Quarkonia Production in Cold and Hot Matters

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2008, March 12th

Disclaimer and apologies

Essentially my quark matter 2008 quarkonia review talk, with a few additions, and to serve as basis for discussions…

The normal introduction

Matsui & Satz, PLB178 (1986) 416

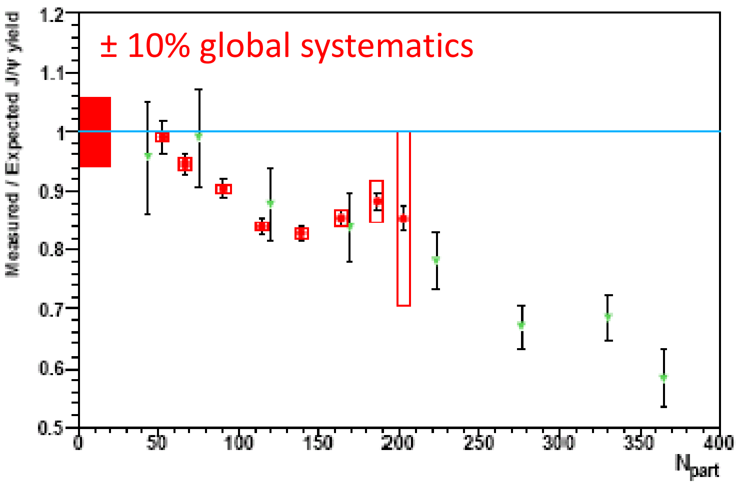
- In 1986, Matsui & Satz predicted an "unambiguous" signature of QGP
  - Onset of quarkonia melting above a certain temperature / energy density threshold
- Example of assumed T_d (but theorists still working on it) :

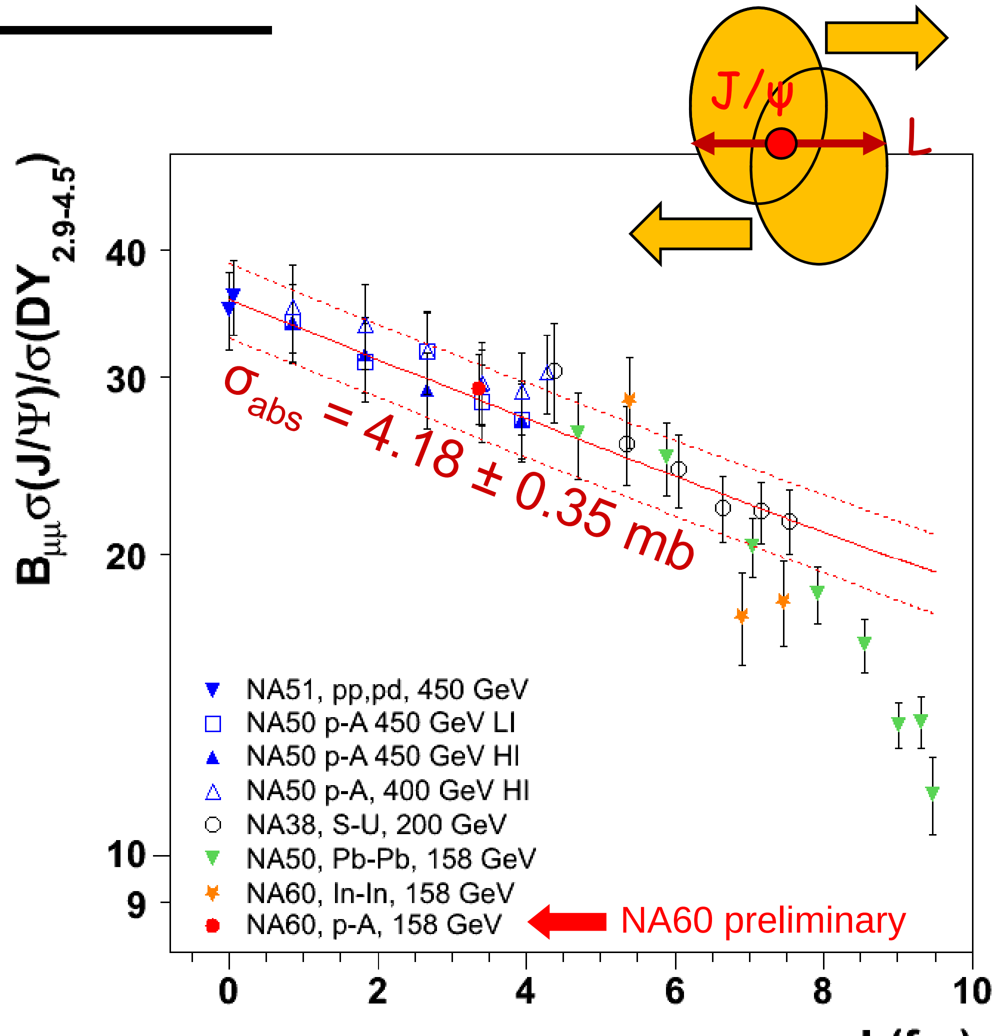
S. H. Lee, Next talk

state	J/$\psi(1S)$	χ_c(1P)	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

Cold and hot matters @ SPS

- Normal nuclear absorption alone does a splendid job describing pA, SU and peripheral InIn and PbPb:
  - $\sigma_{abs} = 4.18 \pm 0.35$ mb
- Beyond is "anomalous suppression"
  - InIn looks like an onset





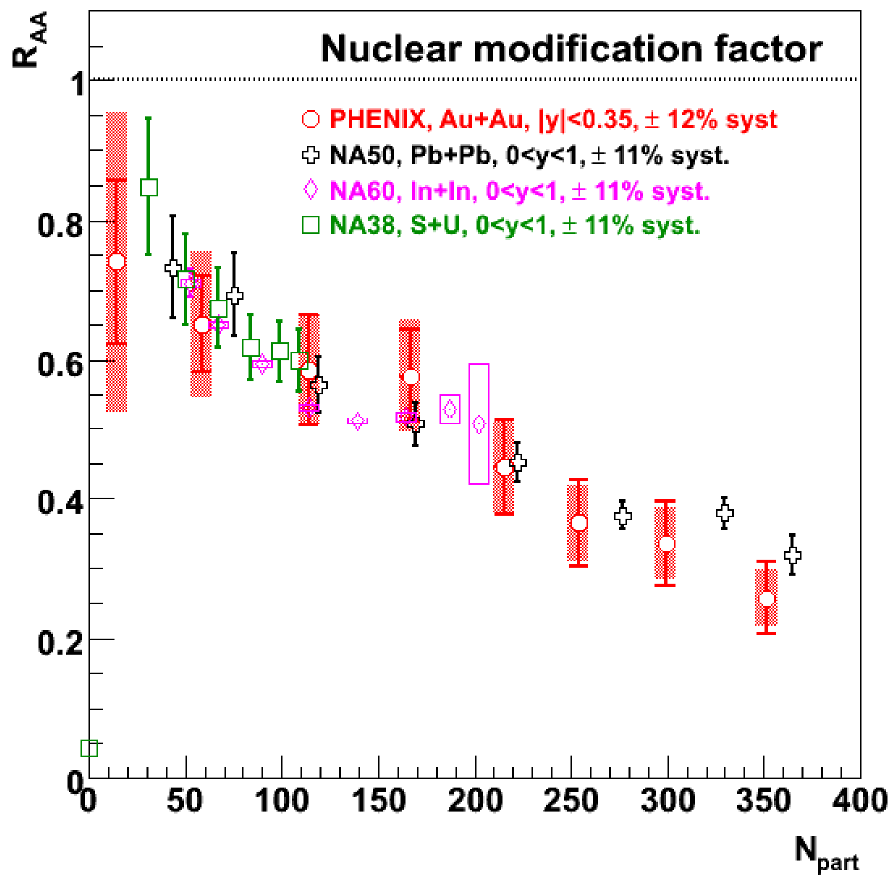
NA50, EPJ C39 (2005) 335
NA60, PRL99 (2007) 132302

At SPS, J/ψ behave pretty much like the predicted golden QGP signature

What about RHIC?

R_{AuAu} (y≈0 in PHENIX) ≈ R_{PbPb} (@ SPS)

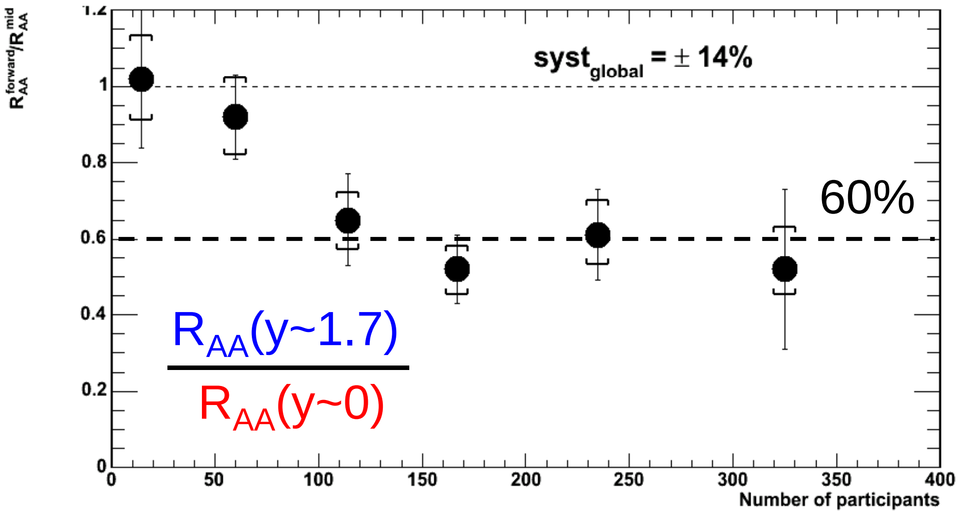
- Lower rapidity R_{AA} looks surprisingly similar, while there are obvious differences:
  - At a given N_{part}, different energy densities…
  - Cold nuclear matter effects ($x_{Bjorken}$, σ_{abs}…)
  - …

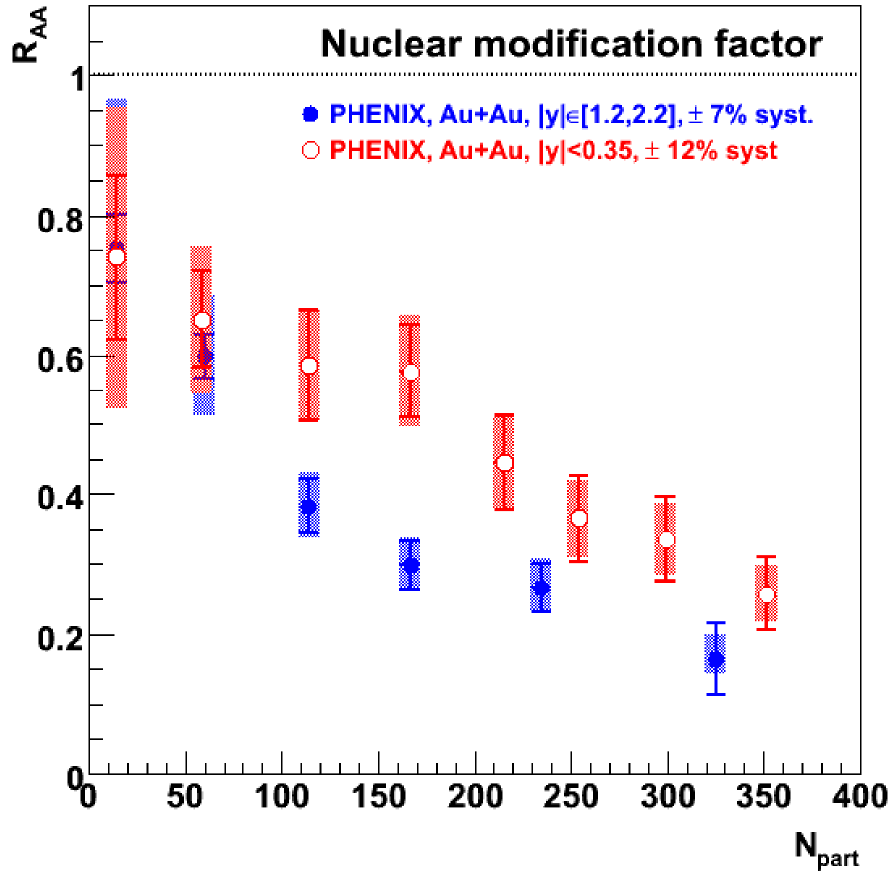


PHENIX, PRL98 (2007) 232301
SPS from Scomparin @ QM06

R_{AuAu} (y≈1.7) < R_{AuAu} (y≈0) in PHENIX

- @ RHIC, more J/ψ suppression at forward rapidity !
- While energy density should be smaller…



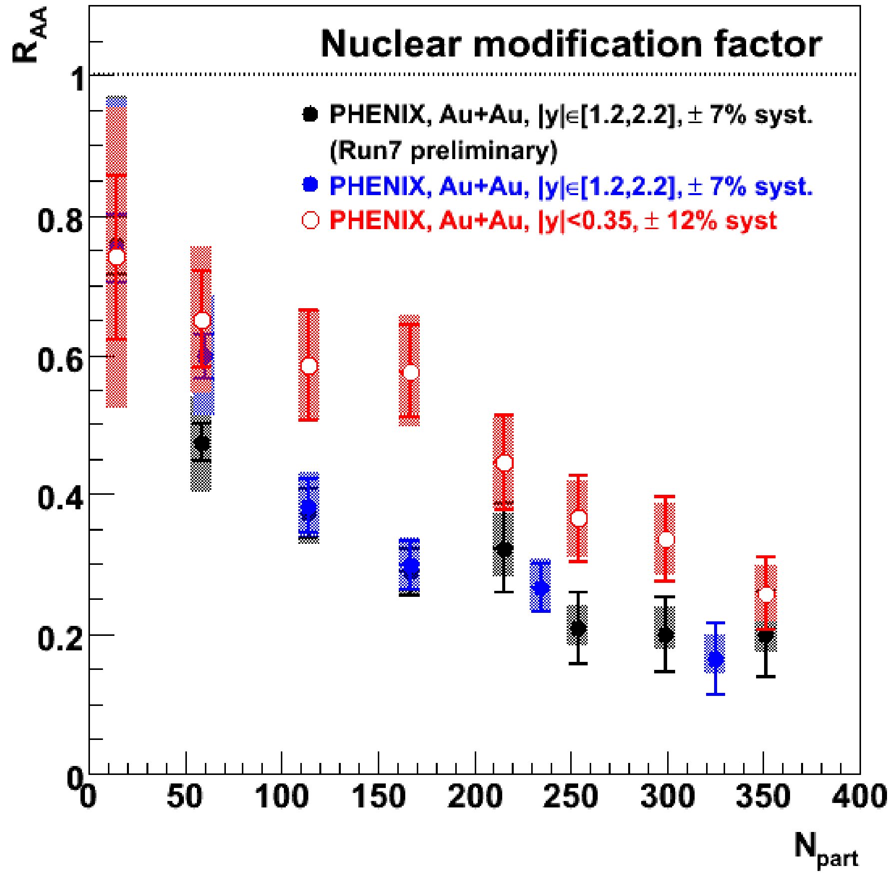


PHENIX, PRL98 (2007) 232301

R_{AuAu} (run 4) = R_{AuAu} (run 7)

NEW

- Forward rapidity only (for now)
- More bins at higher centrality
- Confirm the trend
  - $R_{AA}(y\approx 1.7) < R_{AA}(y\approx 0)$



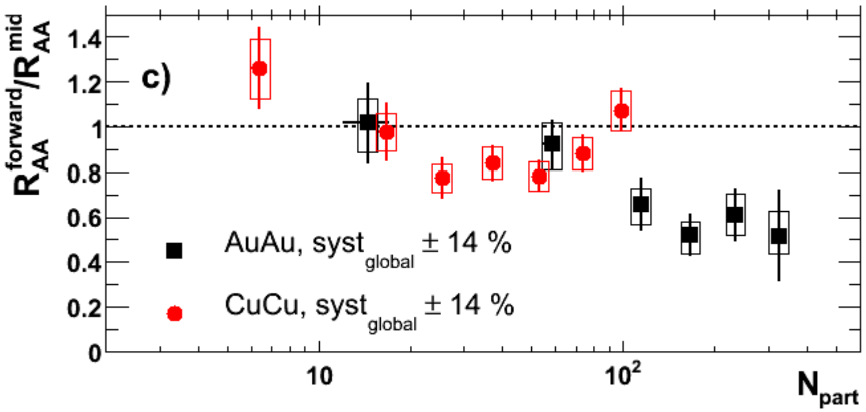
S. Oda, Session 18, Saturday

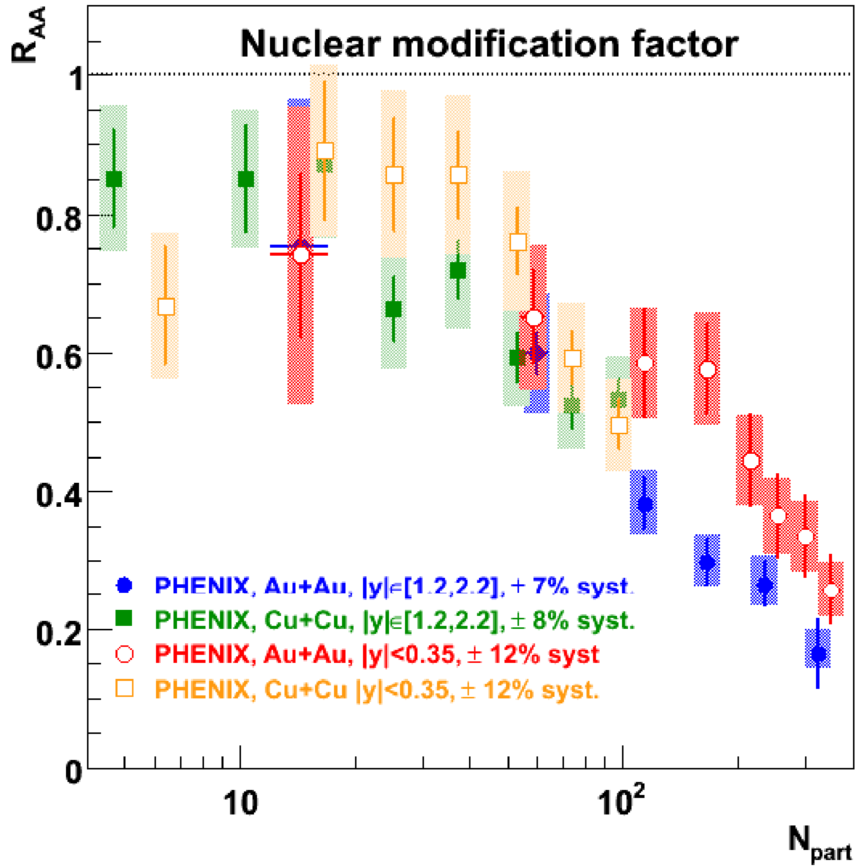
R_{AuAu} vs R_{CuCu} @RHIC

PUB

- Final CuCu analysis
- Slightly below 1 in CuCu

$$\frac{R_{AA}(y\sim1.7)}{R_{AA}(y\sim0)}$$





PHENIX, arXiv:0801.0220

Z. Tang, Session 18, Saturday

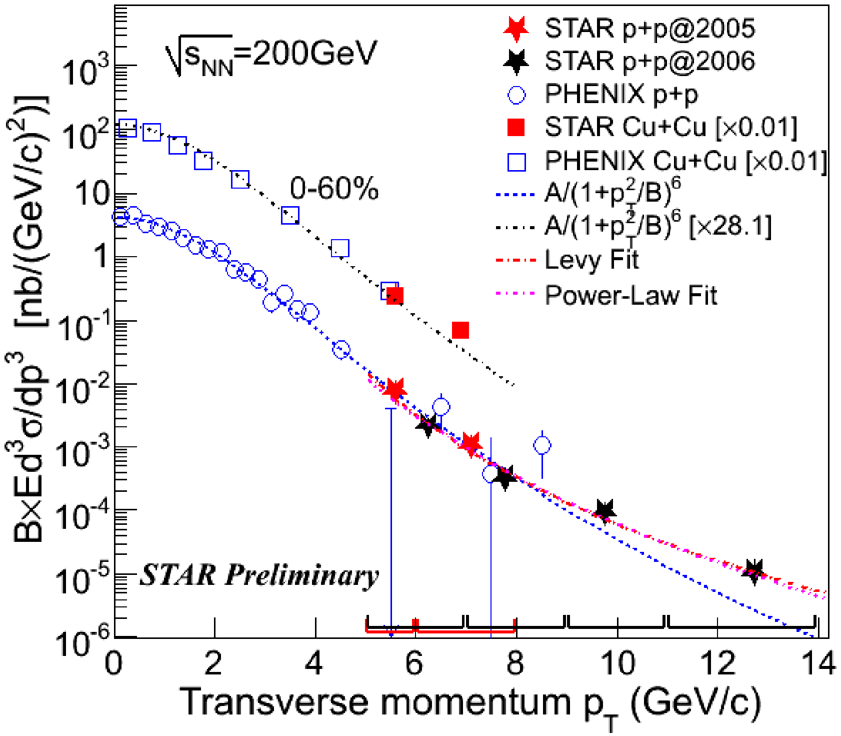
R_{CuCu} (STAR, high p_T) ≈ 1

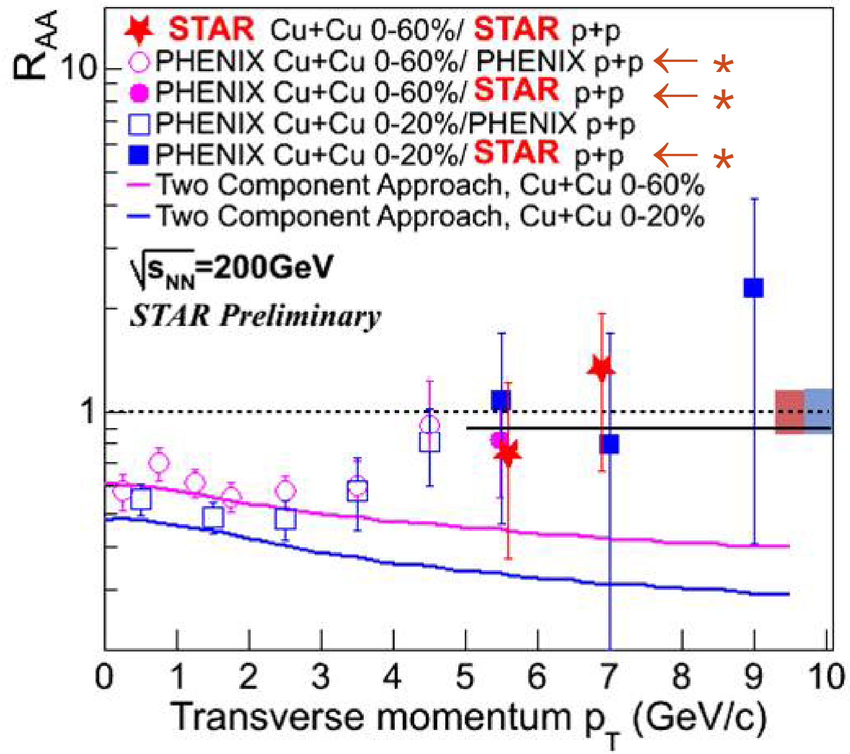
NEW

2 sigma J/ψ signal in Cu+Cu

STAR = PHENIX charm spectra ☺

R_{CuCu} raising with p_T



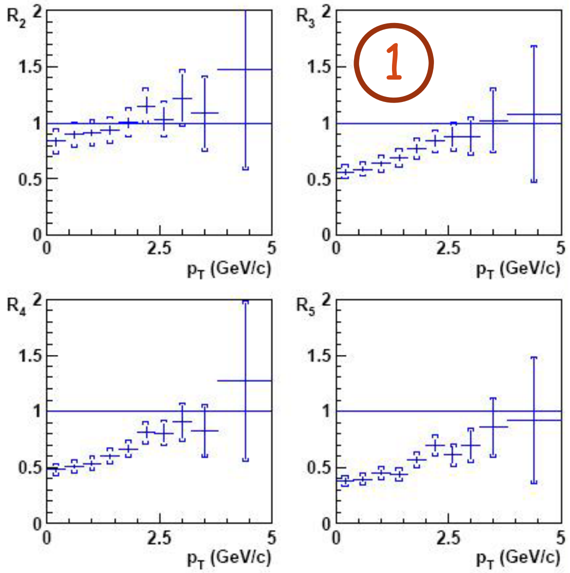


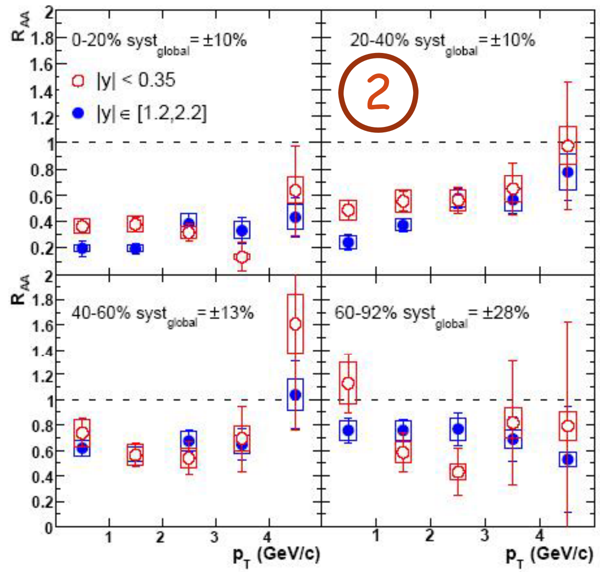
M.R. Cosentino, Poster 109

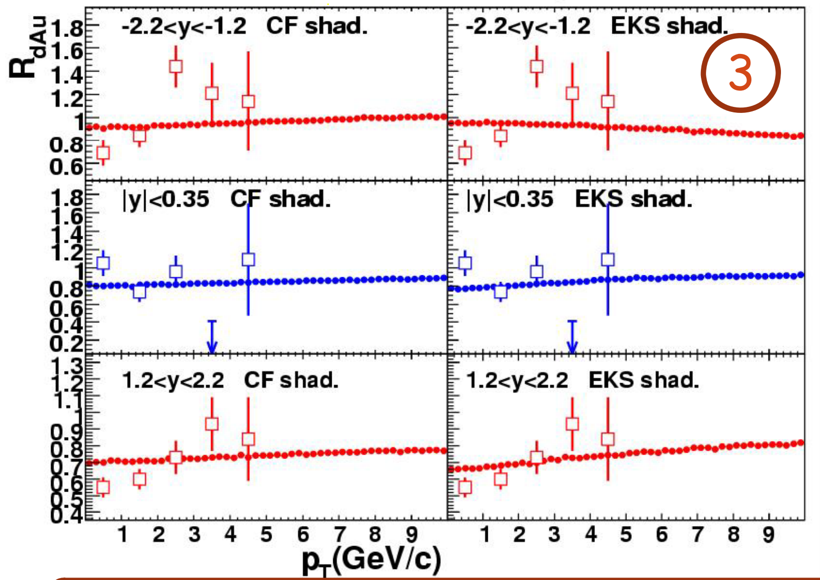
* These are not phenix results yet, but could become as soon as the two experiments talk to each others ☺

Various $R_{XY}(p_T)$

- Several (hints of) $R_{AA}(p_T)$
  1. R_{CP} PbPb (NA50)
  2. R_{AuAu} (PHENIX)
  3. R_{dAu} (PHENIX)
- Several potential reasons:
  - Leakage effect, J/ψ escape
    - High p_T J/ψ forming beyond QGP
  - Cronin effect
  - Raising x_{Bj} = less shadowing
    - 0.02 to 0.05 from 0 to 9 GeV/c
    - See discussion in →
- Think about it…





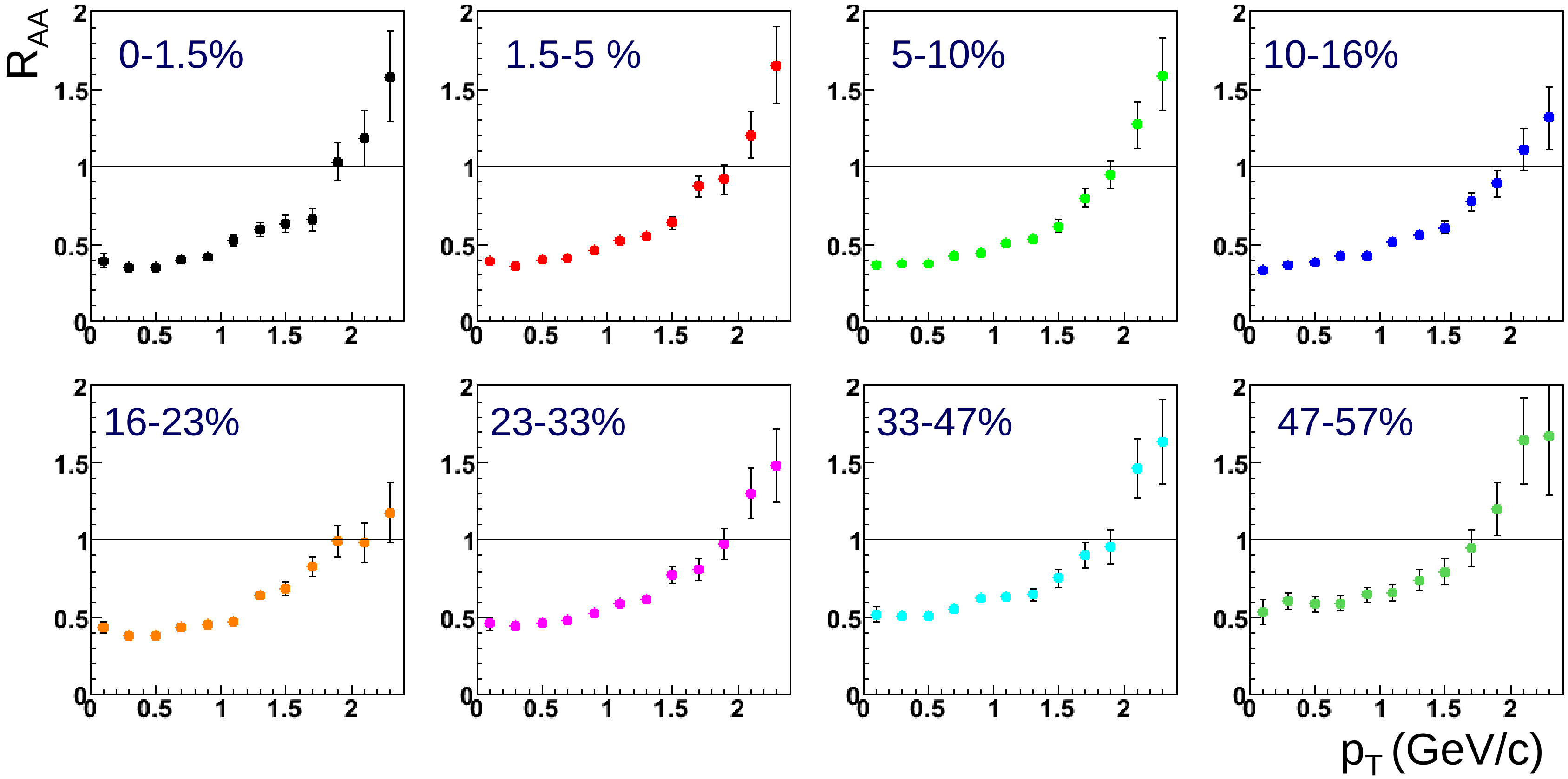


PHENIX, arxiv:0711.3917 compared to Ferreiro, Fleuret, Rakotozafindrabe, arxiv: 0801.4949

Yet another $R_{AA}(p_T)$

R. Arnaldi, Session 18, Saturday

- Indium-Indium data…



@ RHIC, more suppression at forward rapidity !

Two possible theoretical explanations…

Hot : coalescence, regeneration

Cold : saturation, shadowing

A. Andronic, Session 22, Saturday

I. Coalescence, regeneration

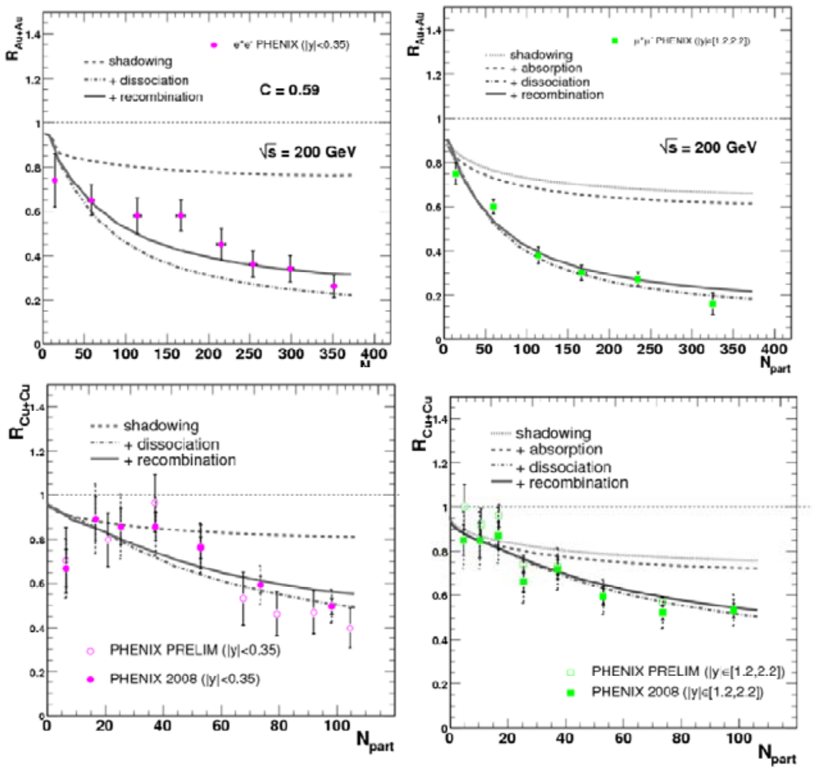
K. Tywoniuk, Session 22, Saturday

- Large variety of approaches, all justify:
  - $R_{AA}(y=0) > R_{AA}(y=1.7)$
  - (more c quarks to recombine at y=0)

Latest references

R. Thews et al, Eur. Phys. J C43, 97 (2005)
Yan, Zhuang, Xu, PRL97, 232301 (2006)
A. Andronic et al., NPA789, 334 (2007)
Ravagli, Rapp, arXiv:0705:0021
Zhao, Rapp, arXiv:0712.2450
A. Capella et al., arXiv:0712.4331 →
O. Linnyk et al., arXiv:0801.4282
(Apologies if I forgot somebody)

- As an example



Capella, Tywoniuk et al.
Fitting Cu+Cu, Au+Au,
Mid and forward rapidity

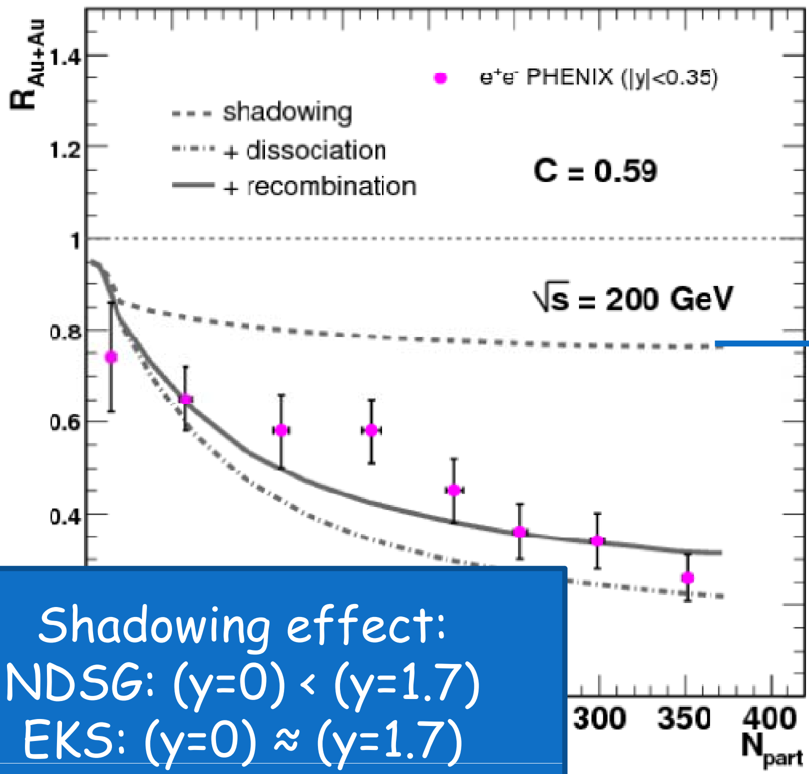
A closer look to this model

Three effects sum up to make $R_{AA}(y\approx0) > R_{AA}(y\approx1.7)$:

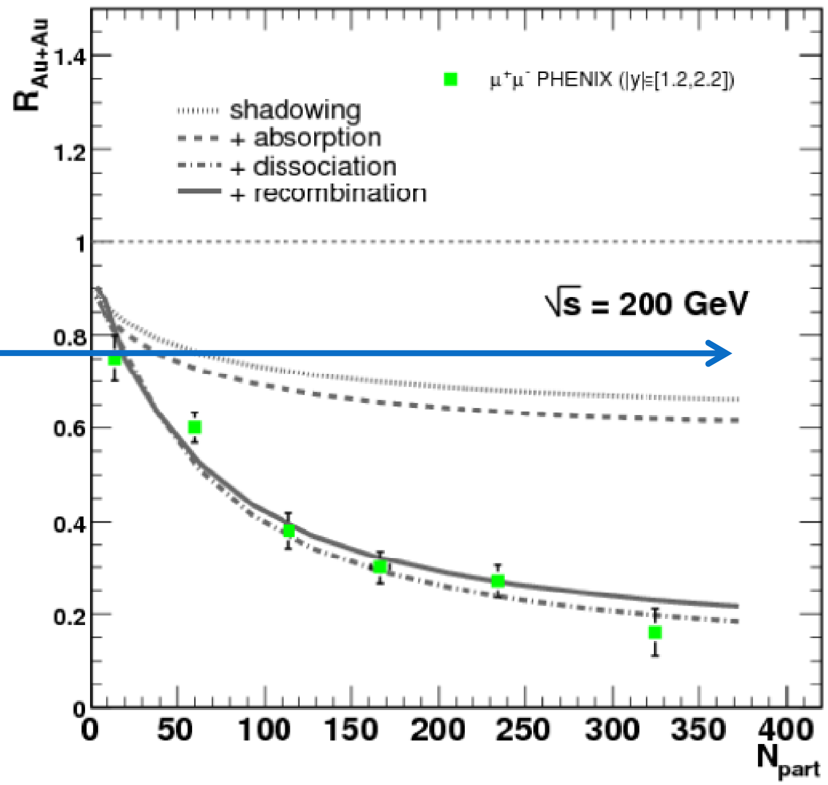
1. Shadowing

2. "E-p conservation" ≈ formation time

3. Regeneration (little role)



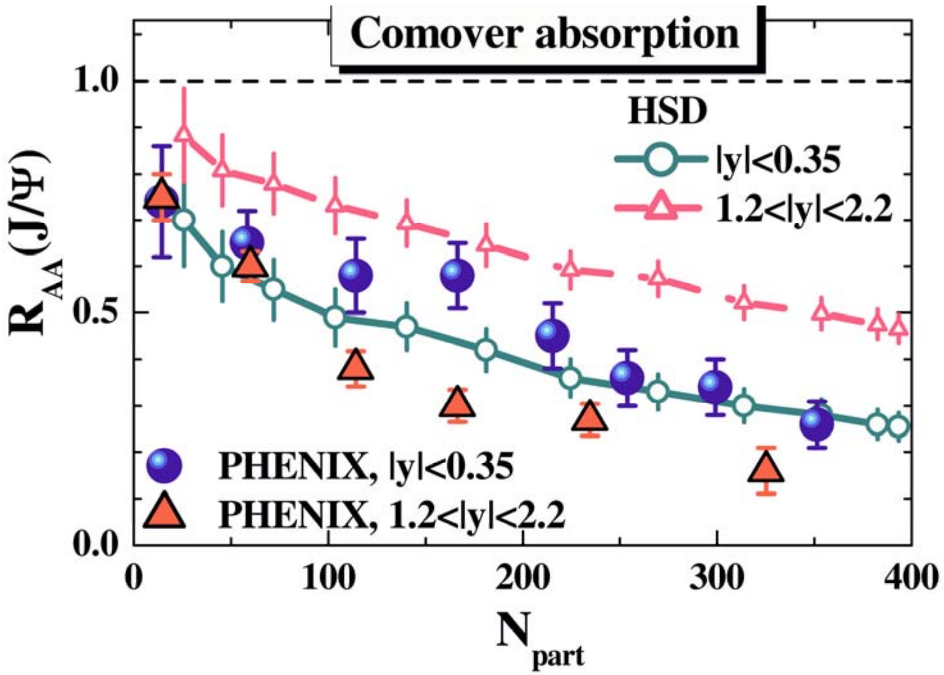
Shadowing effect:
NDSG: (y=0) < (y=1.7)
EKS: (y=0) ≈ (y=1.7)
Schwimmer: (y=0) > (y=1.7)



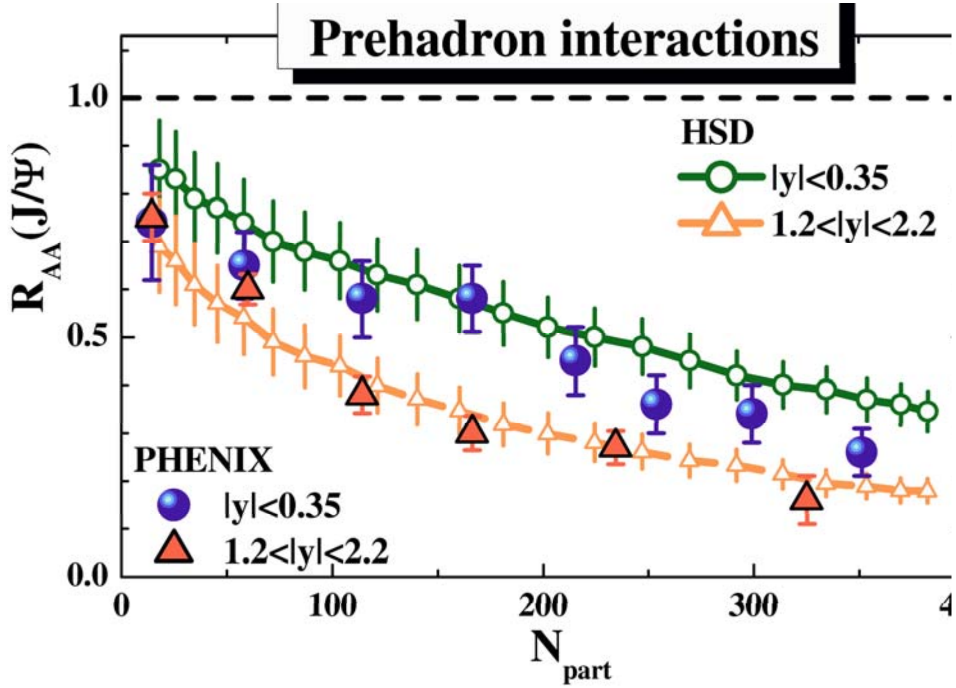
Capella et al, arXiv:0712.4331

A look to another one?

Without regeneration



With regeneration



O. Linnyk et al., arXiv:0801.4282

M. Nardi, Session 6, Tuesday

II. A trick of cold matter ?

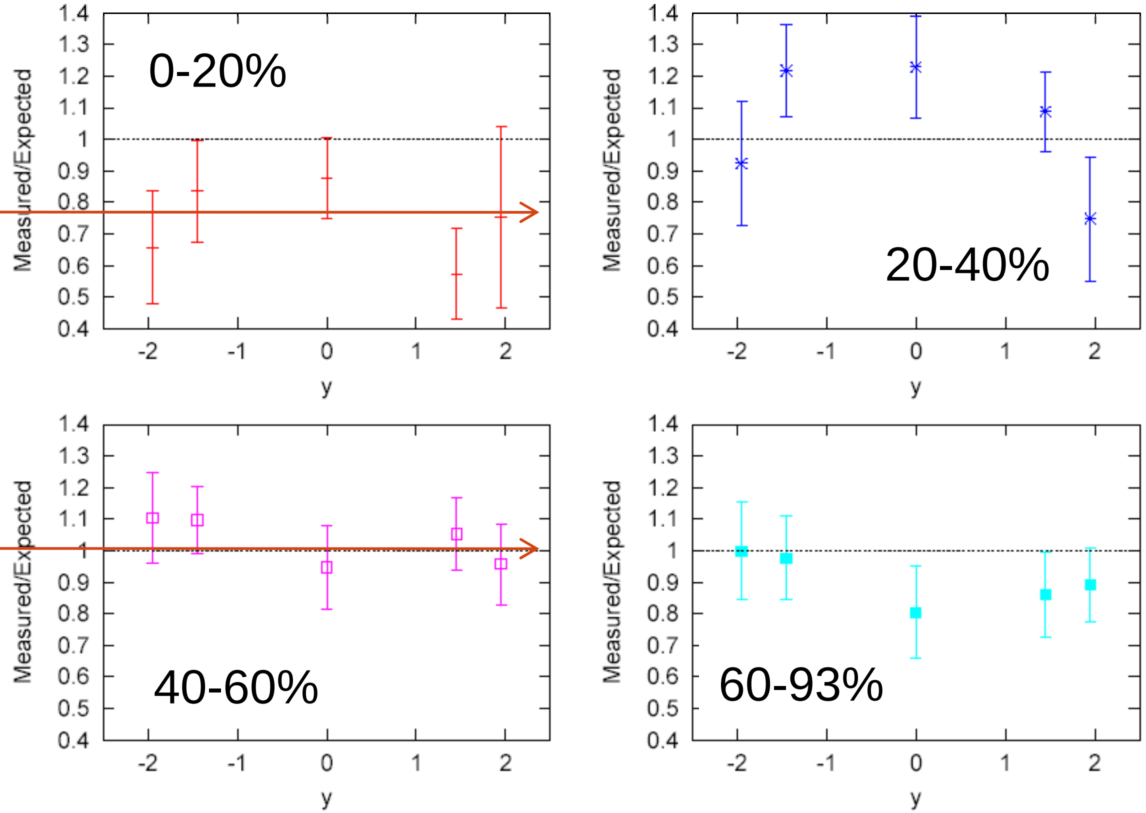
NEW

- Saturation could suppress forward J/ψ in AuAu
- First numerical estimate, <u>work in progress</u>…

$\frac{\text{Experiment}}{\text{Saturation}}$

"Flat anomalous" suppression here ?

Normalisation here ?



How to move forward experimentally ?

Y. Zhang,
few minutes ago

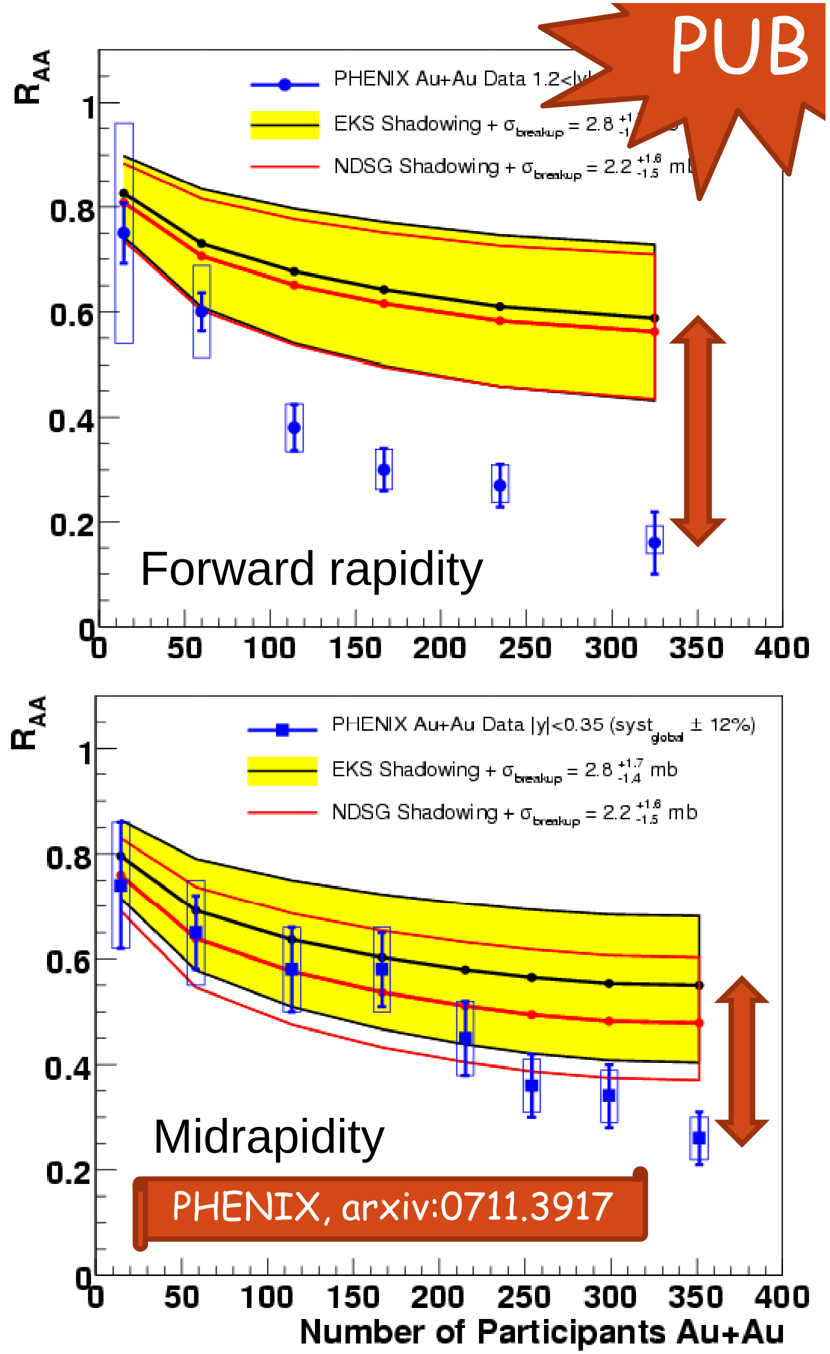
1. Be more open? (Measure cc to constrain regen.)
2. Calm down? (Better pA/dA reference)
3. Broaden interest? (in transverse momentum)
4. Let it flow? (elliptically)
5. Get excited? (ψ', χ_c)
6. Get high? (in mass, looking at upsilons)
7. Be upset? (and search for onset)
8. Give up? And move to the LHC?

Some progress on all these points at this meeting !

M. Wysocki, Session 6, Tuesday

2. Cold matter

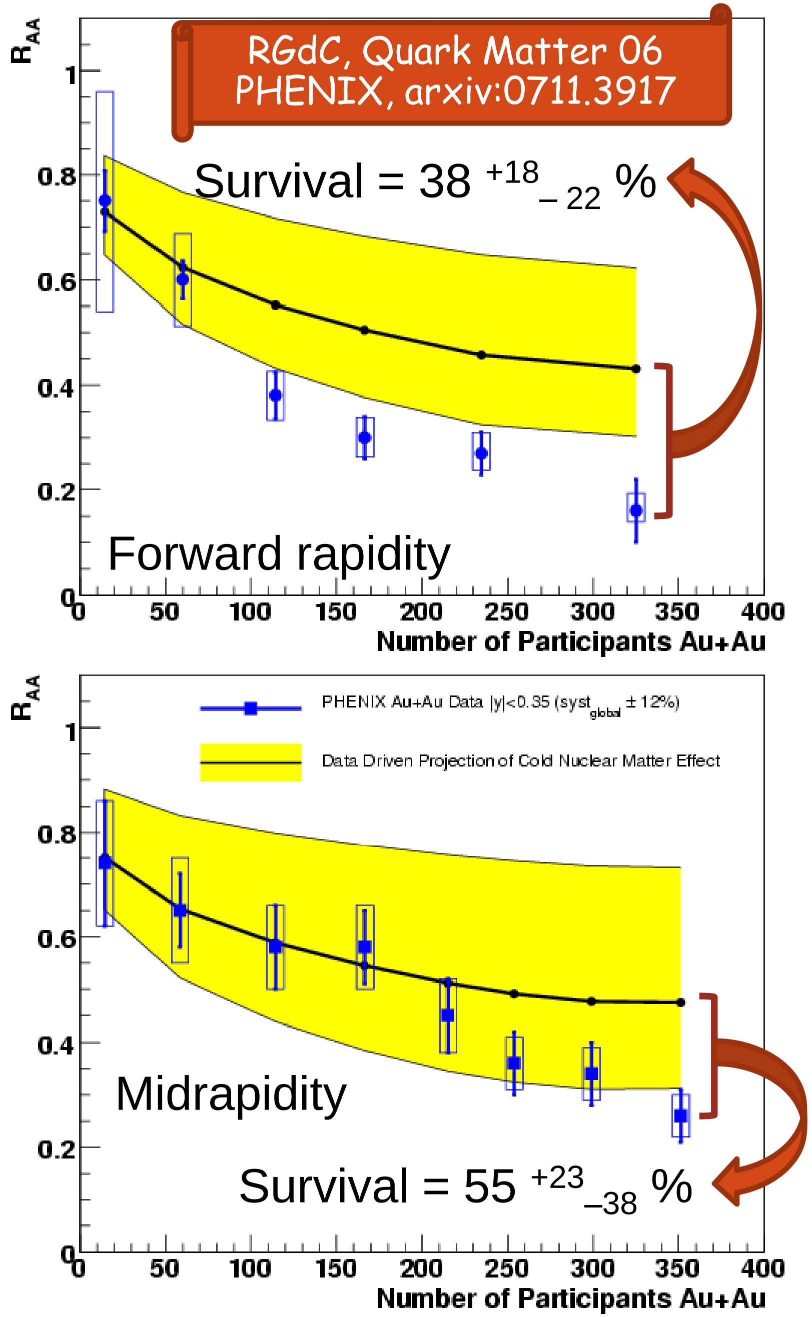
- New analysis of PHENIX dAu
  - (and same pp reference as AA)
- Assuming two shadowing schemes, derive a breakup cross sections from $R_{dA}(y)$
  - $\sigma_{EKS} \approx 2.8\ ^{+1.7}_{-1.4}$ mb
  - $\sigma_{NDSG} \approx 2.2\ ^{+1.6}_{-1.5}$ mb
  - Proper error on σ is ≈ 2 mb
- And extrapolate to AuAu collisions →
  - (Also available for CuCu)
  - Mid and forward are correlated through shadowing scheme
  - If you believe this shadowing, large anomalous suppression, larger at forward rapidity.



M. Wysocki, Session 6, Tuesday

2. Cold matter

- More model independent…
- In a Glauber data-driven model, propagate what we know from R_{dA}(y,centrality)
  - $R_{AA}(y,b) = \Sigma_i \; R_{dA}(-y,b^i_1) \times R_{dA}(+y,b^i_2)$
  - No shadowing scheme nor absorption scheme
  - Mid and forward are not correlated, less model dependent → larger uncertainties (esp. y≈0)
- Anomalous suppression at least at forward rapidity!
- Anomalous suppression could be identical at midrapidity
- (No dCu, so no CuCu)



S. Oda,
Session 18,
Saturday

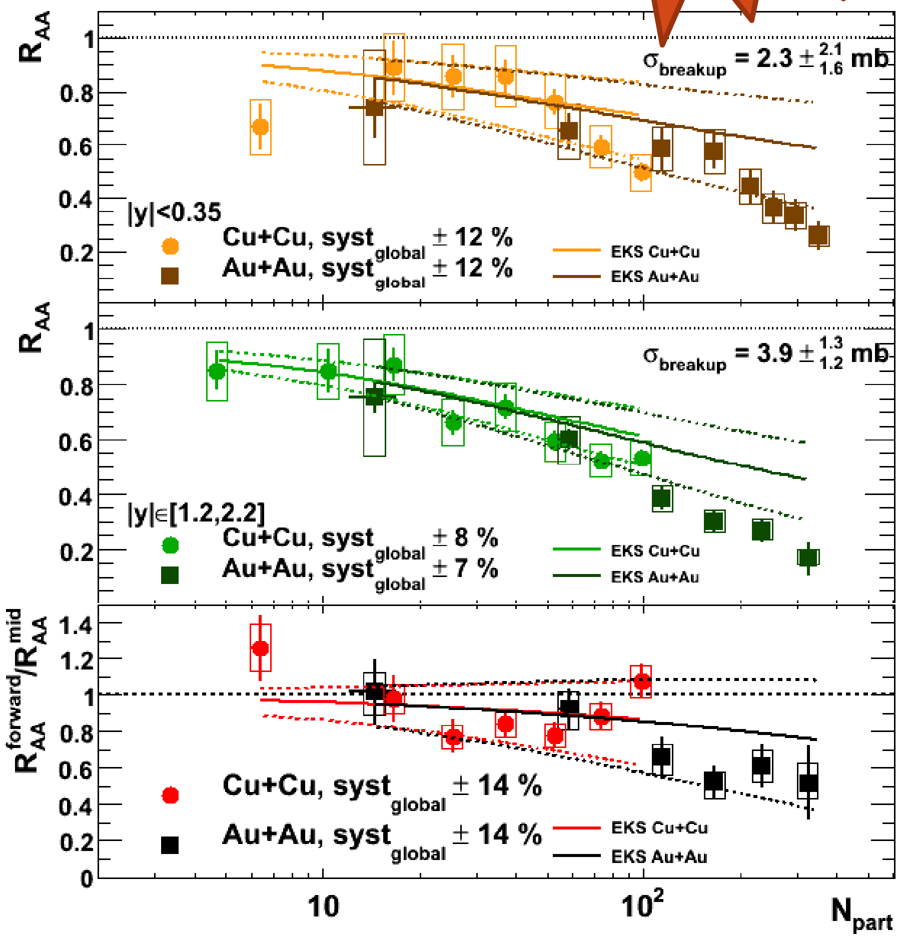
2. Cold matter again ?

PUB

- Fitting an effective break-up cross section (depending on y) and extrapolate to CuCu and AuAu…

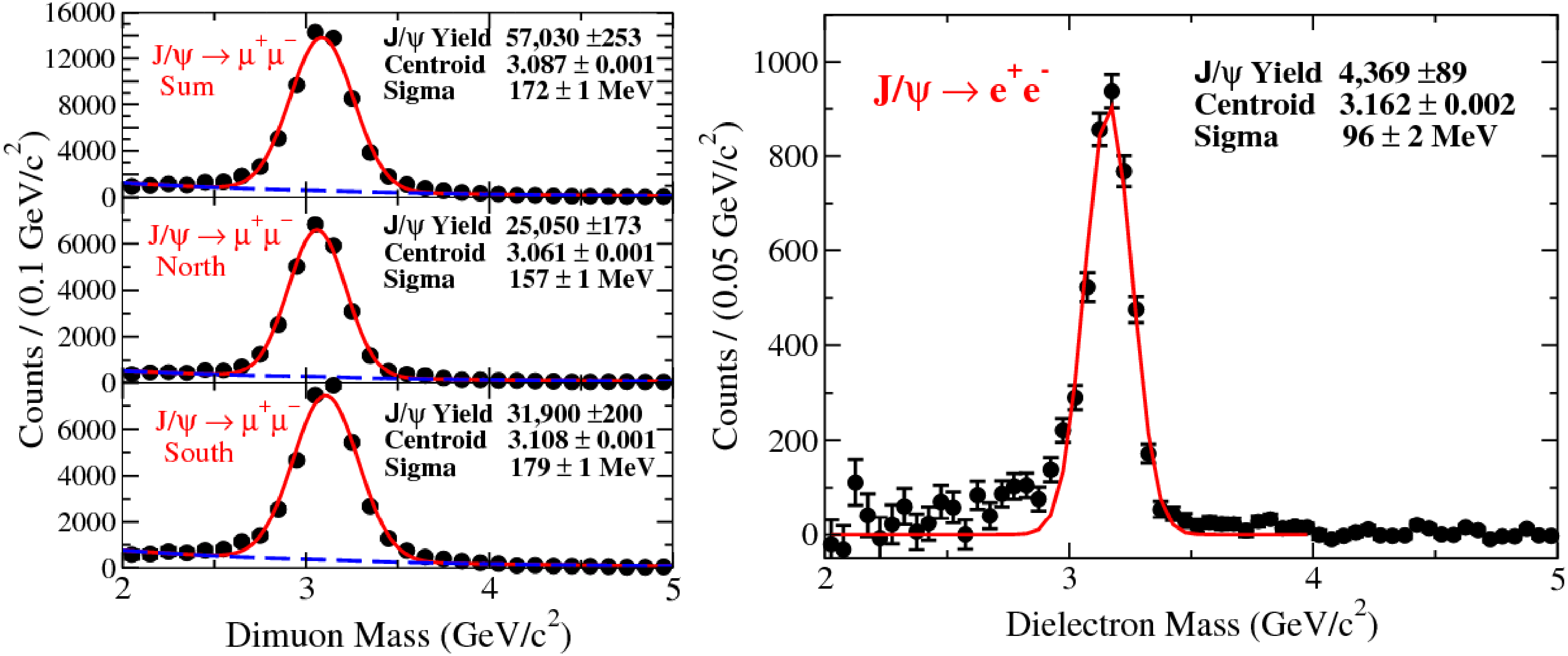
STOP

- Do you agree that we have poor handle on the cold nuclear matter effect?



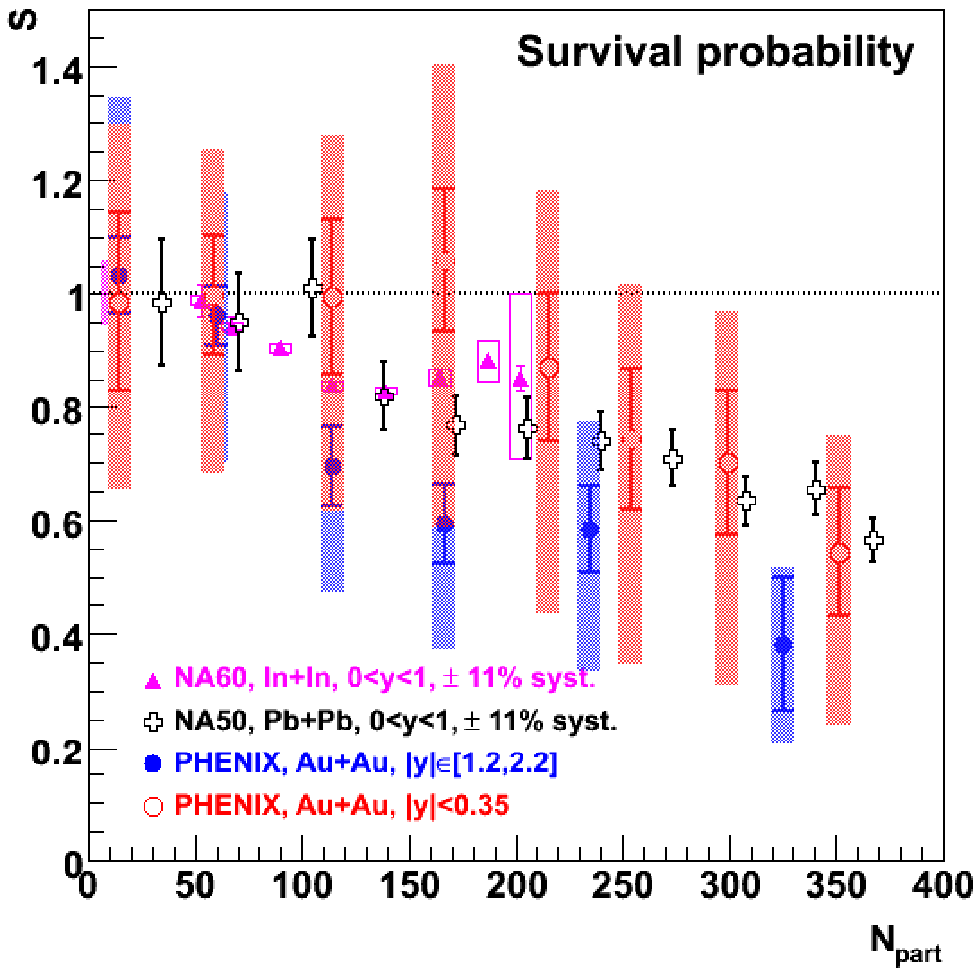
PHENIX, arxiv:0801.0220

RHIC run 8 dAu ≈ 30 x run 3 !



- Let's wait for this run analysis before to say more about cold matter (and derive decent survival probabilities)

Indecent conclusion…



PHENIX, PRL98 (2007) 232301
divided by
PHENIX, arxiv:0711.3917
(data driven method)

- RAA / CNM from data driven method
- Anomalous suppression could :
  - be the same at forward and midrapidity ☺
  - And different between SPS and RHIC ☺

Look at other observables

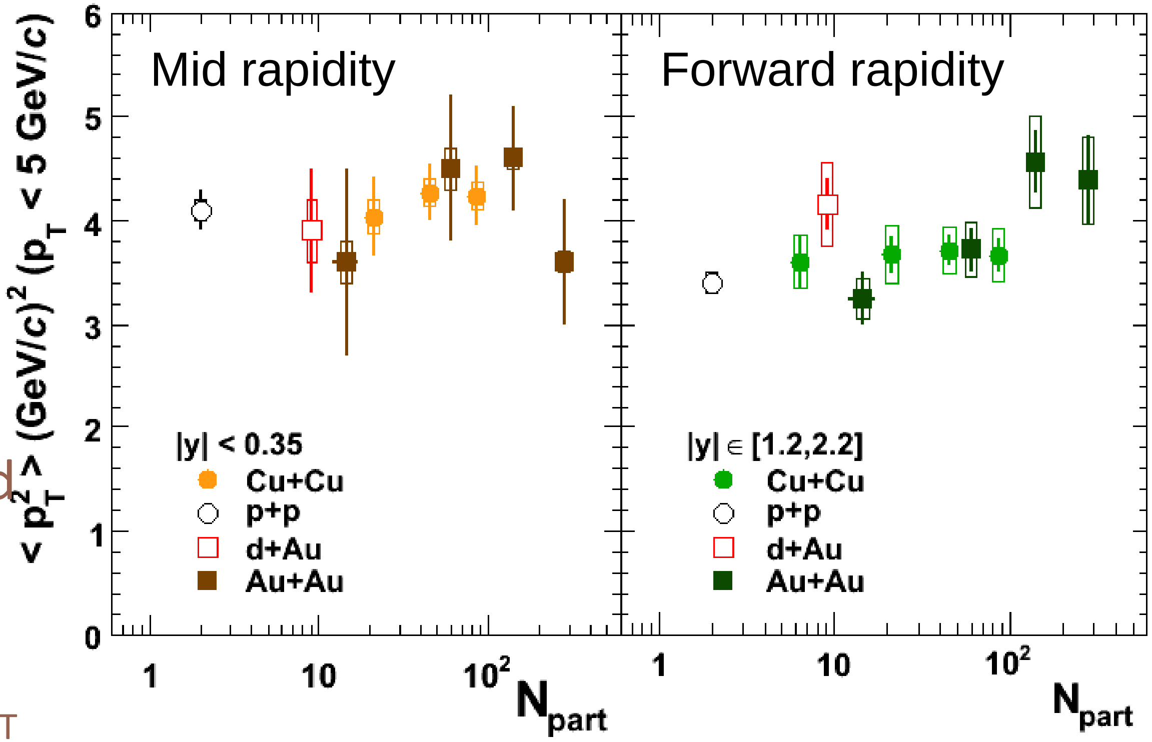
3. p_T broadening
4. Elliptic flow

3. p_T broadening @ RHIC ? vs N_{part} ?

PHENIX, arxiv:0801.0220

- Widely unknown initial charm production:
  - Recombined R_{AA} are poorly constrained…
- Instead look at p_T:
  - Hot: Inherited p_T should be lower than initial
  - Cold: Cronin effect should broaden initial p_T
- Cronin goes like:

$$\langle p_T^2\rangle_{AB} = \langle p_T^2\rangle_{pp} + \alpha \times L$$



- No strong $\langle p_T^2\rangle$ dependence…
- Modest rise at forward rapidity
- Could be broadening
- No need for recombination here

3. p_T broadening @ RHIC ? vs thickness ?

- Widely unknown initial charm production:
  - Recombined R_{AA} are poorly constrained…
- Instead look at p_T:
  - Hot: Inherited p_T should be lower than initial
  - Cold: Cronin effect should broaden initial p_T
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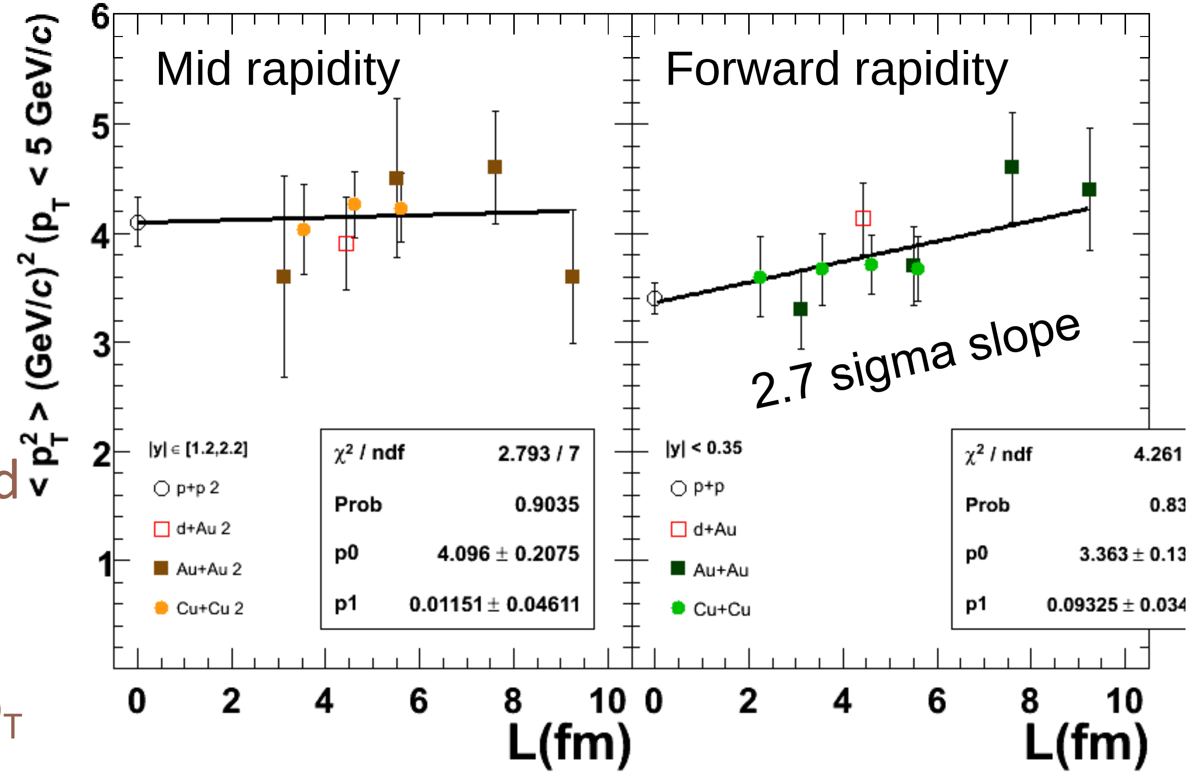
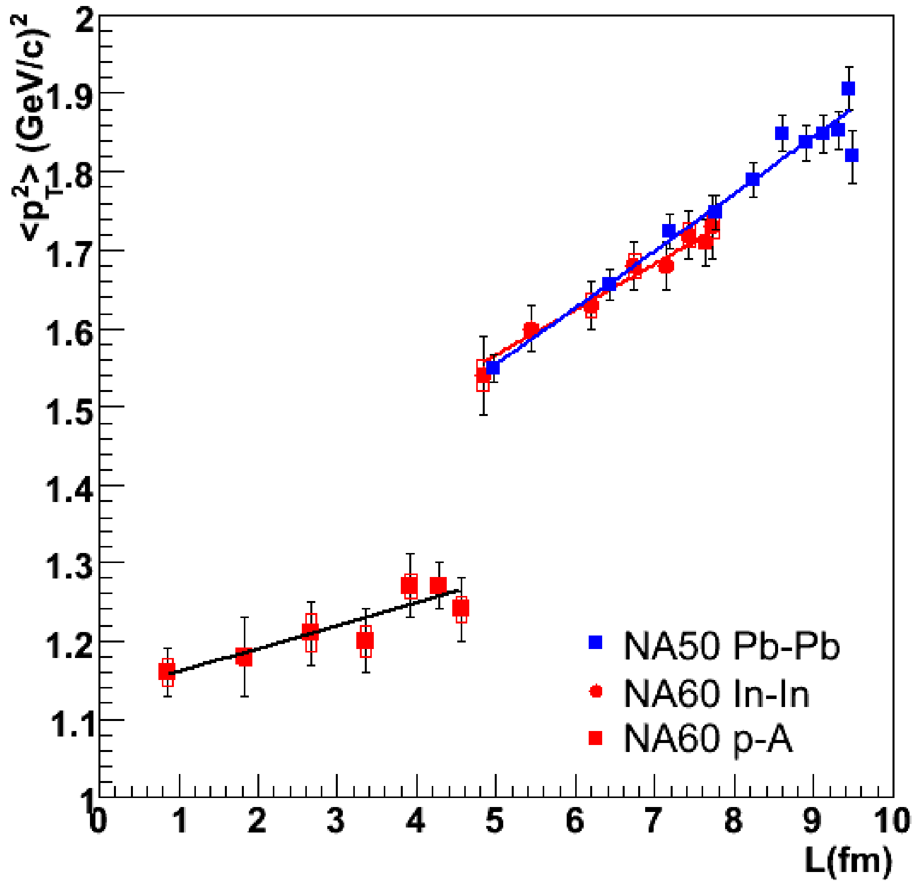


- No strong $\langle p_T^2 \rangle$ dependence…
- Modest rise at forward rapidity
- Could be broadening
- No need for recombination here

3. p_T broadening @ SPS ?

- Different scaling in pA and AA collisions
- Something else going on in AA?
  - High p_T J/ψ escape?

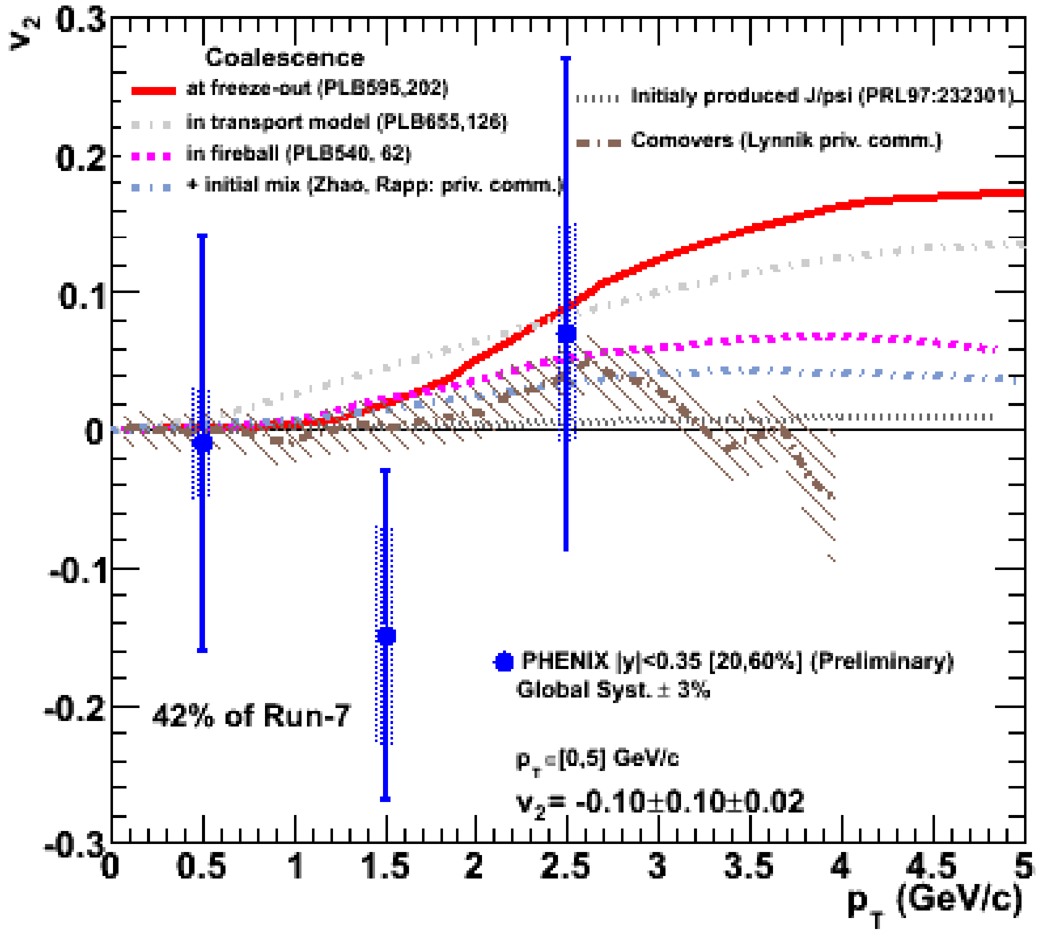


C.L. Silva, Poster 85

4. J/ψ flow in PHENIX?

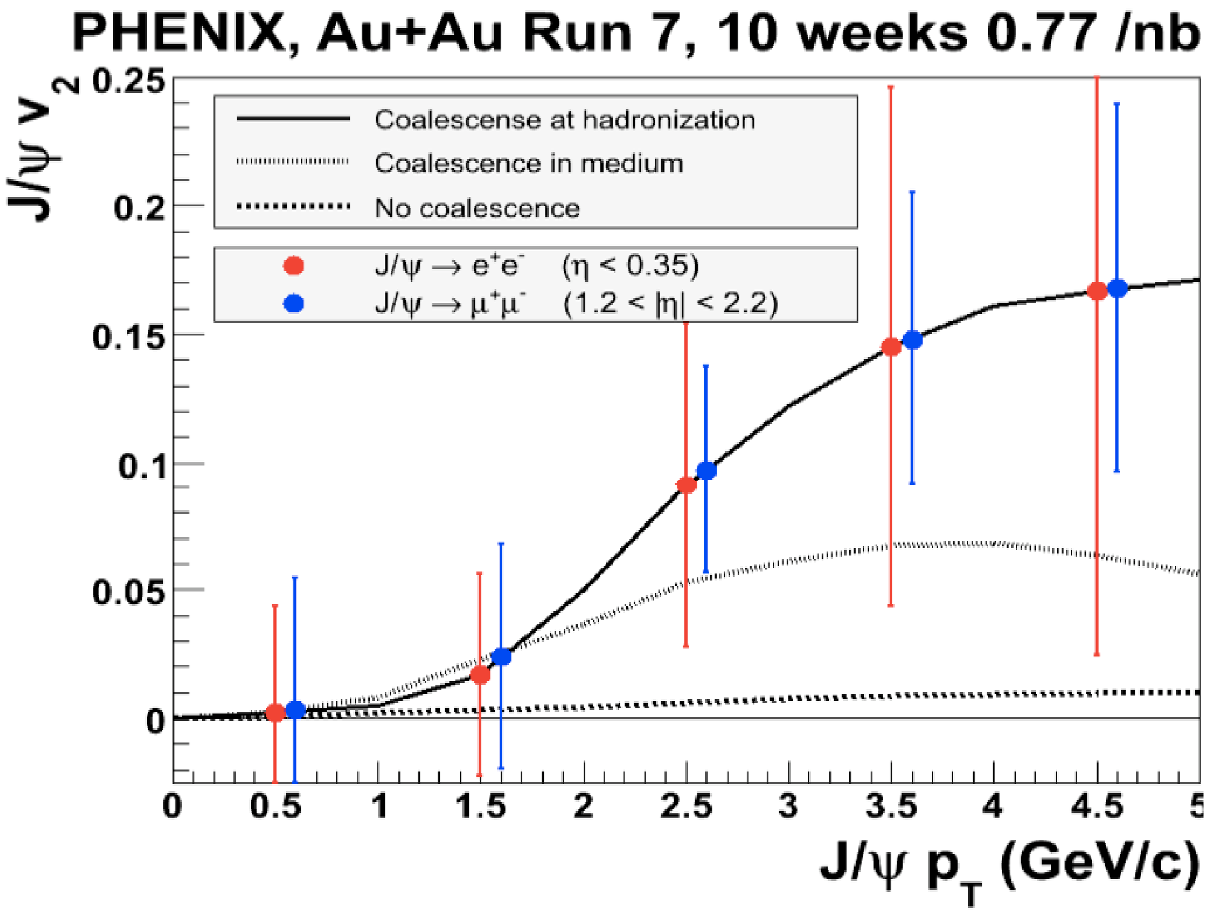
C. Silvestre, Session 18, Saturday

- If recombined, J/ψ should inherit the (rather large) charm quark elliptic flow
- First measurement by PHENIX:
  - $v_2 = -10 \pm 10 \pm 2 \pm 3$ %
- Proof of principle
- Does not allow to elect best scenario



What we were hoping for…

- Midrapidity:
  - Still missing half the statistics
  - HBD…
  - Preliminary calibrators?
  - Something else?
- Forward rapidity:
  - Under study…

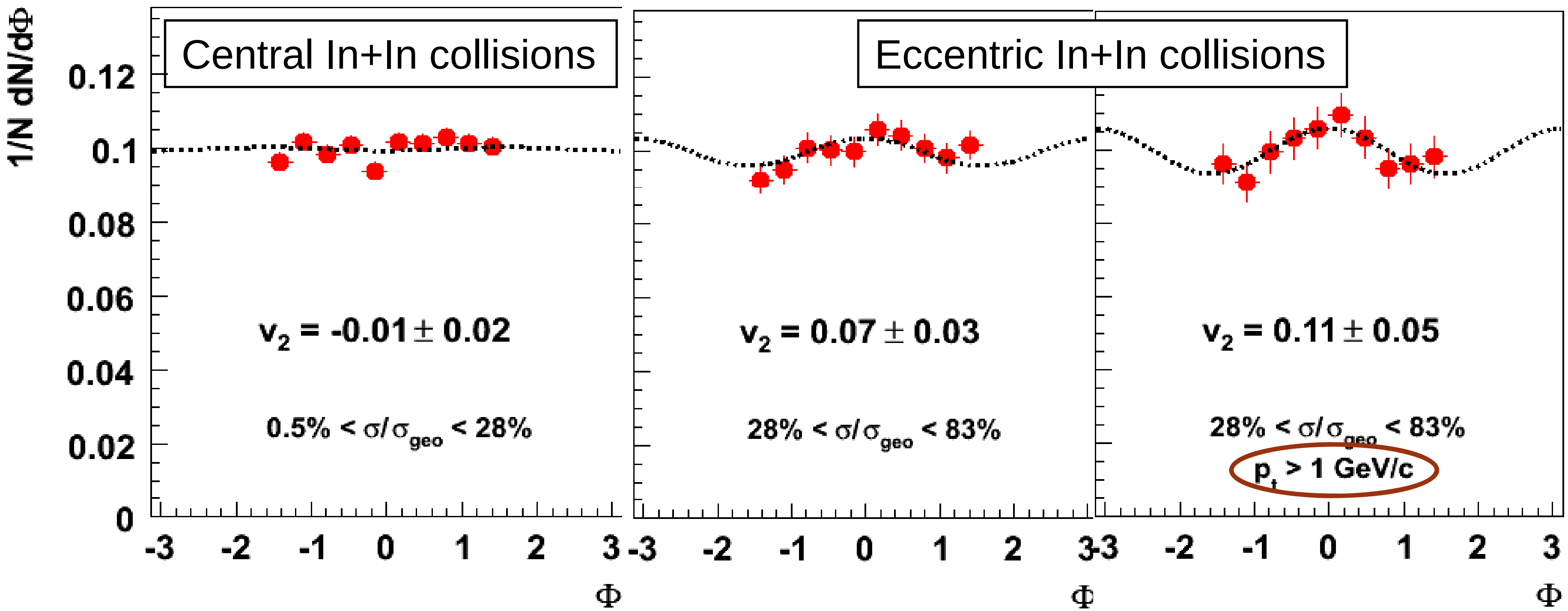


- Anyway, we'll need a new sample!

R. Arnaldi, Session 18, Saturday

4. Elliptic flow in NA60 ?

NEW



- Seems large for In+In (no recombination)
- To be understood…

Somewhat killing the regeneration easy interpretation for RHIC…

Look at other particles

5. Feed down to J/ψ
6. Upsilons

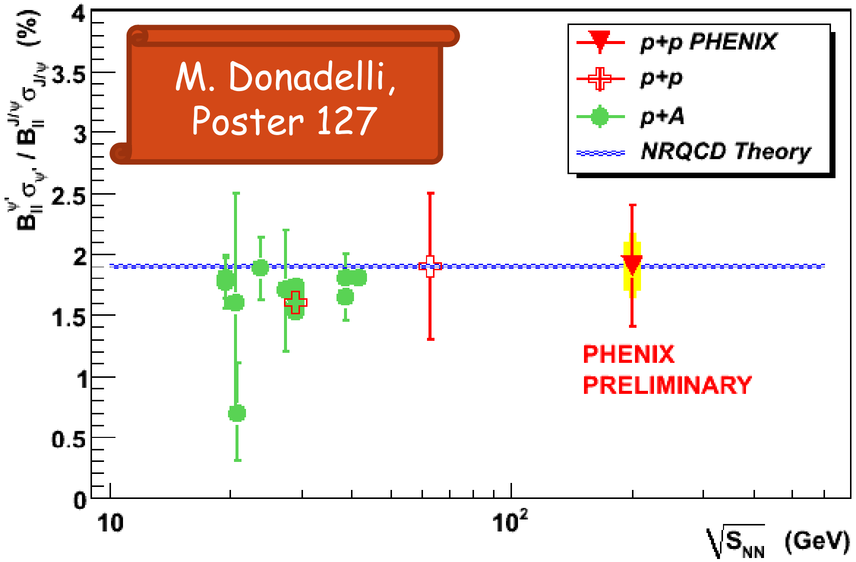
5. Feed down to J/ψ (from pp collisions)

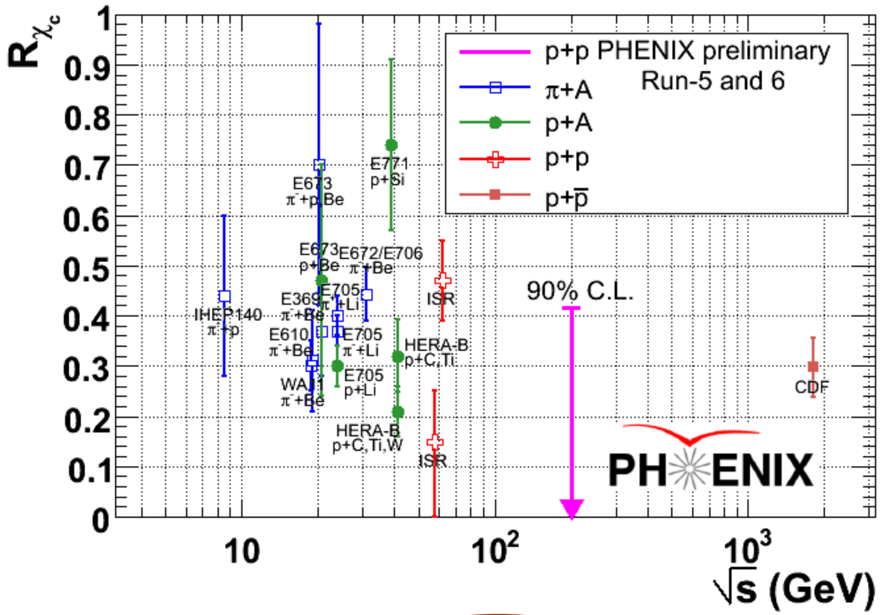
NEW

S. Oda, Session 18, Saturday

ψ from ψ' = 8.6 ± 2.5%

ψ from χ_c < 42% (90% CL)





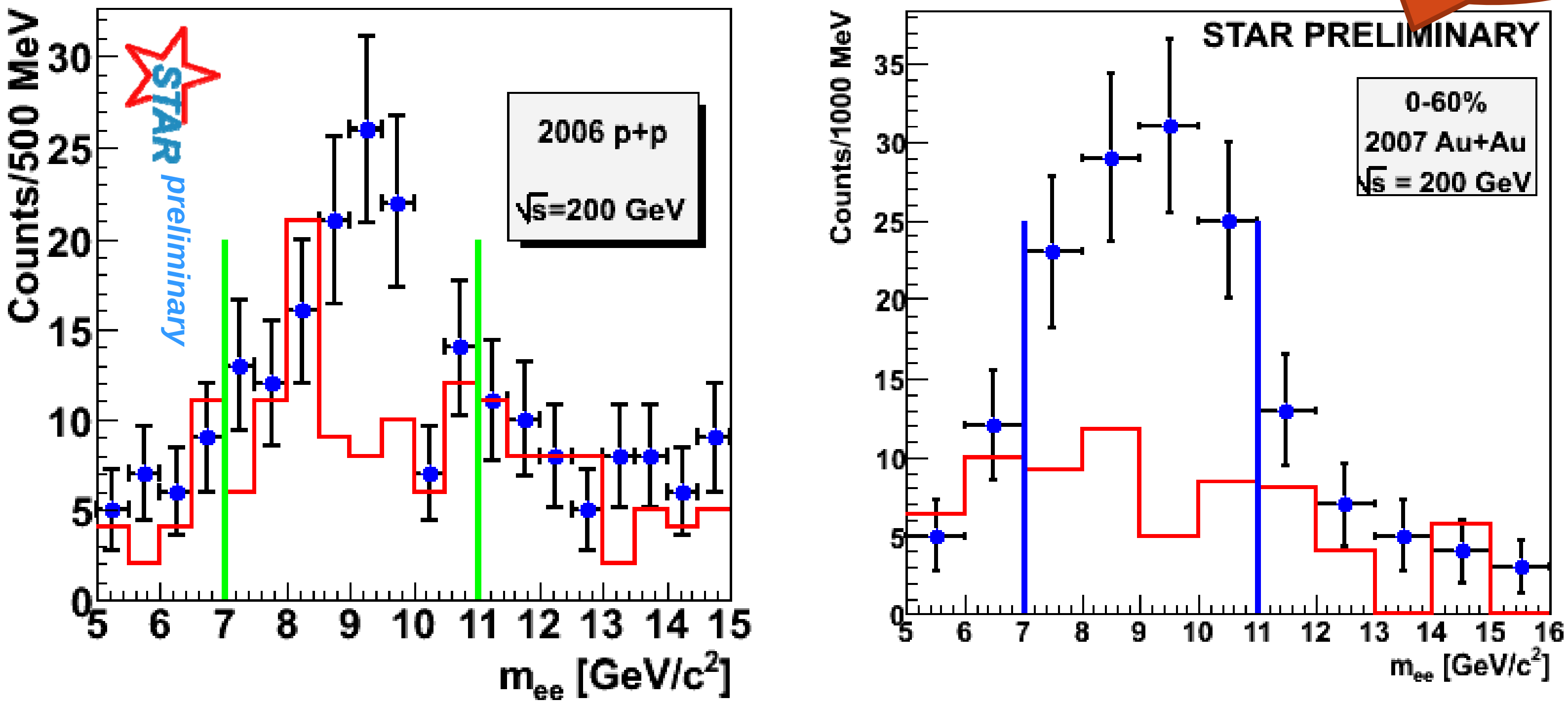
Y. Morino, Session 14, Friday

Also measure of beauty cross section

ψ from B = 4^{+3}_{-2} %

6. STAR upsilon's

D.Das,
Session 22,
Saturday



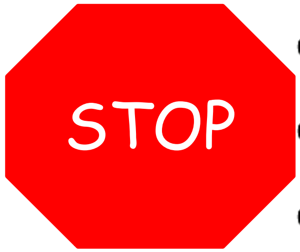
- Proof of principle: dozens of Y in p+p & A+A!
- Nuclear modification factor to come soon
- Suffers less from cold matter (x=0.02 to 0.1=EKS antishadow)
  - (should be checked with run8 d+Au)
- Should measure (unseparated) excited states melting

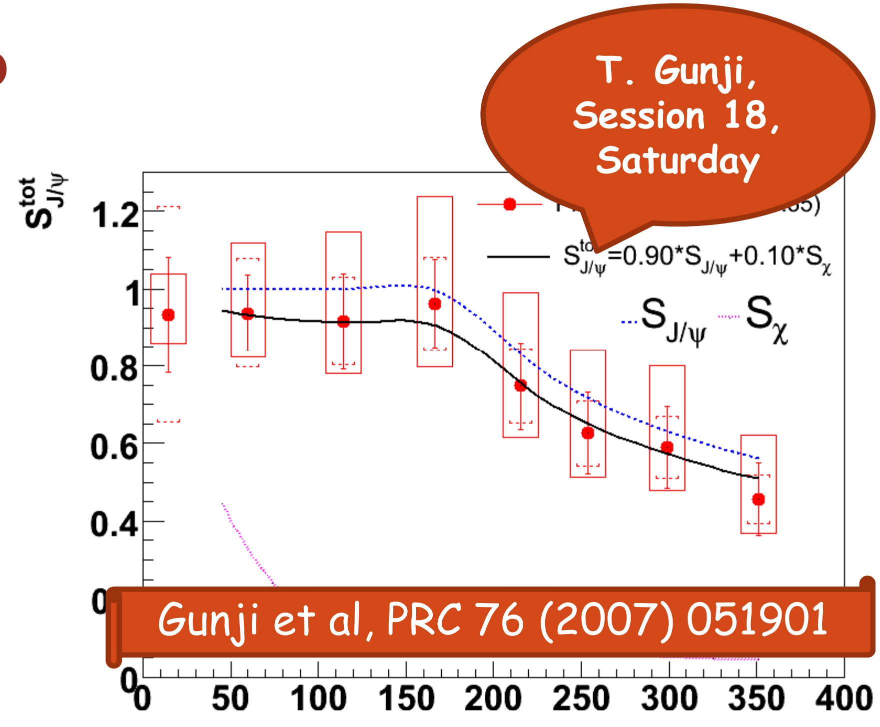
What else ?

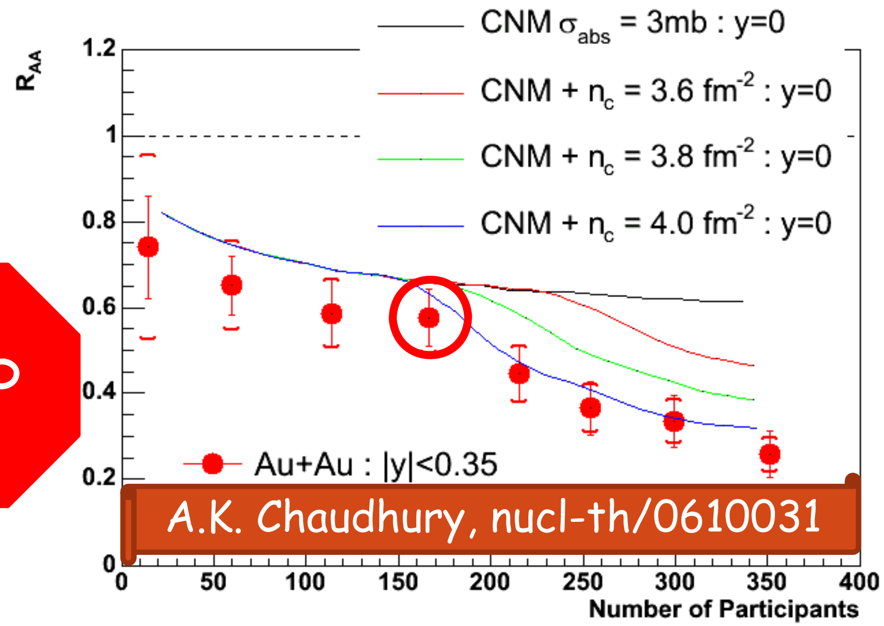
7. Look for onsets
8. Go to LHC

7. Search for an onset?

- Onset curves fit the midrapidity AuAu data…
  - Chaudhury, nucl-th/0610031
  - Gunji et al, hep-ph/0703061
    - (after CNM subtraction)
- But so do smooth curves !
  - Nagle nucl-ex/0705.1712
- Density threshold @ y=0 is incompatible with SPS onset
  - Linnyk & al, nucl-th/0705.4443
- No onset @ y=1.7 ?
- Wait for run7 analysis & CNM constraints!





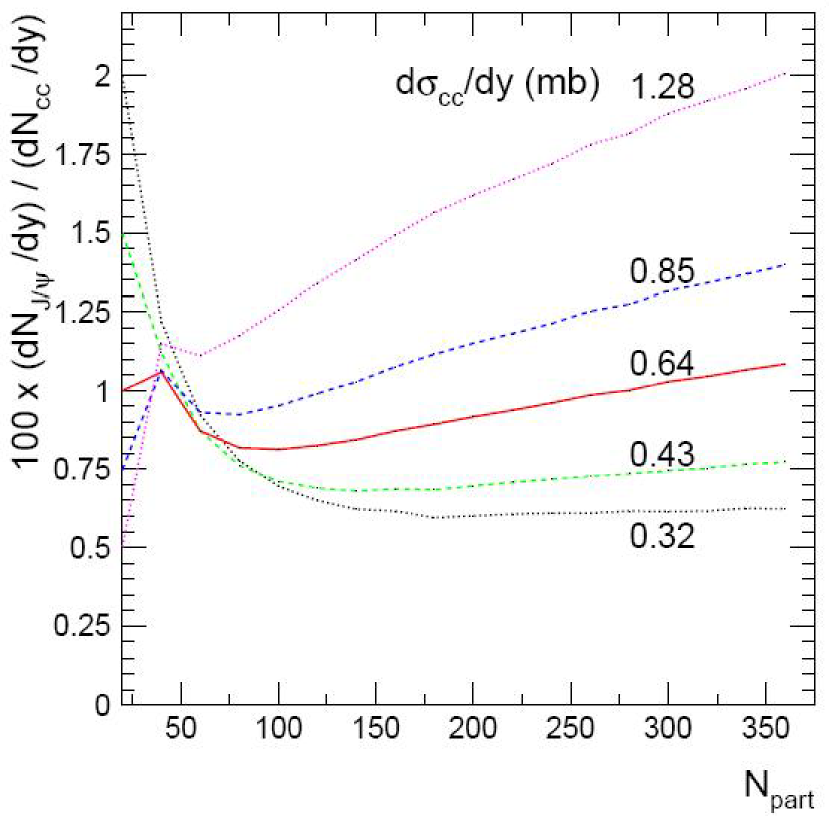


8. LHC ?

A. Andronic, Session 22, Saturday

- A new story will begin
  - ↓ More J/ψ melting
  - ↓ Larger shadowing / saturation effects
  - ↑ Larger recombination (more pairs)
- If recombination prevails → golden signal
- If not, expect same or worse difficulties as at RHIC…
- (Also Upsilon's story)

- Example of prediction



Anomalous conclusions

- J/ψ production is not (well and yet) understood at RHIC
- Forward/mid rapidity difference could be due to:

1. Regeneration ?
2. Saturation ?
3. Something else ?

M. Mishra
P132

- However, conservative cold matter approaches still gives significant anomalous suppression at least at forward rapidity…
  - The hot matter is deconfining some quarkonia
- More to come soon
  - dAu data ! Upsilon, ψ' in AA collisions and much more…

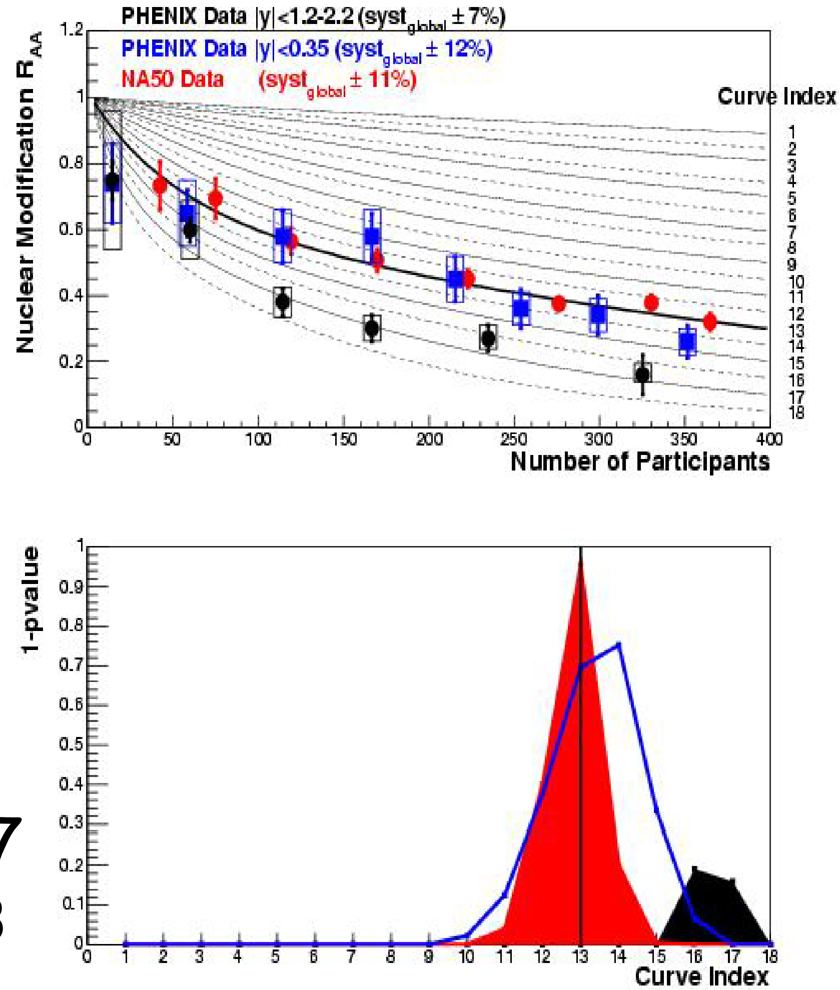
H. Liu
P98

That’s all folks

Back up slides…

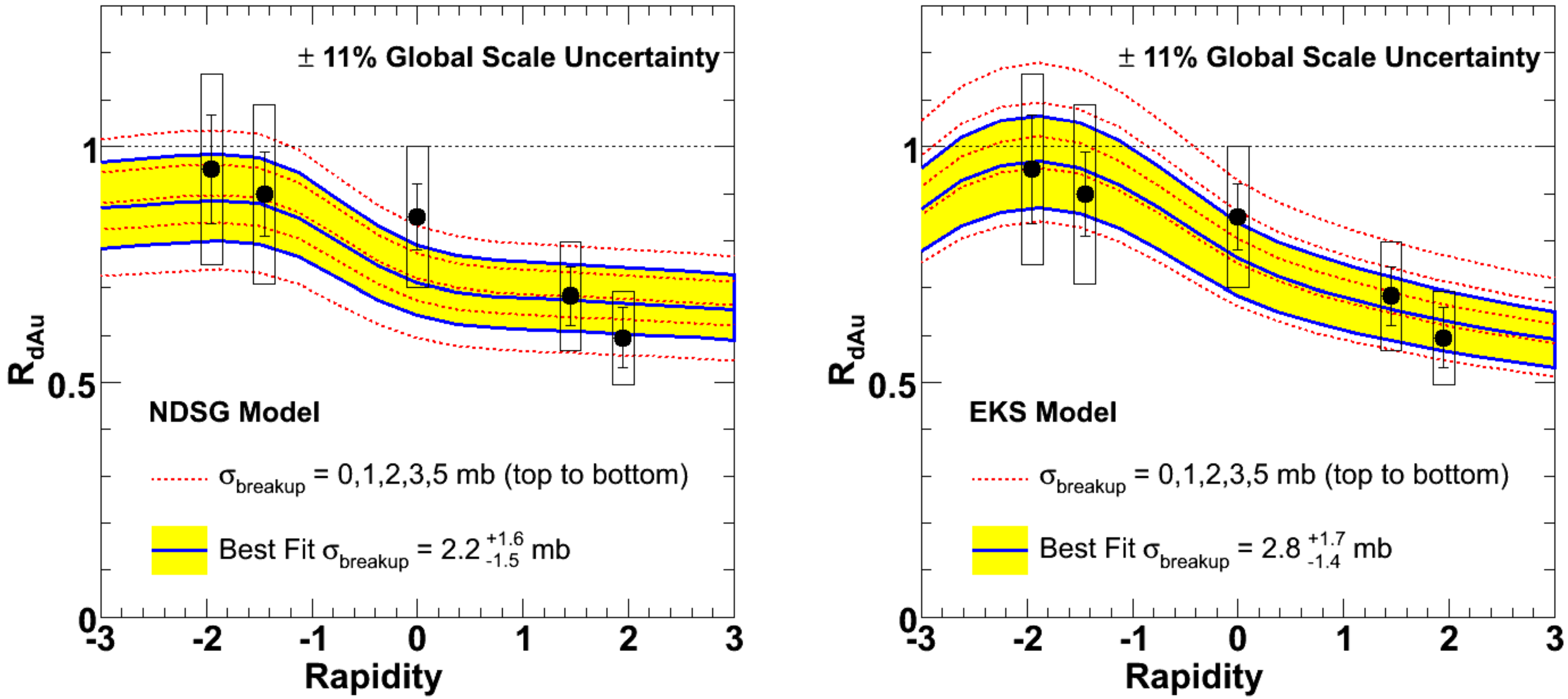
Density threshold ? No !

- 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



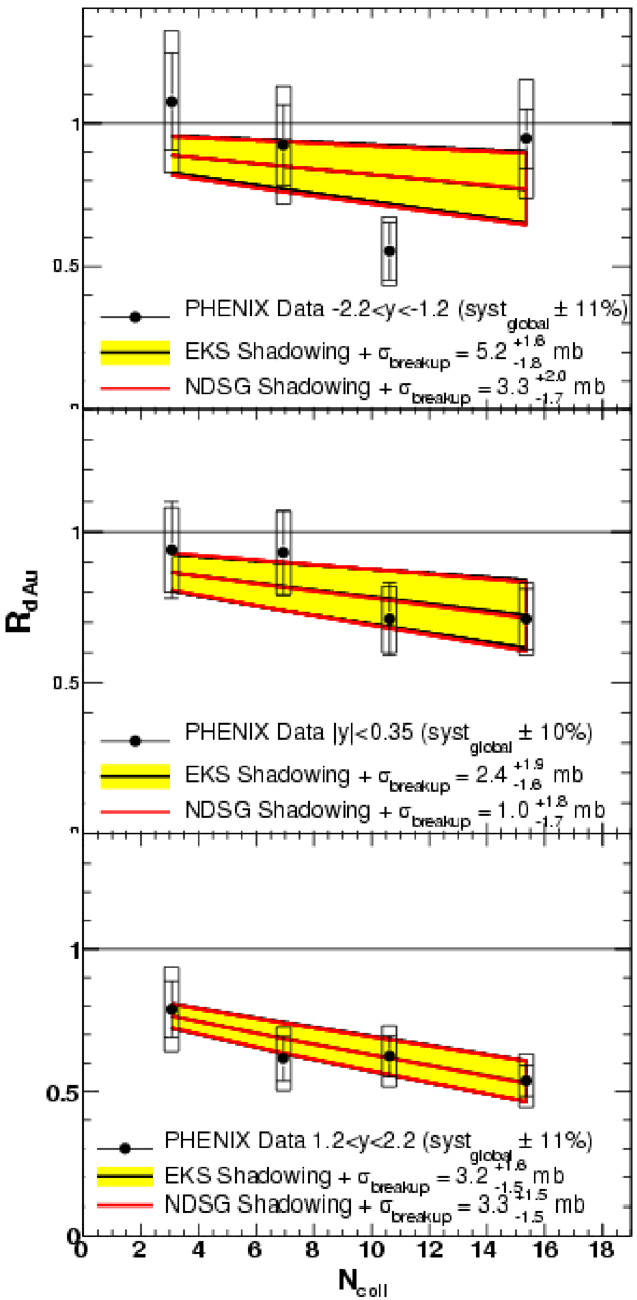
J. Nagle, nucl-ex/0705.1712

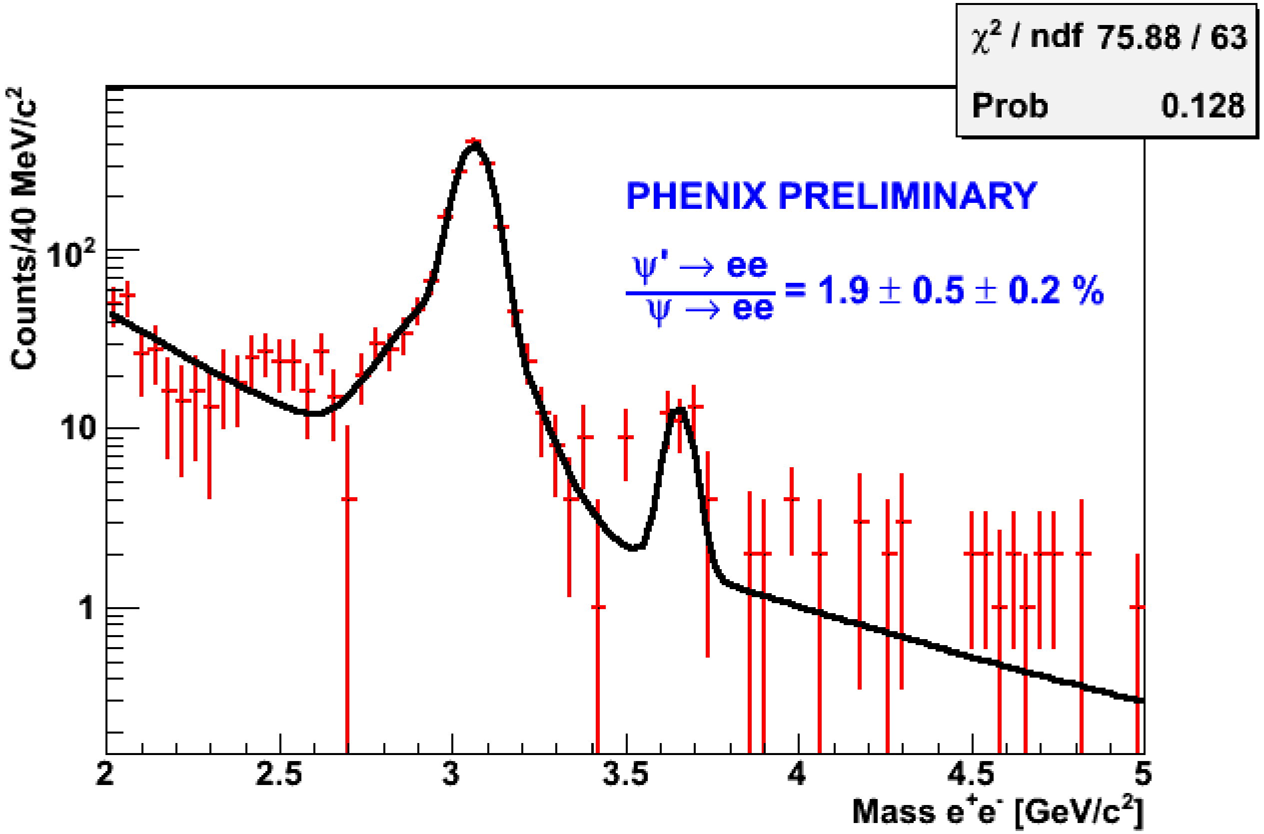
RdAu(y)



± 11% Global Scale Uncertainty
NDSG Model
σbreakup = 0,1,2,3,5 mb (top to bottom)
Best Fit σbreakup = 2.2 +1.6 -1.5 mb
RdAu
Rapidity
± 11% Global Scale Uncertainty
EKS Model
σbreakup = 0,1,2,3,5 mb (top to bottom)
Best Fit σbreakup = 2.8 +1.7 -1.4 mb
RdAu
Rapidity

RdAu(centrality,y)

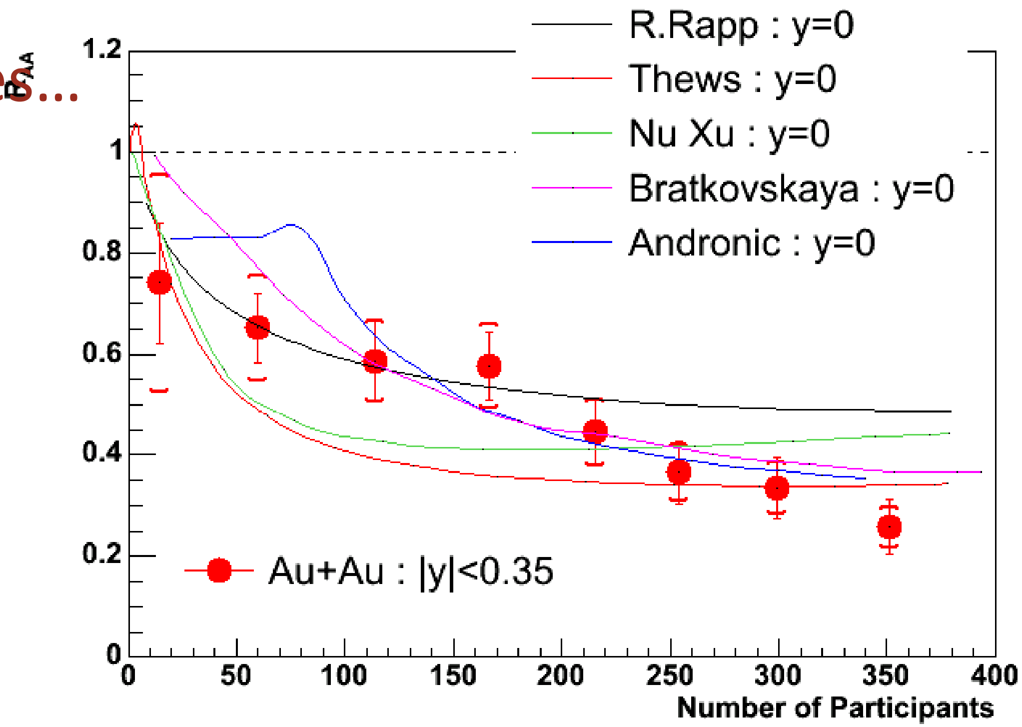




χ^2 / ndf 75.88 / 63
Prob 0.128
PHENIX PRELIMINARY
$\frac{\psi' \to ee}{\psi \to ee} = 1.9 \pm 0.5 \pm 0.2$ %
Counts/40 MeV/c^2
Mass e^+e^- [GeV/c^2]

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)

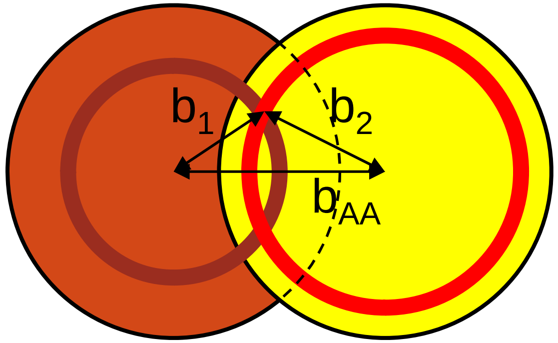
From dA to AA @ RHIC

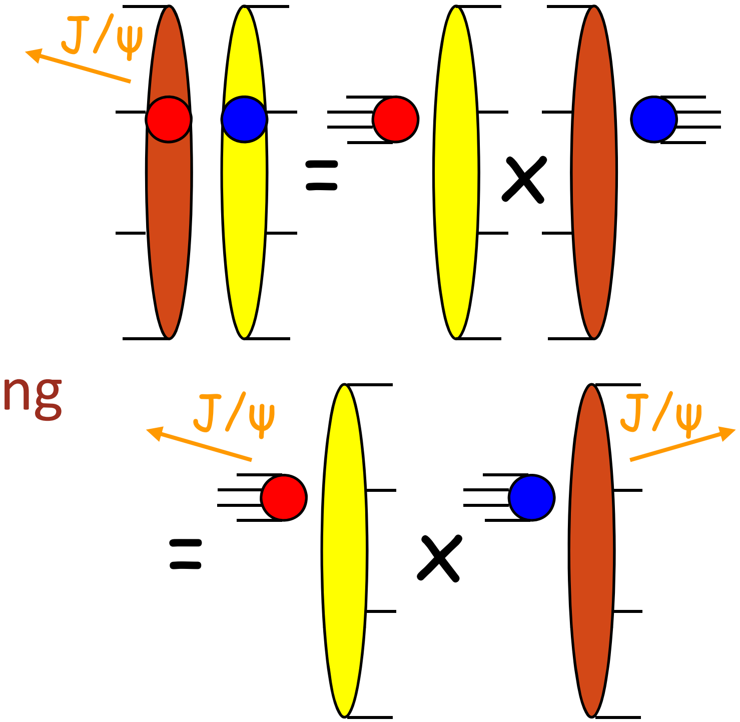
- For a given A+A collision at b_{AA}, Glauber provides a set of N+N collisions occurring at b_i^1 and b_i^2
- One minimal assumption is rapidity factorization: $R_{AA}(|y|,b_{AA}) =$

  $\Sigma_{collisions}\ [R_{dA}(-y,b_i^1) \times R_{dA}(+y,b_i^2)]\ /\ N_{coll}$
- Works (at least) for absorption & shadowing since production

  ~ pdf1 x pdf2 x exp $-\rho\sigma(L_1+L_2)$

RGdC, hep-ph/0701222

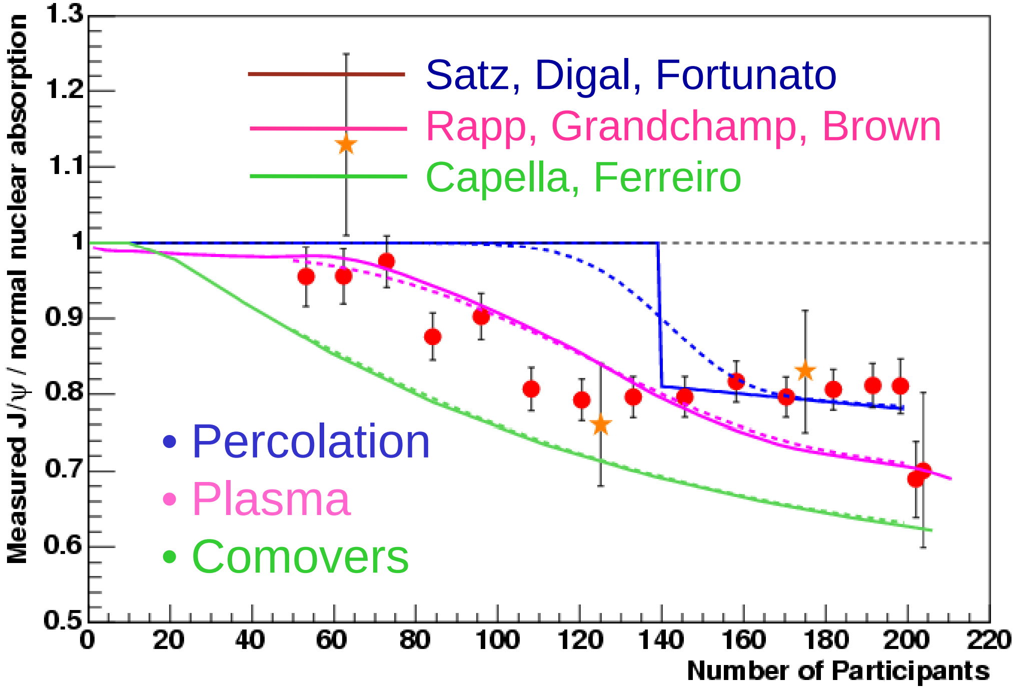




What's going on @SPS ?

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

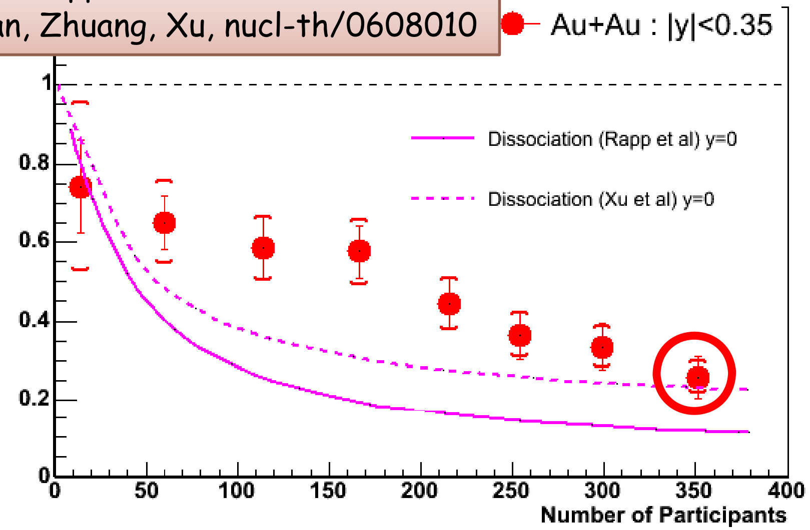
Roberta Arnaldi, QM05
Final in nucl-ex/0706.4361



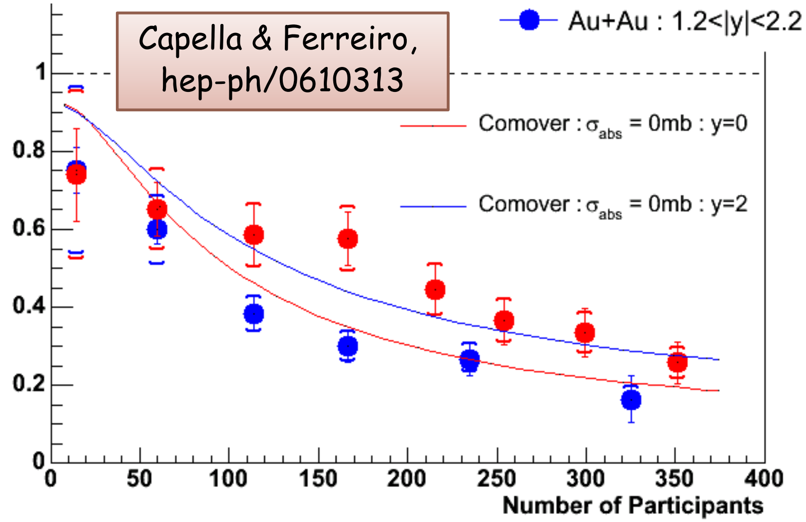
“NA50 only” effects @ RHIC

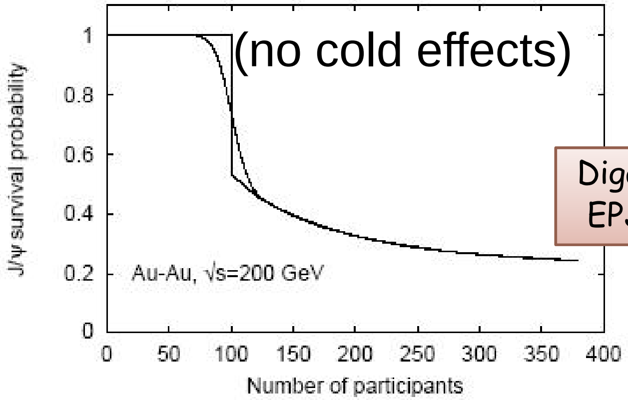
- Most of the models that did a good job @ SPS fail @ RHIC
  - Gluon dissociation (y~0) doesn’t give the right trend and/or amount of suppression
  - Comovers (of unknown partonic/hadronic nature) give $R_{AA}(y=2) > R_{AA}(y=0)$
  - Parton percolation has an onset at N_{part} ~ 90 and simultaneous $J/\psi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

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



Capella & Ferreiro, hep-ph/0610313

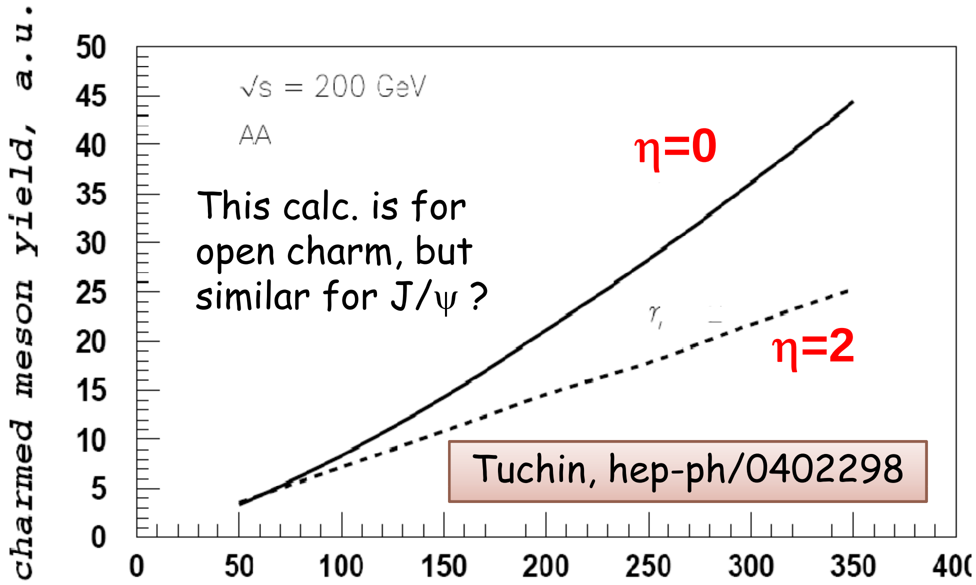


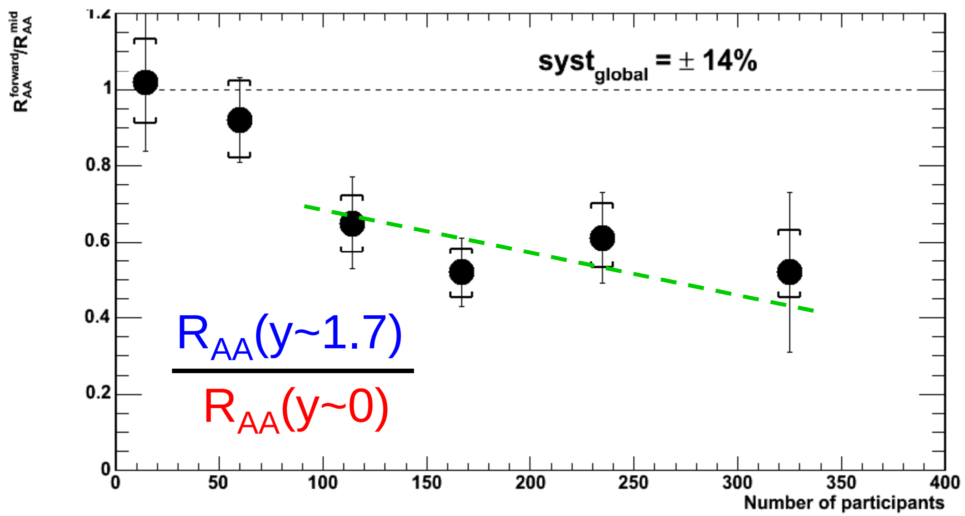


Digal, Fortuno, Satz, EPJC32 (2004) 547

Unaccounted CNM ?

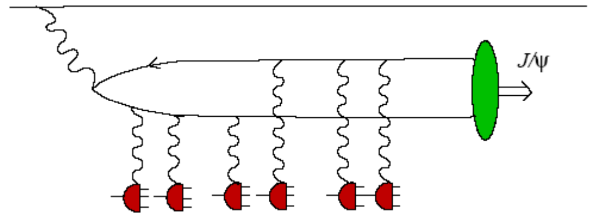
- Strong initial states effect ala color glass condensate ?
  - But they have to violate rapidity symmetrisation $R_{AA}(|y|) = R_{dA}(-y) \times R_{dA}(+y)$
  - (otherwise taken into account in CNM extrapolation)
- Could this + sequential melting produce $R_{AA}(y\sim0)$ and $R_{AA}(y\sim1.7)$?
- Double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

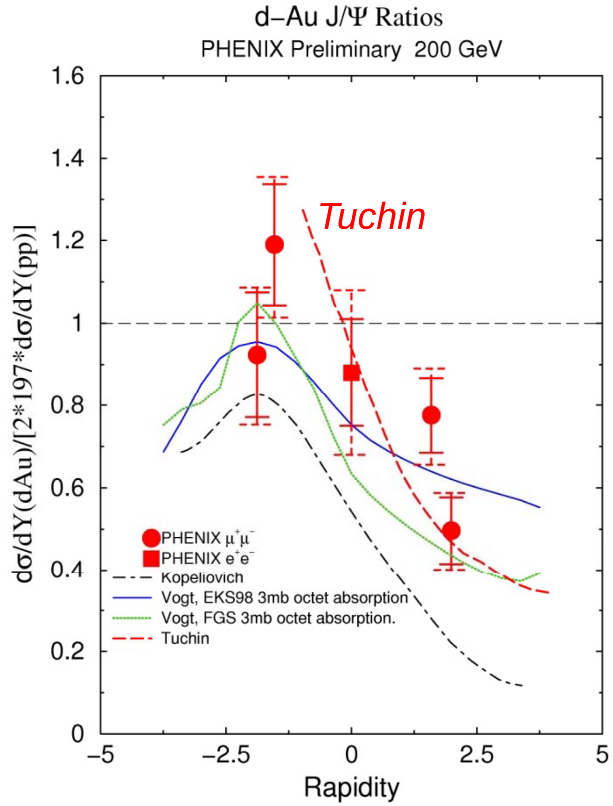




Tuchin & Kharzeev

- Hard probes 2004
  - 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