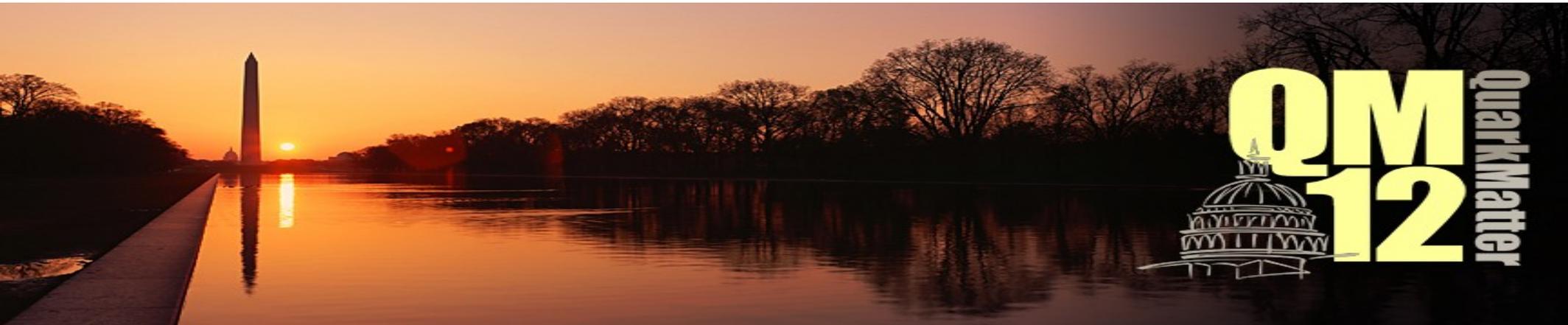




# Recent Heavy Quarkonia Results from PHENIX

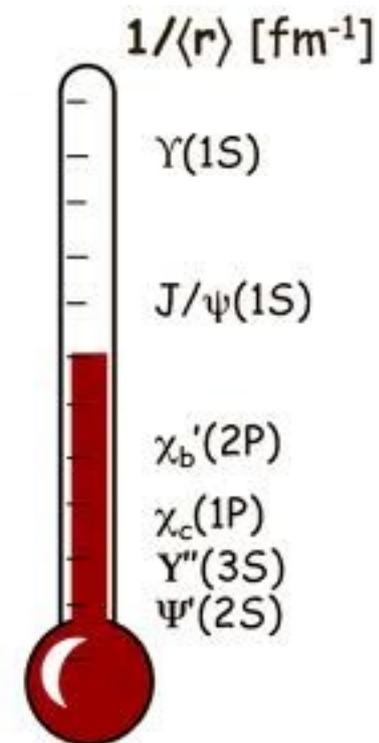
Darren McGlinchey  
Florida State University  
QM 2012 - 8/14/2012



Heavy quarkonia is an ideal tool to measure the screening length in the QGP.

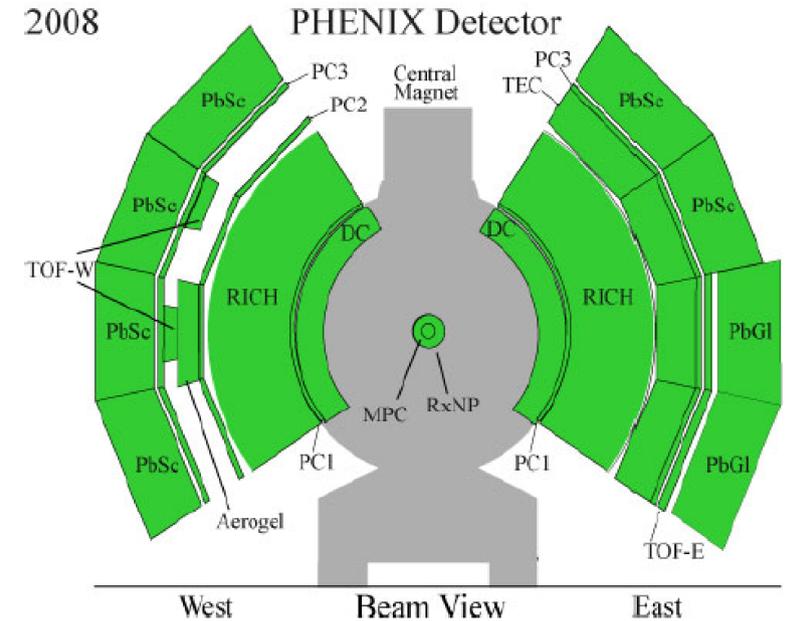
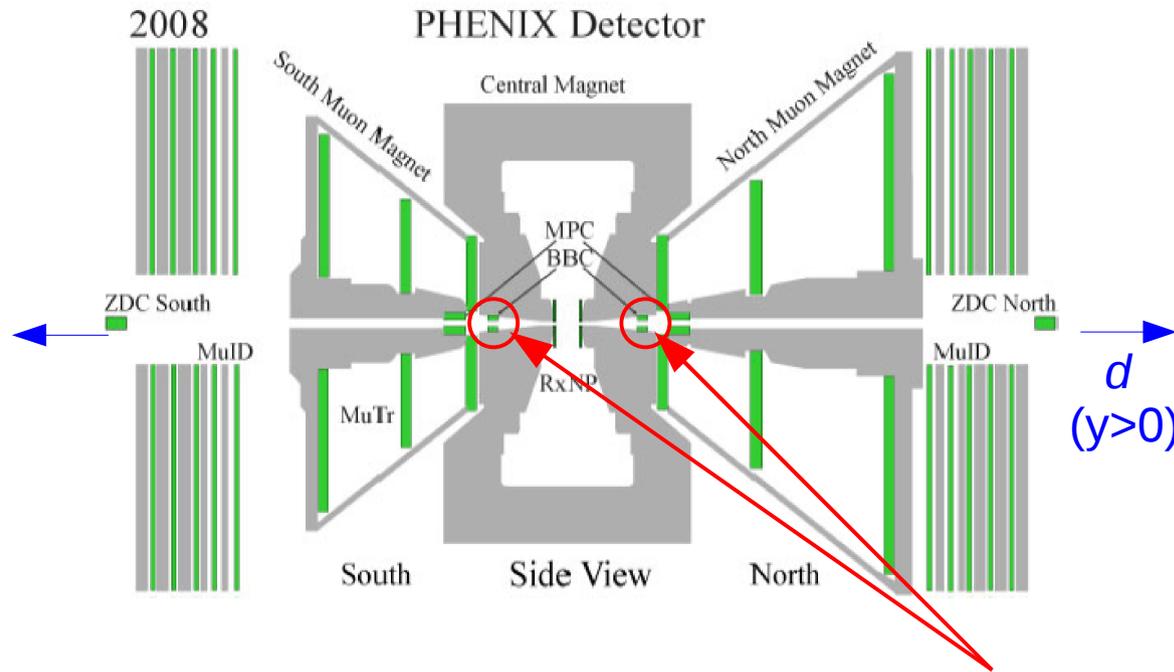
Only works if we know **all** our references!  
(Need p+p & p+A)

- Recent results from PHENIX:
  - $J/\psi R_{AA}$  at 39 & 62 GeV
  - $J/\psi R_{dAu}$  vs  $p_T$
  - $\psi' R_{dAu}$  at  $|y| < 0.35$
  - $\chi_c$  at  $|y| < 0.35$



See R. Hollis Talk for  
Cu+Au J/ψ Result.  
(Parallel 7D)

2008 Run



## Muon Arms

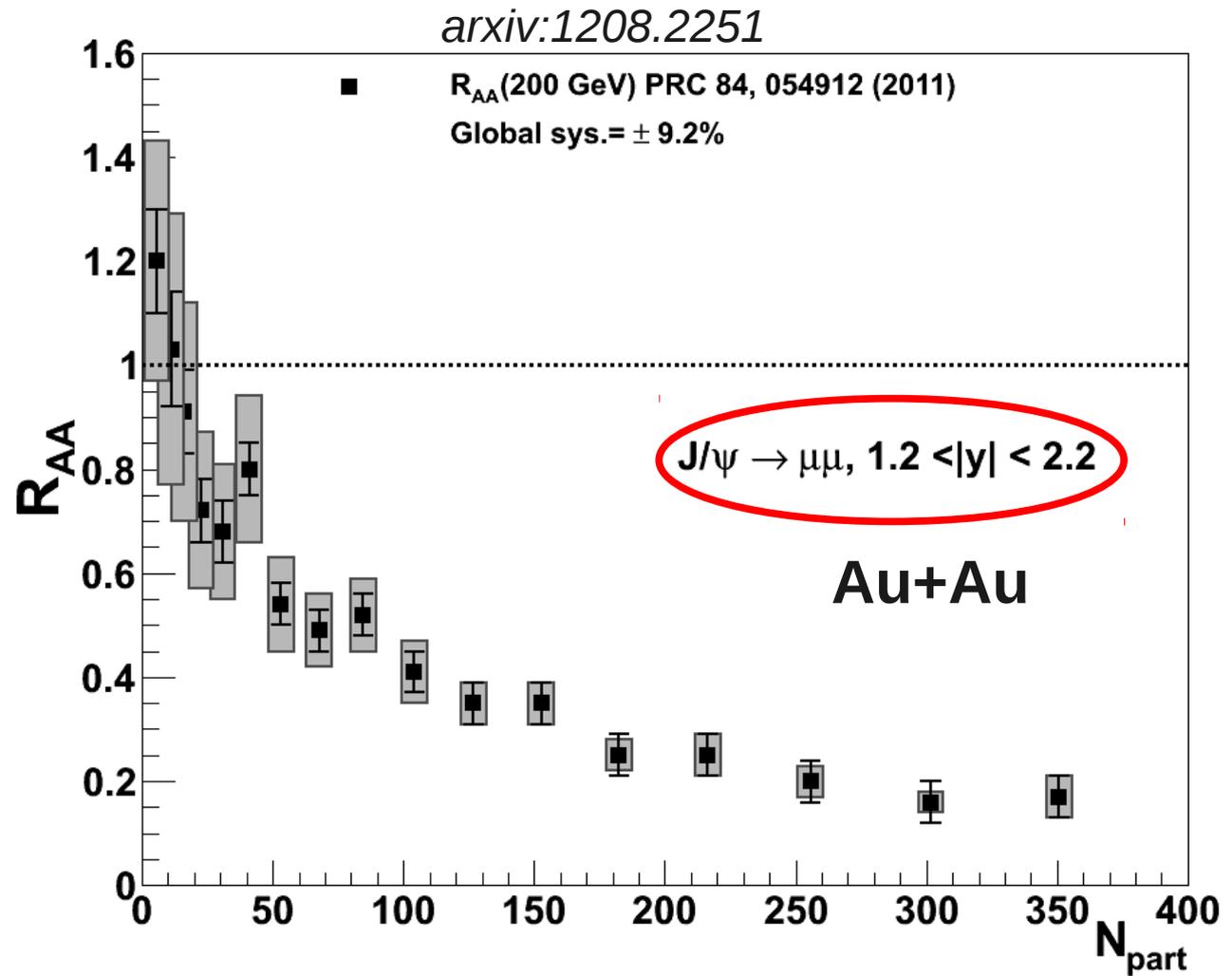
- Muons
- $1.2 < |\eta| < 2.4$
- $\Delta\phi = 2\pi$
- $J/\psi \rightarrow \mu^+\mu^-$

## Beam-Beam Counters

- Measure Centrality (impact parameter) as a percentage of BBC charge

## Central Arms

- Charged particles
- $|\eta| < 0.35$
- $\Delta\phi = \pi$
- $J/\psi \rightarrow e^+e^-$

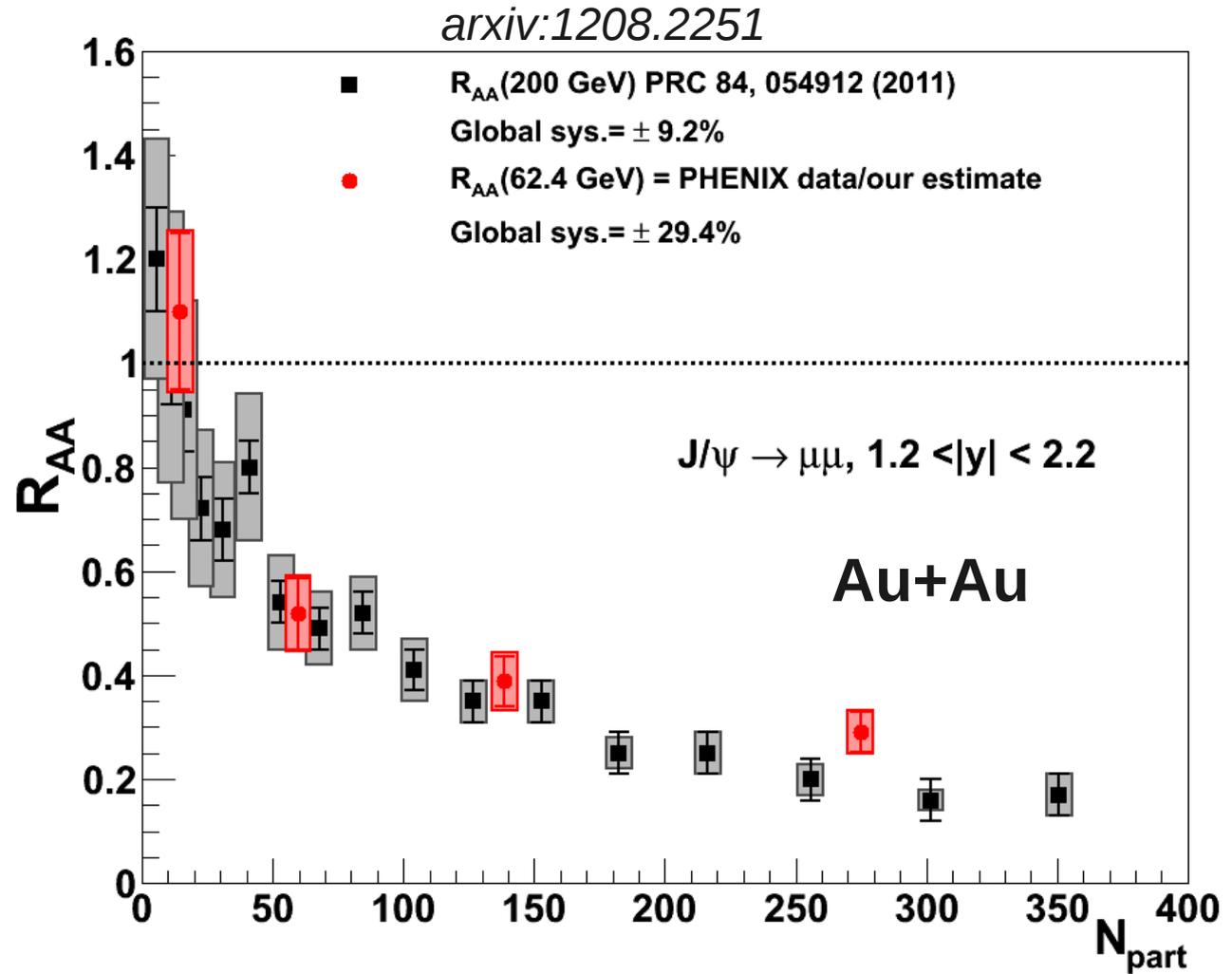


Previously published results on J/ψ  $R_{AA}$  at 200 GeV

New paper on J/ψ R<sub>AA</sub> at 39 & 62 GeV at forward rapidity

Observe similar suppression at 200 & 62 GeV.

No PHENIX p+p baseline at 62.4 GeV. Use extrapolation from measurements at the ISR.

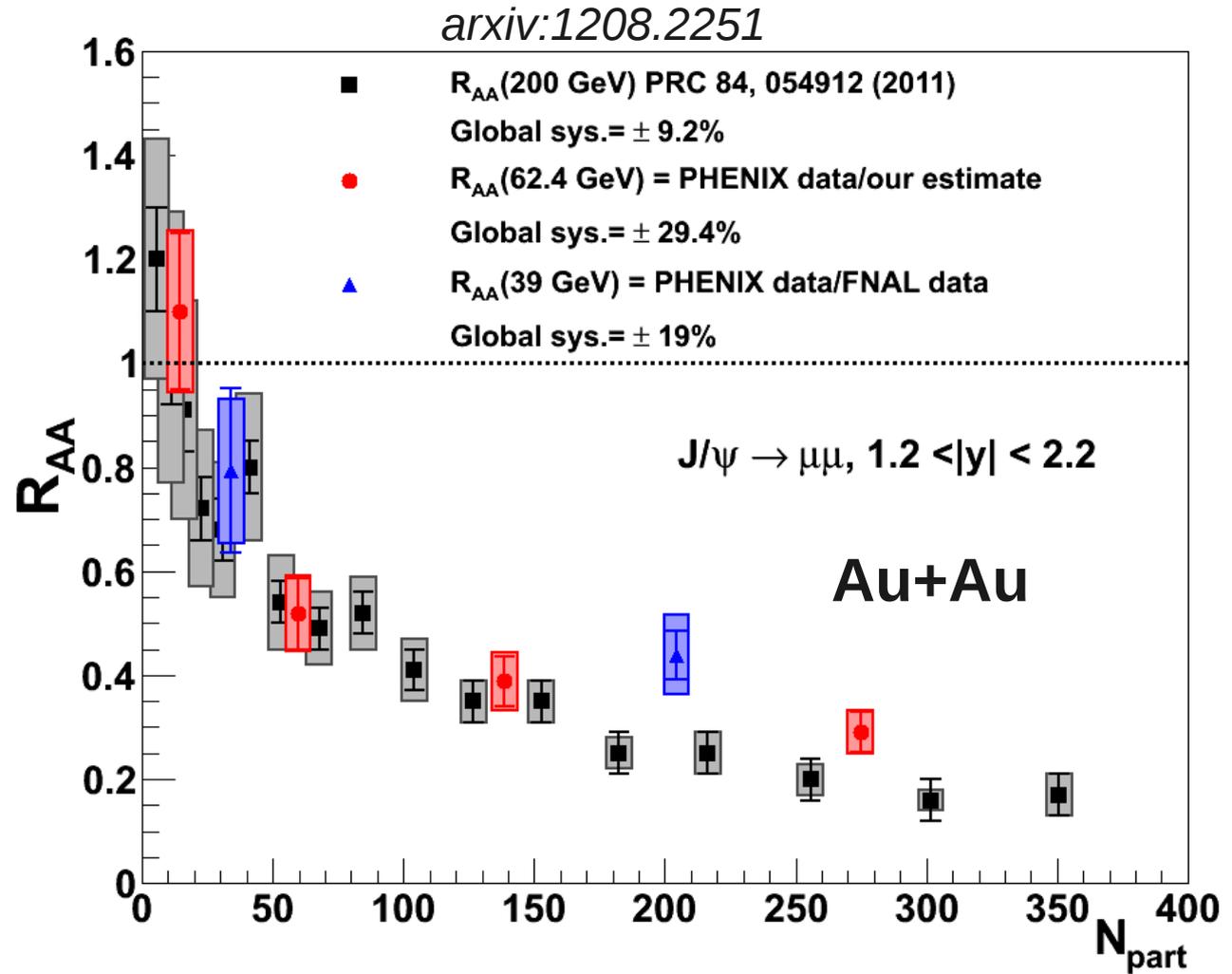


New results on J/ψ R<sub>AA</sub> at 62.4 GeV

New paper on J/ψ R<sub>AA</sub> at 39 & 62 GeV at forward rapidity

Observe similar suppression at 200 & 62 & 39 GeV.

No PHENIX p+p baseline at 39 GeV. Use extrapolation of results from Fermilab E789 and E866/NuSea.

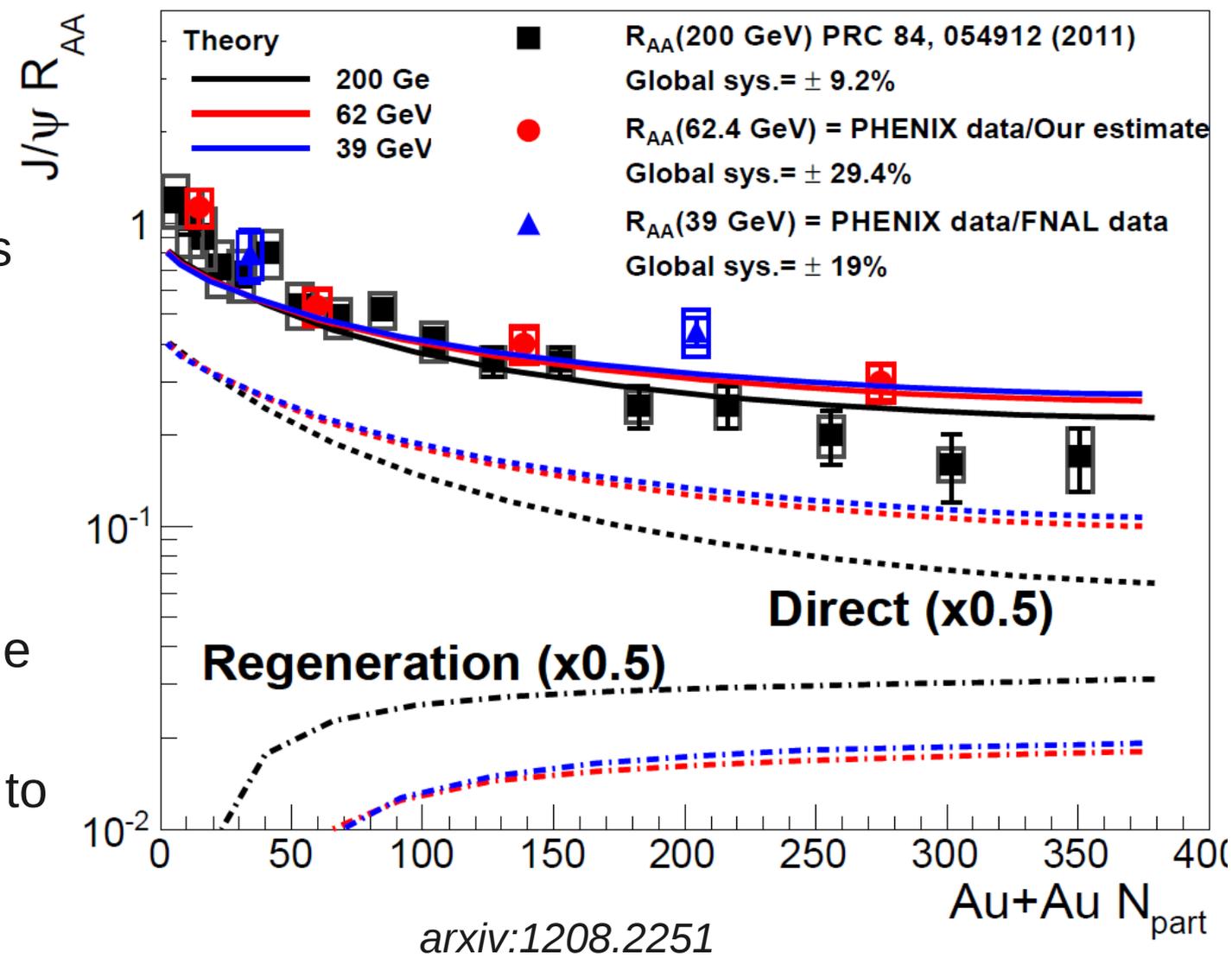


## New results on J/ψ R<sub>AA</sub> at 39 GeV

New paper on J/ψ R<sub>AA</sub> at 39 & 62 GeV at forward rapidity

Calculations by Zhao and Rapp. Include some CNM effects.

- Combined QGP effects are similar at each energy.
  - Direct suppression changes by ~50%
  - Regeneration compensates for the change.
- CNM effects expected to be different at the different energies.

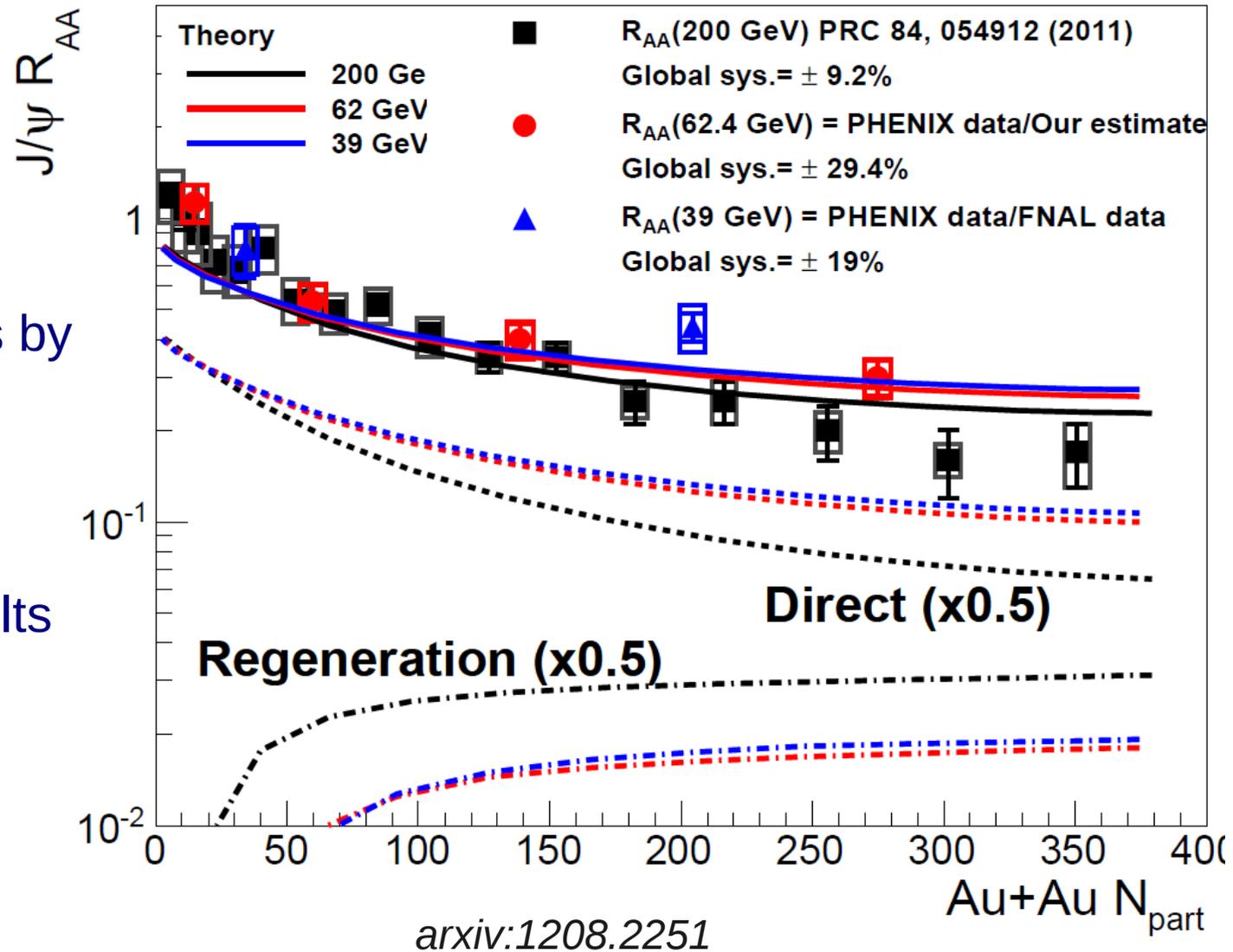


New paper on J/ψ  $R_{AA}$  at 39 & 62 GeV at forward rapidity

Calculations by Zhao and Rapp. Include some CNM effects.

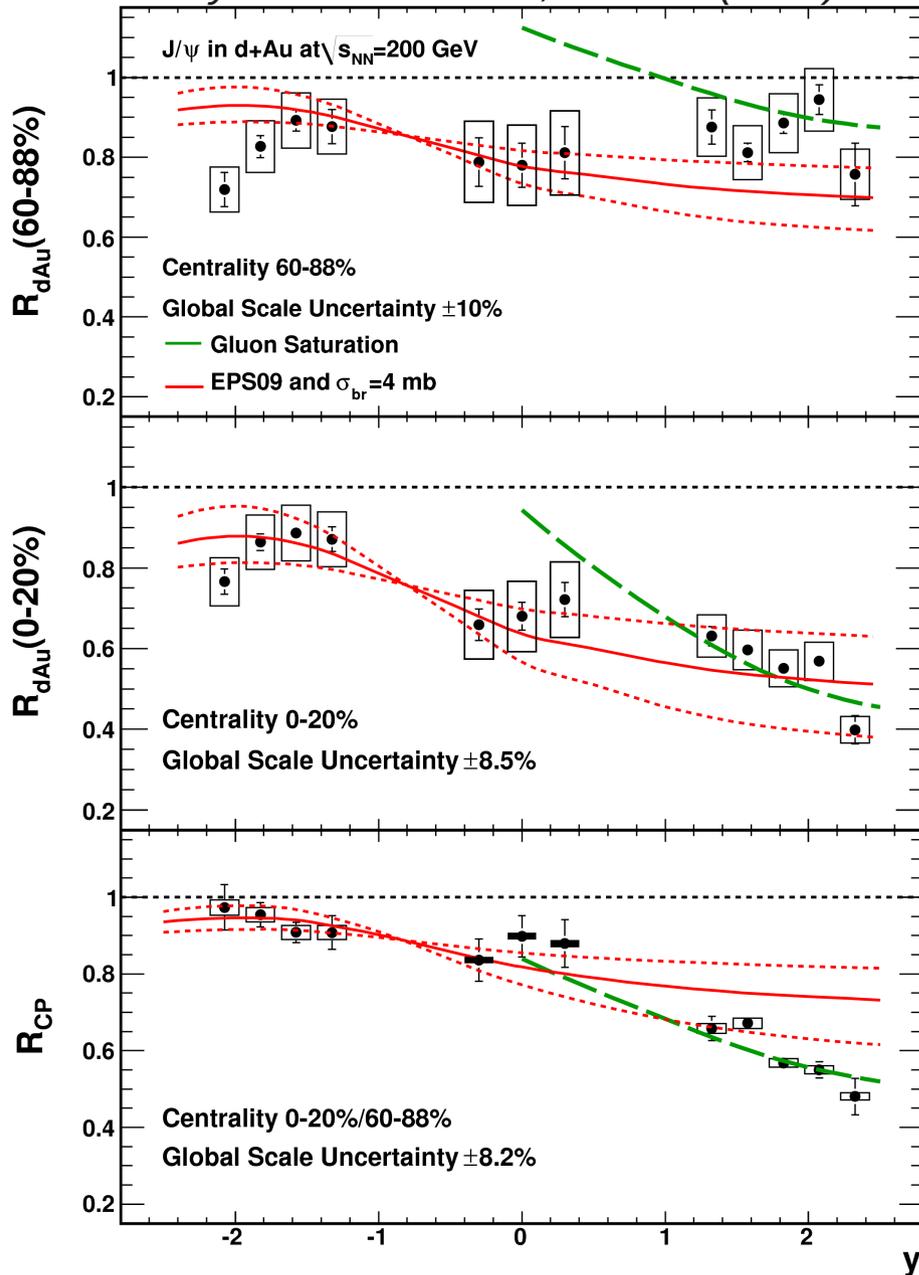
- Available p+A data:

- p+A measurements by E866/NuSea & 39 GeV.
- No p+A at 62 GeV
- d+Au PHENIX results at 200 GeV



- High statistics d+Au data set taken in 2008.
  - $J/\psi$  at backward, mid, and forward rapidities as a function of centrality,  $y$ , and (new)  $p_T$ .
  - (new)  $\psi'$  at midrapidity as a function of centrality.
  - (new)  $\chi_c$  at midrapidity
  - Upsilon at backward, mid(coming soon), and forward rapidities.
    - See posters by Kwangbok Lee & Shawn Whitaker

Phys. Rev. Lett. 107, 142301 (2011)



- Strong centrality dependence of  $J/\psi$   $R_{dAu}$ .
- Centrality dependence at forward rapidity unexplained by EPS09 with linear dependence on the nuclear thickness plus nuclear breakup.
- Described well by CGC at far forward rapidity.
  - Unclear how valid CGC model is in peripheral events?

- Minimum bias (centrality integrated)

$$R_{dAu}$$

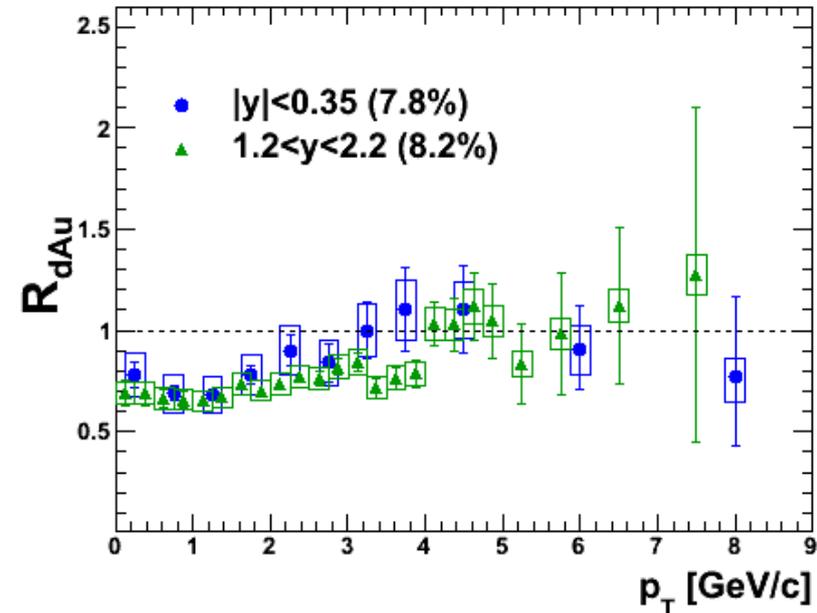
- Similar suppression pattern at **mid** & **forward** rapidity.

- Suppression for  $p_T < 4$  GeV/c.

- $R_{dAu} \approx 1$  for  $p_T > 4$  GeV/c.

$$R_{dAu}(i) = \frac{dN_{J/\psi}^{dAu}/dy(i)}{\langle N_{coll}(i) \rangle dN_{J/\psi}^{pp}/dy}$$

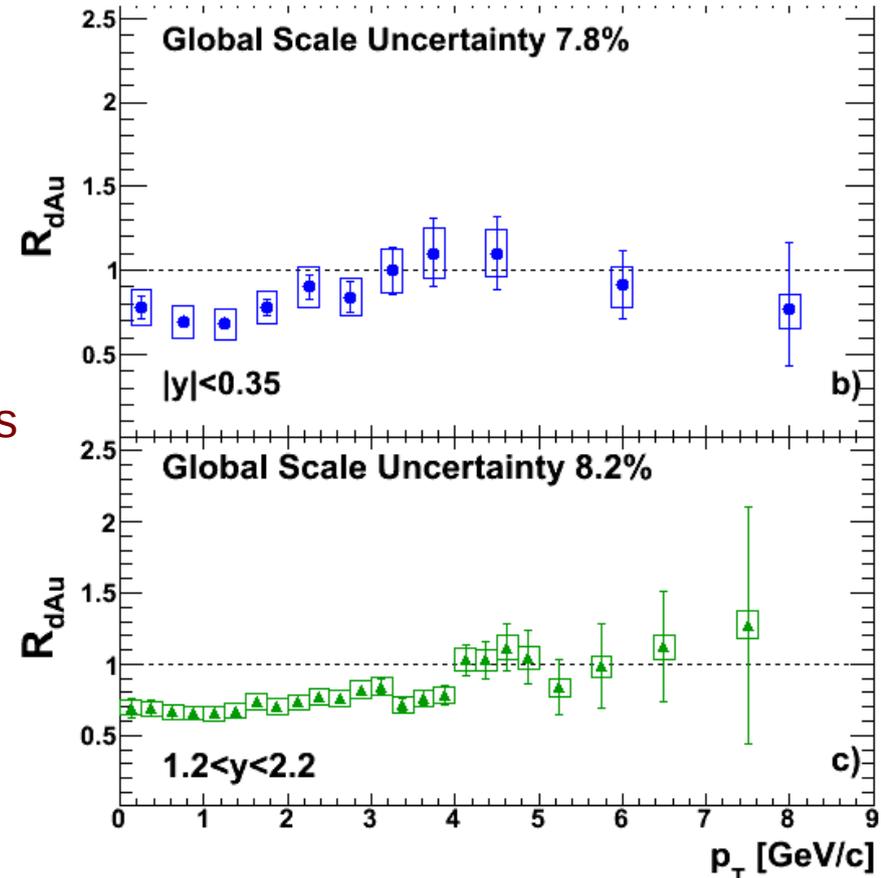
arXiv:1204.0777



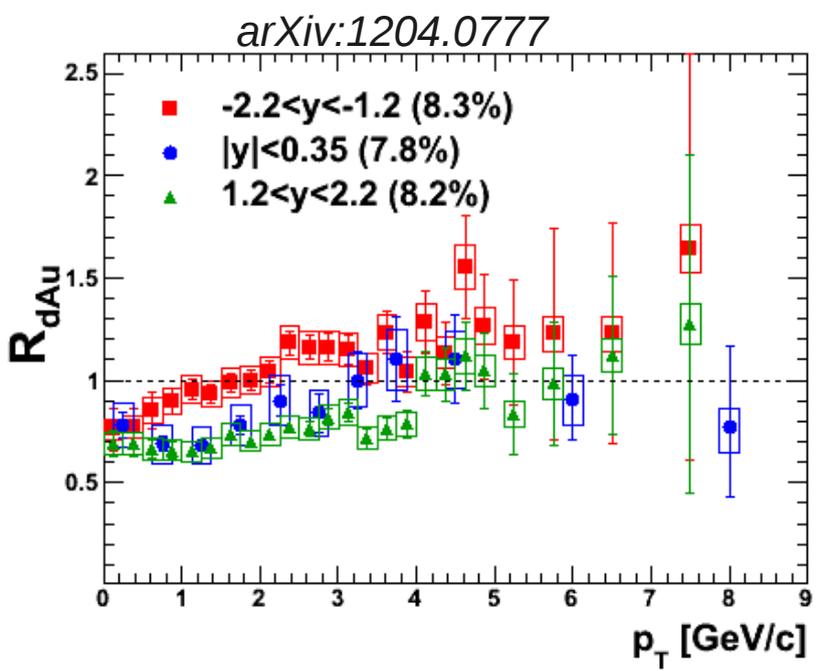
Vertical Error bars  
– uncorrelated  
uncertainties

Boxes – point-to-  
point correlated  
uncertainties.

arXiv:1204.0777

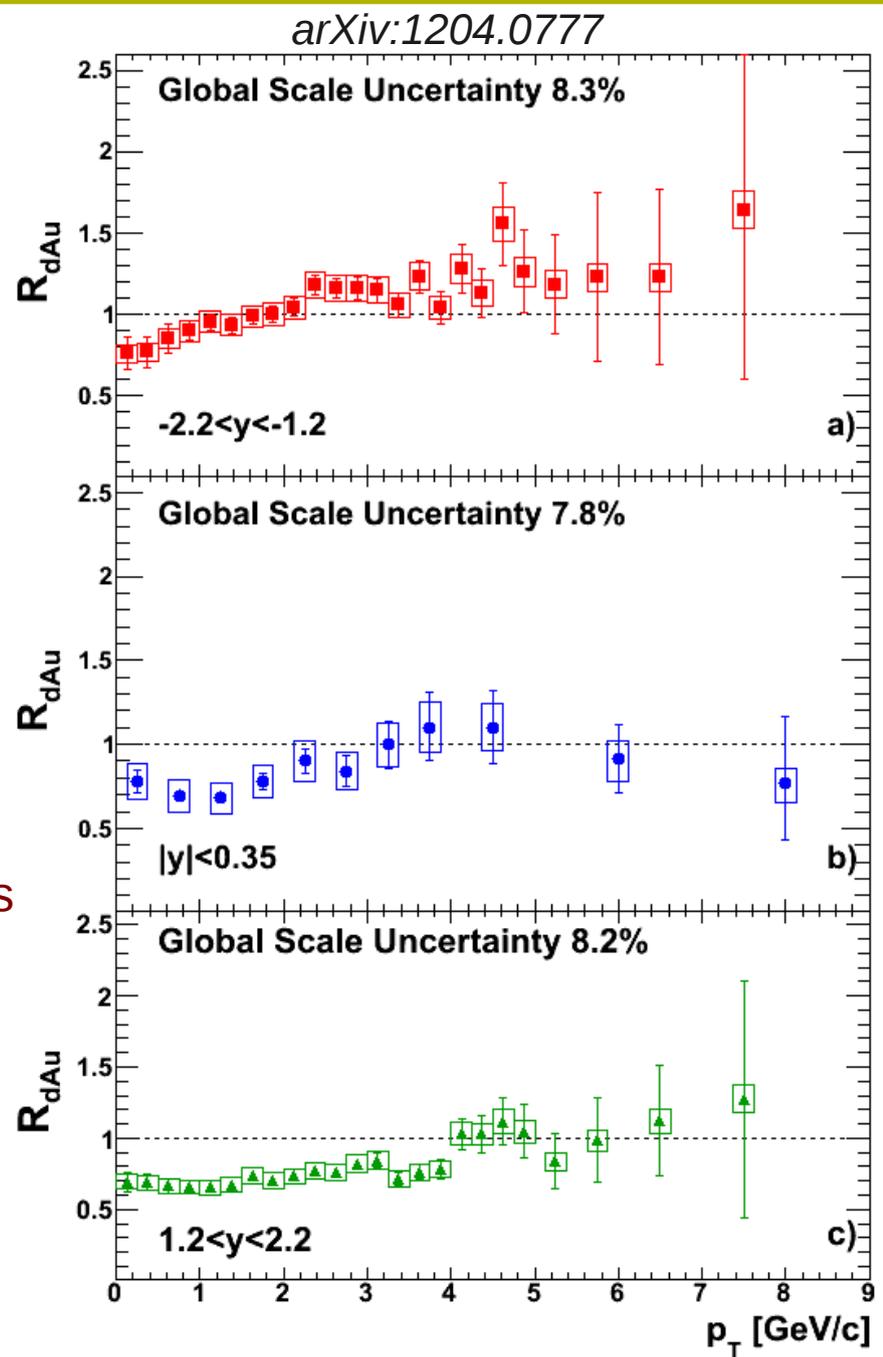


- Shape of  $R_{dAu}$   $p_T$  distribution different at **backward** rapidity.
- $R_{dAu} > 1$  for  $p_T > 2$  GeV/c.

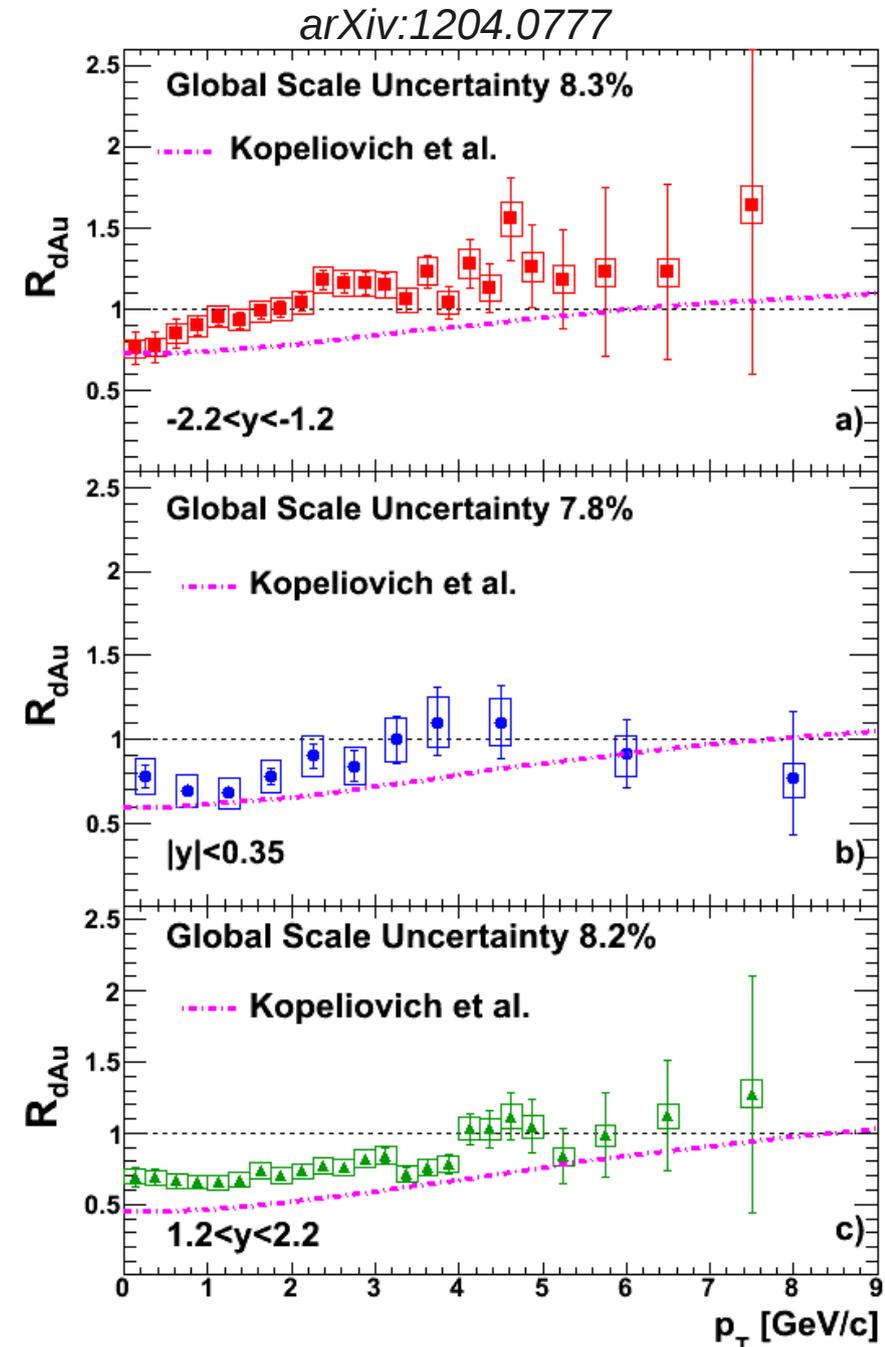


Vertical Error bars  
– uncorrelated  
uncertainties

Boxes – point-to-  
point correlated  
uncertainties.

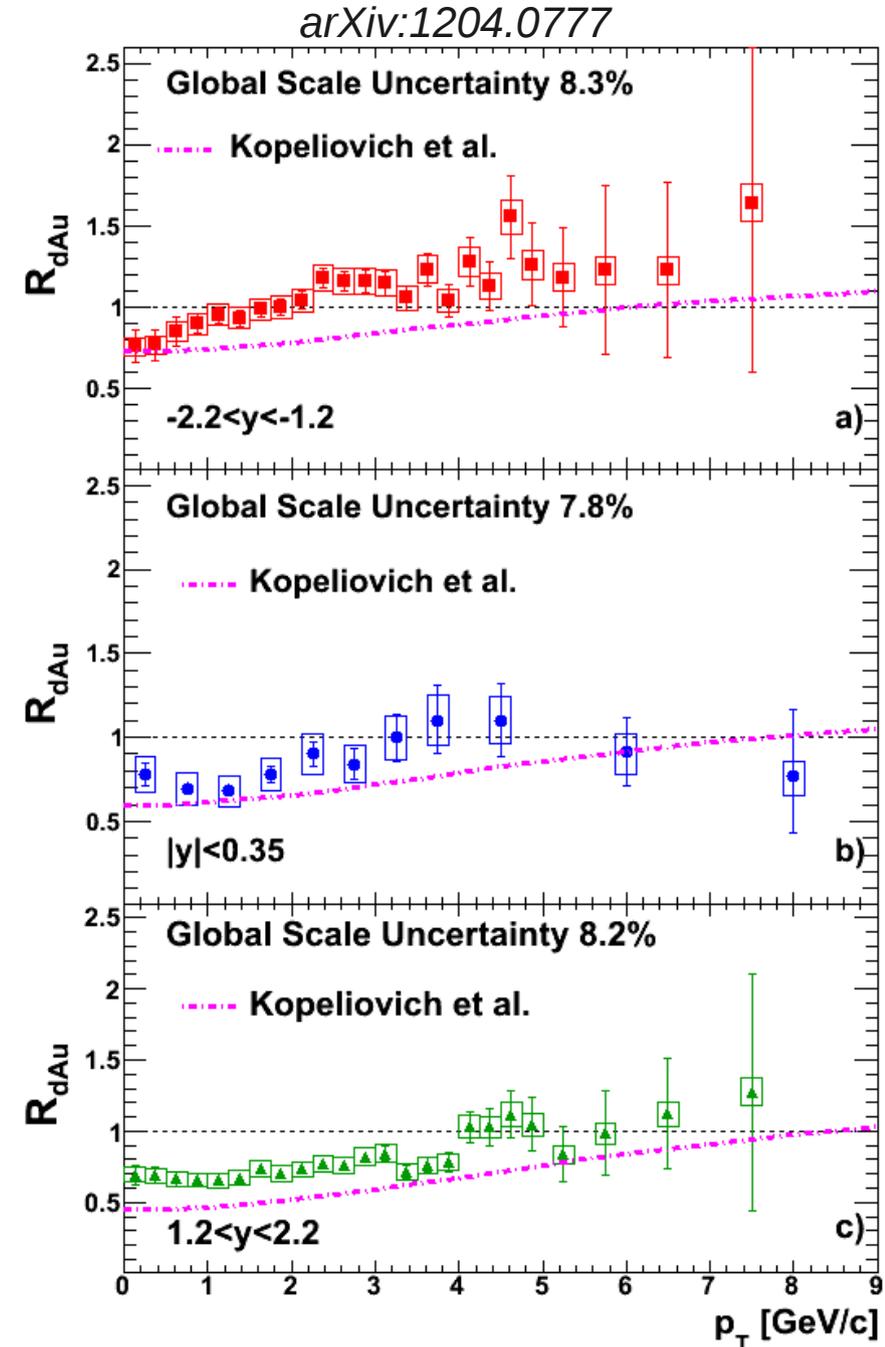


- Calculations from Kopeliovich et al. (*Nucl. Phys. A* **864**, 203 (2011))
- Nuclear Shadowing → nDSg nPDF set.
- Nuclear Break-up → frozen dipole approximation.
  - Not parameterized from RHIC data.
- Includes Cronin Effect.



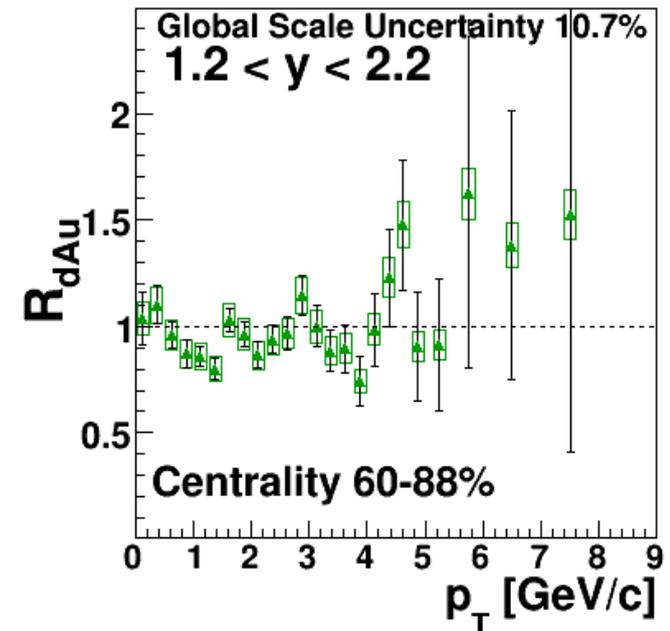
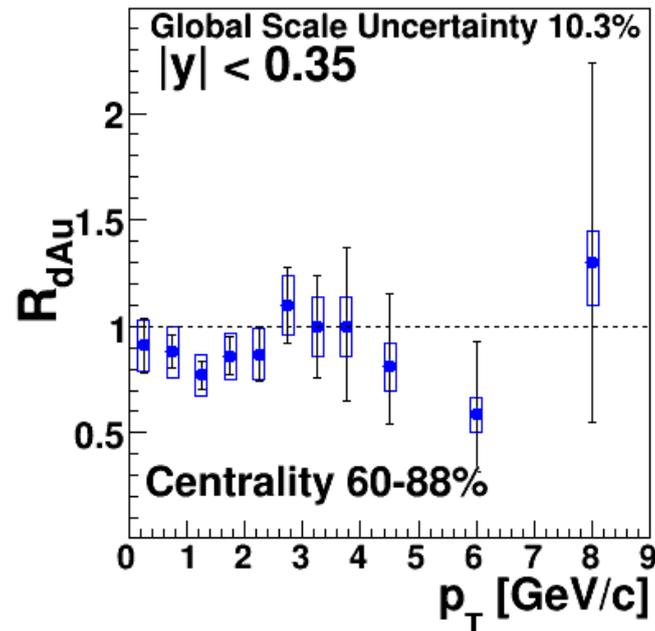
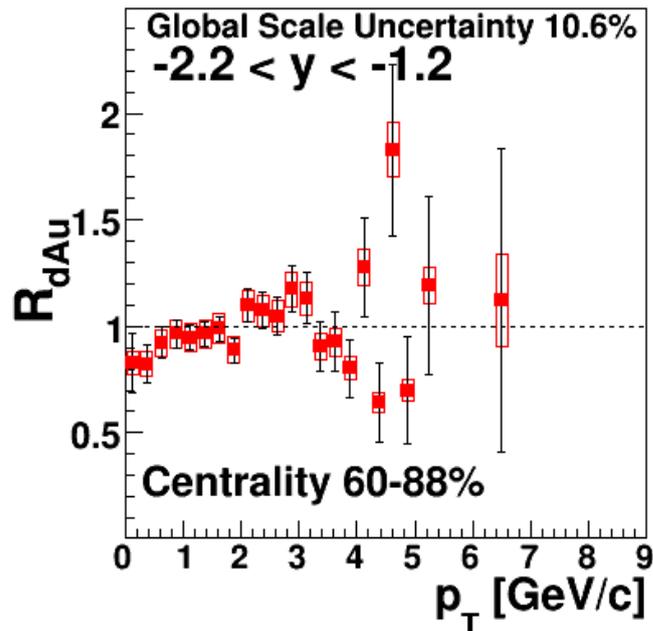
- Calculations from Kopeliovich et al. (*Nucl. Phys. A* **864**, 203 (2011))
- Nuclear Shadowing → nDSg nPDF set.
- Nuclear Break-up → frozen dipole approximation.
  - Not parameterized from RHIC data.
- Includes Cronin Effect.

No clear explanation of the backward rapidity result!



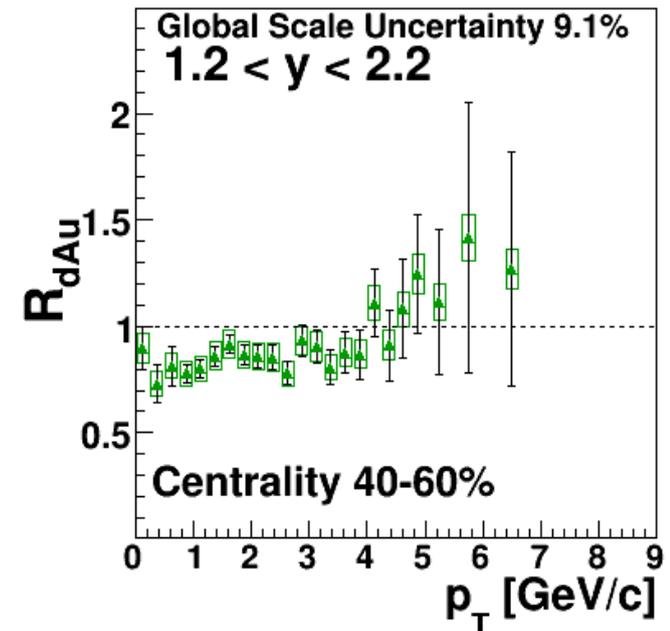
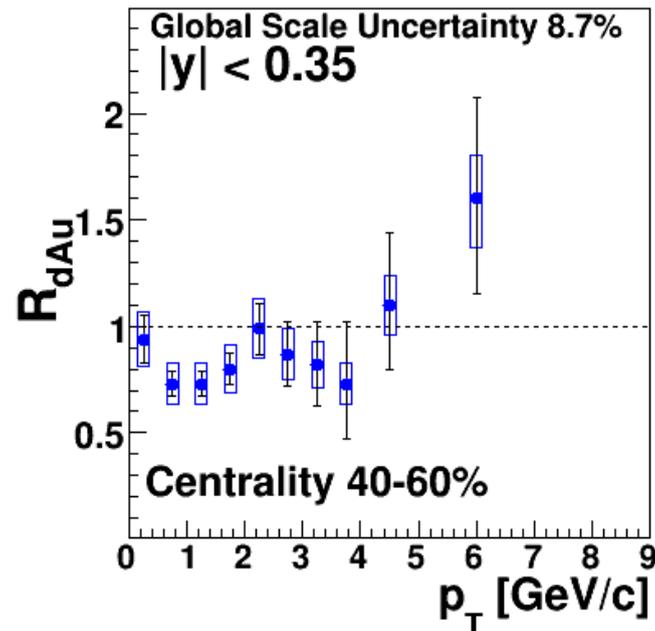
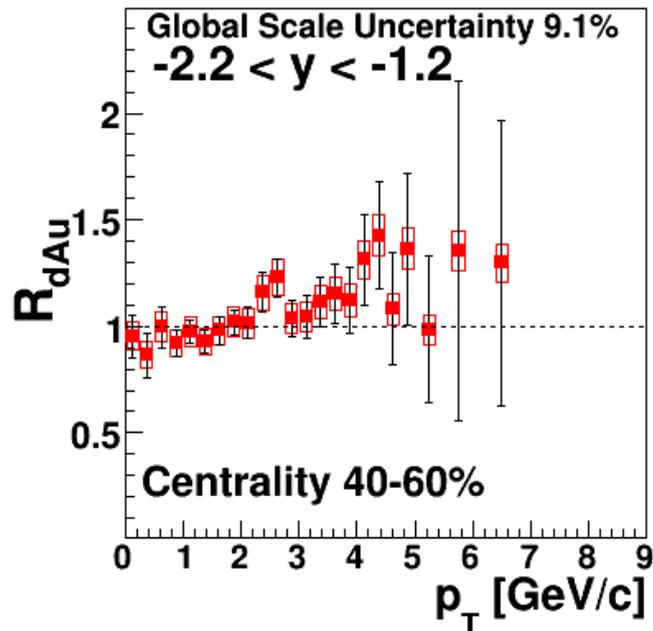
## 60-88%

$R_{dAu}$  consistent with 1 at all  $p_T$  for peripheral collisions



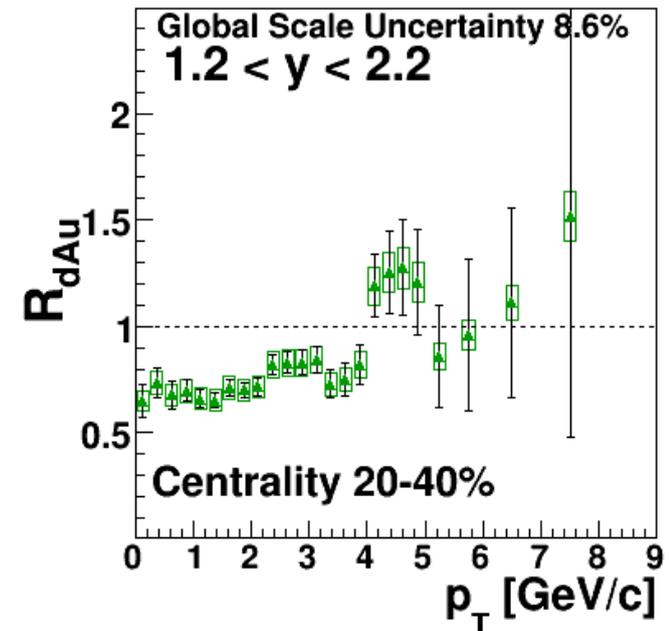
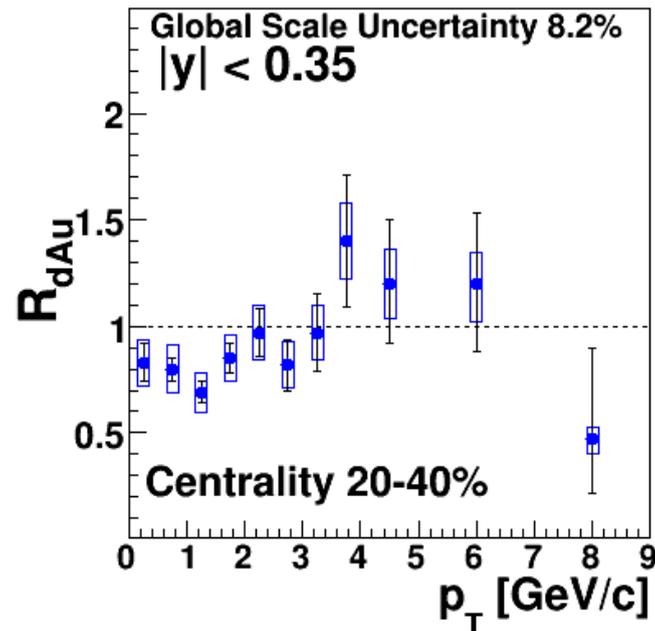
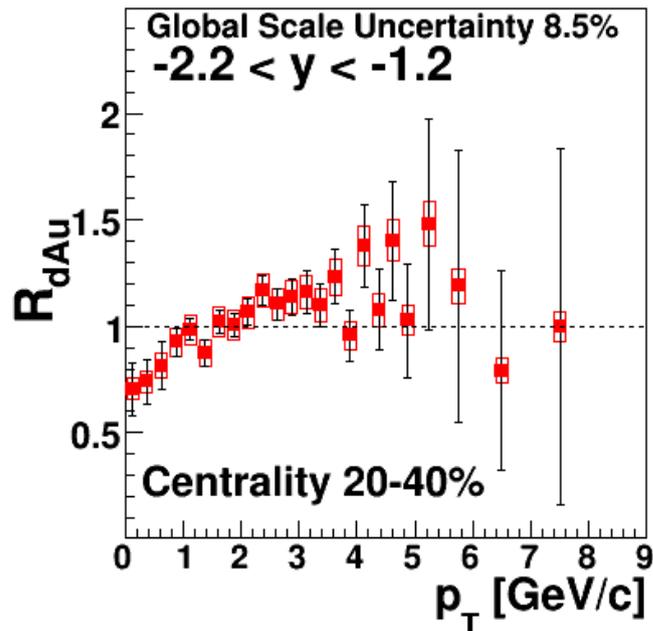
## 40-60%

Increasing suppression at low- $p_T$  when moving to central events



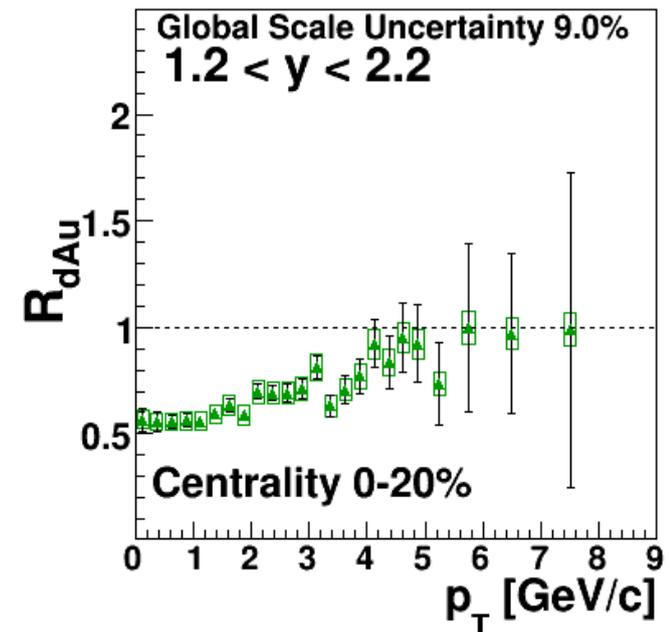
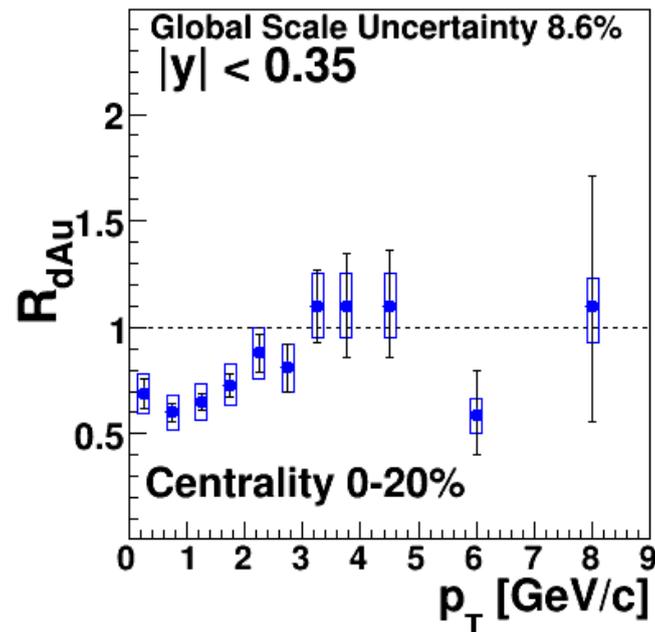
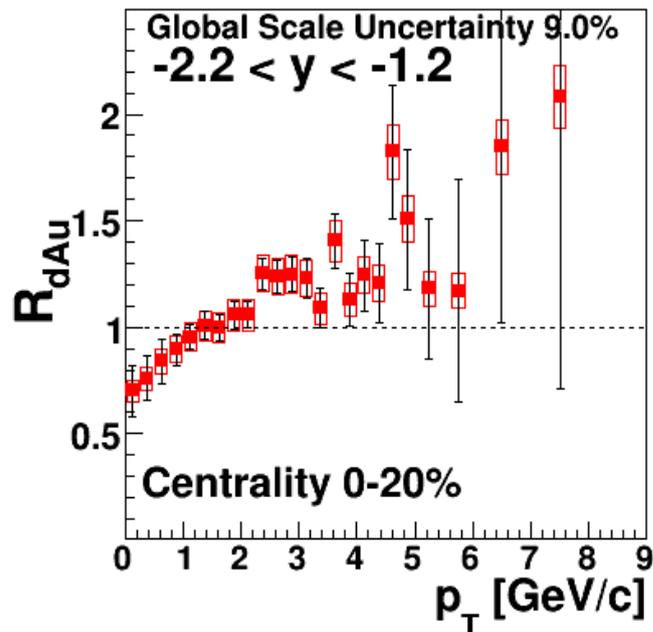
## 20-40%

Increasing suppression at low- $p_T$  when moving to central events



## 0-20%

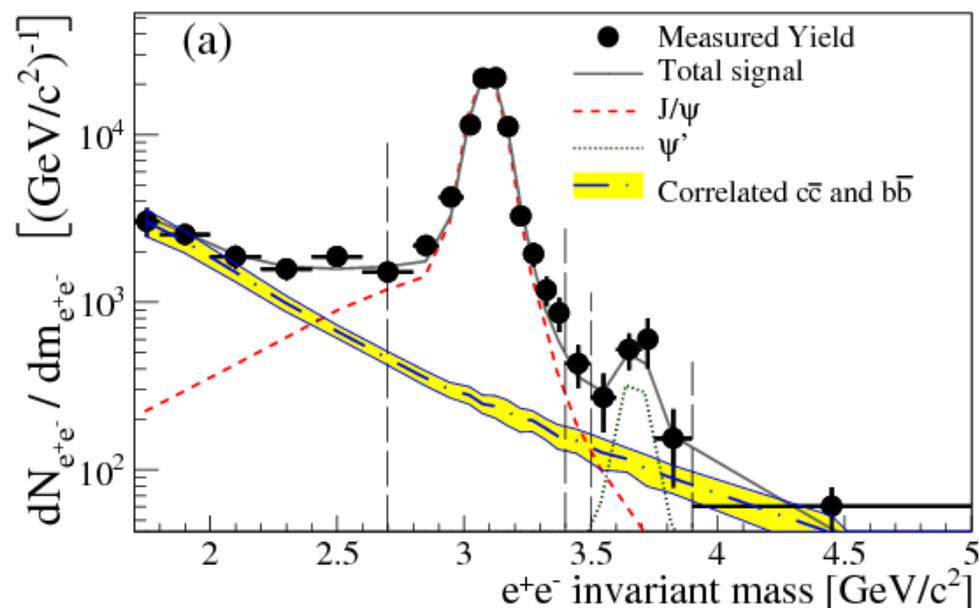
Increasing suppression at low- $p_T$  when moving to central events



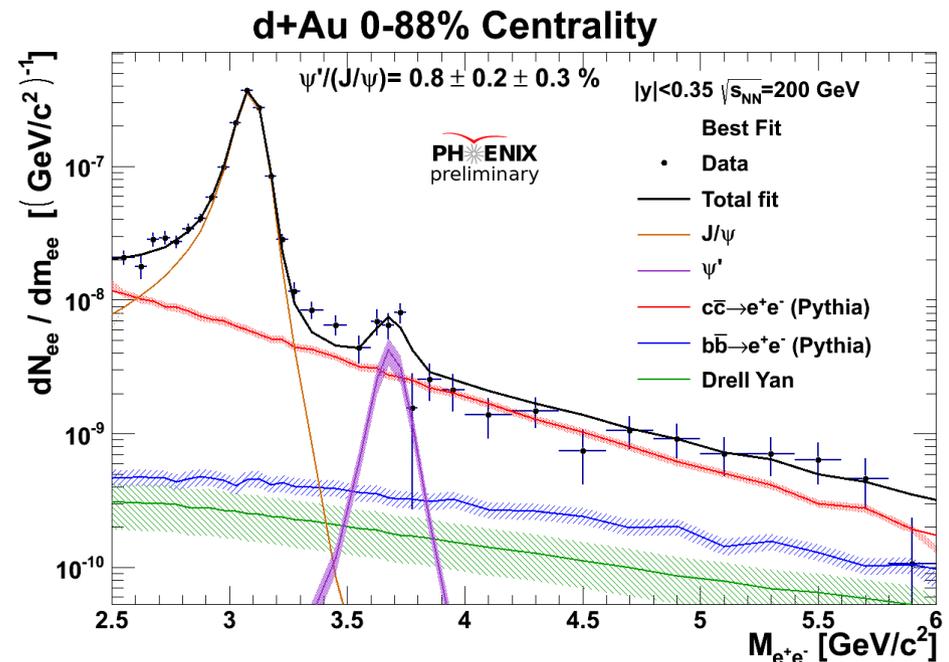
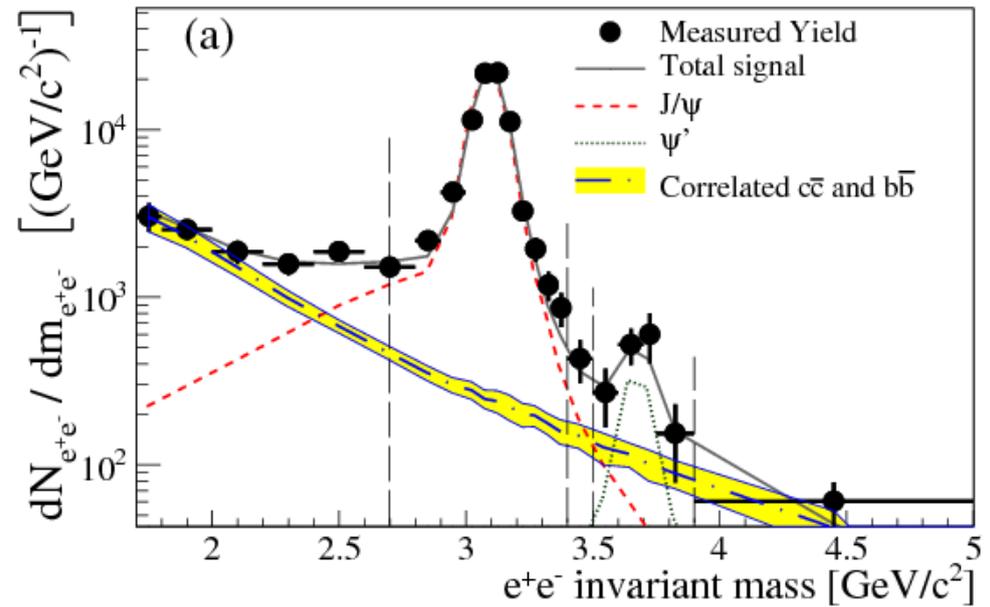
Enhancement at high- $p_T$  at backward rapidity

Implies  $R_{AA}(\text{CNM}) \geq 1$  at high- $p_T$  in Au+Au

- In p+p PHENIX found a  $\psi'/(J/\psi)$  ratio of  $2.1 \pm 0.5\%$  (*Phys.Rev. D85 (2012) 092004*).

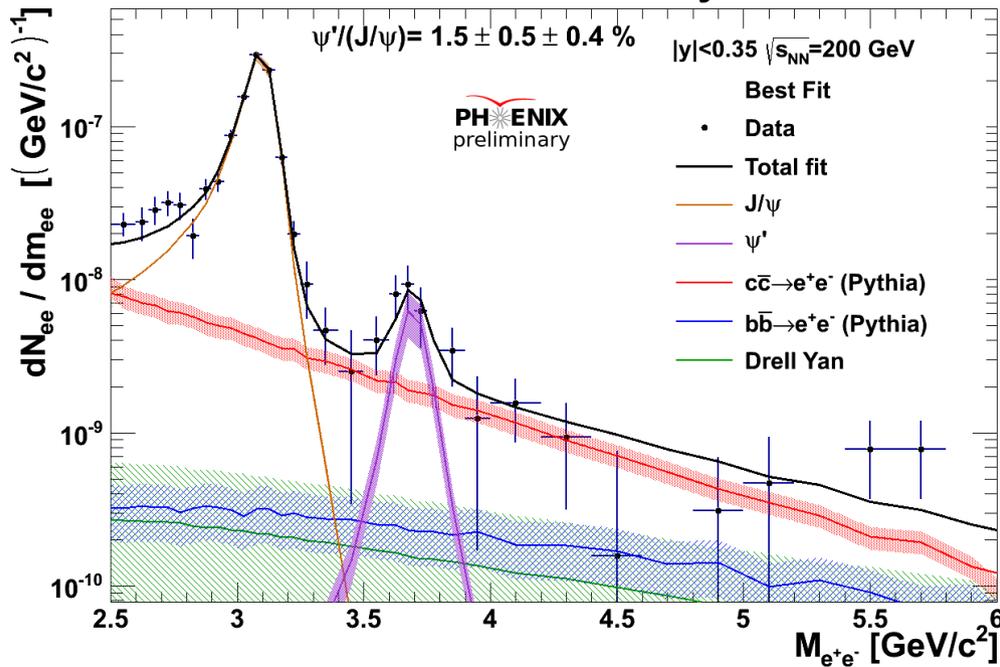


- In p+p PHENIX found a  $\Psi'/(J/\Psi)$  ratio of  $2.1 \pm 0.5\%$  (*Phys.Rev. D85 (2012) 092004*).
- Extract the  $\Psi'/(J/\Psi)$  ratio in d+Au.
- Fit the mass distribution's in d+Au to extract  $\Psi'/(J/\Psi)$  ratio.
  - Include dielectrons from DY, open charm & open bottom as well as  $J/\Psi$  and  $\Psi'$  decays.
- Variations in the ratio due to the fit assumptions are included in the systematic uncertainty.



Investigate the centrality dependence

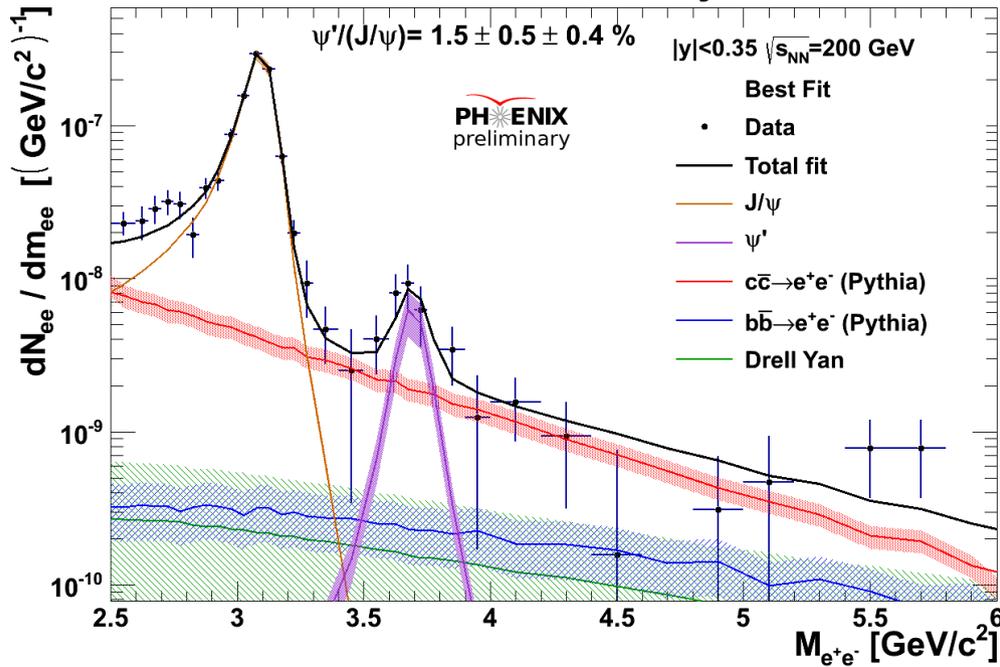
d+Au 40-60% Centrality



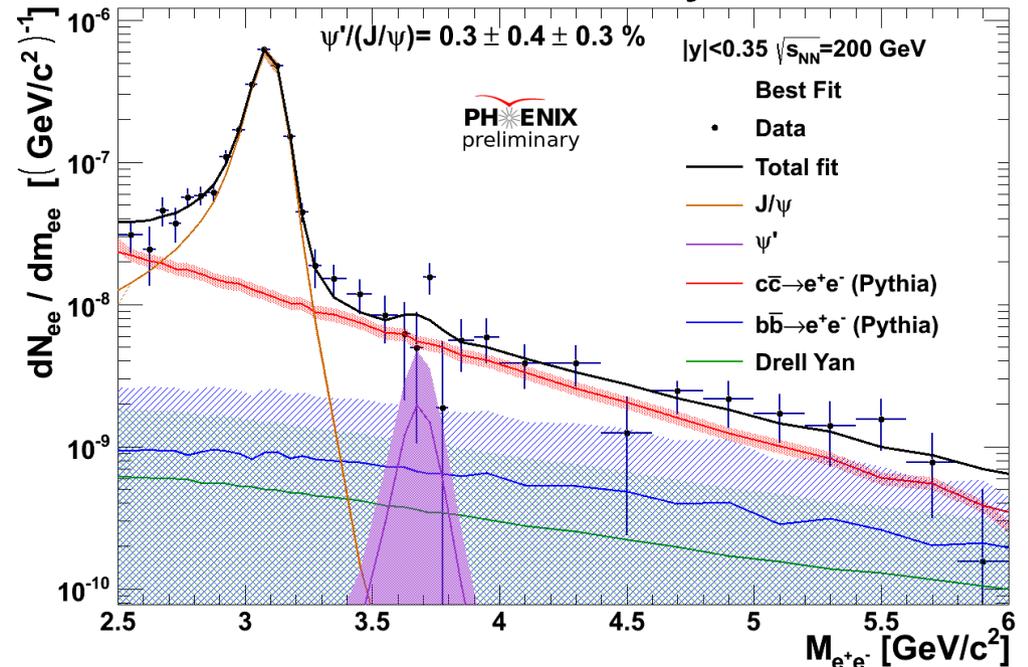
Little suppression in mid-peripheral events.

## Investigate the centrality dependence

d+Au 40-60% Centrality



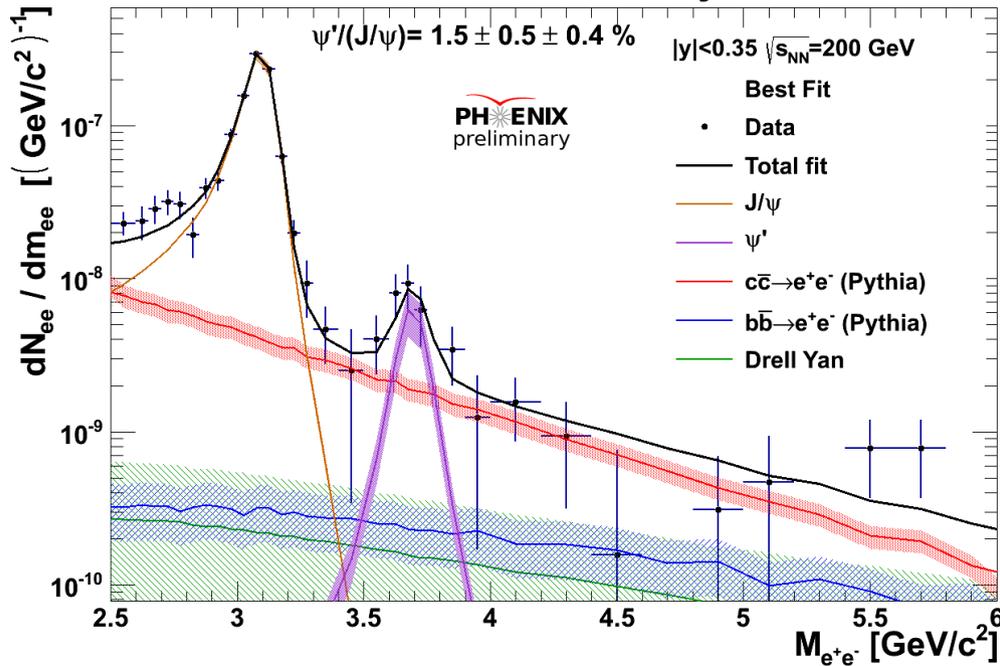
d+Au 0-20% Centrality



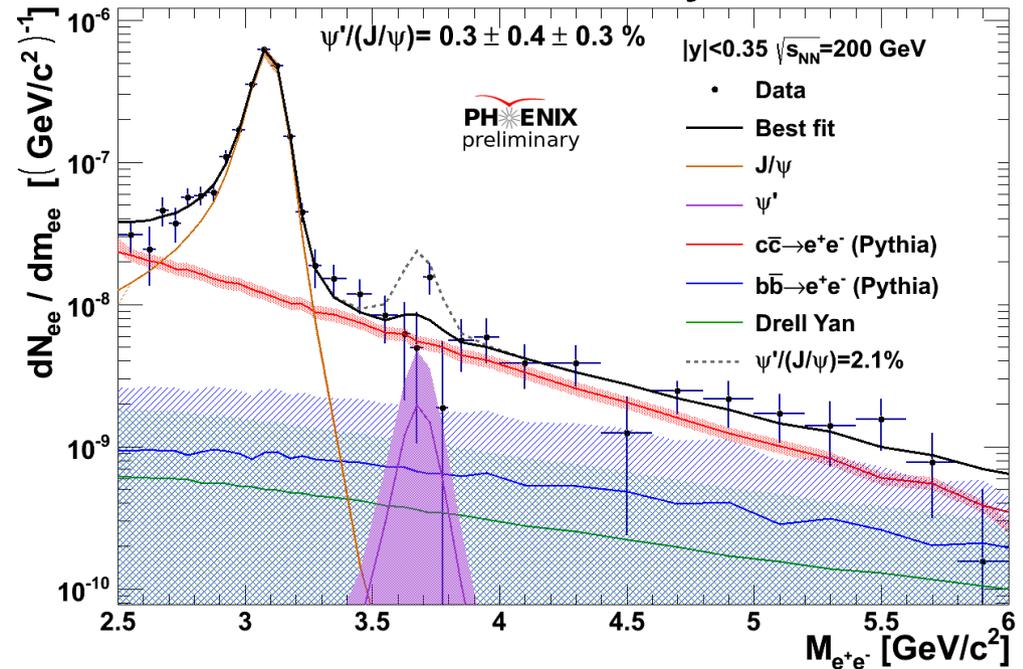
Strong suppression in central events!

## Investigate the centrality dependence

### d+Au 40-60% Centrality

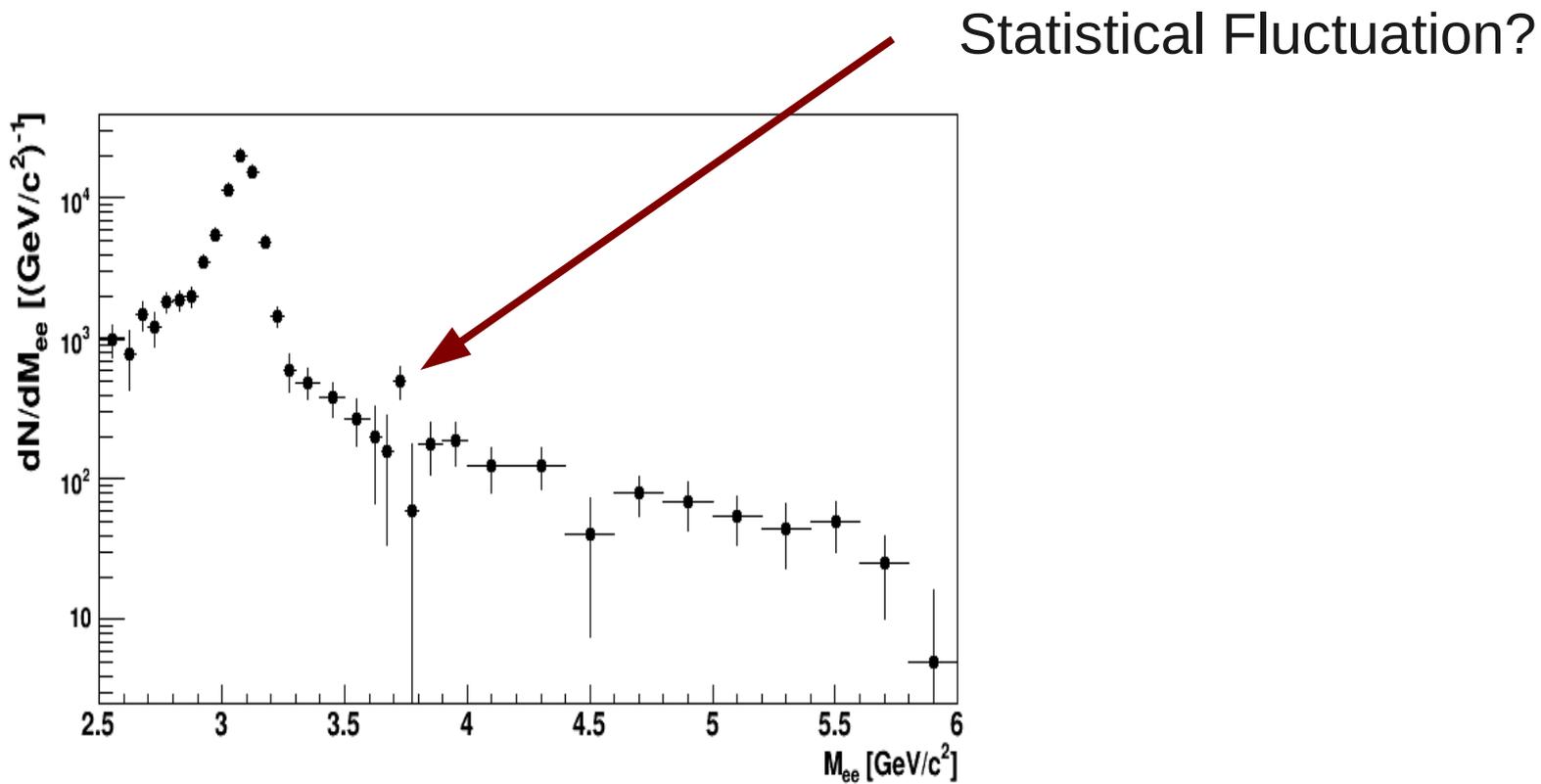


### d+Au 0-20% Centrality

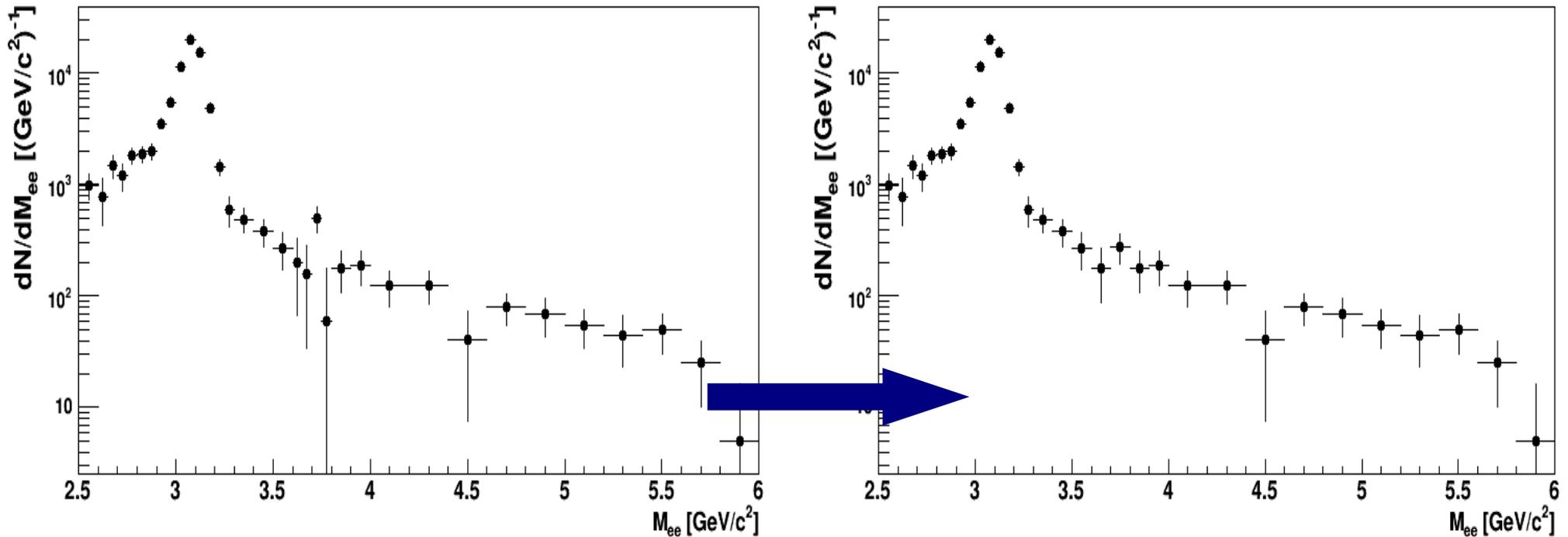


Dashed line –  $\Psi' / (J/\psi)$  ratio fixed to p+p value (2.1%)

Likelihood ratio test gives probability for p+p ratio of  $< 10^{-6}$

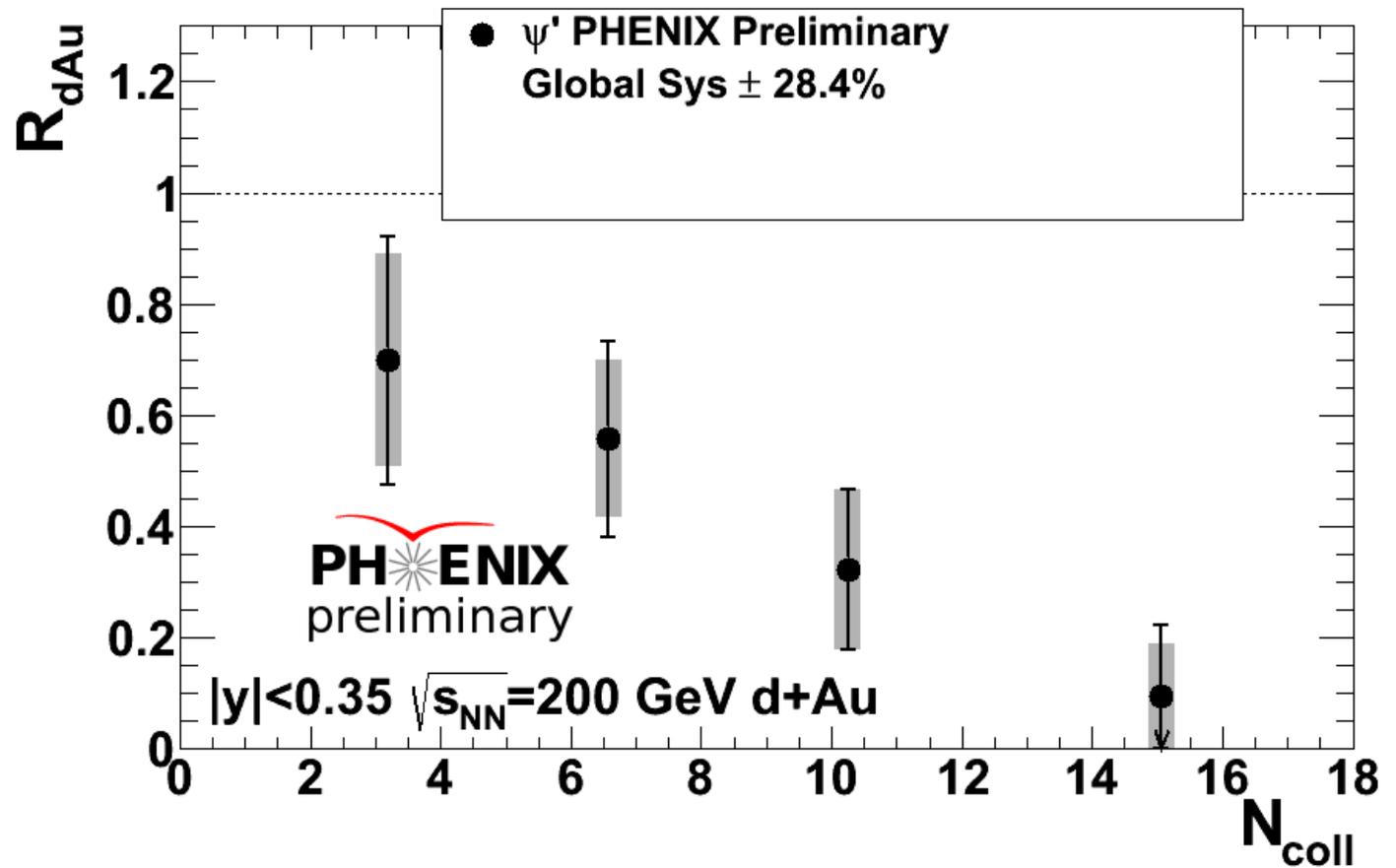


Rebin the data points in the range  $3.4 < M_{ee} < 3.8 \text{ GeV}$  by 2



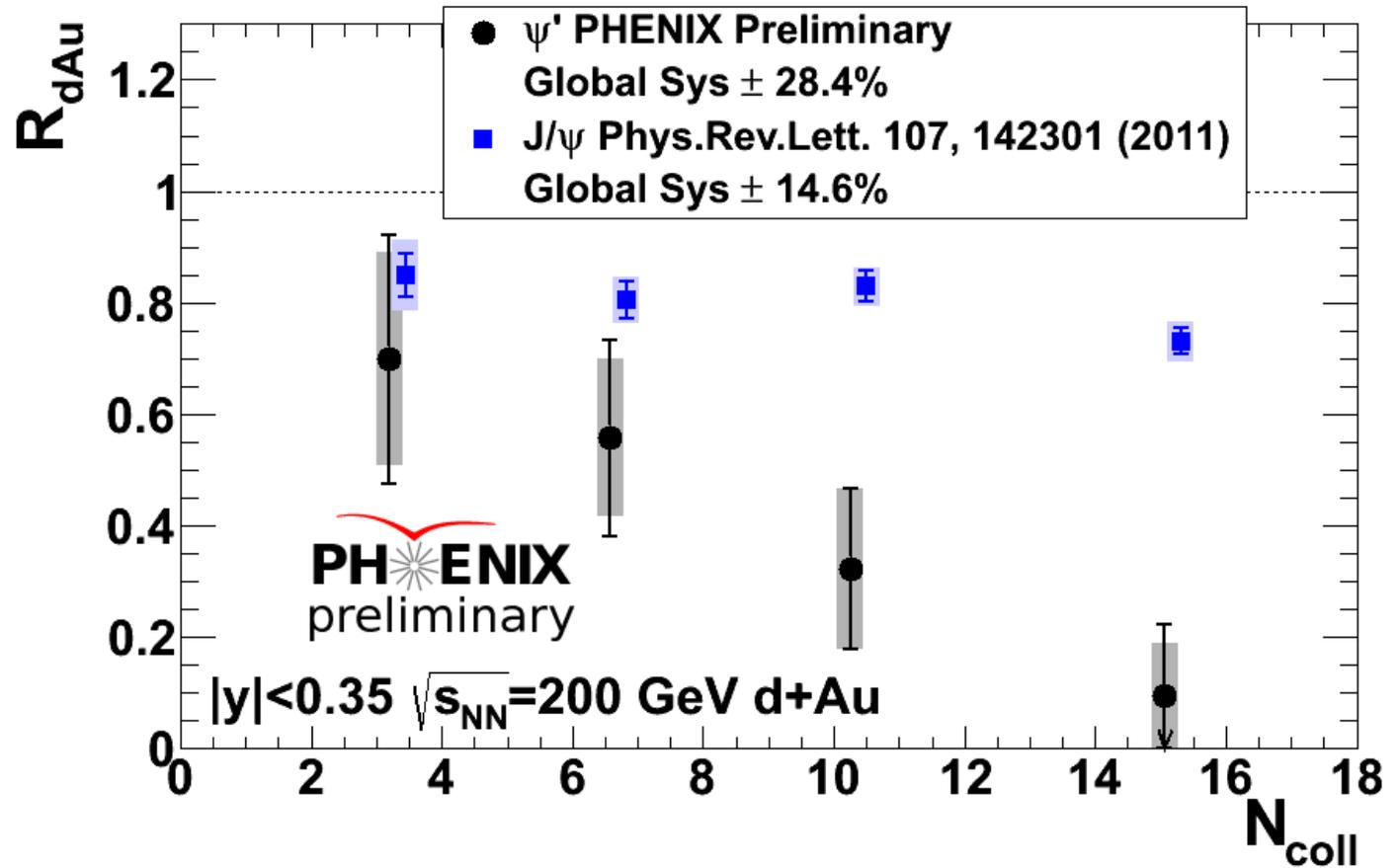
Strong suppression  
with increasing  $N_{coll}$ !

$$R_{dAu}^{\psi'} = \frac{[\psi' / (J/\psi)]^{dAu}}{[\psi' / (J/\psi)]^{pp}} R_{dAu}^{J/\psi},$$



Centrality dependence of suppression much stronger than  $J/\psi$  result at midrapidity.

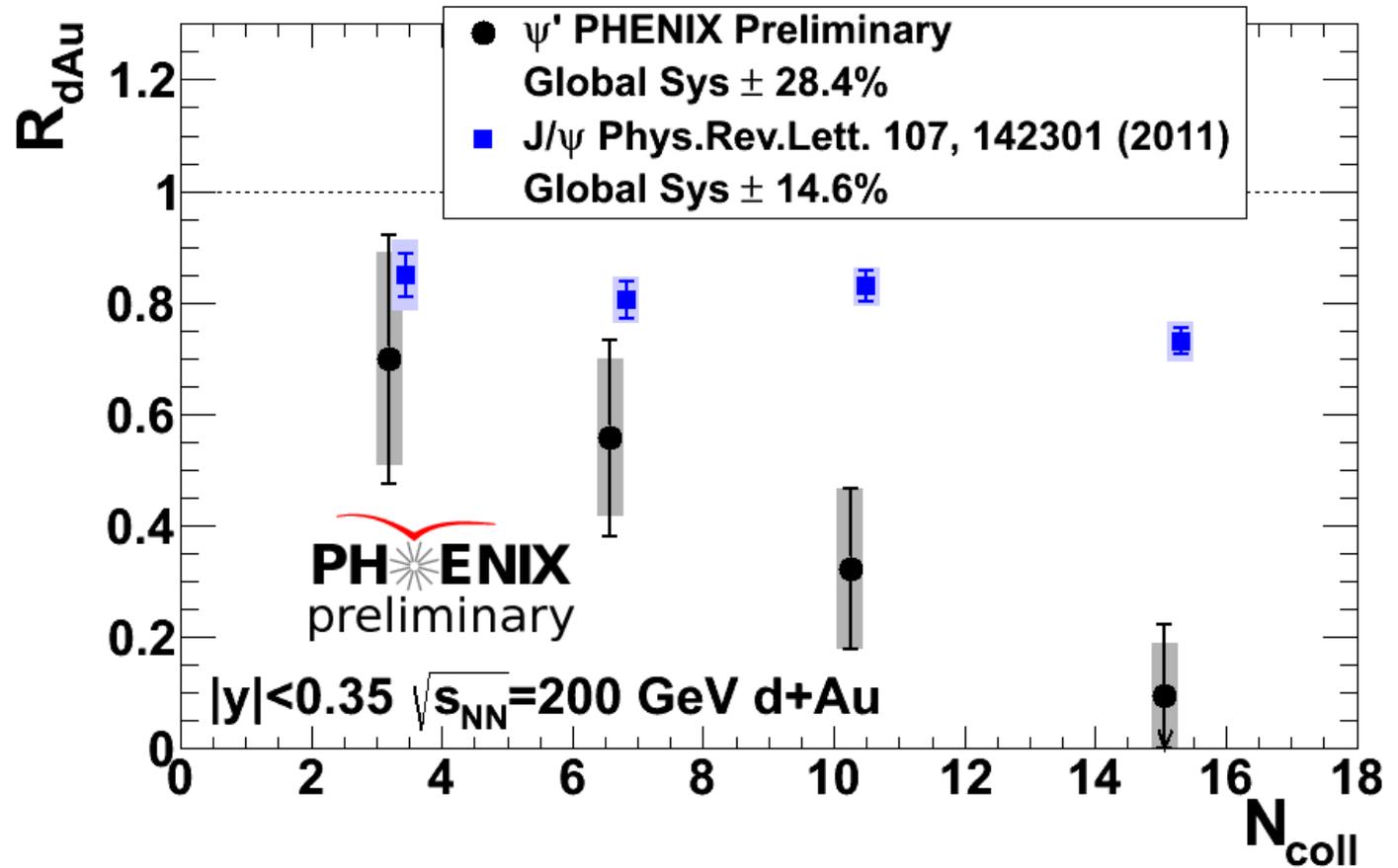
$$R_{dAu}^{\psi'} = \frac{[\psi' / (J/\psi)]^{dAu}}{[\psi' / (J/\psi)]^{pp}} R_{dAu}^{J/\psi},$$



Centrality dependence of suppression much stronger than  $J/\psi$  result at midrapidity.

$$R_{dAu}^{\psi'} = \frac{[\psi' / (J/\psi)]^{dAu}}{[\psi' / (J/\psi)]^{pp}} R_{dAu}^{J/\psi},$$

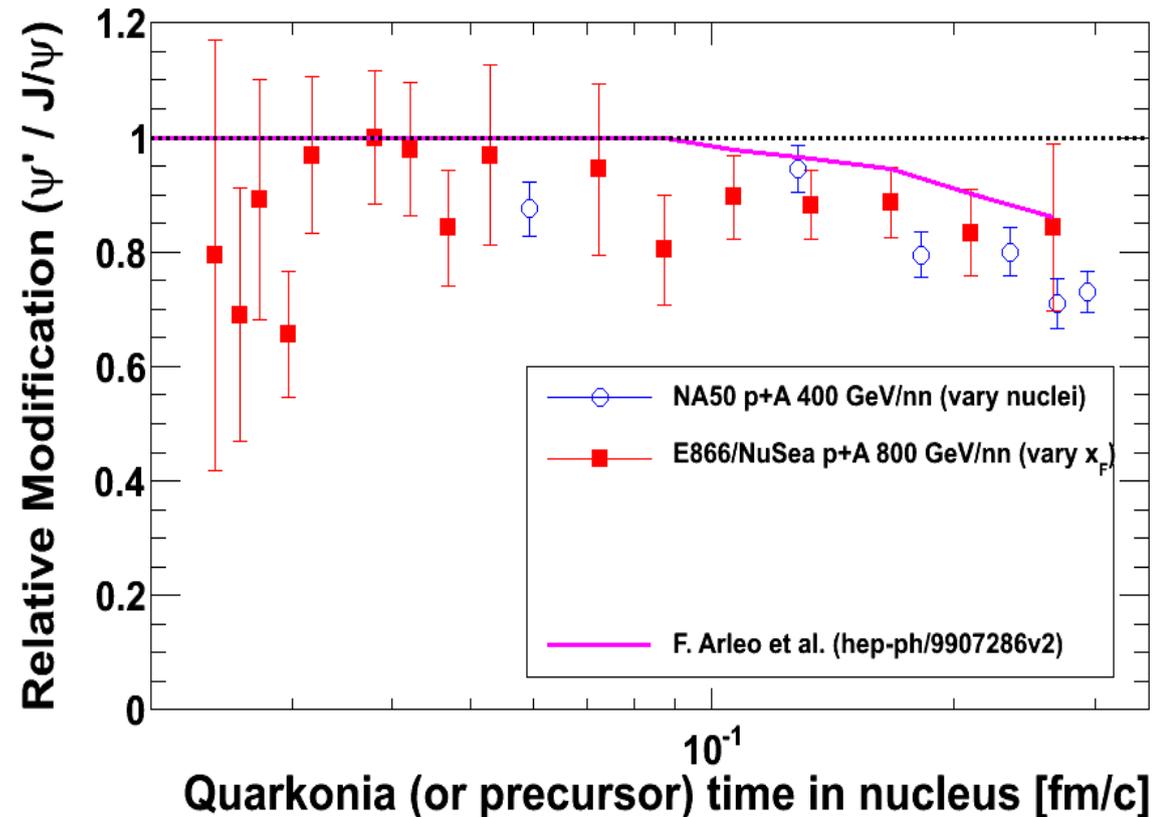
How does this result fit with the picture drawn from data at lower energy?



- Physics idea based on low energy results:
  - If the formation time of the  $J/\psi(\psi')$  is shorter than the time spent traversing the nucleus, a larger suppression of the  $\psi'$  will be seen due to a larger nuclear breakup effect.
- Calculation based on this idea (**pink line**) in agreement with NA50 & E866 data

Plot the  $\psi'/(J/\psi)$  relative modification vs the proper time spent in the nucleus

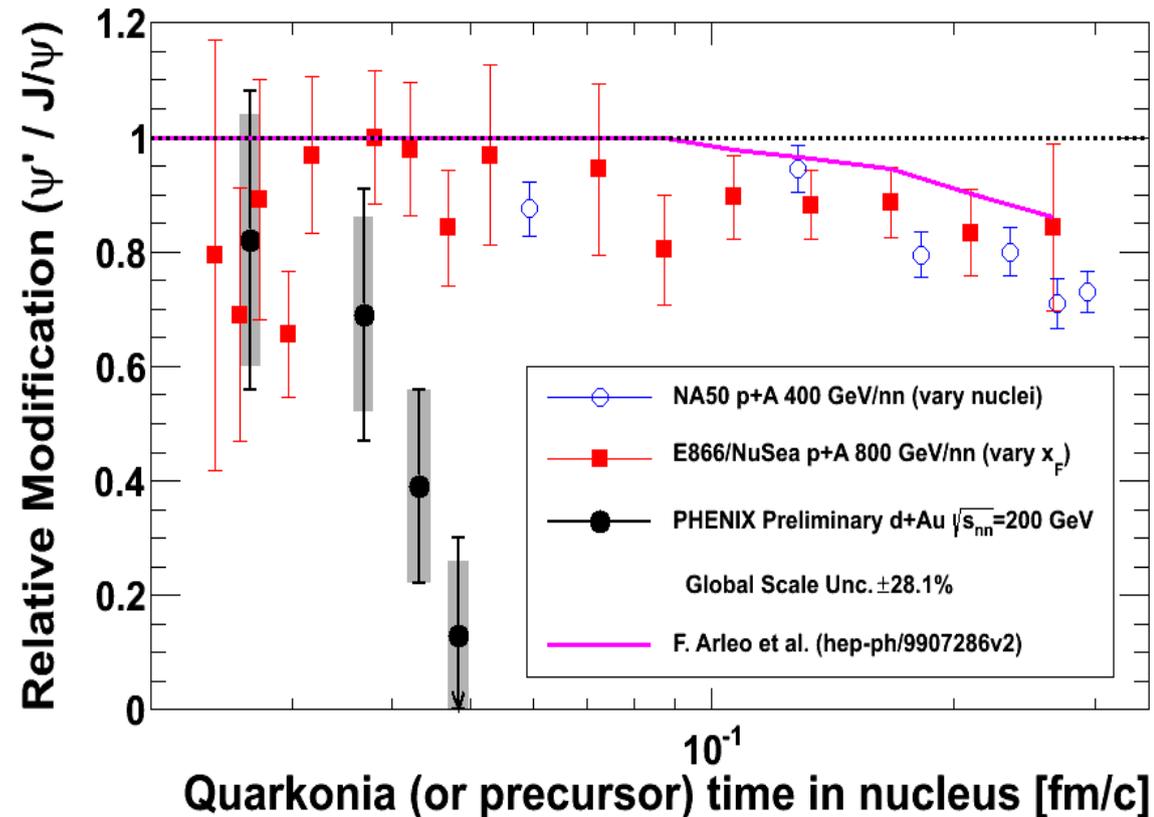
Using  $y(x_F)$ ,  $\sqrt{s}$ , and  $\langle L \rangle$ , calculate the time spent traversing the target nucleus.



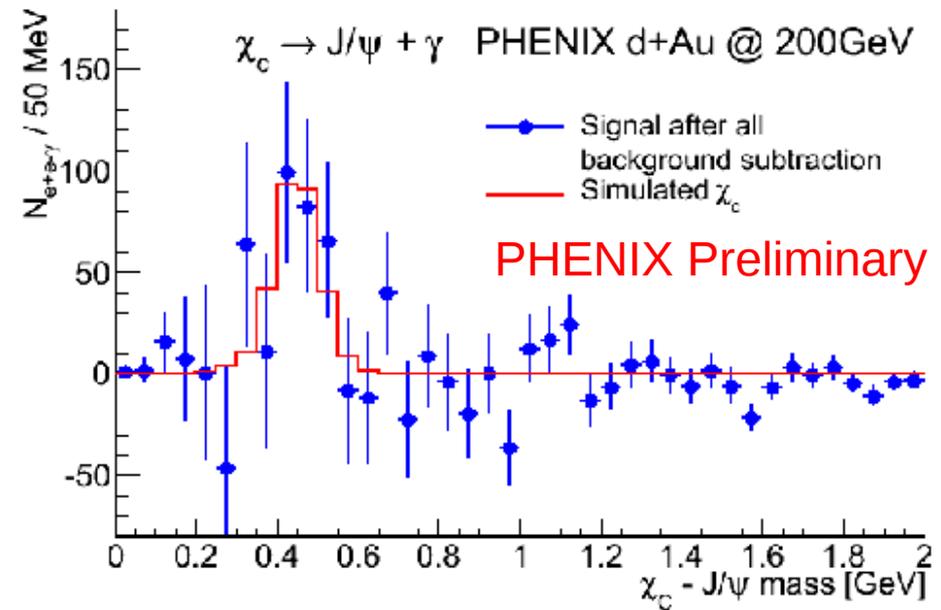
- Physics idea based on low energy results:
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- Calculation based on this idea (**pink line**) in agreement with NA50 & E866 data

This explanation does not seem to hold at RHIC energies!

Using  $y(x_F)$ ,  $\sqrt{s}$ , and  $\langle L \rangle$ , calculate the time spent traversing the target nucleus.

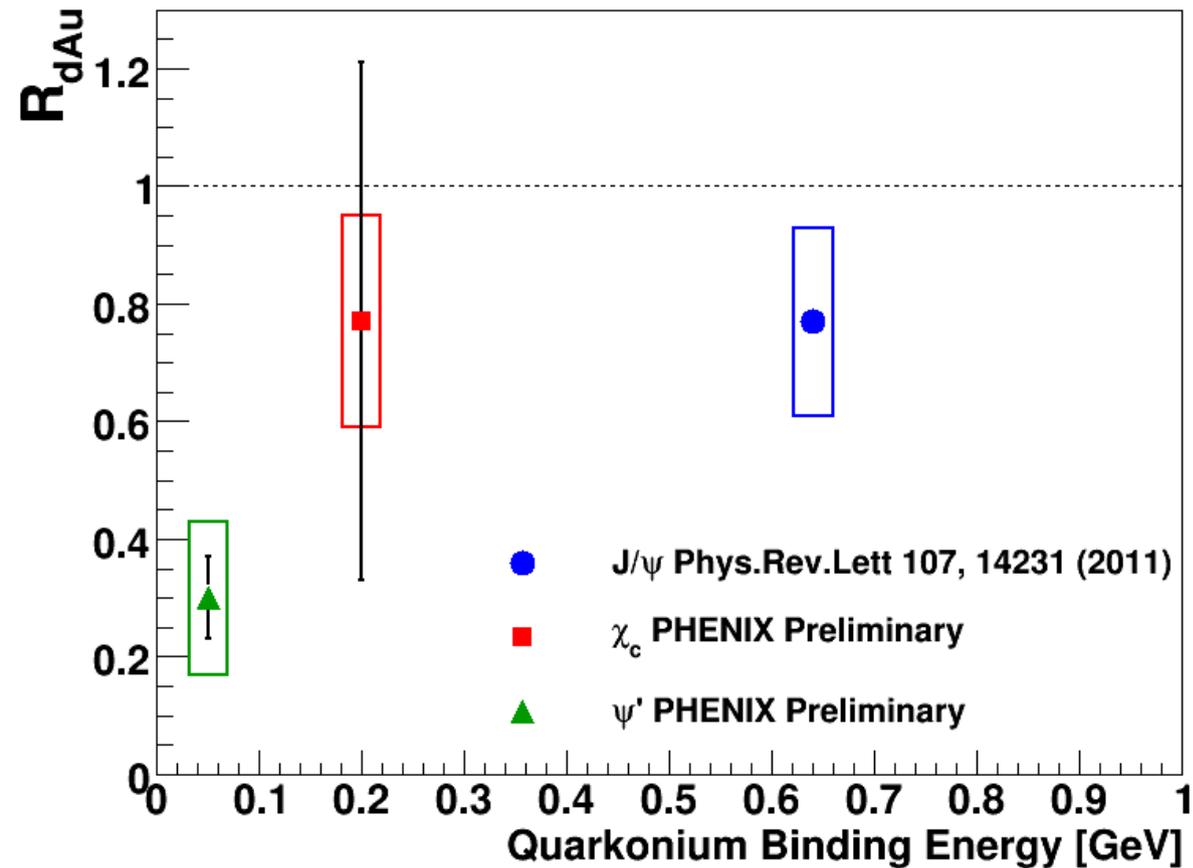
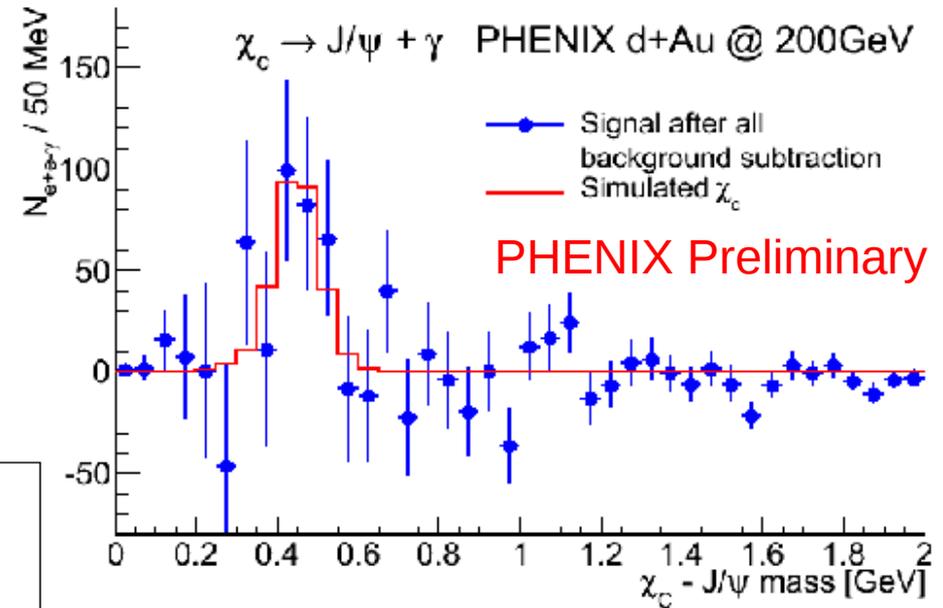


First measurement of  $\chi_c$  production in d+Au.



$$F_{\text{dAu}}(\chi_c \rightarrow J/\psi) = 0.32 \pm 0.09(\text{stat}) \pm 0.03(\text{corr})$$

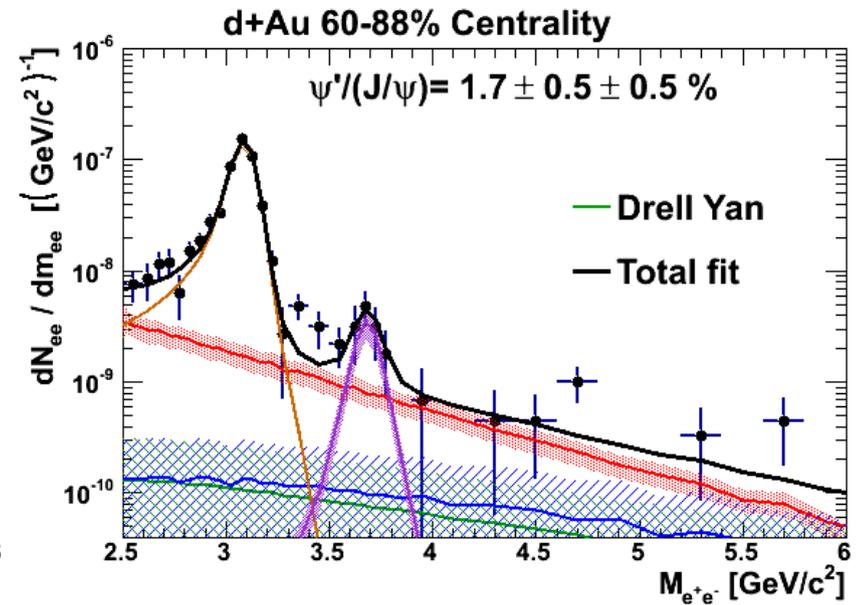
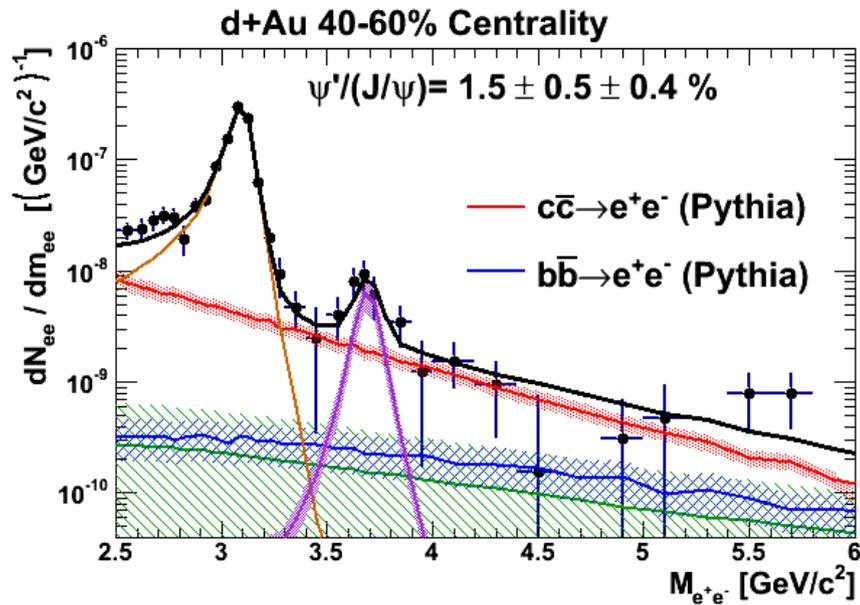
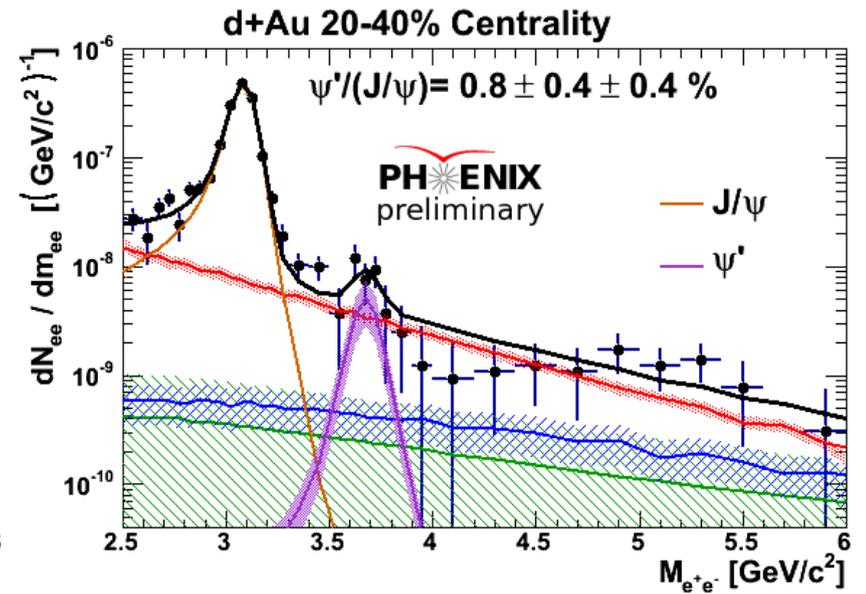
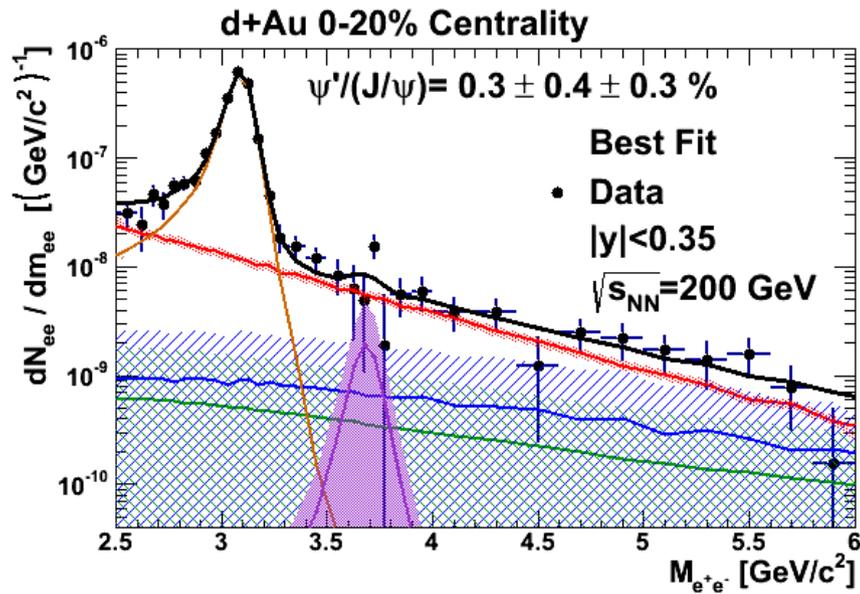
First measurement of  $\chi_c$  production in d+Au.



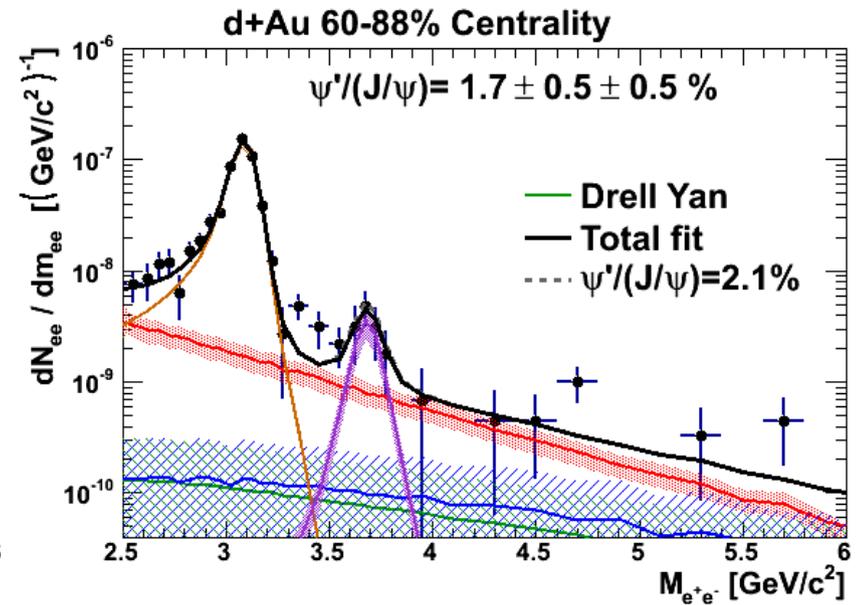
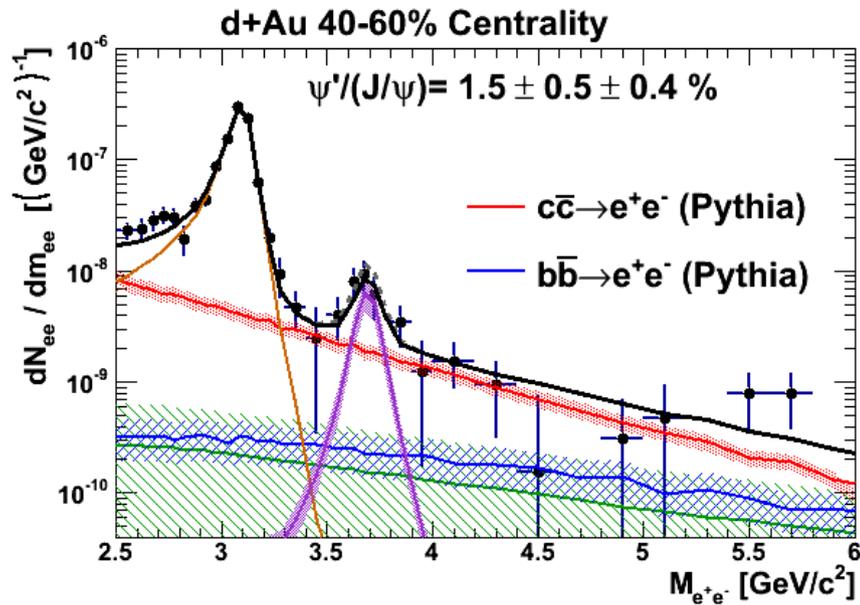
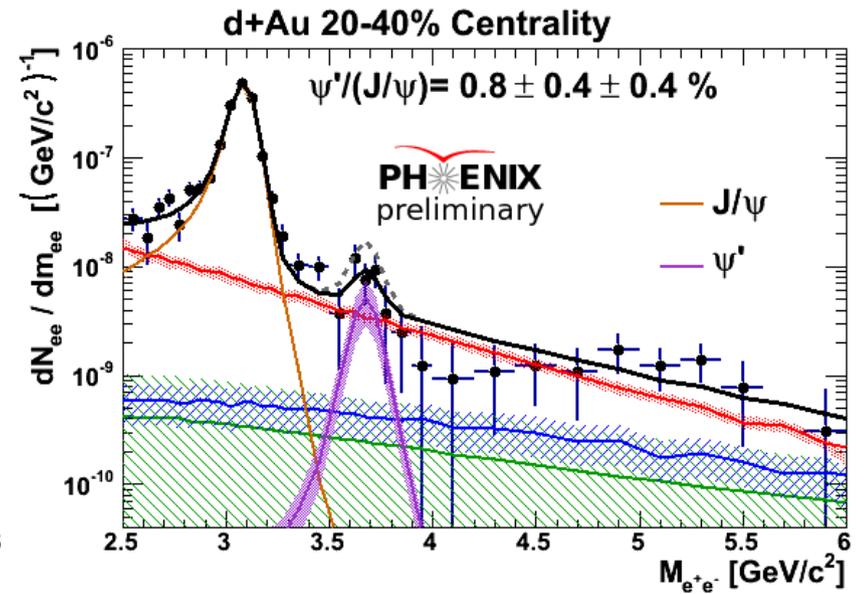
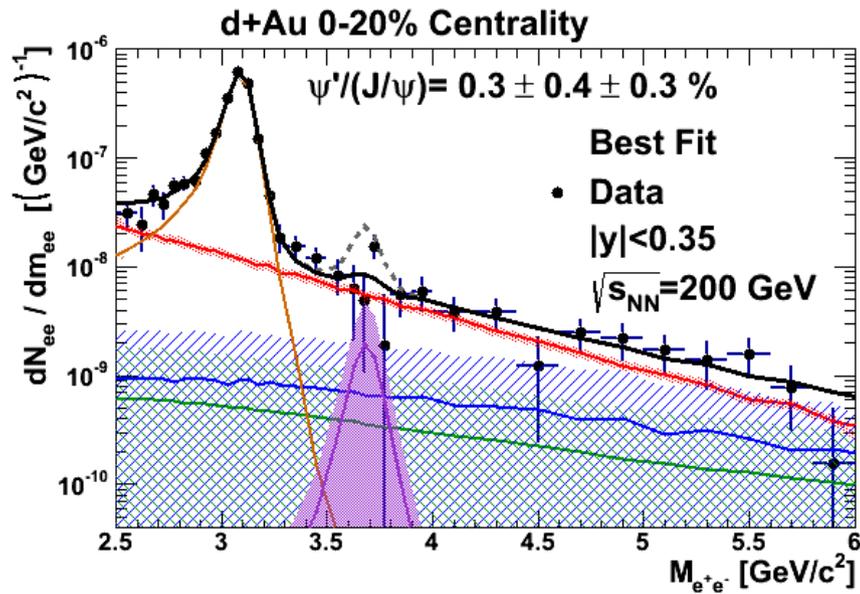
Charmonia  $R_{dAu}$  vs binding energy.

- $J/\psi$   $R_{AA}$  similar at 39, 62 & 200 GeV.
  - Need p+p and CNM references at low energy!
- $J/\psi$   $R_{dAu}$  centrality dependence nonlinear at forward rapidity.
- $p_T$  dependence of  $J/\psi$   $R_{dAu}$  different at backward rapidity from mid and forward rapidity.
  - Unexplained by current theories.
- Large suppression of  $\psi'$  in central d+Au events.
  - Time spent in nucleus very small at RHIC.
  - Why is  $\psi'$  so much more suppressed than  $J/\psi$ ?

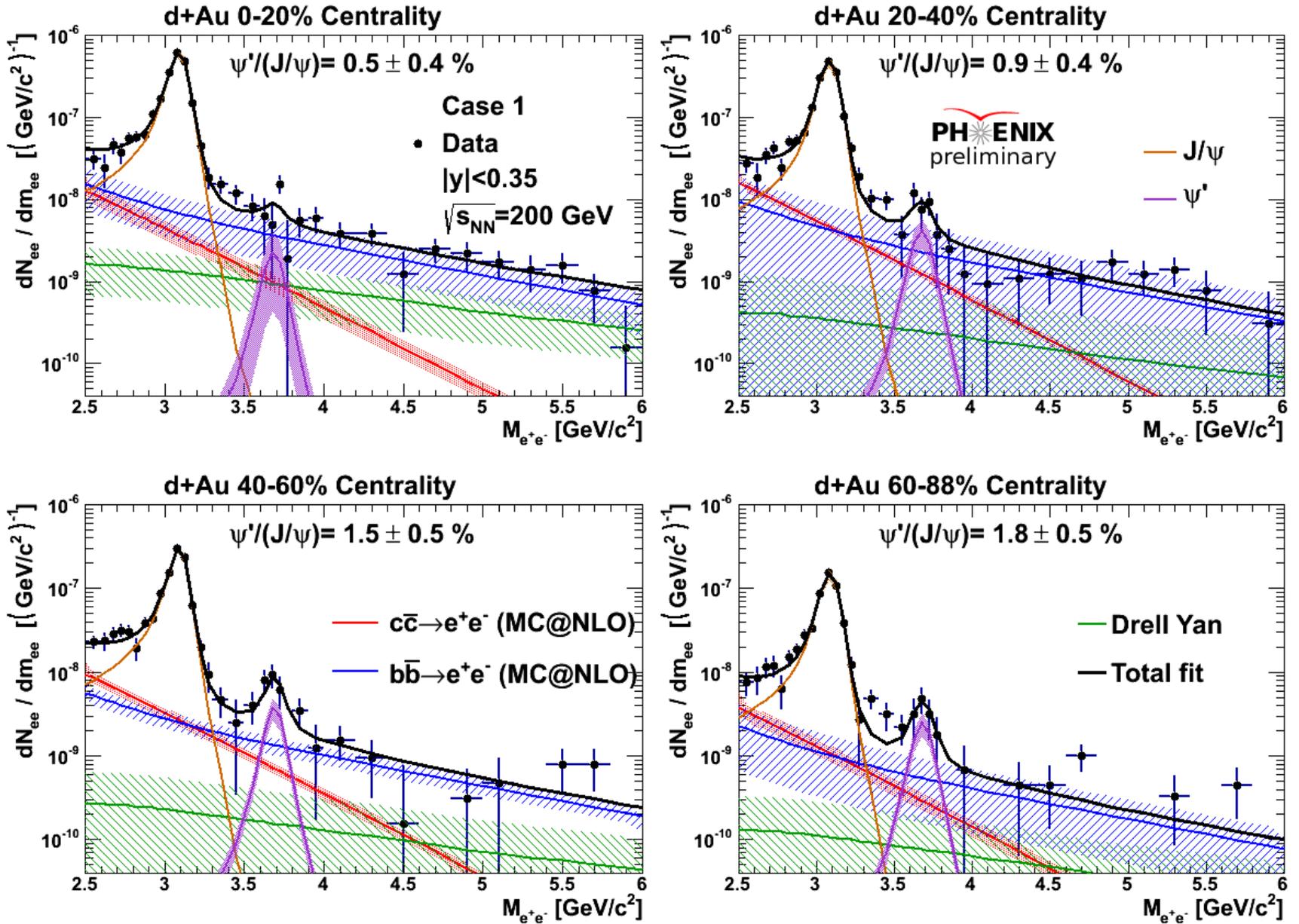
# Backup



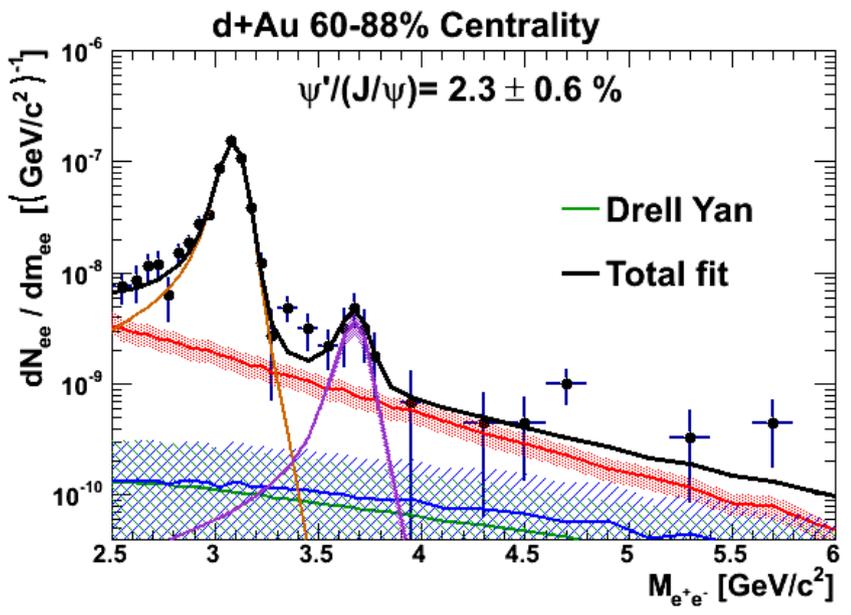
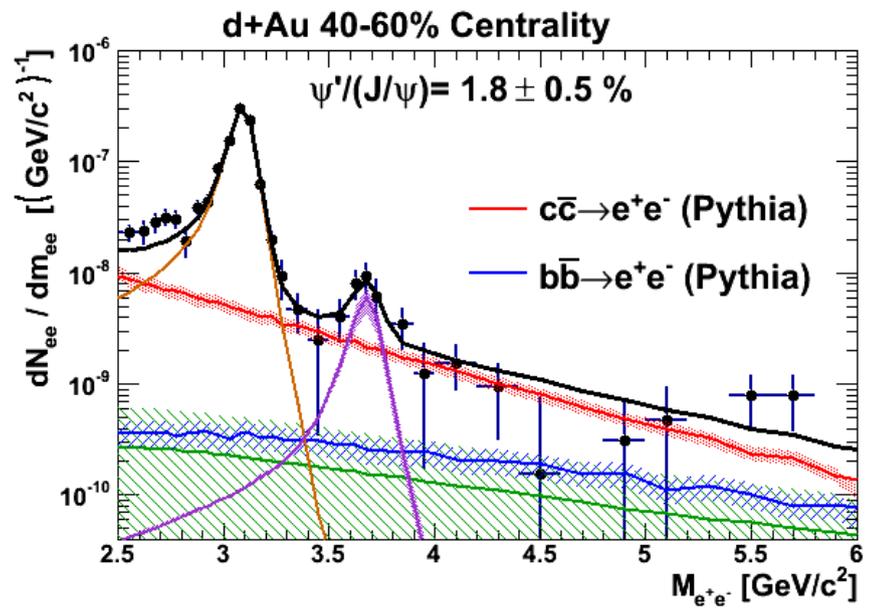
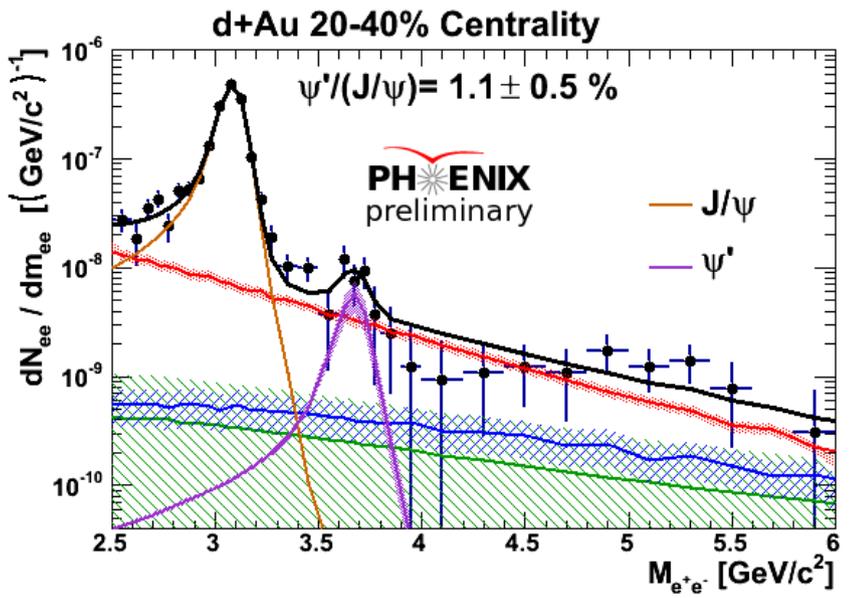
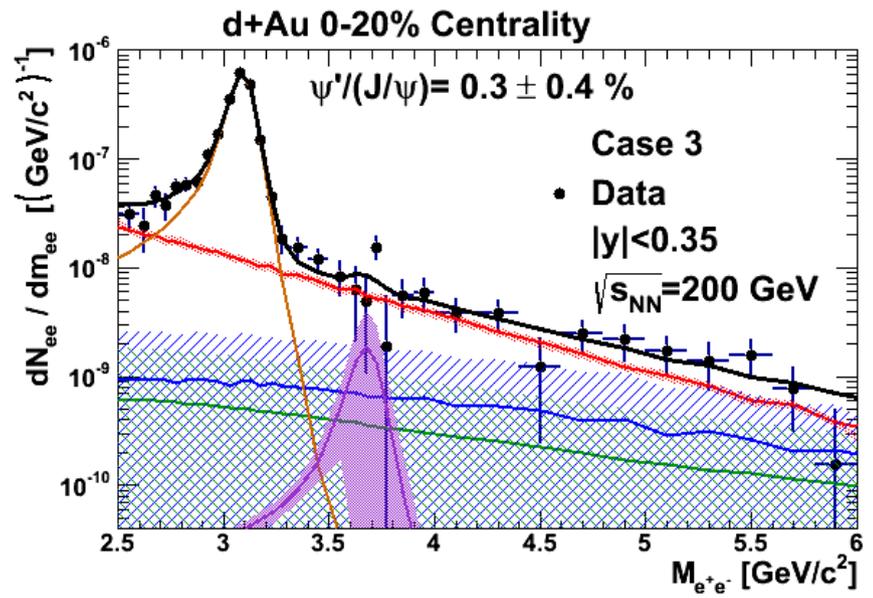
# Fits: Best w/ p+p ratio

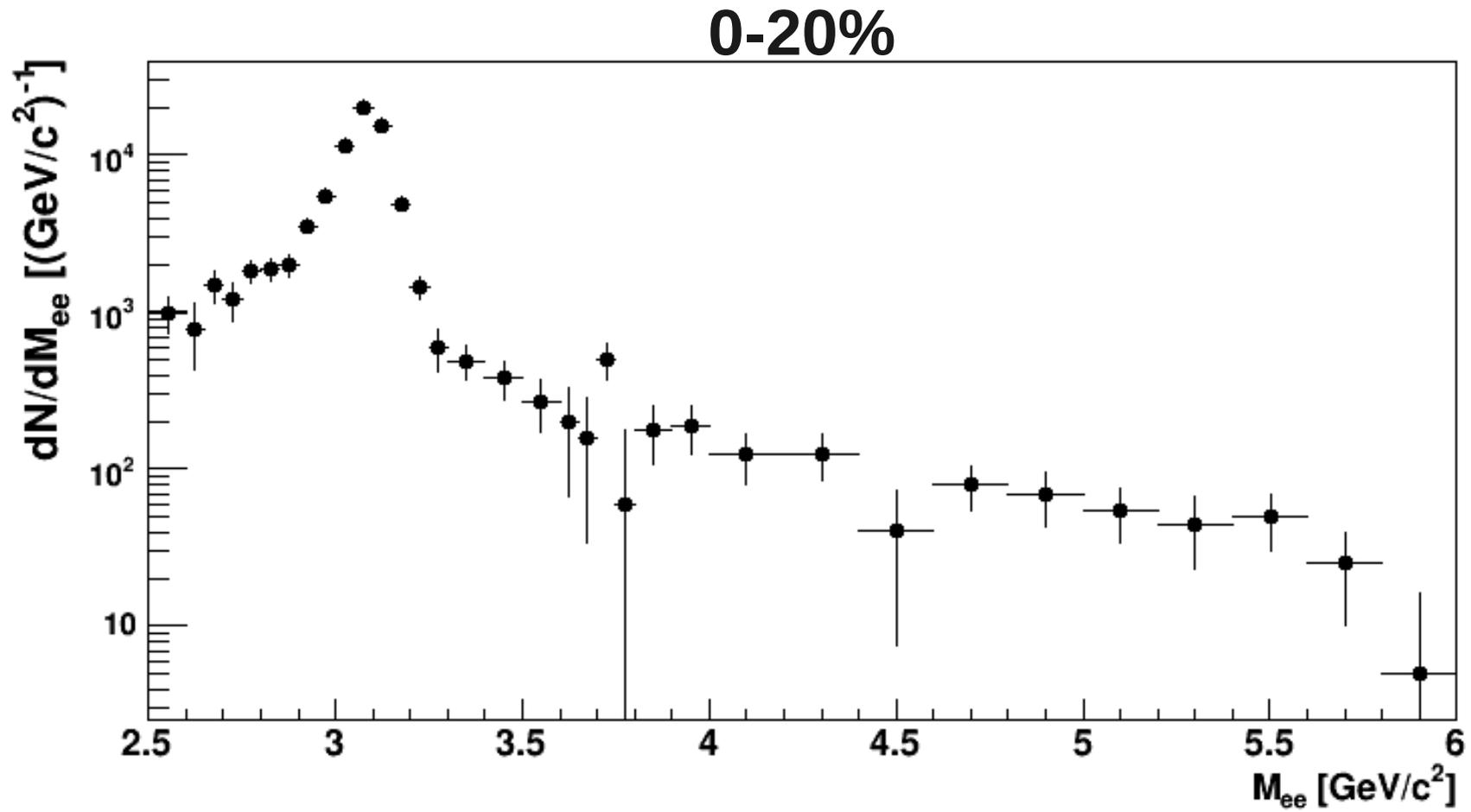


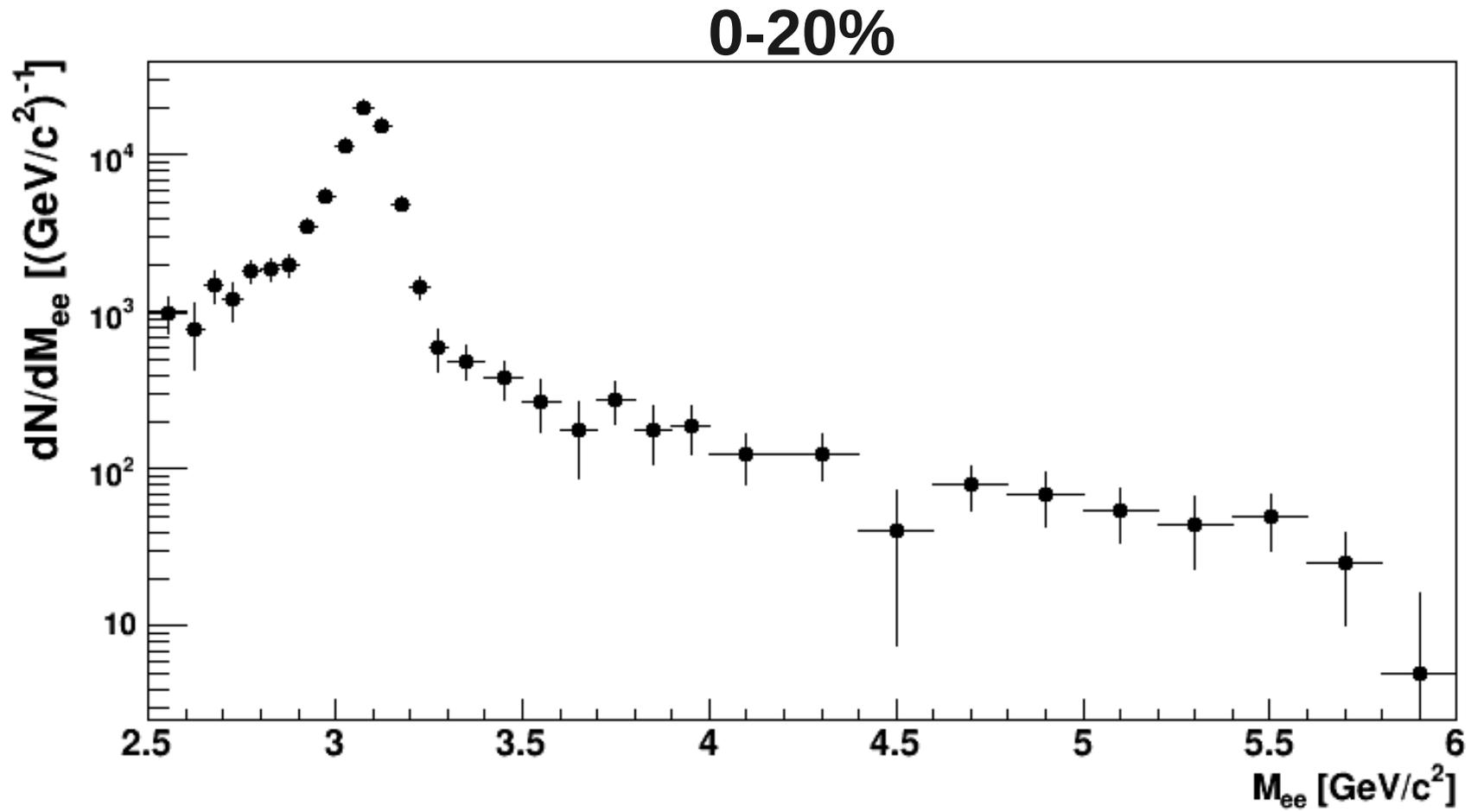
Use MC@NLO predictions for open charm and bottom



Fix the  $J/\psi$  and  $\psi'$  line shapes to be the same.



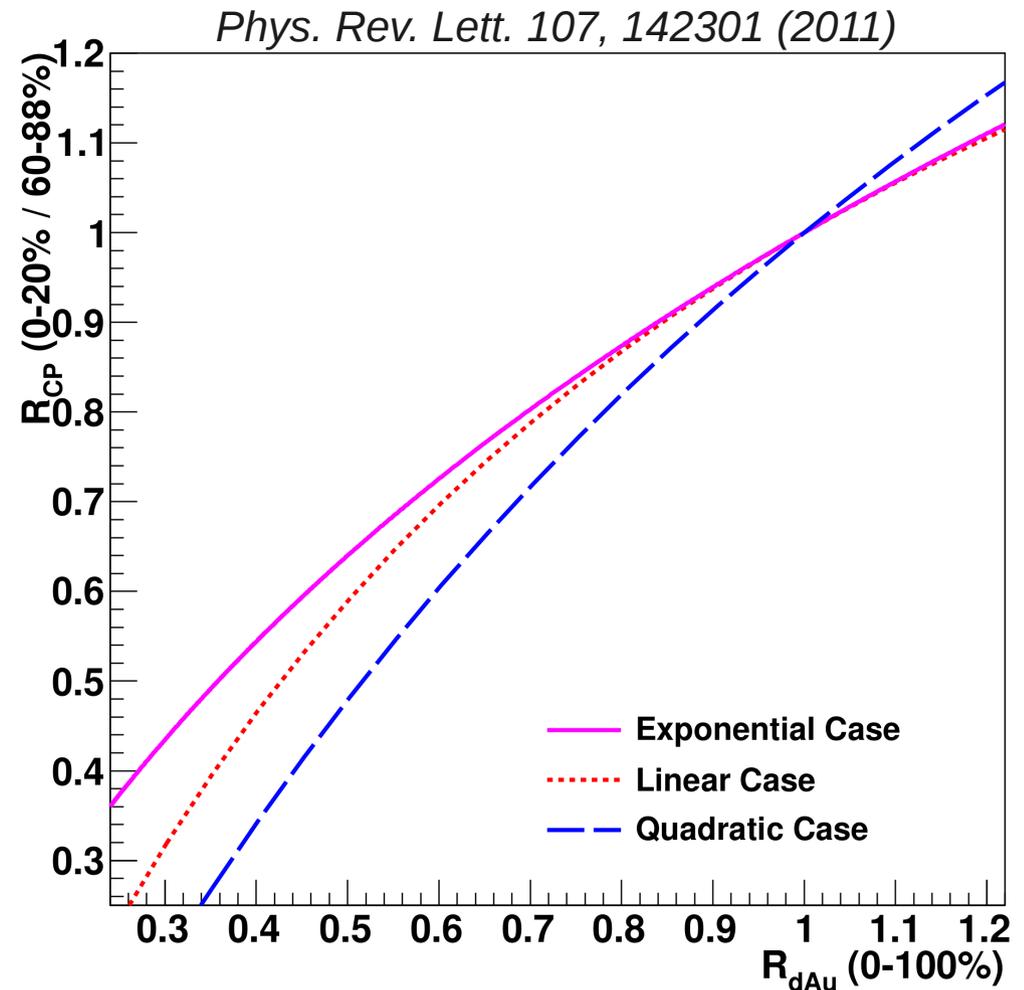




- $R_{dAu}$  (0-100%) is a measure of the **average** suppression.
- $R_{cp}$  is a measure of the **change** in suppression from central to peripheral events.
- Assume modification is dependent on the nuclear thickness.

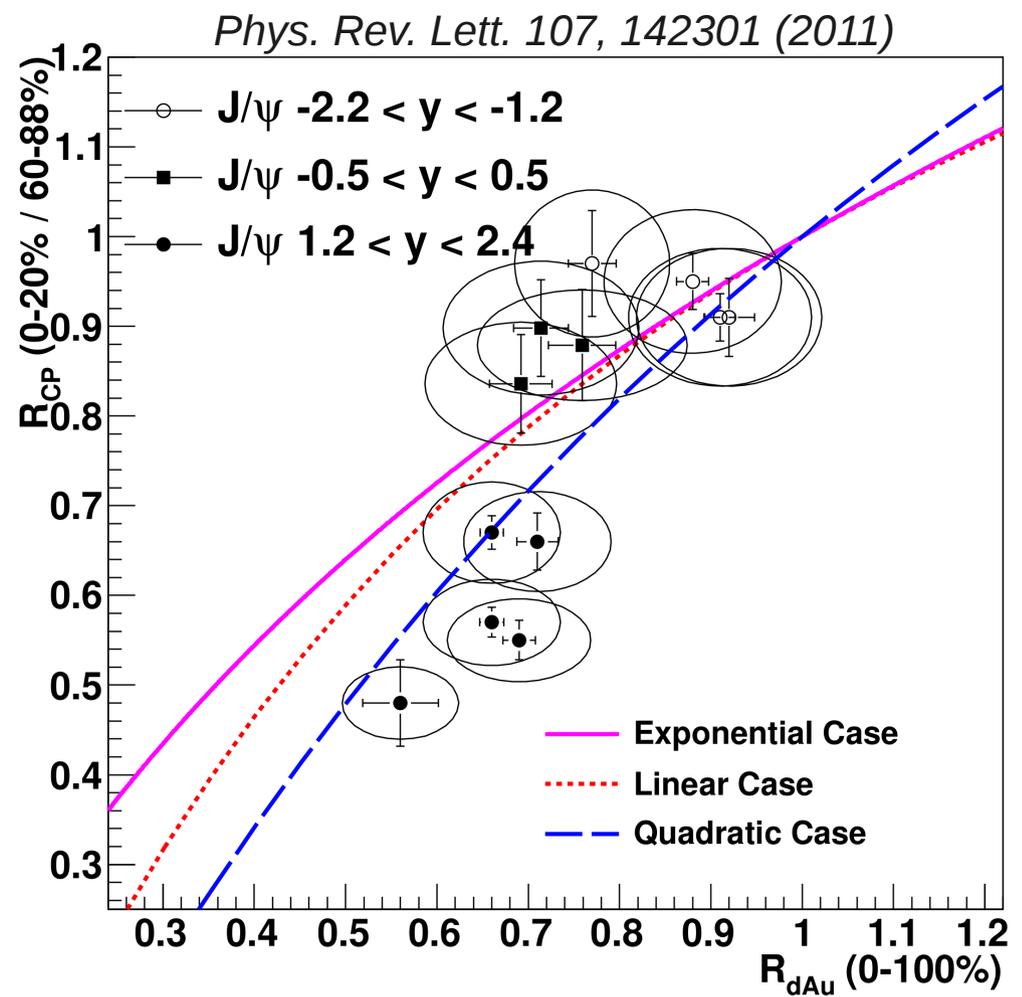
$$\Lambda(r_T) = \frac{1}{\rho_0} \int dz \rho(z, r_T)$$

- Try three simple forms.
  - **Linear:**  $M(r_T, a) = 1 - a\Lambda(r_T)$
  - **Quadratic:**  $M(r_T, a) = 1 - a\Lambda(r_T)^2$
  - **Exponential:**  $M(r_T, a) = e^{-a\Lambda(r_T)}$
- Each form maps out a unique curve on this plane.

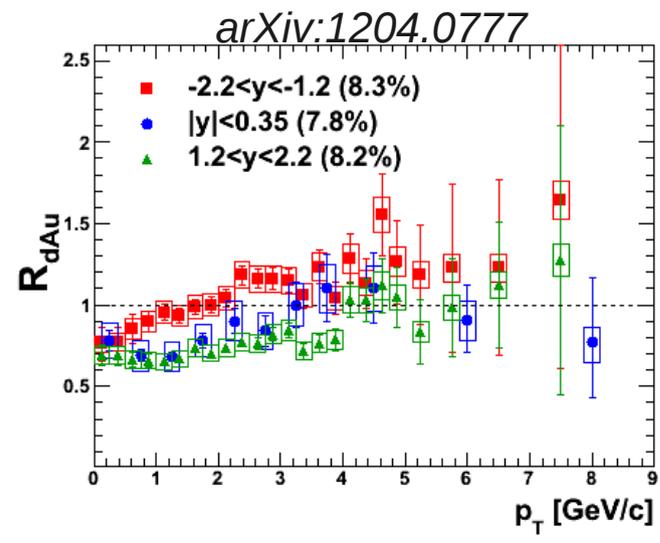


- Backward and mid rapidity data is unable to distinguish between the three cases shown here.
- Forward rapidity data requires stronger than linear or exponential dependence on the thickness.
- Agreement with linear only gets worse if you add exponential.
- Use data to extract thickness dependence!

**Vertical(horizontal) bars** show point-to-point uncorrelated errors  
**Ellipses** show point-to-point correlated systematic errors

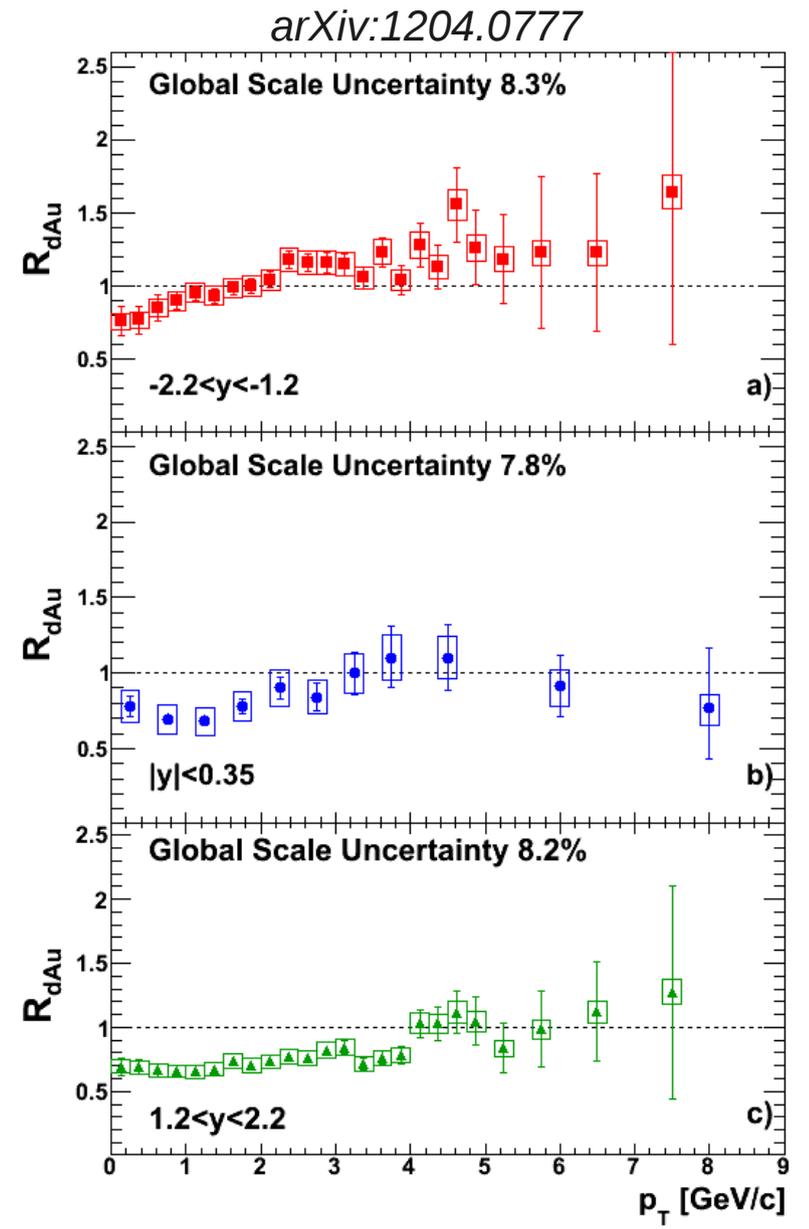


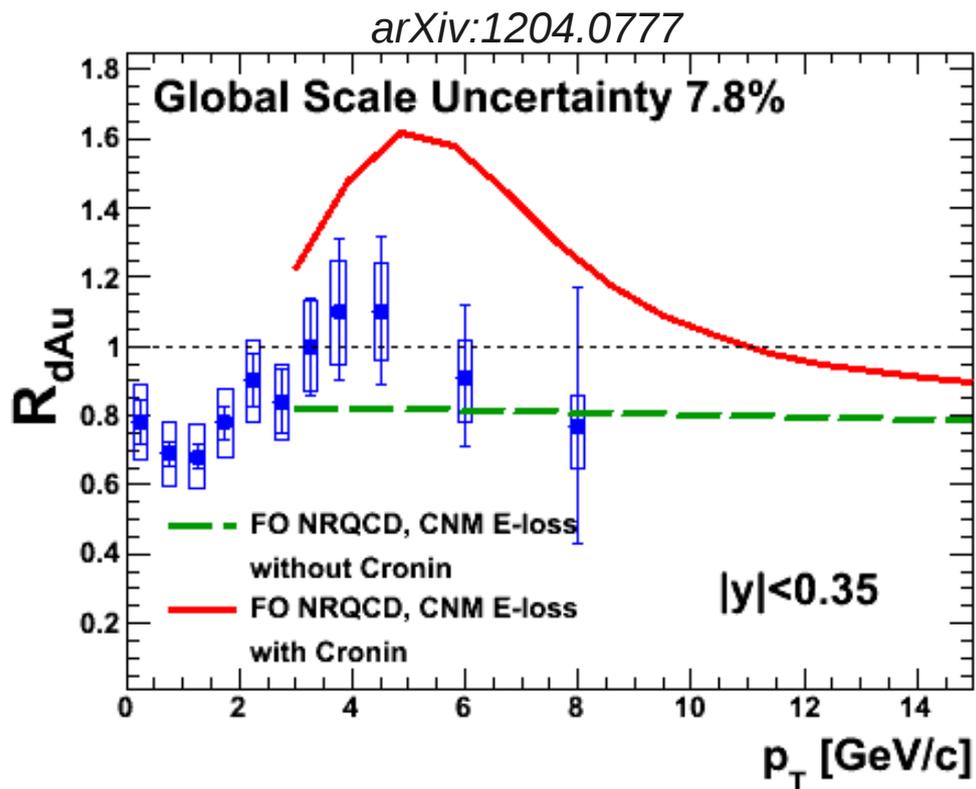
- Implies a CNM baseline in AA of  $\sim 1$  for  $p_T > 4$  GeV/c at midrapidity.
- Implies a CNM baseline in AA of  $> 1$  for  $p_T > 4$  GeV/c at forward rapidity.



Vertical Error bars – uncorrelated uncertainties

Boxes – point-to-point correlated uncertainties.

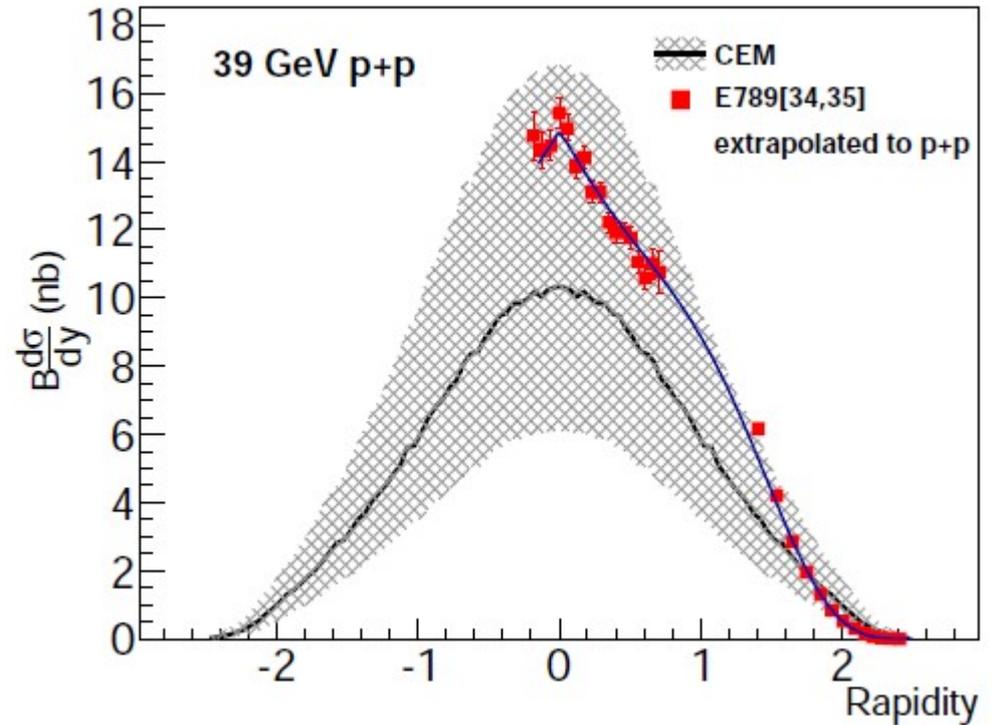
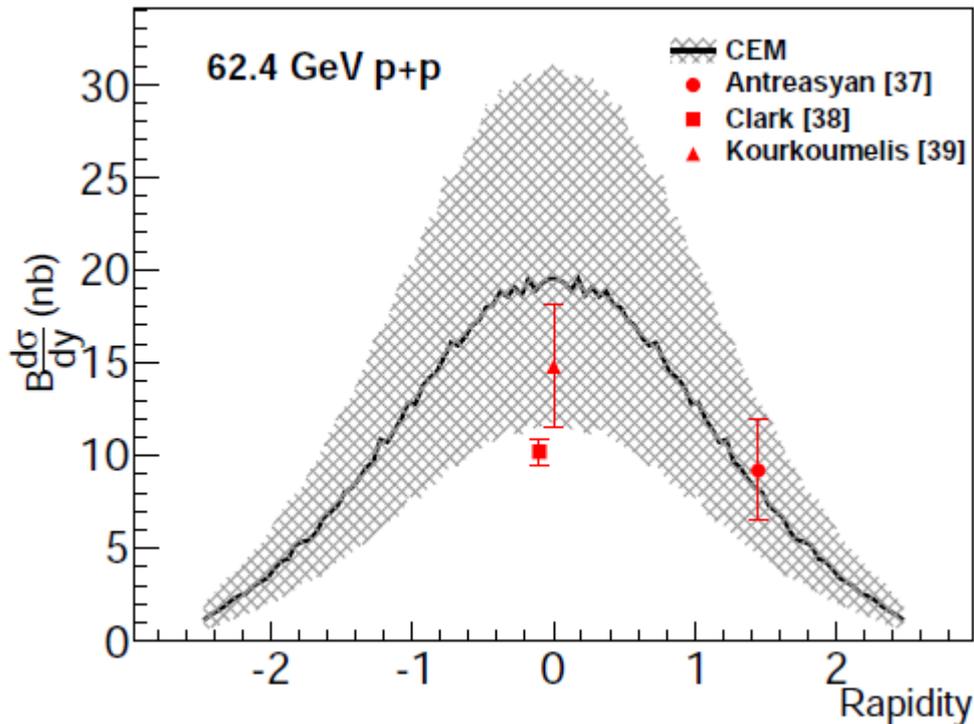




- Calculations by Sharma and Vitev (*arXiv:1203.0329*).
- Nuclear Shadowing - EKS98
- Includes initial state energy loss.
- **Dashed Curve** – No Cronin Effect.
- **Solid Curve** – With Cronin Effect.

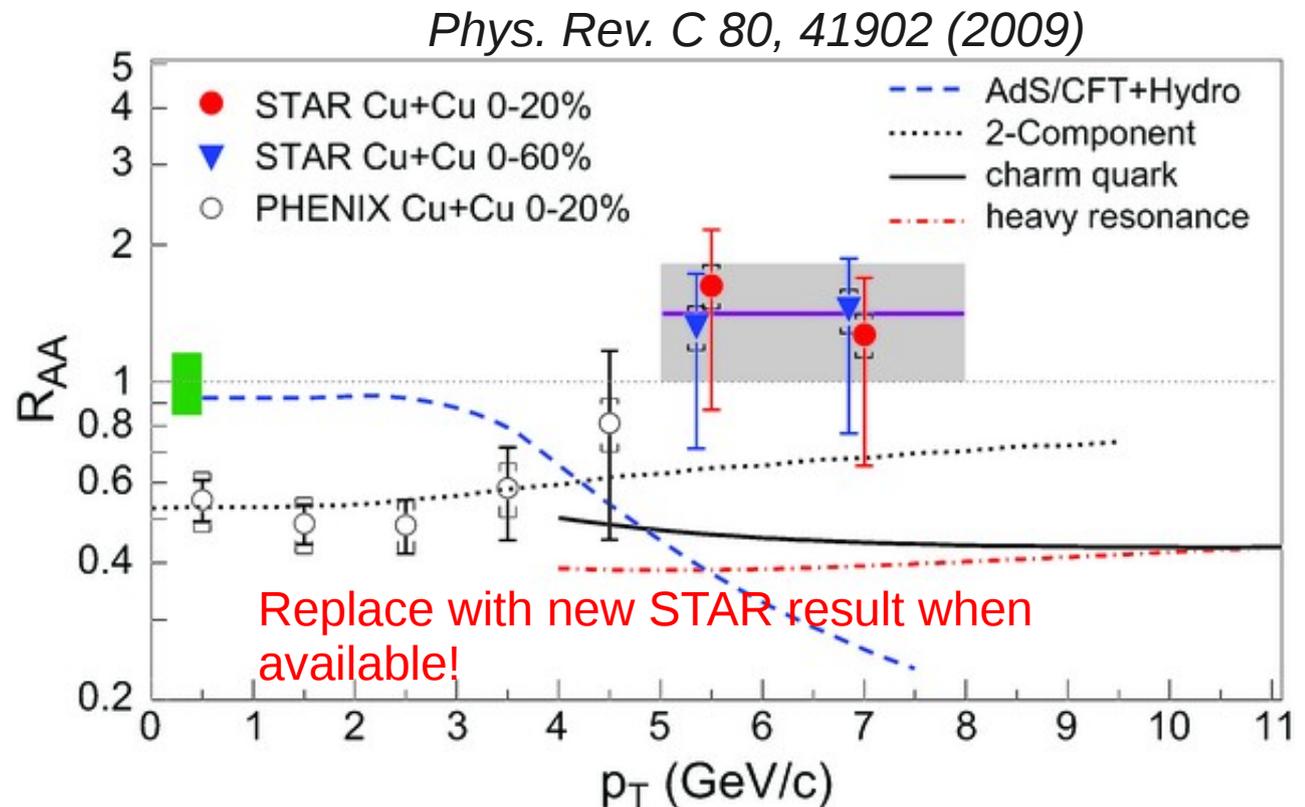
Shape is in reasonable agreement with the data  
 Magnitude of Cronin effect is too large?

At 39 GeV use available data from Fermilab E789 & E866/NuSea.



At 62.4 GeV, integrate shape of CEM calculations normalized to Antreasyan data point

- At midrapidity  $R_{dAu}$  implies CNM baseline in A+A at high- $p_T$  of  $\sim 1$ .
- A+A CNM effects at forward rapidity are a combination of backward and forward rapidity  $R_{dAu}$ , implies CNM baseline at high- $p_T$  of  $\geq 1$ .
- Rise in  $R_{AA}$  with  $p_T$  may be due to changing CNM effects.

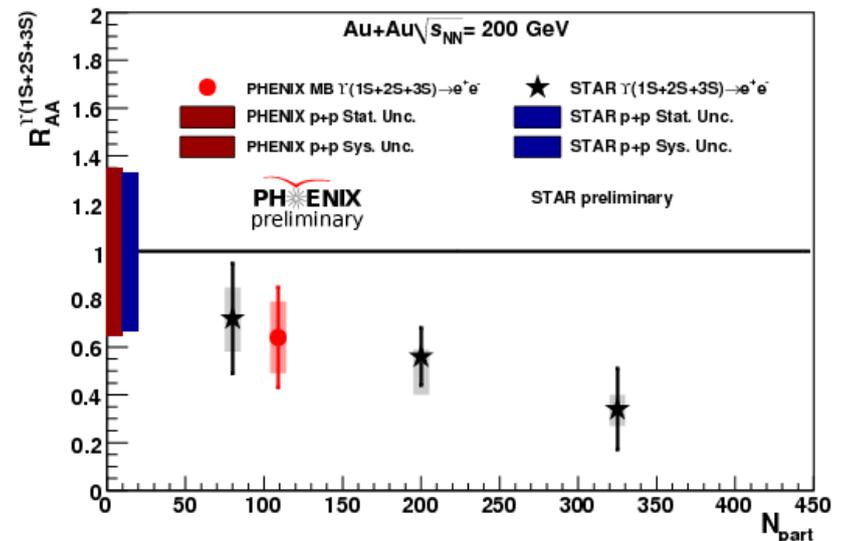
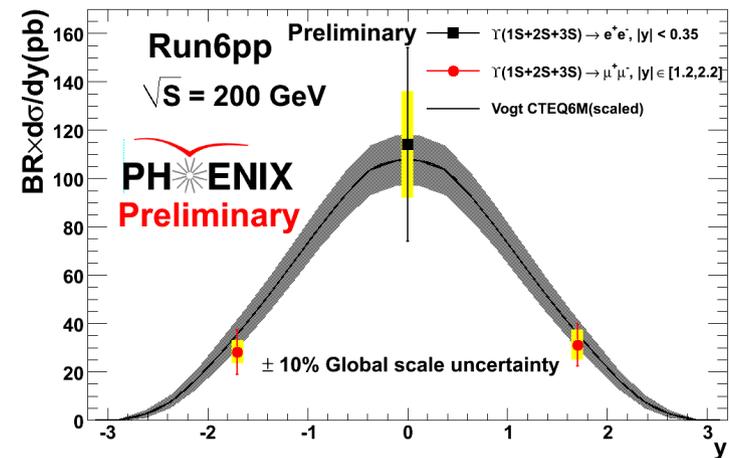


- New results in the works:

- $R_{dAu}$  at midrapidity
- $R_{AA}$  at forward rapidity

- Final results on the way:

- p+p production at backward, mid, and forward rapidity
- $R_{dAu}$  at forward/backward rapidity
  - See poster by Kwangbok Lee.
- $R_{AA}$  at midrapidity
  - See poster by Shawn Whitaker.



- Calculations from Ferreiro et al. (*arXiv:1201.5574*)
- Nuclear Shadowing → nDSg nPDF set.
- Nuclear Break-up → effective  $\sigma_{\text{abs}} = 4.2 \text{ mb}$ .
- No Cronin Effect.

