Quarkonia from SPS to RHIC and from pA to AA

Raphaël Granier de Cassagnac
LLR – École polytechnique / IN2P3

Early Time Dynamics
in Heavy Ion Collisions
Montréal, 2007, July 16th

The "normal" introduction…

Matsui & Satz, PLB178 (1986) 416

- In 1986, Matsui & Satz predicted an "unambiguous" signature of QGP
  - Disappearance of quarkonia above a certain temperature / energy density threshold
- Where do we stand today?
  - What is the J/ψ nuclear modification factor?

$$R_{AB} = \frac{N_{\psi}^{AB}}{N_{\psi}^{pp} \times \langle N_{coll} \rangle}$$

  - Remembering that heavy flavours should and do scale with N_{coll}

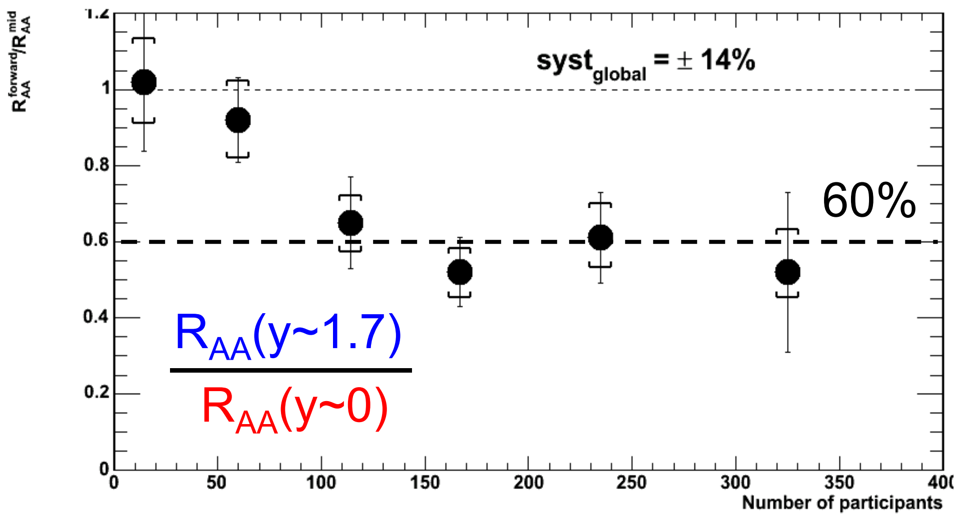
PHENIX, PRL94 (2005) 082301

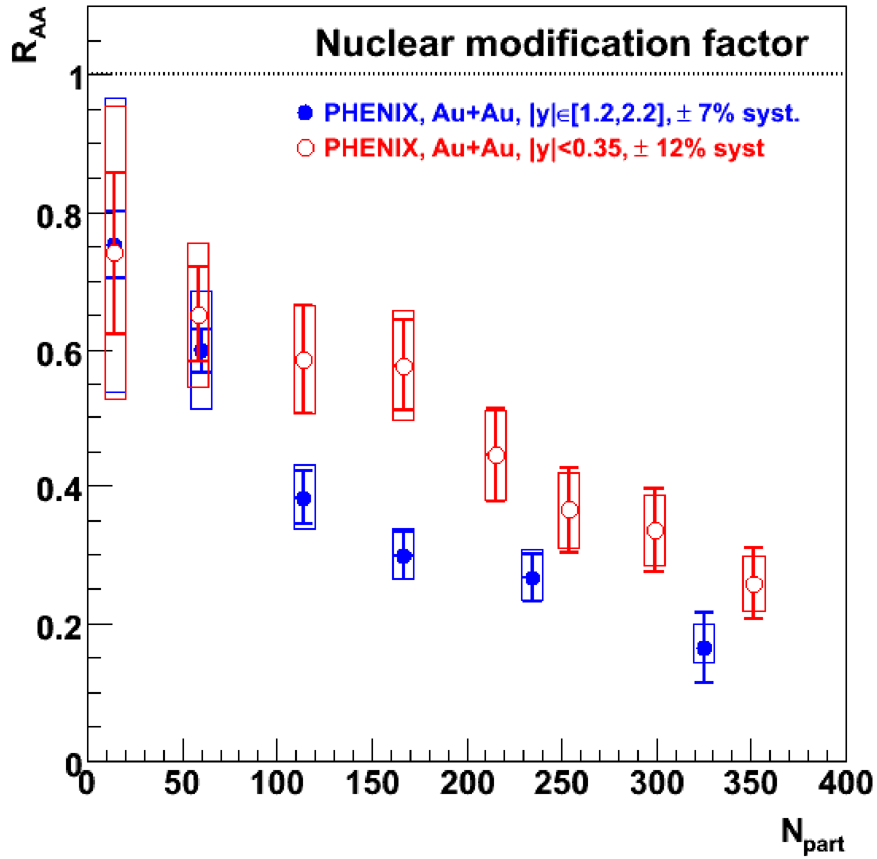
J/ψ in AA, the experimental facts

PHENIX: PRL 98 (2007) 232301
NA50: EPJ C39 (2005) 335
NA60: nucl-ex/0706.4361, to appear in PRL

R_{AuAu} (y~0) > R_{AuAu} (y~1.7)

- @ RHIC, more J/ψ suppression at forward rapidity !

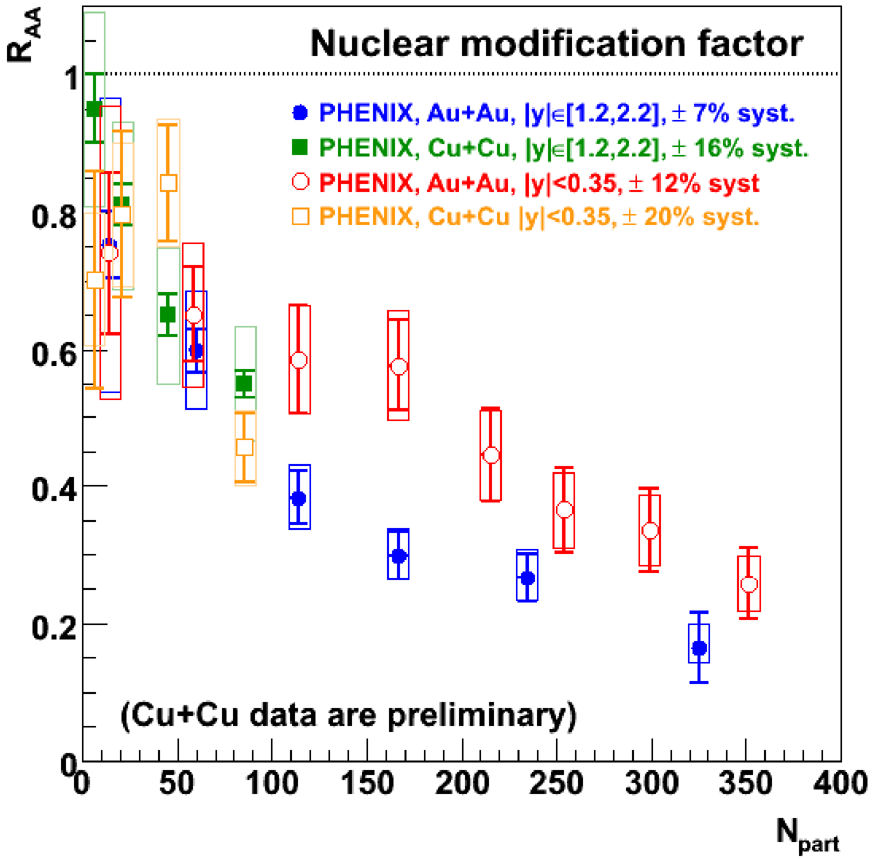




PHENIX, PRL98 (2007) 232301

R_{AuAu} vs R_{CuCu} @RHIC

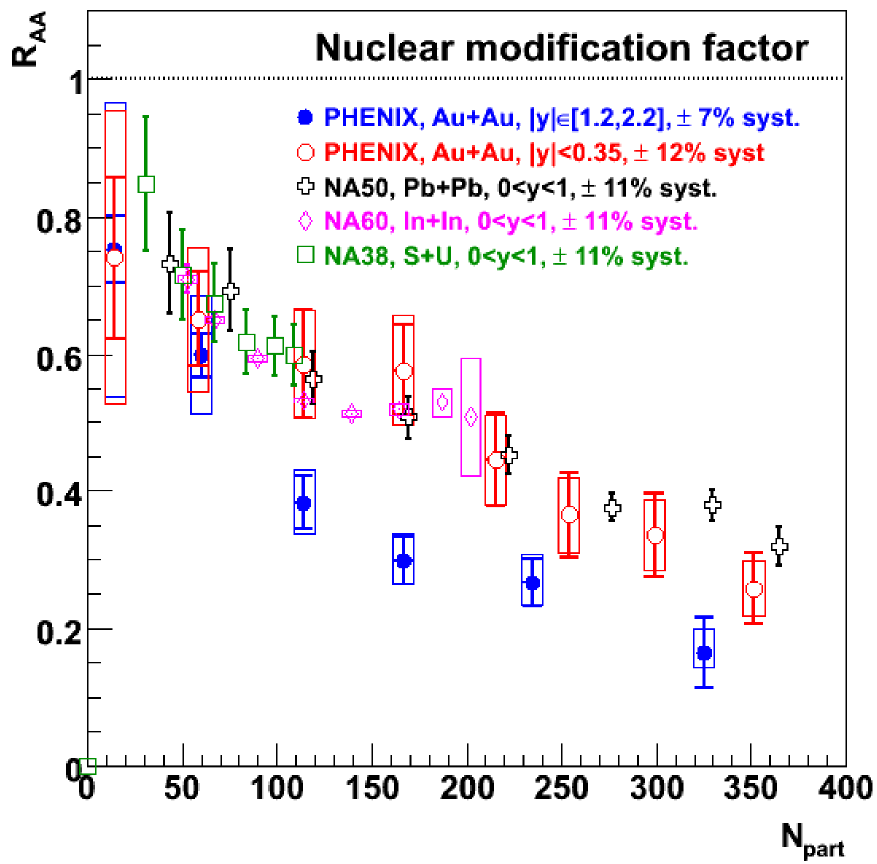
- Wait for Cu+Cu, still preliminary, soon final…



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

R_{AuAu} (y~0) ~ R_{AuAu} (SPS)

- Lower rapidity R_{AA} look surprisingly similar, while there are obvious differences:
  - At a given N_{part}, different energy densities…
  - Cold nuclear matter effects ($x_{Bjorken}$, σ_{abs}…)
  - …



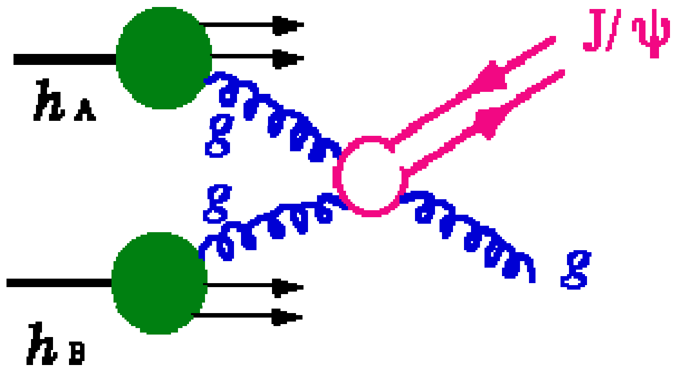
PHENIX, PRL98 (2007) 232301
Scomparin's talk @ QM06

First, beware of
cold nuclear matter
(CNM) effects !

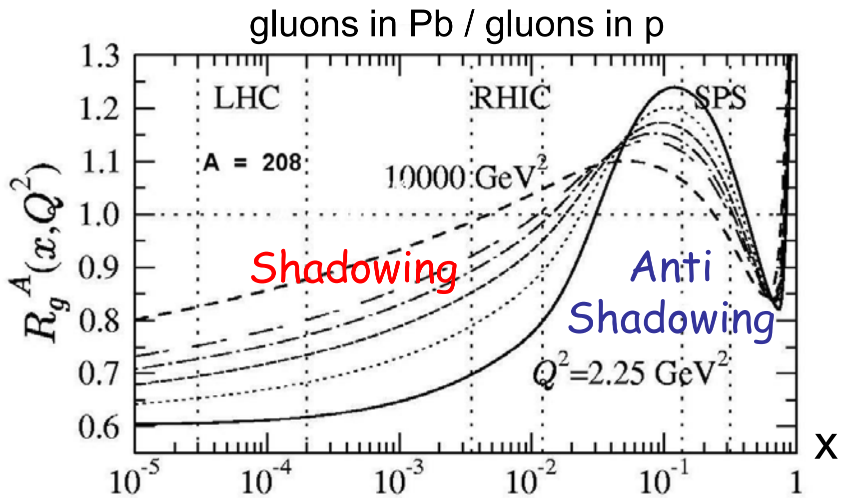
Cold nuclear matter effects ?

- Many possible effects:
  - J/ψ (or $c\bar{c}$) absorption
  - (Anti) shadowing
    (gluon saturation, CGC…)
  - Energy loss of initial parton
  - p_T broadening "Cronin "
  - Complications from feeddown ψ' & χ_c ?
  - Something else ?

- Not well predicted, need pA (or dA) measurements!



An example of gluon shadowing prediction



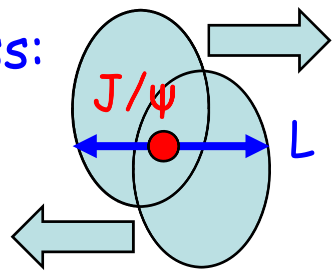
Eskola, Kolhinen, Vogt, NPA696 (2001) 729

Cold nuclear matter @ SPS

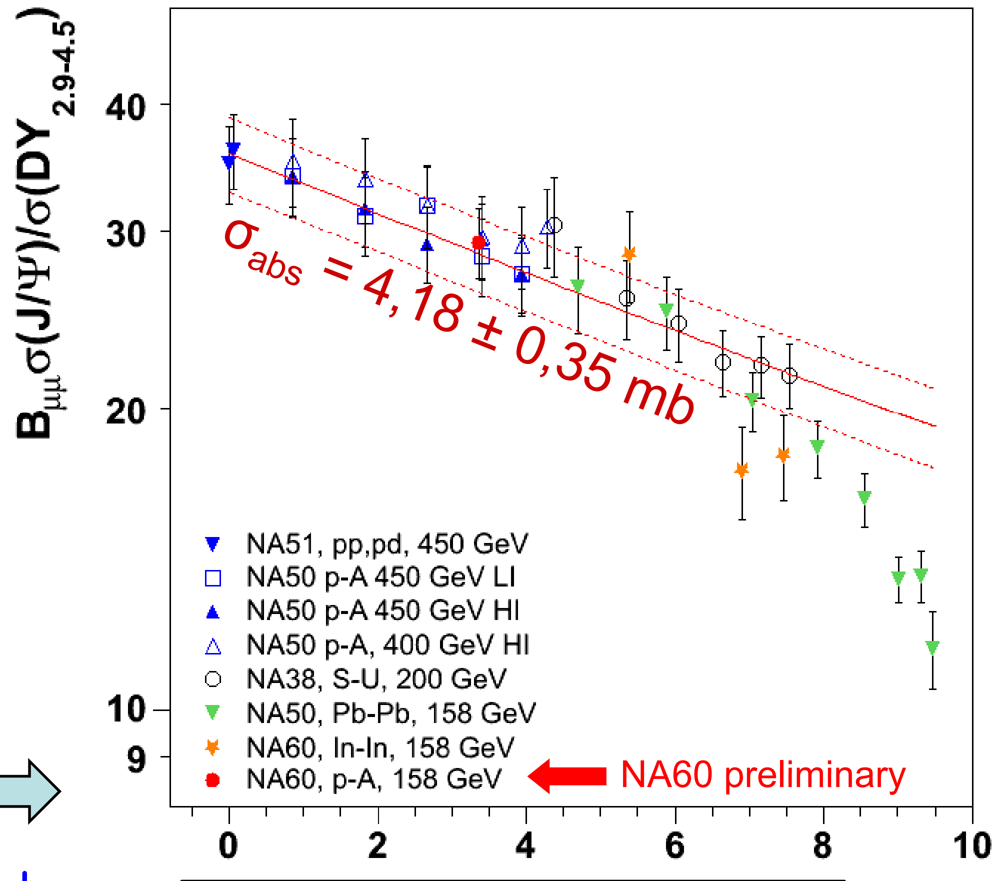
Normal nuclear absorption alone does a splendid job in describing pA, SU, and peripheral PbPb & InIn…

- (including preliminary pA @ 158 GeV from NA60)

- $\exp(-\sigma_{abs}\,\rho_0\,L)$
  - (or in Glauber model)
  - $\sigma_{abs} = 4{,}18 \pm 0{,}35$ mb
  - L nuclear thickness:



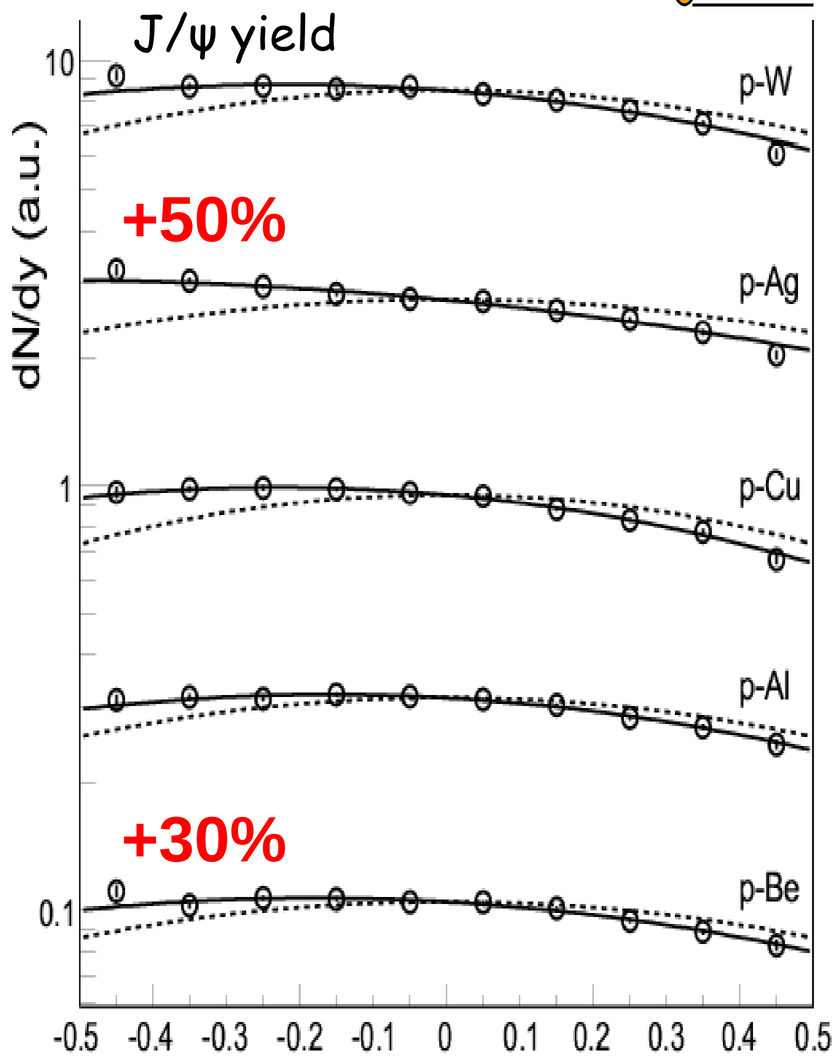
J/ψ / DY rescaled to 158 GeV



NA50, EPJ C39 (2005) 335 & Scomparin's QM06 talk

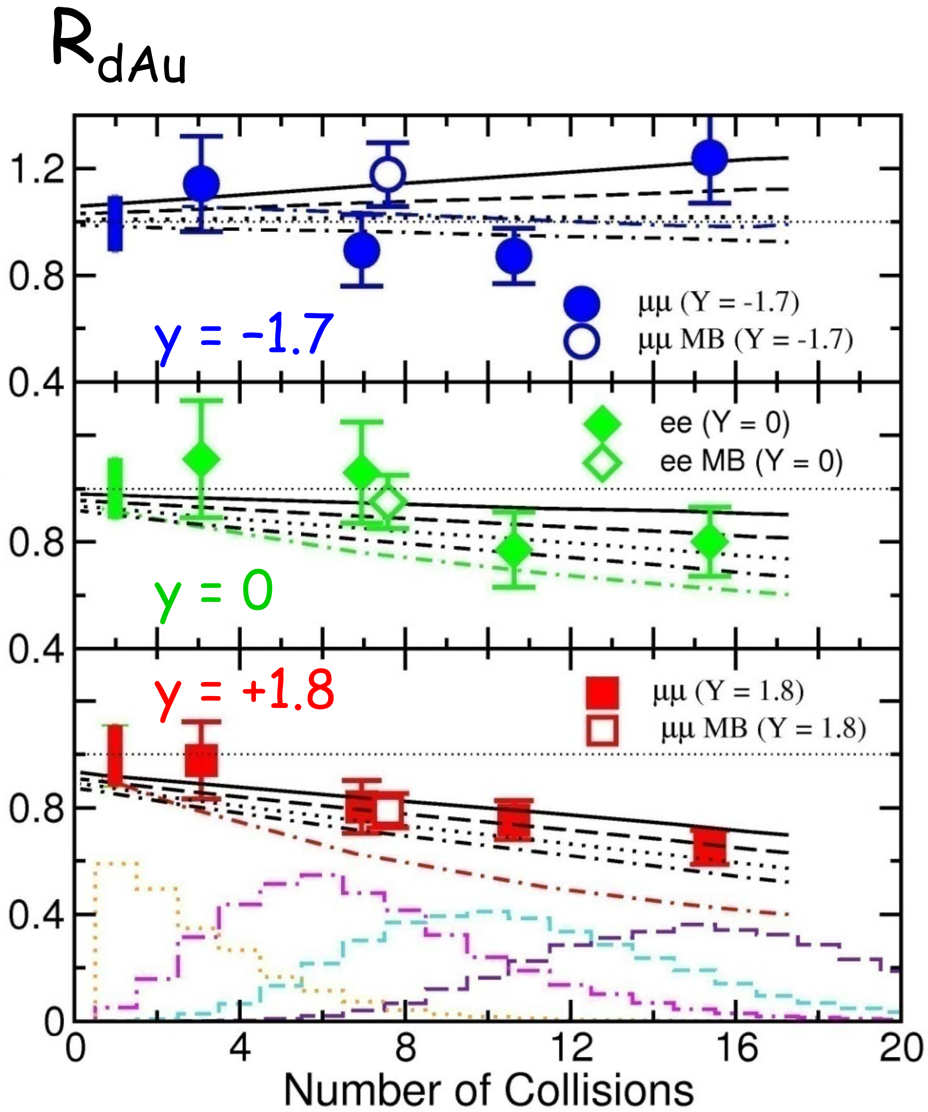
Something odd @ SPS?

- Do we fully understand CNM @ SPS ?
- Not these surprising rapidity distribution asymmetries →
  - Variation of ~30 to ~50% in one unit of rapidity !
  - Seems large to be (anti)shadowing…
  - Not taken into account in CNM extrapolation…



NA50, EPJ. C48 (2006) 329

Cold nuclear matter @ RHIC



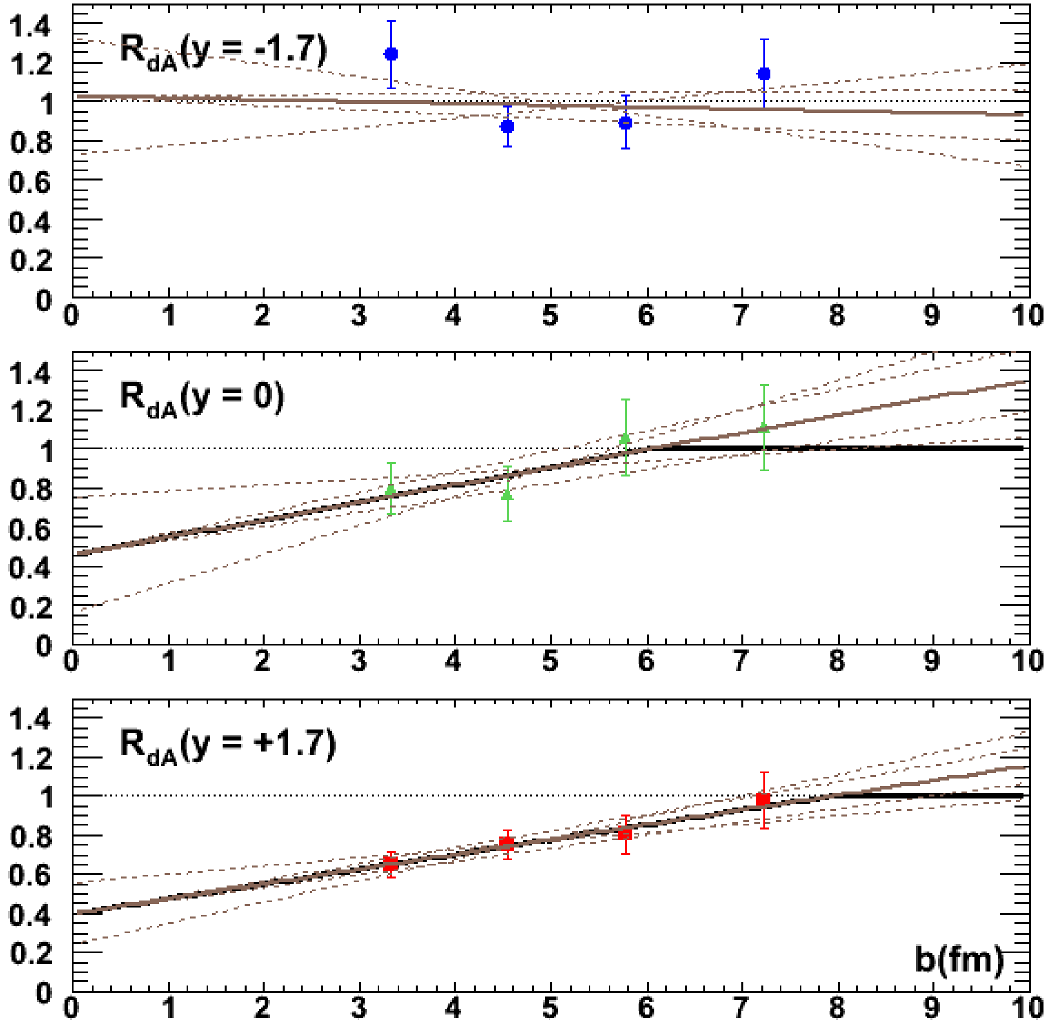
- Only centrality dependence in dA (or pA) of J/ψ production !
  ~ 10% global error not to be forgotten…
- Reproduced by Ramona Vogt
  - Black lines: EKS98 shadowing + σ_{abs} = 0 to 3 mb
  - Colored lines: FGS shadowing + σ_{abs} = 3 mb
- Favoring moderate shadowing + moderate absorption…

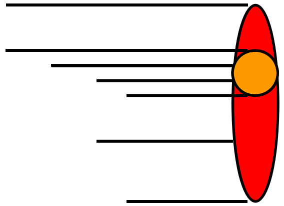
PHENIX, PRL96 (2006) 012304
Klein,Vogt, PRL91 (2003) 142301

From dA to AA @ RHIC

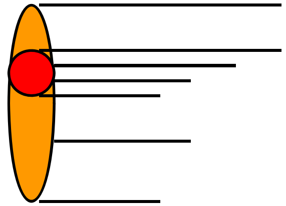
What's on the market?

1. Modeling nuclear absorption + inhomogeneous (anti)shadowing
   - Vogt, nucl-th/0507027
2. exp $-(\sigma_{diss}(y)+\sigma_{diss}(-y))\rho_0 L$
   - Karsch, Kharzeev & Satz, PLB637(2006)75
   - σ_{diss} from fit on dAu data
   - Assume exp $(-\sigma_{diss}\rho_0 L)$
   - No error propagation
3. dAu data driven Glauber approach
   - RGdC, hep-ph/0701222
   - Fit RdA(b) →

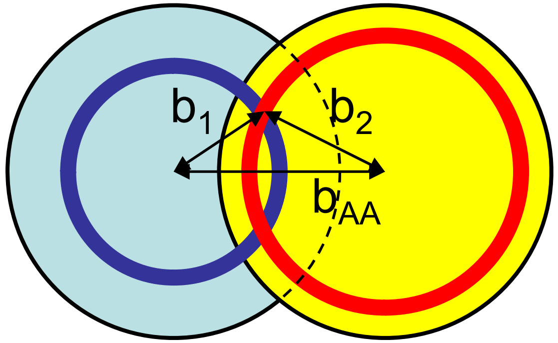




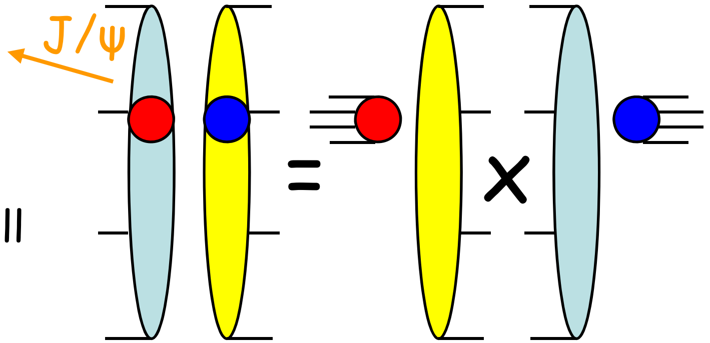
From dA to AA @ RHIC



- For a given A+A collision at b_{AA}, Glauber provides a set of N+N collisions occurring at b_i^1 and b_i^2

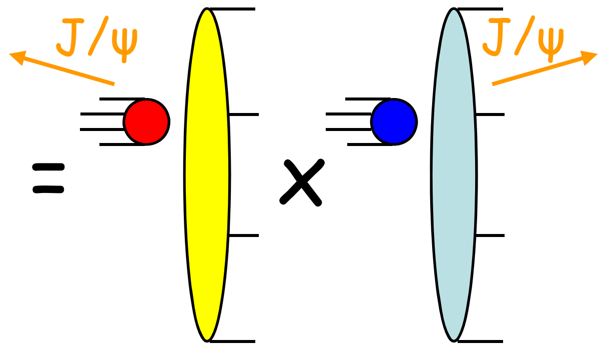


- One minimal assumption is rapidity factorization: $R_{AA}(|y|,b_{AA}) = \Sigma_{collisions}\,[R_{dA}(-y,b_i^1) \times R_{dA}(+y,b_i^2)]\,/\,N_{coll}$

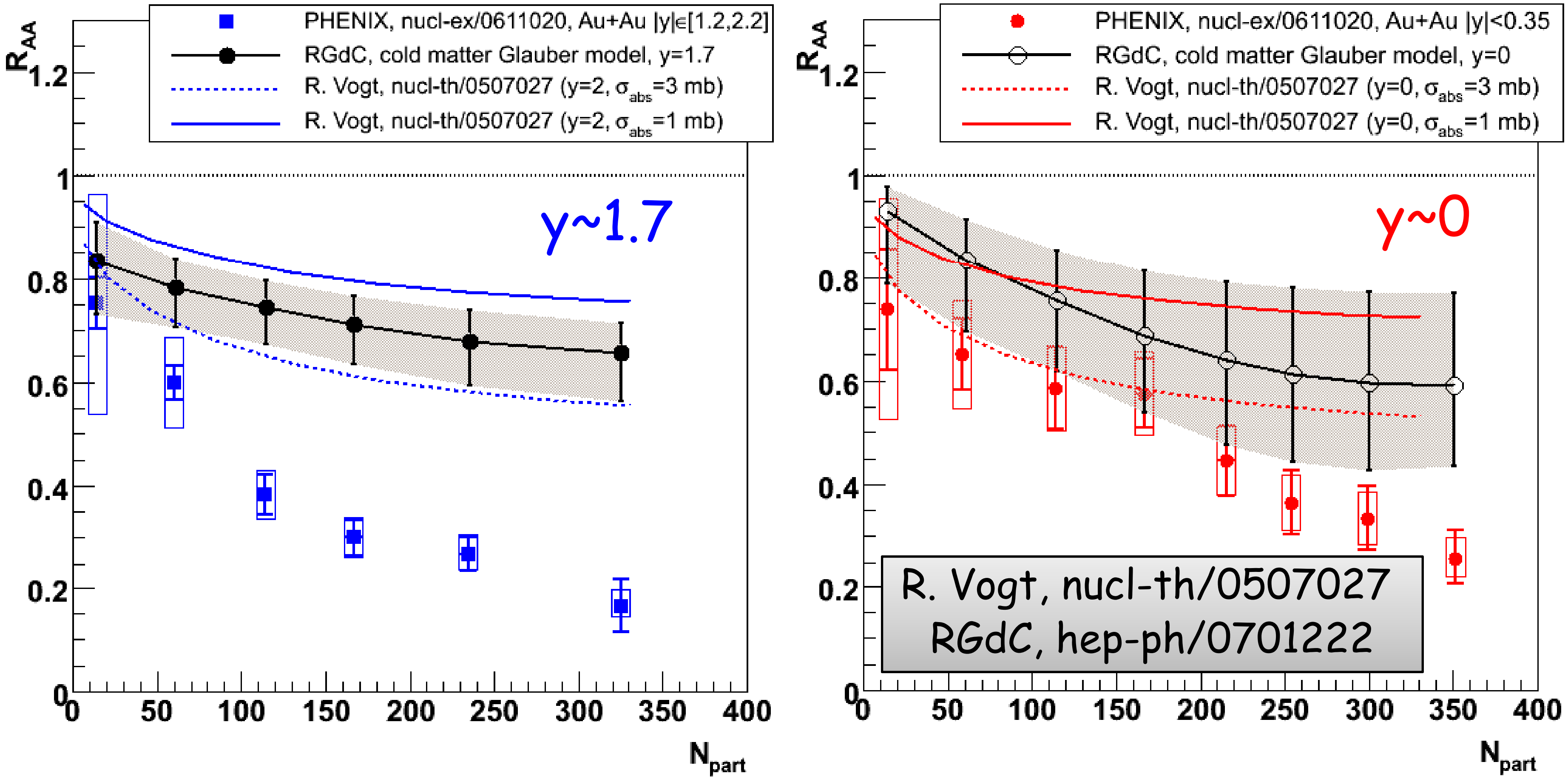


- Works (at least) for absorption & shadowing since production $\sim$ pdf1 x pdf2 x $\exp -\rho\sigma(L_1+L_2)$

RGdC, hep-ph/0701222



R_{AA} from cold nuclear matter

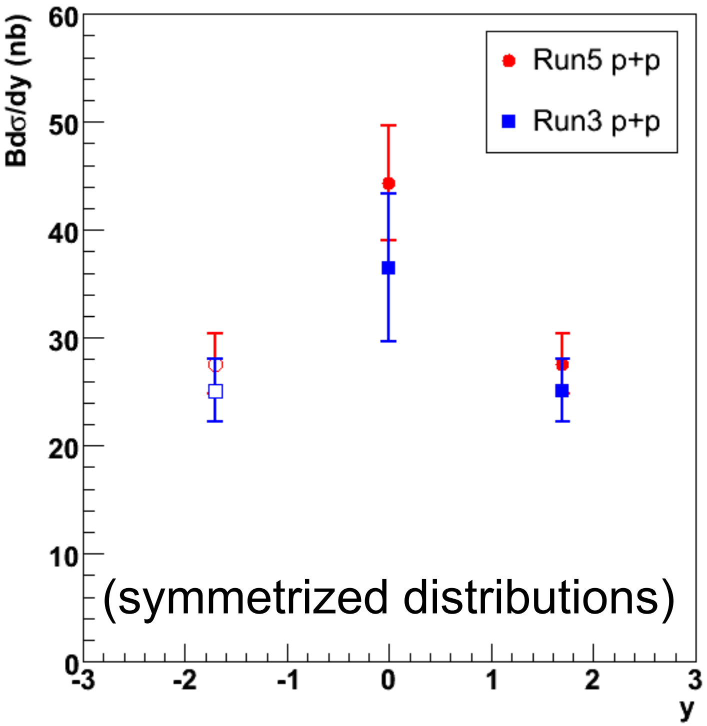


- Two CNM methods agree quite well:
  EKS shadowing+absorption by Vogt & dA-driven Glauber by RGdC
- Clear anomalous suppression (stronger @ y~1.7)

Temptation to divide R_{AA} / CNM is great, but beware of p+p baselines !

p+p cross section vs rapidity

- Different p+p references used for R_{AA} and R_{dA}



PHENIX, PRL96 (2006) 012304
PHENIX, PRL98 (2007) 232002

- J/ψ survival probability
  $\sim R_{AA} / (R_{dA})^2$
  $= (AA/run5pp) / (dA/run3pp)^2$

- Run3pp < Run5pp
  - More suppression from CNM have to be taken into account…
  - $(run5pp/run3pp)^2 = 1.21$ @ y=1.7
  - $(run5pp/run3pp)^2 = 1.49$ @ y=0 !
  - But systematic errors cancelation to be revisited…
  - Work in progress in PHENIX…
  - For now ~ 30% syst. error !

- Is σ_{abs} really smaller @RHIC ?

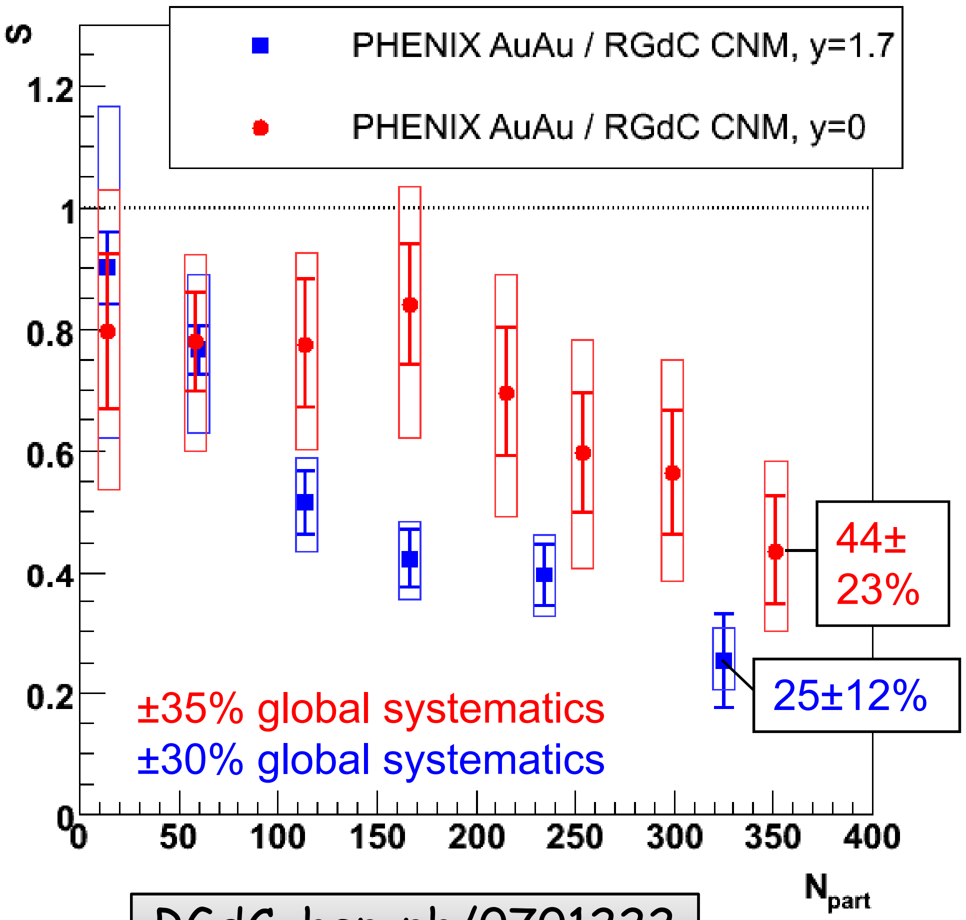
R_{AA} / CNM @ RHIC

- First R_{AA}/CNM extraction including (proper) error propagation
  - d+Au and p+p errors
  - Systematics from Glauber

  & function used for RdA(b)
- Boxes are correlated errors from AuAu & <u>dominant</u> CNM
- Accounting for all errors :
  - $S(J/\psi) = 44 \pm 23\%$ @y=0
  - $S(J/\psi) = 25 \pm 12\%$ @y=1.7

  in the most central collisions…

J/ψ survival beyond CNM



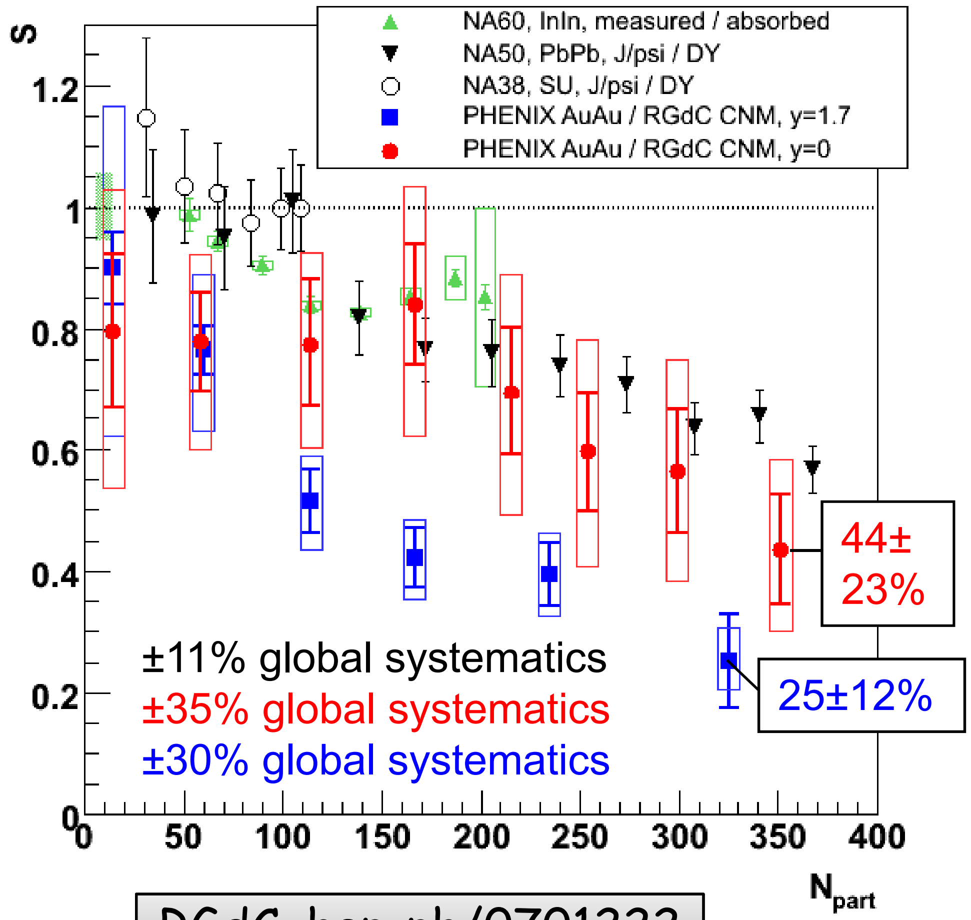
RGdC, hep-ph/0701222

R_{AA} / CNM @ RHIC & SPS

- At mid-rapidity, the amount of surviving J/ψ @ RHIC is still compatible with SPS (~60%) but depends a lot on CNM (and pp references)…

- At forward rapidity, RHIC anomalous suppression is much stronger !

J/ψ survival beyond CNM



RGdC, hep-ph/0701222

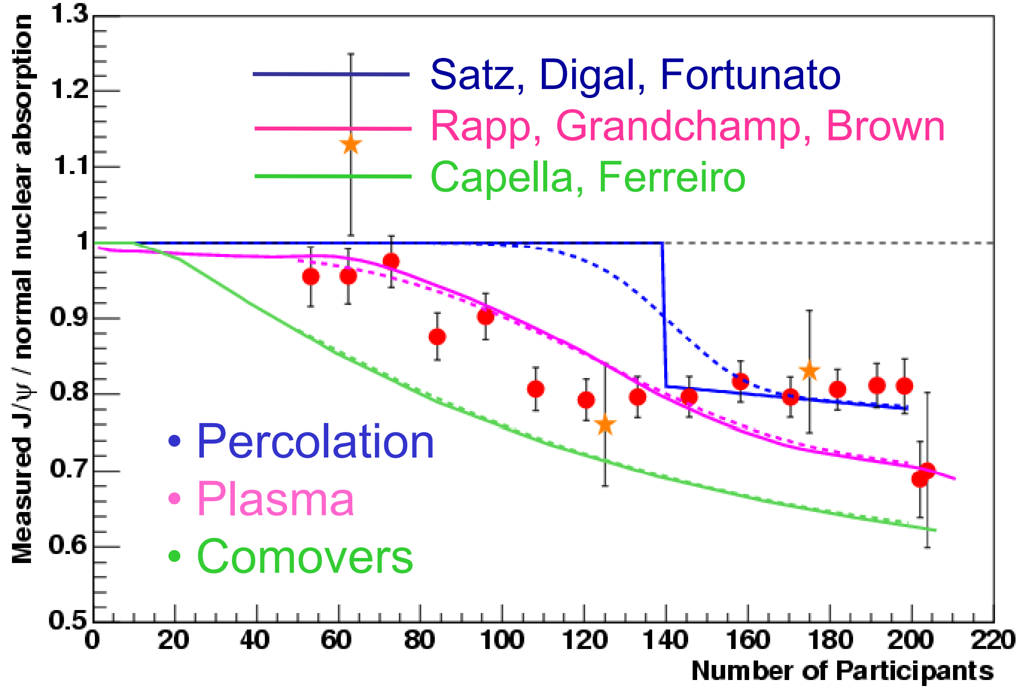
Now… What's going on with the anomalous suppression ?

What's going on @SPS ?

- Several models could fit NA50
  - Plasma (either thermal or percolative)
  - Comovers (hadronic or partonic ?)
- Now NA60…
  - Difficult to reproduce…

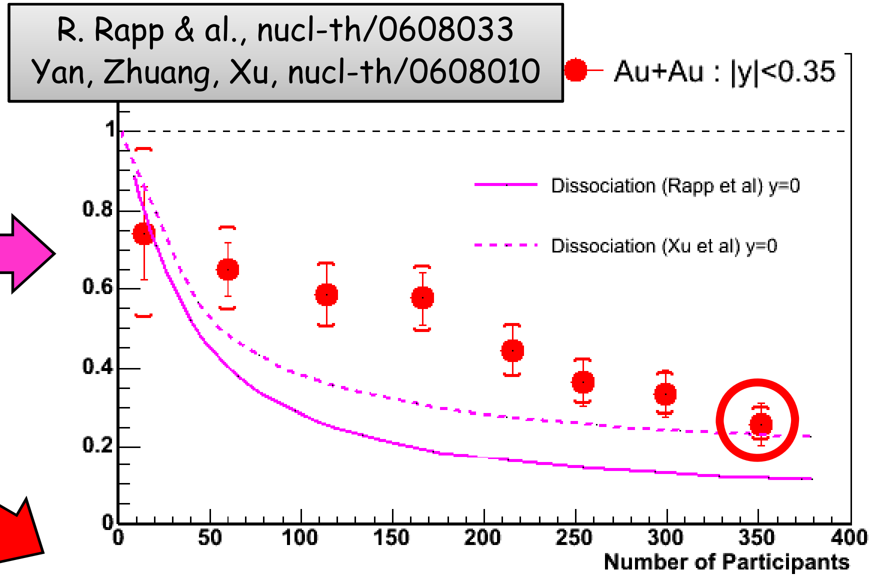
Roberta Arnaldi, QM05
Final in nucl-ex/0706.4361

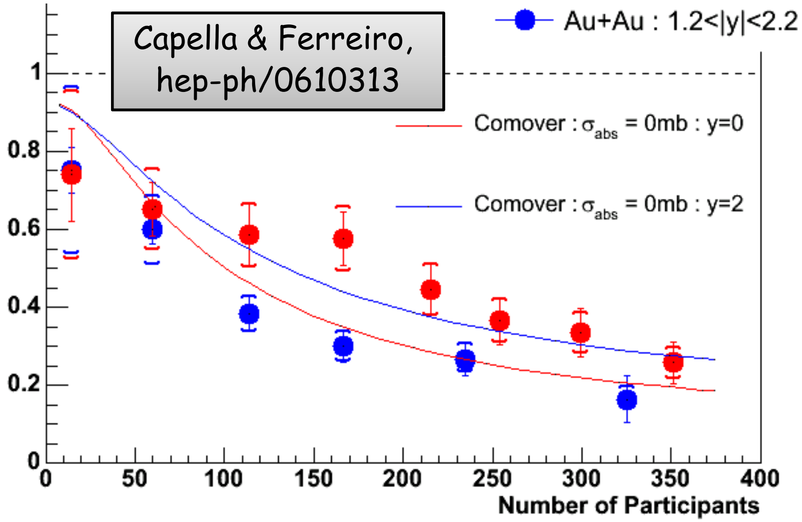
See Carlos Lourenço's talk…

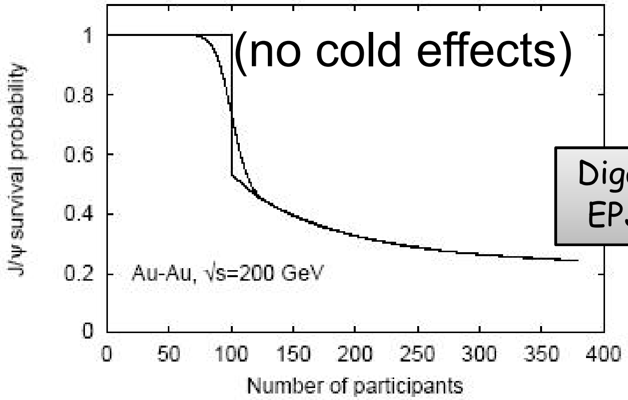


"NA50 only" effects @ RHIC

- Most of the models that did a good job @ SPS fail @ RHIC
  - Gluon dissociation (y~0) doesn't give the right trend and/or amount of suppression
  - Comovers (of unknown partonic/hadronic nature) give $R_{AA}(y=2) > R_{AA}(y=0)$
  - Parton percolation has an onset at N_{part} ~ 90 and simultaneous $J/\psi + \chi_c + \psi'$ melting





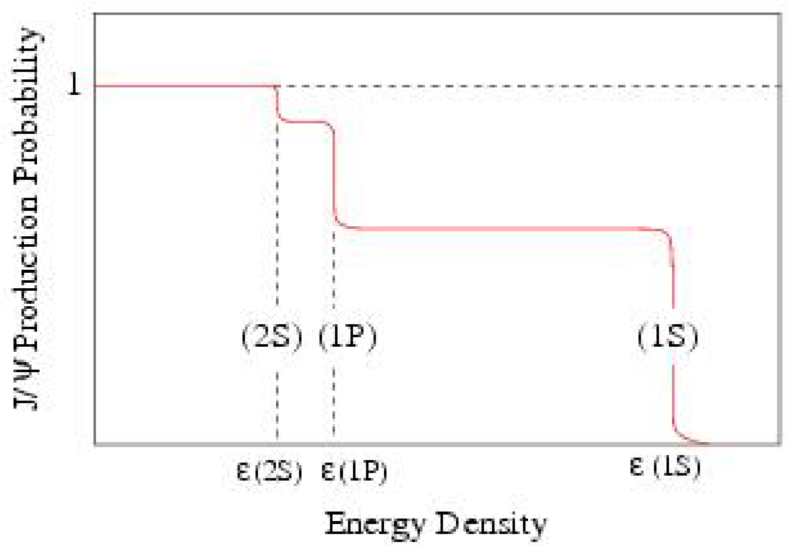


Digal, Fortuno, Satz, EPJC32 (2004) 547

nucl-th/sequential melting

- $J/\psi \sim 0.6 J/\psi + 0.3\chi_c + 0.1\psi'$
- Was a consensus that
  - J/ψ melt at ~$2T_c$ (~$32\varepsilon_c$!)
  - Excited states around 1.1 T_c

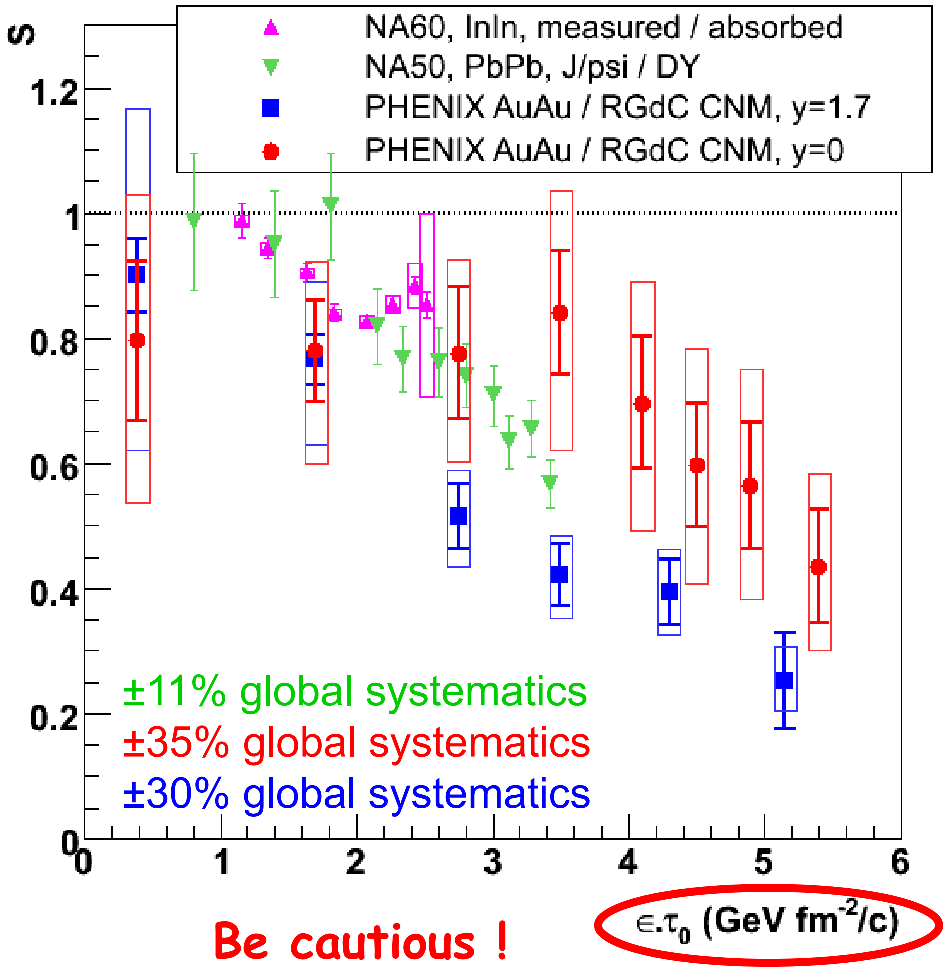
(see eg Satz, hep-ph/0512217)



- Ratio not (well) known
  - At least ~10% uncertainty
  - HERAB: $0.21\ \chi_c + 0.07\ \psi'$
    - Faccioli, Hard Probes 06
- Theorists still working on temperatures…
  - Mócsy melts J/ψ @ Tc
    - hep-ph/0704.2183
  - Umeda melts χ_c> 1.4 Tc
    - hep-lat/0701005

See Ágnes Mócsy's talk…

nucl-ex/sequential melting



- No precise scaling!
  (blame it on CNM@RHIC)
- S = (25±12)% @ y=1.7

→ direct J/ψ do melt !

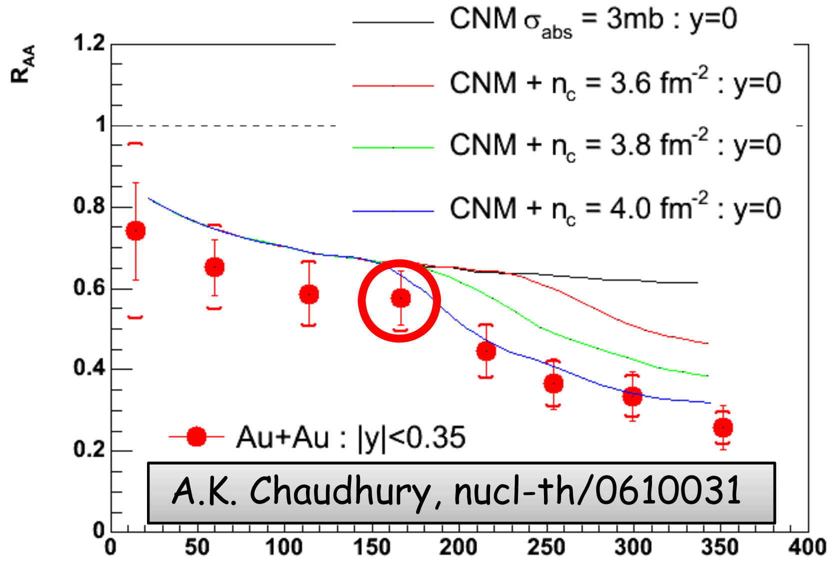
- Why not/less @ y~0 ?
- R_{AA}(y~0) > R_{AA}(y~1.7) ruling out all density-induced suppression effects?

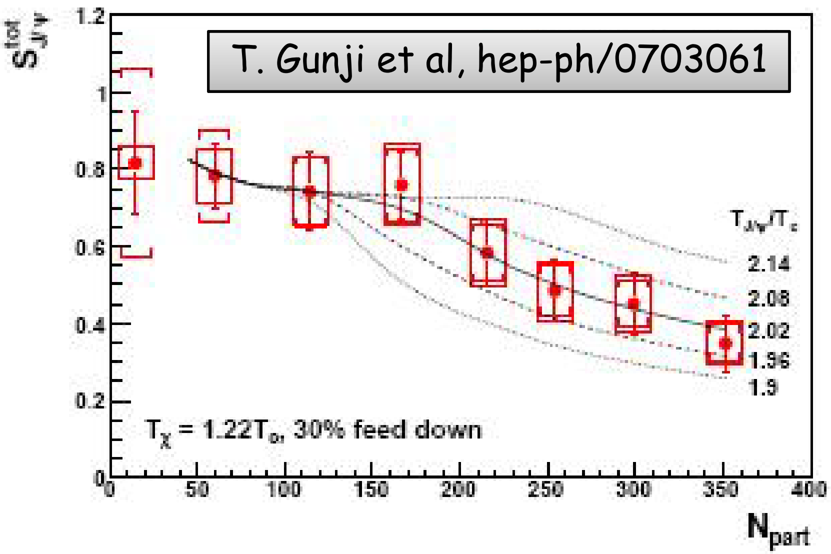
Be cautious !

- Formation time may be different @ RHIC and SPS
- SPS 1.6 fm/c crossing time a bit large for Bjorken formula

Density threshold ? Yes ?

- Onset curves fit the midrapidity data…
  - Chaudhury, nucl-th/0610031
  - Gunji et al, hep-ph/0703061 (after CNM subtraction)

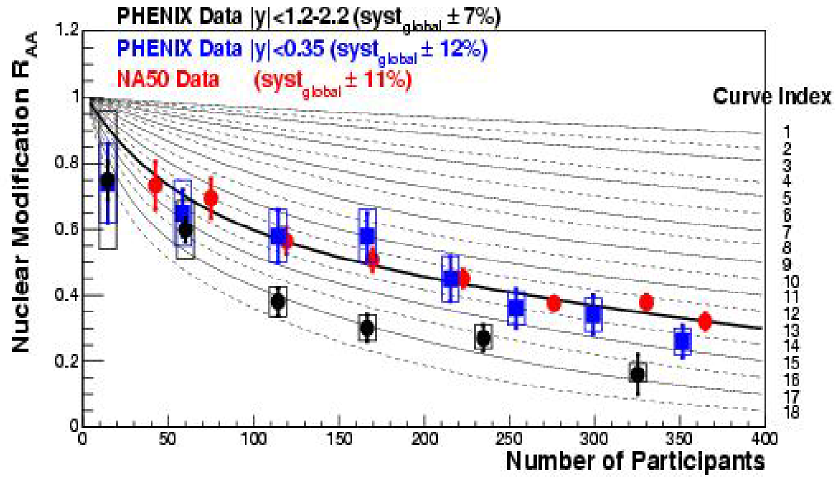


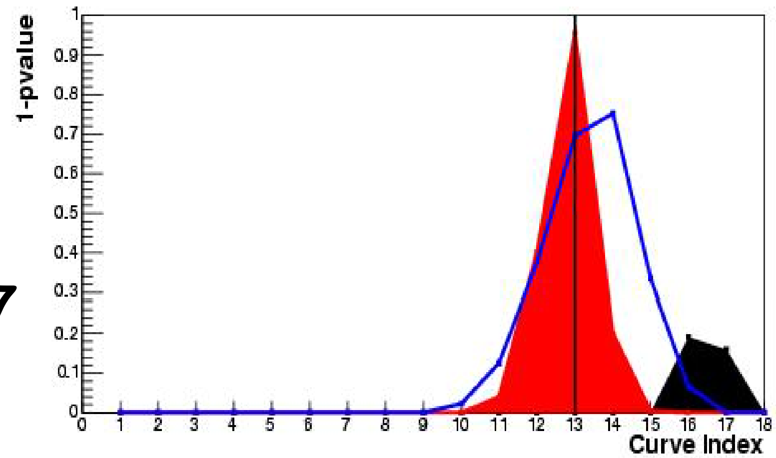


Density threshold ? No !

- Onset curves fit the midrapidity data…
  - Chaudhury, nucl-th/0610031
  - Gunji et al, hep-ph/0703061 (after CNM subtraction)
- So do smooth curves !
  - Nagle nucl-ex/0705.1712
- Density threshold @ y=0 is incompatible with SPS onset or larger suppression @ y=1.7
  - Linnyk & al, nucl-th/0705.4443

See Olena Linnyk's talk…

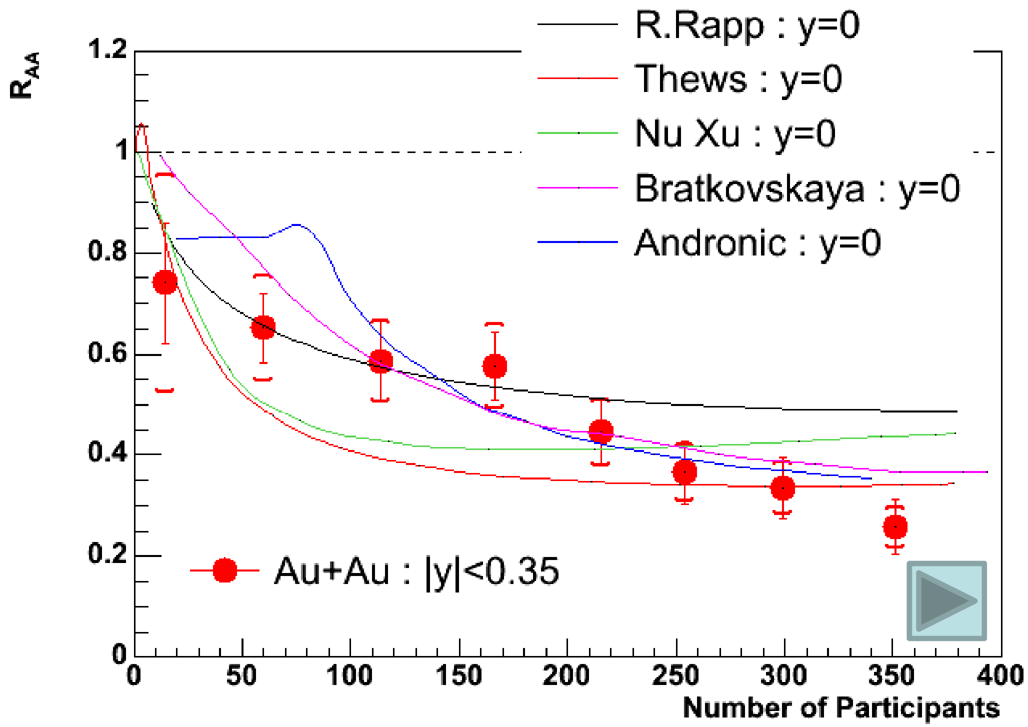




J. Nagle, nucl-ex/0705.1712

Regeneration ?

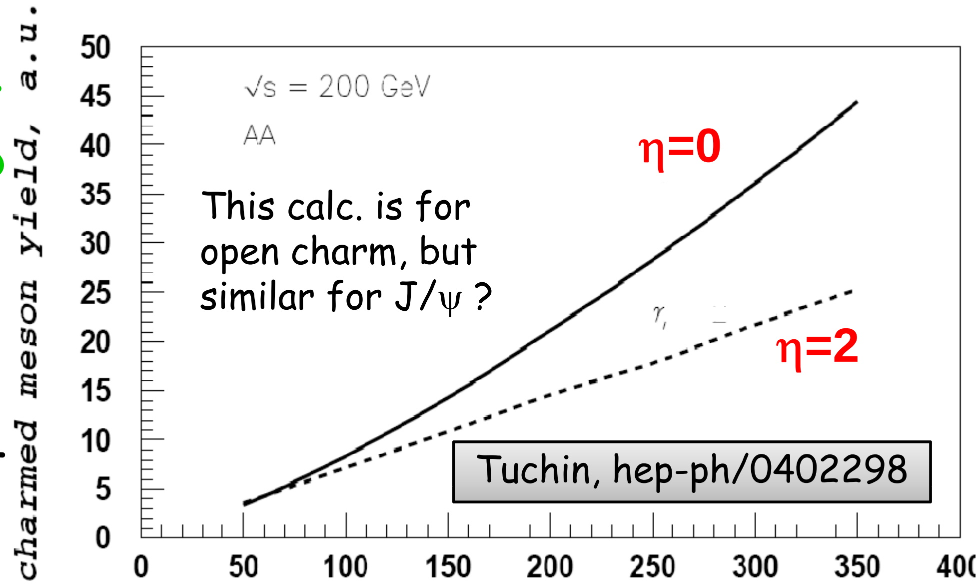
- Various coalescence / recombination approaches…
- Better match to data
  - (look in particular Bratkovskaya's)
- Depend a lot on poorly known cc reference
- But can accommodate:
  - $R_{AA}(y=0) > R_{AA}(y=1.7)$
  - Density-induced enhancement mechanism…
  - $\langle p_T^2 \rangle$ flatness

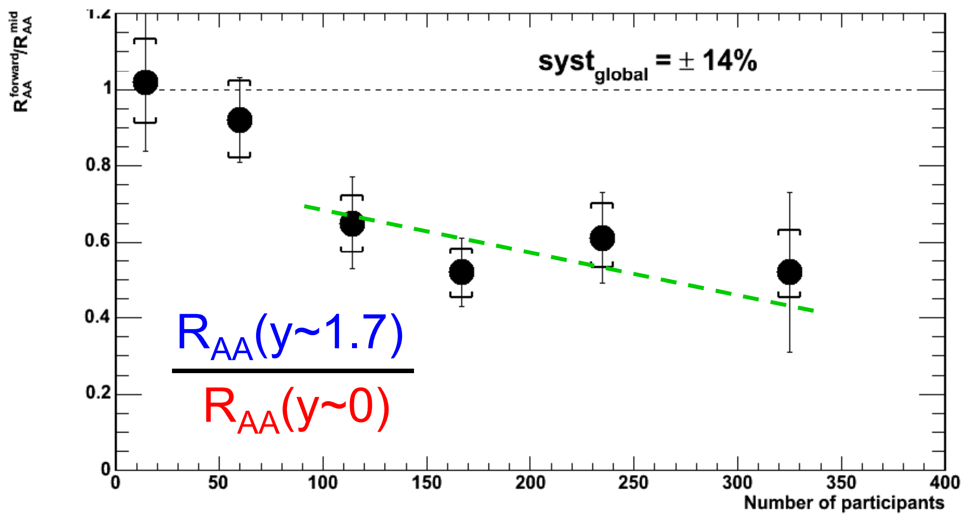


R. Rapp et al.PRL 92, 212301 (2004)
R. Thews et al, Eur. Phys. J C43, 97 (2005)
Yan, Zhuang, Xu, PRL97, 232301 (2006)
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al., NPA789, 334 (2007)

Unaccounted CNM ?

- Strong initial states effect ala color glass condensate ?
  - But they have to violate rapidity symmetrisation $R_{AA}(|y|) = R_{dA}(-y) \times R_{dA}(+y)$
  - (otherwise taken into account in CNM extrapolation)
- Could this + sequential melting produce $R_{AA}(y\sim0)$ and $R_{AA}(y\sim1.7)$?
- Double ratio should drop…
- A possibility…



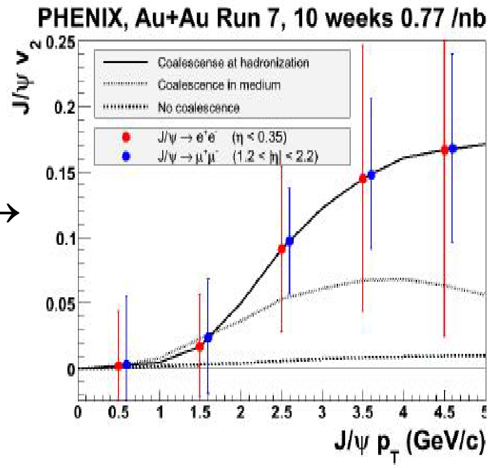


"Anomalous" conclusions

Two qualitative possible scenarios @ RHIC

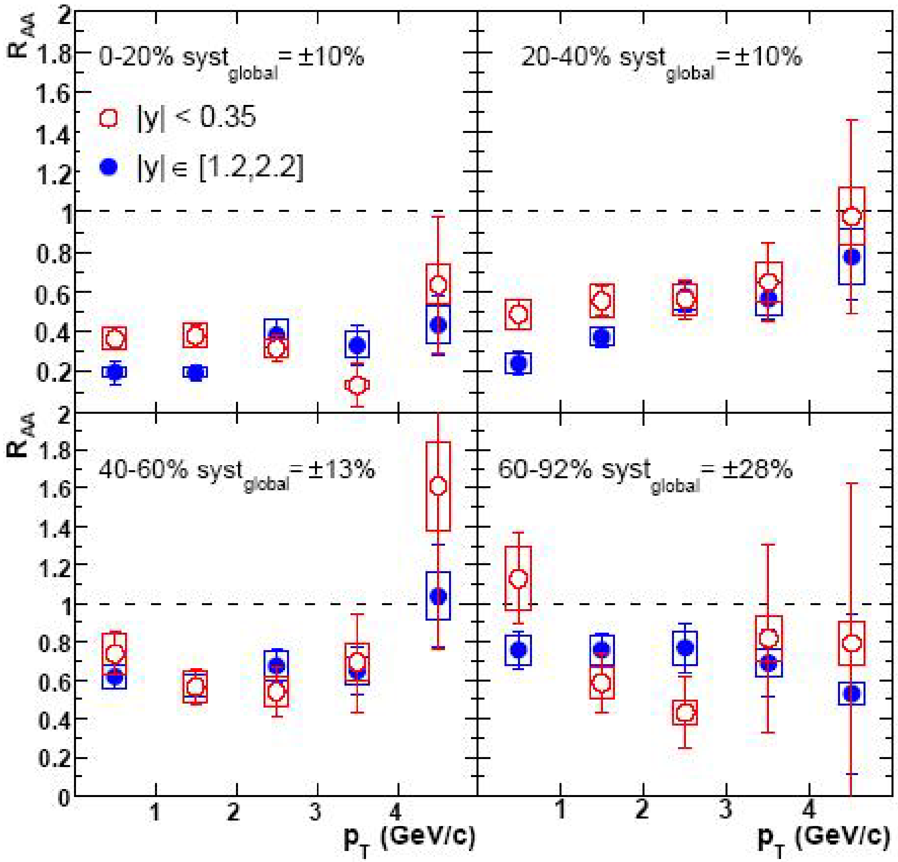
1. Large melting + some regeneration
2. Initial effects (CGC) + melting (of ψ', χ_c?)

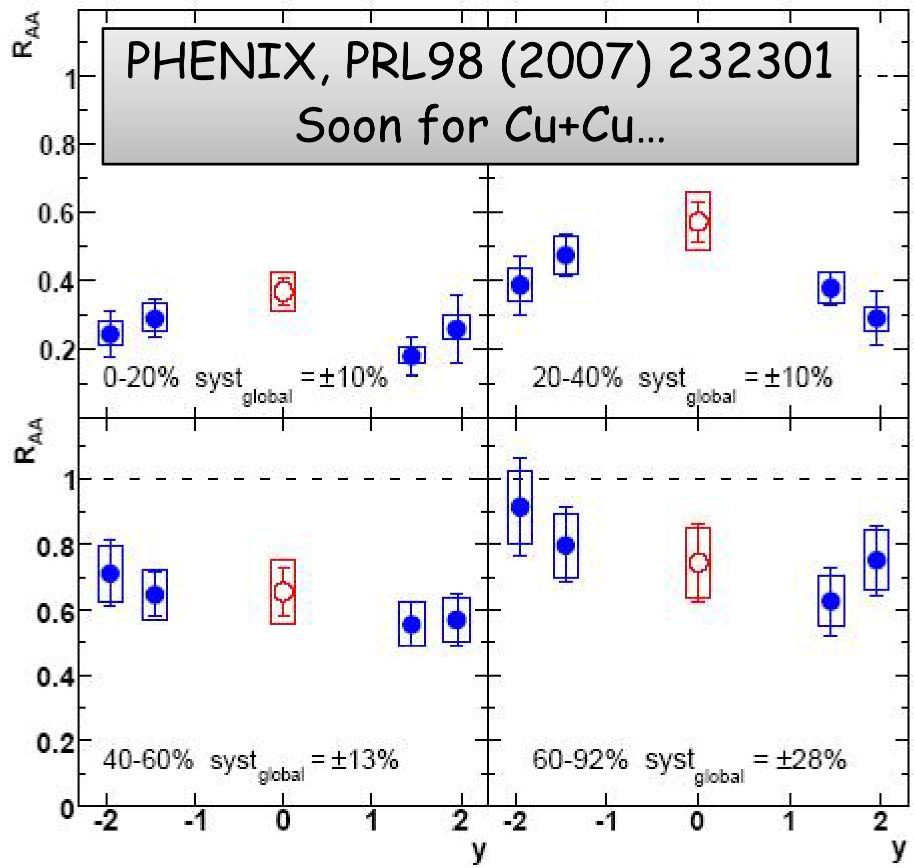
- Need better handle of CNM (Run8 dAu @ RHIC)
- Need better open charm measurements (Run9+)
- Smoking gun would have been a J/ψ rise…
  - Wait for LHC…
- J/ψ v_2 could bring more information
  - Finished run7 should allow to measure →
  - Beware : these are fake points !



All this, assumes deconfinment !

Back to the facts



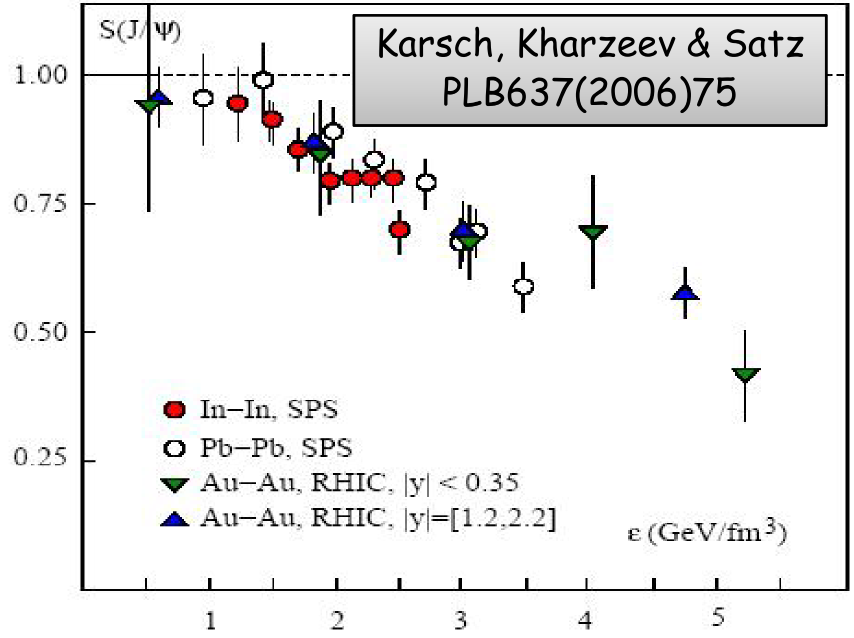


- Much more than what I discussed…
- Should help constraint the models…

Back-up slides

Sequential melting ?

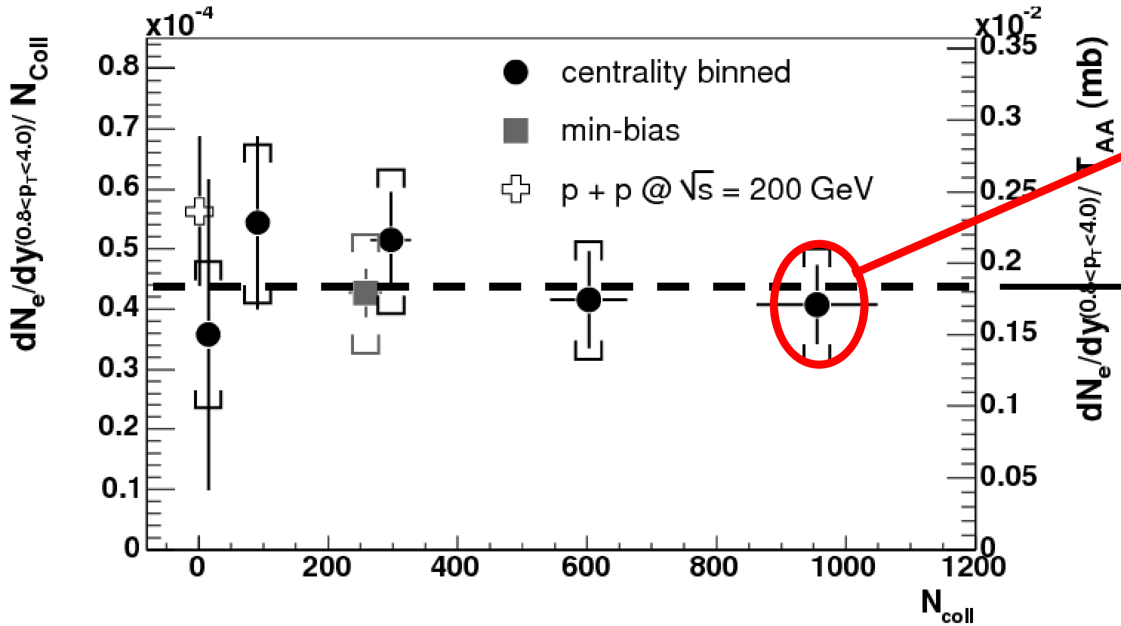
- Before QM06, it was conceivable that only the excited states melt
  $J/\psi \sim 0.6 J/\psi + 0.3\chi_c + 0.1\psi'$
  (with ~10% uncertainty)
- Now, survival = (25±12)%
  → direct J/ψ do melt @y~1.7 ?
- Why not/less @y~0 ?
- Isn't R_{AA}(y~0) > R_{AA}(y~1.7) ruling out all "density" effects ?



Please, be careful with this plot !
- No systematic uncertainties on PHENIX points
- No uncertainties from CNM…
- ε is given by Bjorken formula for τ_0 = 1fm/c but is the formula applicable for SPS crossing time of 1.6 fm/c ?

Quick look to open charm

- Through semileptonic decays ($D \rightarrow e$)



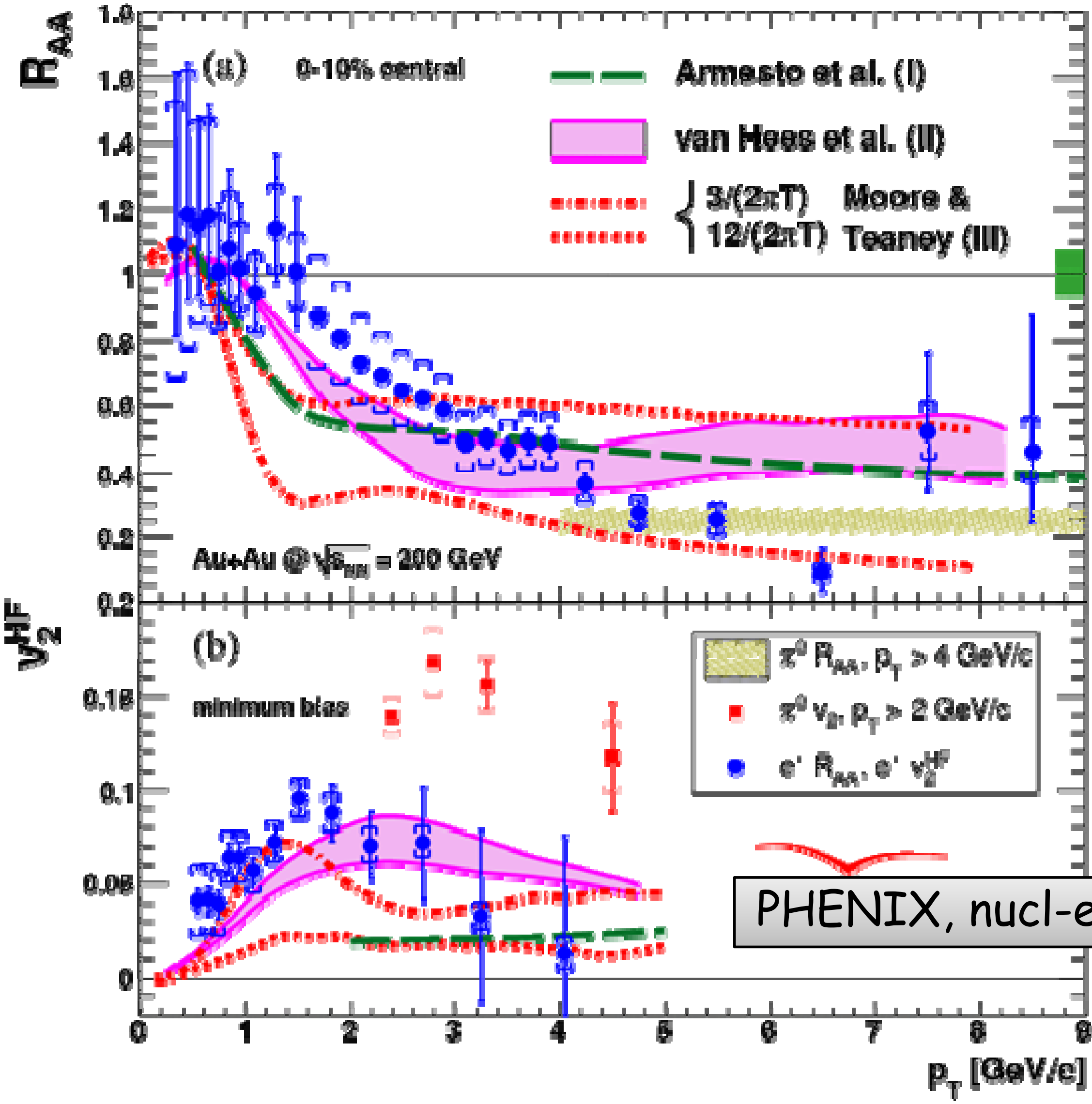
10 to 20 $c\bar{c}$ pairs !
($\rightarrow$ 40 acc. STAR)

N_{coll} scaling

PHENIX, PRL94 (2005) 082301

~25% systematic uncertainties (without Silicon vertex detector upgrade)

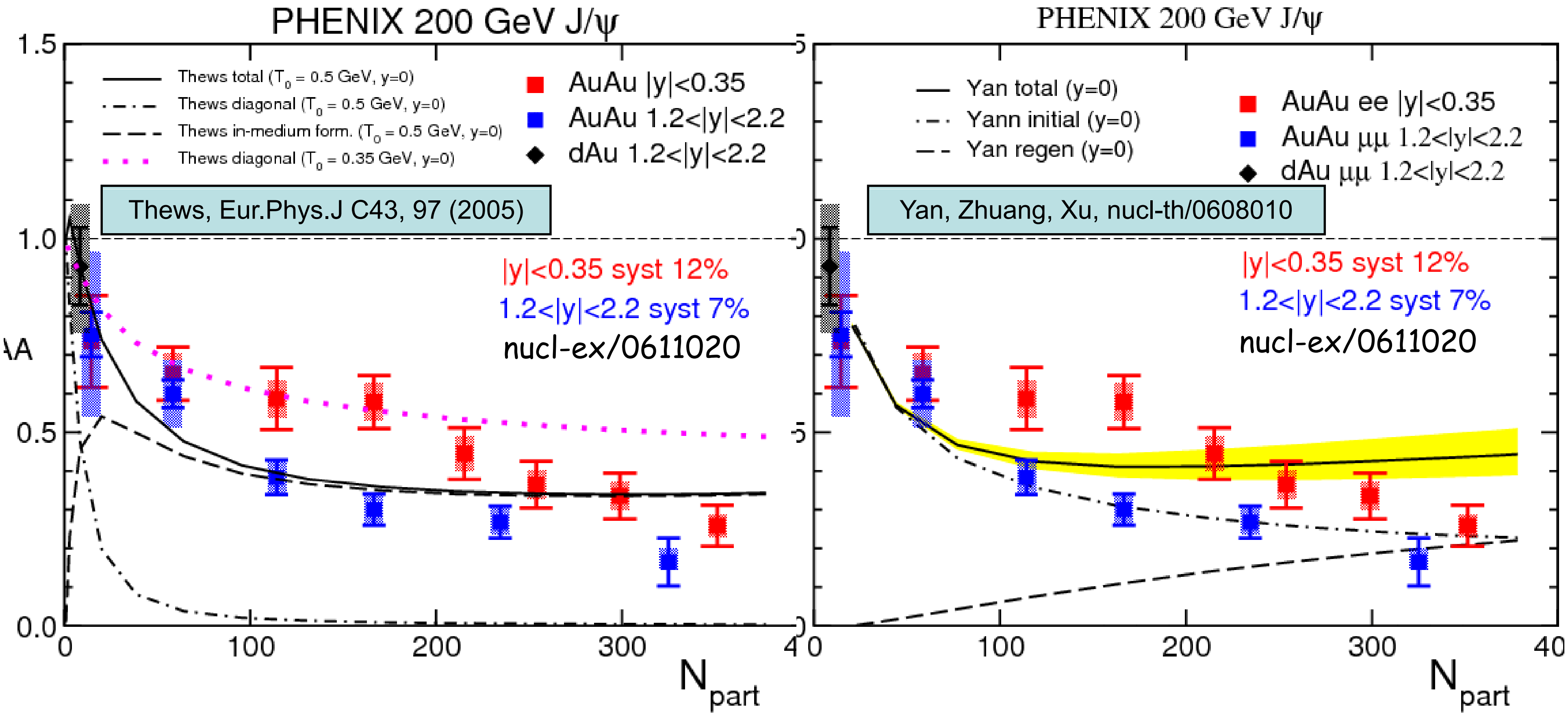
Open charm R_{AA} & $v_2(p_T)$



PHENIX, nucl-ex/0611018

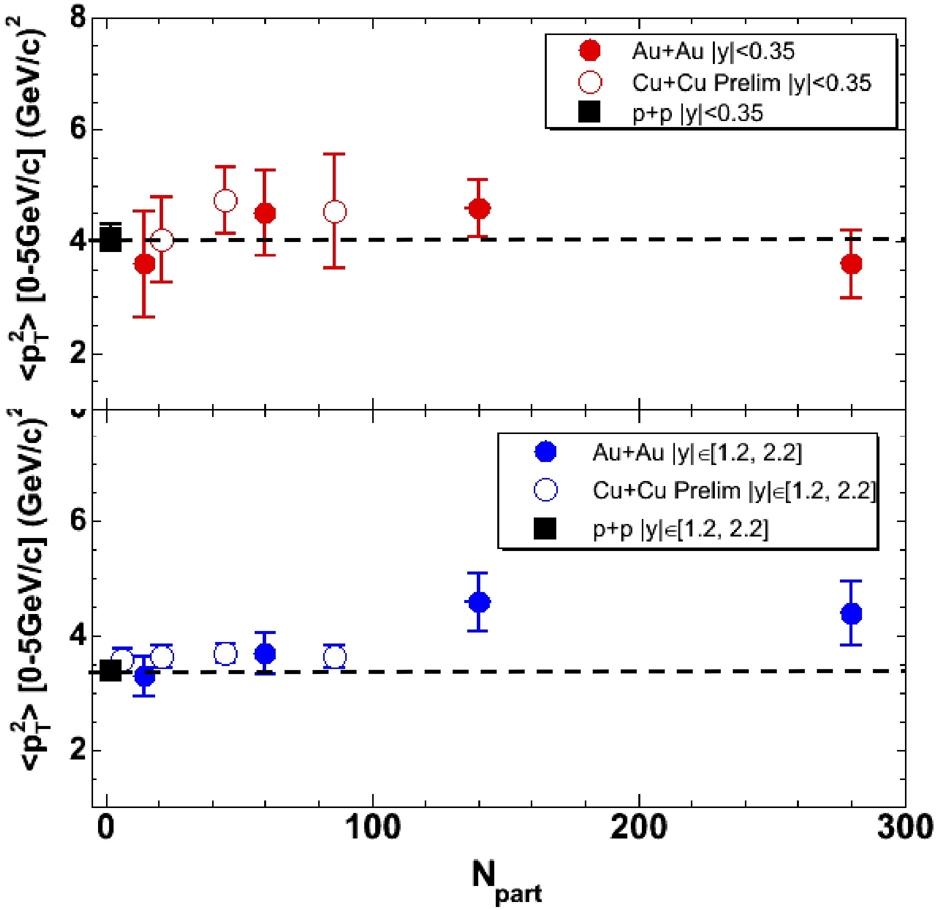
Veterans/newbies balance

- Detailed shape is not easy to get!
- Experimental J/ψ keep falling down…



$\langle p_T^2 \rangle$

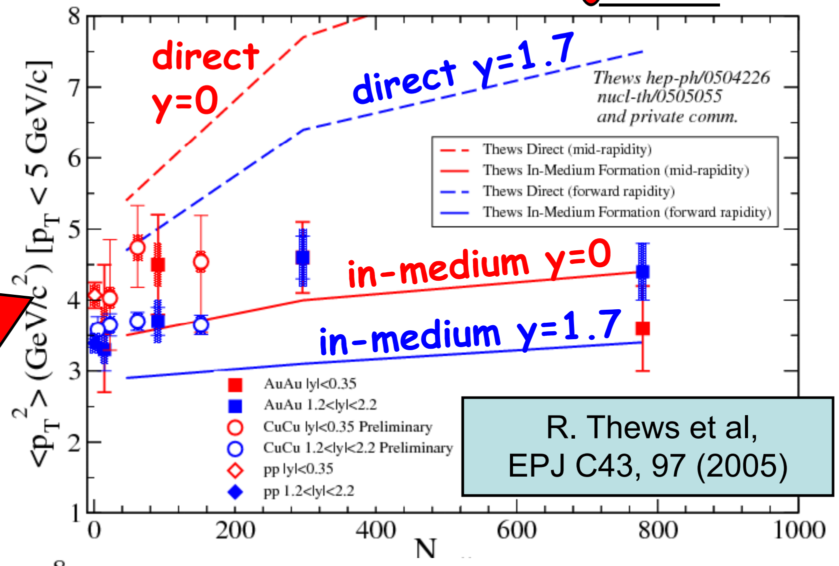
- No dependence of $\langle p_T^2 \rangle$
  - Maybe a modest rise at forward rapidity
- No sizeable Cronin



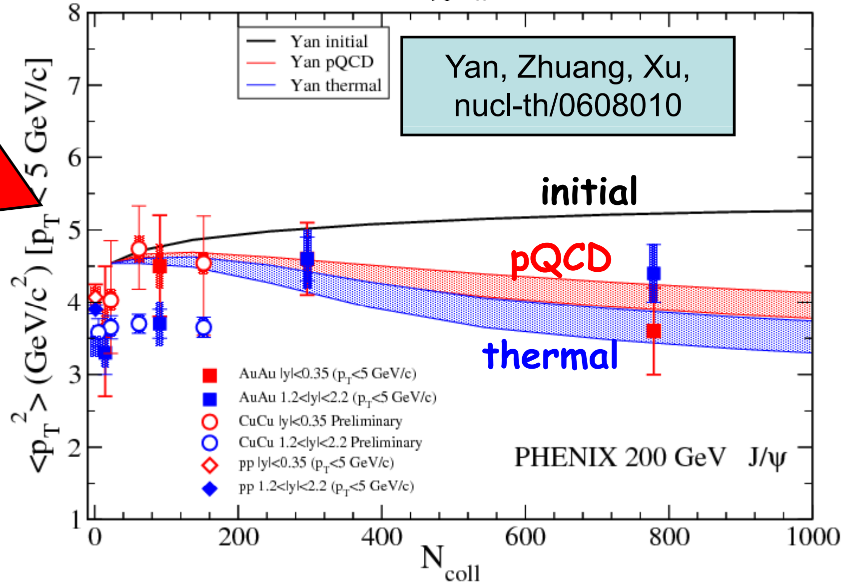
$\langle p_T^2 \rangle$ vs recombination ?

- Initial production depends a lot on initial p_T broadening (Cronin effect)
  - Earlier (run3) dAu/pp data showed clear broadening @y~1.7
  - Not clear with new (run5) pp data

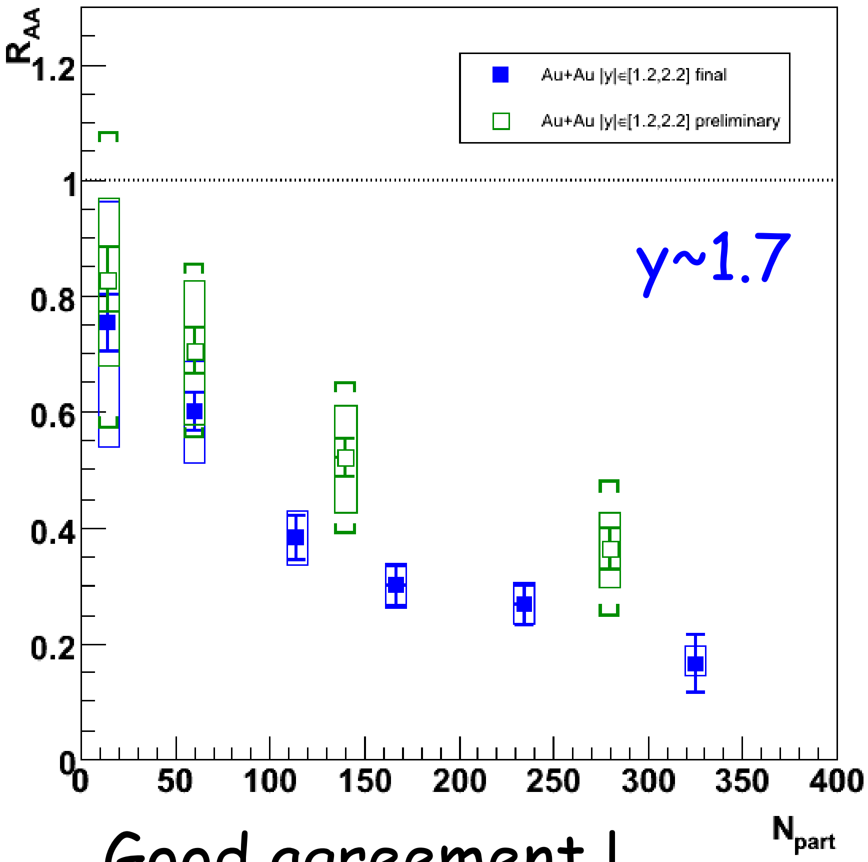
used here

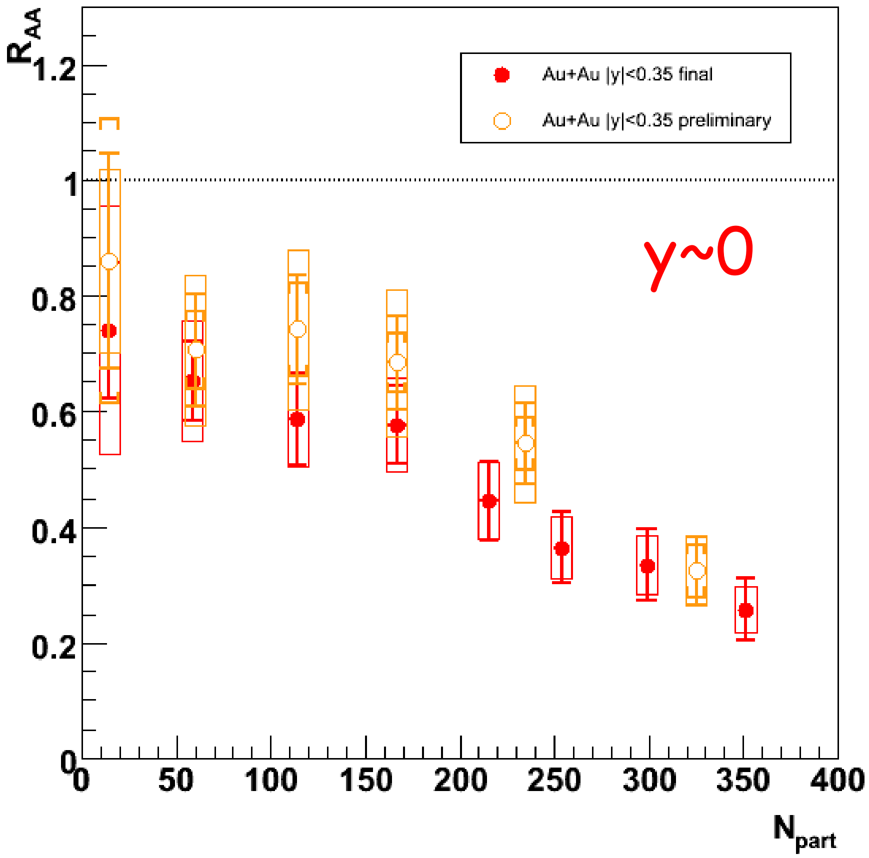


not here



QM06 versus QM05



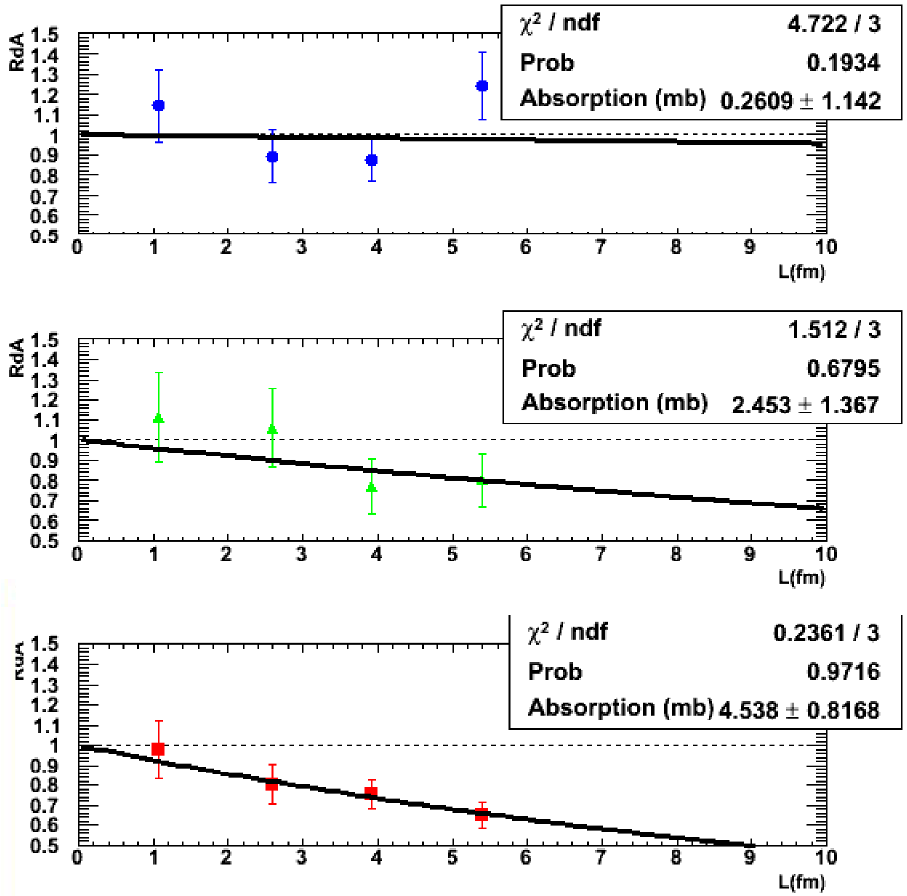


Good agreement !

- At forward rapidity, on the lower edge of systematics
  - (better handling of backgrounds and new pp reference)
- At midrapidity, less <u>subjective</u> "onset" like shape…

Nuclear absorption only

- Compute L with Glauber model
- Fit $\exp(-\sigma_{abs}\, \rho_0\, L)$
- Results are different wrt KKS numbers



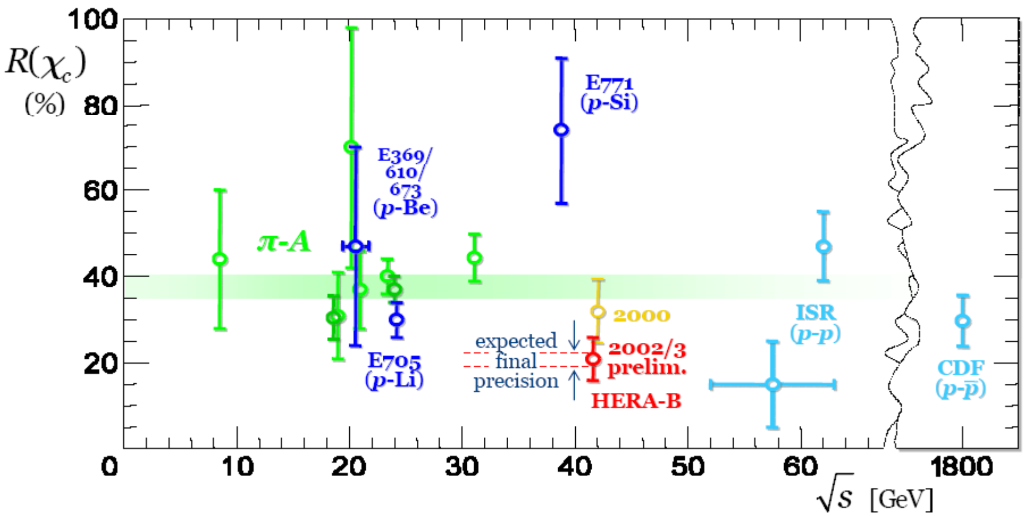
Rapidity	KKS fit [4]	My fit
$y = -1.7$	-0.1 ± 0.2 mb	0.3 ± 1.1 mb
$y = 0$	1.2 ± 0.4 mb	2.4 ± 1.4 mb
$y = 1.8$	3.1 ± 0.2 mb	4.5 ± 0.8 mb

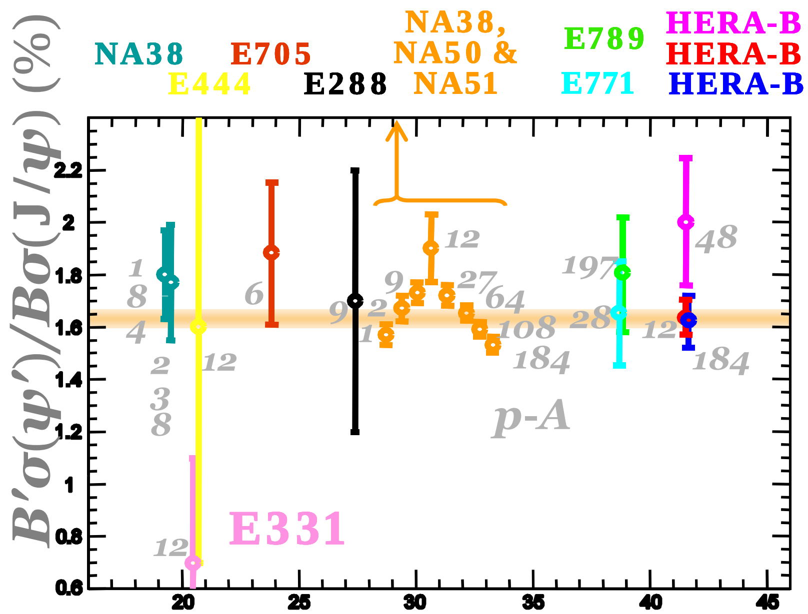
TAB. 1 – σ_{diss} values from KKS and my analysis.

KKS, PLB637(2006)75

Feed down ratio's ?

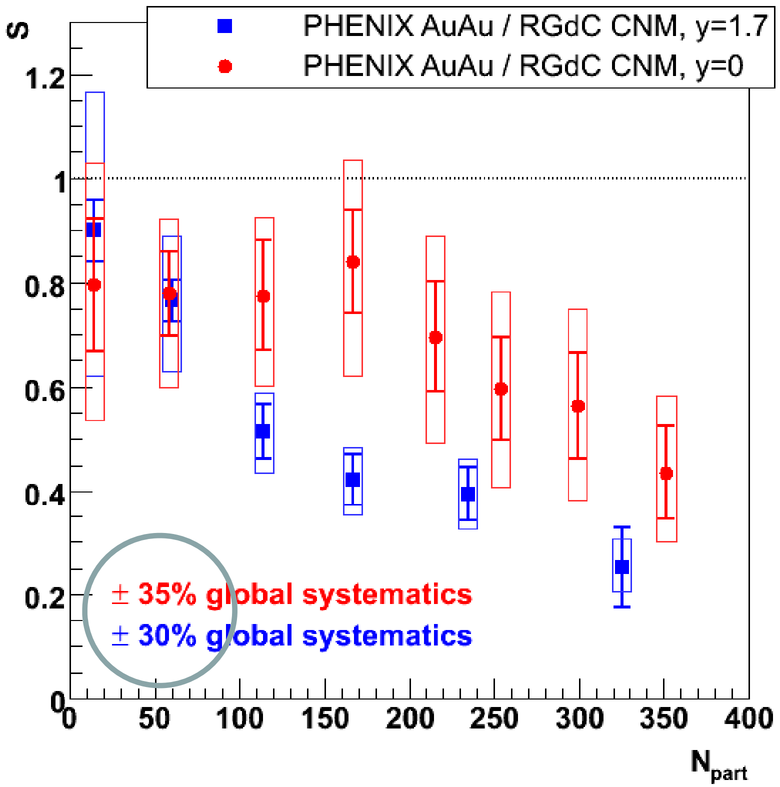
- From HERA-B (pA $\sqrt{s}$=41.6 GeV)
  - 7.0 ± 0.4 % from ψ'
  - 21 ± 5 % from χ_c
  - 0.065 ± 0.011 % from B

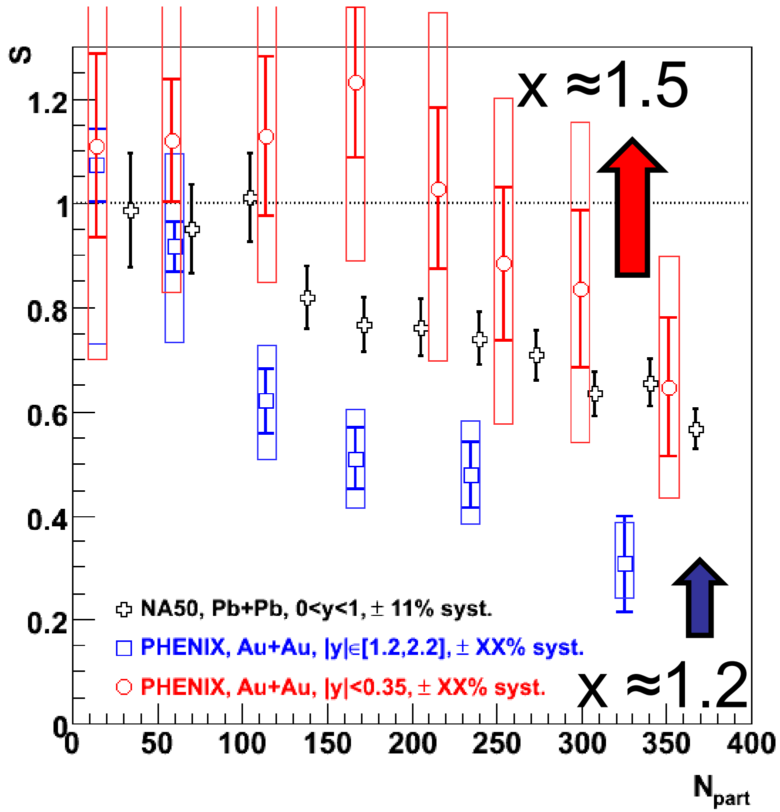




Faccioli, Hard Probes 2006

Rescaling survival probabilities…



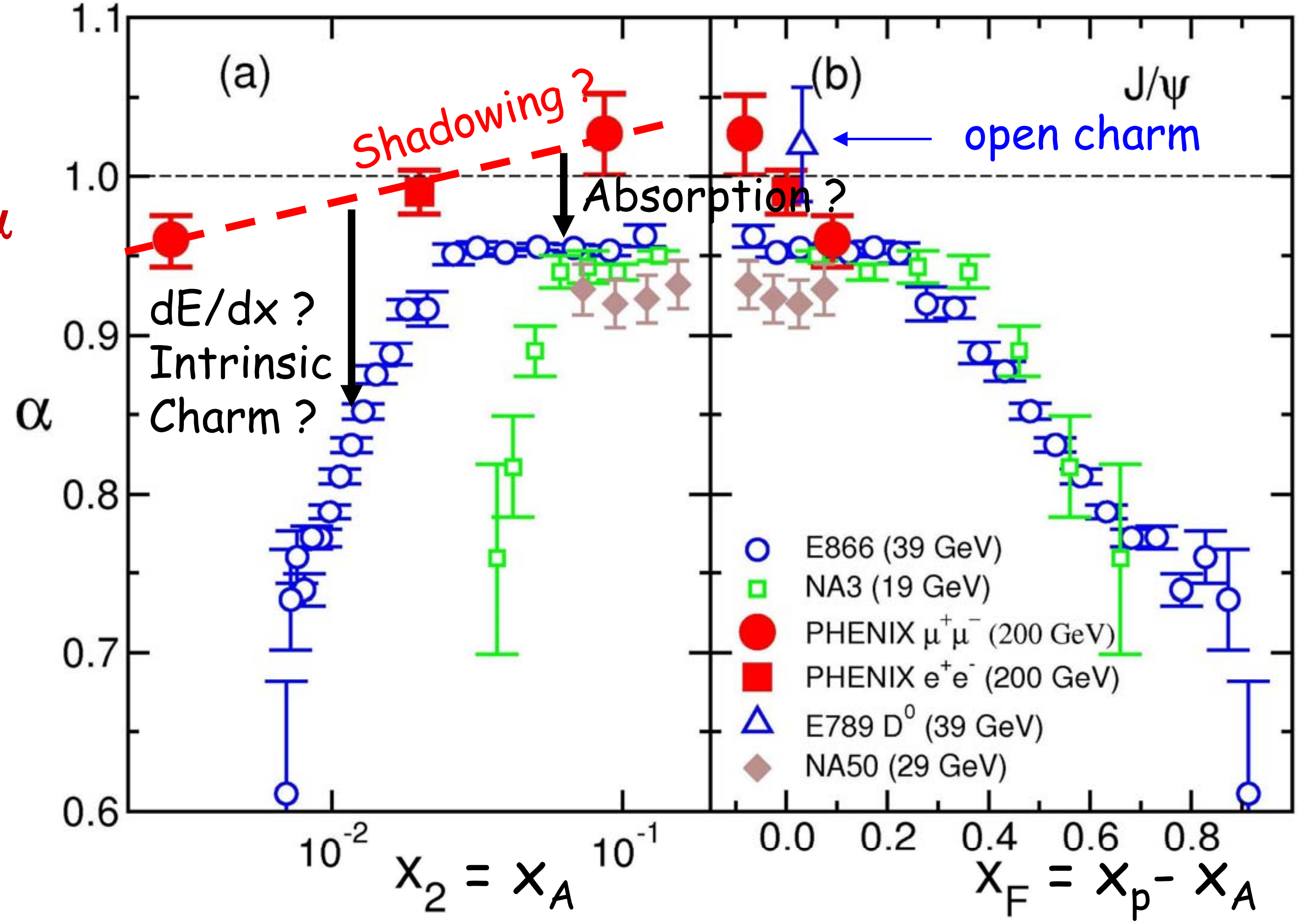


R_{dA} rescaled by run5pp, different systematics, wait for PHENIX reanalysis !

Cold nuclear matter effects ?

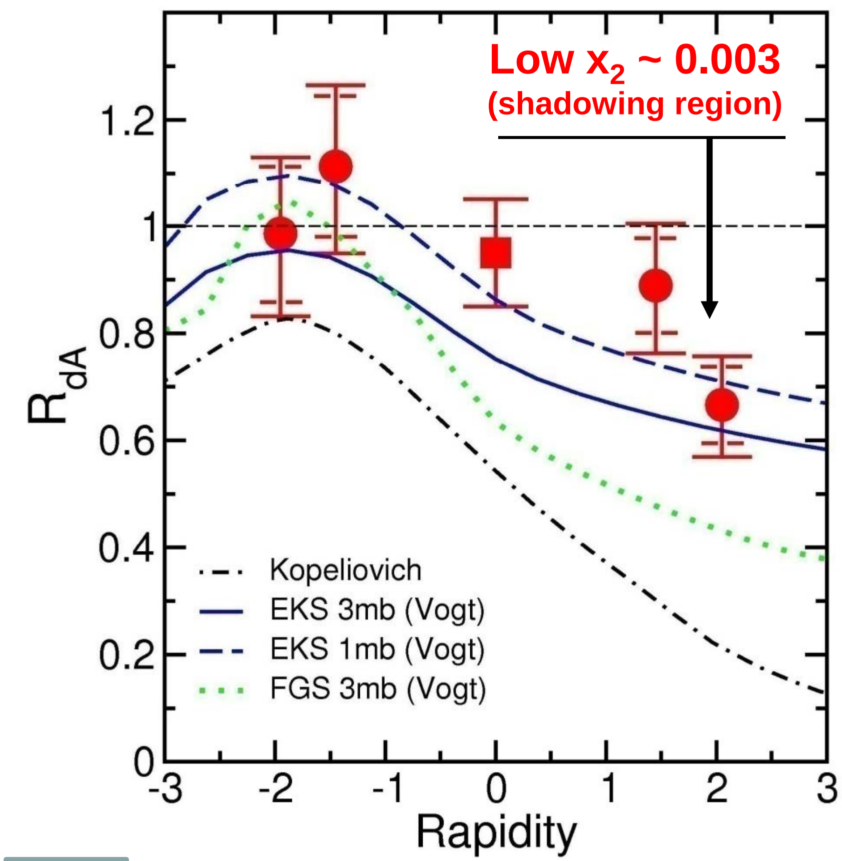
A real puzzle ! Especially when one goes to low x_2, high x_F…

$\sigma_\psi(pA) = \sigma_\psi(pp) \times A^\alpha$



R_{dAu} vs rapidity @ RHIC

R_{dA}

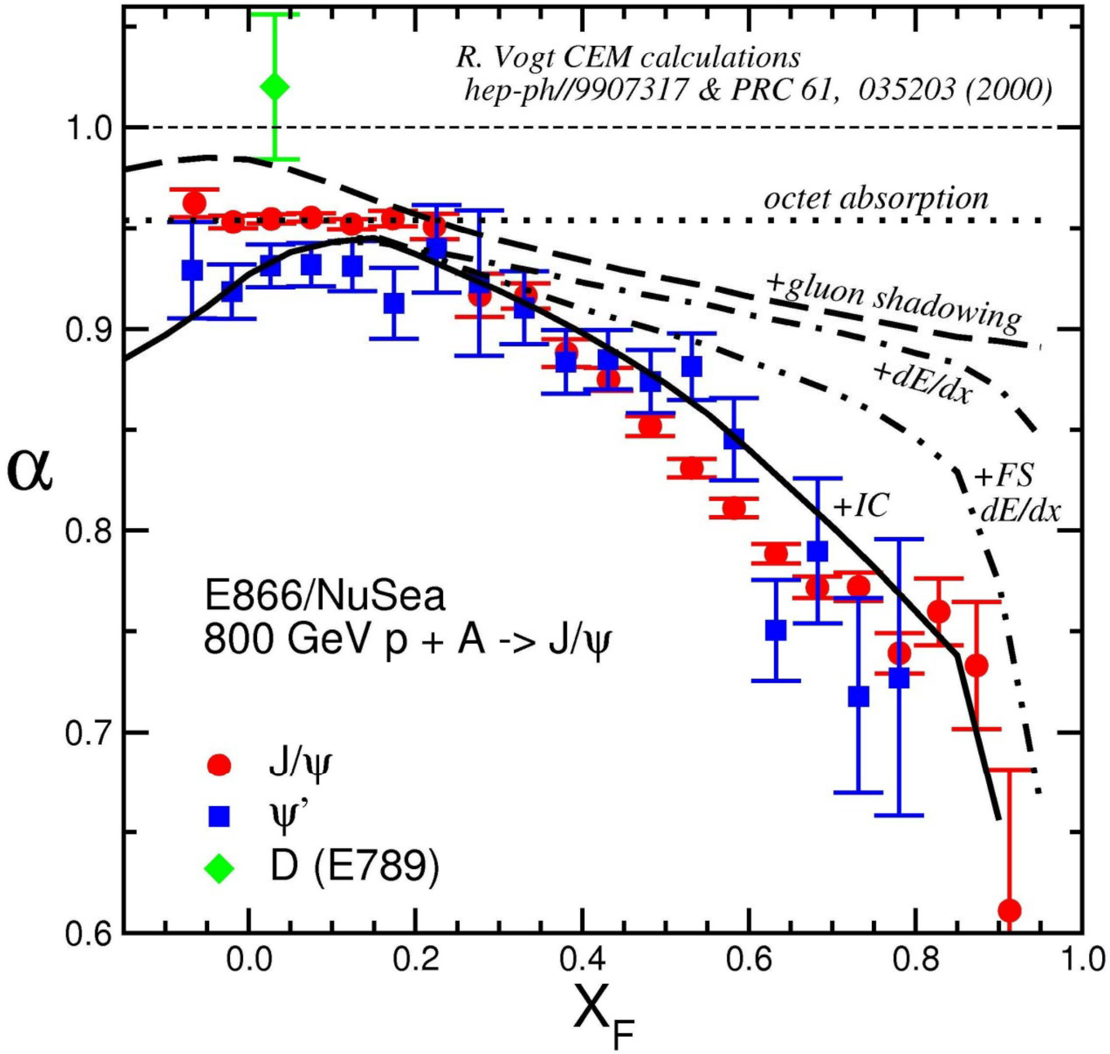


- Data favours
  - (weak) shadowing
    Eskola, Kolhinen, Salgado prescription matches better
  - (weak) absorption
    σ_{abs} ~ 1 to 3 mb !
    (4.18 ± 0.35 mb @SPS)
- But with limited statistics difficult to disentangle nuclear effects !

PHENIX, PRL96 (2006) 012304
Klein,Vogt, PRL91 (2003) 142301
Kopeliovich, NPA696 (2001) 669

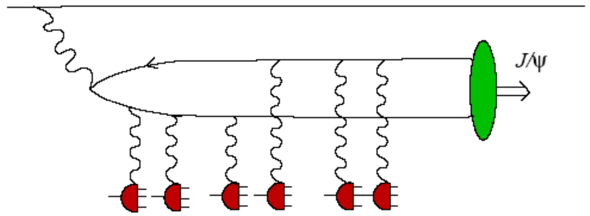
How to get x_F scaling ?

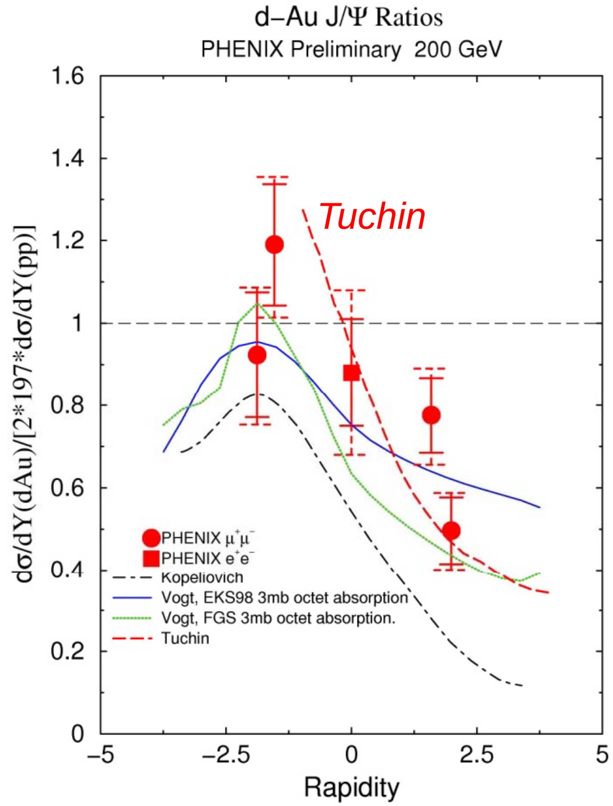
E866/NuSea, $\sigma = \sigma_N * A^\alpha$



Tuchin & Kharzeev

- Hard probes 2004
  - [hep-ph/0504133](hep-ph/0504133)
- Coherent production of charm (open or closed)
  - (y<0 production time to low to make computation)
  - Shadowing from CGC computation…





Tuchin & Kharzeev…

+ absorption for SPS & fermilab