Progress Towards Understanding Quarkonia at PHENIX

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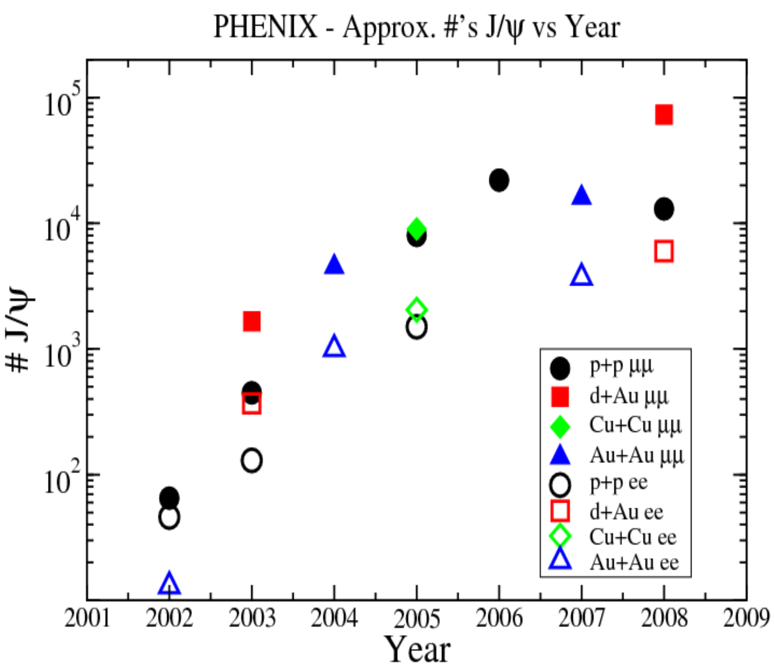
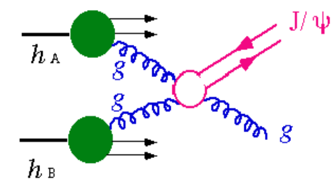
WWND 08 - South Padre Island, TX - 5-12 April 2008

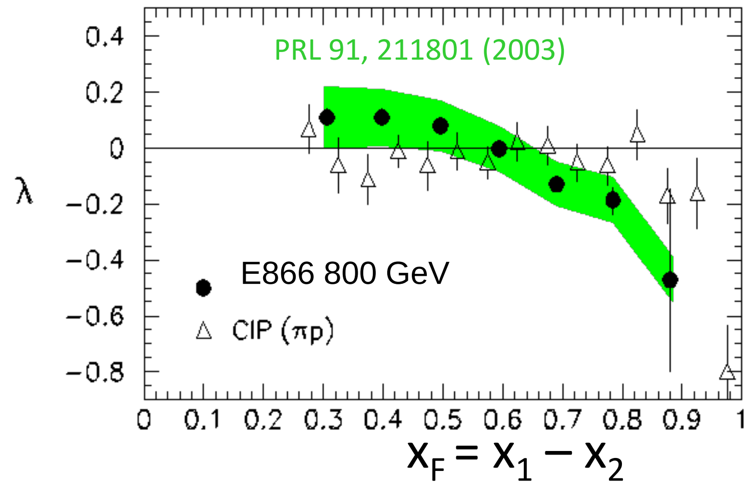
- How are quarkonia produced?
- What CNM effects are important?
- How does the sQGP effect quarkonia?
- What are the CNM effects in AA collisions?
- Transverse Momentum Broadening
- Heavier Quarkonia
- Detector Upgrades & Luminosity for the future



How are Quarkonia Produced?



- Gluon fusion dominates
- Color singlet or octet $c\bar{c}$: absolute cross section and polarization? Difficult to get both correct!
- Configuration of $c\bar{c}$ is important for pA cold nuclear matter effects
- Complications due to substantial feed-down from higher mass resonances (ψ', χ_c)

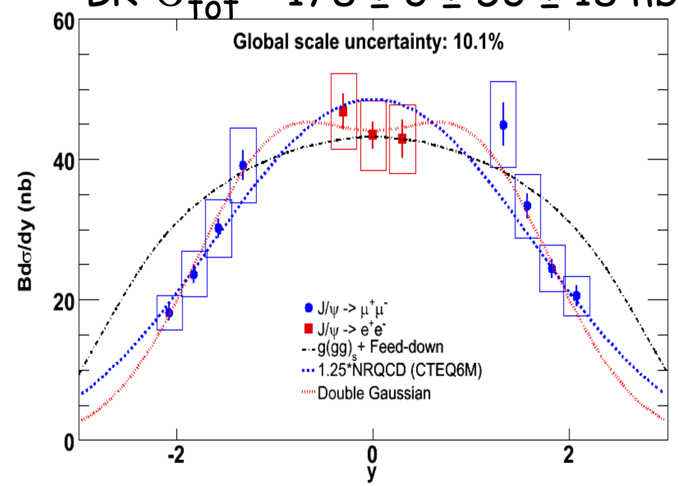


Polarization

NRQCD models predict large transverse polarization (λ>0) at large p_T

- but E866 & CDF show small or longitudinal (λ<0) polarization
- *recently, Haberzettl, Lansberg, PRL 100, 032006 (2008) - looks better*

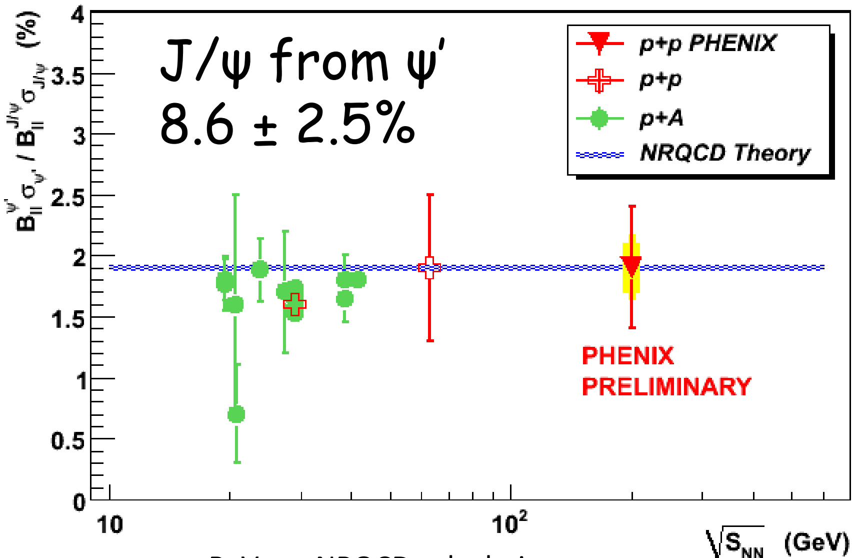
$BR \cdot \sigma_{tot}$ = 178 ± 3 ± 53 ± 18 nb



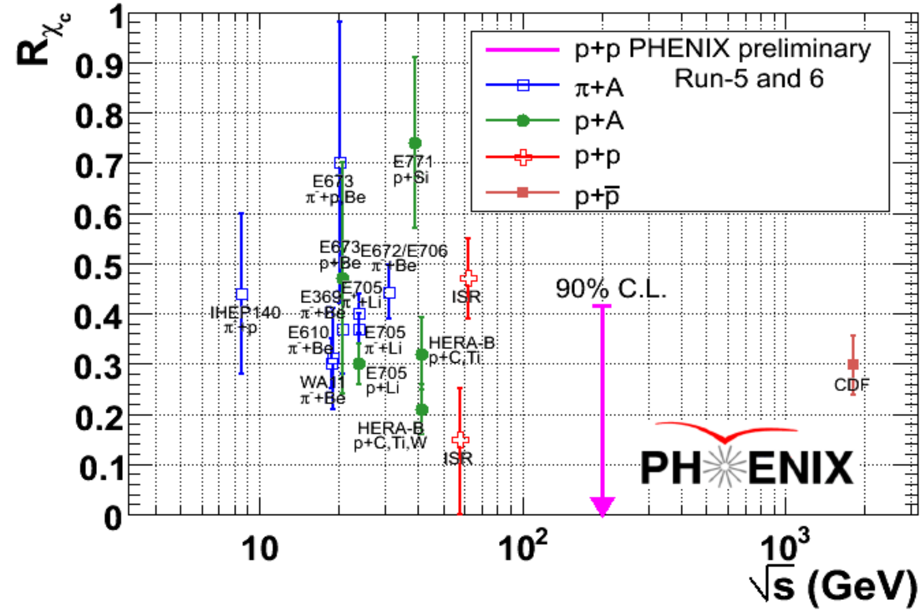
Cross Sections

PHENIX Run5 p+p data (PRL 98:232002,2007) begins to constrain shape of cross section vs rapidity & p_T, but higher accuracy needed

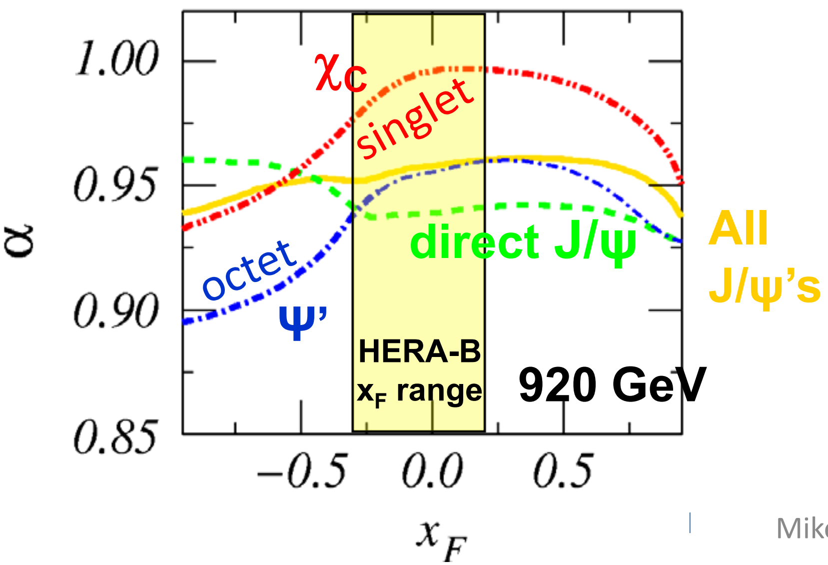
How are Quarkonia Produced? Feeddown to J/ψ



J/ψ from χ_c < 42% (90% CL)



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



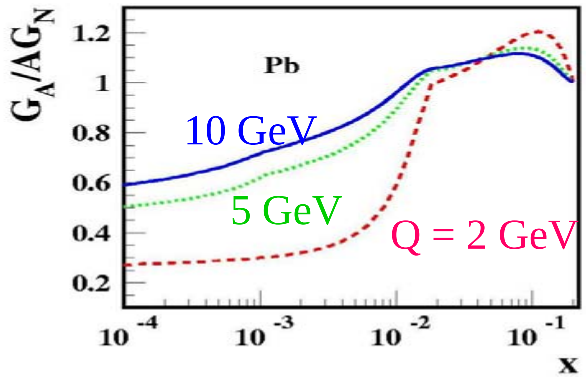
Nuclear dependence of (parent) resonance, e.g. χ_c is probably different than that of the J/ψ

Also measure of $B \rightarrow J/\psi$ - 4^{+3}_{-2} %

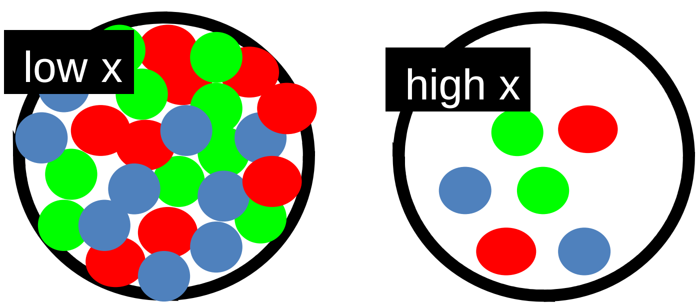
see Y. Morino talk on Wed

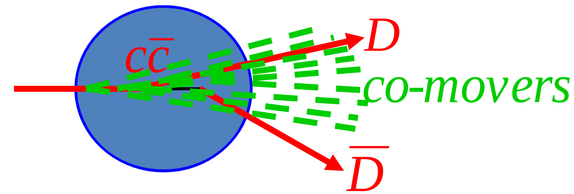
What CNM effects are important?
(CNM = Cold Nuclear Matter)

Traditional shadowing from fits to DIS or from coherenece models



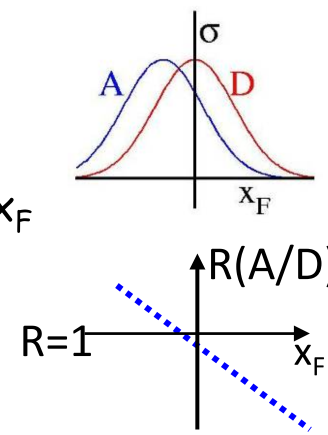
Gluon saturation from non-linear gluon interactions for the high density at small x; amplified in a nucleus.



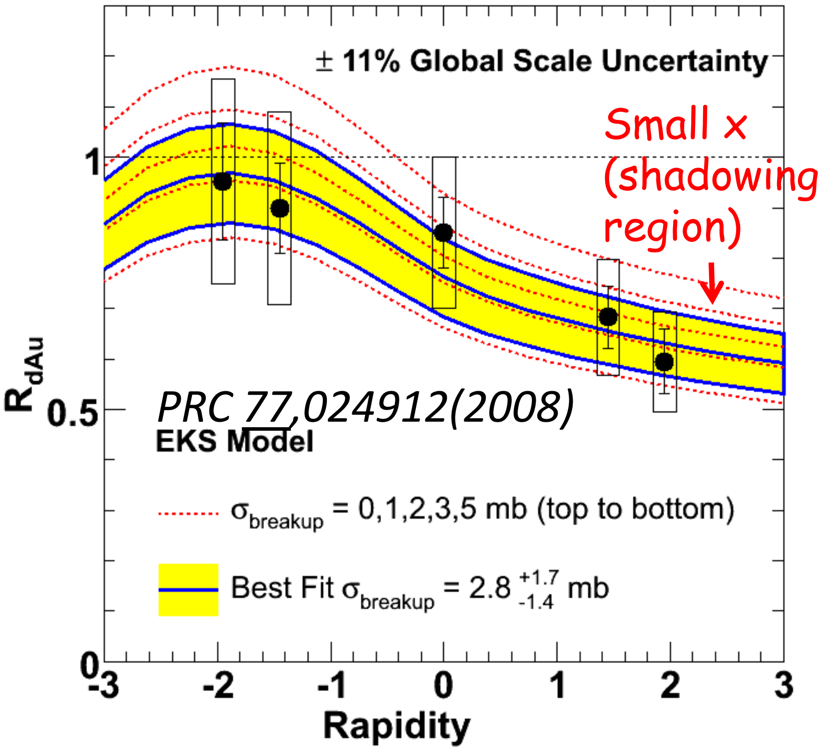


Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

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



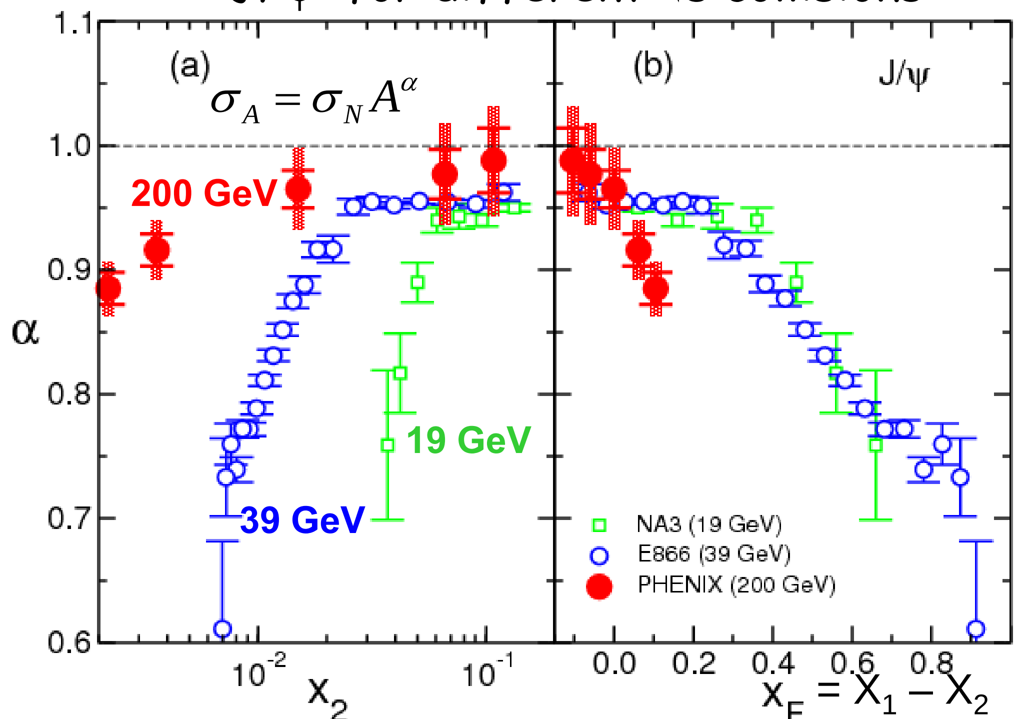
What CNM effects are important? (CNM = Cold Nuclear Matter)



New Analysis of Run3 data consistent with EKS shadowing & absorption - clear need for new dAu data

- *latest shadowing (EPS08) ≥ 2x stronger (Brahms forw. data in fit)*

J/ψ for different √s collisions



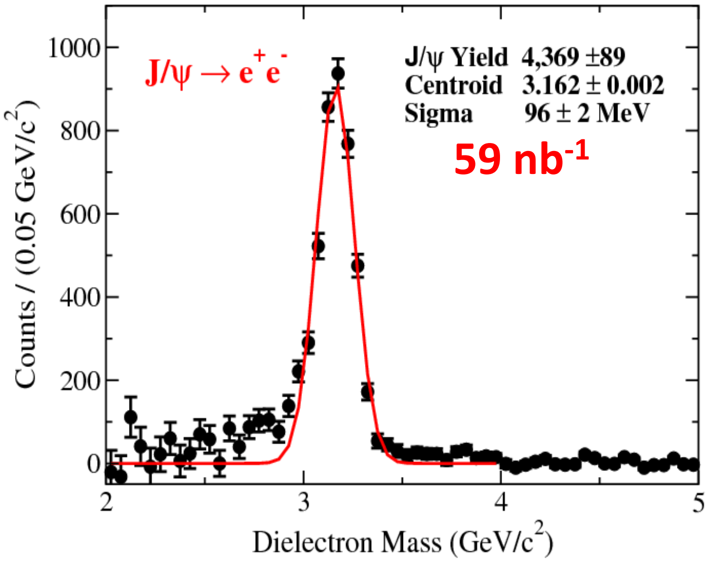
(x_2 is x in the nucleus)

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

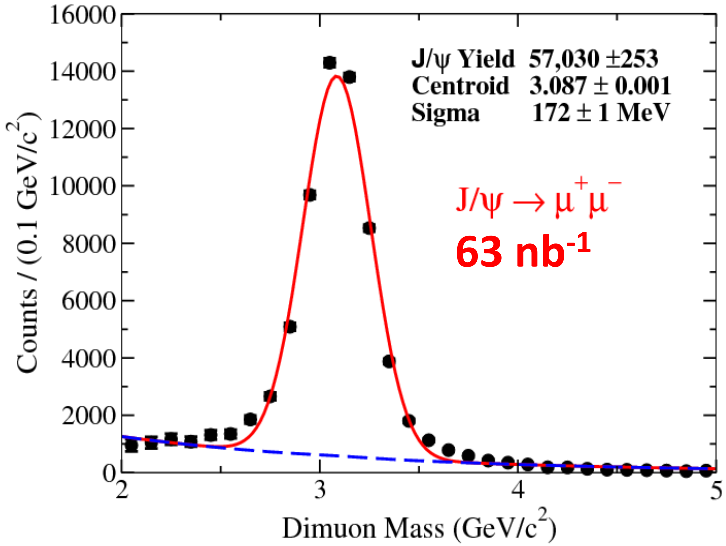
- initial-state gluon energy loss?
- gluon saturation?
- Sudakov suppression (energy conservation)?

What CNM effects are important? Latest PHENIX J/ψ's from Run8

200 GeV d+Au

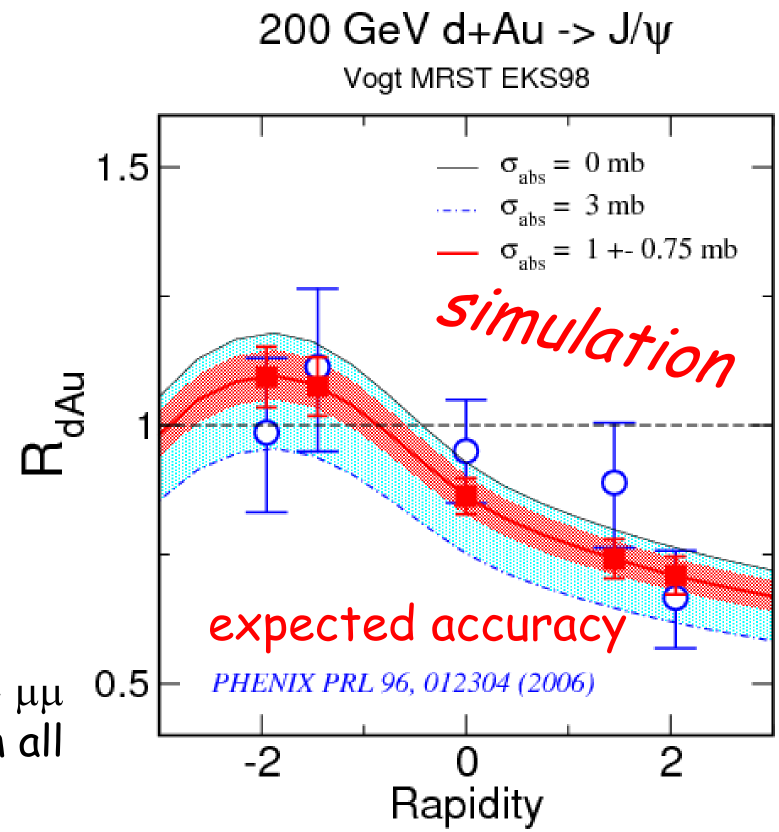


4,369 $J/\psi \rightarrow ee$ (~6,000 from all data)



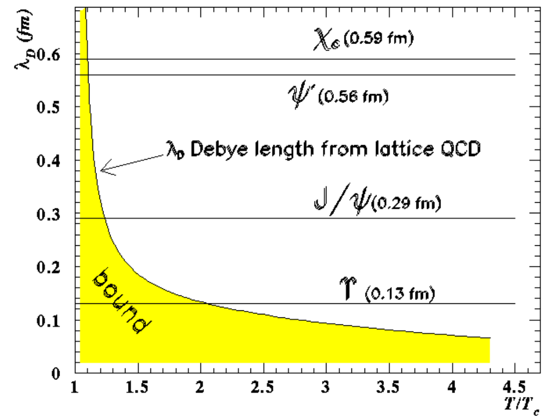
57,030 $J/\psi \rightarrow \mu\mu$ (~73,000 from all data)

Expected improvement in CNM constraints (red) compared to Run3 (blue)



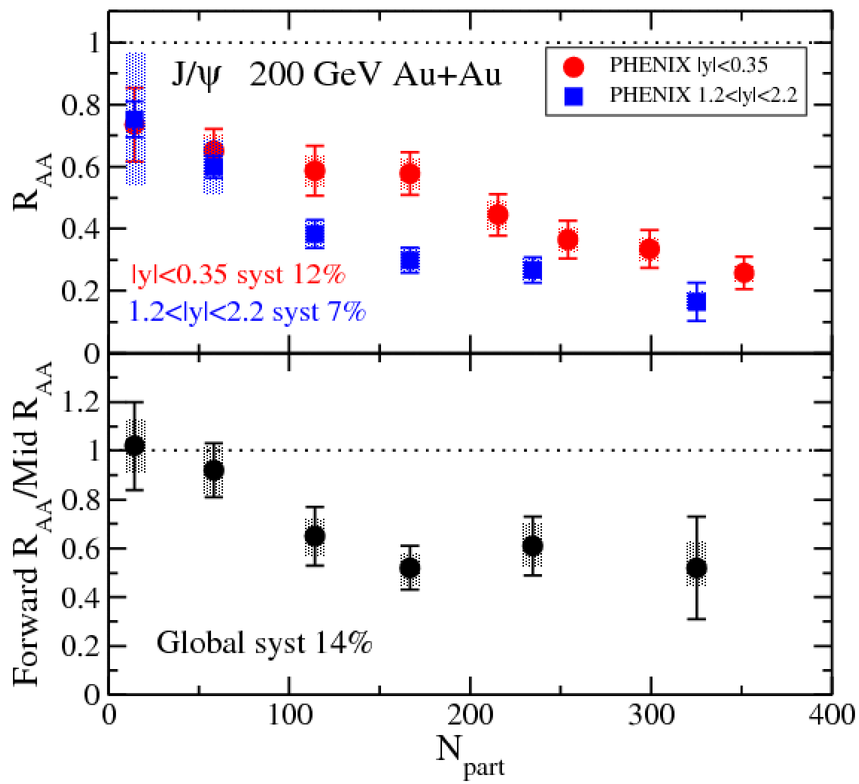
How does the QGP affect Quarkonia?

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.



PHENIX AuAu 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 RAA ratio looks flat above N_{part} = 100

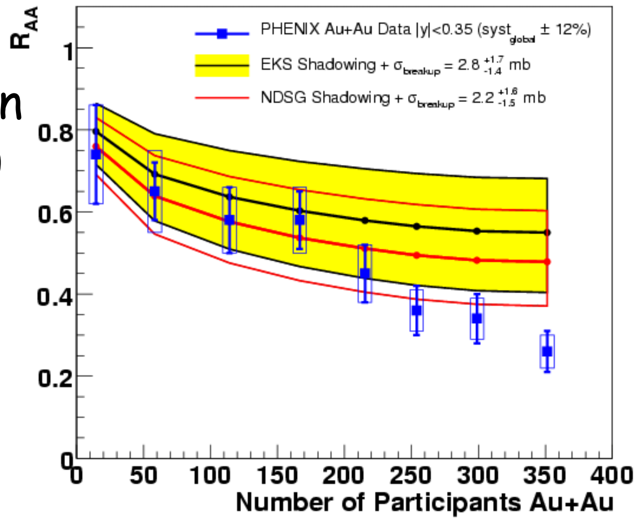


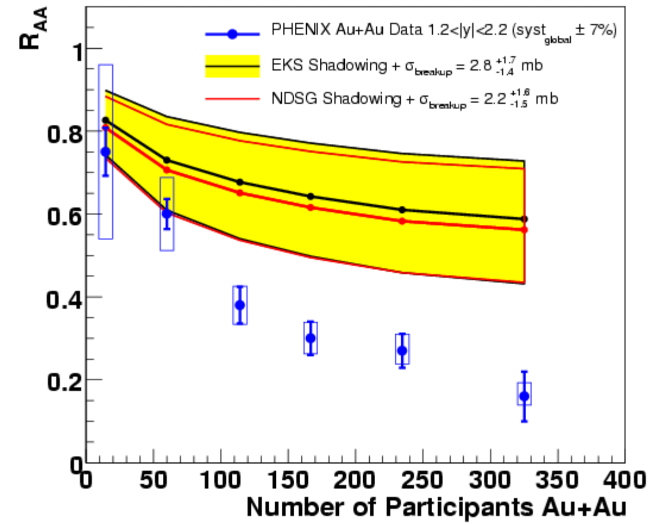
Several alternative scenarios can be considered:

- Cold nuclear matter (CNM) effects
  - in any case are always present
- Sequential suppression
  - screening only of χ_C & ψ'- removing their feed-down contrib. to J/ψ
- Regeneration models
  - give enhancement that compensates for screening

How does the QGP affect Quarkonia?
CNM Effects

CNM effects (EKS shadowing & dissocation – see earlier dAu slide) give large fraction of observed AuAu suppression, especially at mid-rapidity

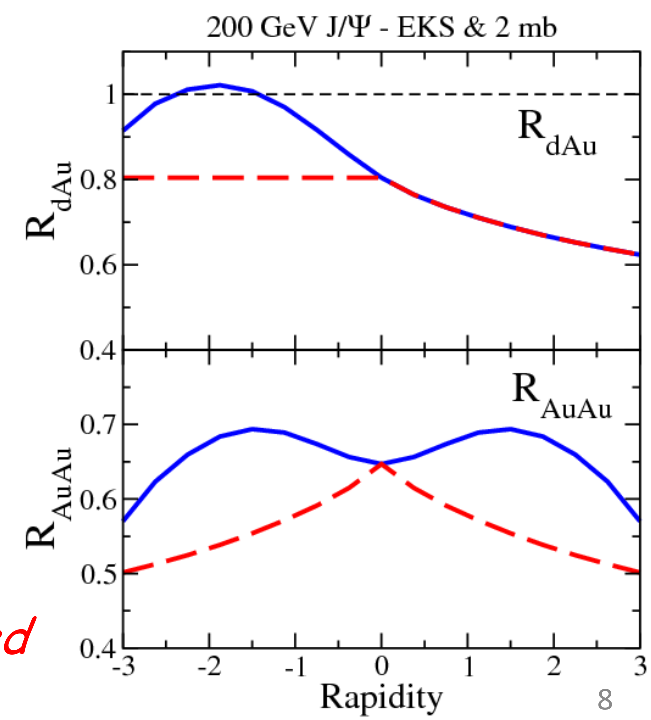




Normal CNM descriptions (blue) give similar (or even smaller) suppression at mid vs forward rapidity

• but if peaking in "anti-shadowing" region were flat instead (red dashed) then one would get larger suppression for forward rapidity as has been observed in AuAu data

• this could come from gluon saturation or from a shadowing prescription that has no anti-shadowing



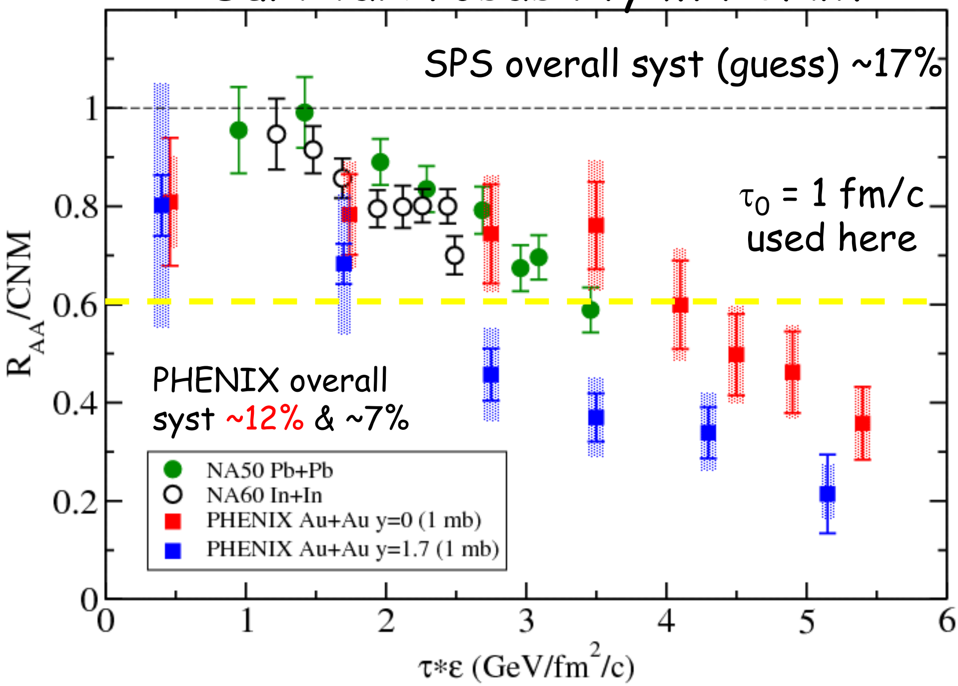
In any case more accurate dAu data is sorely needed

How does the QGP affect Quarkonia? Sequential Screening and Gluon Saturation

Recent lattice calculations suggest J/ψ not screened after all.

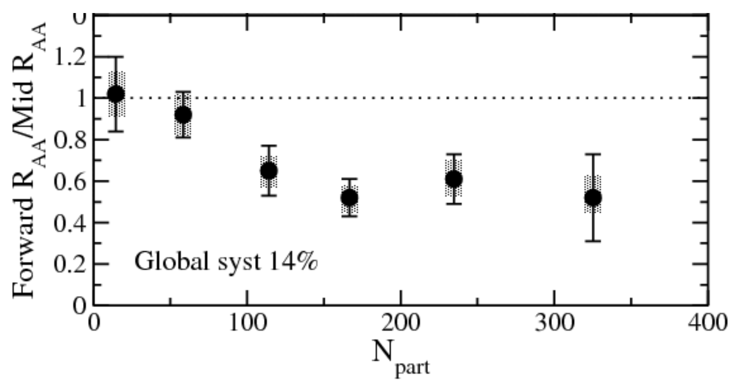
- suppression then comes only via feed-down from screened χ_C & ψ'
- the situation could be the same at lower energies (SPS) as for RHIC mid-rapidity
- and the stronger suppression at forward rapidity at RHIC could come from gluon saturation (previous slide)

Survival Probability wrt CNM



Issues:

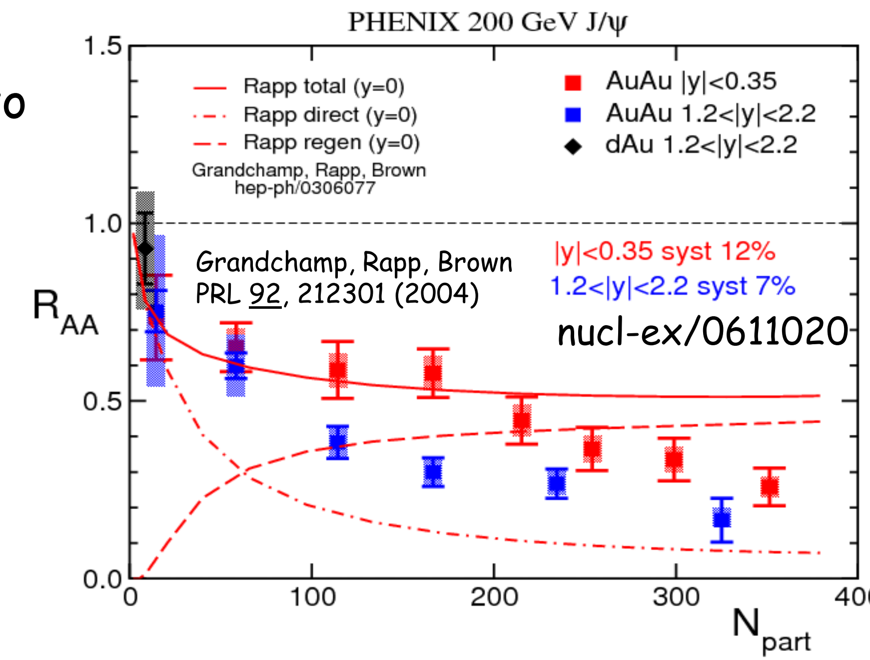
- *Is suppression stronger than can come from χ_C & ψ' alone?*
- *Can this picture explain saturation of the forward/mid RAA ratio?*



How does the QGP affect Quarkonia?
Regeneration

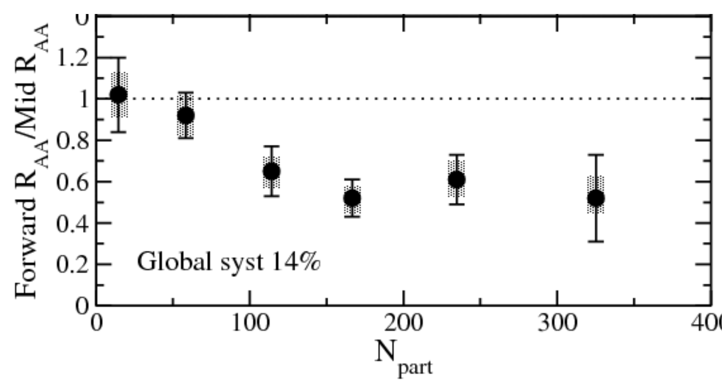
Regeneration models give enhancement that compensates for screening

- larger gluon density at RHIC expected to give stronger suppression than SPS
- but larger charm production at RHIC gives larger regeneration
- very sensitive to poorly known open-charm cross sections
- forward rapidity lower than mid due to smaller open-charm density there
- expect inherited flow from open charm
- regeneration much stronger at the LHC!



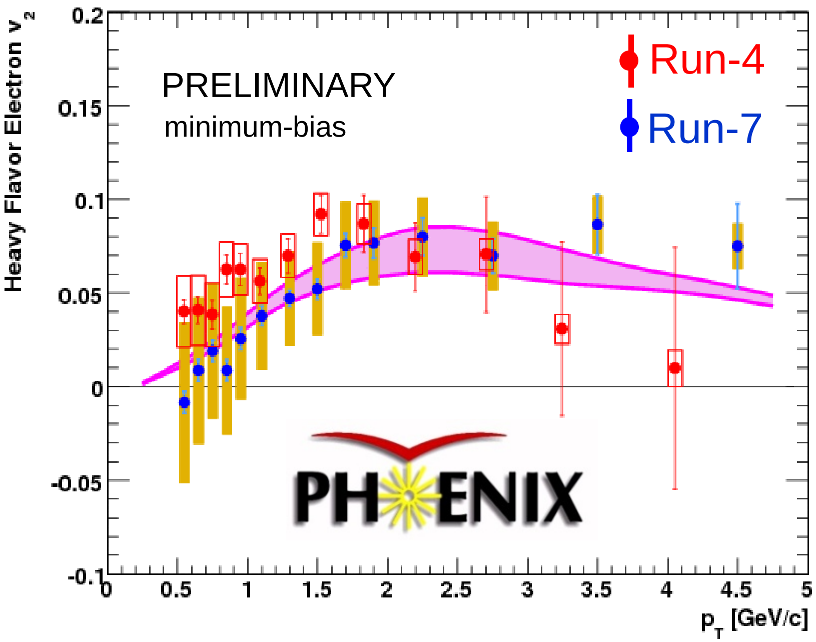
Issues:

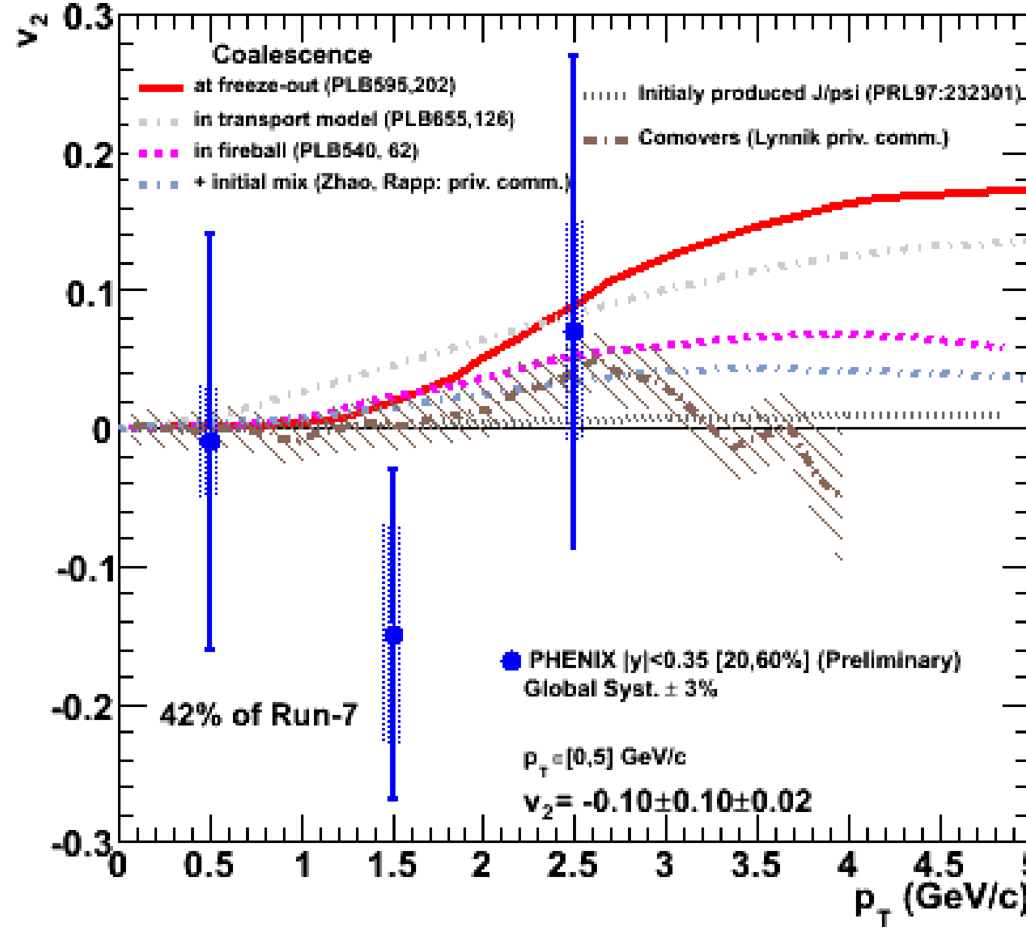
- *need to know what happens to χ_C & ψ' & measure J/ψ flow*
- *flat forward/mid RAA seems inconsistent with increasing regeneration & screening for more central collisions*



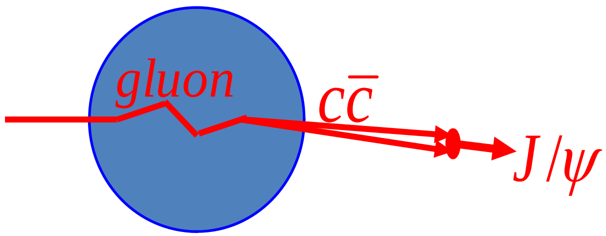
How does the QGP affect Quarkonia?
J/ψ flow

- J/ψ's from regeneration should inherit the large charm-quark elliptic flow
- First J/ψ flow measurement by PHENIX:
  - $v_2 = -10 \pm 10 \pm 2 \pm 3$ %

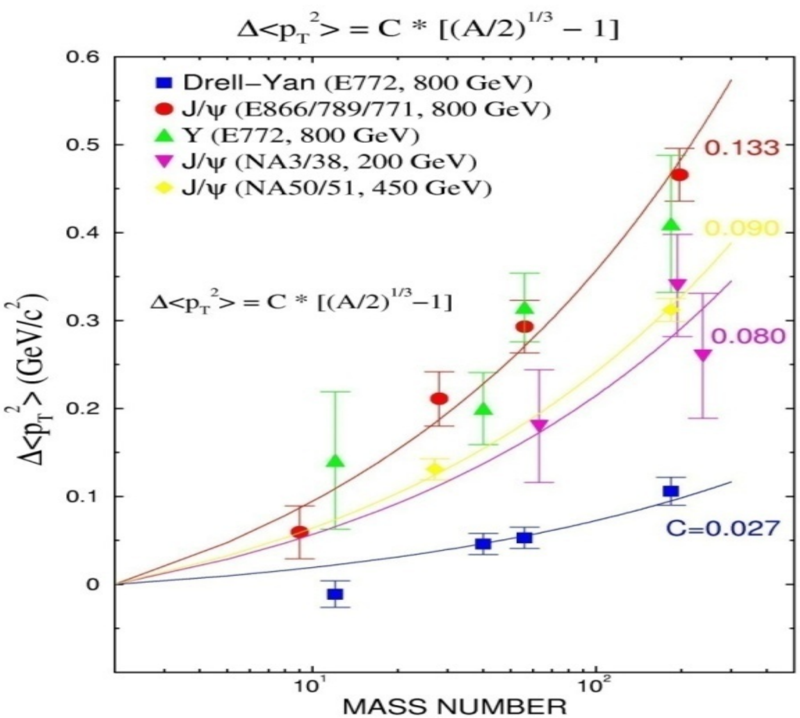




Transverse Momentum Broadening
Another Cold Nuclear Matter Effect



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

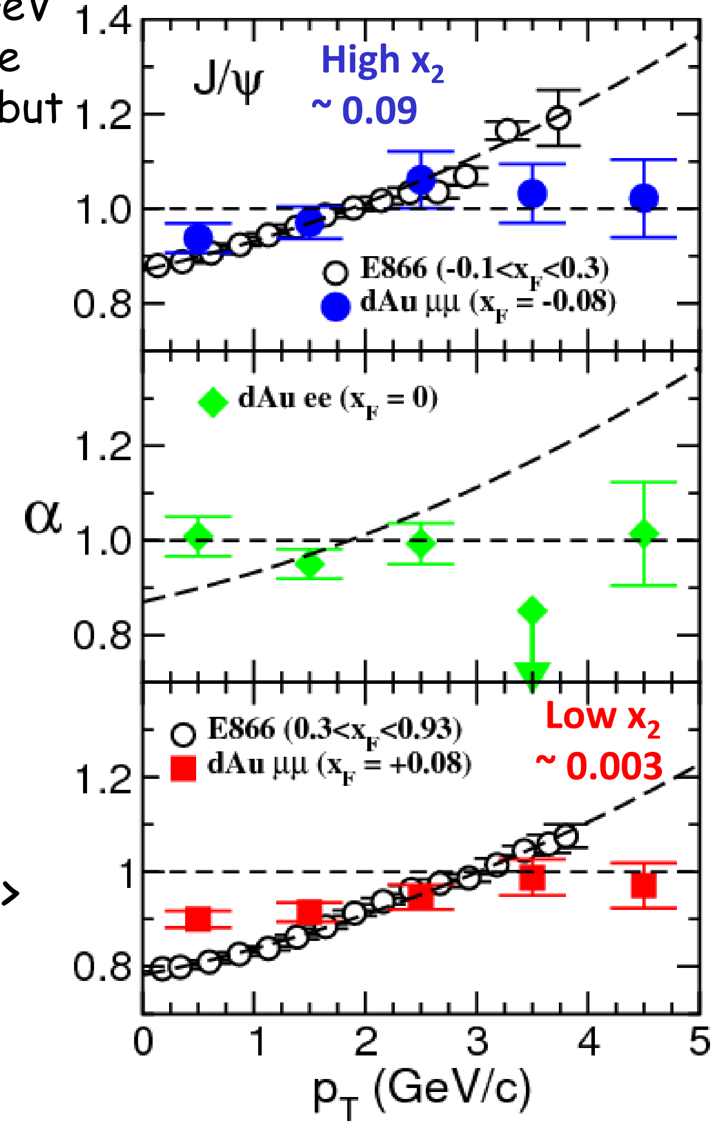


PHENIX 200 GeV dAu shows some p_T broadening, but may be flatter than at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

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

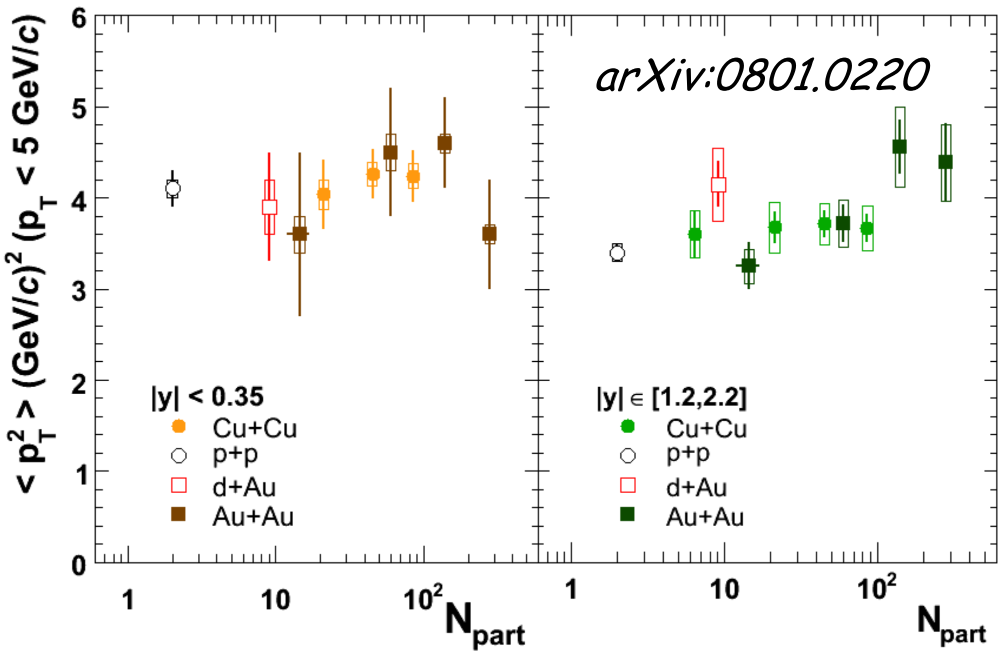
Also can be looked at in terms of $\Delta\langle p_T^2\rangle$

PRC 77, 024912 (2008)

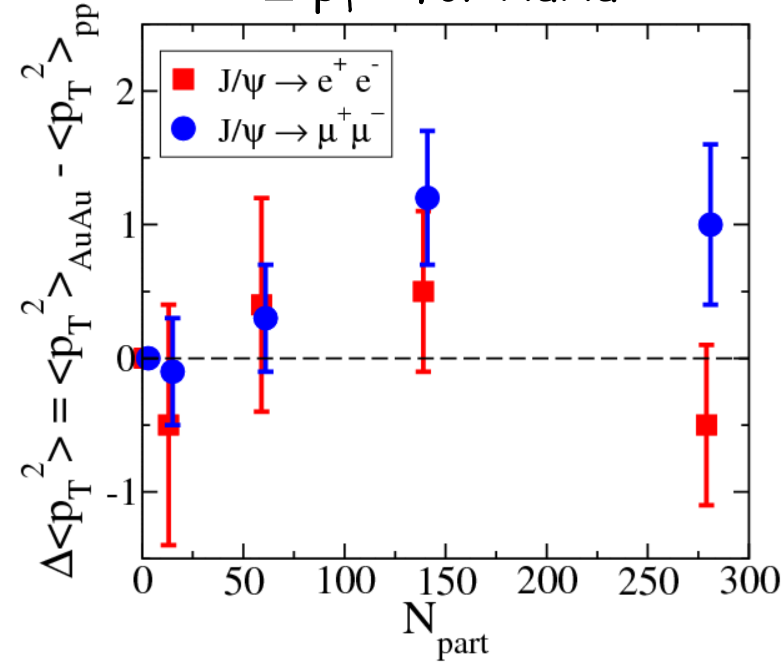


Transverse Momentum Broadening in AA Collisions

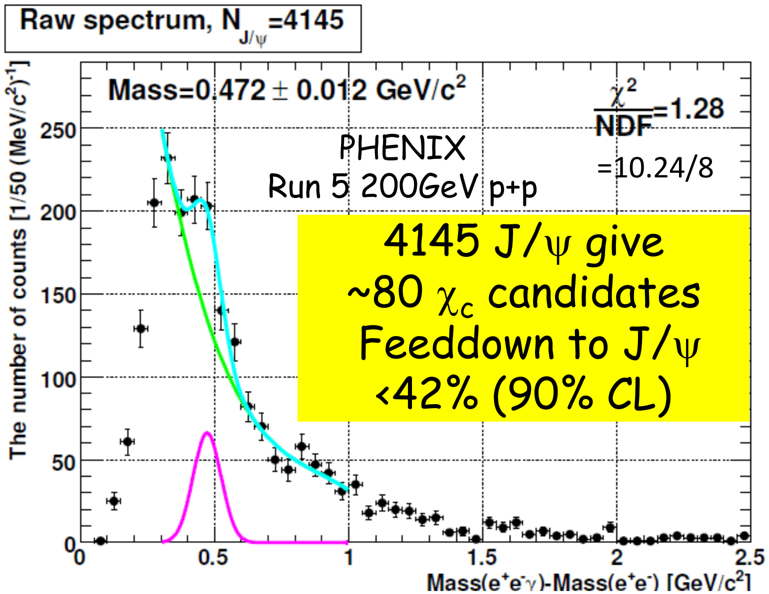
- Relatively flat with centrality - slight increase at forward rapidity
- CNM effects should broaden p_T
  - initial-state mult. scatt. for both gluons
- Regeneration should narrow p_T
  - square of small-p_T peaked open-charm cross section
- Other effects in the presence of a QGP?
  - early escape at high- p_T?
  - "hot wind" suppression at high-p_T (5-9 GeV/c)?



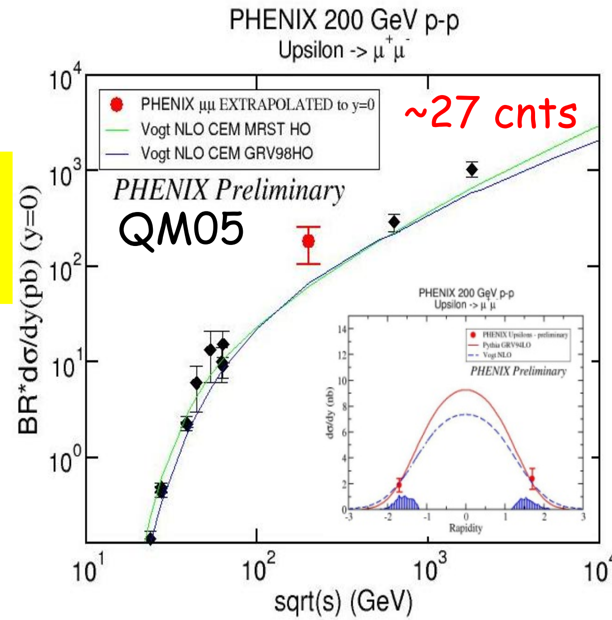
$\Delta\langle p_T^2\rangle$ for AuAu

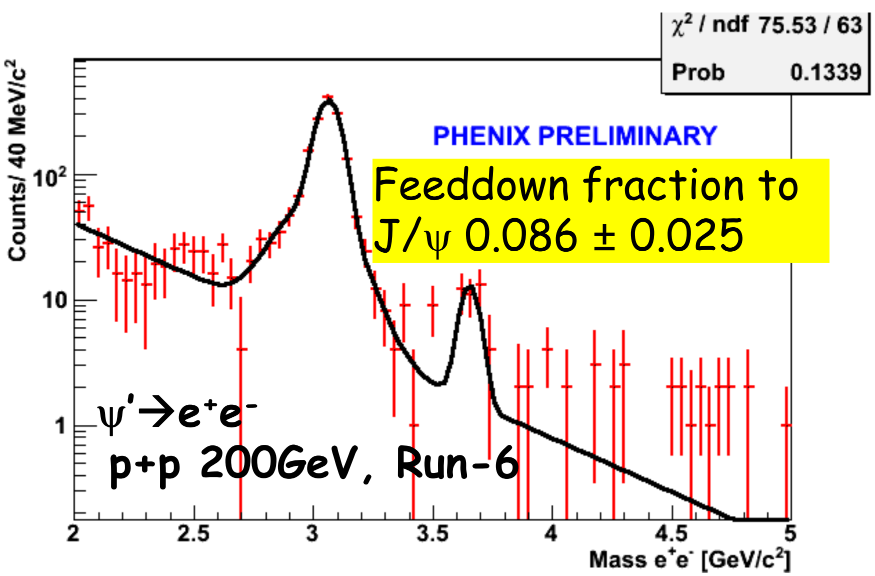


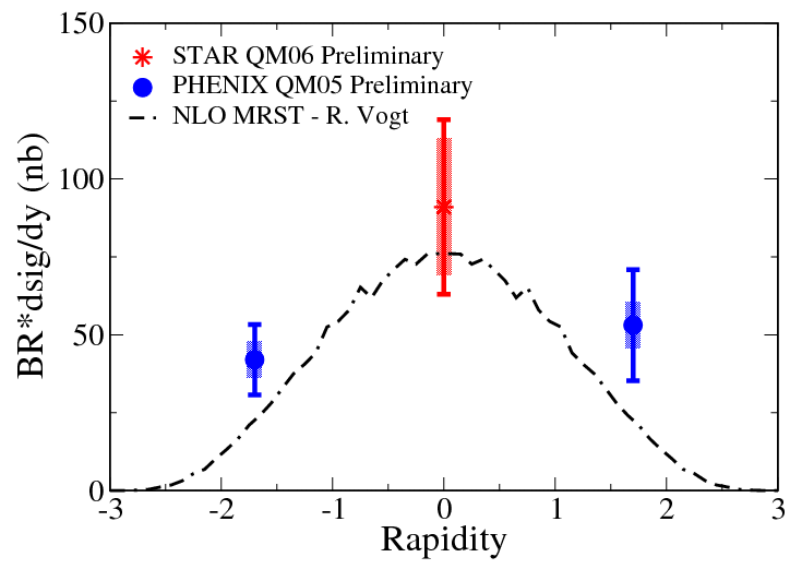
Other pieces of the J/ψ puzzle: the χ_c, ψ′, ϒ



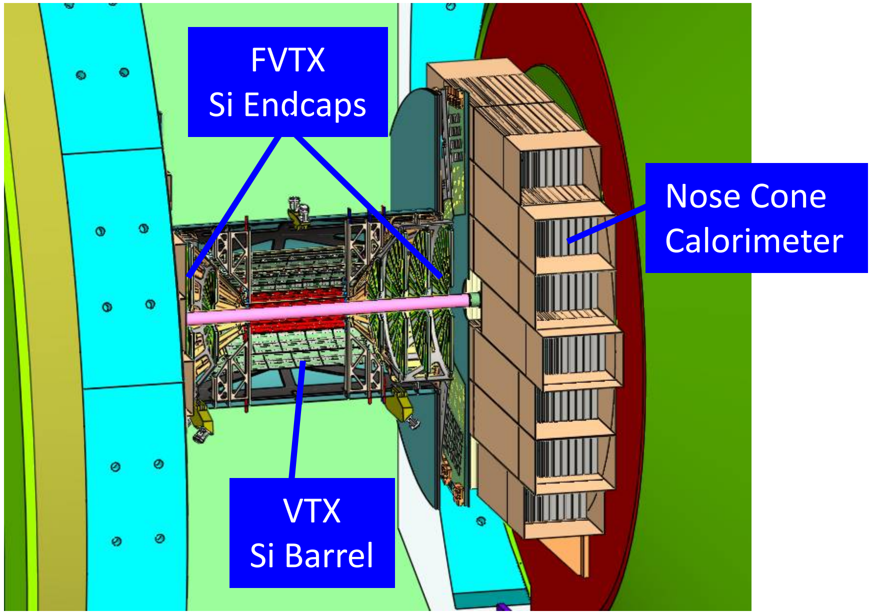
1st Upsilons at RHIC





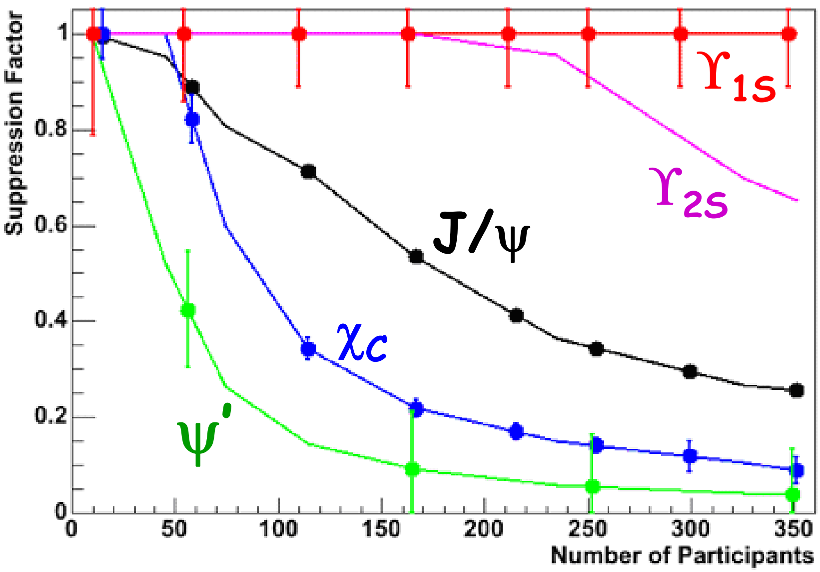


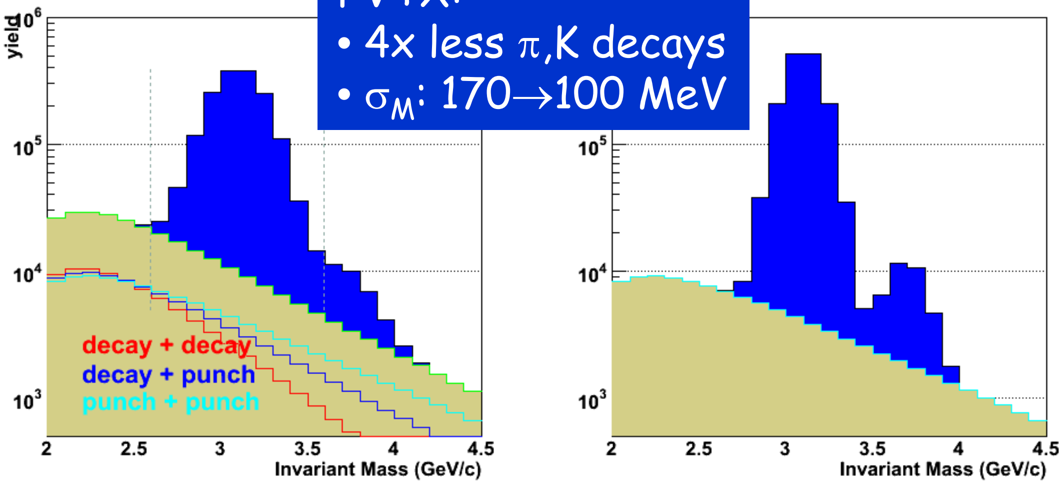
PHENIX Upgrades



Vertex detectors (VTX,FVTX) & forward calorimeter (NCC) will give:

- ψ' msmt with reduced combinatoric background + sharper mass resolution
- χ_C msmt with photon in NCC
- precise open-heavy measurements to constrain regeneration picture

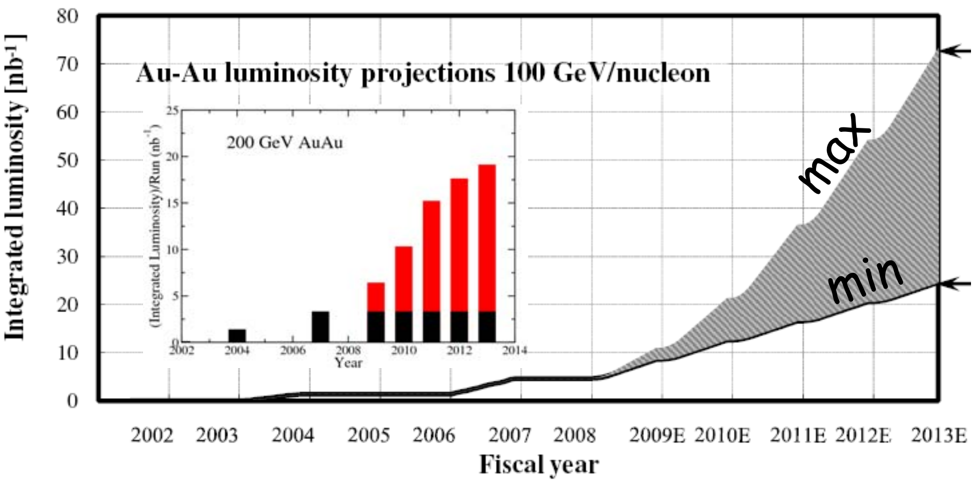


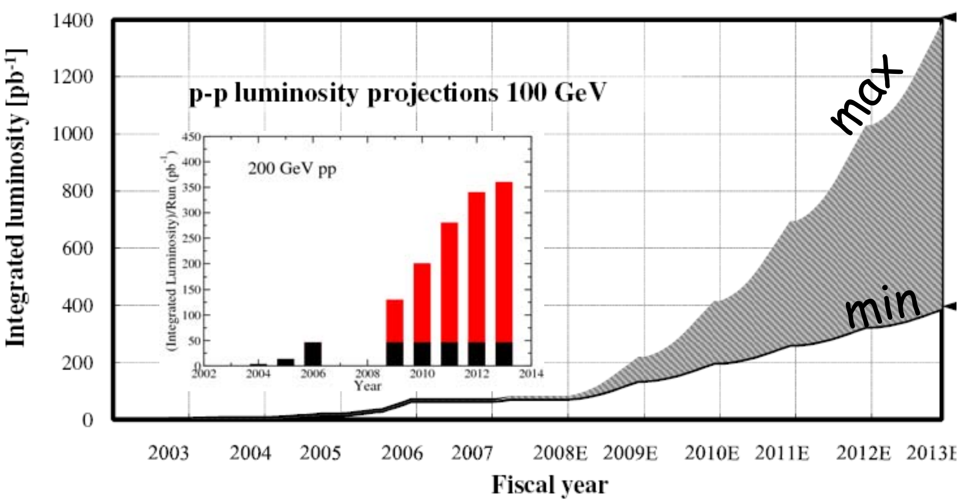


FVTX:

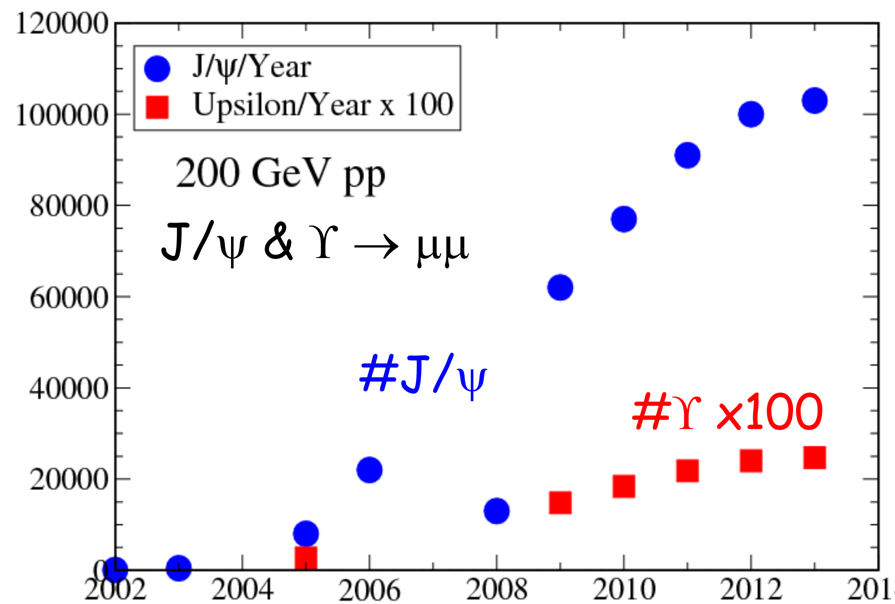
- 4x less π,K decays
- σ_M: 170→100 MeV

RHIC Luminosity Advances will Enable Access to Heavier Quarkonia

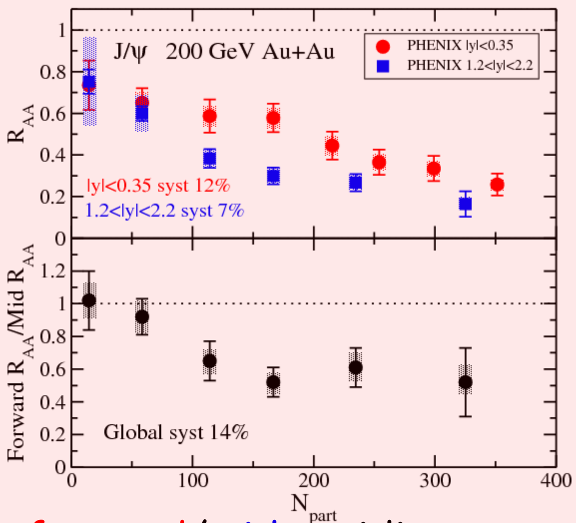




100,000 $J/\psi \rightarrow \mu\mu$ and ~250 $\Upsilon \rightarrow \mu\mu$ per year at highest RHIC luminosities

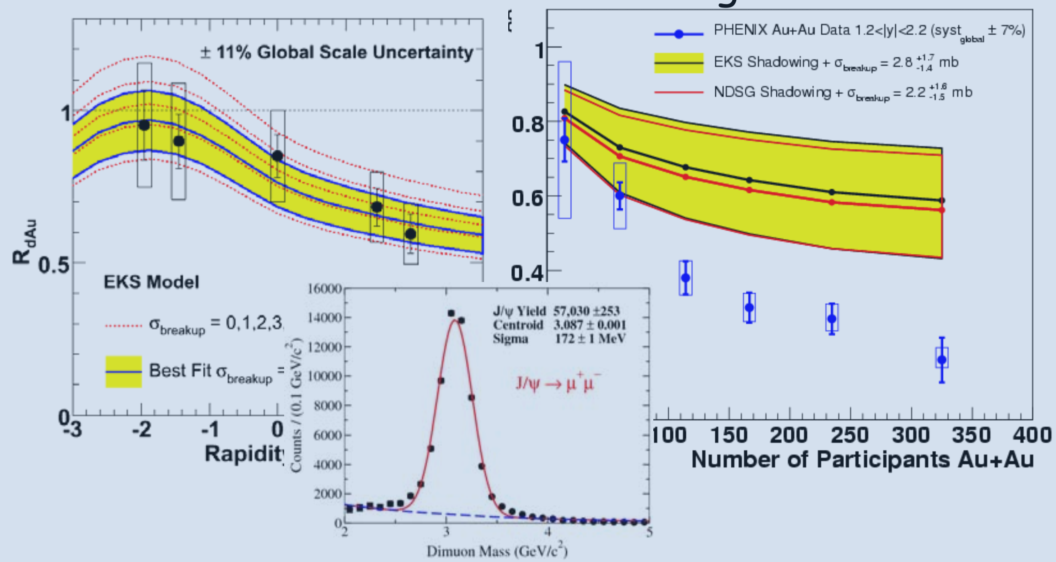


Progress Towards Understanding Quarkonia at PHENIX - Summary

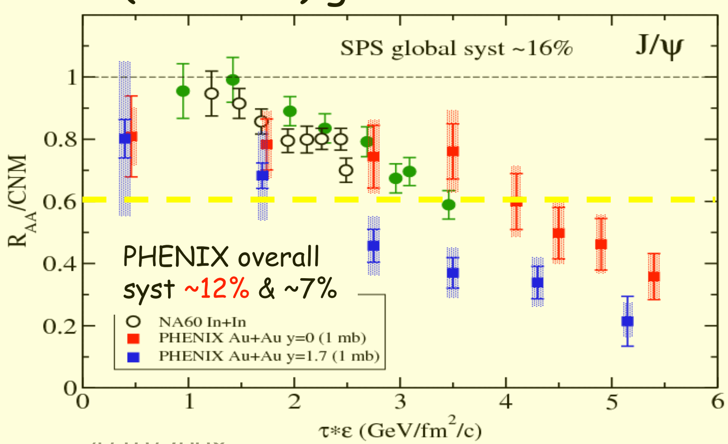


forward/mid rapidity super-ratio saturates @~0.6

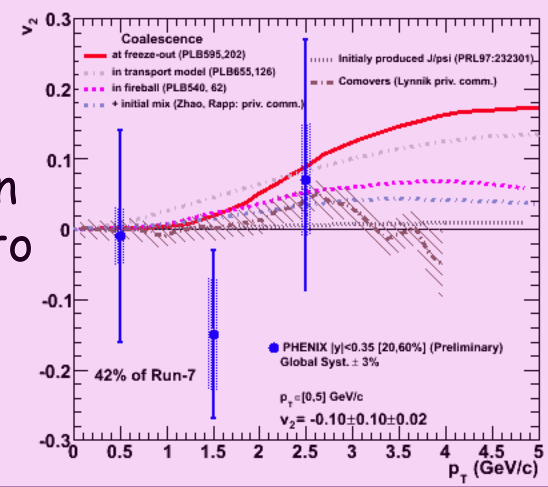
Better CNM baseline coming from Run8!



Sequential screening & (forward) gluon saturation?



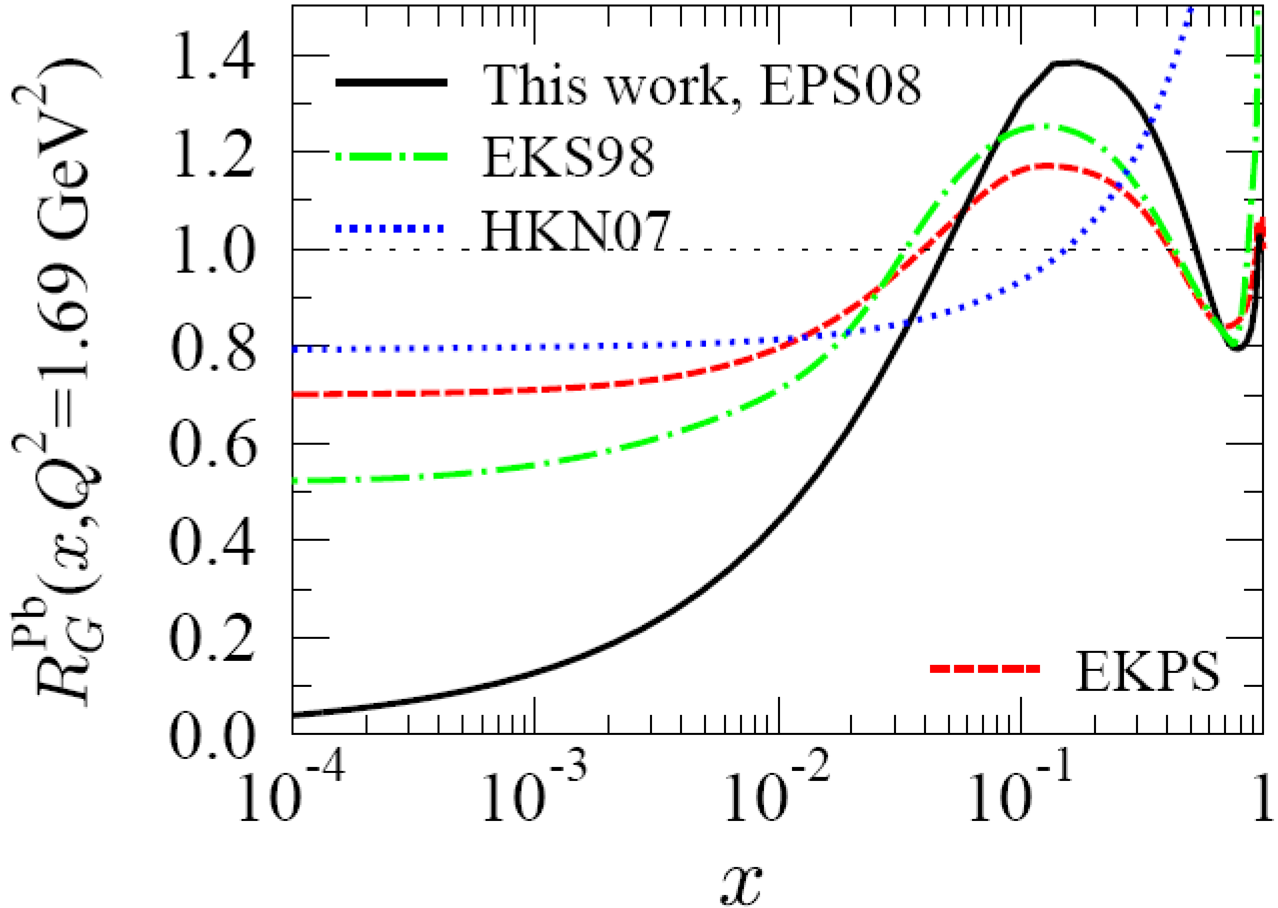
flow from regeneration is difficult to see



Backup Slide(s)

EPS08 (Strong) Shadowing

Eskola, Paukkunen, Salgado, hep-ph 0802.0139v1



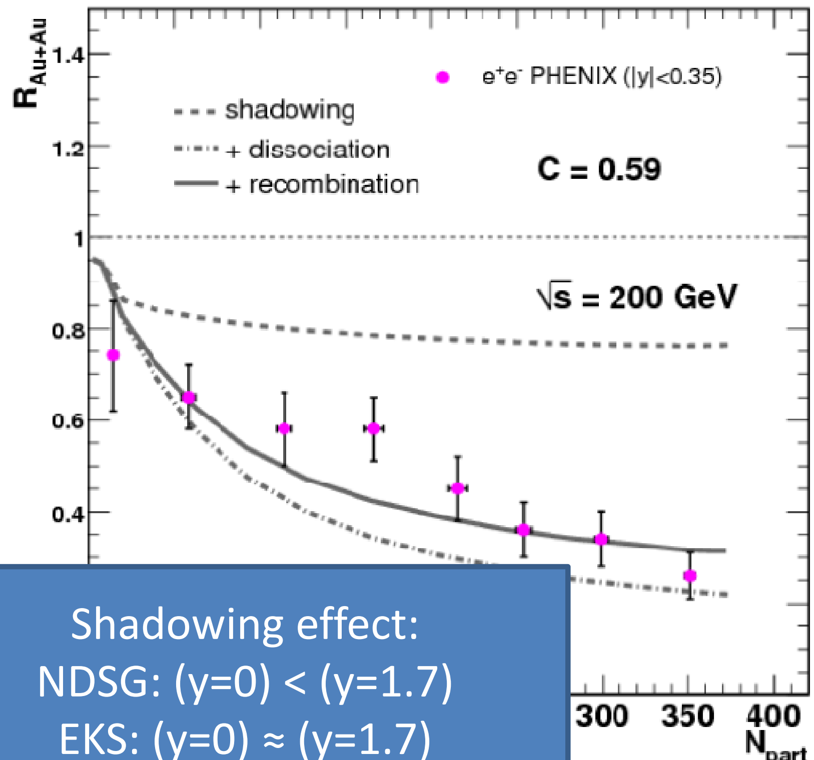
Fit includes RHIC (Brahms) forward hadron data (as well as the usual DIS and DY data)

Another shadowing scheme?

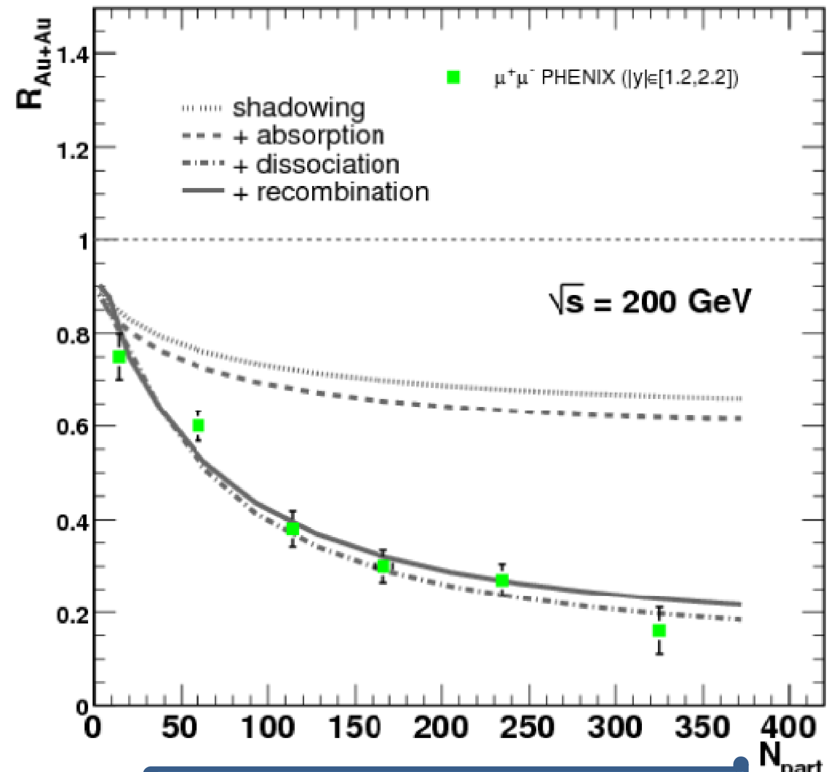
Shadowing from Schwimmer multiple scattering :

+ E-p conservation

+ regeneration



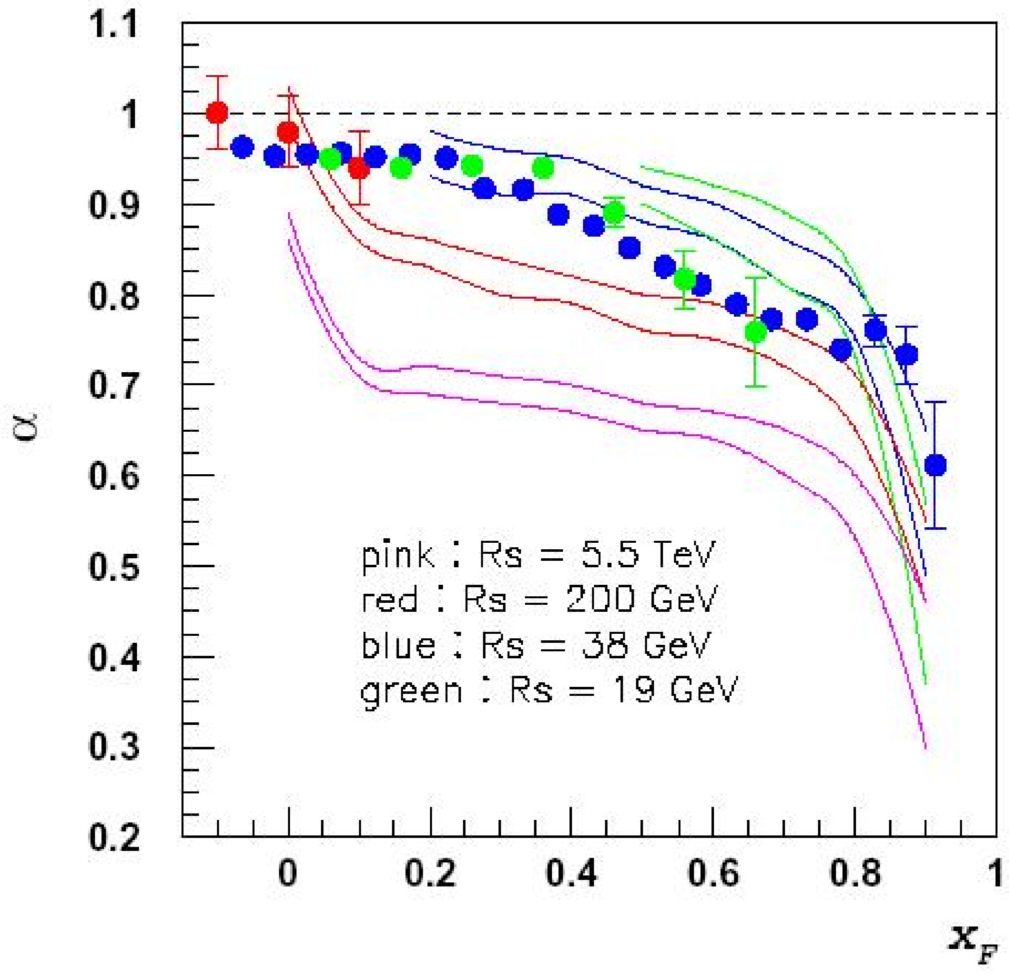
Shadowing effect:
NDSG: (y=0) < (y=1.7)
EKS: (y=0) ≈ (y=1.7)
Schwimmer: (y=0) > (y=1.7)



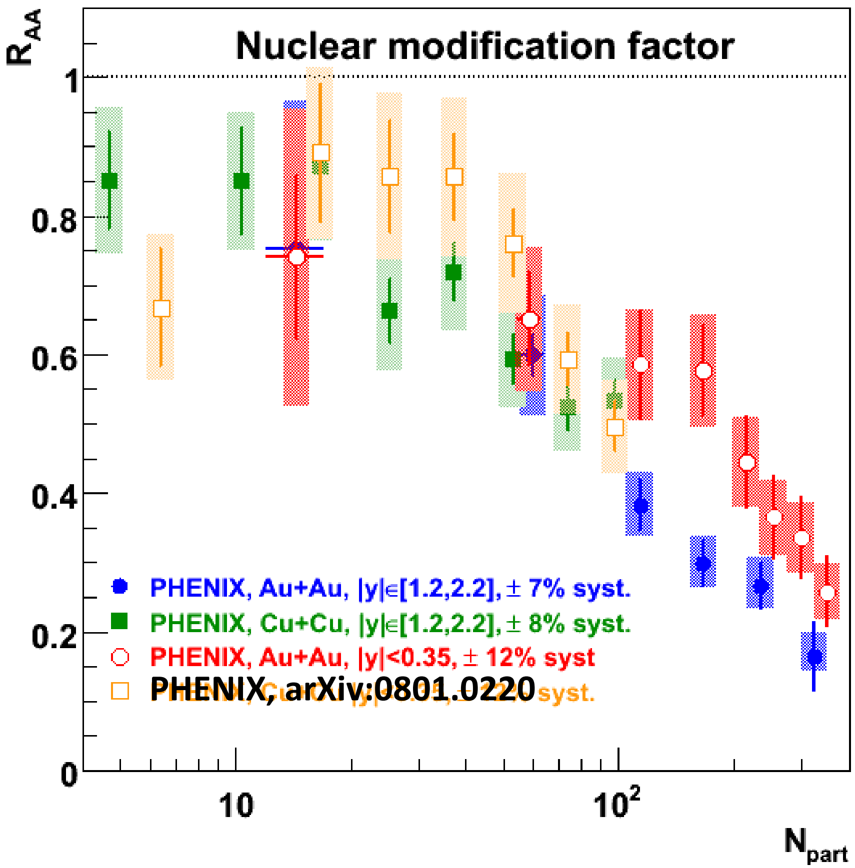
Capella et al, arXiv:0712.4331

Tuchin & Kharzeev…

Gluon saturation (CGC) can give x_F scaling of pA J/ψ suppression at various energies

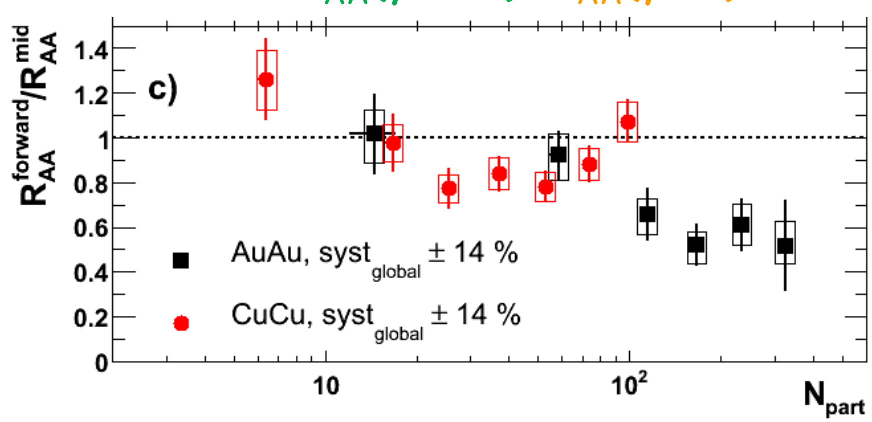


R_{AuAu} vs R_{CuCu}



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

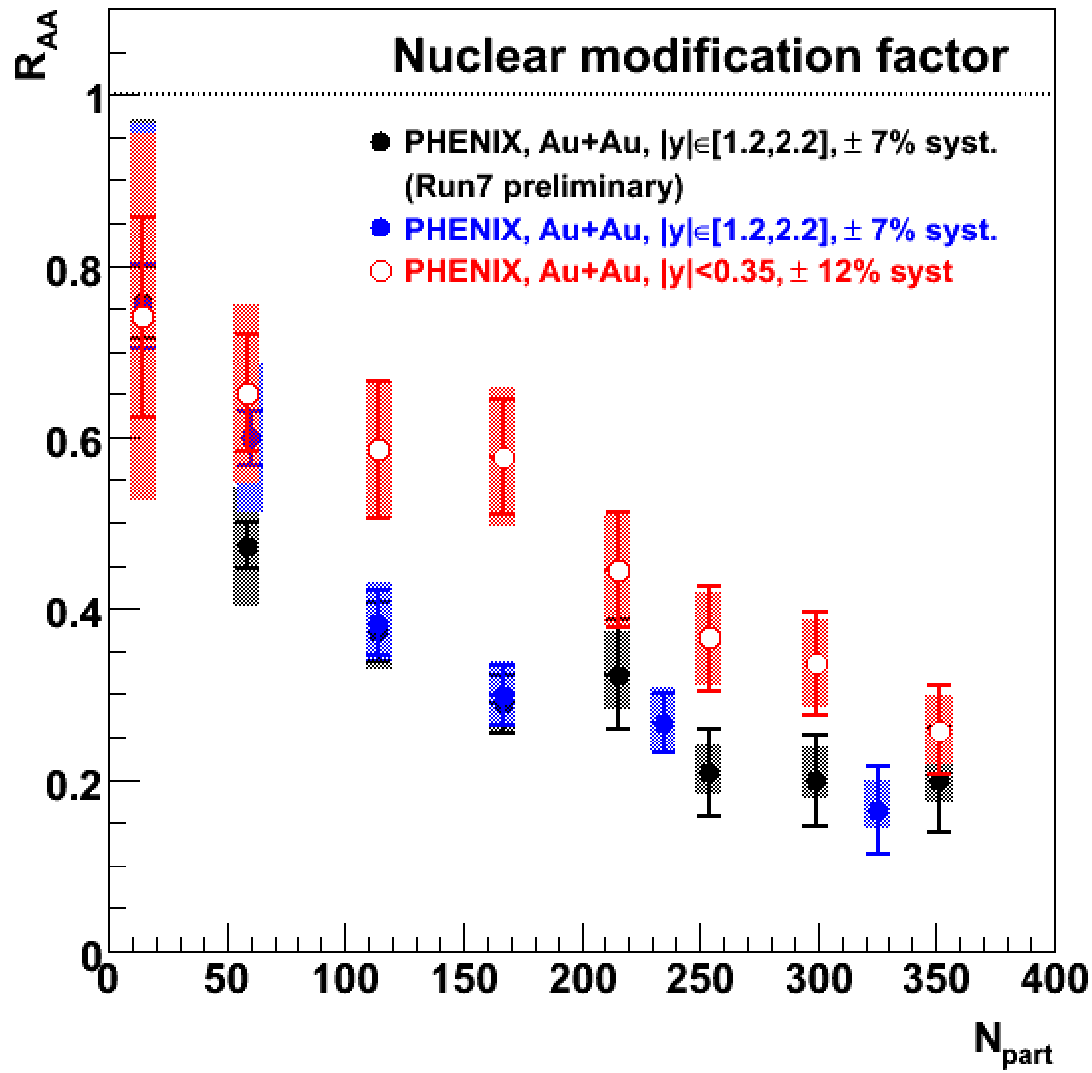
$R_{AA}(y\sim1.7)/R_{AA}(y\sim0)$



New results from Run7 AuAu data

Preliminary analysis of new Run7 AuAu

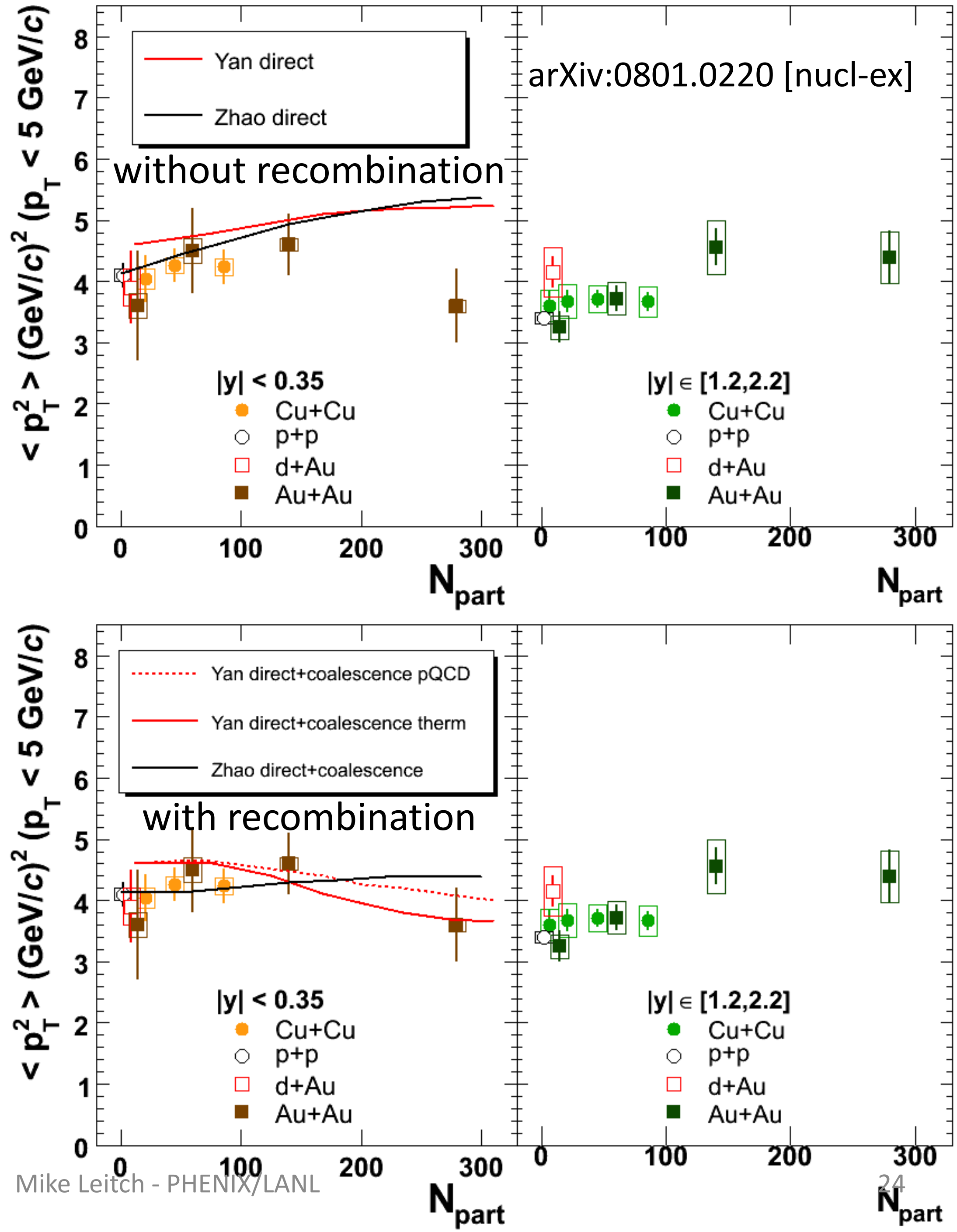
forward rapidity (dimuon) J/ψ data (black points) is consistent with published results (blue points) from Run4



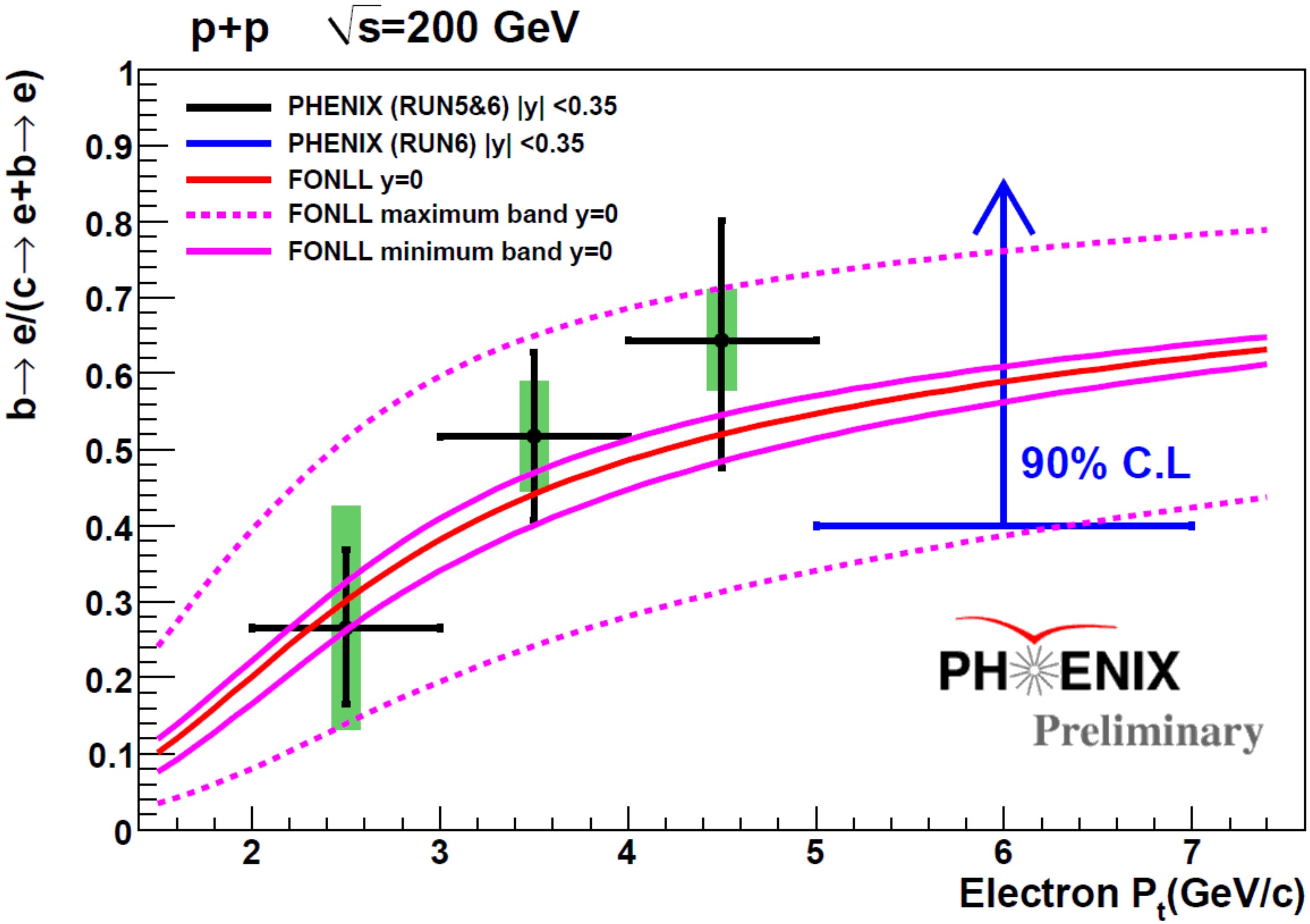
$\langle p_T^2 \rangle$ vs N_{part}

- Recombination of charm quarks could cancel the Cronin and leakage effects.
- Need more statistics to draw a conclusion.

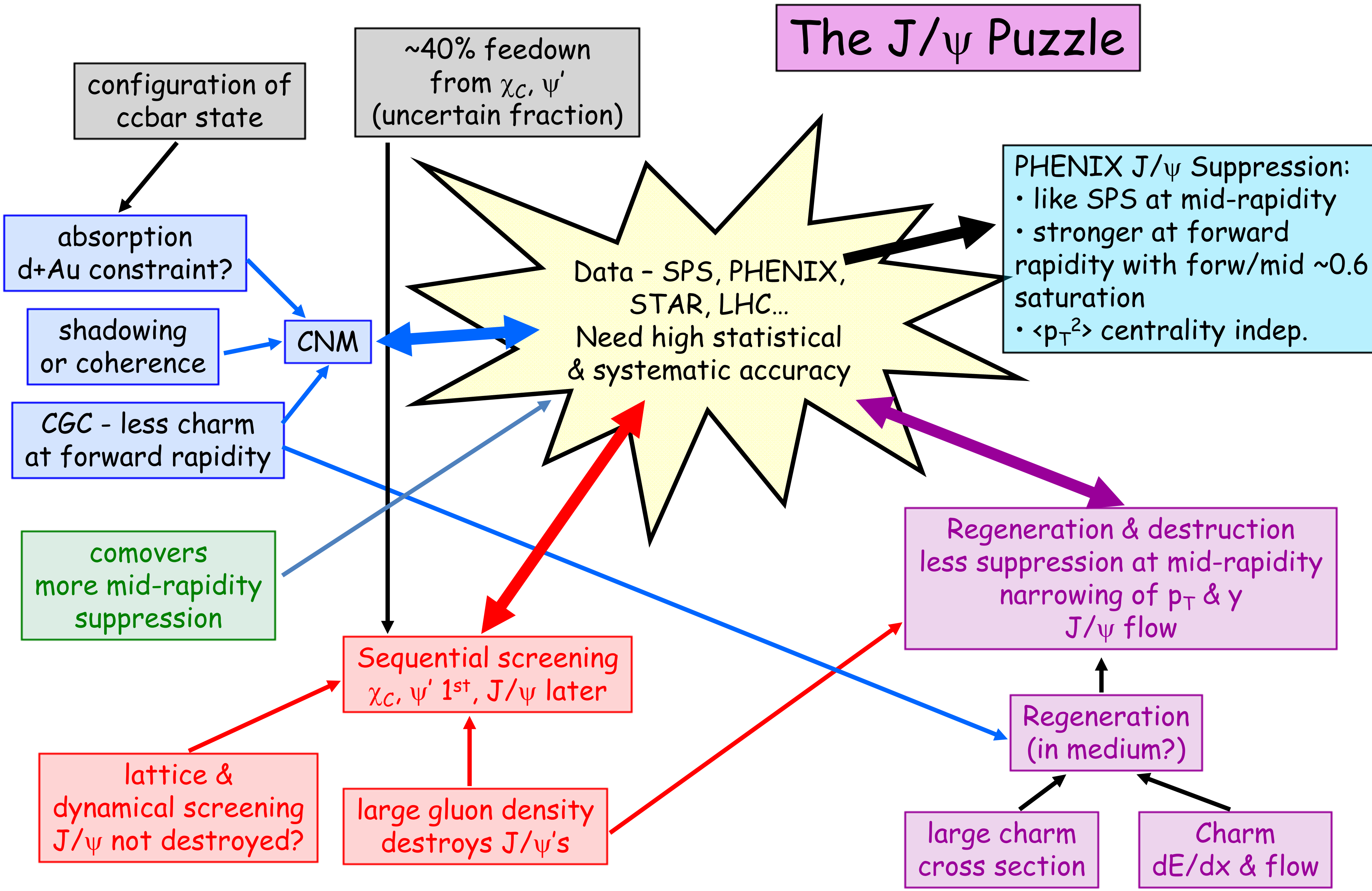
- L. Yan, P. Zhuang and N. Xu, Phys. Rev. Lett. 97, 232301 (2006)
- X. Zhao and R. Rapp, arXiv:0812.2407 [hep-ph]



bottom fraction in non-photonic electron



- The result is consistent with FONLL


The J/ψ Puzzle
configuration of ccbar state
~40% feedown from χC, ψ′ (uncertain fraction)
absorption d+Au constraint?
shadowing or coherence
CNM
CGC - less charm at forward rapidity
comovers more mid-rapidity suppression
Data – SPS, PHENIX, STAR, LHC… Need high statistical & systematic accuracy
PHENIX J/ψ Suppression:
• like SPS at mid-rapidity
• stronger at forward rapidity with forw/mid ~0.6 saturation
• <pT2> centrality indep.
Regeneration & destruction
less suppression at mid-rapidity
narrowing of pT & y
J/ψ flow
Sequential screening
χC, ψ′ 1st, J/ψ later
Regeneration (in medium?)
lattice & dynamical screening J/ψ not destroyed?
large gluon density destroys J/ψ's
large charm cross section
Charm dE/dx & flow