the QGP and how charm quarks surprisingly behave…

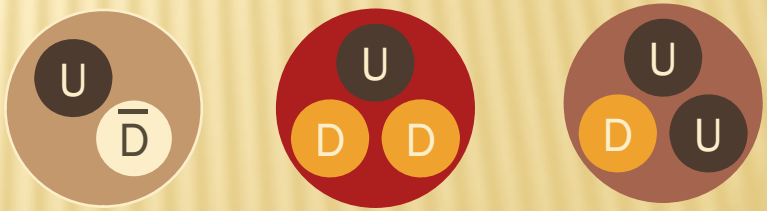
What ? Where ? When ? How ?

THE QUARK GLUON PLASMA

QUARKS, MESONS, BARYONS

- Protons and neutrons are made of quarks tightly bound together by gluons carriers of the strong interaction
- 6 quarks discovered
  - (up, charm, top) charge +2/3
  - (down, strange, beauty) –1/3
- Allowed combinations:
  - Baryons = 3 quarks
    - p (uud), n (udd), etc.
  - Mesons = quark + antiquark
    - pion ($u\bar{d}$), etc.



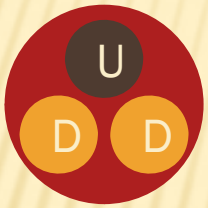


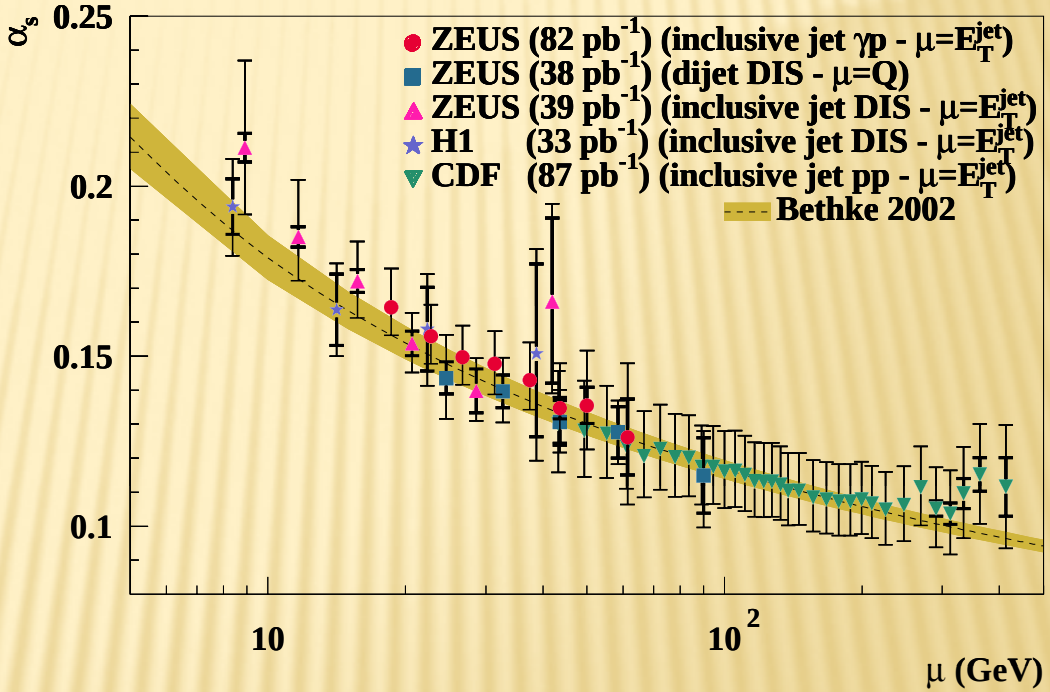
pion neutron proton

(gluons not depicted)

THE STRONG INTERACTION…

- … is strong at low energy, i.e. short distance (≈1fm) ⟶ confinement
  - → No free quark

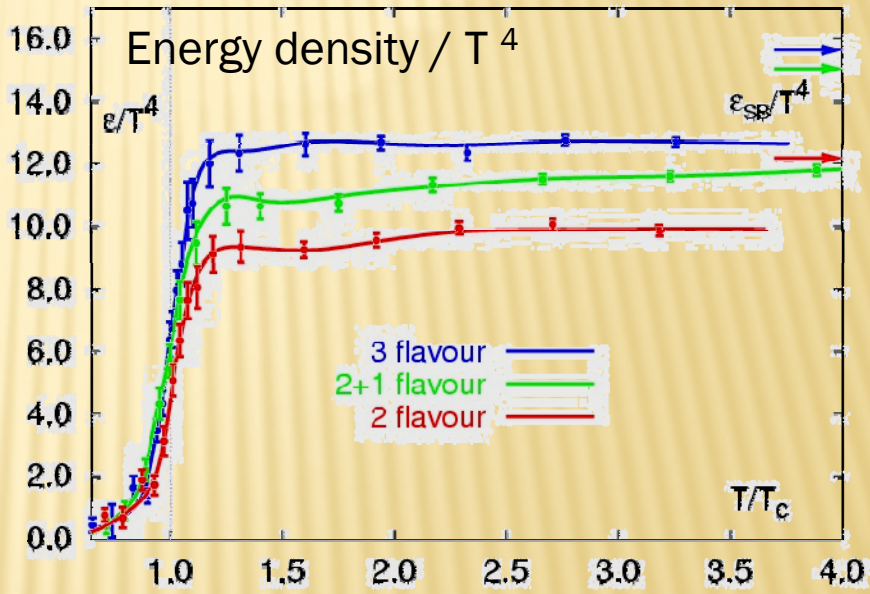




- … but weak at high energy ⟶ asymptotic freedom
- as seen from data and predicted by quantum chromodynamics (QCD)

A STRONG PREDICTION

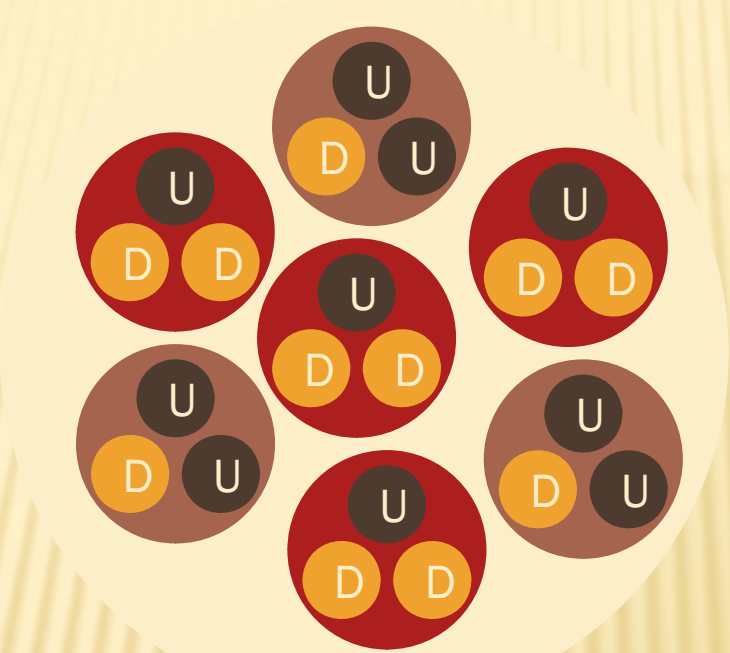
- (Lattice) QCD predicts a phase transition from nuclear matter to a Quark Gluon Plasma (QGP)
- Critical parameters:
  - $T_c \approx 160$ MeV (2×10^{12} K)
    - $\approx 20\,000 \times T_{sun}$
  - $\varepsilon_c \approx 1$ GeV/fm^3
    - $\approx 5 \times$ nuclear density



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

A (VERY) NAIVE PICTURE OF THE QGP

- Above T_c

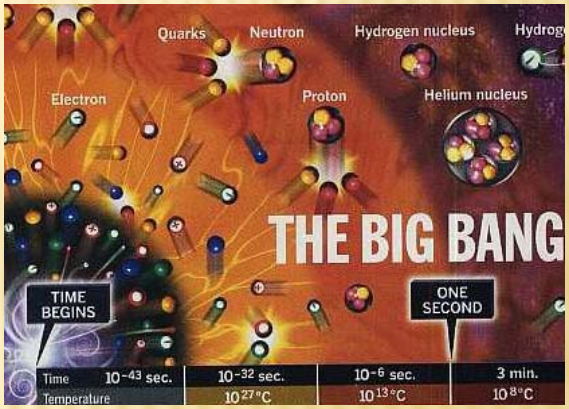


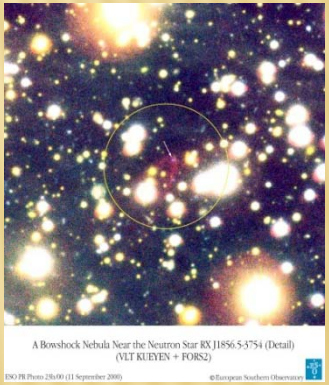
Sorry, powerpoint animated…

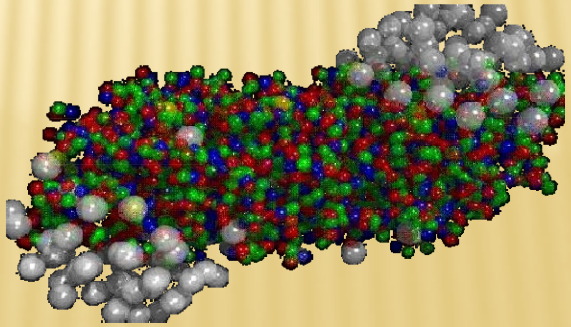
(gluons and secondaries not depicted)

WHERE/WHEN CAN WE FIND THE QGP?

1. Early in the universe (t < 10μs)
   + But little chance to leave relics
2. Core of a compact star
   + No smoking gun candidate so far
3. In the lab, colliding heavy ions
   + Freedom for the quarks…
   + … for some 10^{-23} s





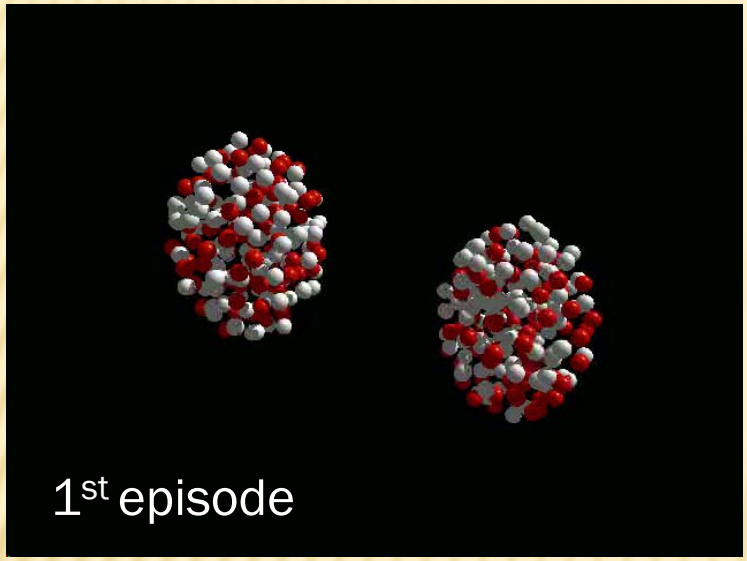


HEAVY ION COLLISIONS

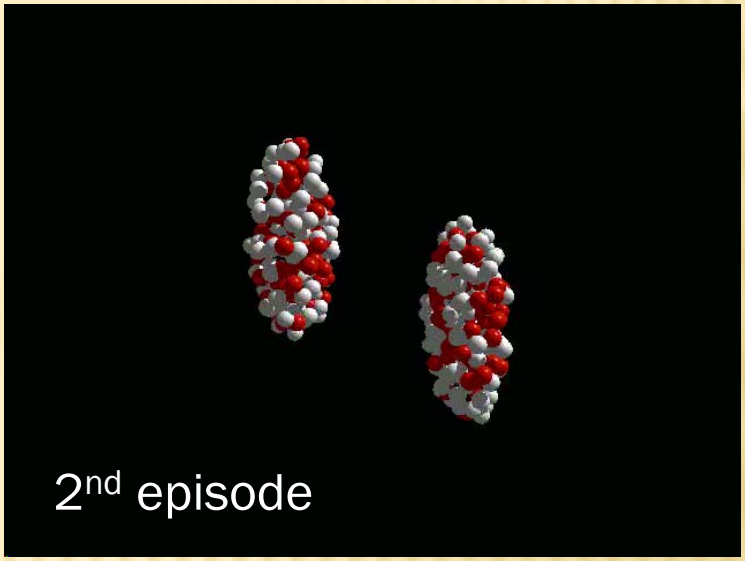
$\sqrt{s_{nn}}$

FIXED TARGET COLLISIONS

1986 BNL - AGS 4 GeV



1994 CERN - SPS 20 GeV



2000 BNL - RHIC 200 GeV

2008? CERN - LHC 5 TeV

FIXED TARGET COLLISIONS

(simulations © RQMD)

EPISODE 2, THE PAST

- SPS: Super Proton Synchrotron
- @ CERN (Geneva)
- Fixed target experiments
  - (WA98, CERES, NA44, NA49, NA57, NA50, NA60…)
- Various collisions p+p, p+A, A+A up to Pb+Pb
- $\sqrt{s_{NN}} \approx 20$ GeV

→ Estimated energy density $\varepsilon \approx 3$ GeV/fm^3 > ε_c

→ In principle, QGP have been produced…

EPISODE 3, THE PRESENT…

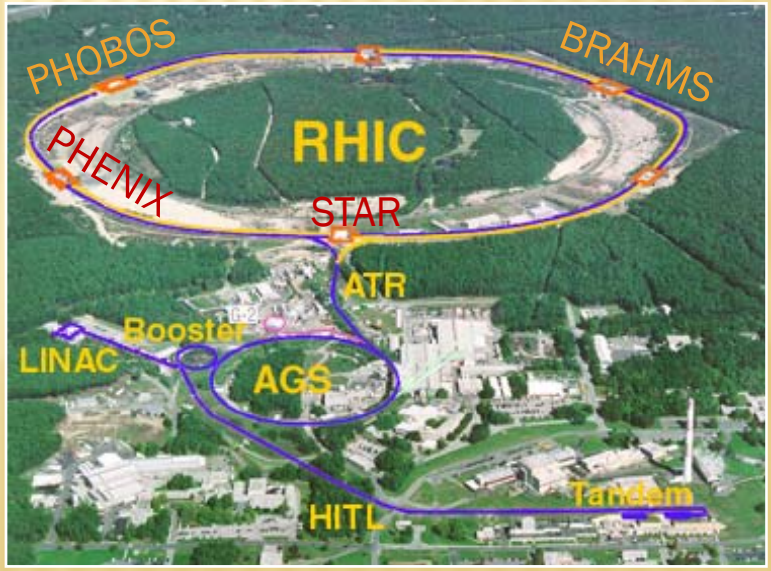
- RHIC: Relativistic Heavy Ion Collider

@ Brookhaven National Lab. (New-York)

  + First collisions in 2000
  + 2 large (STAR & PHENIX)
  + 2 smaller (PHOBOS & BRAHMS) experiments

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

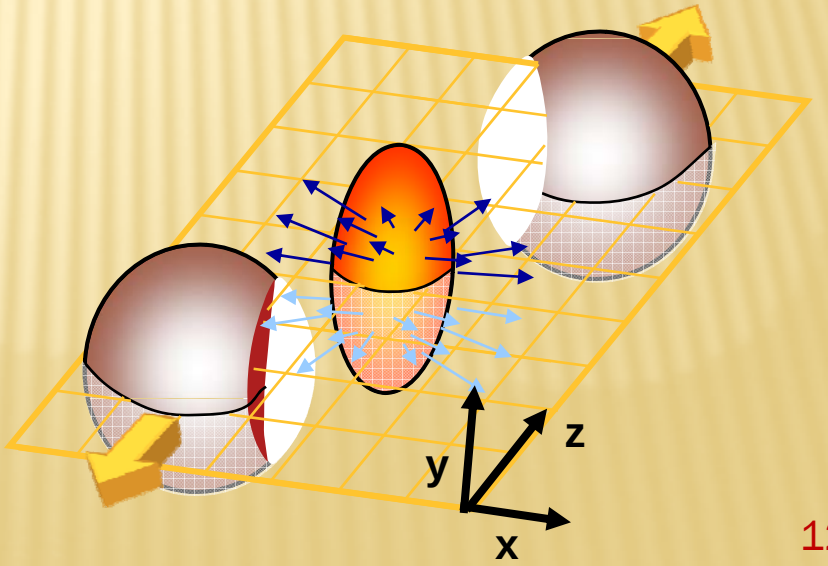
to Au+Au (up to 200GeV per nucleon pairs)



HOW TO FIND THE QGP?

- A theorist predicts a QGP signature
- Experimentalists look at it versus A+A collision centrality →
- Then compare to p+p
- Then compare to p+A
  - Check that normal nuclear matter cannot account for deviations…

- Non zero impact parameter
  - Some spectators
  - Number of participants N_{part}
  - Number of elementary (n+n) collisions N_{coll}



WHICH SIGNATURES?

QGP hints seen at RHIC:

- ✖ Total multiplicity
- ✖ High p_T suppression
- ✖ Back to back jets
- ✖ Elliptic flow
- ✖ Baryon/meson ratio
- ✖ J/ψ suppression
- ✖ Thermal radiation
- ✖ …

But others ones were also predicted!

"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?

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 others ones were also predicted!

"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

One of the quark gluon plasma signature

CHARMING CHARMONIA

THE CHARM QUARK

- 4^{th} quark to have been discovered (1974)
  - Was expected from weak interaction
    - "It appeared like a charm" around 1964
    - A partner to the strange quark
    - GIM mechanism (1970)
    - Strong theoretical need for a fourth quark

Glashow, Iliopoulos, Maiani, PRD2 (1970) 1285

Lepton	Neutrino
Electron	ν_e
Muon	ν_μ

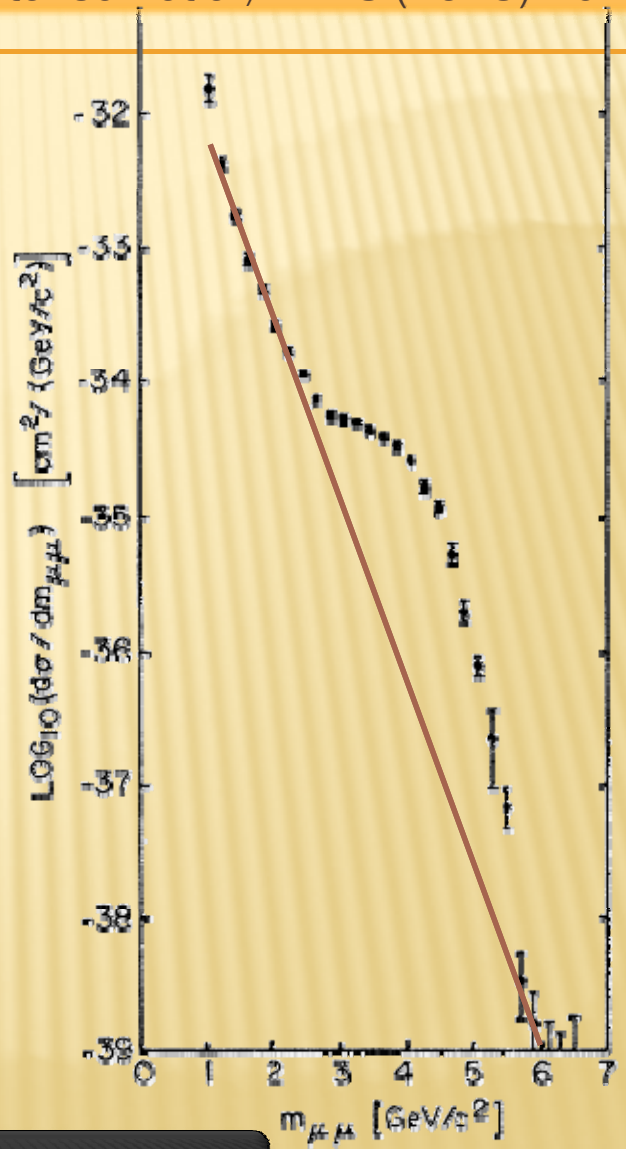
Quark +2/3	Quark -1/3
Up	Down
???	Strange

Charm is summoned by theoretical magic

1973: NON DISCOVERY

Christenson et al, PRD8 (1973) 2016

- $p+U \rightarrow \mu^+\mu^-$ (@ 30 AGeV)
- An excess above continuum
  - around 3 GeV/c^2
- No conclusion
  - Poor resolution (~500 MeV/c^2)
- We now know this was
  - Bound state of ($c\bar{c}$) $\rightarrow \mu^+\mu^-$

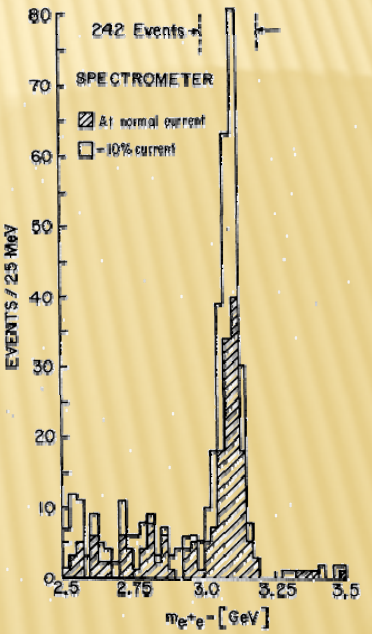


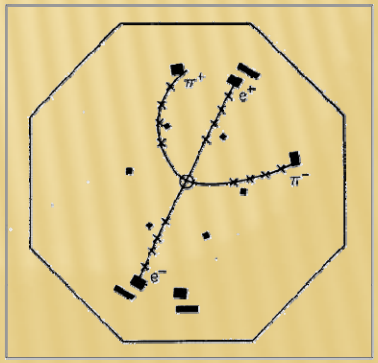
Charm appears without being noticed...

1974: J & Ψ DISCOVERY

Augustin et al, PRL33 (1974) 1404
Aubert et al, PRL33 (1974) 1406
Ting and Richter, Nobel prize 1976

- With much better resolutions, two teams discover at the same time:
  - *"Experimental Observation of a Heavy Particle J"*
  - *"Discovery of a Narrow Resonance in e^+e^- Annihilations"* → ψ
- First particle containing charm
  - $(c\bar{c})$ most stable bound state J/ψ
  - Other "charmonia" soon after: ψ', χ_c...

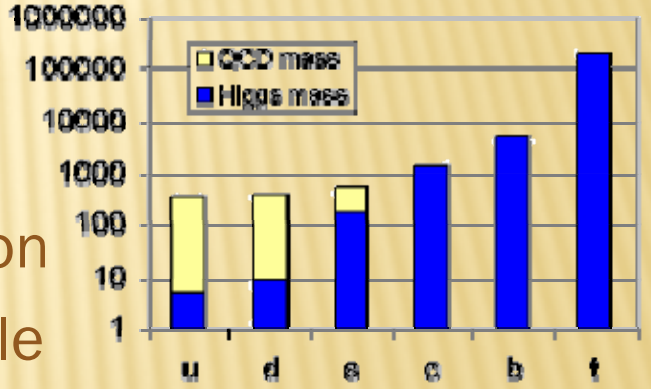


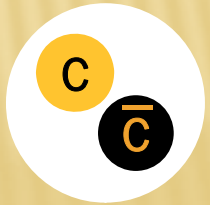


Charm is seen simultaneously in two different places...

THE CHARM QUARK

- 4th quark to have been discovered (1974)
  - Was expected from weak interaction
    - "it appeared like a charm"
  - But interesting strong properties
    - Heavy (1.5 GeV/c^2) more than a proton
    - Its dynamics are in principle calculable
    - Very few charm quarks produced (by $c\bar{c}$ pairs)
  - A few bound to form a "charmonia" (3.1 GeV/c^2)
    - Fast formation $\approx 10^{-25}$ s
    - "Slow" leptonic decay $\approx 10^{-21}$ s
  - Excellent QGP ($\approx 10^{-23}$ s) probe



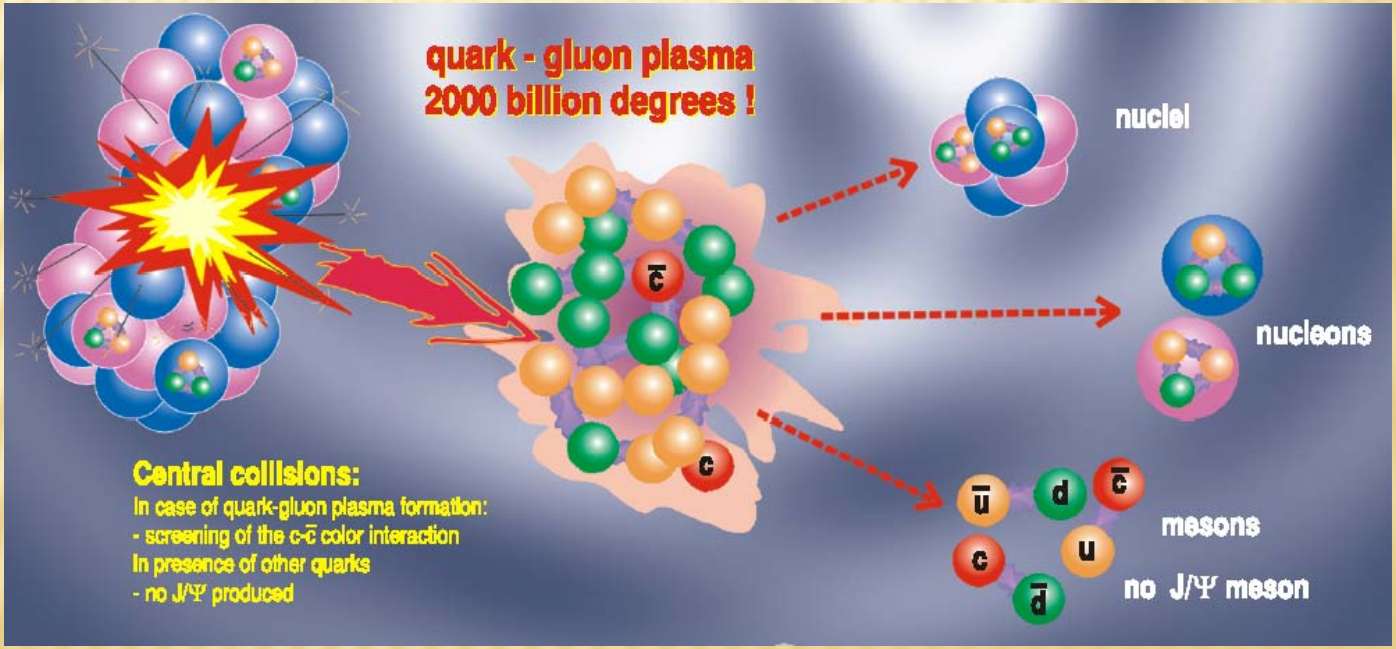


J/ψ

1986: J/Ψ IN QGP

Matsui & Satz, PLB178 (1986) 416
(Another Bielefeld paper, 1060 citations)

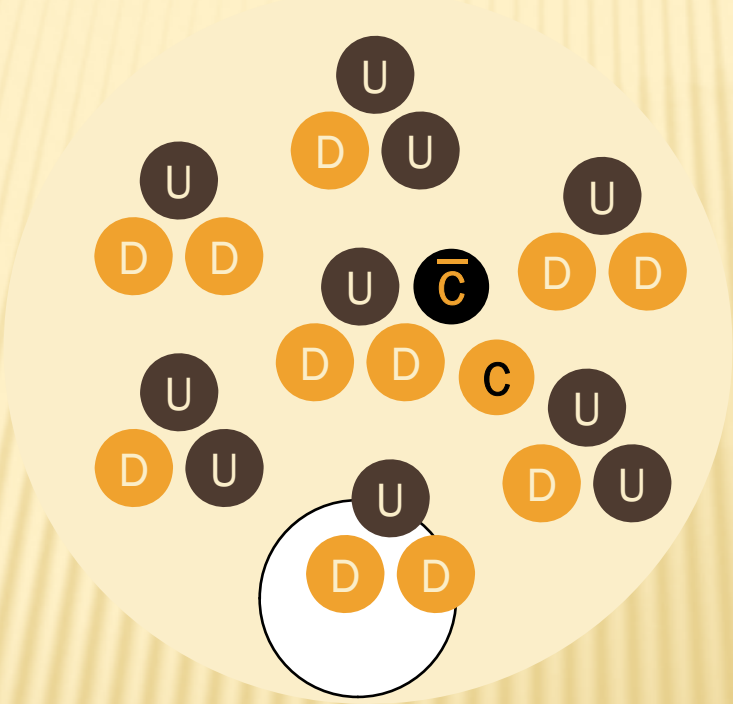
- J/ψ should melt in the QGP, just above T_c
  - Due to screening of the $c\bar{c}$ interaction
  - *"Unambiguous signature of quark gluon plasma"*



✵ *The magical potion should make charmonia disappear...*

THE NAIVE PICTURE OF J/Ψ SUPPRESSION

- Creation of $c\bar{c}$ (always in pairs)
- Separated by QGP



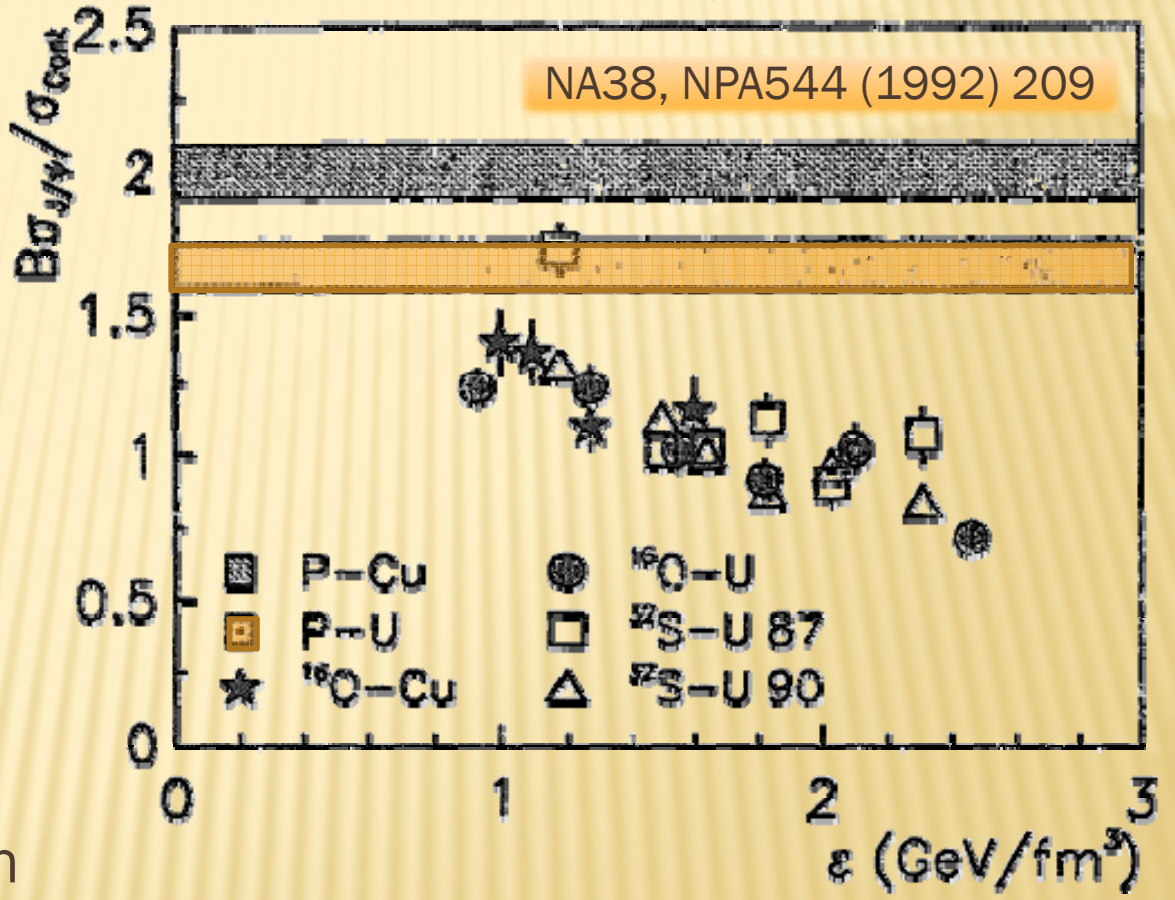
Sorry, powerpoint animated…

→ D meson

(gluons and secondaries not depicted)

1986–92: 1ST J/Ψ SUPPRESSION @ SPS

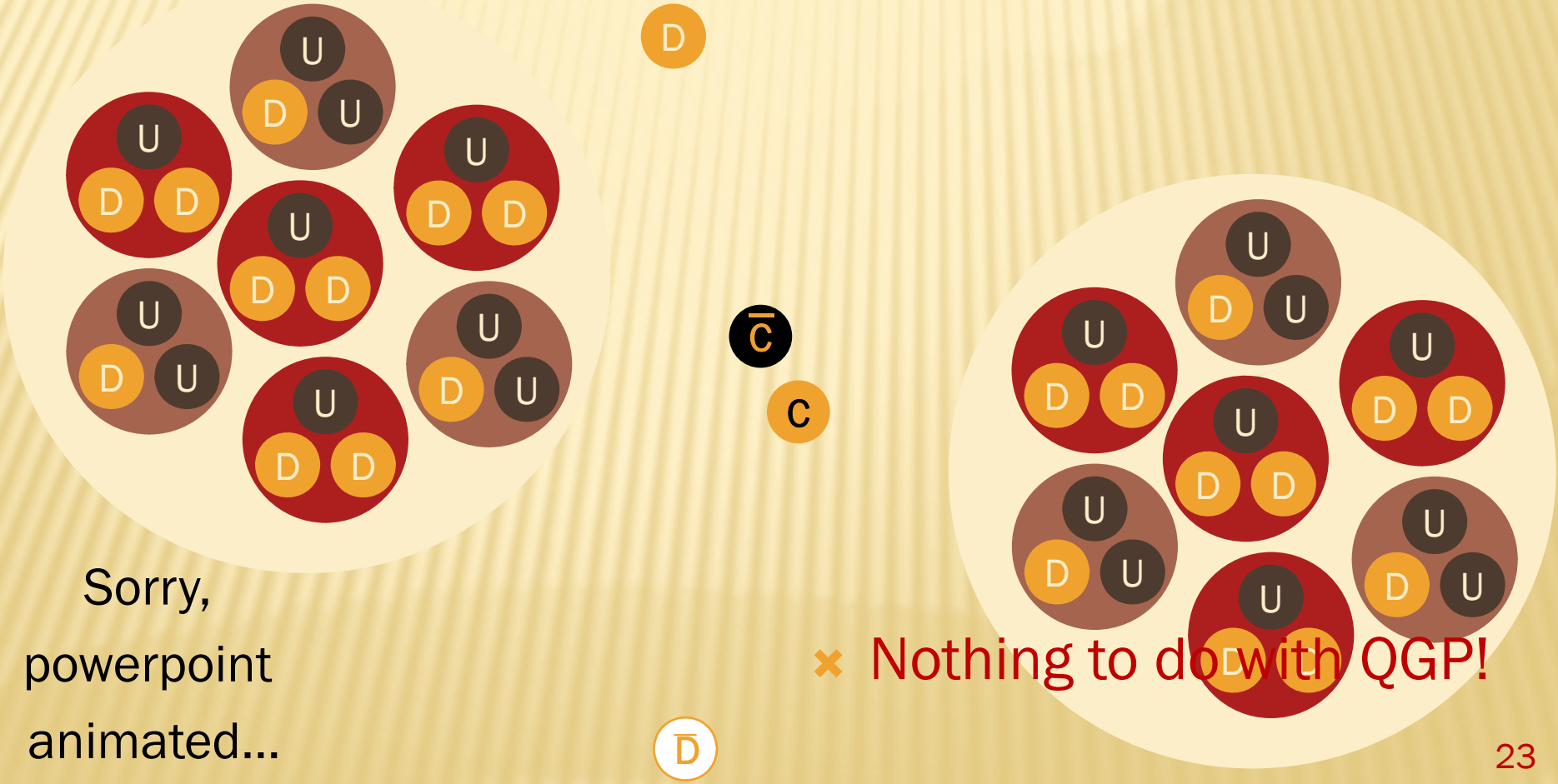
- Quickly, NA38 saw J/ψ suppression
  - normalized to the $\mu^+\mu^-$ continuum
  - in S+U versus p+U collisions
- But this was an illusion
  - not due to QGP !
  - Nuclear absorption



✵ *Charmonia disappear by (nuclear) dark magic*

J/Ψ NORMAL NUCLEAR ABSORPTION

- @SPS, nuclei take 5×10^{-24} s to cross (1.6 fm/c)
- They can separate $c\bar{c}$ (formation time $\approx 10^{-25}$ s)

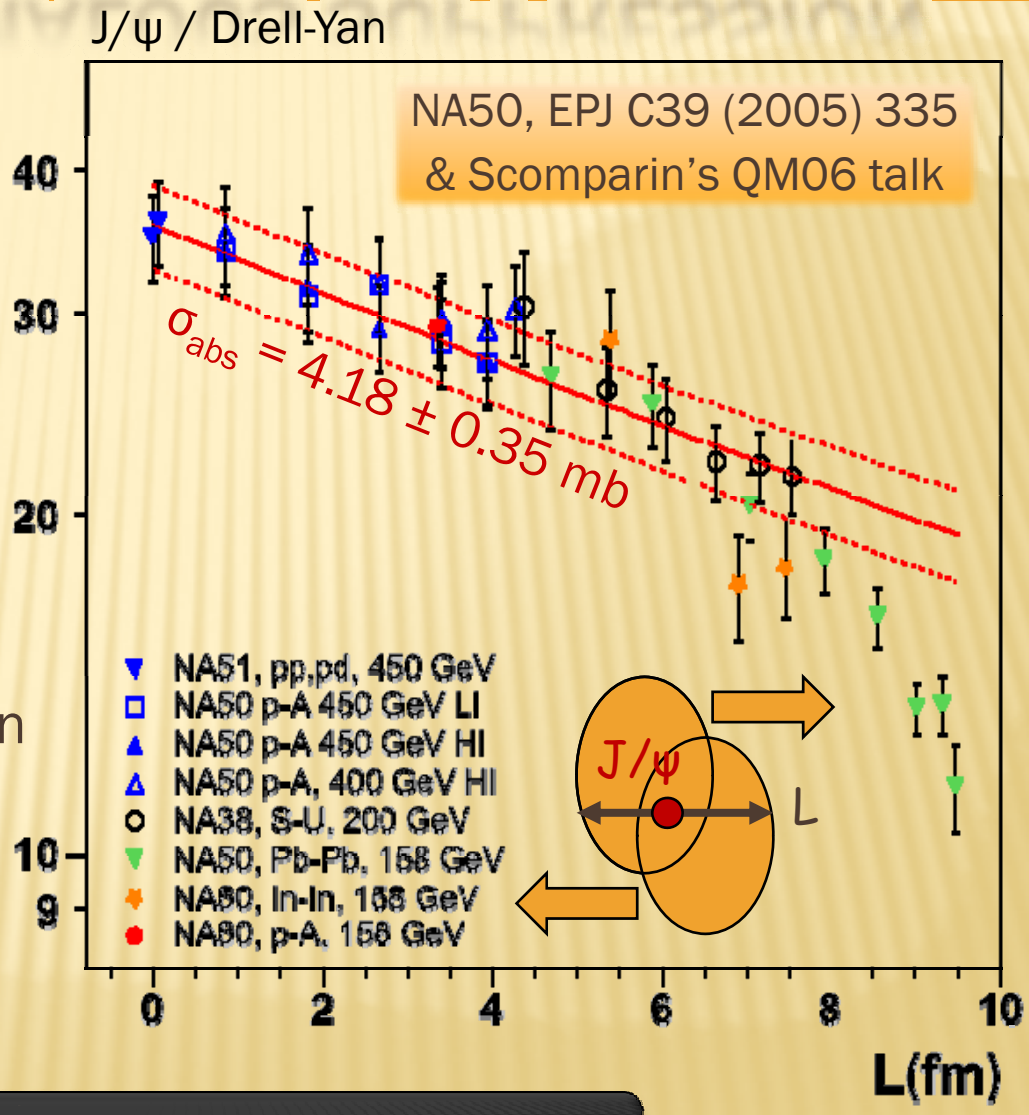


Sorry, powerpoint animated...

- Nothing to do with QGP!

1995–2000: ANOMALOUS SUPPRESSION

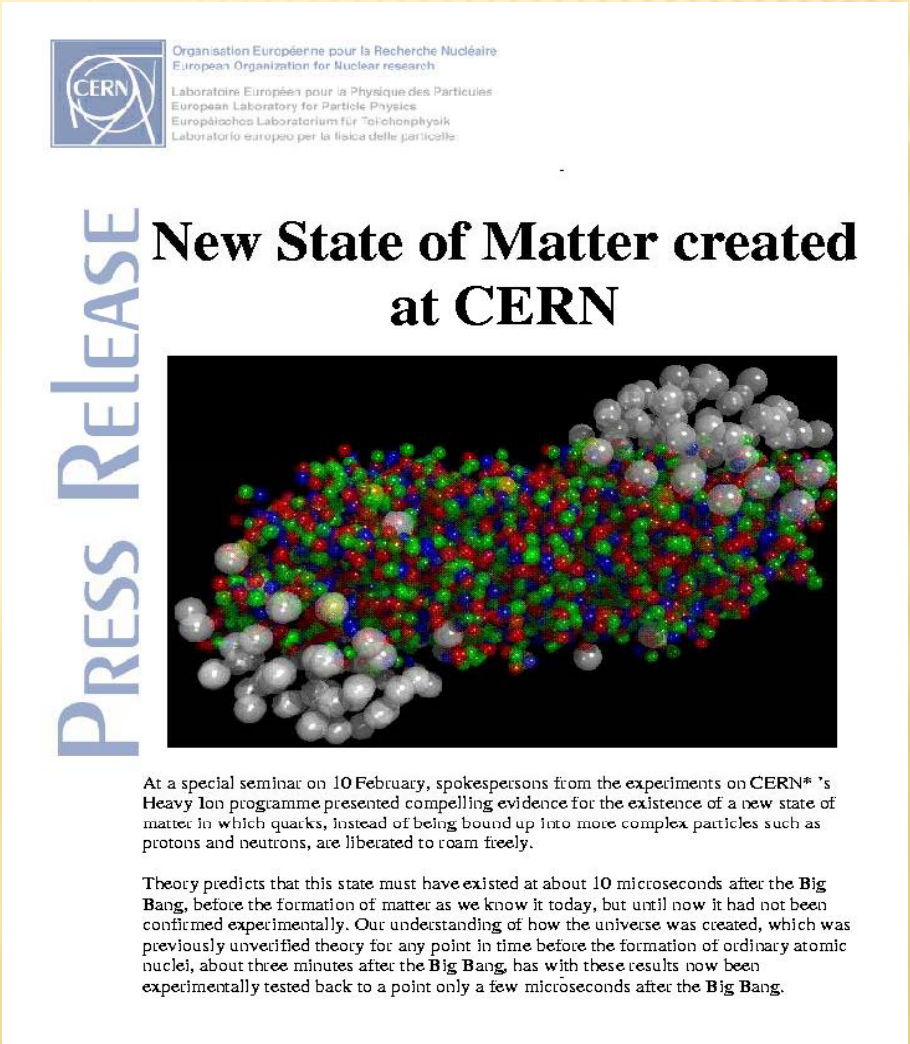
- J/ψ / Drell-Yan
  - DY = $q\bar{q} \rightarrow$ gamma $\rightarrow \mu\mu$
  - Unaffected by QGP
- As a function of L
  - Nuclear thickness
  - Related to centrality
- In p+A, S+U collisions:
  - $\exp(-\sigma_{abs}\, \rho_0\, L)$
  - Normal nuclear absorption
- In central Pb+Pb:
  - Anomalous suppression
  - Likely to be due to QGP !



✵ *Charmonia finally vanish in the plasma!*

AN ANNOUNCEMENT

- Based on this (and a bit more) CERN announced the discovery of QGP on February 10th 2000
- First collisions at RHIC began soon after
- J/ψ was expected to melt further…



Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear research
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics
Europäisches Laboratorium für Teilchenphysik
Laboratorio europeo per la fisica delle particelle

PRESS RELEASE

New State of Matter created at CERN

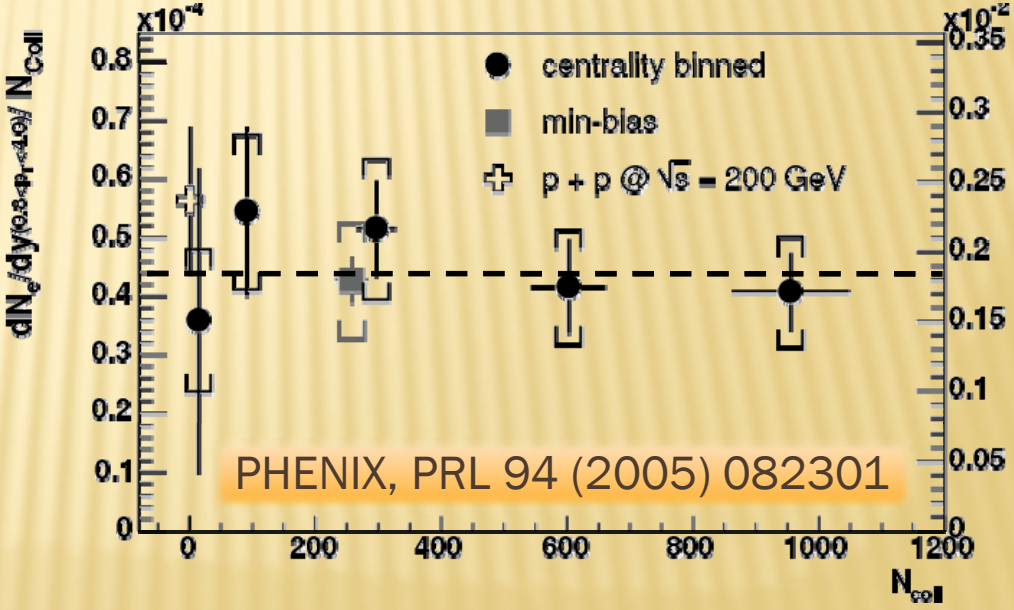
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

J/Ψ @ RHIC, WHAT REFERENCE?

- No Drell-Yan to refer to
- We define a nuclear modification factor R_{AA}
  - J/ψ normalized by the number of elementary collisions N_{coll}
- Limited open charm (Dmesons = $u\bar{c}$…) results:
  - ≈ 25% uncertainty
  - Do scale with N_{coll}
  - Same initial state a J/ψ

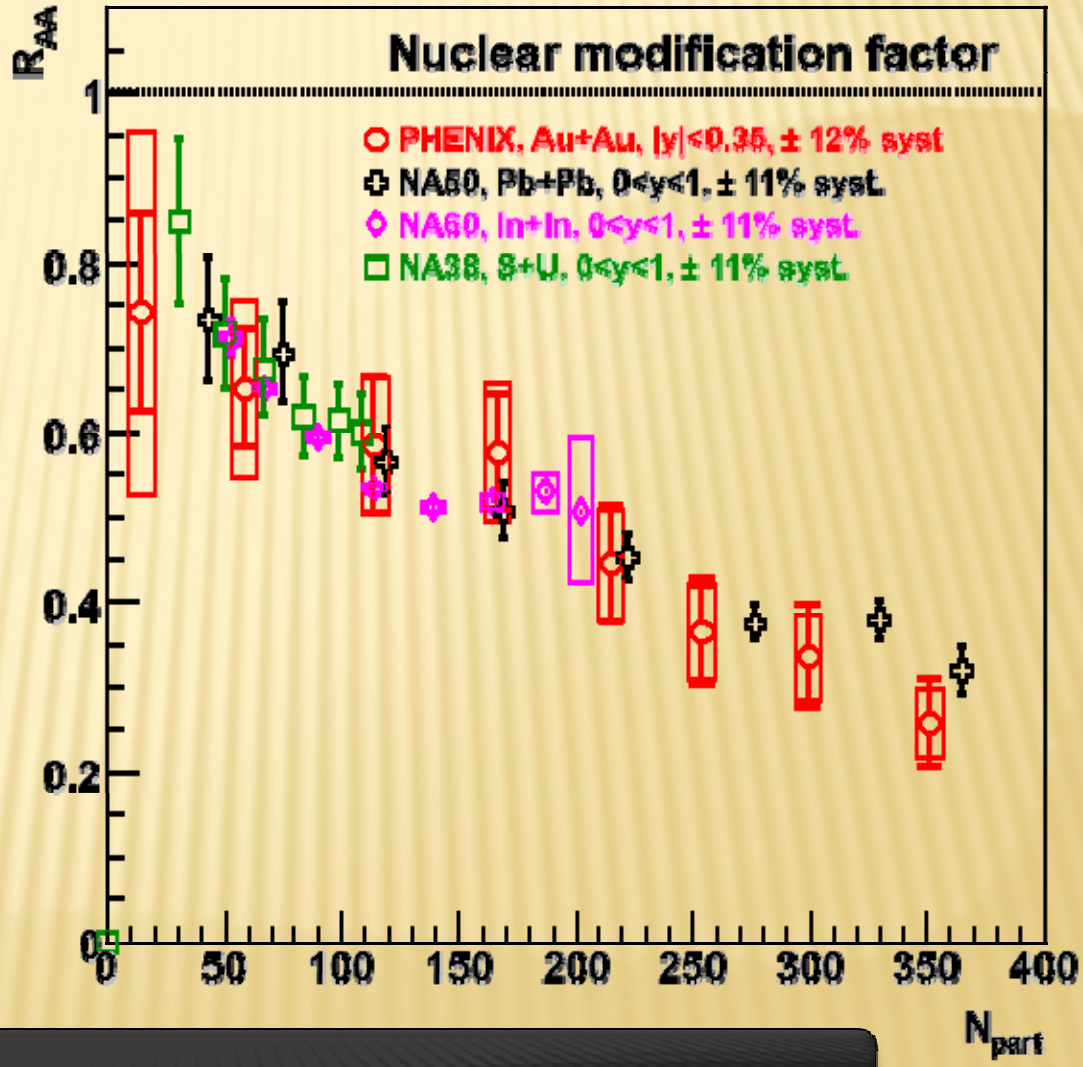
$$R_{AA} = \frac{dN^{AuAu}}{dN^{pp} \times \langle N_{coll} \rangle}$$



Charm quarks have reached immortality

J/Ψ @ RHIC AND @ SPS

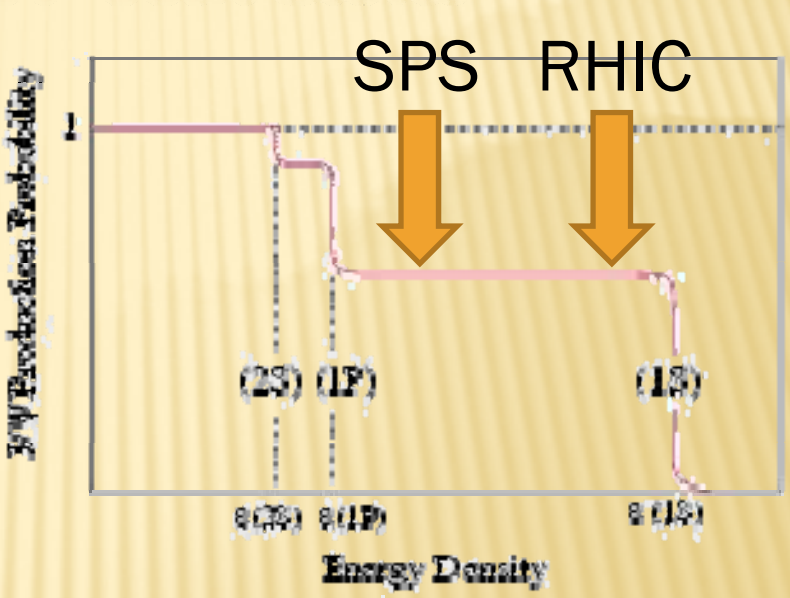
- Unexpectedly similar pattern
  - Energy density is higher @ RHIC
  - Different normal suppression
- This brings the idea of sequential melting…



RHIC alchemists change Pb in Au but do not melt more charmonia

THE IDEA OF SEQUENTIAL MELTING

- Some J/ψ come from excited $c\bar{c}$ states:
  - $\Psi' \rightarrow J/\Psi + \ldots$
  - $X_c \rightarrow J/\Psi$ + photon
  - Ratio not known better than 10%
  - $J/\Psi \approx 0.7\ J/\Psi + 0.2\ \Psi' + 0.1\ X_c$
- They melt at different temperatures
  - Theoretically not under control, but some says:
    - $T(J/\psi) \approx 2\ T_c$
    - $T(\psi') \approx T(\chi_c) \approx 1\ T_c$

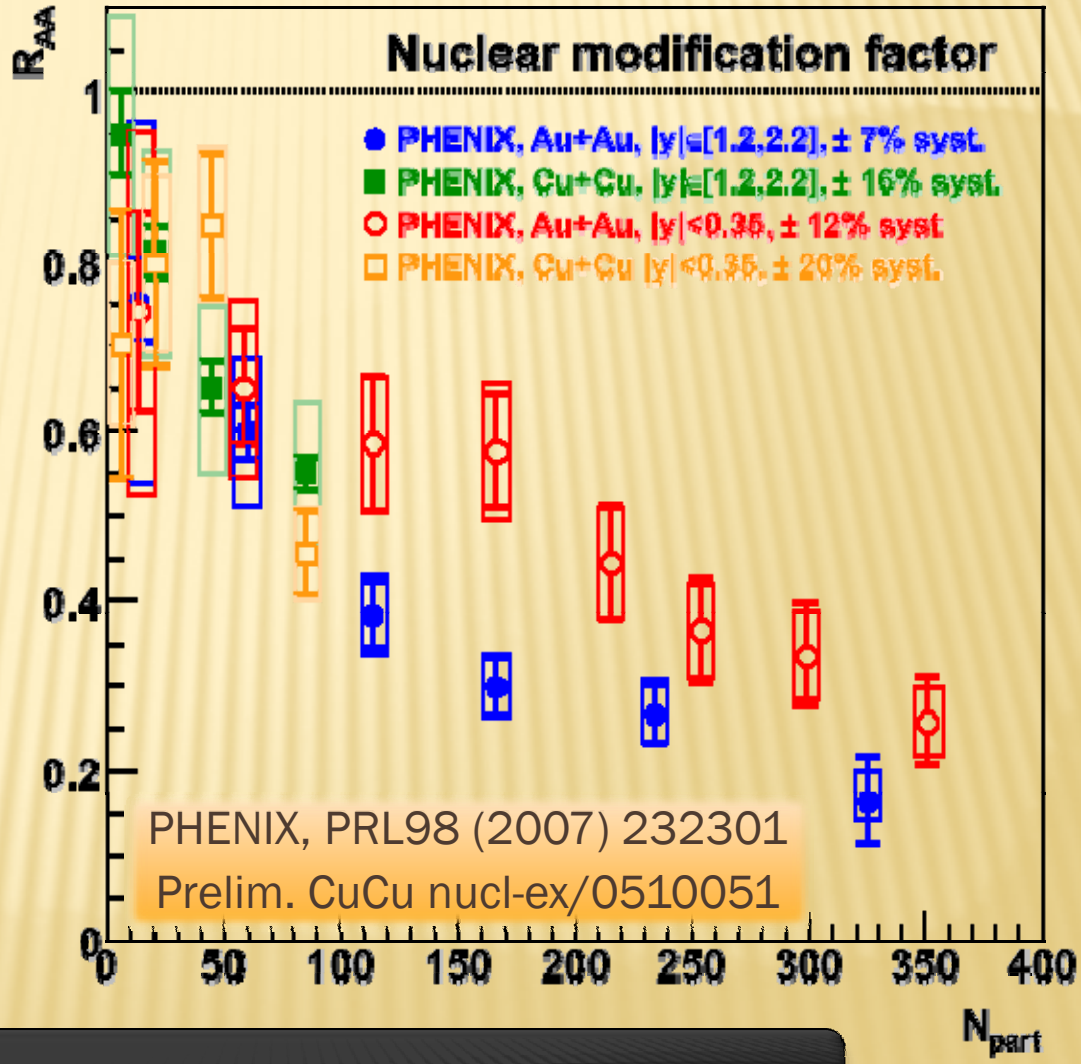


- Anomalous suppression: compatible with 0.7 @SPS
- Direct J/ψ could survive both @SPS and @RHIC

→ A good idea, but there is another result @ RHIC…

MORE OR LESS J/Ψ @ RHIC

- Higher suppression @ forward rapidity
- While the energy density should be lower there…
- Density-induced enhancement mechanism ?



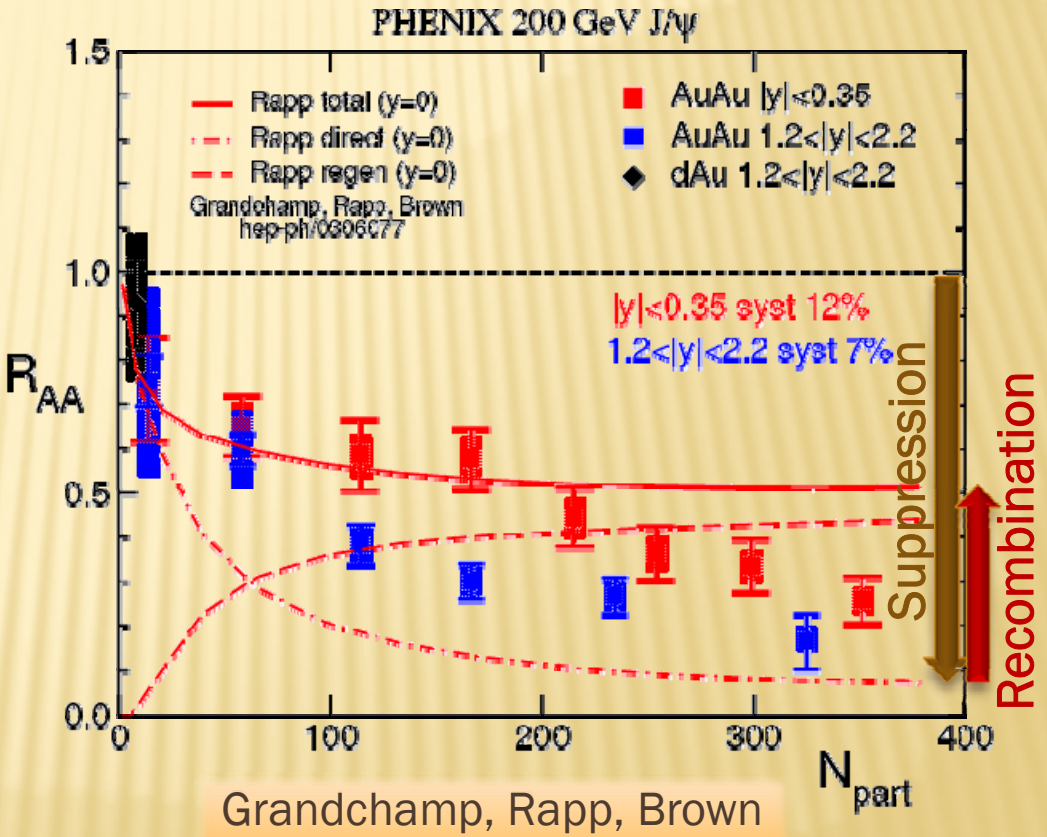
PHENIX, PRL98 (2007) 232301
Prelim. CuCu nucl-ex/0510051

✵ *Charmonia may be reappearing by enchantment*

THE IDEA OF RECOMBINATION

- A lot of $c\bar{c}$ pairs
  - (10 to 20 in central collisions @ RHIC)
- Uncorrelated $c\bar{c}$ could meet at freeze-out and form new charmonia
- Enhanced production
  - $N(J/\psi) \propto (c\bar{c})^2$
- Suppression vs. enhancement

→ A recombination prediction (among many others)

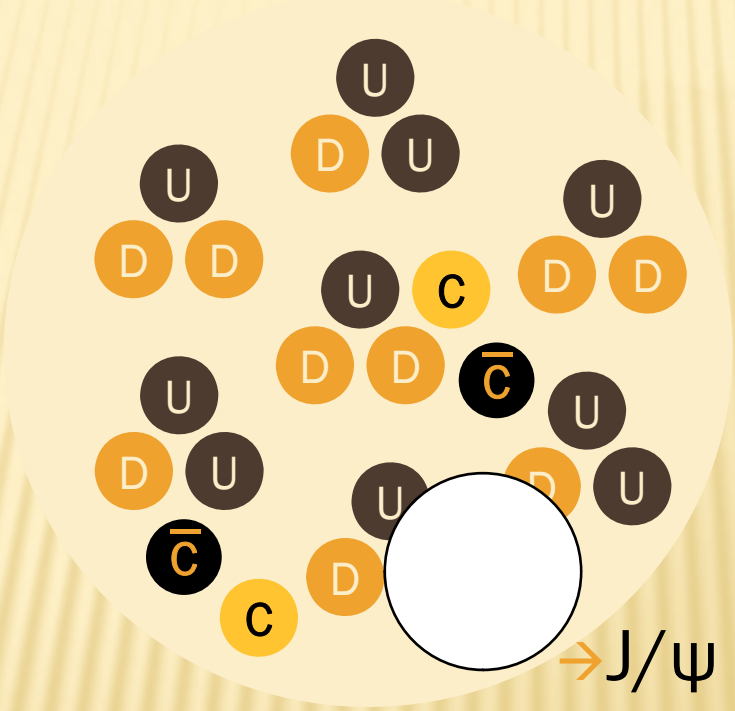


Grandchamp, Rapp, Brown
PRL 92,(2004) 212301

→ A good idea, but predictions not enough constrained...

THE NAIVE PICTURE OF RECOMBINATION

- Uncorrelated $c\bar{c}$ could meet in QGP



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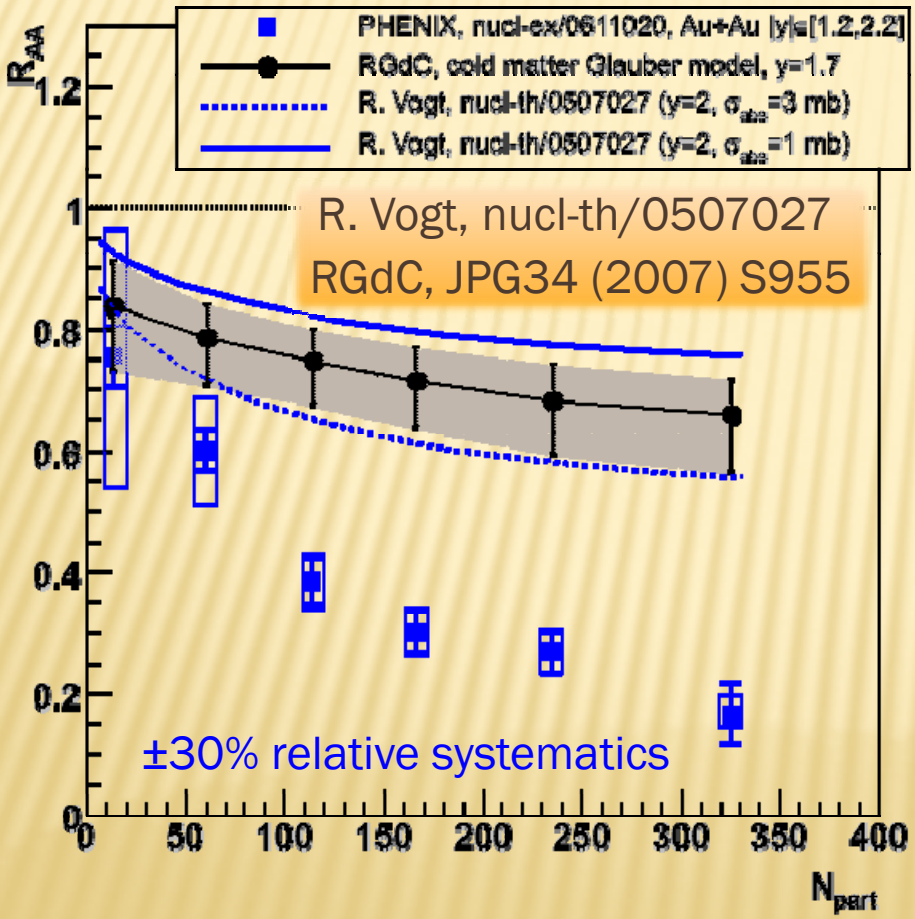
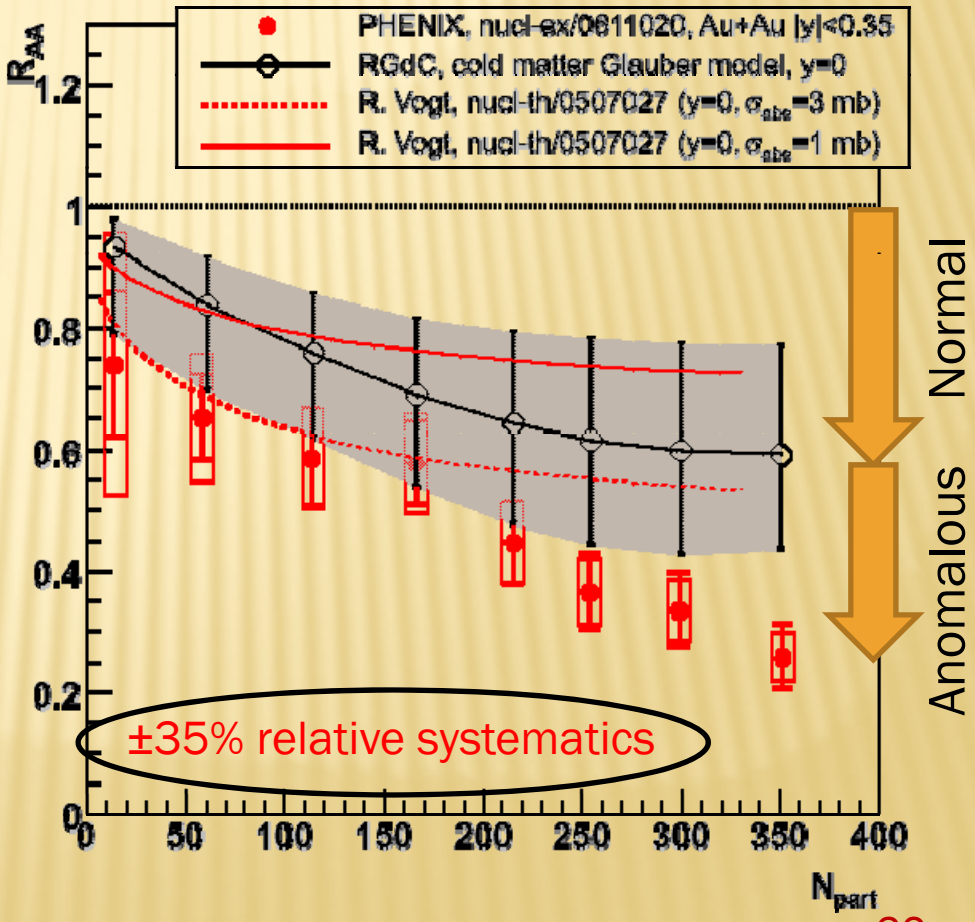
(gluons and secondaries not depicted)

NORMAL SUPPRESSION @ RHIC ?

- Not well measured
  - + Very low p+A statistics
- Large uncertainty once extrapolated to A+A

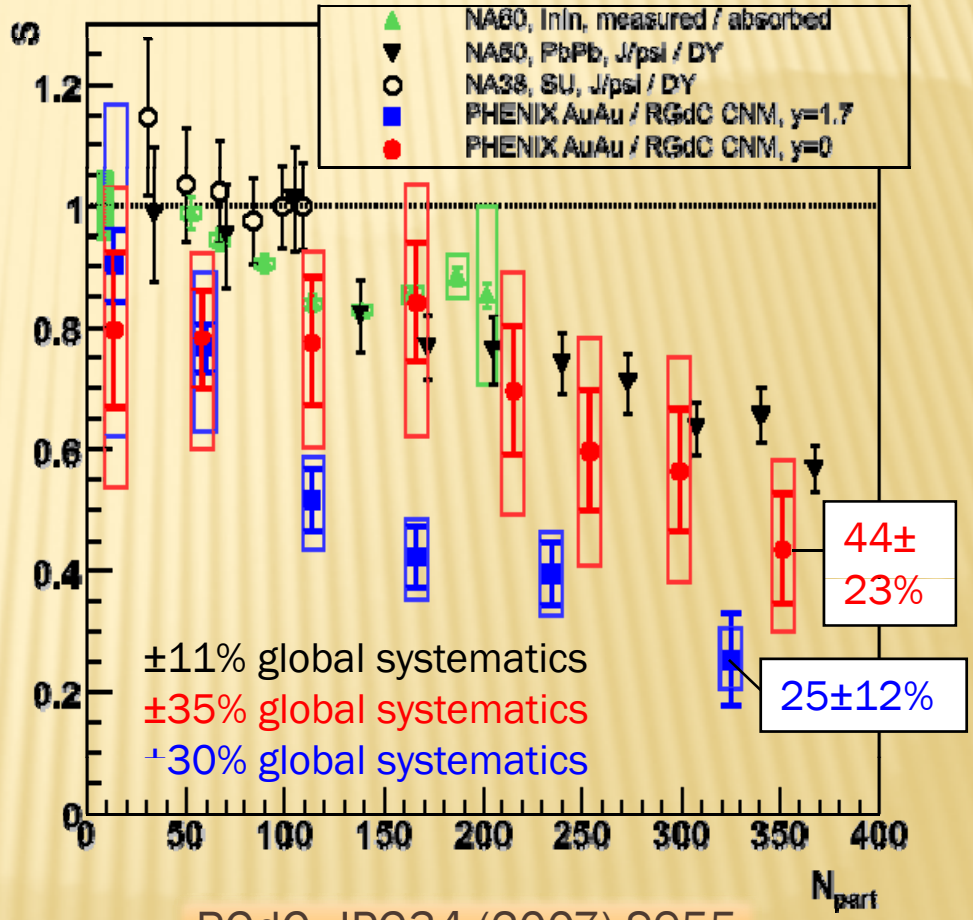




A LAST J/Ψ PICTURE

- J/ψ in A+A divided by normal suppression extrapolations (poorly known @ RHIC)
  - Need better constraint on normal suppression
  - Could account for rapidity dependence ?
- However J/ψ do melt anomalously…
  - In particular direct J/ψ

J/ψ survival probability in QGP



RGdC, JPG34 (2007) S955

ANOMALOUS CONCLUSION

- J/ψ melt anomalously @ SPS and RHIC
- Not understood @ RHIC
  - Less density = more suppression !
    - Recombination ?
    - Normal suppression ? (+ sequential melting ?)
  - Large uncertainties, but new measurements are expected!
- However, even if the details are not understood, this is one of the QGP signs @ RHIC !

Charmonia have charming unexpected behaviours

Charm quarks and the golden signatures

OTHER CHARMS

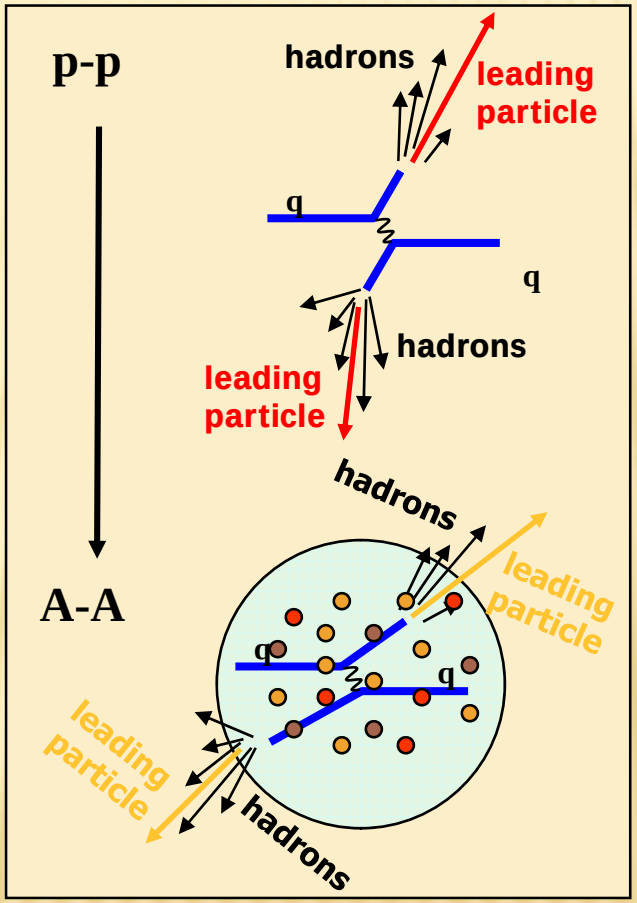
GOLDEN SIGNATURES @ RHIC

- Two striking features of RHIC data (at least)
  1. "Jet quenching "
  2. "Elliptic flow"
- Measured with numerous light particles
- Are signatures of the quark gluon plasma

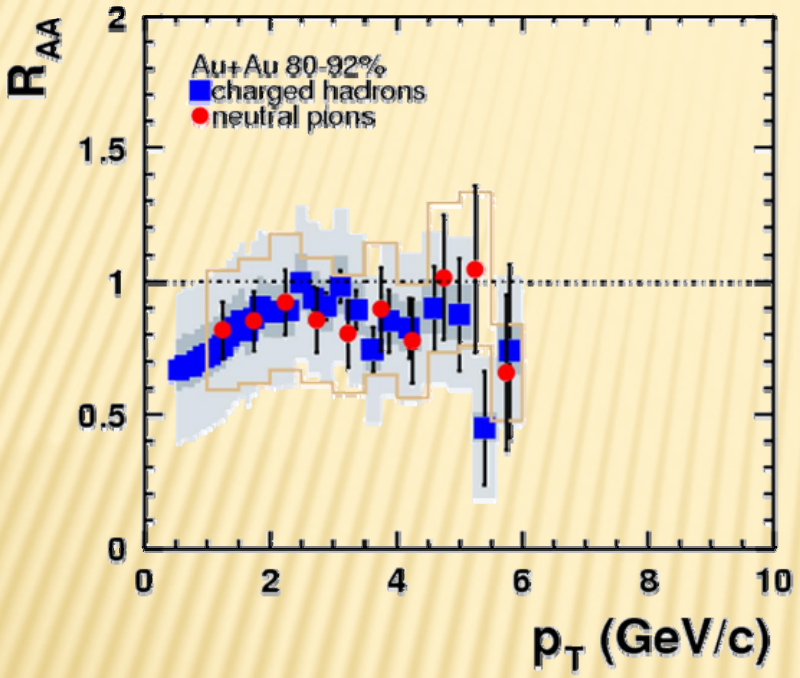
- How heavier (charm) particles behave?

1. JET QUENCHING

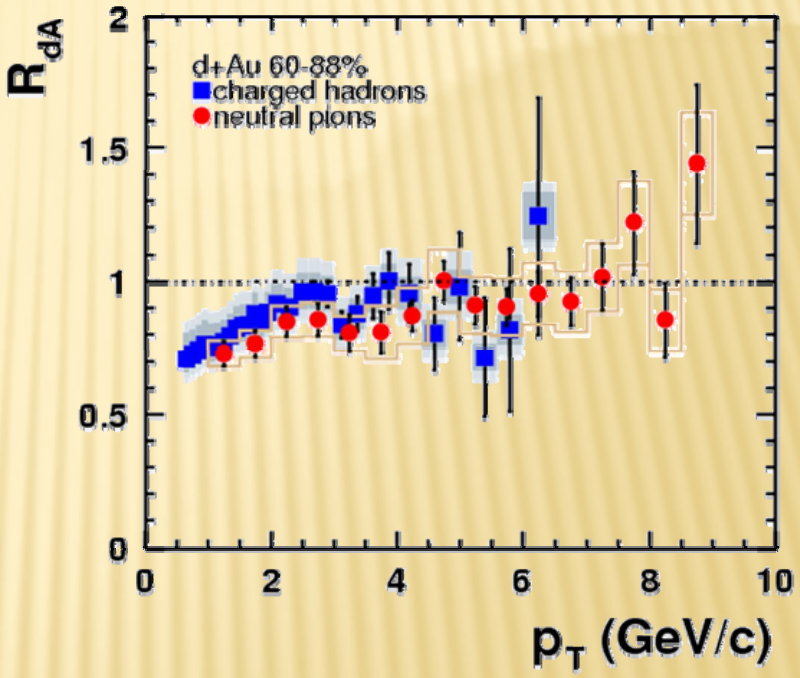
- RHIC smoking gun signature !
  - Two PRL covers
- Energy loss in the matter, looking at high p_T (>2GeV)
  - Mostly from jet fragmentation
- "Jet quenching"



Au-Au (80-92%)



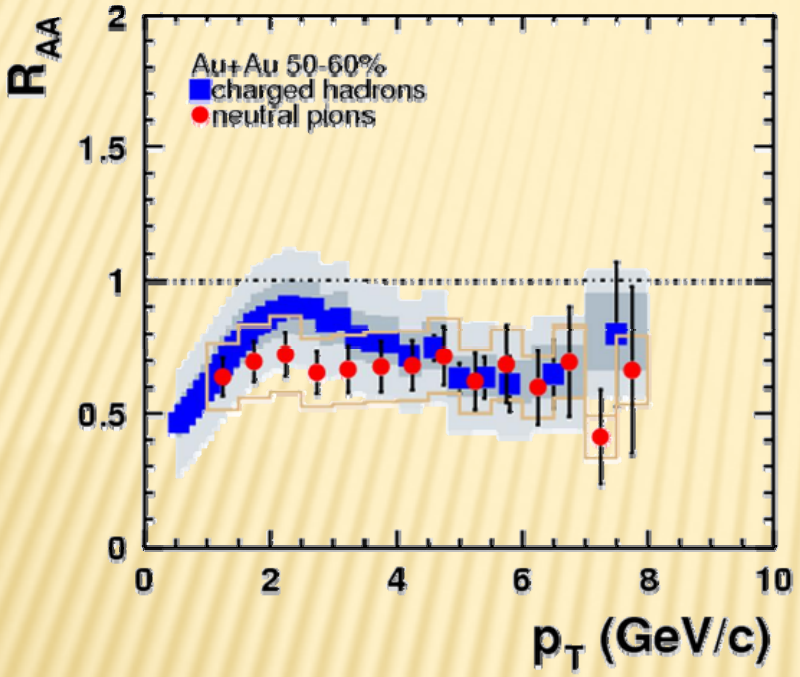
d+Au (60-88%)



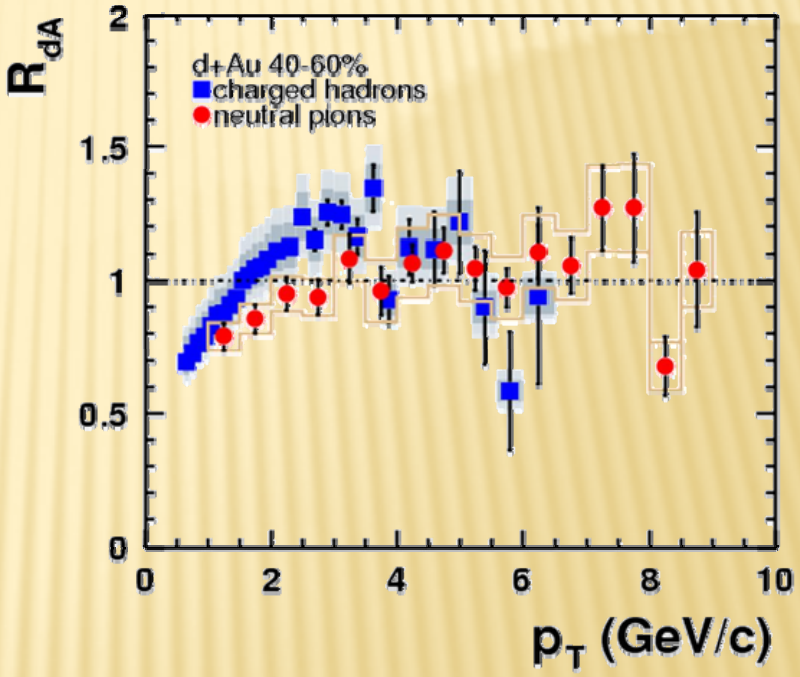
MOST PERIPHERAL COLLISIONS…

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

Au-Au (50-60%)



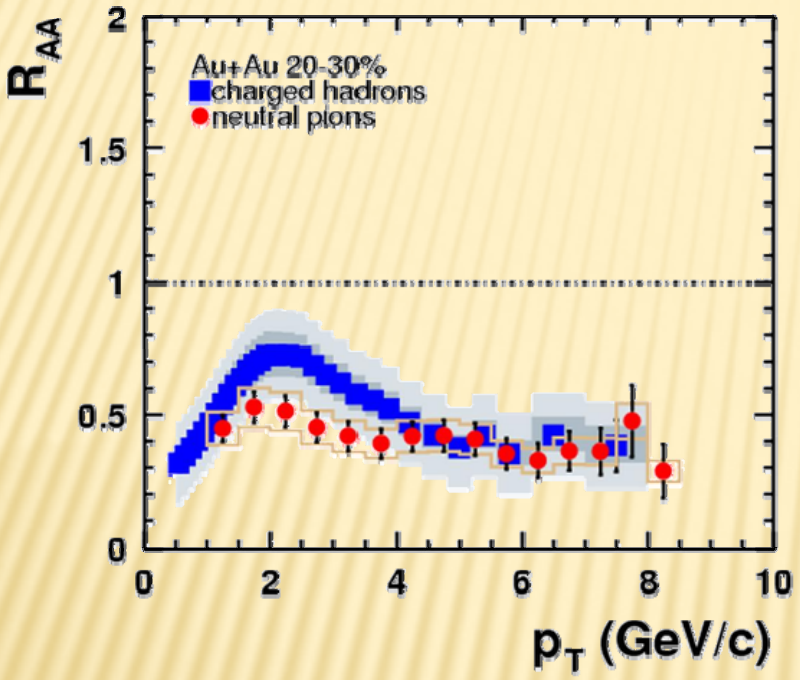
d+Au (40-60%)



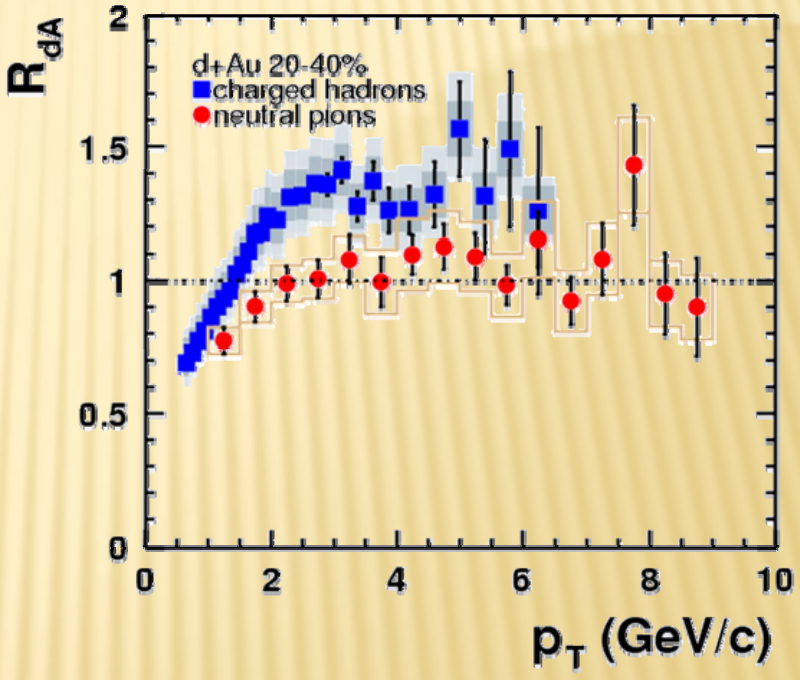
LESS PERIPHERAL COLLISIONS…

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

Au-Au (20-30%)



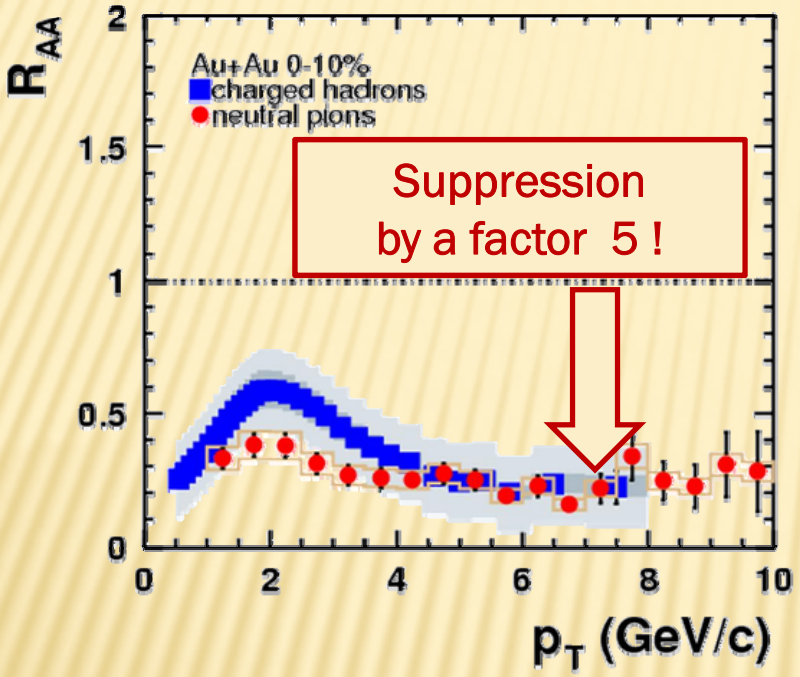
d+Au (20-40%)



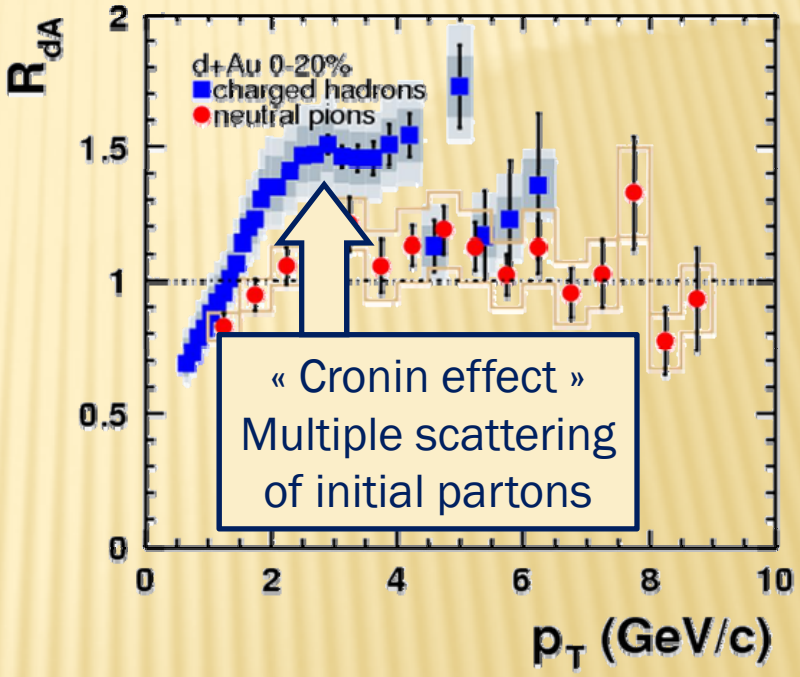
MORE CENTRAL COLLISIONS...

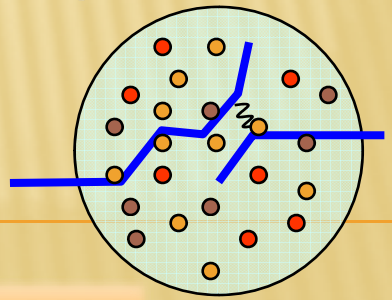
(slightly old, but pedagogical, data) PHENIX, PRL 91 (2003) 072303

Au-Au (0-10%)



d+Au (0-20%)





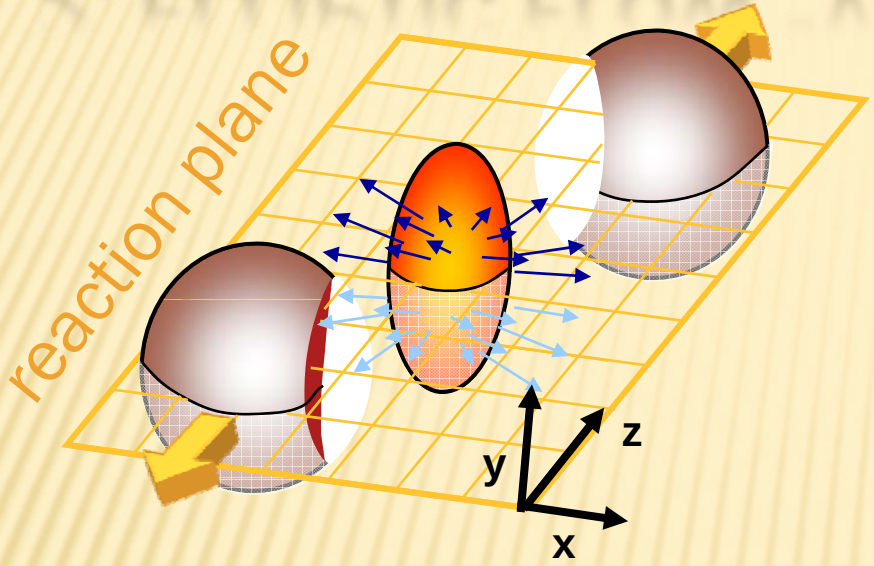
MOST CENTRAL COLLISIONS!

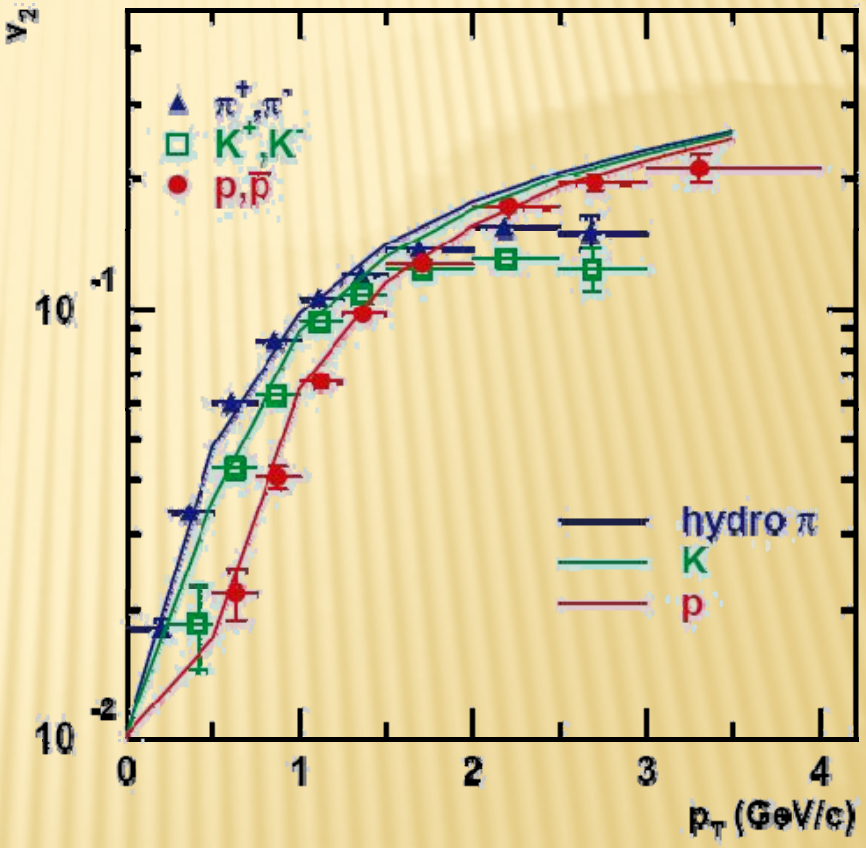
(slightly old, but pedagogical, data)

PHENIX, PRL 91 (2003) 072303

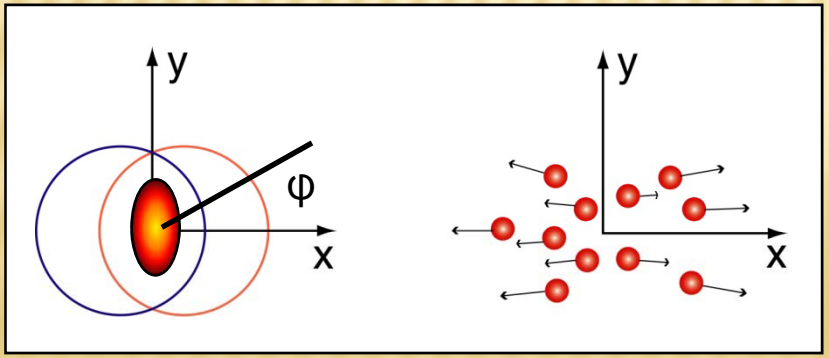
2. ELLIPTIC FLOW "v_2"

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





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



→ Strong collective behavior

IDEAL HYDRODYNAMICS

- Ideal hydrodynamics…
  - + QGP EoS,
  - + Early thermalization
    - × (0.6 fm/c)
  - + High density
    - × (~30 GeV/fm^3)
- Little need for viscosity!

… reproduces fairly well

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

- PQG is not the foreseen ideal partonic gas!

→ Quarks are strongly interacting (“sQGP”)

→ In a liquid like manner (“perfect fluid”)

HEAVY QUARKS ?

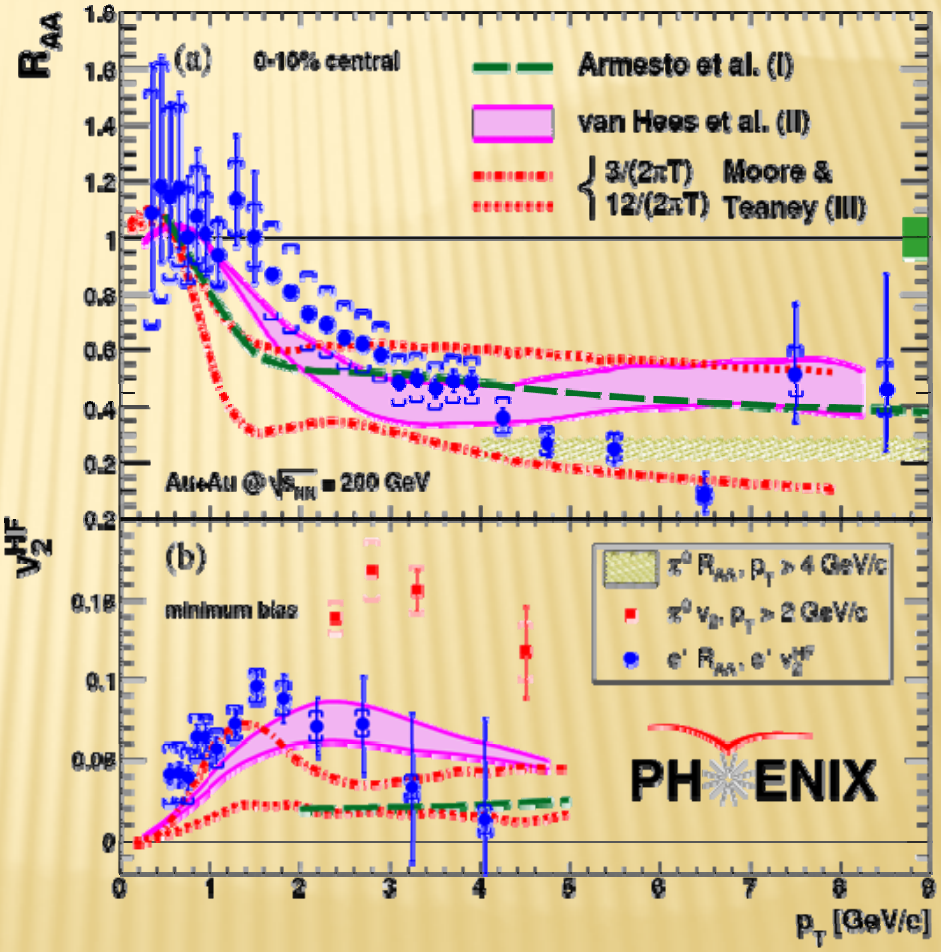
PHENIX, PRL98, (2007) 172301

- Electrons from heavy flavour's decay (mostly charm, but some beauty)

1. Most of charm (low p_T) scale with N_{coll} but high p_T are suppressed
   + As much as light particles
2. Charm quark also have large elliptic flow
   + Thermalization?

- Two suprises !
  + Not well understood yet

D,B → e + …



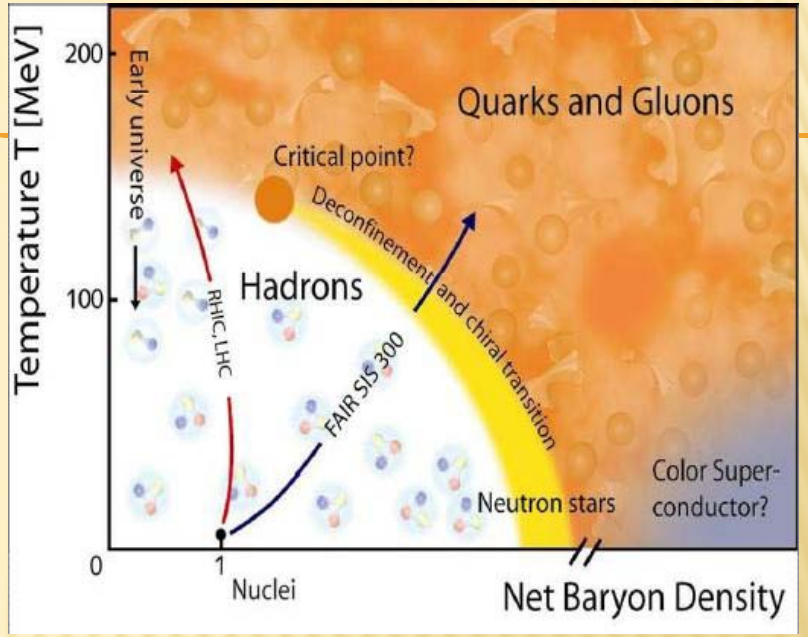
Charm quarks have charming collective behaviours

CONCLUSIONS

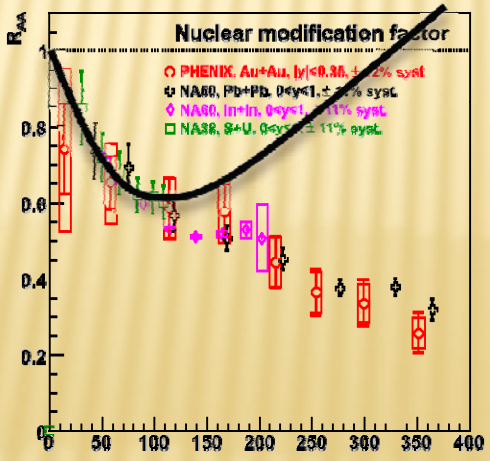
- The quark gluon plasma is surprising
- Unambiguous signatures become ambiguous
  - J/ψ suppression
- Others become golden signature
  - Jet quenching

- This, is the charm of this field…

EPISODE 4: THE FUTURE

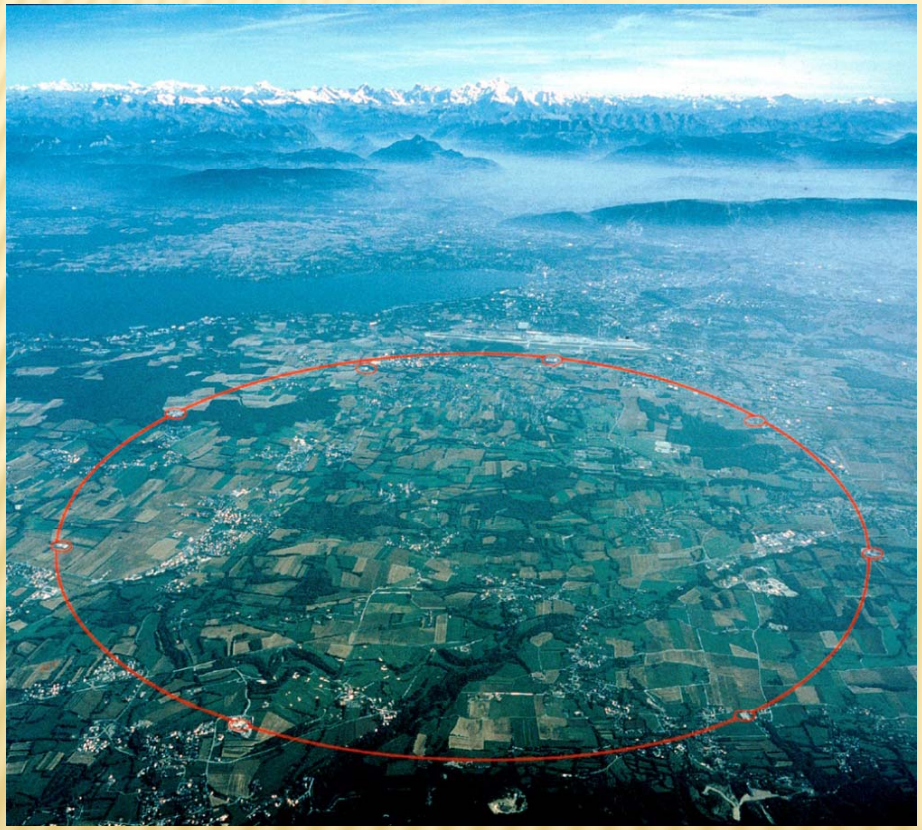


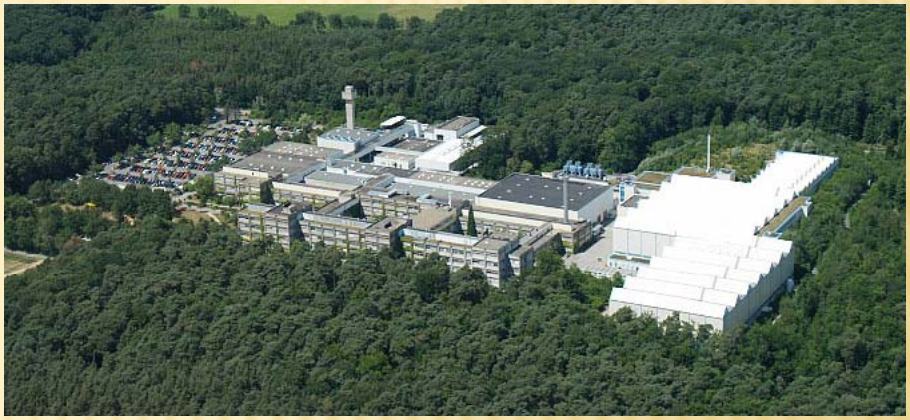
1. Back to CERN, always higher in energy
   - + (i.e. temperature)
   - × Large Hadron Collider :
     - + Pb+Pb @ $\sqrt{s_{nn}}$ = 5.5 TeV
     - + First collisions (p+p) in 2008?
   - × Recombined J/ψ could raise with centrality?
   - × Golden sign → (empirical line)

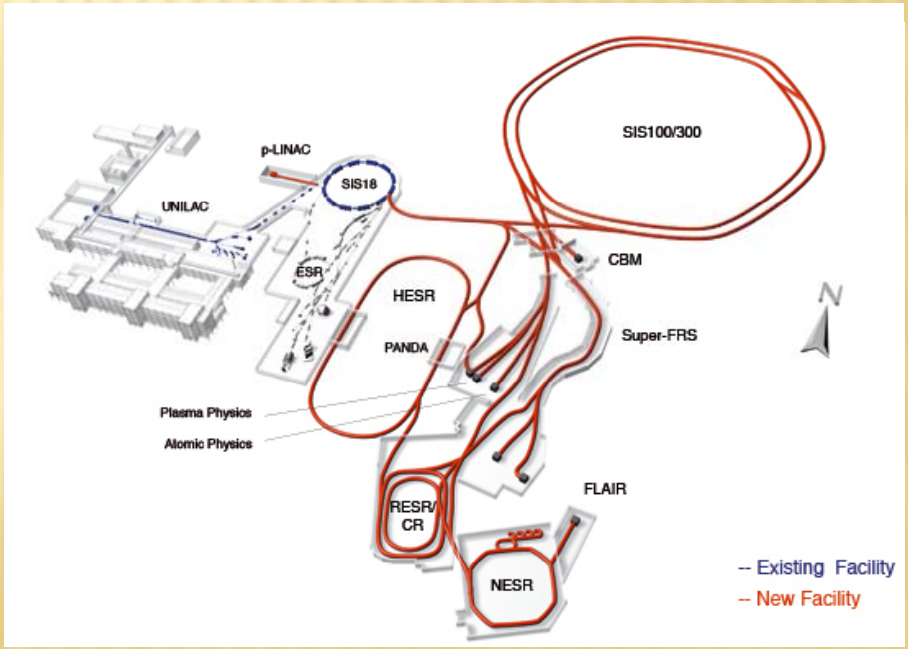


2. @ GSI, FAIR gets higher baryon densities
   - ≈ 10 times nuclear
   - + Critical point?
   - + Collision by 2015?

EPISODE 4: THE FUTURE





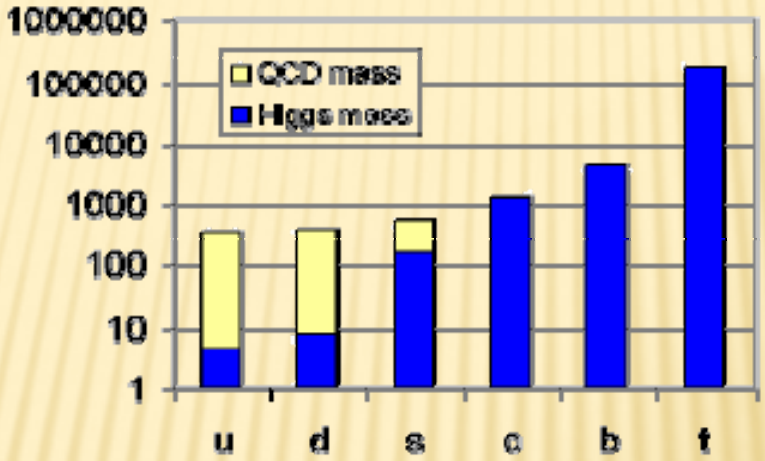


Back-up slides

THAT'S ALL FOLKS

☺ THE ORIGIN OF (MY) MASS…

~ 98% from QCD + 02% from Higgs !



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

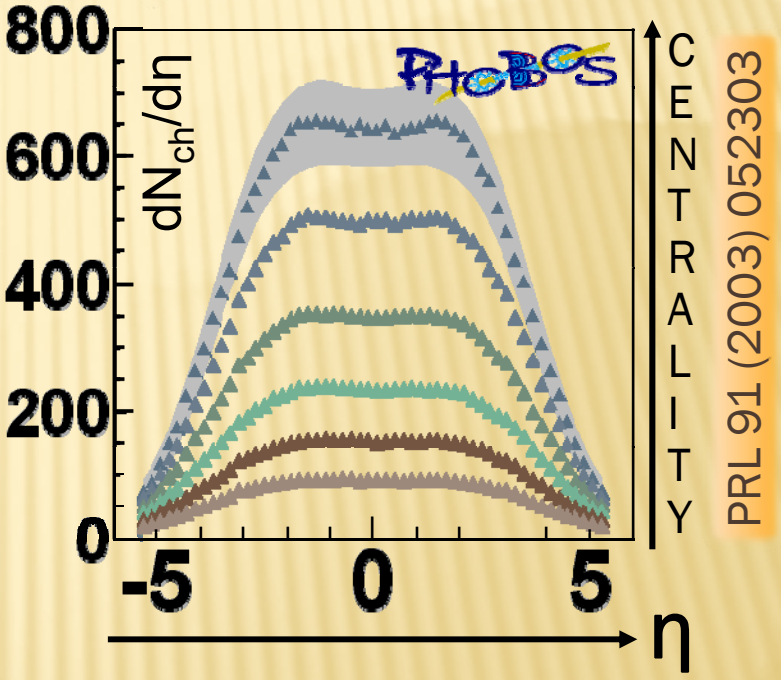
- We are mostly made of confinement…
- Thus, let's look at deconfinement…

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

TOTAL MULTIPLICITY (AND E_T)

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

→The (initial) matter saturates

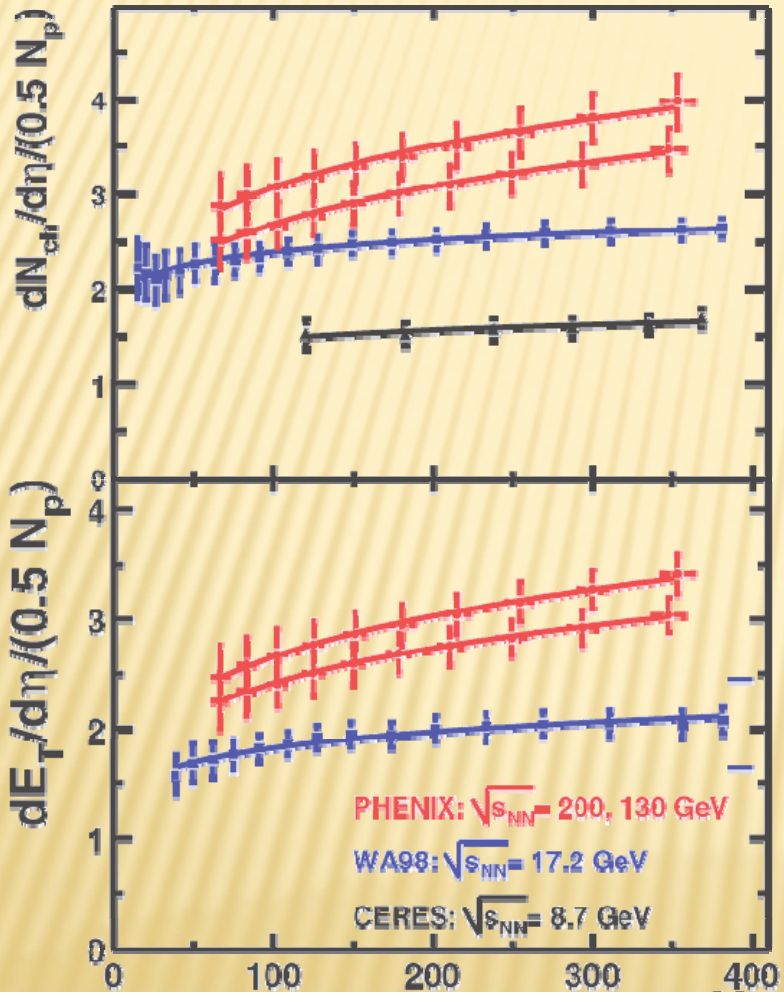


PRL 91 (2003) 052303

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

HOW TO ESTIMATE ENERGY DENSITY ?

~ Transverse energy @ y=0



Bjorken formula

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

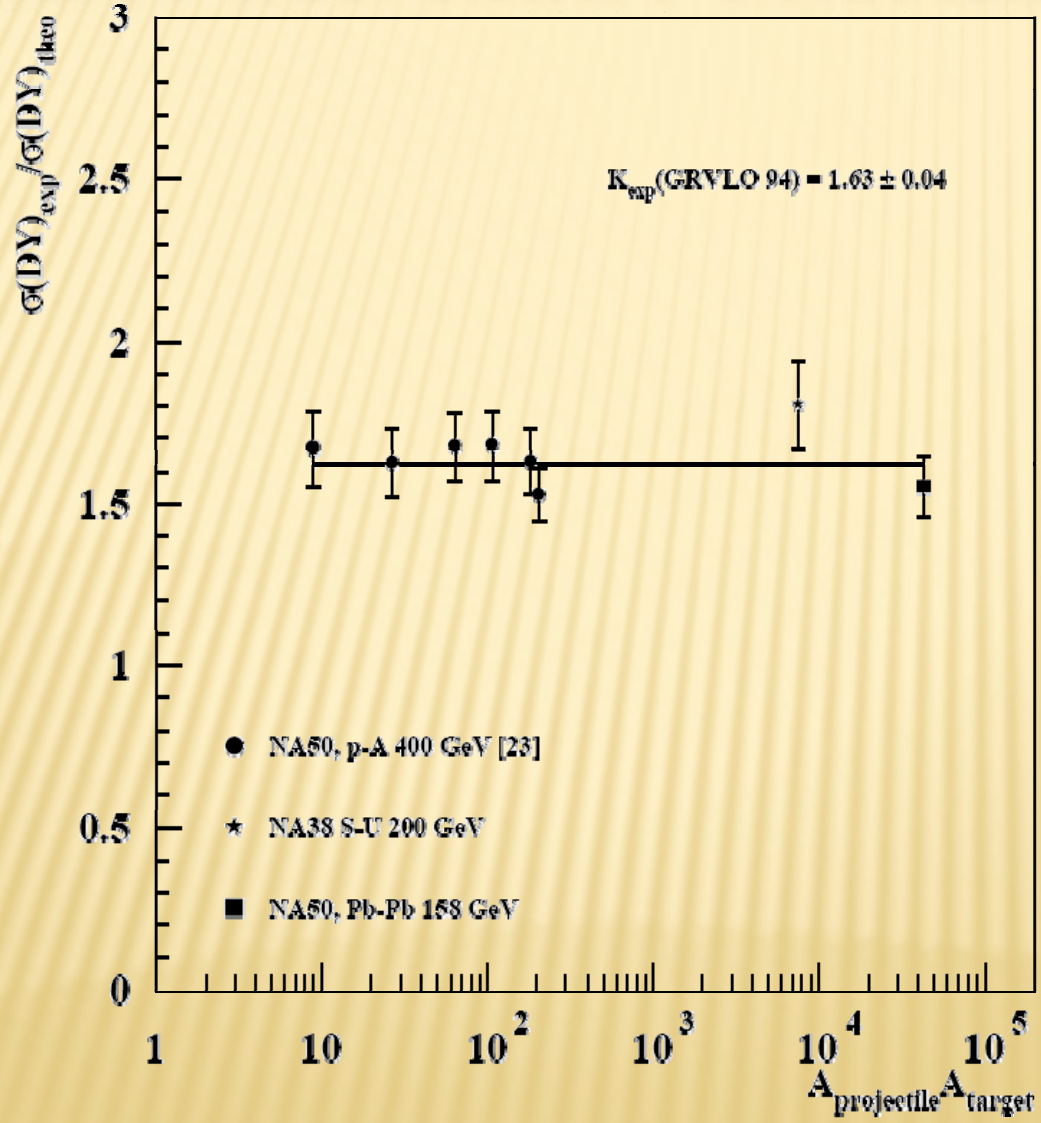
τ_0 formation time
0,35 à 1 fm/c

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

$\varepsilon > 6$ GeV/fm^3

Bjorken, PRD27 (1983) 140

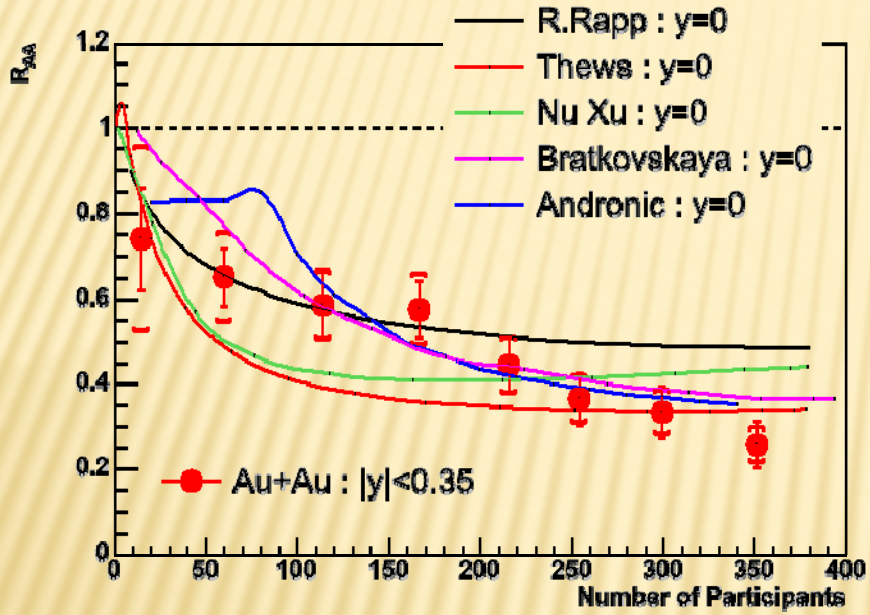
DRELL-YAN NCOLL SCALING



J/Ψ VERSUS MODELS...

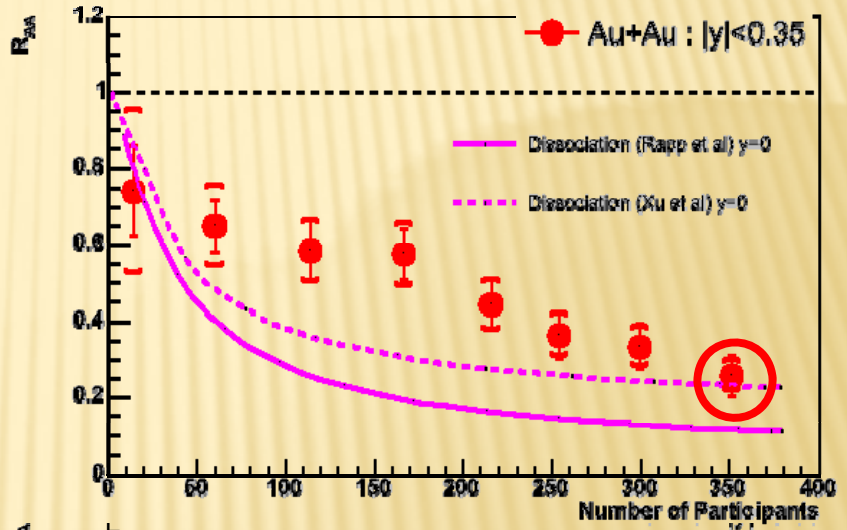
R. Rapp & al., nucl-th/0608033
Yan, Zhuang, Xu, nucl-th/0608010

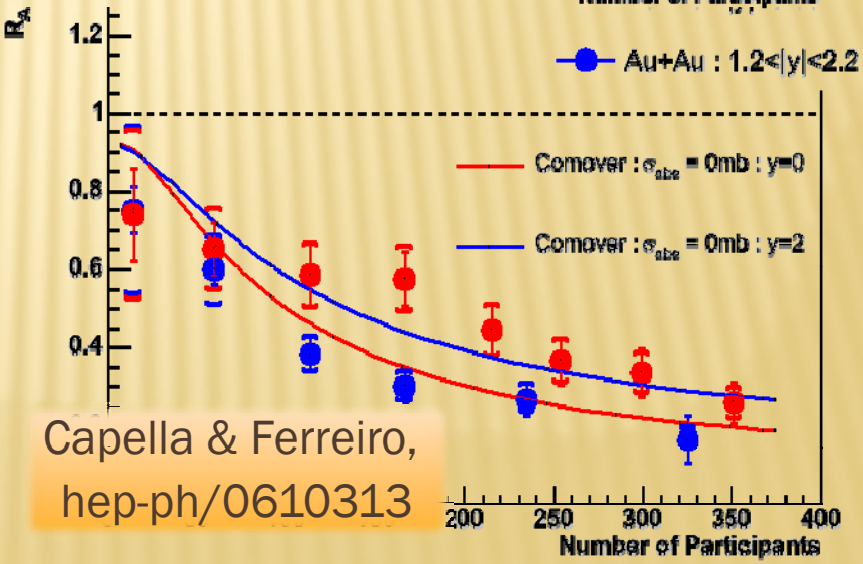
- Recombination...



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

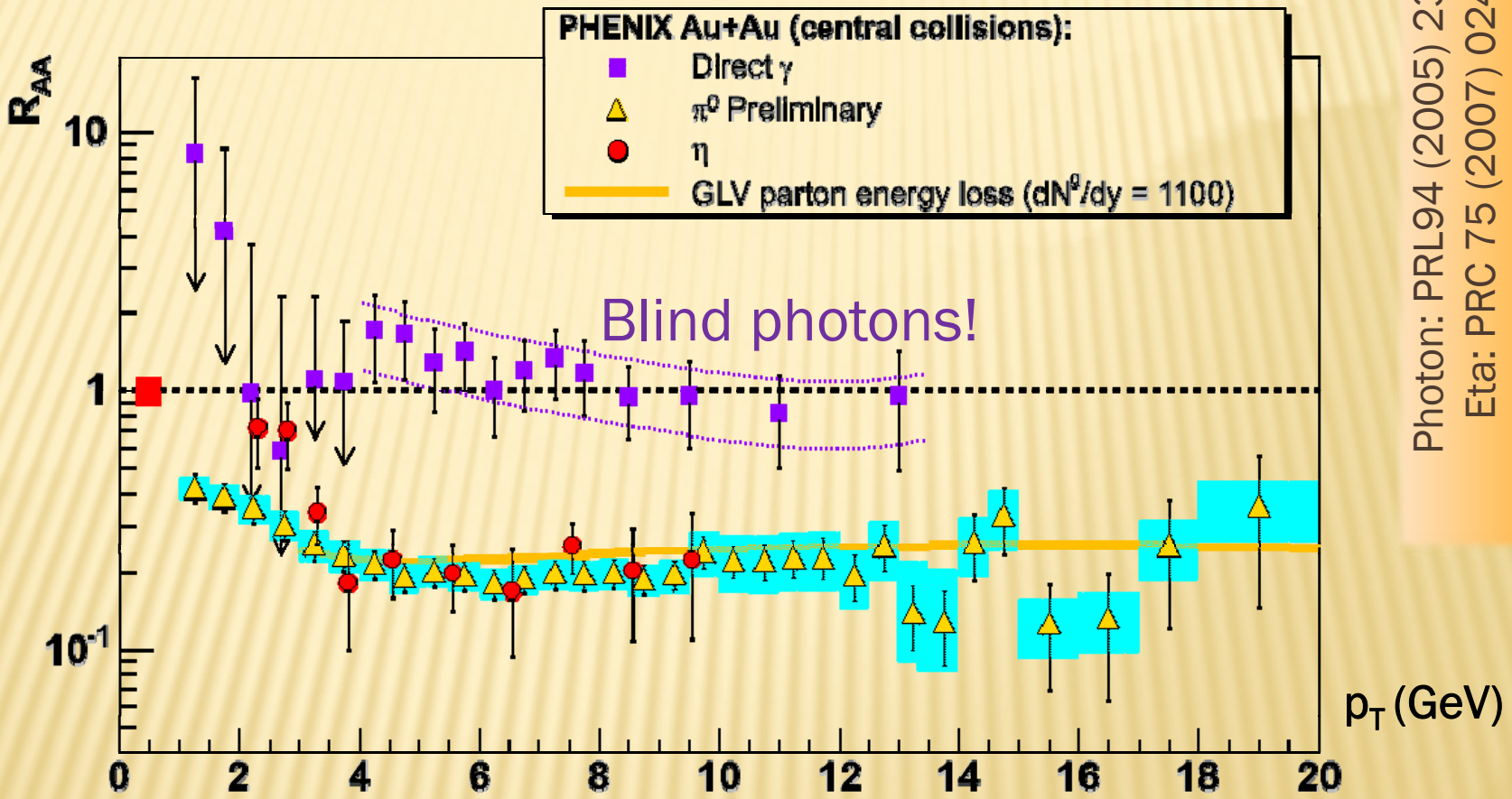
- SPS like...





Capella & Ferreiro, hep-ph/0610313

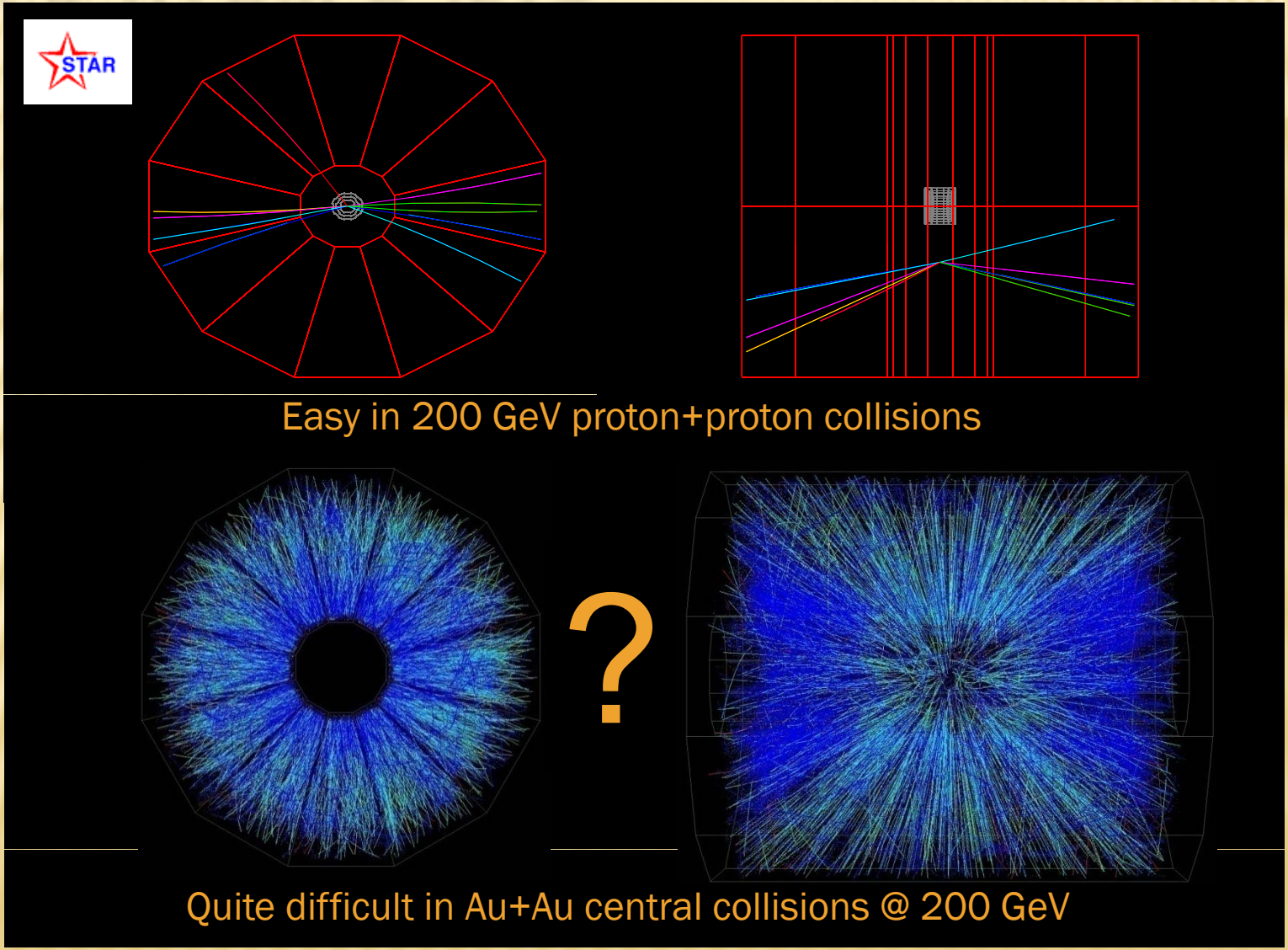
HIGH P_T SUPPRESSION



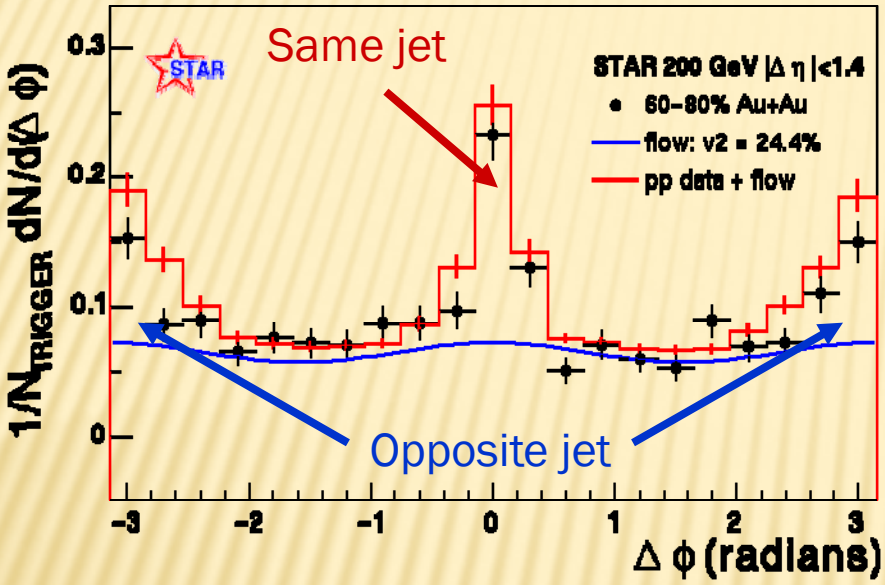
→ The matter is dense ! >1000 gluons per Δy

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

BACK TO BACK JETS

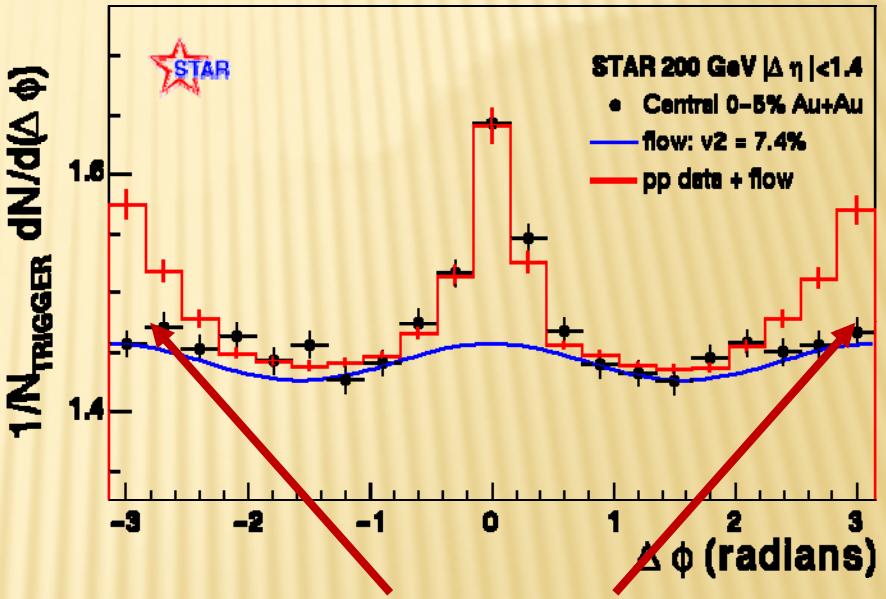


Peripheral collisions (60-80%)



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

Central collisions (0-5%)



In central collision, opposite jets disappear because of jet quenching

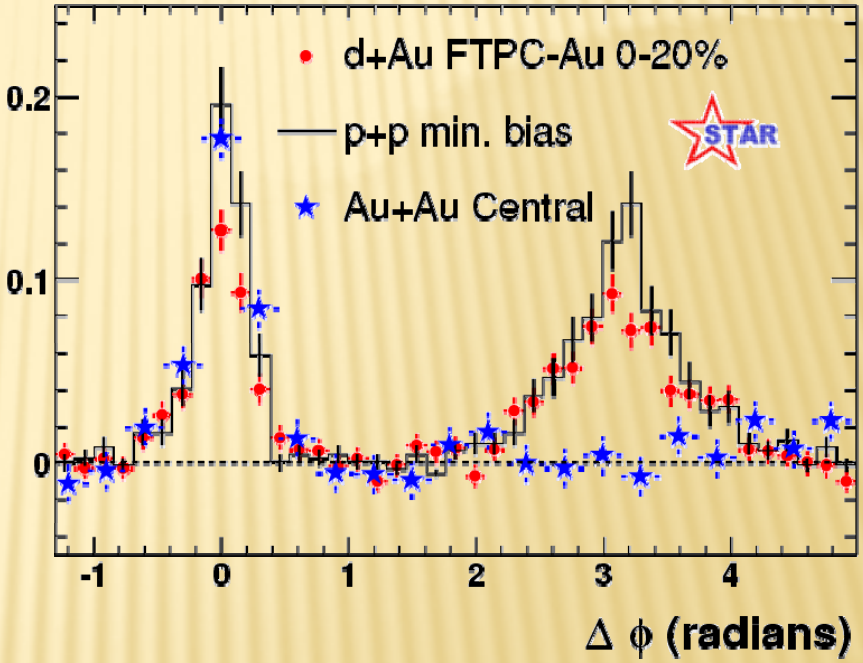
BACK TO BACK JETS

ANOTHER LOOK TO JET QUENCHING…

BACK TO BACK (D+AU)

STAR, PRL 91 (2003) 072304

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

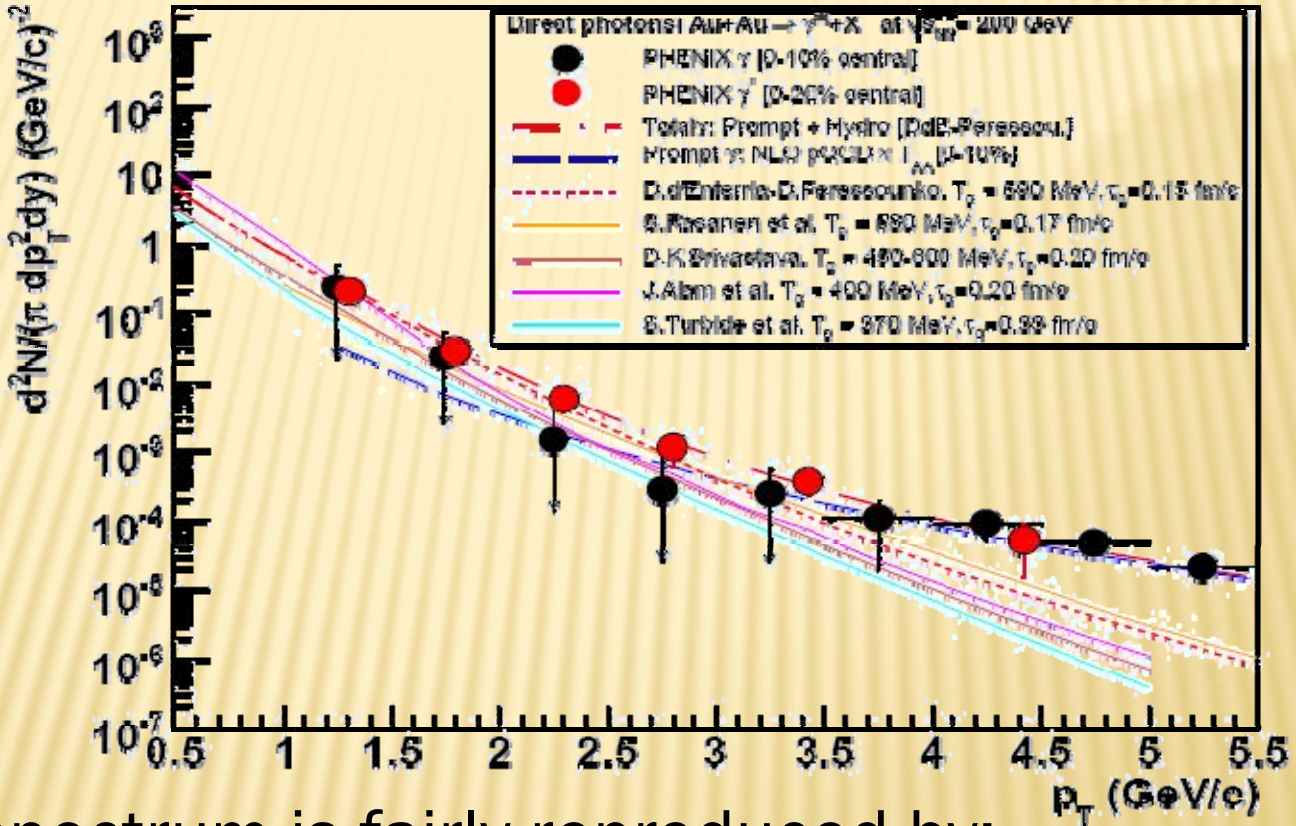


The matter is opaque!

THERMAL RADIATION

The matter is hot !

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



Photon spectrum is fairly reproduced by:

@ high p_T prompt photon (pQCD)

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