J/Ψ production in Cu+Cu and Au+Au collisions at $\sqrt{s}$ = 200 GeV measured by PHENIX at RHIC

Andry Rakotozafindrabe
LLR – École Polytechnique (France)
PHENIX Collaboration

SQM 2006

Physics motivation

- The J/Ψ is a promising hard probe to study the hot and dense matter created in relativistic heavy ion collisions :
  - Produced in the early stages of the collision only and interacts with the surrounding medium

- Changes to the J/Ψ yield can be due to competing effects :
  - Suppression by color screening in a deconfined medium
  - Enhancement at RHIC energy due to recombination of uncorrelated $c\bar{c}$ pairs
  - Cold nuclear effects (shadowing, nuclear absorption)

- p+p measurement is used as a reference, while d+Au measurement is used to evaluate the cold nuclear effects.

- At lower energy, NA50 (CERN) experiment measured an anomalous J/Ψ suppression in Pb+Pb collisions, in excess of the normal suppression expected from the nuclear absorption.

  (NA50 Collaboration, Phys. Lett. **B477** (2000) 28)

PHENIX detector

$J/\Psi \rightarrow e^+e^-$

$|y| < 0.35$

$P_e > 0.2$ GeV/c

$\Delta\Phi = \pi$

- Tracking, momentum measurement with drift chambers, pixel pad chambers
- e ID with EmCAL + RICH

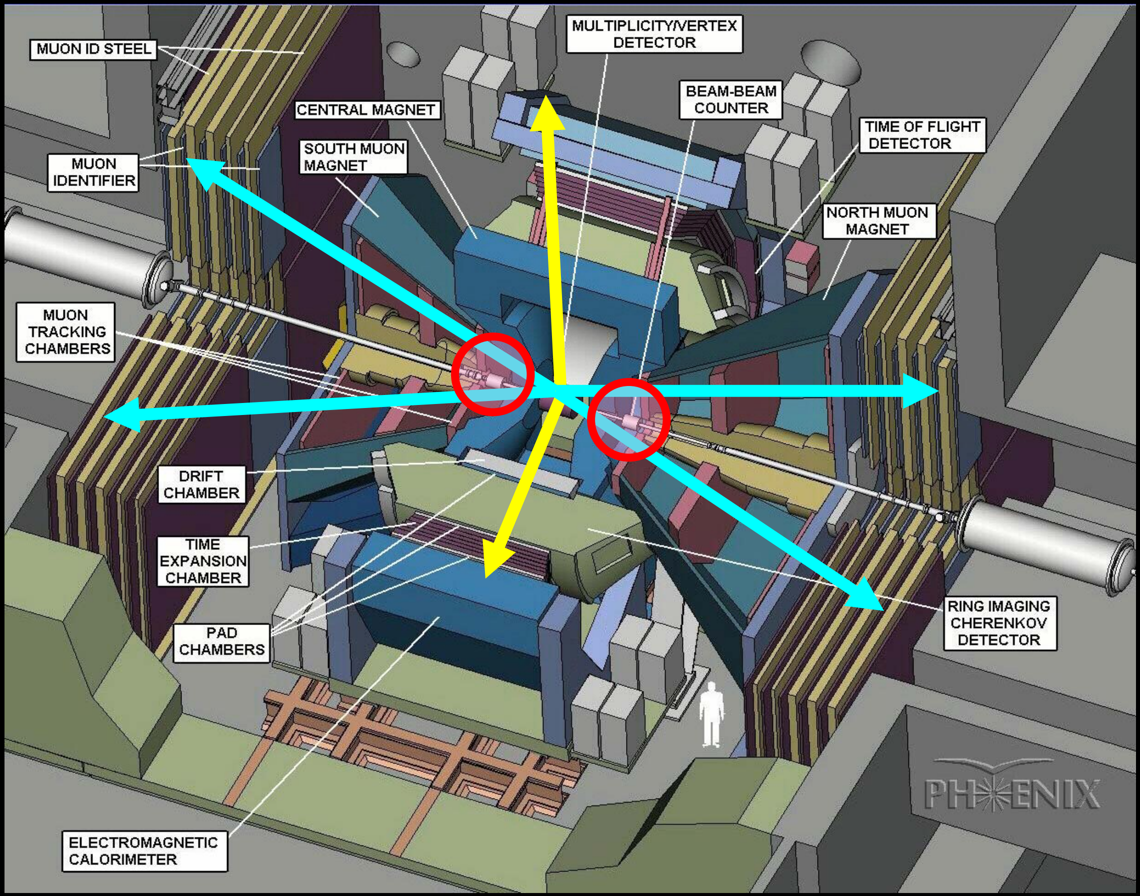
$J/\Psi \rightarrow \mu^+\mu^-$

$1.2 < |y| < 2.2$

$P_\mu > 2$ GeV/c

$\Delta\Phi = 2\pi$

- Tracking, momentum measurement with cathode strip chambers
- μ ID with penetration depth / momentum match



Centrality measurement, vertex position

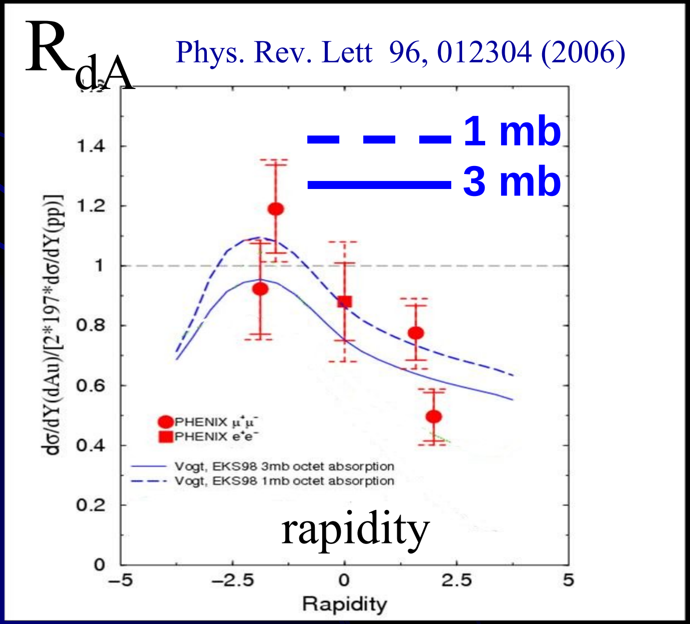
Beam-beam counters (charged particle production)

Zero-degree calorimeters (spectator neutrons)

RHIC : beyond cold nuclear effects ?

- Available d+Au data :
  - Weak shadowing (modification of gluon distribution) and weak nuclear absorption (σ_{abs} ~ 1mb favored)

$$R_{AB} = \frac{yield_{AB}}{\langle N_{Coll} \rangle yield_{pp}}$$



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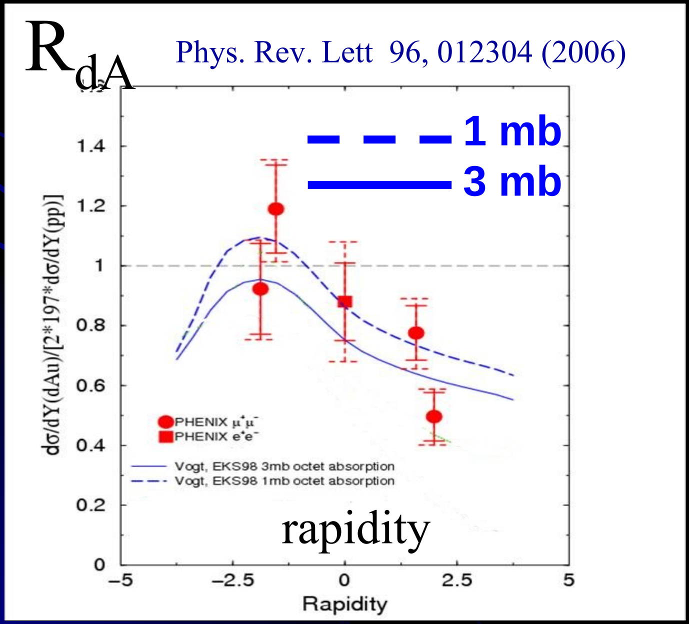

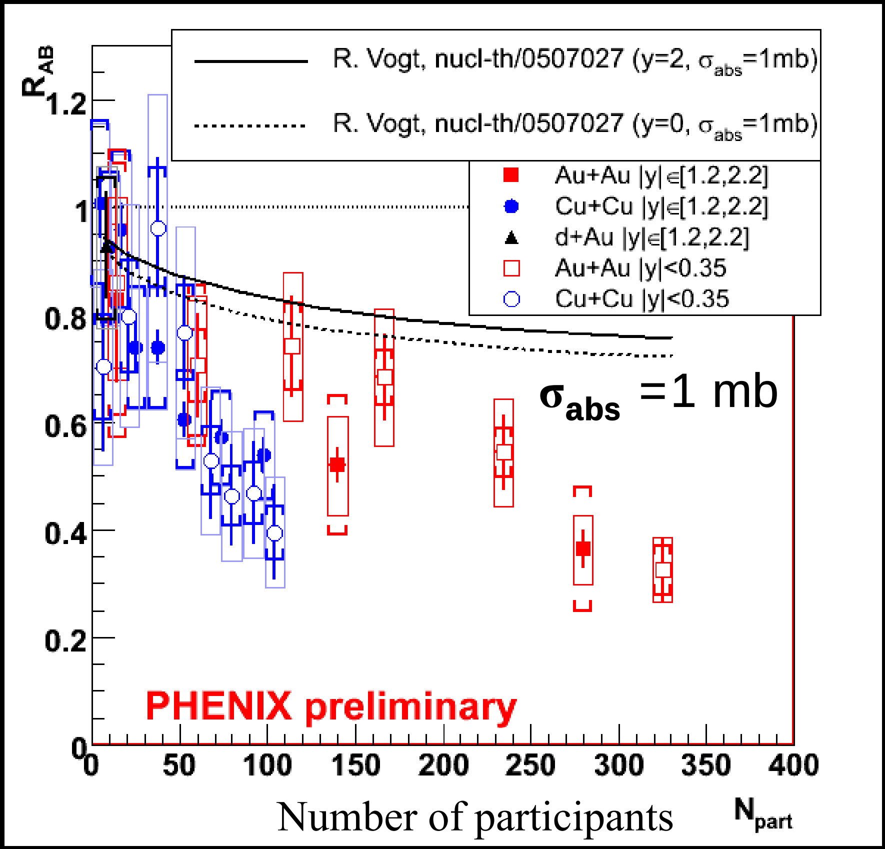

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- Au+Au data : even compared to the « worst » σ_{abs}~ 3mb case

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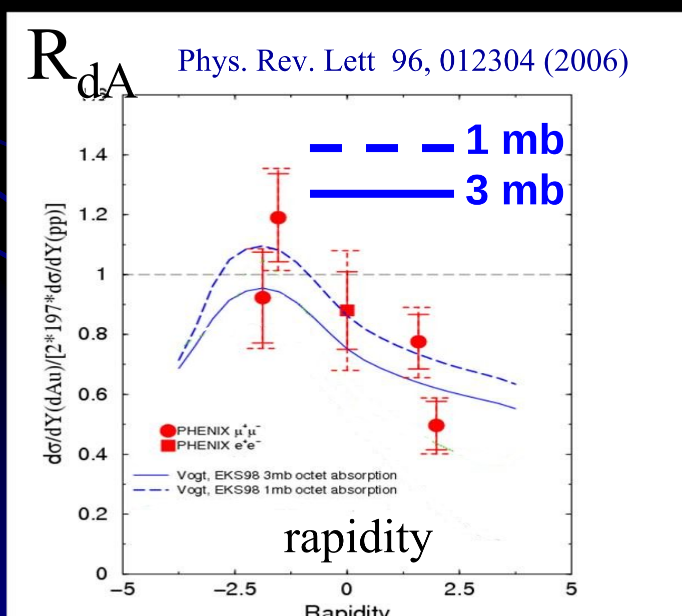

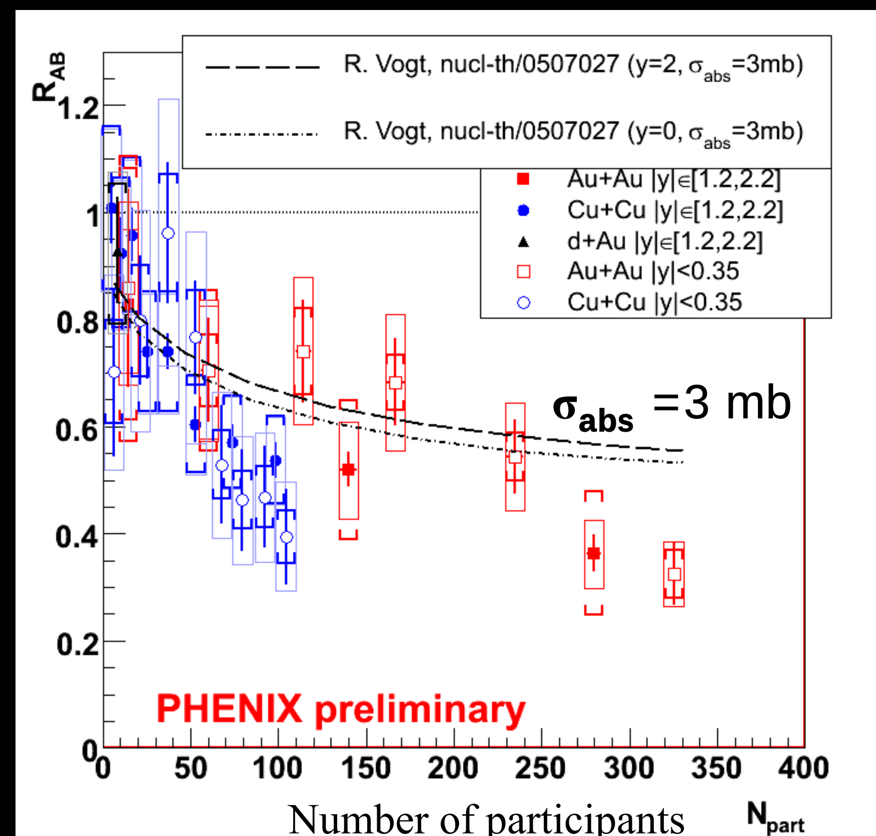

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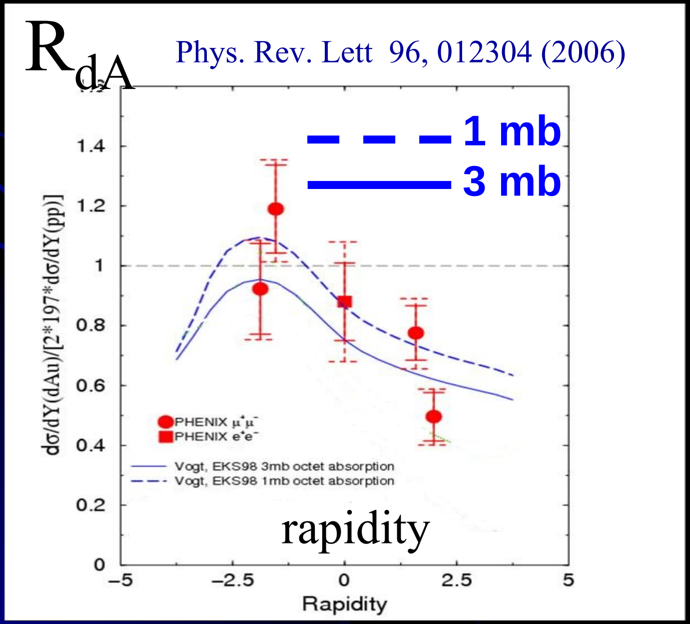
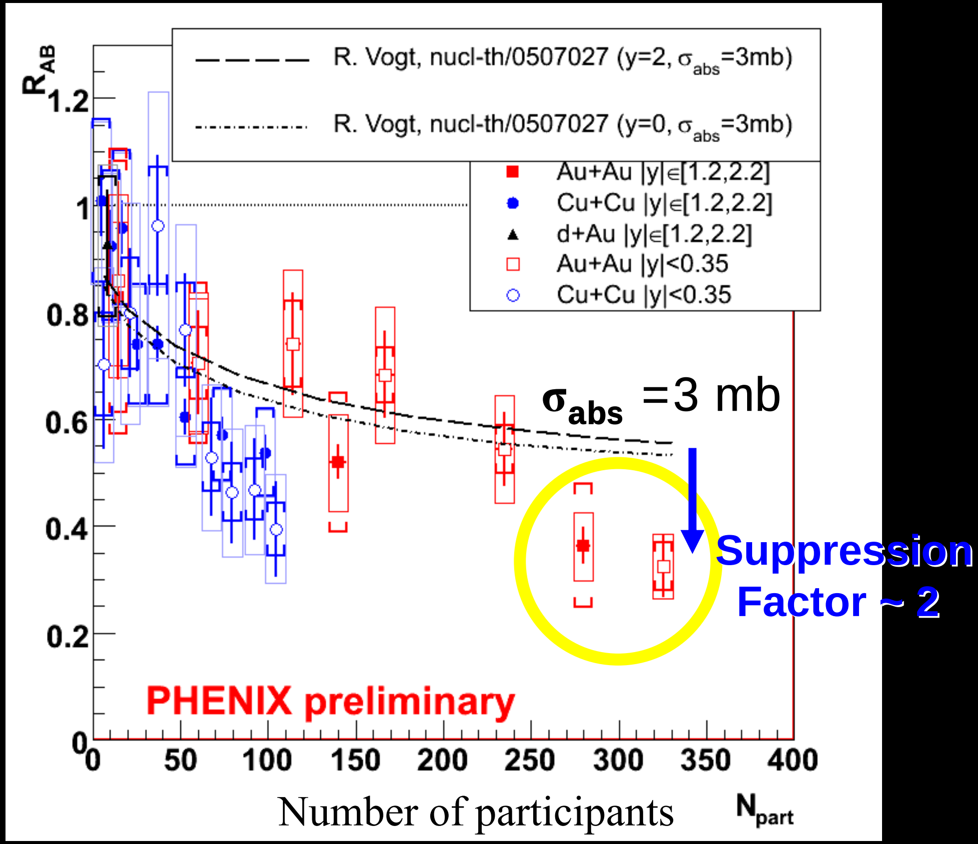
- Available d+Au data :
  - Weak shadowing (modification of gluon distribution) and weak nuclear absorption (σ_{abs} ~ 1mb favored)
- Au+Au data : even compared to the « worst » σ_{abs}~ 3mb case
  - Factor 2 of suppression beyond cold effects in the most central Au+Au bin

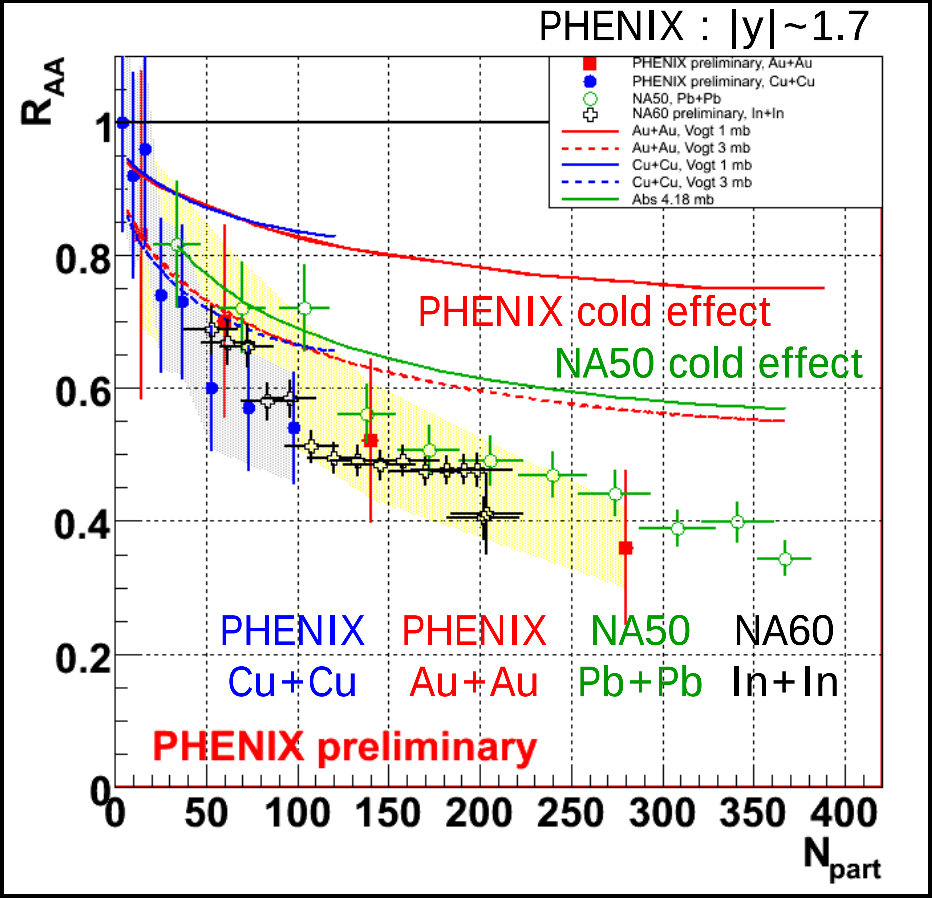
$$R_{AB} = \frac{yield_{AB}}{\langle N_{Coll} \rangle yield_{pp}}$$





RHIC vs SPS (I) : raw comparison

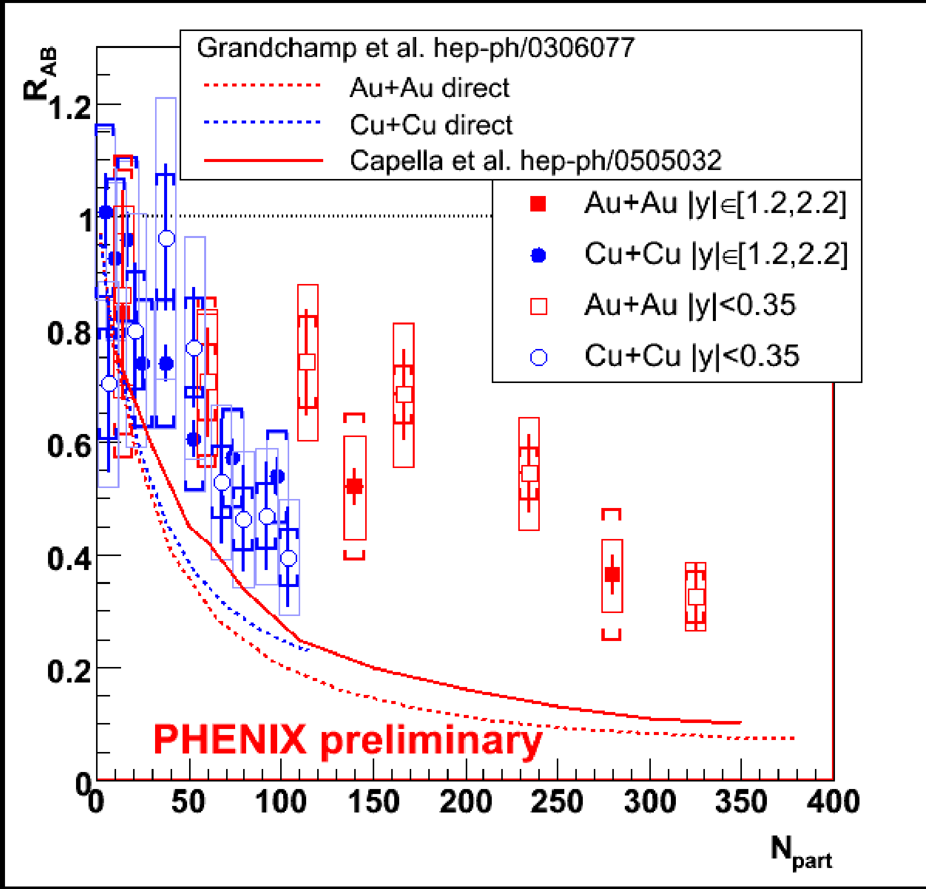
- SPS :
  - $\sqrt{s} \sim 17$ GeV i.e. a factor 10 below RHIC
  - Cold effect = normal nuclear absorption $\sigma_{abs} = 4.18 \pm 0.35$ mb
  - Maximum $\varepsilon \sim 3$ GeV/fm^3 ($\tau_0 = 1$)
- Compare to RHIC :
  - Cold effect = shadowing + nuclear absorption $\sigma_{abs} \sim 1$mb (Vogt, nucl-th/0507027)
  - Maximum $\varepsilon \sim 5$ GeV/fm^3 ($\tau_0 = 1$), higher than at SPS, but still, the same pattern of J/Ψ suppression !



SPS normalized to NA51 p+p value (NA60 preliminary points from Arnaldi, QM05).

RHIC vs SPS (II) : extrapolating suppression models

- Suppression models in agreement with NA50 data overestimate the suppression when extrapolated at RHIC energies :
  - quite striking for mid and most central Au+Au bins
  - already the case for Cu+Cu most central bins ?



(Hadronic?) co-mover scattering

Direct suppression in a hot medium :
Cu+Cu Au+Au

Some recombination effects ?

- Adding some regeneration that partially compensates the suppression : there is a better agreement between the model and the data.

Grandchamp et al. hep-ph/0306077

Direct suppression in a hot medium :

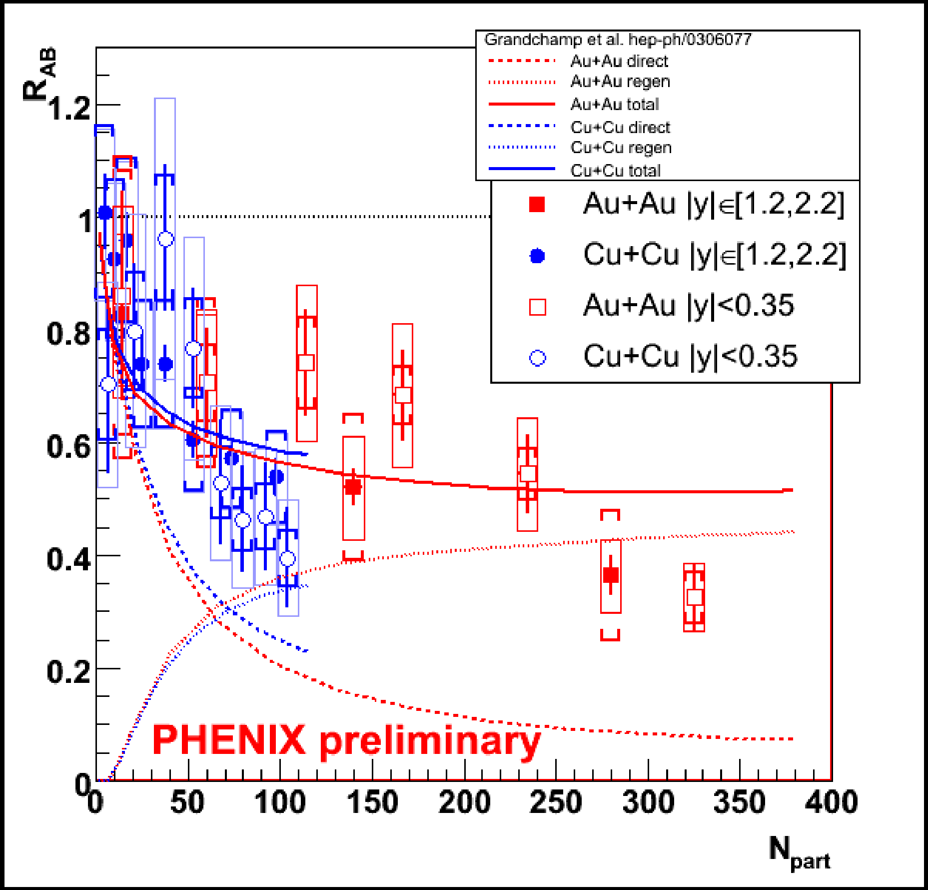
Cu+Cu Au+Au

Regeneration :

Cu+Cu Au+Au

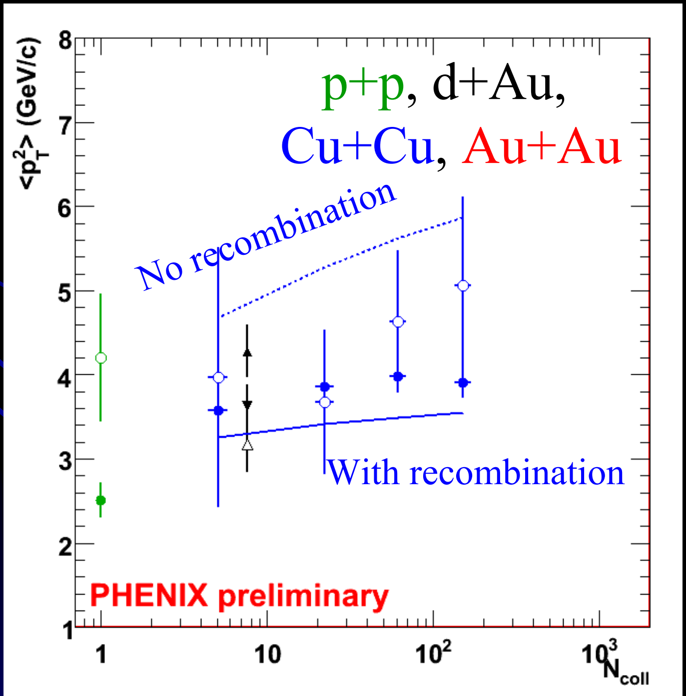
Total :

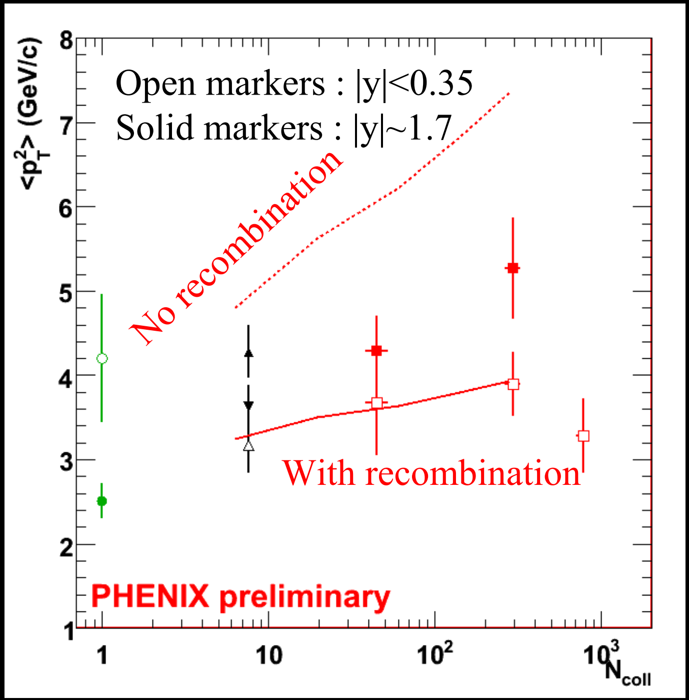
Cu+Cu Au+Au



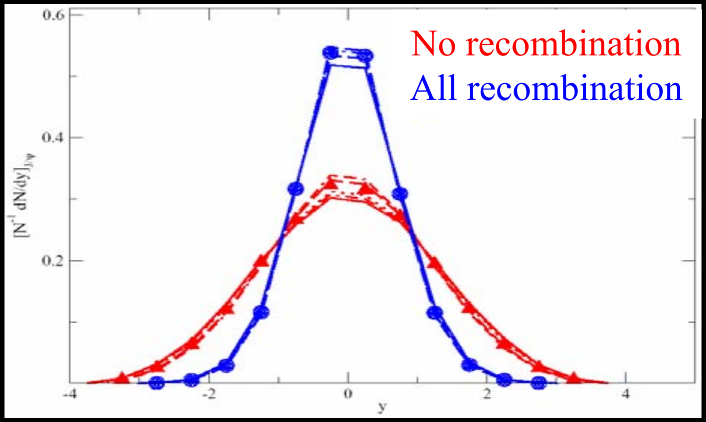
Recombination predictions for $< p_T^2 >$ vs N_{coll}

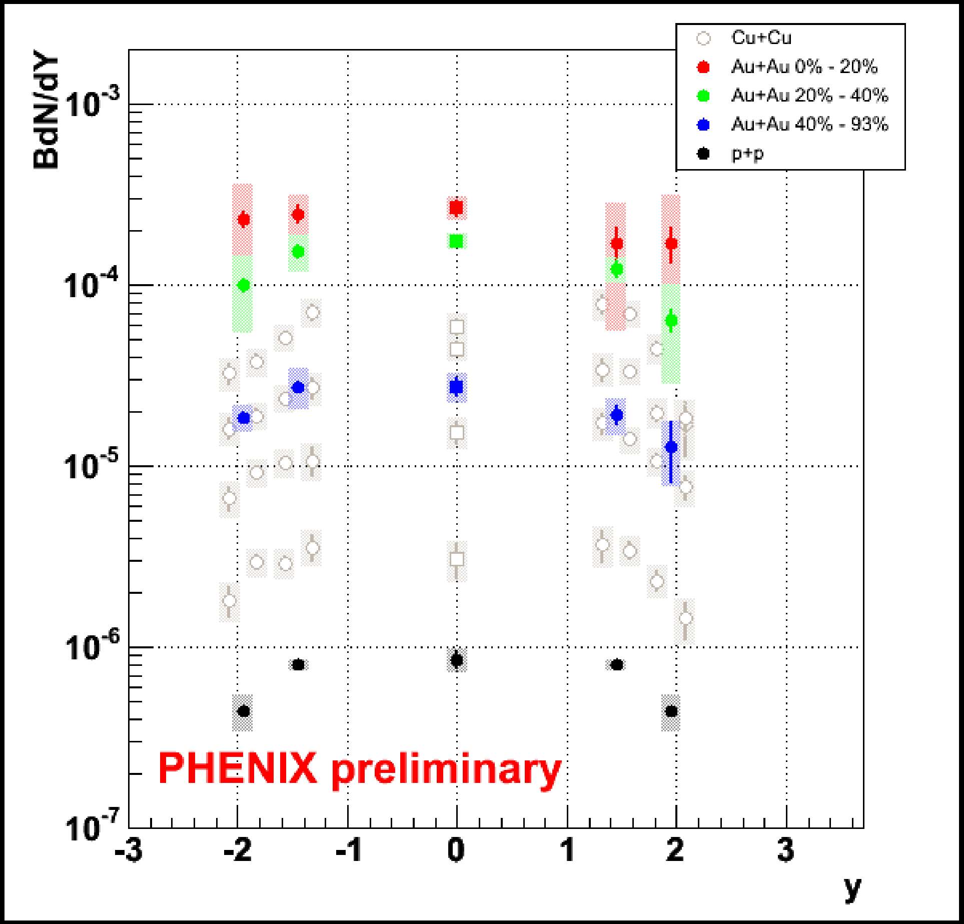
- Recombination (Thews et al., nucl-th/0505055) predicts a narrower p_T distribution with an increasing centrality, thus leading to a lower $<p_T^2>$
- Within the large error bars :
  - $<p_T^2>$ seems to be consistent with a flat dependence
  - data falls between the two hypothesis ⇒ partial recombination ?





Recombination predictions vs rapidity





- Recombination (Thews et al., nucl-th/0505055) predicts a narrower rapidity distribution with an increasing N_{part}.
- Going from p+p to the most central Au+Au : no significant change seen in the shape of the rapidity distribution.

Summary

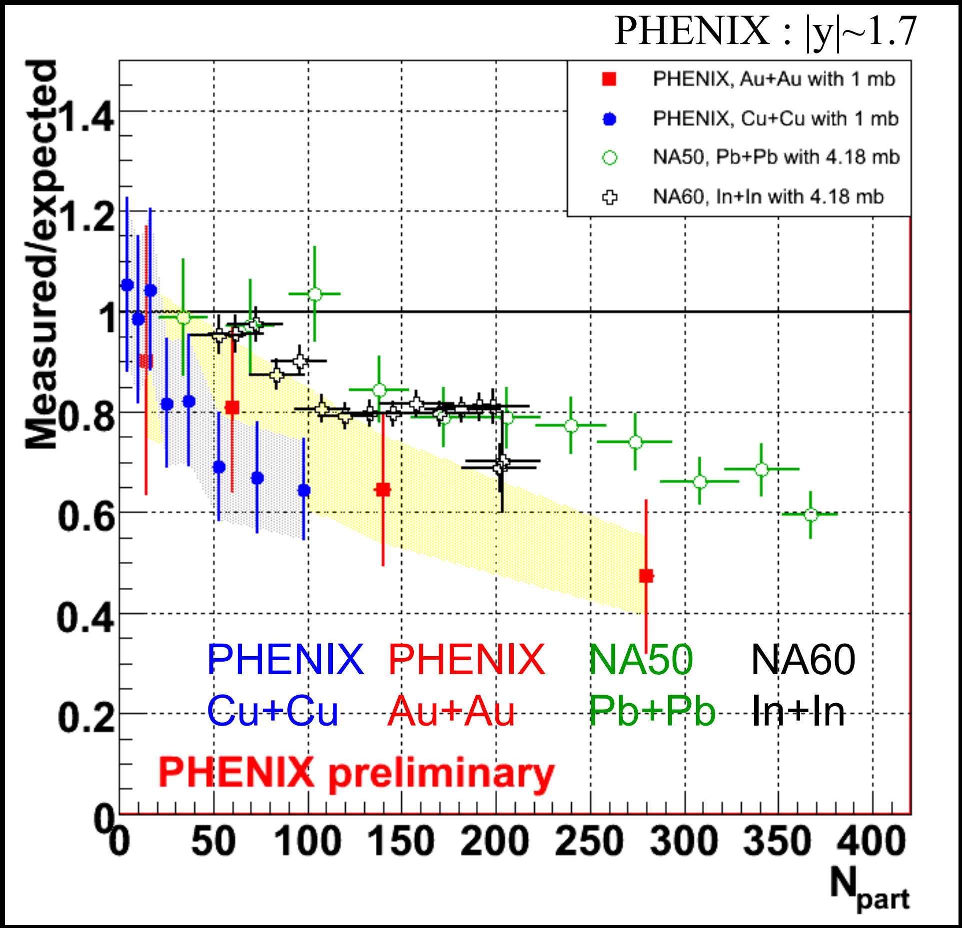
PHENIX preliminary results on J/Ψ→dileptons at forward and mid-rapidity in Cu+Cu and Au+Au :

- Suppression pattern
  - Beyond cold nuclear effects, at least factor 2 of suppression in most central Au+Au events
  - Similar to SPS suppression, despite a higher energy density reached
  - Overestimated by models in agreement with NA50 data and extrapolated at RHIC energy
- Understandable as $c\bar{c}$ recombinations that partially compensate the J/Ψ suppression ?
  - Still open question (test vs $\langle p_T^2 \rangle$ dependance and rapidity distribution)
- Alternate explanations ?
  - Direct J/Ψ is not melting at present energy densities ? Only the higher mass resonances Ψ' and χ_c ? (recent lattice QCD results)
  - J/Ψ transport (with high p_T J/Ψ escaping QGP region) + QGP suppression ?
- Need to improve knowledge on cold nuclear effects at RHIC

Back-up

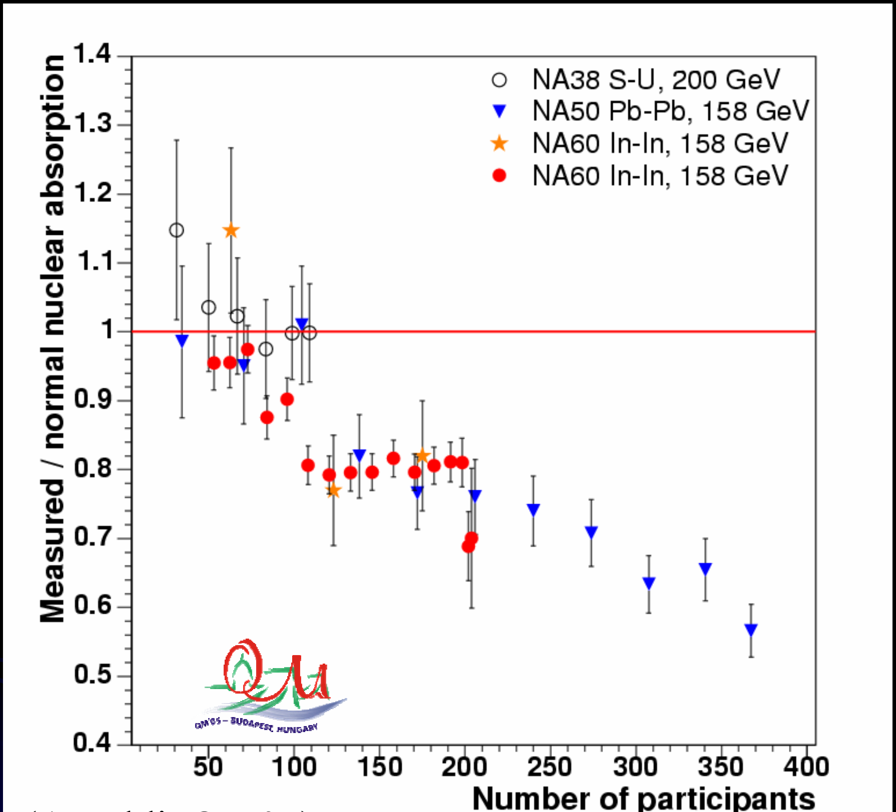
RHIC vs SPS

- Plotted « à la SPS » way i.e. normalize the J/Ψ production with the cold nuclear effects :
  - nuclear absorption with σ_{abs} = 4.18 ± 0.35 mb at SPS
  - Shadowing + nuclear absorption with σ_{abs} ~ 1 mb at RHIC (Vogt, nucl-th/0507027)

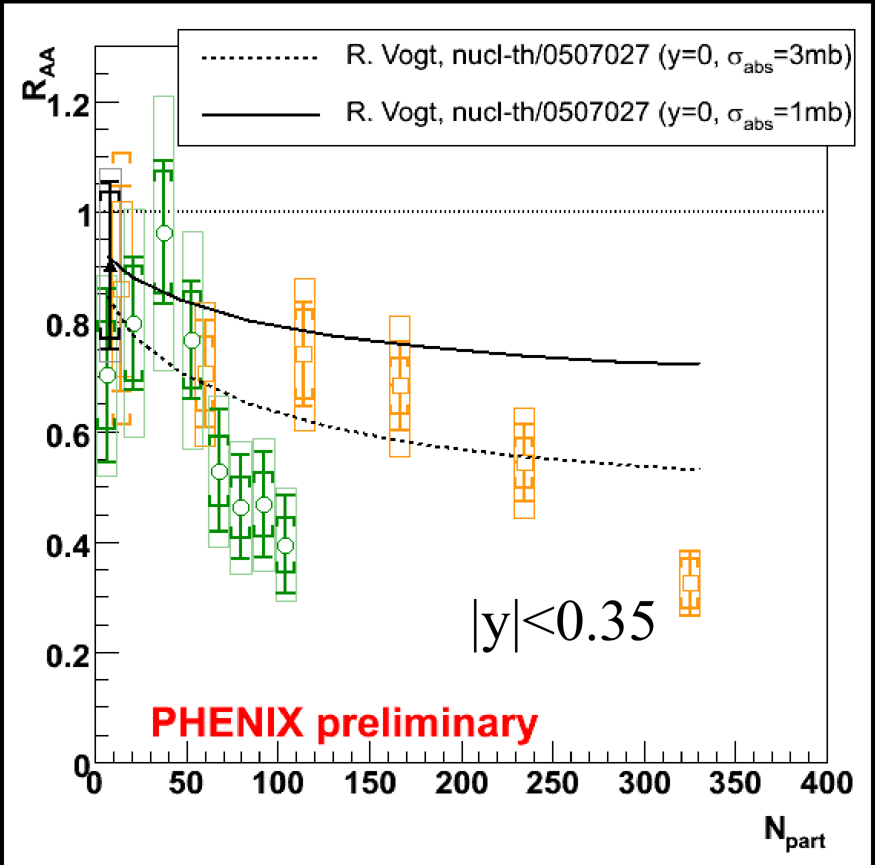


(NA60 preliminary points from Arnaldi, QM05).

SPS vs RHIC

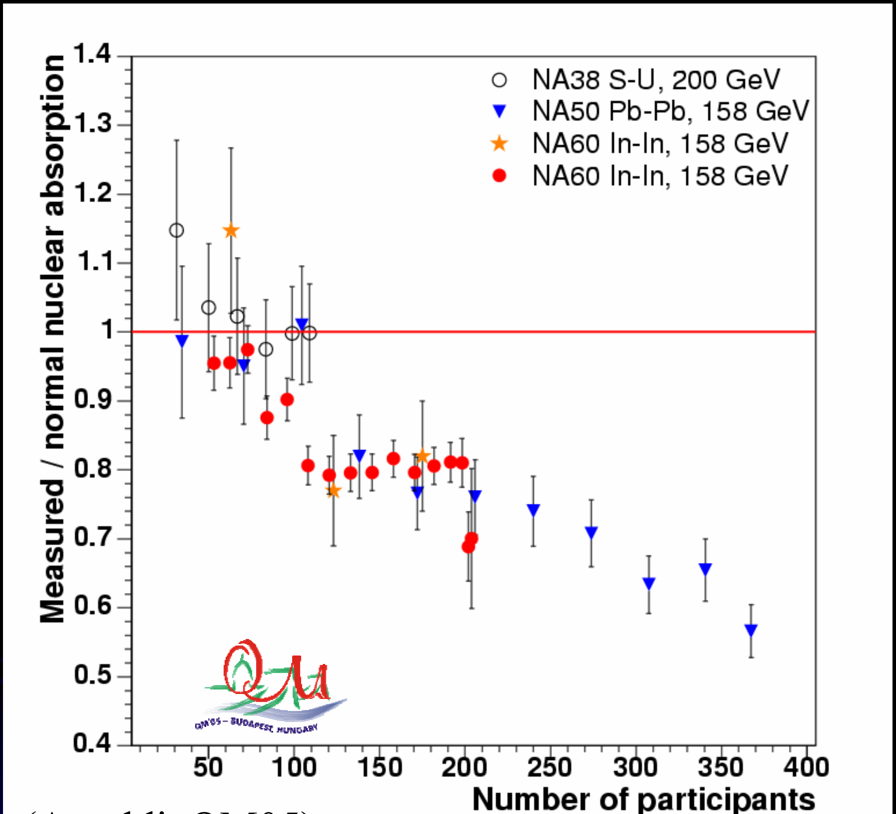


(Arnaldi, QM05)



- SPS :
  - √s ~ 17 GeV
  - Measured/expected
  - measured = J/Ψ / D.Y
  - expected = normal nuclear absorption
    σ = 4.18 ± 0.35 mb
  - NA50: |y*| = [0,1]
- RHIC :
  - √s = 200 GeV
  - R_{AA} i.e. (J/Ψ in A+A) / (Ncoll * J/Ψ in p+p)
  - « expected » = nuclear absorption (σ ~ 1 à 3 mb) + shadowing
  - |y| = [0,0.35] or [1.2,2.2]

SPS vs RHIC



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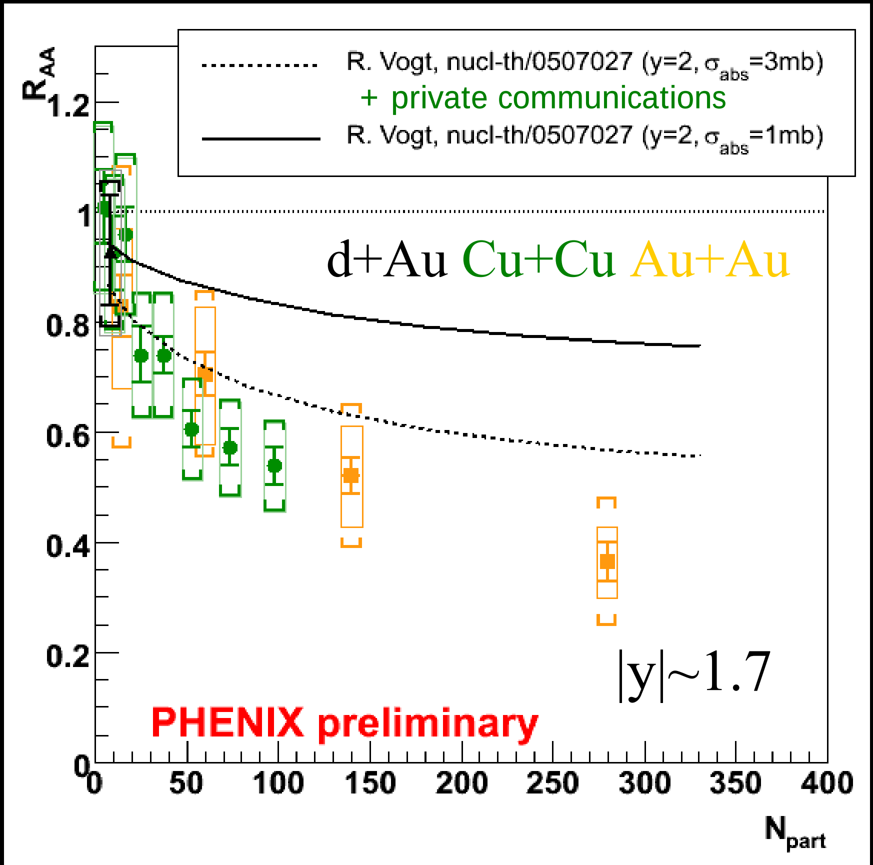

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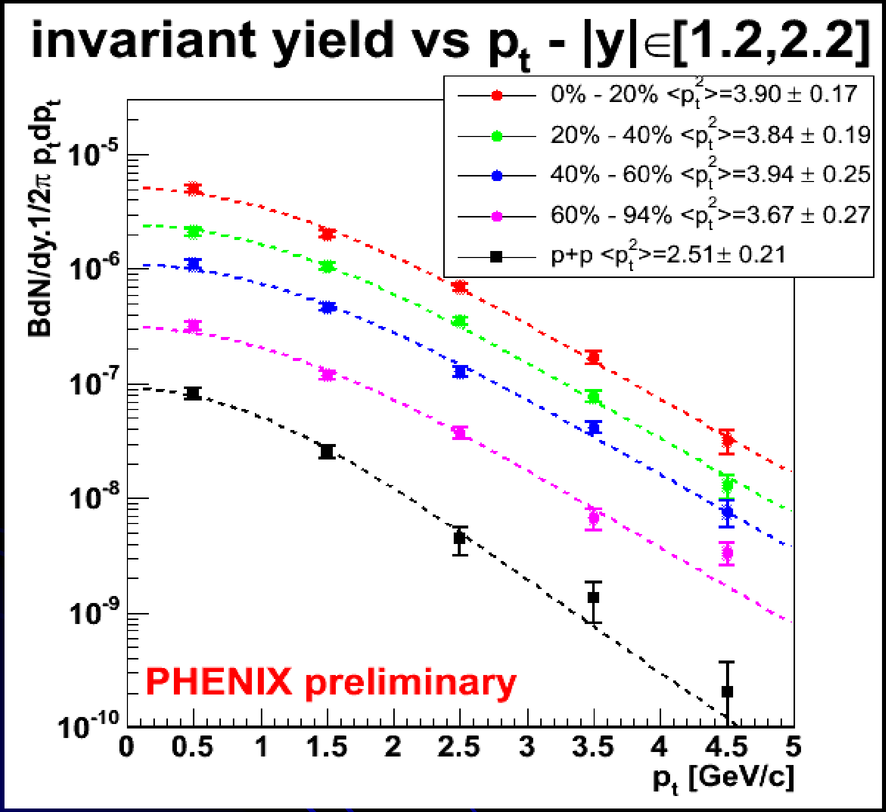
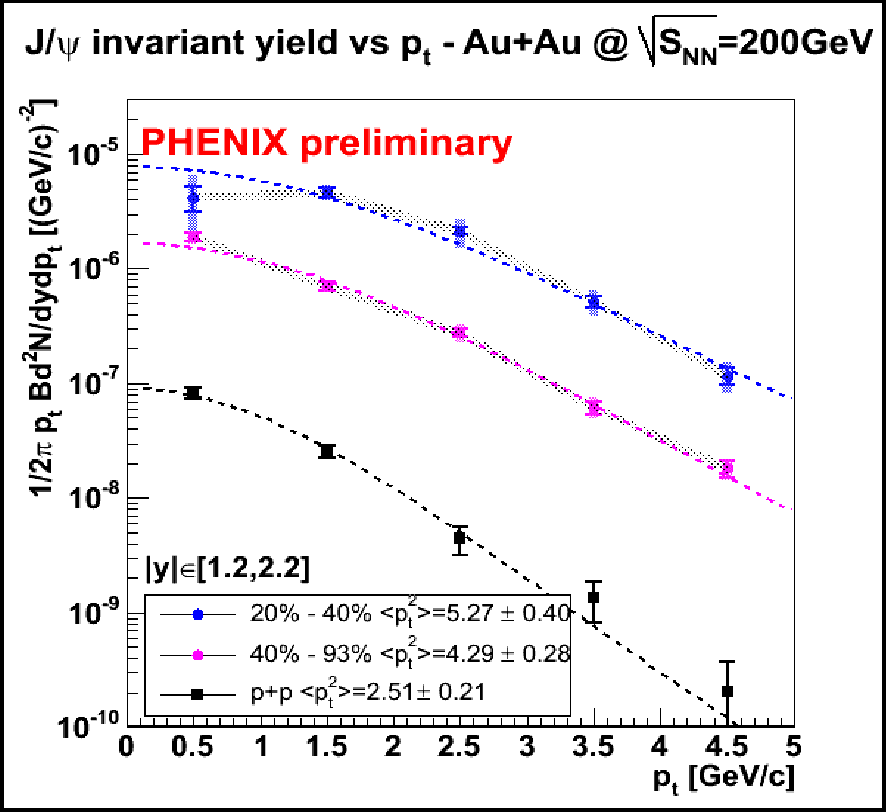
Invariant yield vs p_T

Cu+Cu (|y|∈[1.2,2.2])



Au+Au (|y|∈[1.2,2.2])



- we fit the p_T spectrum using $A[1+(p_t/B)^2]^{-6}$ to extract $<p_T^2>$

Computing the J/Ψ yield

Invariant yield :

$$B_{\mu\mu}\frac{dN^i}{dy}(AA \to J/\psi \to \mu^+\mu^-) = \frac{N^i_{J/\psi}}{\Delta y\ A\varepsilon^i_{J/\psi}\varepsilon^{J/\psi}_{BBC}} / \frac{N^i_{MB}}{\varepsilon^{MB}_{BBC}}$$

i : i-th bin (centrality for e.g.)

$N^i_{J/\psi}$: number of J/ψ 's reconstructed

$A\varepsilon^i_{J/\psi}$: probability for a J/ψ thrown and embeded into real data to be found (considering reconstruction and trigger efficiency)

N^i_{MB} : total number of events

$\varepsilon^{J/\psi}_{BBC}$: BBC trigger efficiency for events with a J/ψ

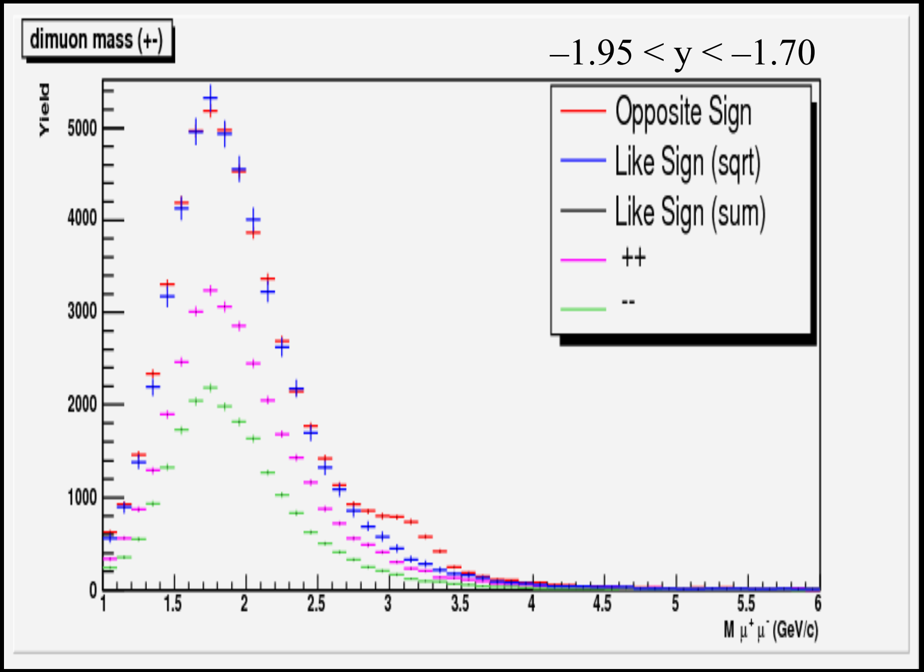
ε^{MB}_{BBC} : BBC trigger efficiency for minimum bias events

For Au+Au or Cu+Cu collision : $\varepsilon^{MB}_{BBC} \sim \varepsilon^{J/\psi}_{BBC}$

Signal extraction in Cu+Cu

$$B_{\mu\mu}\frac{dN_i}{dy}\left(CuCu \to J/\psi \to \mu^+\mu^-\right) = \frac{N^i_{J/\psi}/N^i_{MB}}{\Delta y . A\varepsilon^i_{J/\psi}}$$

- Cuts :
  - Dimuons cuts
    - 2.6 < mass < 3.6 GeV/c²
    - 1.2 < |rapidity| < 2.2
  - Track quality cuts
  - …
- Combinatoric background from uncorrelated dimuons :
  - $N_{bgd} = 2\sqrt{(N^{++} . N^{--})}$



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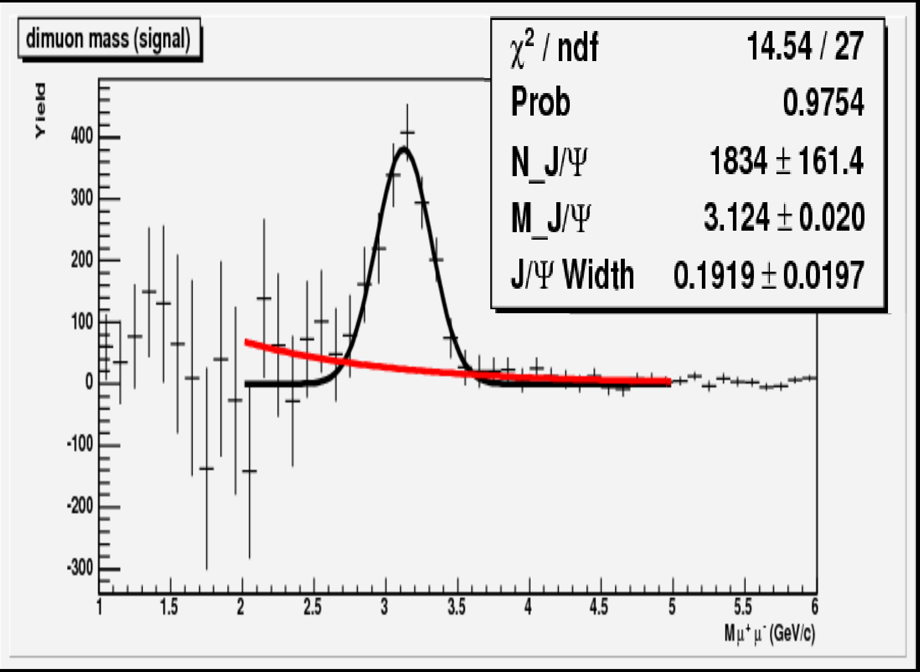

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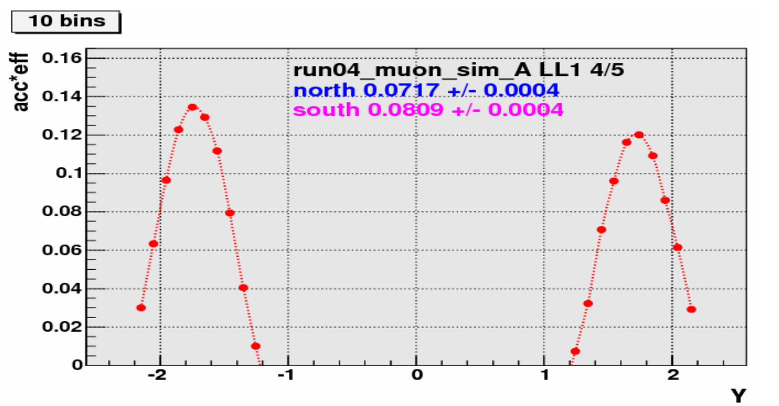
  - …
- Combinatoric background from uncorrelated dimuons :
  - $N_{bgd} = 2\sqrt{(N^{++} . N^{--})}$
- Signal = number of counts within the J/Ψ invariant mass region (2.6 – 3.6 GeV/c²) after subtracting N_{bgd} to the distribution of the opposite sign dimuons.
- Systematic errors : ~10% from varying fits of the background subtracted signal. Also account for the physical background that can be included into the previous counting.

Getting acc*eff correction factors in Cu+Cu

$$B_{\mu\mu}\frac{dN_i}{dy}(CuCu \rightarrow J/\psi \rightarrow \mu^+\mu^-) = \frac{N^i_{J/\psi}/N^i_{MB}}{\Delta y . A\varepsilon^i_{J/\psi}}$$

- Using Monte Carlo J/Ψ generated by PYTHIA over 4π
- embed the J/Ψ within muon arm acceptance into real minimum bias Cu+Cu data
- Apply to them the same triggers and signal extraction method as the ones applied to the data

⇒ Acc.eff(*i*) is the probability that a J/Ψ thrown by PYTHIA in a given bin *i* to survive the whole process followed by the data



Acc*eff vs rapidity (statistical errors only)

Getting acc*eff correction factors in Cu+Cu

$$B_{\mu\mu}\frac{dN_i}{dy}(CuCu \to J/\psi \to \mu^+\mu^-) = \frac{N^i_{J/\psi} / N^i_{MB}}{\Delta y . A\varepsilon^i_{J/\psi}}$$

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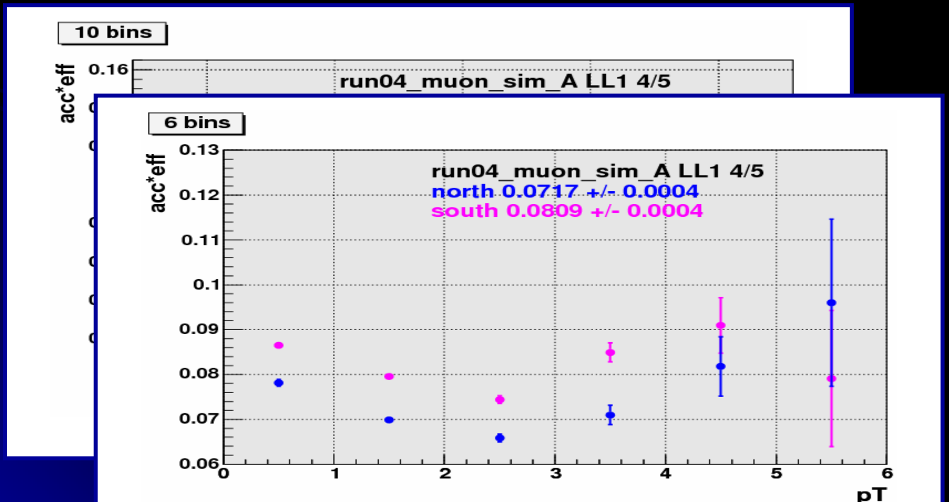

Acc*eff vs p_T (statistical errors only)

Getting acc*eff correction factors in Cu+Cu

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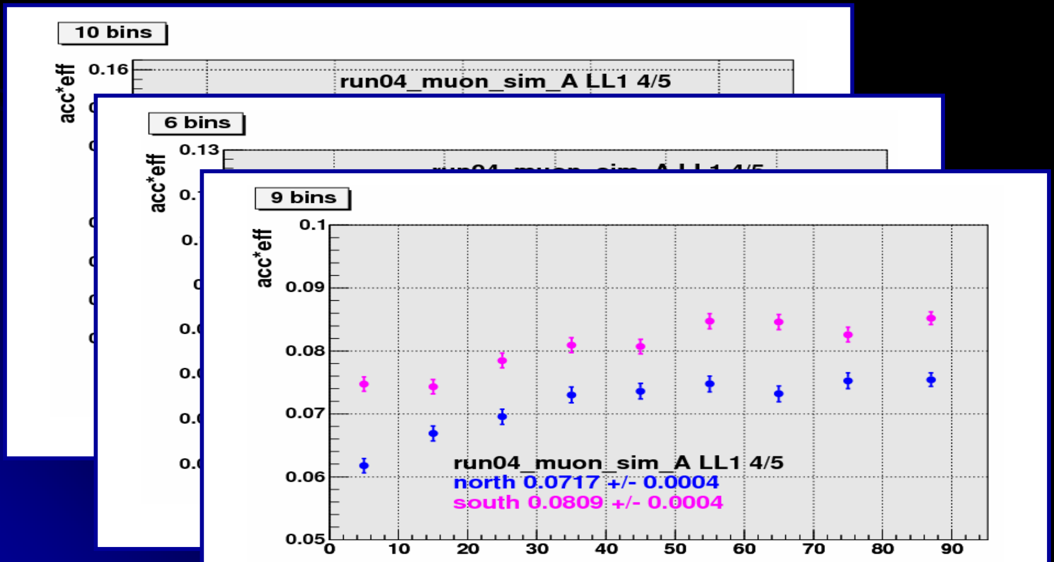


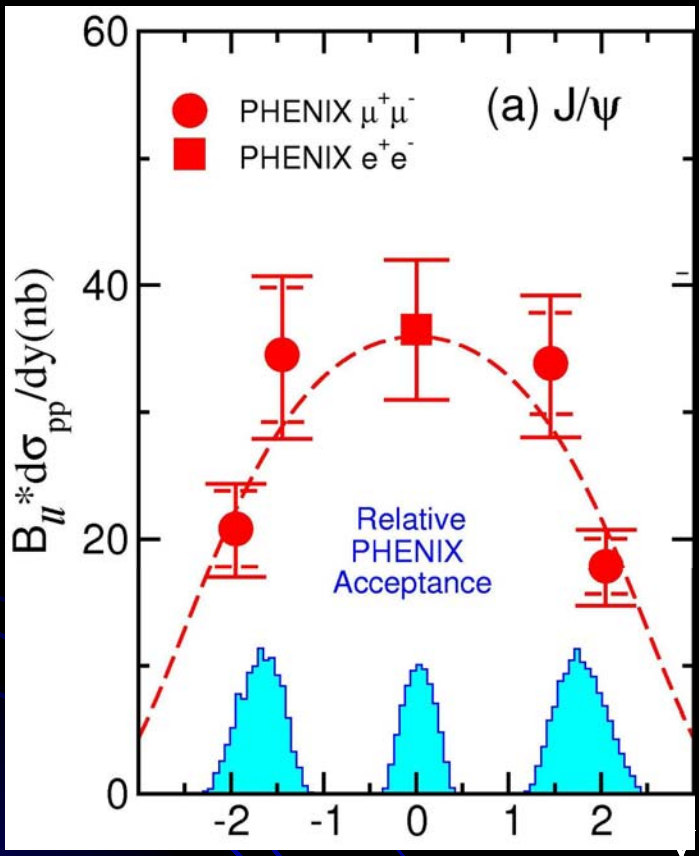
Acc*eff vs centrality (statistical errors only)

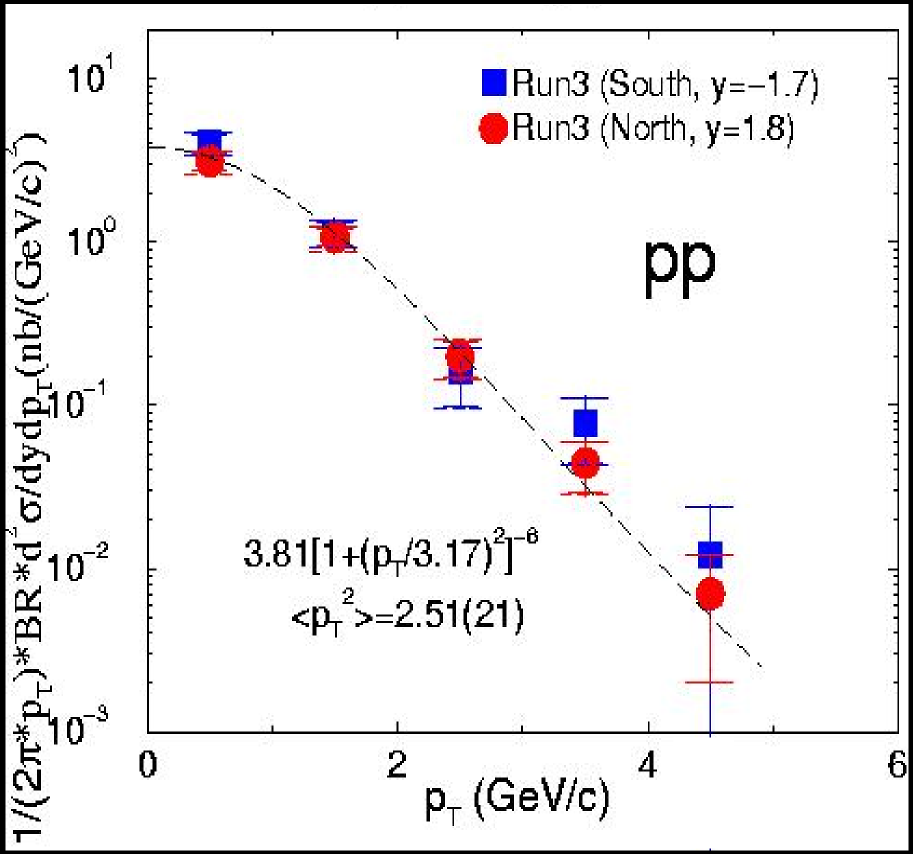
Systematic errors :

- 5% from track/pair cuts and uncertainities in p_T, y and z-vertex input distribution
- 8% from run to run variation (mainly due to the varying number of dead channels in MuTr).

J/Ψ production in p+p

Phys. Rev. Lett. 96, 012304



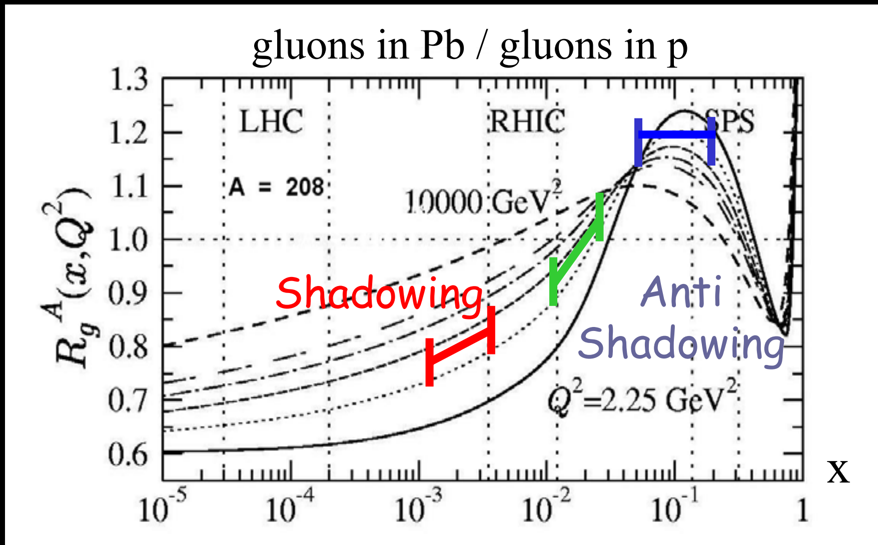


Total cross section in p+p

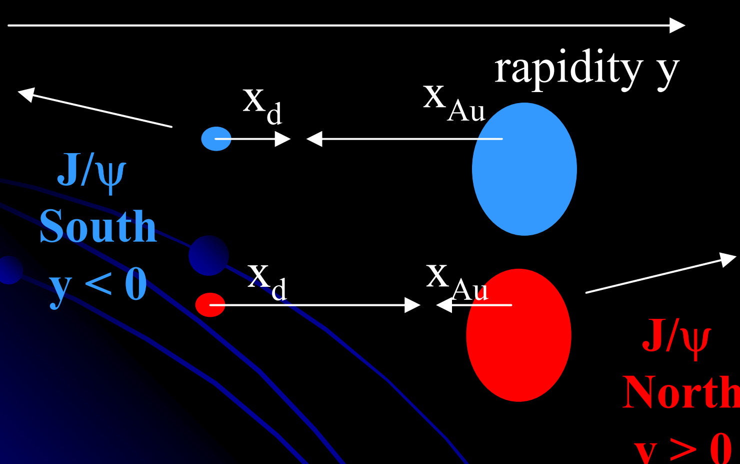
$\sigma = 2.61 \pm 0.20 \pm 0.26\ \mu b$

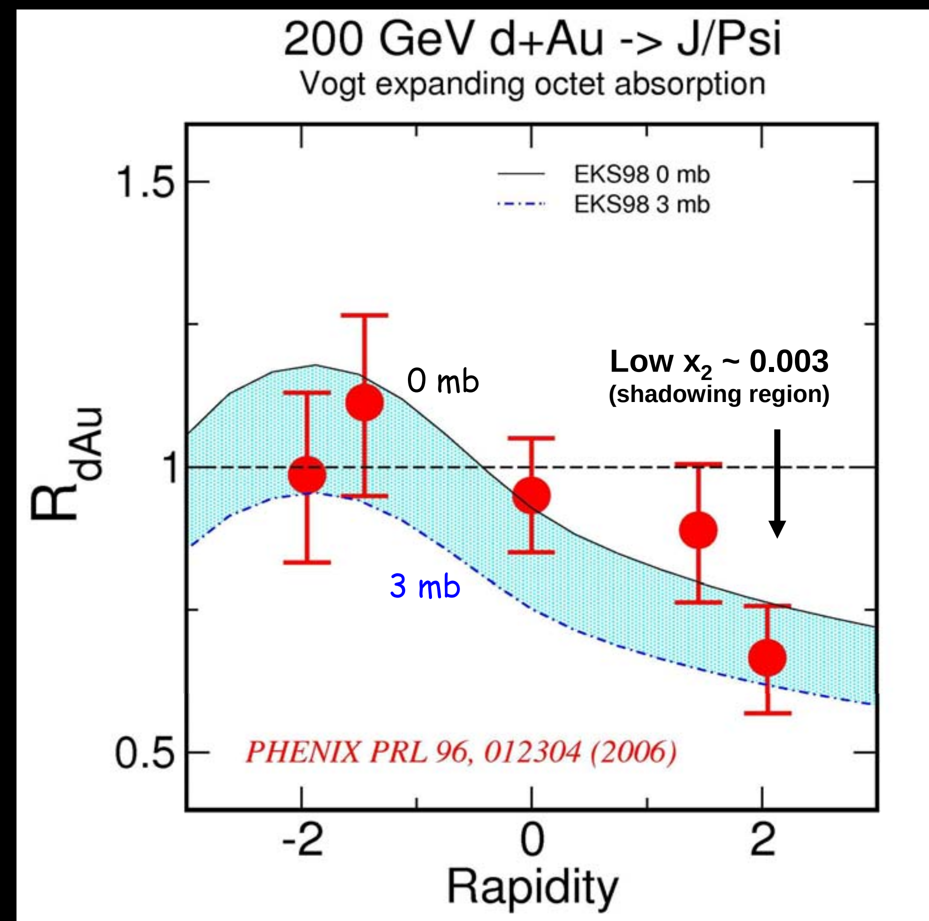
$\langle p_T^2 \rangle = 2.51 \pm 0.21\ (GeV/c)^2$

J/Ψ production in d+Au



Nucl. Phys. A696 (2001) 729-746





y < -1.2 : large x_{Au} ~ 0.090

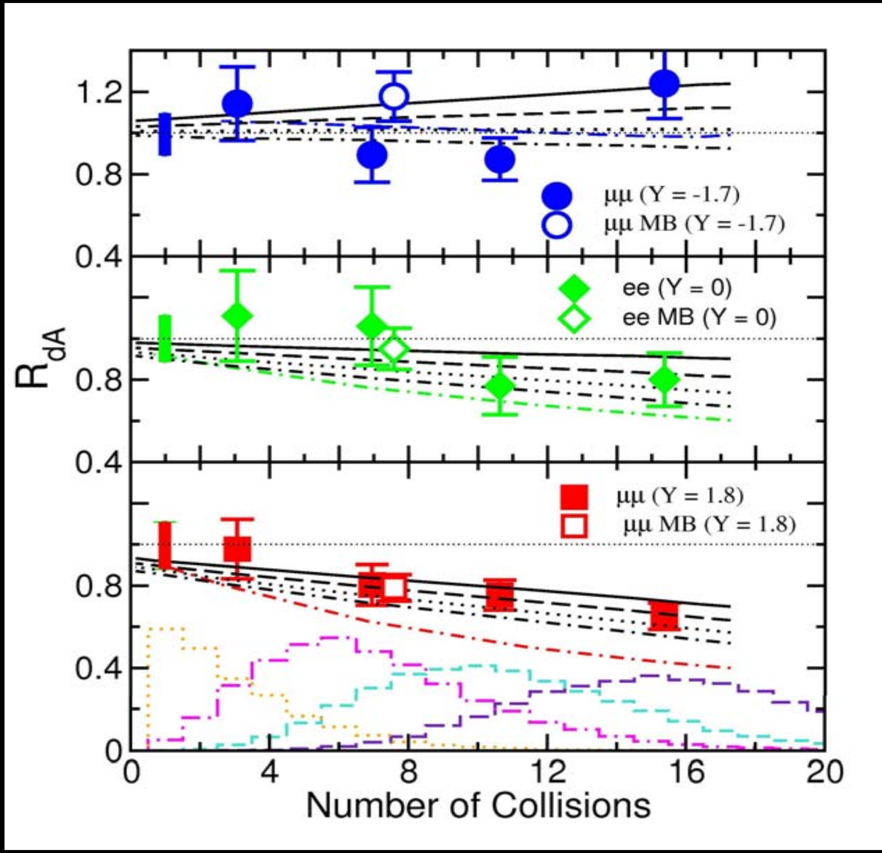
y ~ 0 : intermediate x_{Au} ~ 0.020

y > 1.2 : low x_{Au} ~ 0.003

J/Ψ production in d+Au vs centrality

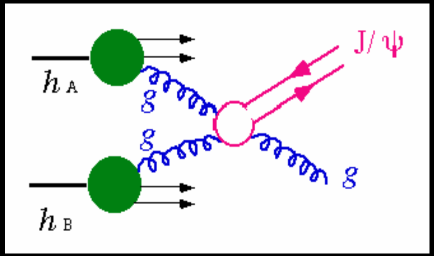
- Small centrality dependence
- Models with absorption + shadowing :
  - shadowing EKS98
  - σ_{abs} = 0 to 3 mb
- σ_{abs} = 1 mb good agreement
- σ_{abs} = 3 mb is an upper limit

⇒ weak shadowing and weak nuclear absorption



J/Ψ and the colour screening in QGP

- Production
  - g+g fusion dominant at RHIC energy

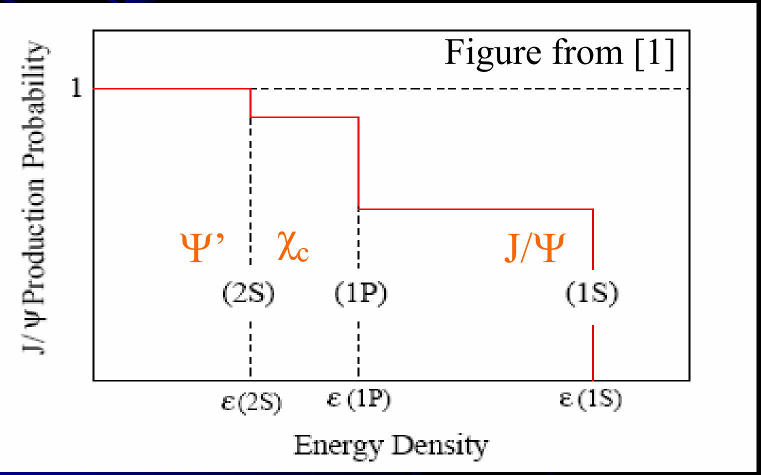


- ~ 60% direct production J/Ψ
  ~ 30% via $\chi_c \rightarrow J/\Psi + x$
  ~ 10% via $\Psi' \rightarrow J/\Psi + x$

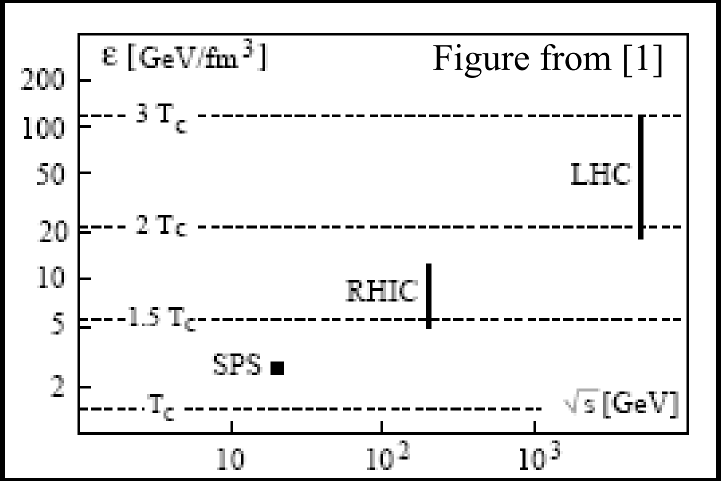
- Temperature of dissociation T_d
  - for χ_c and Ψ': $T_d \sim T_c$
  - for J/Ψ : $T_d \sim 1.5$ to $2\ T_c$

cf. [1] Satz, hep-ph/0512217
[2] Karsch et al. hep-ph/0512239

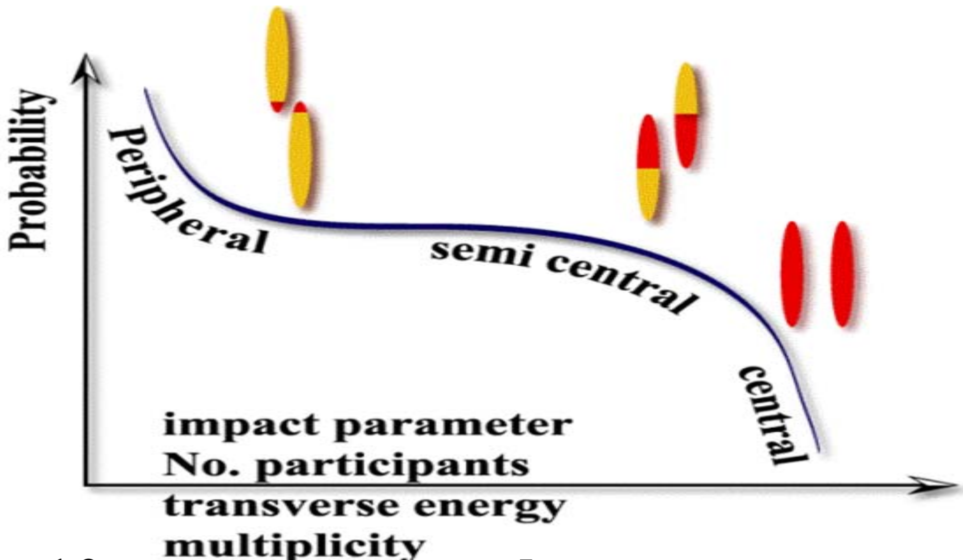
- Sequential dissociation vs energy density



- Energy density vs the max. √s for SPS, RHIC and LHC



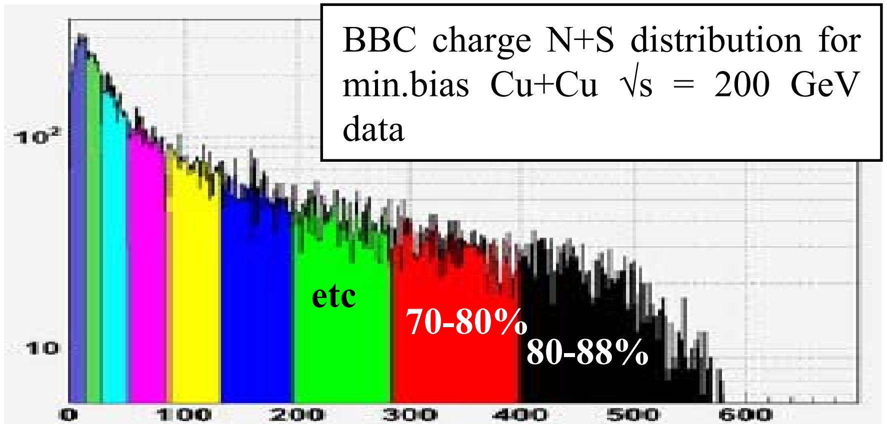
Collision geometry and centrality (eg : Cu+Cu)



10 fm —— b —— 0 fm

0 —— N_{part} —— 104

0 —— N_{coll} —— 198



BBC charge N+S distribution for min.bias Cu+Cu √s = 200 GeV data

Participants (charged particles) → Q_{BBC}

Spectators (neutrons) → E_{ZDC}

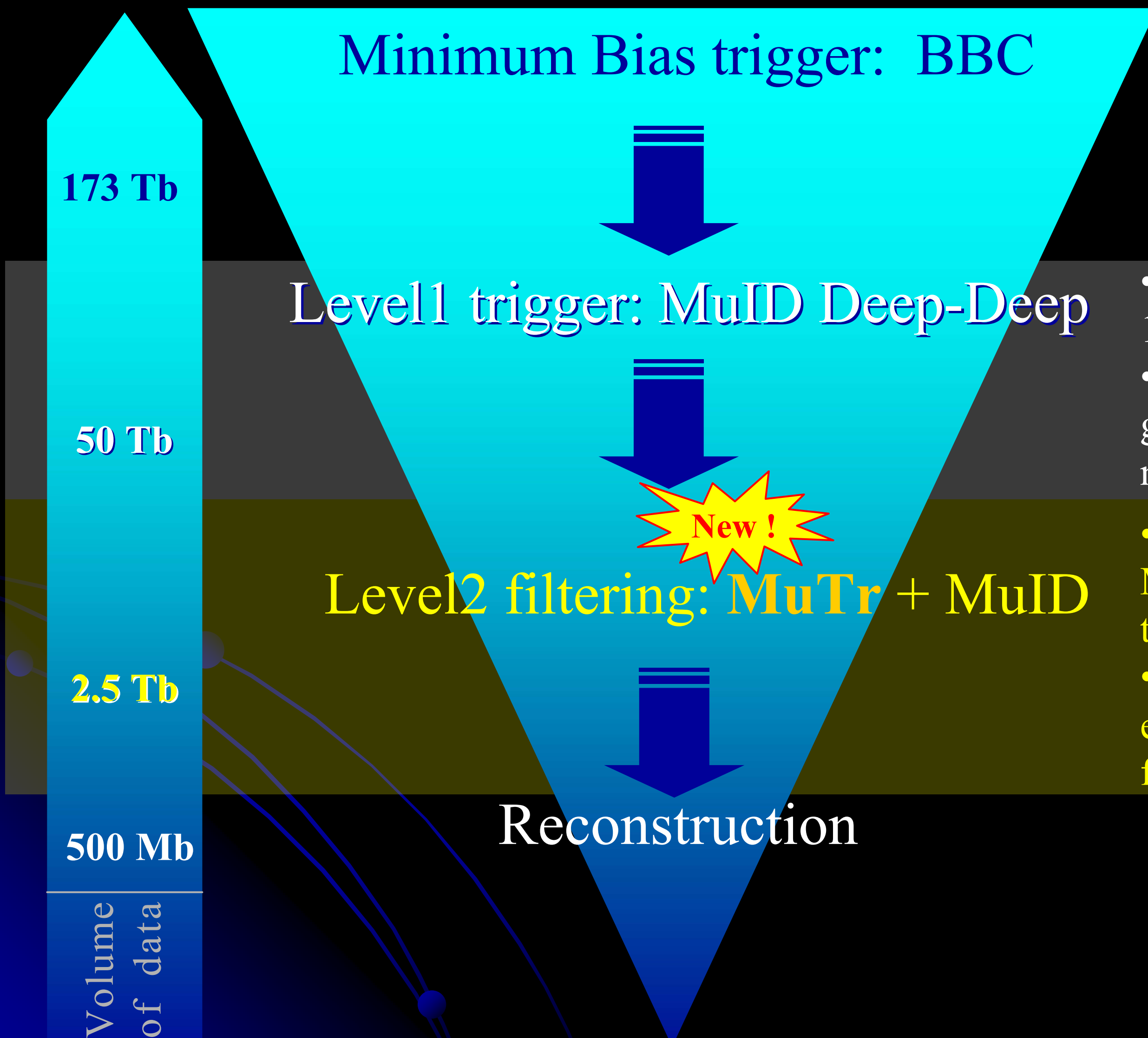
For a given *b*, Glauber model (Woods-Saxon function) predicts:
- N_{part} (No. participants)
- N_{coll} (No. binary collisions)

Monte-Carlo Glauber model
⇓
Probability for a given Npart
⇓
Each participant contributes to a Negative Binomial distribution of hits
⇓
Fit BBC charge distribution

Run 1 to Run 5 capsule history and J/Ψ in PHENIX

	Year	Ions	√s [GeV]	∫Ldt	Number of J/Ψ	Data Size
Run 1	2000	Au+Au	130	1 μb^{-1}	0	3 TB
Run 2	2001	Au+Au	200	24 μb^{-1}	13 + 0	10 TB
	2002	p+p	200	0.15 pb^{-1}	46 + 66	20 TB
Run 3	2002	d+Au	200	2.74 nb^{-1}	300 + 1400	46 TB
	2003	p+p	200	0.35 pb^{-1}	100 + 420	35 TB
Run 4	2004	Au+Au	200	241 μb^{-1}	~600 + 5000	270 TB
		Au+Au	62.4	9.1 μb^{-1}	50 expected	10 TB
		p+p	200	324 nb^{-1}		
Run 5	2005	Cu+Cu	200	3 nb^{-1}	~1200+10000	173 TB
		Cu+Cu	62.4	0.19 nb^{-1}	~40+200	48 TB
		Cu+Cu	22.5	9.1 μb^{-1}		1 TB
		p+p	200	3.8 pb^{-1}	> 6500 expected	262 TB

Cu+Cu 200 GeV data taking: triggers and level2 filtering

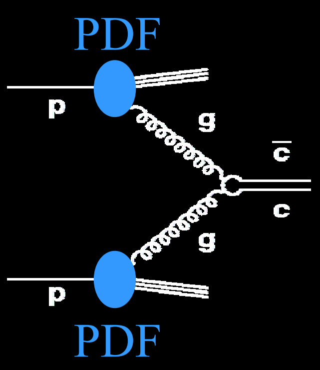


- fast online reconstruction of 1D road in MuID
- di-road accepted if last MuID gap reached (with a minimum number of hit gaps)

- reconstruction of 2D road in MuID used as seed for MuTr track finding
- rough track momentum estimate ⇒ invariant mass cut for tracks pairs at 2 GeV/c^2

J/Ψ as a probe of the produced medium (I)

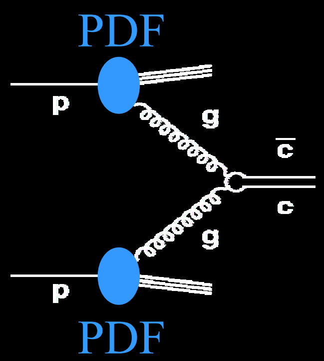
- Hard probe
  - Large charme quark mass ($m_{J/\Psi}$ ~3.1 GeV/c²) ⇒ J/Ψ produced at early stages of the collision
  - Size $r_{J/\Psi}$ ~0.2 fm < typical hadronique size (~1 fm)
  - Recent lattice QCD result : melting temperature in a deconfined medium is T ~ 1.5 à 2 T_C
- Production
  - g+g fusion



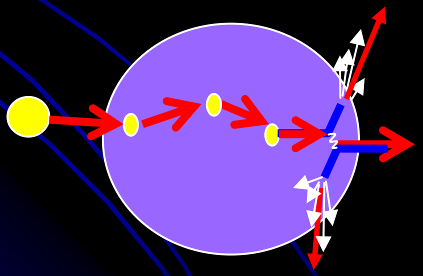
  - ~60% direct production J/Ψ
    ~30% via $\chi_c \rightarrow$ J/Ψ + x
    ~10% via Ψ'→ J/Ψ + x
  - p+p ⇒ reference for p+A or A+A
    - ratios (p+A)/(p+p) or (A+A)/(p+p)
- Suppression or enhancement of the J/Ψ yield :
  - Due to nuclear matter or to deconfined medium ?

J/Ψ as a probe of the produced medium (II)

- Initial state effect
  - CGC, shadowing

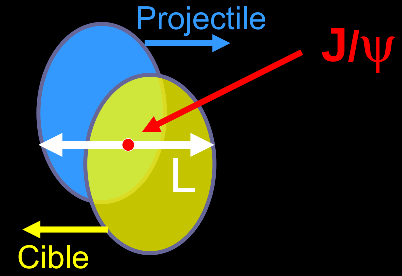


  - Cronin effect : multiple elastic scattering ⇒ p_T broadening

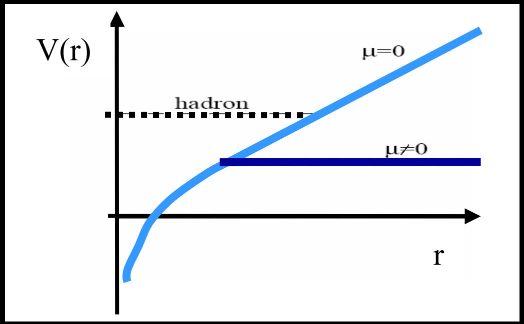


  - Evaluated via p+A ou d+A

- Final state effect
  - Nuclear (hadronic) absorption



  - QGP ?
    - suppression : « colour screening »



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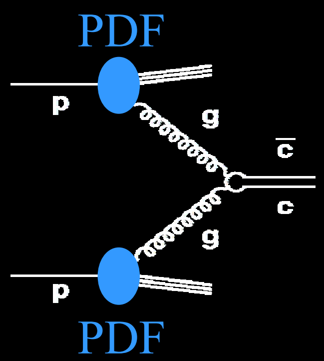

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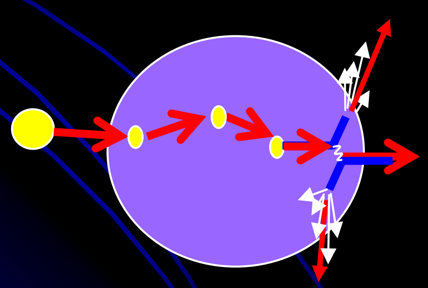

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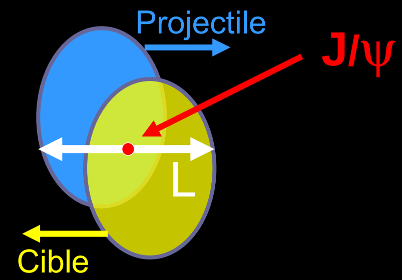

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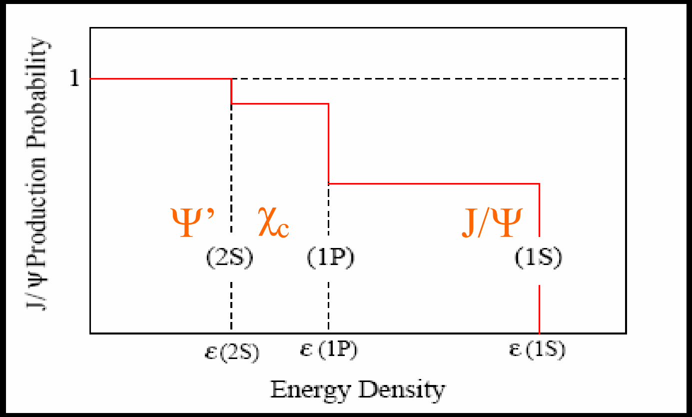

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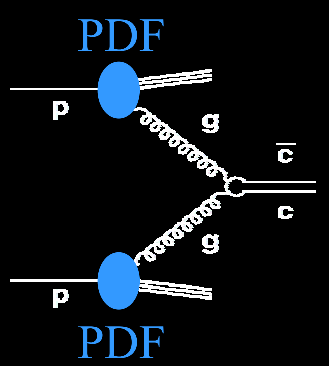

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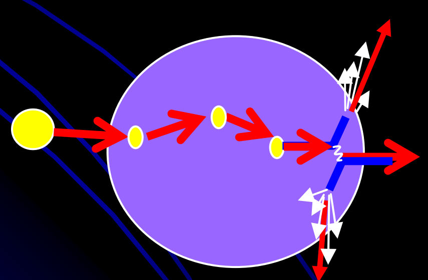

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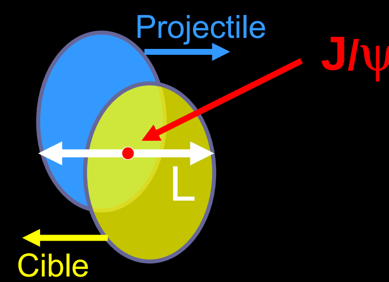
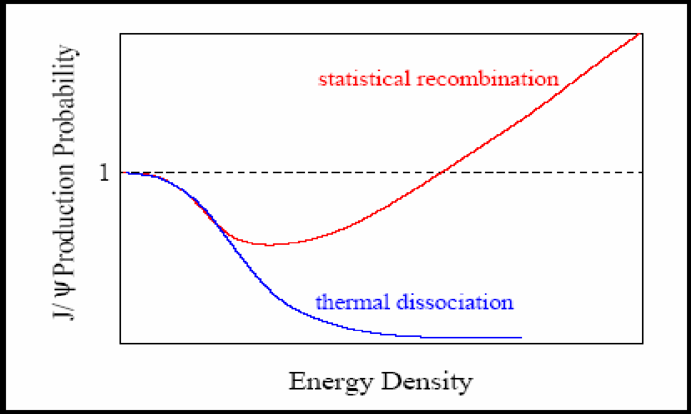


  - QGP ?
    - suppression : « colour screening »
    - or enhancement : recombinaison
      - From 10 to 20 cc in central Au+Au at RHIC



  - Accessible via A+A

Background sources

- Physical background: correleted dimuons
  - Drell-Yan:

  - Open charm:

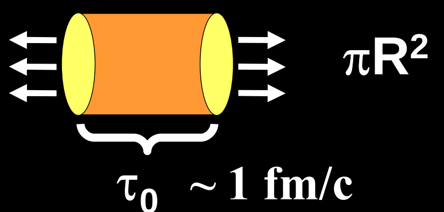
    $D, \overline{D} \rightarrow \mu^{\pm} + \ldots$

- Combinatoric background: uncorrelated dimuons
  - $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \ldots$ (decay before the absorber)

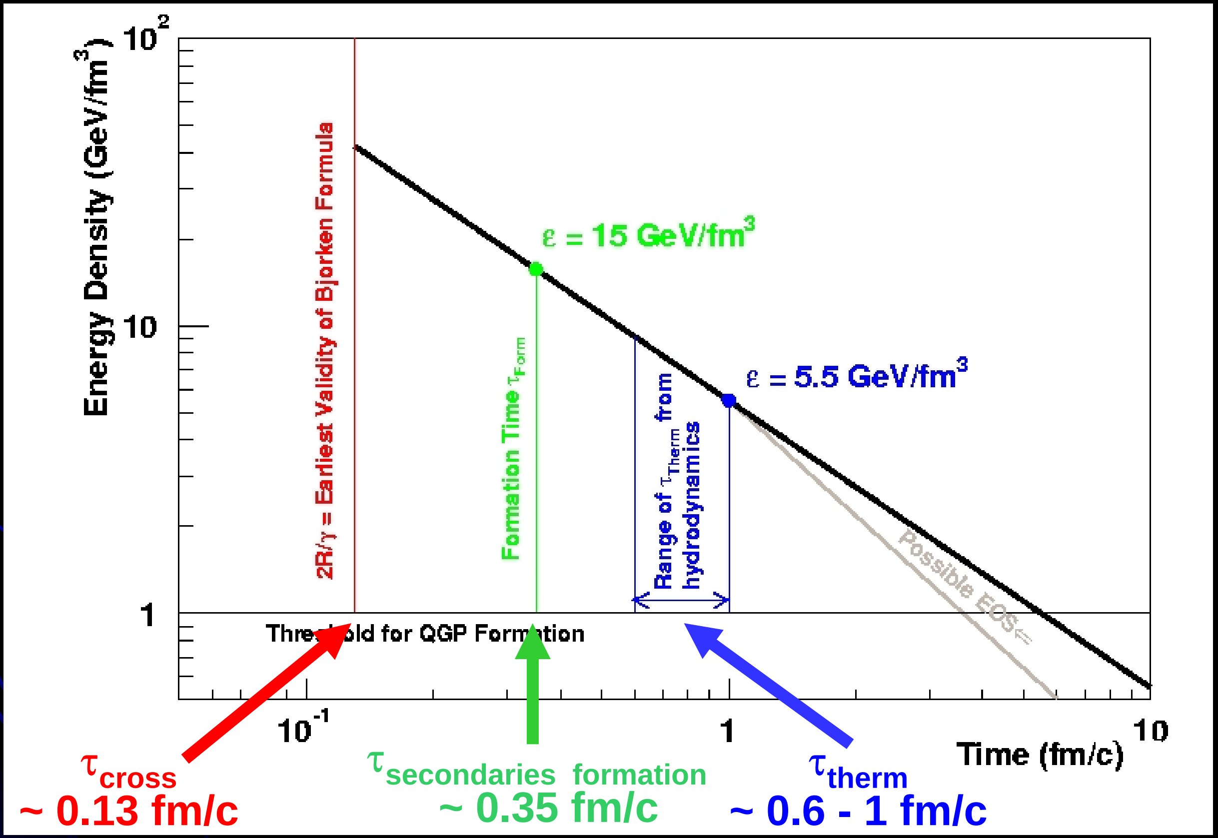
Energy density

- Longitudinally expanding plasma :

$$\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$



  - $dE_T/d\eta$ measurement at mid-rapidity by PHENIX EMCal
  - Which τ_0 ?



Commonly used variables

- **Transverse** : perpendicular to the beam direction
- Transverse momentum : $p_T = sqrt(p^2_x + p^2_y)$
- Rapidity : $y = 1/2 \ ln \ (E+p_z)/(E-p_z)$
- Pseudorapidity : $\eta = 1/2 \ ln \ (p+p_z)/(p-p_z)$
- Invariant mass of a pair : $M^2_{inv} = (E_1 + E_2)^2 - (p_1+p_2)^2$