J/ψ production in relativistic p+p, d+A and A+A collisions at RHIC, measured by the PHENIX experiment

Hugo Pereira Da Costa, for the PHENIX collaboration
CEA Saclay, Los Alamos National Lab.

GHP 2009 – April 29 2009

Motivations

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

	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

- 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.
- as resonances they are *easy* to measure (as opposed to e.g. open heavy flavors)

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

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

Contents

1. J/ψ production in p+p collisions (reference)
2. cold nuclear matter effects in d+A collisions
3. hot nuclear matter effects in A+A collisions
4. Other resonances (ψ', χ_c and Υ)

1. **J/ψ production in p+p collisions**
   reference for A+A
   production mechanism

Production mechanism

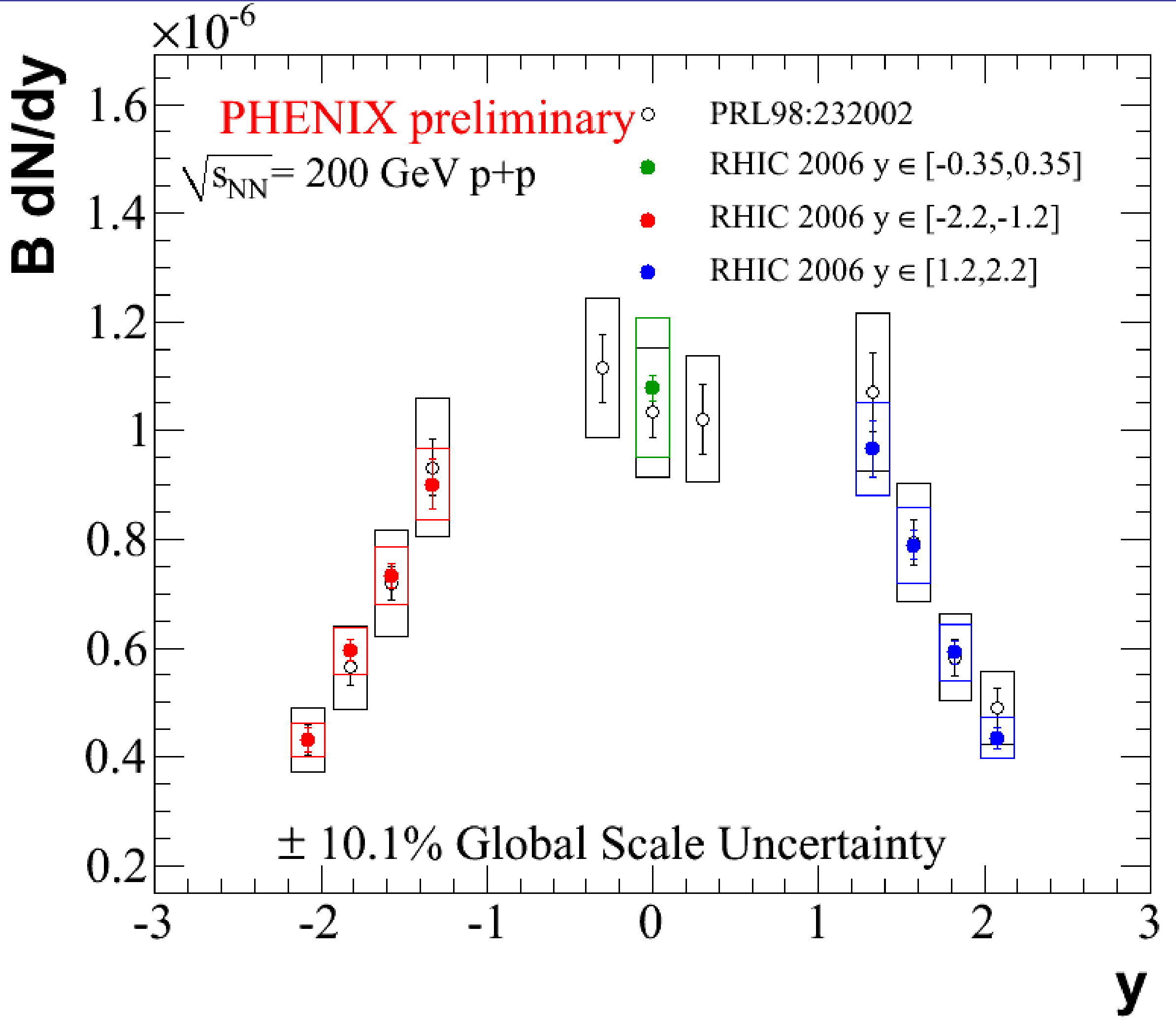
Several models available, that differ mainly on how the $c\bar{c}$ pair formed during the initial parton (gg at RHIC) is neutralized prior to forming the J/ψ

- **Color Singlet Model (CSM)** NLO, NNLO*
  - Improves agreement with CDF p_T spectra (arxiv:0806.3282)
  - NNLO* not applicable below 5-7GeV/c.
  - **s-channel cut**
    (allow quarks to be off mass shell before quarkonia formation)

- **Color Octet Model (COM)** NLO, NNLO*
  - Reduction in transverse polarization for NLO. (arxiv:0802.3727v1)
  - Soon we will have NLO predictions for RHIC.
    But not valid for $p_T < 3$GeV/c.
  - NNLO* same as above.

- **Color Evaporation Model (CEM)**

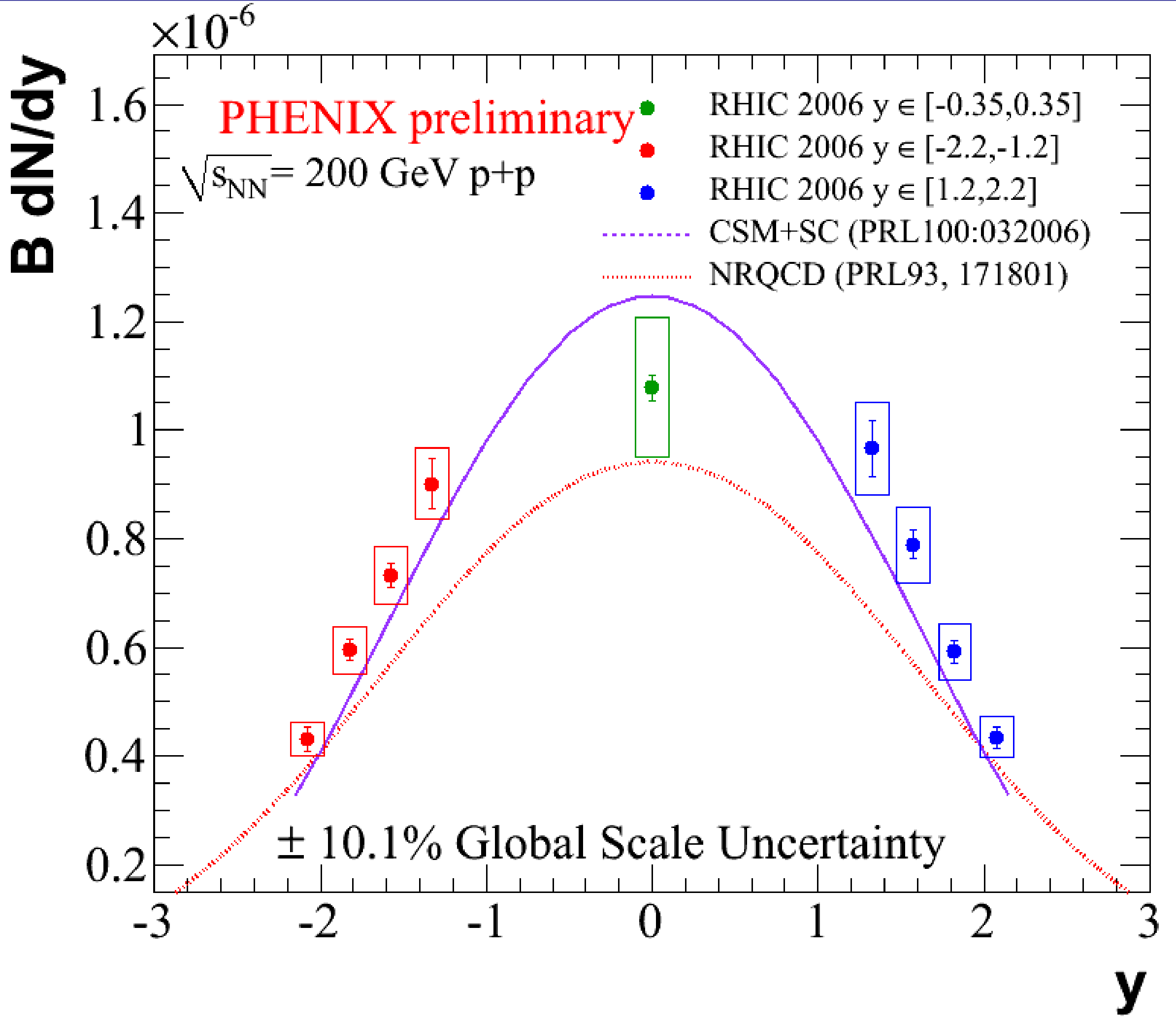
J/ψ production vs rapidity (2005 vs 2006 data)



Higher statistics and better control over systematics
Excellent agreement with published results

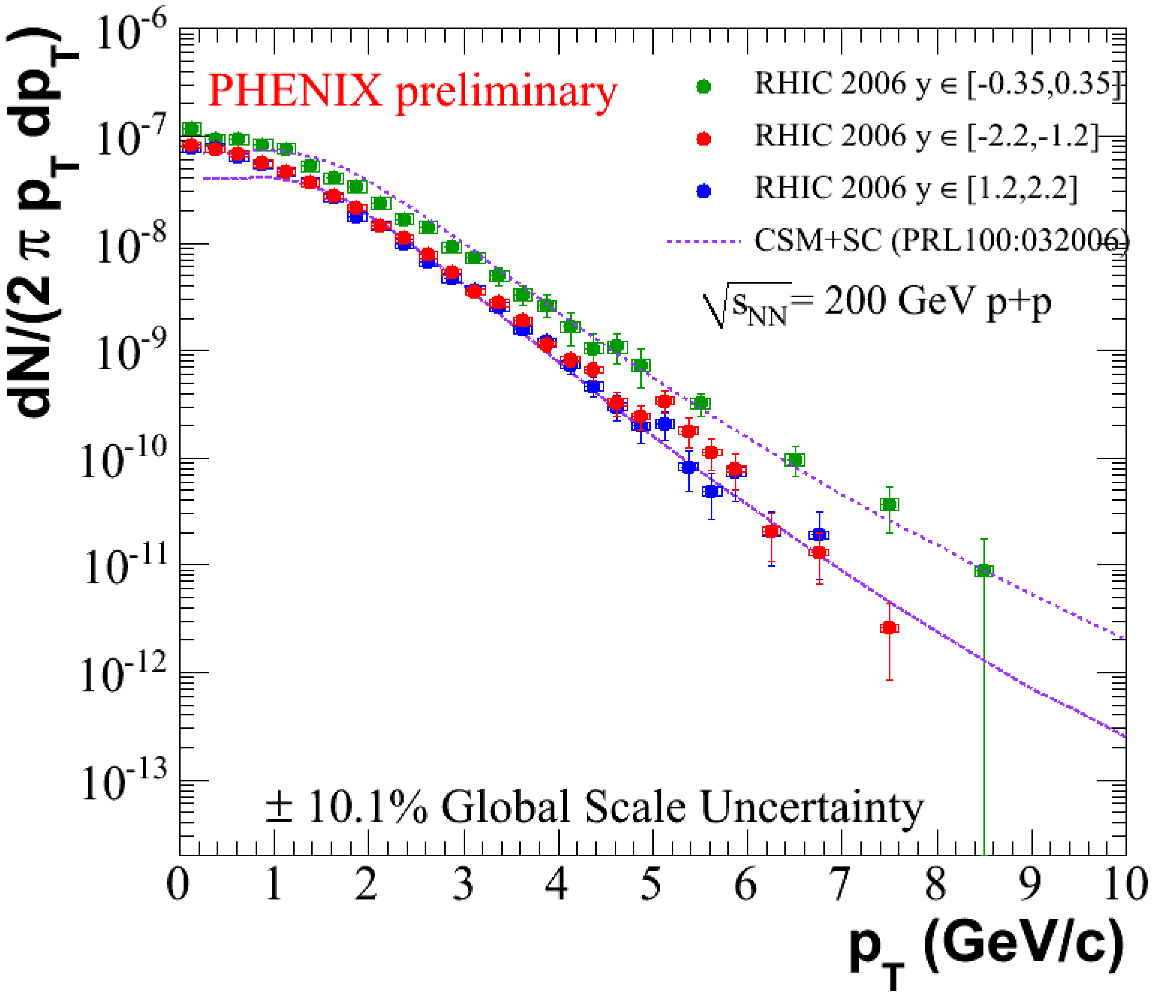
⇒ Better constraints on models

Comparison to models



Models have absolute normalization. They are not scaled to the data. CSM+S channel cut, tuned (parametrized) to CDF, does a fairly good job at reproducing PHENIX data.

J/ψ production vs p_T (2006 data)



Excellent agreement between data at positive and negative rapidity

Harder spectra observed at mid-rapidity.

Data well reproduced by CSM + S channel cut (adjusted on CDF data)

To-do (for experimentalists): have more rapidity bins

J/ψ polarization

J/ψ polarization is measured via λ parameter:

- $\lambda > 0$ transverse polarization
- $\lambda = 0$ no polarization
- $\lambda < 0$ longitudinal polarization

$$\frac{dN}{d\cos\theta} = A(1 + \lambda \cos^2 \theta)$$

with θ the decay lepton angle with respect to J/ψ momentum in J/ψ rest frame (*helicity frame* convention)

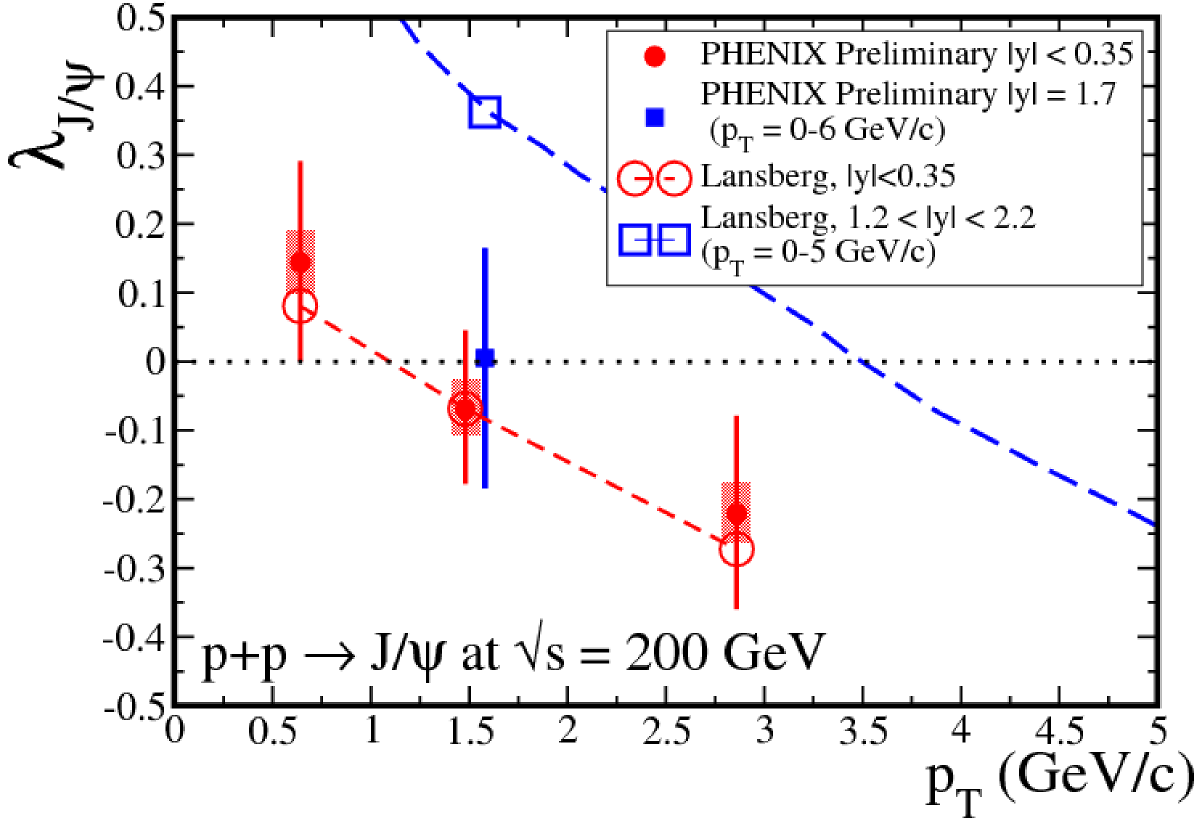
(see ArXiv:0902.4462v1 for other conventions)

COM (LO): predicts transverse polarization at high enough p_T
CSM (LO): predicts longitudinal polarization at high enough p_T
CEM: predicts no polarization

⇒ J/ ψ polarization measurement provides a powerful discriminating tool between models

J/ψ polarization at RHIC

arXiv:0806.4001v1



Measurement performed in *helicity* frame

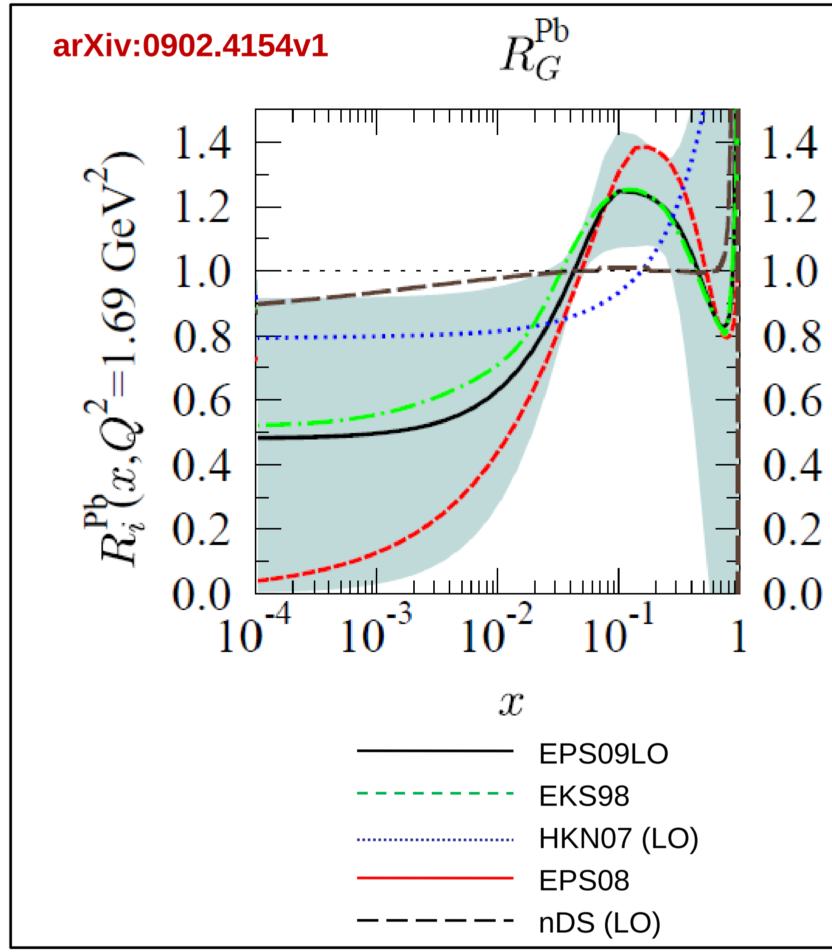
- CSM + S channel cut reproduces the mid-rapidity data well but misses the forward rapidity data by about 2σ;
- CEM cannot be ruled out;
- COM has no prediction for this p_T range.

2. J/ψ production in d+A collisions cold nuclear matter (CNM) effects

Effects that modify the J/ψ production in heavy ion collisions with respect to p+p, without requiring the formation of a Quark Gluon Plasma

Cold nuclear matter effects

- Modification of the parton distribution function (pdf) in nuclei:
- Breakup cross-section $\sigma_{breakup}$
- Initial state energy loss
- Cronin effect
- Other mechanisms (gluon saturation/CGC)

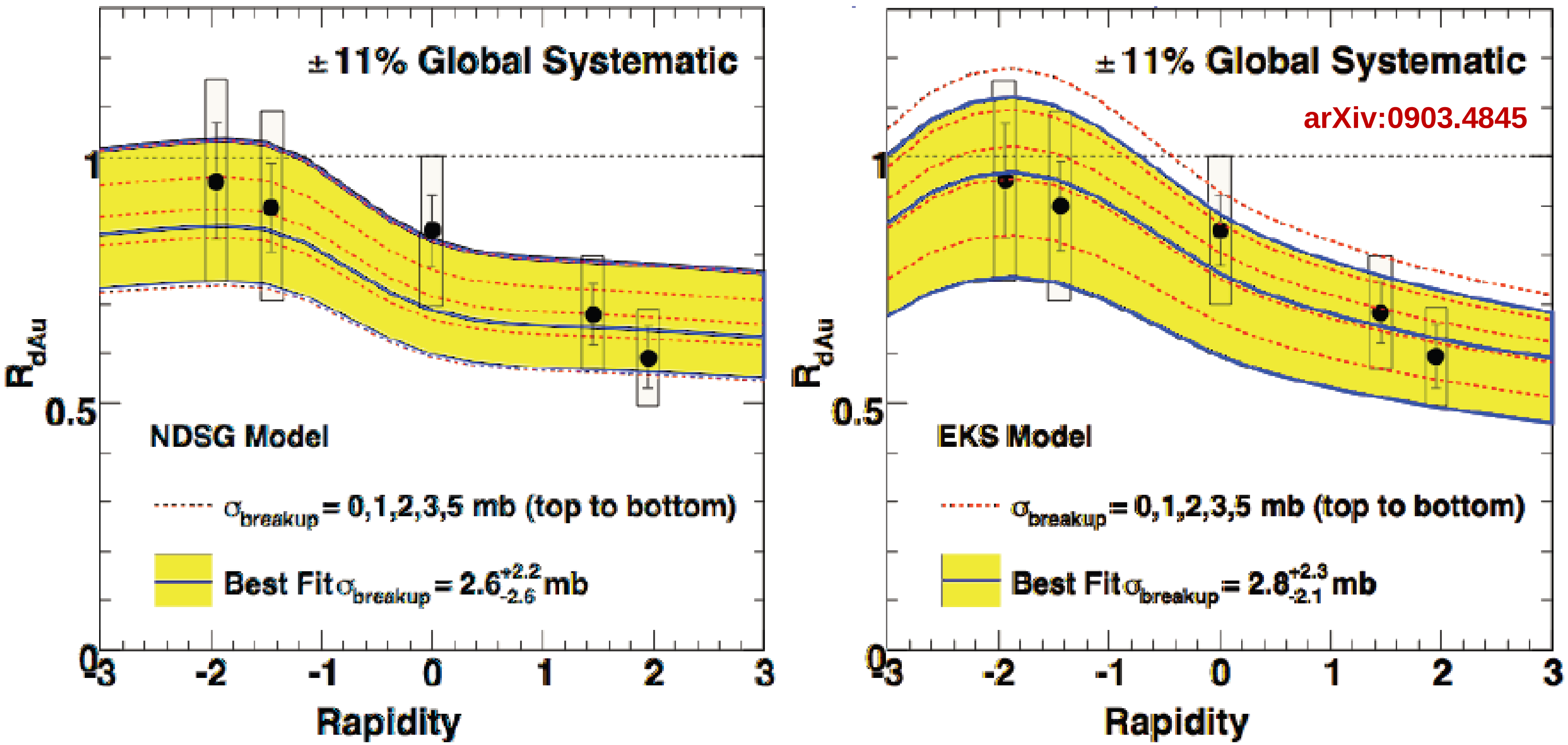


So far, mainly the first two effects have been adressed quantitatively (although fitting $\sigma_{breakup}$ to the data might absorb some of the other effects)

<u>To get quantitative value for $\sigma_{breakup}$:</u>

- Chose a nPDF prescription
- Get prediction for $\sigma_{breakup}$ = 0, 1, 2, 3 (etc.) mb
- Compare to data (and possibly fit)

Published R_{dAu} (2003 data) vs rapidity

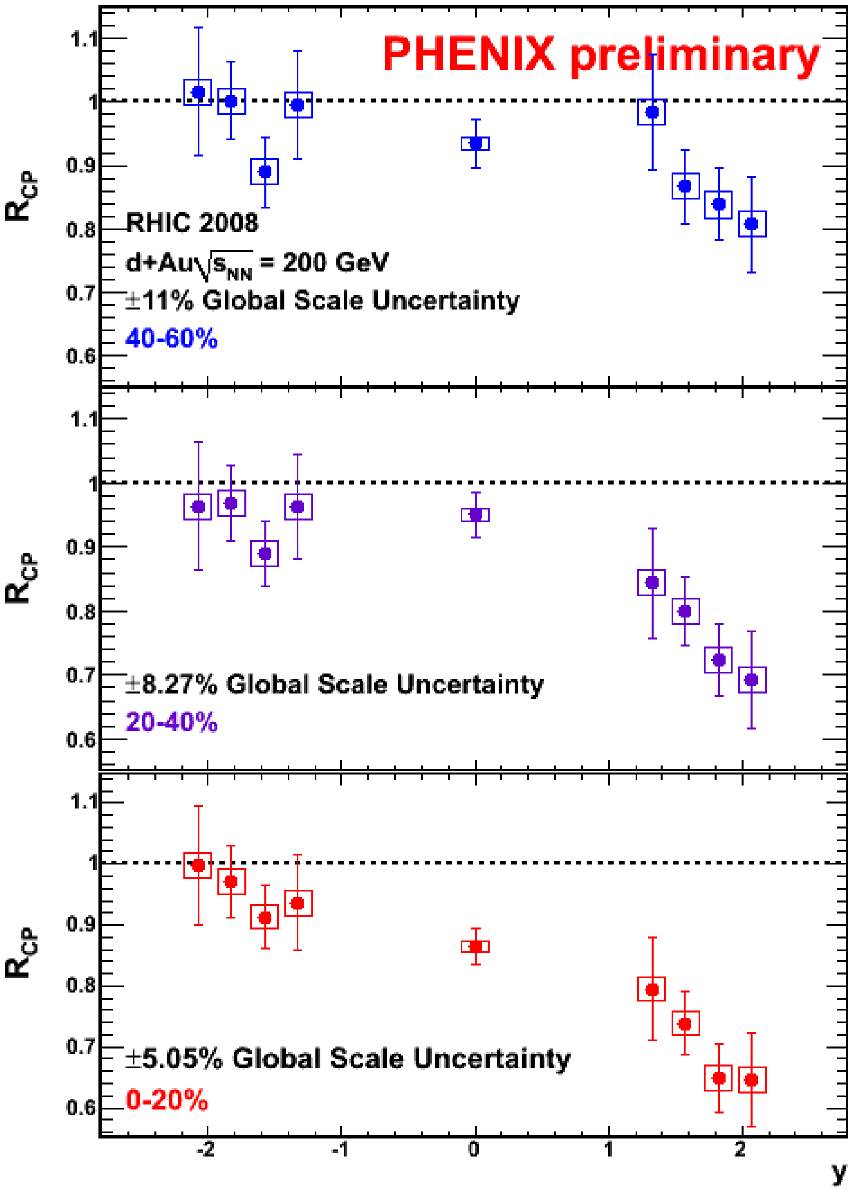


$$R_{dAu} = \frac{N_{inv}^{d+Au}}{n_{coll} . N_{inv}^{p+p}}$$

y<0: Au going side. Large x in Au nuclei
y>0: d going side. Small x in Au nuclei

Two shadowing models are used together with $\sigma_{breakup}$ from 1 to 5 mb.
Fit to the data gives similar $\sigma_{breakup}$, and large error bars (~2mb).

Preliminary R_{cp} (2008 data) vs rapidity



$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} \Big/ \left\langle N_{coll}^{0-20\%} \right\rangle}{N_{inv}^{60-88\%} \Big/ \left\langle N_{coll}^{60-88\%} \right\rangle}$$

Enough statistics to provide 4 different centrality bins.

Systematic errors largely cancel in R_{cp}.

R_{cp} ~1 at negative rapidity
R_{cp} < 1 and decreases with centrality at positive rapidity

Todo:

- Produce R_{dAu}
- Fit $\sigma_{breakup}$ to the data

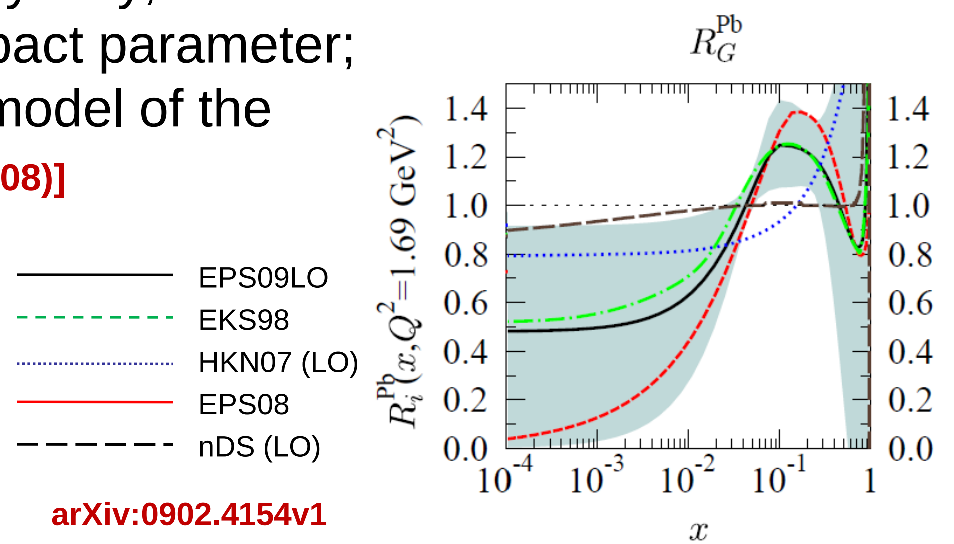
Extrapolation to Au+Au

Model dependent approach:
Use npdf prescription for both nucleii together with $\sigma_{breakup}$ obtained from d+Au data

Data driven approach:
Use R_{dAu} data vs rapidity and centrality only;
Parametrize as a function of *b* the impact parameter;
Extrapolate to Au+Au using Glauber model of the colliding nucleii. **[Phys. Rev. C 77, 024912 (2008)]**

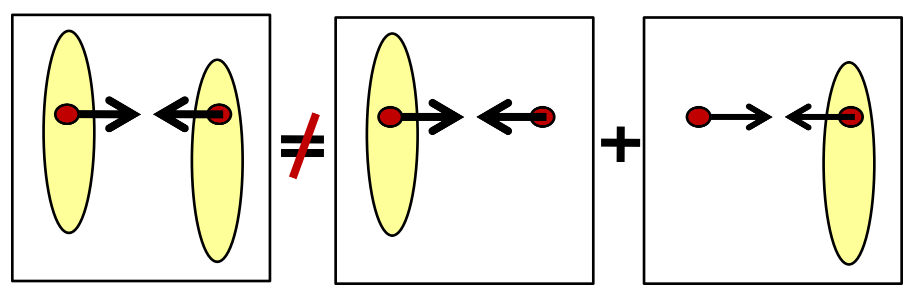
Limitations:

1. Nuclear pdf have errors, that must be accounted for when deriving σ_{abs} or extrapolating to A+A collisions.



arXiv:0902.4154v1

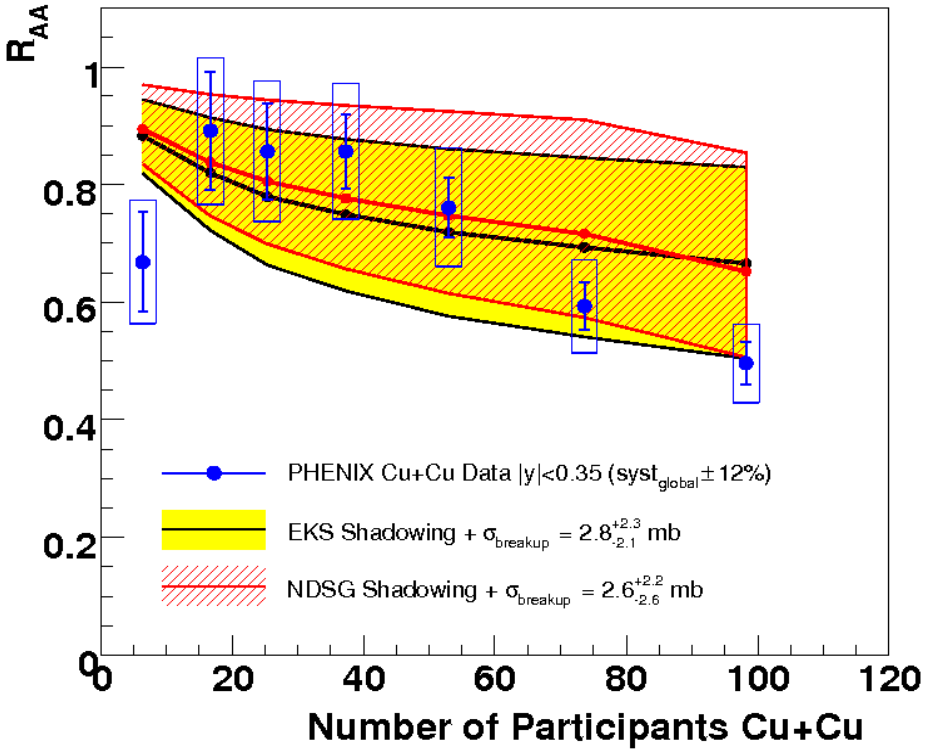
2. d+A cold nuclear matter effects might not factorize easily in A+A, due to gluon saturation.

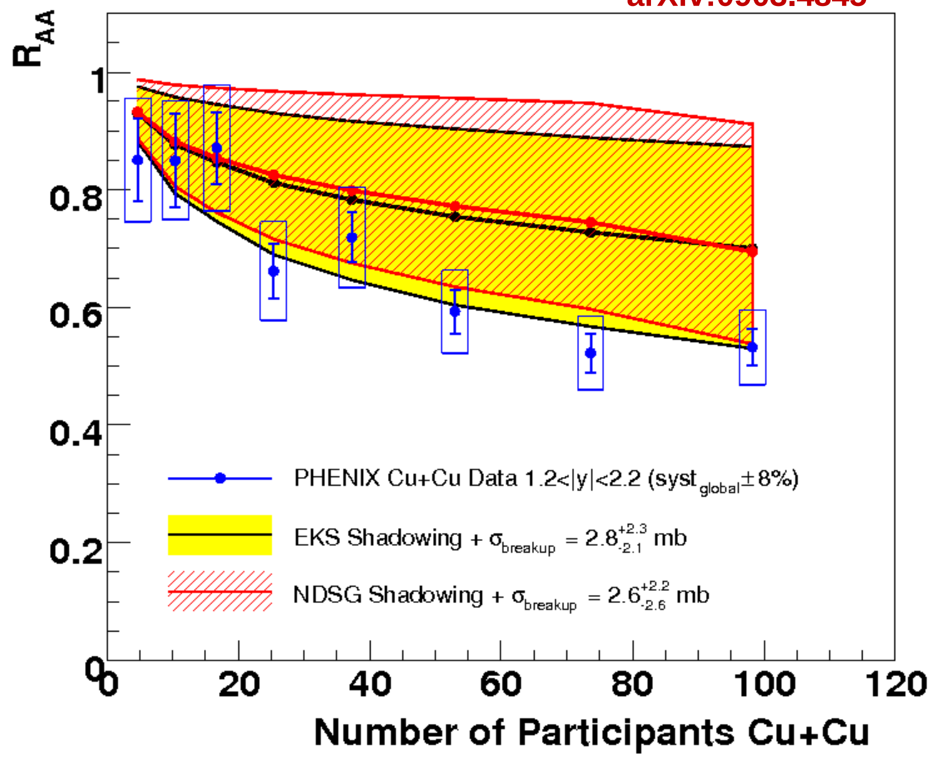


3. J/ψ production in A+A collisions
Hot nuclear matter effects, QGP

J/ψ R_{AA} in Cu+Cu and revised CNM

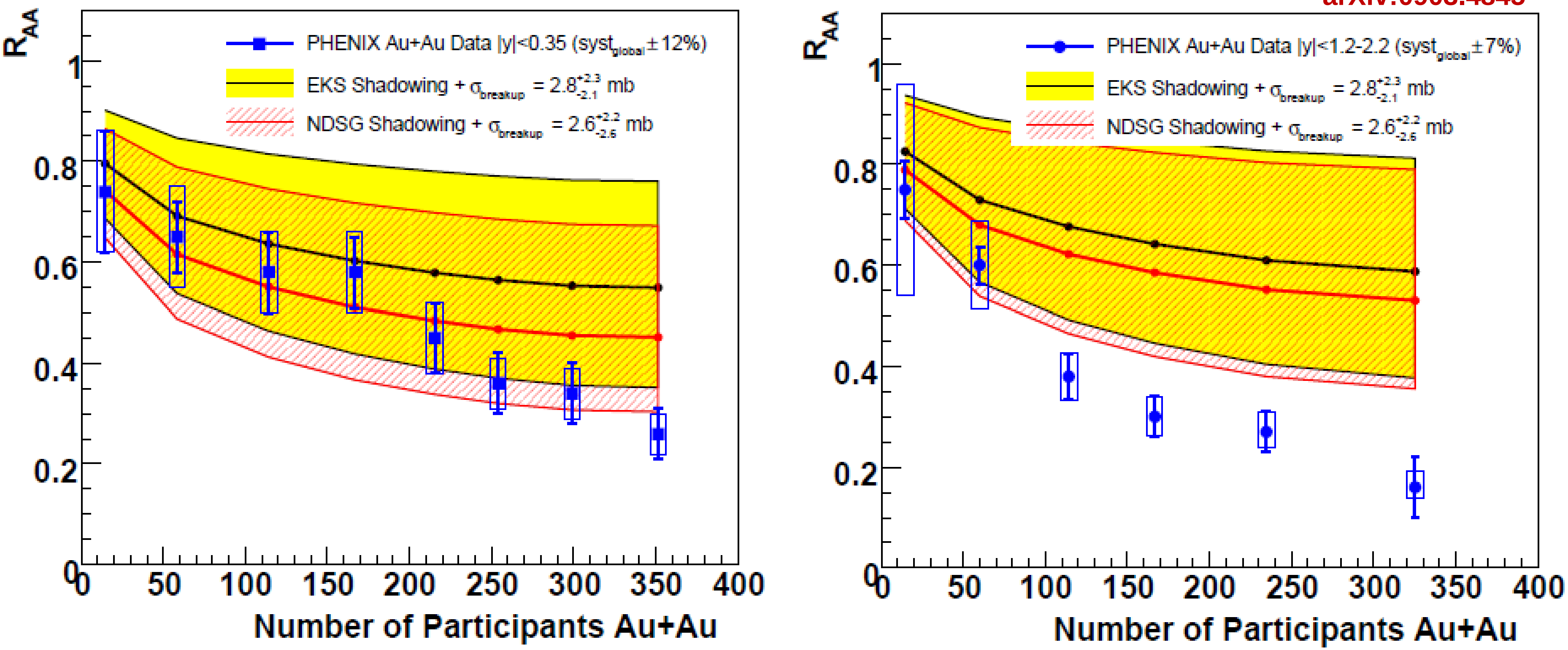
arXiv:0903.4845





J/ψ R_{AA} in Au+Au and revised CNM

arXiv:0903.4845



As long as error bars on extrapolated CNM are so large, it is hard to derive any conclusion on J/ψ anomalous suppression, or compare to models of J/ψ production in QGP

4. Other resonances (ψ', χ_c, Υ)

Motivations

Other heavy quarkonia resonnances should have :

- similar production mechanism (CSM, COM, etc.)
- similar cold nuclear matter effects (shadowing, nuclear absorption, etc.)
- interaction mechanism in QGP (sequential melting, recombination, etc.)

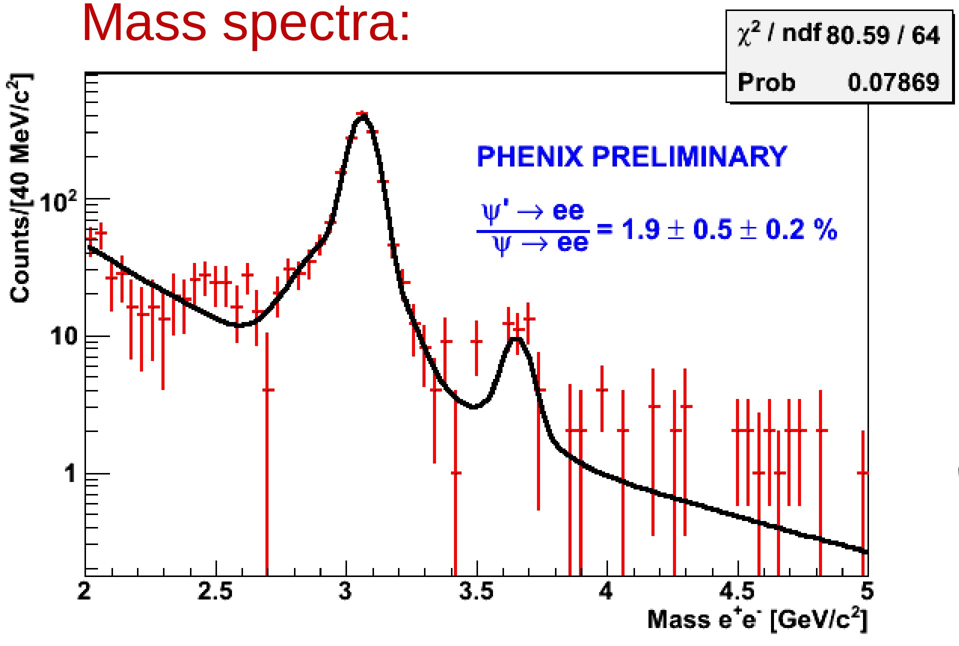
but with different parameters/relative weights

⇒ Additional constrains to models (that should aim at reproducing all resonances simultaneously)

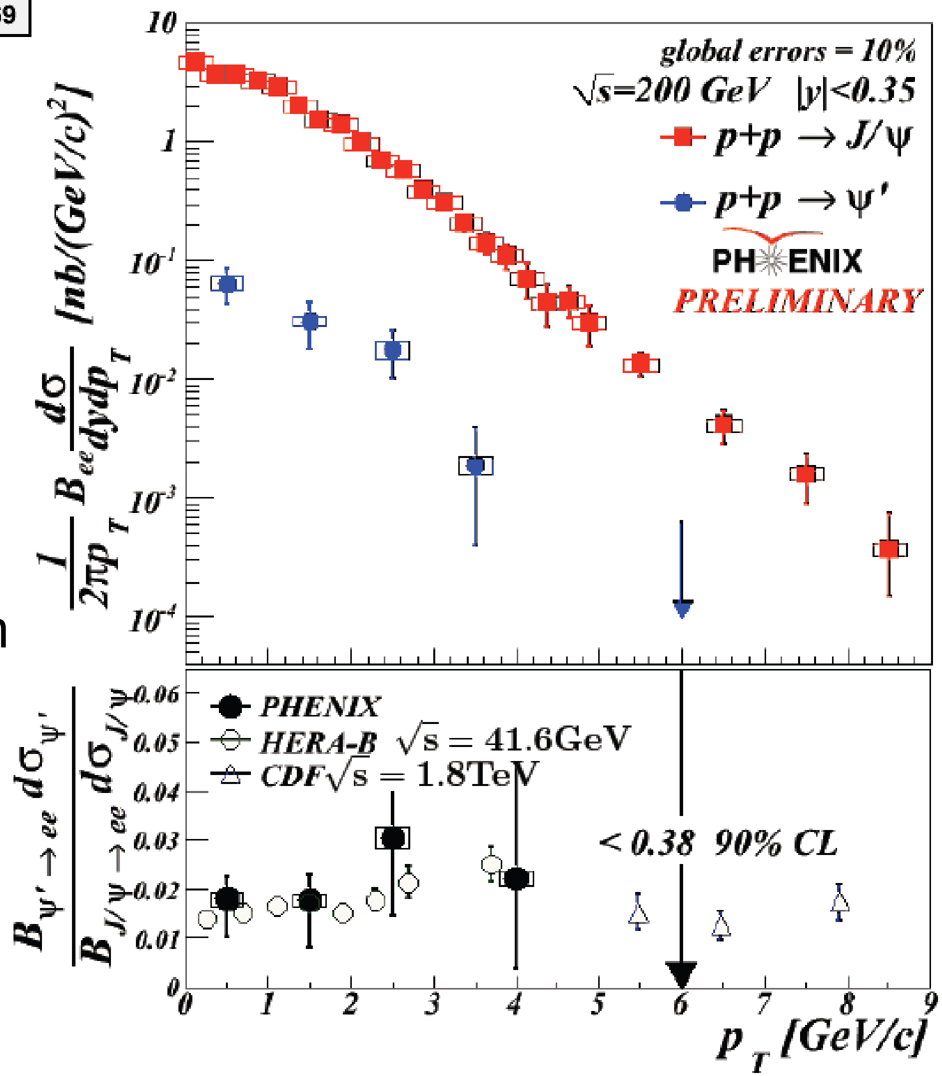
Additionally they are needed to constrain **feed-down contributions** to J/ψ, and thus measure previous effects for **direct J/ψ** only, to which most predictions apply.

ψ’ production in p+p vs p_T

Mass spectra:



Cross section vs p_T:

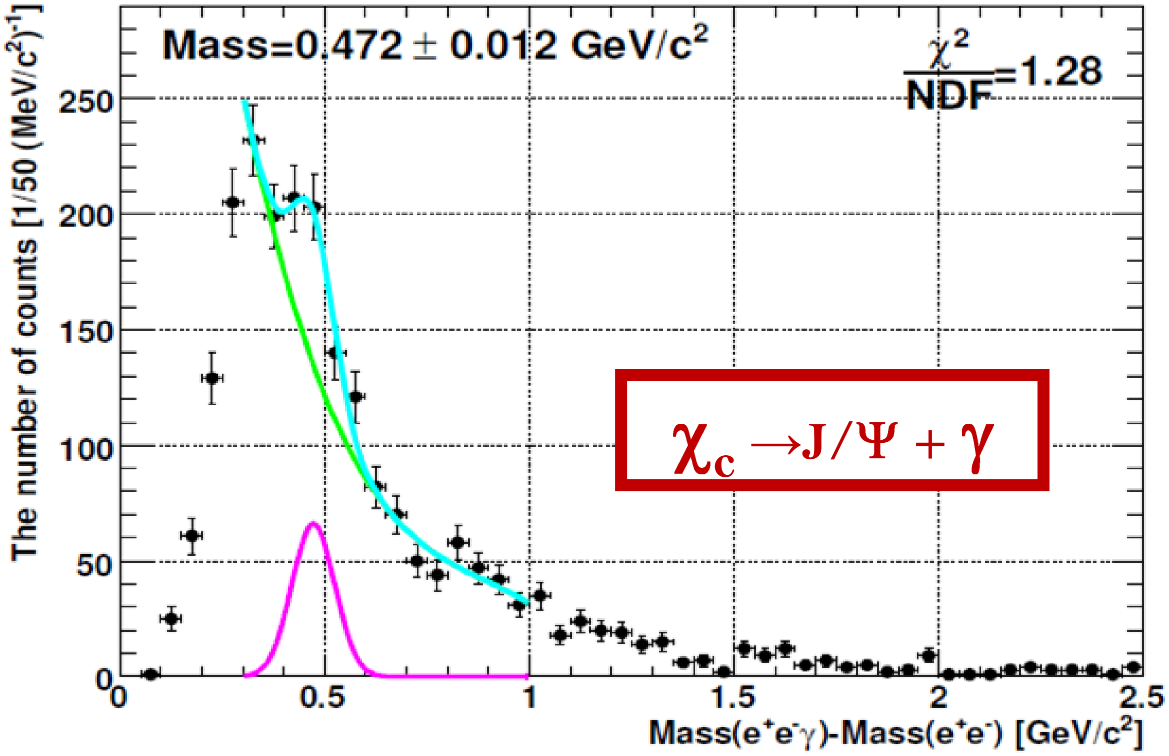


Measured at mid rapidity via di-electron decay. Provides:

- cross-section vs p_T:
  ψ’ over J/ψ ~2%, similar to HERA
- feed-down contribution to J/ψ:

J/ψ from ψ’ = 8.6 ± 2.5 %

χ_c production in p+p

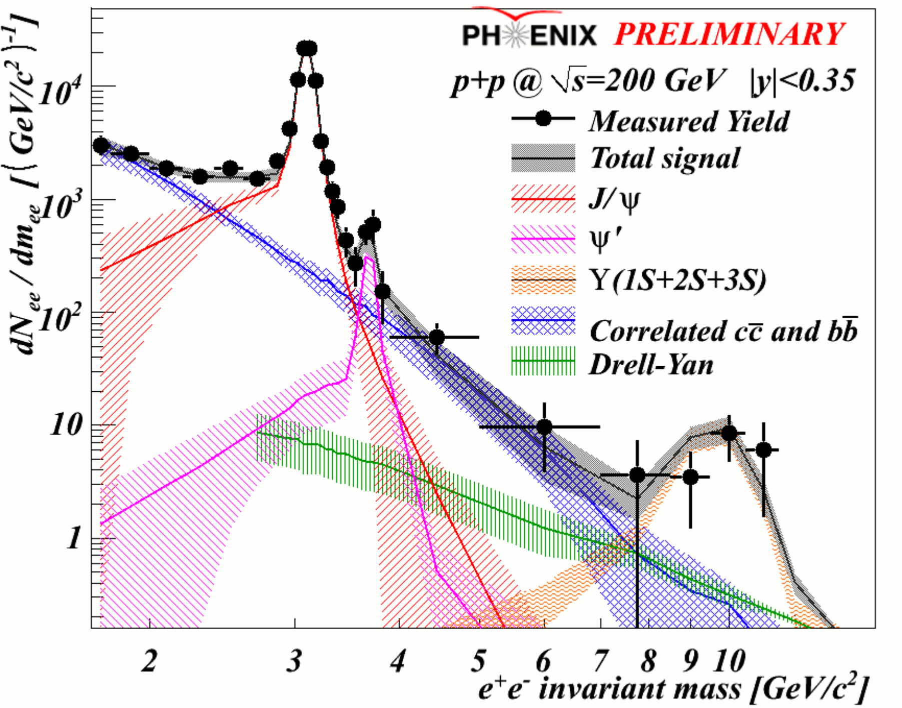


Measured at mid rapidity via di-electron + photon in EMCal
Provides: feed-down contribution to J/ψ

J/ψ from χ_c < 42% (90% CL)

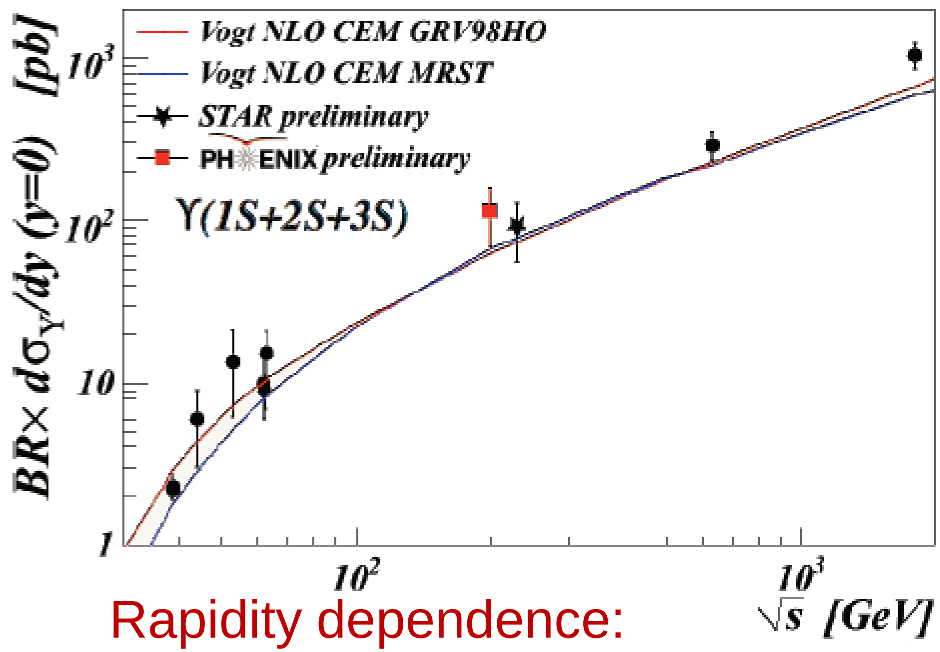
PHENIX preliminary

ϒ production in p+p

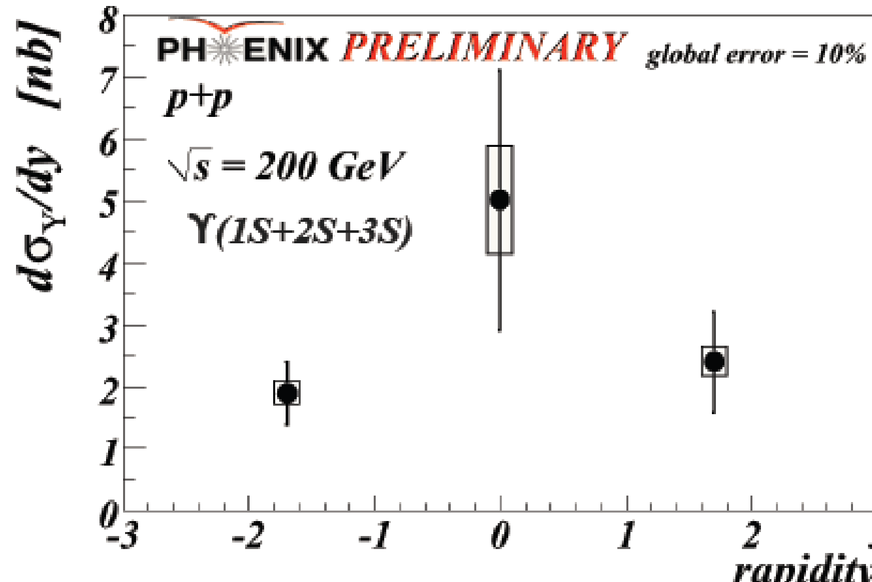


Cross section:

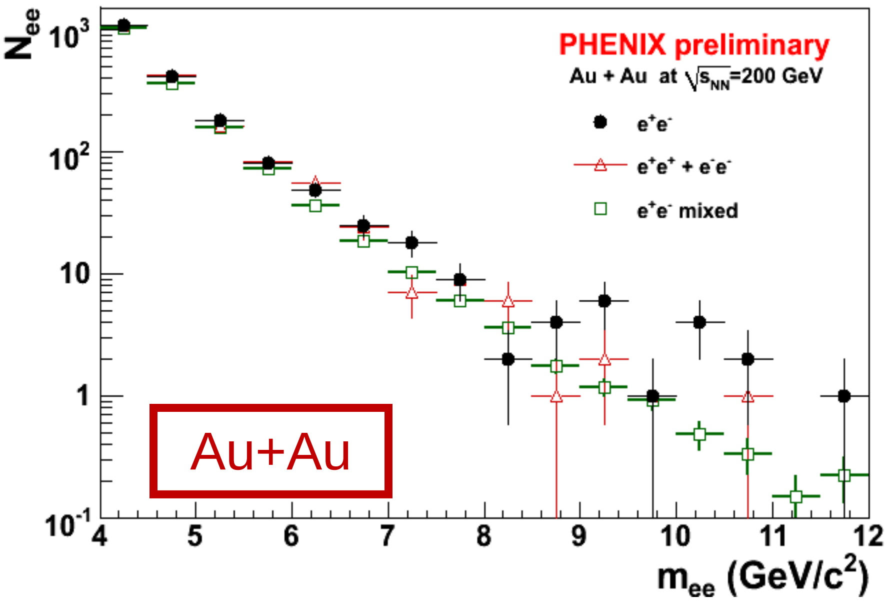
$$BR * \frac{d\sigma}{dy}\Big|_{|y|<0.35} = 114^{+46}_{-45}\ pb$$

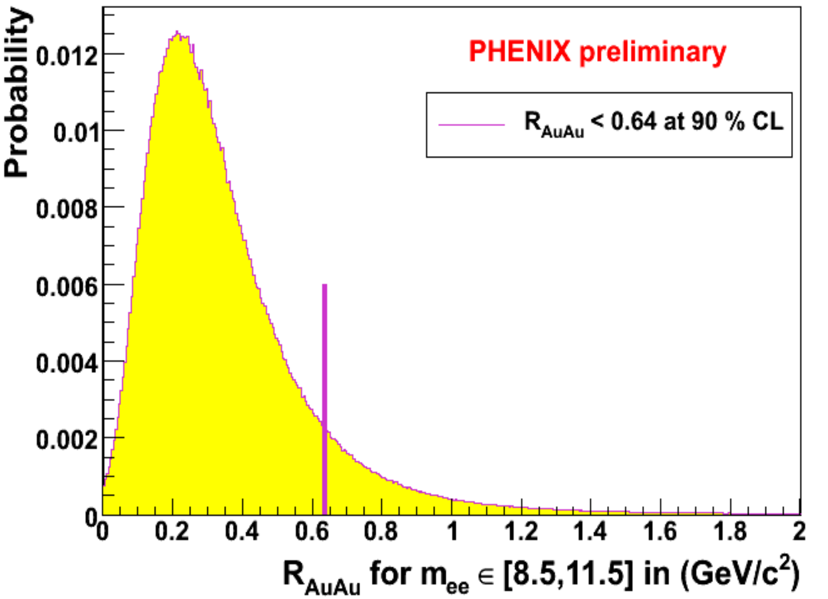


Rapidity dependence:



High mass di-lepton R_{AA} in Au+Au





Excess over combinatorial background at high mass (m>8GeV/c^2) attributed to

- Upsilons
- Open beauty
- Drell-Yan

High mass di-lepton R_{AA}:

R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.

Conclusion

Outlook

p+p collisions:
Increased statistics and better control over systematics
New observables (J/ψ polarization)

d+A collisions:
Much larger statistics available. Analysis is in progress.
New issues to be addressed for quantifying CNM effects and extrapolate to A+A.

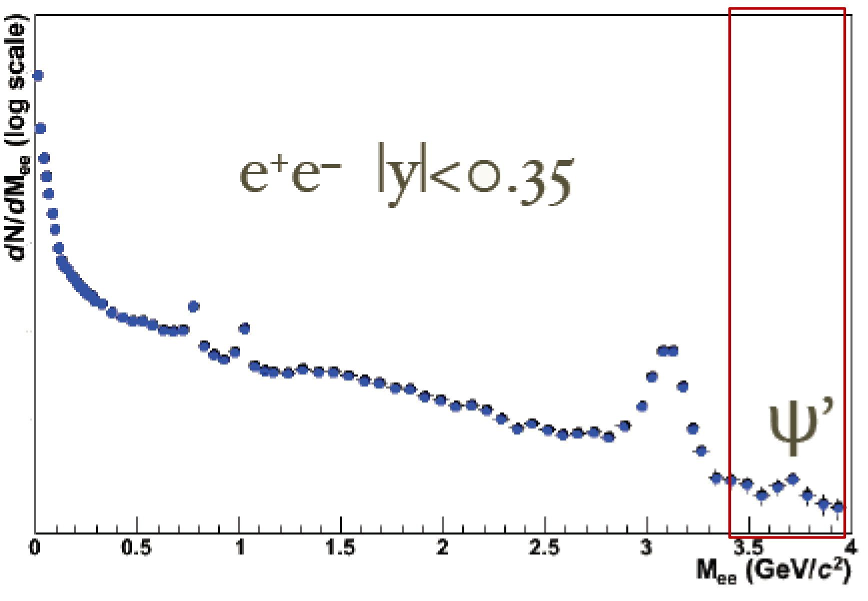
A+A collisions:
No conclusion as long as CNM are so poorly constrained.

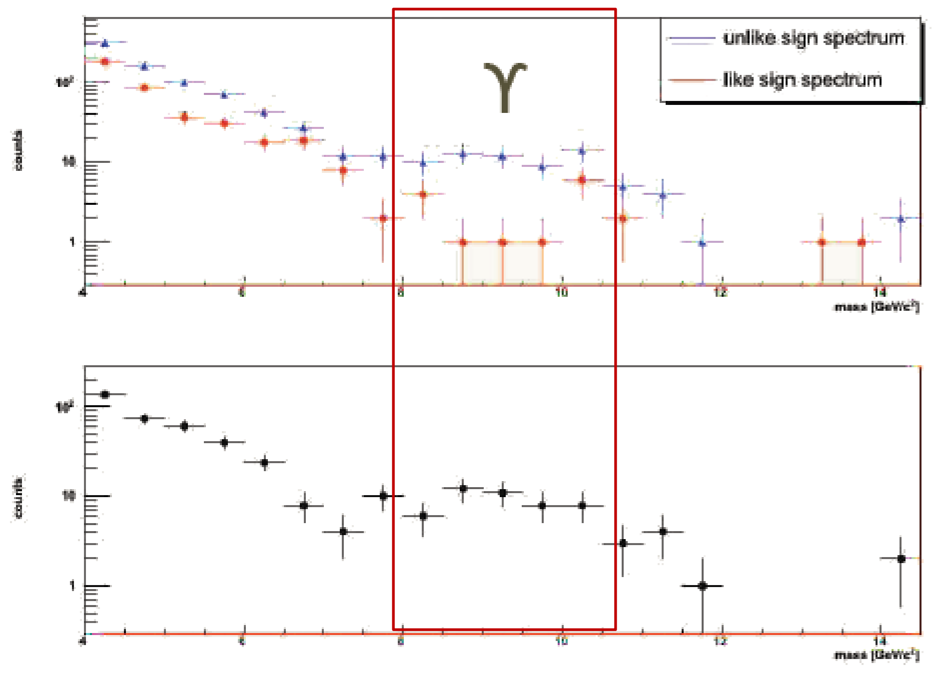
Studying **other resonances** might provide additional handles to discriminate between models and disentangle the mechanism at play, although they are all quite statistically limited so far.

Things to come (1):
ψ' and ϒ in d+Au @ 200 GeV (2008 data)

ϒ at mid rapidity

ψ' rapidity

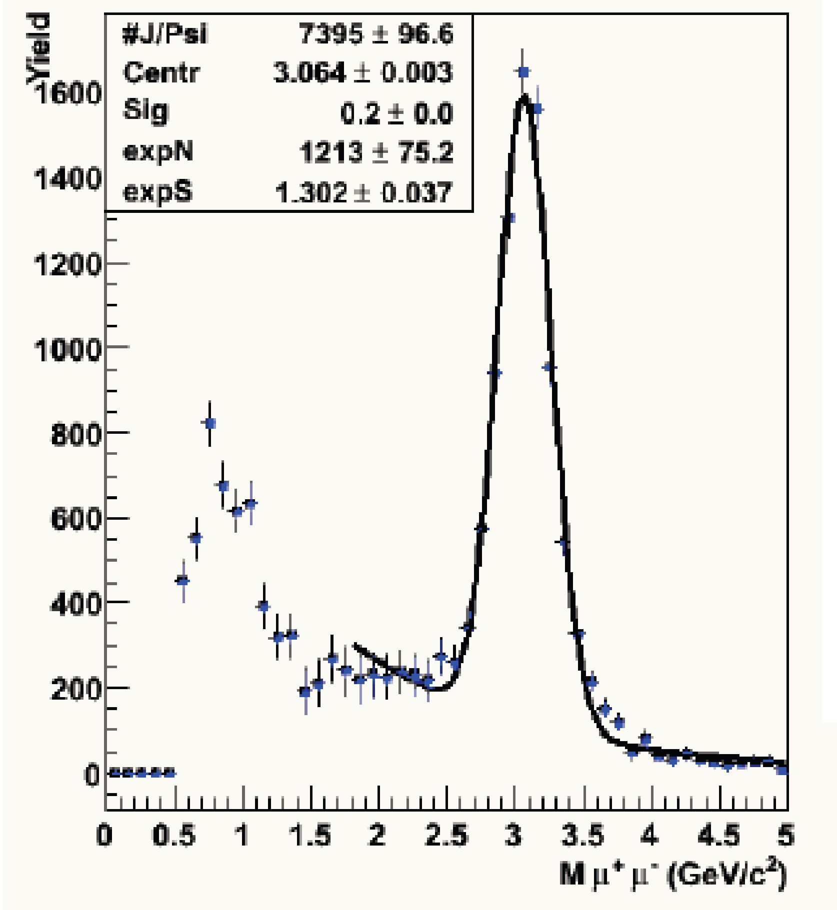




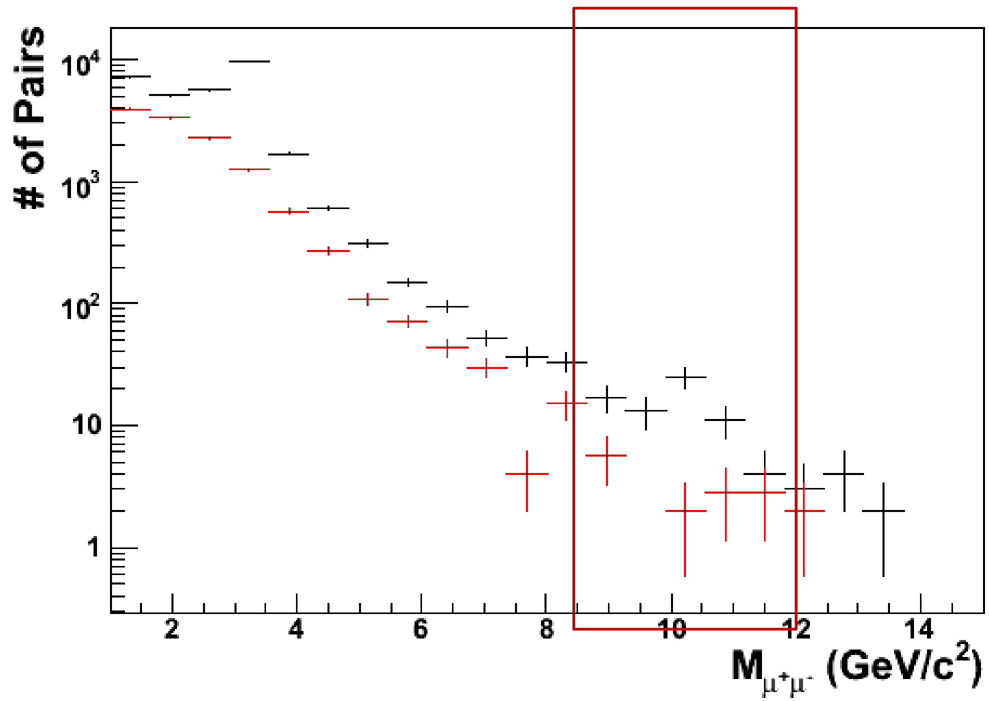
Should give some insight on CNM effects on other resonances

Things to come (2):
J/ψ and ϒ in p+p @ 500 GeV (2009 data)

J/ψ at forward rapidity



ϒ at forward rapidity



BNL and RHIC

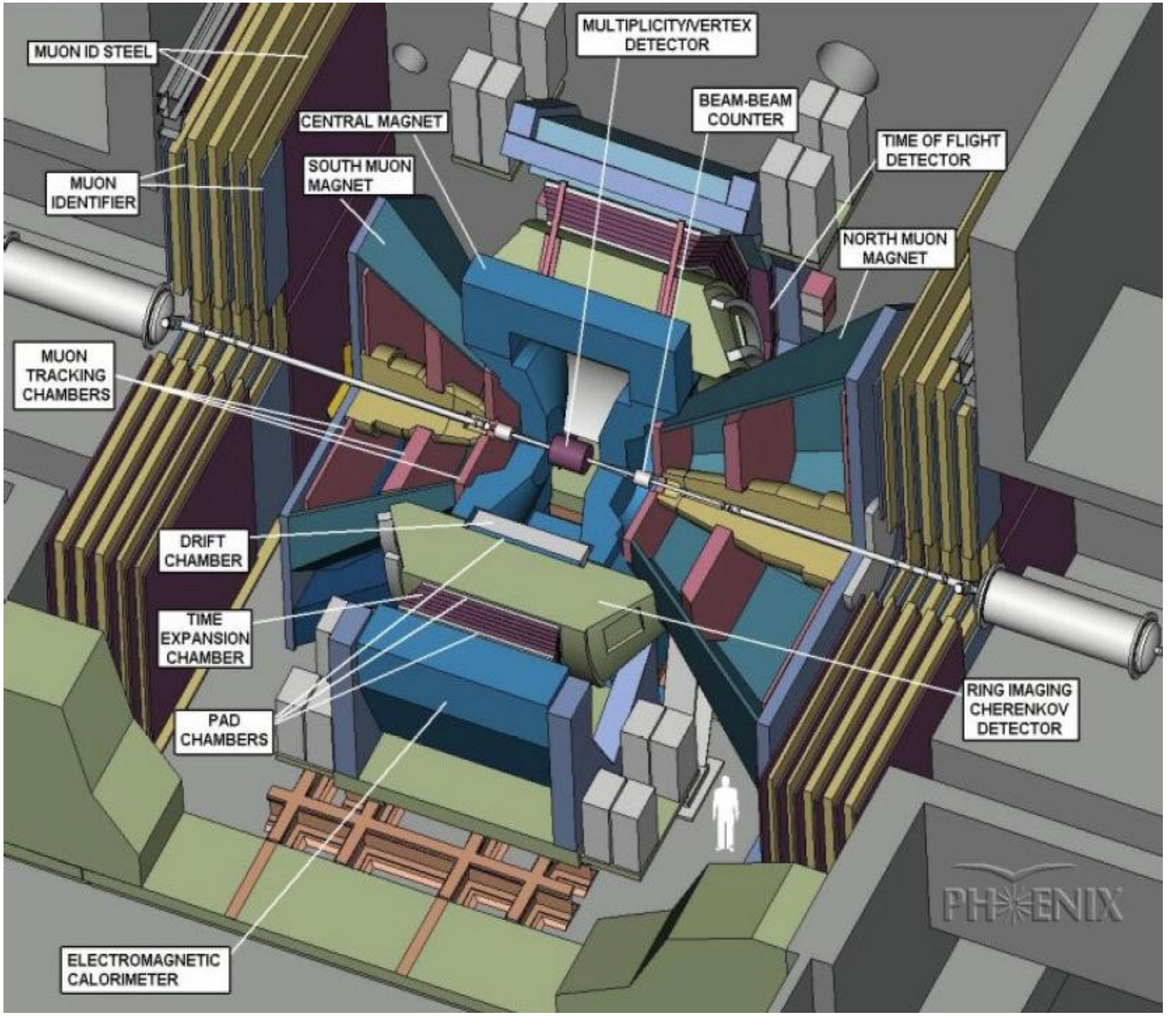
length: 3.83 km

Capable of colliding *any* type of nuclei

Energy:
500 GeV for pp
200 GeV for AA
(per N-N collision)

Two large experiments are still operating today: PHENIX and STAR

The PHENIX experiment



Central arm

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

p>0.2 GeV/c

|y|<0.35

$\Delta\Phi=\pi$

Muon arms

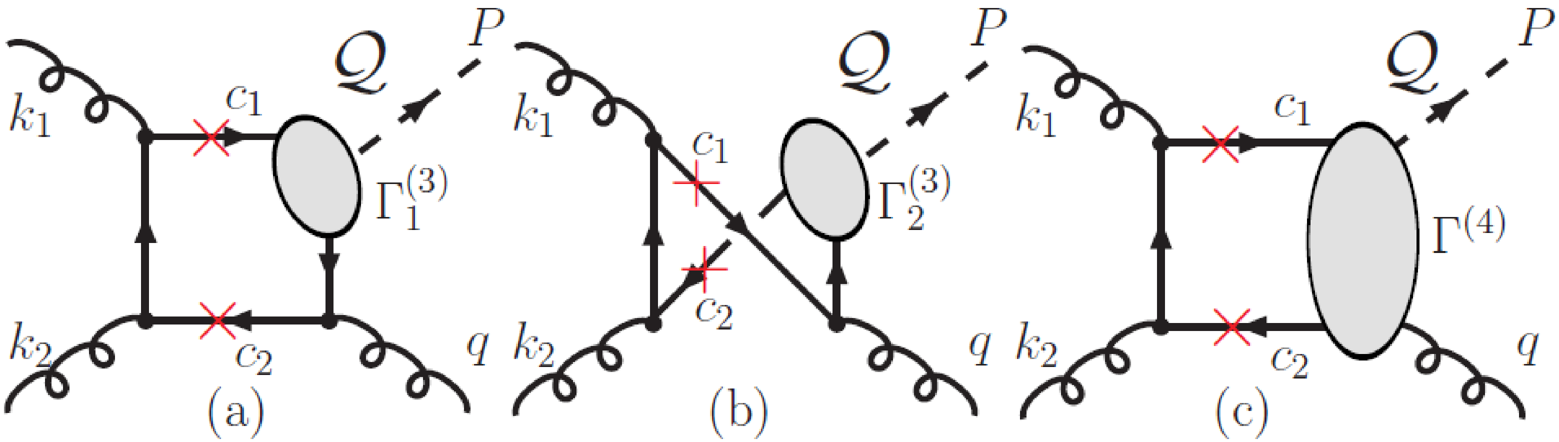
$J/\Psi \rightarrow \mu^+\mu^-$

p>2 GeV/c

|y| E [1.2,2.4]

$\Delta\Phi=2\pi$

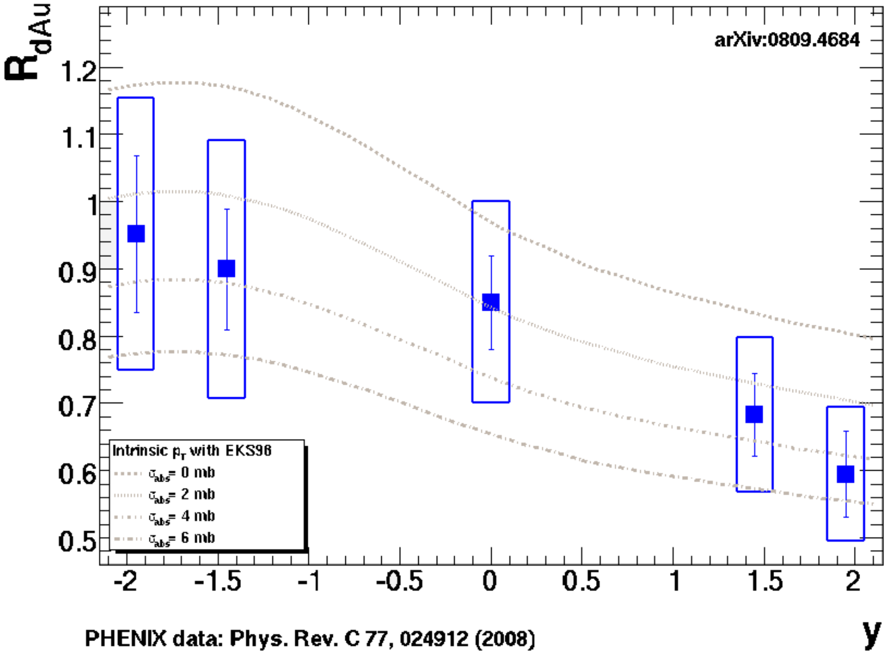
Highlight on CSM + S-channel cut

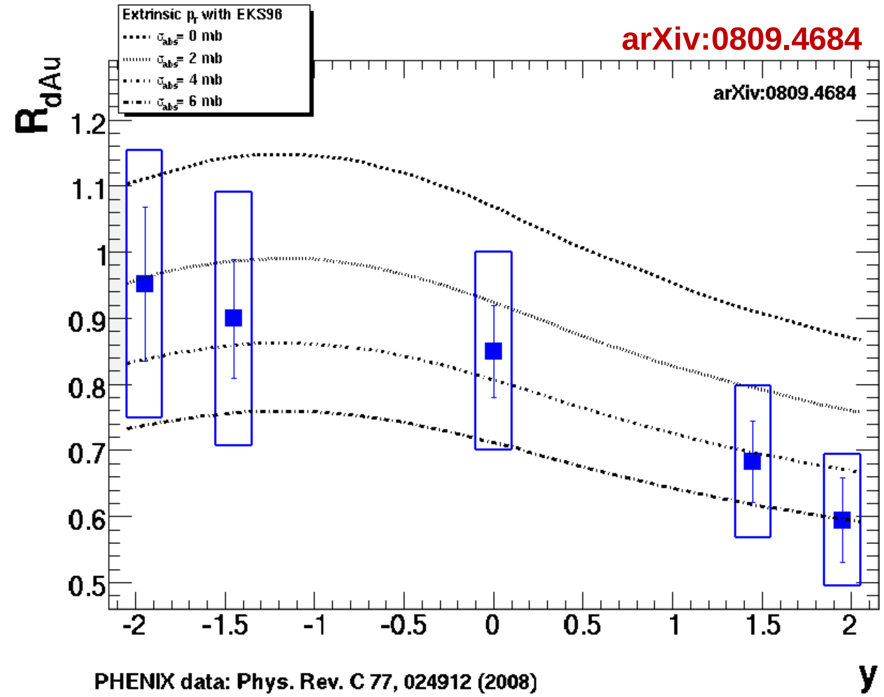


- From CSM, allow off mass shell quarks before quarkonia ($\mathcal{Q}$) formation.
- Requires a four point function to couple the c-cbar to J/ψ state (gg→$\mathcal{Q}$g).

  Note: four point function is parametrized to reproduce the cross section measurements at CDF, then compared to other data.

Production mechanism and CNM



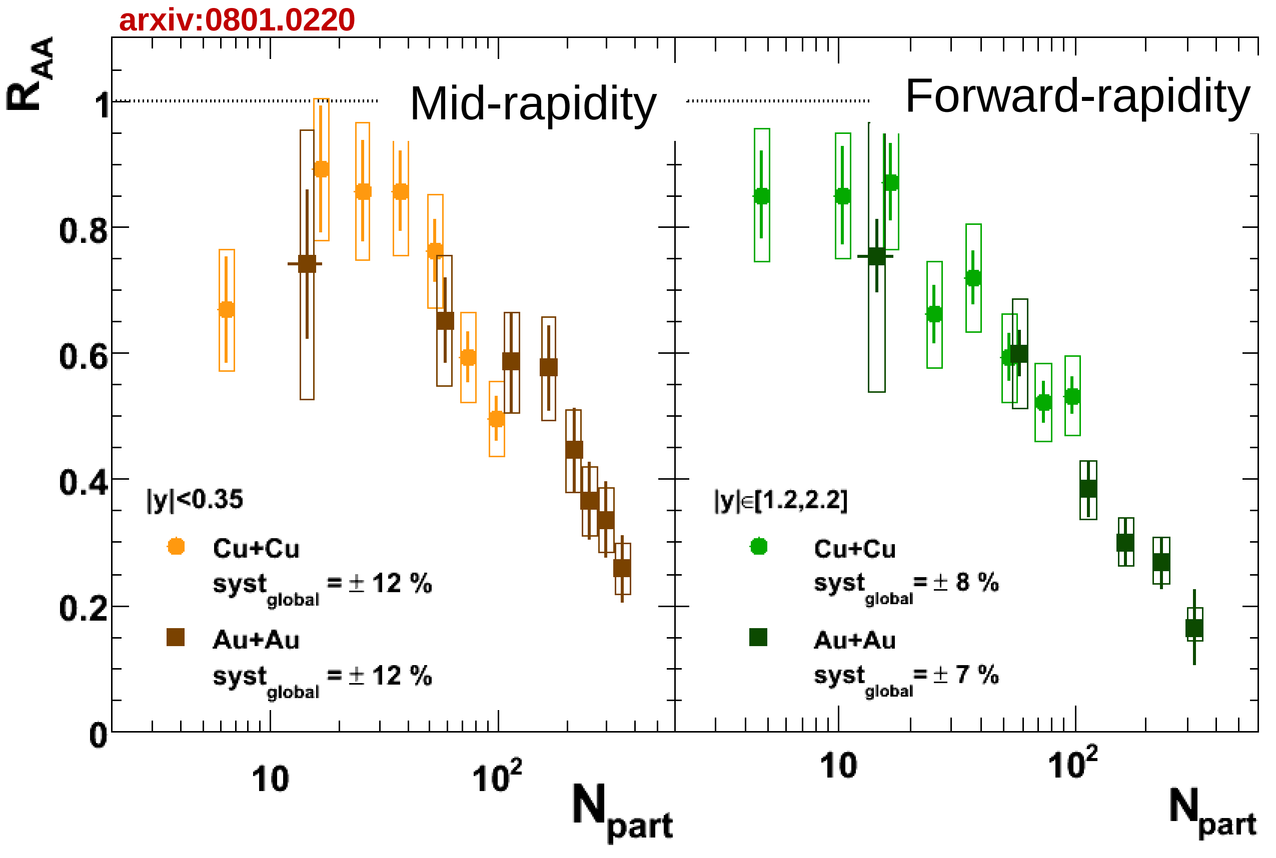


Lines are for $\sigma_{breakup}$ = 0, 1, 2, 3 and 4 mb

EKS98 shadowing is used for both figures.

Two different <u>production</u> mechanism are used for the J/ψ resulting in different CNM, because the parton *x* domain corresponding to a given y bin is different.

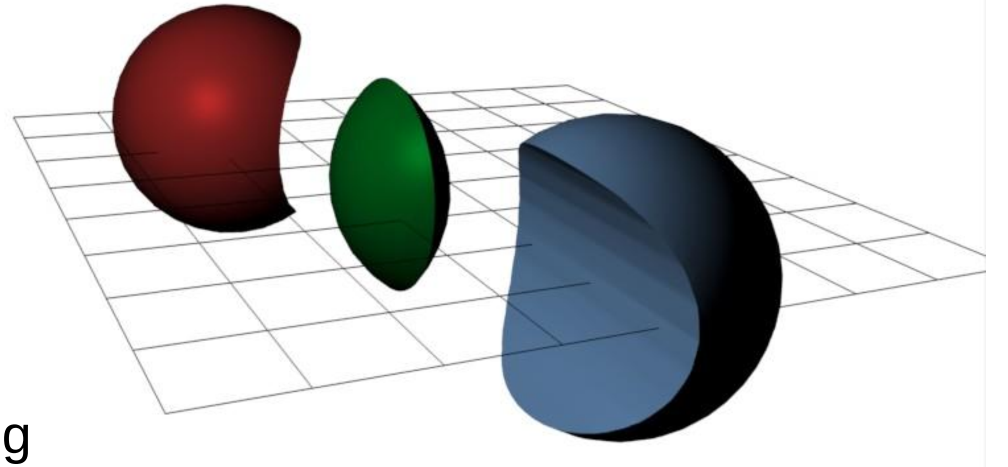
J/ψ R_{AA} in Au+Au and Cu+Cu @200 GeV



Cu-Cu and Au-Au ratios match well where they overlap.

In central collisions there is more suppression at forward rapidity than at mid-rapidity.

Elliptic flow (principle)



The elliptic flow, v_2, characterize the azimuthal anisotropy of particle emission with respect to the collision reaction plane.

Observed v_2 for non-central collisions is interpreted as a consequence of an anisotropic pressure gradient in the overlapping region of the colliding nuclei.

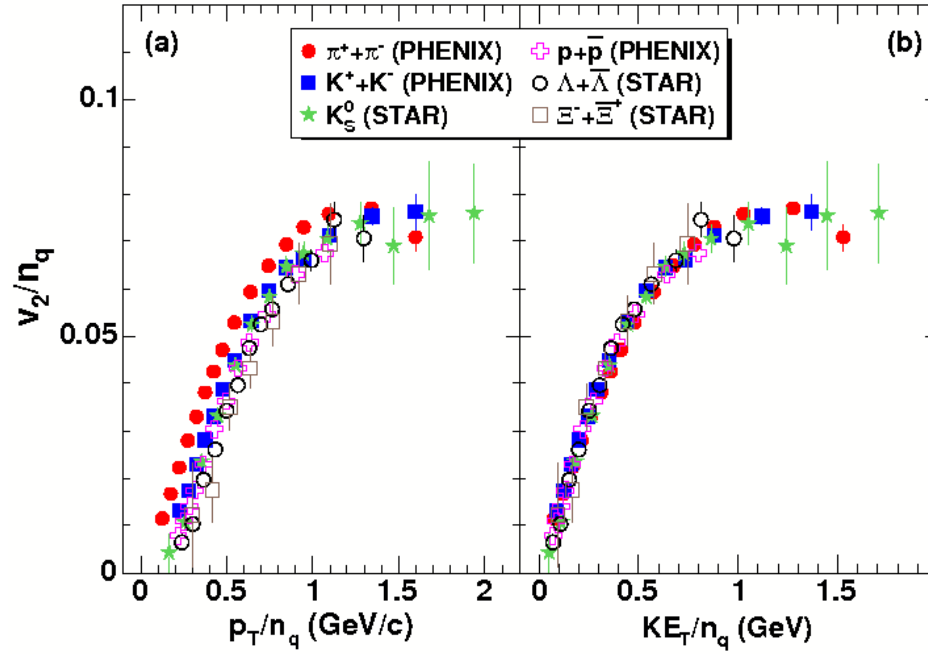
This requires an early thermalization of the medium.

Elliptic flow for light hadrons and heavy flavors

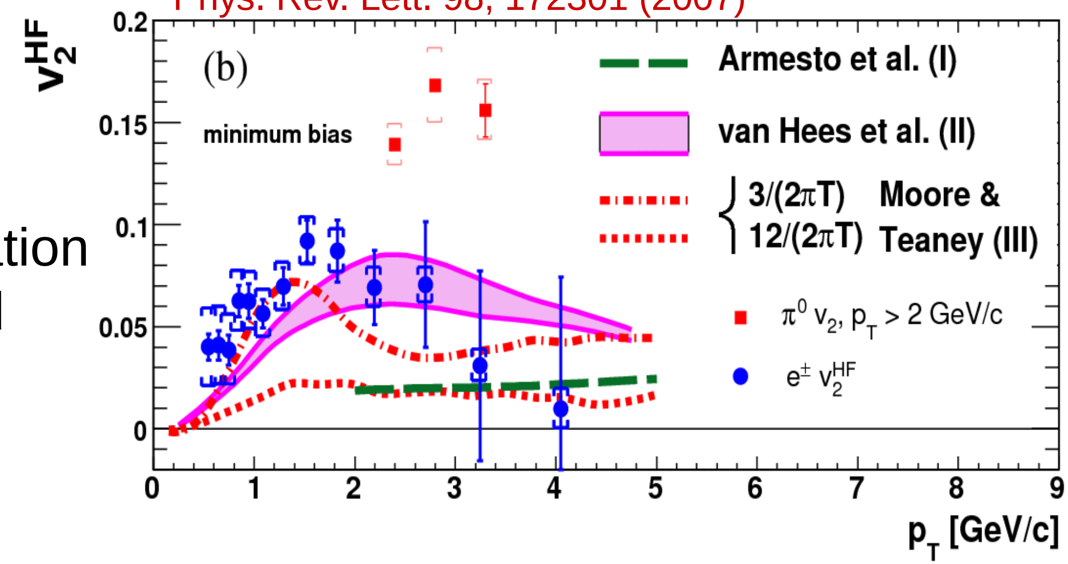
Elliptic flow (v_2) was measured for light hadrons. Observed scaling properties are related to properties of the formed medium and denote pre-hadronic degrees of freedom.

v_2 was also measured for heavy flavored hadrons (D). A large v_2 is also observed.

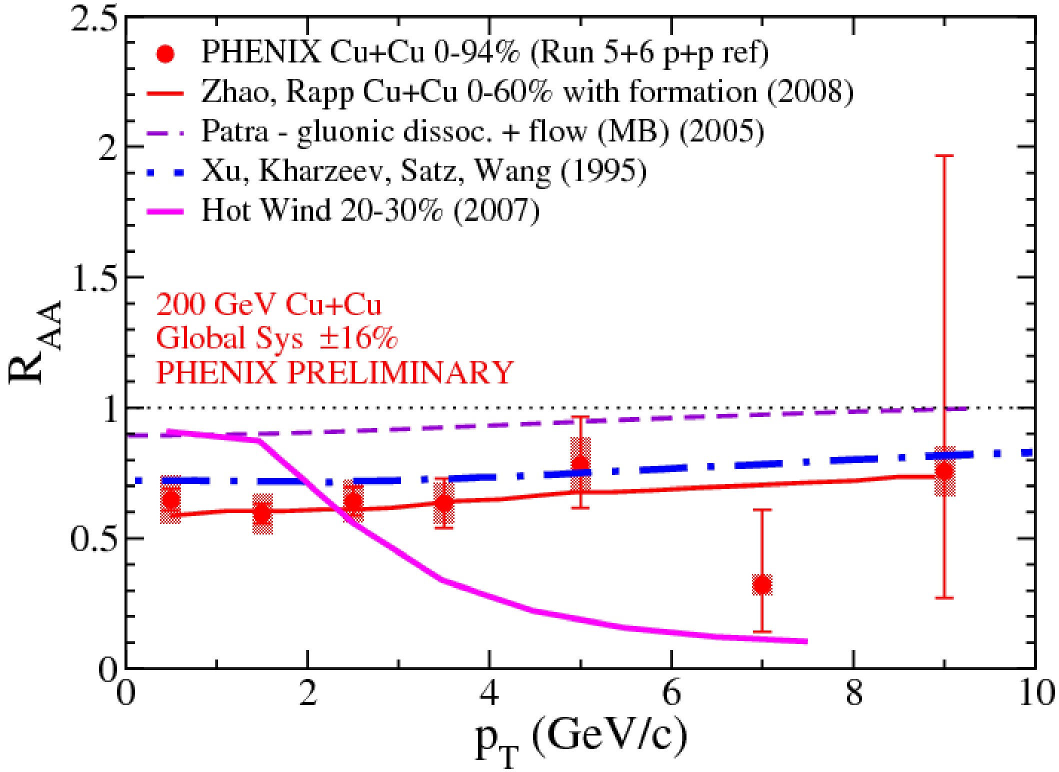
J/Ψ produced by recombination of uncorrelated pairs should also carry a significant v_2, unlike *direct* J/Ψ.



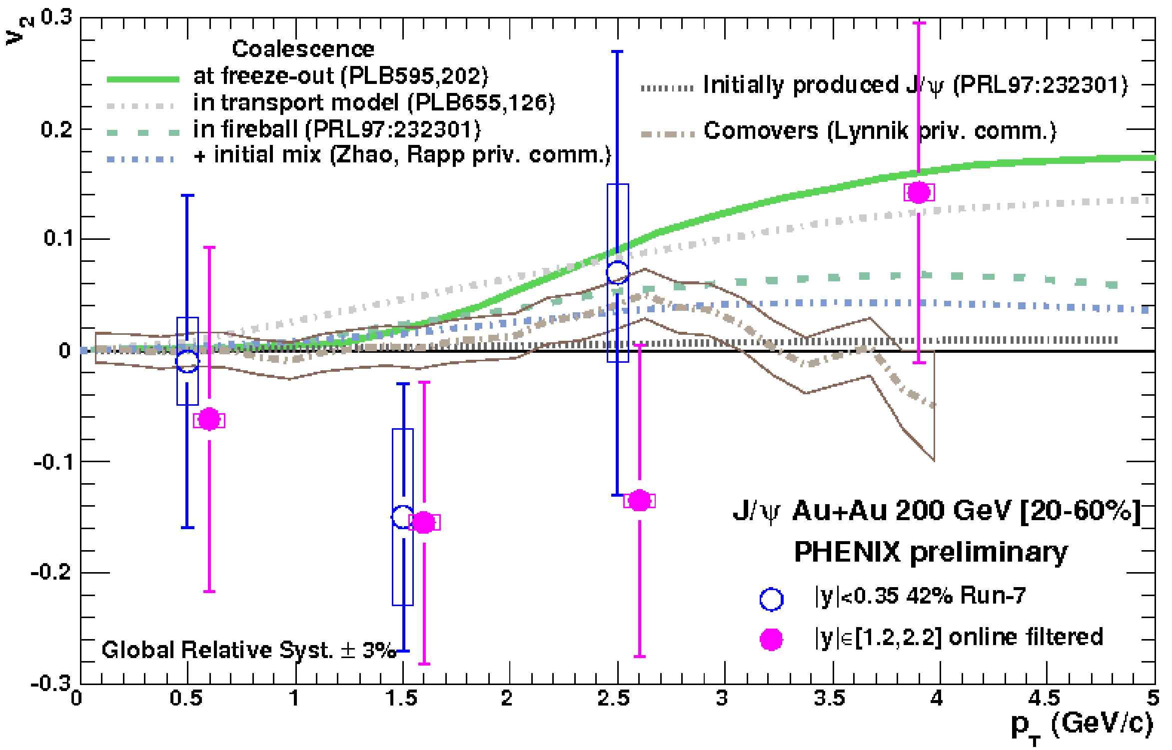
Phys. Rev. Lett. 98, 172301 (2007)



J/ψ R_{AA} vs p_T in Cu+Cu

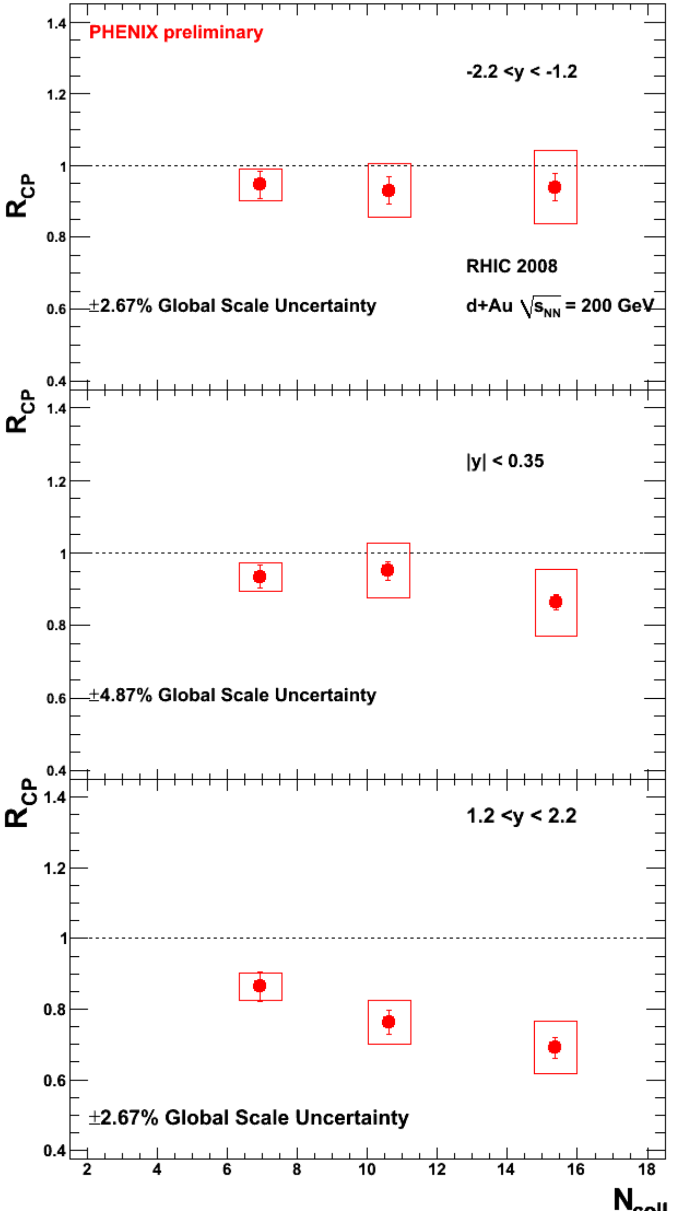


J/ψ elliptic flow in Au+Au



- Measurement is limited by statistics.
  $V_2 = -0.10 \pm 0.10 \pm 0.02 \pm 0.03$ (averaged over all p_T, all rapidity)
- Does not allow one to differentiate between different models in the measured p_T range.
- Expect about $\sqrt{2}$ improvement on errors for final results

J/ψ R_{dAu} vs centrality and rapidity



No effect vs centrality at backward (gold going) and mid-rapidity.

Clear decrease at forward rapidity