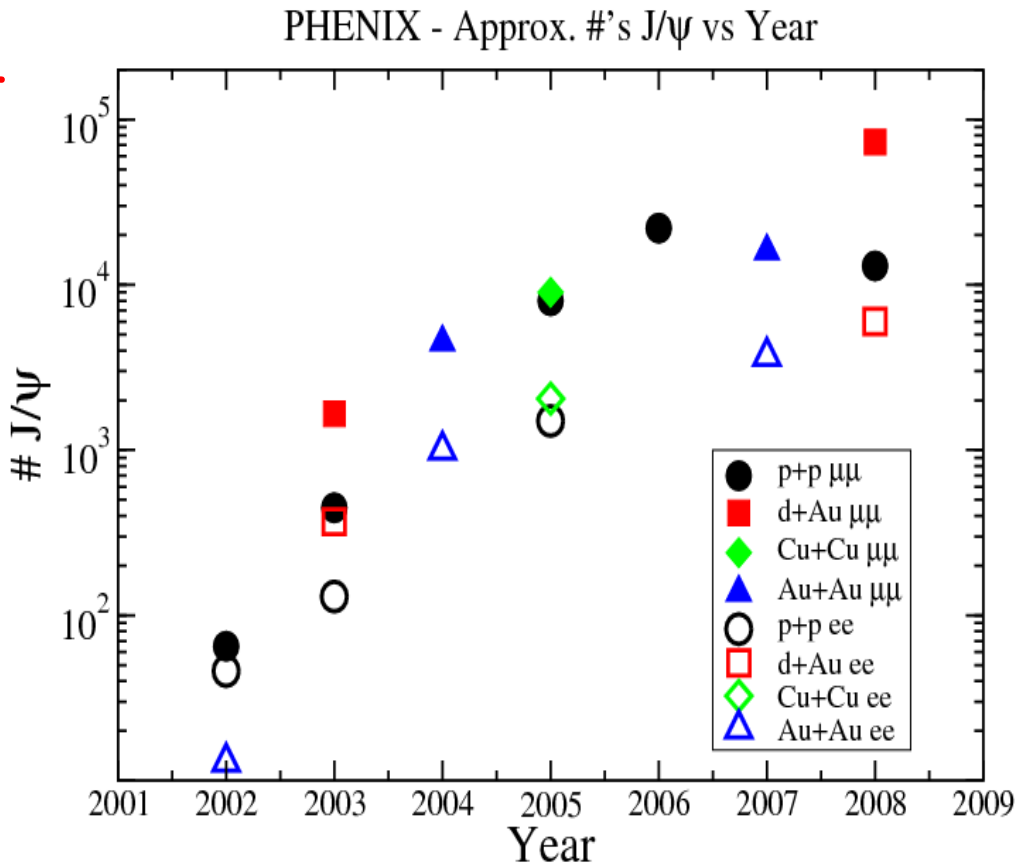
Quarkonia Results from PHENIX

Mike Leitch – LANL– leitch@bnl.gov

UCLA Heavy-Quark Workshop – 23 Jan 2009

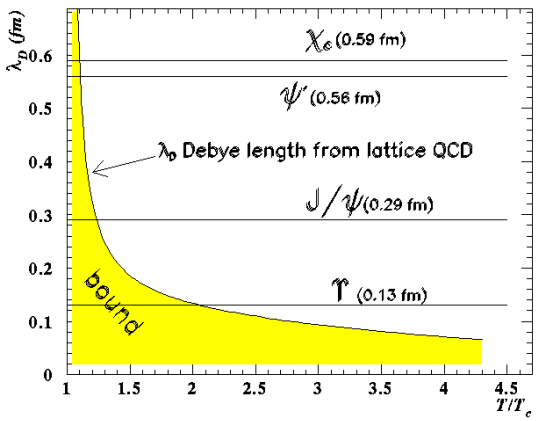
- Quarkonia & Deconfinement
- PHENIX A+A Results
- Cold Nuclear Matter (CNM)
- Production Issues
- Sequential Screening
- Regeneration
- Flow, $\langle p_T^2 \rangle$ & high-p_T
- Heavier Quarkonia



Quarkonia & Deconfinement

For the hot-dense medium (QGP) created in A+A collisions at RHIC:

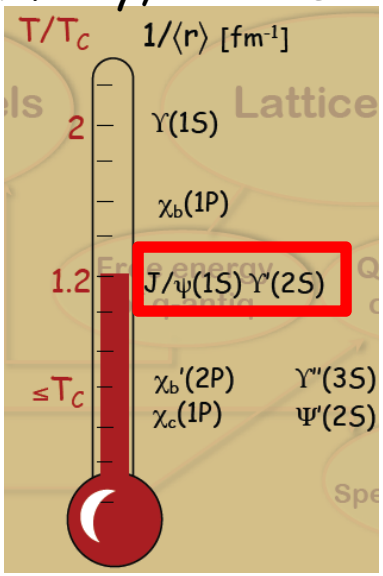
- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks
- Is there deconfinement? → look for Quarkonia screening



Debye screening predicted to destroy J/ψ's in a QGP with other states "melting" at different temperatures due to different sizes or binding energies.

RHIC: T/T_C ~ 1.9 or higher

Mocsy, WWND08



Different lattice calculations do not agree on whether the J/ψ is screened or not – measurements will have to tell!

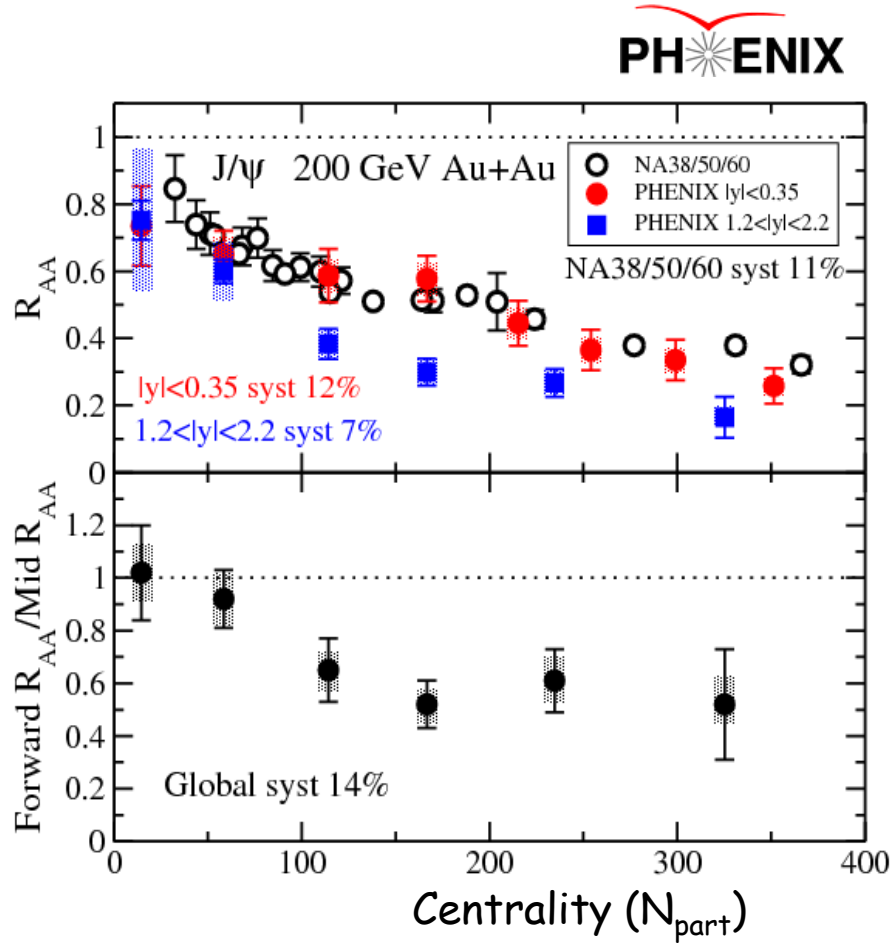
Satz, hep-ph/0512217

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

PHENIX A+A Data and Features

PHENIX Au+Au data shows suppression at mid-rapidity about the same as seen at the SPS at lower energy

- but stronger suppression at forward rapidity.
- Forward/Mid R_{AA} ratio looks flat above a centrality with N_{part} = 100

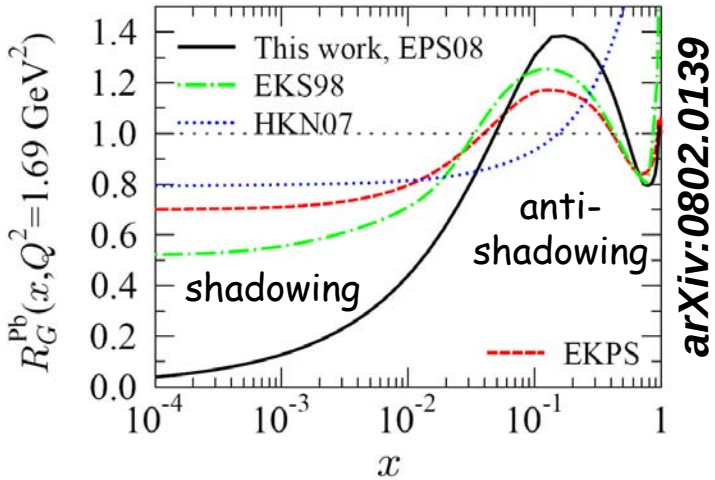


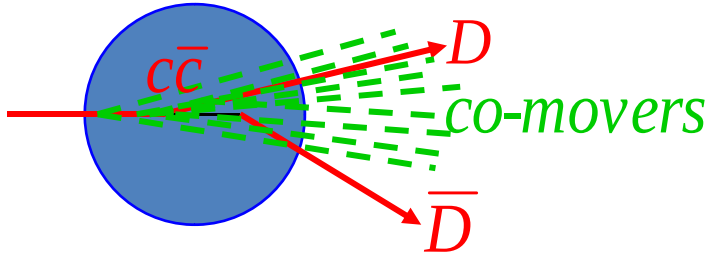
Several scenarios may contribute:

- Cold nuclear matter (CNM) effects
  - in any case are always present
- Sequential suppression
  - QGP screening only of χ_c & ψ'- removing their feed-down contribution to J/ψ at both SPS & RHIC
- Regeneration models
  - give enhancement that compensates for screening

What CNM effects are important?
(CNM = Cold Nuclear Matter)

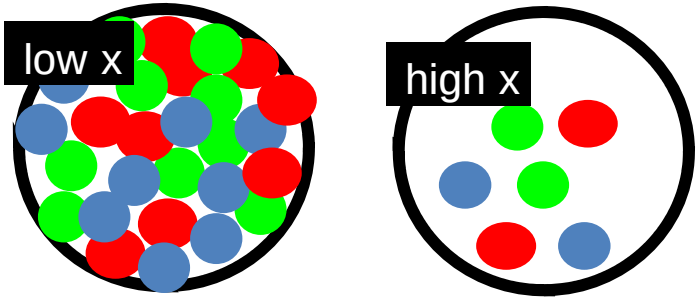
Traditional shadowing from fits to DIS or from coherence models



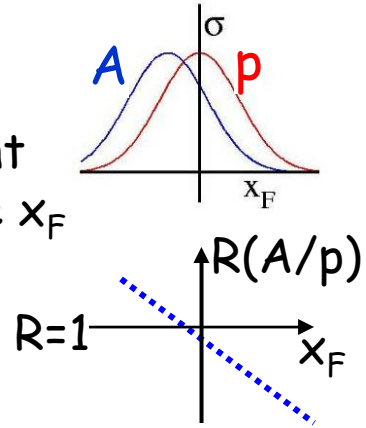


Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

Gluon saturation from non-linear gluon interactions for the high density at small x; amplified in a nucleus.



Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F



CNM Physics – PHENIX, E866, NA3 Comparison

New Analysis of Run3 d+Au with new 2005 p+p baseline

PRC 77,024912(2008)

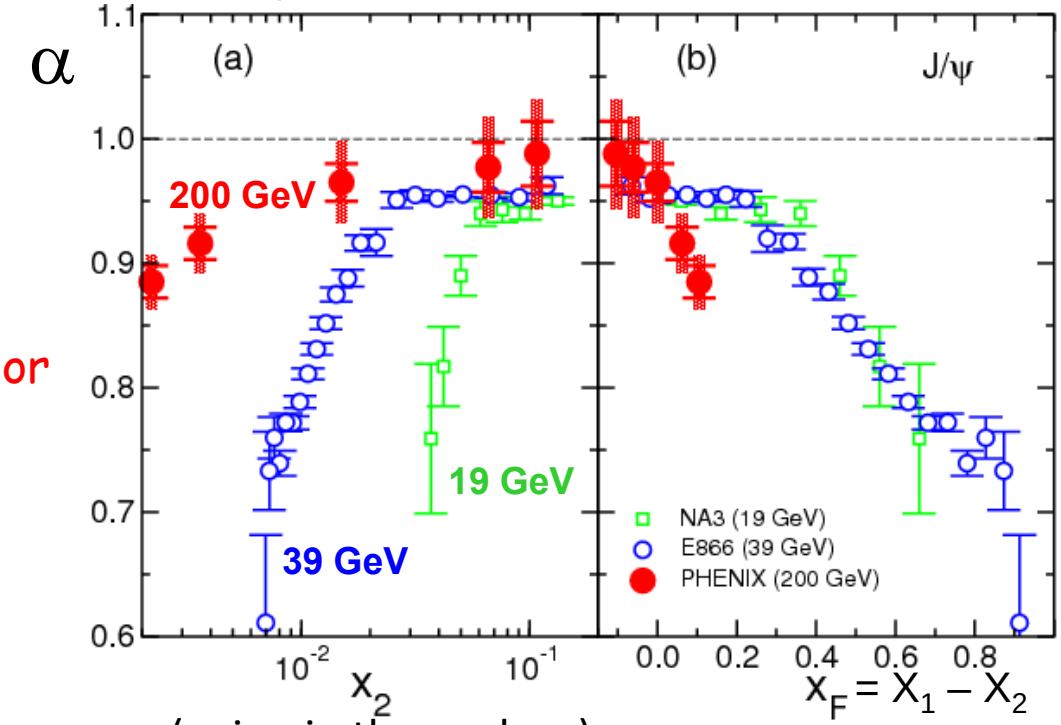
Compared to E866/NuSea p+A results & lower-energy NA3 at CERN

Not universal vs x_2 as expected for shadowing, but closer to scaling with x_F, why?

- initial-state gluon energy loss?
- gluon saturation?

$$\sigma_A = \sigma_N A^{\alpha}$$

J/ψ α for different √s collisions

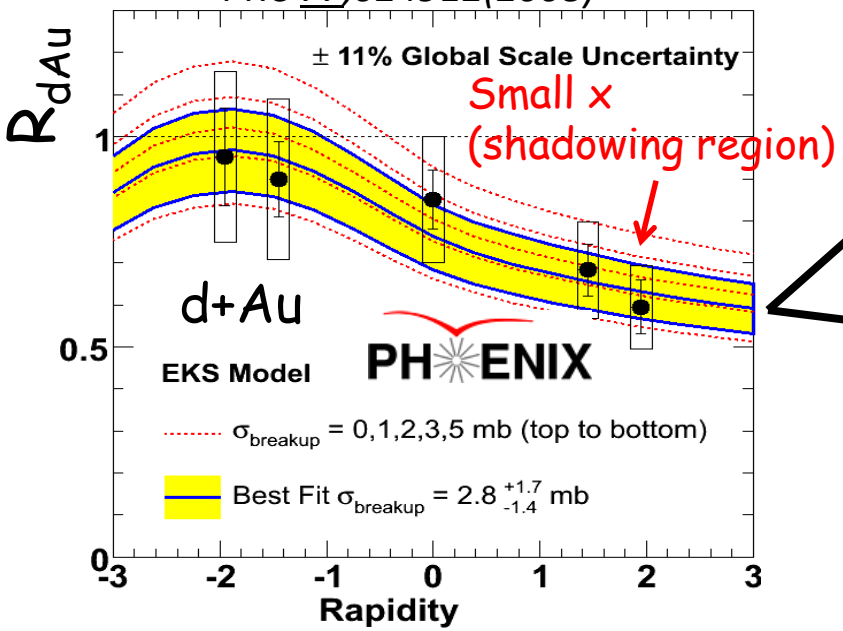


(x_2 is x in the nucleus)

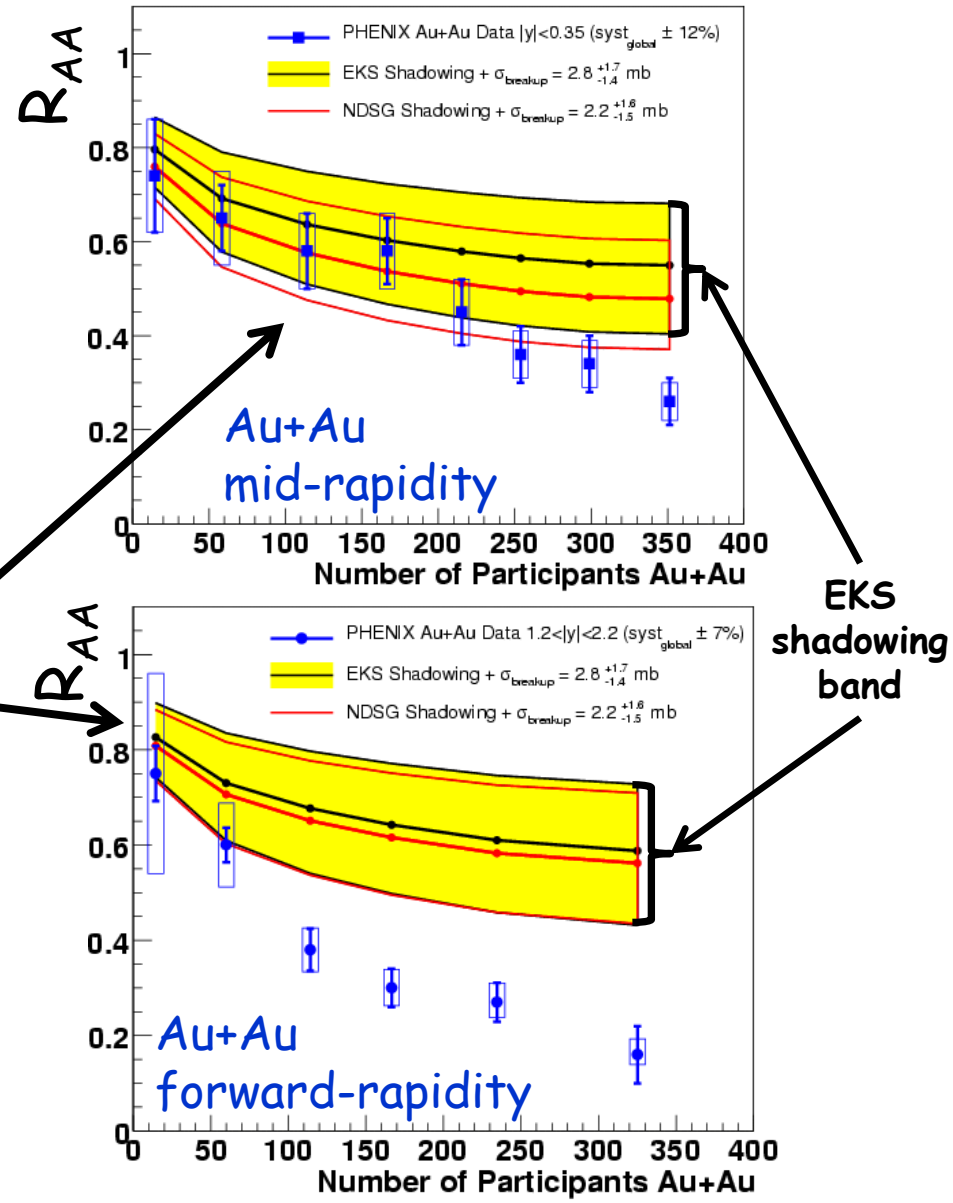
Present CNM Constraints on A+A data

CNM effects (EKS shadowing + dissociation from fits to d+Au data, with R. Vogt calculations) give large fraction of observed Au+Au suppression, especially at mid-rapidity

PRC 77,024912(2008)



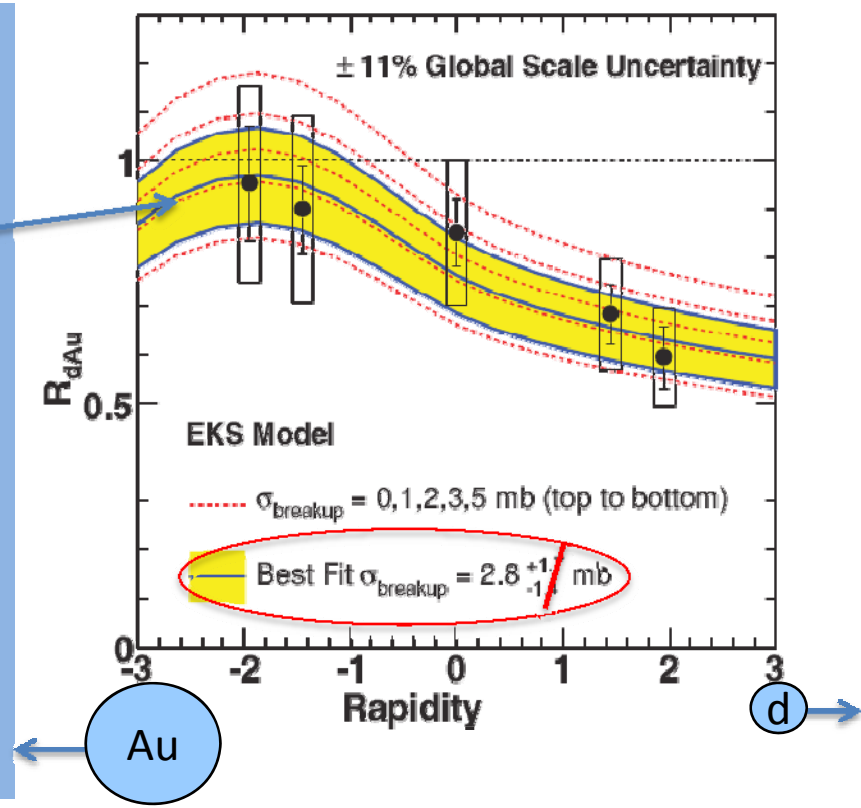
more accurate d+Au constraint badly needed



Mistake in extracting $\sigma_{breakup}$ vs. rapidity

- The data points, statistical and systematic uncertainties in the figure are **correct.**
- The one standard deviation **uncertainty band** for the breakup cross section contains a mistake.
- The band does not account for all the systematic uncertainties, as intended in the paper.
- Correctly including the systematic uncertainties will make the band larger.
- We expect to release **corrected values** soon.

Phys Rev C 77, 024912

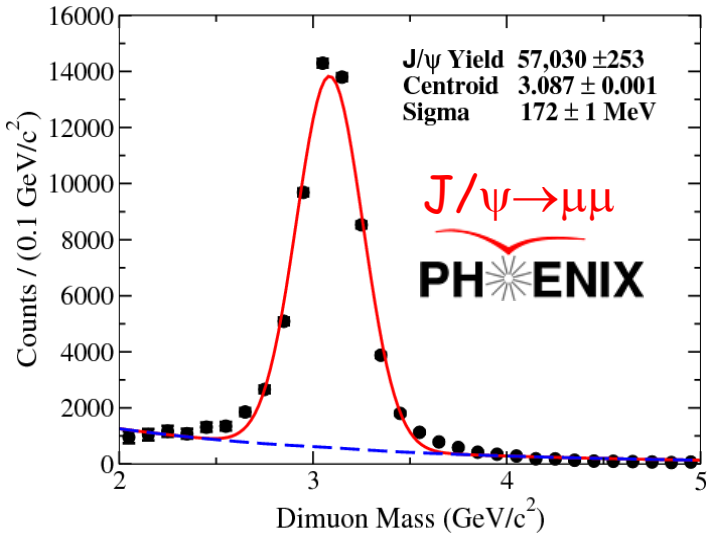


$$\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \left[\left(\sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c - \mu_i(p))^2}{\tilde{\sigma}_i^2} \right) + \epsilon_b^2 + \epsilon_c^2 \right]$$

Phys Rev C 77, 064907

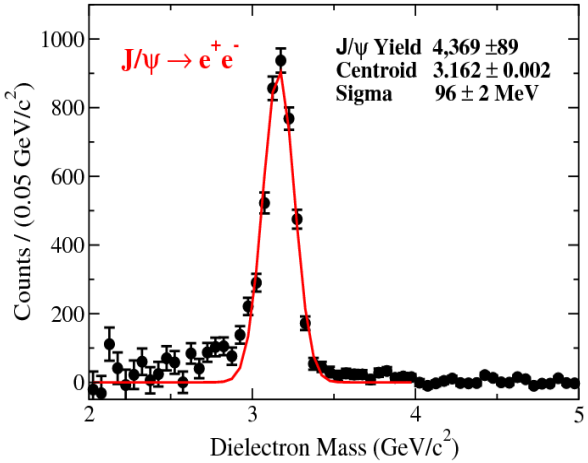
Run-6 & run-8 p+p 200 GeV data.

- Factor of **three** more data in run-6 compared to the previous run-5 p+p baseline

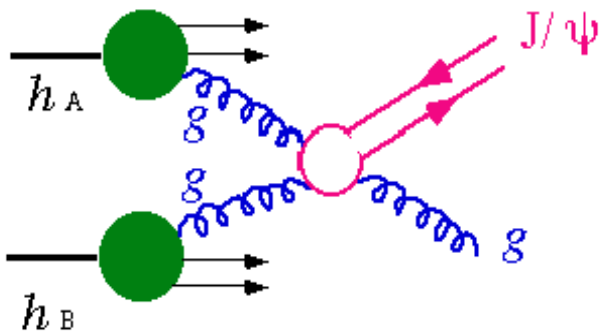


Run-8 d+Au 200 GeV data

- Factor of **thirty** more data in run-8 compared to the previous run-3 d+Au
- Constrain the CNM effects present in HI collisions to make un-ambiguous statements about anomalous suppression.
- The statistics are there! **Main Focus** is on reducing systematics.

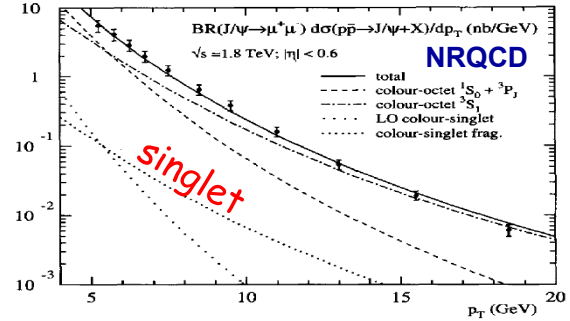


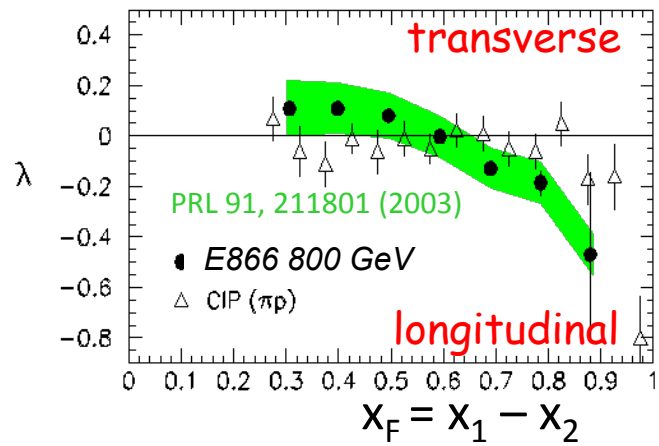
Quarkonia Production is Also an Issue
Lets look at p+p Collisions



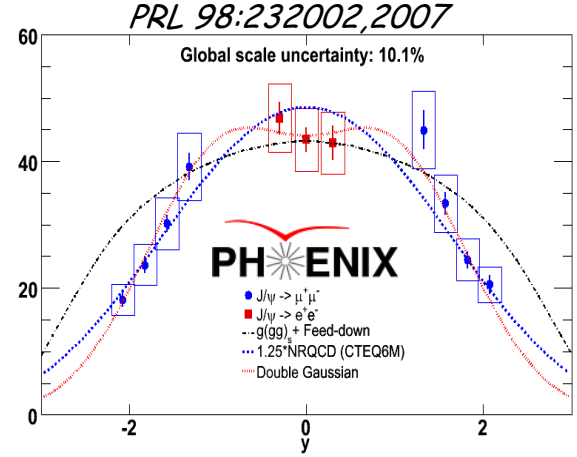
Quarkonia Production is Also an Issue

- gluon fusion dominates
- but is $c\bar{c}$ produced in a color-singlet or –octet state?
    - important for CNM effects
- difficult to get both absolute cross section & polarization correct
    - singlet models under-predict cross sections
    - octet models get cross section but predict transverse polarization at large p_T - but small longitudinal polarization was seen (E866, CDF)
    - recently a new singlet model seems to get both correct (*Haberzettl, Lansberg, PRL 100, 032006 (2008)*)
- Latest PHENIX data starting to define rapidity dependence



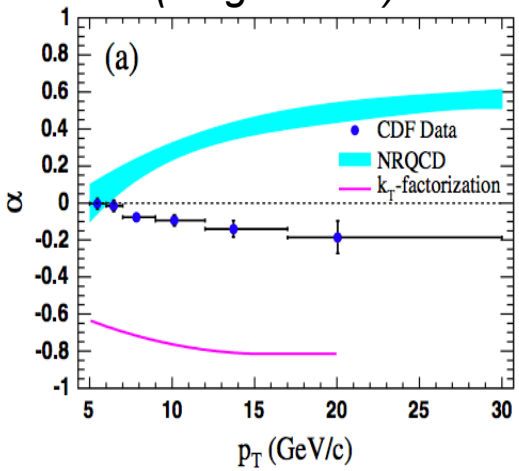


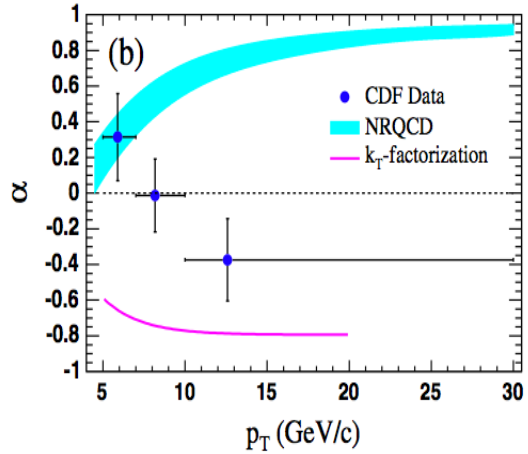
PRL 98:232002,2007

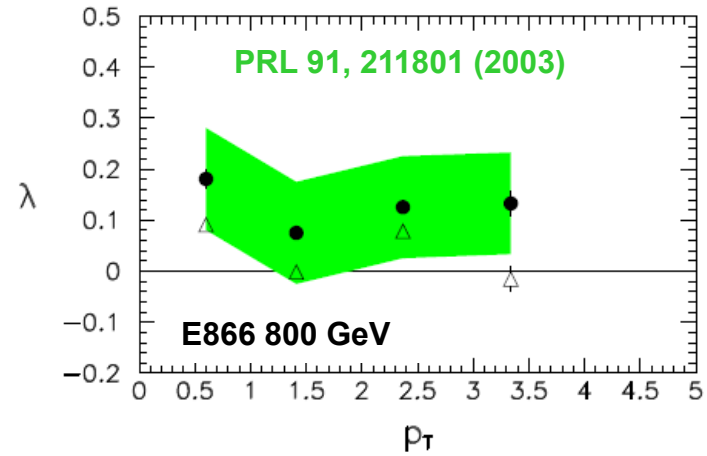


J/ψ Production - Polarization

λ = +1 (transverse)
= -1 (longitudinal)

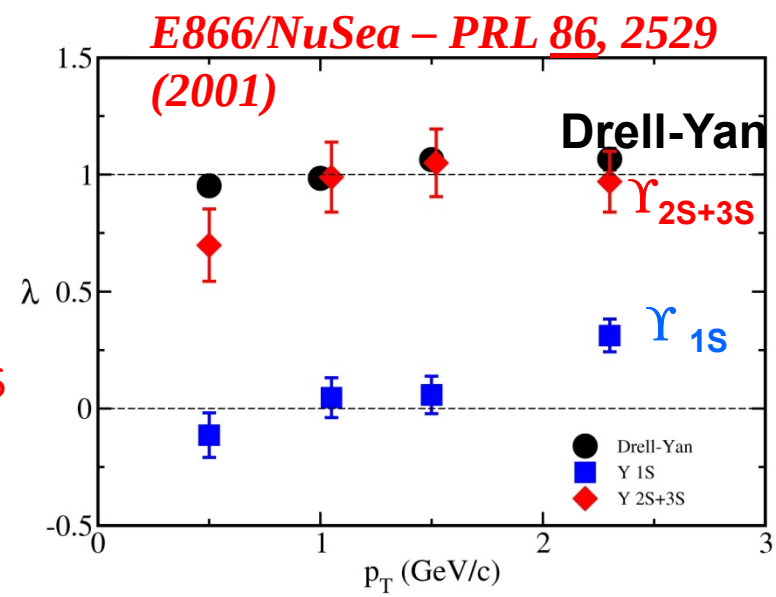




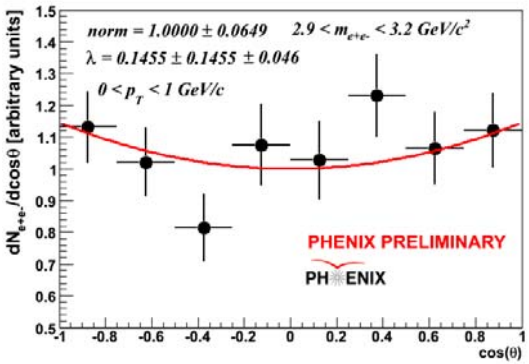


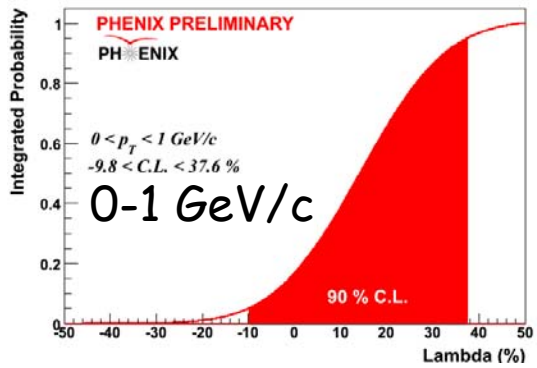
- Octet models get correct cross section size (unlike singlet), but…
- CDF and Fermilab E866 J/ψ data show little polarization & disagree with NRQCD predictions

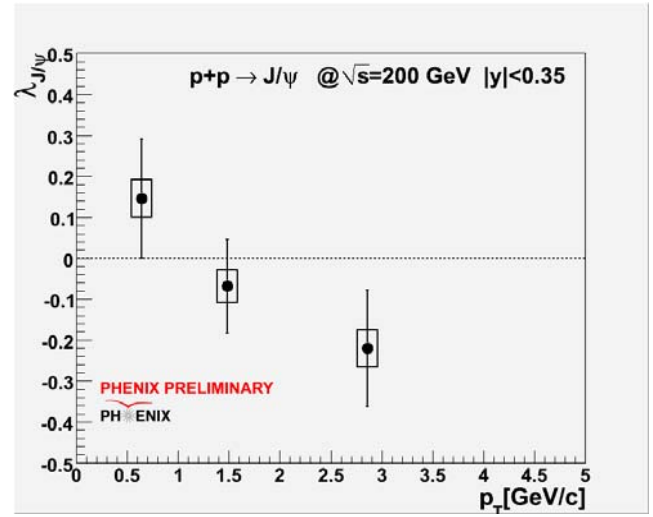
And ϒ maximally polarized for (2S+3S), but NOT (1S)
* Is feed-down washing out polarization? (~40% of 1S from feed-down)
(ψ′ polarization measurement would be helpful here but is very experimentally challenging)

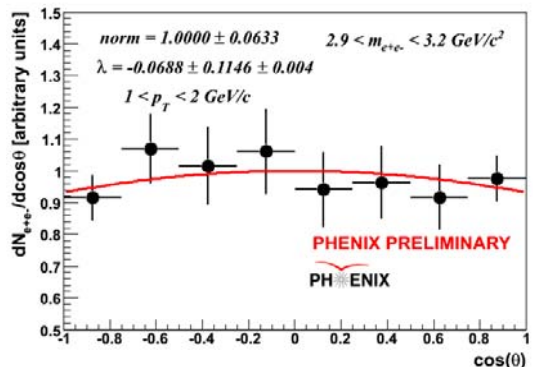


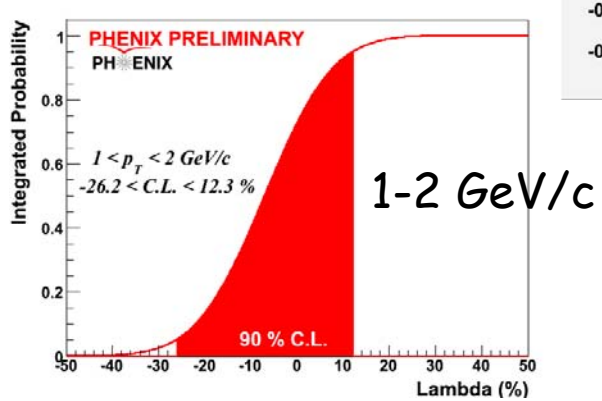
J/ψ polarization at mid-rapidity in PHENIX vs p_T

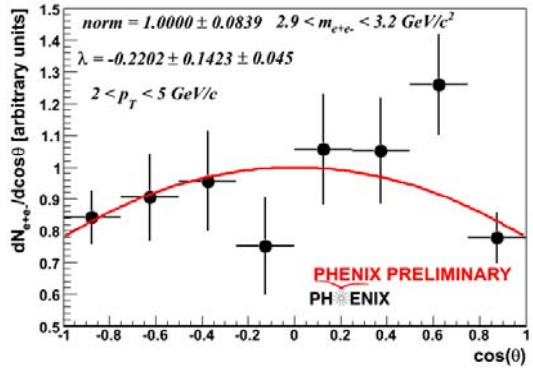


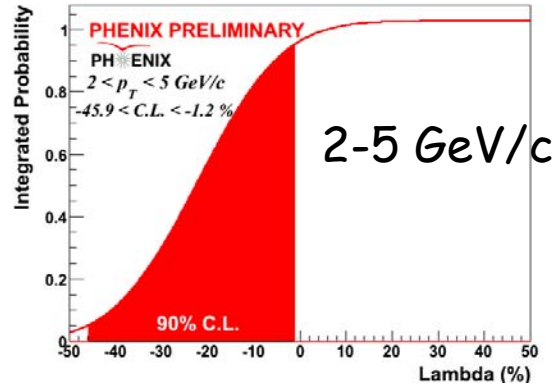






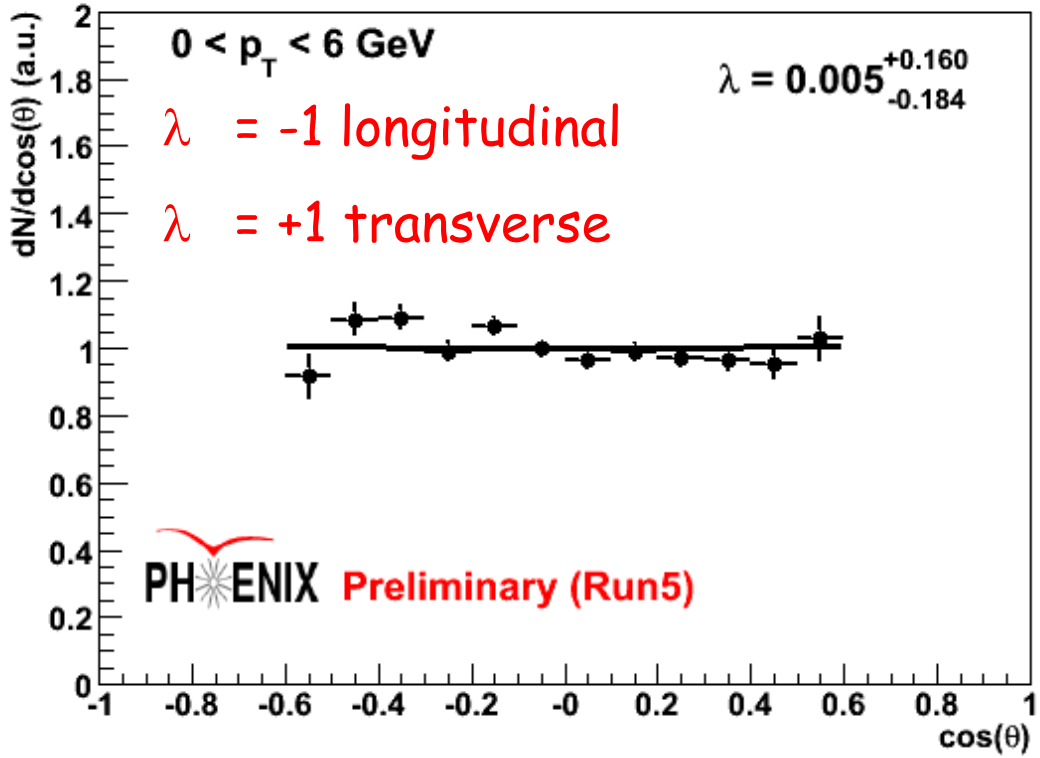






Probably most interesting at the highest p_T (2-5 GeV/c) since this is where theoretical models predict non-zero polarization

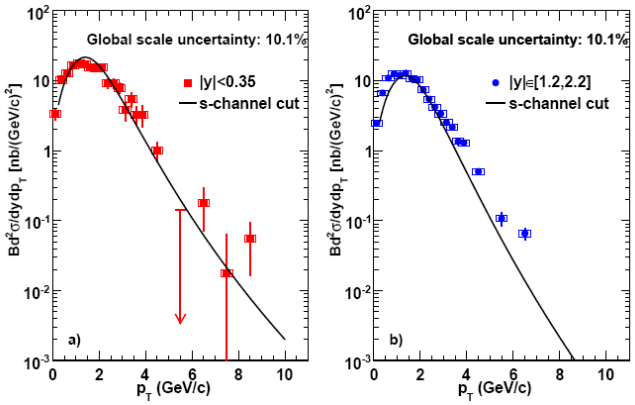
J/ψ Polarization at forward rapidity in PHENIX

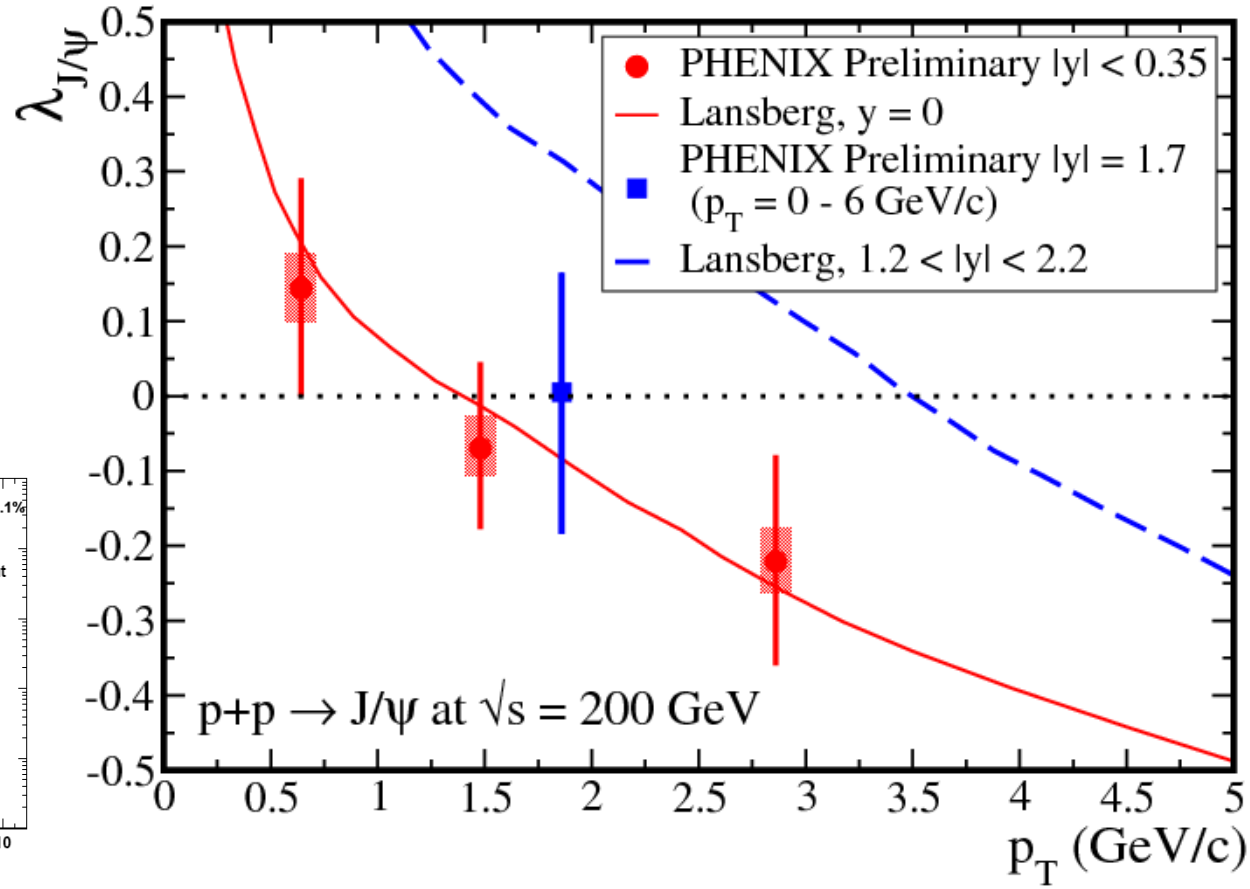


Forward rapidity measurement with dimuons gives zero polarization with large uncertainties, and presently is unable to study vs p_T

J/ψ polarization at in PHENIX vs p_T

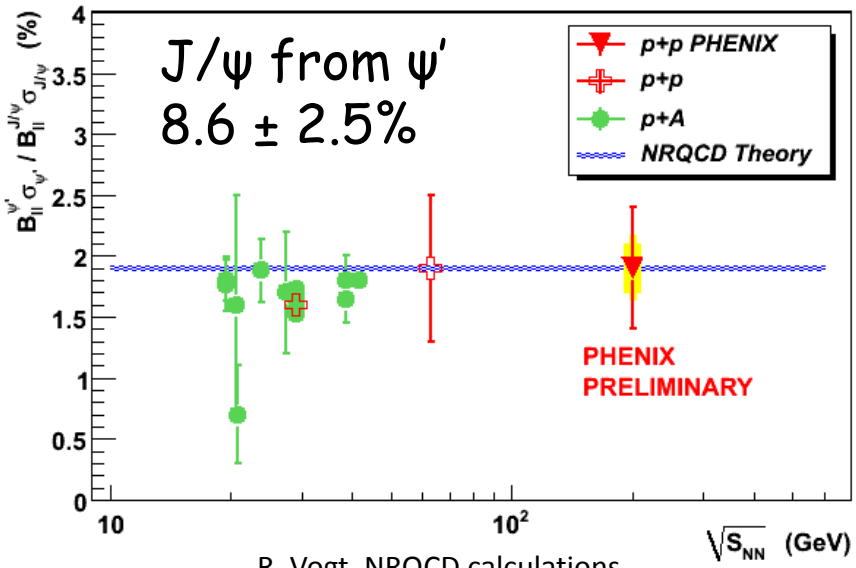
- Small polarization at mid-rapidity seems consistent with s-channel cut theory
- but at forward rapidity data smaller than prediction





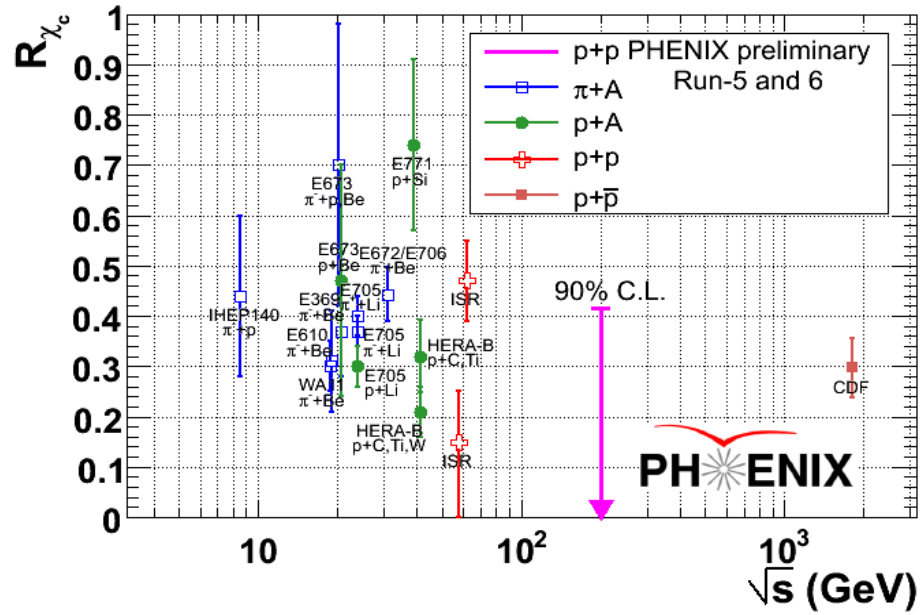
Lansberg & Haberzettl, hep-ph/0806.4001 (2008)
(Singlet model with s-channel cut; does <u>not</u> include effect of feeddown from χ_c & ψ')

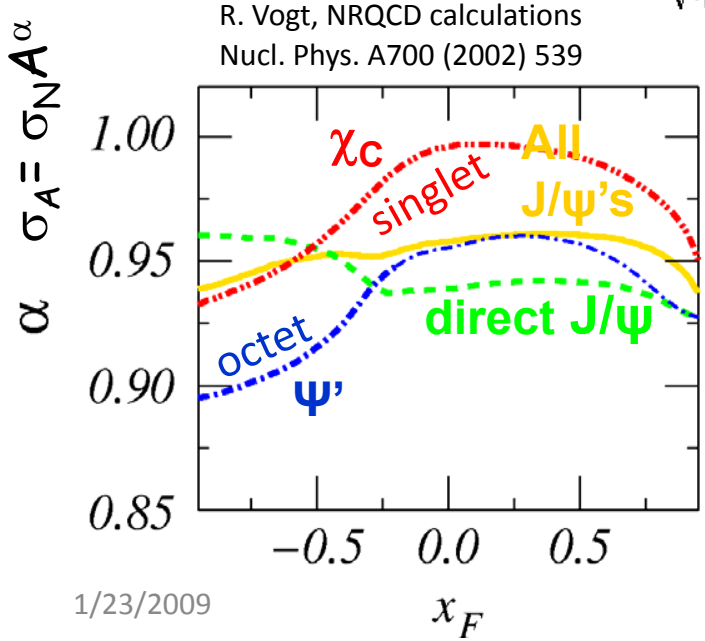
Complications due to substantial feed-down from higher mass resonances (ψ', χ_c)



R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539

J/ψ from χ_c < 42% (90% CL)





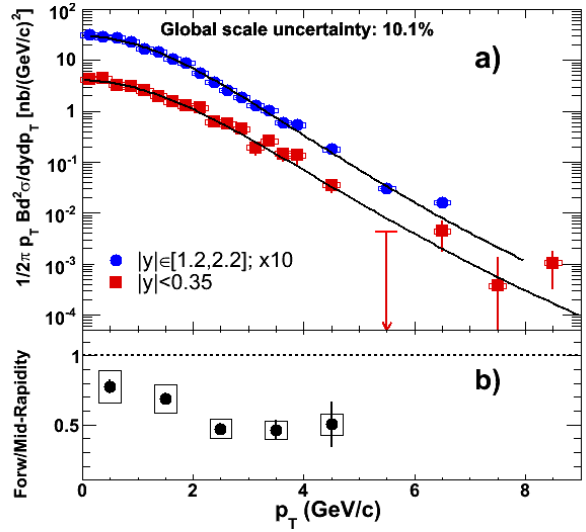
Nuclear dependence of (parent) resonance, e.g. χ_c is probably different than that of the J/ψ

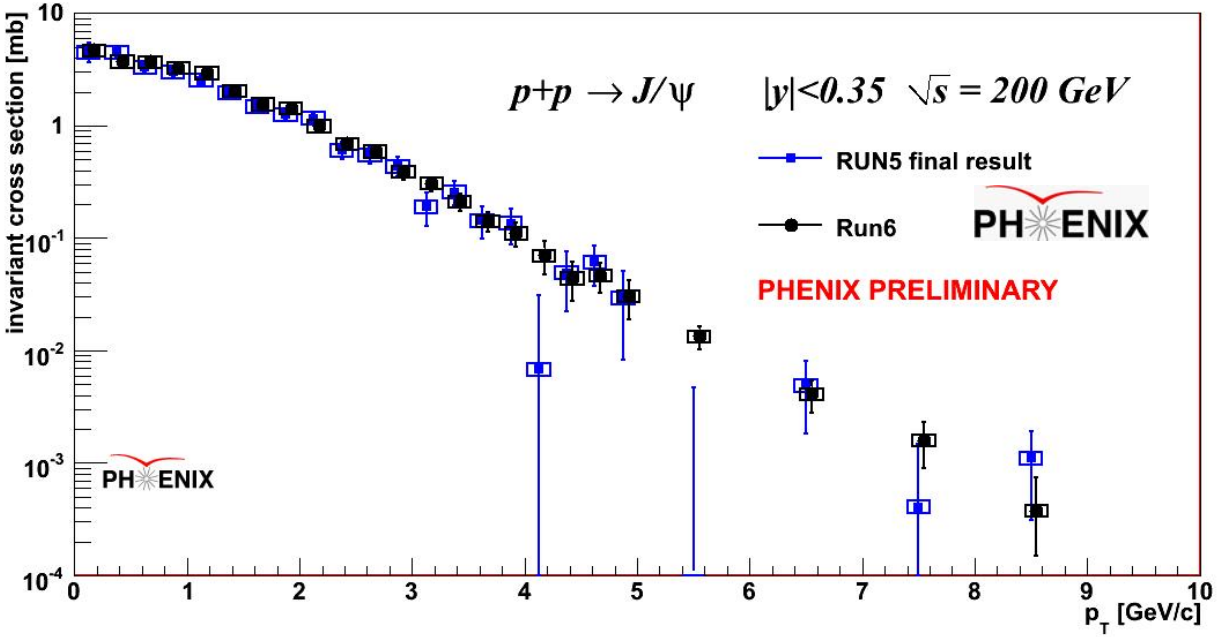
Also measured
B → J/ψ - 4 $^{+3}_{-2}$ %
(but will be strongest at high-p_T)

J/ψ at large p_T in p+p collisions

New invariant yield measurement from larger luminosity Run-6 agrees with published results!

PRL98:232002,2007





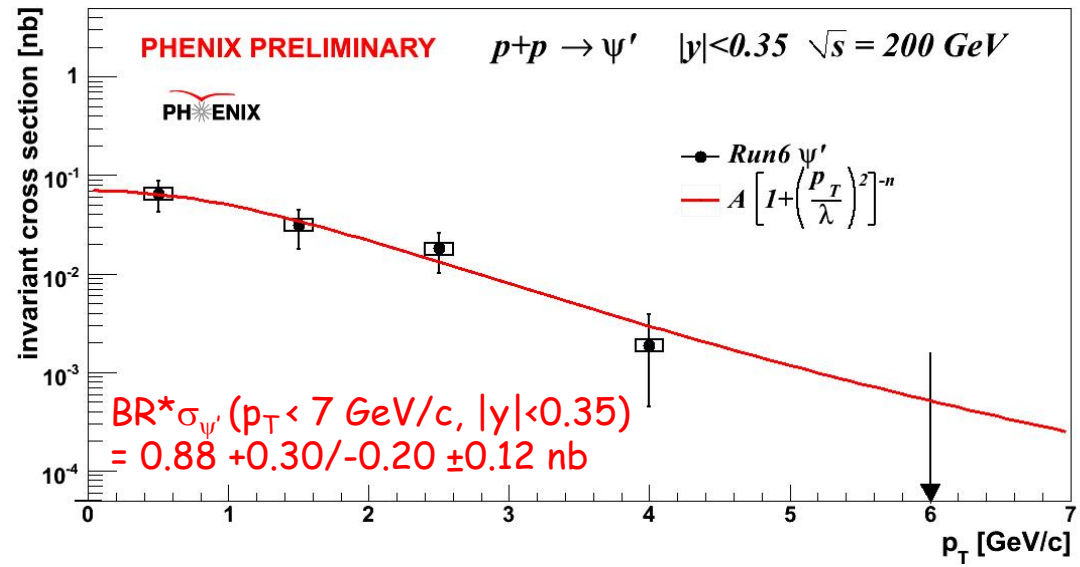
$$B\frac{d\sigma_{J/\psi}}{dy}\Big|_{|y|<0.35} = 45.3 \pm 1.0(stat) \pm 5.4(sys) \pm 4.5(global)nb$$

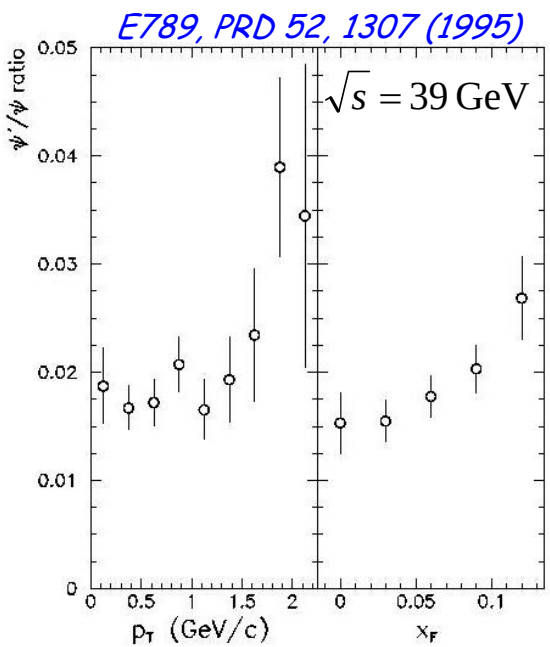
$$B_{J/\psi\to e^+e^-}\sigma_{J/\psi}\Big|_{|y|<0.35}(p_T < 7GeV/c) = 41.0 \pm 0.9(stat) \pm 4.9(sys)\ nb$$

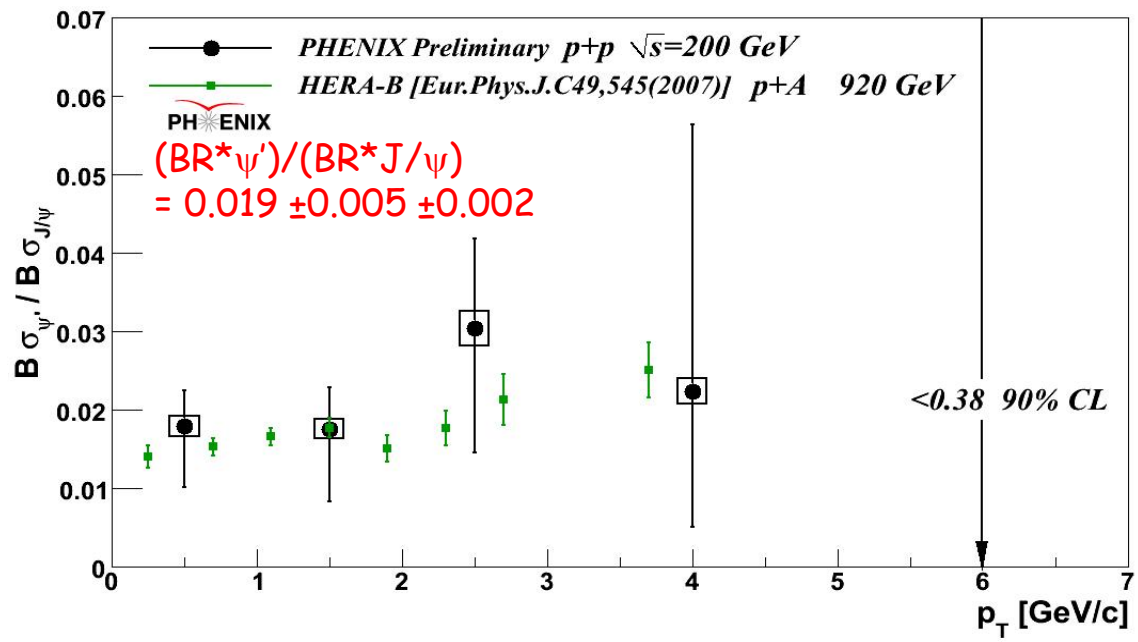
ψ' vs p_T in p+p collisions at mid-rapidity

Within uncertainties $\psi'/(J/\psi)$ agrees with HERA-B & E789 measurements

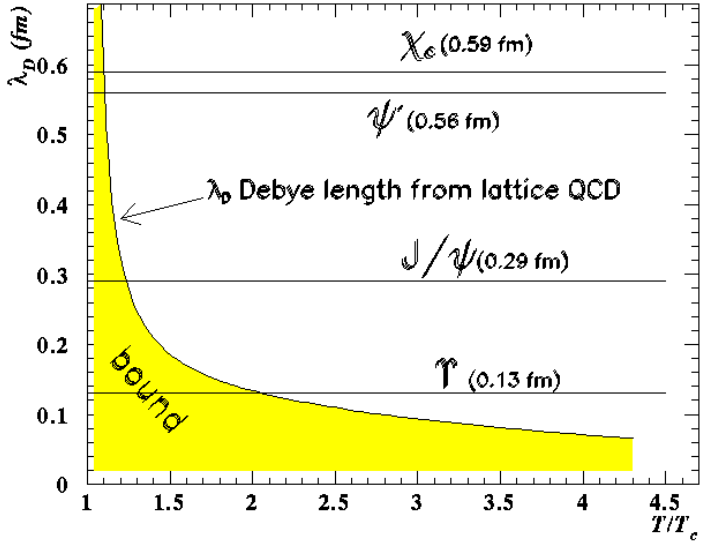
- with $(BR*\psi')/(BR*J/\psi) = 1.9\%$]







And Now back to A+A and the QGP - consider two scenarios



QGP Effects on Quarkonia
Sequential Screening and Gluon Saturation

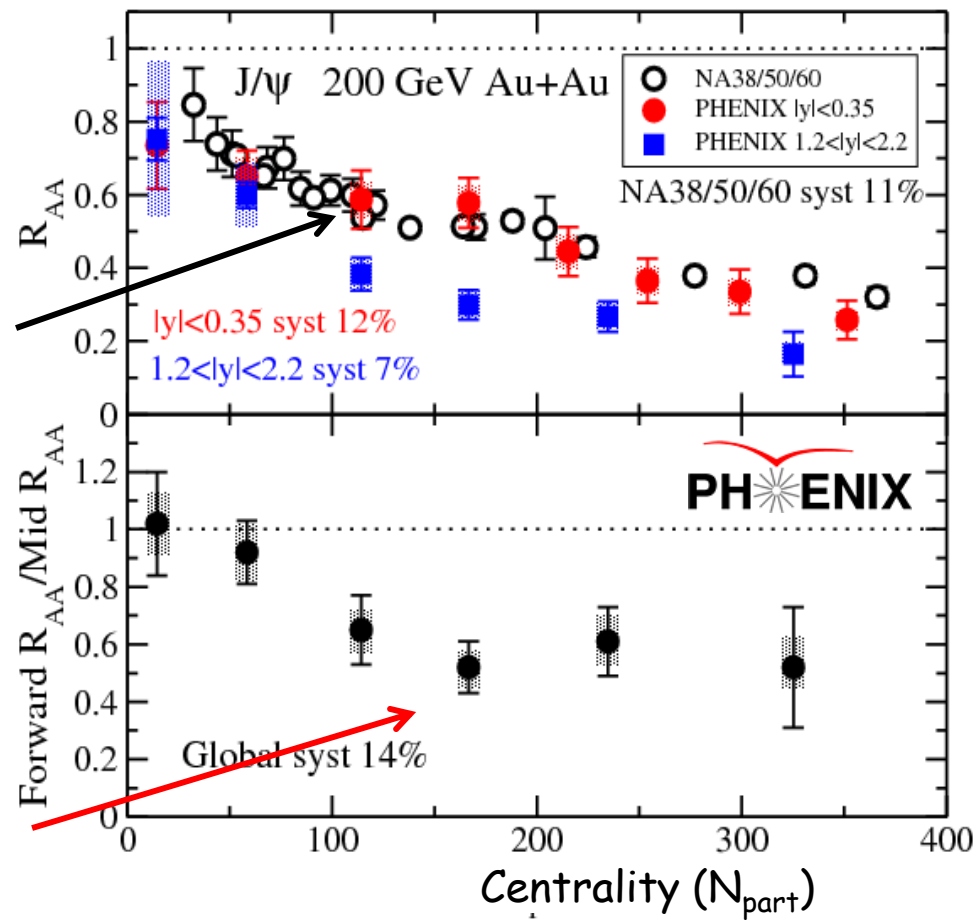
Some recent lattice calculations suggest J/ψ not screened at all

- suppression then comes only via feed-down from screened χ_C & ψ'

- then the situation would be the same at lower energies (NA38/50/60) as for RHIC mid-rapidity

- and the stronger suppression at forward rapidity at RHIC could come from, e.g., gluon saturation

- *But can this picture explain flat forward/mid-rapidity R_{AA} super-ratio?*

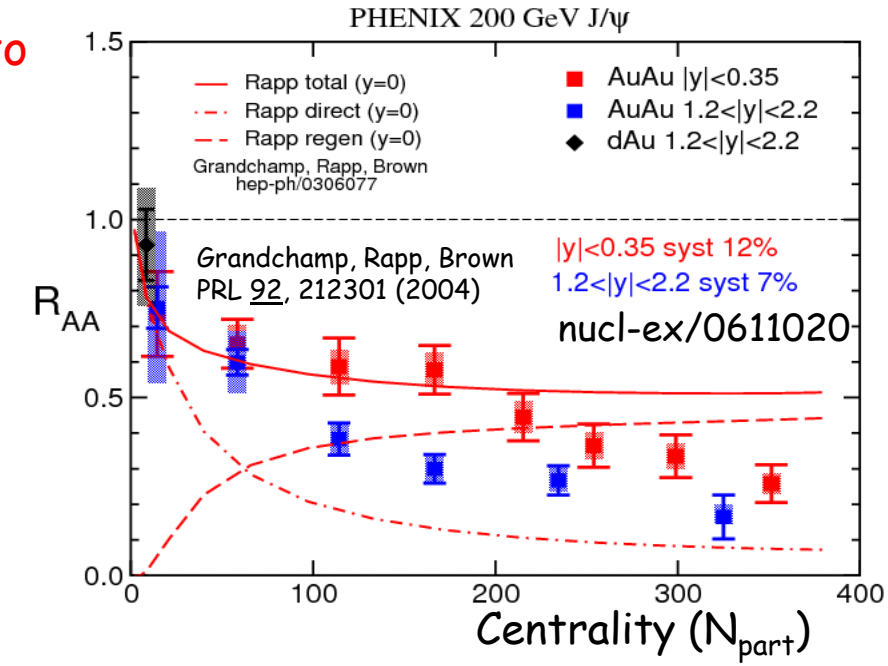


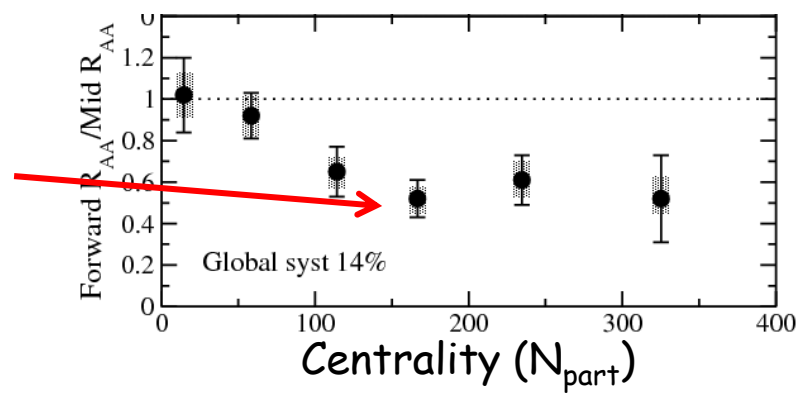
QGP effects on Quarkonia
Regeneration – Compensating for Screening

- larger gluon density at RHIC expected to give stronger suppression than SPS
- but larger charm production at RHIC gives larger regeneration

- forward rapidity lower than mid due to smaller open-charm density there
- very sensitive to poorly known open-charm cross sections
    - Vertex upgrades will help here

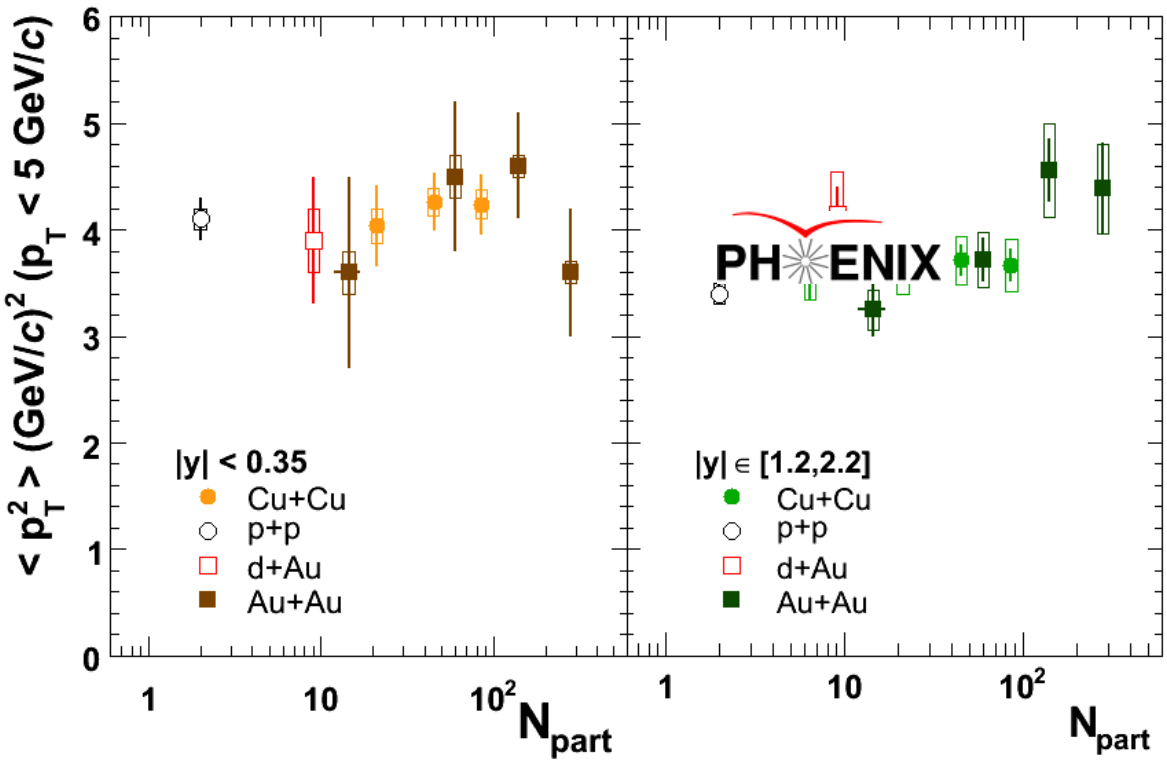
- expect inherited flow from open charm
- regeneration would be HUGE at the LHC!
- *can the two compensating components (screening & regeneration) which may have diff. centrality dependences, give a flat forward/mid-rapidity R_{AA}?*





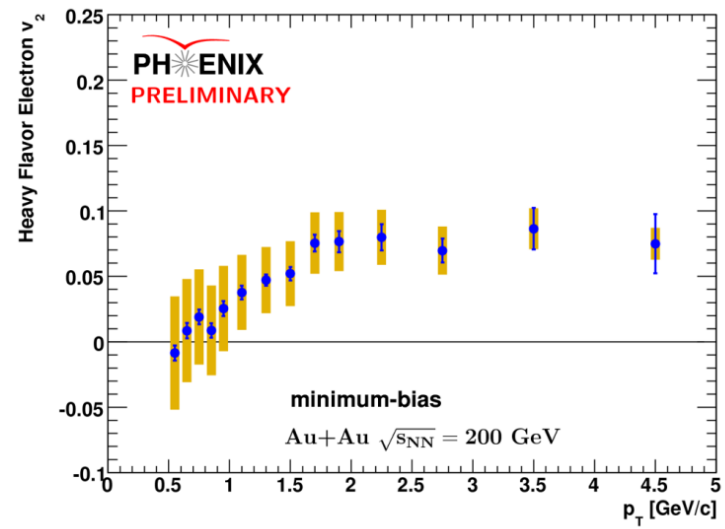
QGP effects on Quarkonia - p_T Broadening

- AA data same as pp & relatively flat with centrality
- CNM effects broaden p_T
  - initial-state mult. scatt. for both gluons
- but regeneration should narrow p_T (compensates for above?)
  - square of small-p_T peaked open-charm cross section



How does the QGP affect Quarkonia? J/ψ flow

J/ψ's from regeneration should inherit the large charm-quark elliptic flow

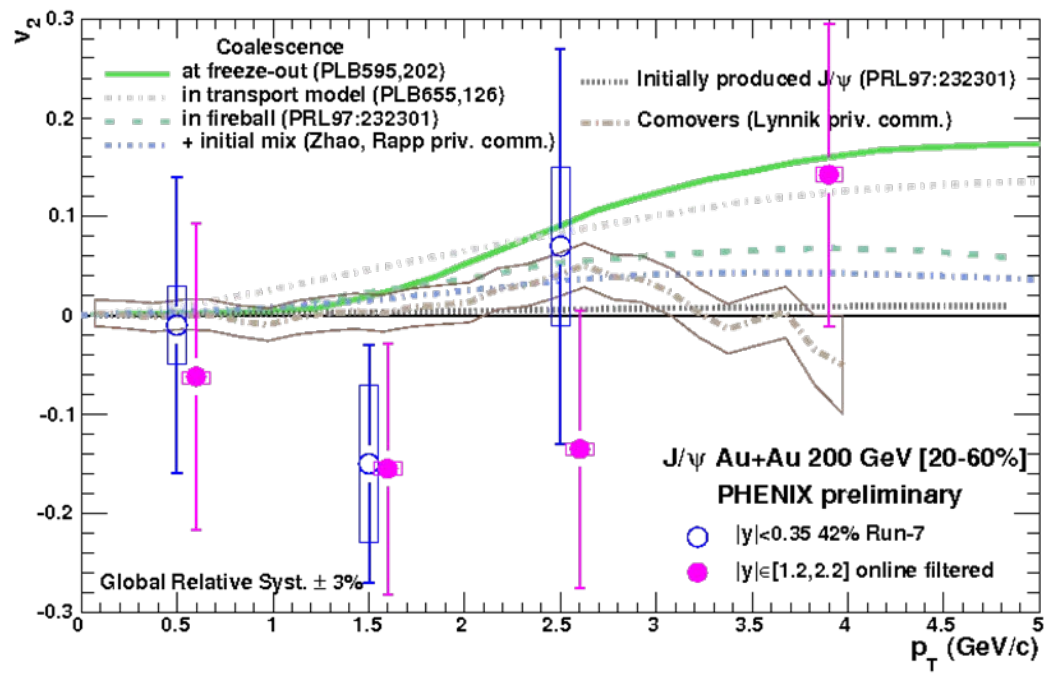


- also need to measure open-charm flow at forward rapidity

This is a first measurement, at both mid and forward rapidity.

Very limited statistics so that no strong conclusion can be drawn.

Need more data, and detector upgrades.



Reaching Higher p_T for J/ψ - probing for the "hot wind"?

New PHENIX R_{CuCu} out to p_T = 9 GeV/c !

- shows large suppression that looks roughly constant up to high p_T
- STAR points with their huge uncertainties were misleading

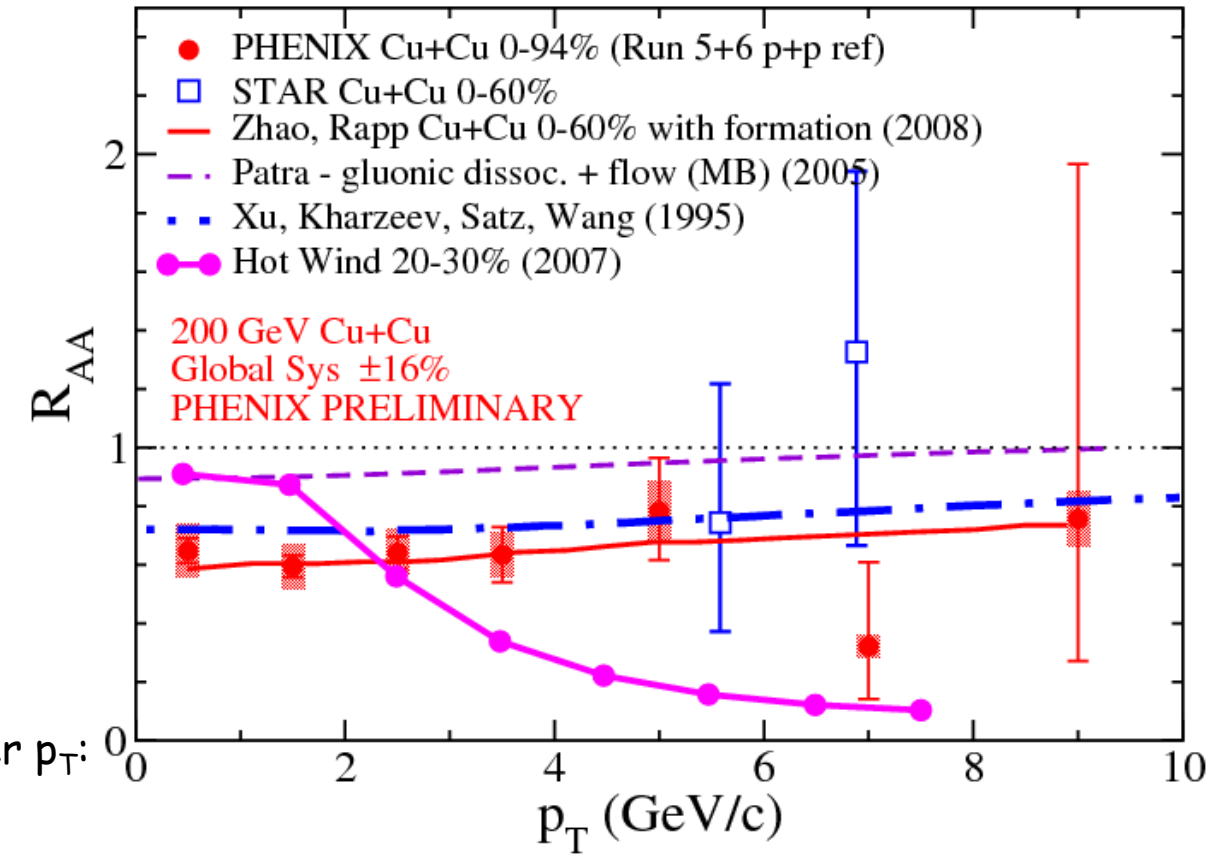
AdS/CFT ("hot wind") - more suppression at high p_T:
Liu, Rajagopal, Wiedemann
PRL 98, 182301(2007)

Regeneration (2-compenent):
Zhao, Rapp
hep-ph/07122407
& private communication

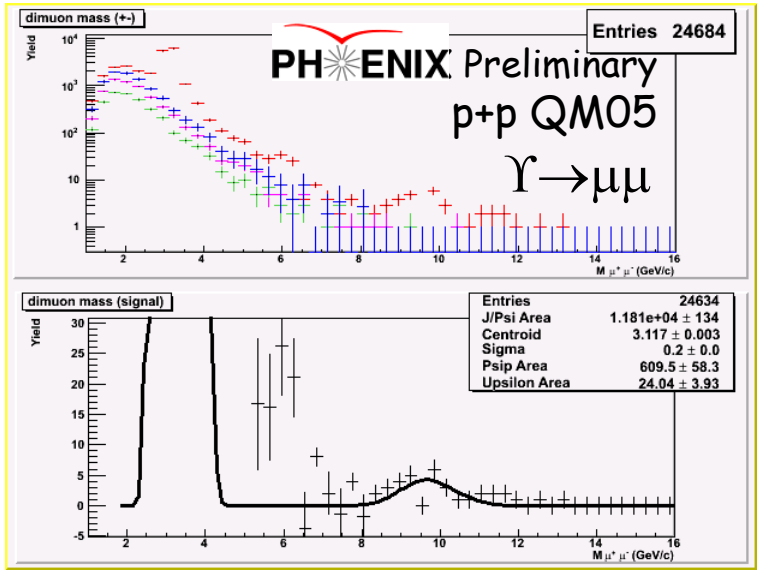
Equilibrating Parton Plasma:
Xu, Kharzeev, Satz, Wang,
hep-ph/9511331

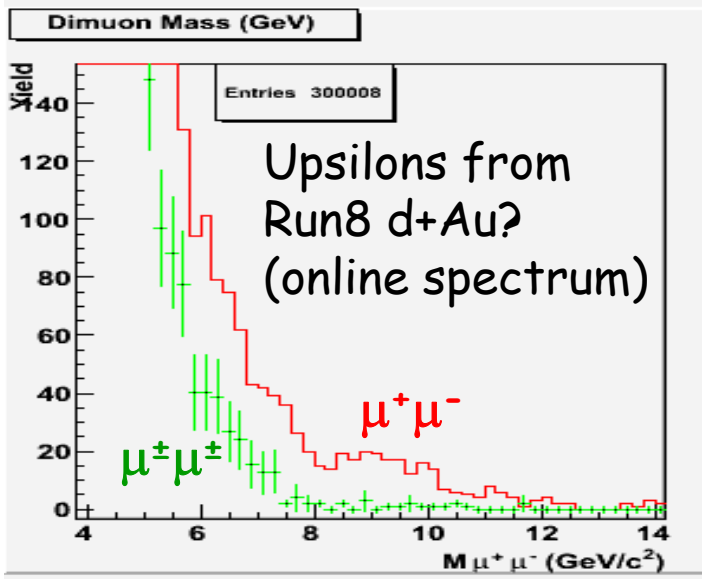
Gluonic dissoc. & flow:
Patra, Menon, *nucl-th/0503034*

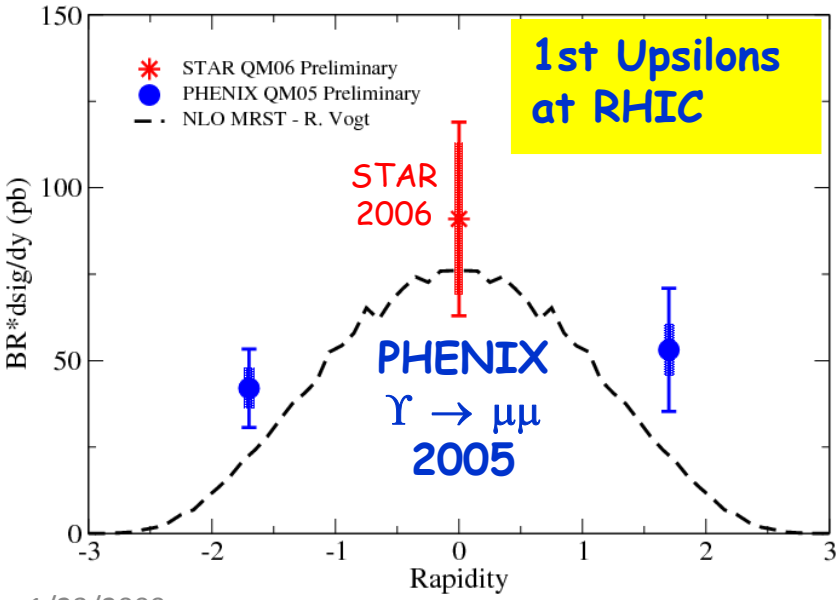
Cronin – less suppression at higher p_T:
use d+Au data as a guide

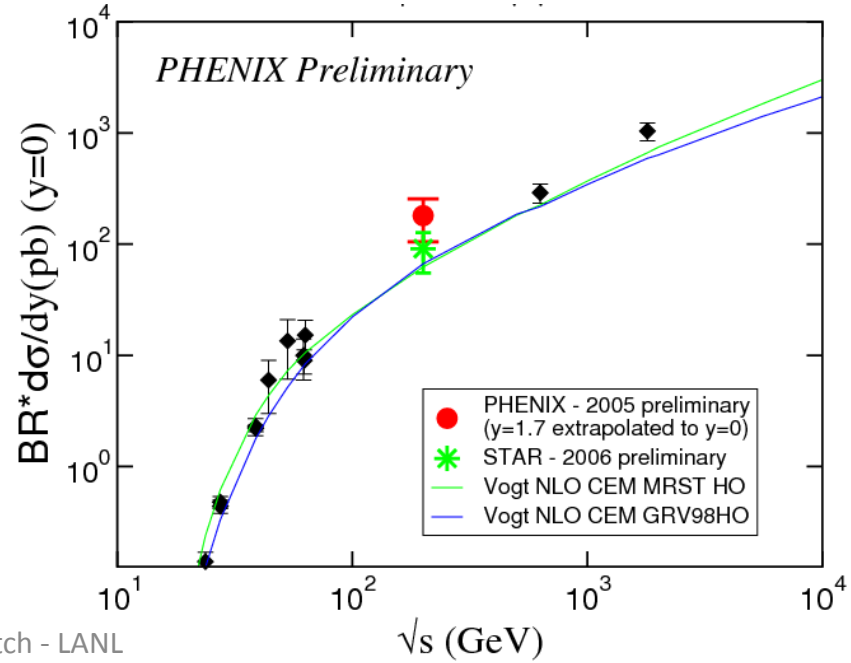


PHENIX & STAR Preliminary Υ p+p Cross Sections



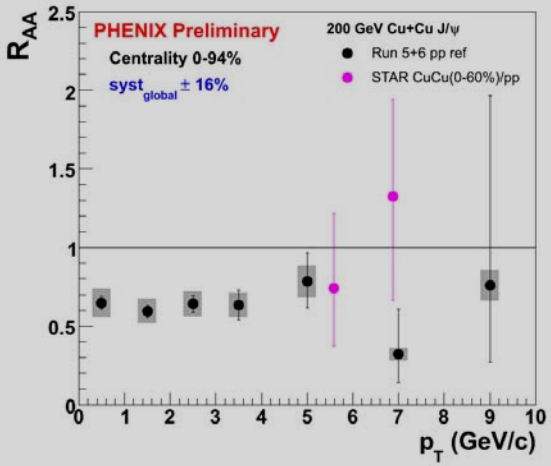




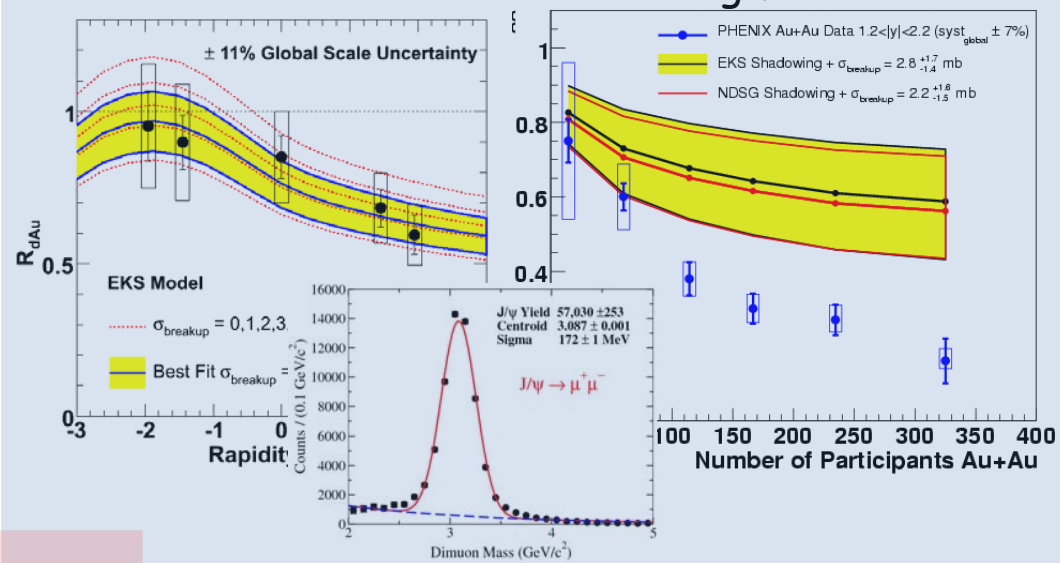


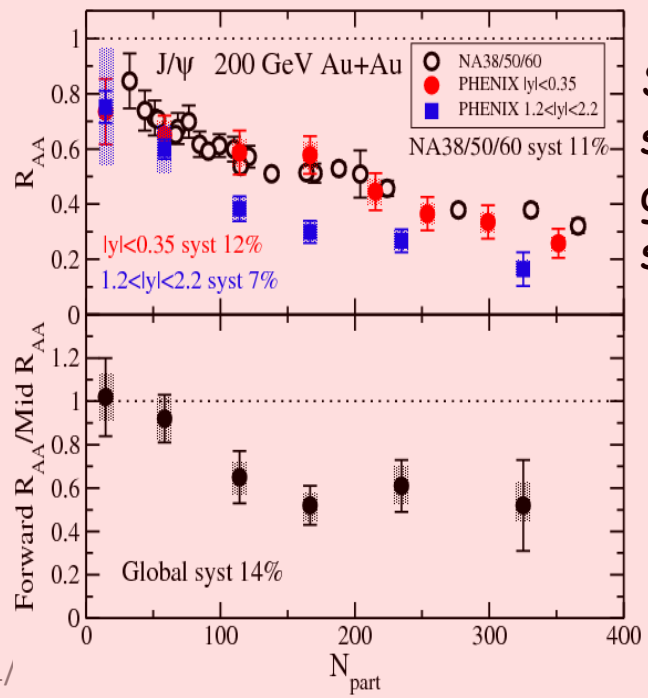
Quarkonia Results from RHIC – Summary

Pushing J/ψ to higher-p_T



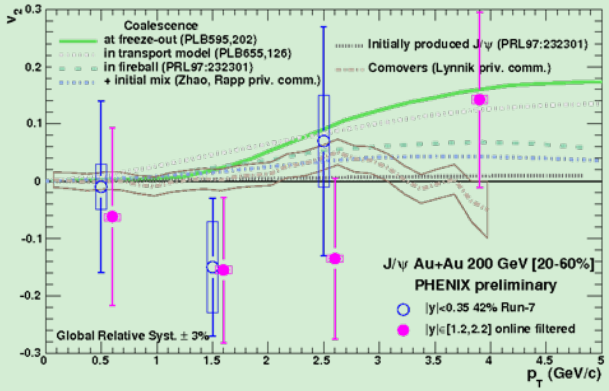
Better CNM baseline coming from Run8!





Sequential screening & gluon saturation

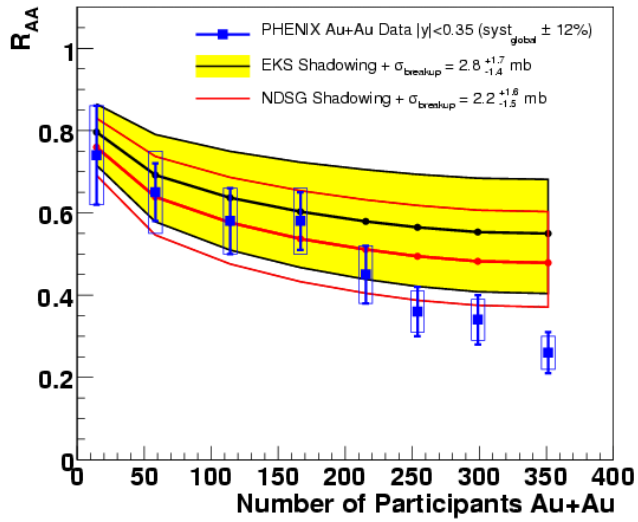
flow from regeneration is difficult to see

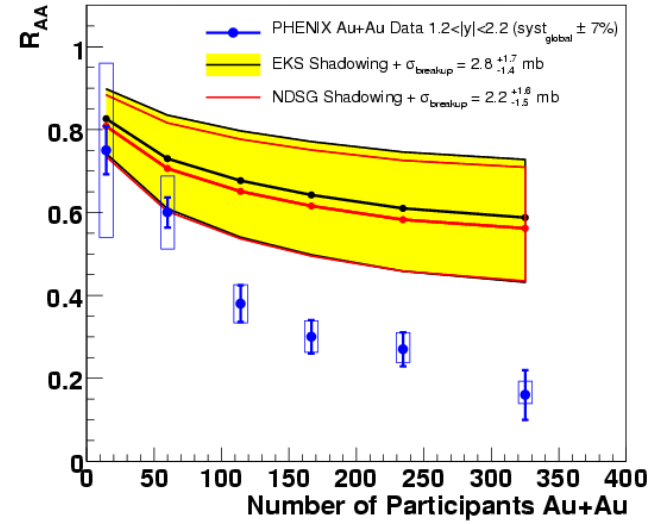


Backup Slides

How does the QGP affect Quarkonia?
CNM Effects

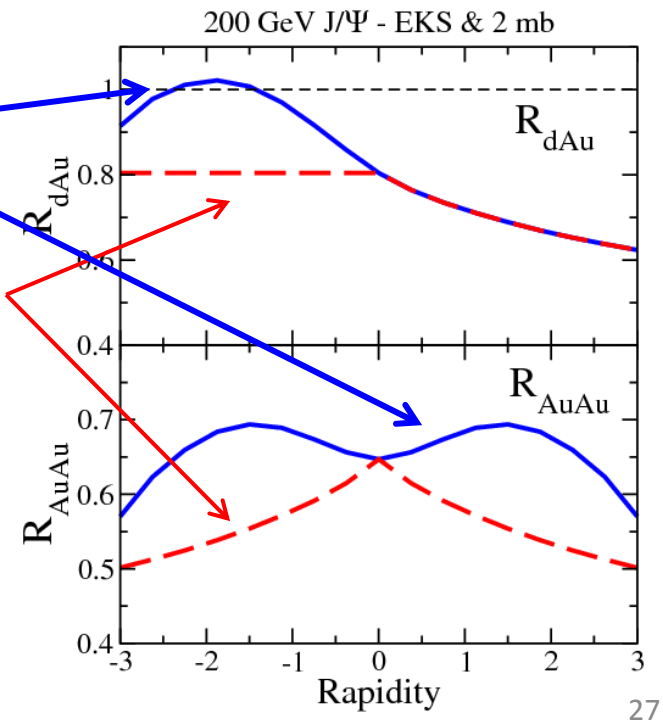
CNM effects (EKS shadowing + dissociation) give large fraction of observed AuAu suppression, especially at mid-rapidity





Normal CNM descriptions give similar AuAu suppression at mid vs forward rapidity

- but if peaking in "anti-shadowing" region were flat instead then one would get larger suppression for forward rapidity as has been observed in AuAu data
- could come from gluon saturation or from a shadowing prescription that has no anti-shadowing



In any case more accurate dAu data is sorely needed

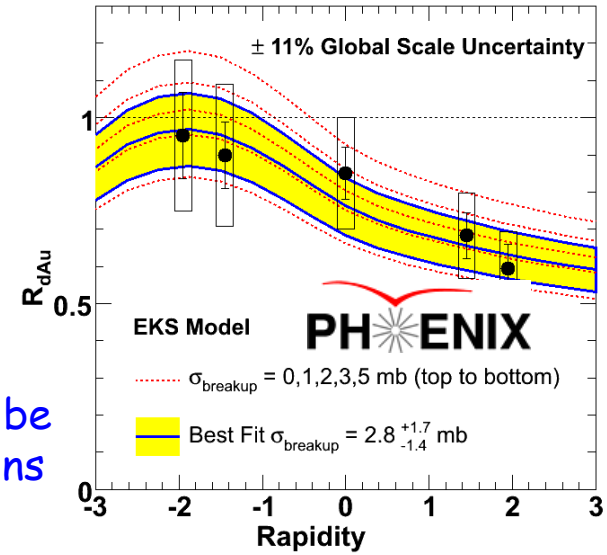
Nuclear Dependence Nomenclature – Ratio (R_{dAu}, R_{AA}) and Alpha (α)

$R_{dAu} = \alpha = 1$ if every N-N collision in a Nucleus contributes as if it were in a free nucleon

$$R_{dAu} = \frac{d\sigma^{dAu}/dy}{2\times 197\cdot(d\sigma^{pp}/dy)}$$

$$= \frac{dN^{dAu}/dy}{\langle n_{coll}^{dAu}\rangle dN^{pp}/dy}$$

$\langle n_{coll}\rangle$ from Glauber model calc. – can also be used for centrality bins

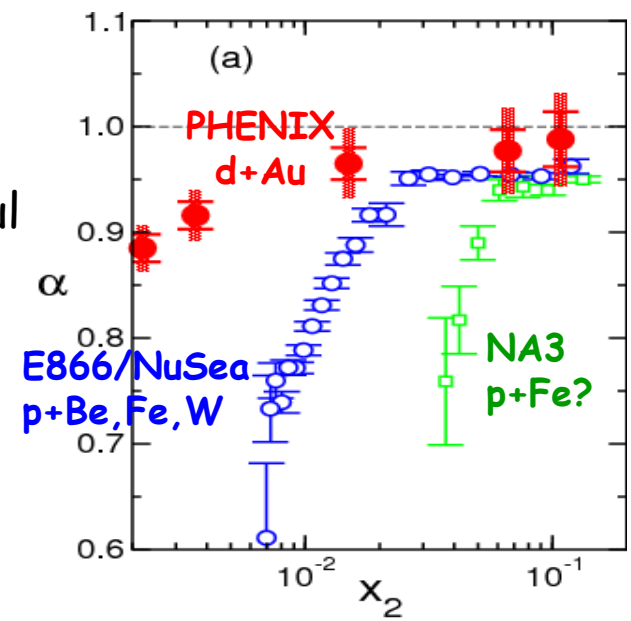


Where dN^{dAu}/dy is an invariant yield w/o absolute normalization factors that would be needed for a cross section (lower systematical uncertainties)

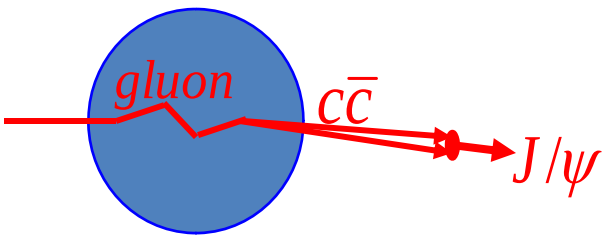
Alternatively, a power law with α – especially useful when comparing expts that used different nuclear targets

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

$$\alpha = 1 + \ln(R_{pA})/\ln(A)$$



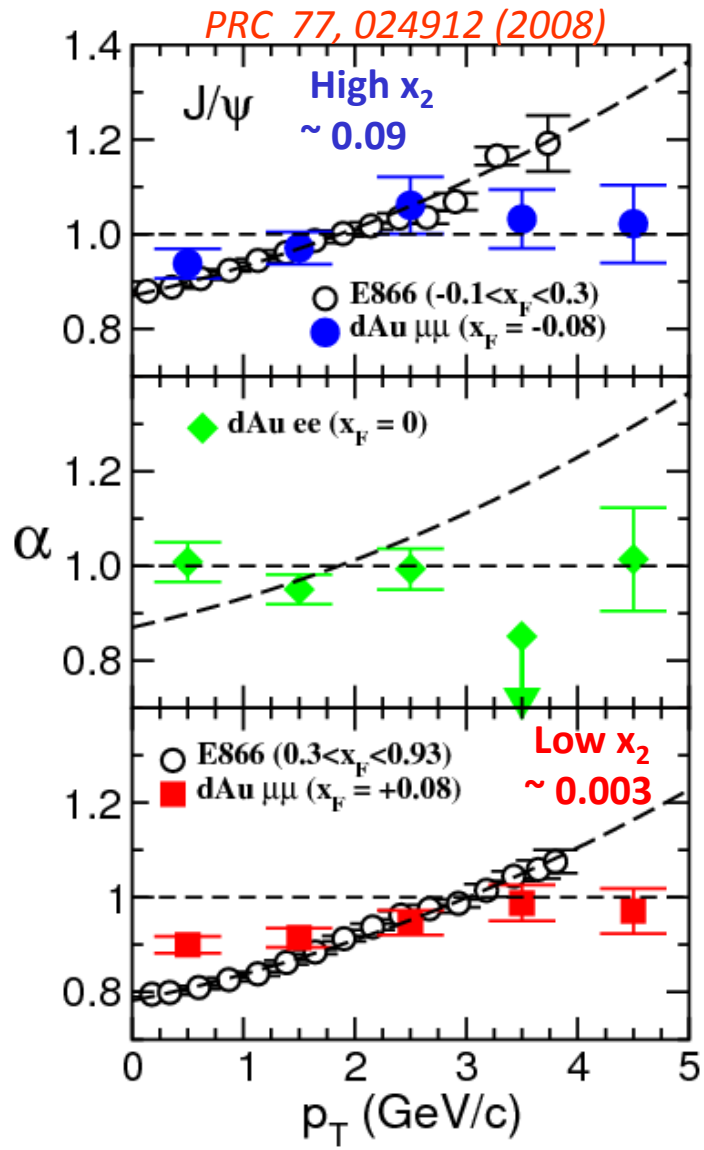
Transverse Momentum Broadening
Another Cold Nuclear Matter Effect



Initial-state gluon multiple scattering causes p_T broadening (or Cronin effect)

$$\sigma_A = \sigma_N A^{\alpha}$$

PHENIX 200 GeV dAu shows some p_T broadening, but may be flatter than at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)



Recent Quarkonia Yields in PHENIX & STAR

					J/ψ		ϒ	
Run	species	Expt.	Lumi	p_T	ee	μμ	ee	μμ
2005	pp	PHENIX	3.8 pb^{-1}		400	1250		27
		STAR	3 pb^{-1}	>2.5	22			
	CuCu	PHENIX	3 nb^{-1}		2k	9k		
		STAR	0.9 nb^{-1}	> 3.75	17			
2006	pp	PHENIX	10.7 pb^{-1}		1.5k	22k		
		STAR	0.4 pb^{-1}		~150			
			11 pb^{-1}	> 4	40			
			9 pb^{-1}				42	
2007	AuAu	PHENIX	0.81 nb^{-1}		3.7k	16k		
		STAR	0.3 nb^{-1}				70	
2008	dAu	PHENIX	80 nb^{-1}		6k	73k		~200
	pp		5.2 pb^{-1}			13k		

Reaching Higher p_T for J/ψ - probing for the "hot wind?"

Approximate ratios by combining PHENIX & STAR data reach higher p_T & appear to be consistent with R_{AA}=0.9±0.2 at high p_T

- but also consistent with lower p_T data at R_{AA} = 0.52
- & regeneration models
- & rough projection from d+Au
- but not with gluon dissociation + flow (*Patra, nucl-th/0503034 2005*)

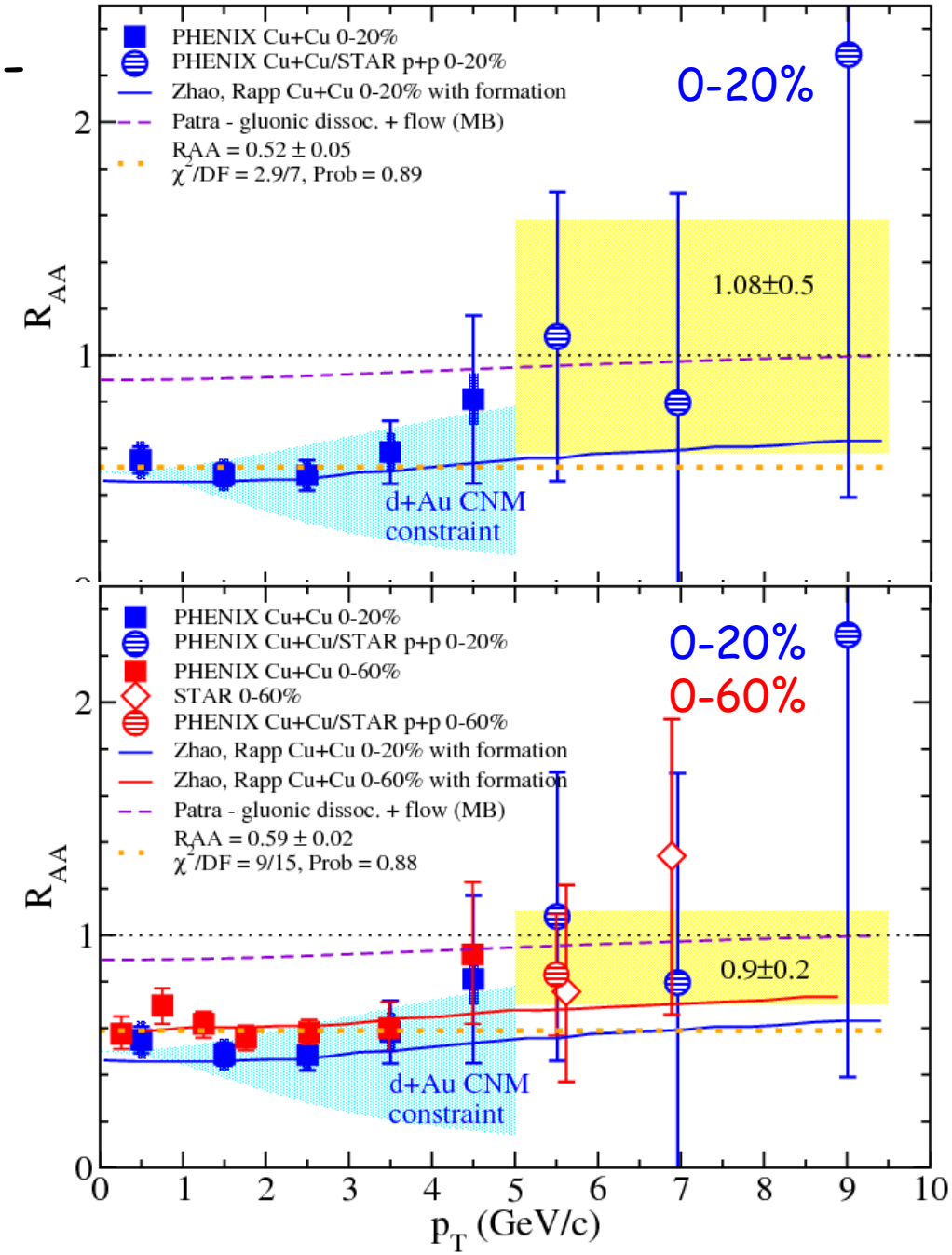
Most models expect a decrease in R_{AA} at high p_T:

AdS/CFT ("hot wind"):

H. Liu, K. Rajagopal and U.A. Wiedemann, PRL 98, 182301(2007) and hep-ph/0607062

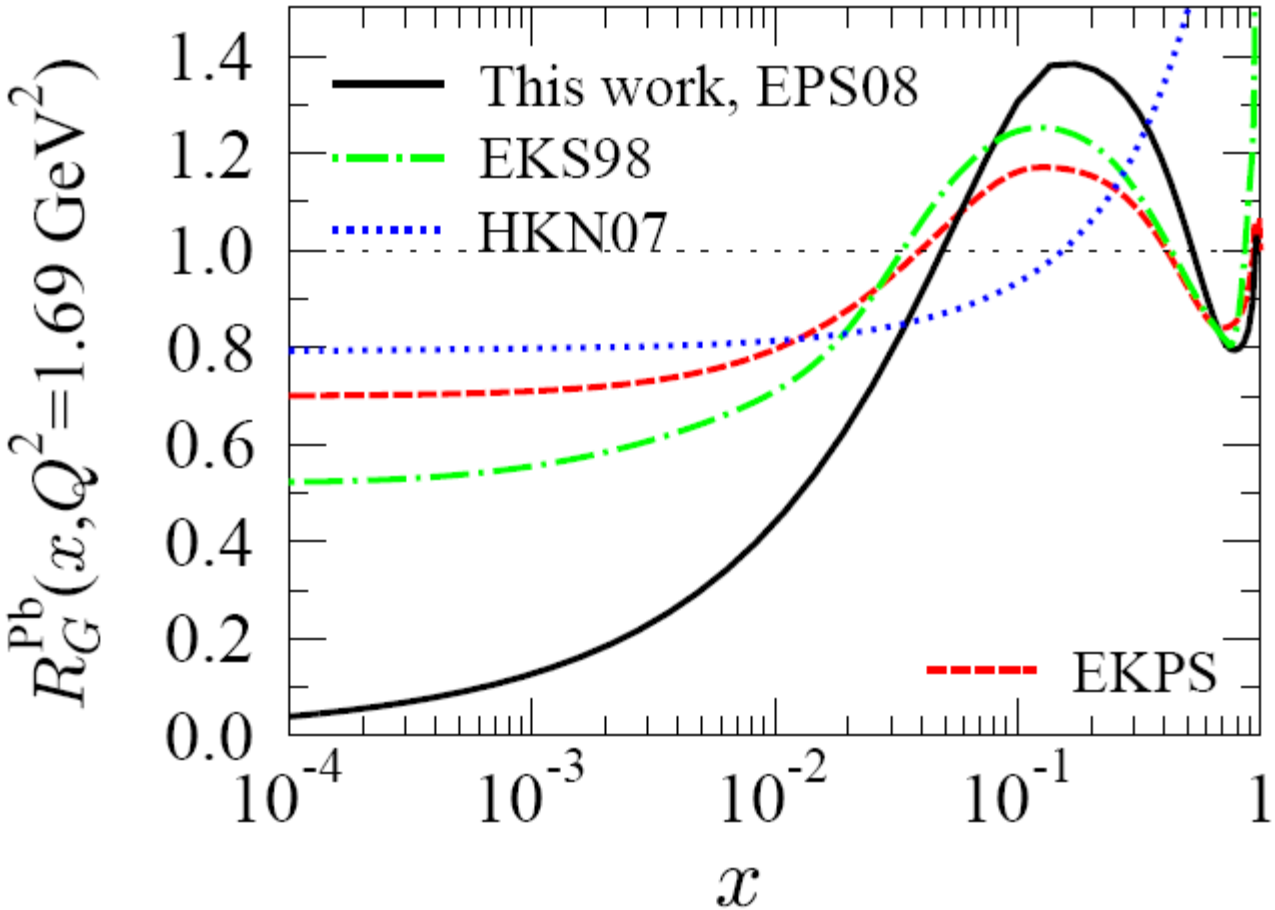
Regeneration (2-compenent):

X. Zhao and R. Rapp, hep-ph/07122407
Private communication



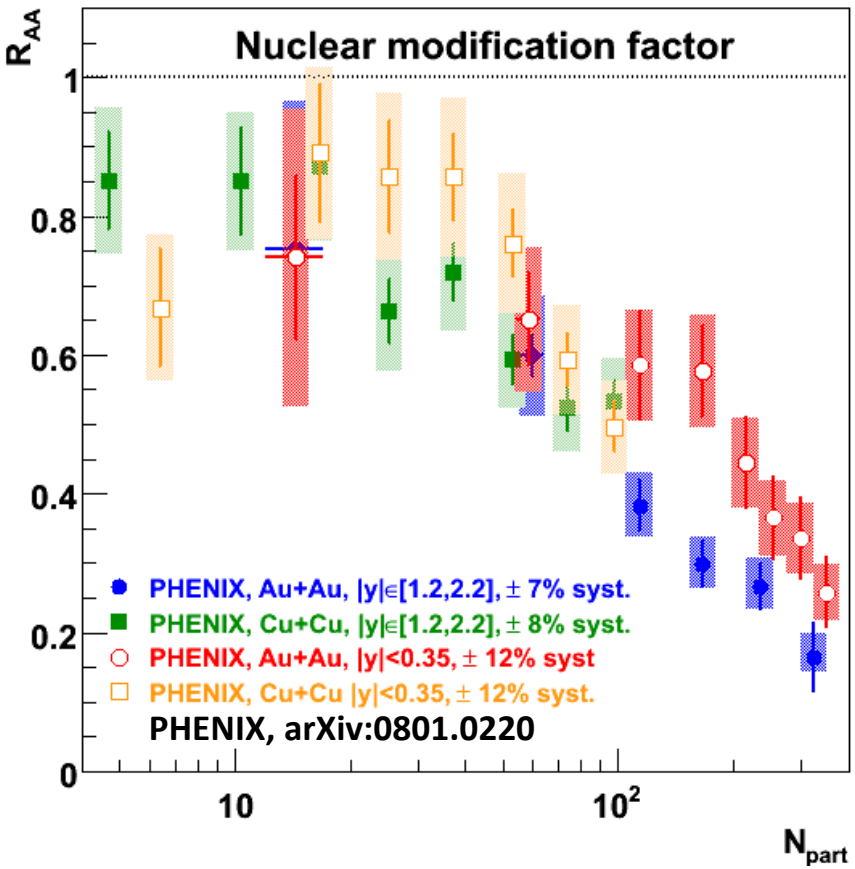
EPS08 (Strong) Shadowing

Eskola, Paukkunen, Salgado, hep-ph 0802.0139v1



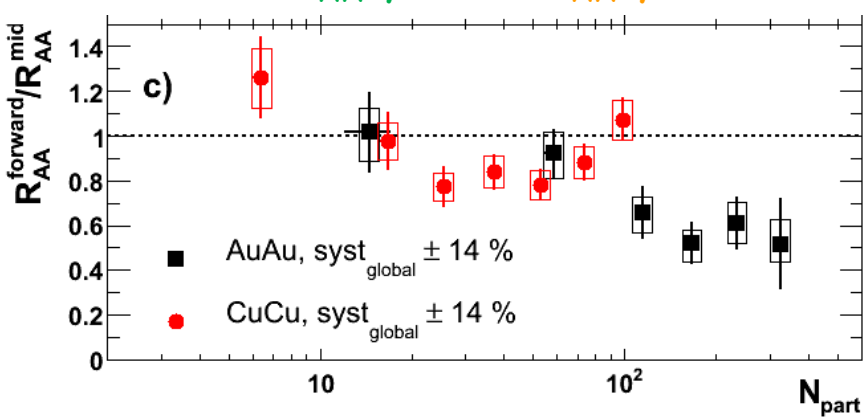
Fit includes RHIC (Brahms) forward hadron data (as well as the usual DIS and DY data)

R_{AuAu} vs R_{CuCu}



CuCu provides more accurate R_{AA} at smaller N_{part}, but within errors confirms the trends seen in AuAu in that region

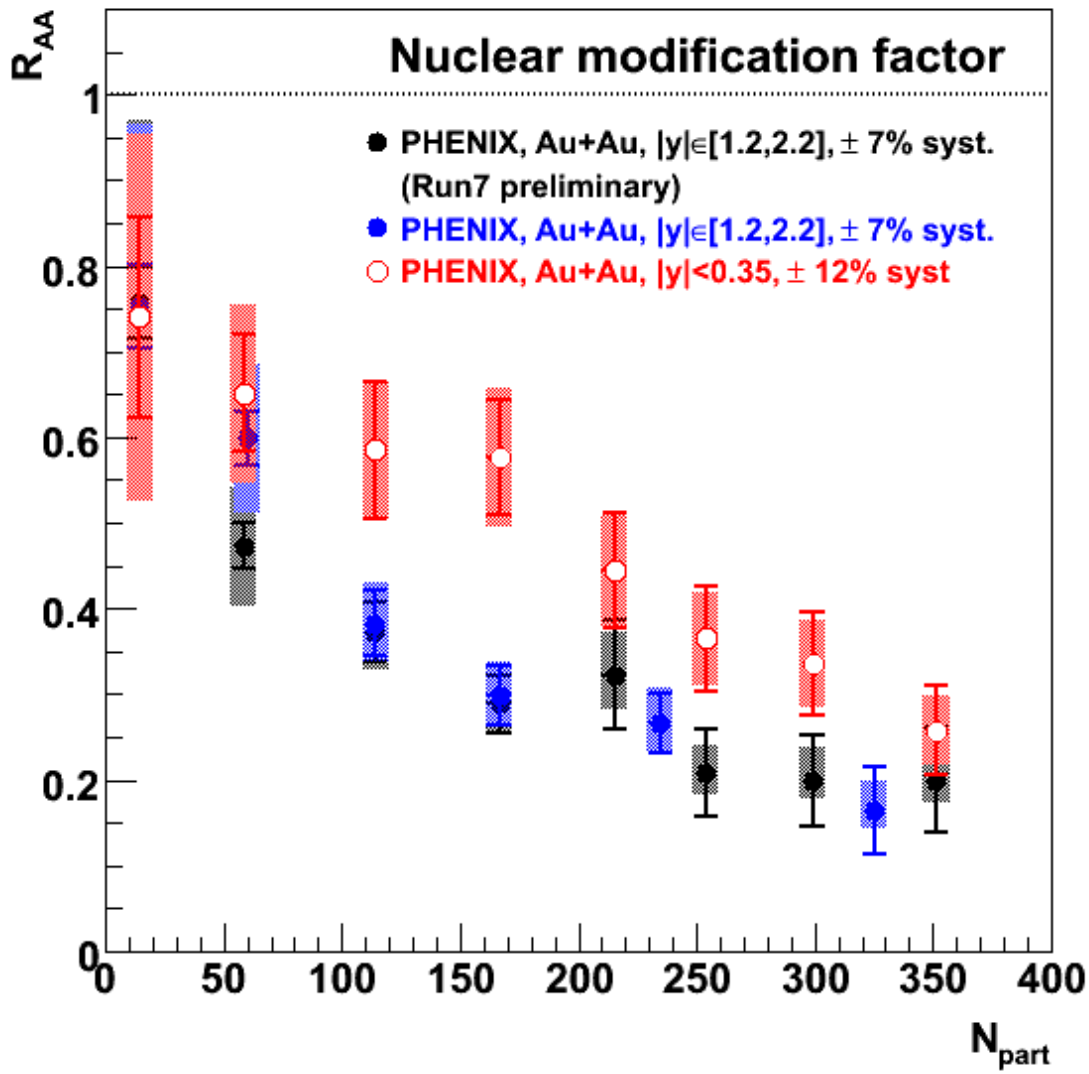
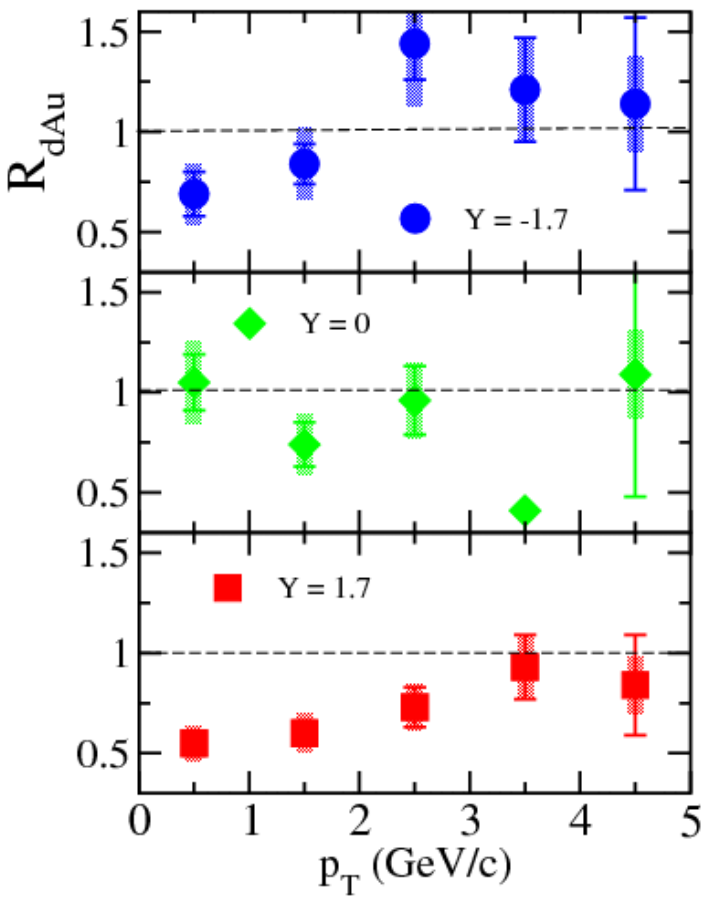
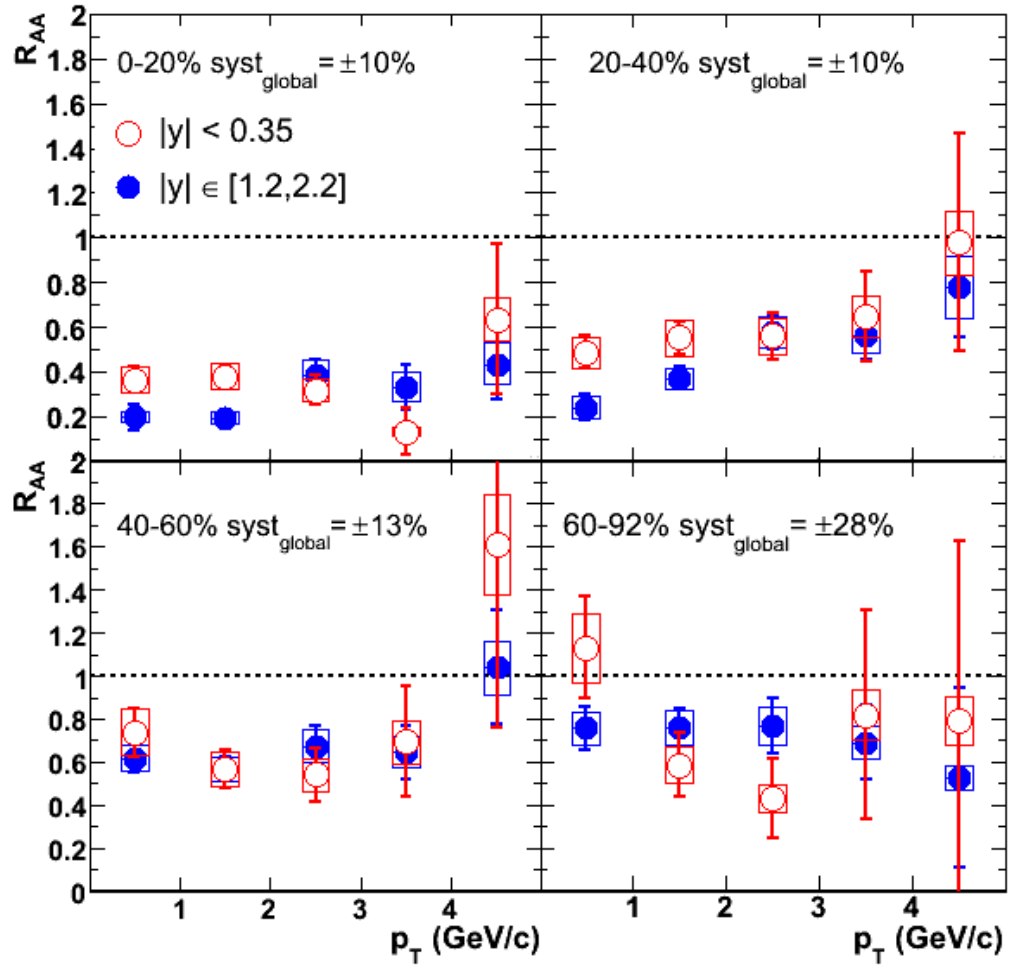
$R_{AA}(y\sim1.7)/R_{AA}(y\sim0)$



New results from Run7 AuAu data

Preliminary analysis of new Run7 AuAu

forward rapidity (dimuon) J/ψ data (black points) is consistent with published results (blue points) from Run4



Ratios vs p_T for d+Au and Au+Au