# Quarkonia Measurements in PHENIX

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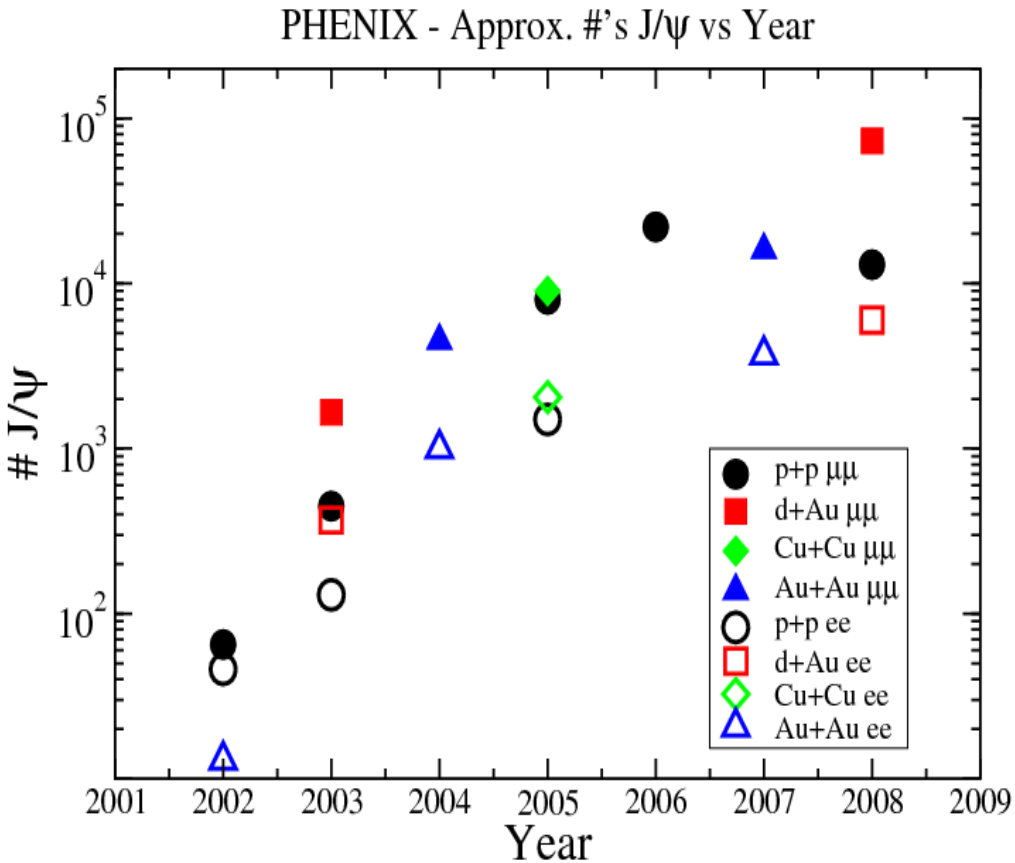
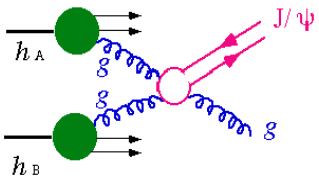
*RBRC – 24 April 2008*

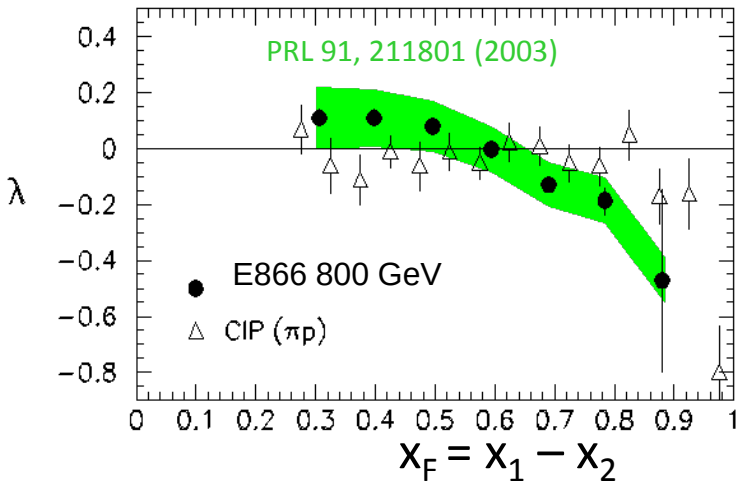
- How are quarkonia produced?
- What CNM effects are important?
- How does the sQGP effect quarkonia?
- What are the CNM effects in AA collisions?
- Transverse Momentum Broadening
- Heavier Quarkonia
- Detector Upgrades & Luminosity for the future



# 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 ($\psi'$, $\chi_c$ )




**Polarization**

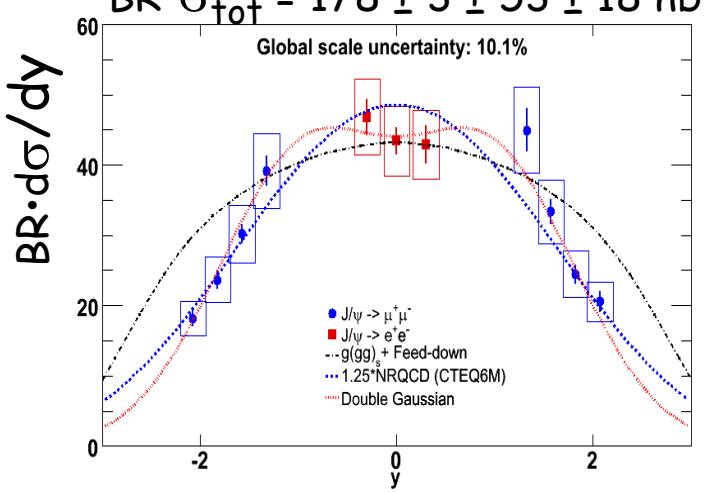
NRQCD models predict large transverse polarization ($\lambda$>0) at large $p_T$

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

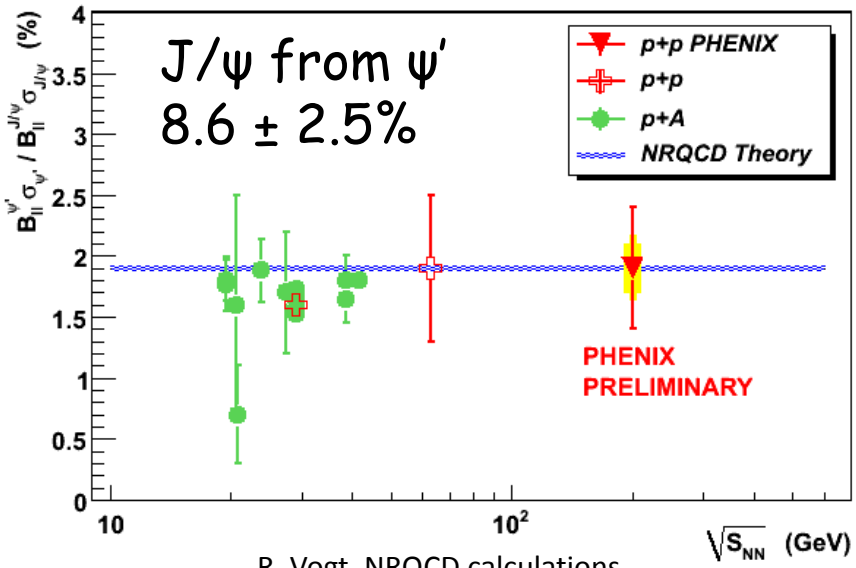
**Cross Sections**

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

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

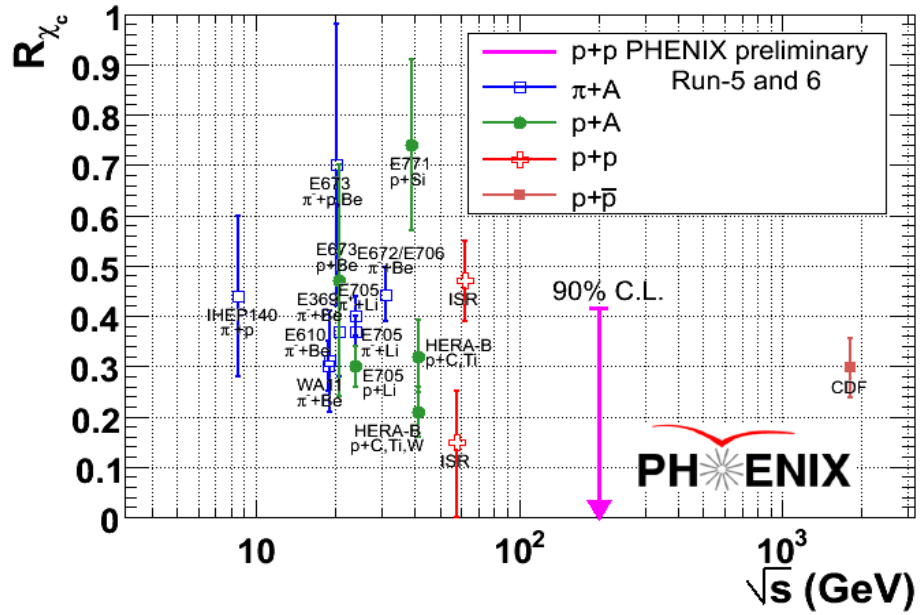


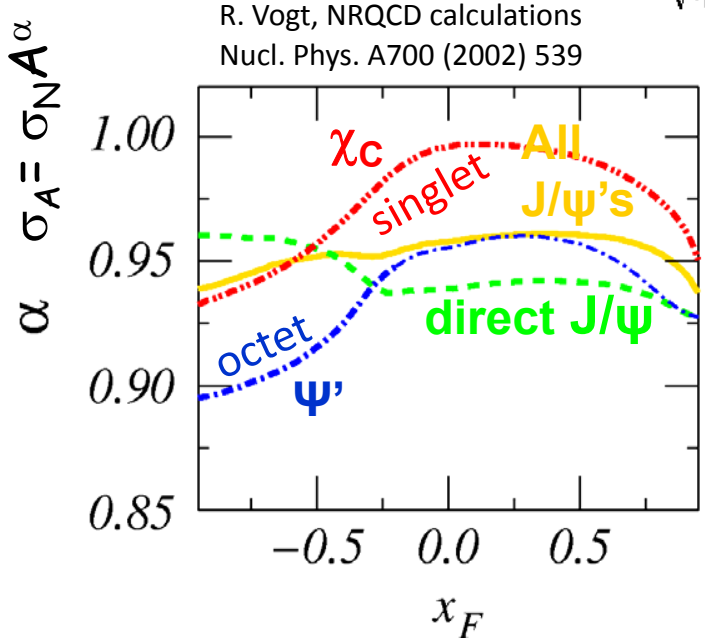
# How are Quarkonia Produced?
# Feeddown to J/ψ




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

J/ψ from $\chi_c$ < 42% (90% CL)



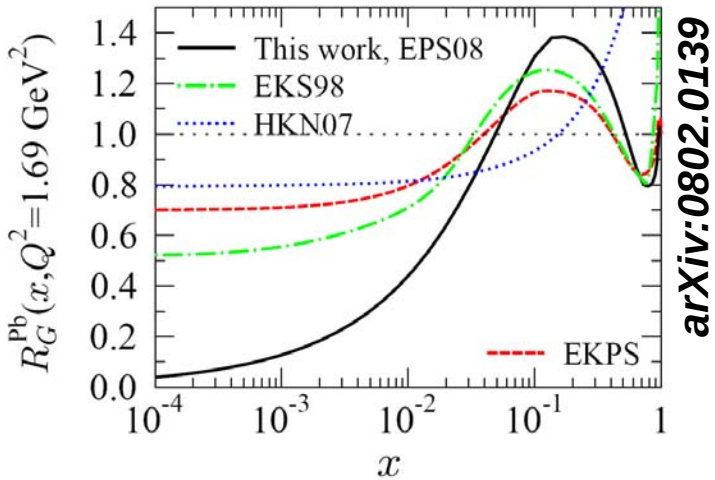



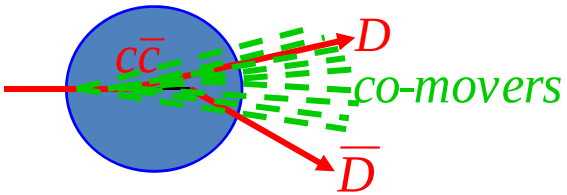

Nuclear dependence of (parent) resonance, e.g. $\chi_c$ is probably different than that of the J/ψ

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

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

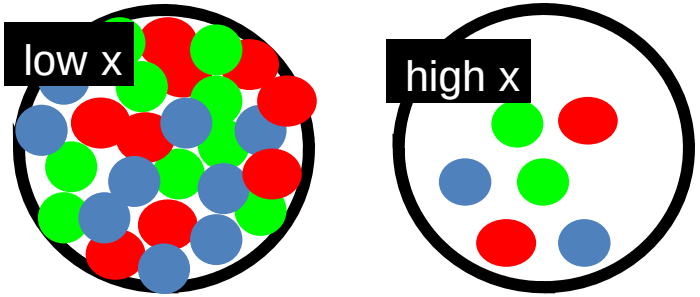
Traditional shadowing from fits to DIS or from coherence models



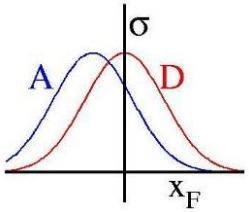



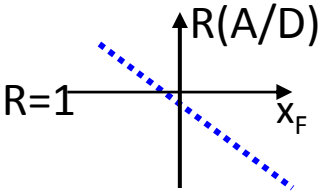

Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

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 $x_F$



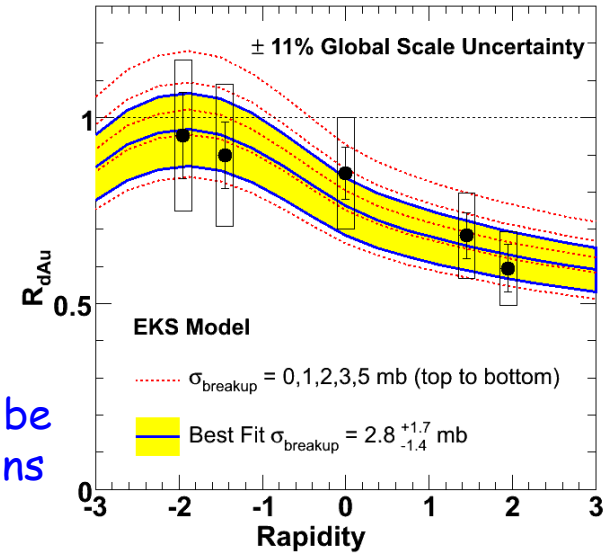
# Nuclear Dependence Nomenclature – Ratio ($R_{dAu}$, $R_{AA}$) and Alpha ($\alpha$)

$R_{dAu} = \alpha = 1$ 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

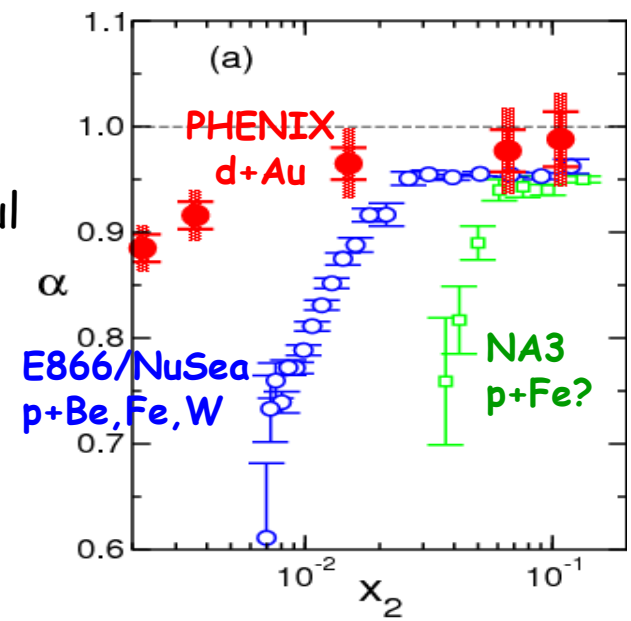



Where $dN^{dAu}/dy$ is an invariant yield w/o absolute normalization factors that would be needed for a cross section (lower systematical uncertainties)

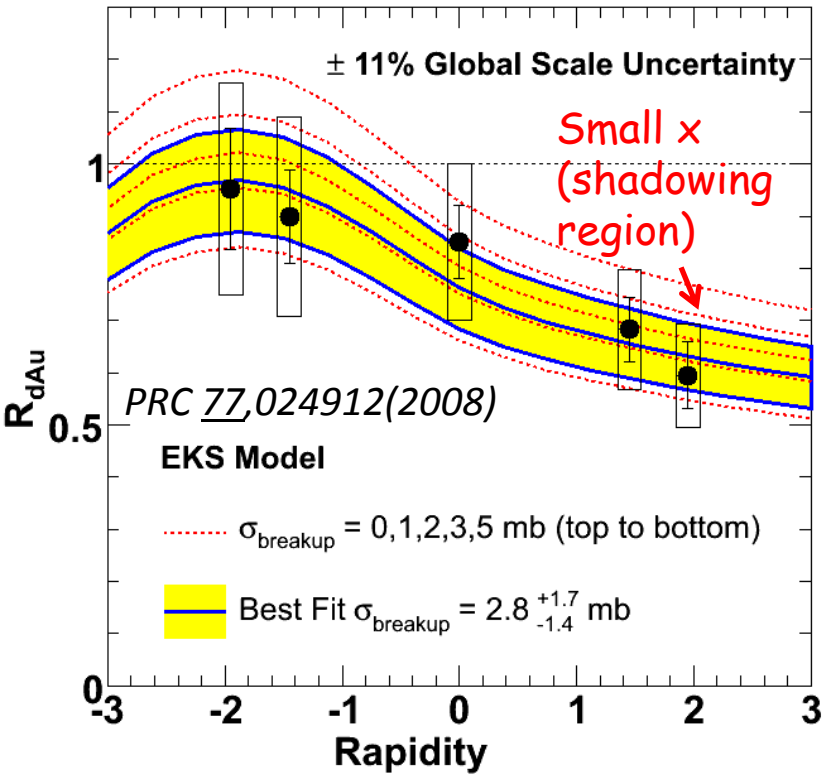
Alternatively, a power law with $\alpha$ – especially useful when comparing expts that used different nuclear targets

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

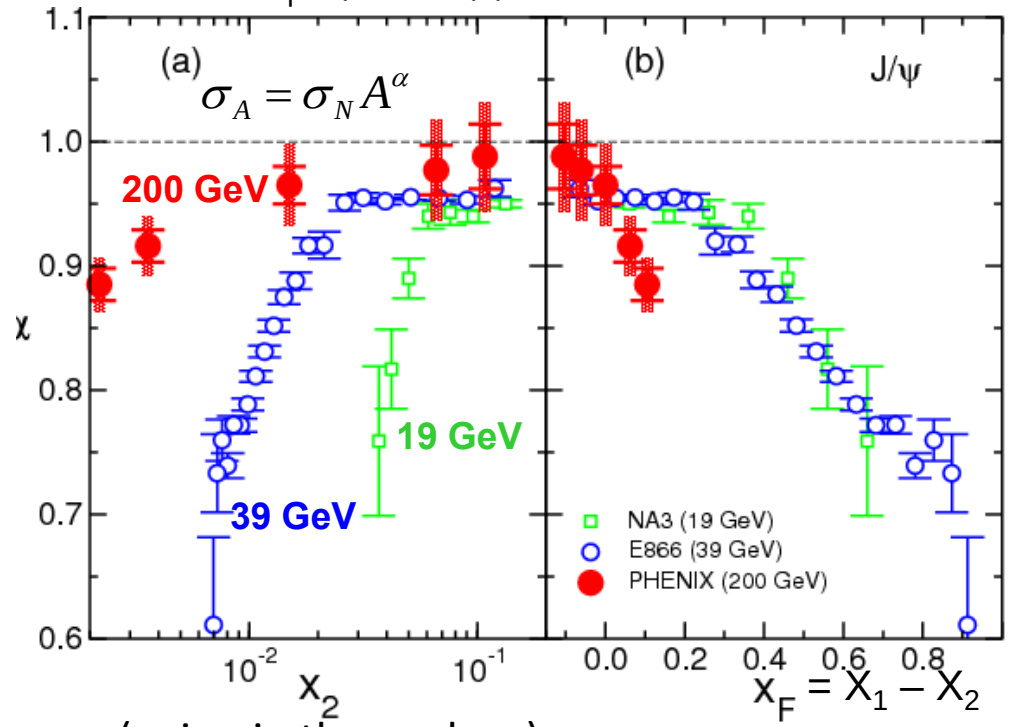
$$\alpha = 1 + \ln(R_{pA})/\ln(A)$$



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




J/ψ for different √s collisions




($x_2$ is x in the nucleus)

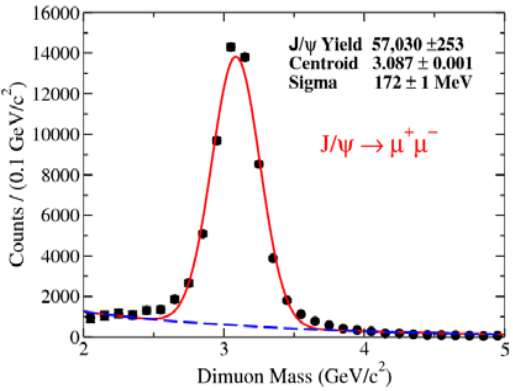
New Analysis of Run3 data consistent with EKS shadowing & absorption - clear need for new dAu data

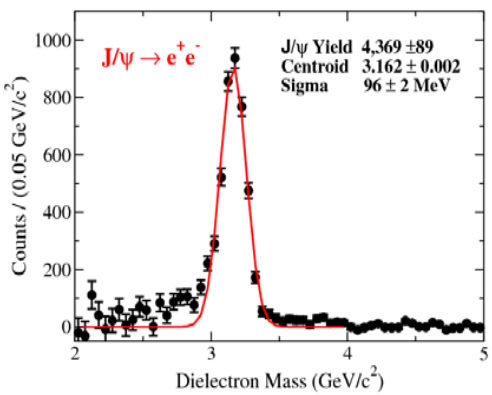
Not universal vs $x_2$ as expected for shadowing, but closer to scaling with $x_F$, why?

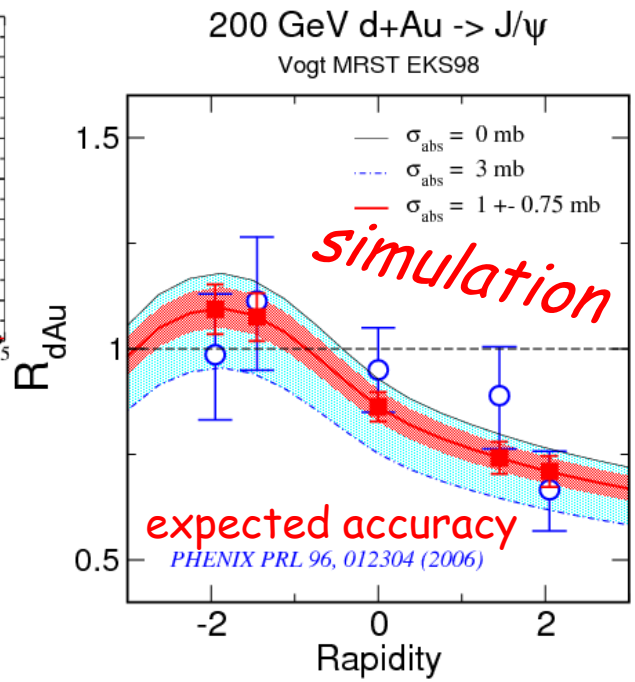
- initial-state gluon energy loss?
- gluon saturation?
- Sudakov suppression (energy conservation)?

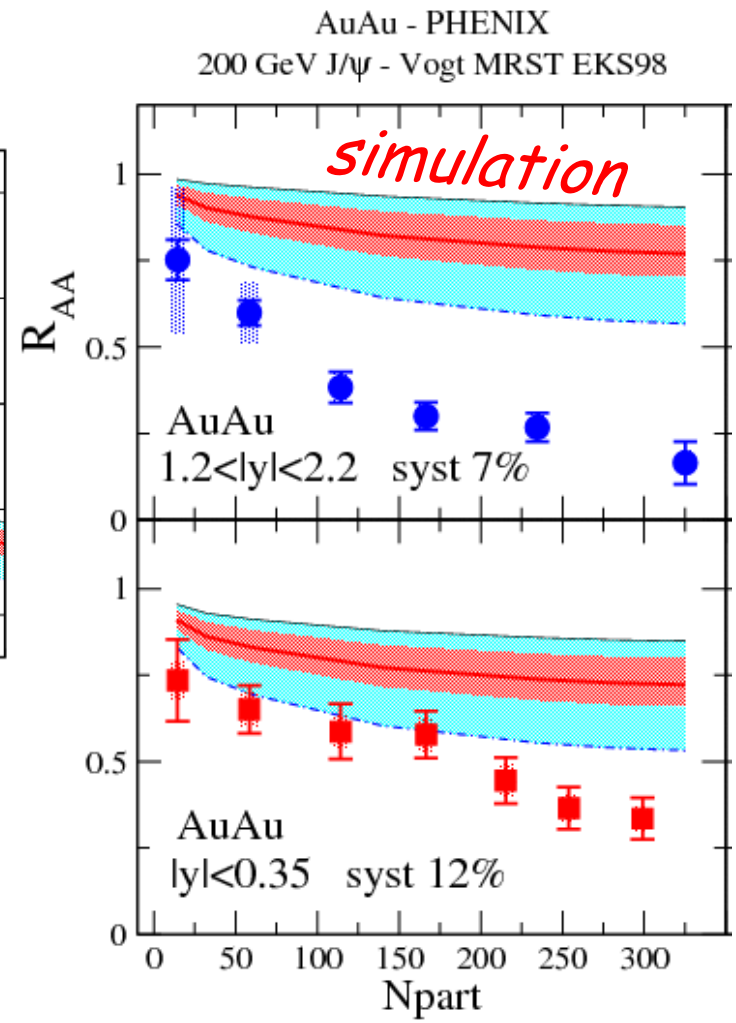
# CNM constraints from new Run8 dAu J/ψ data

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



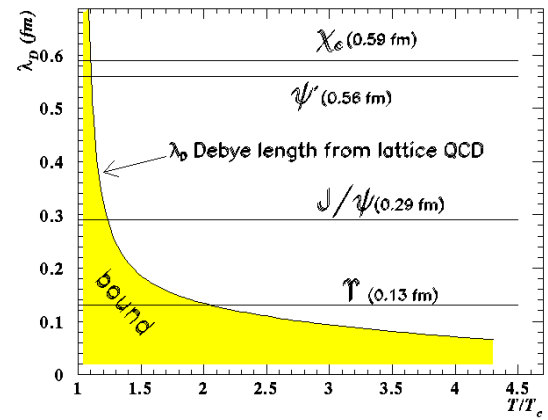



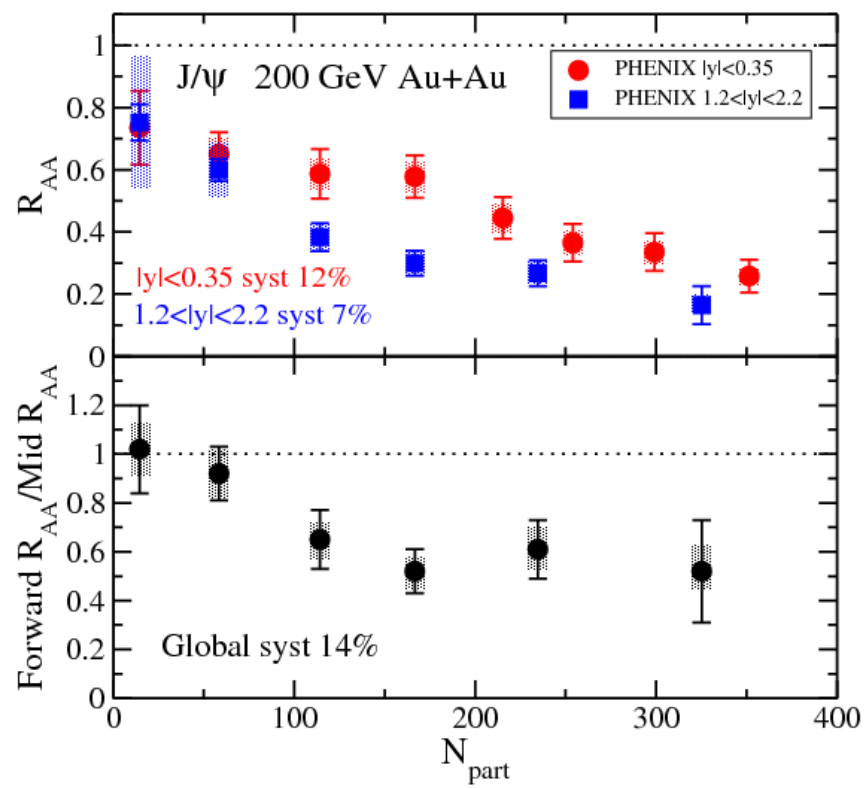
# How does the QGP affect Quarkonia?

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

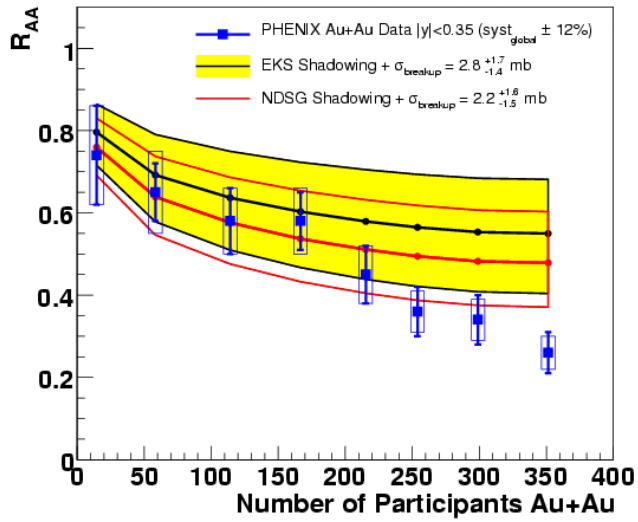


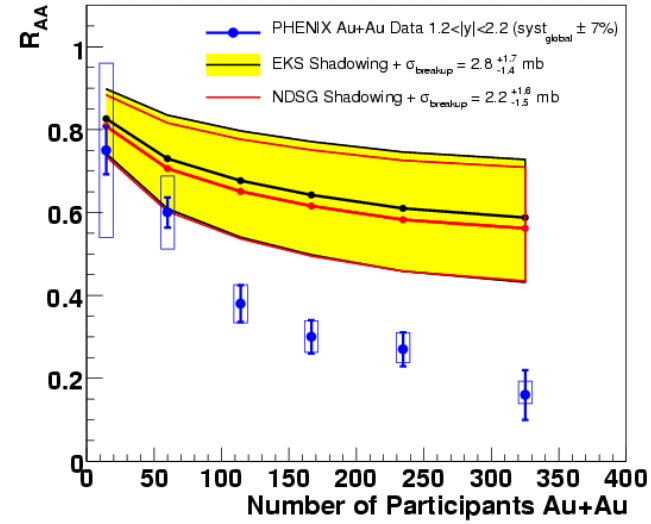

Several scenarios can be considered:

- Cold nuclear matter (CNM) effects
  - in any case are always present
- Sequential suppression
  - screening only of $\chi_c$ & 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

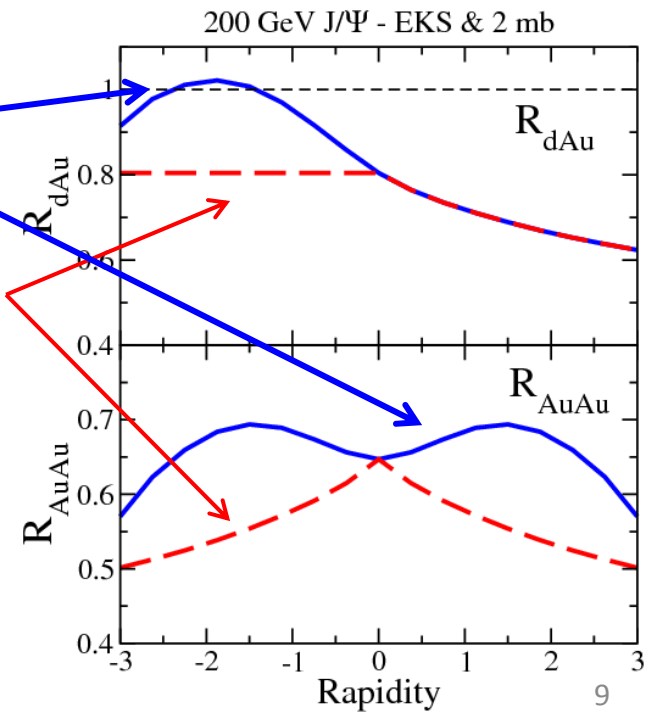
CNM effects (EKS shadowing + dissociation) give large fraction of observed AuAu suppression, especially at mid-rapidity




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

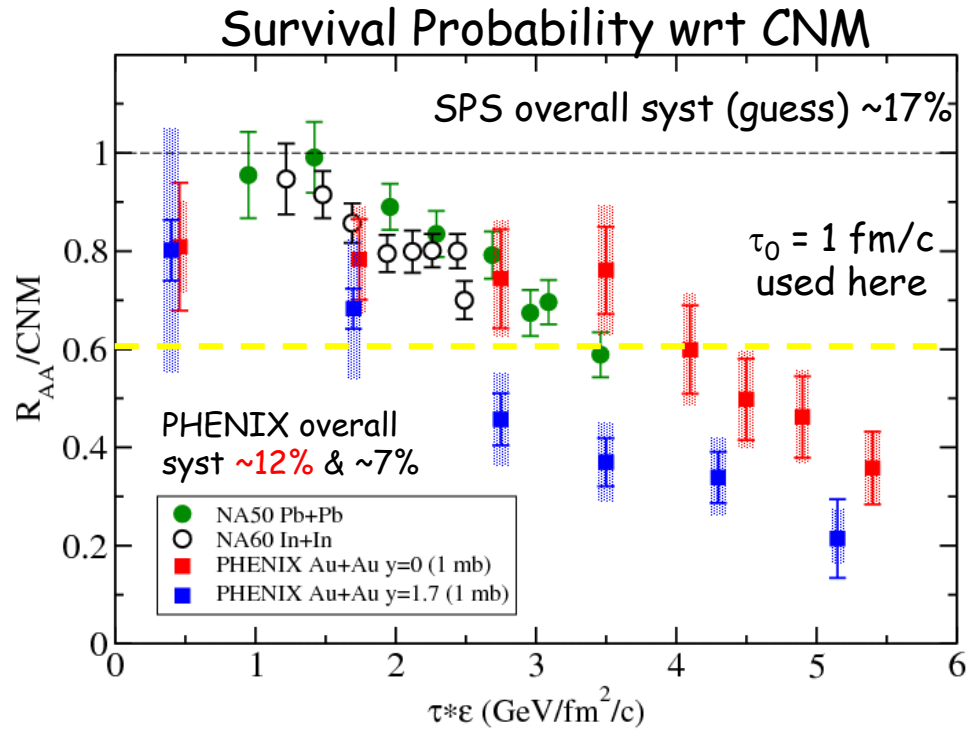



*In any case more accurate dAu data is sorely needed*

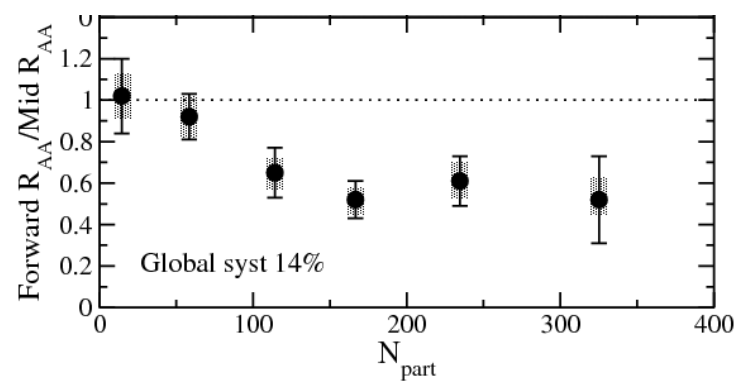
# How does the QGP affect Quarkonia?
# Sequential Screening and Gluon Saturation

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

- suppression then comes only via feed-down from screened $\chi_C$ & $\psi'$
- 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)

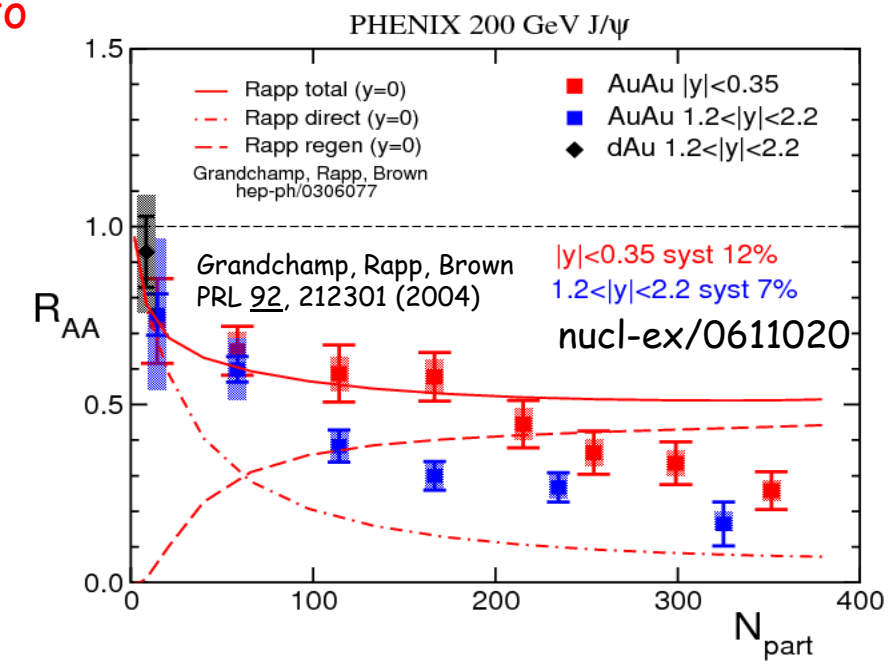



- *Is suppression stronger than can come from $\chi_C$ & $\psi'$ alone?*
- *Can this picture explain saturation of the forward/mid-rapidity RAA super-ratio?*

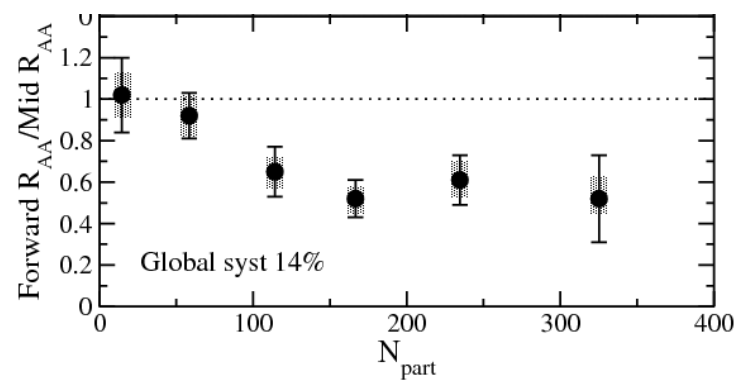


# How does the QGP affect Quarkonia?
# Regeneration – compensating for screening

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

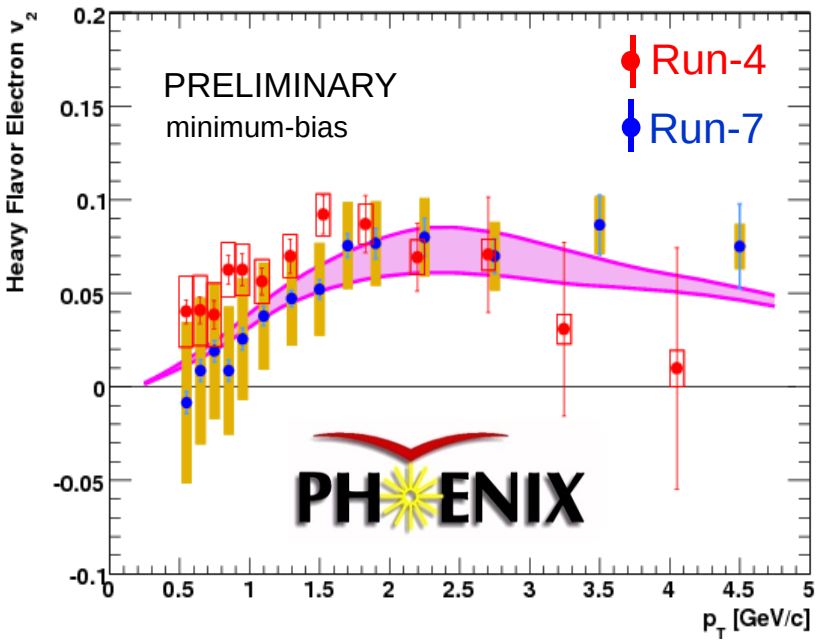


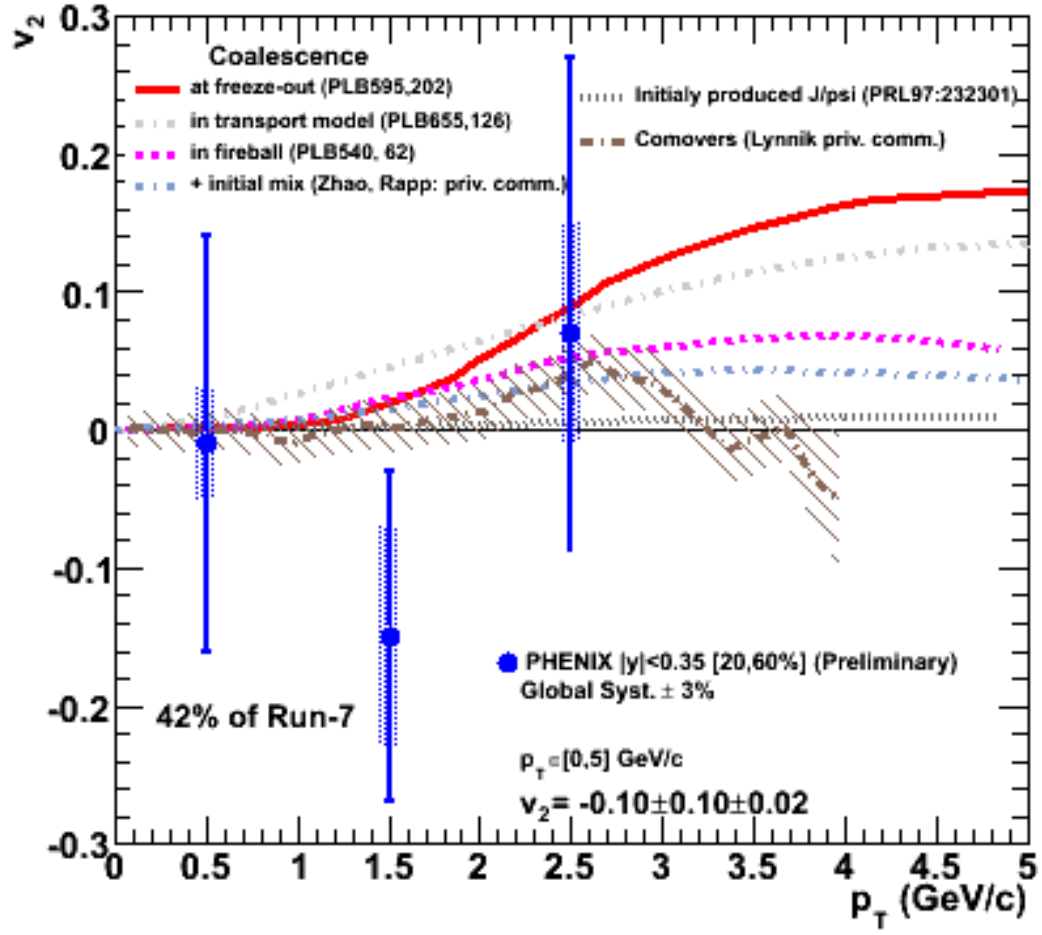

- *need to know what happens to $\chi_c$ & $\psi'$ & measure J/ψ flow?*
- *flat forward/mid-rapidity RAA super-ratio consistent with centrality trends of the two components (screening & regeneration)?*



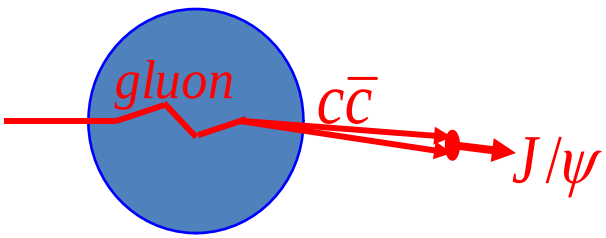
# How does the QGP affect Quarkonia? J/ψ flow

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



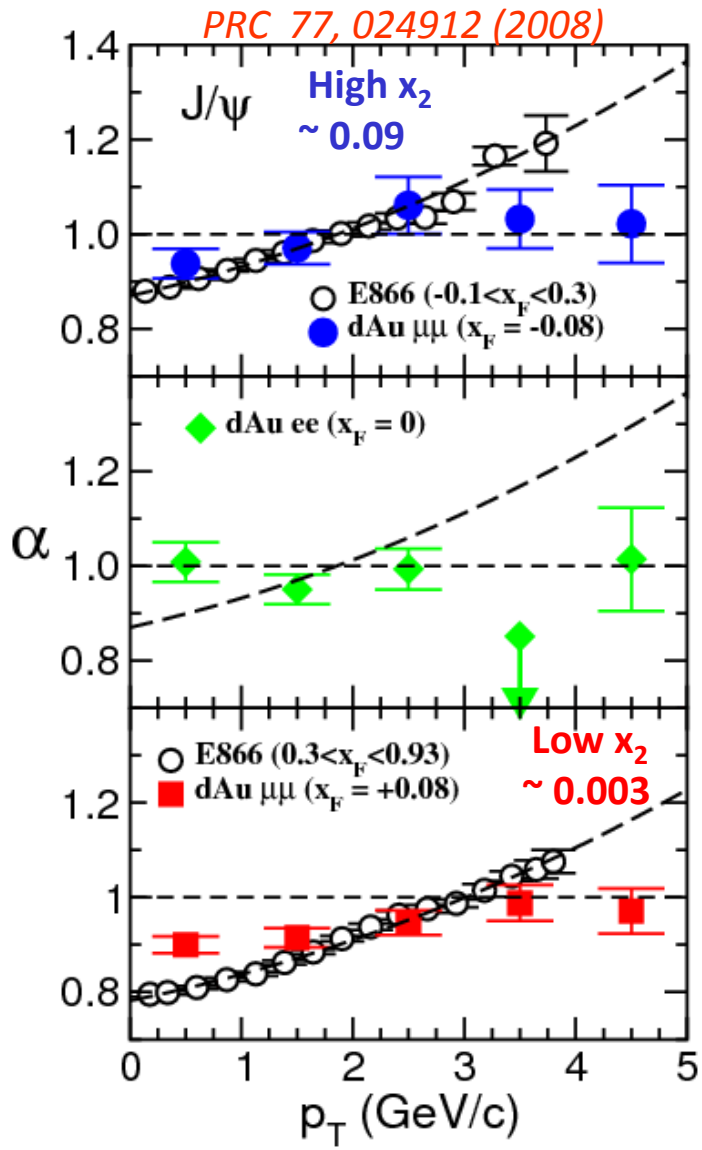
# Transverse Momentum Broadening
# Another Cold Nuclear Matter Effect




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

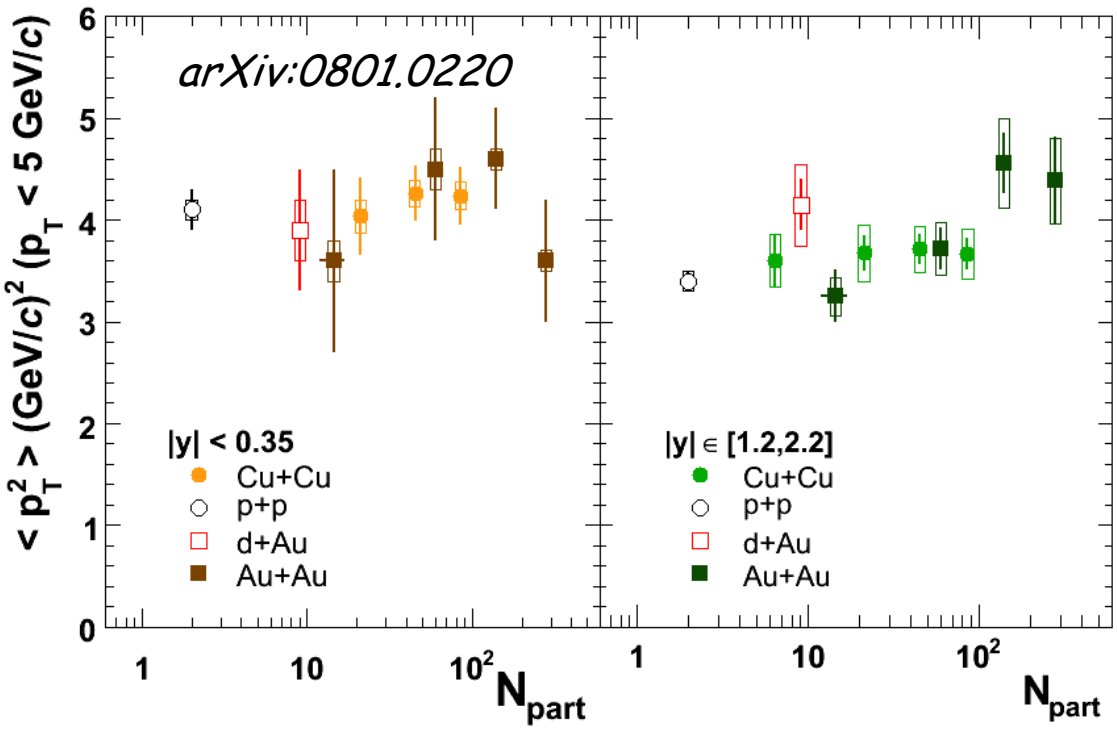
$$\sigma_A = \sigma_N A^{\alpha}$$

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

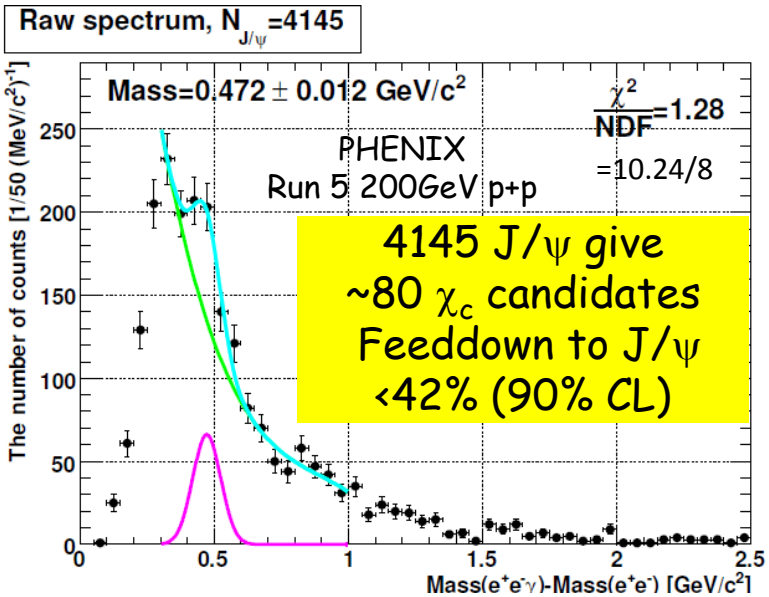


# Transverse Momentum Broadening in AA Collisions

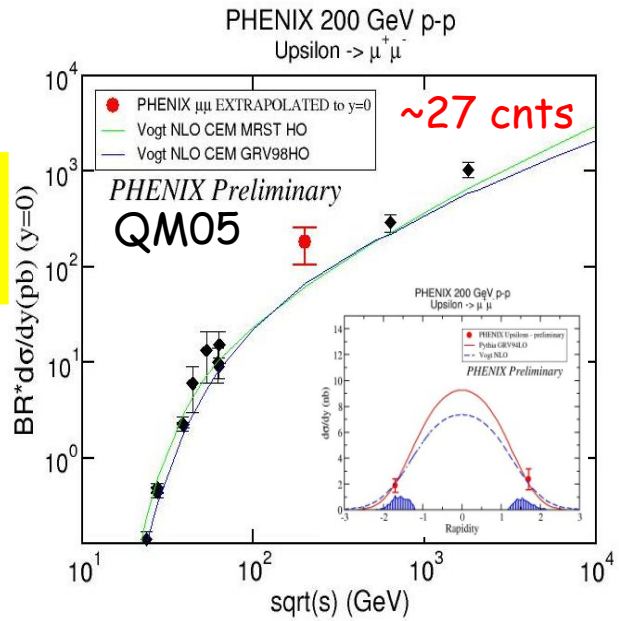
- Relatively flat with centrality - slight increase at forward rapidity
- CNM effects should broaden $p_T$
  - initial-state mult. scatt. for both gluons
- Regeneration should narrow $p_T$
  - square of small-$p_T$ peaked open-charm cross section
- Other effects in the presence of a QGP?
  - early escape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

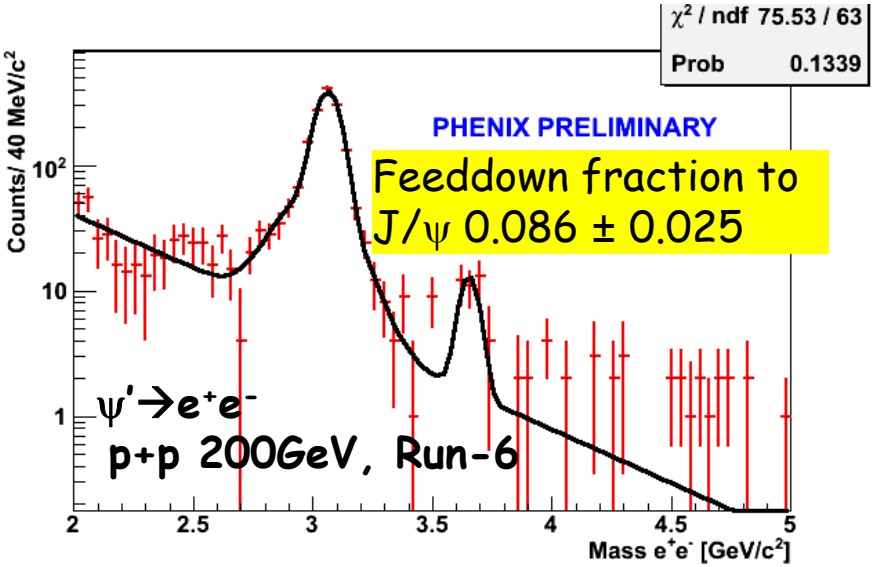


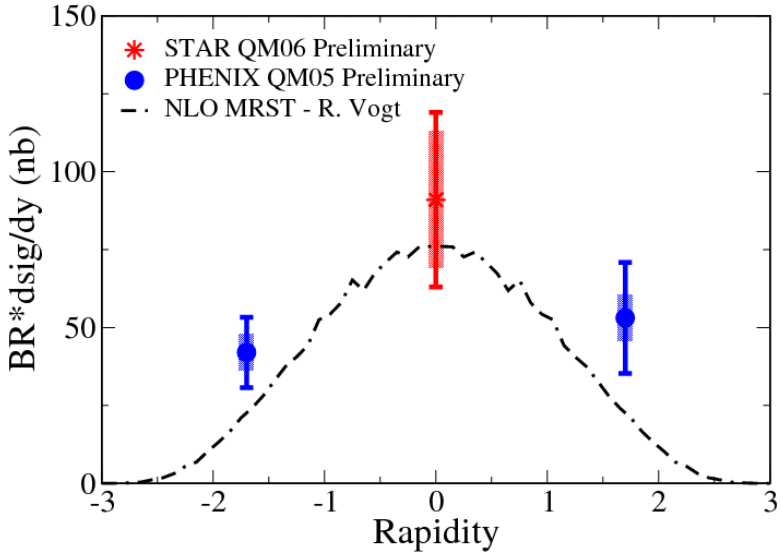
# Other pieces of the J/ψ puzzle: the $\chi_c$, ψ′, ϒ



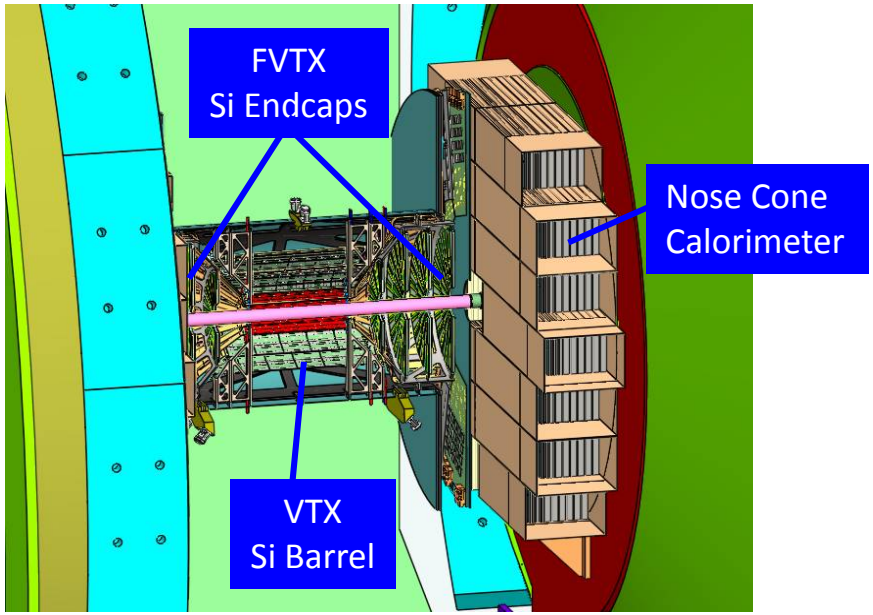

1st Upsilons at RHIC



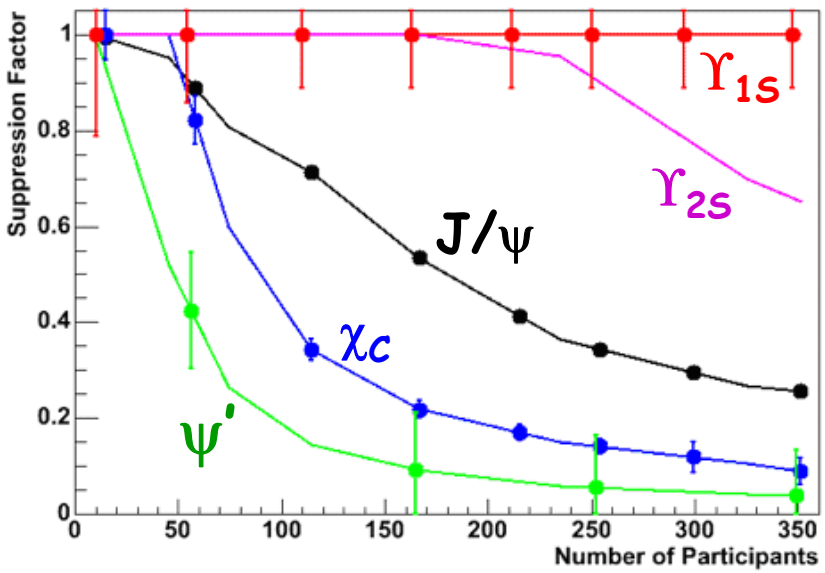



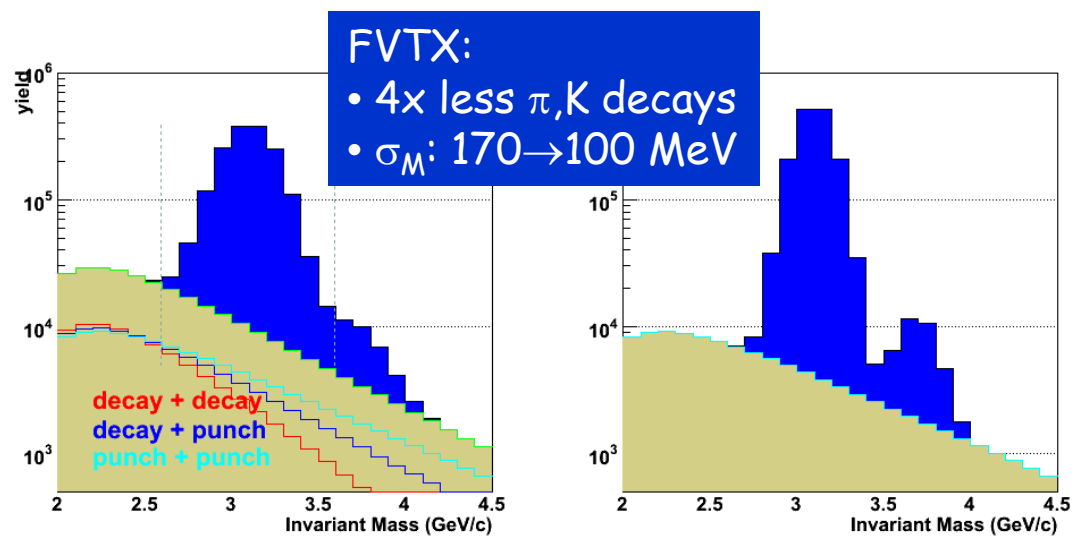
# PHENIX Upgrades



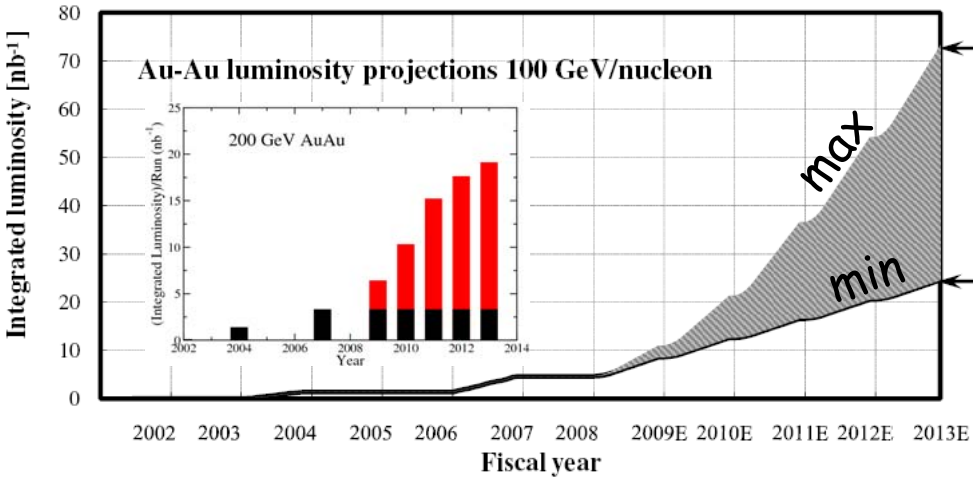

Vertex detectors (VTX,FVTX) & forward calorimeter (NCC) will give:

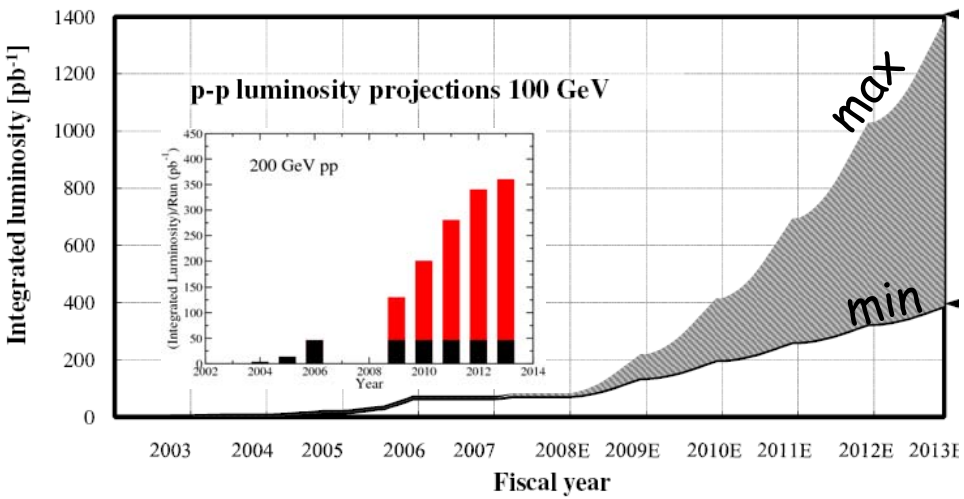
- $\psi'$ msmt with reduced combinatoric background + sharper mass resolution
- $\chi_c$ msmt with photon in NCC
- precise open-heavy measurements to constrain regeneration picture
- installation in 2009 – 2011 period



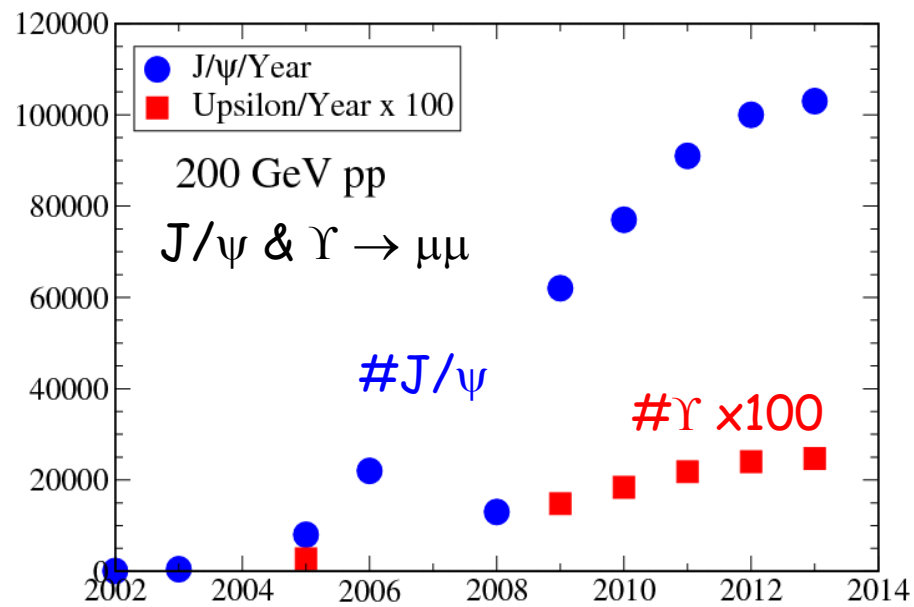



# RHIC Luminosity Advances will Enable Access to Heavier Quarkonia

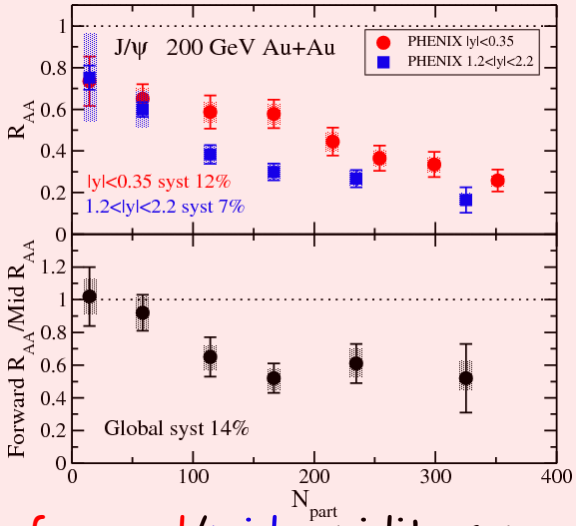



100,000 $J/\psi \rightarrow \mu\mu$
and ~250 $\Upsilon \rightarrow \mu\mu$ per year at highest RHIC luminosities

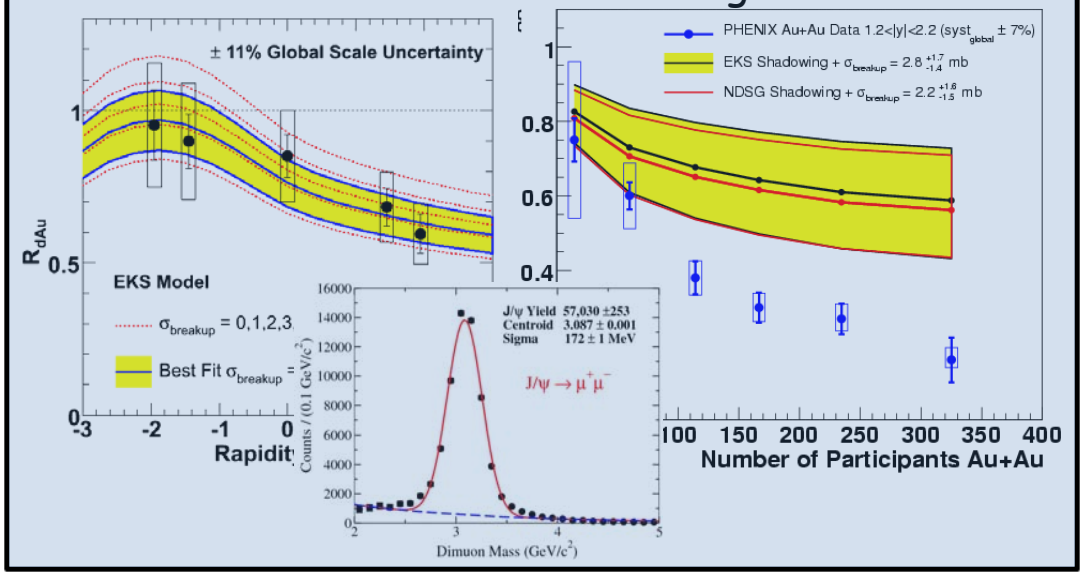


# Progress Towards Understanding Quarkonia at PHENIX - Summary

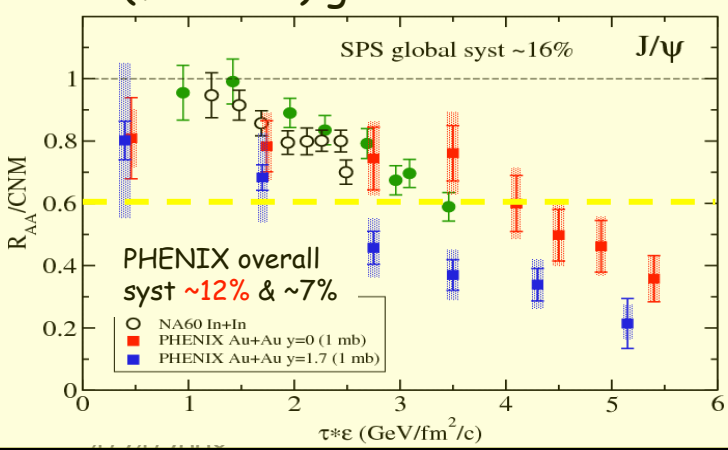



forward/mid rapidity super-ratio saturates @~0.6

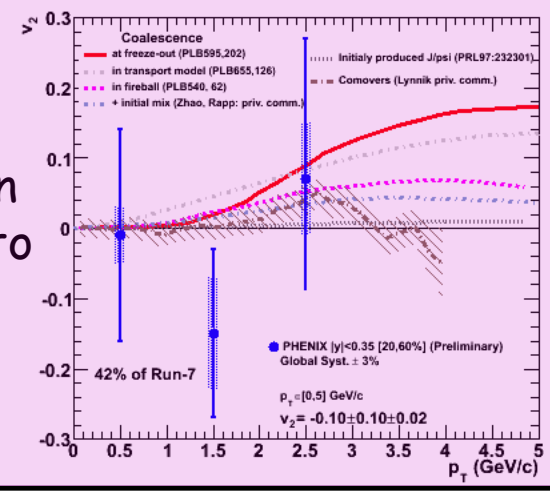
## Better CNM baseline coming from Run8!




## Sequential screening & (forward) gluon saturation?




flow from regeneration is difficult to see

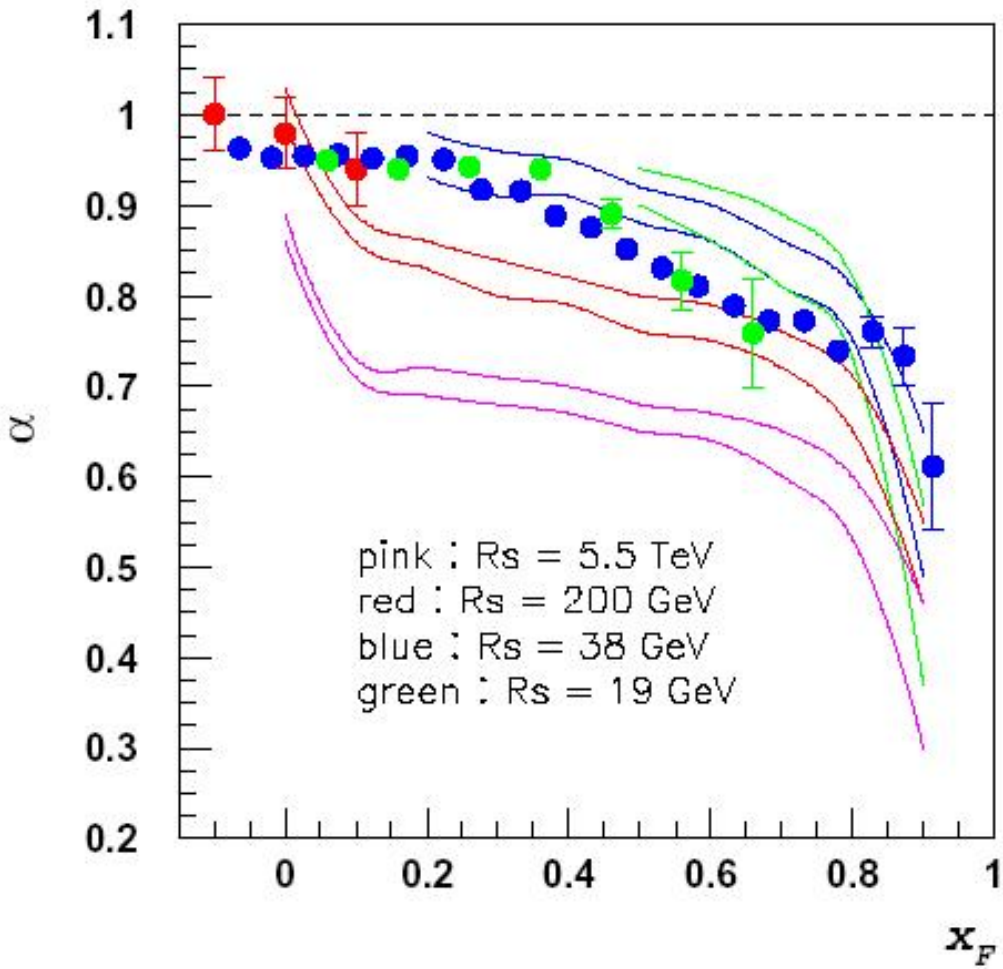


# Backup Slide(s)

# Tuchin & Kharzeev…

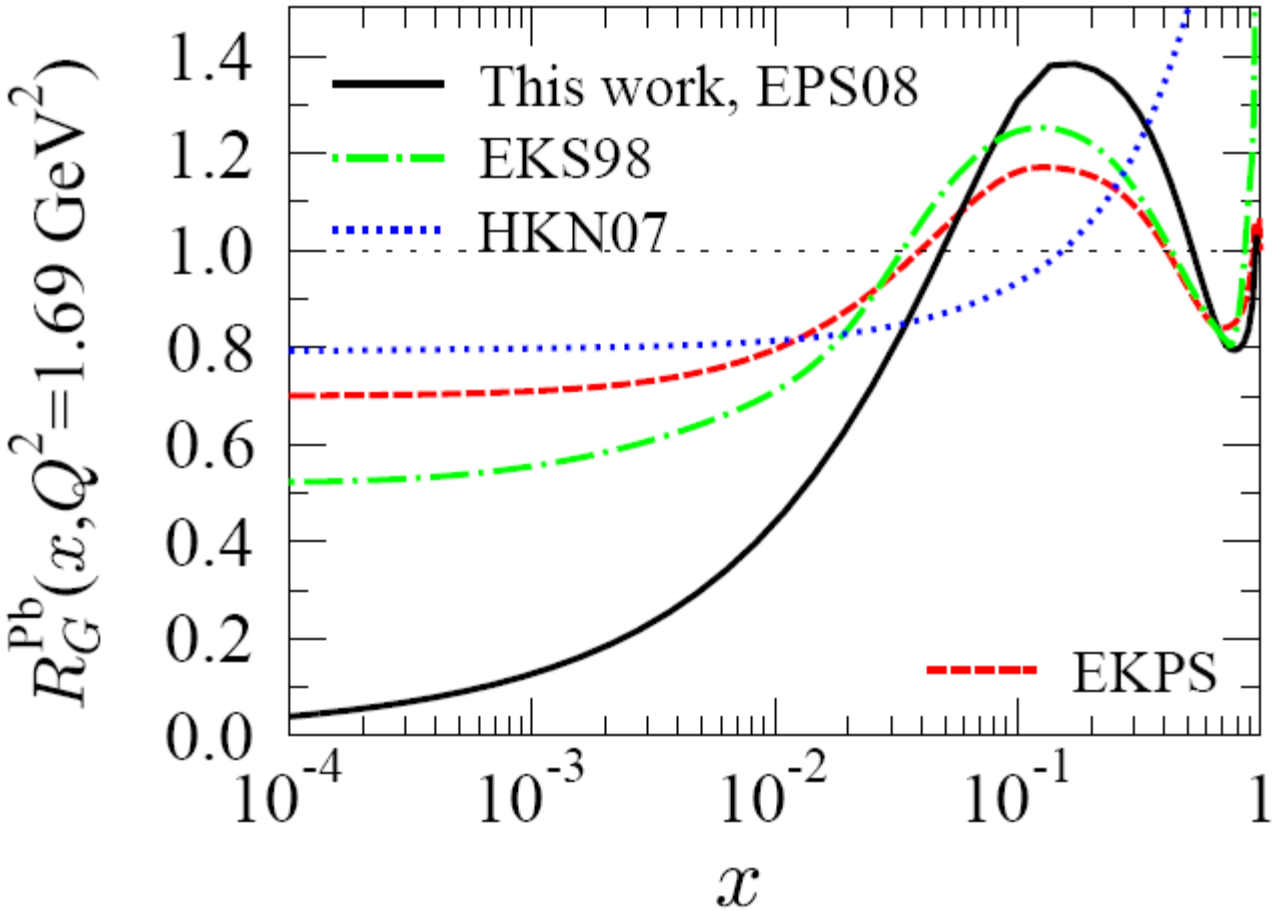
Gluon saturation (CGC) can give $x_F$ scaling of pA J/ψ suppression at various energies

hep-ph_0510358v1



# EPS08 (Strong) Shadowing

*Eskola, Paukkunen, Salgado, hep-ph 0802.0139v1*



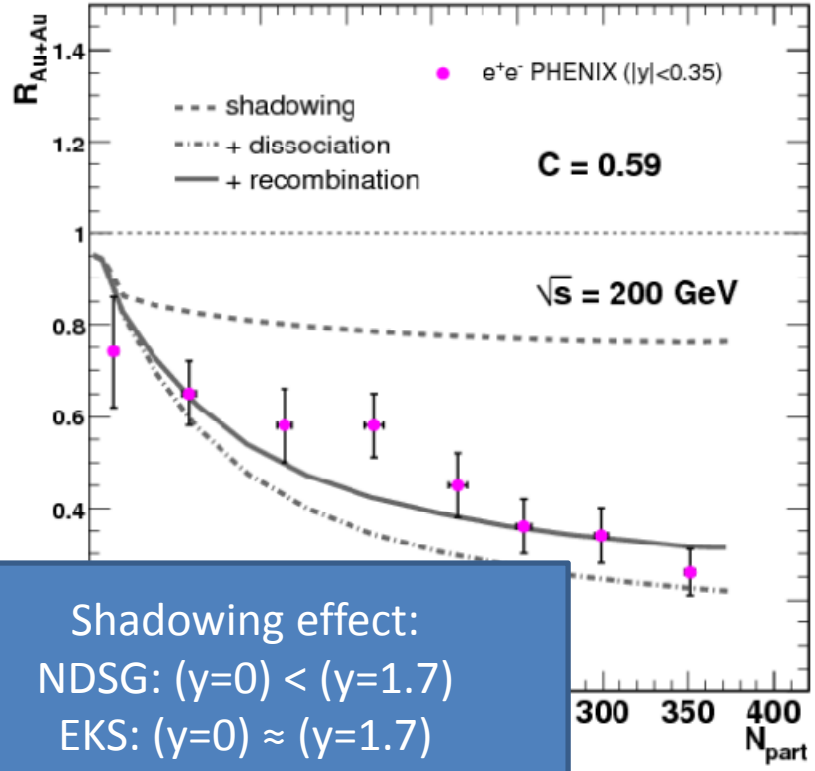

Fit includes RHIC (Brahms) forward hadron data (as well as the usual DIS and DY data)

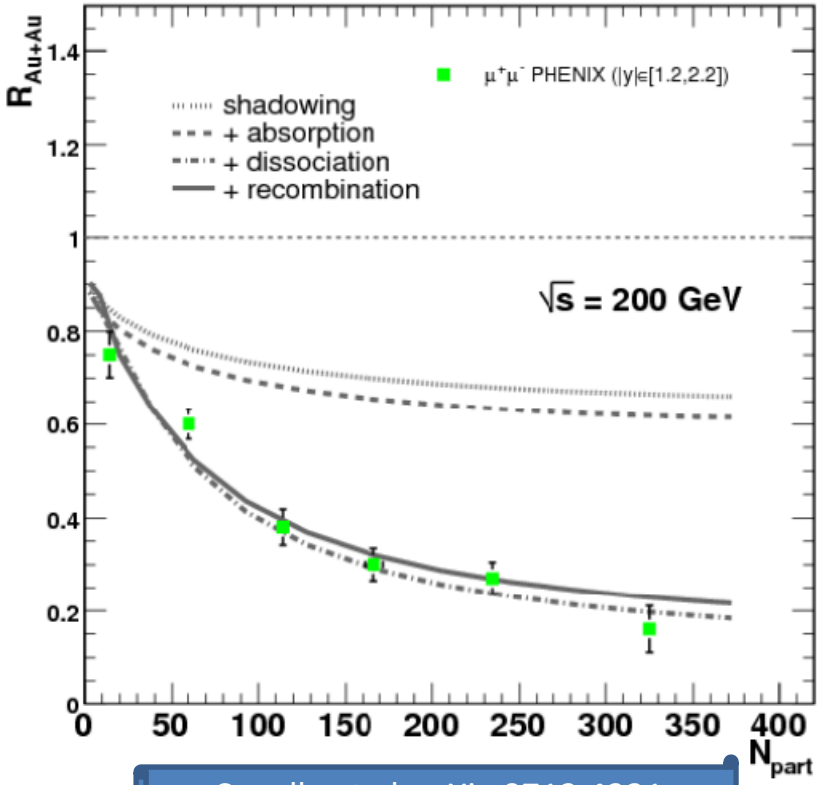
# Another shadowing scheme?

Shadowing from Schwimmer multiple scattering :

+ E-p conservation

+ regeneration

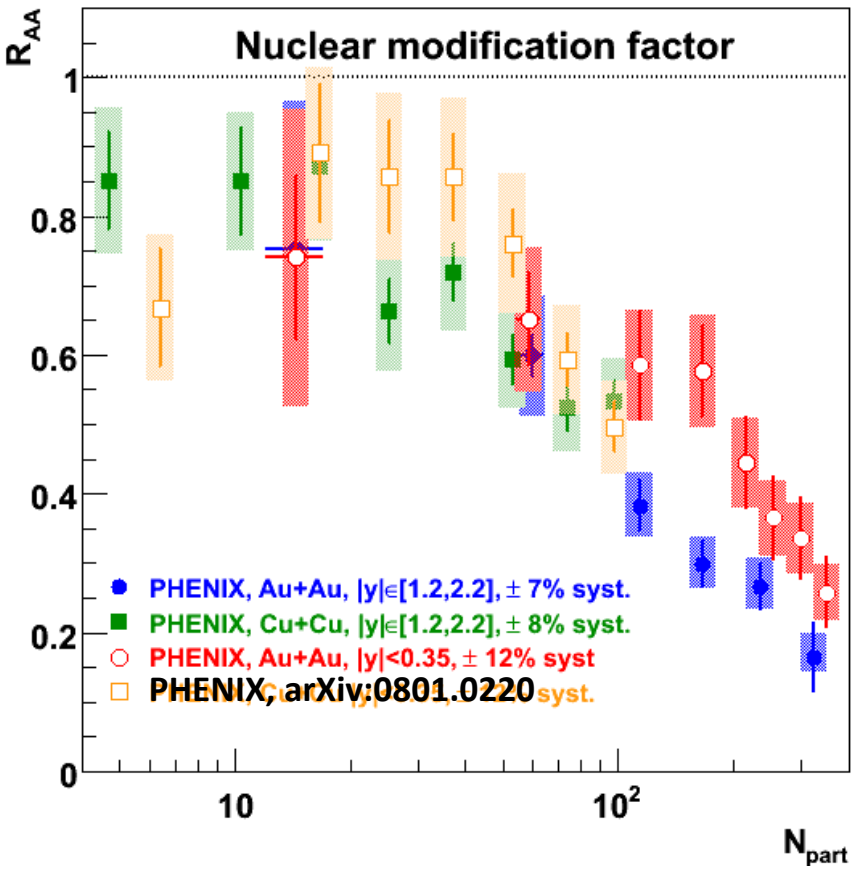



Shadowing effect:
NDSG: (y=0) < (y=1.7)
EKS: (y=0) ≈ (y=1.7)
Schwimmer: (y=0) > (y=1.7)

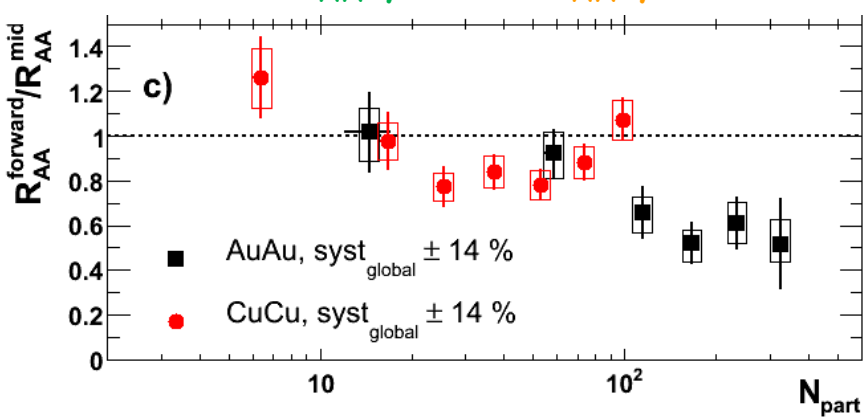
Capella et al, arXiv:0712.4331

# $R_{AuAu}$ 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

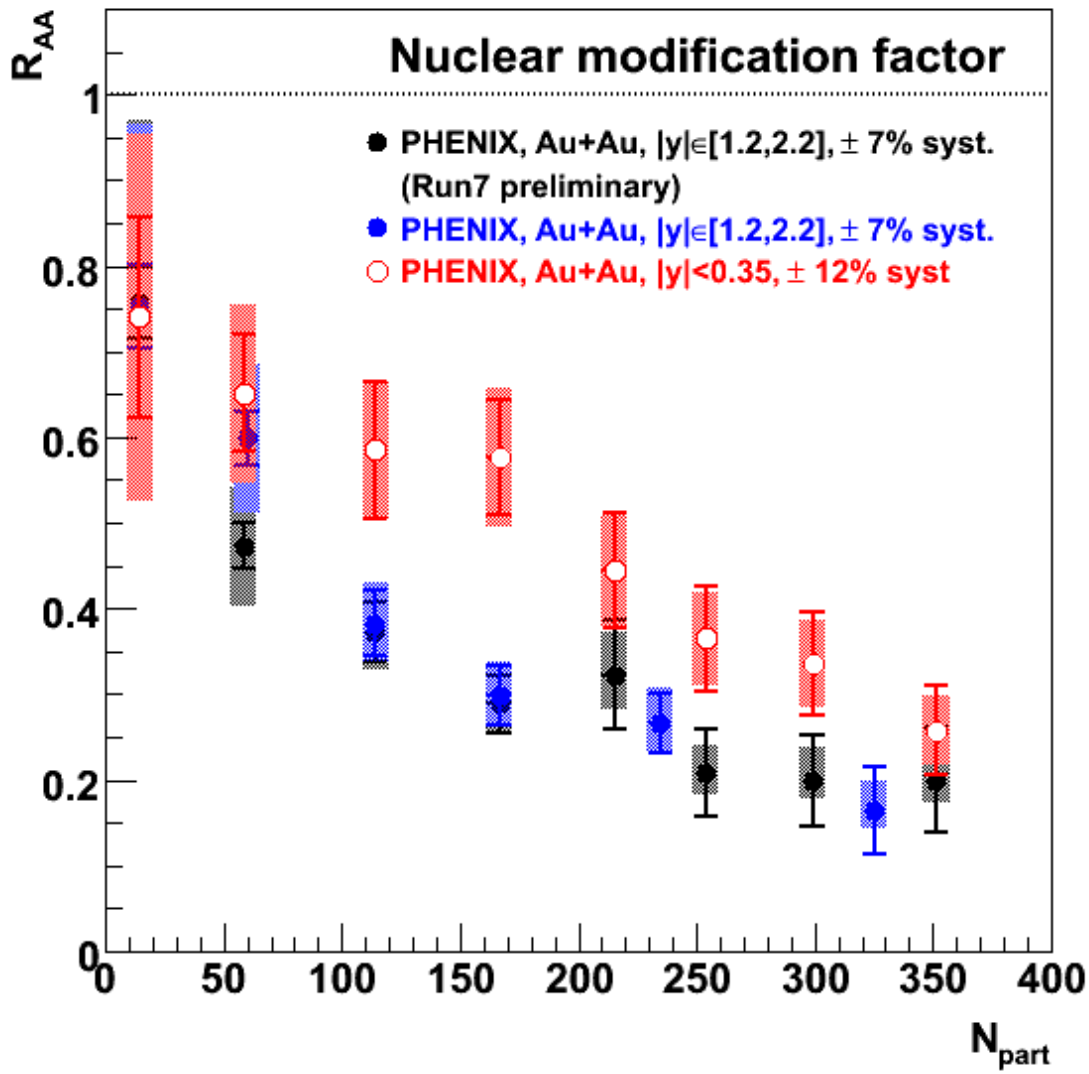
$R_{AA}(y\sim1.7)/R_{AA}(y\sim0)$



# New results from Run7 AuAu data

Preliminary analysis of new Run7 AuAu

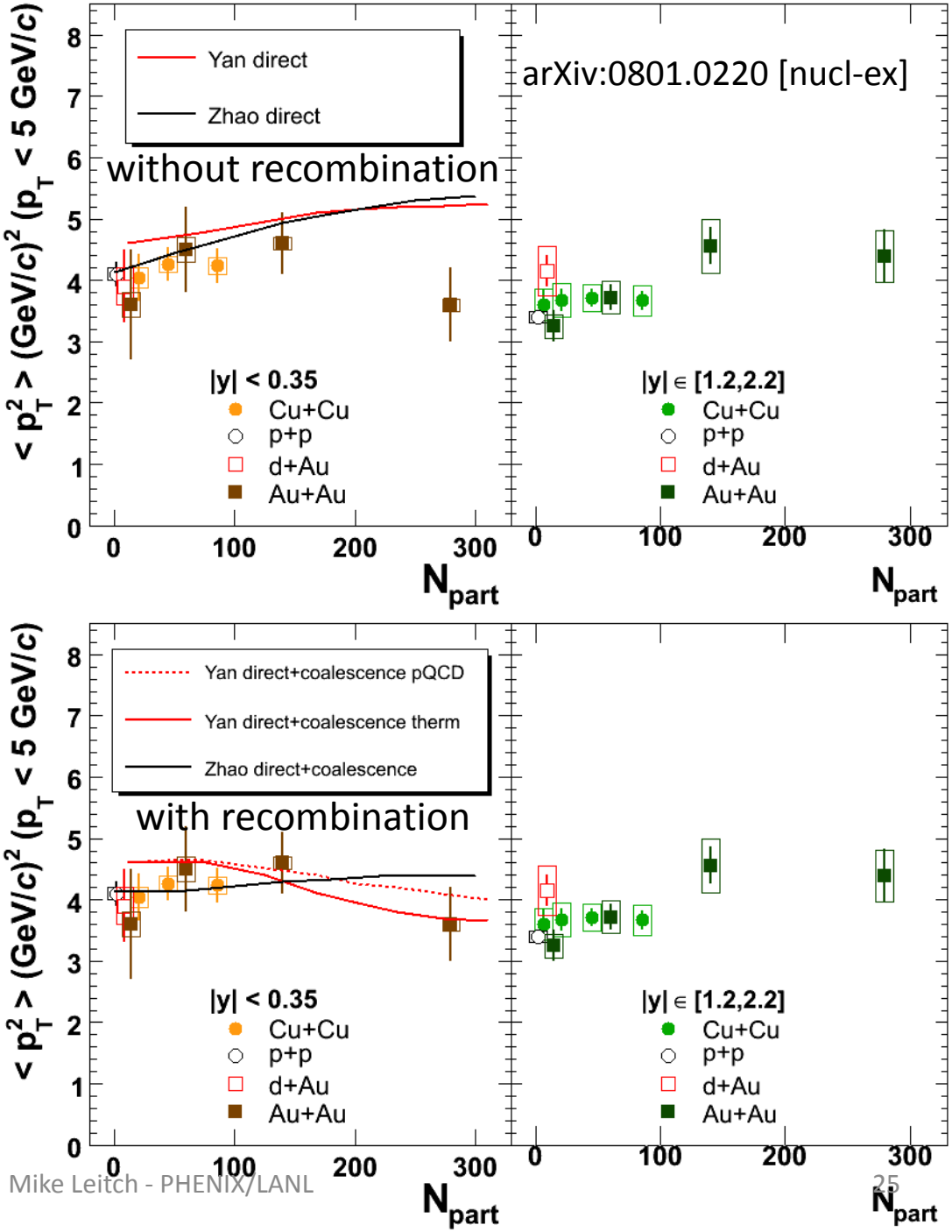
forward rapidity (dimuon) J/ψ data (black points) is consistent with published results (blue points) from Run4



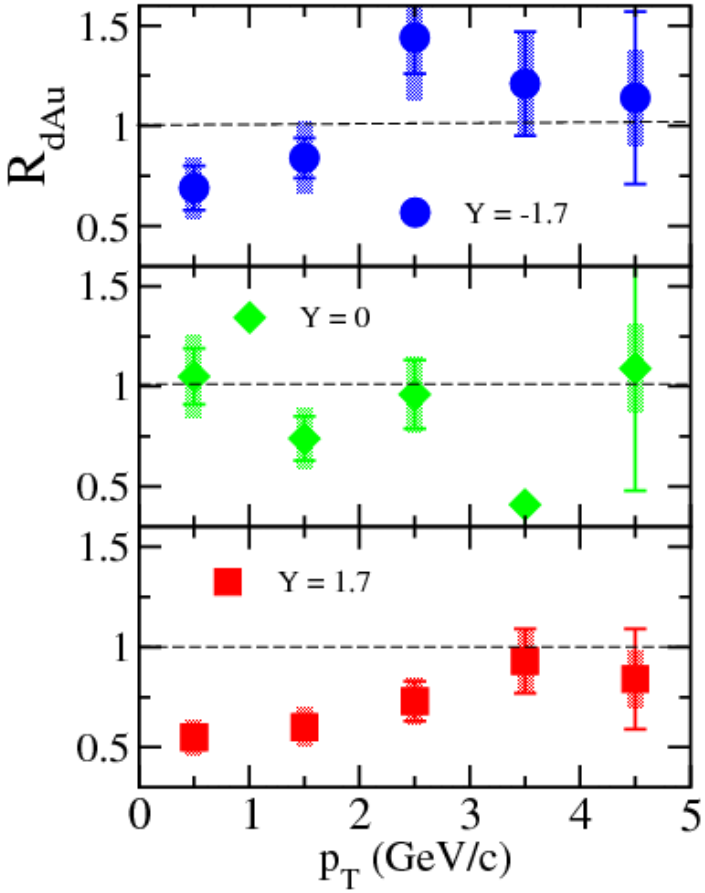
# $\langle p_T^2 \rangle$ vs $N_{part}$

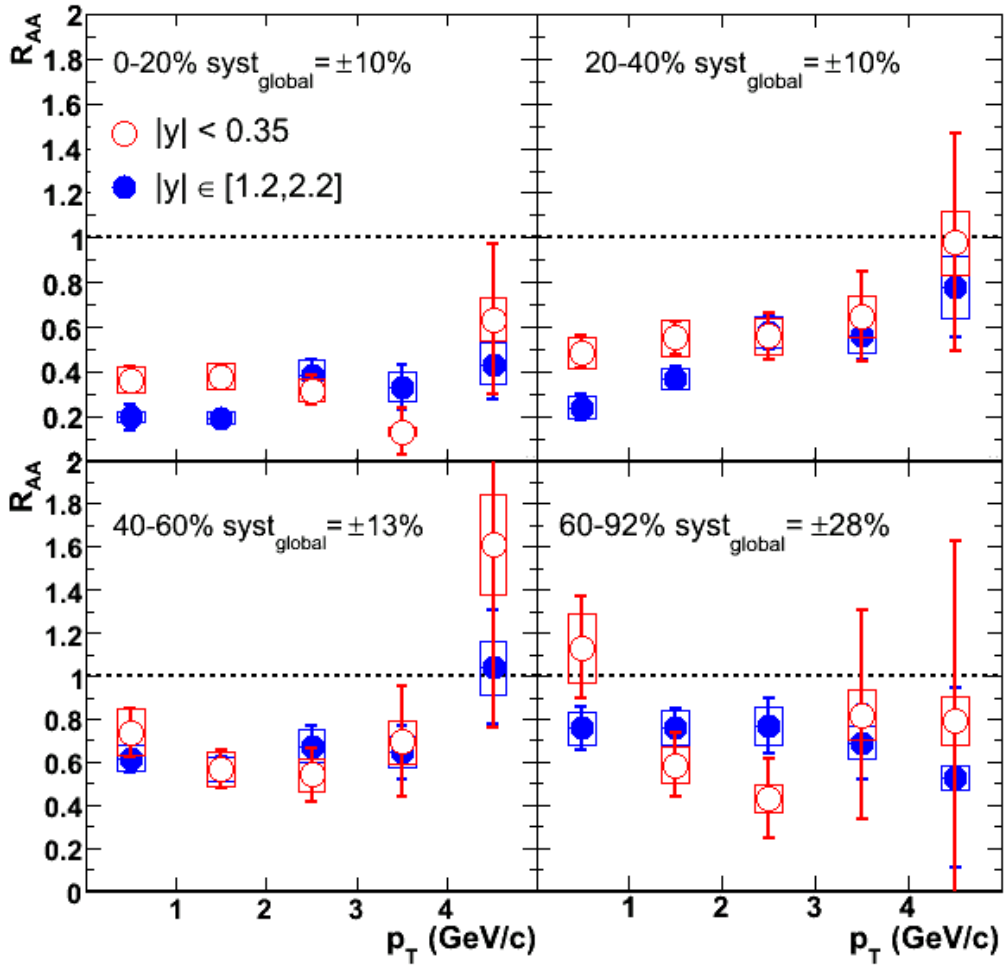
- Recombination of charm quarks could cancel the Cronin and leakage effects.
- Need more statistics to draw a conclusion.

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



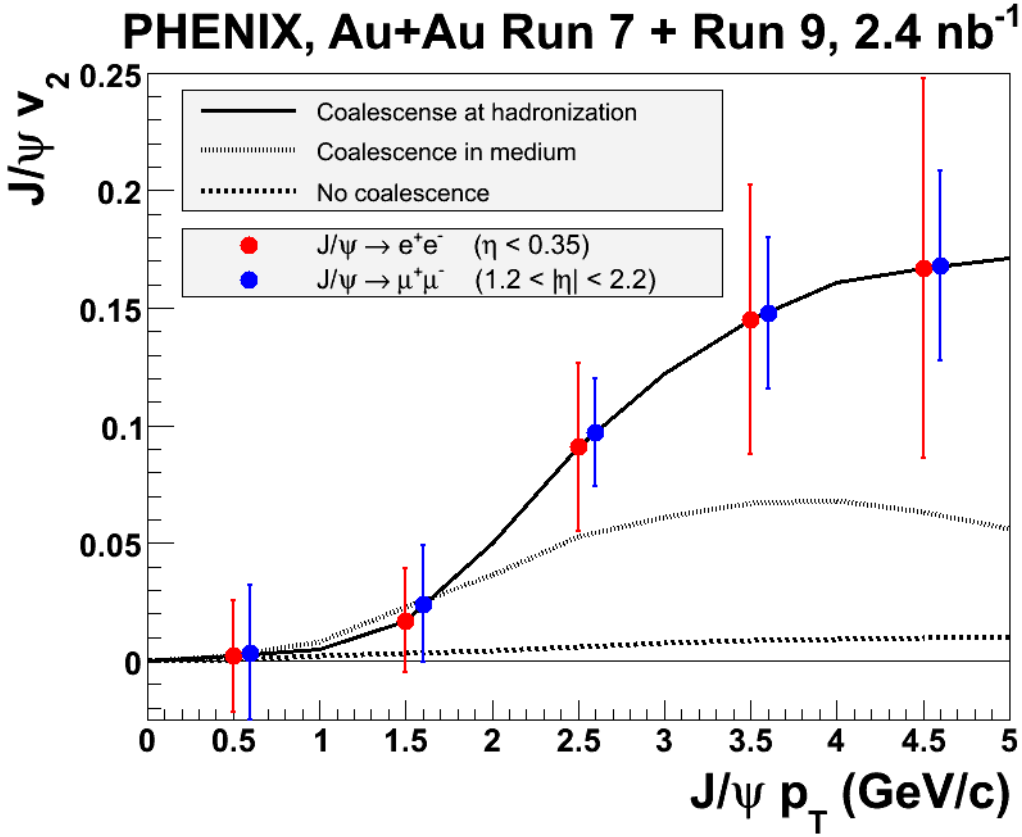
# Ratios vs $p_T$ for dAu and AuAu

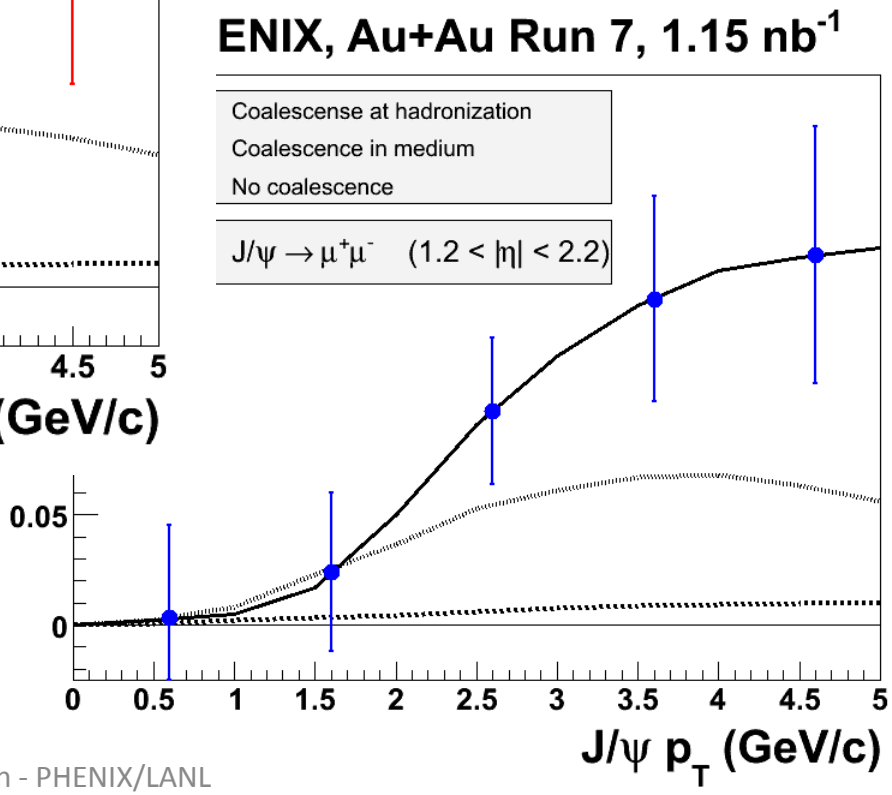


From run8 BUP presentation

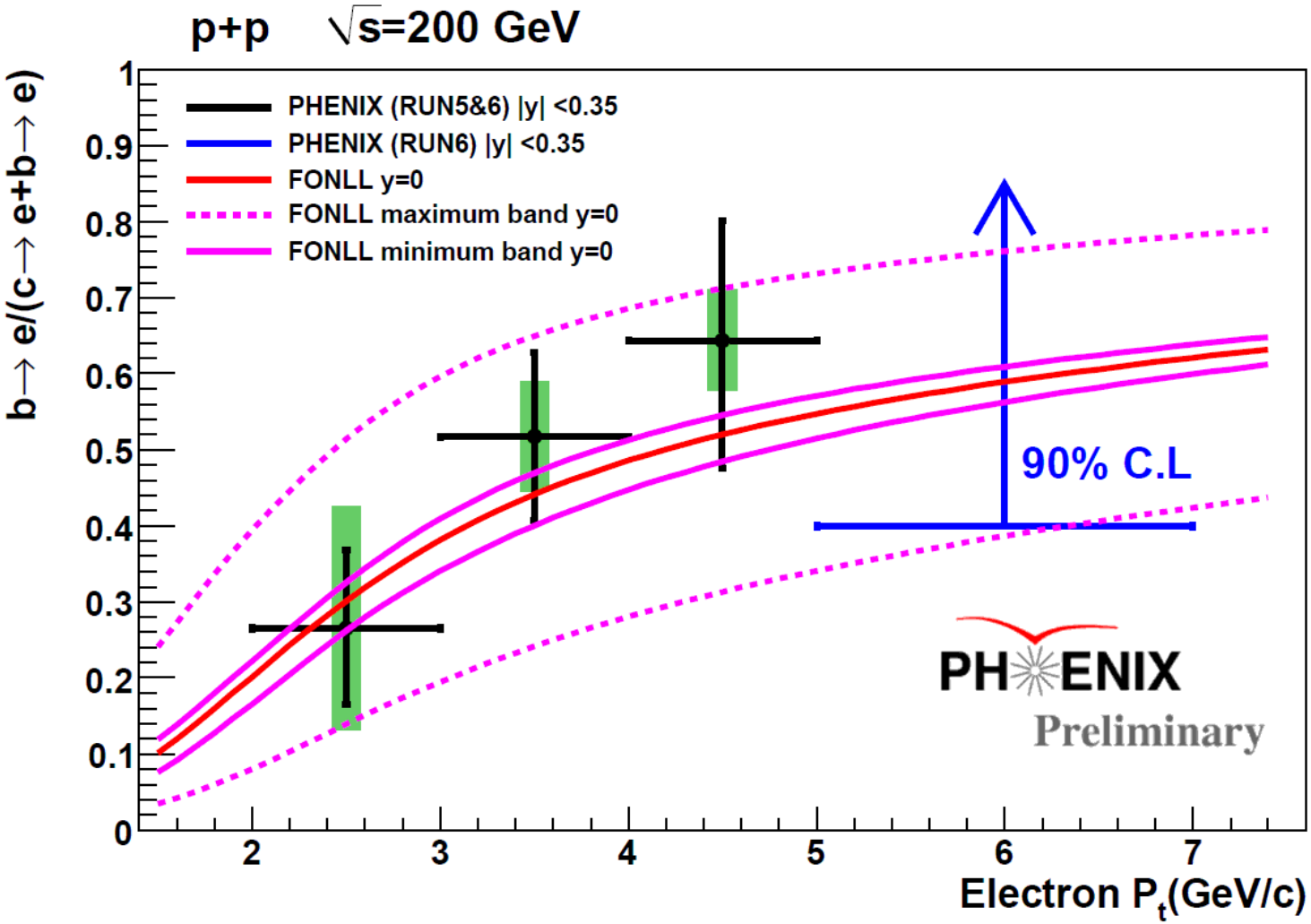
# Precision of J/ψ $v_2$ measurement

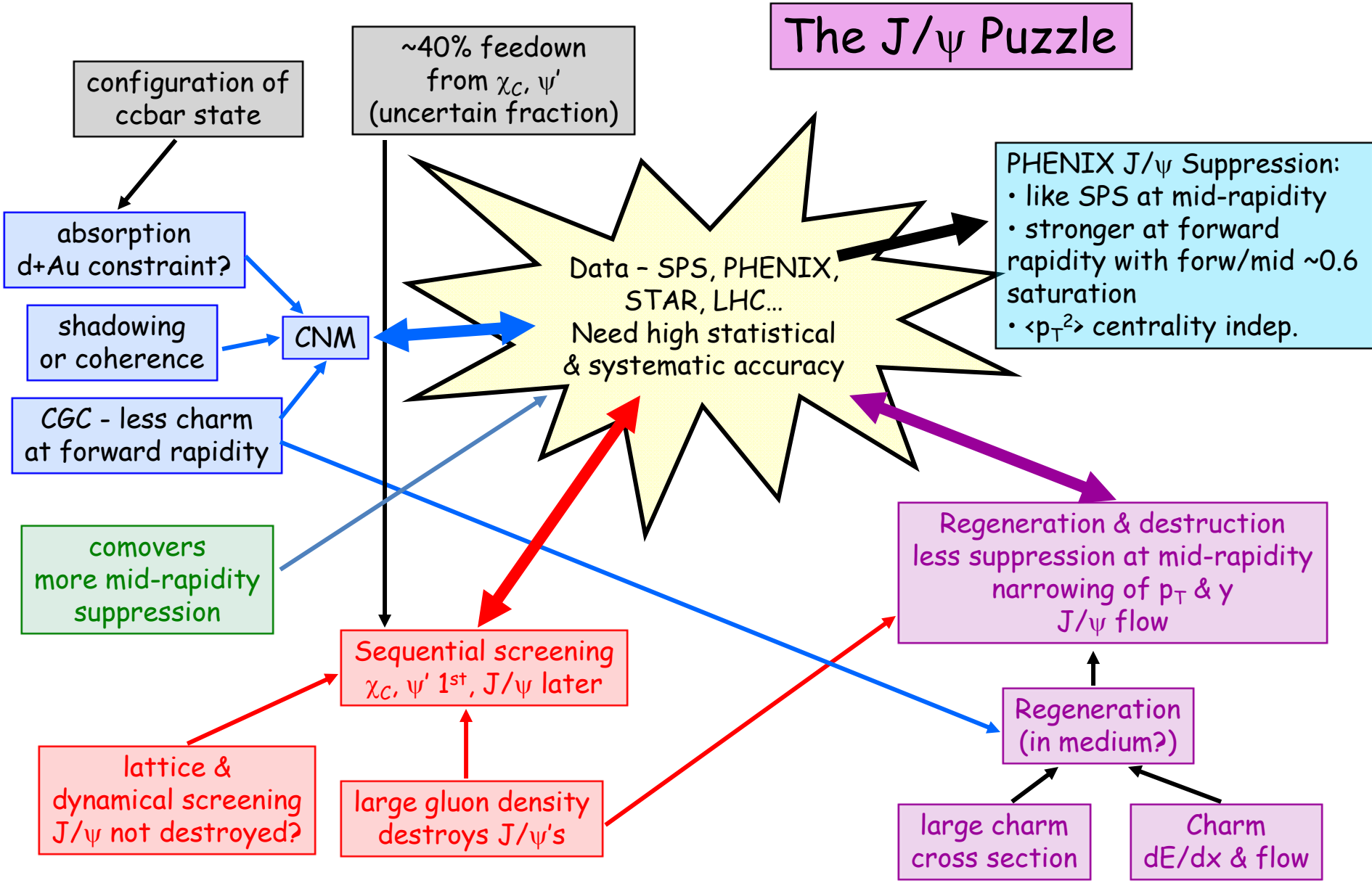



Run-7 will tell if J/ψ $v_2$ is zero or not

# bottom fraction in non-photonic electron




- The result is consistent with FONLL

# The J/ψ Puzzle