Charmonium suppression from SPS to RHIC

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PHENIX & CMS experiments

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Introduction

- *"overview talk on experimental status of charmonium suppression."*
- Setting up the firm ground of observations
- Leaving on the side
  - Production mechanisms, polarization, feed-downs, fermilab and hera-b…
- Some redundancy with at least
  - Rapp, Redlich, Stachel, Frawley, Lansberg, Tuchin, Faccioli, Leitch, Woehri, Linden-Levy, Lourenço…

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, remember yesterday):

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

0. The published situation

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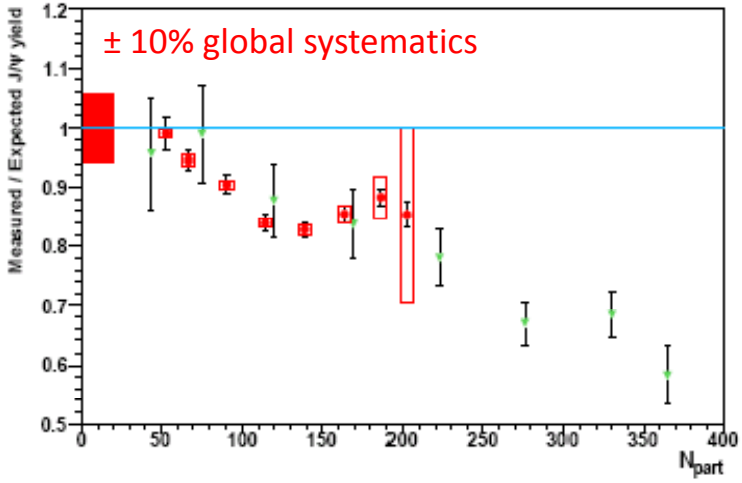
before new SPS and RHIC

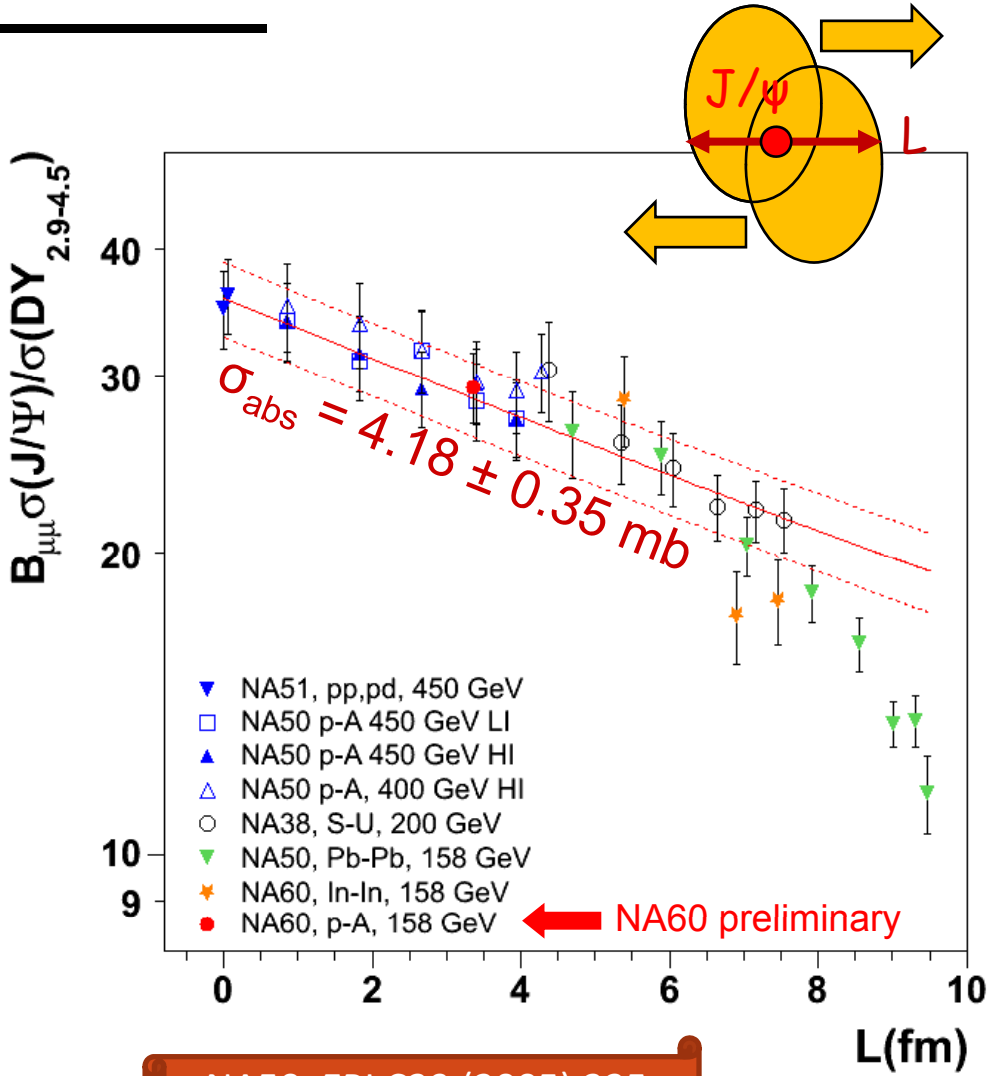
preliminary references

shown at QM09

Cold and hot matter @ SPS

- Normal nuclear absorption alone does a splendid job describing pA, SU and peripheral InIn and PbPb:
  - σ_{abs} = 4.18 ± 0.35 mb
  - Scaled from 400 to 158 AGeV
- Beyond is "anomalous suppression"
  - InIn looks like an onset

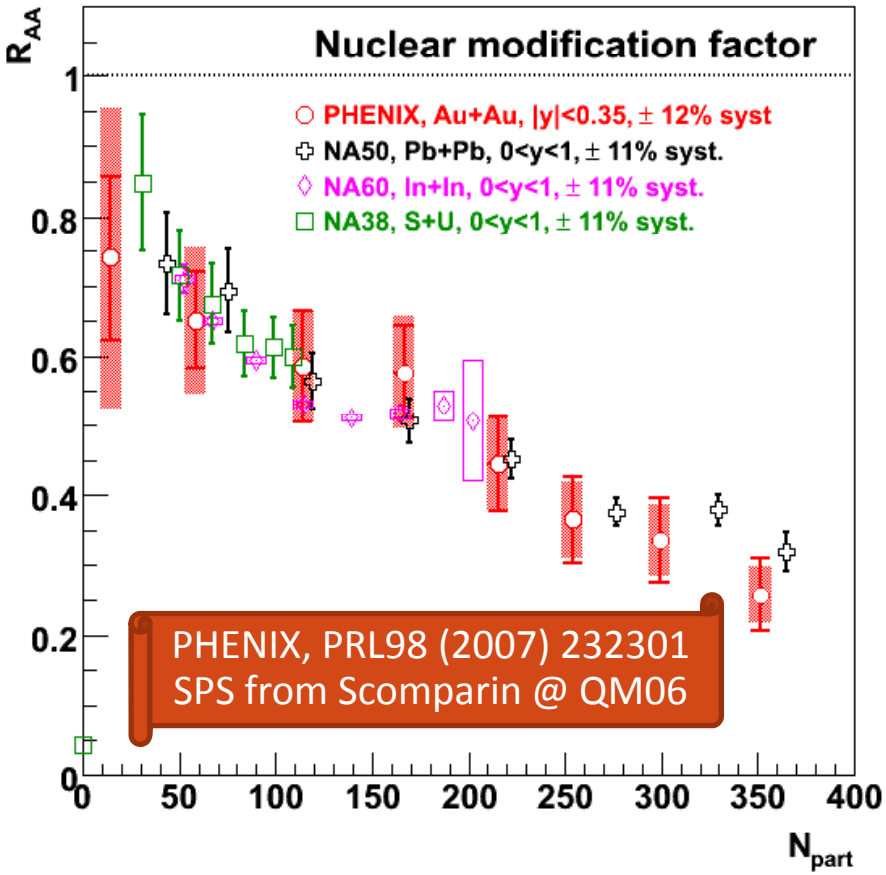




NA50, EPJ C39 (2005) 335
NA60, PRL99 (2007) 132302

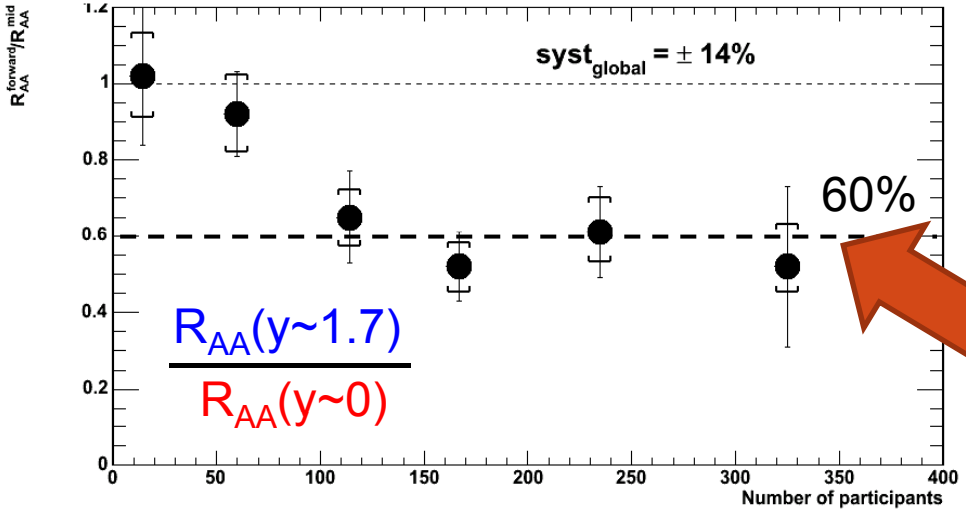
R_{AuAu} (y≈0 in PHENIX) ≈ R_{PbPb} (@ SPS)

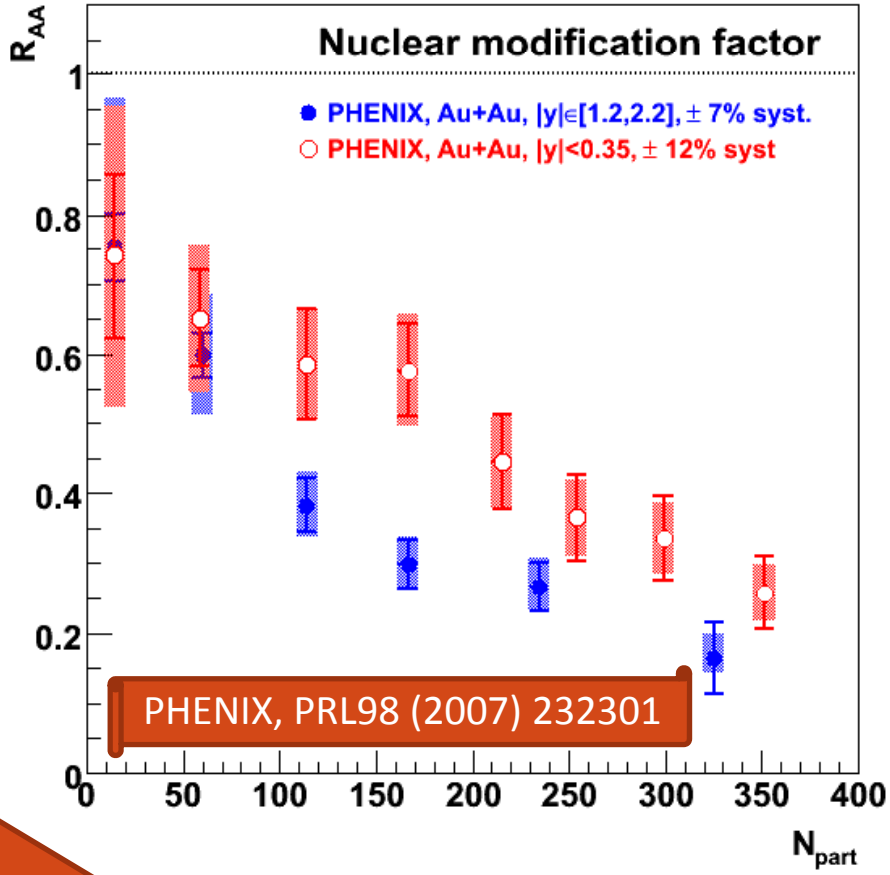
- Lower rapidity R_{AA} looks surprisingly similar, while there are obvious differences:
  - At a given N_{part}, different energy densities…
  - Cold nuclear matter effects ($x_{Bjorken}$, σ_{abs}…)
  - …



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…





What is this further 40% suppression due to?

@ RHIC, more suppression
at forward rapidity!

Two possible theoretical explanations…

A. One hot: coalescence, regeneration

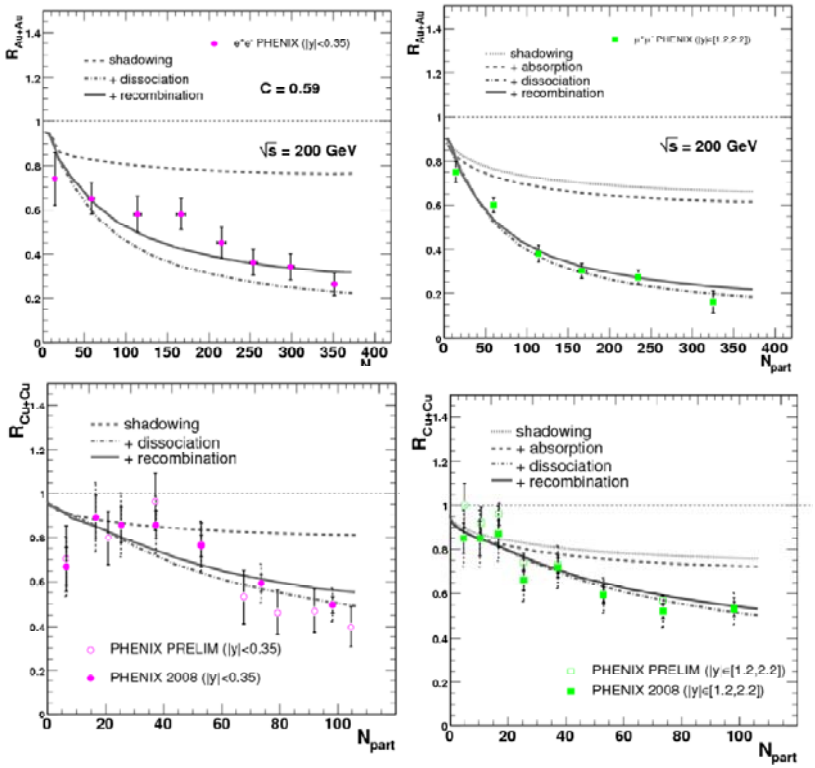
B. One cold: saturation, shadowing

A. Hot coalescence, regeneration

- 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, EPJ C43, 97 (2005)
Yan, Zhuang, Xu, PRL97, 232301 (2006)
A. Andronic et al., NPA789, 334 (2007)
Ravagli, Rapp, PLB655, 126 (2007)
Zhao, Rapp, PLB664, 253 (2008)
A. Capella et al., EPJ C58, (2008) →
O. Linnyk et al., NPA807, 79 (2008)
Rapp and Stachel at Seattle
(Apologies if I forgot somebody)

- As an example

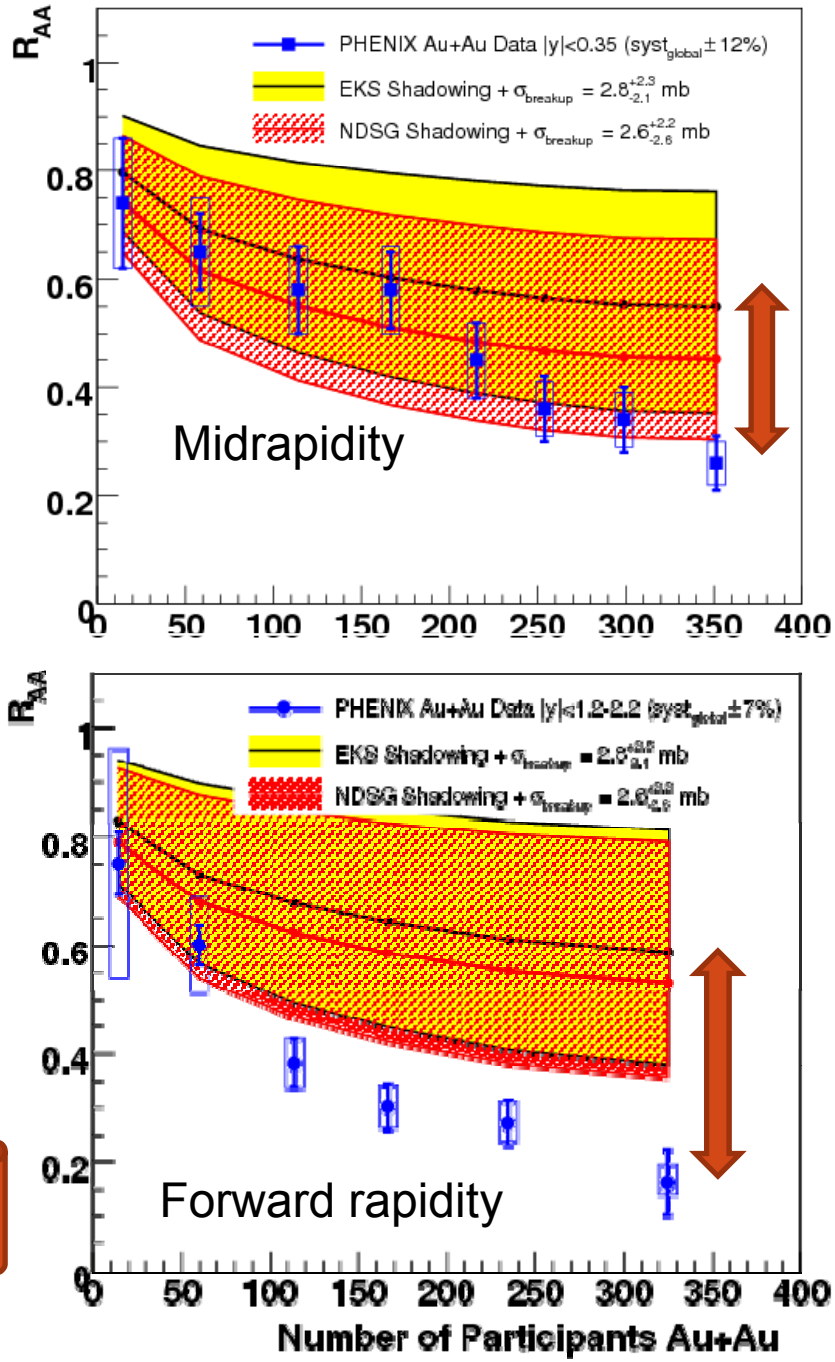


Capella, Ferreiro, Tywoniuk et al.
Fitting Cu+Cu, Au+Au,
Mid and forward rapidity

B. Cold matter

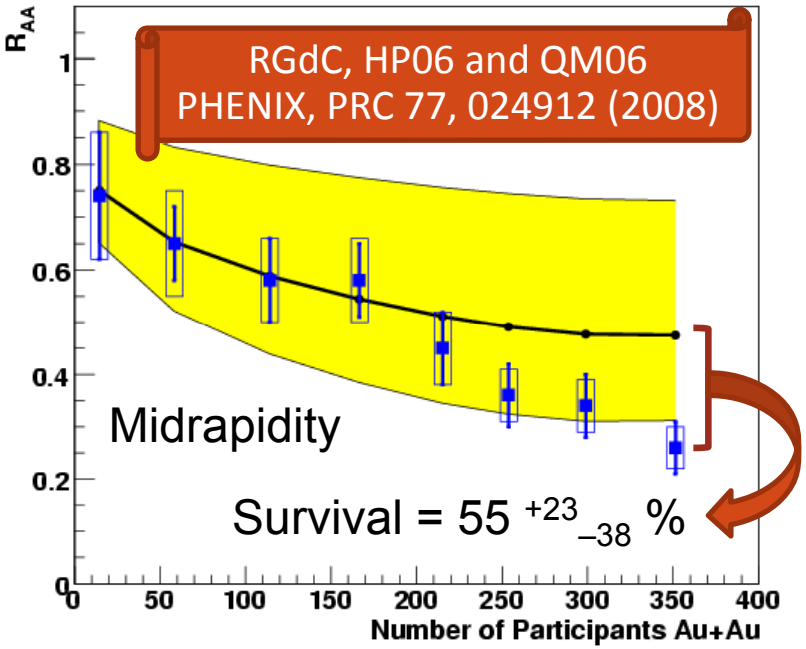
- Assuming two shadowing schemes, derive breakup cross sections from $R_{dA}(y)$
  - $\sigma_{EKS} \approx 2.8\ ^{+2.3}_{-2.1}$ mb
  - $\sigma_{NDSG} \approx 2.6\ ^{+2.2}_{-2.6}$ mb
- Extrapolate to AuAu →
  - (Also available for CuCu)
  - Mid and forward are correlated through shadowing scheme
  - If you believe this shadowing + absorption, there is anomalous suppression, larger at forward rapidity.

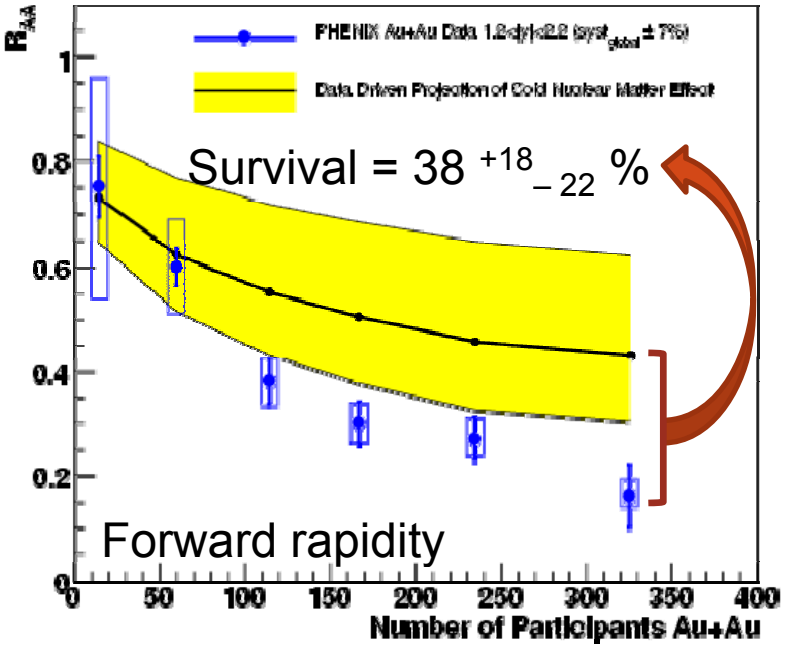
PHENIX, PRC 77 (2008) 024912
& erratum: PRC 79 (2009) 059901



B. Cold matter

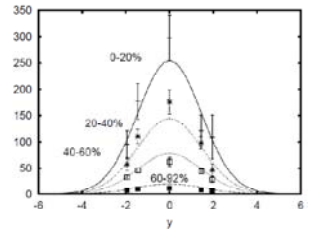
- More model independent…
- In a Glauber data-driven model, propagate what we know from $R_{dA}(y,centrality)$
  - $R_{AA}(y,b) = \Sigma_i R_{dA}(-y,b^i_1) \times R_{dA}(+y,b^i_2)$
  - No shadowing nor absorption schemes
  - Mid and forward are not correlated, less model dependent → larger uncertainties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



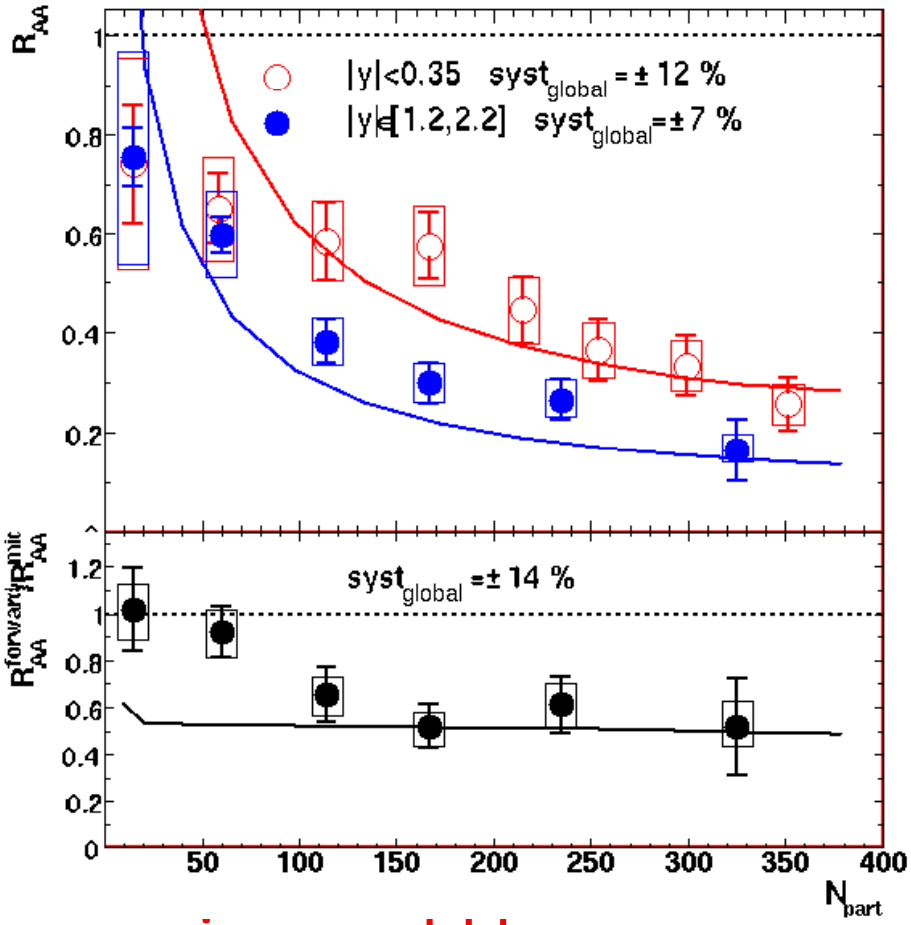


B. Recent CGC paper

Kharzeev, Levin, Nardi, Tuchin
PRL102 (2009) 152301
and arXiv: 0809.2933



- Gluon saturation could further suppress forward J/ψ in AuAu
  - First numerical estimate
  - Absolute amount of suppression is fitted to the AuAu data!
  - Waiting forward to new dAu data to fit them first
  - However, rapidity dependence should be ok
  - But it does not reproduce peripheral data →
  - Anyway…



→ Again, J/ψ anomalous suppression could be identical at mid and forward rapidity!

How to disentangle these
two scenarios experimentally?
(now moving to preliminary material)

Two possible theoretical explanations…

A. One hot: coalescence, regeneration

B. One cold: saturation, shadowing

How to move forward experimentally?

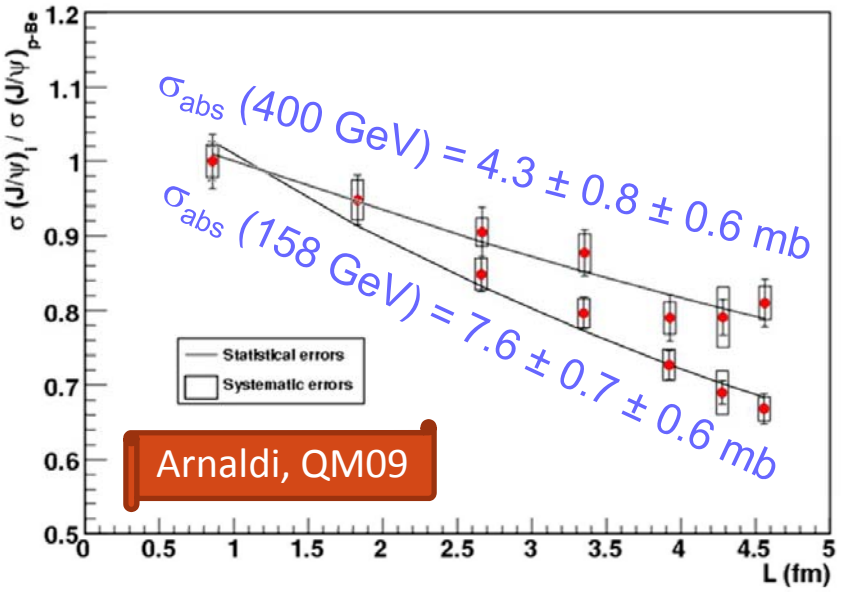
RGdC, Quarkonia in hot and cold matters, Quark Matter 08

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

Some progress on all these points at this meeting !

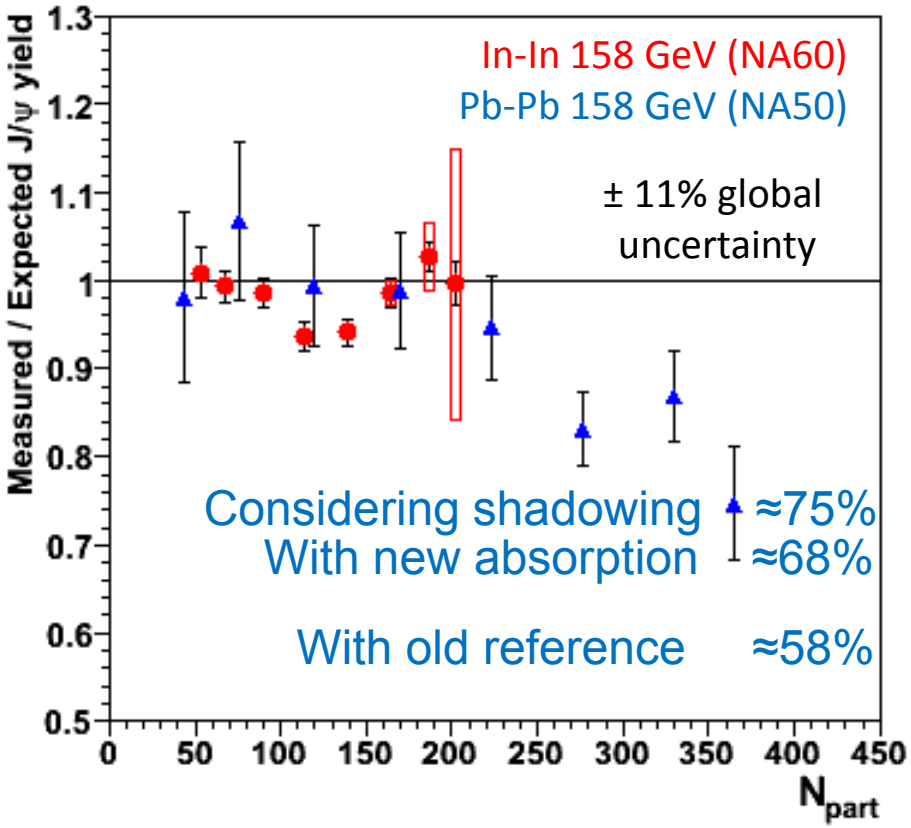
1. New preliminary reference @ SPS

NA60 pA @ 158 GeV →

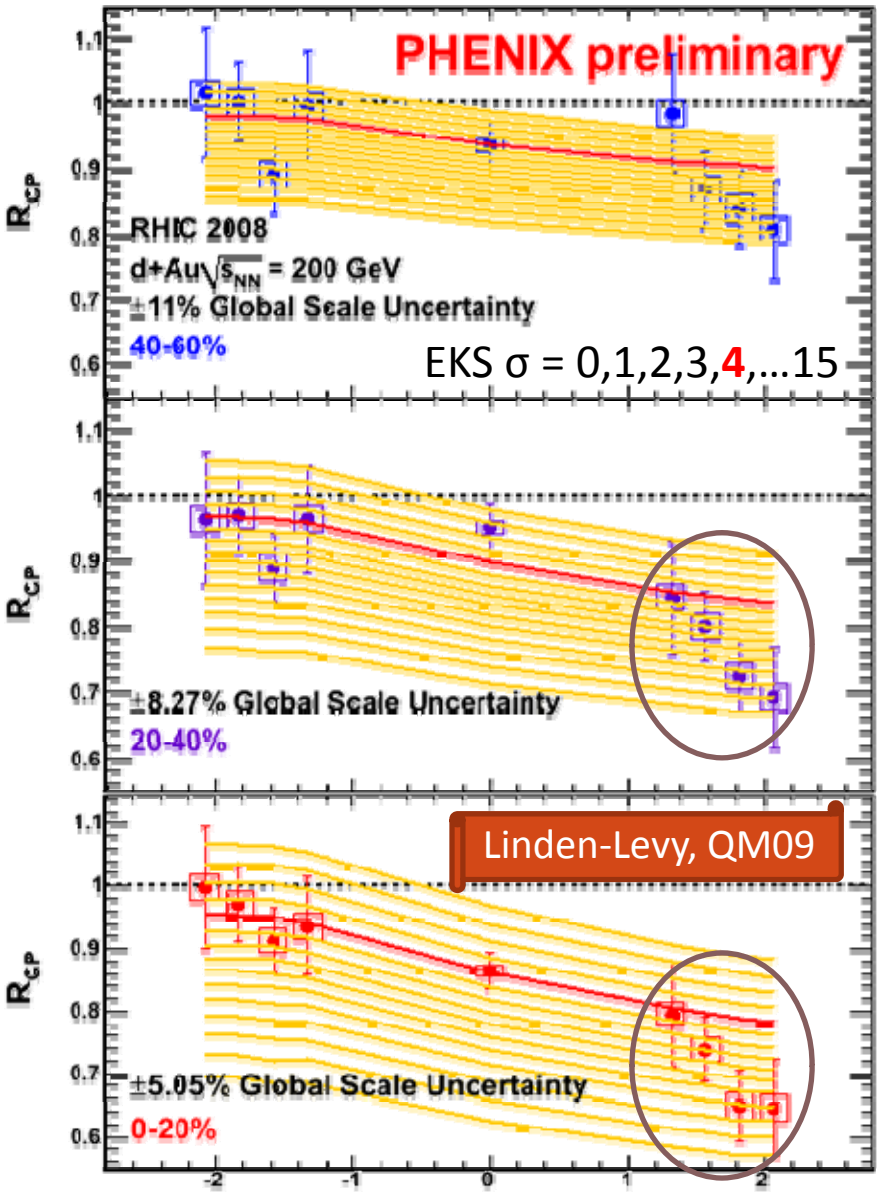


- Still anomalous suppression in Pb+Pb (of ψ' and χ_c?)
- Not sizeable in In+In, but such a peculiar shape…

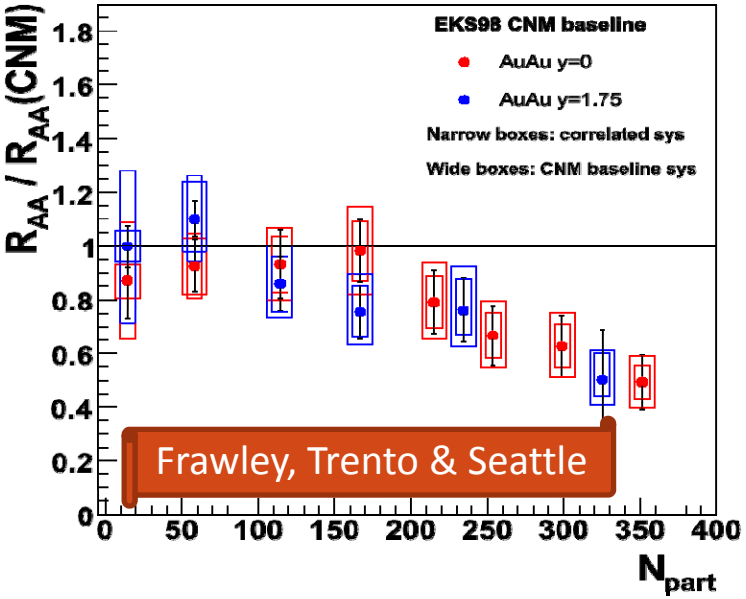
New absorption, considering also antishadowing (EKS98)…



1. New preliminary reference @ RHIC

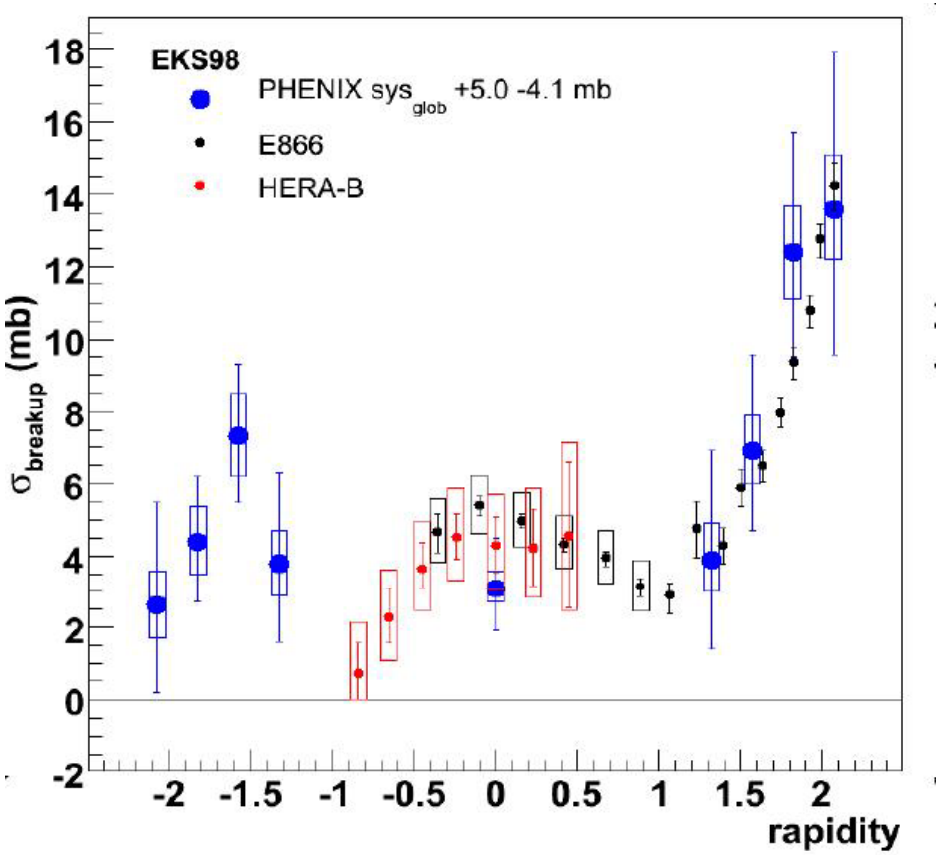


- R_{dA} not yet available
  - No data driven method
- Shadowing & σ_{abs} do not describe data anymore
- One way is to use various (effective) σ_{abs} vs rapidity



Now, a little word of caution

- Tony's extrapolation of the dAu Phenix preliminary R_{CP} does reinforce the cold hypothesis to explain the R_{AA} rapidity difference…
- However, need different σ_{abs} for different rapidity
  - also seen at SPS, Fermilab →
- So, something else or different is going on there…
  - Something for which the extrapolation to R_{AA} may or may not be appropriate…
- So let us think!
  - (and wait for final R_{dA})

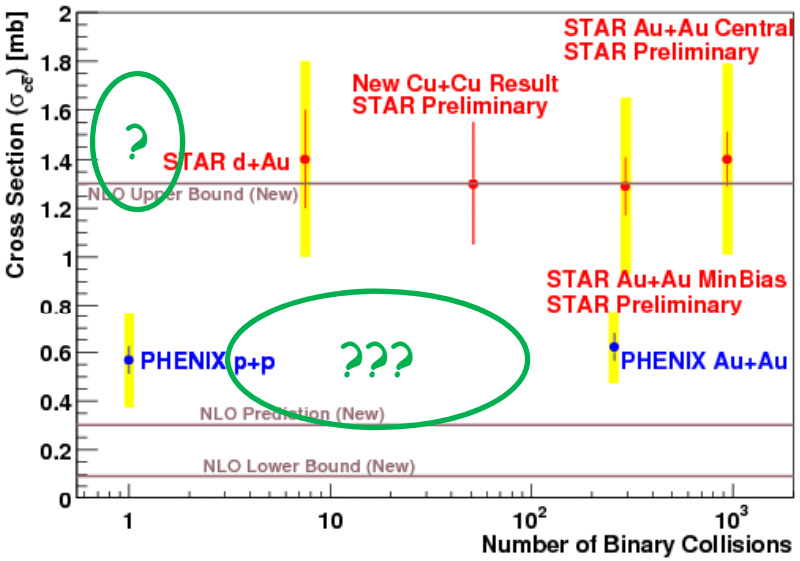


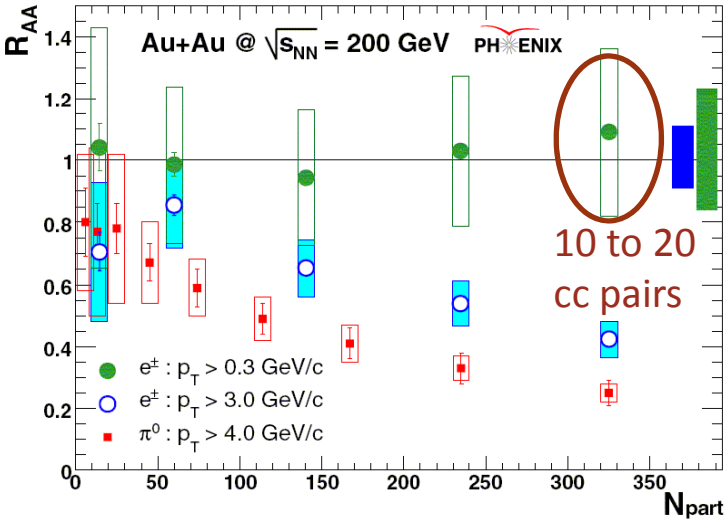
Lourenço, Vogt, Woehri , JHEP 0902:014
Frawley, Trento & Seattle

What else could bring information?

2. Open charm?

2. Measuring open charm…





… could constrain both

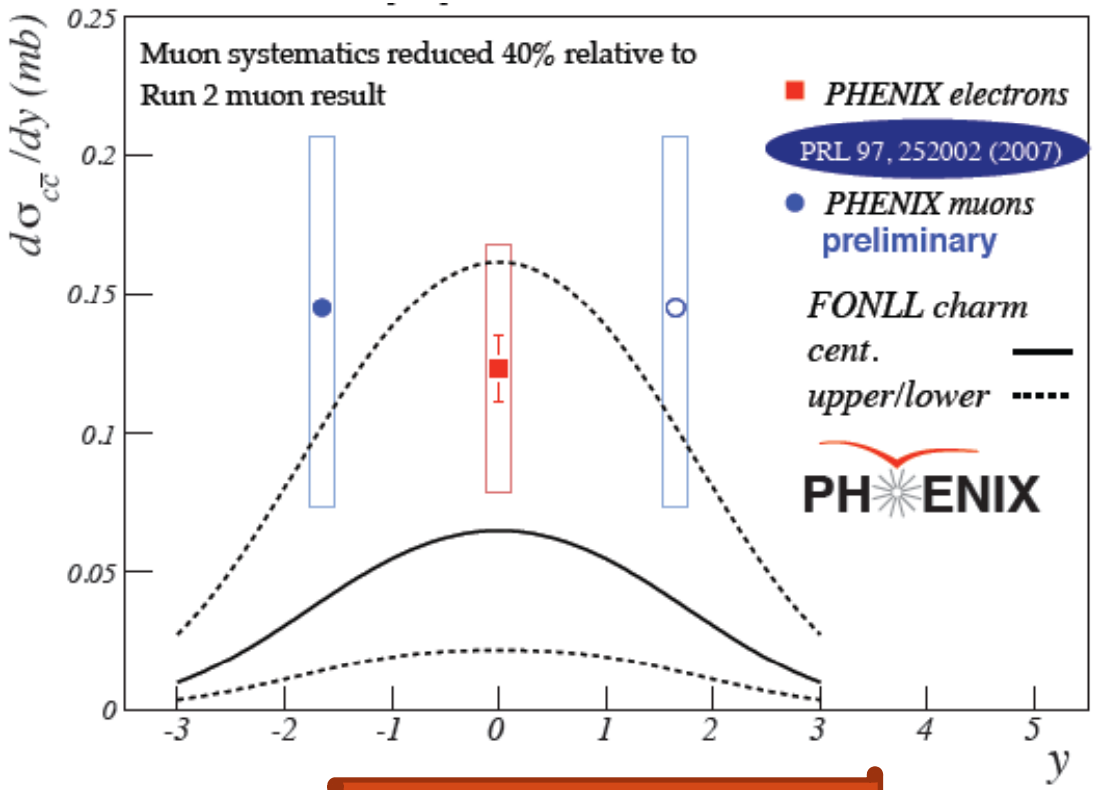
- Regeneration α $(N_{cc})^2$
- Initial state effect (shadowing…) shared with J/ψ

- A factor of 2 difference between experiments
- ≈25% systematic error
- But binary scaling (within uncertainties…)
- At SPS too: 1.16 ± 0.16

PHENIX, PRL98 (2007) 172301
NA60, EPJ.C59 (2009) 607

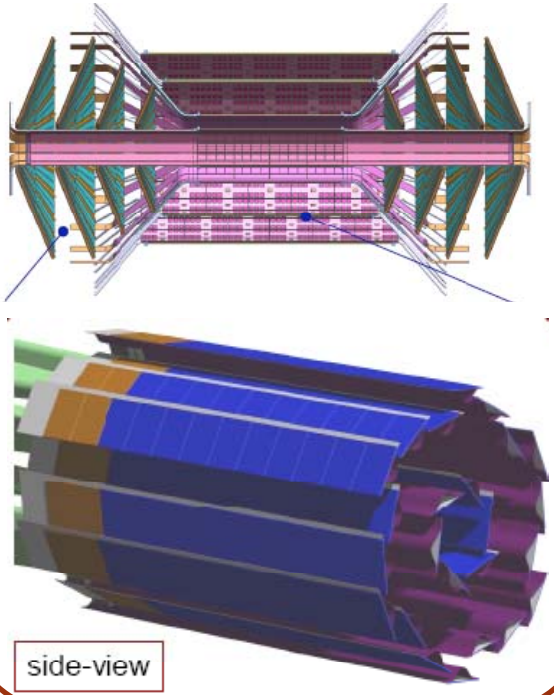
2. Open charm vs rapidity

- Only pp, and very poorly known



D. Hornback, PHENIX, QM08

To know more about open charm, wait for silicon upgrades in Phenix and Star



Look at other quarkonia

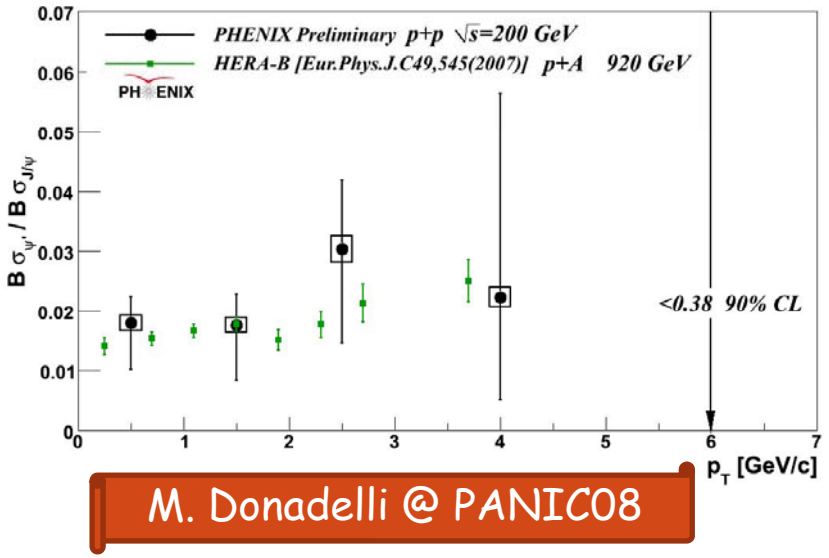
3. Excited charmonia

4. Upsilons

3. Excited states (feed down to J/ψ)

- Excited states should…
  - A. melt if J/ψ suppression is cold effects + sequential melting
  - B. also regenerate if J/ψ do (and maybe even more)
- At RHIC, unfortunately only p+p for now…
  - →Feeddown ratio
  - – ψ‘ dAu is feasible
  - – ψ‘ AuAu needs new run

- ψ from ψ’ = 8.6 ± 2.5%

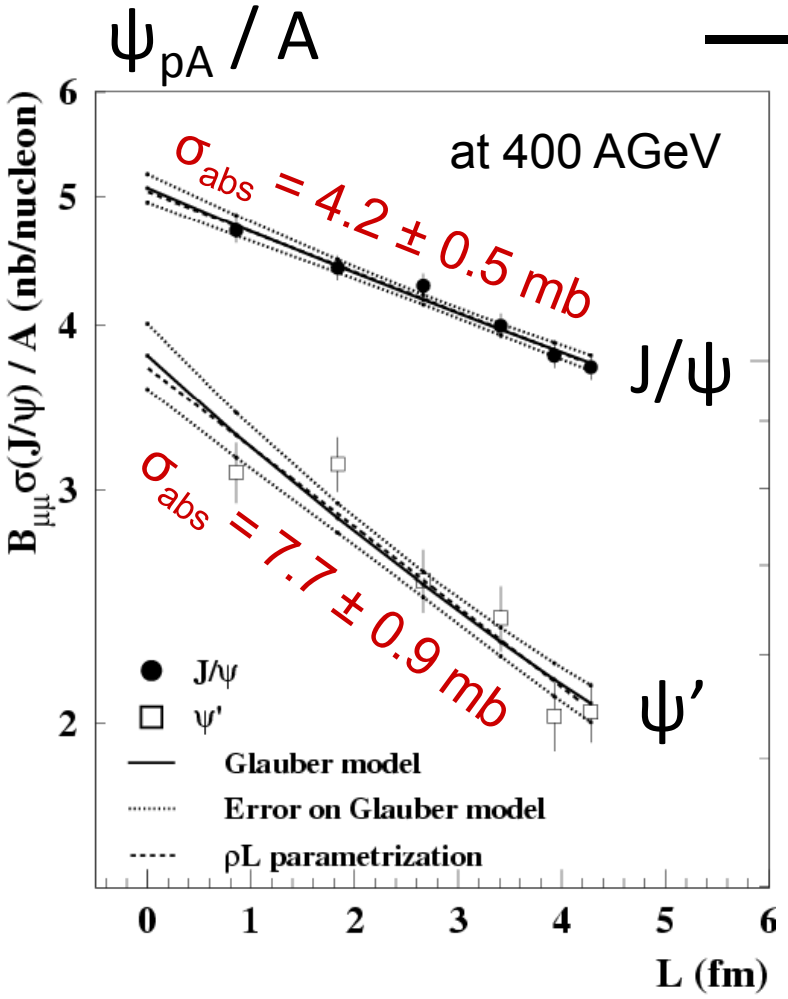


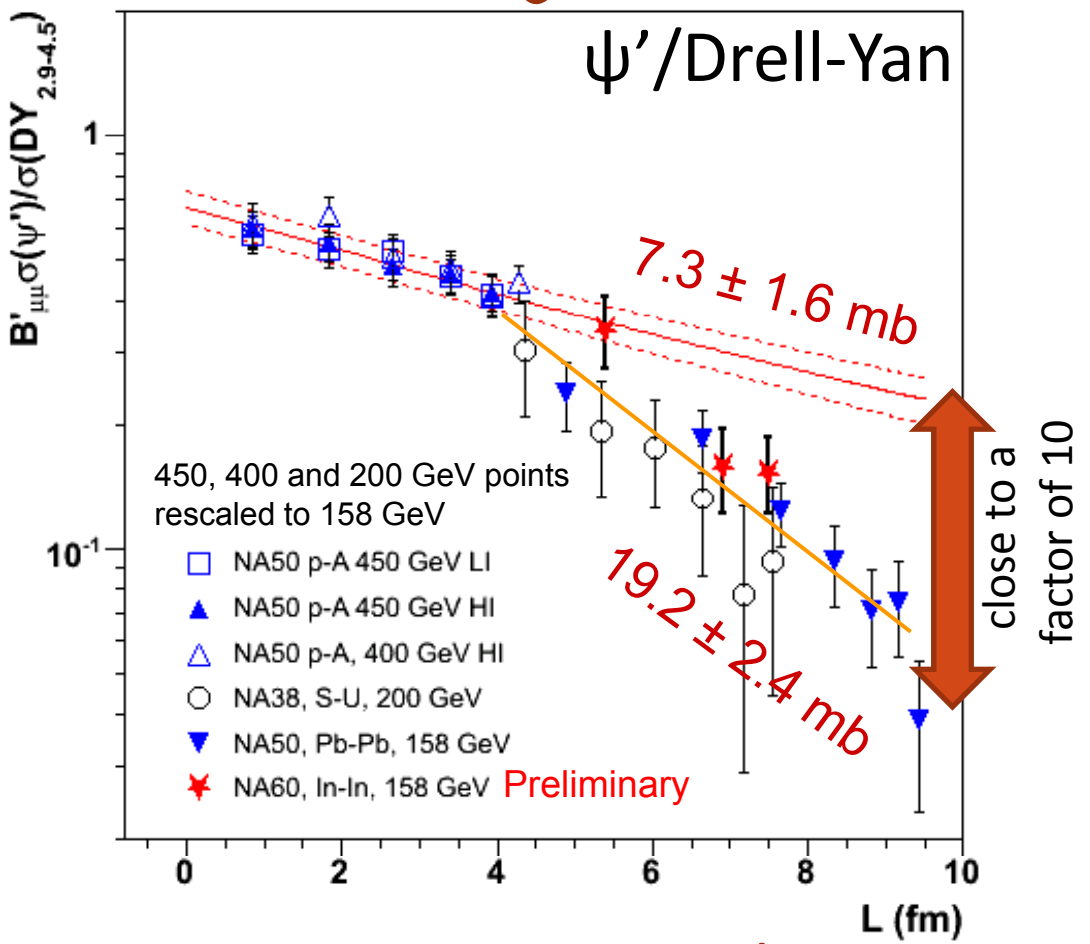
M. Donadelli @ PANIC08

- ψ from χ_c < 42% (90%CL)
- Beauty cross section → ψ from B = 4^{+3}_{-2} %

ψ' at SPS

NA50, EPJC48 (2006) 329
NA50, EPJC49 (2007) 559
Scomparin @ Trento



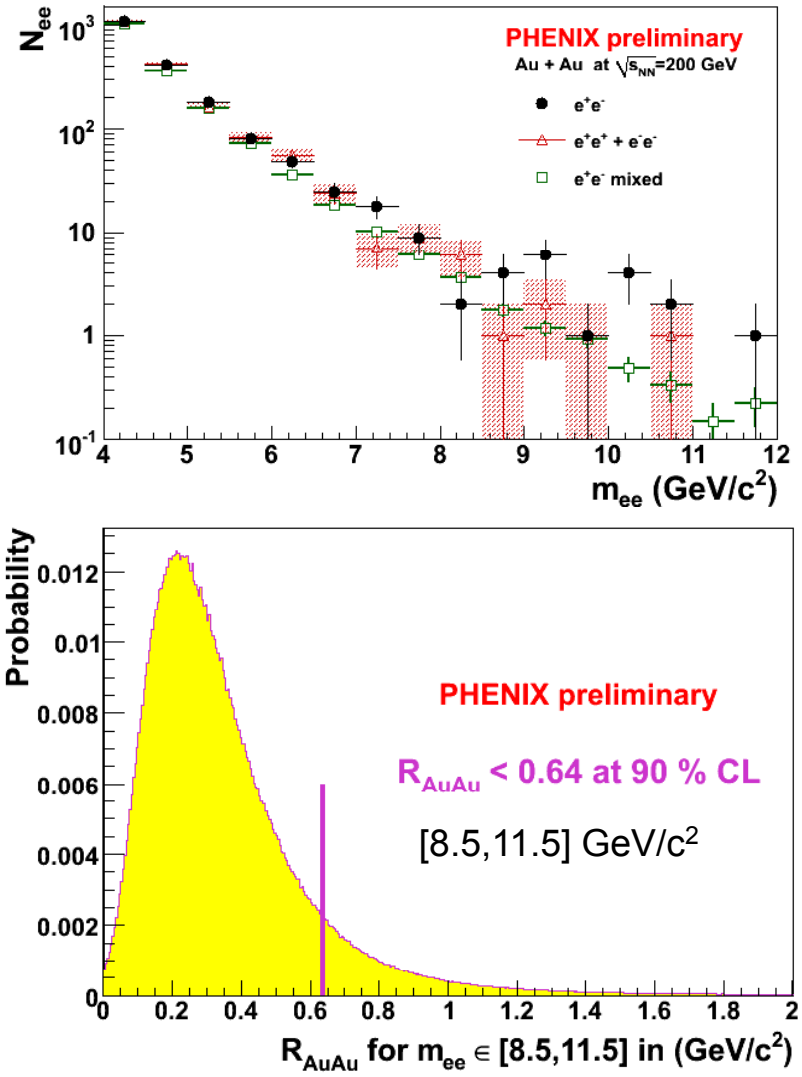


- ψ' are more absorbed and suppressed than J/ψ
  - σ_{abs} (158 AGeV) not available

4. Beginning of a bottomonia story

Atomssa, Liu, Conesa del Valle @ QM09

- $R_{dAu} = 0.98 \pm 0.32 \pm 0.28$ (from STAR)
- $R_{AuAu} < 0.64$ @ 90% CL (from PHENIX →)
  - Could be cold effects
  - No continuum subtraction
    - (but < 15% from pp)
  - Feeddown of χ_b important
    - 50% for $p_T > 8$ GeV/c at CDF
- Stay tuned…



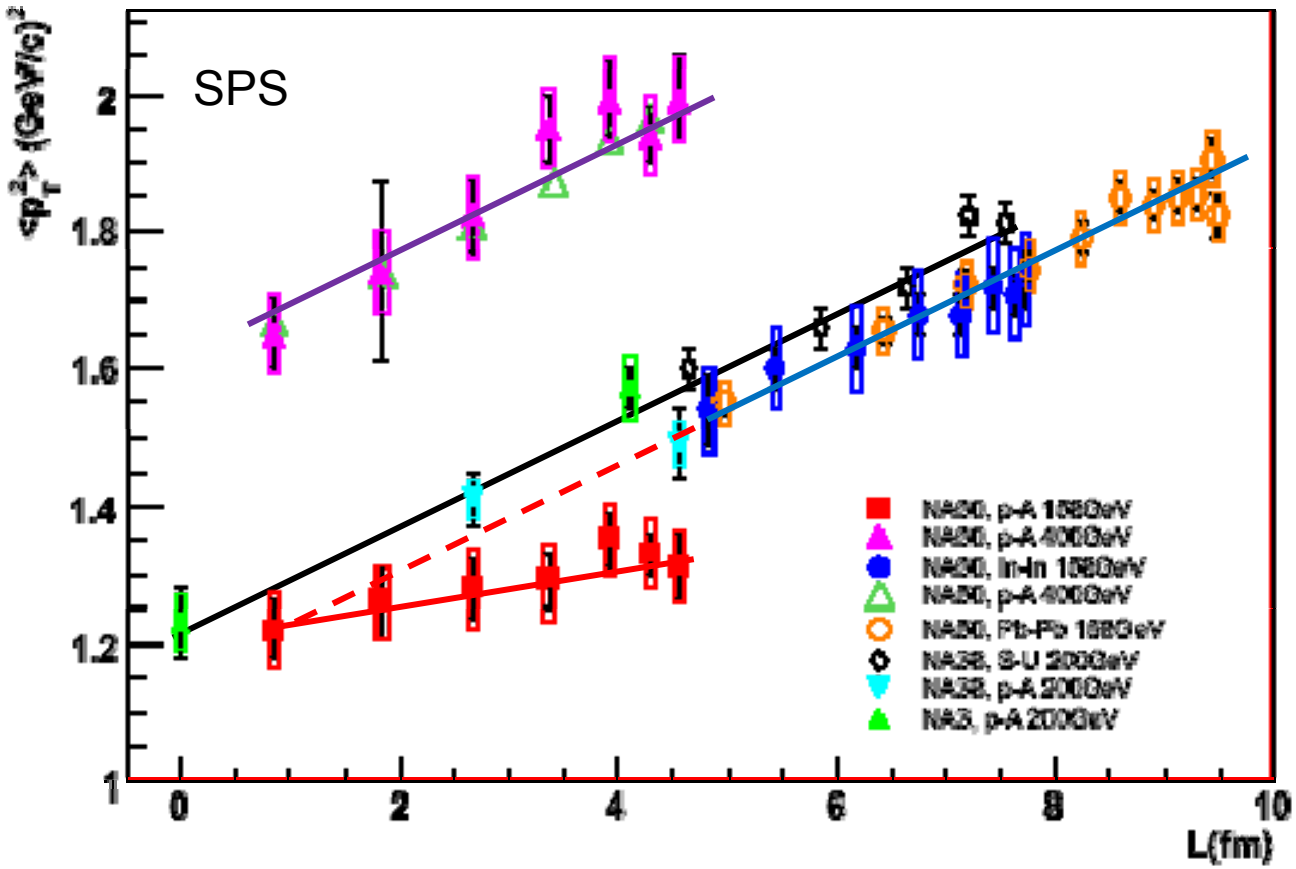
Look at other observables

5. p_T (broadening)

6. Elliptic flow

5. p_T broadening @ SPS ?

- Tested on many systems… NA60 pA slope is unique…
- Cronin goes like: $\langle p_T^2 \rangle_{AB} = \langle p_T^2 \rangle_{pp} + \alpha \times L$



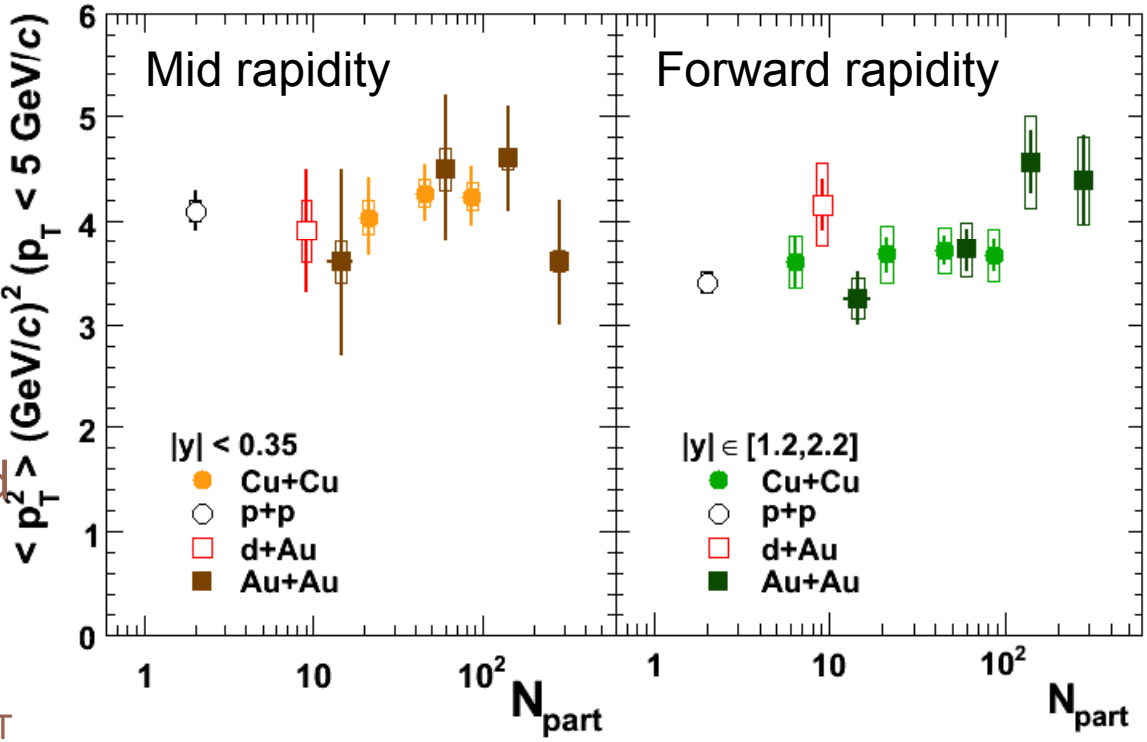
Cortese (NA60), Hard probes 08 + homemade powerpoint fits

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

- 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:

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

PHENIX, PRL 101, 122301 (2008)

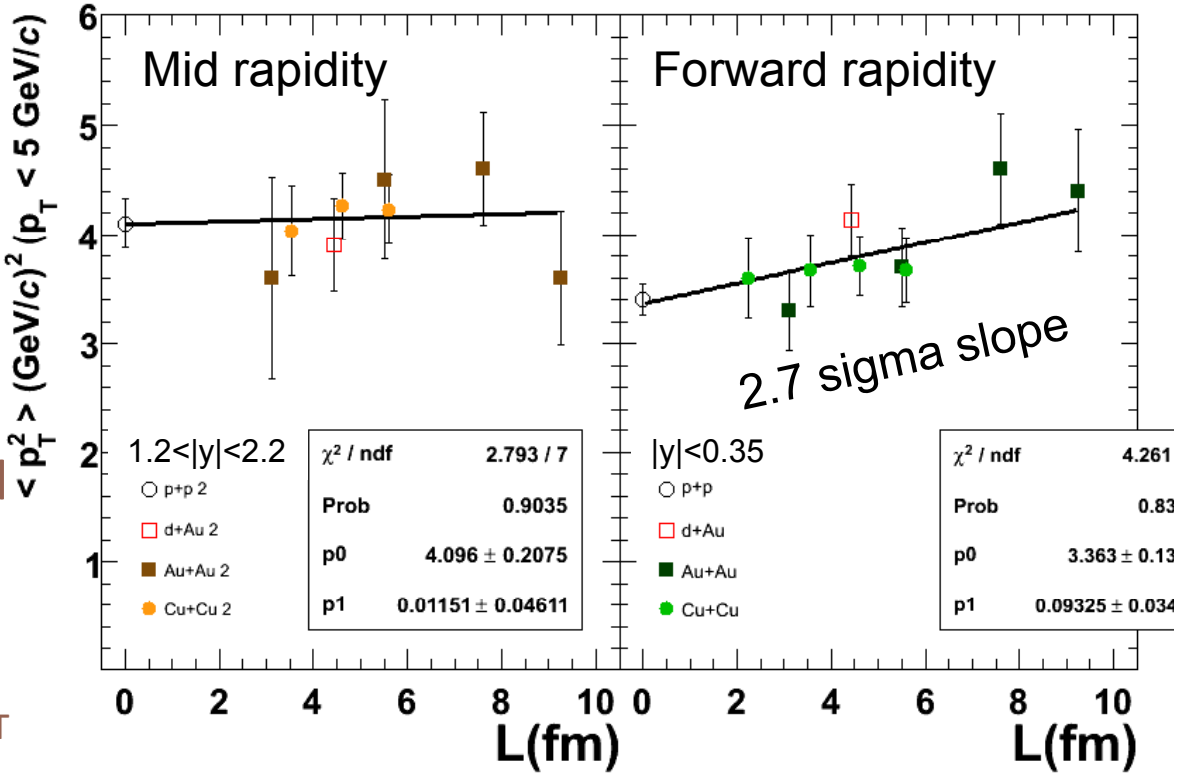


- No strong $\langle p_T^2 \rangle$ dependence…
- Modest rise at forward rapidity
- Could be broadening
- No need for recombination here

5. 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
- Cronin goes like:

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

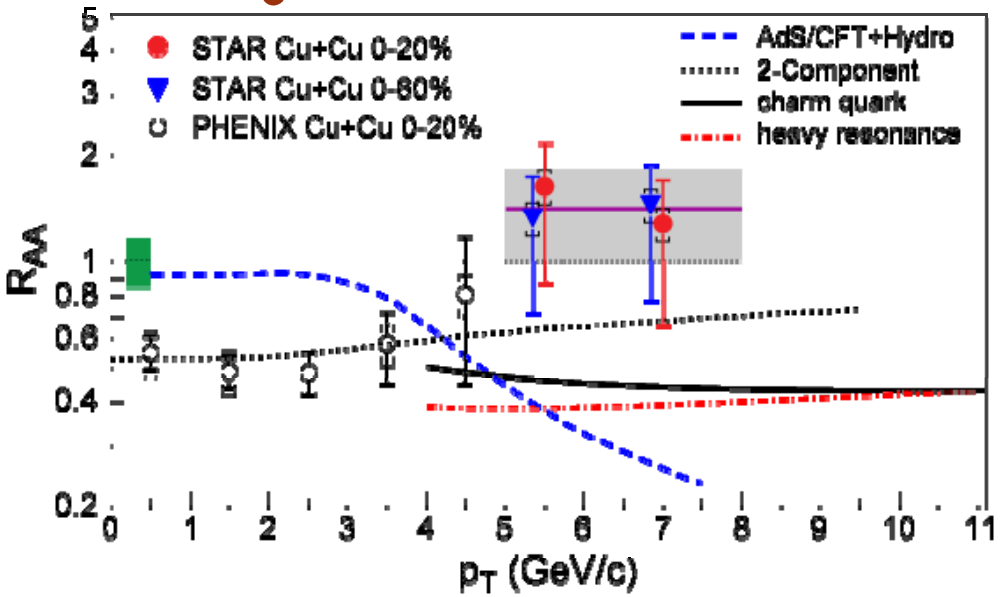


- No strong $\langle p_T^2 \rangle$ dependence…
- Modest rise at forward rapidity
- Could be broadening
- No need for recombination here

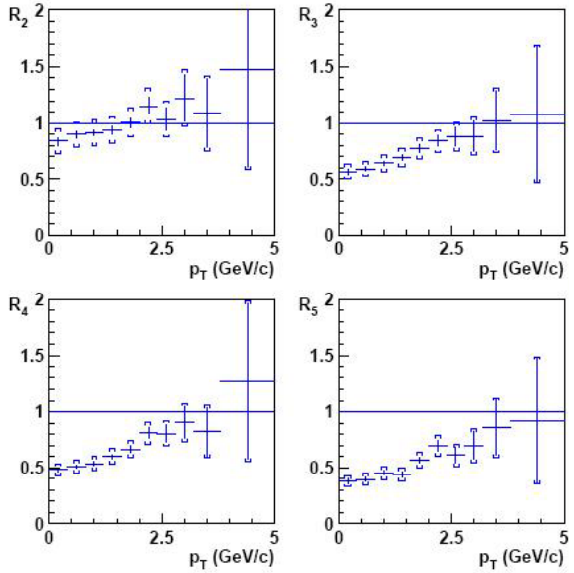
5. Reaching higher p_T

- STAR's R_{CuCu} (high p_T) ≈ 1
- Hot wind scenario → 0
  - Screening length from AdS/CFT…
- But several reasons for R_{AA} to grow at high p_T
  - Cronin effect,
  - Bottom contribution,
  - Leakage,
  - (Anti)shadowing…
- Already seen at SPS!
  - R_{CP} of Pb-Pb data →
- IMHO, not a big deal…

STAR, arXiv:0904.0439
Rapp & Zhao, arxiv:0806.1239

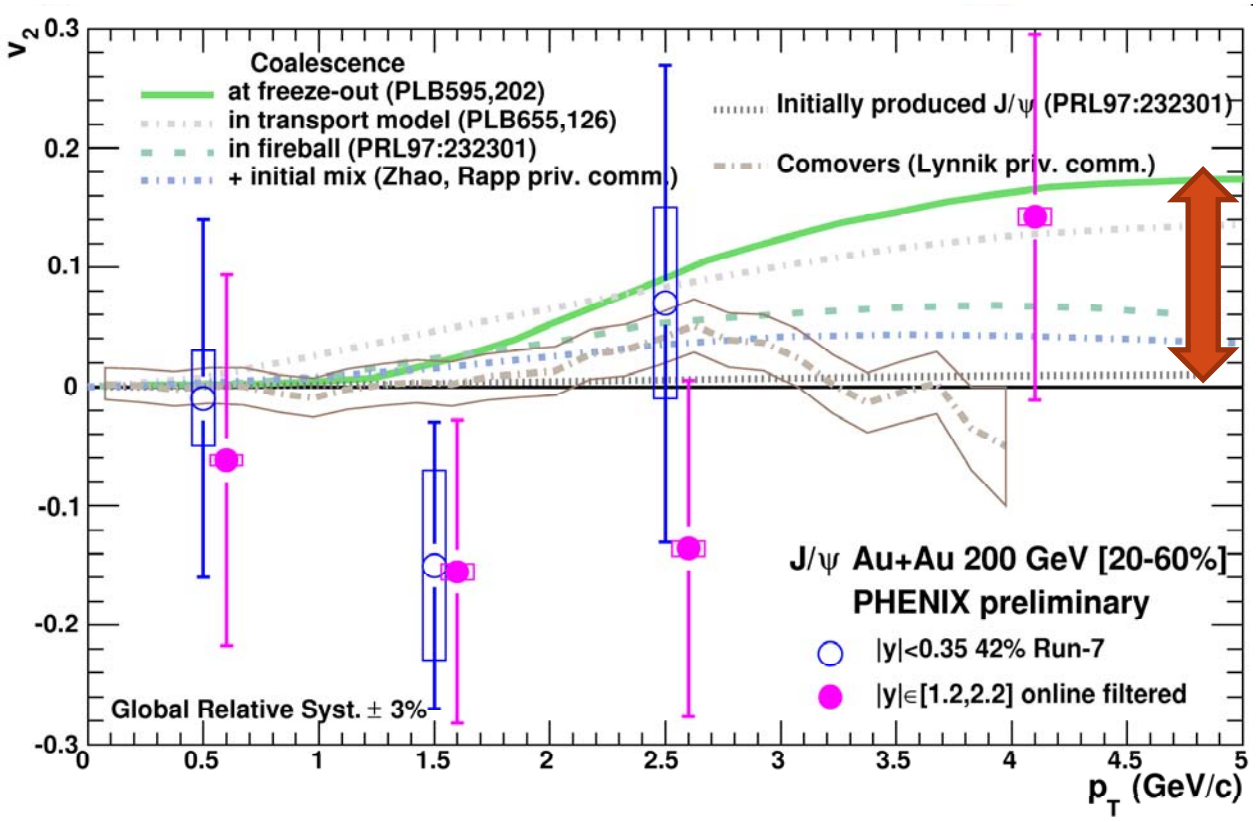


NA50, L. Ramello, QM05



6. J/ψ elliptic flow in PHENIX

- If recombined, J/ψ should inherit the (rather large) charm quark elliptic flow. First measurement:



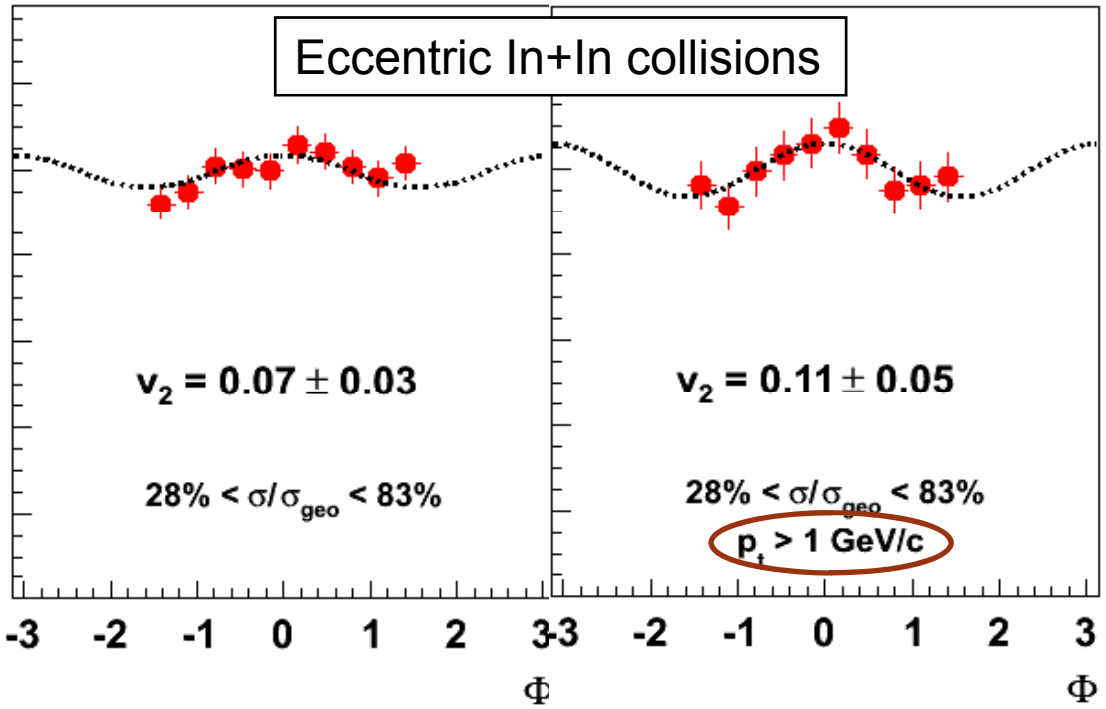
C. Silvestre @ QM08
E.T. Atomssa @ HP08

Various levels of recombination…

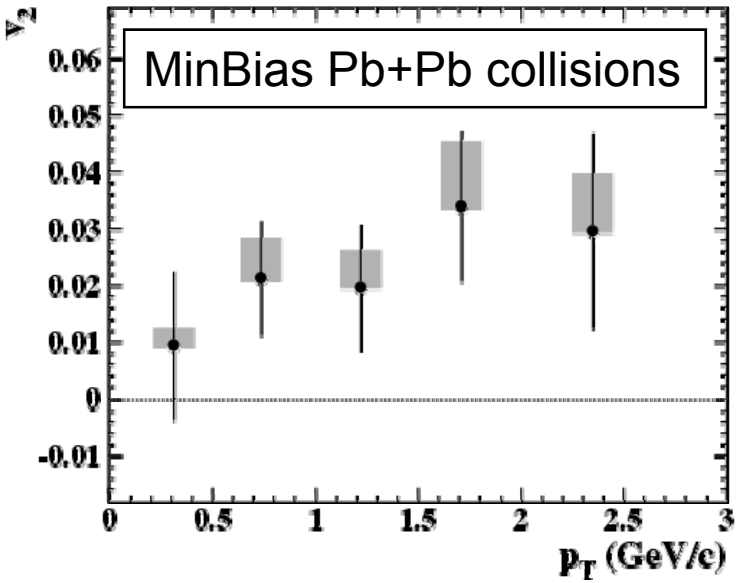
Will require RHIC2 for a discriminating measurement

6. But also J/ψ elliptic flow @ SPS

R. Arnaldi @ QM08



F. Prino @ HP08



- Cannot be due to recombination
  - (≈0.05 cc pairs in In+In)
- Needs confirmation and <u>understanding</u>

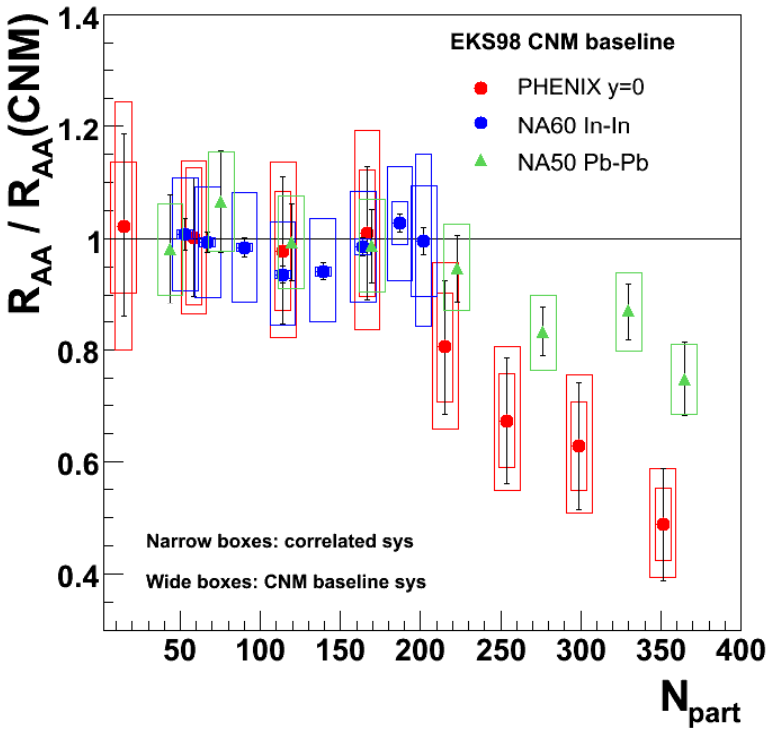
What else ?

7. Look for onsets

8. Go to LHC, the uncharted territory

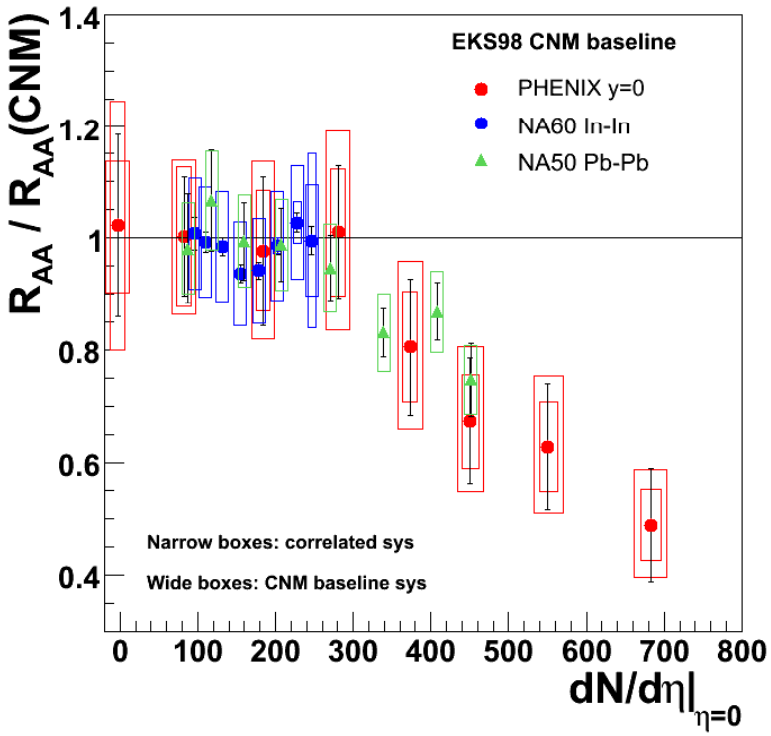
7. Common onset at SPS and RHIC?

Clear misalignment wrt N_{part}



R. Arnaldi + T. Frawley, Trento
More next week…

Better wrt dN/dη

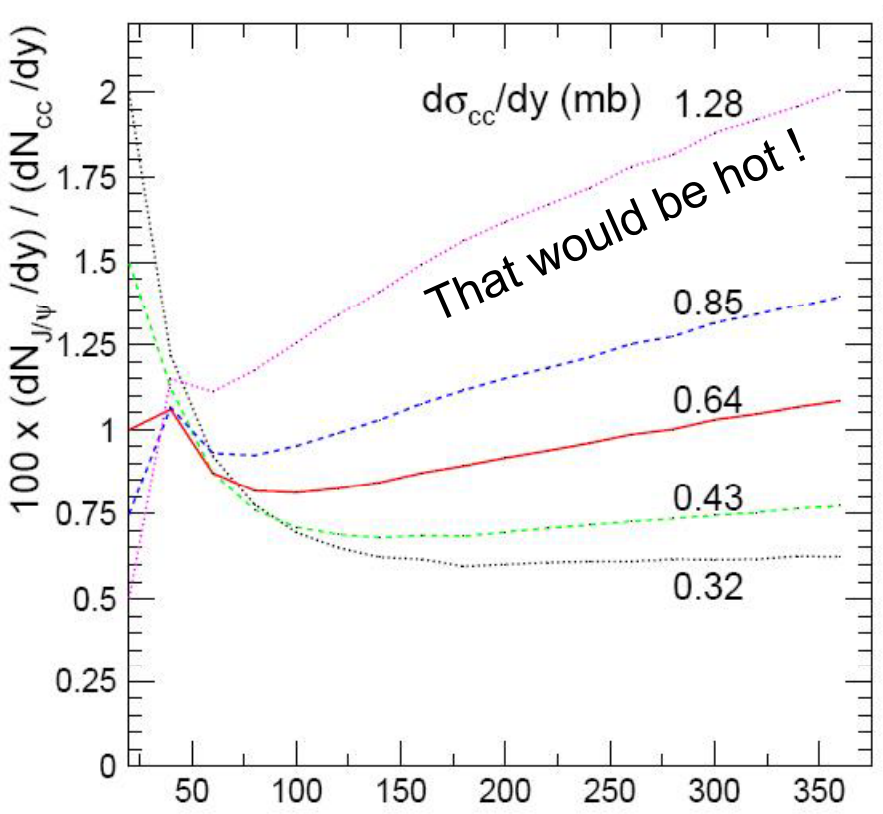


Getting closer to energy density, more next week…

8. J/ψ at LHC ?

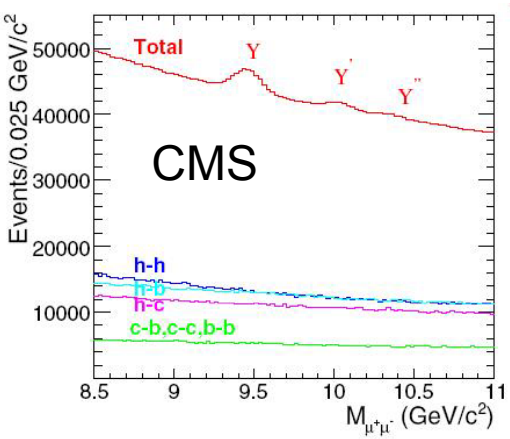
- A new story will begin
  - ↓ More J/ψ melting
  - ↓ Larger shadowing / saturation effects
  - ↑ Larger recombination (maybe 200 cc pairs)
- If recombination prevails → golden signal
- If not, expect same or worse difficulties as at RHIC…

- Example of prediction



A. Andronic et al., NPA789 (2007) 334
J. Stachel, Seattle

8. More quarkonia @ LHC



- A lot of Upsilons
  - Υ' and Υ'' should be suppressed
  - Υ shouldn't (apart from 50% χ_b feeddown)

Signal	ALICE	$\|\eta\|$	CMS	$\|\eta\|$	ATLAS	$\|\eta\|$
$J/\psi \to \mu^+\mu^-$	677,000	$2.5-4$	184,000	< 2.4	$8,000 - 100,000$	< 2.5
$J/\psi \to e^+e^-$	121,100	< 0.9				
$\psi' \to \mu^+\mu^-$	18,900	$2.5-4$	≈ 3,700 (10 σ) ?		$1,400 - 1,800$	< 2.5
$\psi' \to e^+e^-$						
$\Upsilon \to \mu^+\mu^-$	9,600	$2.5-4$	37,700	< 2.4	15,000 (21,200)	< 2.0 (< 2.5)
$\Upsilon \to e^+e^-$	1,800	< 0.9				
$D^0 \to K^\pm\pi^\mp$	13,000	< 0.9				

Pb-Pb 0,5 nb^{-1}

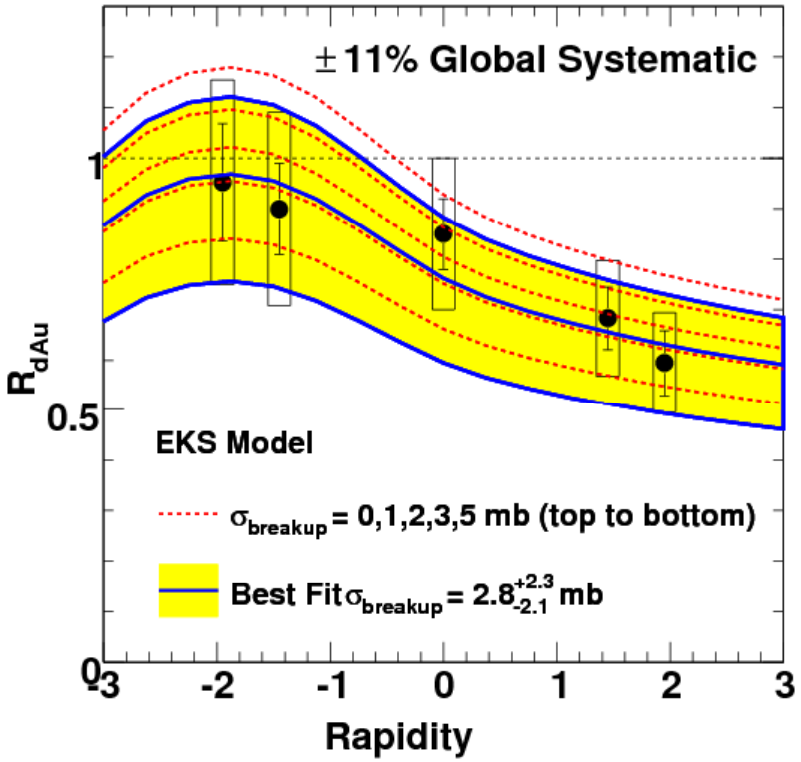
Frawley, Ullrich, Vogt, Phys Rept 462 (2008) 125

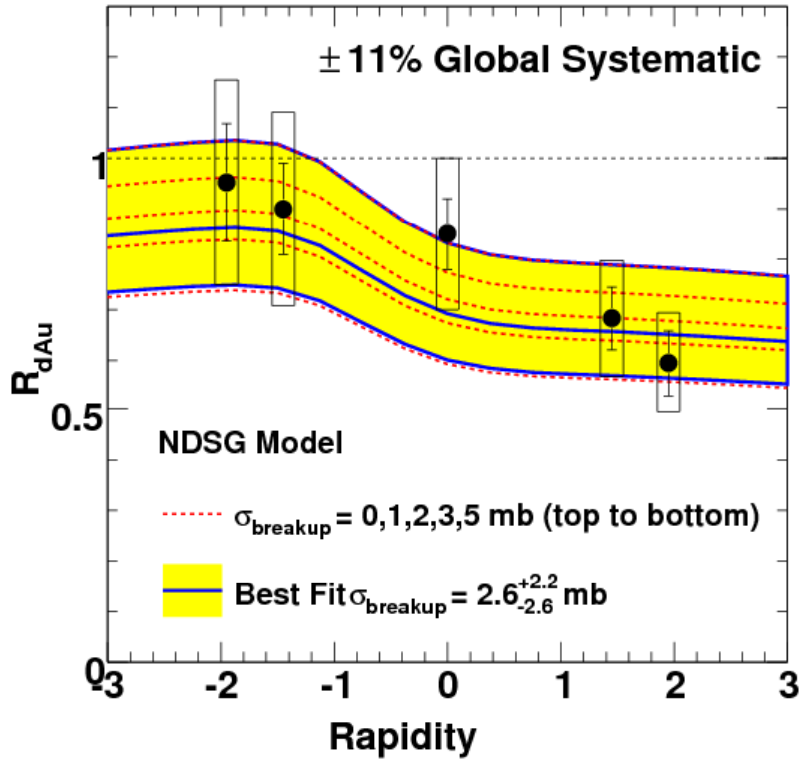
Anomalous conclusions

- One strong conclusion:
  - "J/ψ suppression is not (well and yet) understood"
  - Cold and hot effects going in the same direction…
- Forward/mid rapidity difference could be due to:
  A. Regeneration / coalescence of cc pairs?
  B. Cold effects? ← more and more favored (next talk)
- However, conservative cold matter approaches still give significant anomalous suppression at least at SPS and at forward rapidity…
  - The hot matter is deconfining some quarkonia
  - Could be only ψ' and χ_c at SPS…
- New data helps further understanding
  - dAu and pA data, ψ' and Upsilon, RHIC2 and LHC…

That’s all folks

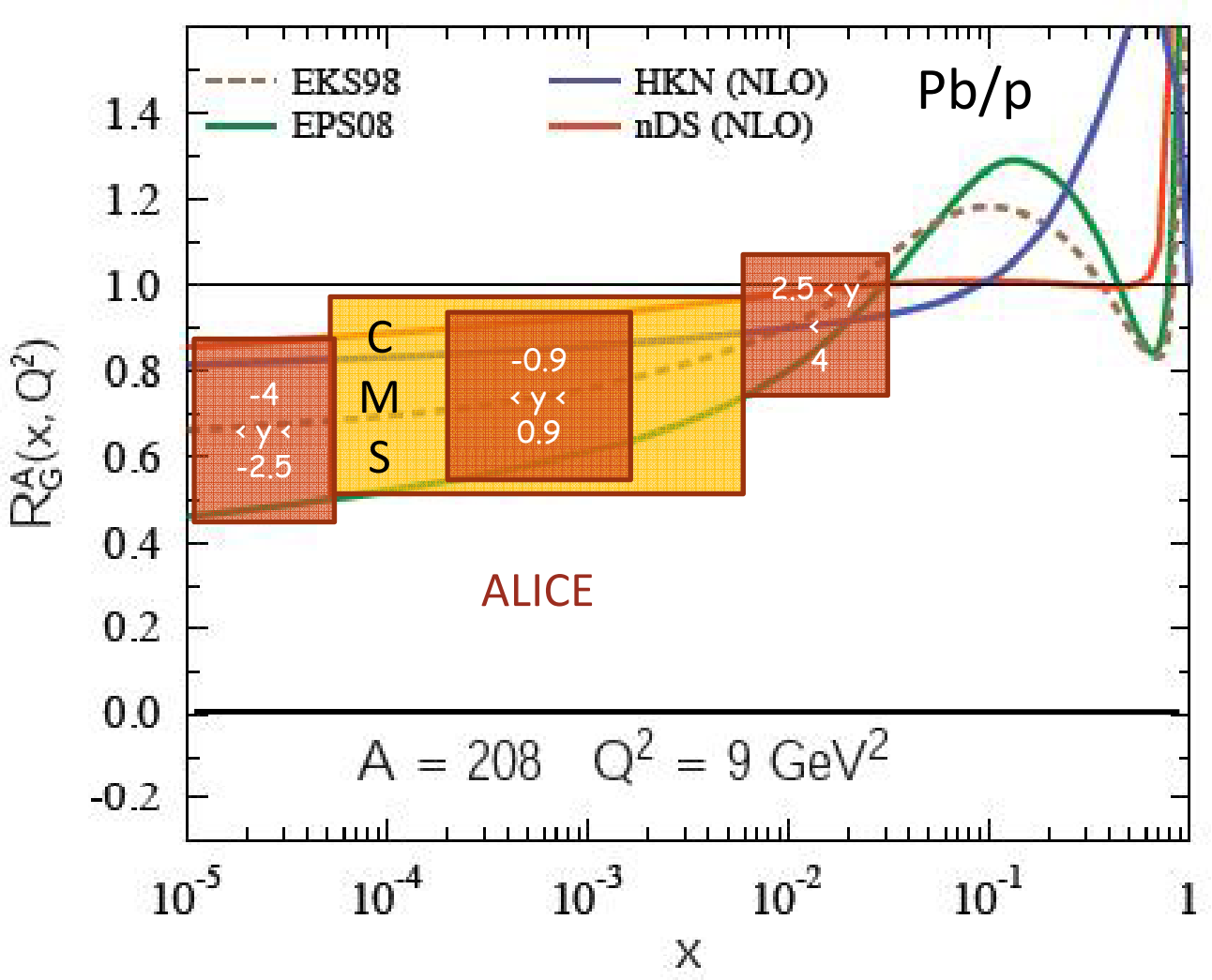
1. R_{dAu} versus rapidity





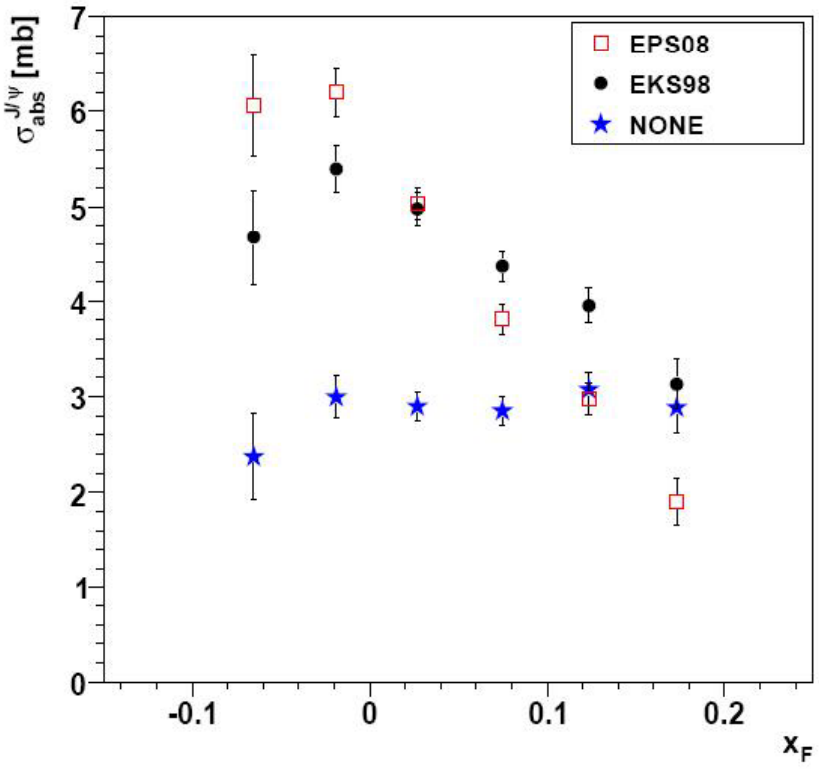
8. Quick look at shadowing on J/ψ

- (emitted gluons and p_T are neglected)
- A factor of ≈2x2 uncertainty on charm production from current shadowing knowledge

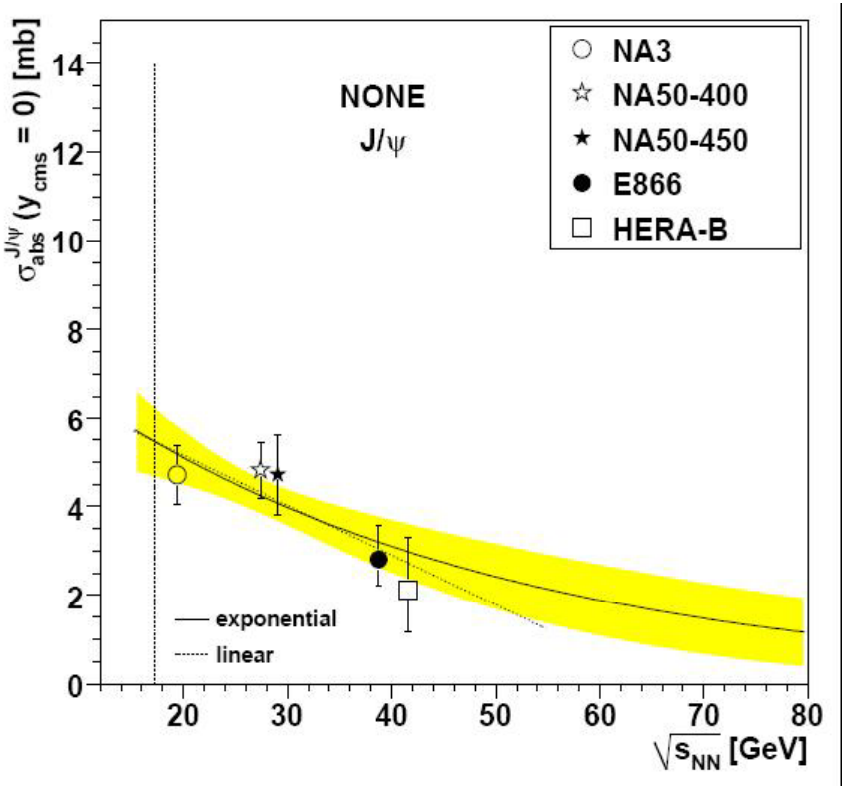


Lourenço et al, arxiv:0901.3054

E866 : flat with x_F if no shadowing is assumed…

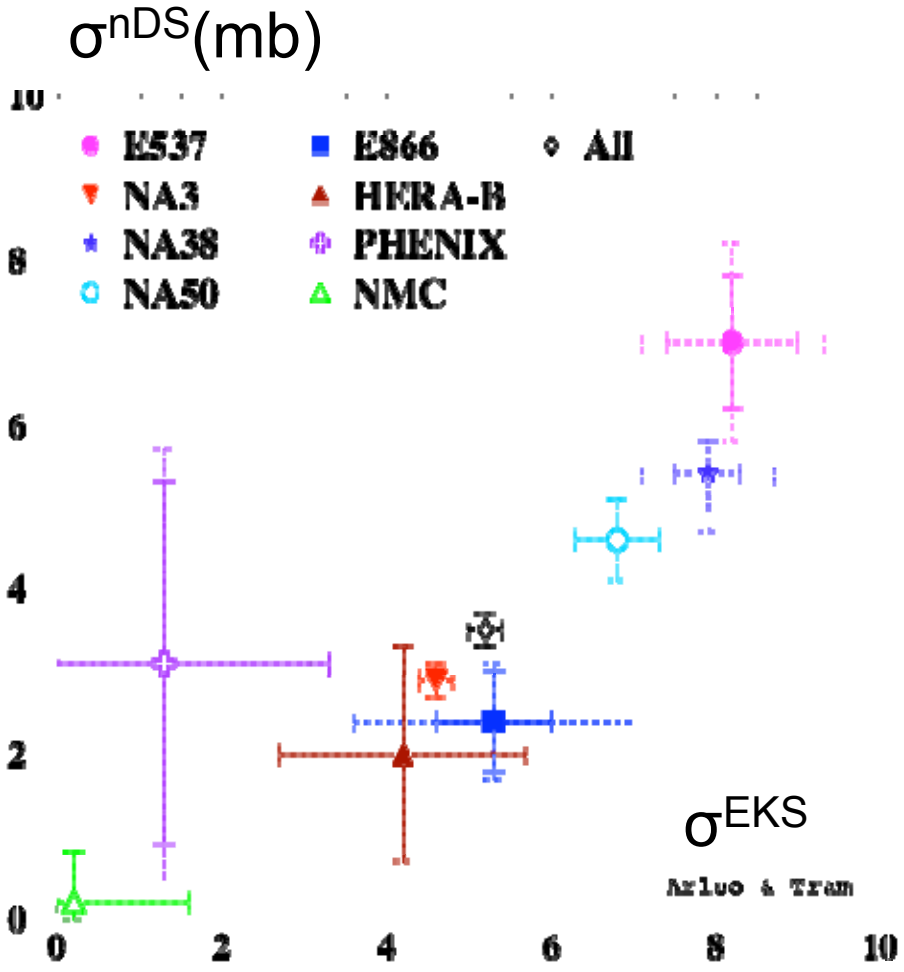


Even with no shadowing, little √s dependence of σ_{abs}



Still open questions at SPS…

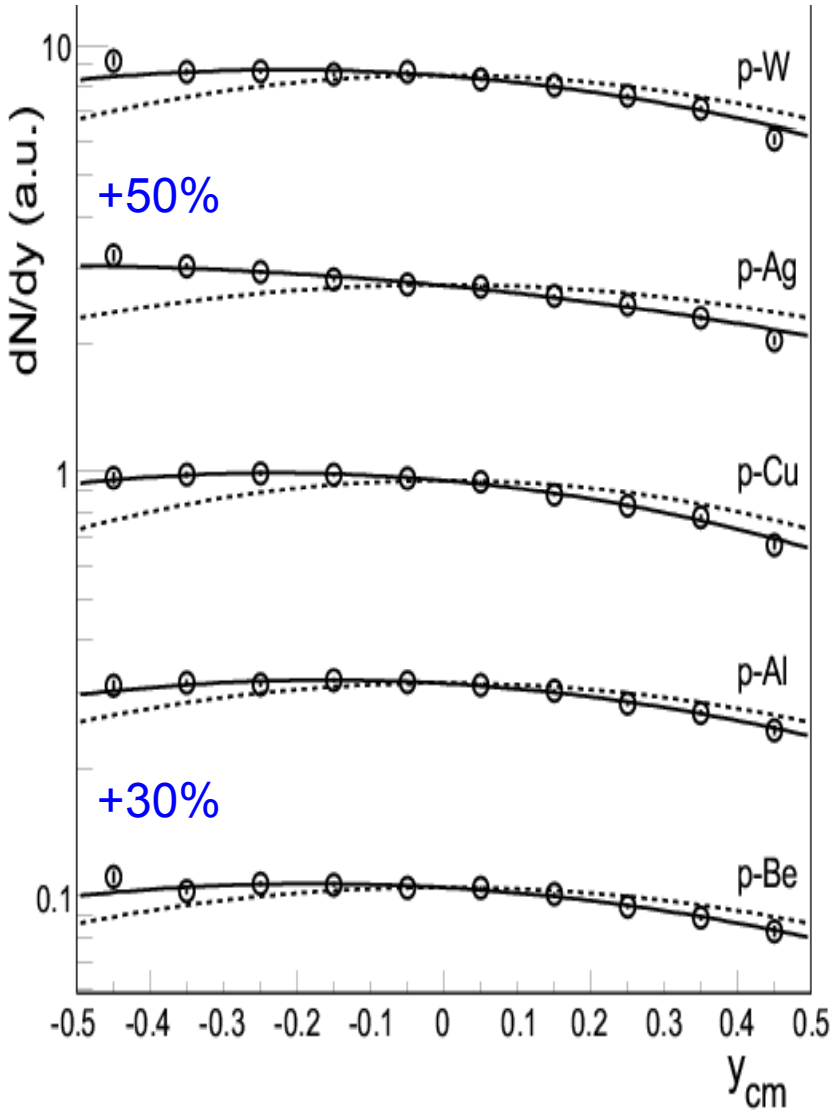
- Interplay shadowing – absorption →
- √s dependence of absorption?
  - Lourenço et al, arxiv:0901:3054.
- NA60, pA @ 168 GeV?
  - HP08? QM09?
- Unexplained rapidity dependence in pA?
  - Eur.Phys.J.C48:329,2006



Tram & Arleo, EPJ. C 55, 449-461 (2008)

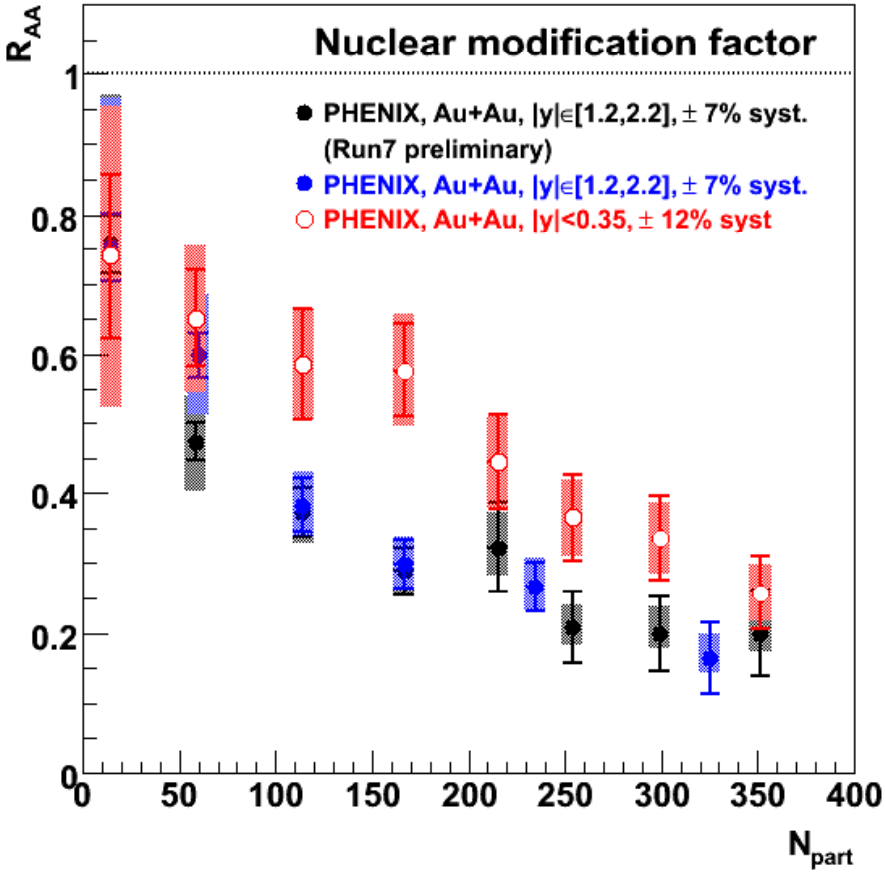
J/ψ in pA, NA50

- In pA, an unsolved rapidity dependence…
- EPJ…



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

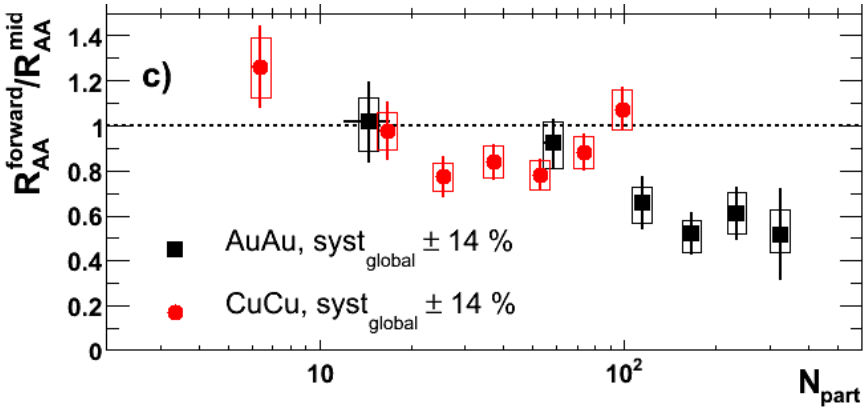
- Forward rapidity only (for now)
- More bins at higher centrality
- Confirm the trend
  - $R_{AA}(y\approx1.7) < R_{AA}(y\approx0)$

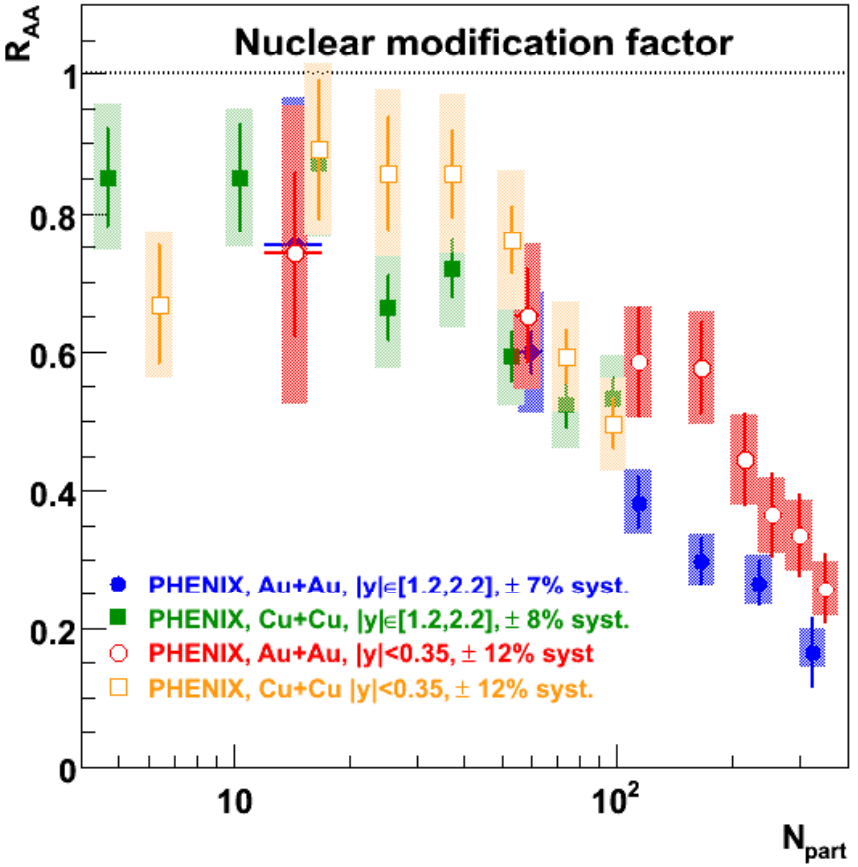


R_{AuAu} vs R_{CuCu} @RHIC

- Final CuCu analysis
- Slightly below 1 in CuCu

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





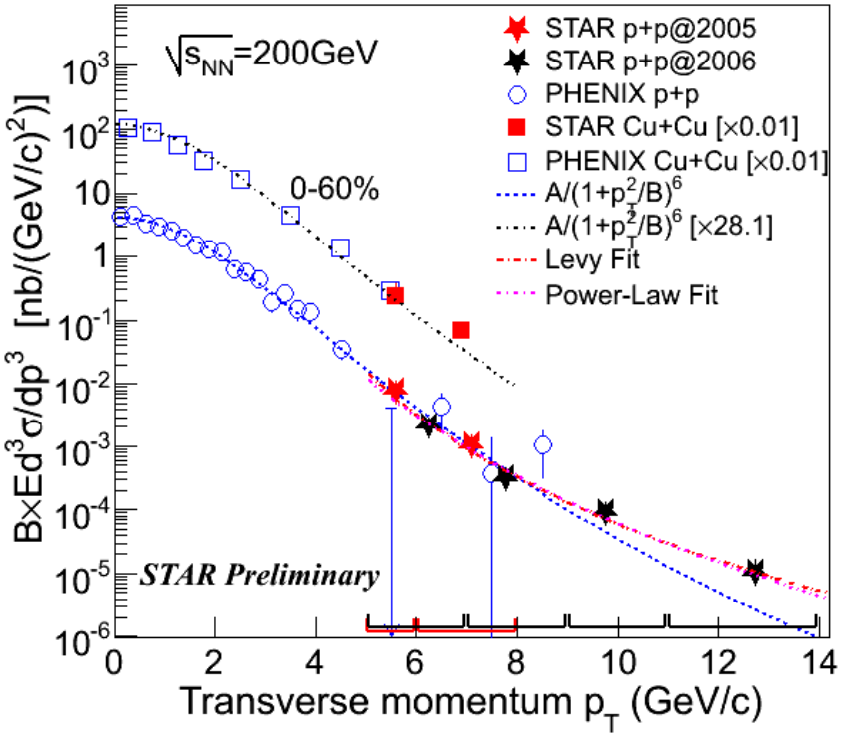
PHENIX, arXiv:0801.0220

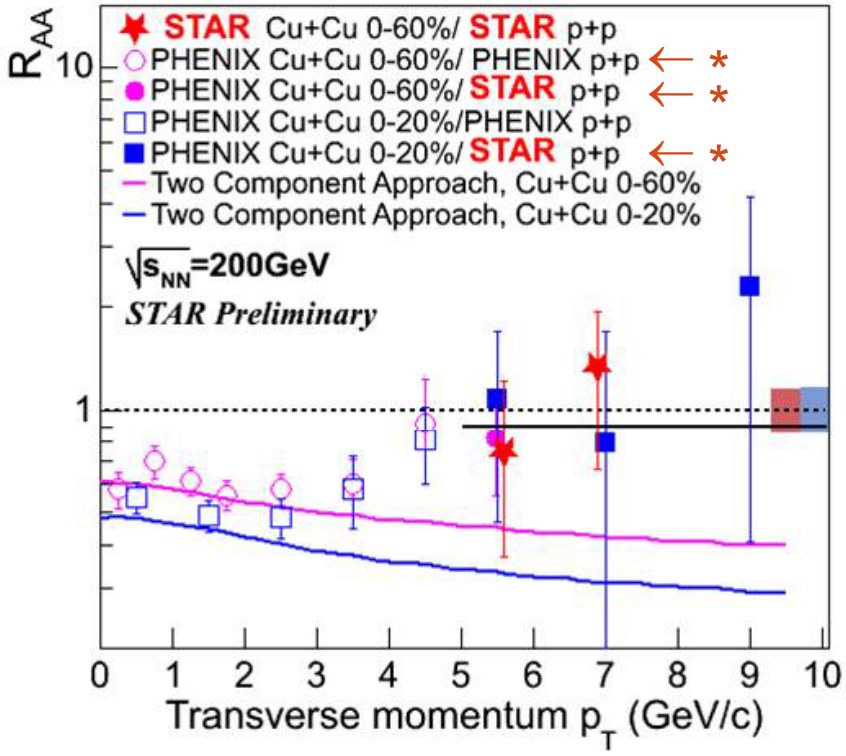
R_{CuCu} (STAR, high p_T) ≈ 1

2 sigma J/ψ signal in Cu+Cu

STAR = PHENIX charm spectra ☺

R_{CuCu} raising with p_T

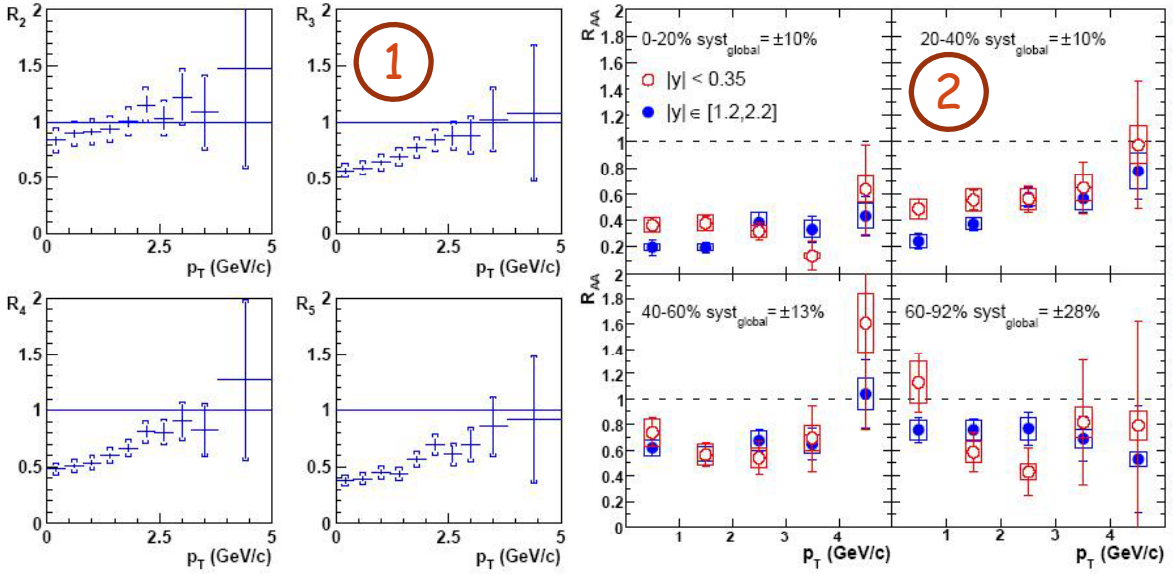


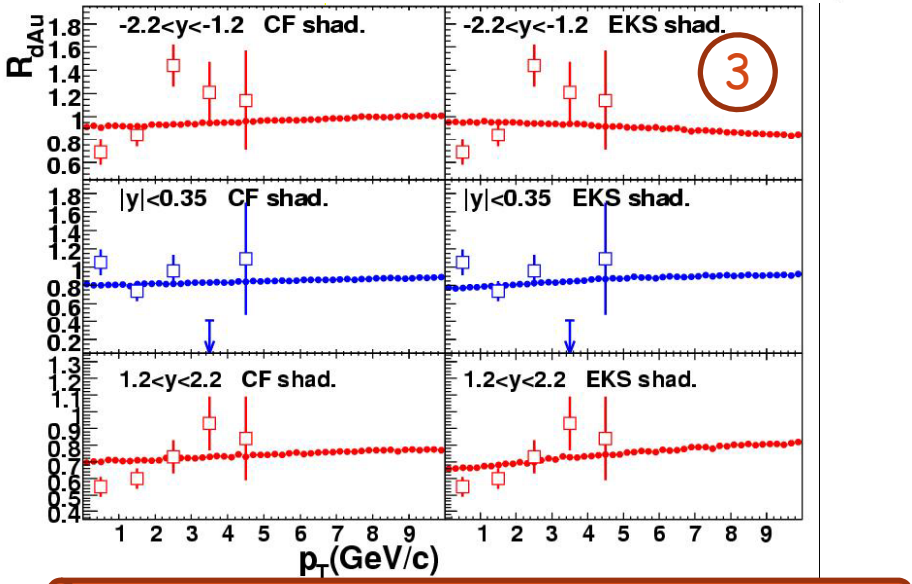


* These are not phenix results yet, but could become as soon as the two experiments talk to each others ☺

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…



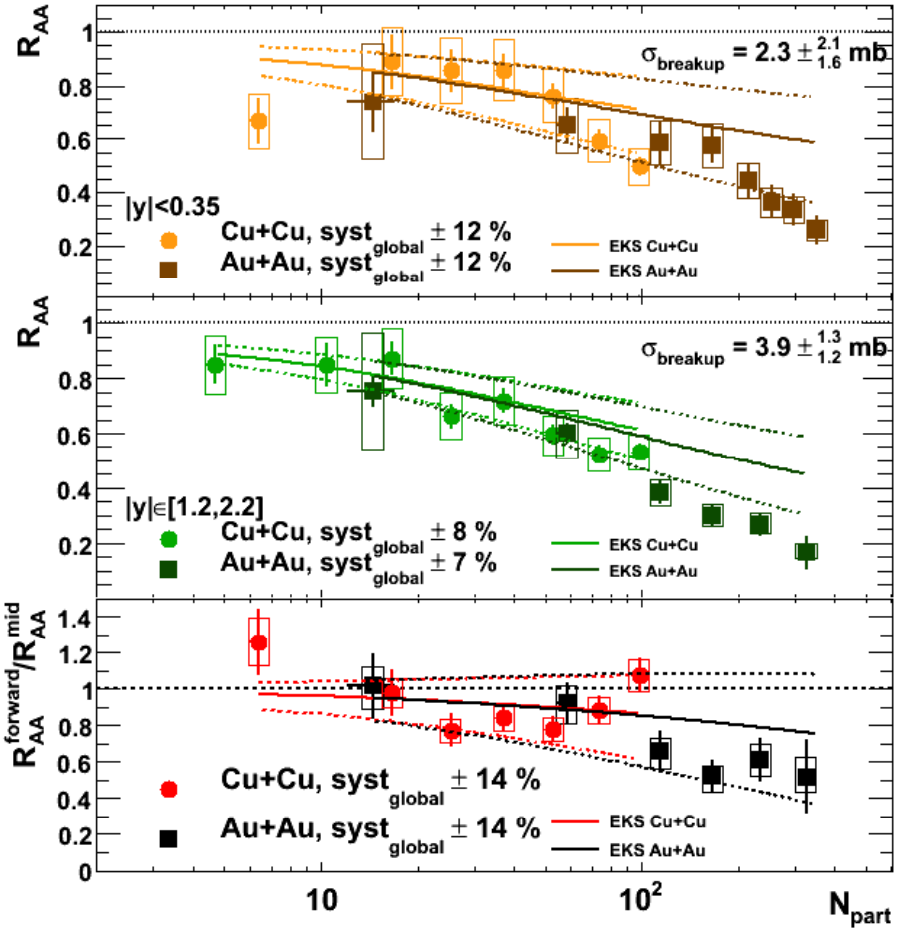


PHENIX, arxiv:0711.3917 compared to Ferreiro, Fleuret, Rakotozafindrabe, arxiv: 0801.4949

2. Cold matter again ?

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

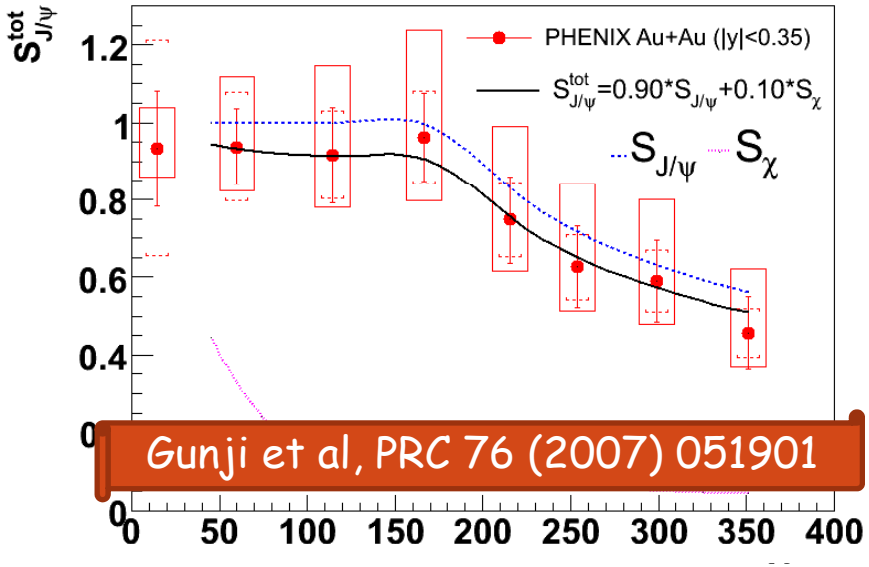
- Do you agree that we have poor handle on the cold nuclear matter effect?

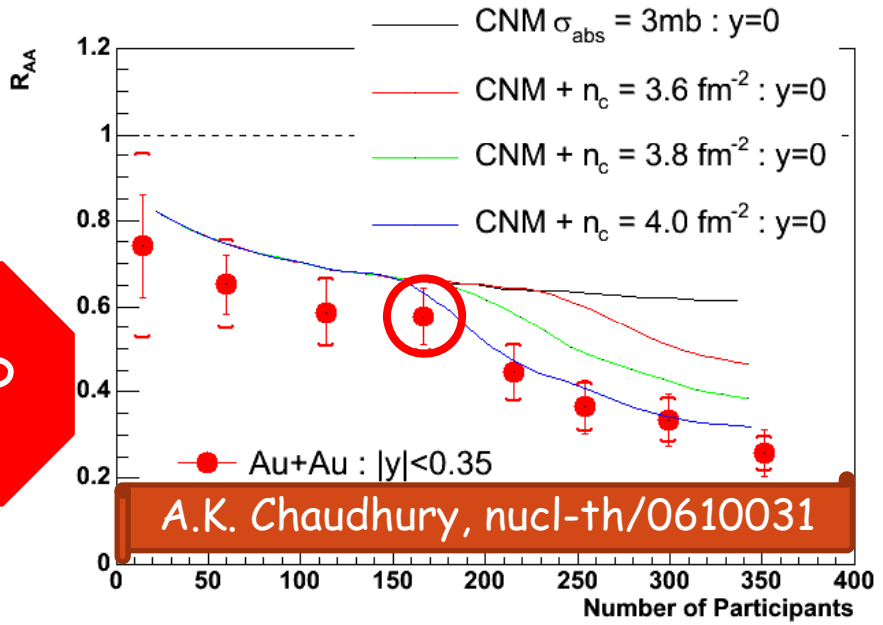


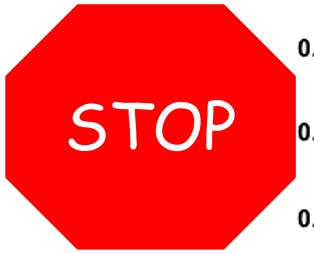
PHENIX, arxiv:0801.0220

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!

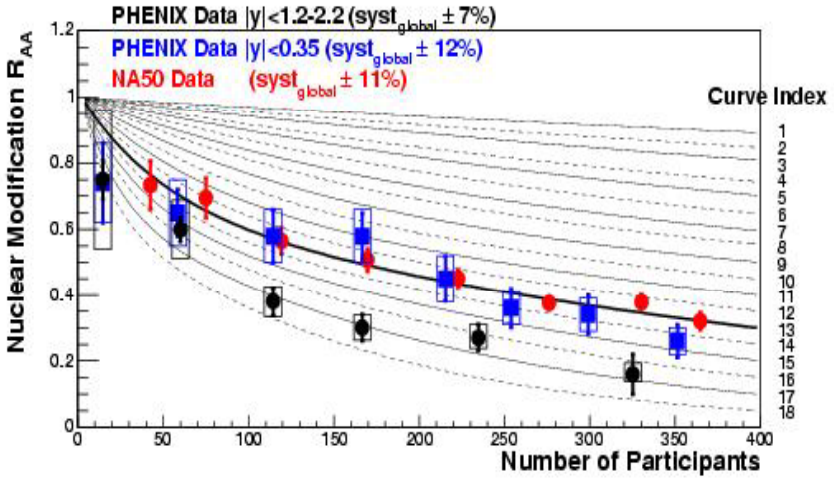


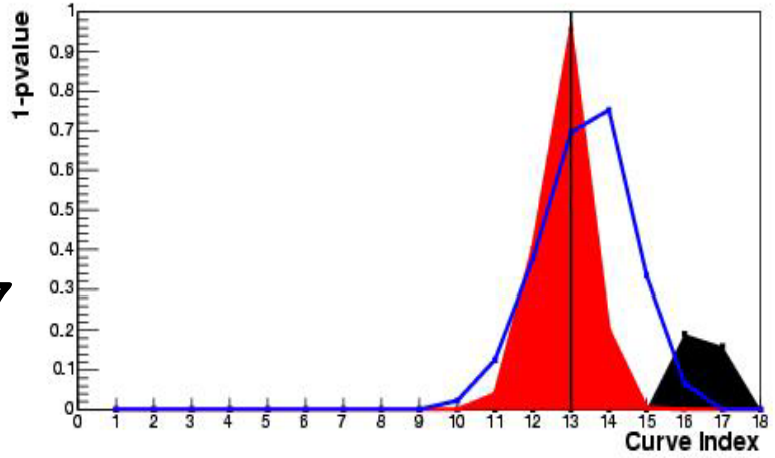




Density threshold ? No !

- 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

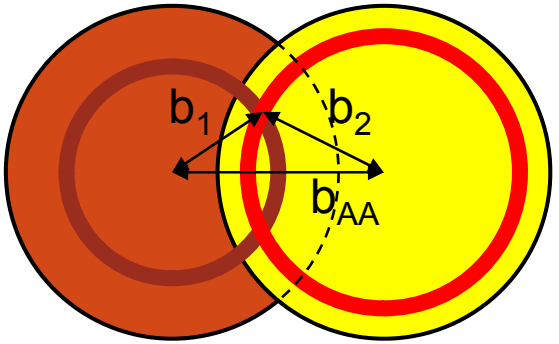




J. Nagle, nucl-ex/0705.1712

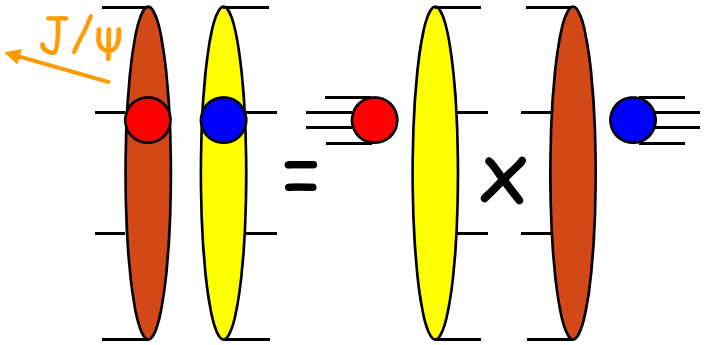
From dA to AA @ RHIC

- 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



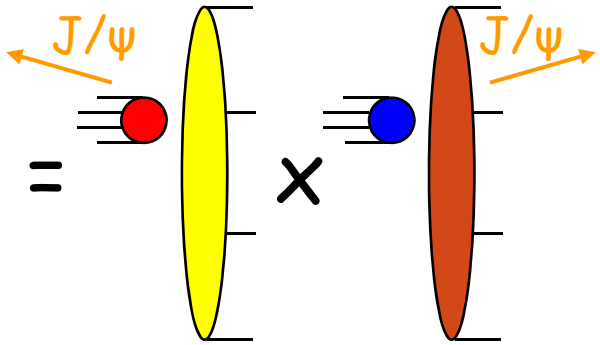
- One minimal assumption is rapidity factorization: $R_{AA}(|y|,b_{AA}) =$

  $\Sigma_{collisions}\ [R_{dA}(-y,b_i^1) \times R_{dA}(+y,b_i^2)] / N_{coll}$



- Works (at least) for absorption & shadowing since production

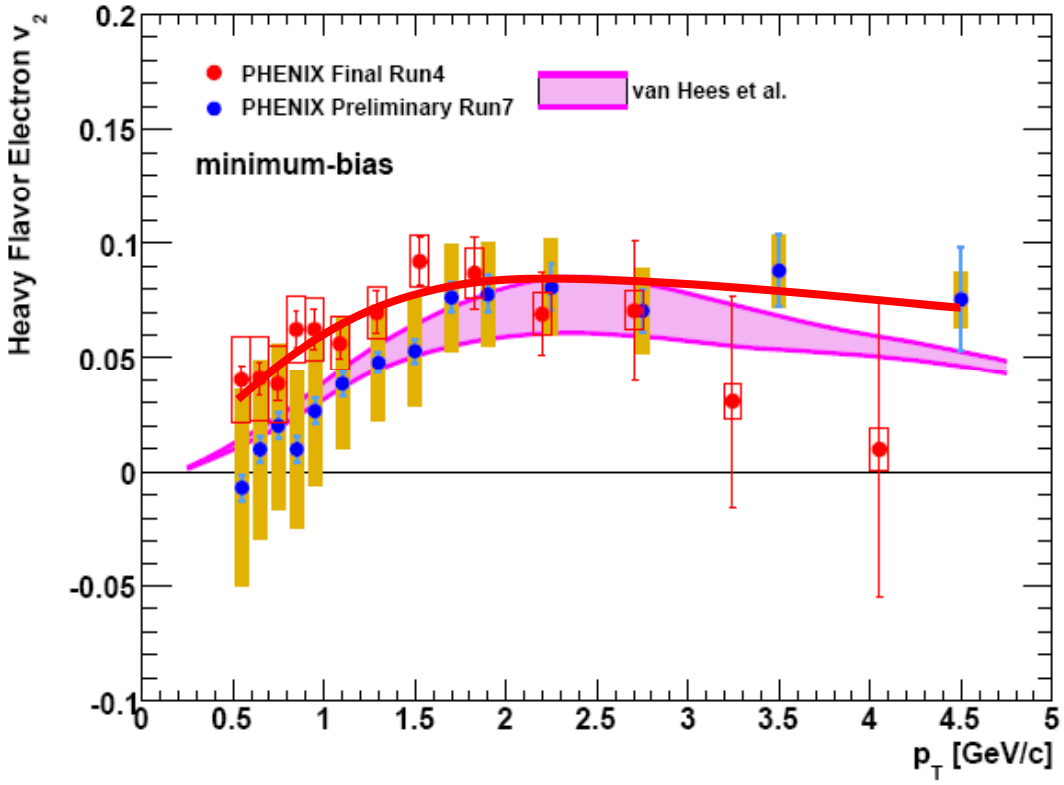
  ~ pdf1 x pdf2 x exp $-\rho\sigma(L_1+L_2)$



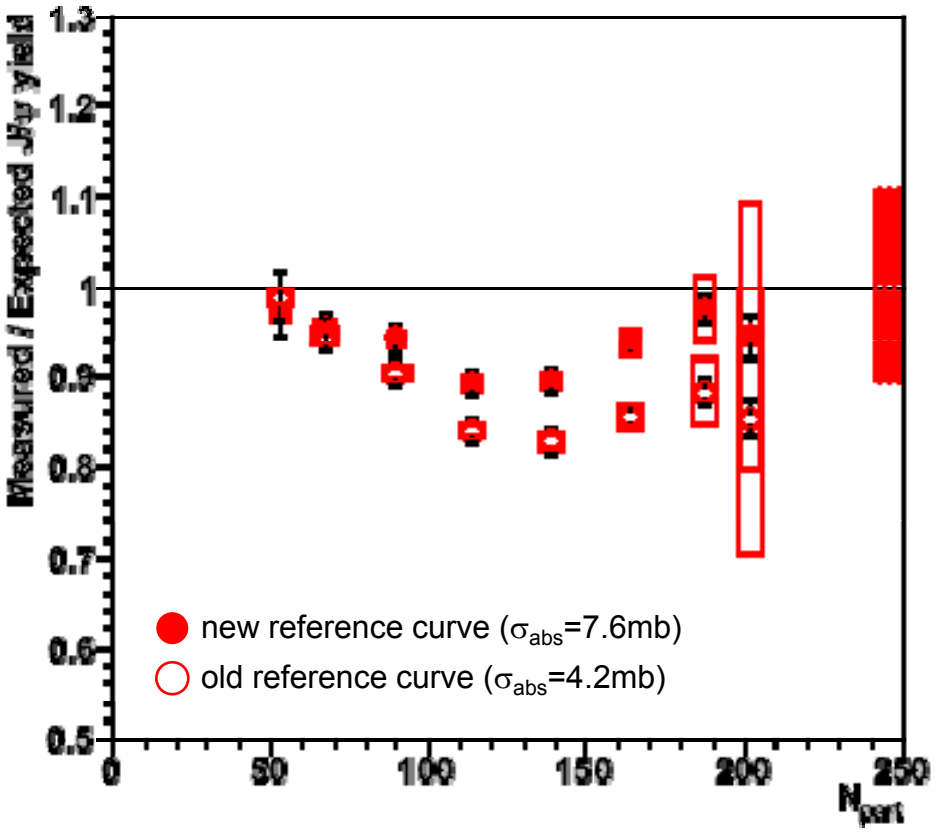
RGdC, hep-ph/0701222

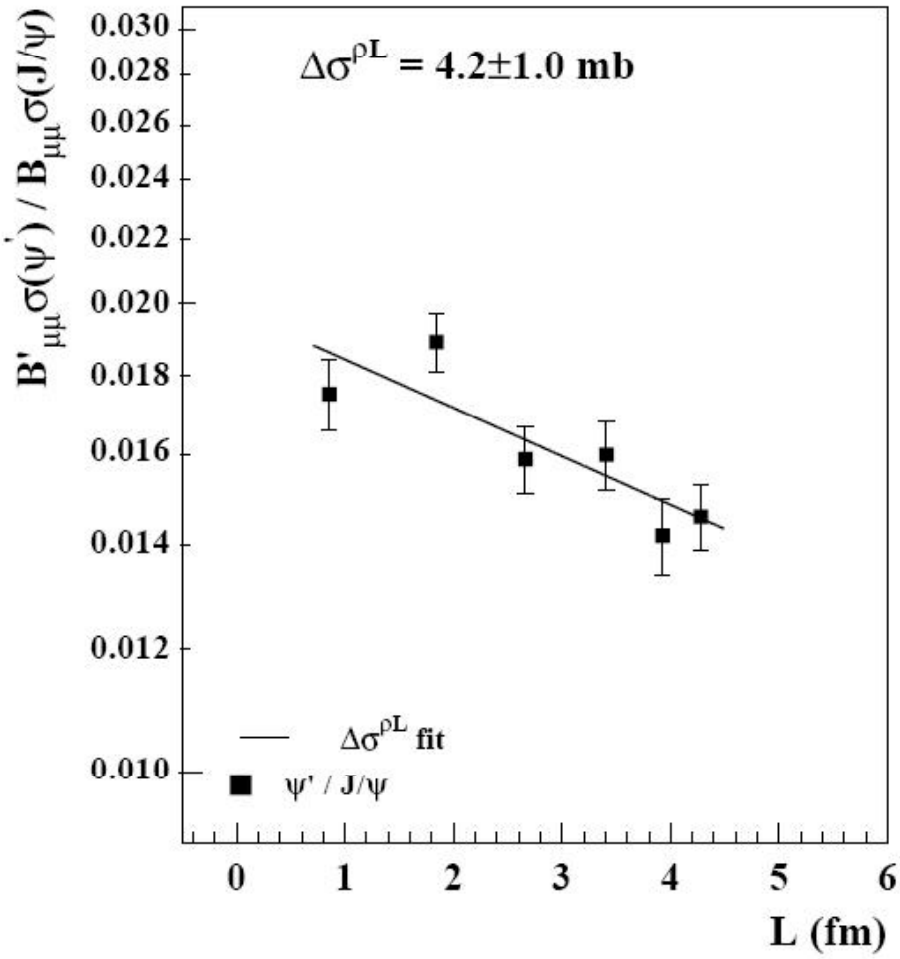
Heavy flavor elliptic flow

- Also a surprise!
- Now, do bees fly?
  - Need the b/c+b in AA to properly estimate the b flow…
- (todo : average the 2 datasets cause they have different stat/syst balance)



NA60 In+In


Measured / Expected J/ψ yield
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
50
100
150
200
250
N_part
new reference curve (σ_abs=7.6mb)
old reference curve (σ_abs=4.2mb)


$\Delta\sigma^{\rho L}$ = 4.2±1.0 mb
$B'_{\mu\mu}\sigma(\psi') / B_{\mu\mu}\sigma(J/\psi)$
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
$\Delta\sigma^{\rho L}$ fit
ψ' / J/ψ
0
1
2
3
4
5
6
L (fm)