Recent results on heavy quarkonia production in p+p and heavy ion collisions at RHIC

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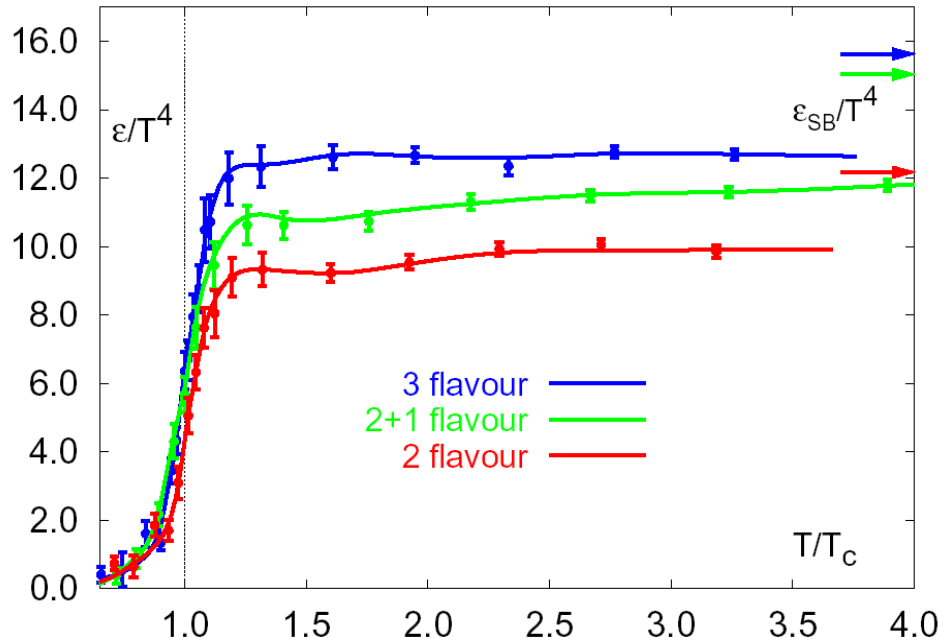
DIS 2008, April 9 2008

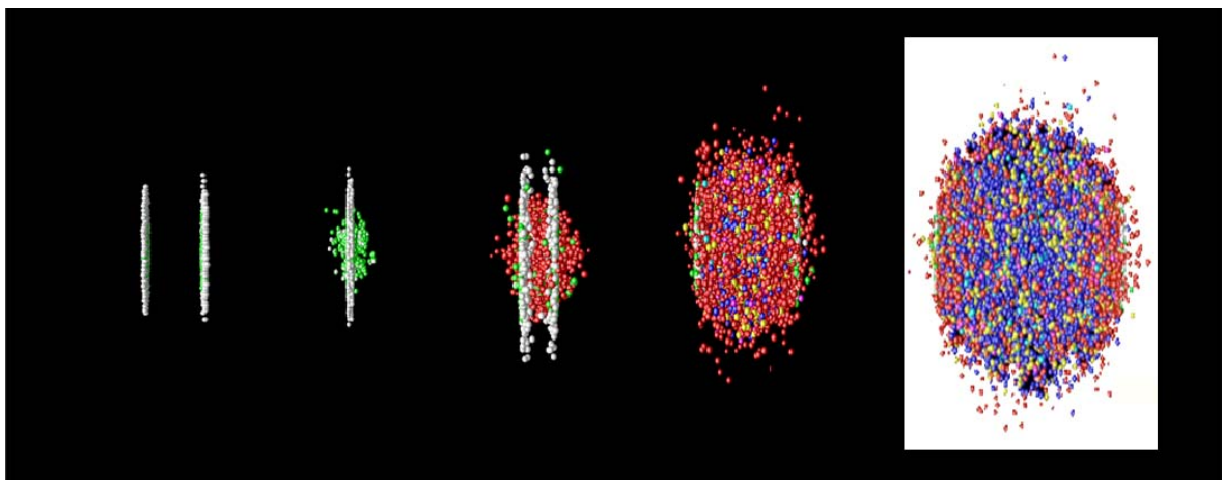
Introduction

The quark gluon plasma

RHIC aims to study the possible formation of a plasma of quark and gluons at high temperature and energy density.



Relativistic heavy ion collisions:



Heavy quarkonia as a QGP probe

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

BNL and RHIC

length: 3.83 km

Capable of colliding *any* type of nuclei

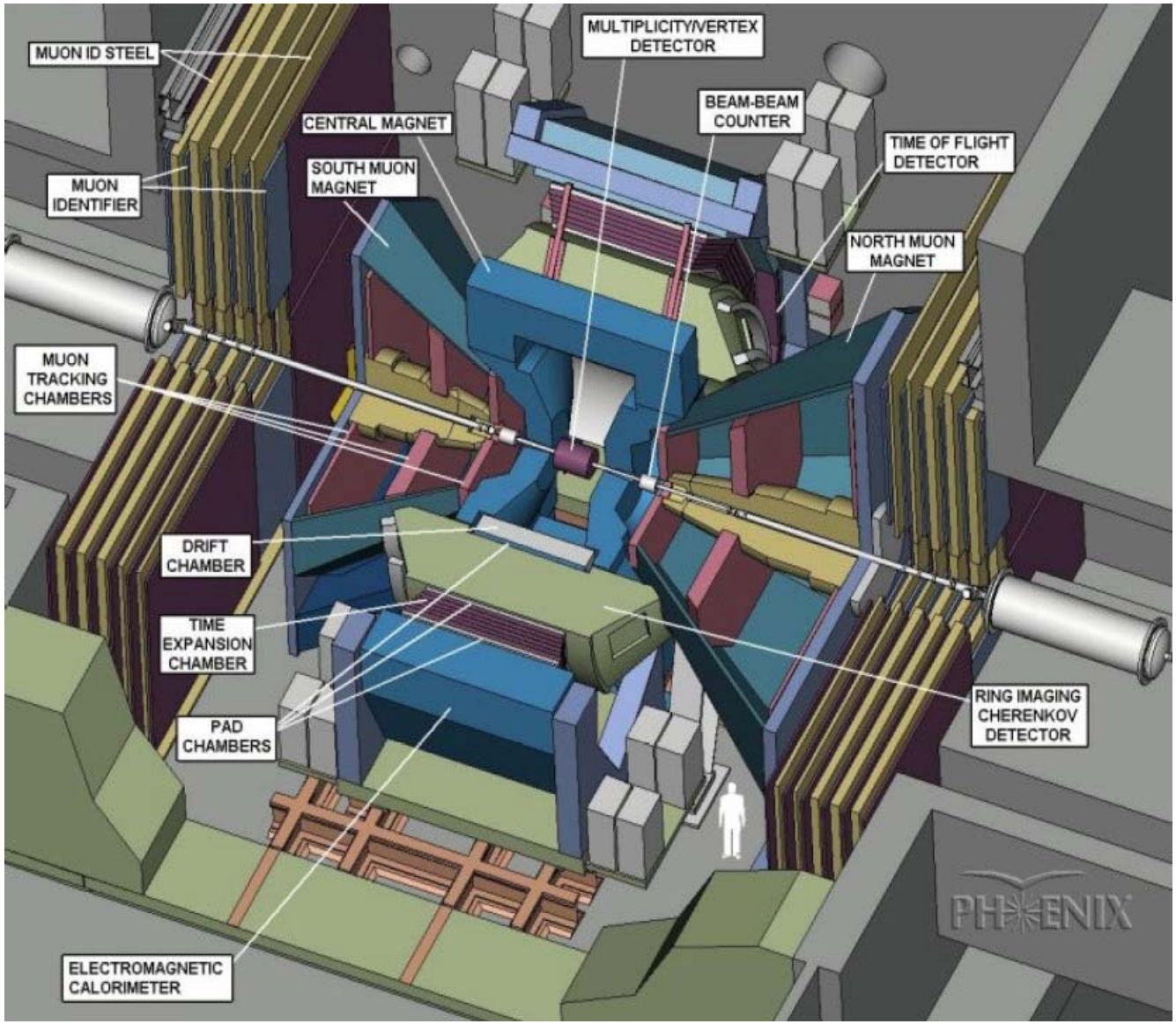
Energy:

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

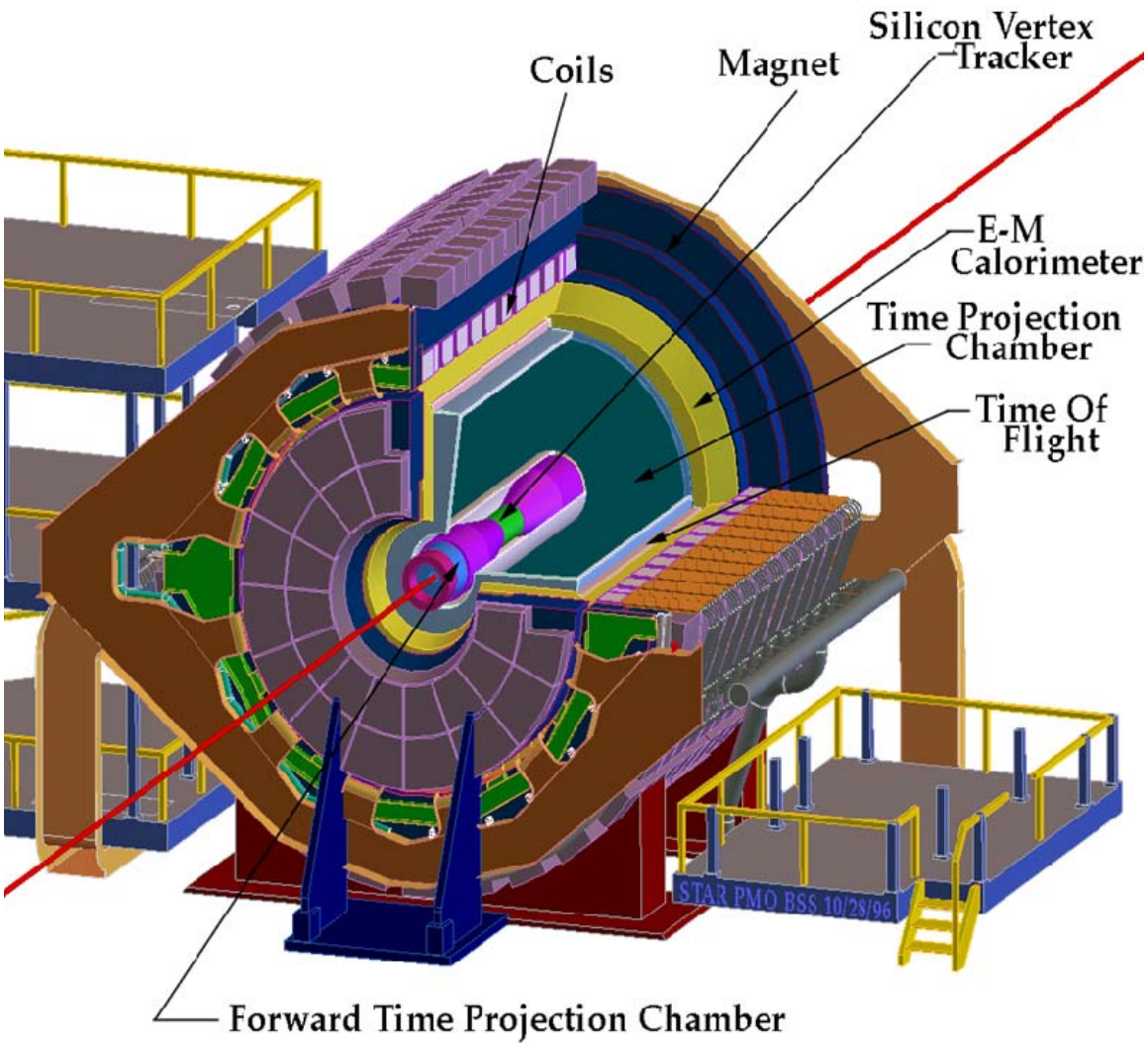
$J/\Psi \rightarrow \mu^+\mu^-$

$p>2$ GeV/c

$|y|$ E [1.2,2.4]

$\Delta\Phi=2\pi$

The STAR experiment



$J/\Psi \rightarrow e^+e^-$
$|y| < 1$
$\Delta\Phi = 2\pi$

Electrons measured with TPC and EMCal

Triggered with EMCal

Observables

- Cross-section vs p_T, rapidity (in pp collisions, as a reference)

- Nuclear modification factor R_{AA} vs p_T, rapidity, collision centrality

$$R_{AA} = \frac{\text{yield in AA (or dA)}}{N_{col}.\ \text{yield in pp}}$$

N_{col} = number of nucleon-nucleon collisions equivalent to one AA collision at a given centrality

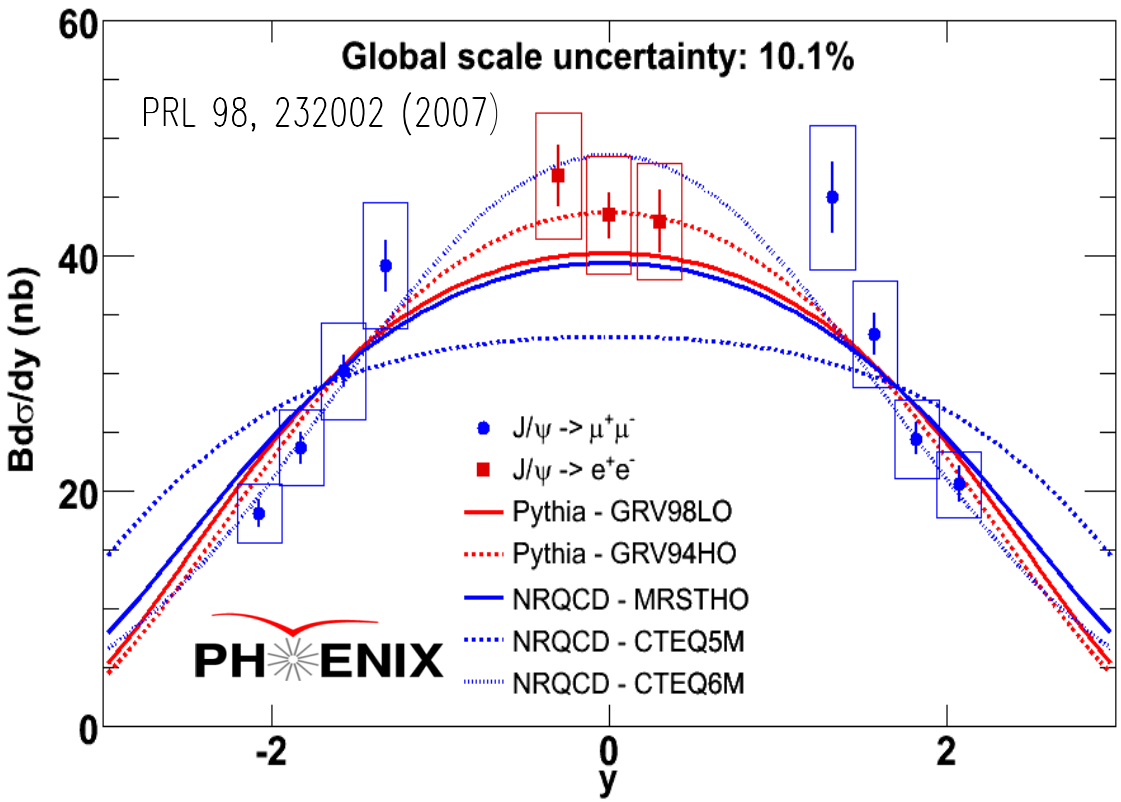
For *hard* processes and if everything in AA behaves like in pp, $R_{AA}=1$

Outline

- p+p collisions: reference for heavy ions
- d+Au collisions: cold nuclear matter effects
- Cu+Cu and Au+Au: hot nuclear matter effects
- Other quarkonia states
- Other observables: elliptic flow

1. p+p collisions

J/Ψ production cross-section vs rapidity



vertical lines: uncorrelated statistical and systematic errors

boxes: correlated systematic errors

10% global systematic

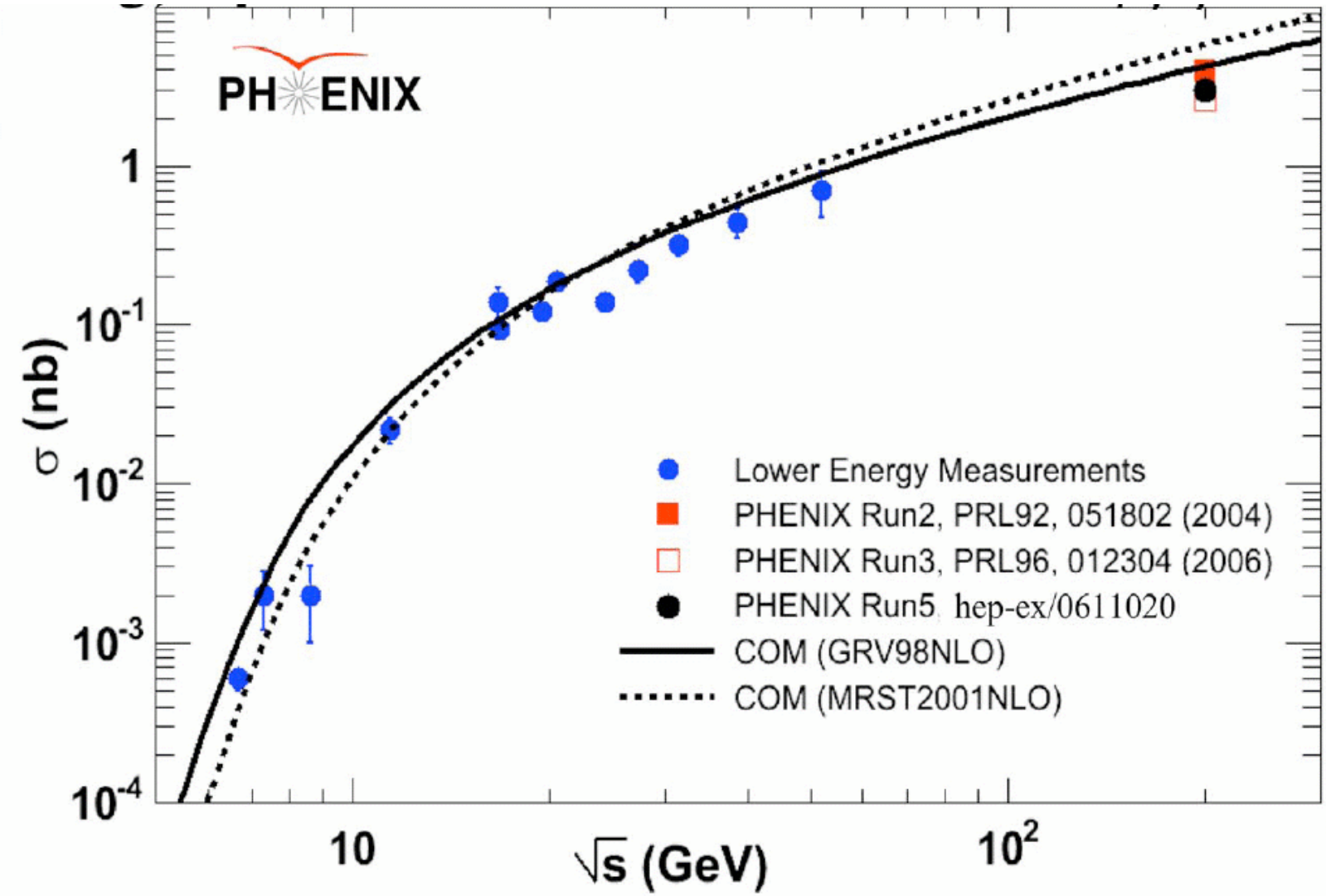
Measurement includes both direct J/Ψ and feed-down contributions from Ψ', χ_c and B

Measure dσ/dy as a function of rapidity;

Fit with various predictions and empirical line-shapes to get total cross-section and systematic error:

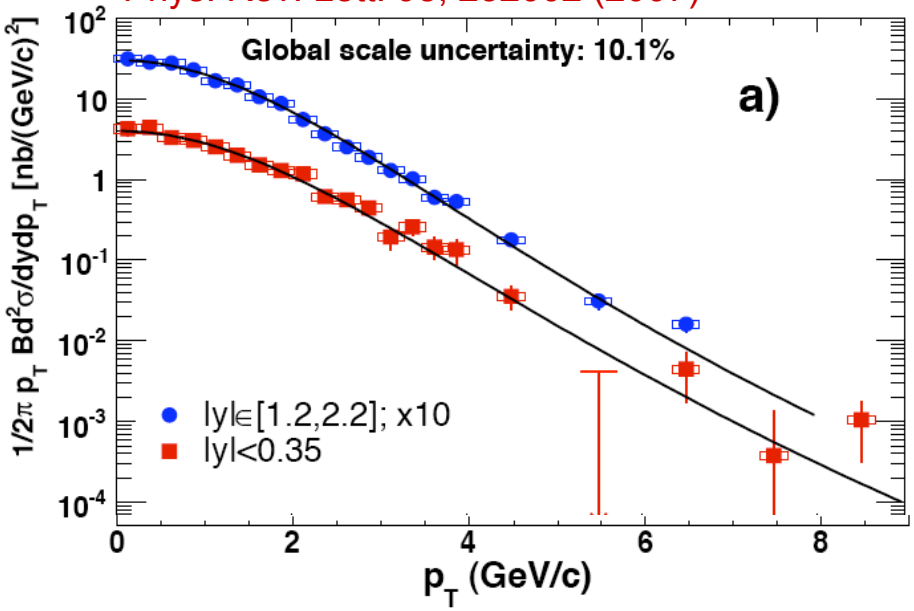
$$B_{ll}\ \sigma_{J/\Psi} = 178 \pm 3\ (stat) \pm 53\ (sys) \pm 18\ (norm)\ nb$$

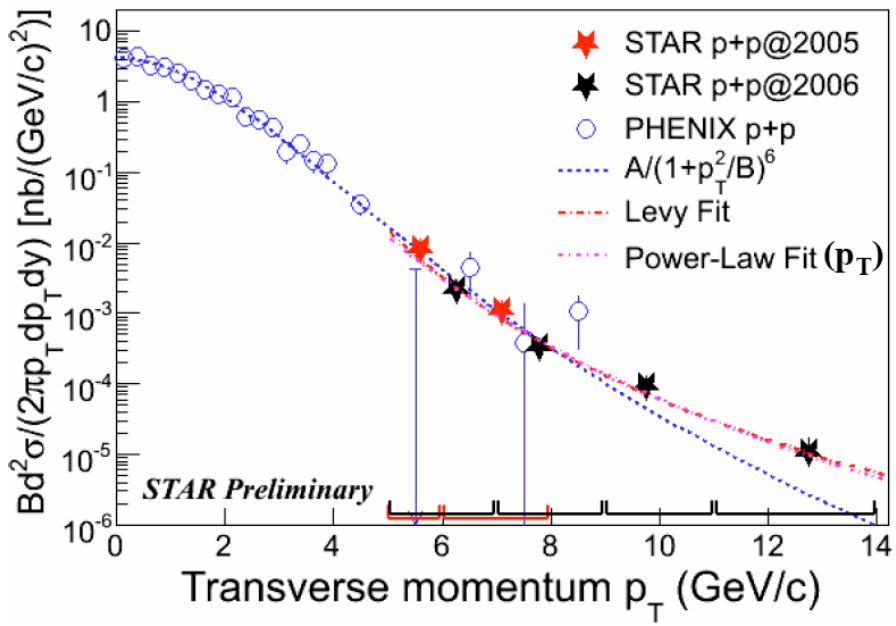
J/Ψ production cross-section vs energy



J/Ψ production cross-section vs p_T

Phys. Rev. Lett. 98, 232002 (2007)





Used to extract $\langle p_T^2 \rangle$

$\lvert y\rvert<0.35$:	$\langle p_T^2 \rangle = 4.25 \pm 0.24 \pm 0.14\ (\mathrm{GeV/c})^2$
$1.2< \lvert y\rvert <2.2$:	$\langle p_T^2 \rangle = 3.57 \pm 0.06 \pm 0.15\ (\mathrm{GeV/c})^2$

Also needed as reference for dA and AA measurements.

2. d+Au collisions:
cold nuclear matter effects
break-up cross-section

Cold nuclear matter effects

Modification of the J/Ψ production with respect to pp in *normal* nuclear matter (that is: without the formation of a QGP)

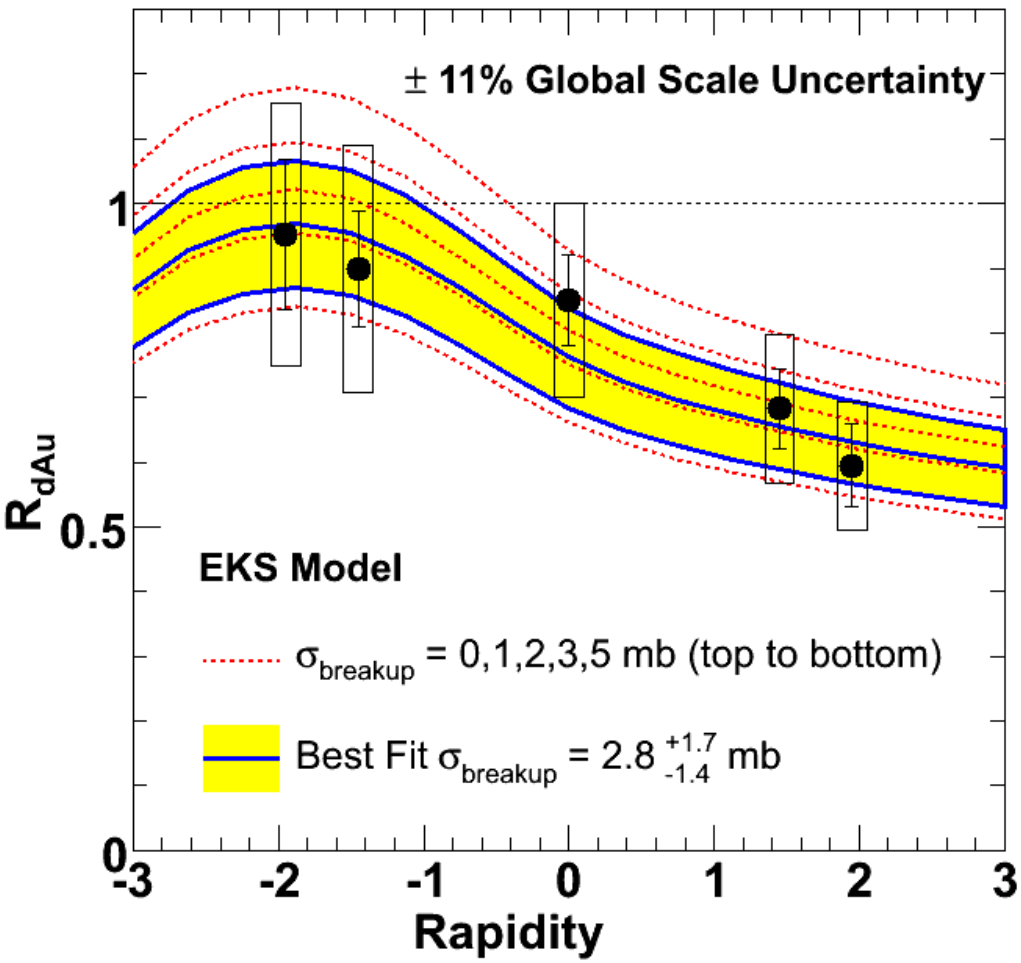
- **Modifications of the incoming parton distribution functions**
  shadowing, anti-shadowing
  saturation (at low-x)

- **Elastic scattering of the J/Ψ precursors (Cronin effect)**
  Affects the J/Ψ p_T spectrum but not the p_T integrated cross-section

- **Inelastic scattering of the J/Ψ precursors and nuclear absorption**
  These decrease the total J/Ψ production cross-section.
  Modeled using a break-up cross-section, and fitted to the data.

J/Ψ R_{dA} vs rapidity in d+Au collisions

arxiv:0711.3917



y<0: Au-going direction. Probe large x in the Au nucleus

y>0: d-going direction. Probe small x in the Au nucleus, where shadowing is expected.

The rapidity dependency is accounted for by the shadowing model (here EKS).

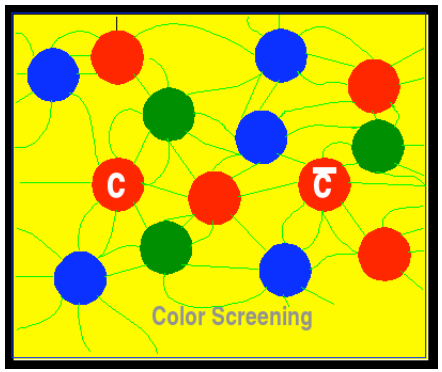
The overall magnitude is accounted for by a break-up cross-section, fitted to the data.

Once the shadowing model and breakup cross-section are known you can extrapolate CNM to AA collisions.

3. Cu+Cu and Au+Au collisions: Hot nuclear matter effects

Hot nuclear matter effects

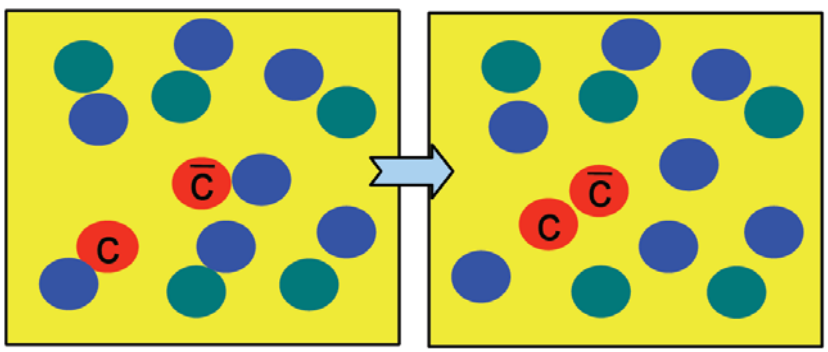
- **Debye screening in colored matter**



Mechanism originally proposed by Matsui & Satz, Also validated on the lattice, although with higher dissociation temperatures.

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

- **Dissociation by interaction with (partonic) co-movers**
- **Recombination/coalescence of uncorrelated charm quark pairs**

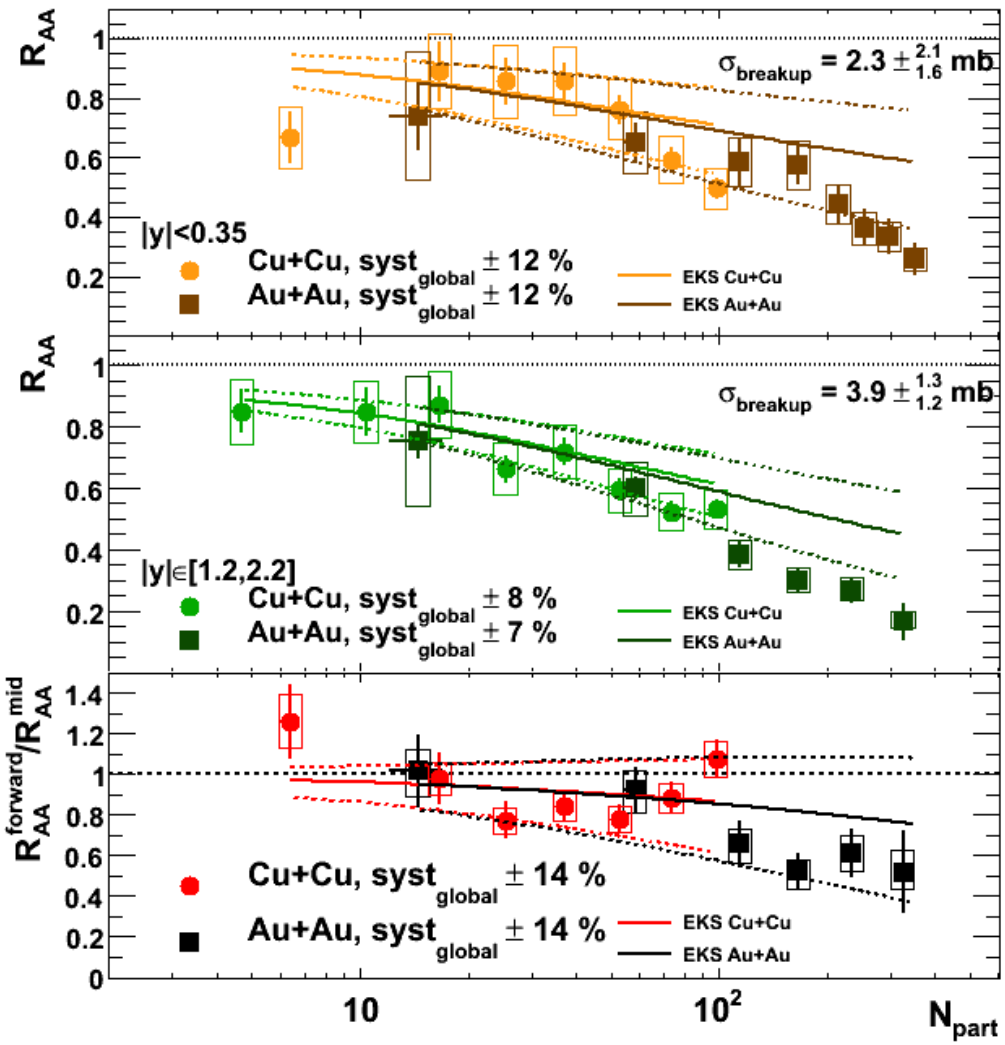


10 to 20 c,cbar pairs per event in most central Au+Au collisions.

Recombination goes like N_{cc}^2

J/Ψ R_{AA} vs centrality (N_{part}) in Au+Au and Cu+Cu

arxiv:0801.0220



Data are from 2005 Cu-Cu and 2004 Au-Au. Lines are cold nuclear matter effects extrapolated from d-Au

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

In Au+Au the suppression is larger than expected from CNM

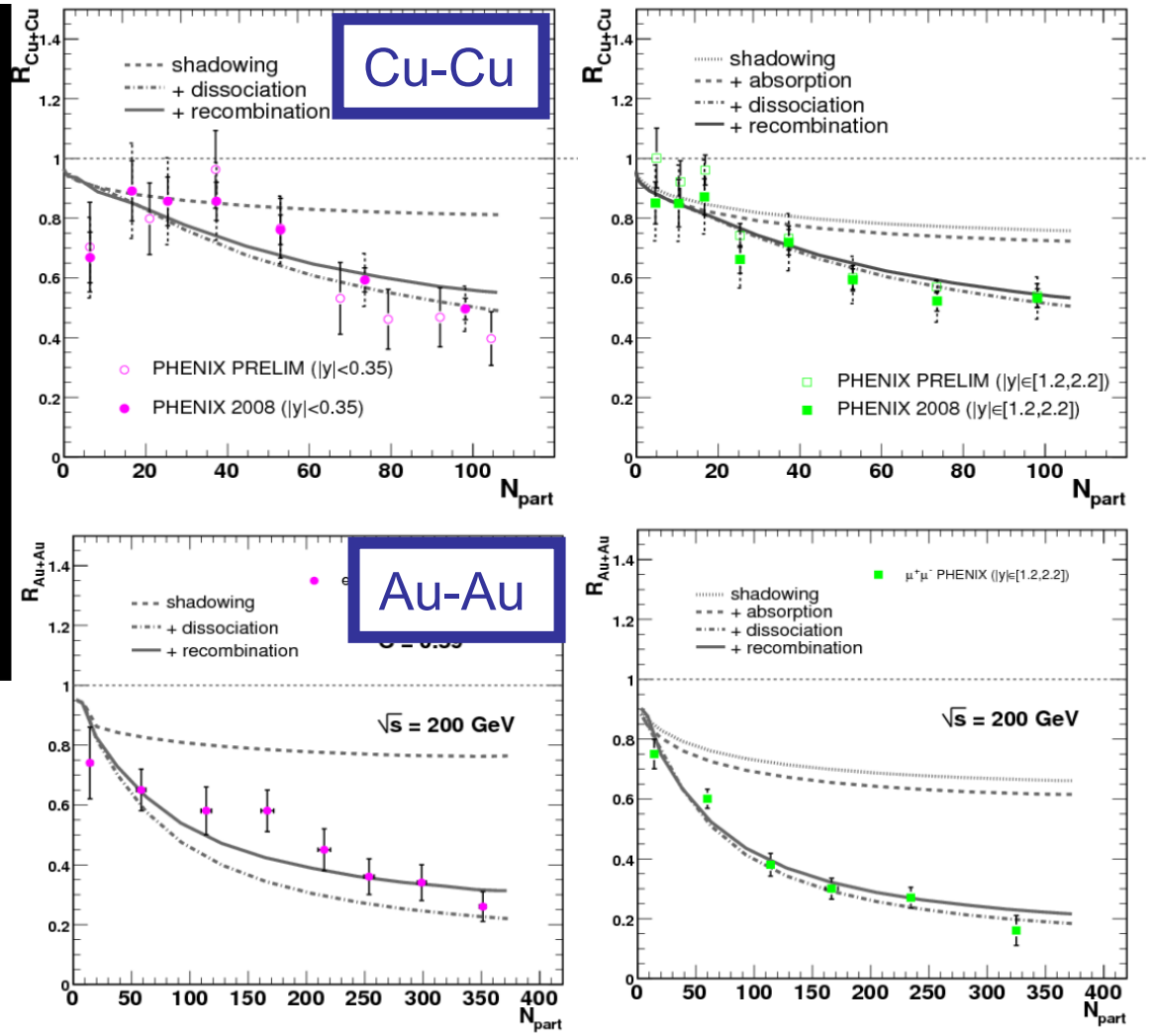
There is more suppression at forward rapidity than at mid-rapidity.

J/Ψ R_{AA} vs centrality (N_{part}) in Au+Au and Cu+Cu

More suppression at forward rapidity is unexpected.

Possible explanations:

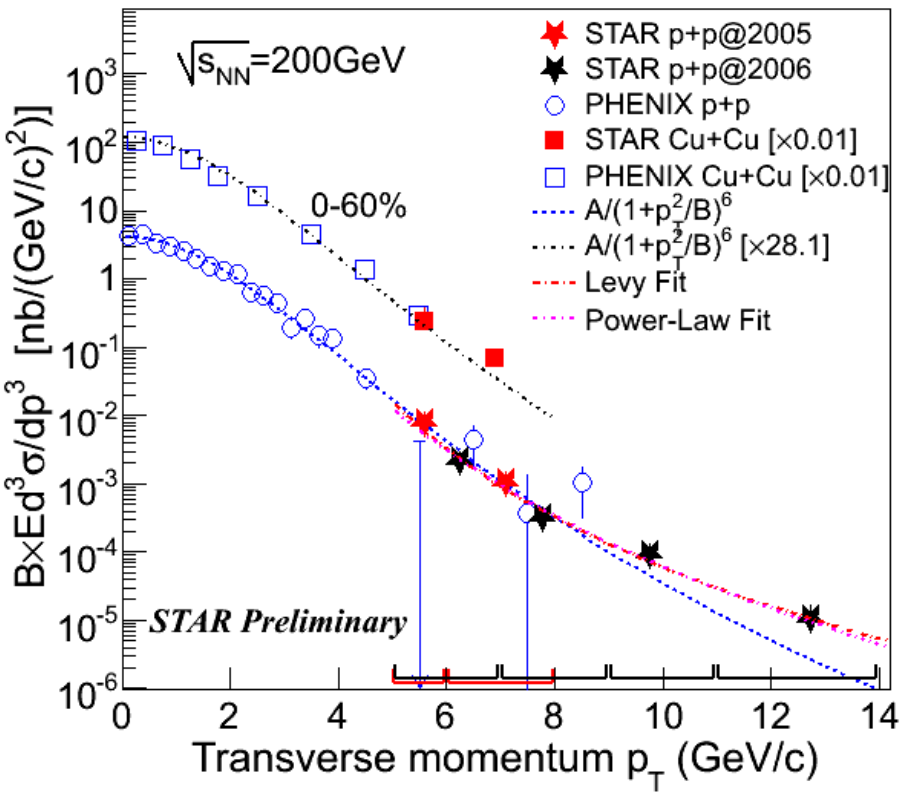
- more recombination at mid rapidity
- more CNM effects (notably saturation) at forward rapidity

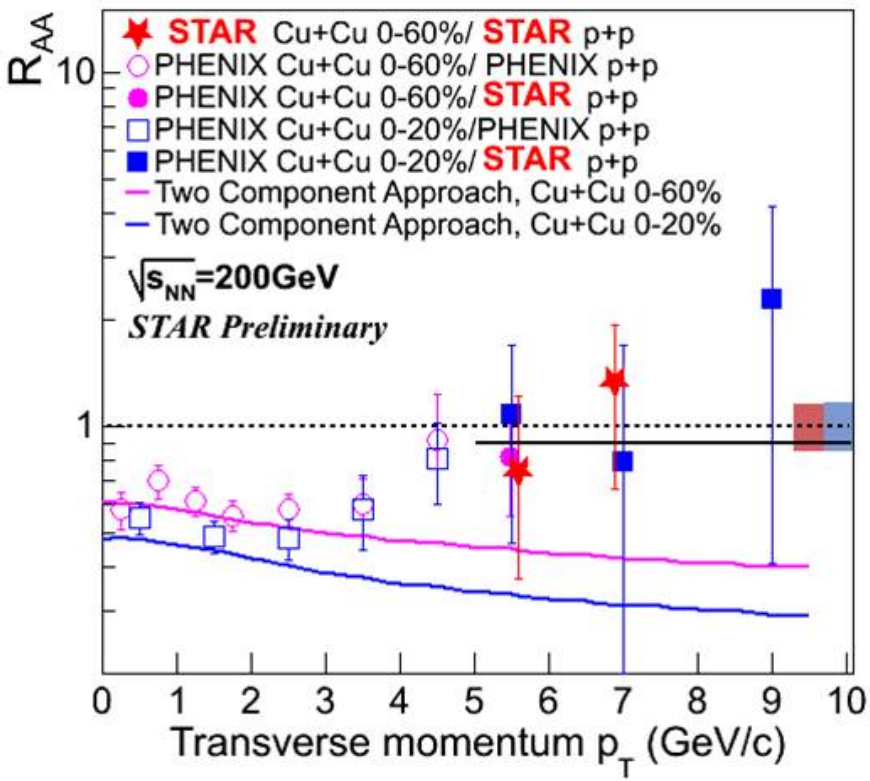


As an example:
Capella, Tywoniuk et al.
Fitting Cu+Cu, Au+Au, mid and forward rapidity

J/Ψ R_{AA} vs p_T

Modification of the J/Ψ p_T distribution should also help constrain the mechanisms at play.





4. Other heavy quarkonia: Ψ', χ_c, Υ

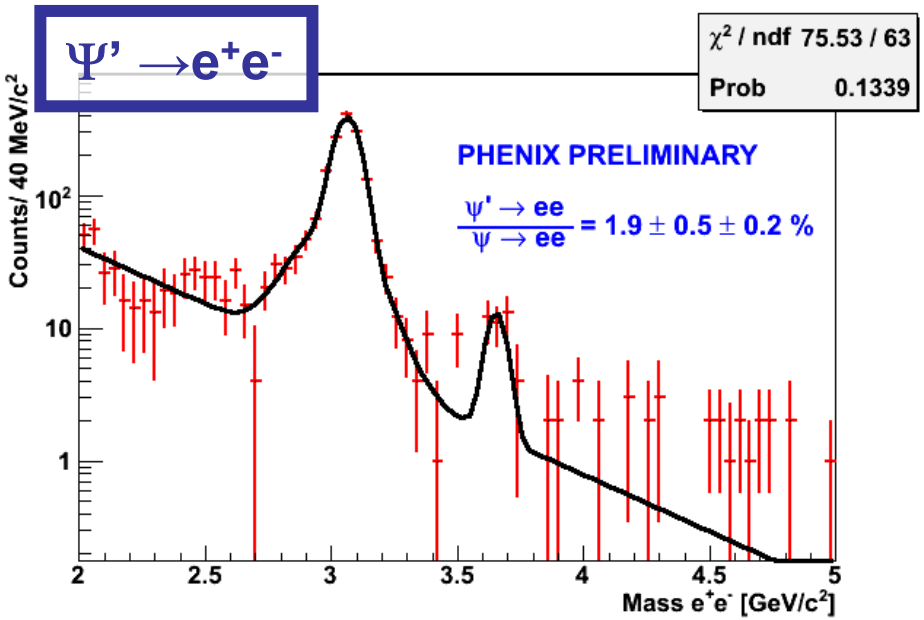
Motivation

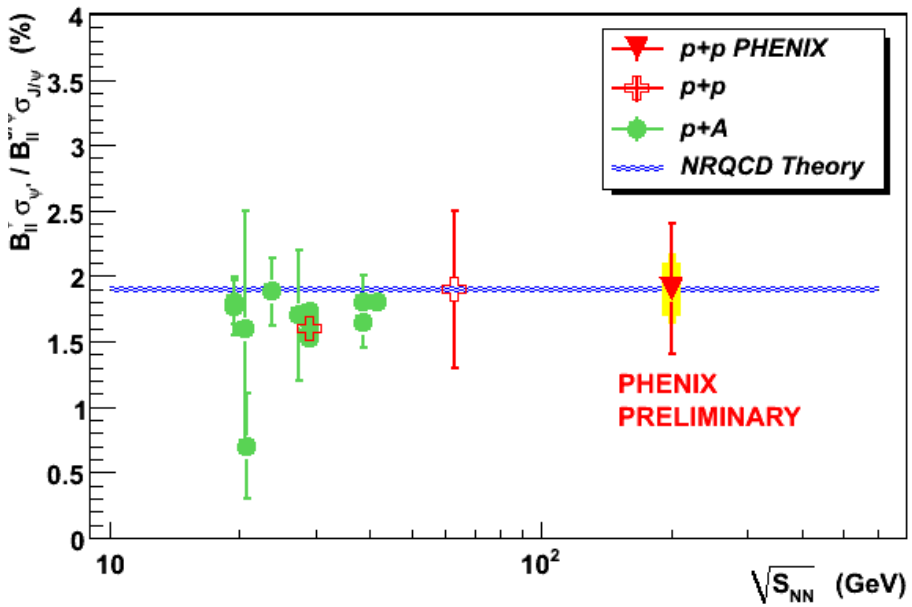
- direct measurements of Ψ',χ_c, B in p+p collisions constrain feed-down contributions to J/Ψ

- are first step towards similar measurements in dA and AA collisions, needed to disentangle effects on direct J/Ψ and resonances.

- Upsilon measurements give intermediate energy reference towards future LHC measurements.

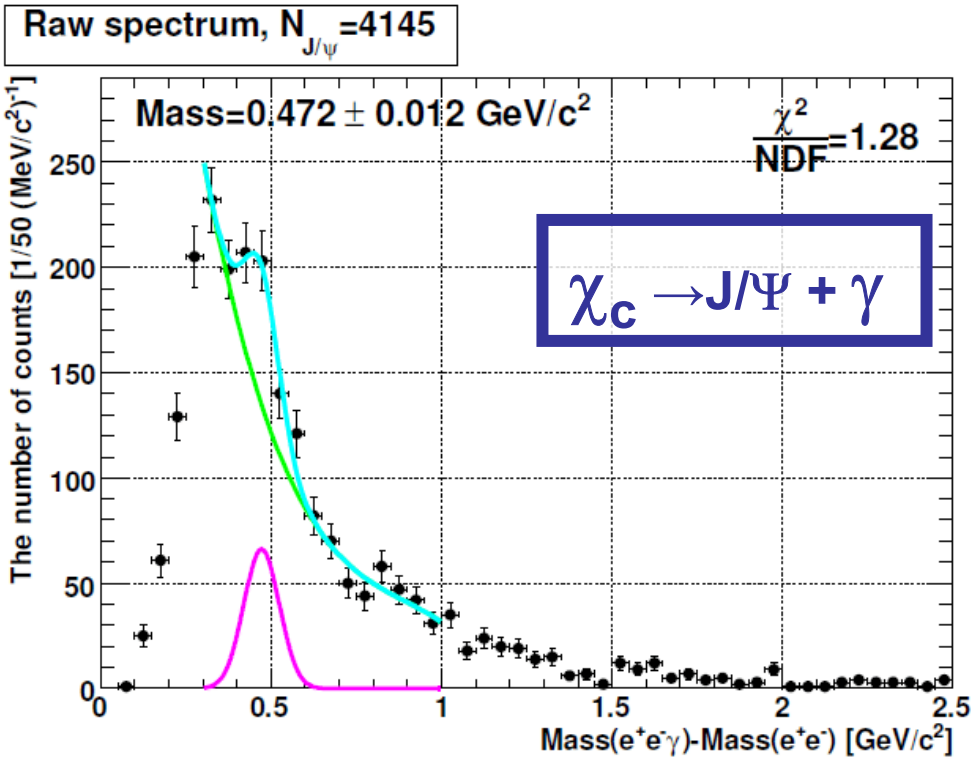
J/Ψ from Ψ'

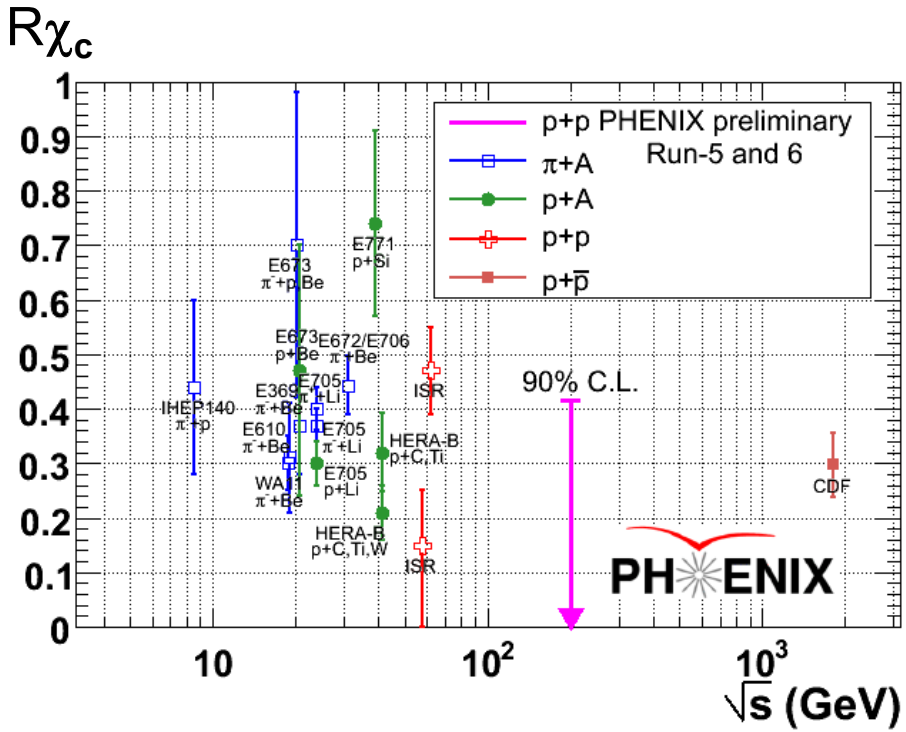




	PHENIX	Theory
J/Ψ from Ψ'	0.086 ± 0.025	0.08 Digal et al., Phys. Rev. D 64 (2001) 94015

J/Ψ from χ_c

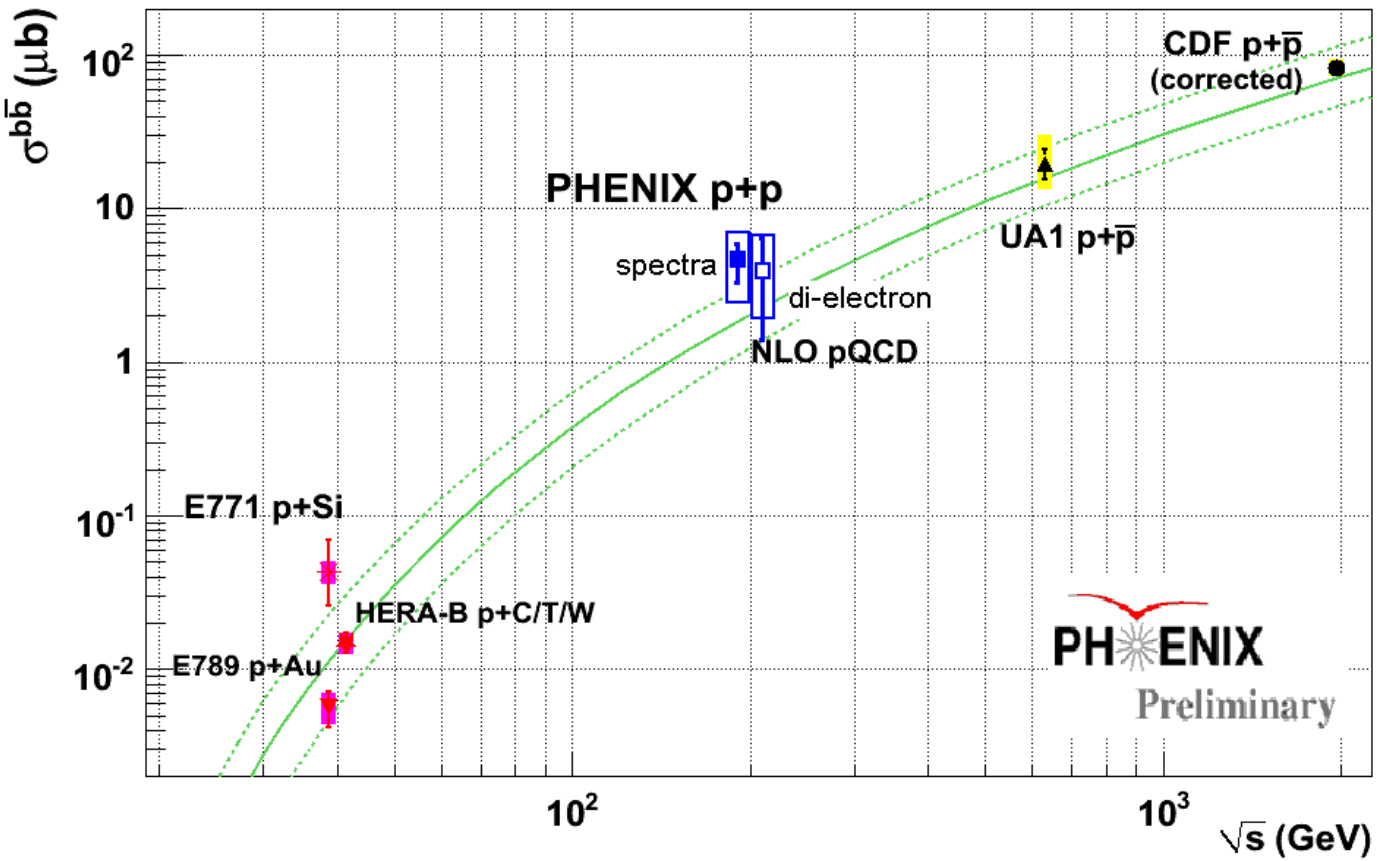




	PHENIX	Theory
J/Ψ from χ_c	< 0.42 (90% CL)	0.30 Digal et al., Phys. Rev. D 64 (2001) 94015

J/Ψ from B

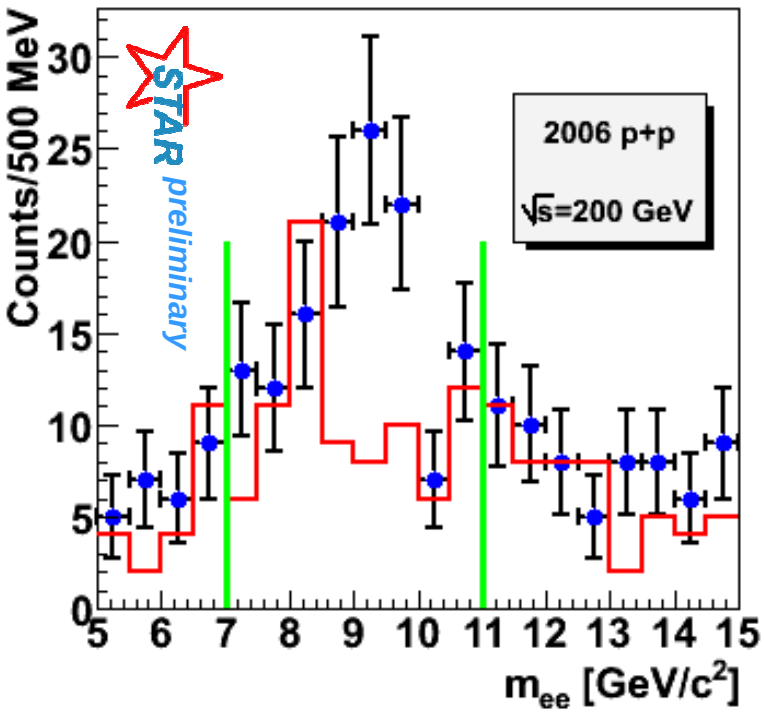
total cross section of bottom

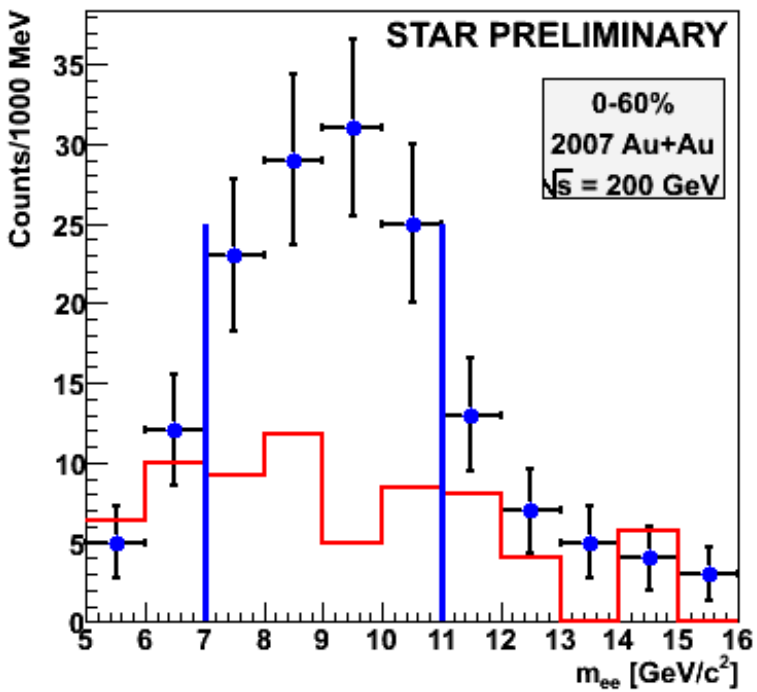


e-h correlations
di-electron

	PHENIX	Theory
J/Ψ from B	0.036 ± 0.025	0.02 ± 0.01 (NLO pQCD extrapolation)

Upsilon





First measurement of Y in A-A collisions.

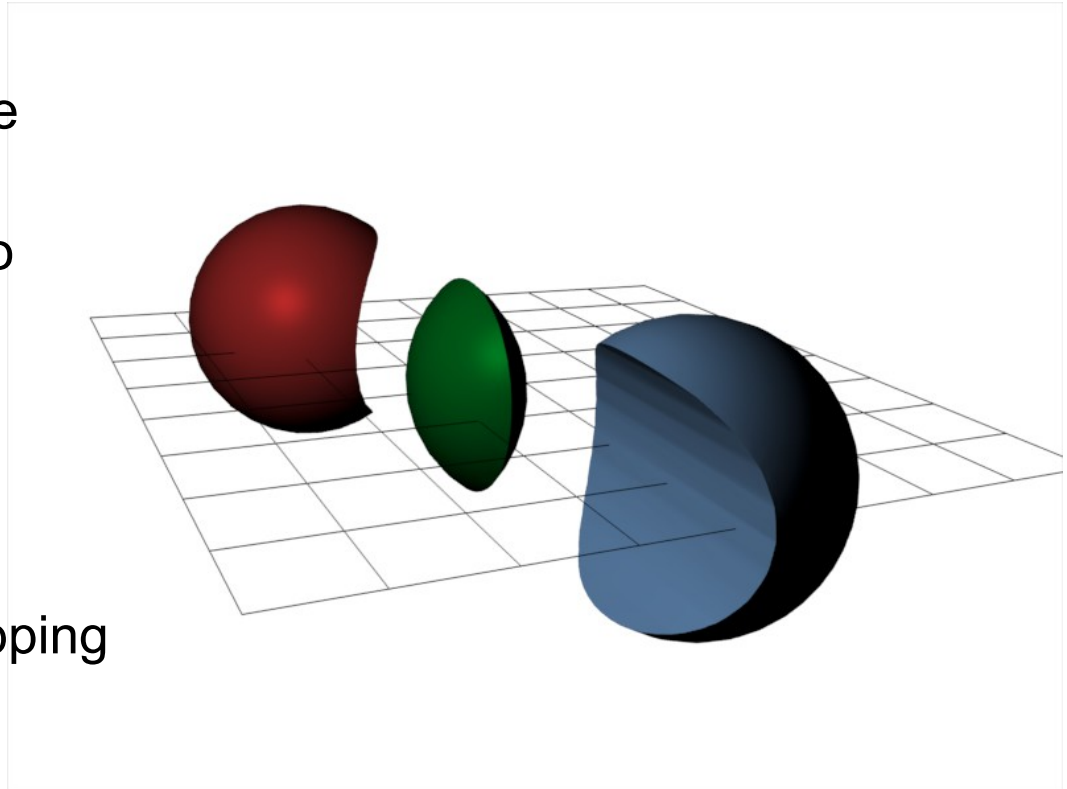
Still working on getting total cross-section (in pp) and R_{AA} (in Au+Au)

5. J/Ψ elliptic flow

Elliptic flow (principle)

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

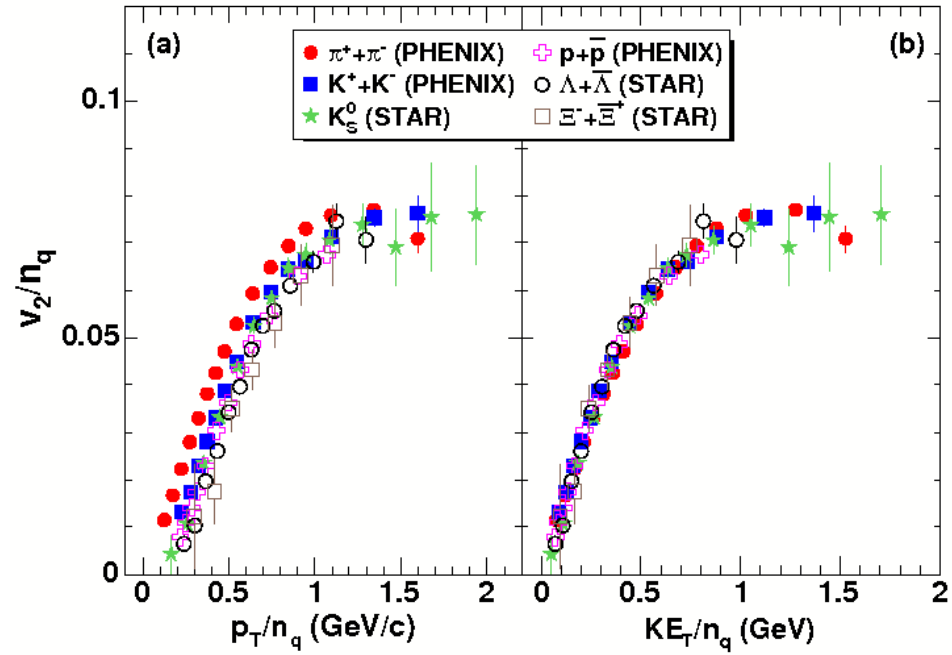
Observed v_2 for non-central collisions is interpreted as a consequence of an anisotropic pressure gradient in the overlapping region of the colliding nuclei.



This requires an early thermalization of the medium.

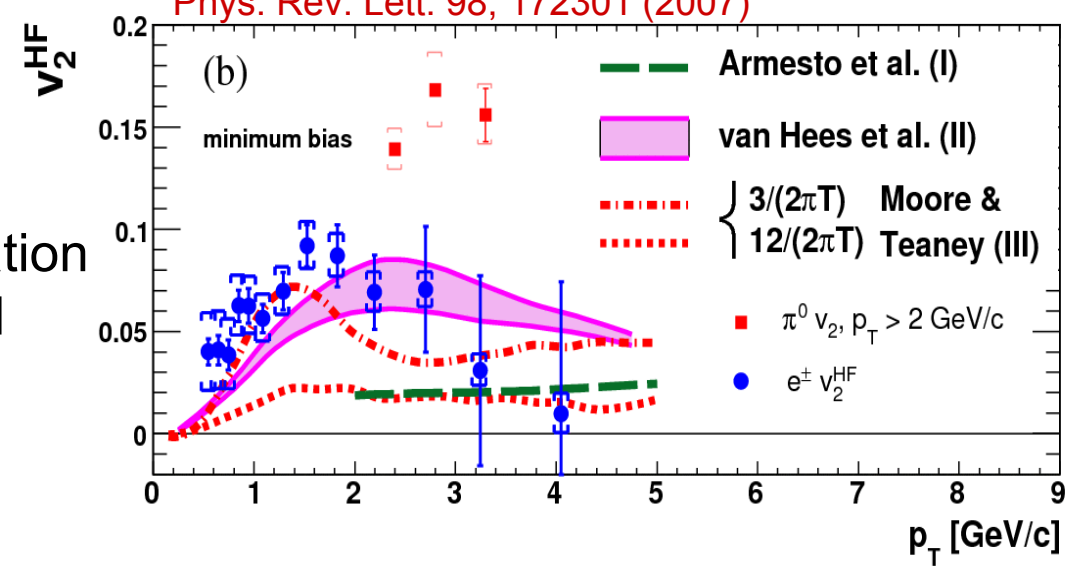
Elliptic flow for light hadrons and heavy flavors

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.

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



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

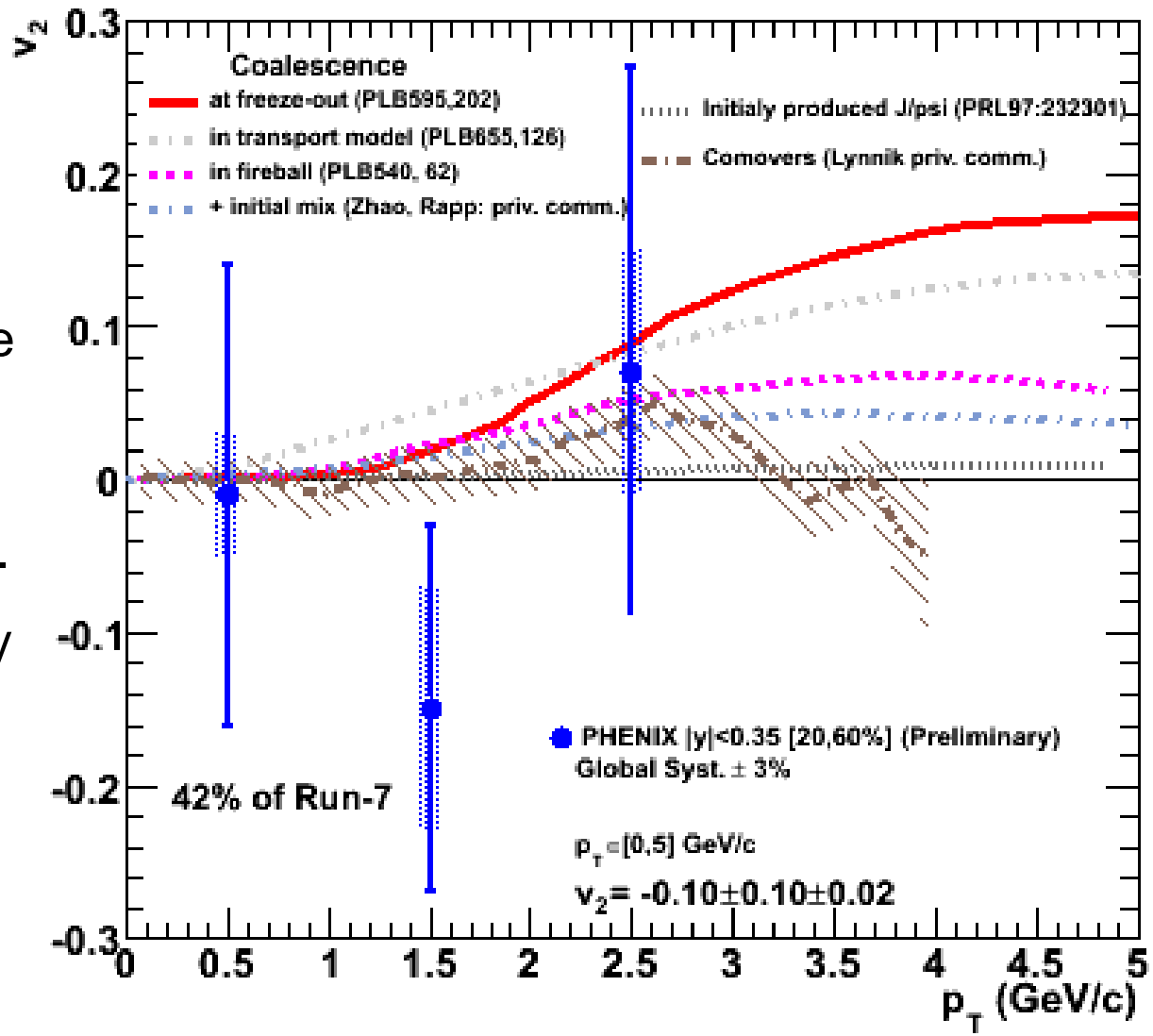
first measurement of J/Ψ v_2 at mid-rapidity

Statistics is poor and the measurement is rather a proof-of-principle.

More statistics is still to be analyzed from 2007 run.

More should be available during coming RHIC runs.

Results at forward rapidity should become available soon.



Conclusion and perspectives

in p+p collisions

solid reference for dA and AA measurements.
However the J/Ψ production mechanism is still not well understood.

Better understanding would require:

- more statistics (notably 2006 data)
- better control on feed-down contributions (work in progress)
- other observables (J/Ψ polarization)

In p+p, J/Ψ can also help the measurement on polarized pdfs (wait for more statistics and 500 GeV proton beams).

in d+Au collisions

More statistic is needed to constrain the cold nuclear matter effects and extrapolate to AA collisions. (work in progress using 2008 data)

In Cu+Cu, Au+Au collisions

An anomalous suppression is observed even after conservative cold nuclear effects are accounted for.

R_{AA} vs N_{part} can be more or less reproduced using a cocktail of (largely unconstrained) mechanisms:

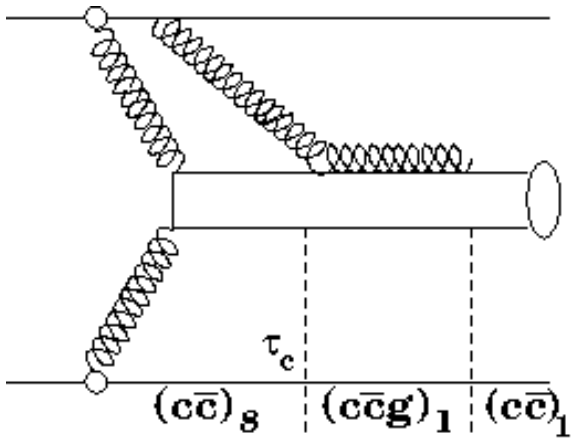
- cold nuclear matter effects
- co-mover suppression and/or color-screening
- regeneration by coalescence

A better understanding requires notably:

- better control on the cold nuclear matter effects (from d+Au collisions)
- better constrain on the open charm production (wait for PHENIX/STAR upgrades)
- more precise measurement of J/Ψ p_T spectrum (2007 Au+Au dataset)
- other observables (such as J/Ψ v_2) (2007 and future datasets)
- other resonances (Ψ', χ_c and Y)

Backup

J/Ψ production mechanism

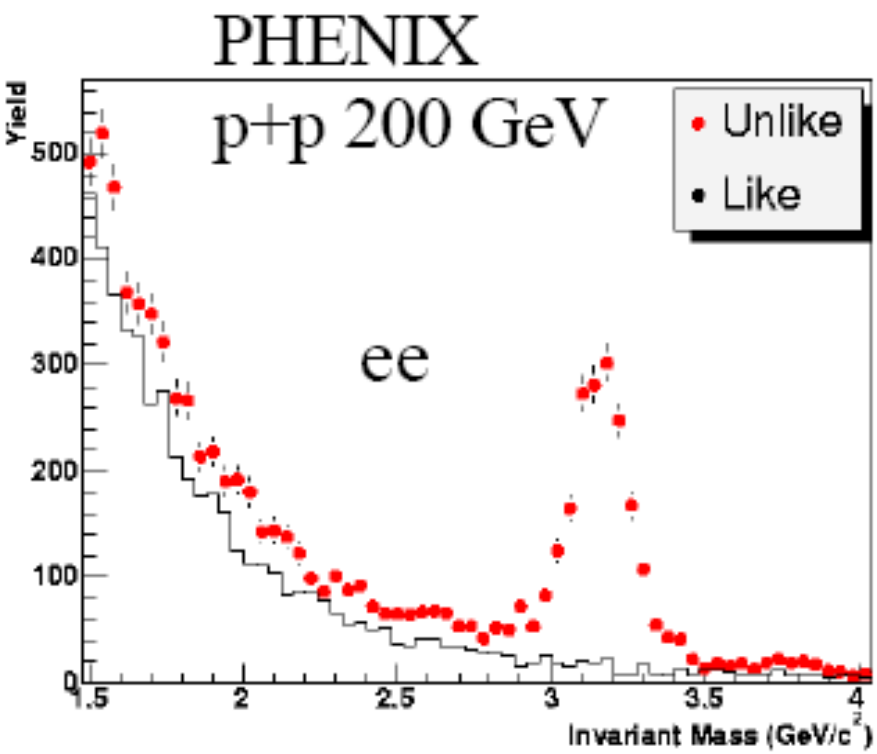


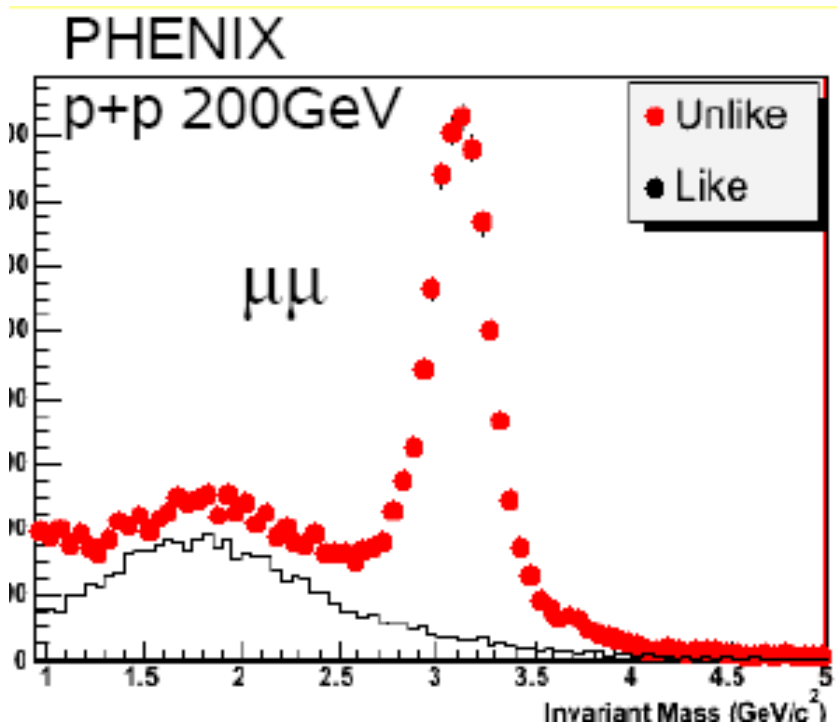
At RHIC, production is dominated by gluon fusion. A third (non-perturbative) gluon is needed to color-neutralize the J/Ψ.

Various approaches to handle the color-neutralization:

- Color Singlet Model
- NRQCD Color Octet Model
- Color Evaporation Model
- KT factorization

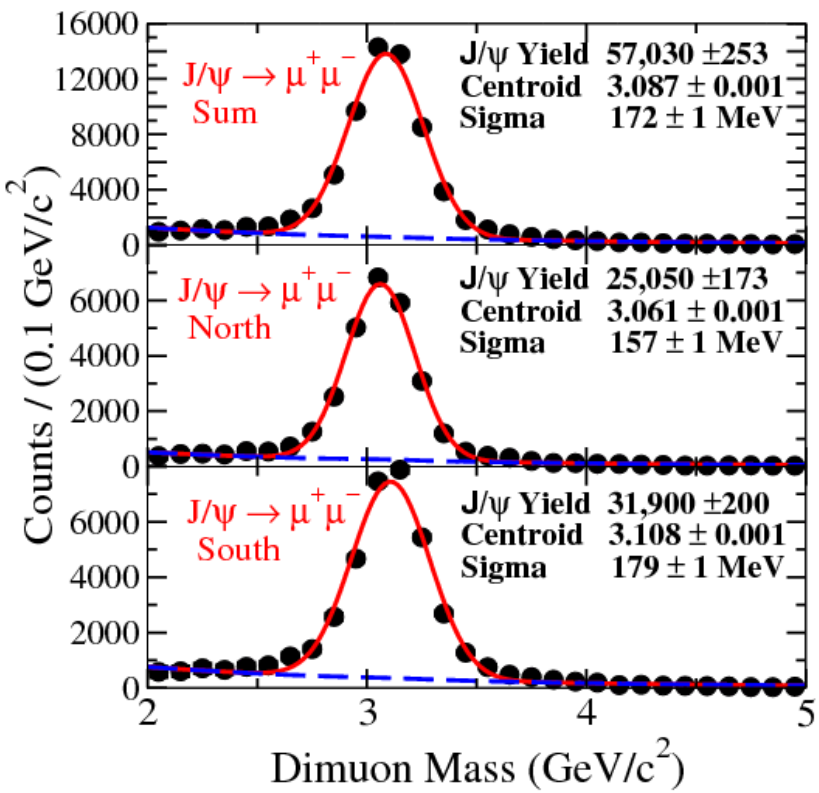
J/Ψ signal in p+p collisions @ PHENIX

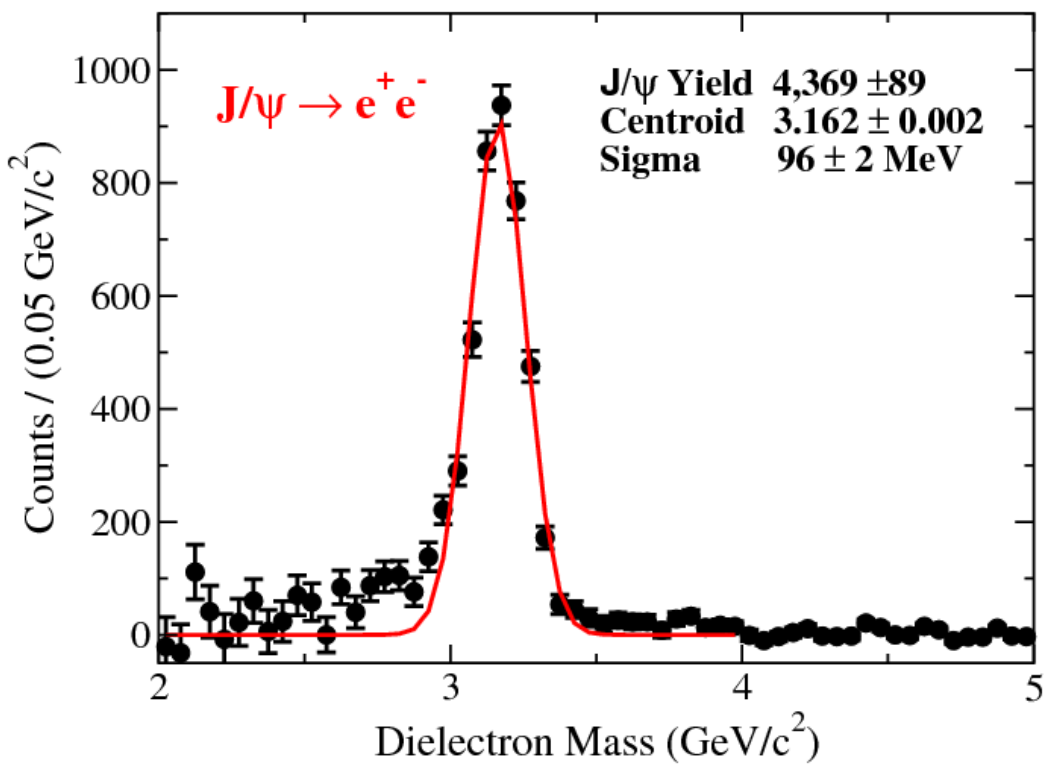




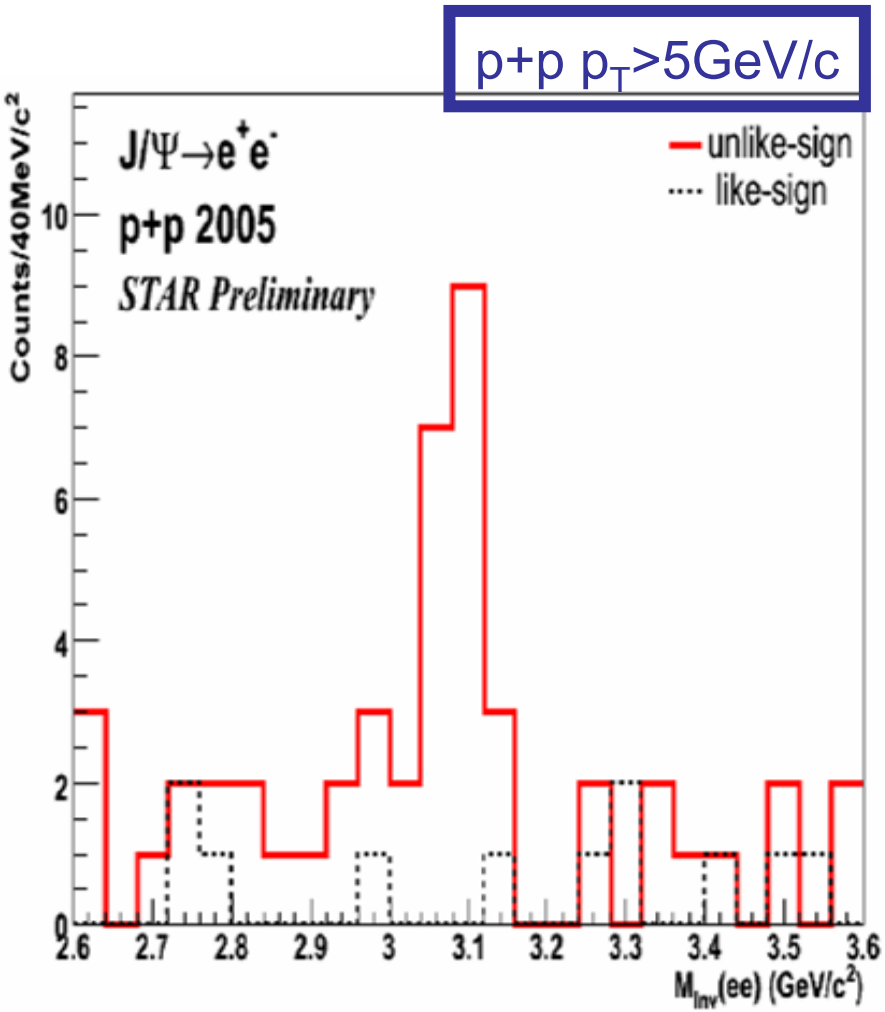
J/Ψ signal in d+Au collisions @ phenix (from 2008)

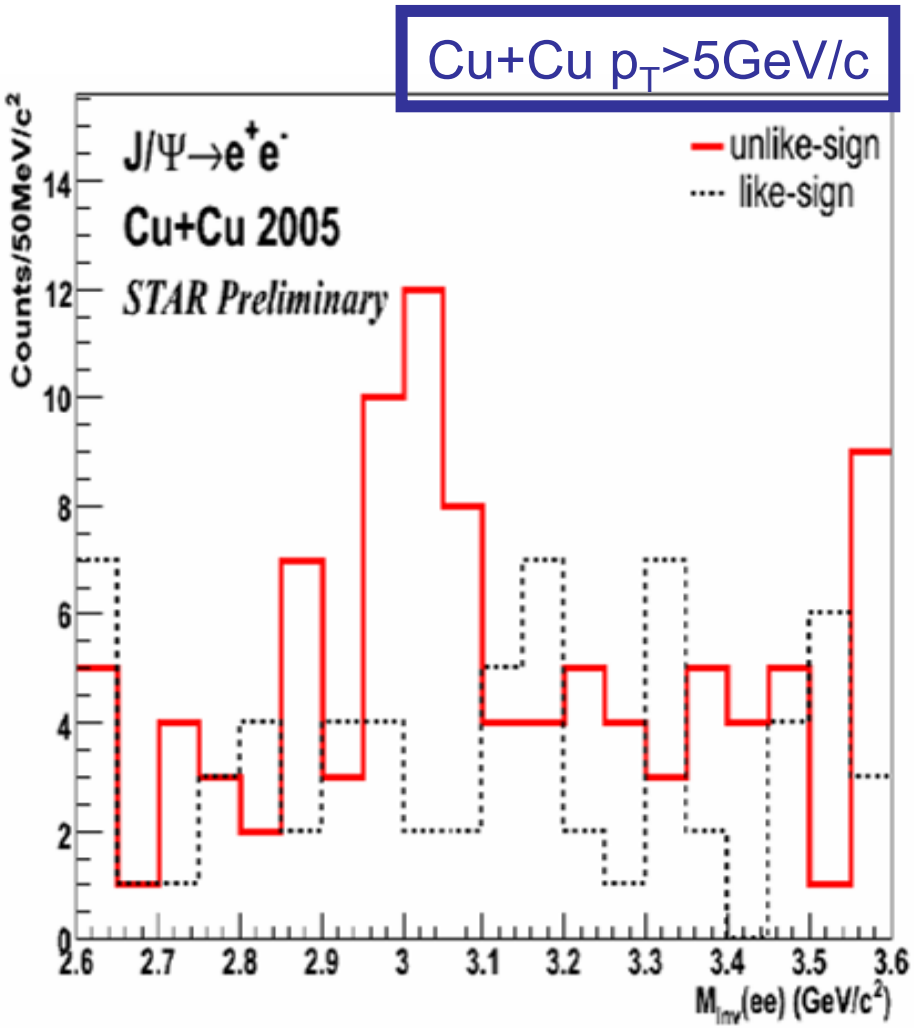
About 30x more statistics than published data.
Analysis in progress.
Will improve a lot constraints on cold nuclear matter effects.





J/Ψ signal in p+p and Cu+Cu collision @ STAR





Proton spin structure via heavy flavor

Proton spin structure is probed using longitudinally polarized proton beams. Beam polarization is flipped from bunch to bunch.

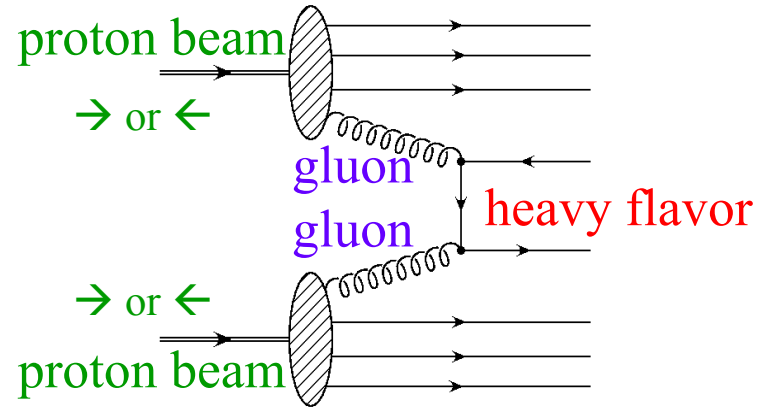
Measure J/Ψ yields in each configuration, since it is sensible to the underlying parton distribution function

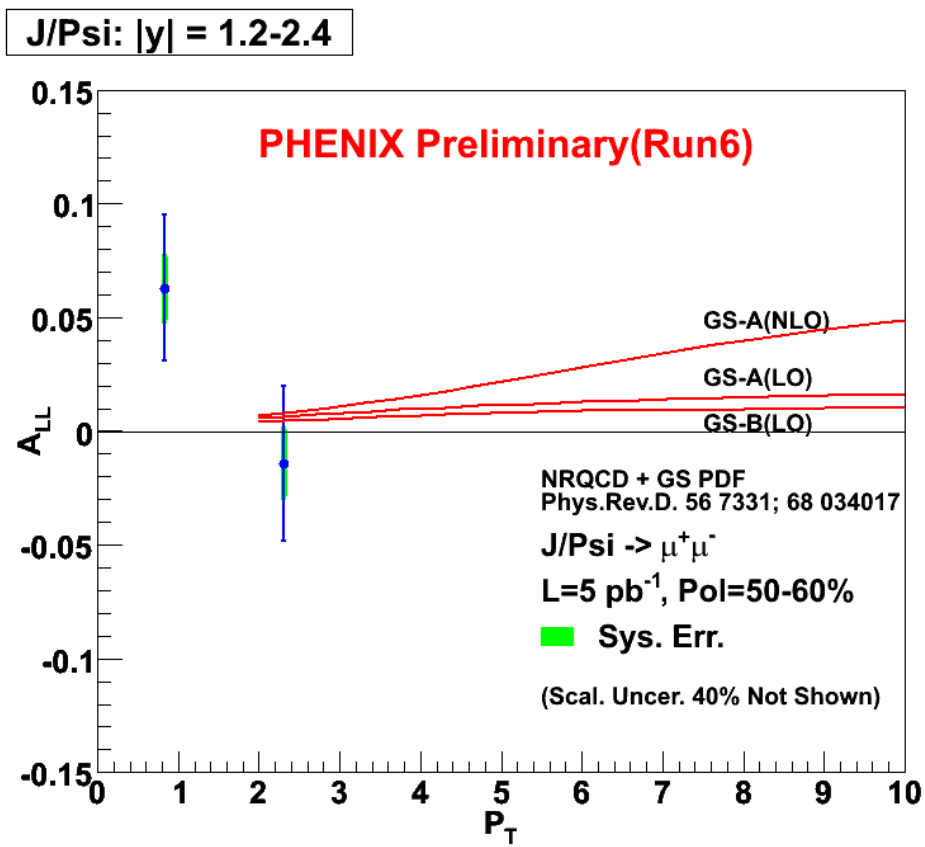
Form asymmetries:

$$A_{LL}^{incl} = \frac{1}{<P_B><P_Y>} \frac{N^{++} - R \cdot N^{+-}}{N^{++} + R \cdot N^{+-}}$$

$$A_{LL}^{J/Psi} = \frac{A_{LL}^{incl} - f_{BG} \cdot A_{LL}^{BG}}{1 - f_{BG}}$$

$$\approx \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)} a_{LL}^{gg \to Q\bar{Q}}$$

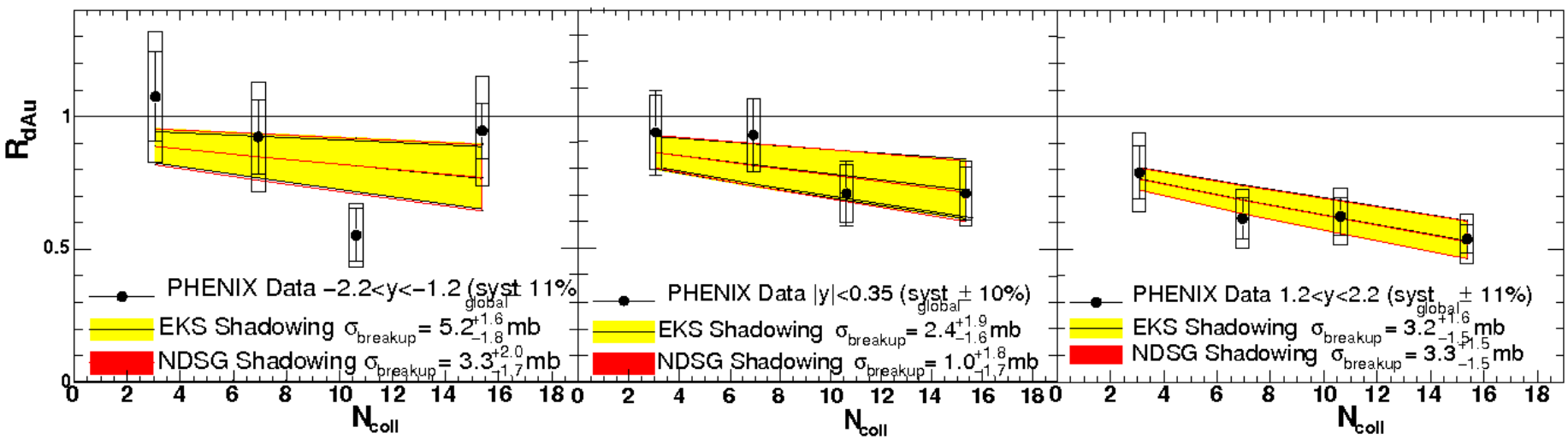




J/Ψ R_{dA} vs centrality in d+Au collisions

Alternatively one can fit the centrality dependency of R_{dA} in each rapidity range with different break-up cross-sections.

arxiv:0711.3917

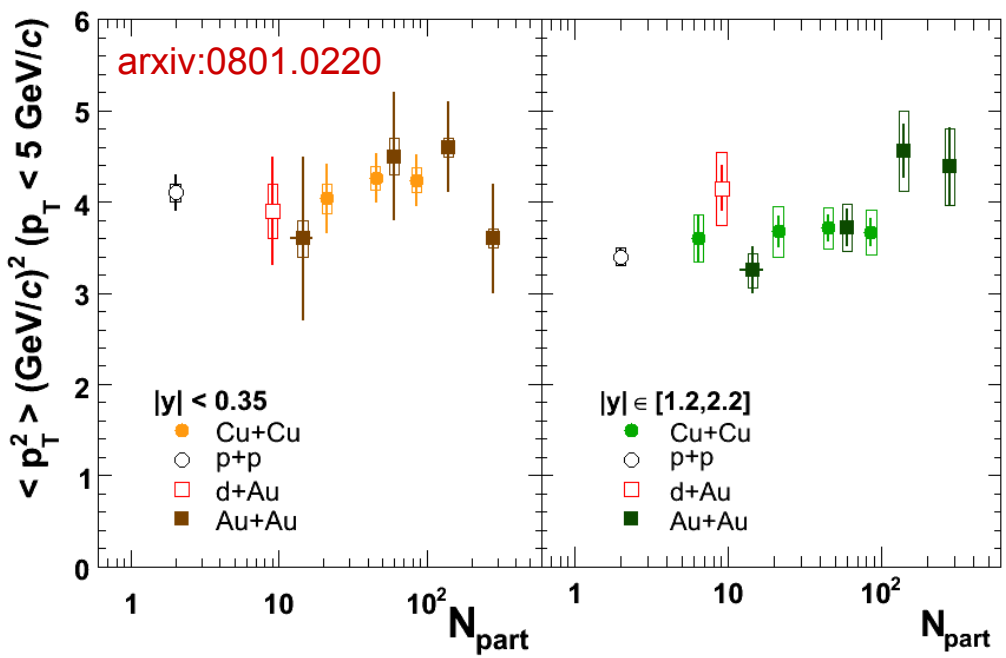


The underlying shadowing model is used to extrapolate from dA to AA collisions, but not to constrain the differences between the three rapidity ranges.

Modification of the p_T distribution with centrality

Study of the p_T spectrum (notably $<p_T^2>$ vs centrality) should give more hints of the mechanism at play.

Cronin effect should increase the $<p_T^2>$ wrt N_{part}, but does not affect J/Ψs produced by recombination.

The measurement is difficult because of the poor constraints at high p_T.

$<p_T^2>$ vs N_{part} for p_T < 5 GeV/c