J/ψ production in p+p, d+Au and Au+Au collisions at RHIC

Hugo Pereira Da Costa, for the PHENIX collaboration
CEA Saclay

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Introduction

Heavy quarkonia in HI collisions (1)

Heavy Quarkonia are good candidates to probe the QGP in heavy ion collisions because:

- they have large masses and are (dominantly) produced at the early stage of the collision, via hard-scattering of gluons.
- they are strongly bound (small radius) and weakly coupled to light mesons.

	mass	radius
ψ'	3.68 GeV	0.90 fm
χ_c	3.53 GeV	0.72 fm
J/ψ	3.1 GeV	0.50 fm
ϒ	9.5 GeV	0.28 fm

Sensitive to the formation of a quark gluon plasma via color screening.

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

PLB 178, 416 (1986)

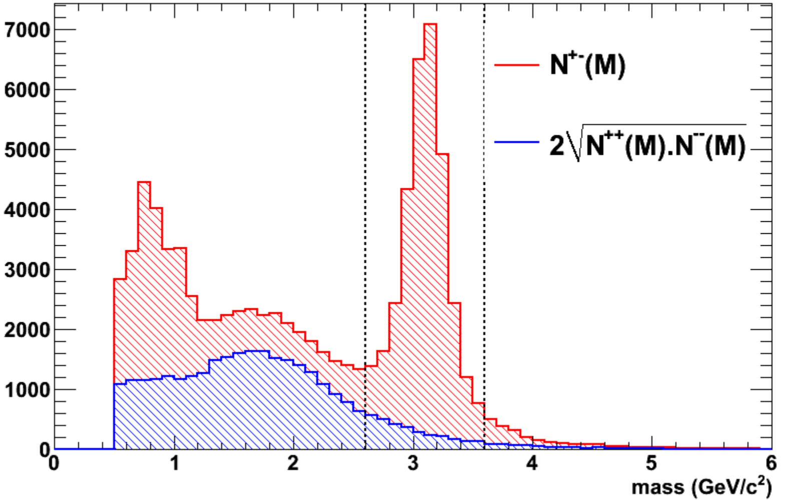
Heavy quarkonia in HI collisions (2)

However:

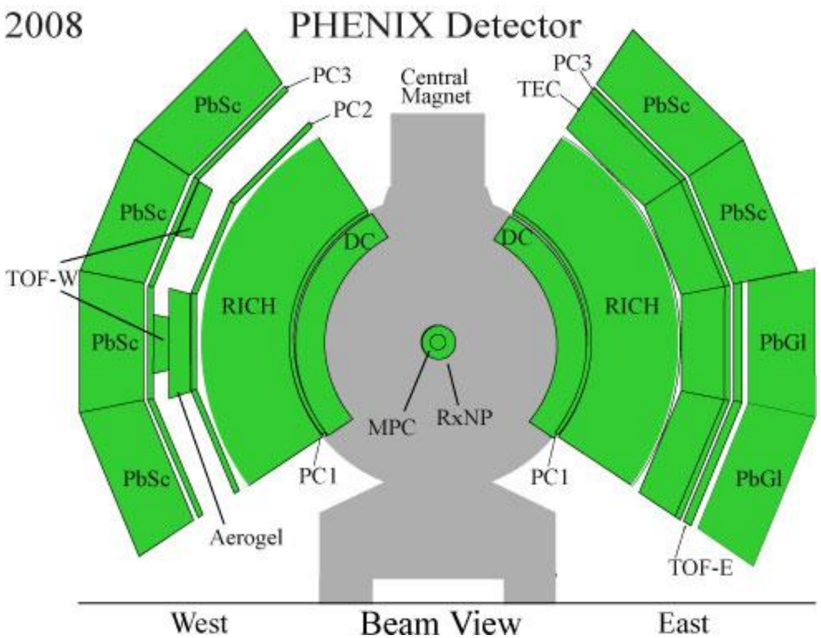
1. Although heavy quarkonia are hard probes, the production mechanism (in p+p) in not well understood;
2. There are many effects that can alter this production in presence of normal nuclear matter (in e.g. p(d)+A);
3. It is unclear how to extrapolate, and subtract these effects from what is measured in A+A, to single-out QGP effects.

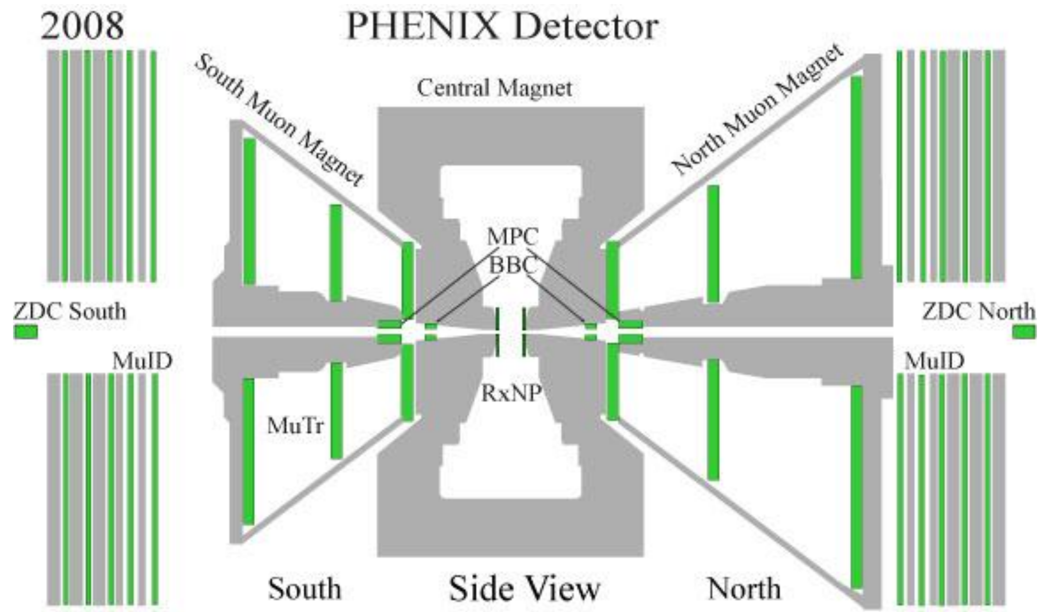
Still:

As a resonance, heavy quarkonia are *easy* to measure (and separate from background) as opposed to most other hard probes (photons, open heavy flavors, jets)



Heavy quarkonia measurements in PHENIX





Mid rapidity: $J/\psi \rightarrow e^+e^-$
$|\eta|<0.35$, $\Delta\Phi = 2 \times \pi/2$, $p>0.2$ GeV/c

Forward rapidity: $J/\psi \rightarrow \mu^+\mu^-$
$1.2<|\eta|<2.2$, $\Delta\Phi=2\pi$, $p>2$ GeV/c

Electrons identified using RICH and EMCAL; tracked using pad and drift chambers

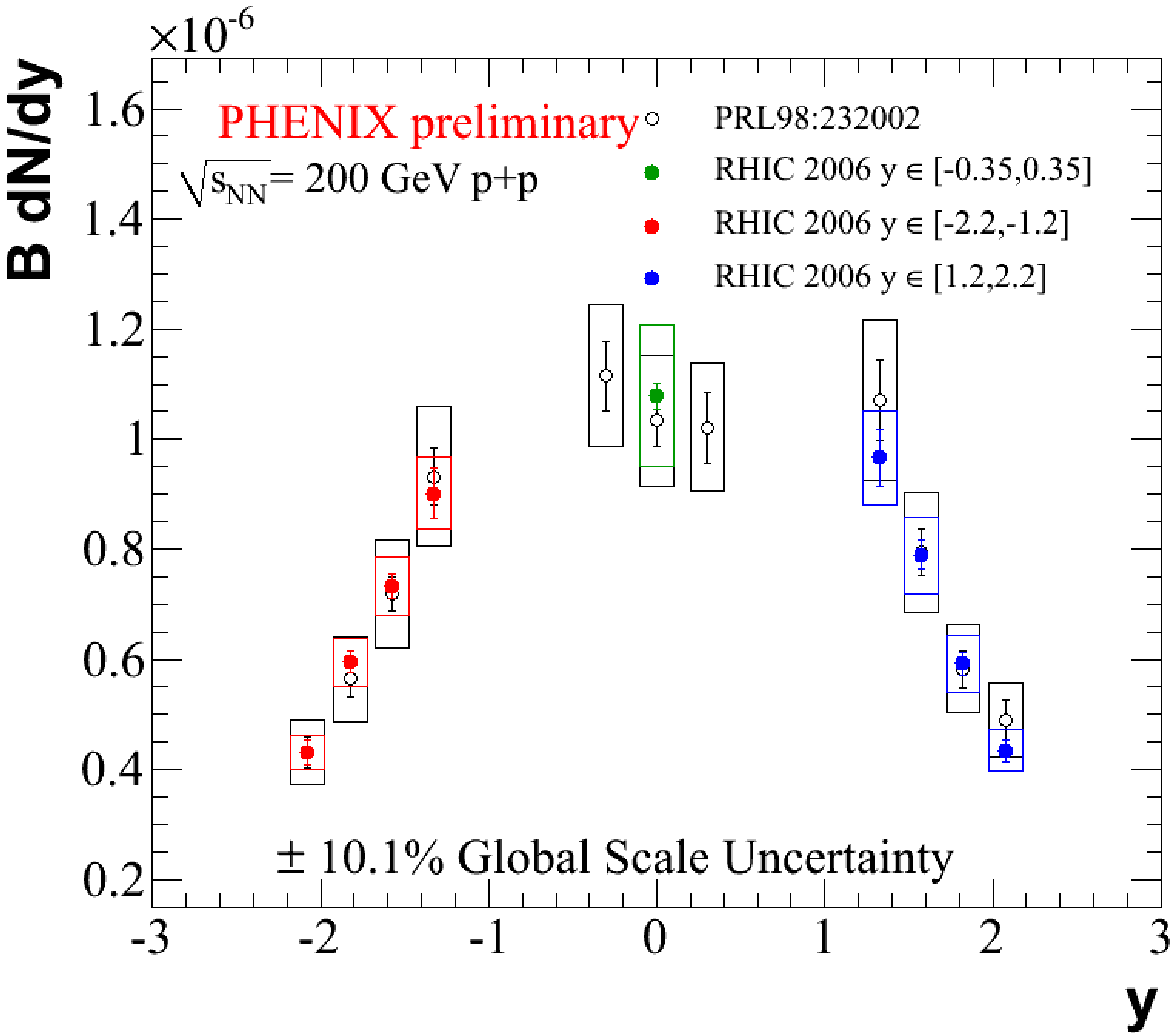
Muons identified using layered absorber + Iarocci tubes; tracked using 3 stations of cathode strip chambers, in radial magnetic field

Outline

- p+p collisions:
  baseline for d+A and A+A collisions
- d+Au collisions:
  cold nuclear matter effects
- Cu+Cu and Au+Au:
  hot nuclear matter effects

I. p+p collisions:
Baseline for d+A and A+A collisions

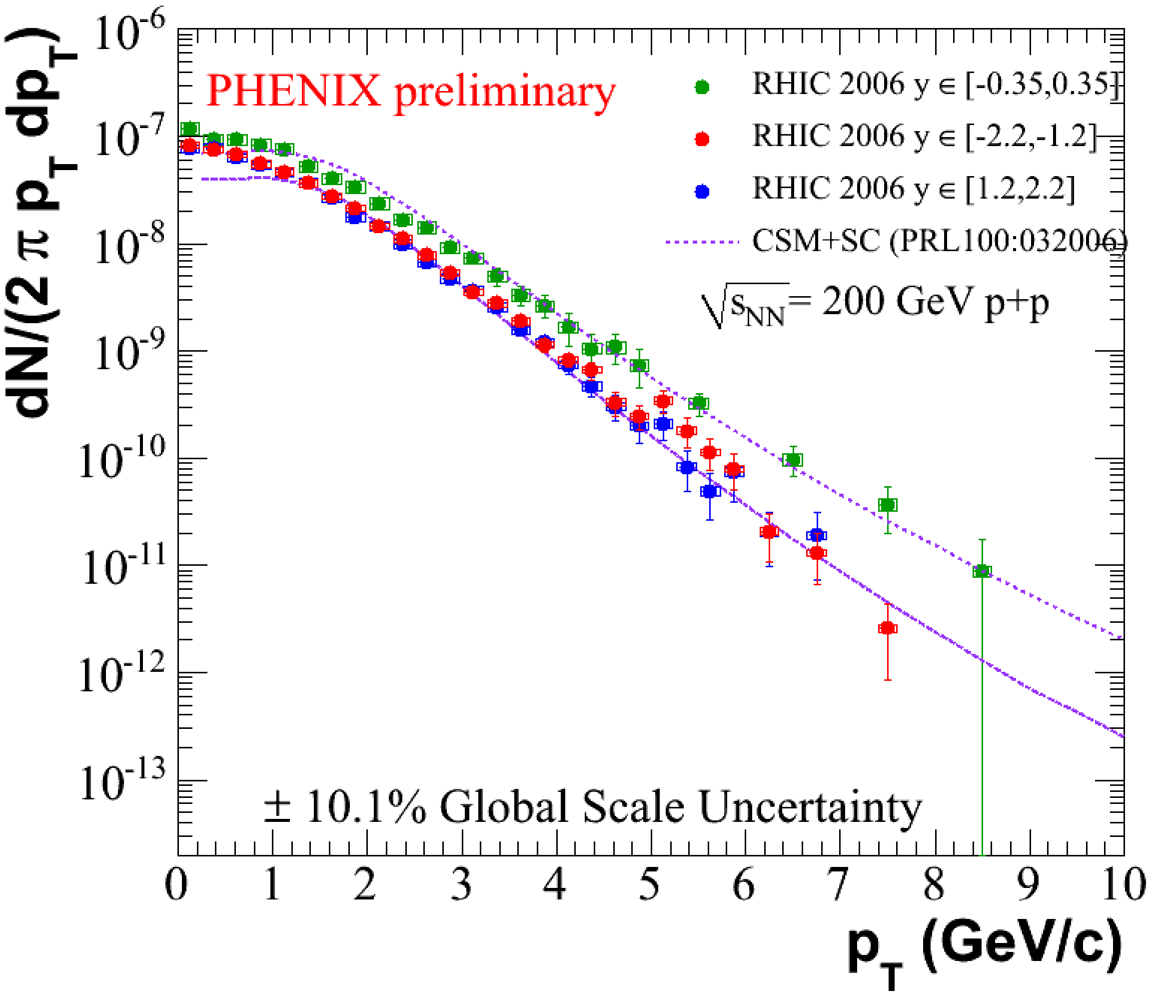
J/ψ measurements (1)



Higher statistics and better control over systematic uncertainties.

Excellent agreement with published results.

J/ψ measurements (2)



Excellent agreement between data at positive and negative rapidity.

Harder spectra observed at mid-rapidity.

Lines correspond to **one** calculation of J/ψ p_T distributions, namely: CSM (LO)+S channel cut

PRL 100, 032006 (2008)

Note: there are concerns about the validity of s-channel cut approach and the magnitude of the obtained contribution

PRD 80, 034018 (2009)

II. d+Au collisions:
Cold nuclear matter effects

Cold nuclear matter effects (CNM)

Anything that can modify the production of heavy quarkonia in heavy nuclei collisions (as opposed to p+p) in absence of a QGP

Initial state effects:
- Energy loss of the incoming parton
- Modification of the parton distribution functions (npdf)
- Gluon saturation (CGC)

Final state effects:
Dissociation/breakup of the J/ψ (or precursor $c\bar{c}$ quasi-bound state)
Modeled using a break-up cross-section $\sigma_{breakup}$

Modified PDF (npdf)

npdf refer to the fact that parton distributions (as a function of x_{bj}) inside a nucleon differ whether the nucleon is isolated or inside a nuclei.

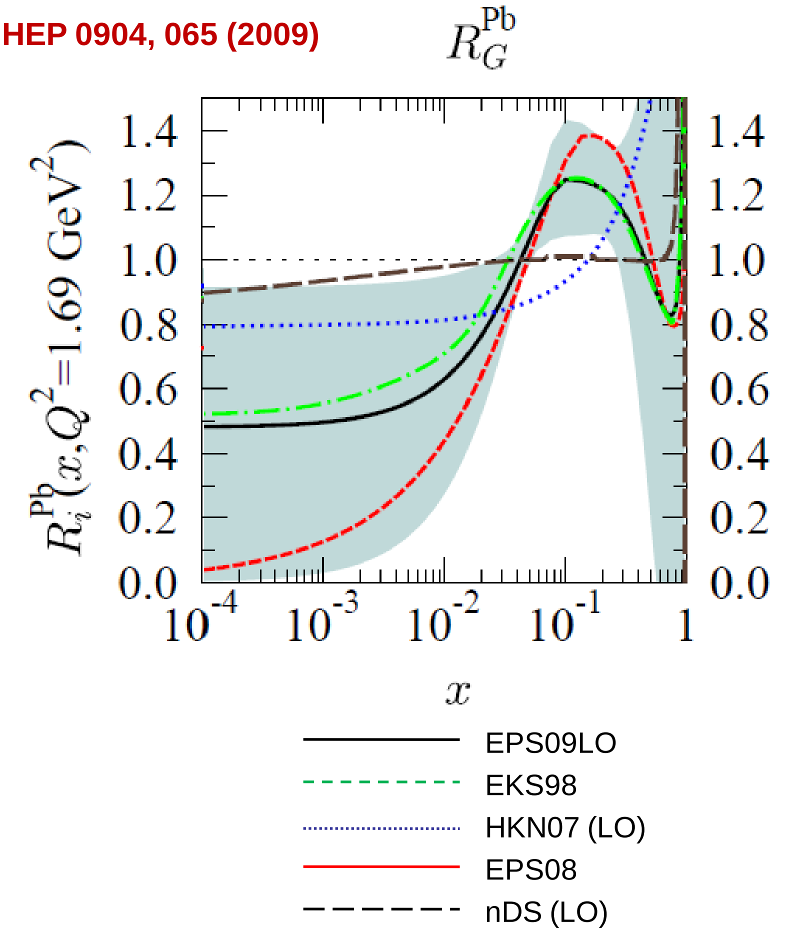
Gluon nuclear npdfs are poorly known, especially at low x (shadowing region).

Various parametrizations range from

- little shadowing (HKN07, nDS, nDSg)
- moderate shadowing (EKS98, EPS09)
- large shadowing (EPS08)

Grayed area correspond to uncertainty due to limited data available for constrain.

JHEP 0904, 065 (2009)

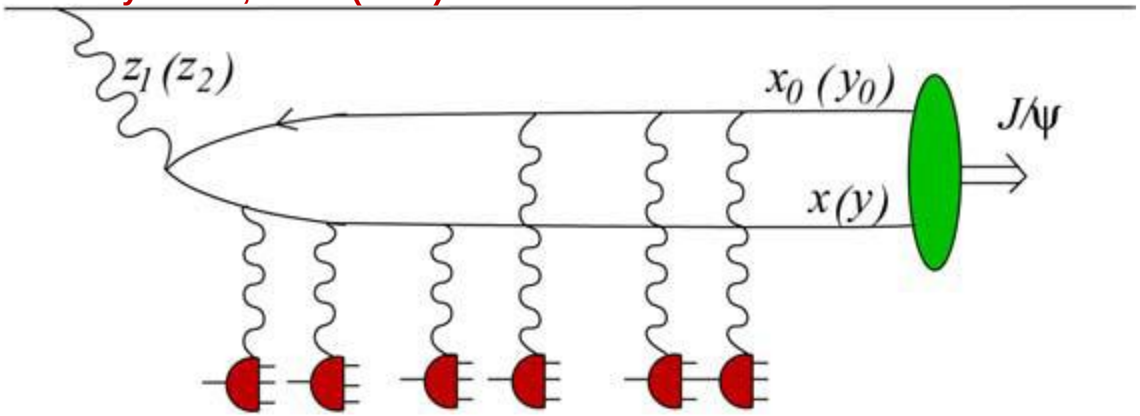


Gluon saturation

Provides a different picture of the dAu collision and how J/ψ is produced

At low enough x_2 (in the target nuclei), the gluon wave functions overlap. The $c\bar{c}$ pair from the projectile parton interacts coherently with all nucleons from the target, resulting in the J/ψ formation.

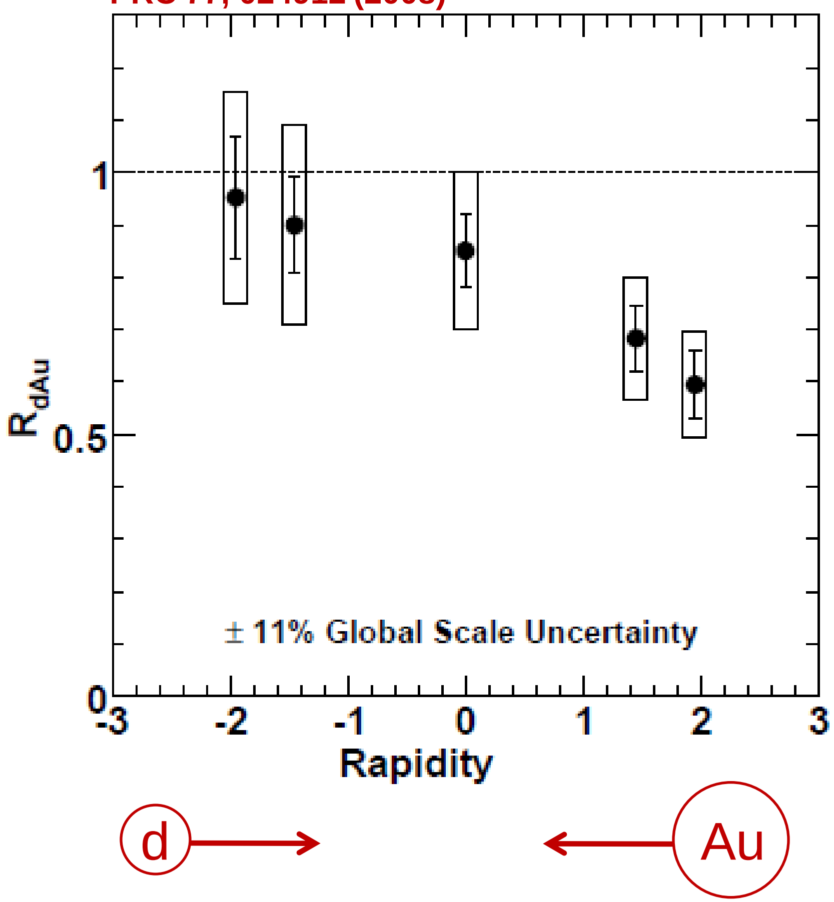
Nucl.Phys.A770, 40-56 (2006)



This is applicable at low x_2 (forward rapidity) only;

J/ψ production in d+Au (1) 2003 data

PRC 77, 024912 (2008)



Nuclear modification factor:

$$R_{dA} = \frac{\text{yield in dA}}{N_{coll}.\ \text{yield in pp}}$$

N_{coll}: number of equivalent p+p collisions for one d+Au collision at a given centrality

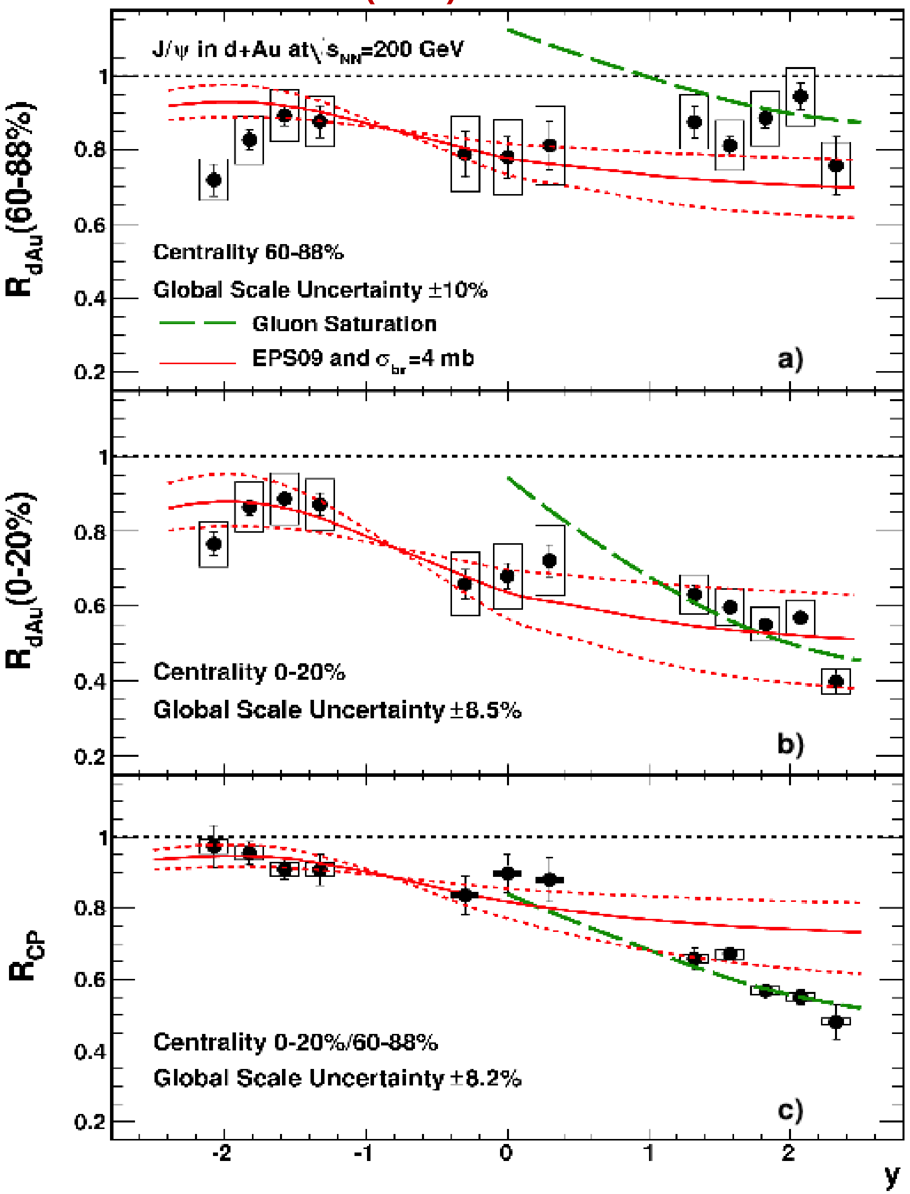
R_{dA} should be flat, equal to 1 in the absence of effects with respect to scaled p+p

y<0: Au going side. Large x (gluon momentum) in Au nuclei

y>0: deuteron going side. Small x in Au nuclei.
Suppression is observed

npdf + $\sigma_{breakup}$ vs (2008) data

arXiv:1010.1246 (2010)



npdf + breakup cross-section

- Take an npdf prescription (here EPS09)
- Add a breakup cross-section
- Calculate CNM as a function of the collision centrality
- Compare to (more precise) 2008 data.

At forward rapidity, this approach (red lines) cannot describe both the peripheral and the central data. This is best illustrated by forming the ratio of the two (Rcp)

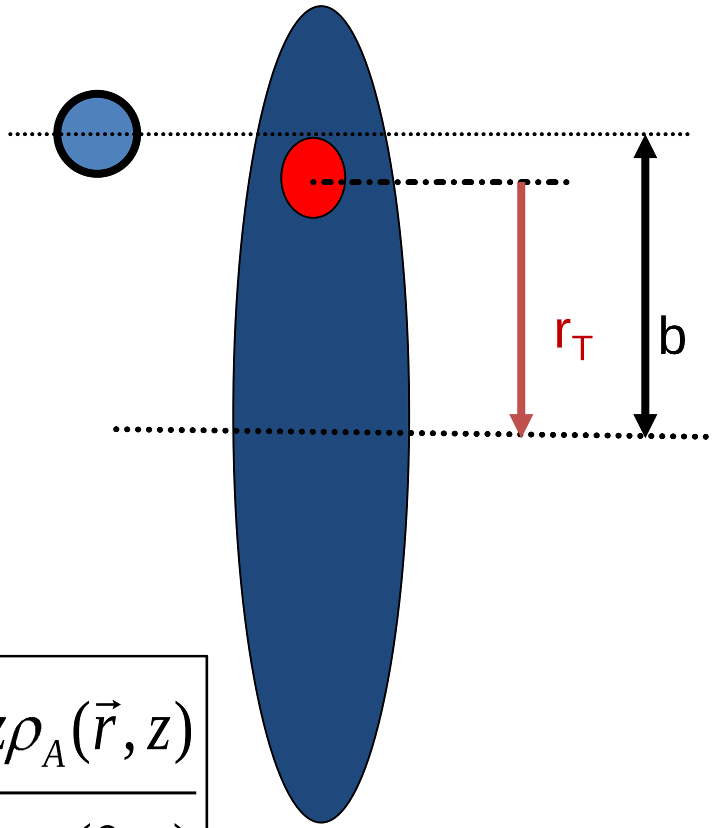
Color Glass Condensate:

On the other hand, data are reasonably well reproduced at forward rapidity by CGC (green lines) for all centralities.

Centrality dependence of CNM effects (1)

Centrality dependence is expressed as a function of the (density weighted) longitudinal thickness $\Lambda(r_T)$ of the Au nucleus, with r_T the distance of the target nucleon to the nucleus center:

$$\Lambda(r_T) = \frac{1}{\rho_0} \int dz \rho(z, r_T)$$



For illustration:

$$S^j_{P,\rho}(A, x, Q^2, \vec{r}) = 1 + N_\rho [S^j_P(A, x, Q^2) - 1]. \frac{\int dz \rho_A(\vec{r}, z)}{\int dz \rho_A(0, z)}$$

R. Vogt, arXiv:hep-ph/0411378v1 (2004)

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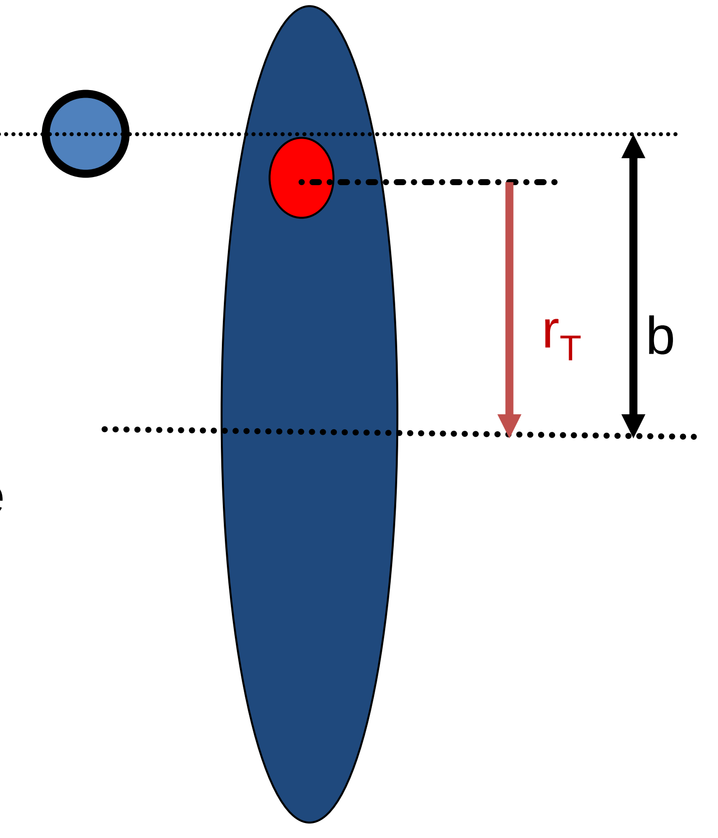


One can assume several functional forms for the dependence of the J/psi suppression vs Λ(rt):

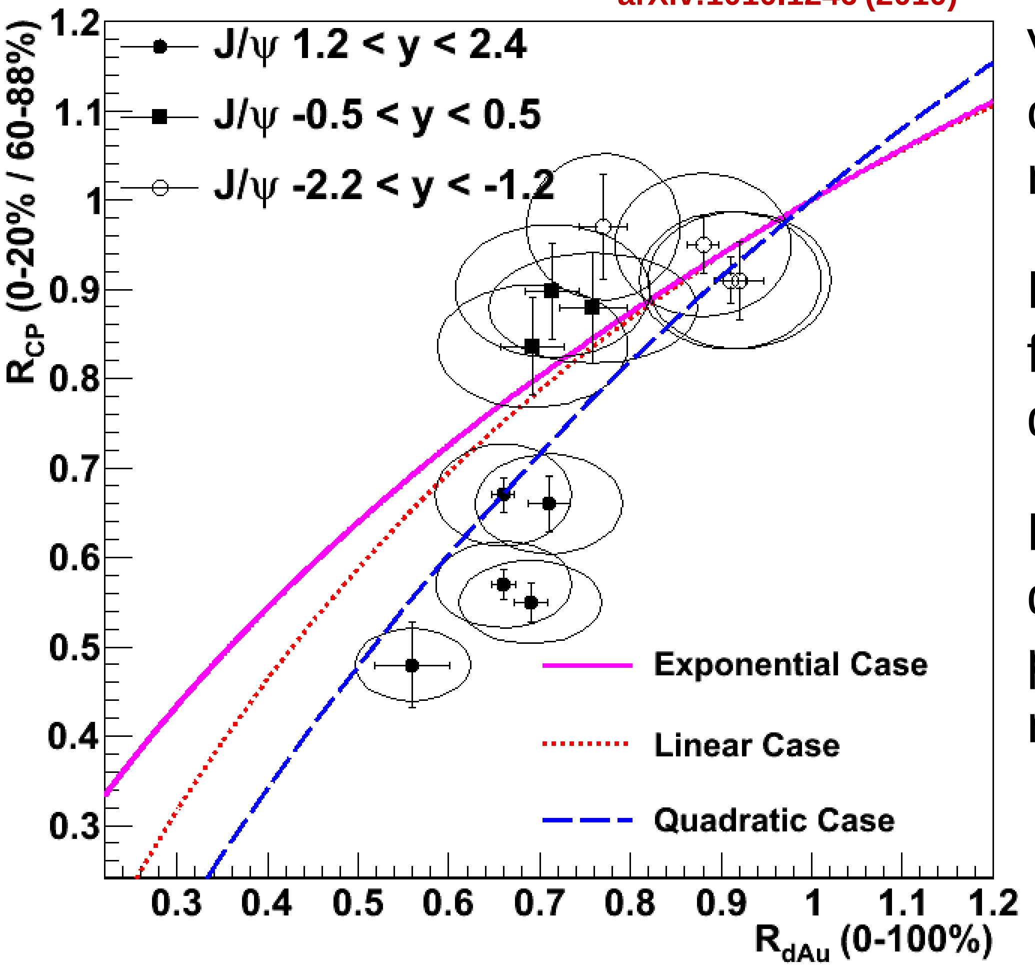
exponential:	$S(r_T) = e^{-a\Lambda(r_T)}$
linear:	$S(r_T) = 1 - a\Lambda(r_T)$
quadratic:	$S(r_T) = 1 - a\Lambda(r_T)^2$

Knowing the distribution of r_T vs centrality, each form induces a unique (parameter free) relationship between R_{CP} and R_{dA} (in arbitrary centrality bins)

One can plot these relationships, and compare to data (as well as models)

Centrality dependence of CNM effects (2)

arXiv:1010.1246 (2010)



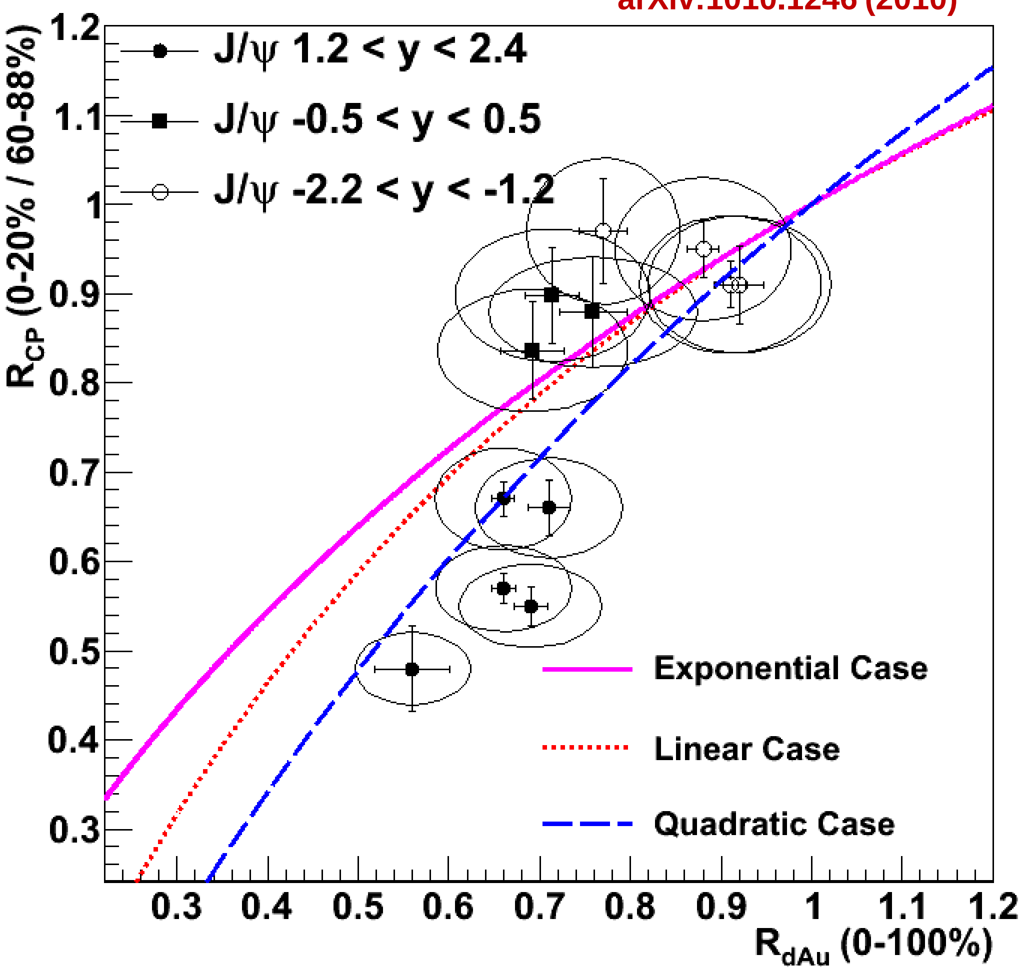
Various thickness dependencies chosen for illustration differ mostly at forward rapidity.

Mid and backward rapidity points favor exponential or linear dependency.

Forward rapidity data show a different behavior, possibly pointing to different (or additional) mechanism at play.

Centrality dependence of CNM effects (2)

arXiv:1010.1246 (2010)



Use of npdf (EKS98, EPS09, etc.) to make centrality dependent predictions assumes <u>linear dependence</u>

Addition of break-up cross-section (usually) assumes <u>exponential dependence</u>

consequently, all such models lie between the red and the purple curve (and miss the forward rapidity points)

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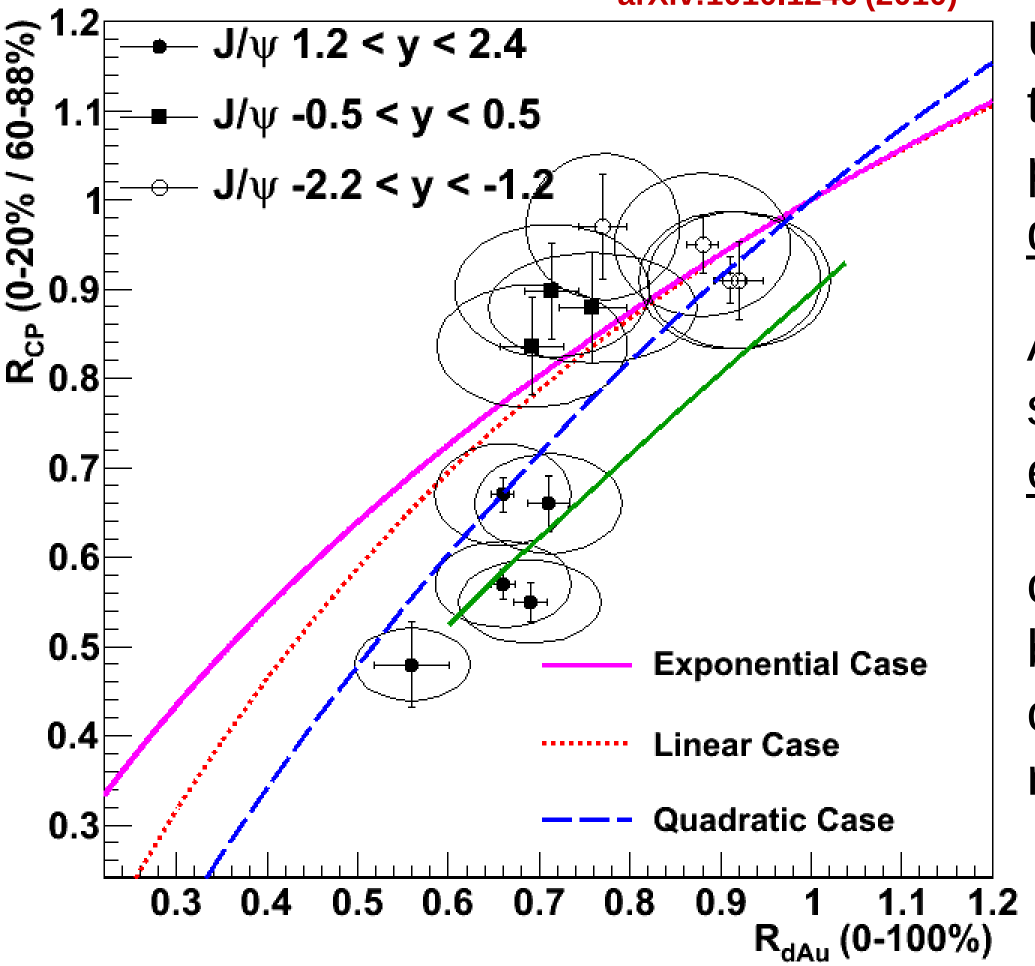
arXiv:1010.1246 (2010)



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For comparison, one CGC calculation is shown here as a green line

Nucl.Phys.A770, 40-56 (2006)

More details in arXiv:1011.4534.

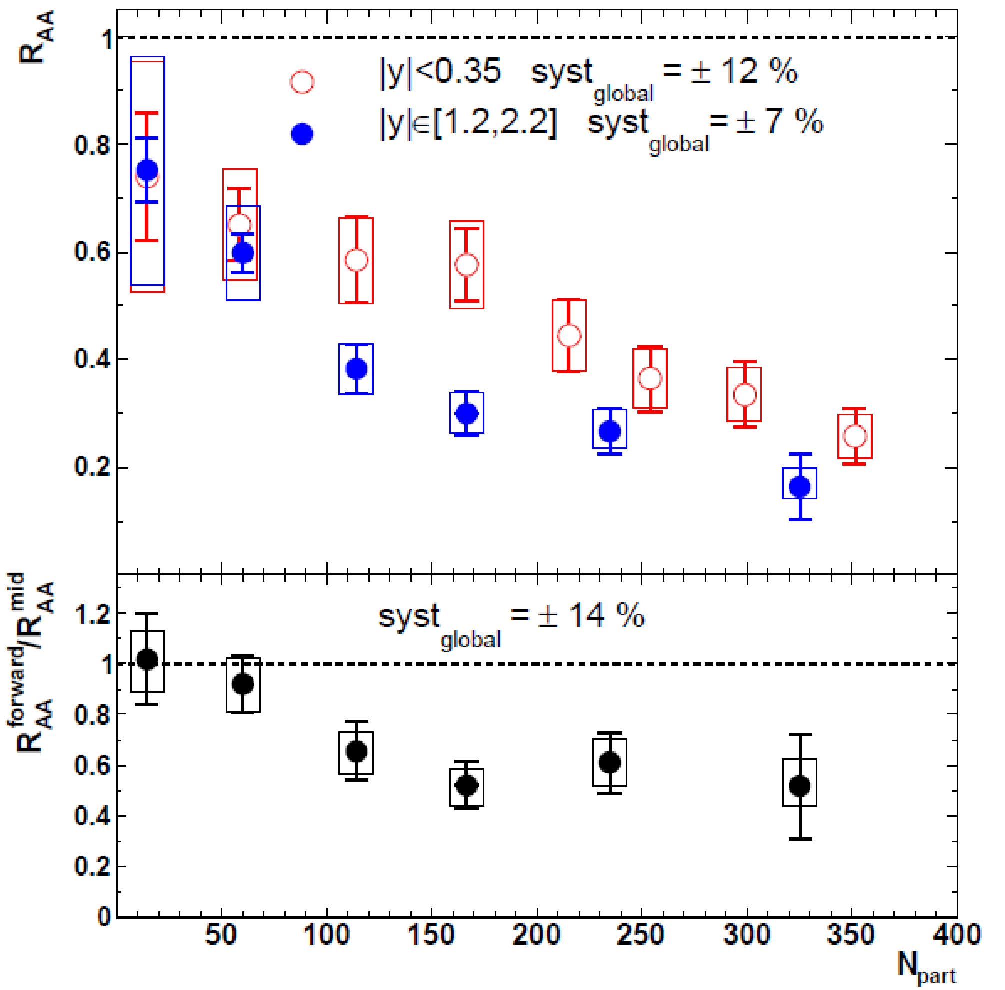
III. A+A collisions:
anomalous suppression ?

J/ψ R_{AA} vs N_{part} (1)

2004 data published in
PRL 98, 232301 (2007)
J/ψ R_{AA} vs N_{part}, p_T and rapidity

A suppression is observed for more central collisions at both mid and forward rapidity.

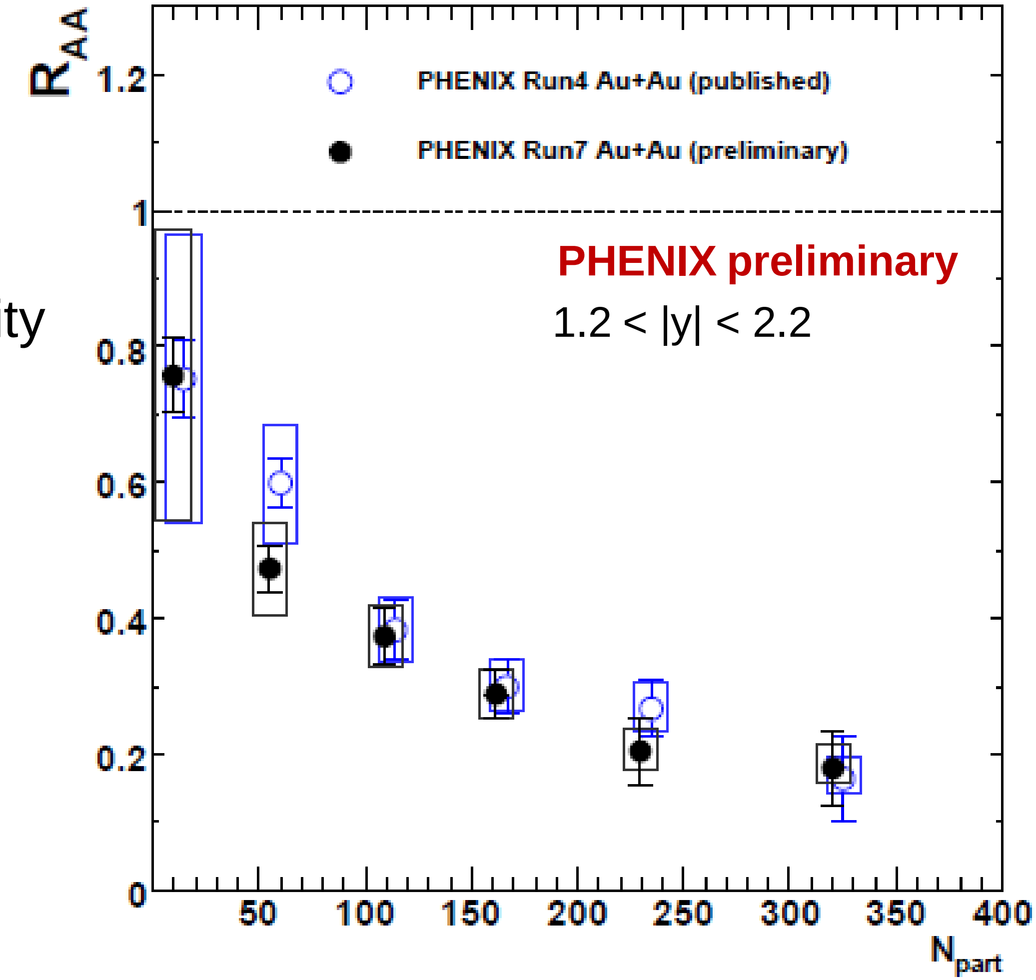
Suppression is larger as forward rapidity than at mid rapidity, which is counter-intuitive, based on energy density arguments.



J/ψ R_{AA} vs N_{part} (2)

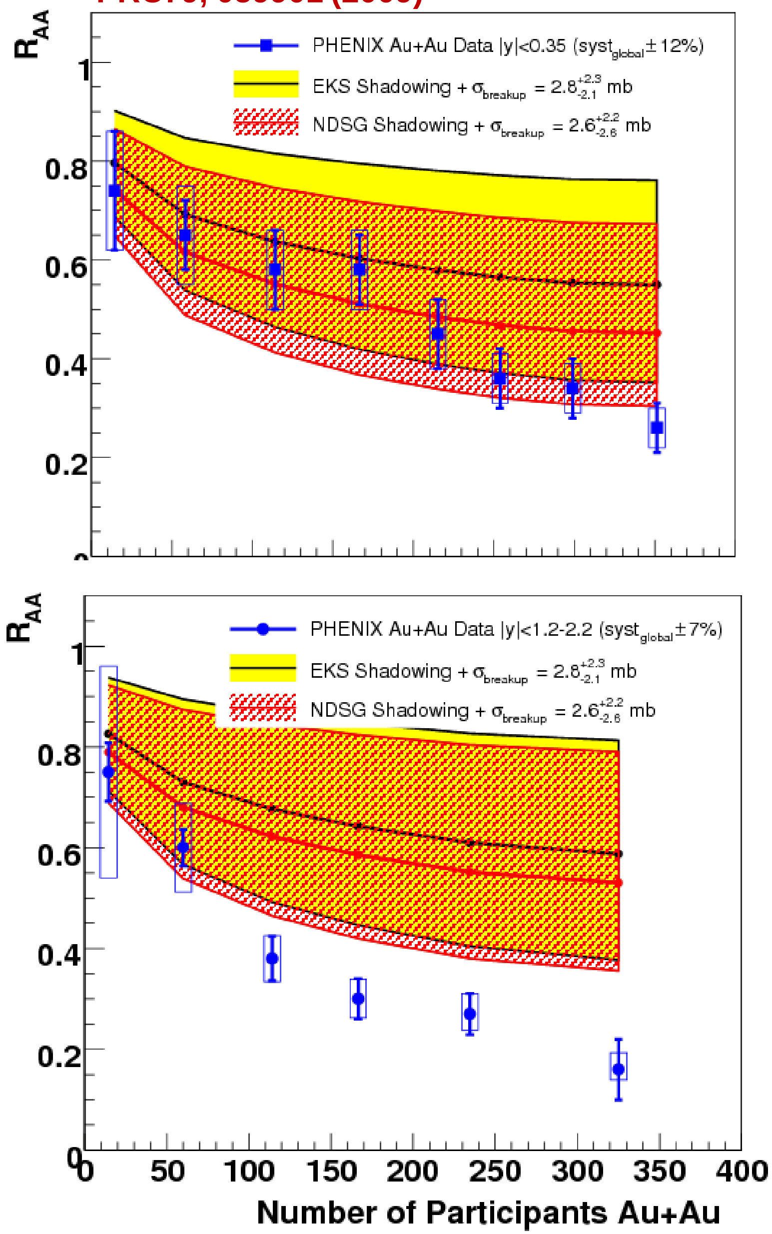
2007 data set provides x4 statistics. Preliminary R_{AA} is in excellent agreement with published result.

Paper is in preparation and will notably provide updated comparisons to models vs centrality and p_T



J/ψ R_{AA} and extrapolated CNM (1)

PRC79, 059901 (2009)



Here a unique break-up cross section is derived from the mid and forward rapidity d+Au data (2003), for two npdf prescriptions, and extrapolated to Au+Au

Error bars from CNM are large;

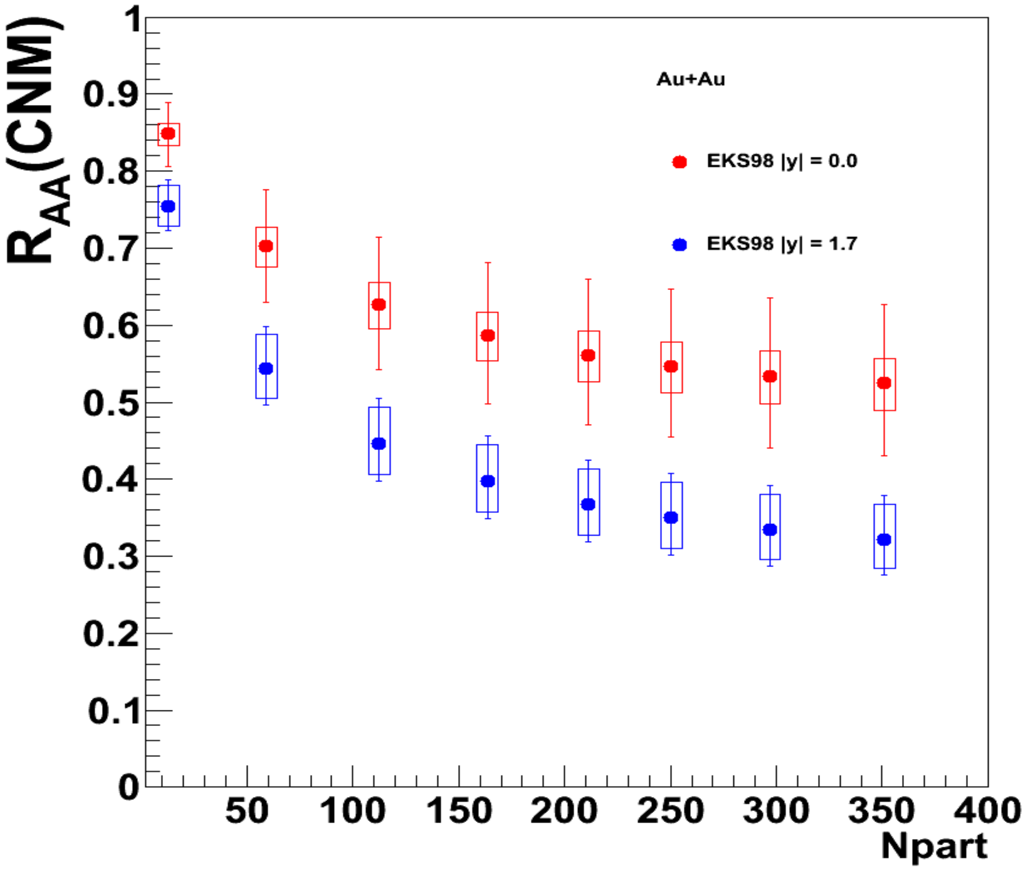
Difference between npdf prescriptions is modest;

Even in the worst case, there is some additional suppression observed in most central Au+Au collisions, beyond CNM, at forward rapidity.

J/ψ R_{AA} and extrapolated CNM (3)

CNM effects estimated using 2008 d+Au dataset, EPS09 npdf, and different breakup cross-sections for mid and forward rapidity; extrapolated to Au+Au collisions.

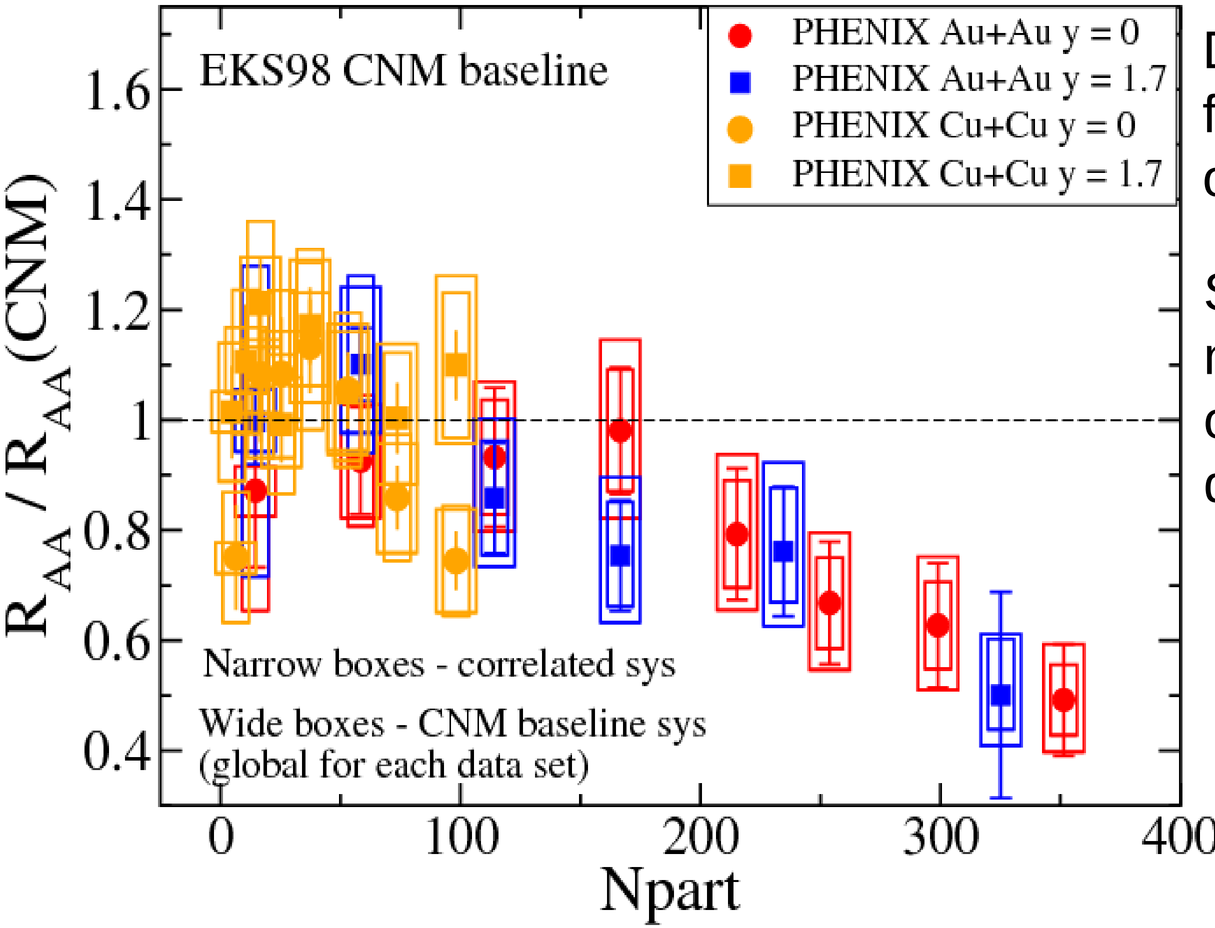
(Frawley INT workshop 2009)



The combination of a strong suppression observed in d+Au collisions at y>0, and little to no effect at y≤0 results in stronger suppression (from CNM) at forward rapidity in Au+Au collisions

J/ψ R_{AA} over CNM in Cu+Cu and Au+Au

R_{AA}/R_{AA}(CNM) vs N_{part}
using extrapolated CNM from previous slide

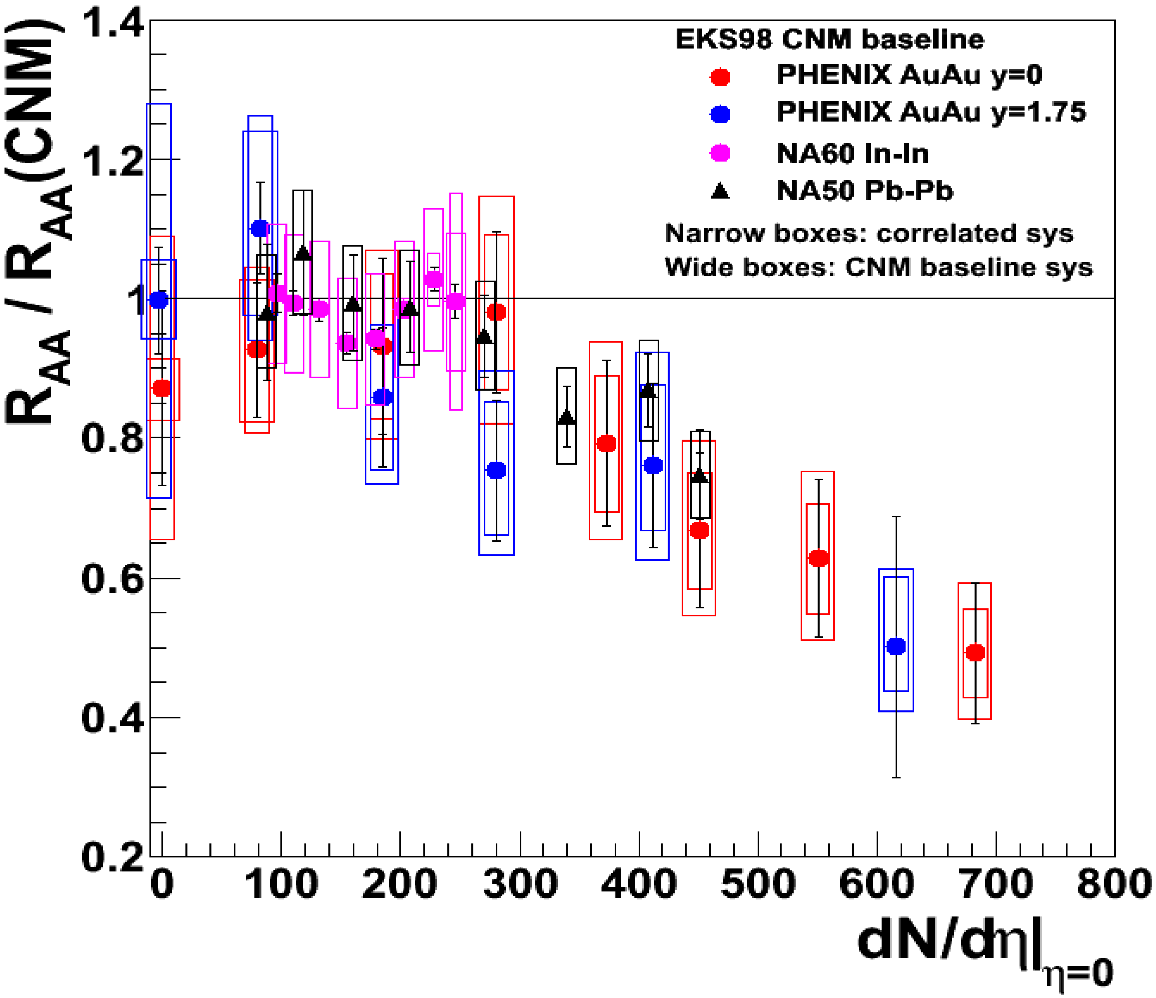


Differences between mid and forward rapidity are washed out.

Suppression beyond cold nuclear matter effects is observed, consistent with deconfinement

Comparison to SPS data

$R_{AA}/R_{AA}(CNM)$ vs $dN/d\eta$ (at $\eta=0$)



Here the *anomalous* J/ψ suppression is compared between SPS and RHIC, as a function of the number of charged particles at mid-rapidity.

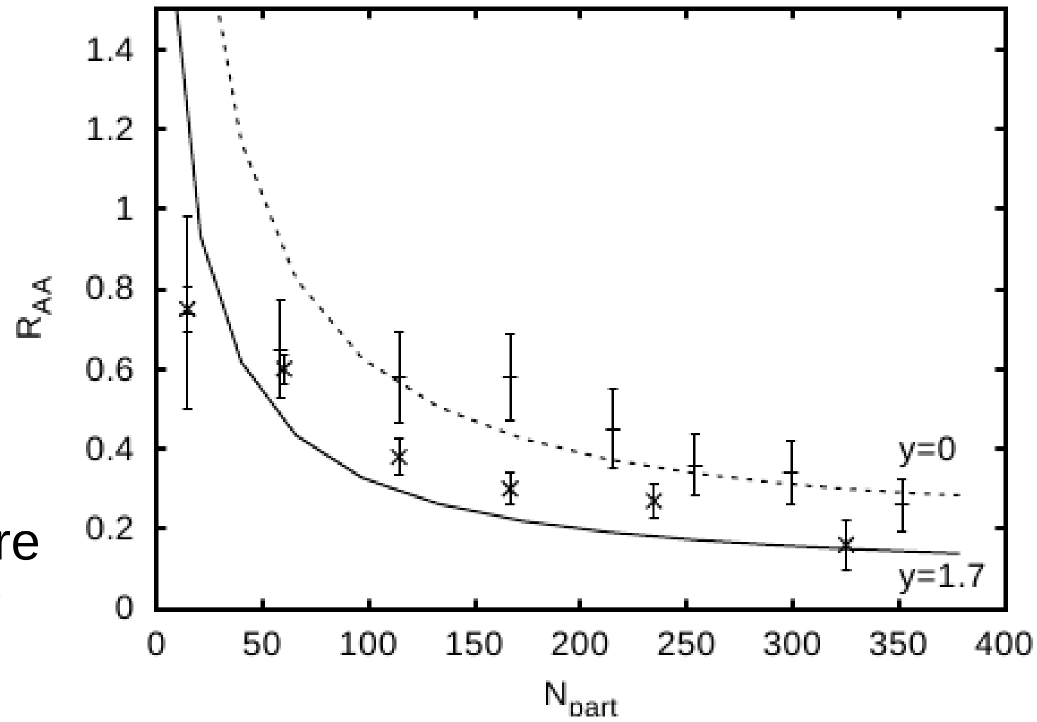
Comparisons to models (1): CGC

CGC calculation reproduces qualitatively the magnitude of the suppression and its rapidity dependency

However this calculation has one free "normalization factor", fitted to the data.

Calculations of this normalization are in progress. They should reduce by x2 the effect of the CGC (private communication), but the forward vs mid-rapidity difference remains.

Nucl. Phys. A830, 230 (2009)



Comparisons to models (2): Regeneration

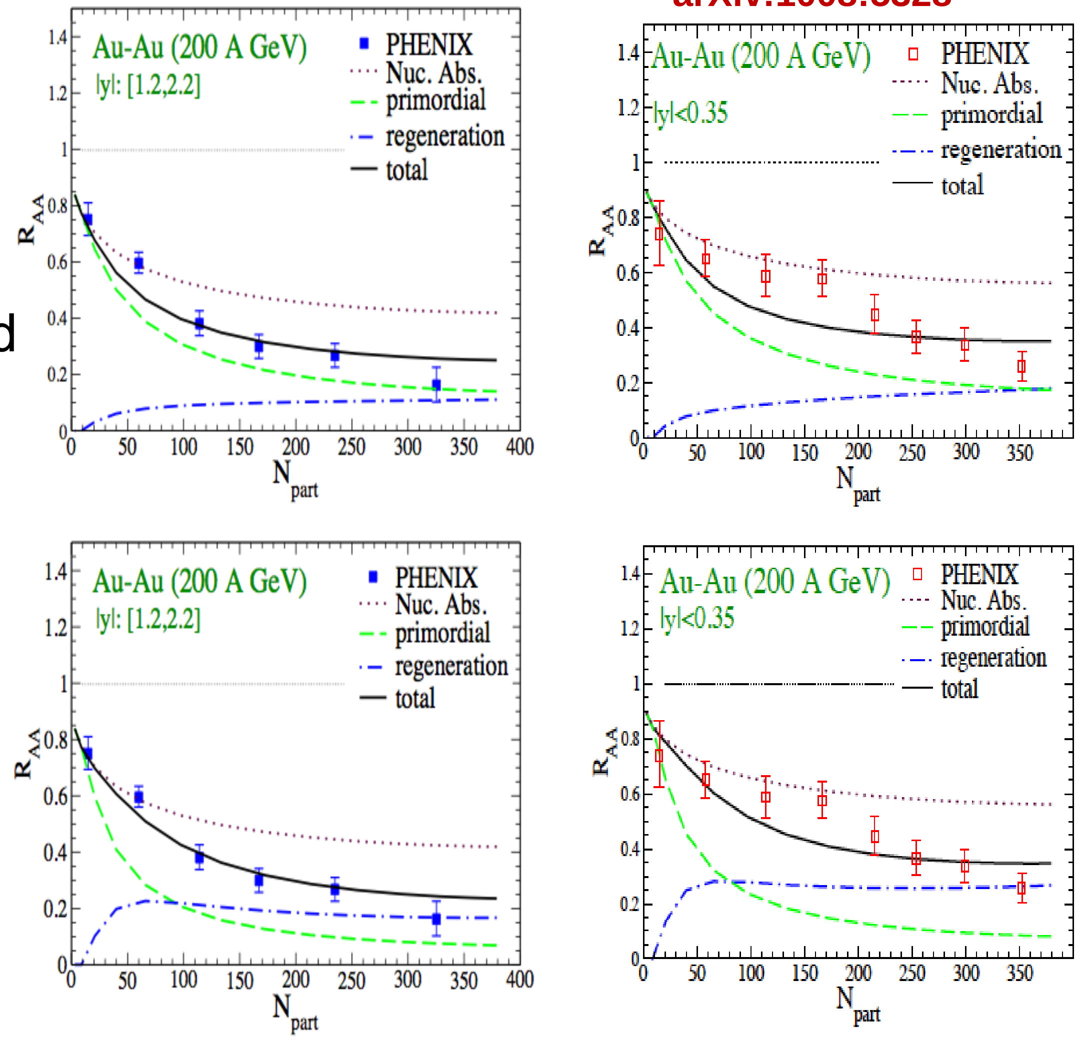
Ingredients to Zhao and Rapp calculation:

- Cold nuclear matter estimates guided by 2008 PHENIX d+Au R_{CP} data.
- prompt J/ψ dissociation in QGP
- J/ψ regeneration by uncorrelated $c\bar{c}$ pair recombination
- Feed-down contributions from B

Top: Strong binding ($T_d=2T_c$)
Bottom: Weak binding ($T_d=1.2T_c$)

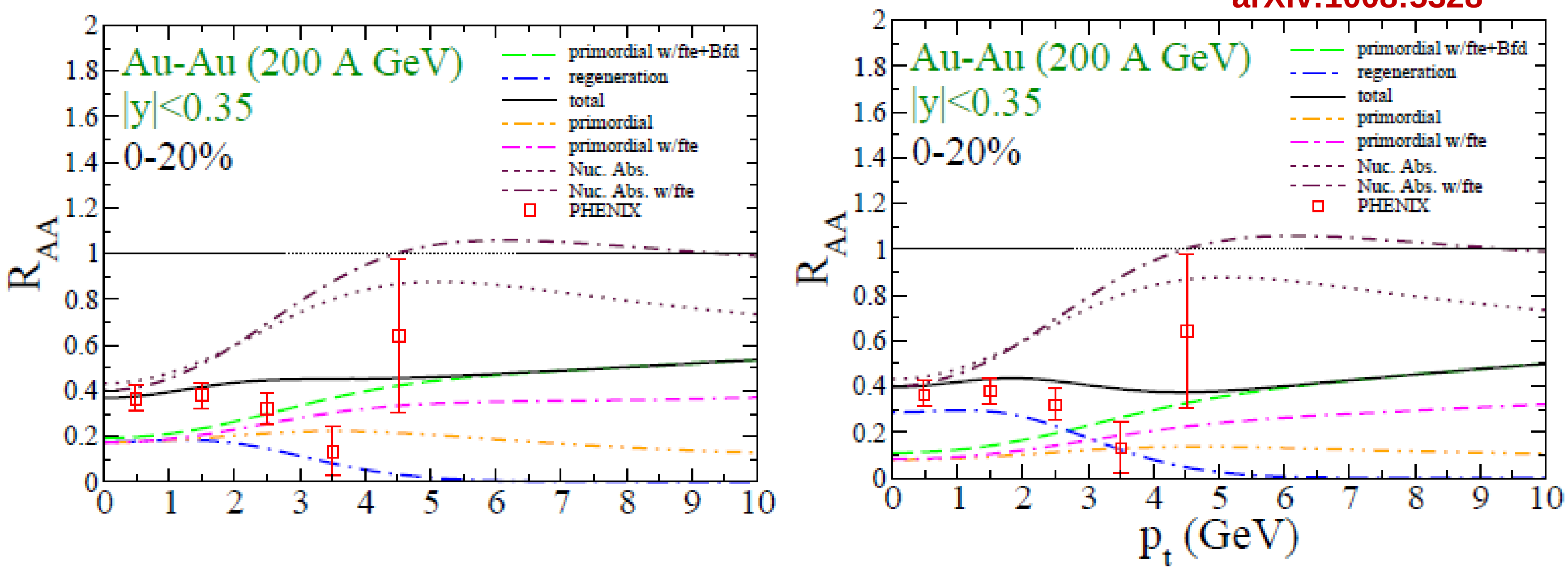
One notes that a large fraction of the mid/forward difference is accounted for by CNM

arXiv:1008:5328



Comparisons to models (3): p_T dependence

arXiv:1008:5328



Same calculation from Zhao and Rapp as for Cu+Cu (and R_{AA} vs N_{part})

Left: Strong binding (T_d=2T_c)
Right: Weak binding (T_d=1.2T_c)

Qualitative agreement is achieved (with weak dependency on J/ψ binding strength), but data are statistically limited

Conclusion (1)

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- (poorly constrained) npdf + initial energy loss + $\sigma_{breakup}$
  it cannot describe latest PHENIX data at forward rapidity. Additional effects might be at play (such as initial state energy loss).
- gluon saturation CGC
  It provides an alternative description of the collision at low x_2 (y>0) and (at least qualitative) explanations to some of the observed effects, e.g. forward/mid difference in AA.

None of these approach fully describes the d+Au data
None of these approach can account for the suppression observed in Au+Au

$\Rightarrow$ anomalous suppression in Au+Au is observed

Conclusion (2)

Many models available to try describe the Au+Au J/ψ data.
Need to account for many effects to achieve ‘qualitative’ agreement.

Notably: observed forward/mid rapidity differences might be largely accounted for by CNM effects.

J/ψ suppression beyond CNM effects is:

- Non zero
- Roughly consistent with suppression observed at SPS
- Smaller than expected from SPS based models, and requires the use of extra component(s)

It is crucial to add more measurements (p_T dependence, feed-down contributions, higher energy); and to ask models to reproduce all available observables.