# Quarkonia Production in d-Au collisions Measured by the PHENIX Detector

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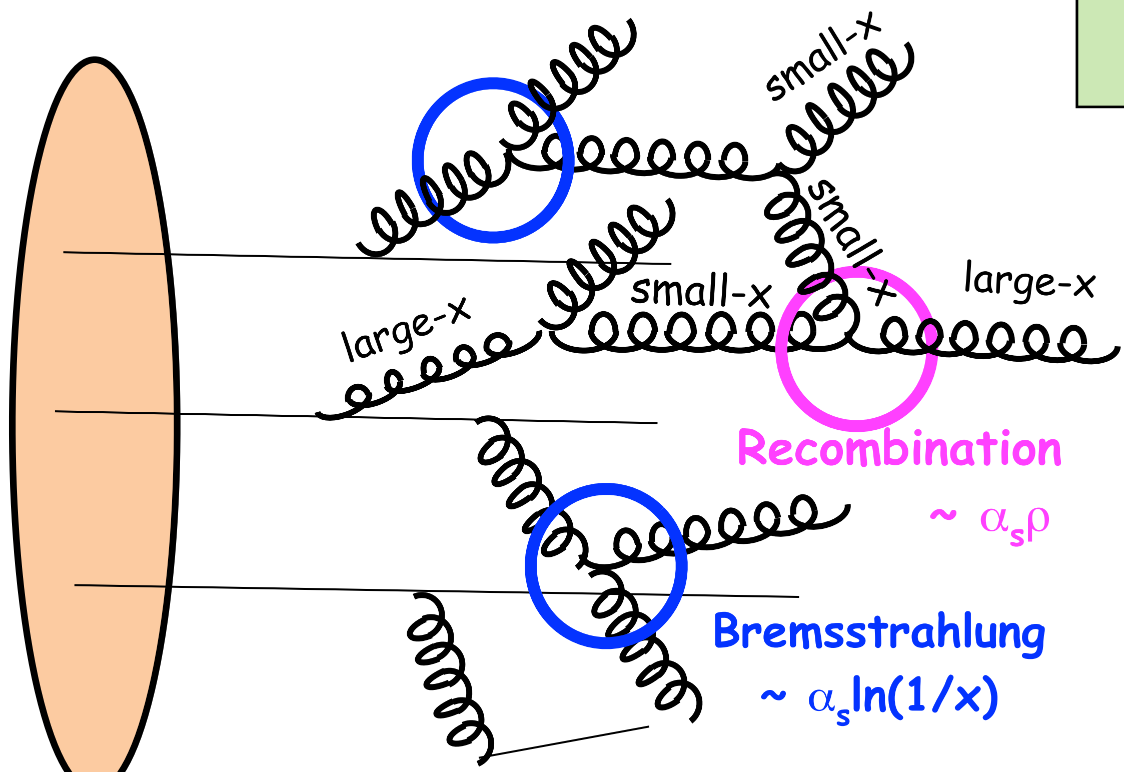
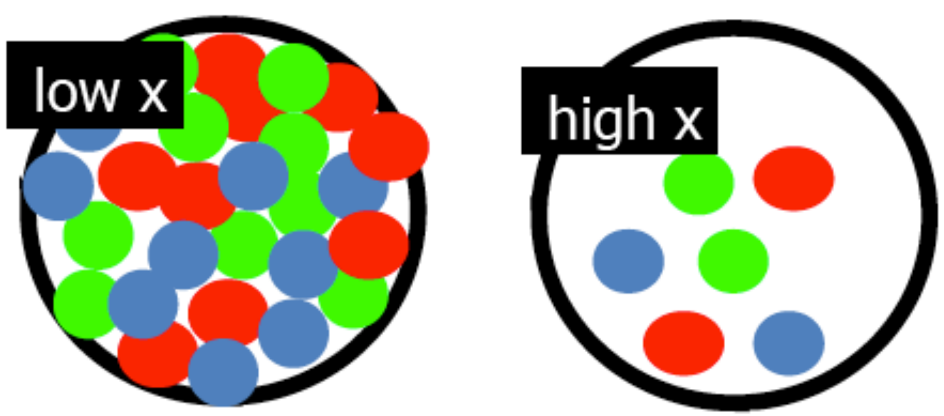
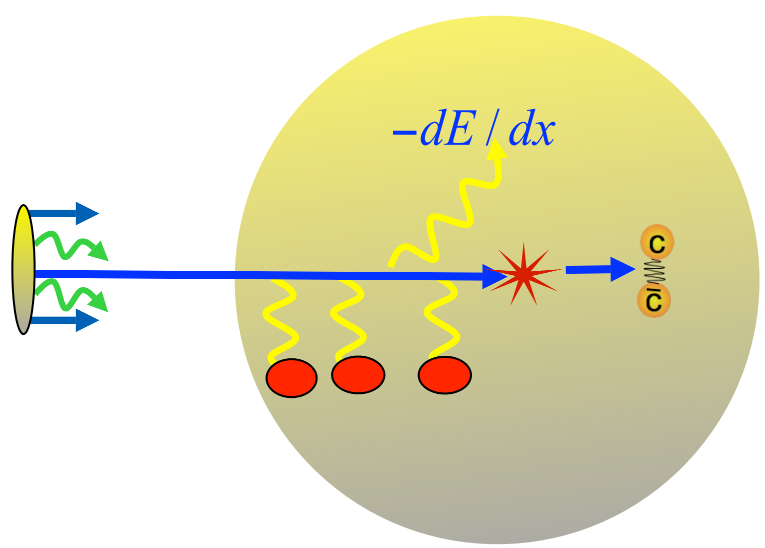
p+A @ RHIC Workshop - BNL - Jan-2013

# Cold Nuclear Matter effects upon a quarkonia state

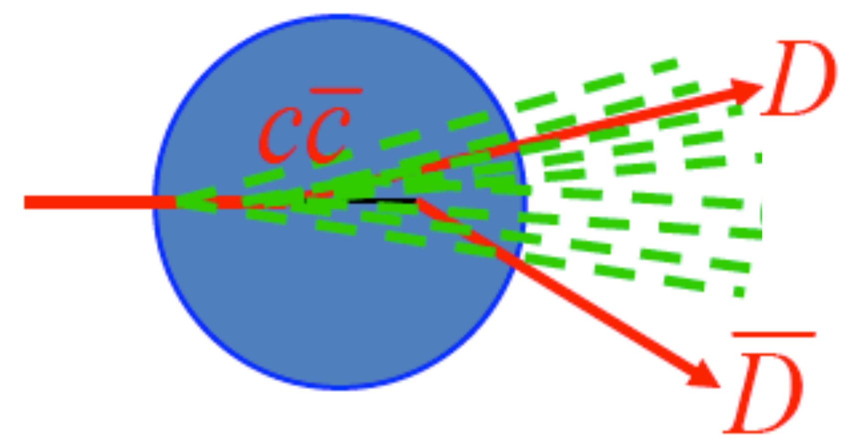
## Pre $Q\bar{Q}$ formation

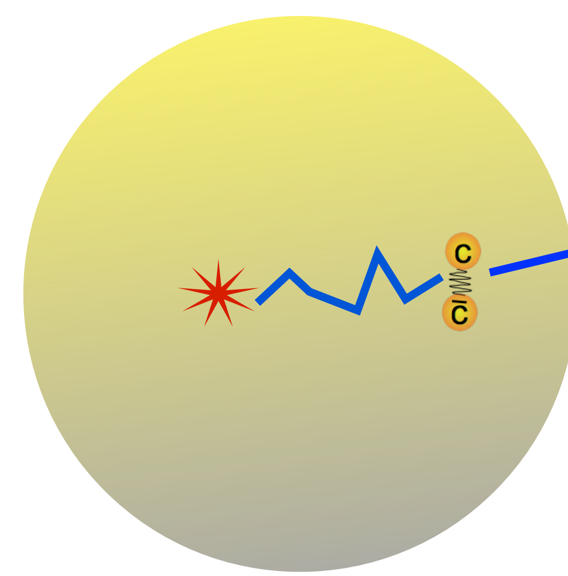



## Effects on a formed $Q\bar{Q}$



# How quarkonia at PHENIX can probe initial and final state cold nuclear matter effects

PHENIX

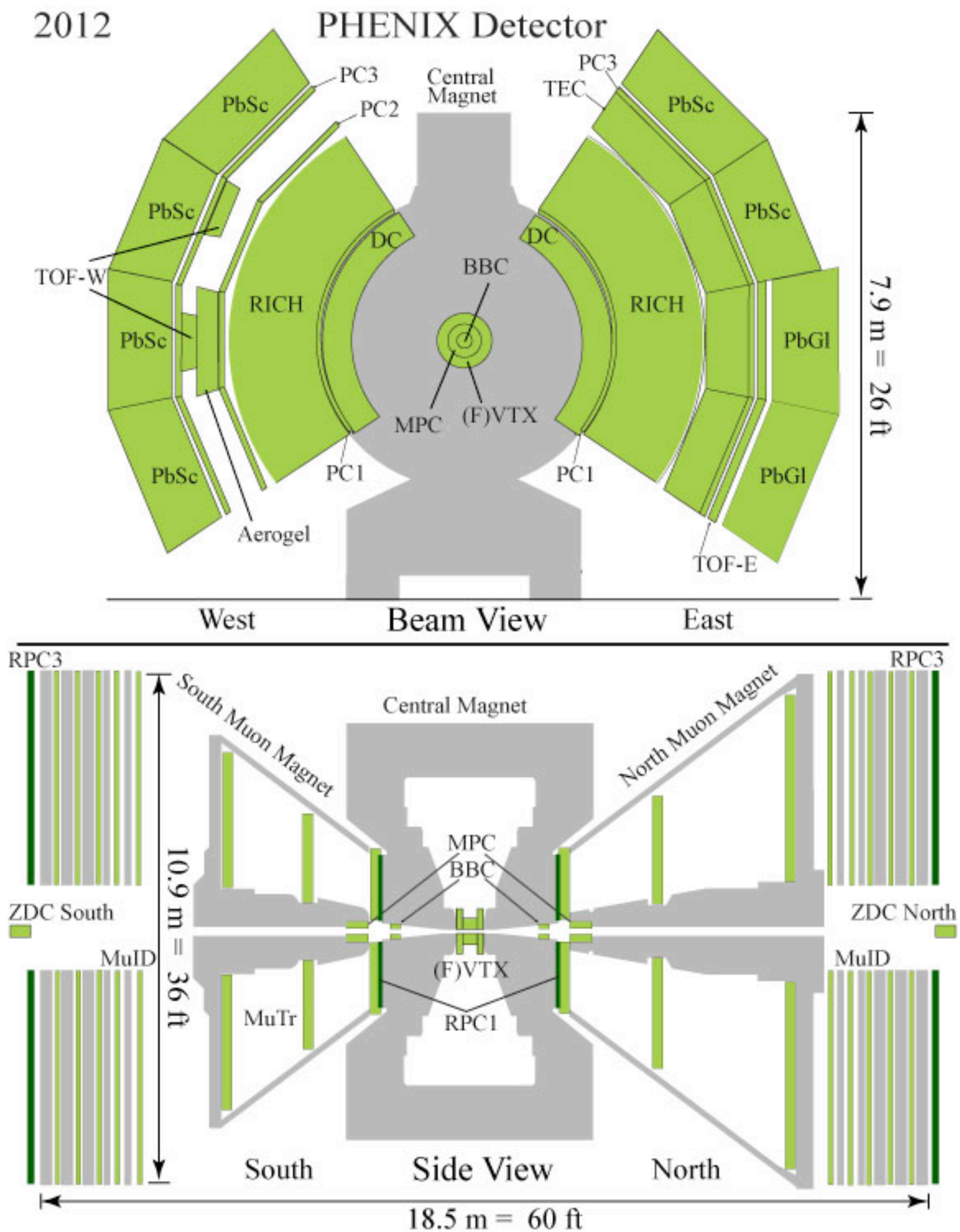
$|y|<0.35$ $\Delta\Phi=2\times\pi/2$

PHENIX can measure quarkonia from zero momentum

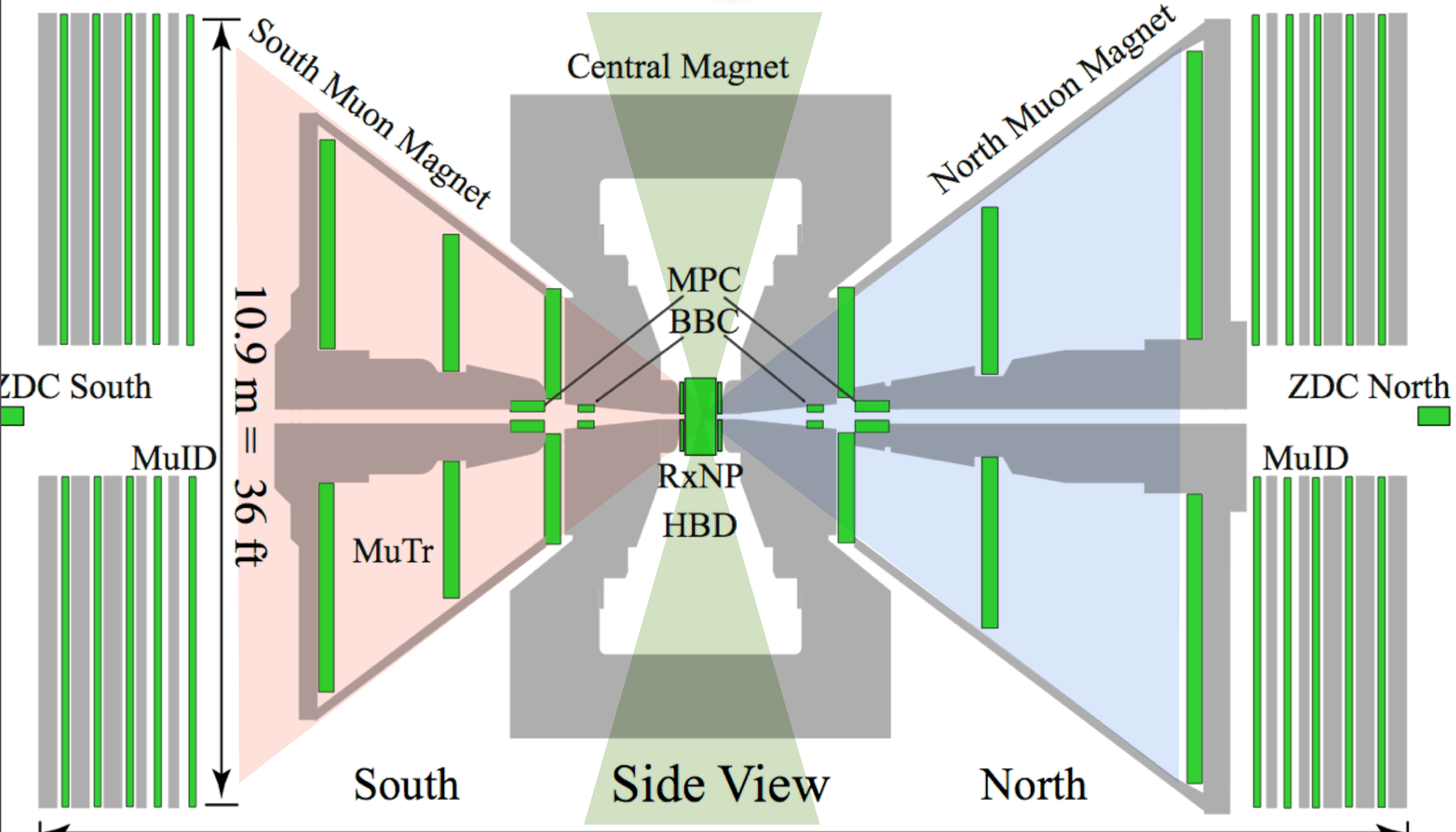
dilepton decays: $J/\psi$, $\psi'$, $\Upsilon$
radiative decays: $\chi_c \rightarrow e^+e^-\gamma$

Can probe hadronic breakup with different quarkonia sizes and binding energies

$1.2<|y|<2.2$ $\Delta\Phi=2\pi$



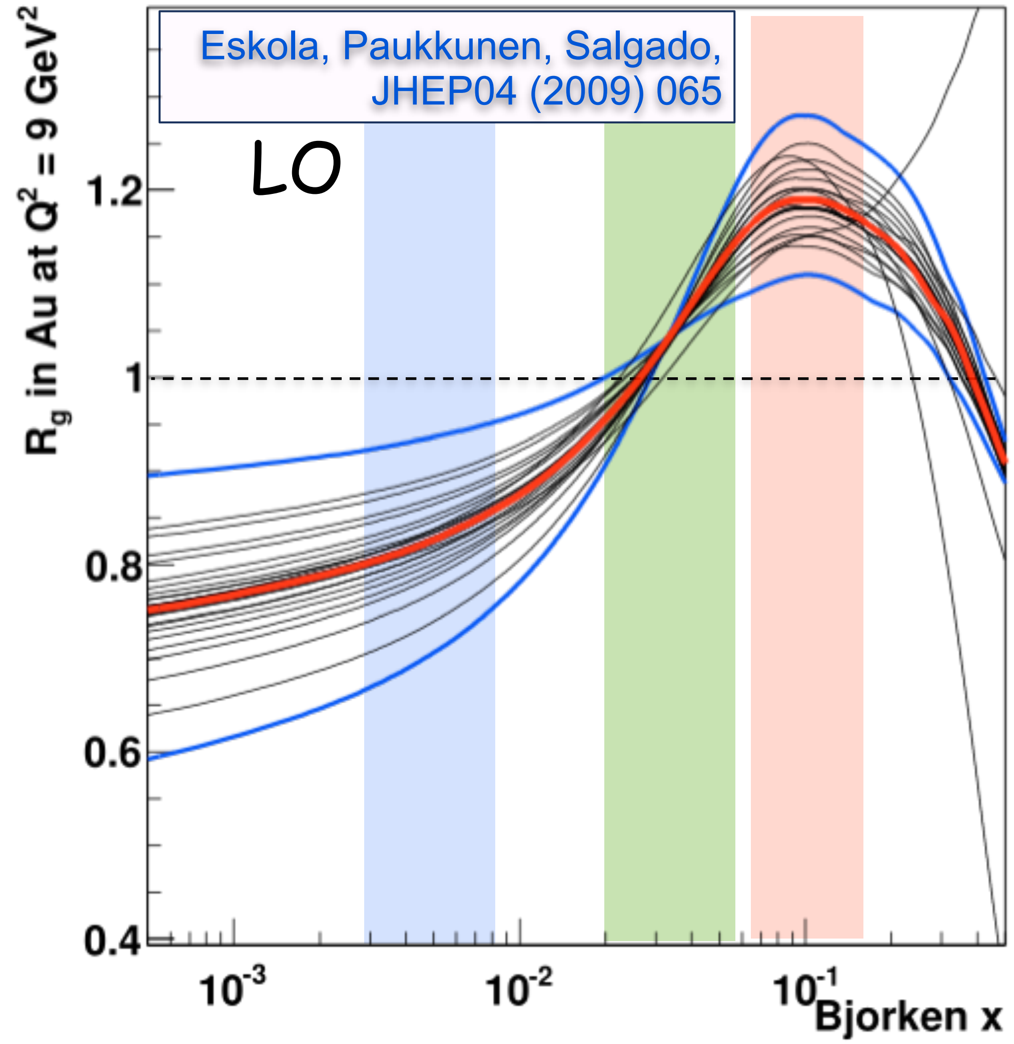
# Probing Cold Nuclear Matter effects

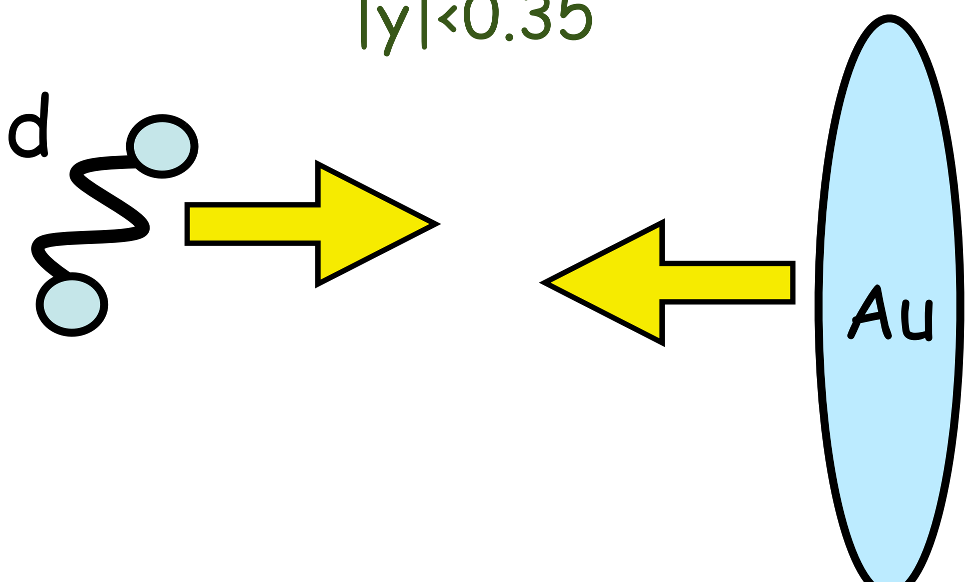



-2.2<y<-1.2

|y|<0.35

1.2<y<2.4




PHENIX covers Bjorken x ranges where EPS09 expects

- suppression (shadowing region)
- suppression-enhancement transition
- enhancement (anti-shadowing)

PHENIX

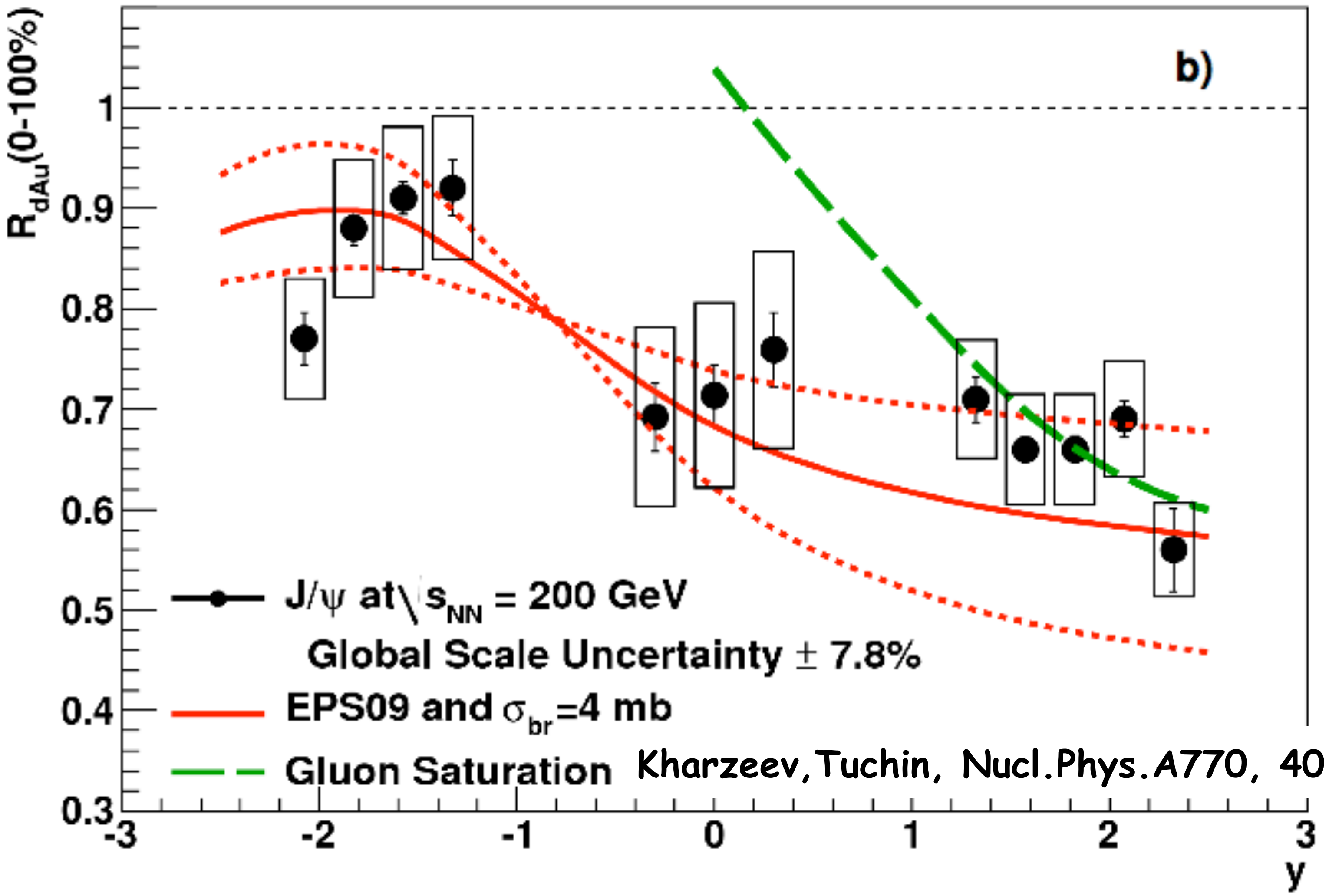
# Initial State Effects

PHENIX

# Charmonia

$d + Au \quad \sqrt{s_{NN}} = 200 GeV$

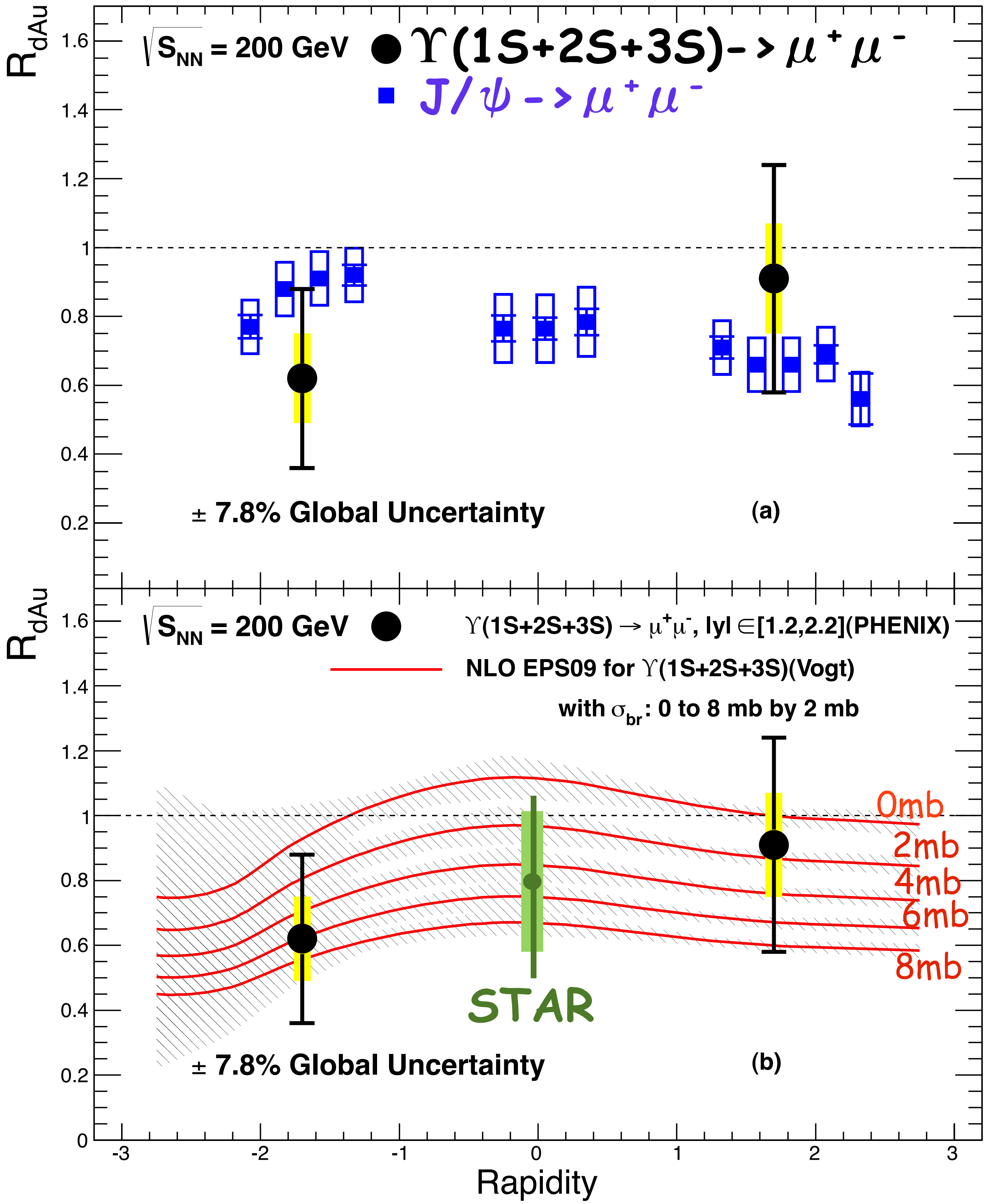
PRL107, 142301 (2011)




- EPS09 assuming 2->1 process + J/$\psi$ breakup in hadronic matter
- qualitatively describes Minimum Bias $R_{dAu}$ data
- gluon saturation describes small-x region

# Bottomonia

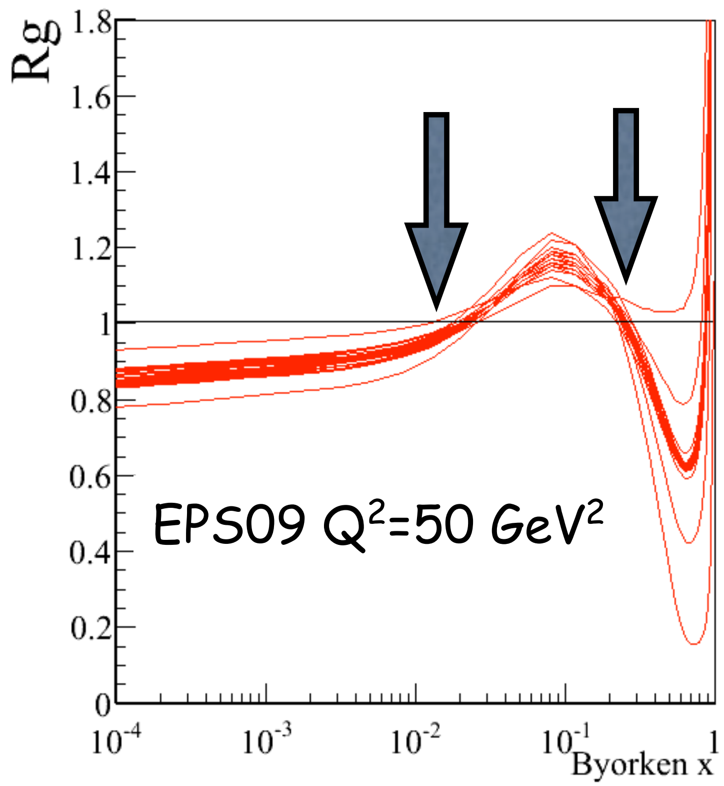
arXiv:1208.1293




ϒ family:

NEW

- 37% 1S
- 27% $\chi_b$ (decay to 1S)
- 25% 2S (prompt + decayed to 1S)
- 11% 3S (prompt + decayed to 1S)

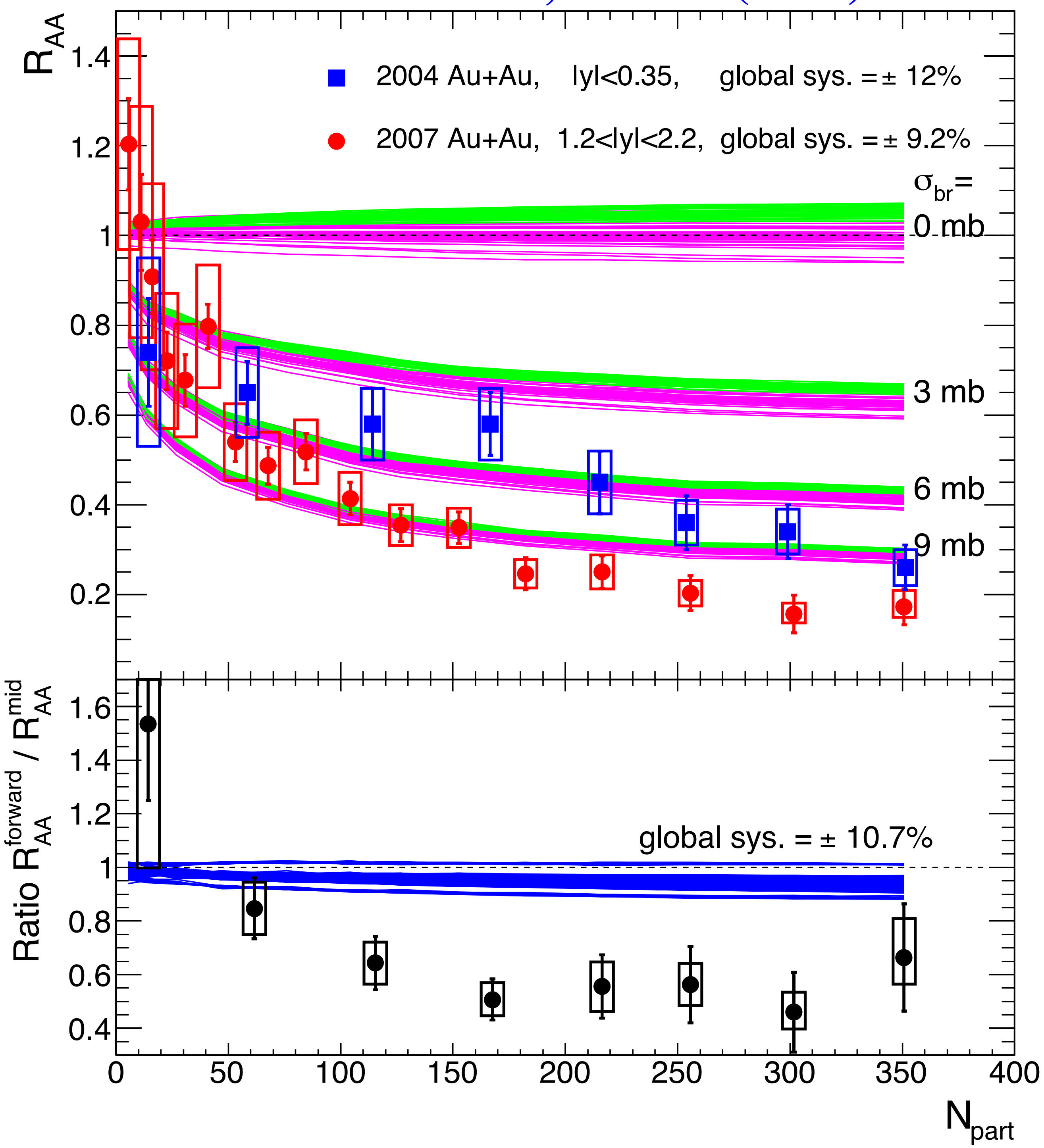



- probe larger gluon $Q^2$ and x than charmonia
- more sensitive to EMC region at y<0

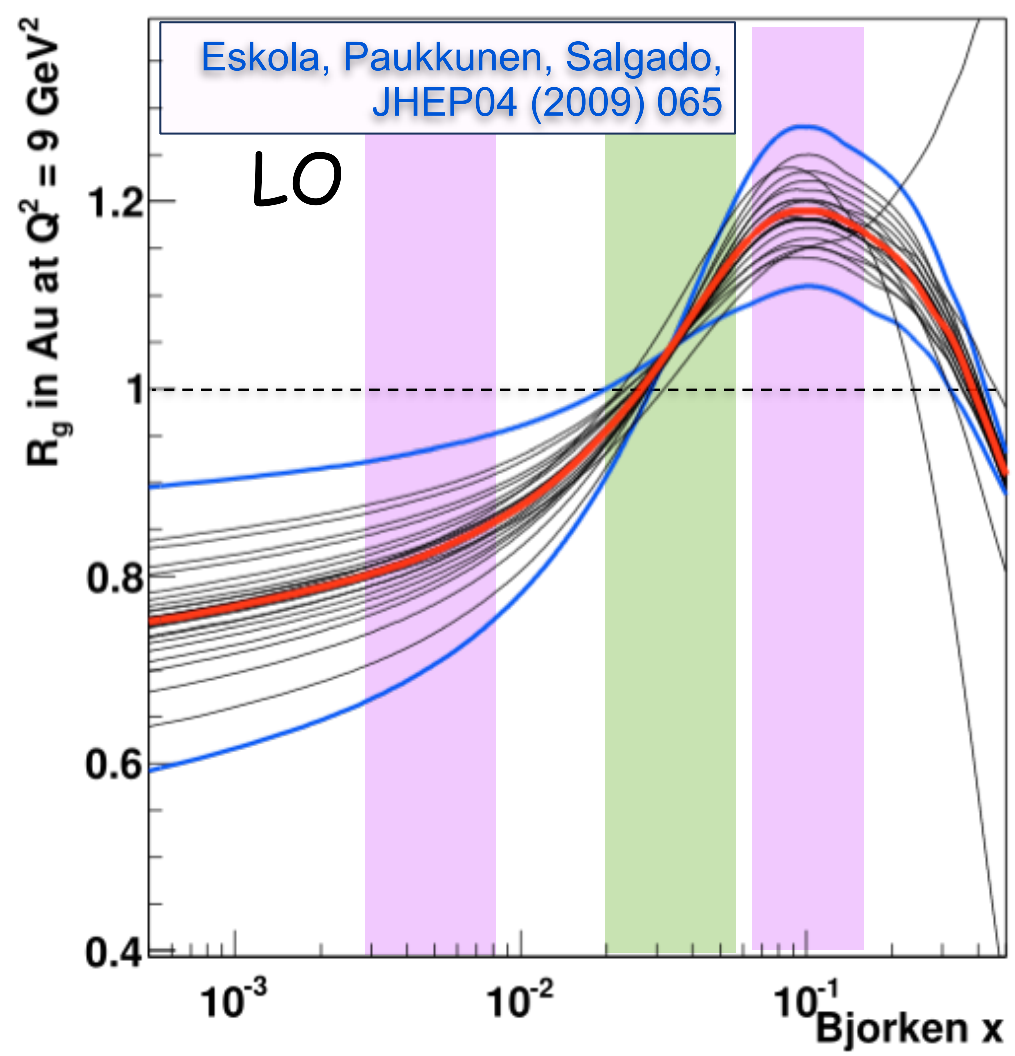
# Propagation of nPDF+breakup to J/ψ in Au+Au

nPDF cannot describe the stronger suppression observed at forward rapidity in Au+Au collisions

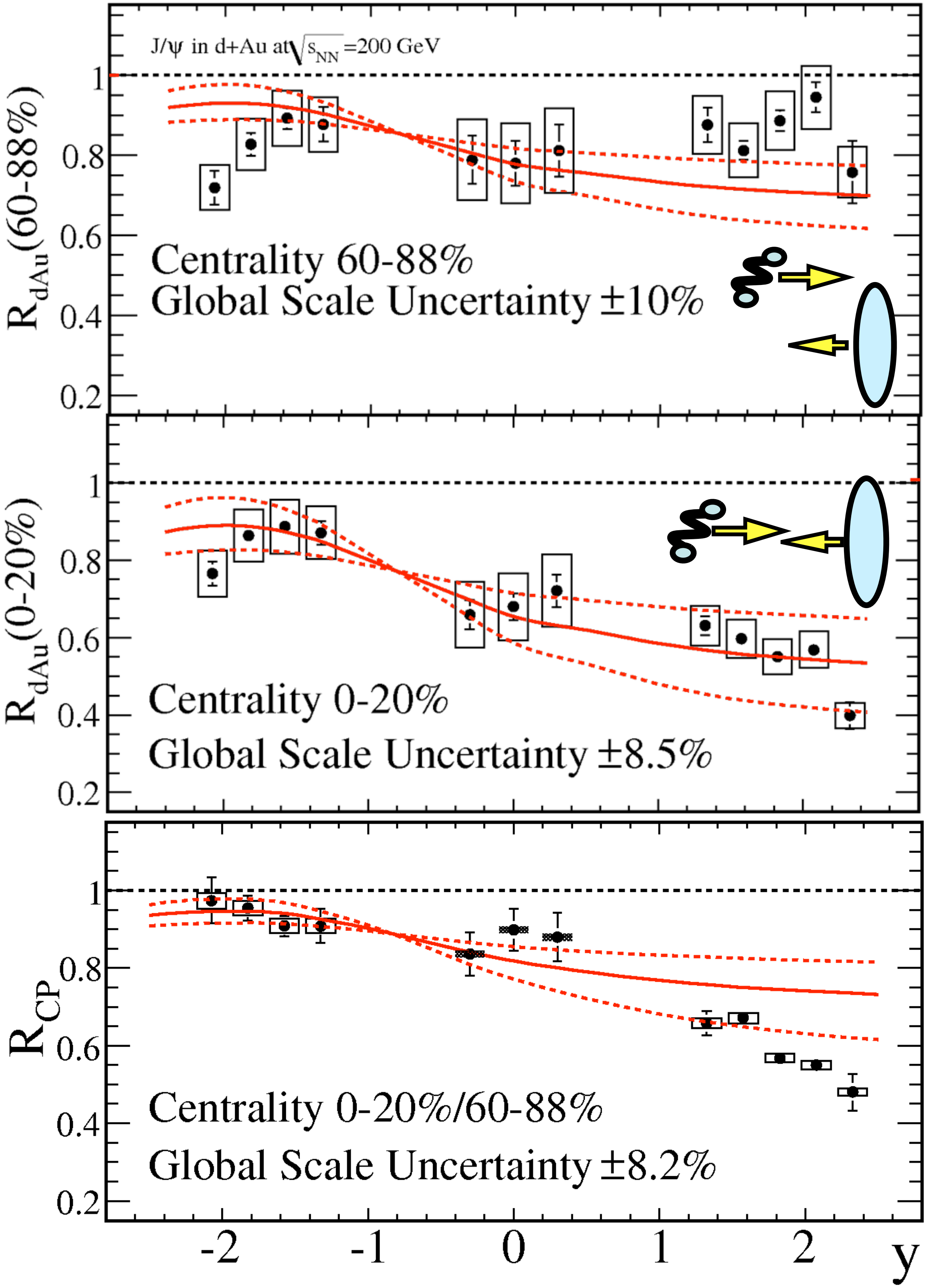
**PRC84, 054912 (2011)**



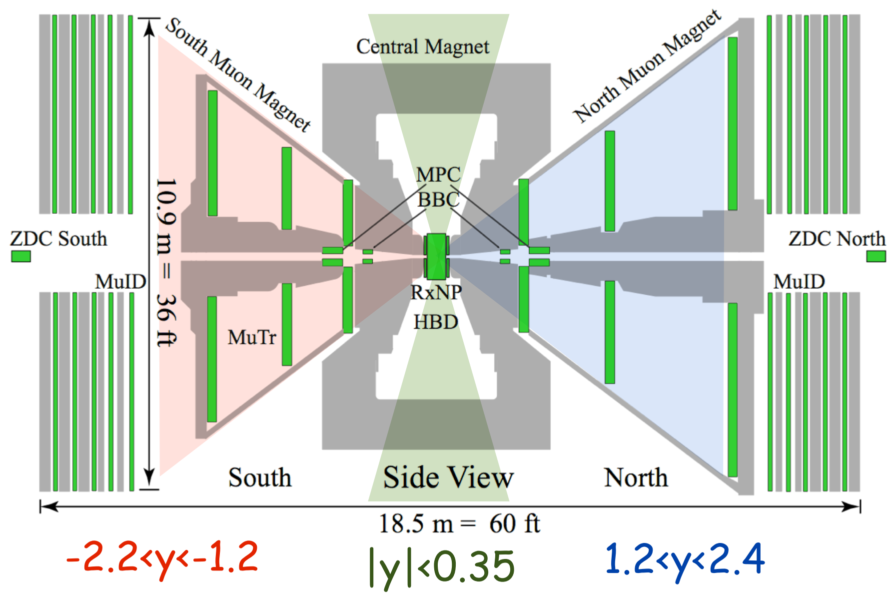

Forward rapidity in Au+Au is a mix of small-x, large-x effects which cancel out

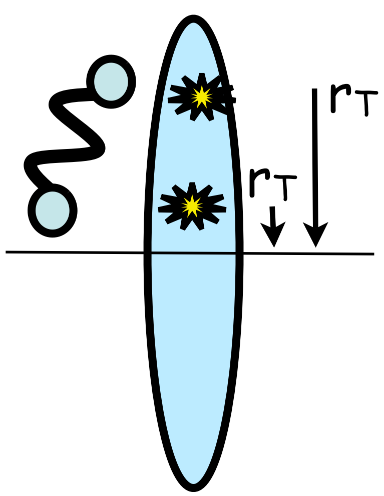


PHENIX **PRL107, 142301 (2011)**




- EPS09 cannot reproduce either $R_{dA}$ in peripheral events or $R_{cp}$
- nPDF needs centrality dependence




$$\Lambda(r_T) \equiv \frac{1}{\rho_0}\int dz\rho(z, r_T)$$

$$\rho(z, r_T) \equiv \text{Woods-Saxon}$$

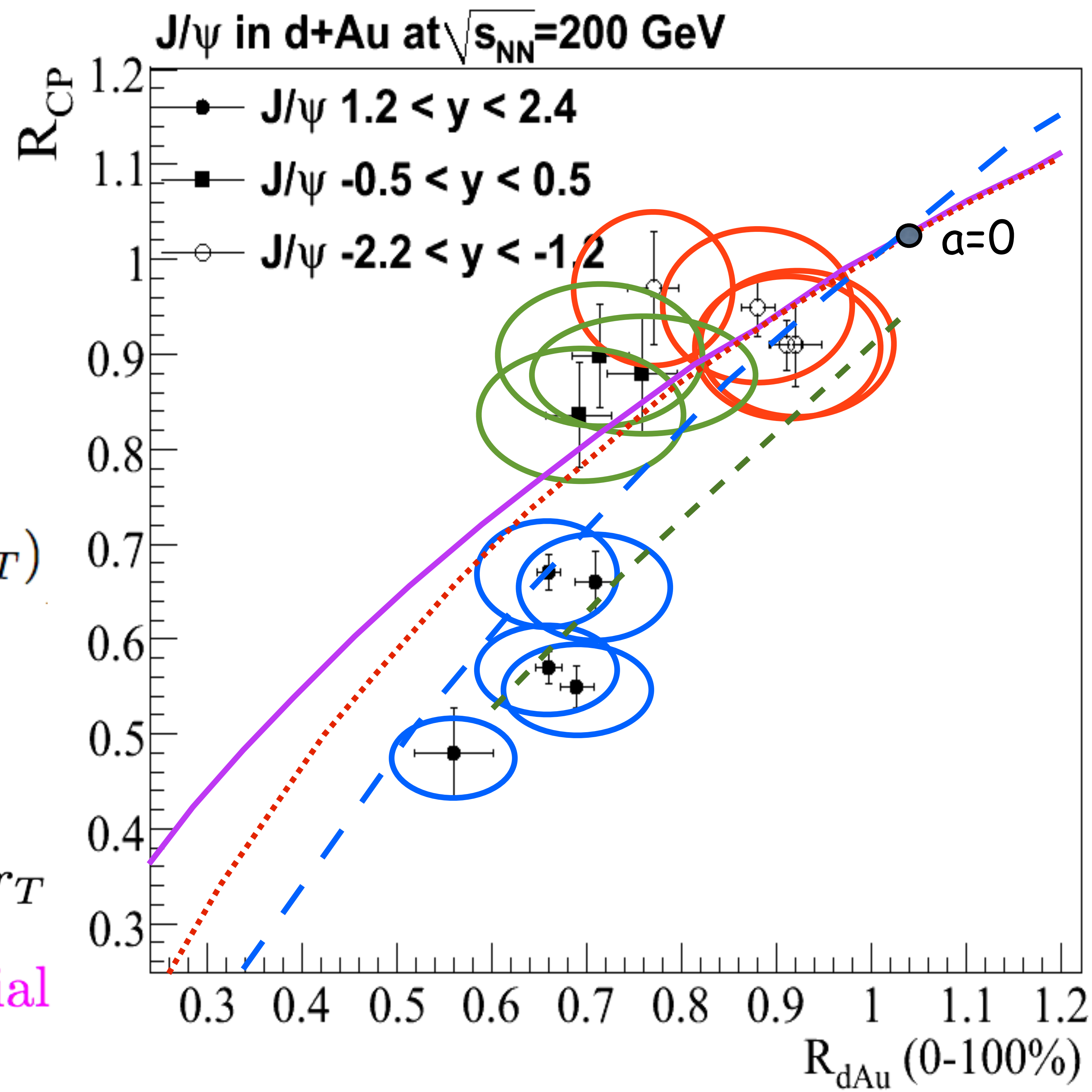
$$R_{dAu,i}(a) = \int f_i\,(r_T)\,M\,(r_T; a)\,dr_T$$

$M(r_T; a) = e^{-a\Lambda(r_T)}$ exponential

$M(r_T; a) = 1 - a\Lambda(r_T)$ linear

$M(r_T; a) = 1 - a\Lambda(r_T)^2$ quadratic

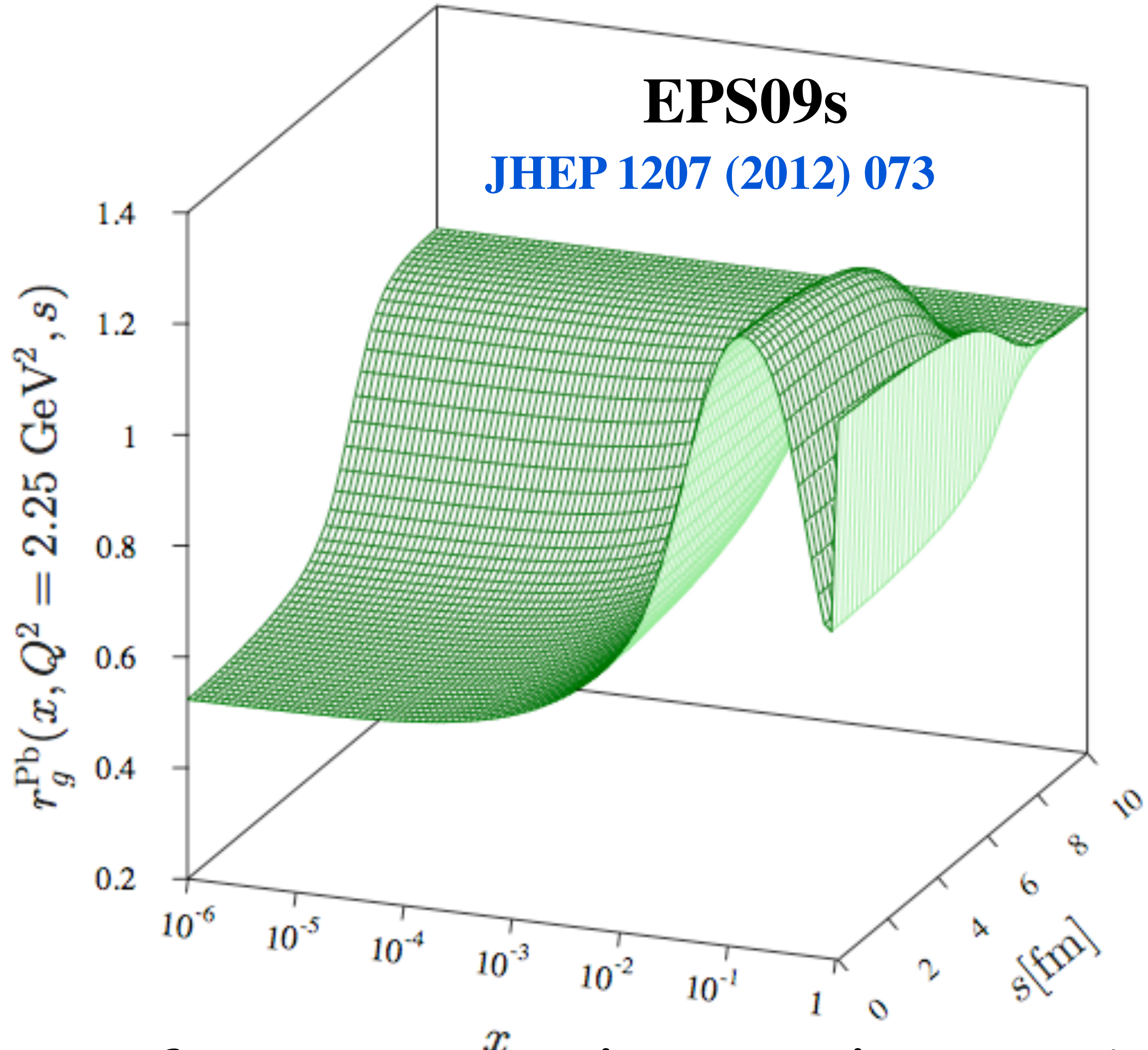
PRL107, 142301 (2011)



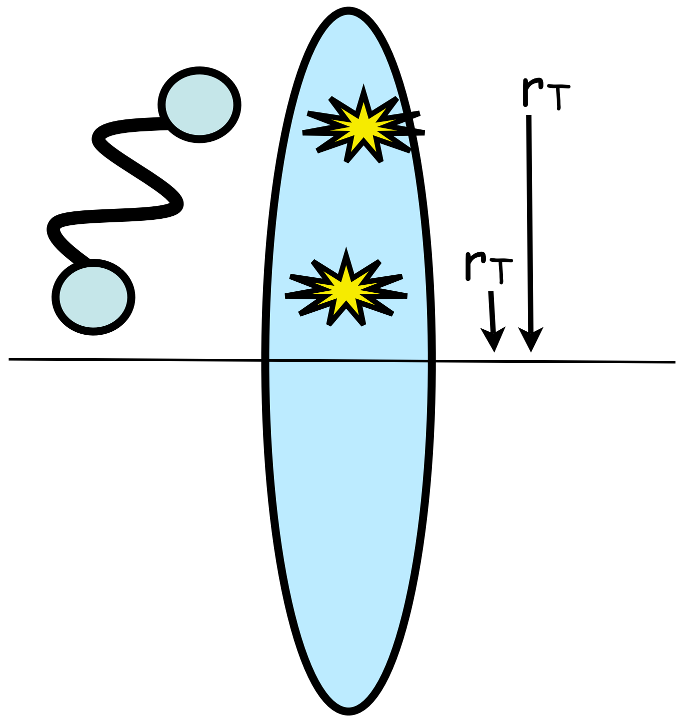

- qualitatively agreement with CGC model as well

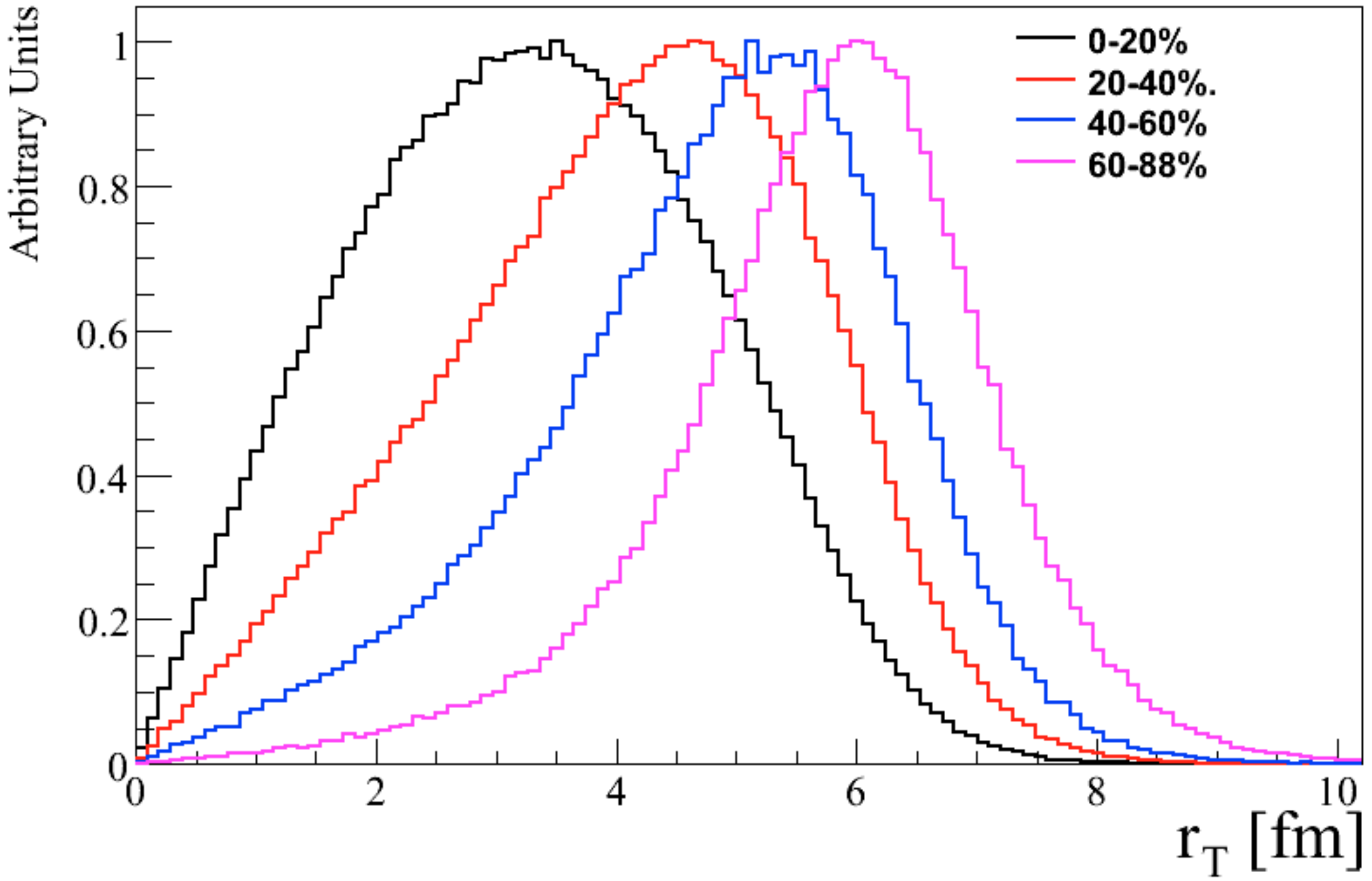
[Kharzeev and Tuchin, Nucl. Phys. A770, 40 (2006)]

PHENIX




- EPS09s uses data from several A nuclei to obtain impact parameter dependence of the nPDF
- should nPDF for a fixed impact parameter be different in different nuclei ?
  - coherent effects ?
  - weaker parton modification on the nucleus surface independently of the nucleus size ?
  - difractive processes



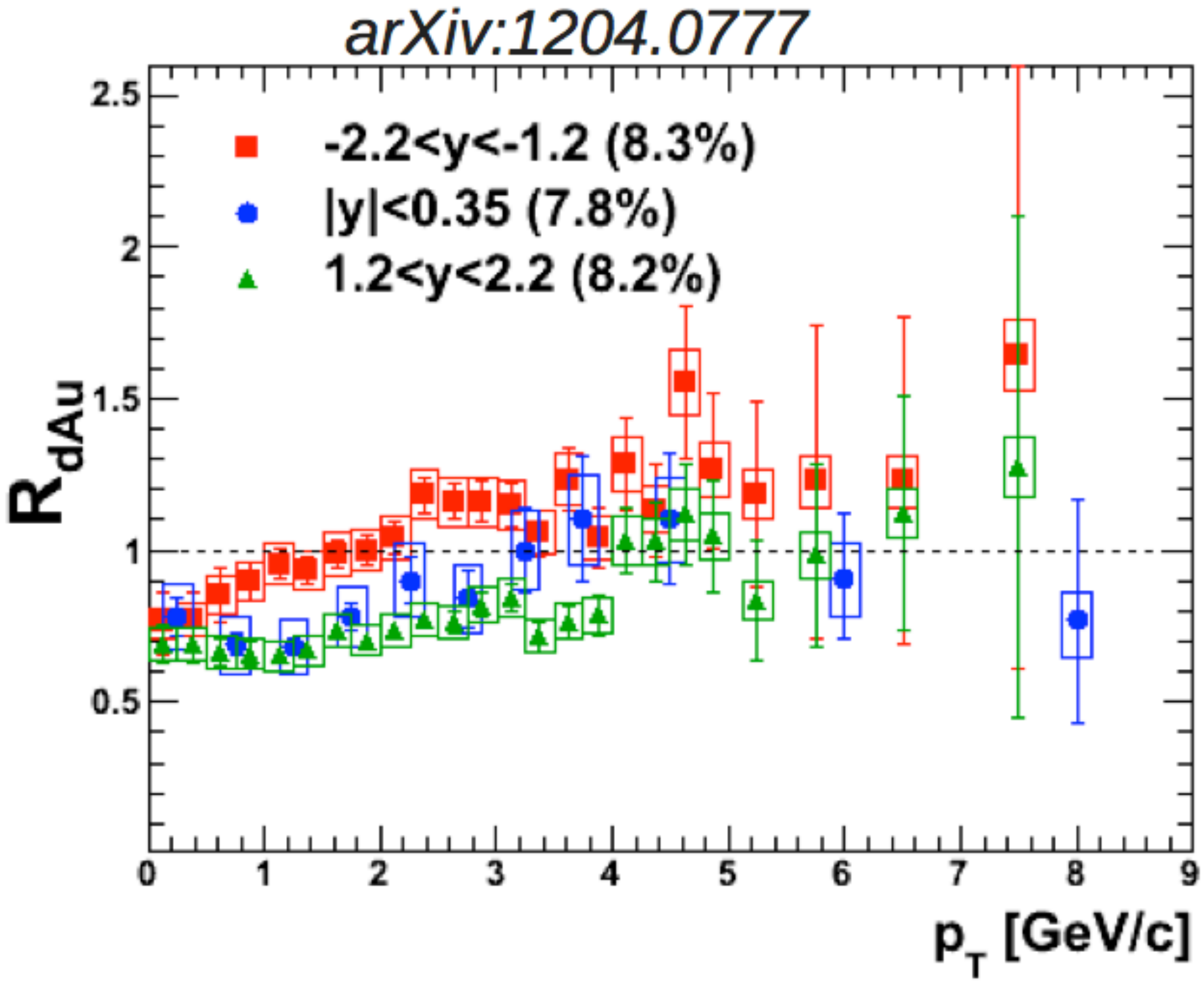

- impact parameter is still poorly determined in d+Au collisions

- p+Au collisions can provide a more controlled impact parameter determination

- however, Poisson fluctuations in particle multiplicities will still limit the precision in determining the impact parameter

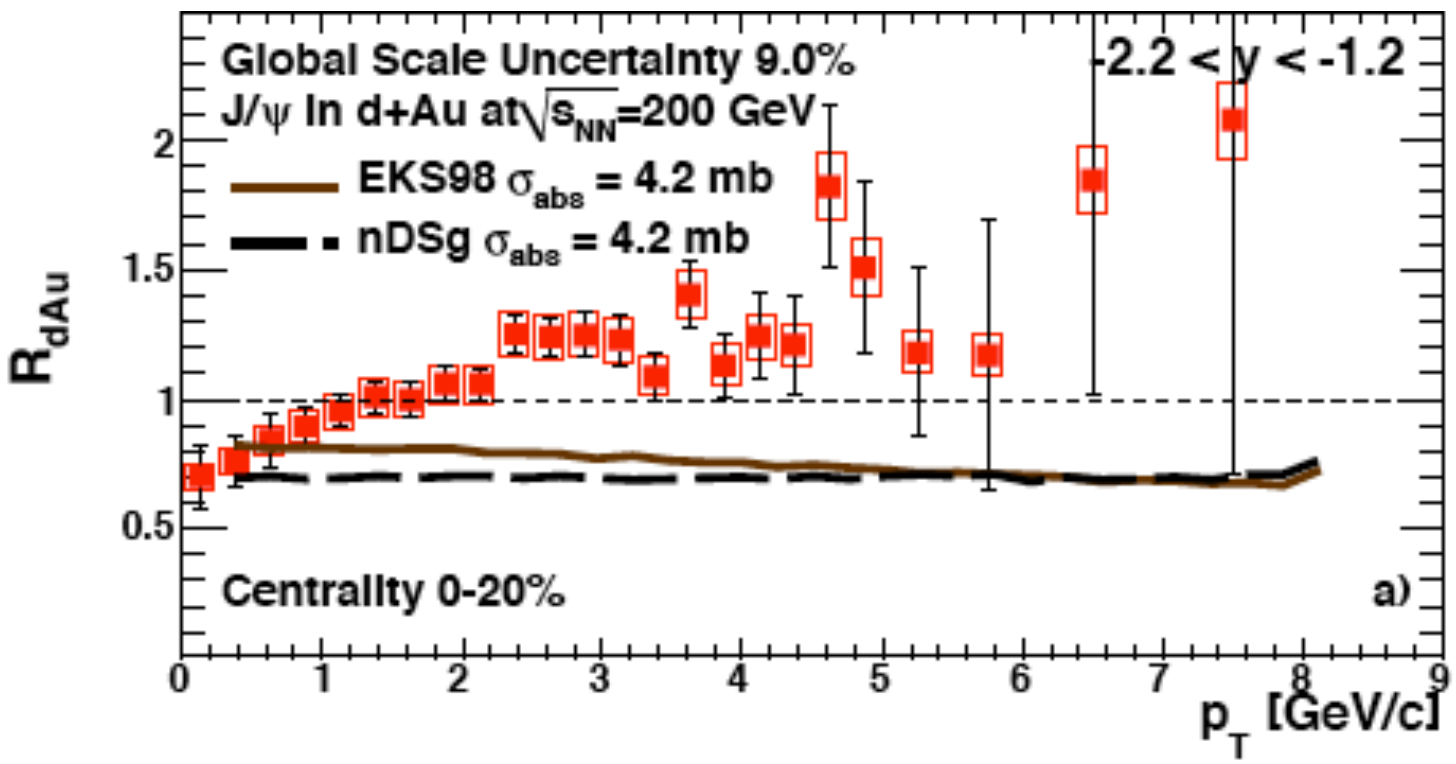
# Final State Effects

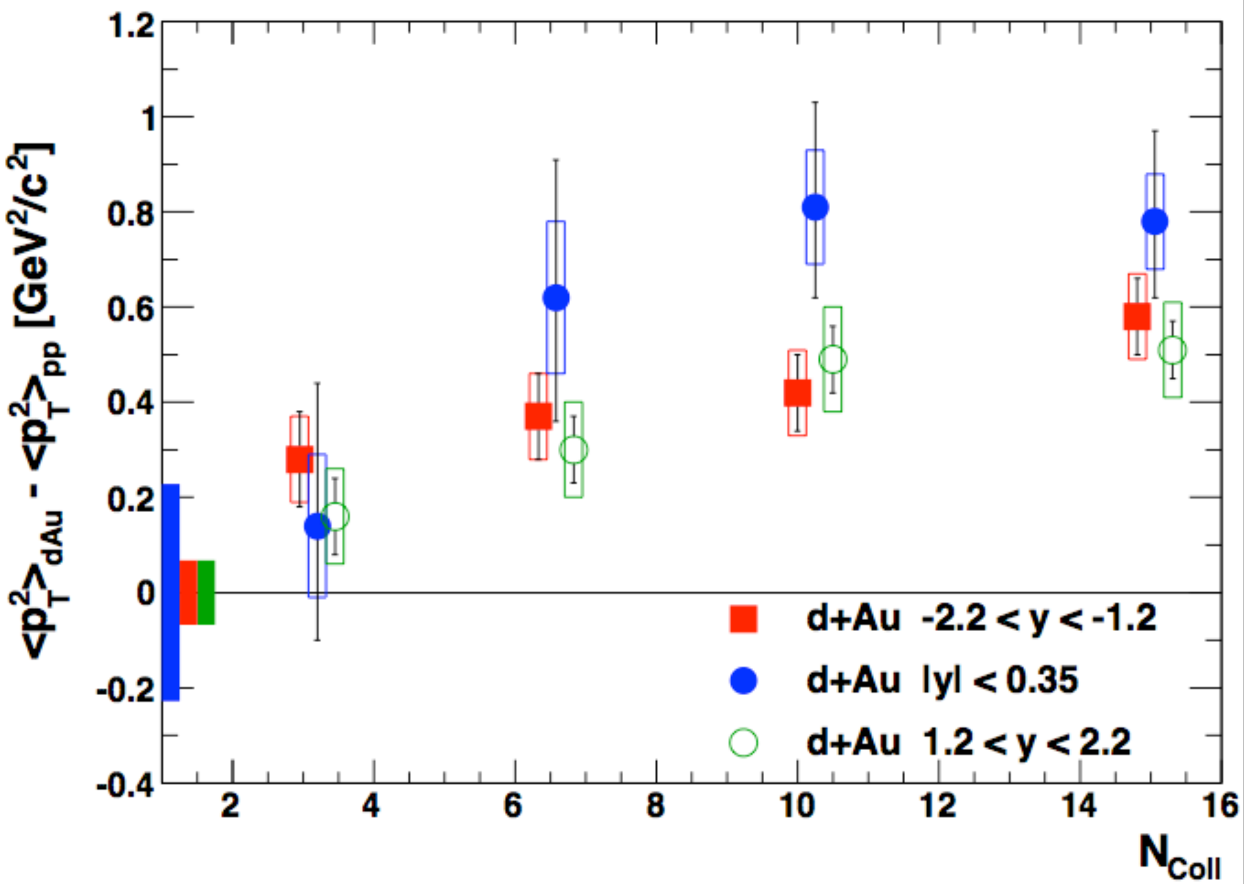
# $p_T$ dependence



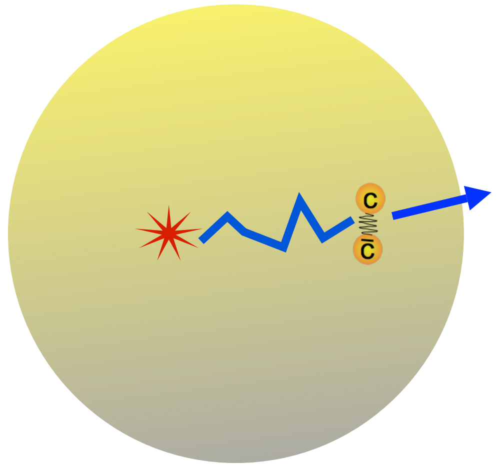

- increase with $p_T$ in all rapidities
- result can explain the smaller $J/\psi$ suppression at high $p_T$ in A+A

# $p_T$ dependence




**Significant Cronin effect**




- $R_{dA}$ increasing with $p_T$ is larger than what is expected from shadowing/anti-shadowing

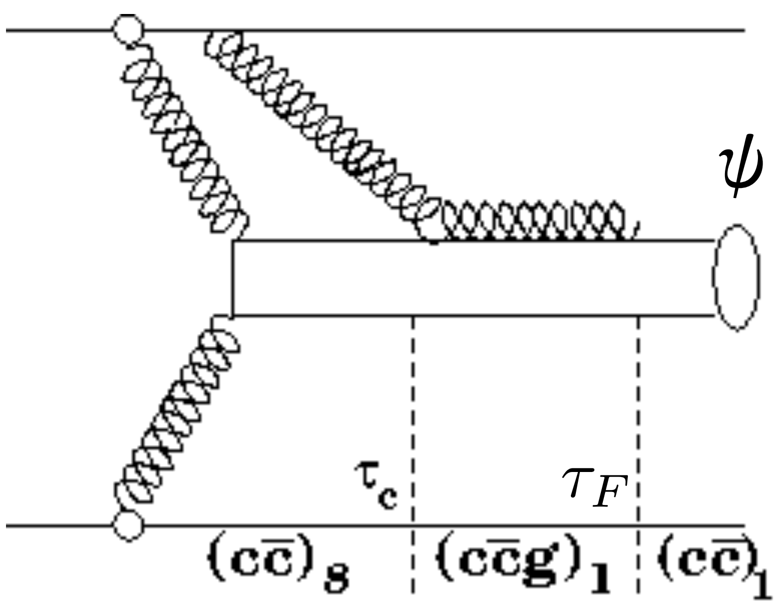
- increase of $\langle p_T^2 \rangle$ with number of collisions supports the multiple scattering effect

# Breakup in hadronic matter

- breakup should depend on the binding energy

| State | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi'_b$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| Mass (GeV) | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| $\Delta E$ (GeV) | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |
| $\Delta M$ (GeV) | 0.02 | −0.03 | 0.03 | 0.06 | −0.06 | −0.06 | −0.08 | −0.07 |
| $r_0$ (fm) | 0.50 | 0.72 | 0.90 | 0.28 | 0.44 | 0.56 | 0.68 | 0.78 |

- however, color octet charmonium is in a pre-resonant stage for y>-2 in p+A collisions at RHIC




$$\tau_F = \frac{2}{M_{D\bar{D}} - M_\psi} \frac{E_g}{M_\psi} \quad (J/\psi \text{ rest frame})$$

$$\tau_F(\text{RHIC}) \approx 41 e^{y} \text{ fm}$$

[Nucl. Phys. A770,40(2006)]

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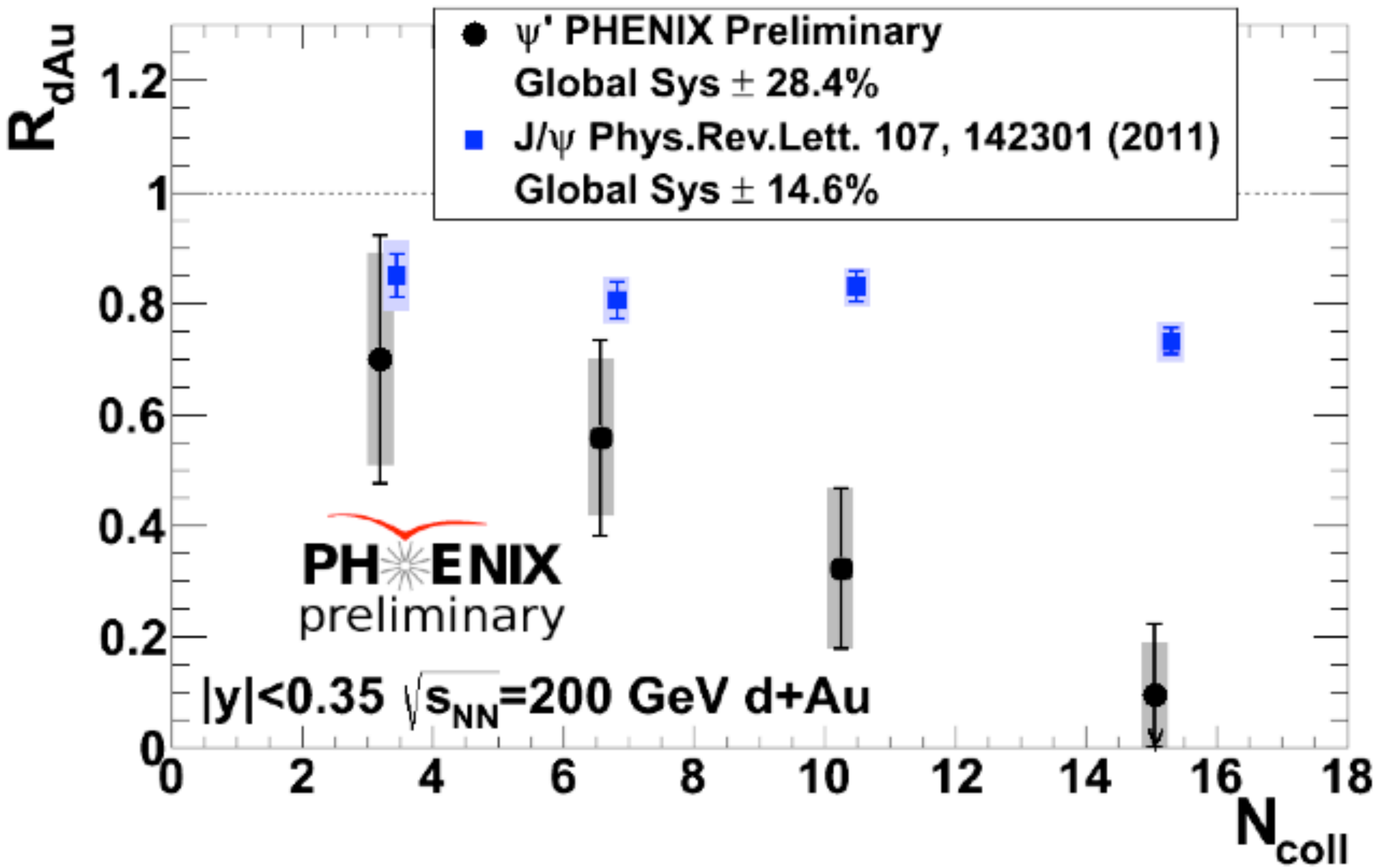
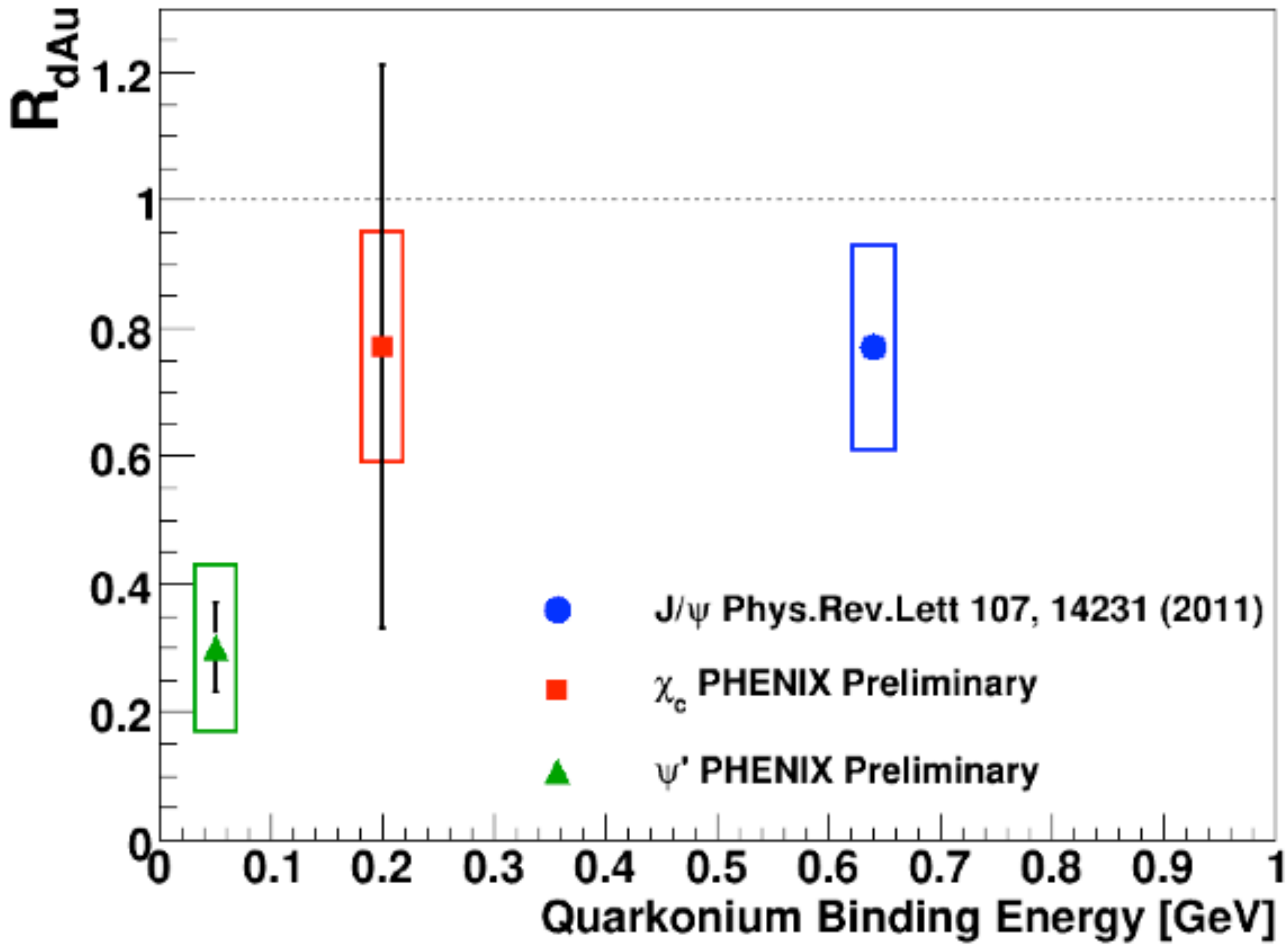
# J/ψ, ψ' $R_{dA}$ in d+Au at mid-rapidity




- same initial-state effects for J/ψ and ψ'
- stronger suppression of ψ' indicates $c\bar{c}$ cross the nucleus as distinct objects

# Binding energy dependence




CAVEATS:

- $\chi_c$ is produced as a color singlet and may be fully formed when crossing the nucleus
- measured $J/\psi$ includes ~10% of $\psi'$ and ~30% of $\chi_c$ feed-down

# Next Measurements

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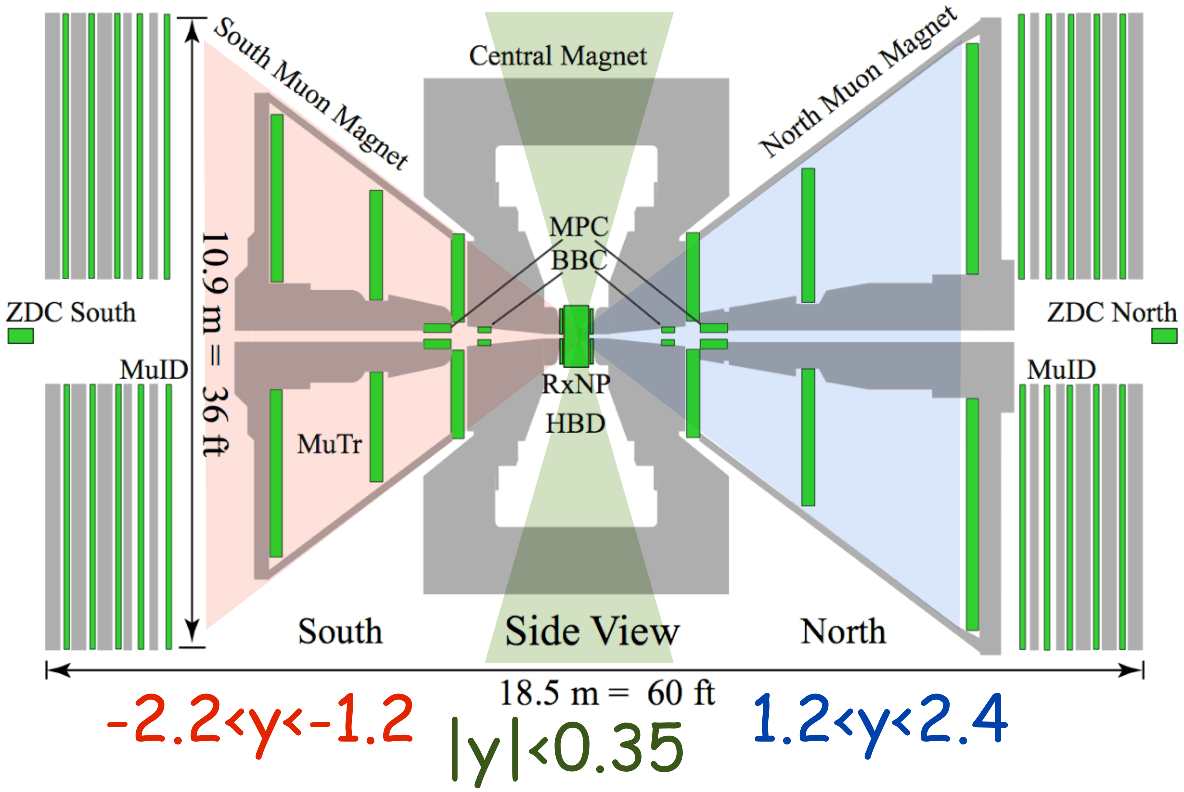
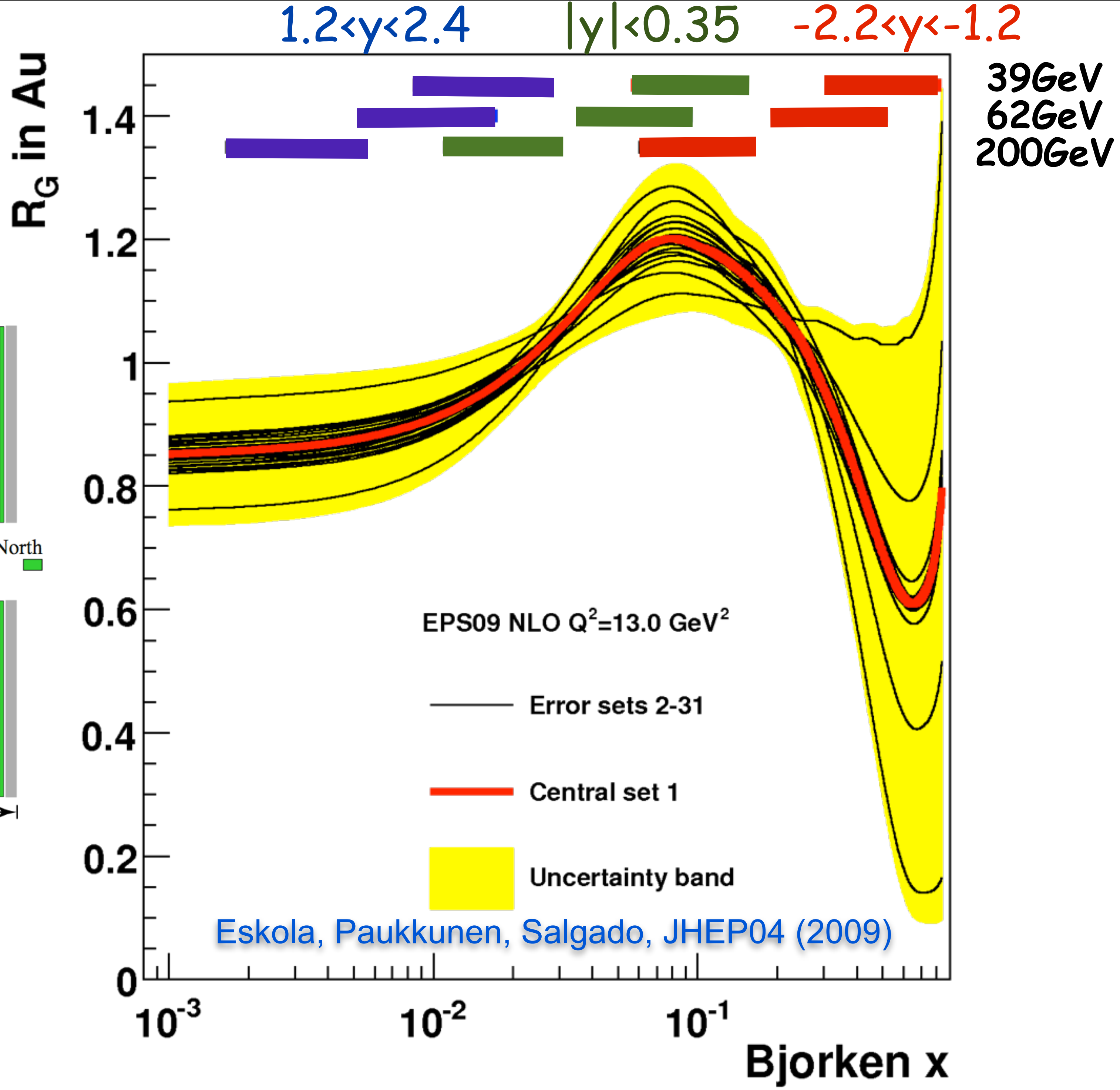


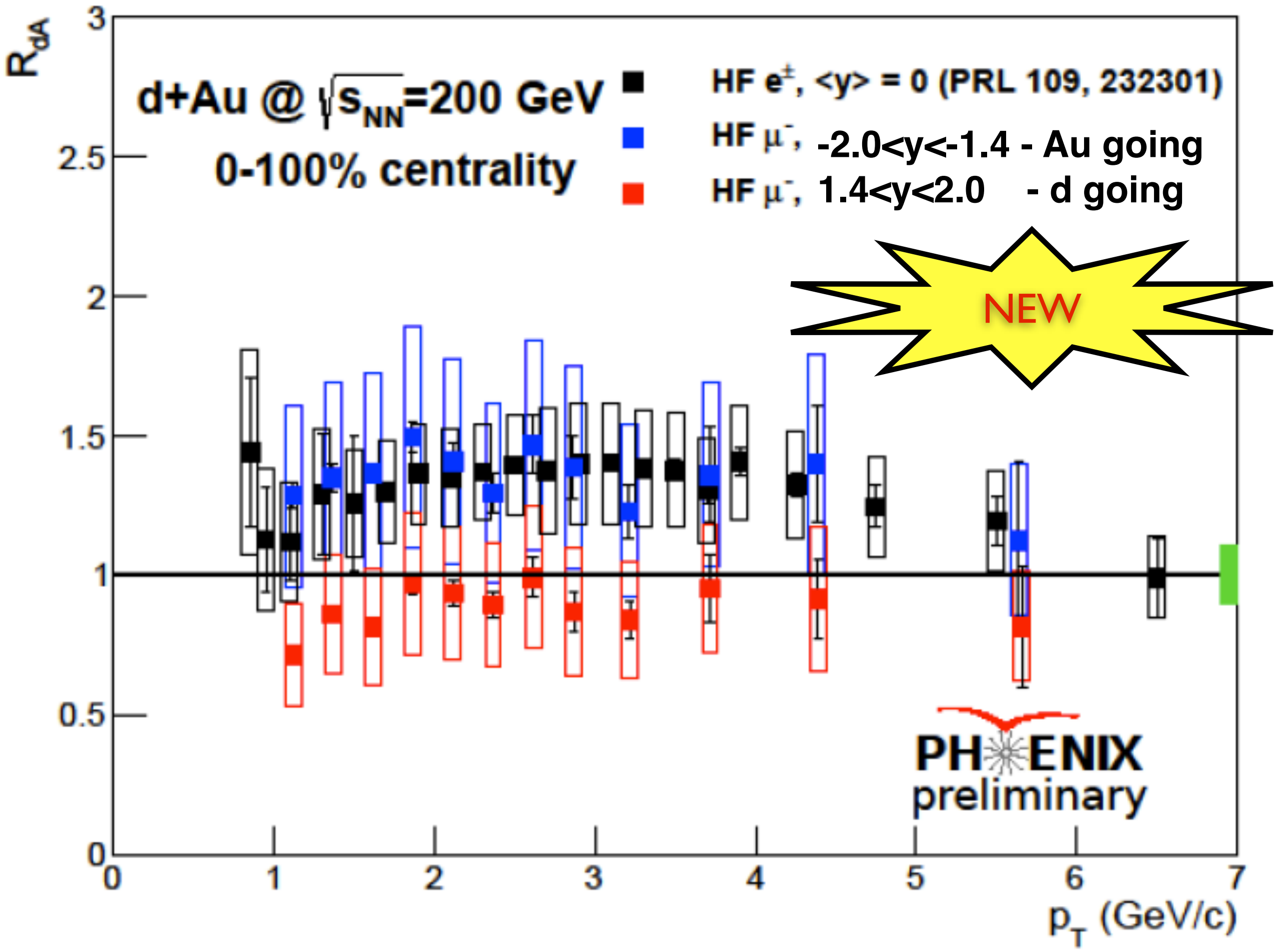




Variation of the nucleus and the energy collisions can allows

- control path length, saturation scale, nucleus size dependence of nPDF
- scanning of larger x at the same rapidity range if luminosity allows

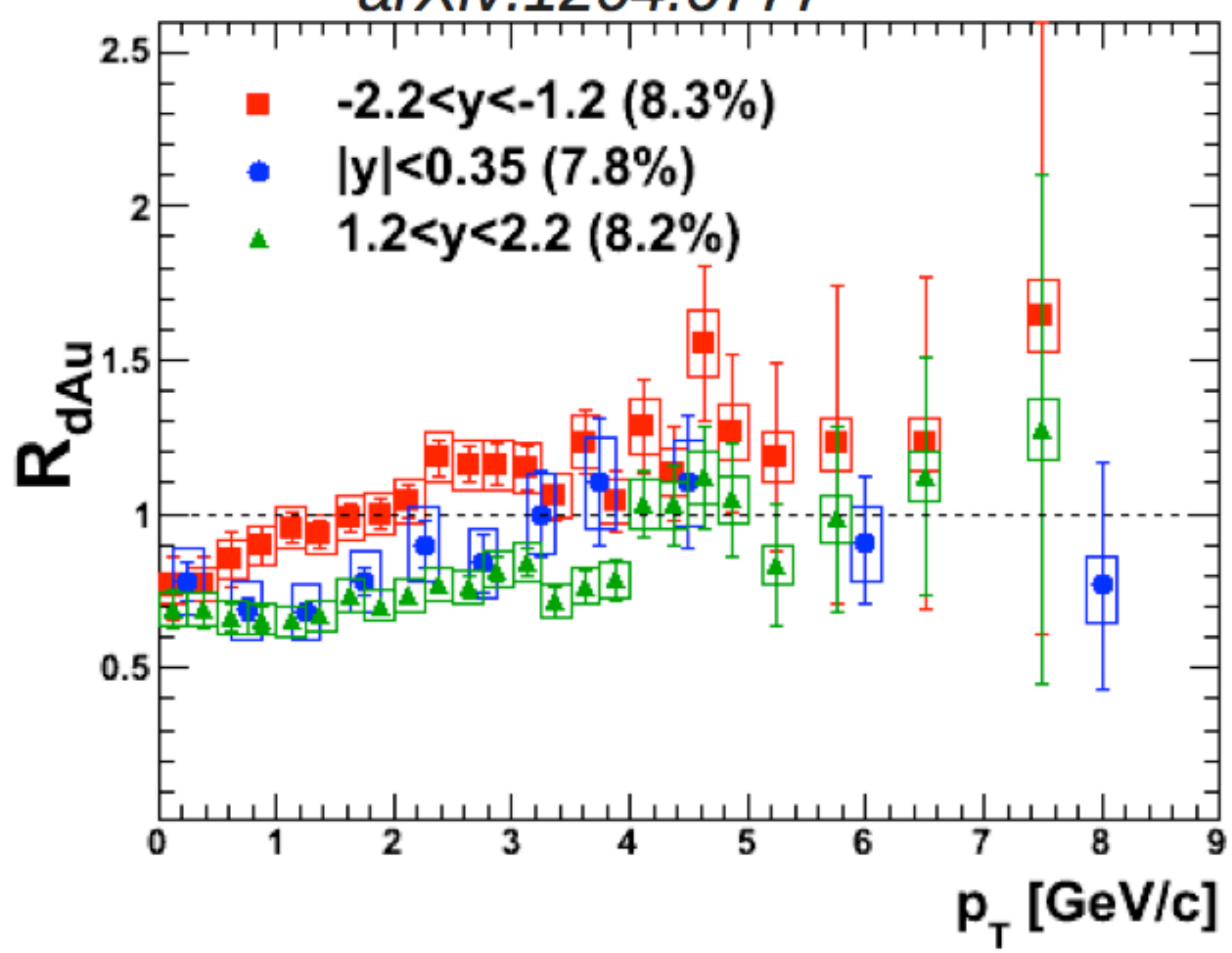
PHENIX

# Muons from Heavy Flavor




# J/ψ

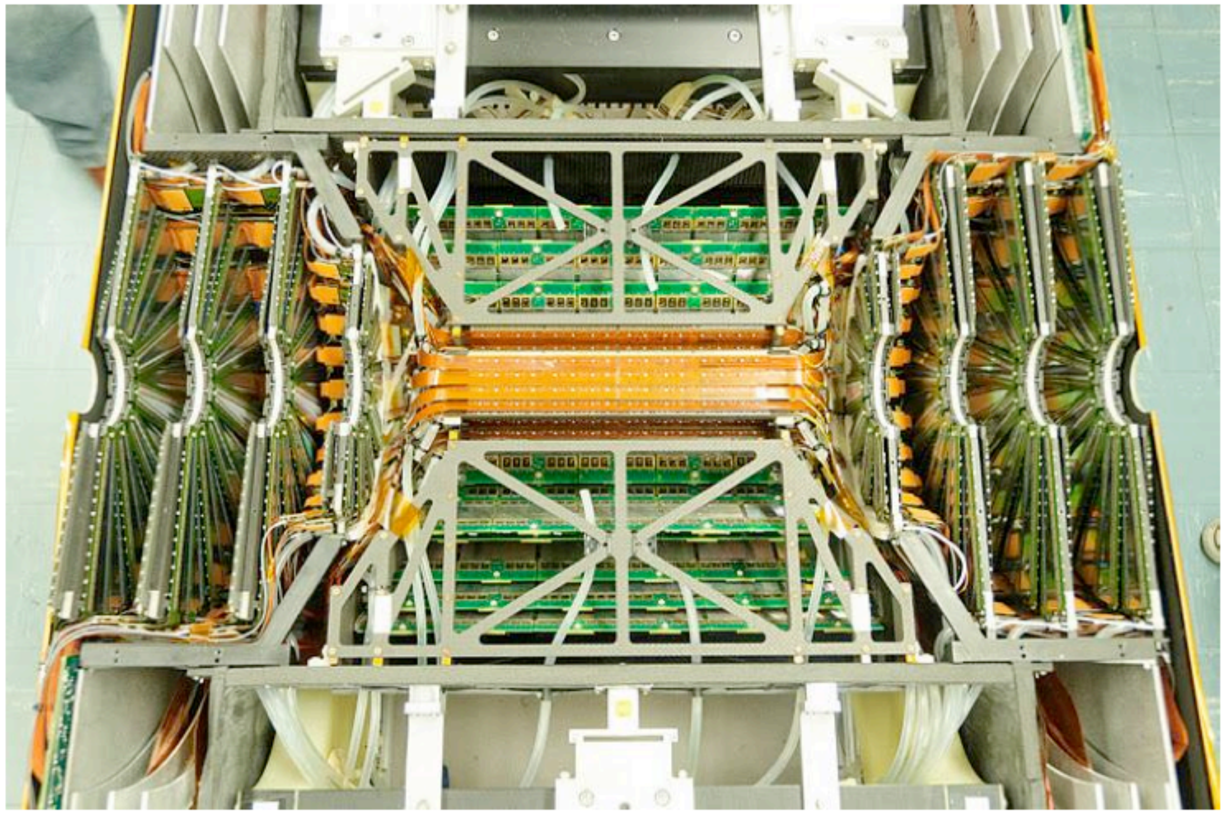
*arXiv:1204.0777*

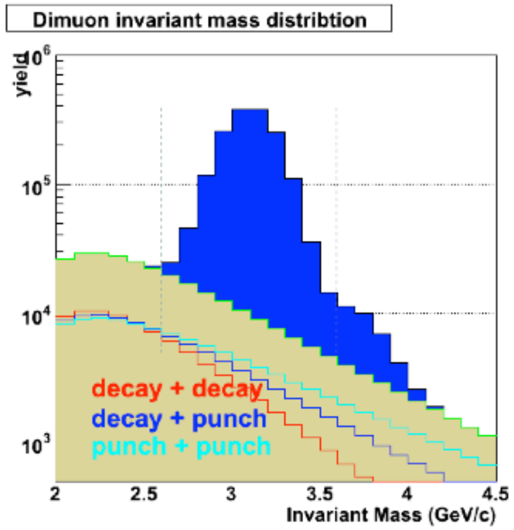


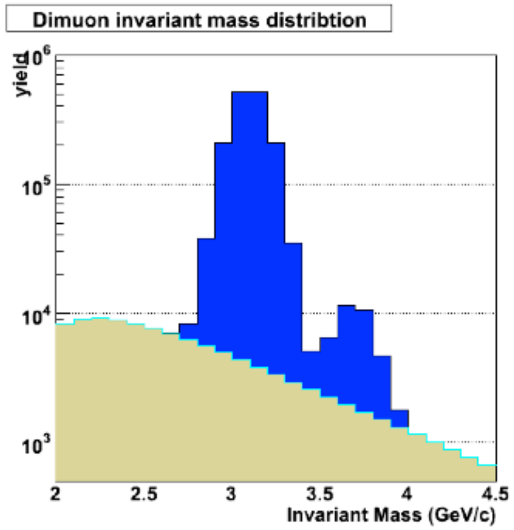

- starting to have data from heavy flavor in low and high-x
- quarkonia $R_{dA}$ relative to HF can isolate final state effects

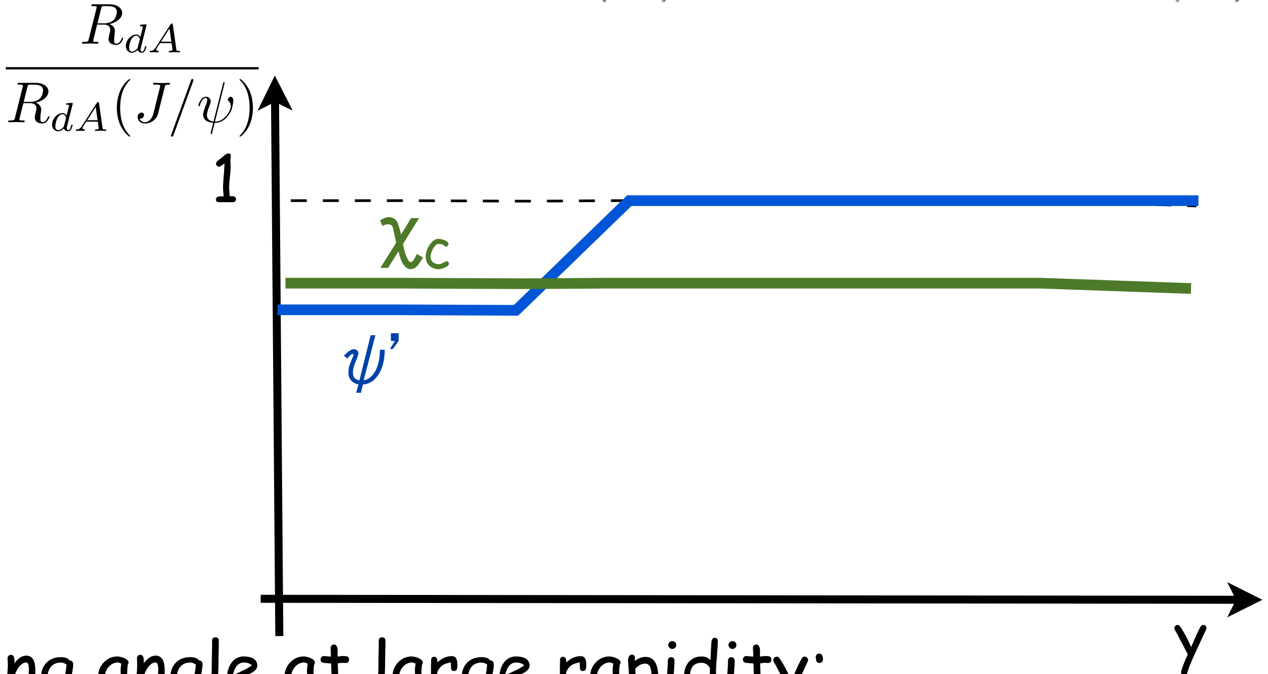
# PRESENT and FUTURE

## Installed vertex detectors: VTX and FVTX



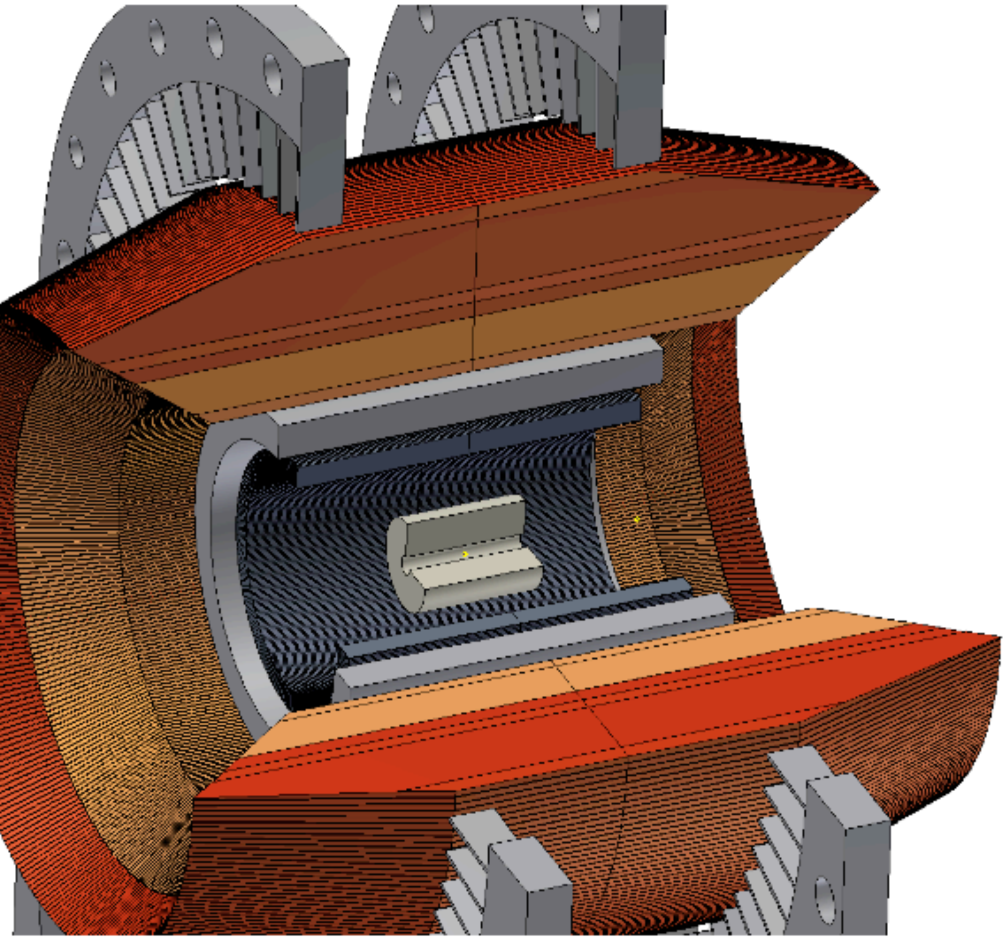


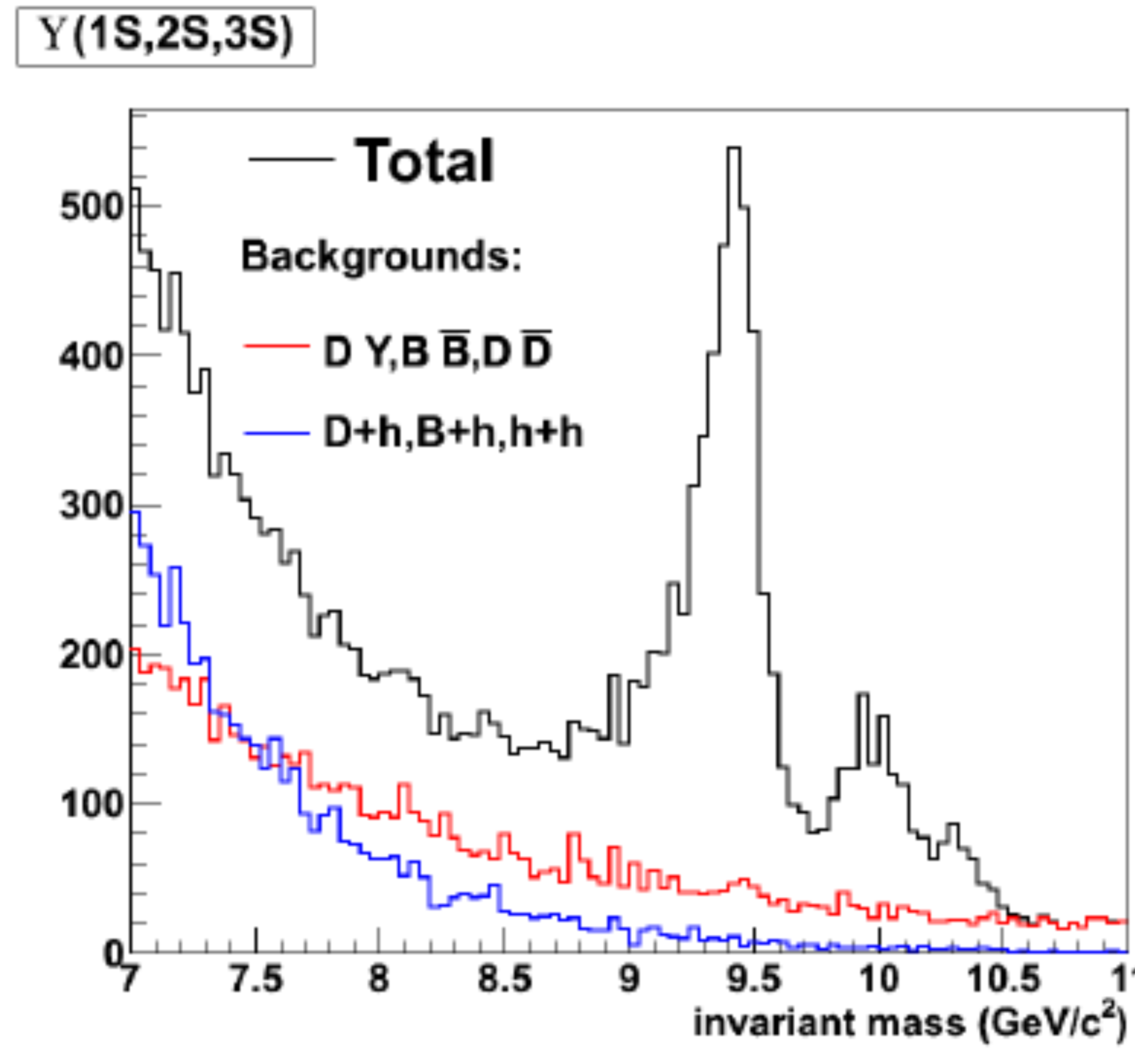



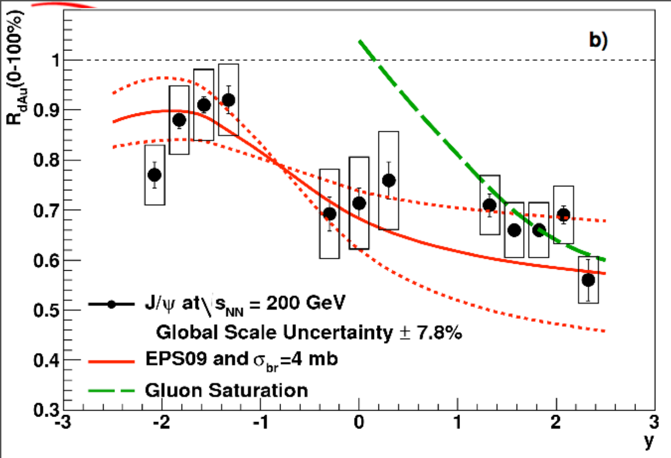

- measure open heavy flavor
- better measurement of dimuon opening angle at large rapidity:
  - $J/\psi$, $\psi'$ separation
  - study of formation/neutralization times when looking rapidity dependence
- open the possibility to study radiative decay of $\chi_c$ using $\gamma$ conversions in VTX

# FUTURE
## solenoidal PHENIX (sPHENIX)

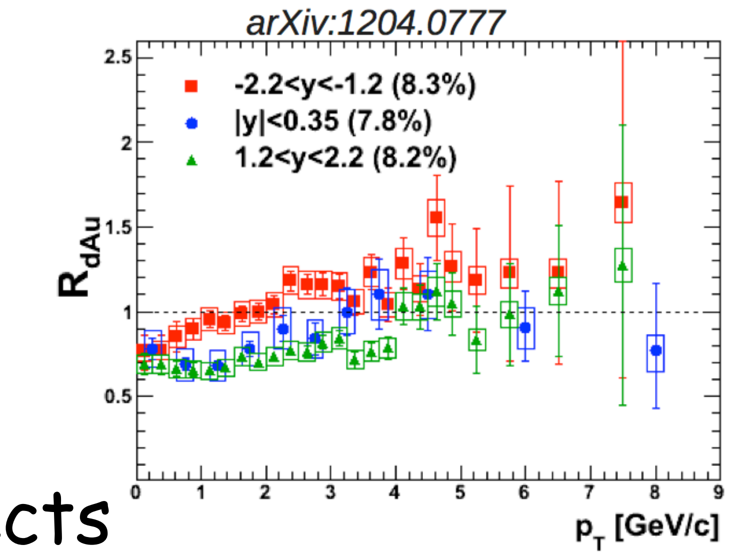




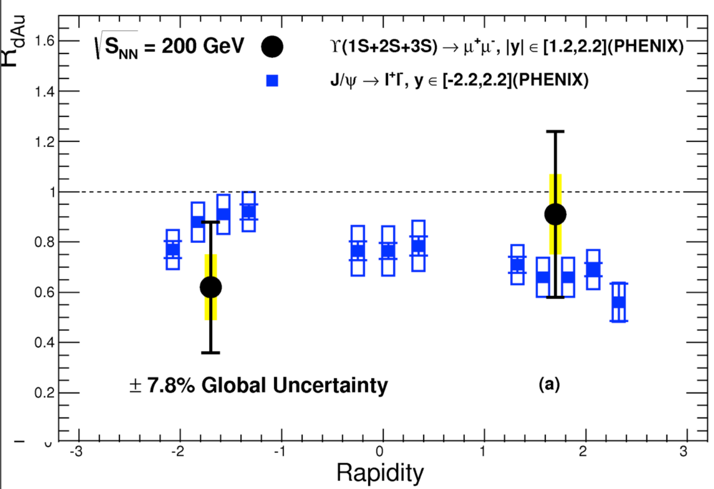

- high luminosities
- full azimuthal, $-1.1<\eta<4$ coverage
- calorimetry at large $\eta$ will allows rapidity dependence of $\chi_c$ measurement
- 2T solenoid provides $\Upsilon$(1S), $\Upsilon$(2S+3S) separation at mid- and forward rapidity

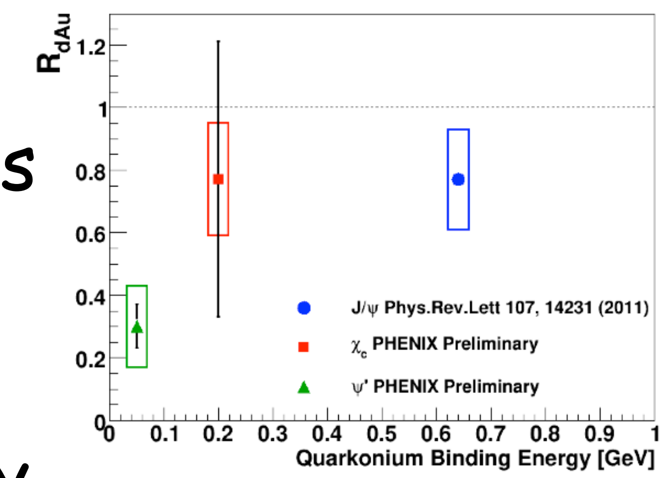



# Conclusions

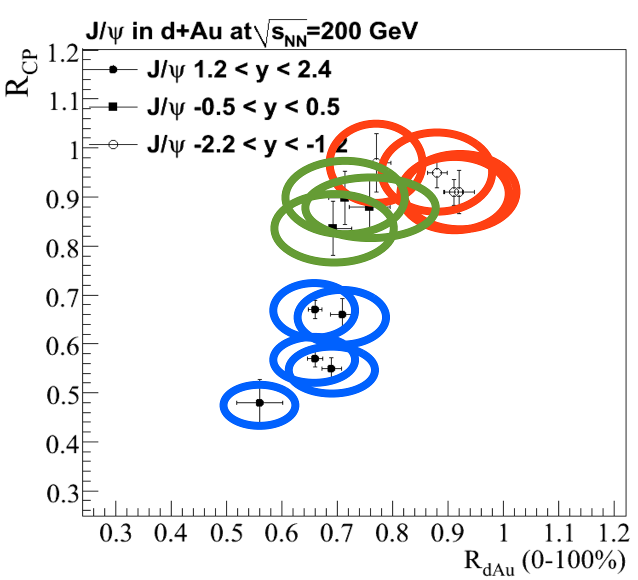


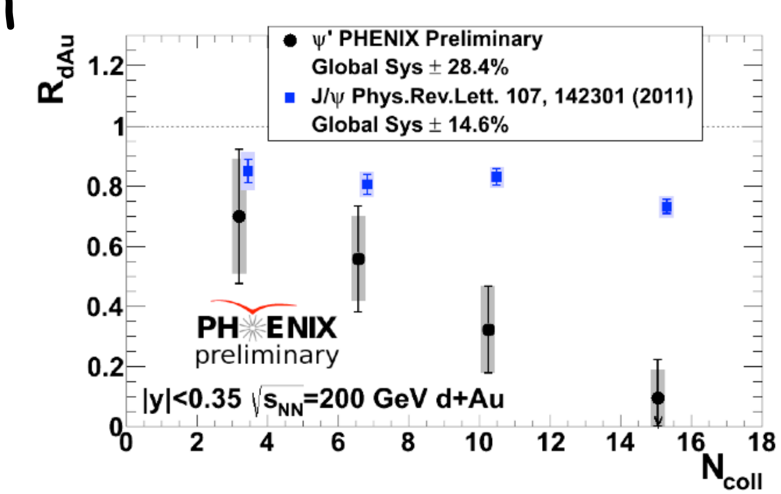

PHENIX has explored several aspects of CNM effects with different states of quarkonia.



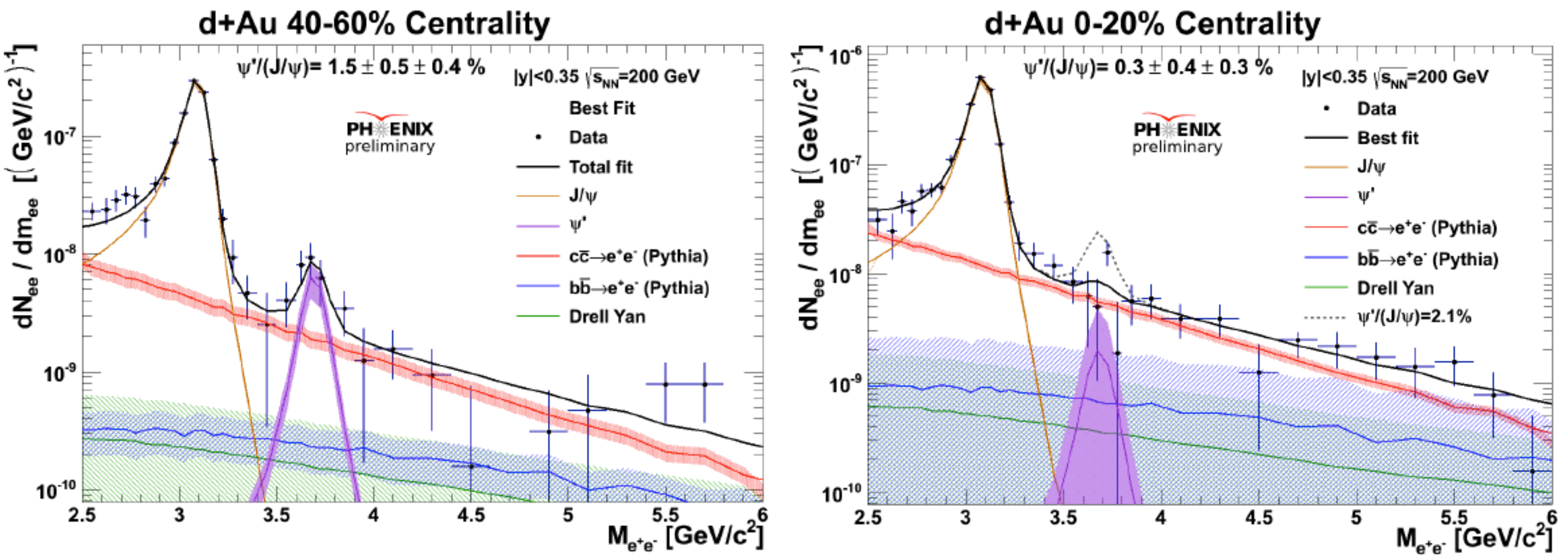

More is coming in future p+A collisions where nucleus size and energy variations along with new detectors will introduce more knobs in the study of initial and final state effects on particle production in heavy ion collisions.



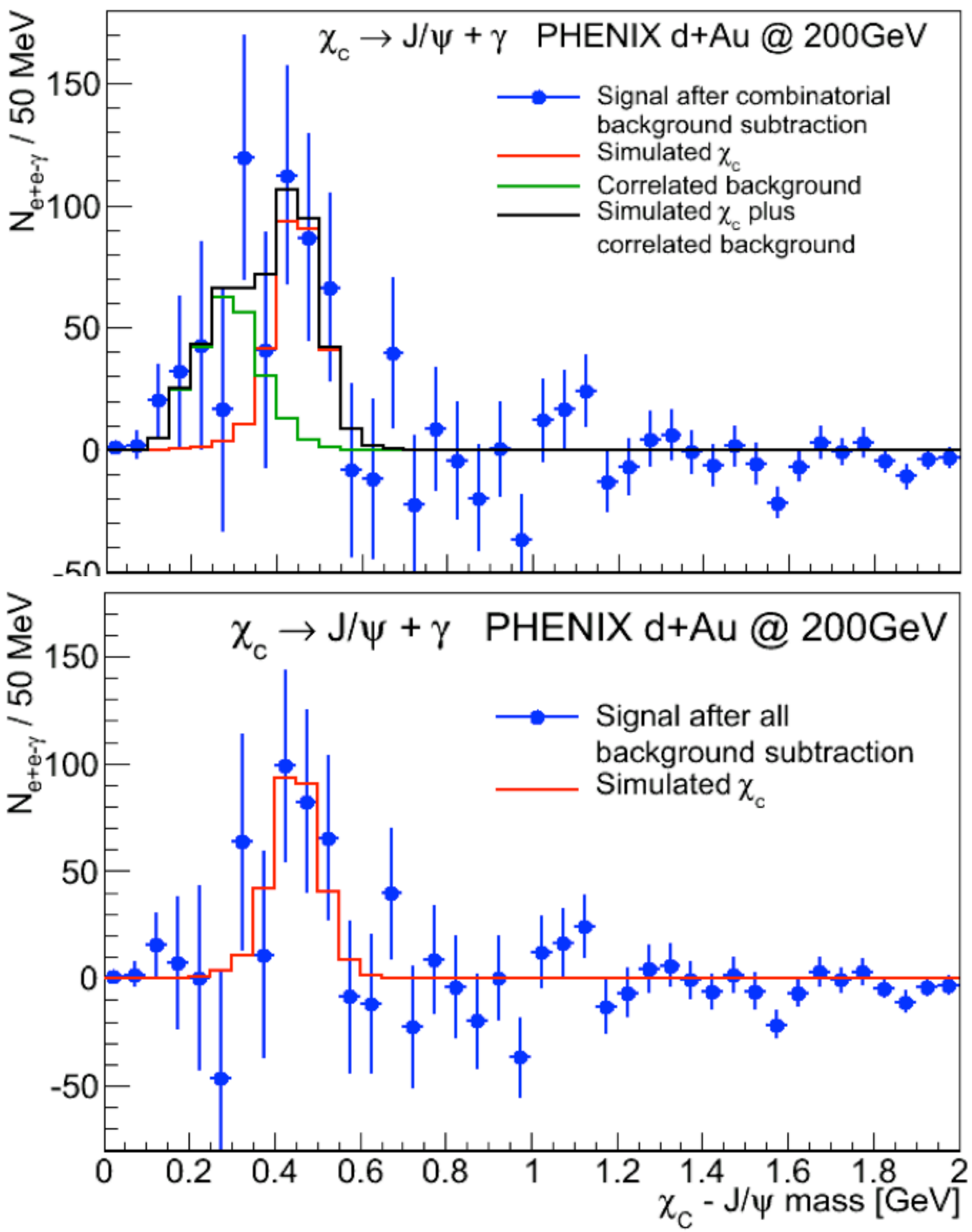



# BACKUP SLIDES

PHENIX



d+Au 40-60% Centrality
ψ'/(J/ψ)= 1.5 ± 0.5 ± 0.4 %
|y|<0.35 √sNN=200 GeV
Best Fit
Data
Total fit
J/ψ
ψ'
cc̄→e+e- (Pythia)
bb̄→e+e- (Pythia)
Drell Yan
PHENIX preliminary
dNee / dmee [(GeV/c²)-1]
Me+e- [GeV/c²]
d+Au 0-20% Centrality
ψ'/(J/ψ)= 0.3 ± 0.4 ± 0.3 %
|y|<0.35 √sNN=200 GeV
Data
Best fit
J/ψ
ψ'
cc̄→e+e- (Pythia)
bb̄→e+e- (Pythia)
Drell Yan
ψ'/(J/ψ)=2.1%
PHENIX preliminary
dNee / dmee [(GeV/c²)-1]
Me+e- [GeV/c²]


χc → J/ψ + γ PHENIX d+Au @ 200GeV
Signal after combinatorial background subtraction
Simulated χc
Correlated background
Simulated χc plus correlated background
χc → J/ψ + γ PHENIX d+Au @ 200GeV
Signal after all background subtraction
Simulated χc
Ne+e-γ / 50 MeV
χC - J/ψ mass [GeV]