Quarkonia (and heavy flavors) at RHIC

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QGP – France, Étretat 2006

Physics motivation – the starting point

- What are the properties of the hot and dense matter produced in relativistic heavy ion collisions ?

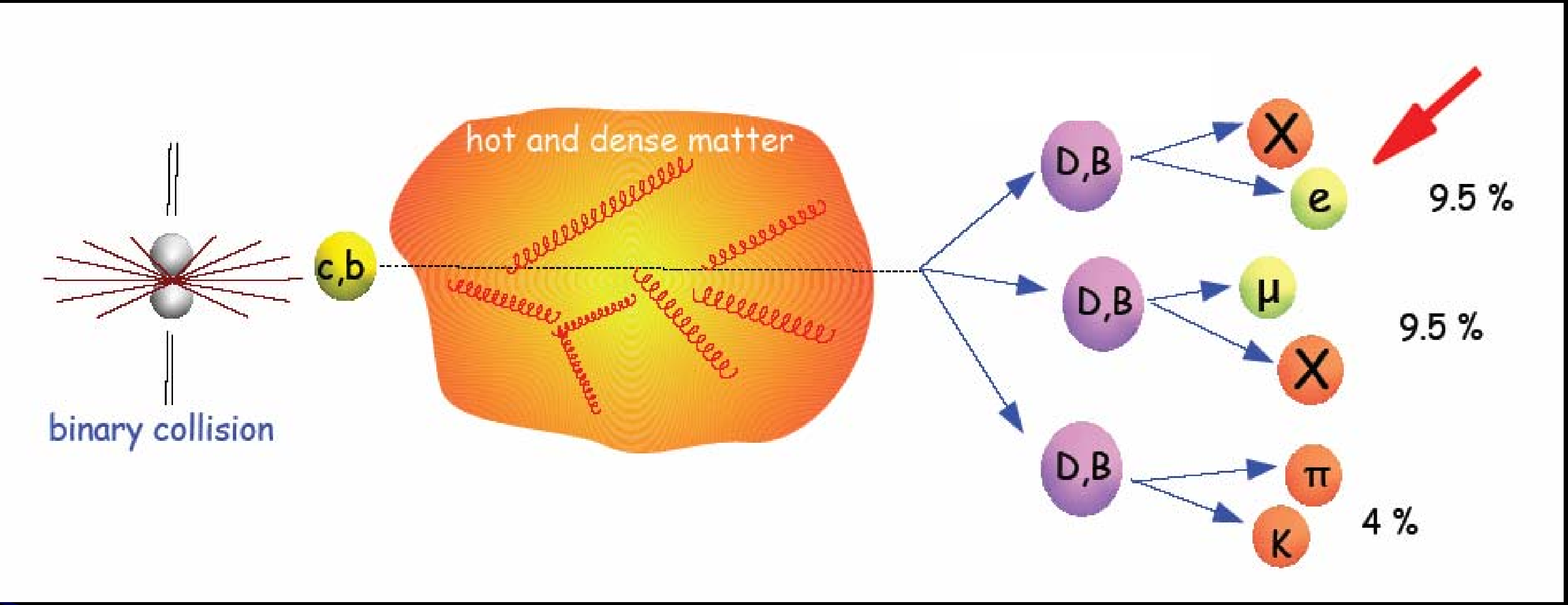
- c and b are produced in the initial parton collisions, so they can be used to probe the created medium :

  - open charm (or beauty) energy loss → energy density
    - Only a few words here (from a newbie ☺)

  - $c\bar{c}, b\bar{b}$ (quarkonia) suppressed by color screening → deconfinement
    - We will focus on quarkonia in this talk, especially on hidden charm.

Heavy quarks

Heavy quarks dynamic



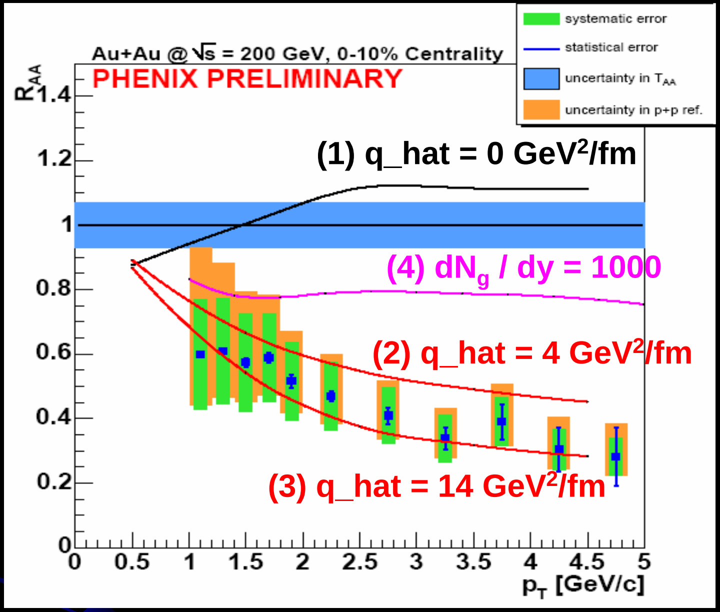
- Measuring non-photonic electrons at RHIC:
  - R_{AA}
  - v_2

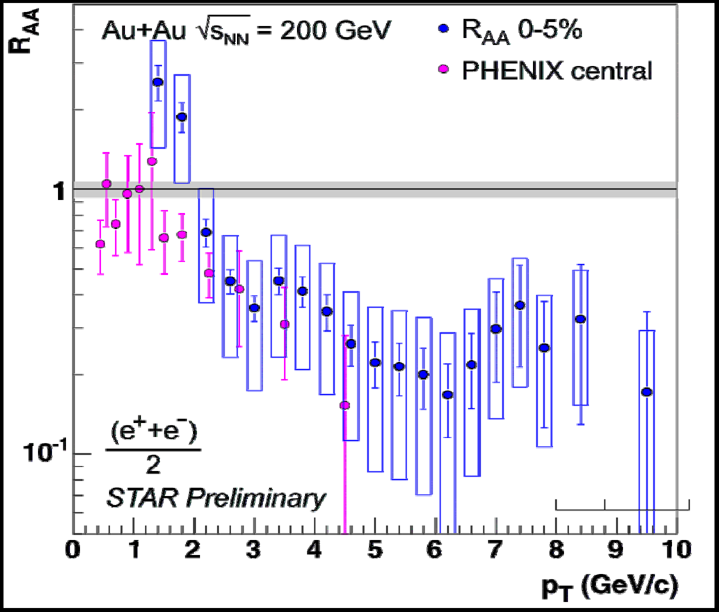
Heavy quark (radiative?) energy loss

(1-3) N. Armesto et al., PRD 71, 054027 (charm contribution only)

(4) M. Djordjevic et al., PRL 94, 112301 (beauty included)

V. Greene, S. Butsyk; QM05





J. Dunlop, J. Bielcik; QM05

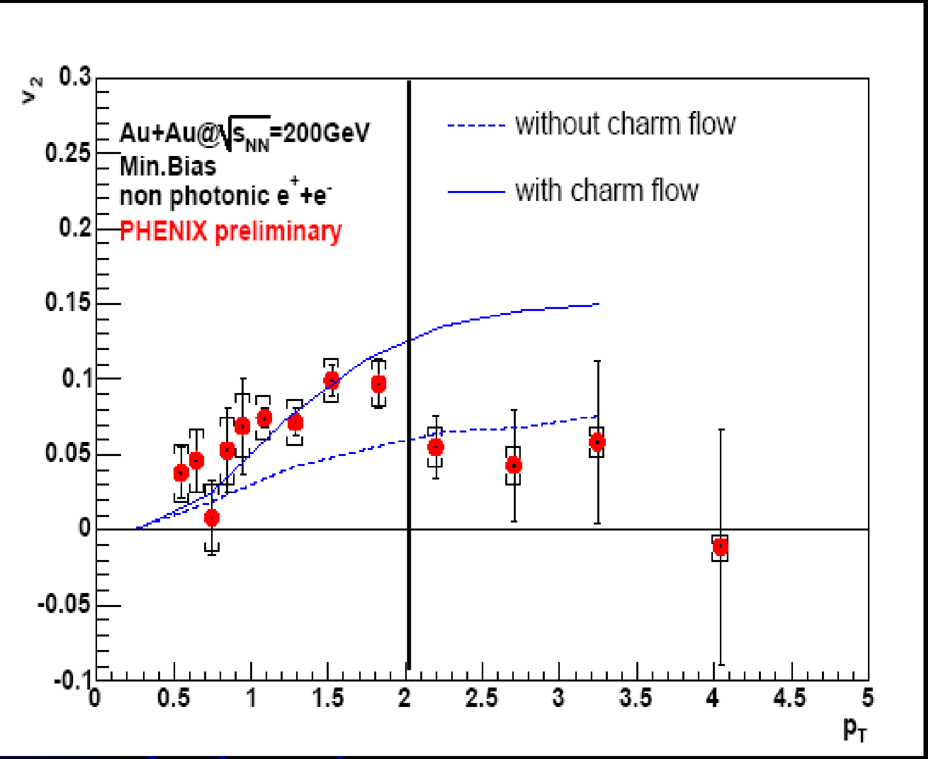
- Agreement between both experiments
- Significant reduction at high pT suggests sizeable heavy quark energy loss.
- Data favors a strong transport coefficient* q_hat ~14 GeV²/fm (radiative energy loss only model) ⇔ large initial gluon density ~ 3500! Too high! Should take into account the collisionnal energy loss? (see M. Djordjevic, nucl-th/0603066)

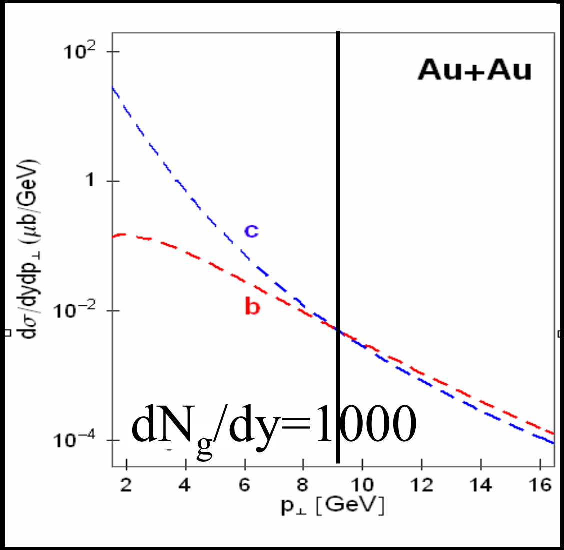
*q_hat ∝ density of scattering centers in the medium

Charm flow

S.Butsyk QM05 Greco, Ko, Rapp, PLB 595 (2004) 202

M. Djordjevic et al., Phys.Lett.B632 (2006) 81





c and *b* quark p_T distributions at mid-rapidity before fragmentation : b contribution is dominant at high pT

- Significant flow observed for heavy flavor electrons
- Indication for reduction of v_2 at $p_T > 2$ GeV/c. Due to beauty contribution?

Quarkonia

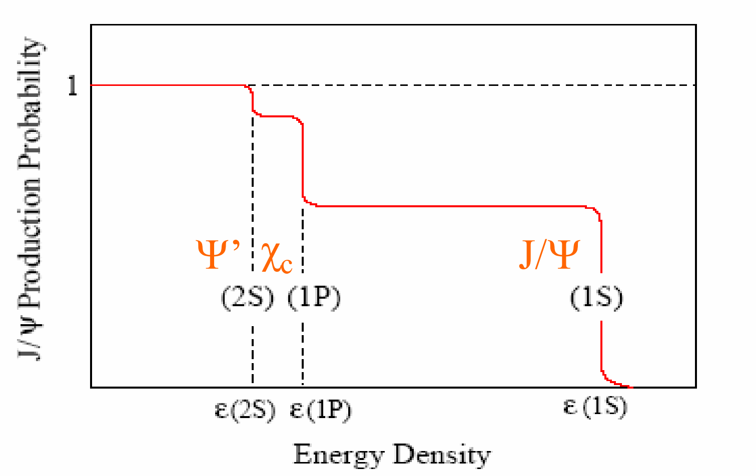
Mostly J/Ψ (mostly PHENIX results)

Screening the J/Ψ in a QGP

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

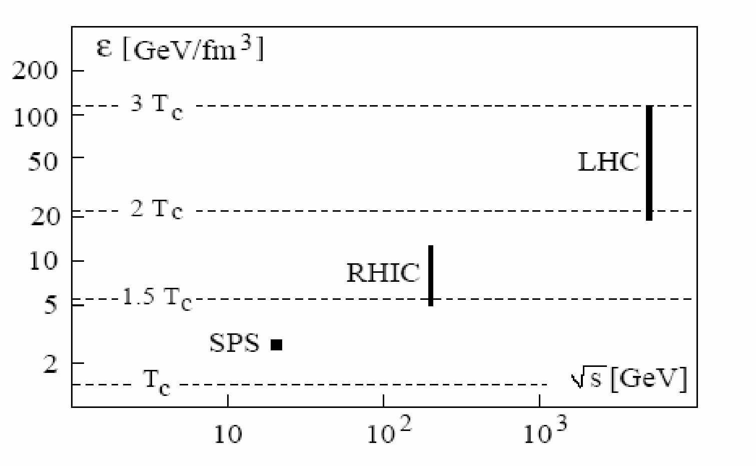
⇒ Sequential dissociation as the temperature (or energy density) increases :

Satz, hep-ph/0512217



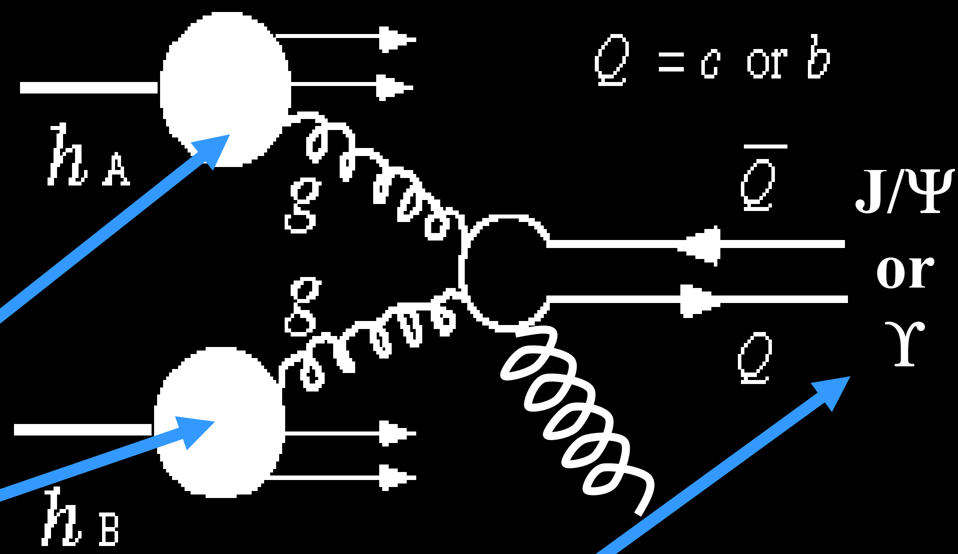
- Temperature of dissociation T_d
  - for χ_c and Ψ': $T_d \sim 1.1\ T_c$
  - for J/Ψ : $T_d \sim 1.5$ to $2\ T_c$

- Energy density (τ_0 = 1fm) vs the max. √s for SPS, RHIC and LHC



Physics motivation – a few complications

- quarkonia production
  - *g+g* fusion dominant at RHIC energies



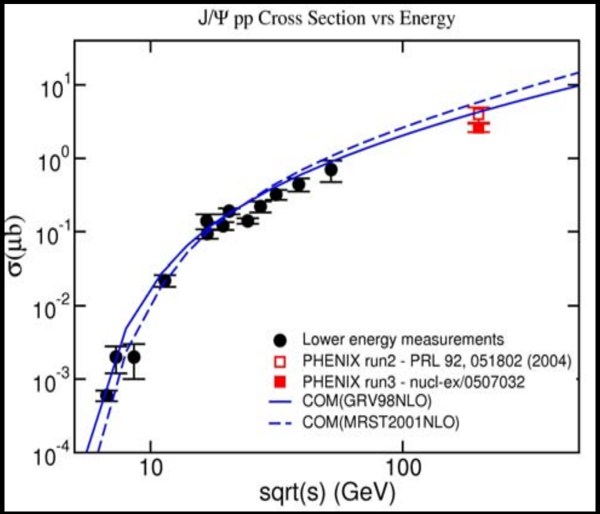
- Sensitive to:
  - Initial state
    - Modification of the parton distribution functions (shadowing, CGC)
    - p_T broadening (Cronin effect)
    - Parton energy loss in the initial state ?
  - Final state
    - "Normal" nuclear absorption
    - Absorption by (hadronic ?) comovers ?
    - Color screening ?
    - In-medium formation (recombination) ?
    - Flow ?

+ feed-down b, Ψ, $\chi_c \rightarrow$ J/Ψ + x

Production baseline : p+p→J/Ψ

Cross section vs : energy rapidity p_T

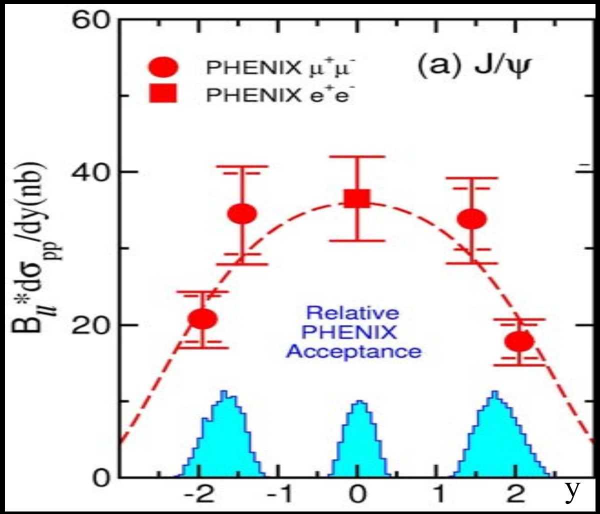
Phys. Rev. Lett. 96, 012304



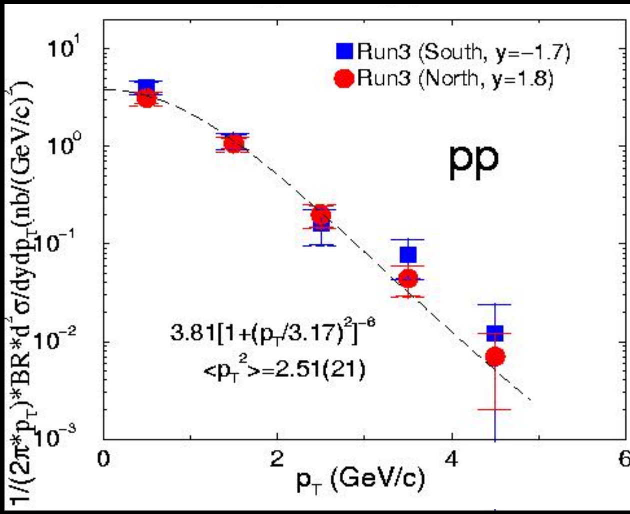
Total cross section in p+p

σ= 2.61 ± 0.20 ± 0.26 μb

in agreement with COM



Cross section vs rapidity follow PYTHIA shape



Cross section vs pT

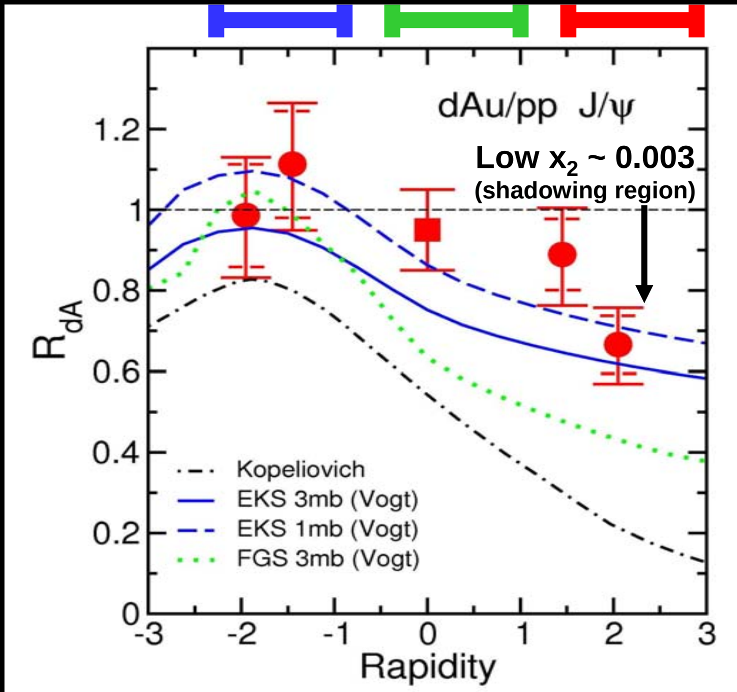
$\langle p_T^2 \rangle = 2.51 \pm 0.21\ (GeV/c)^2$

p+p→J/Ψ measurement will be used as a reference for A+B→J/Ψ :

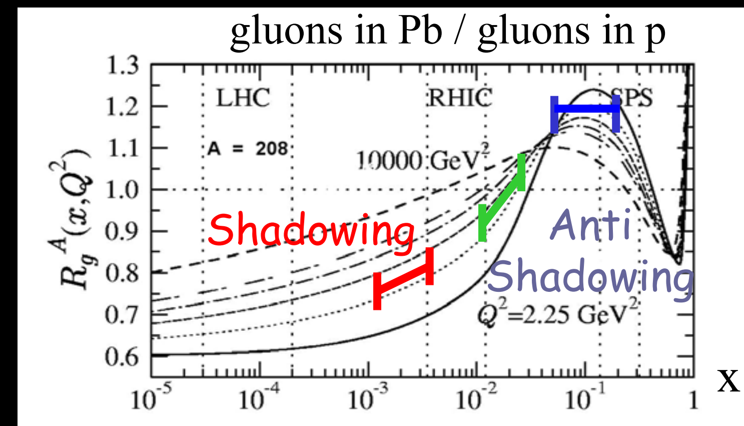
$$R_{AB} = \frac{yield_{AB}}{\langle N_{Coll} \rangle yield_{pp}}$$

Cold nuclear effects : d+Au→J/Ψ

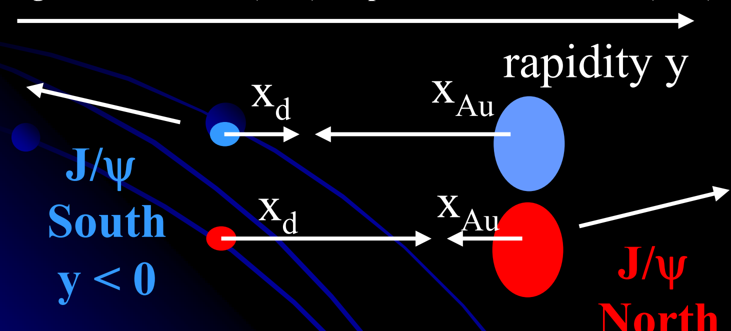
Phys. Rev. Lett. 96 (2006), 012304



Vogt, PRC71, 054902 (2005), Kopeliovich, NP A696, 669 (2001)



Nucl. Phys. A696 (2001) 729-746



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

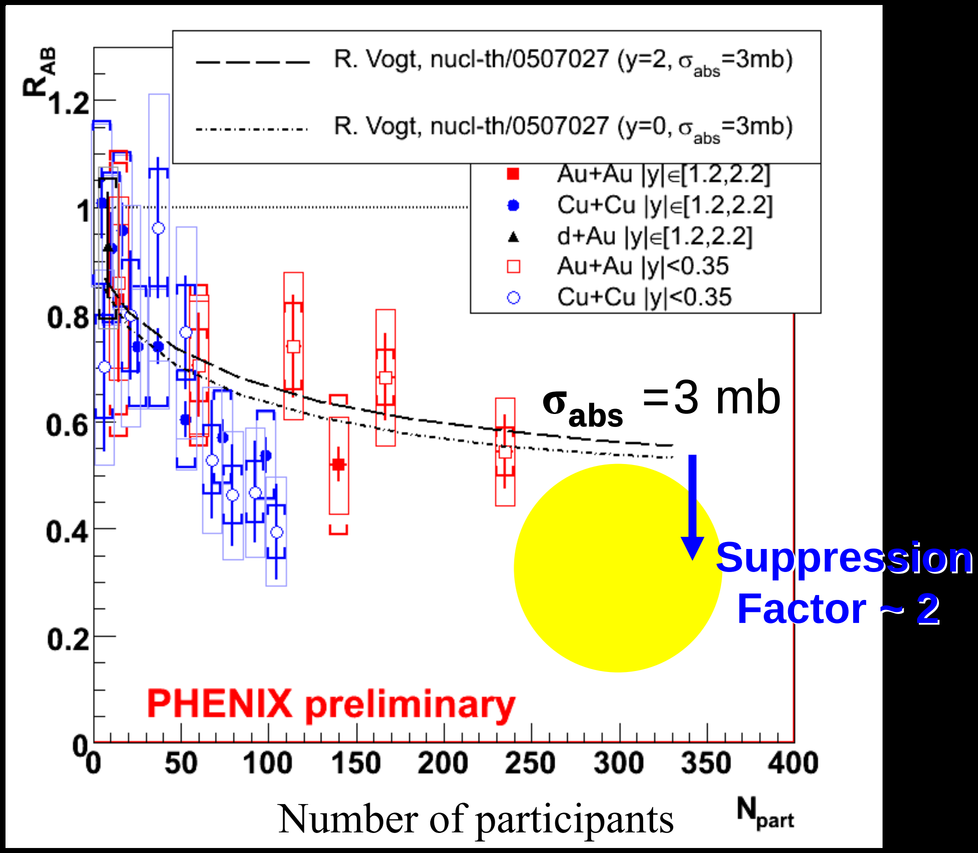
y ~ 0 : intermediate x_{Au} ~ 0.020

y > 1.2 : low x_{Au} ~ 0.003

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

RHIC : beyond cold nuclear effects ?

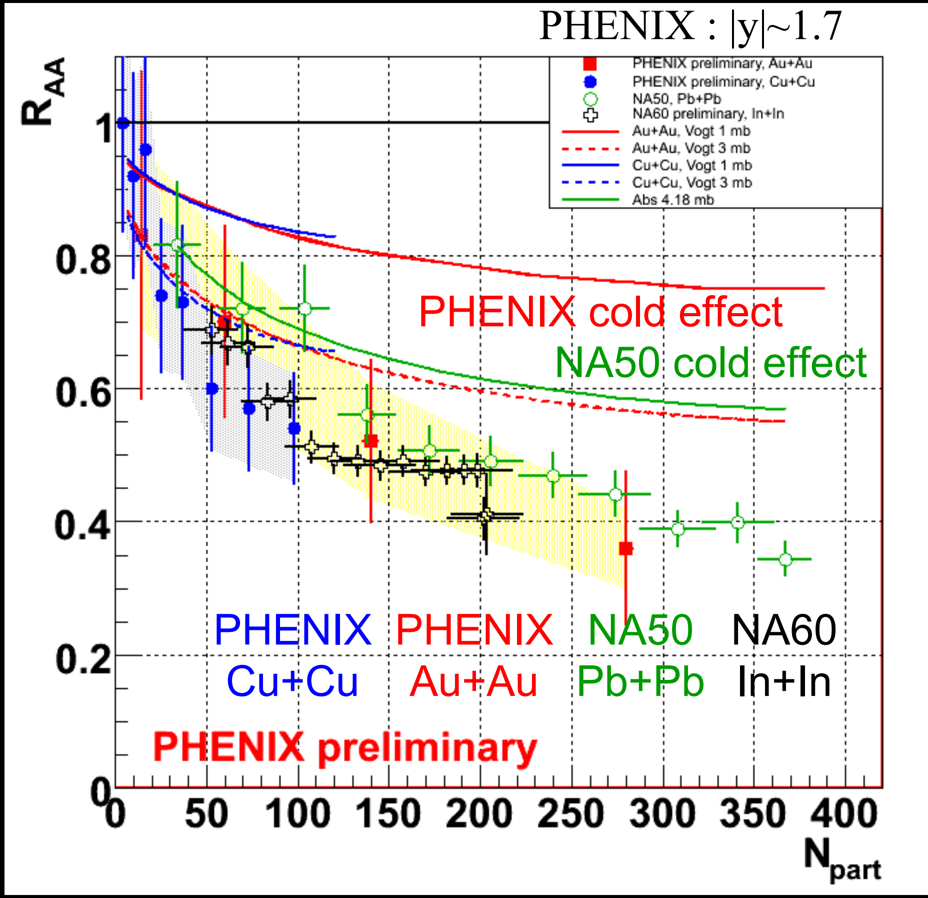
- Au+Au data : even compared to the « worst » σ_{abs}~ 3mb case
  - Factor 2 of suppression beyond cold effects in the most central Au+Au bin



Cold nuclear matter predictions from Vogt, nucl-th/0507027 (shadowing + σ_{abs} = 1, 3mb)

RHIC vs SPS (I) : raw comparison

- SPS :
  - $\sqrt{s}$ ~ 17 GeV i.e. a factor 10 below RHIC
  - Cold effect = normal nuclear absorption σ_{abs} = 4.18 ± 0.35 mb
  - Maximum ε ~ 3 GeV/fm^3 (τ_0 = 1)
- Compare to RHIC :
  - Cold effect = shadowing + nuclear absorption σ_{abs} ~ 1mb (Vogt, nucl-th/0507027)
  - Maximum ε ~ 5 GeV/fm^3 (τ_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).

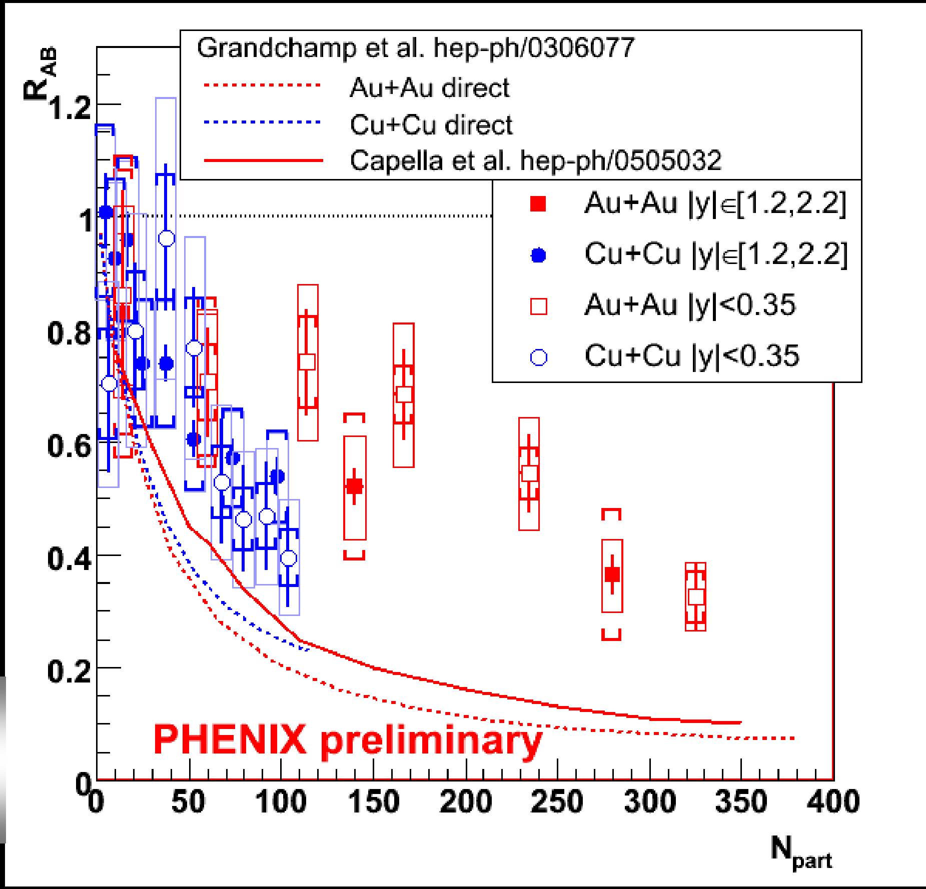
RHIC vs SPS (II) : extrapolating suppression models

- 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 :

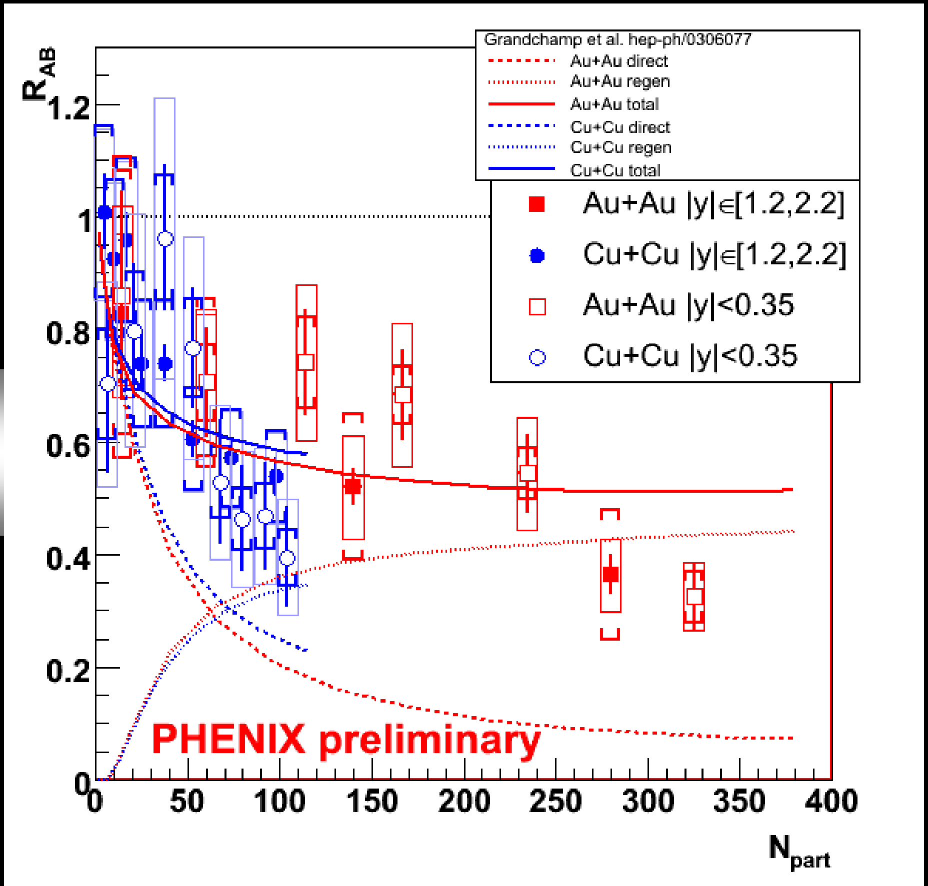
Cu+Cu Au+Au

Regeneration :

Cu+Cu Au+Au

Total :

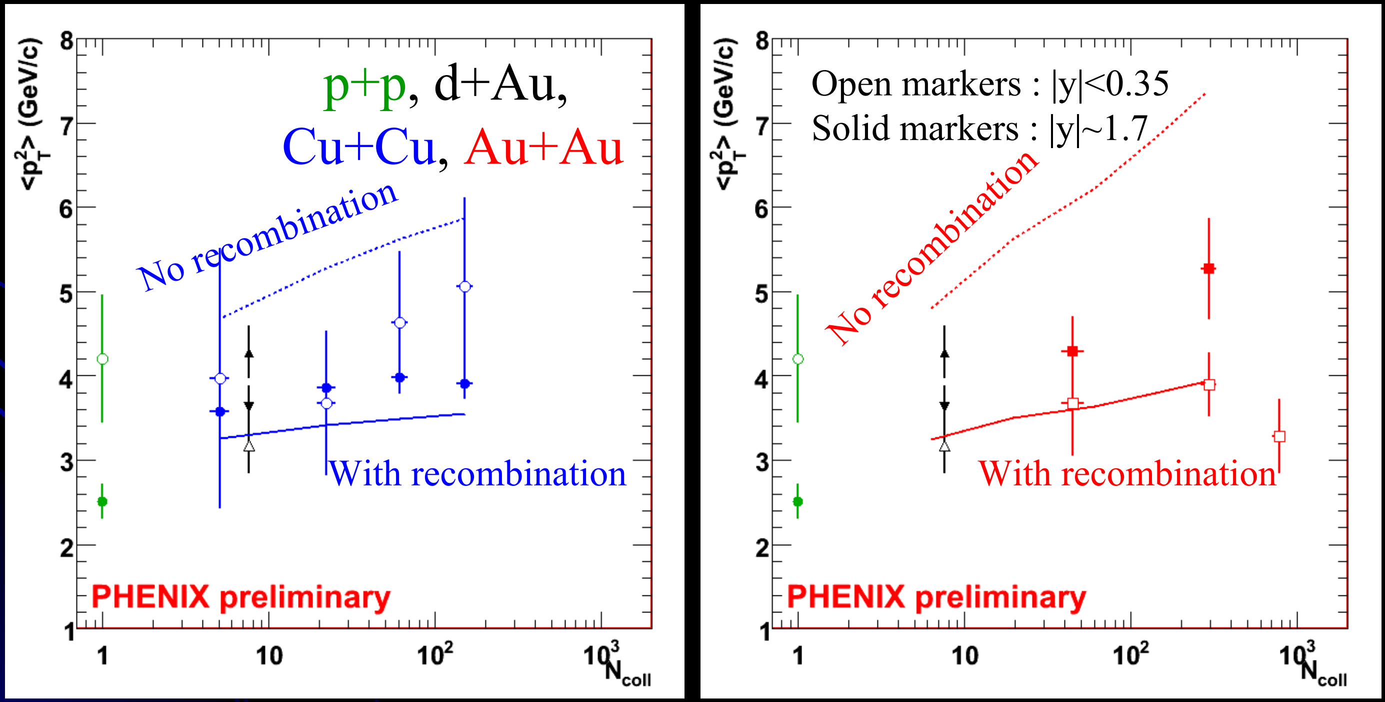
Cu+Cu Au+Au



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

- Recombination 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 ?

Thews & Mangano, PRC73 (2006) 014904c



Predictions for $< p_T^2 >$ vs N_{coll} : Cronin effect ?

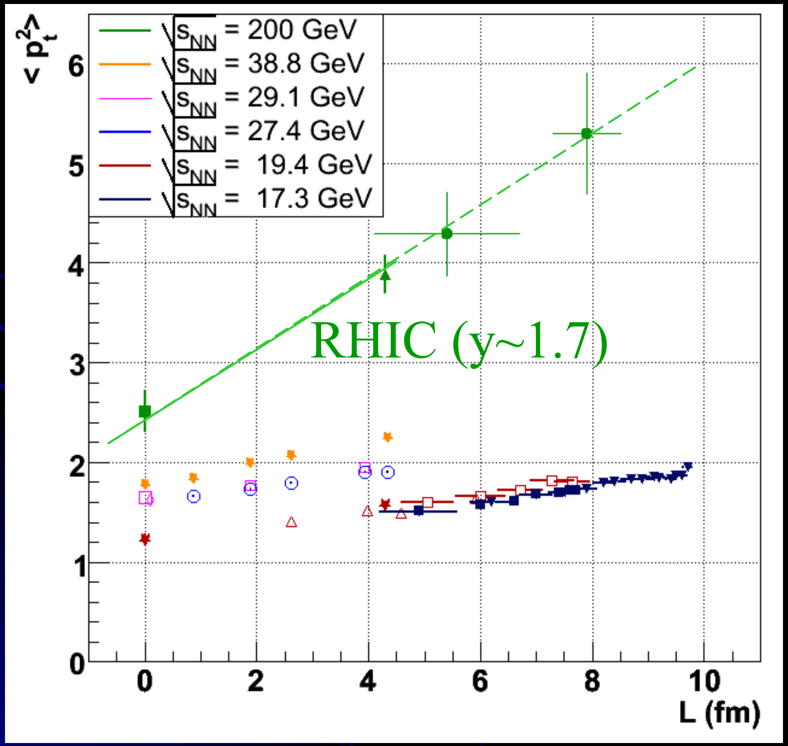
- Random walk of the initial gluons in the transverse plane :

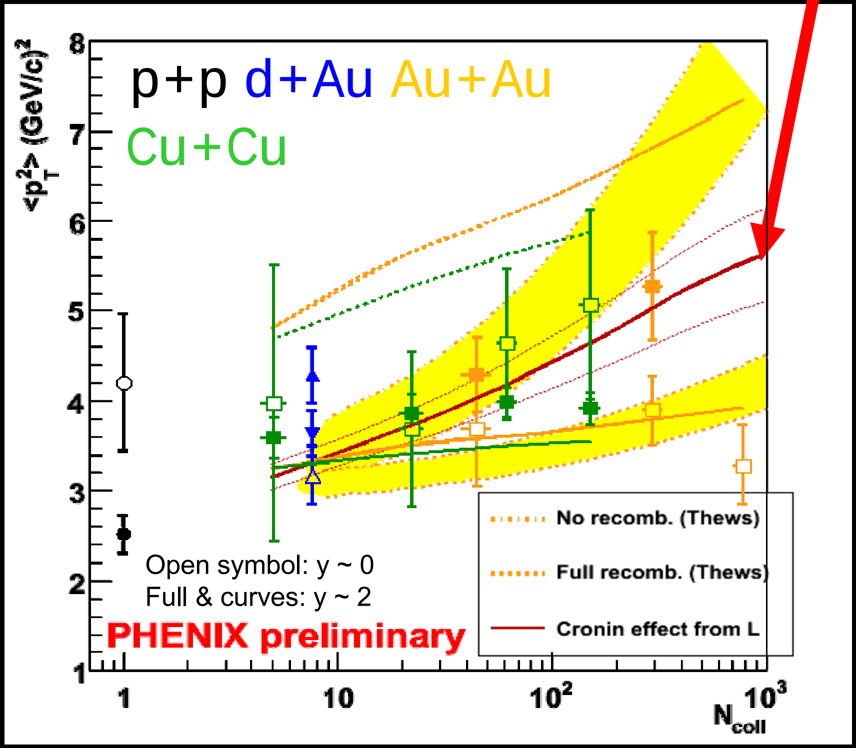
$$\langle p_T^2\rangle_{AA} = \langle p_T^2\rangle_{pp} + \rho_0\, \sigma_{g\text{-}N}\, \Delta p_T^2\, L_{AA}$$

- Use this linear L dependence to fit the $\langle p_T^2\rangle$ brodening seen in dimuon data from p+p to d+Au at RHIC
- Using $L \leftrightarrow N_{coll}$, plot the result vs N_{coll}

$\langle p_T^2\rangle = 2.51+0.32*L$

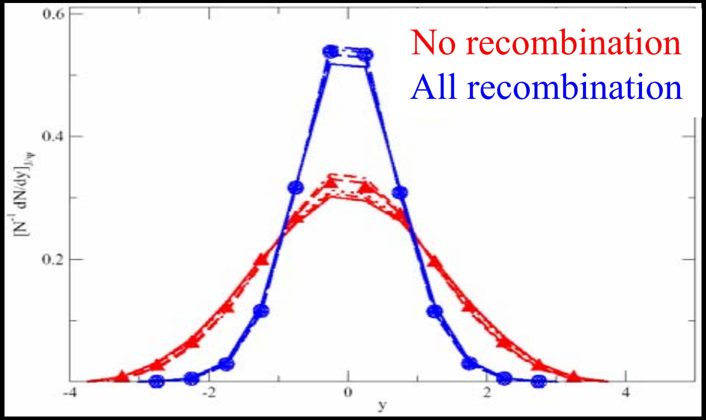
VN Tram, Moriond 2006 & PhD thesis



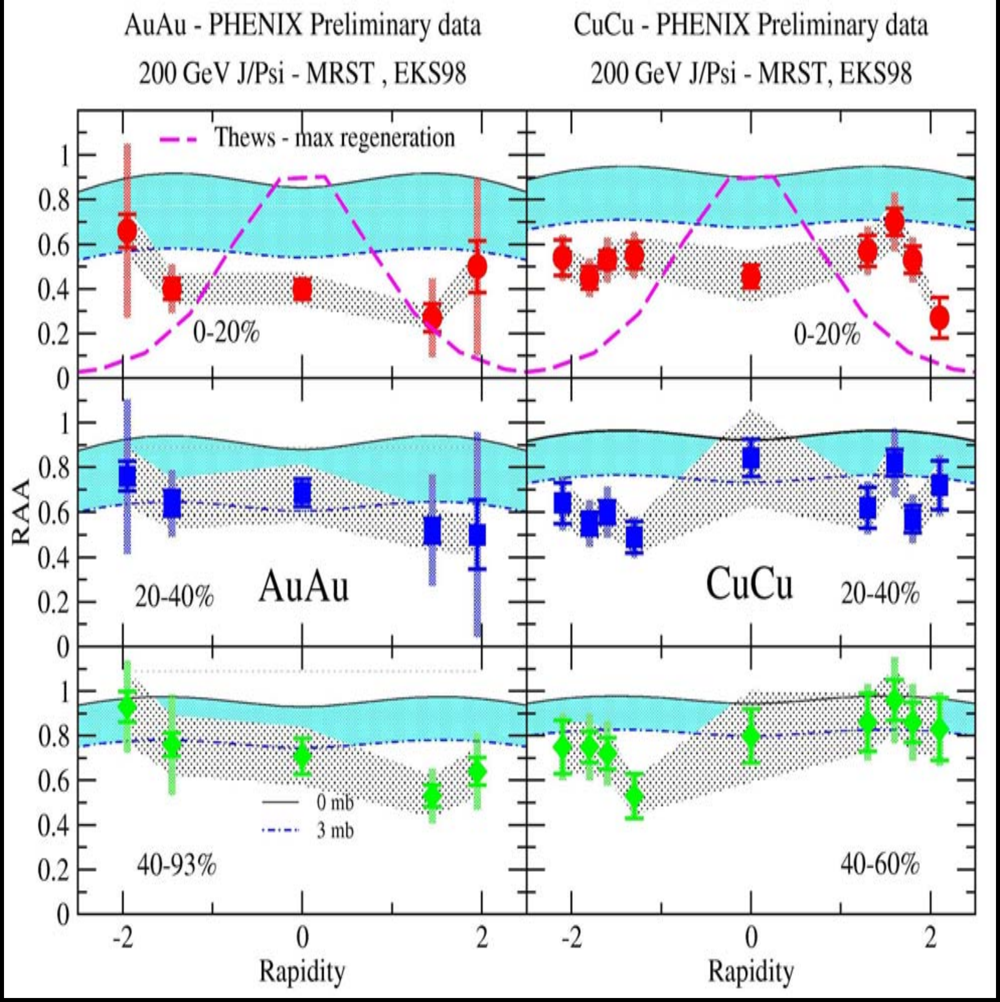


Recombination predictions vs rapidity

Thews & Mangano, PRC73 (2006) 014904c



- Recombination predicts a narrower rapidity distribution with an increasing N_{part}.
- Going from Cu+Cu to the most central Au+Au : no significant change seen in the shape of the rapidity distribution.



Blue bands: cold nuclear matter prediction from Vogt, nucl-th/0507027 (shadowing + σ_{abs} = 0, 3mb)

Karsch, Kharzeev & Satz, PLB 637 (2006) 75

Ending where it began: revisiting the sequential dissociation

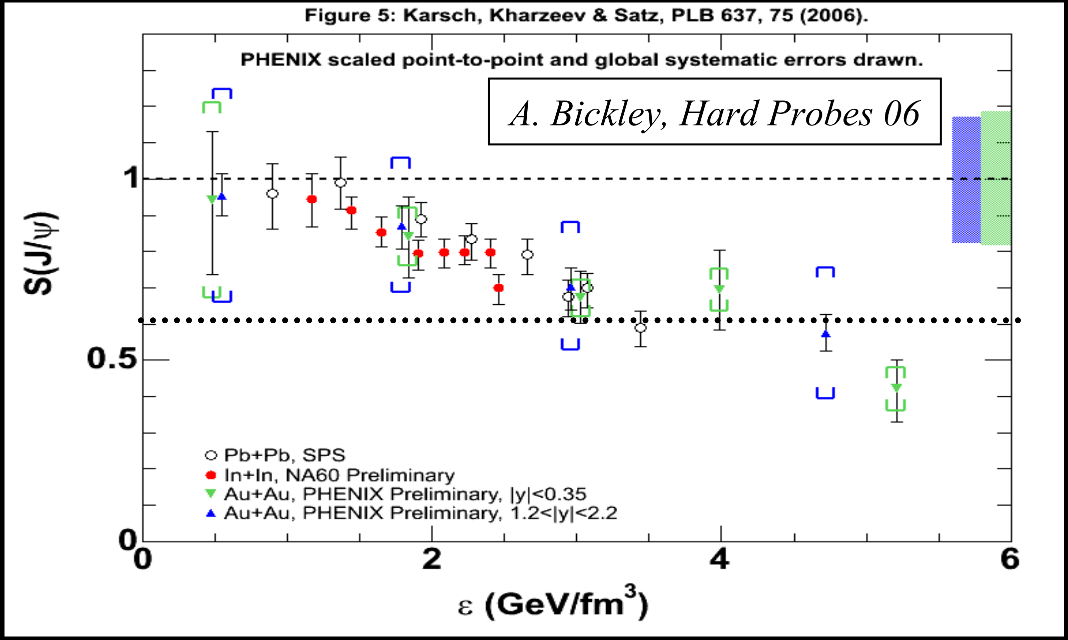
- Data driven parametrization of cold nuclear effect (expected)
- Sequential melting ⇒ overall J/Ψ survival probability (measured/expected):

$$S = 0.6\, S_{\text{direct } J/\Psi} + 0.4\, S_{J/\Psi \leftarrow \Psi', \chi c}$$

- Excited states melting from ψ′ suppression pattern @ SPS
- Recent lattice QCD results : direct J/Ψ melting at 10-30 GeV/fm^3

Real Au+Au systematic errors i.e. pt-to-pt and global scale added (small systematic errors associated with NA50 published data)

- SPS and RHIC data seems to be consistent with the sequential melting.



Summary (I)

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 $c\,\overline{c}$ recombinations that partially compensate the J/Ψ suppression ?
  - Still open question (test vs $\langle p_T^2 \rangle$ dependance and rapidity distribution)

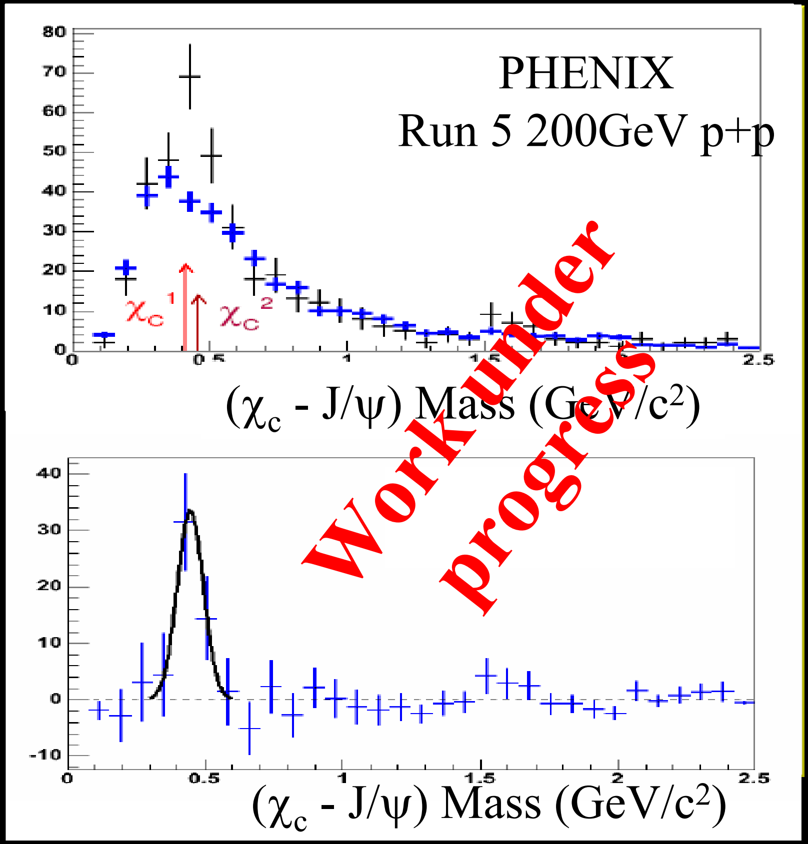
Summary (II)

- 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 ? (Zhu, Zhuang, Xu, PLB607 (2005) 107)
- Need to improve knowledge on cold nuclear effects at RHIC

Hint of things to come

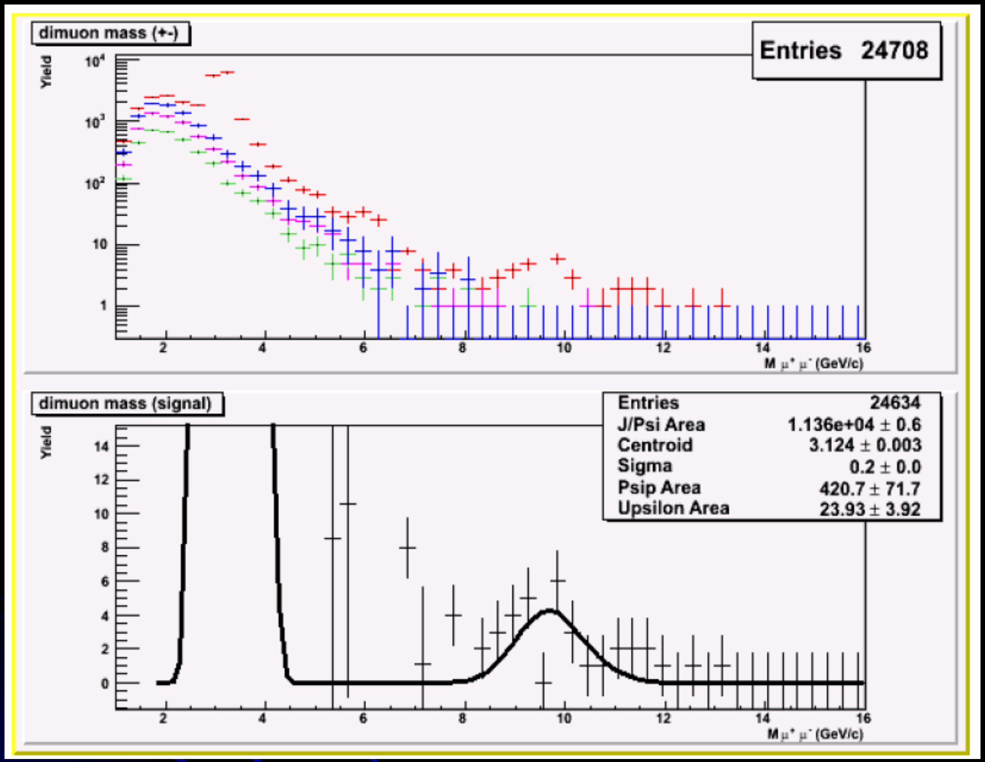
- Improved reference p+p :
  - x10 higher statistics from run 5
  - x30 higher statistics from run 6
- Future measurements in Ψ' ?
- Future measurements in χ_c
- Planning d+Au (28 nb^{-1} vs 2.7 nb^{-1} in run 3) and Au+Au (1 nb^{-1} vs 0.24 nb^{-1} in run 4) with high luminosity

A. Bickley, Hard Probes 06

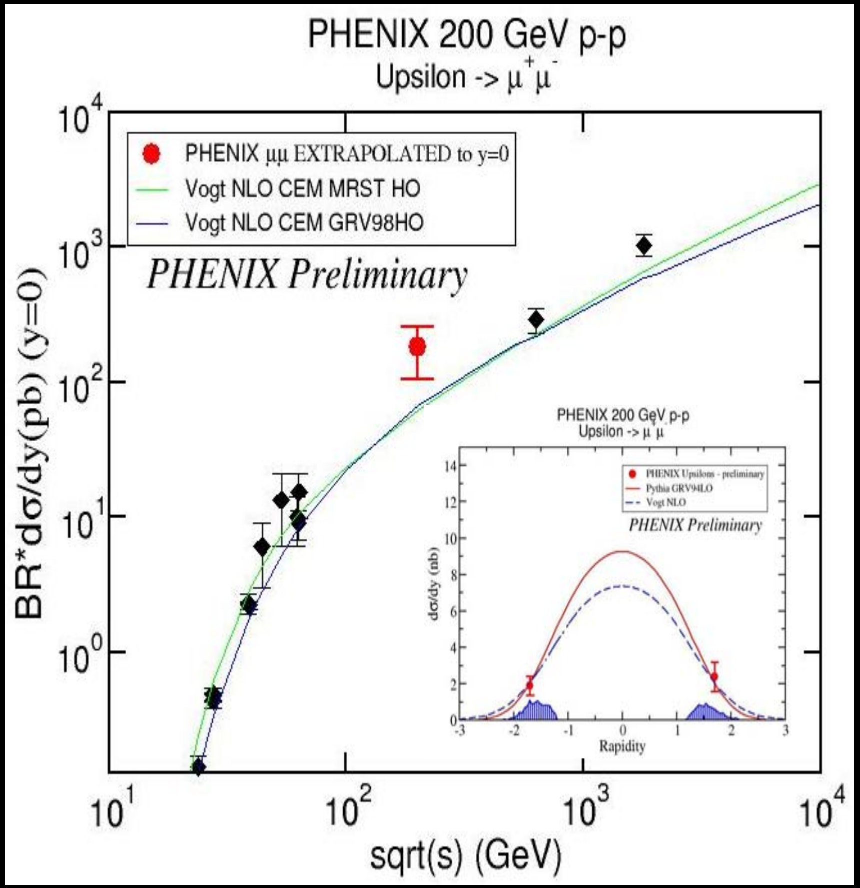


First upsilon measurement

Hie Wei, QM05



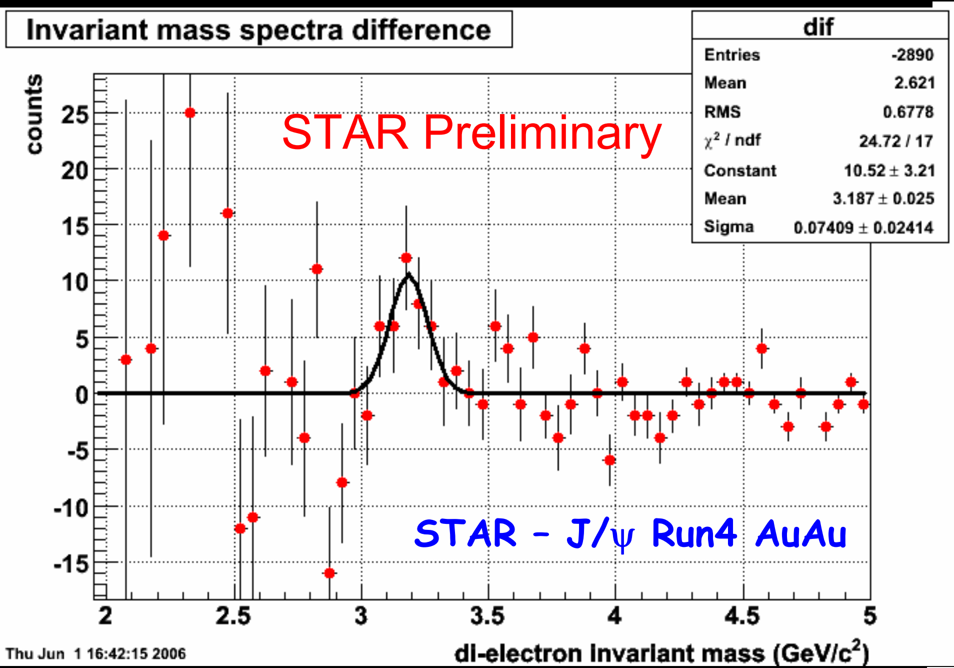
Dimuon mass spectrum for the two muon arms added together.

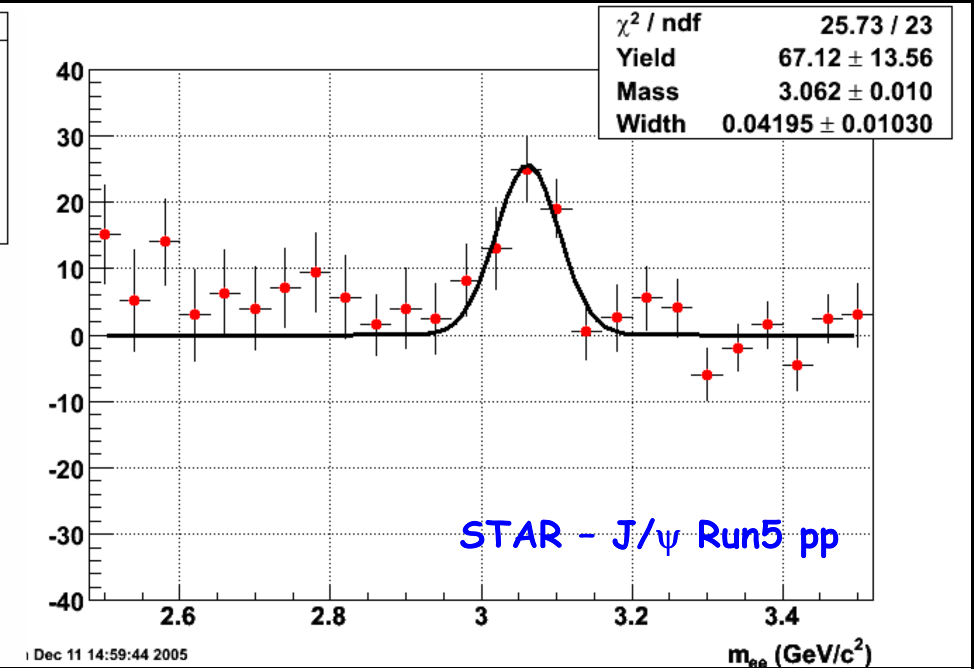


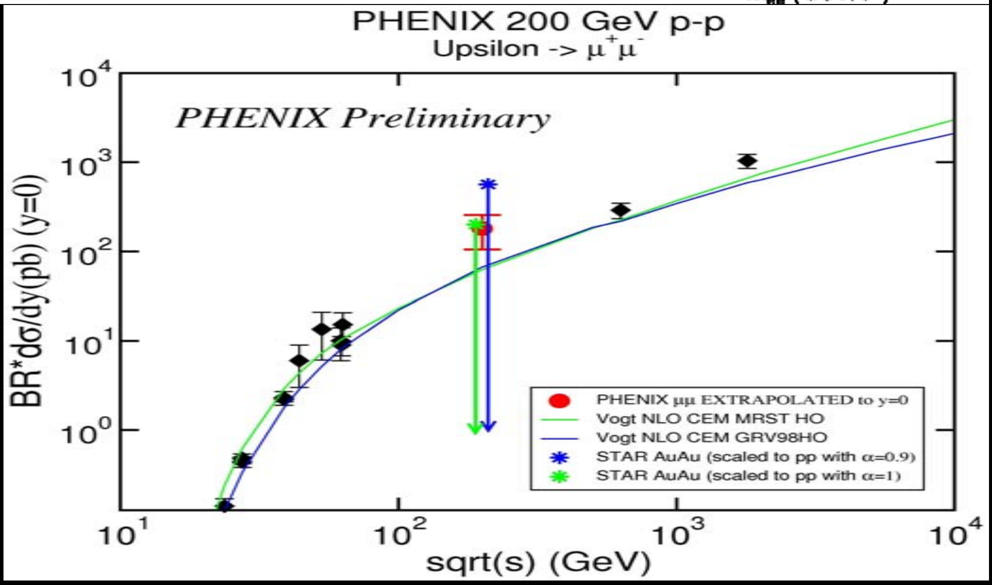
1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

STAR results and near future

M. Cosentino, QWG06







- Dataset Au+Au@200 GeV :
  - No trigger due to high background
  - Just a faint signal
  - For efficient J/ψ trigger, full barrel ToF is needed (just patch in Run5)
- p+p@200GeV (Run5):
  - trigger commissioning (~1.7M events)
- Run 6 (this year): expect 500-1000 (work in progress)

Back-up

Heavy flavour energy loss?

$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

average energy loss

Casimir coupling factor

transport coefficient of the medium

distance travelled in the medium

→ R.Baier et al., Nucl. Phys. **B483** (1997) 291 ("BDMPS")

Energy loss for heavy flavours is expected to be reduced:

i) Casimir factor

- light hadrons originate predominantly from gluon jets, heavy flavoured hadrons originate from heavy quark jets
- C_R is 4/3 for quarks, 3 for gluons

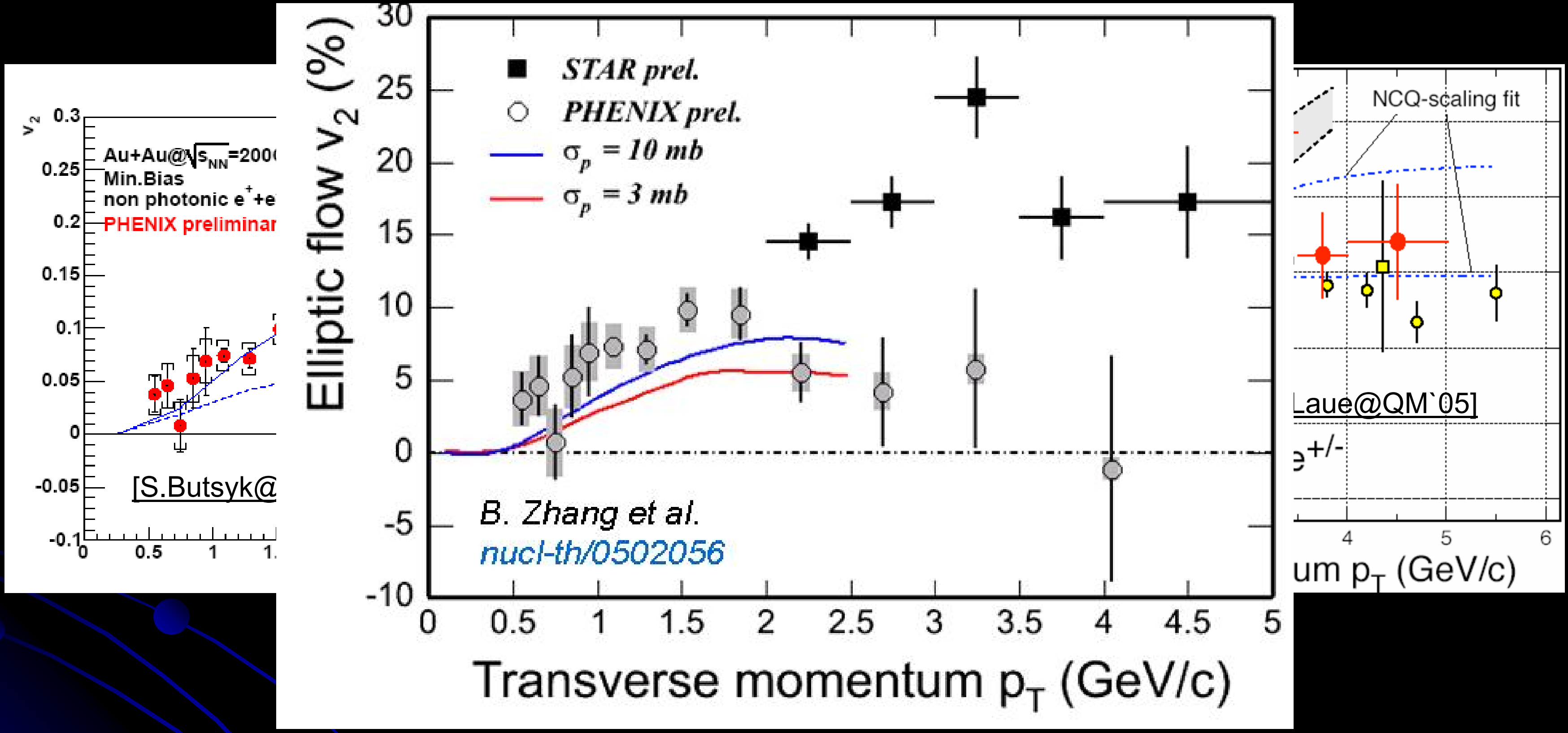
ii) dead-cone effect

- gluon radiation expected to be suppressed for $\theta < M_Q/E_Q$

  [Dokshitzer & Karzeev, Phys. Lett. **B519** (2001) 199]

  [Armesto et al., Phys. Rev. D69 (2004) 114003]

Charm flow



- Disagreement between STAR and PHENIX v_2

Alternate model : Hydro + J/Ψ transport

One detailed QGP hydro + J/ψ transport (Zhu et al)

- g + J/ψ → c + c

First published without cold nuclear effects, but here :

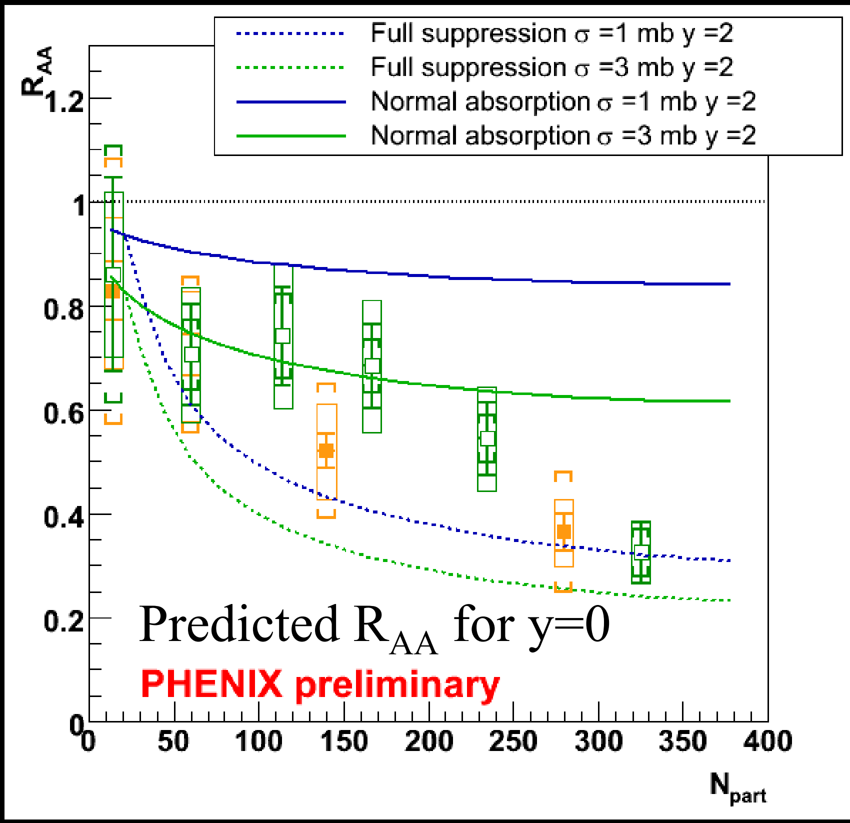
+ Nuclear absorption (1 or 3 mb)

+ Cronin effect from dAu

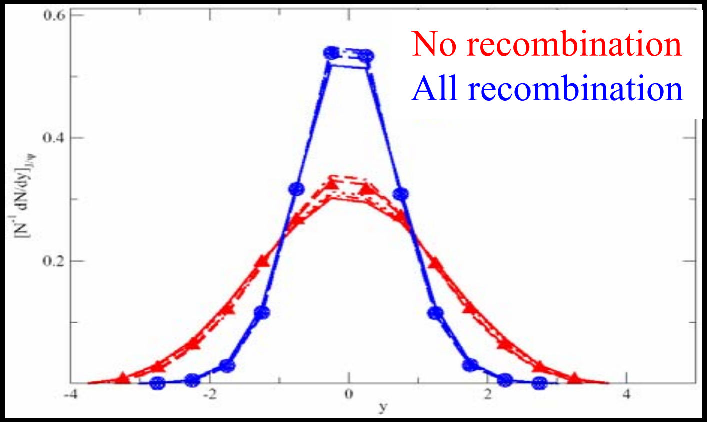
<$p^T{}_2$> ok (as on previous slide)

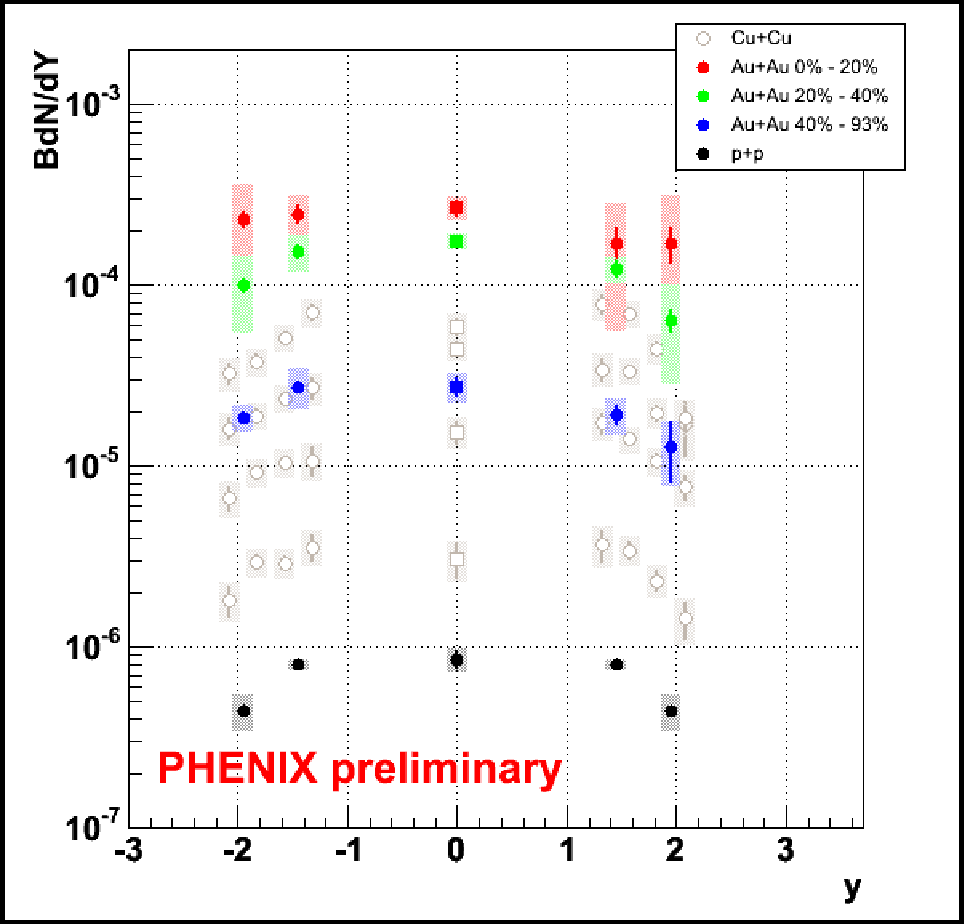
- Model should be valid for y=0
  - But match y=1.7
  - (and central y=0)

Zhu, Zhuang, Xu, PLB607 (2005) 107
+ private communication



Recombination predictions vs rapidity





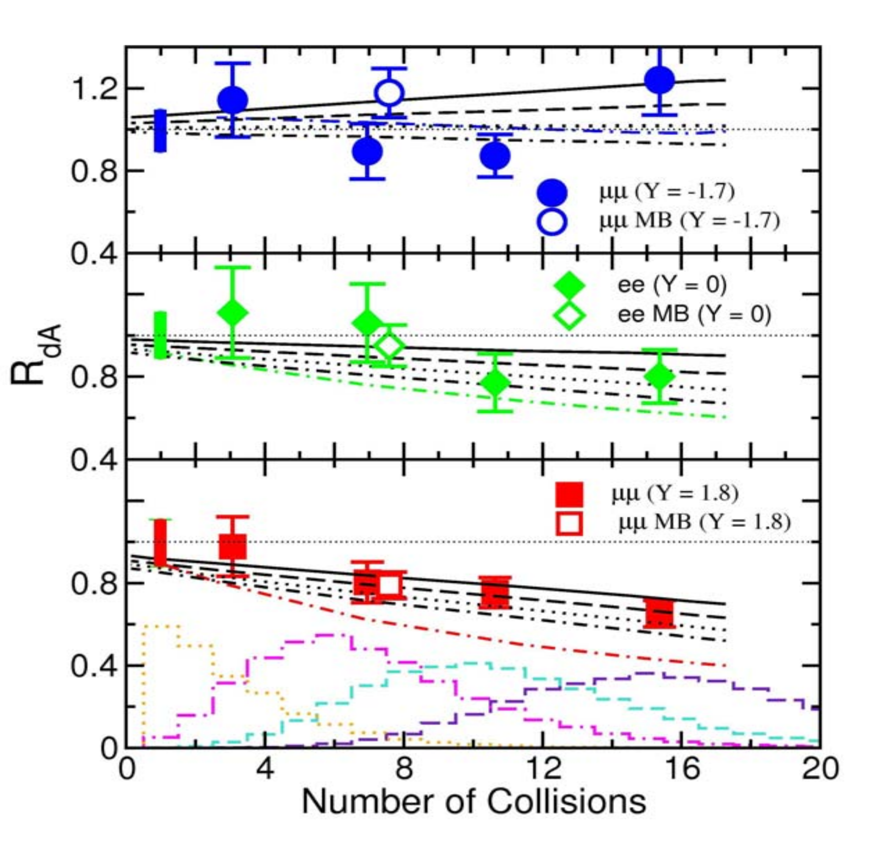
- Recombination (Thews et al., nucl-th/0505055) predicts a narrower rapidity distribution with an increasing N_{part}.
- Going from p+p to the most central Au+Au : no significant change seen in the shape of the rapidity distribution.

J/Ψ production in d+Au vs centrality

High x_2 ~ 0.09

- Small centrality dependence
- Model with absorption + shadowing (black lines*):
  - 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

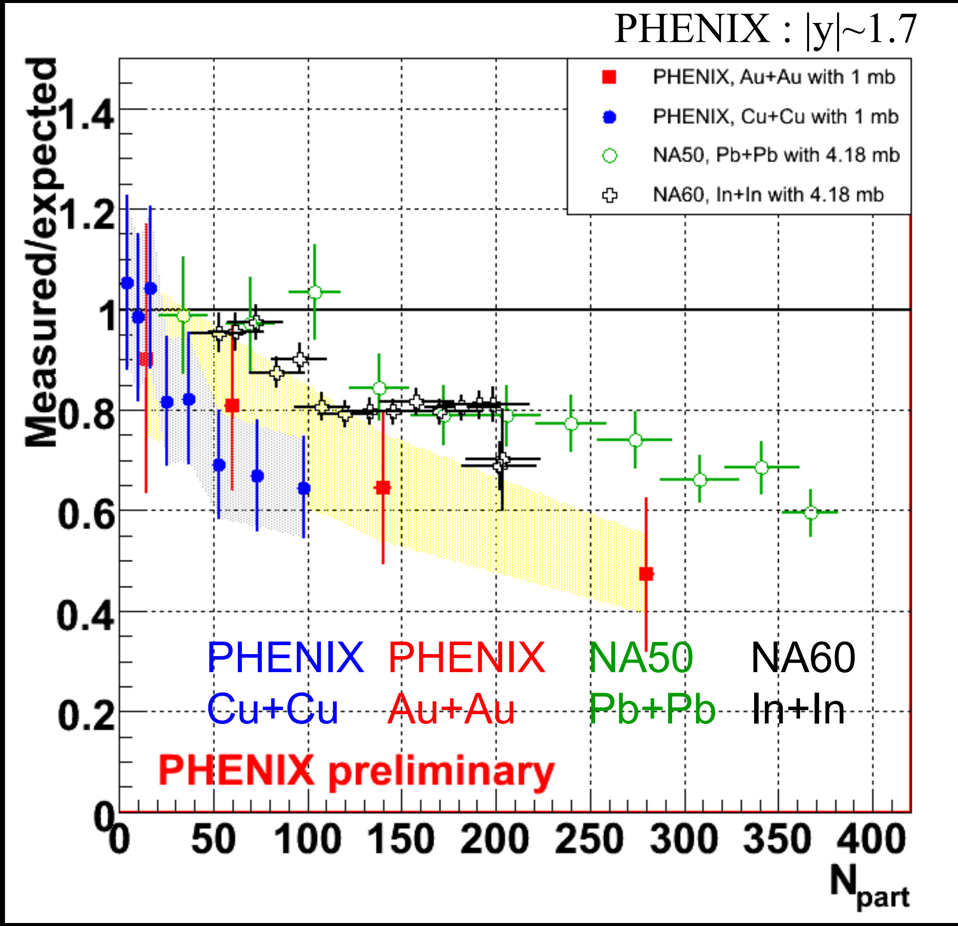


Low x_2 ~ 0.003

*Colored lines: FGS shadowing for 3 mb

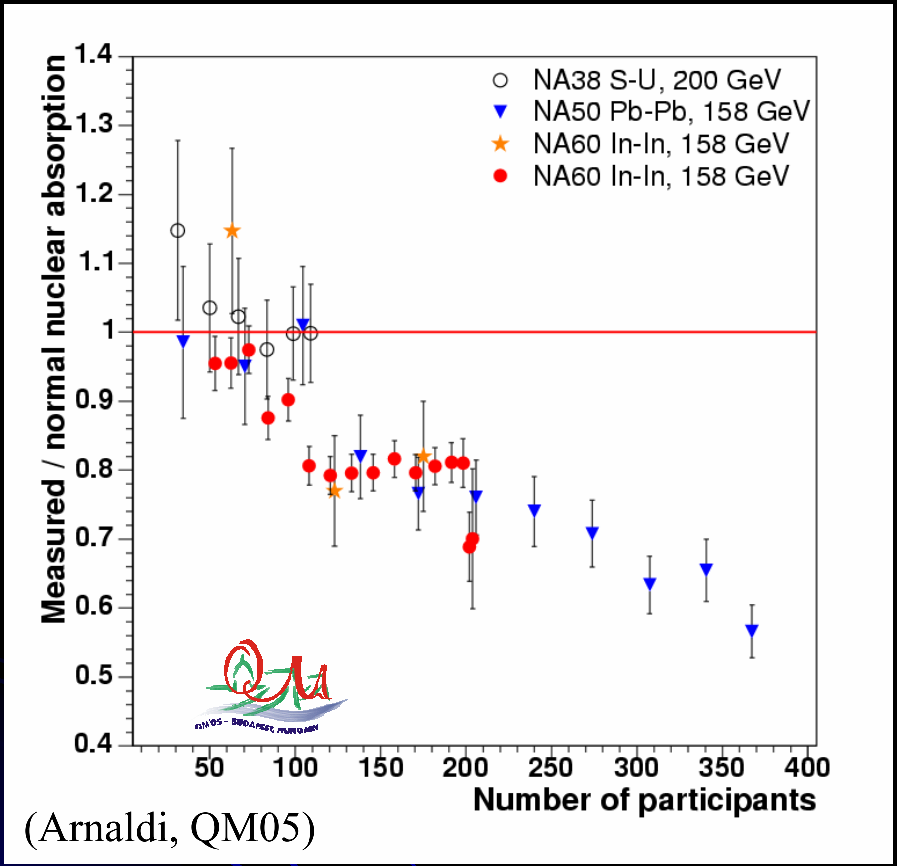
RHIC vs SPS

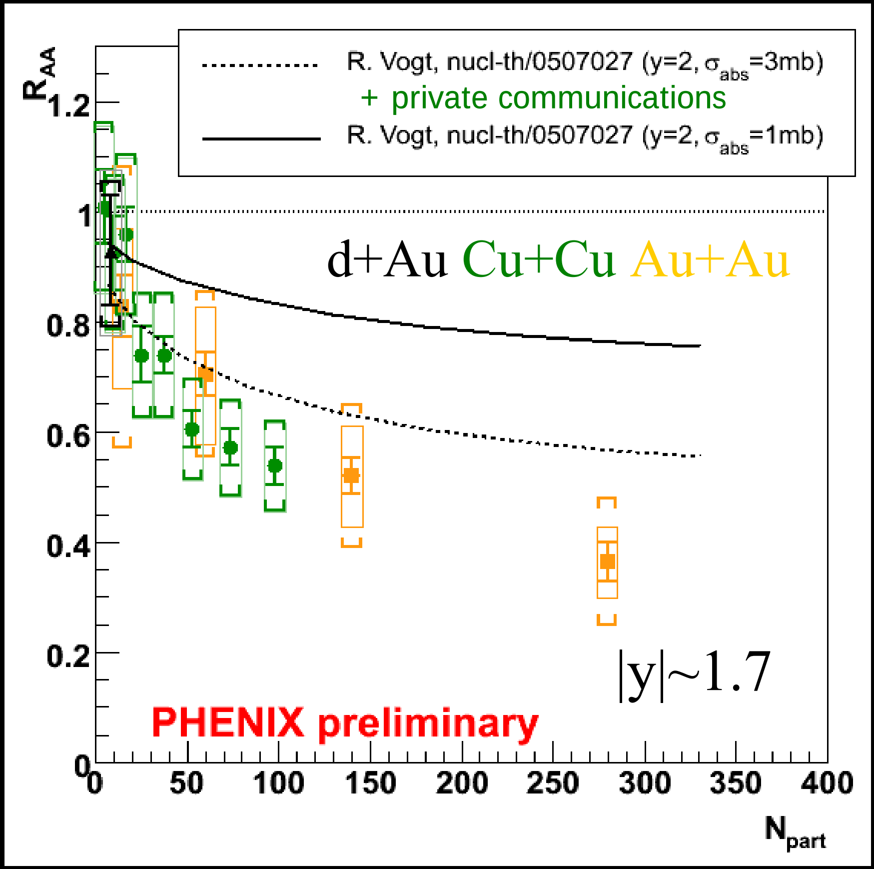
- Plotted « à la SPS » way i.e. normalize the J/Ψ production with the cold nuclear effects :
  - nuclear absorption with σ_{abs} = 4.18 ± 0.35 mb at SPS
  - Shadowing + nuclear absorption with σ_{abs} ~ 1 mb at RHIC (Vogt, nucl-th/0507027)



(NA60 preliminary points from Arnaldi, QM05).

SPS vs RHIC





- 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]

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

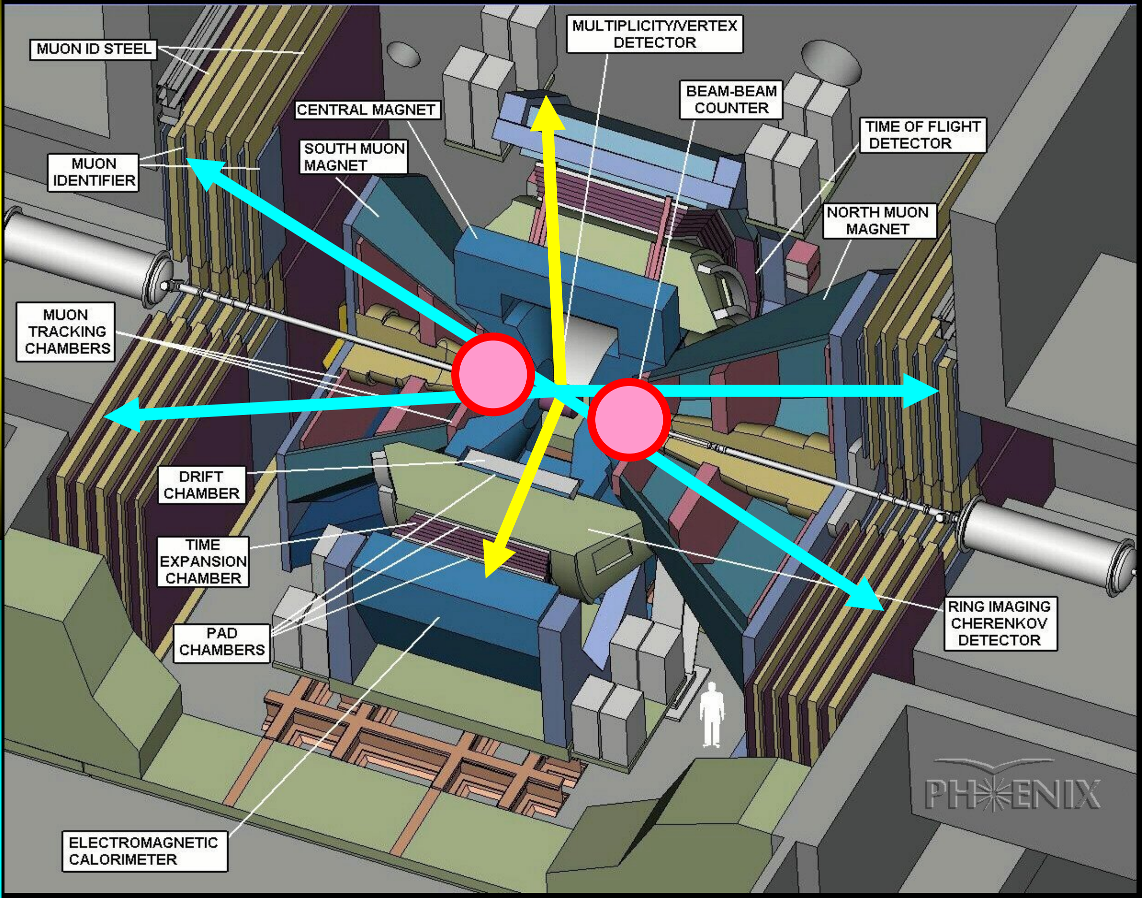
$J/\Psi \rightarrow \mu^+\mu^-$

$1.2 < |y| < 2.2$

$P_\mu > 2$ GeV/c

$\Delta\Phi = 2\pi$

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



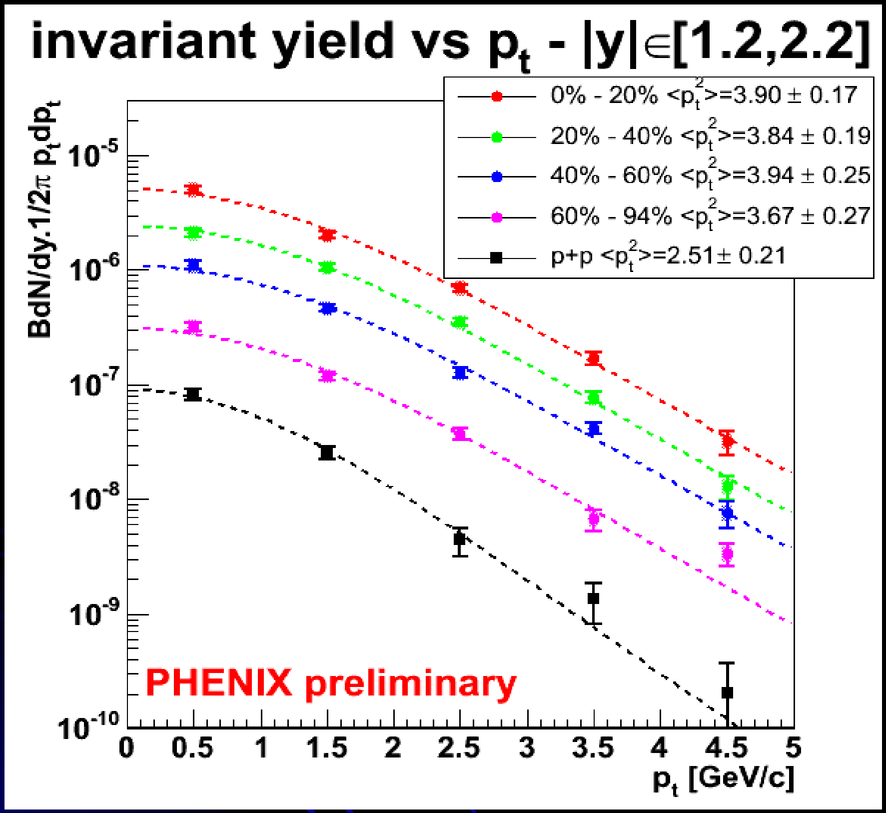
Centrality measurement, vertex position

Beam-beam counters (charged particle production)

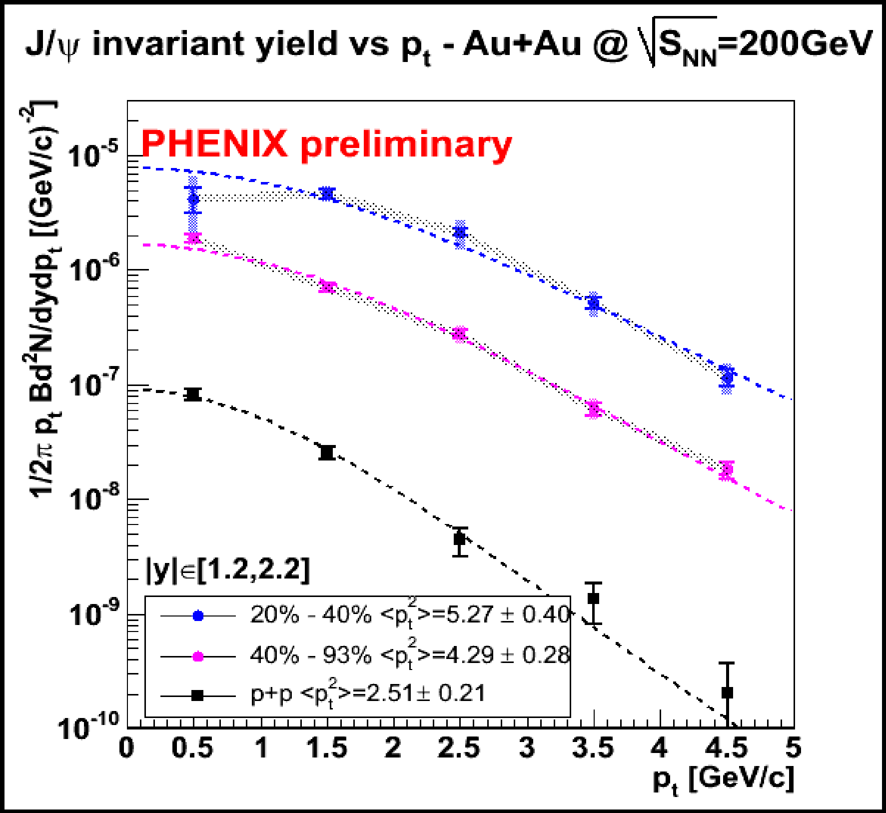
Zero-degree calorimeters (spectator neutrons)

Invariant yield vs p_T at forward rapidities

Cu+Cu (|y|∈[1.2,2.2])



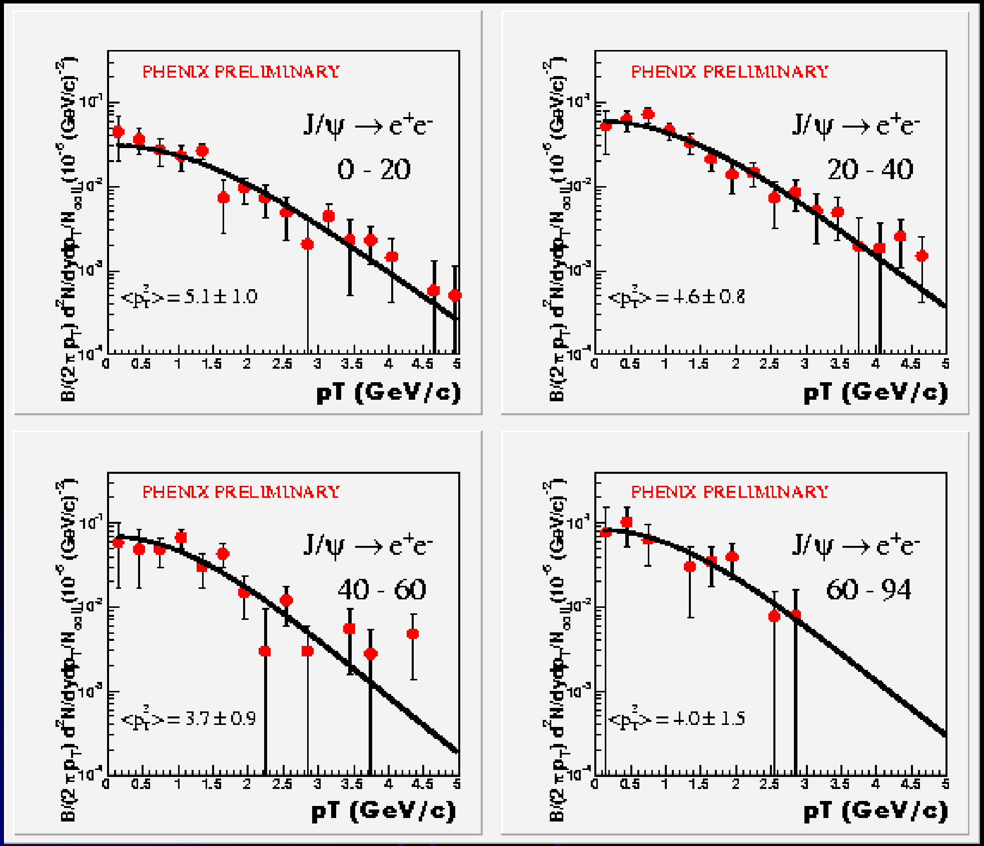
Au+Au (|y|∈[1.2,2.2])



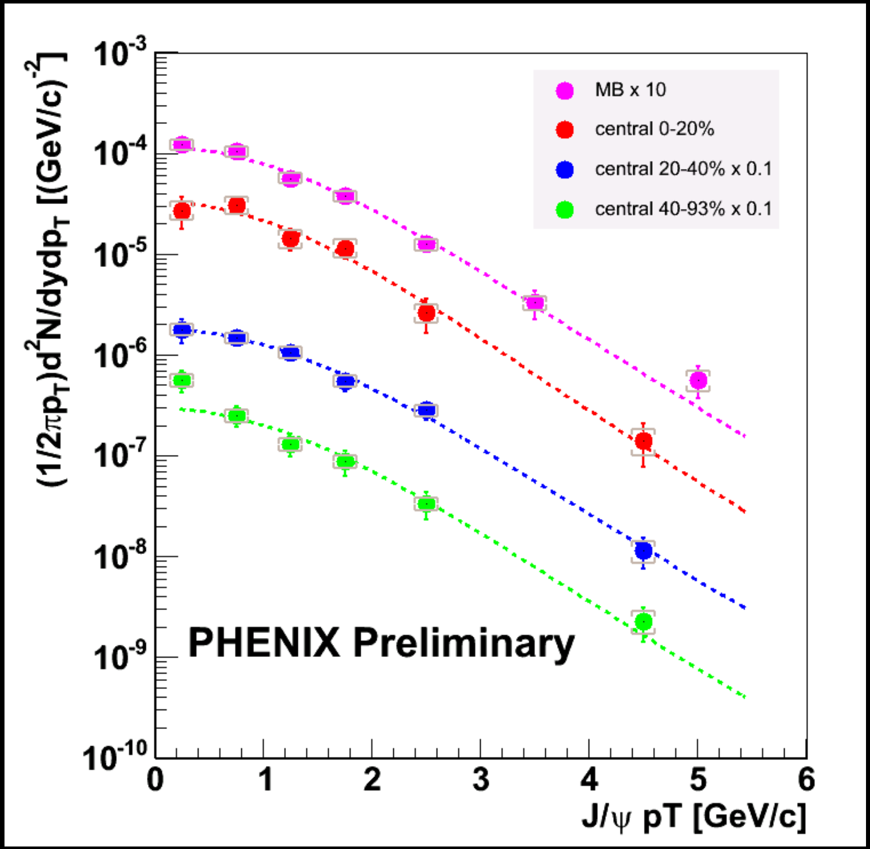
- we fit the p_T spectrum using $A[1+(p_t/B)^2]^{-6}$ to extract $\langle p_T^2 \rangle$

Invariant yield vs p_T at mid-rapidity

Cu+Cu (|y|~0.35)



Au+Au (|y|~0.35)



- 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 :

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

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

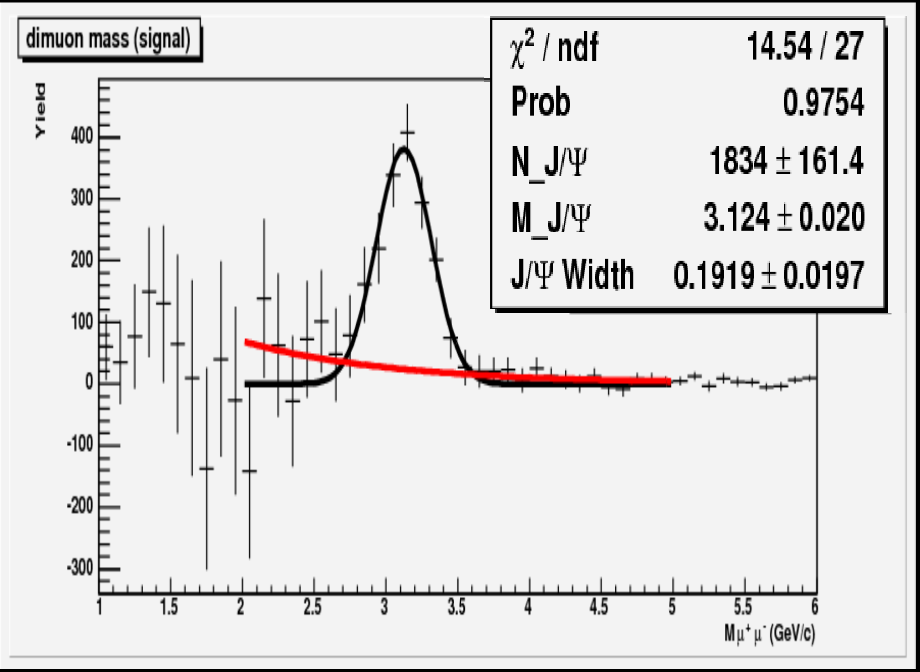
ε^{MB}_{BBC} : BBC trigger efficiency for minimum bias events

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

Signal extraction in Cu+Cu

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

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



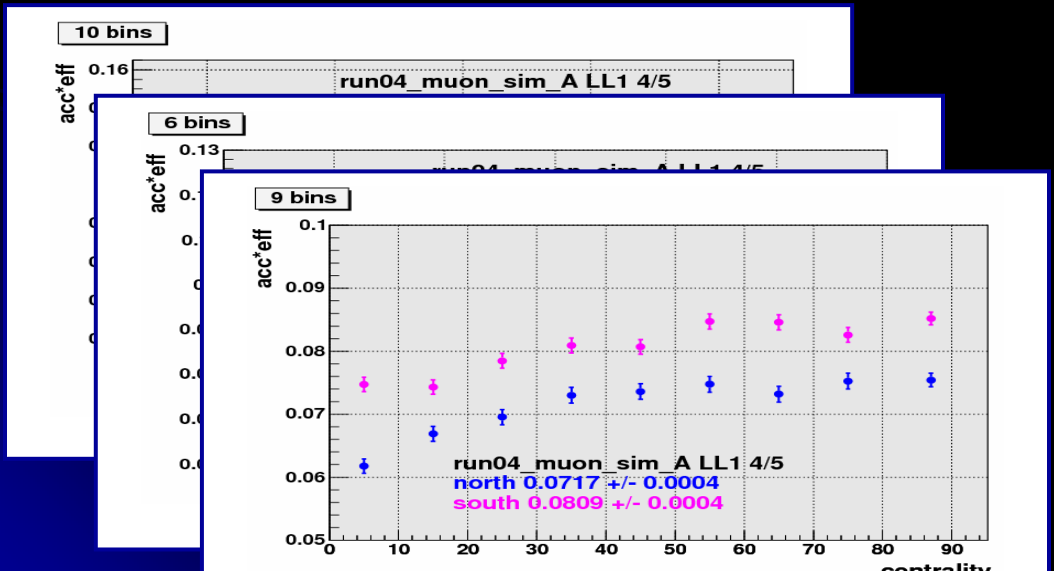
- Signal = number of counts within the J/Ψ invariant mass region (2.6 – 3.6 GeV/c²) after subtracting N_{bgd} to the distribution of the opposite sign dimuons.
- Systematic errors : ~10% from varying fits of the background subtracted signal. Also account for the physical background that can be included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



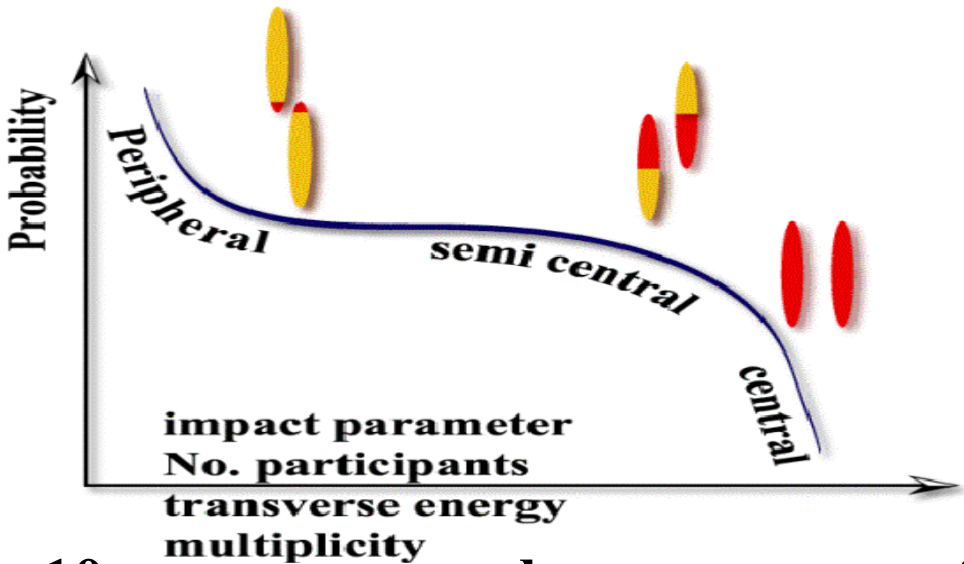
Acc*eff vs centrality (statistical errors only)

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).

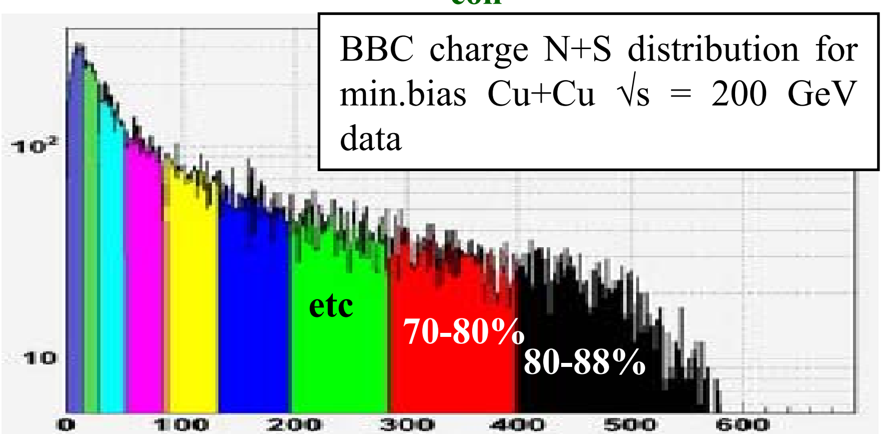
Collision geometry and centrality (eg : Cu+Cu)



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)

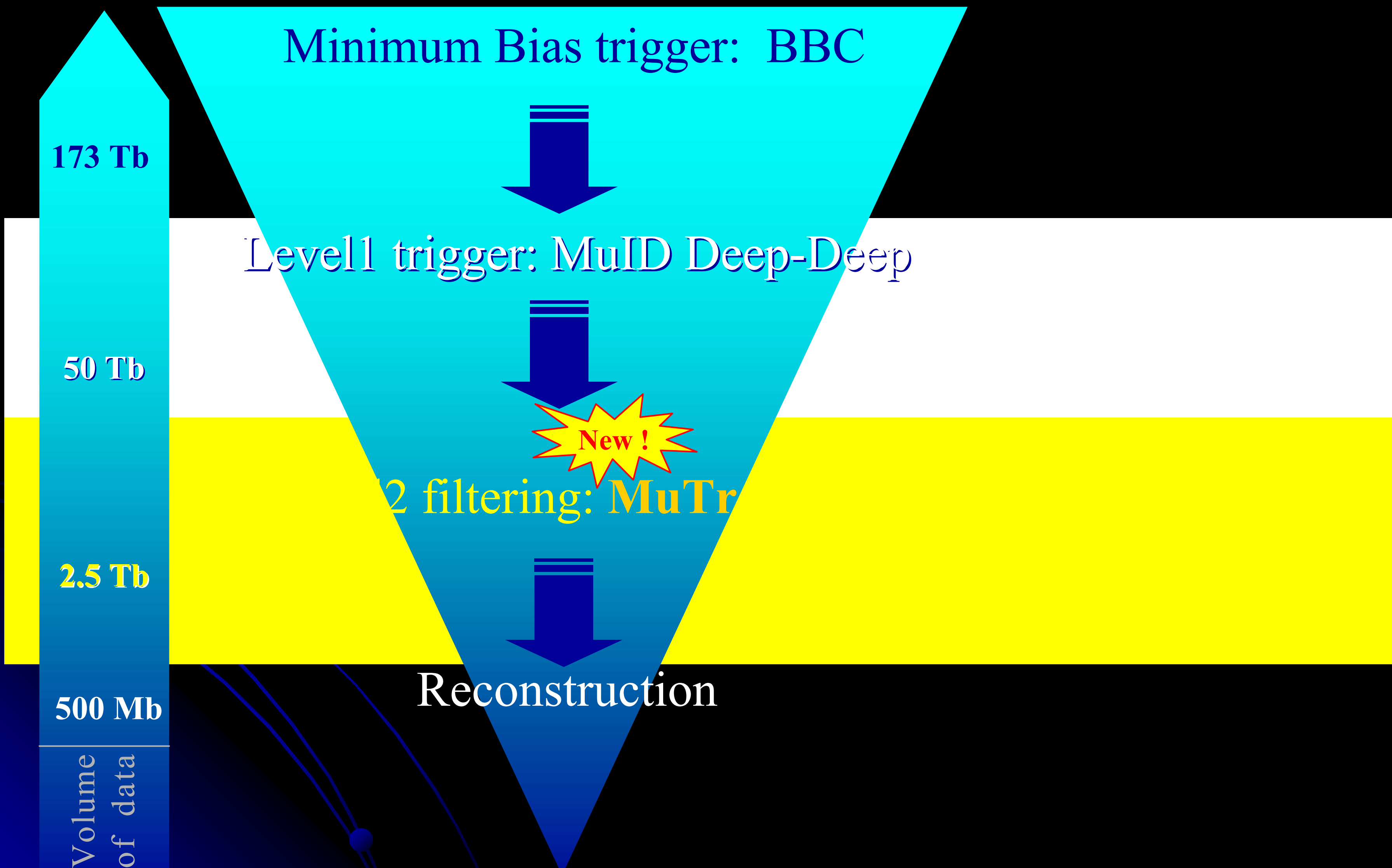
Monte-Carlo Glauber model
⇓
Probability for a given Npart
⇓
Each participant contributes to a Negative Binomial distribution of hits
⇓
Fit BBC charge distribution

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

[1] PRL92 (2004) 051802
[2] PRC69 (2004) 014901
[3] PRL96 (2006) 012304
[4] QM05, nucl-ex/0510051

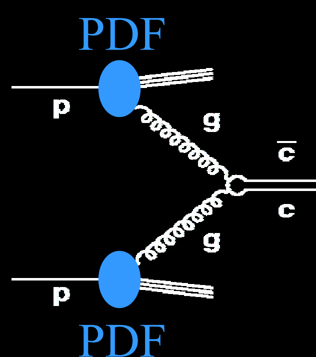
Year	Ions	$\sqrt{s_{NN}}$	Luminosity	Status	J/Ψ (ee + μμ)
2000	Au-Au	130 GeV	1 μb^{-1}	Central (electrons)	0
2001	Au-Au	200 GeV	24 μb^{-1}	Central	13 + 0 [1]
2002	p-p	200 GeV	0.15 pb^{-1}	+ 1 muon arm	46 + 66 [2]
2002	d-Au	200 GeV	2.74 nb^{-1}	Central	360 + 1660 [3]
2003	p-p	200 GeV	0.35 pb^{-1}	+ 2 muon arms	130 + 450 [3]
	Au-Au	200 GeV	240 μb^{-1}	preliminary	~ 1000 + 5000 [4]
2004	Au-Au	63 GeV	9.1 μb^{-1}	analysis	~ 13
	p-p	200 GeV	324 nb^{-1}		
	Cu-Cu	200 GeV	4.8 nb^{-1}	preliminary	~ 1000 + 10000 [4]
2005	Cu-Cu	63 GeV	190 mb^{-1}	analysis	~ 10 + 200
	p-p	200 GeV	3.8 pb^{-1}		~ 1500 + 10000
2006	p-p	200 GeV	~10 pb_{-1}	Just done…	~3000 + 30000

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



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

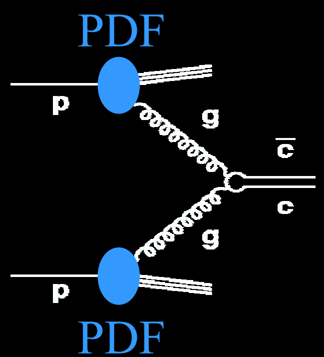
- Hard probe
  - Large charme quark mass ($m_{J/\Psi}$ ~3.1 GeV/c²) ⇒ J/Ψ produced at early stages of the collision
  - Size $r_{J/\Psi}$ ~0.2 fm < typical hadronique size (~1 fm)
  - Recent lattice QCD result : melting temperature in a deconfined medium is T ~ 1.5 à 2 T_C
- Production
  - g+g fusion



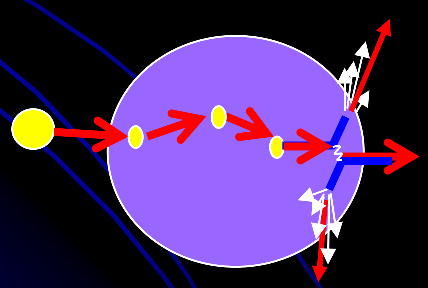
  - ~60% direct production J/Ψ
    ~30% via $\chi_c \rightarrow$ J/Ψ + x
    ~10% via Ψ'→ J/Ψ + x
  - p+p ⇒ reference for p+A or A+A
    - ratios (p+A)/(p+p) or (A+A)/(p+p)
- Suppression or enhancement of the J/Ψ yield :
  - Due to nuclear matter or to deconfined medium ?

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

- Initial state effect
  - CGC, shadowing

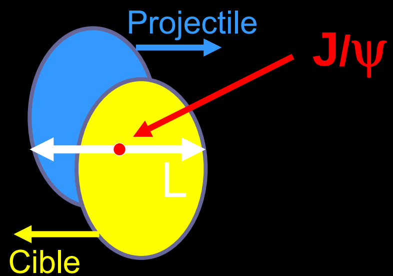


  - Cronin effect : multiple elastic scattering ⇒ p_T broadening

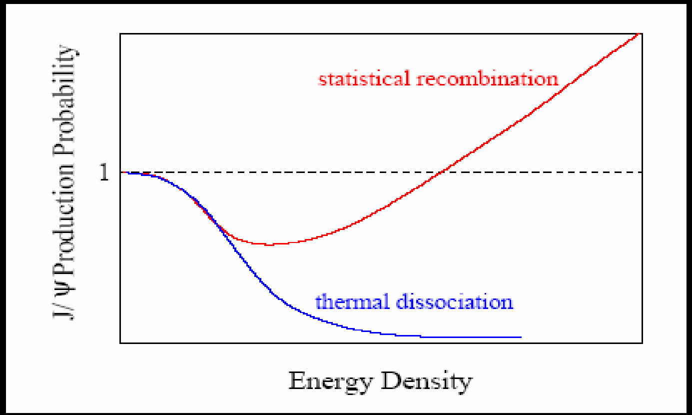


  - Evaluated via p+A ou d+A

- Final state effect
  - Nuclear (hadronic) absorption



  - QGP ?
    - suppression : « colour screening »
    - or enhancement : recombinaison
      - From 10 to 20 $c\bar{c}$ in central Au+Au at RHIC



  - Accessible via A+A

Background sources

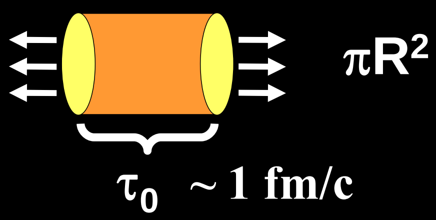
- Physical background: correleted dimuons
  - Drell-Yan:

  - 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)

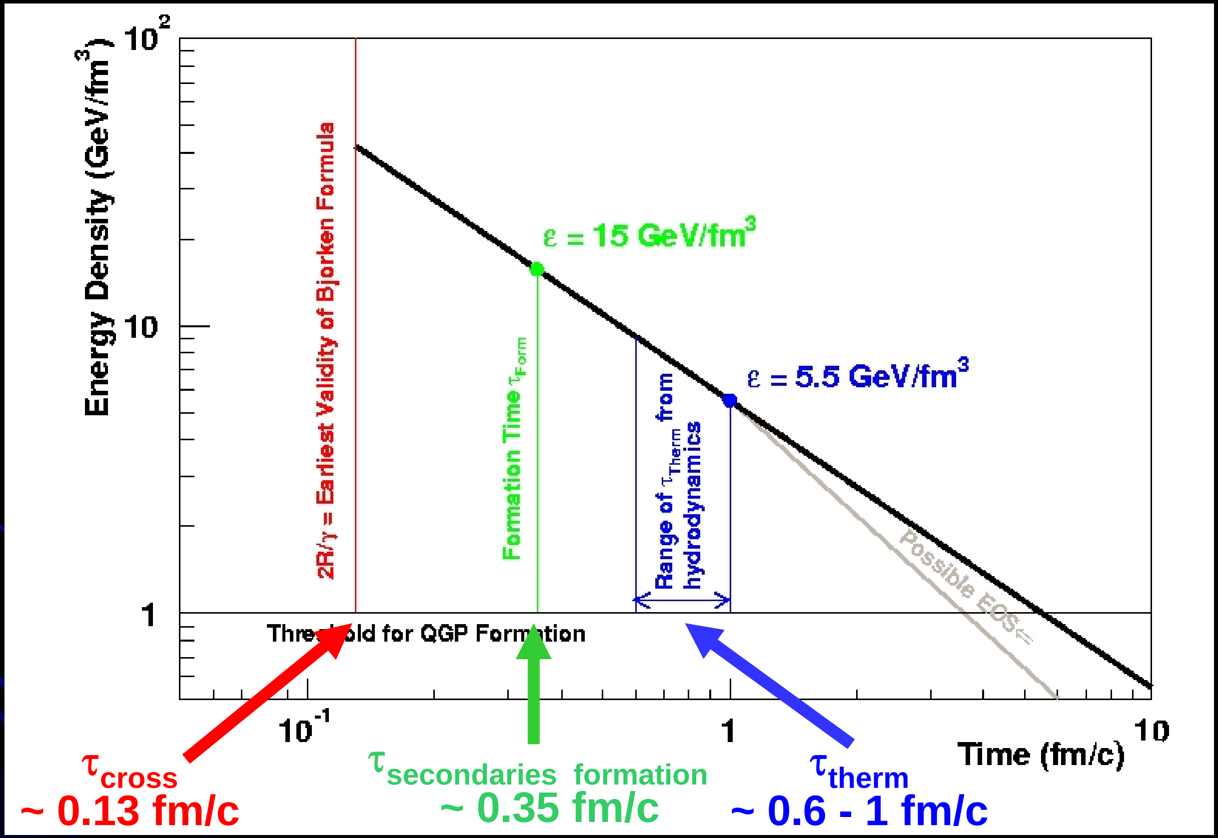
Energy density

- 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 : $M^2_{inv} = (E_1 + E_2)^2 - (p_1+p_2)^2$