

# Quarkonium Production Results from PHENIX

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On behalf of the PHENIX Collaboration

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## Latest quarkonium data from PHENIX:

U+U J/ $\psi$  suppression from RHIC 2012 Run

Phys. Rev. C 93, 034903 (2016)

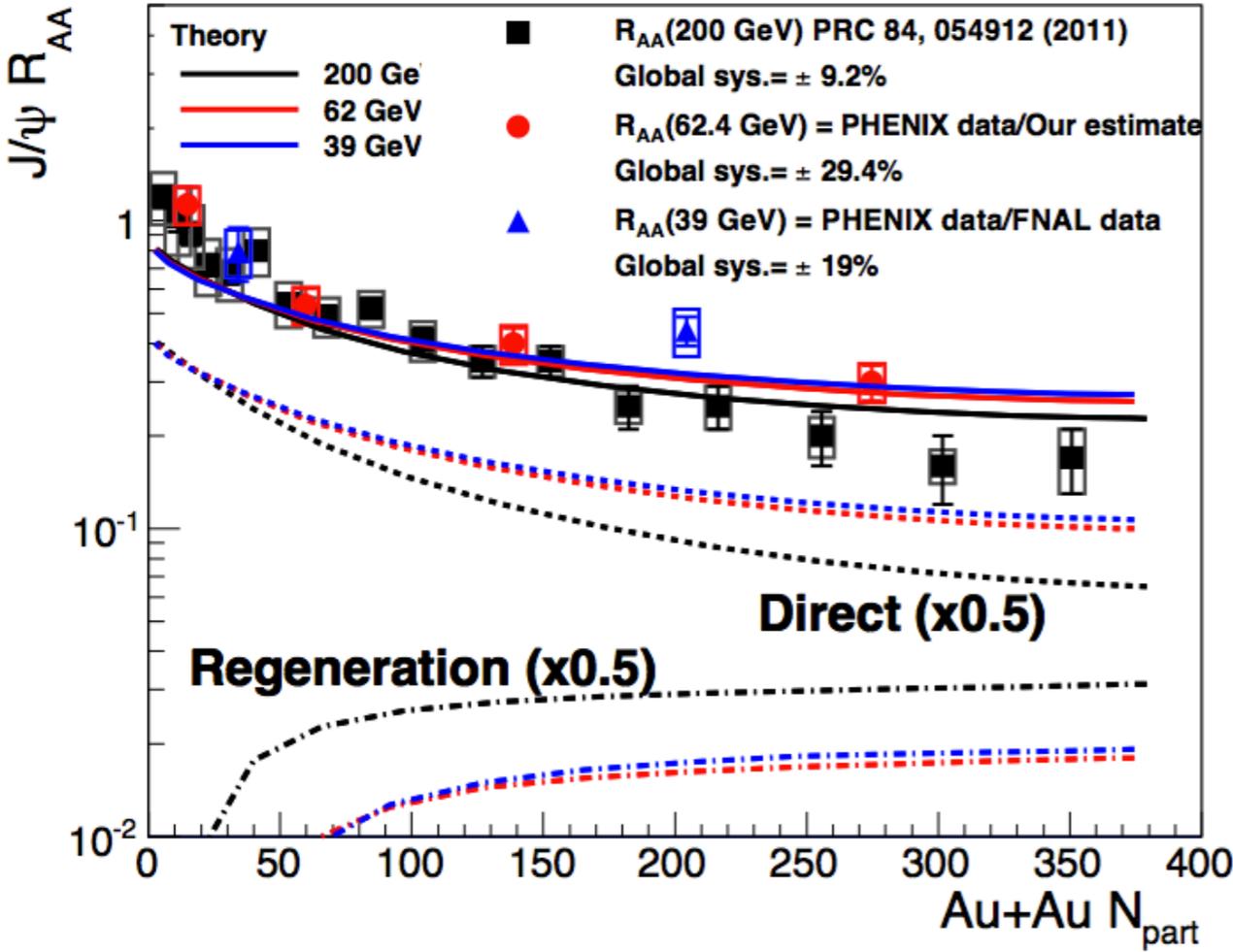
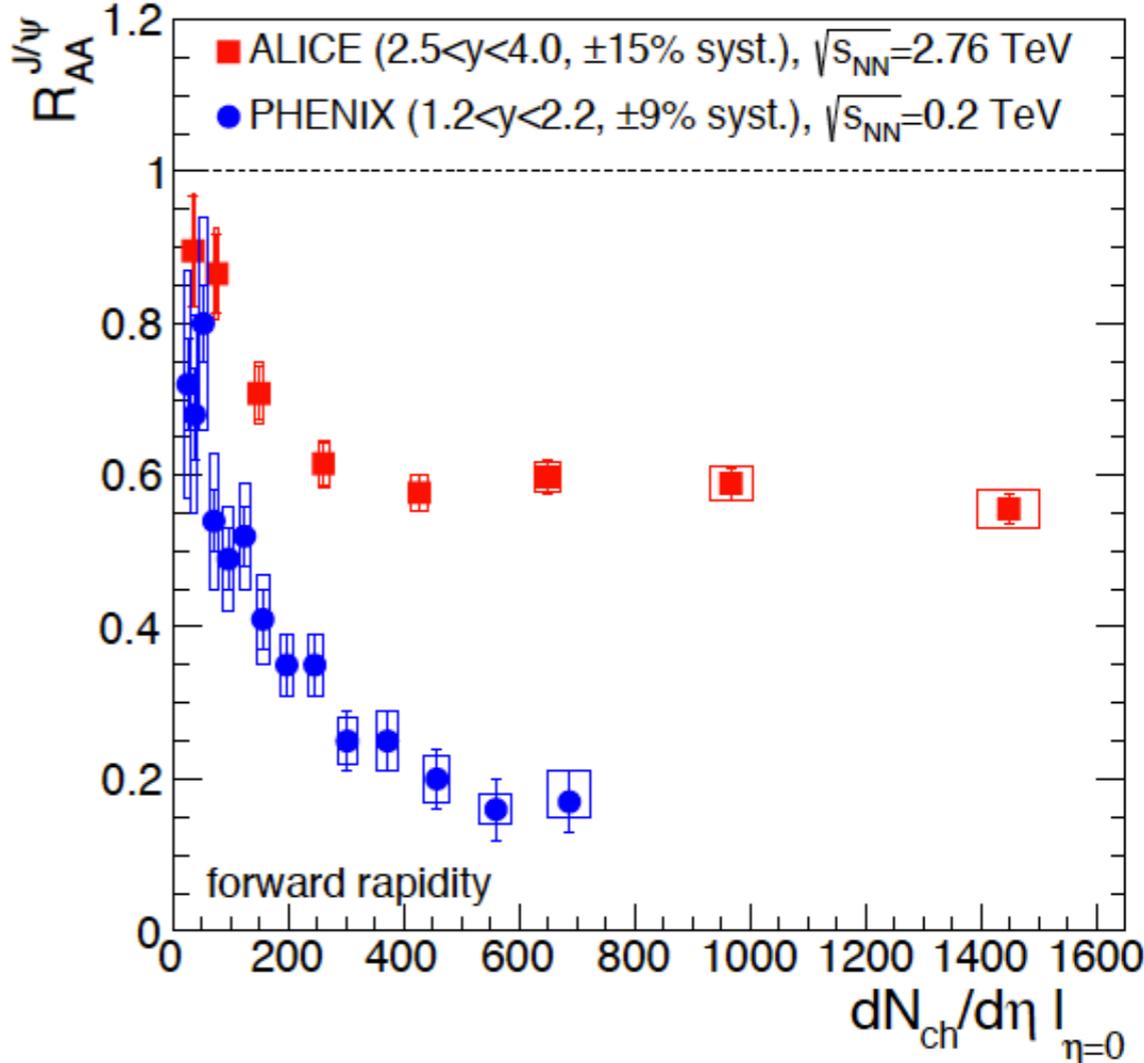
$\psi(2S)$  /  $\psi(1S)$  ratios in p+p, p+Au, p+Al from 2015 Run

- Tracks measured with muon arms + FVTX detector
- Improved opening angle resolution separates J/ $\psi$  from  $\psi'$  in mass spectrum

# LHC energy brings strong charm coalescence

$J/\psi$  suppression much stronger at 200 GeV than 2.76 TeV for similar energy density - strong **coalescence**

At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression  
 - perhaps strongest at 200 GeV



In the model (PRC82, (2010) 064905) this similarity is due to a **balance** between color screening and coalescence

# Where does coalescence start to dominate?

U+U collisions allow us to go to higher energy density at RHIC

Central U+U collisions should have:

- 15-20% higher energy density than Au+Au collisions
  - stronger **color screening**
- Increased charm production from  $\sim 25\%$  larger  $N_{coll}$  values
  - stronger **coalescence**

J/ $\psi$  production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production

# U+U measurements

In RHIC Run 12 we recorded 1.08 B minbias  $\sqrt{s_{NN}} = 193$  GeV U+U events

The **p+p reference** for  $R_{AA}$  is from the RHIC 2008 run

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

The p+p cross section was **reduced by 0.964**

- Accounts for 200  $\rightarrow$  193 GeV energy difference between p+p and U+U data
- derived from PYTHIA p+p simulations

Final  $J/\psi$  data from the muon arms ( $1.2 < |y| < 2.2$ ) are now available

- Phys. Rev. C 93, 034903 (2016)

# U deformation

Need  $N_{coll}$  to get  $R_{AA}$  for U+U. Requires a **deformed Woods Saxon** distribution of the nucleons in the U nucleus

$$\rho = \frac{\rho_0}{1 + \exp([r - R']/a)}$$

where

$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

We considered two parameterizations of the deformation of the U nucleus:

**Set 1** (Phys. Lett. B 679, 440 (2009)) - “conventional” description of the U deformation

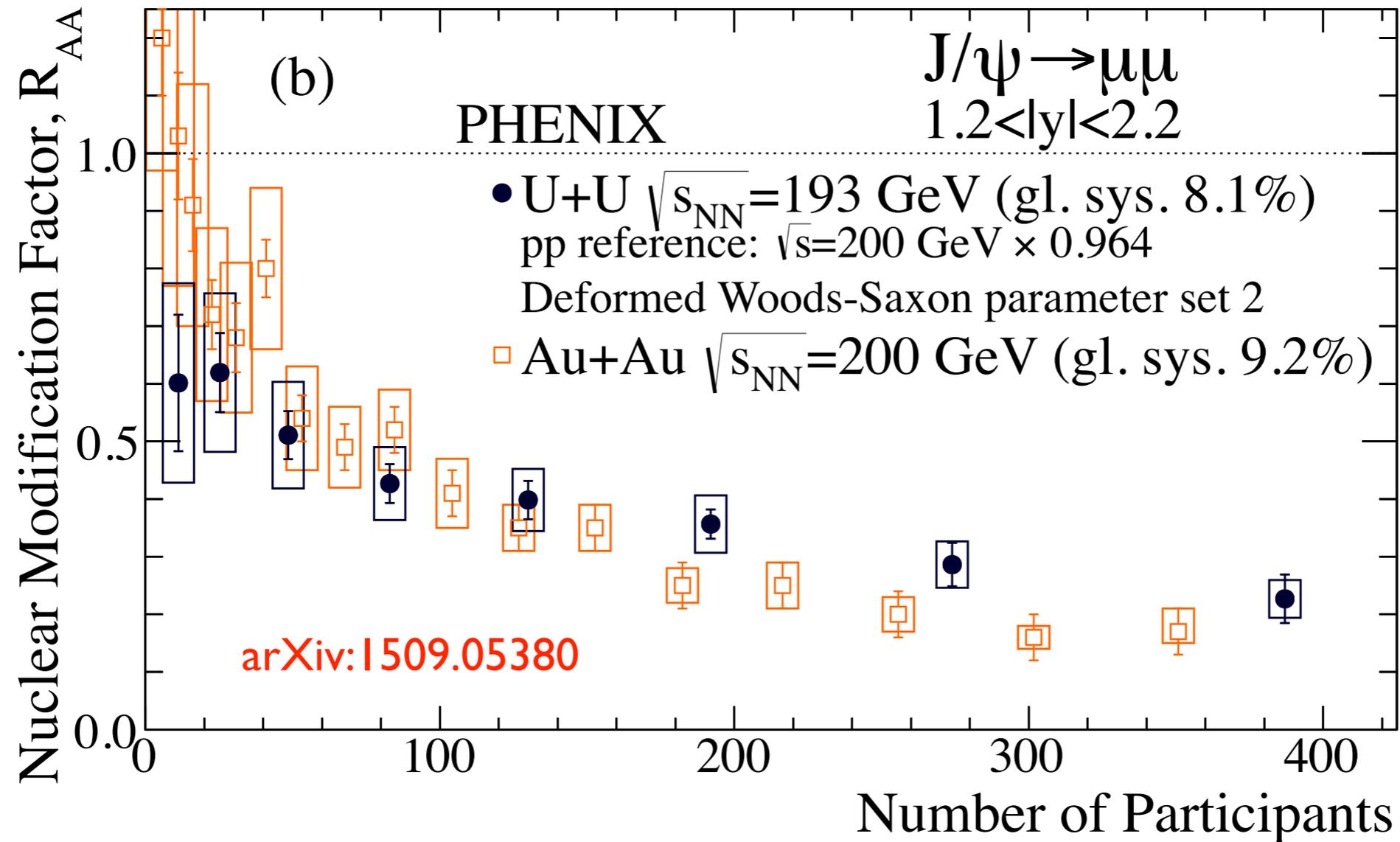
- The mean radius and diffuseness are taken from electron scattering

**Set 2** (Phys. Lett. B 749, 215 (2015)) differs in 2 ways:

- Takes into account the finite radius of the nucleon
- Averages over all orientations of axis-of-symmetry
  - match average radius and diffuseness to values reported from electron scattering

# The U+U $R_{AA}$

Start with the latest parameter set (2) to calculate  $R_{AA}$



The U+U  $R_{AA}$  is noticeably larger than that for Au+Au

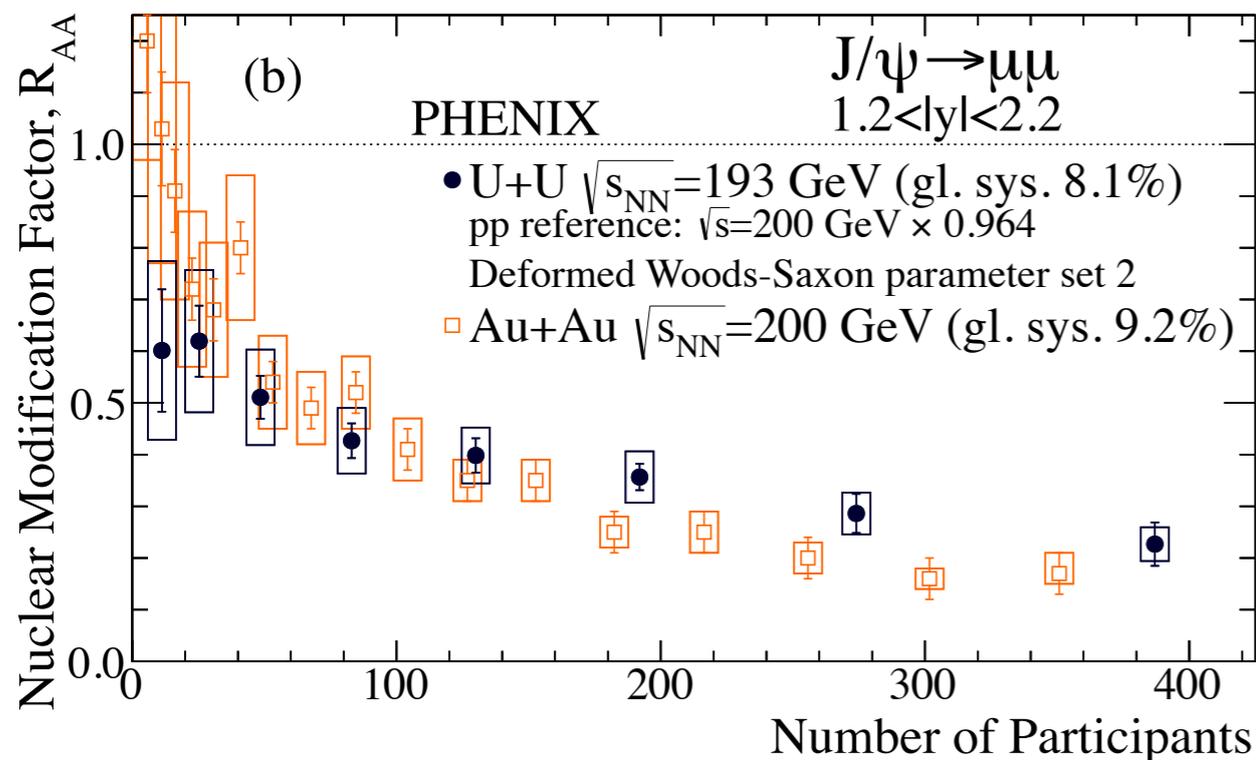
# Effect of U deformation model

The parameters for set I are significantly different in their **surface diffuseness**:

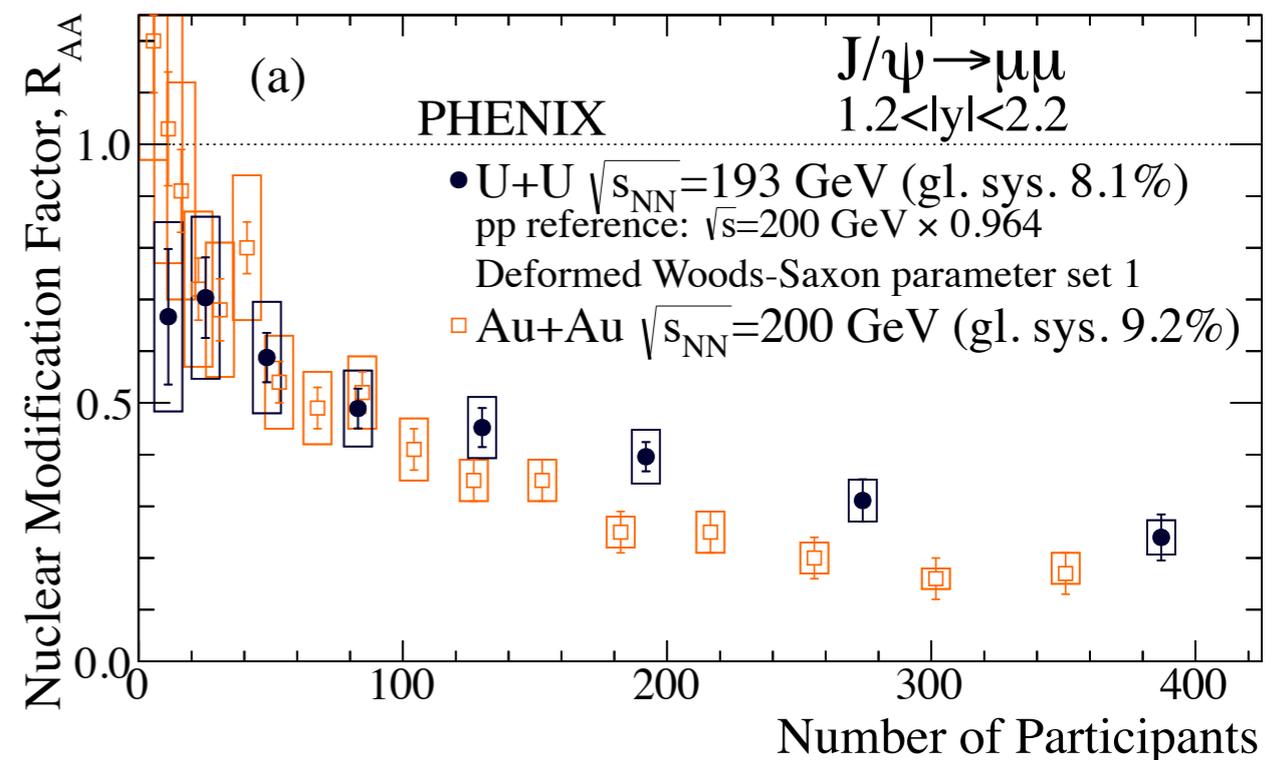
Parameter	set 1	set 2
$R$ (fm)	6.81	6.86
$a$ (fm)	0.6	0.42
$\beta_2$	0.28	0.265
$\beta_4$	0.093	0

Larger surface diffuseness for set I results in a less compact nucleus, a larger reaction cross section by 12%, and  $N_{coll}$  values that are smaller by 6 - 15%

Set 2



Set I



# Ratio of $dN/dy$ for U+U and Au+Au

Make the experimental ratio of  $dN/dy$  values.

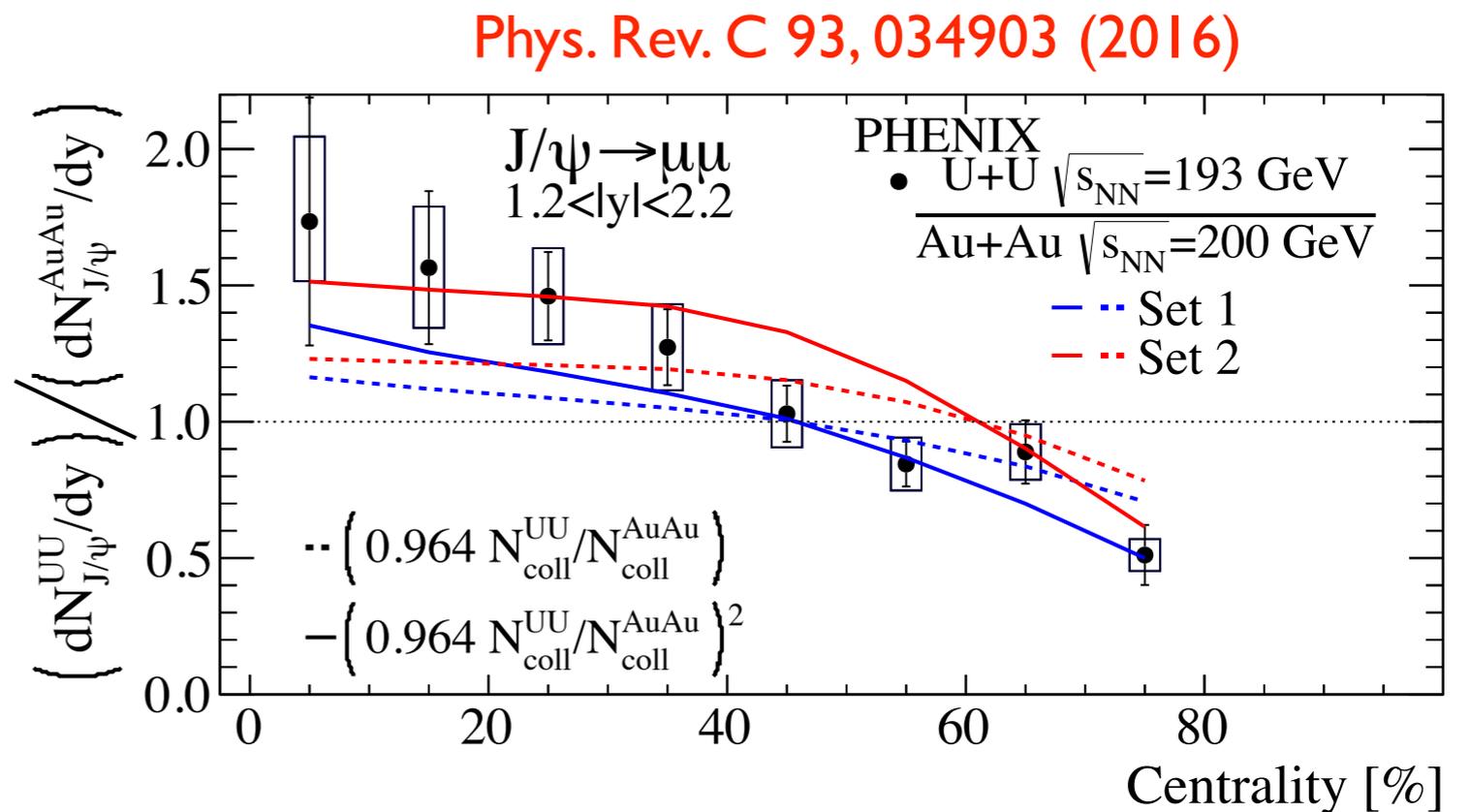
- Has the advantage that it does not rely on  $N_{coll}$
- However our **expectation** for its behavior is determined by  $N_{coll}$

Compare with curves showing how the ratio would depend on centrality if  $J/\psi$  production scaled with

- $N_{coll}$  (dashed)
- $N_{coll}^2$  (solid)

Curves shown for sets 1 and 2

For set 2, for central collisions the ratios tend to favor the  $N_{coll}^2$  curve



For set 1, the ratios are consistent with both curves across centrality, slightly favoring  $N_{coll}^2$  for most central collisions

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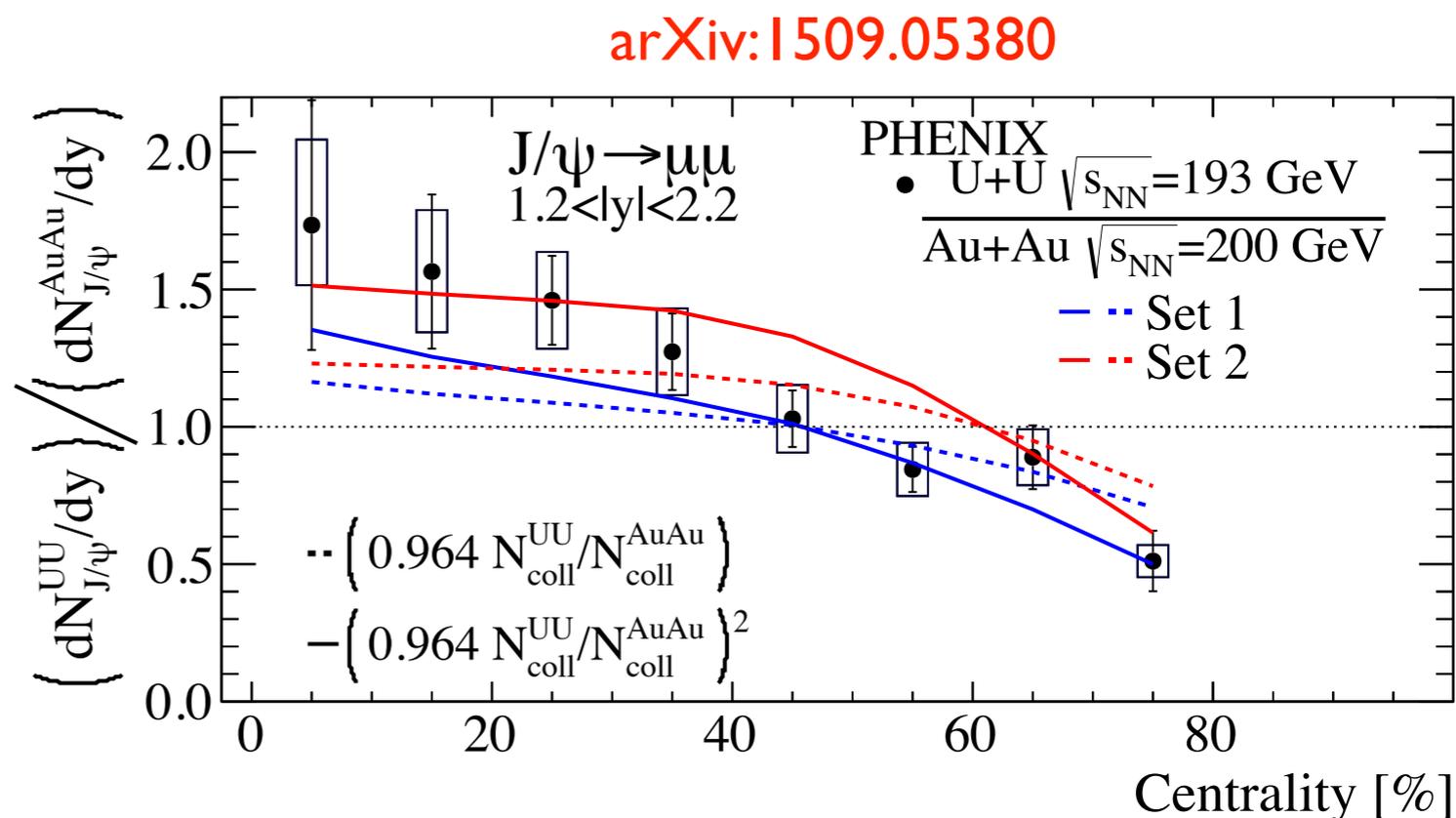
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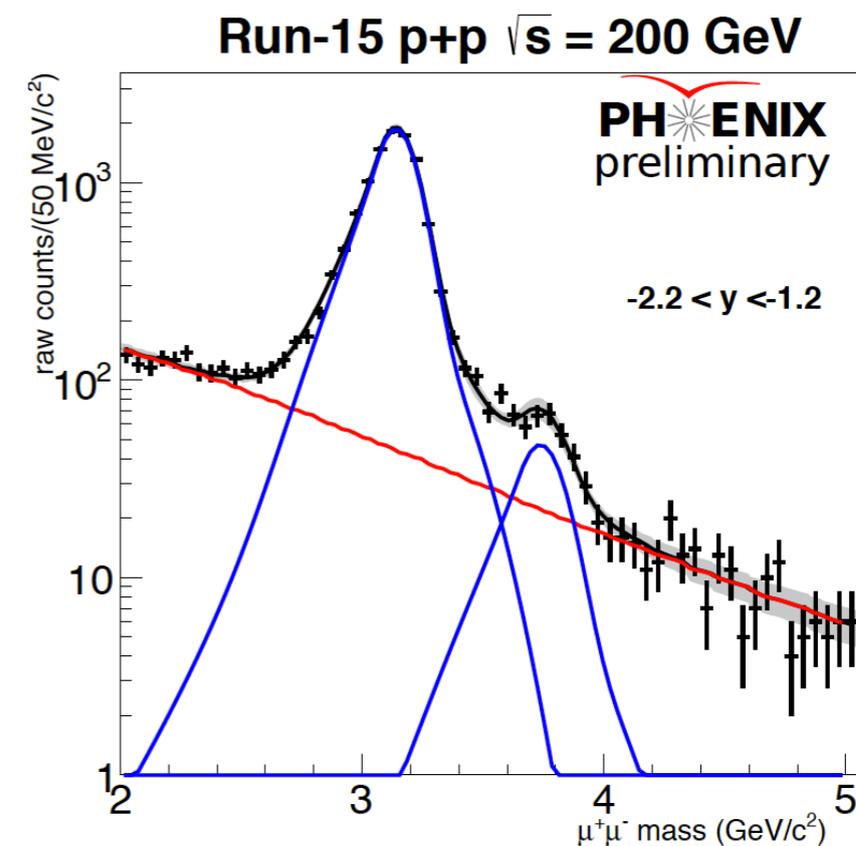
Consistent with a picture in which the increase in charm coalescence becomes more important than the increased color screening when going from Au+Au to U+U

Preliminary  $\psi' / J/\psi$  ratios in  $p+p$ ,  $p+Al$  and  $p+Au$

# Preliminary $\psi'$ / $J/\psi$ ratios in $p+p$ & $p+Au$

$p+p$ , collisions

$\psi'$  and  $J/\psi \rightarrow \mu^+\mu^-$   $1.2 < |y| < 2.2$

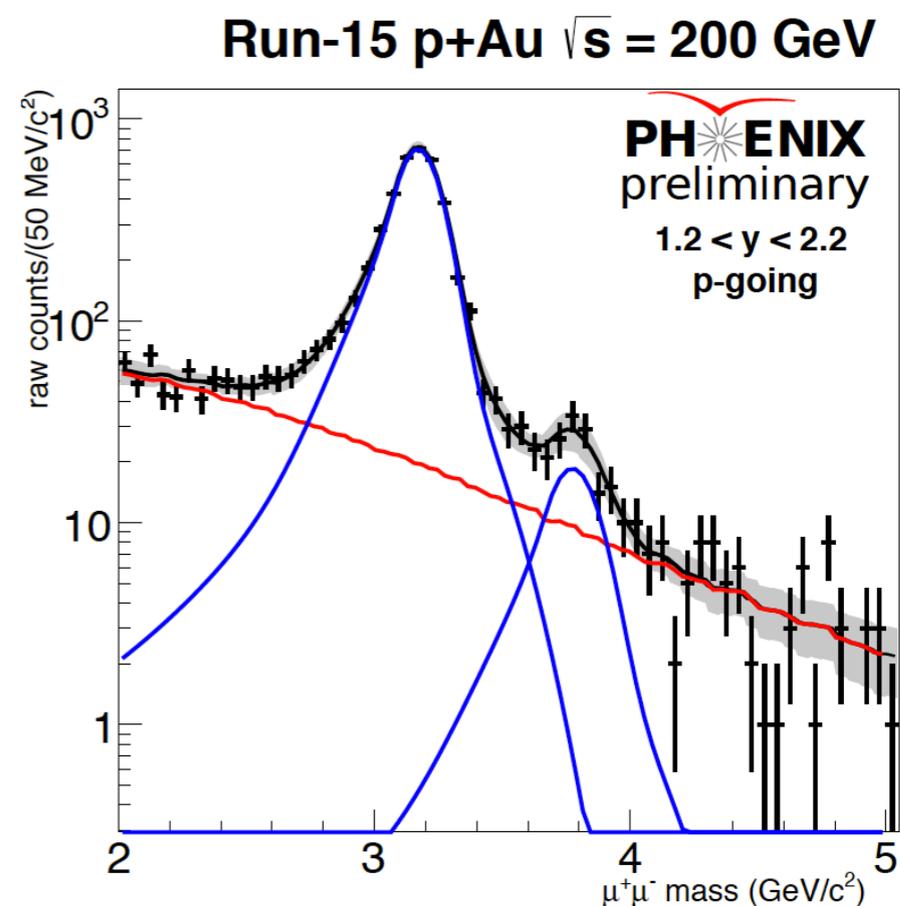
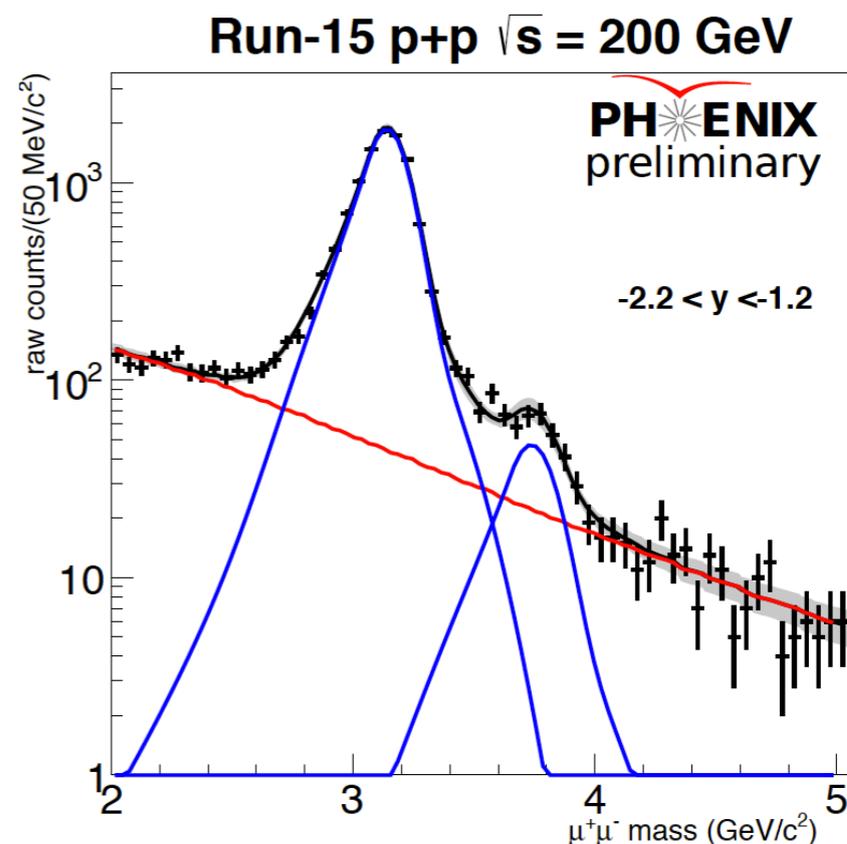


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Fit method and cuts in  $p+Au$  identical to  $p+p$  analysis



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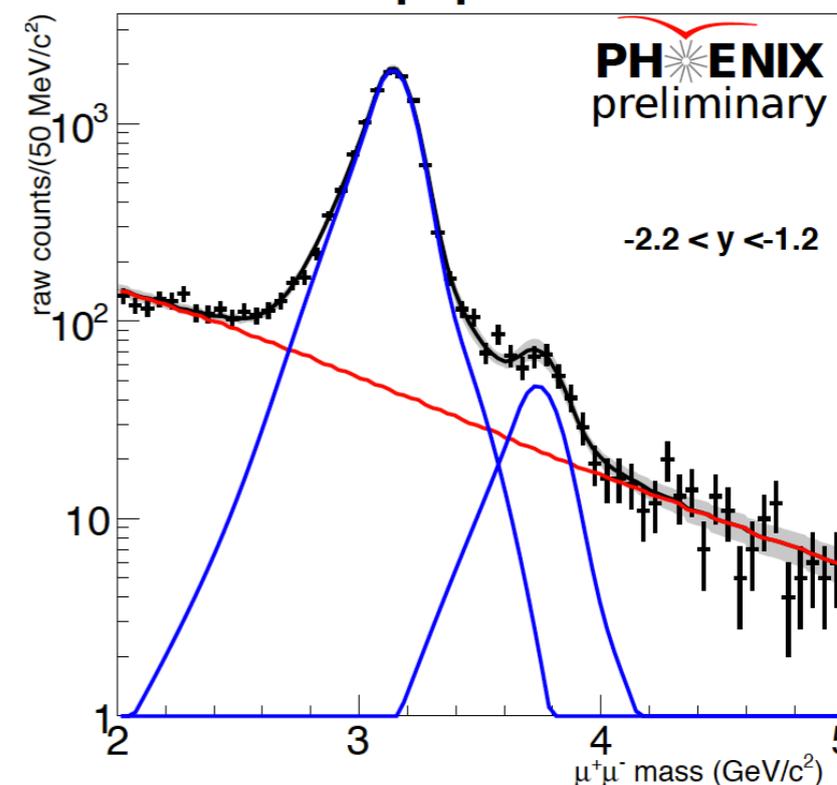
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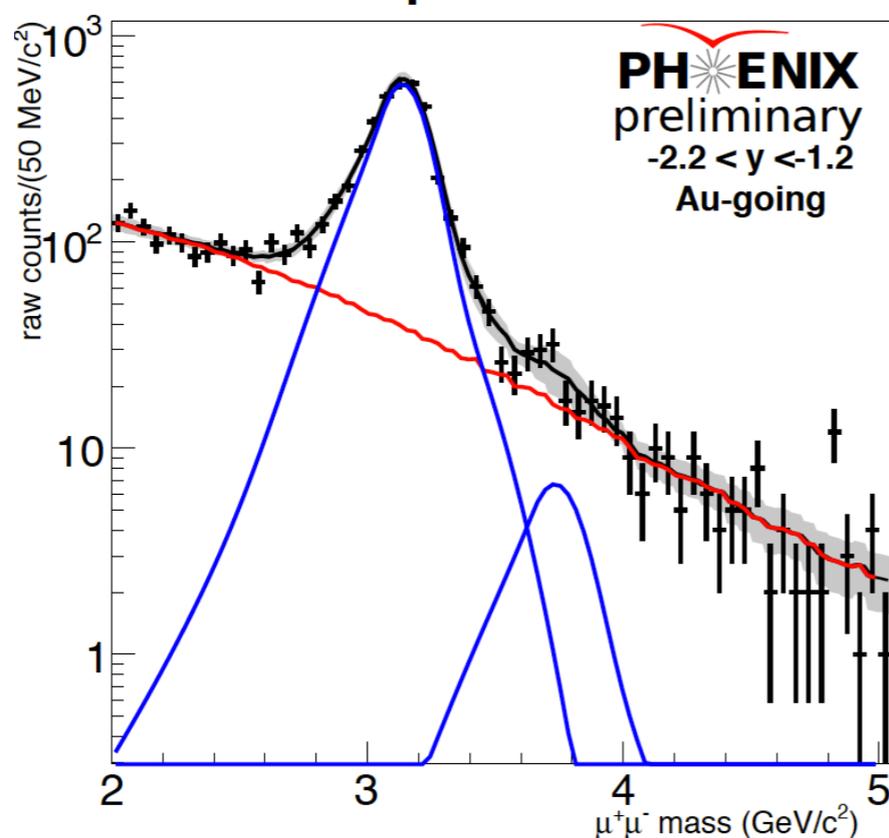
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Stronger suppression evident in Au going direction

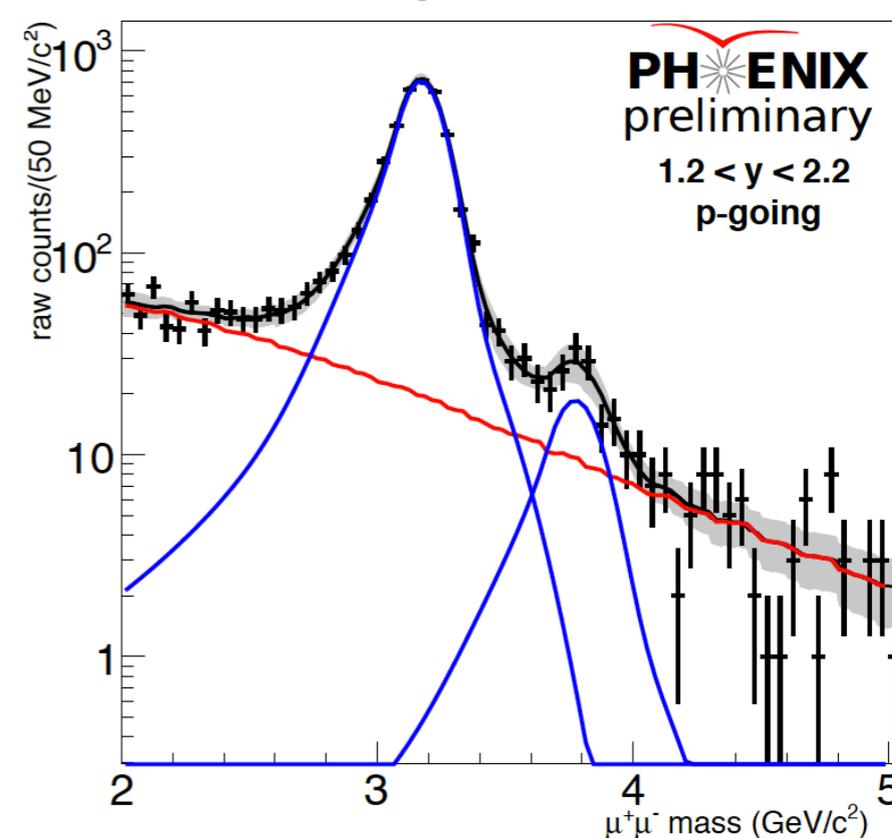
Run-15  $p+p$   $\sqrt{s} = 200$  GeV



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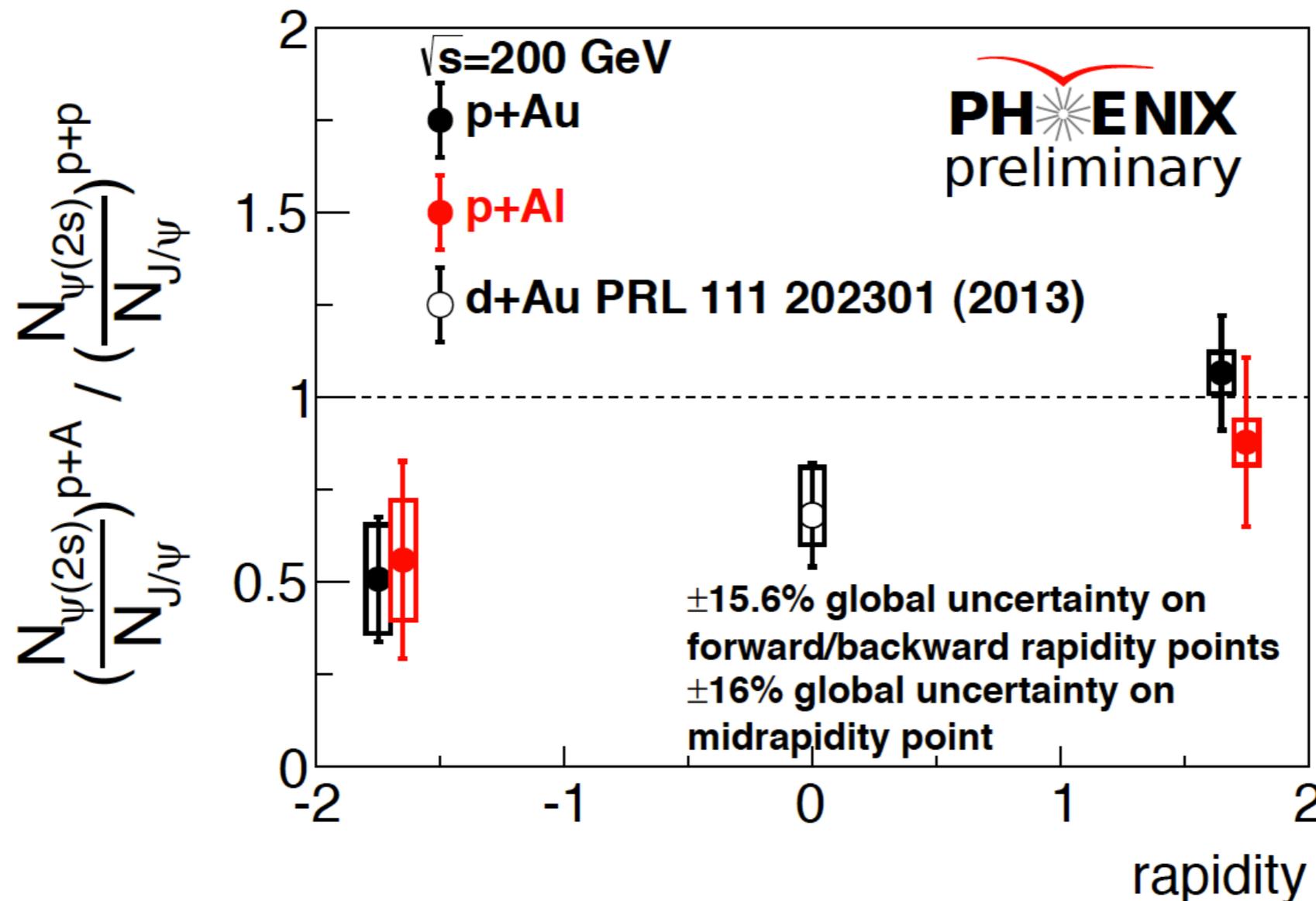


# $\psi' / J/\psi$ ratios in p+Au and p+Al vs rapidity

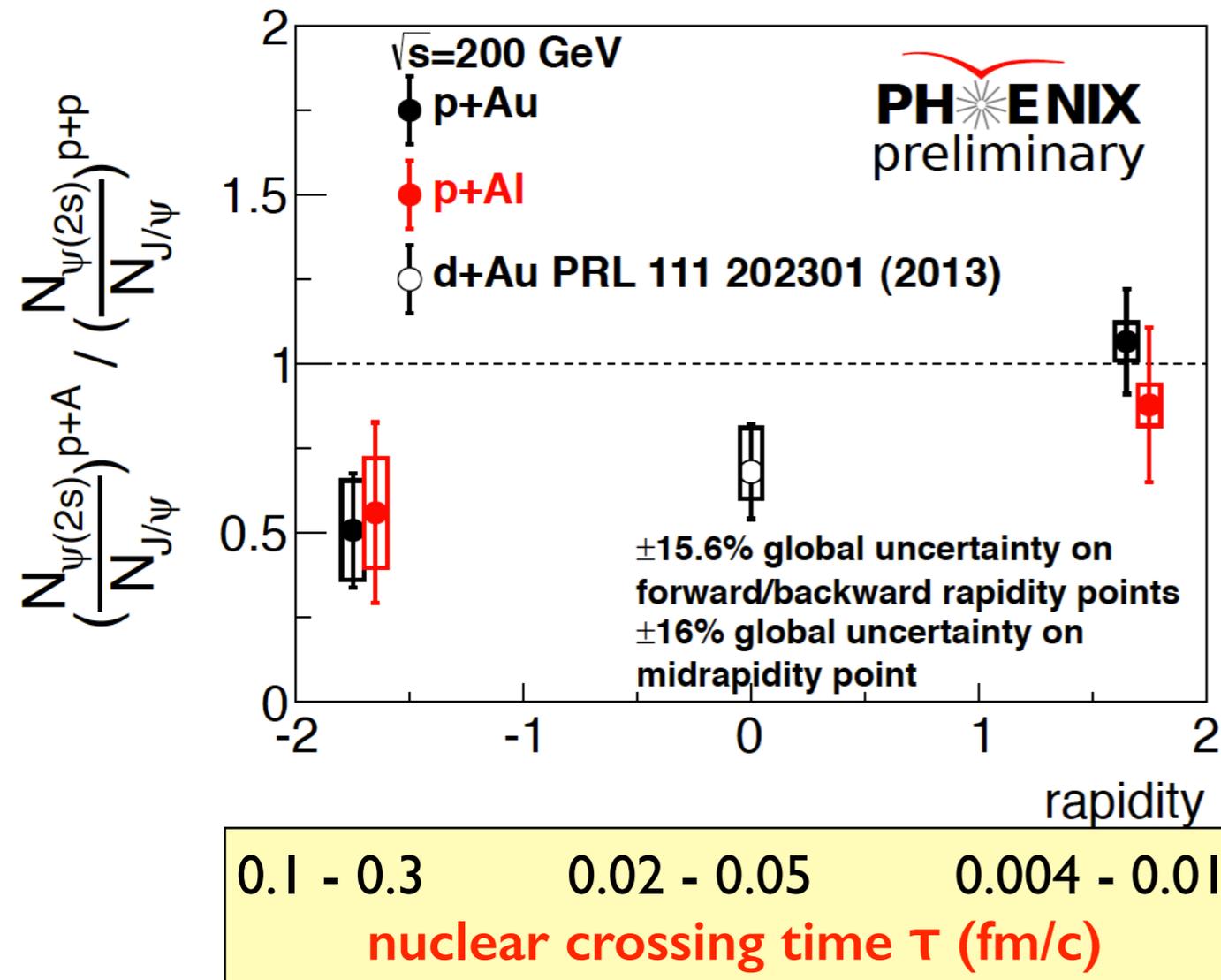
Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

Midrapidity point is from d+Au

Strong suppression at backward rapidity, no suppression at forward rapidity



# What causes the differential suppression?



Can breakup in collisions with nucleons explain the differential suppression at  $y = -1.7$ ?

**No - the effect is much too small!**

From PRC 87 (2013) 054910 - model of  $\tau$  dependence fitted to world's data

Get  $\sim 1\% - 7\%$  effect in  $-1.2 < y < -2.2$

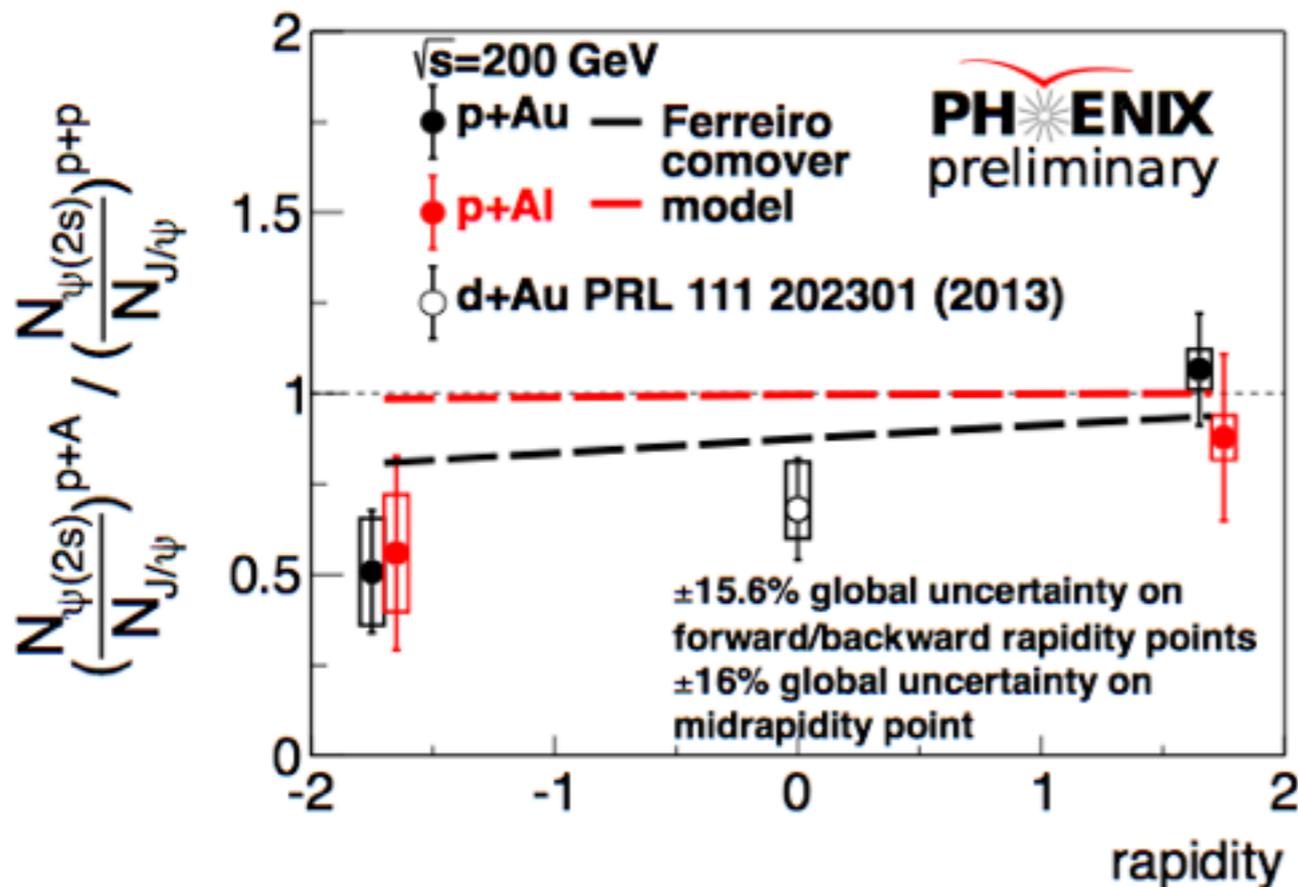
# What causes the differential suppression?

Since we have eliminated breakup, there is no CNM mechanism that could explain the strong suppression at backward rapidity

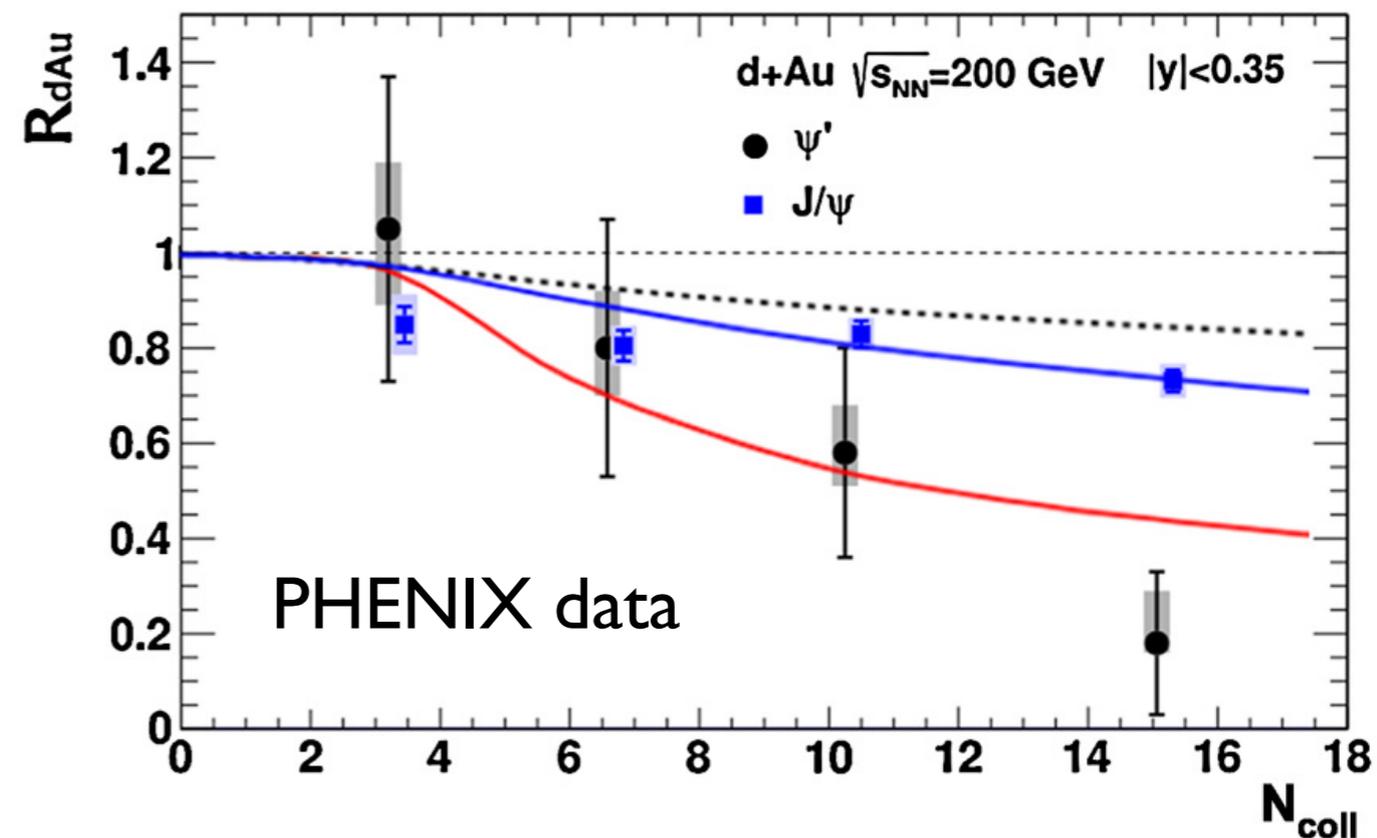
- That leaves final state effects

## Final state effects:

- Suppression is caused by interactions with **produced** particles
- So it can occur **after the charmonium leaves the target**
- i.e. when the meson is fully formed



Ferreiro (PLB 749 (2015) 98)  
 “Comovers” in final state



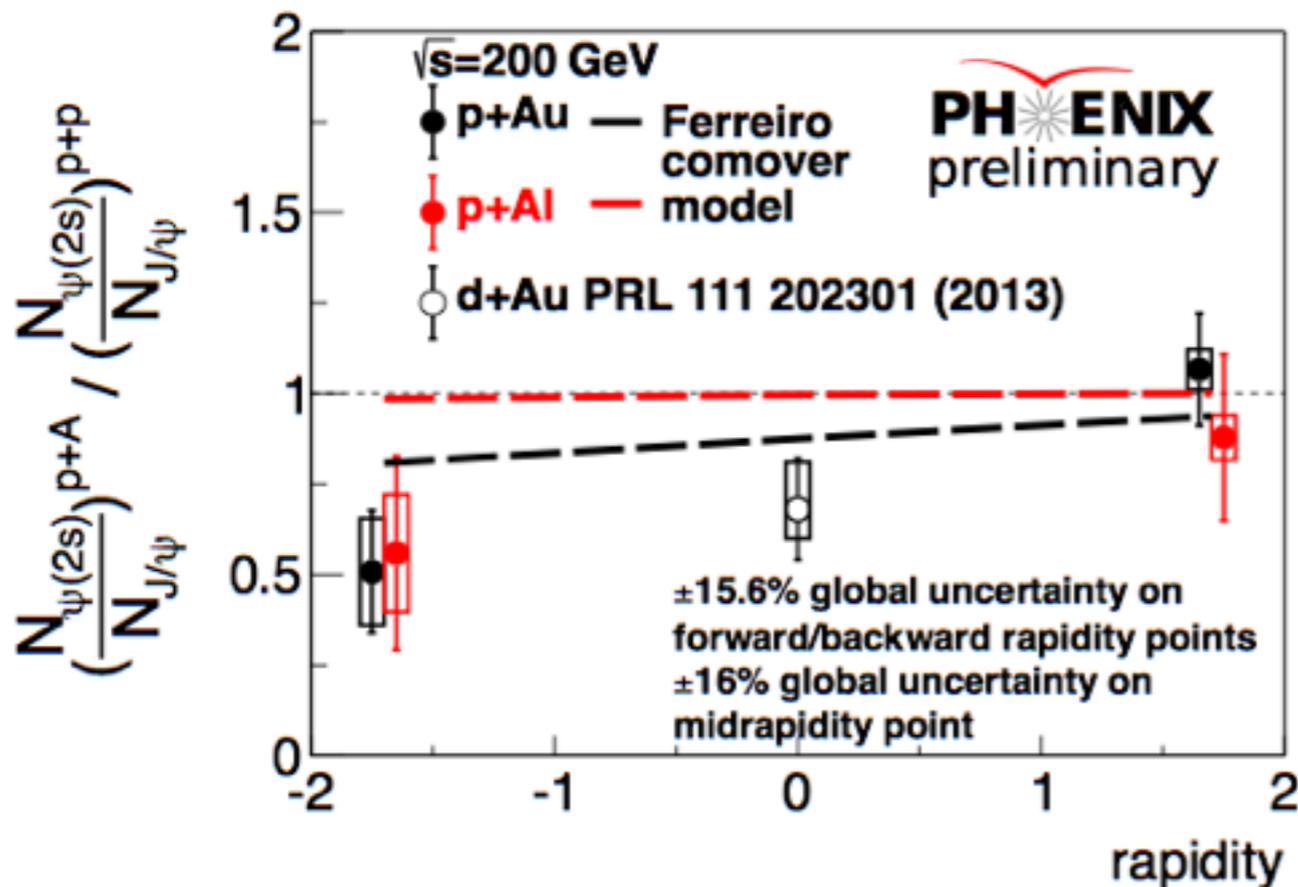
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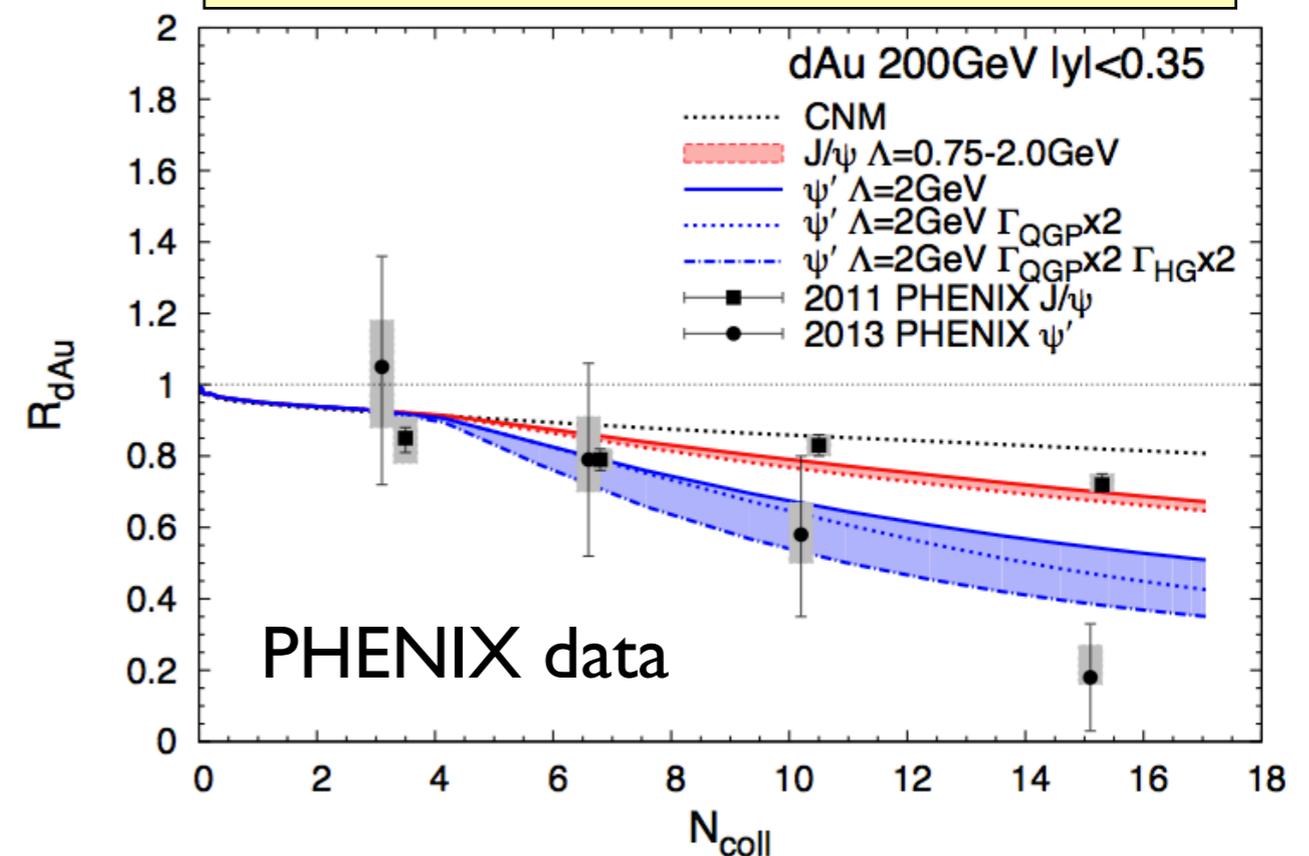
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Du & Rapp arXiv:1504.00670

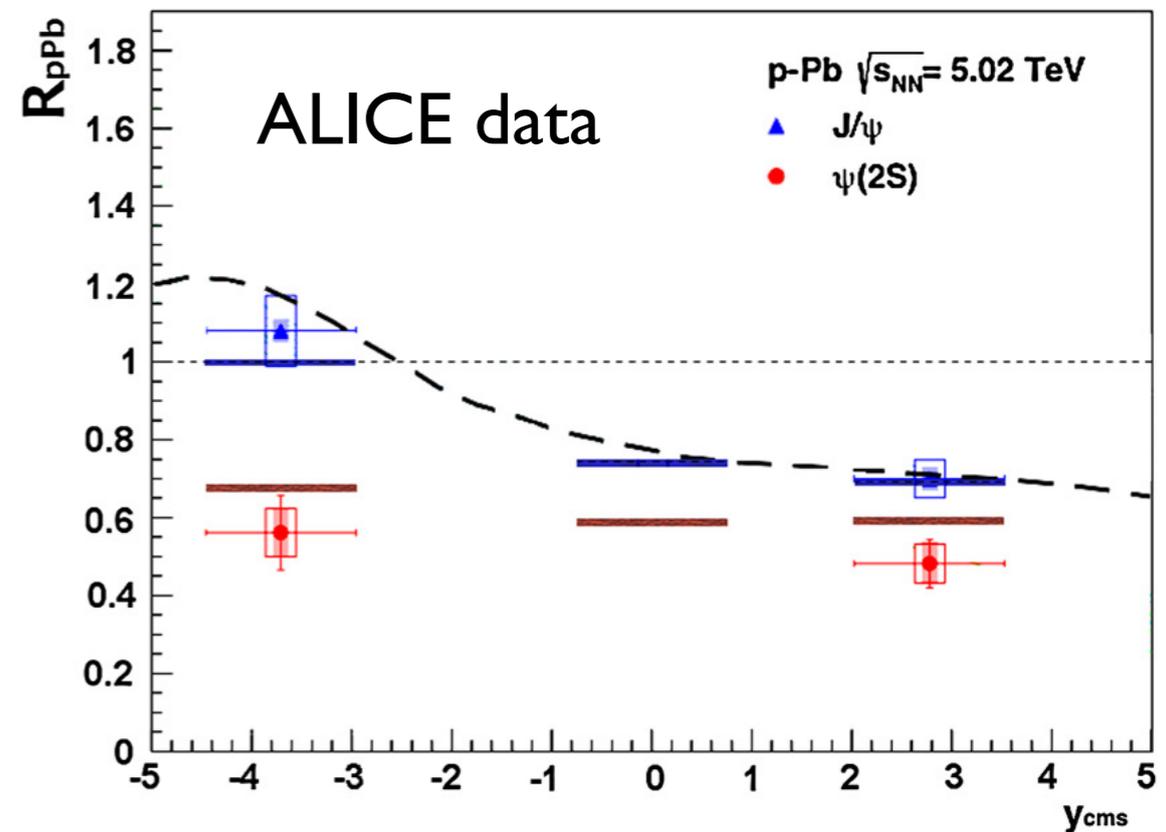
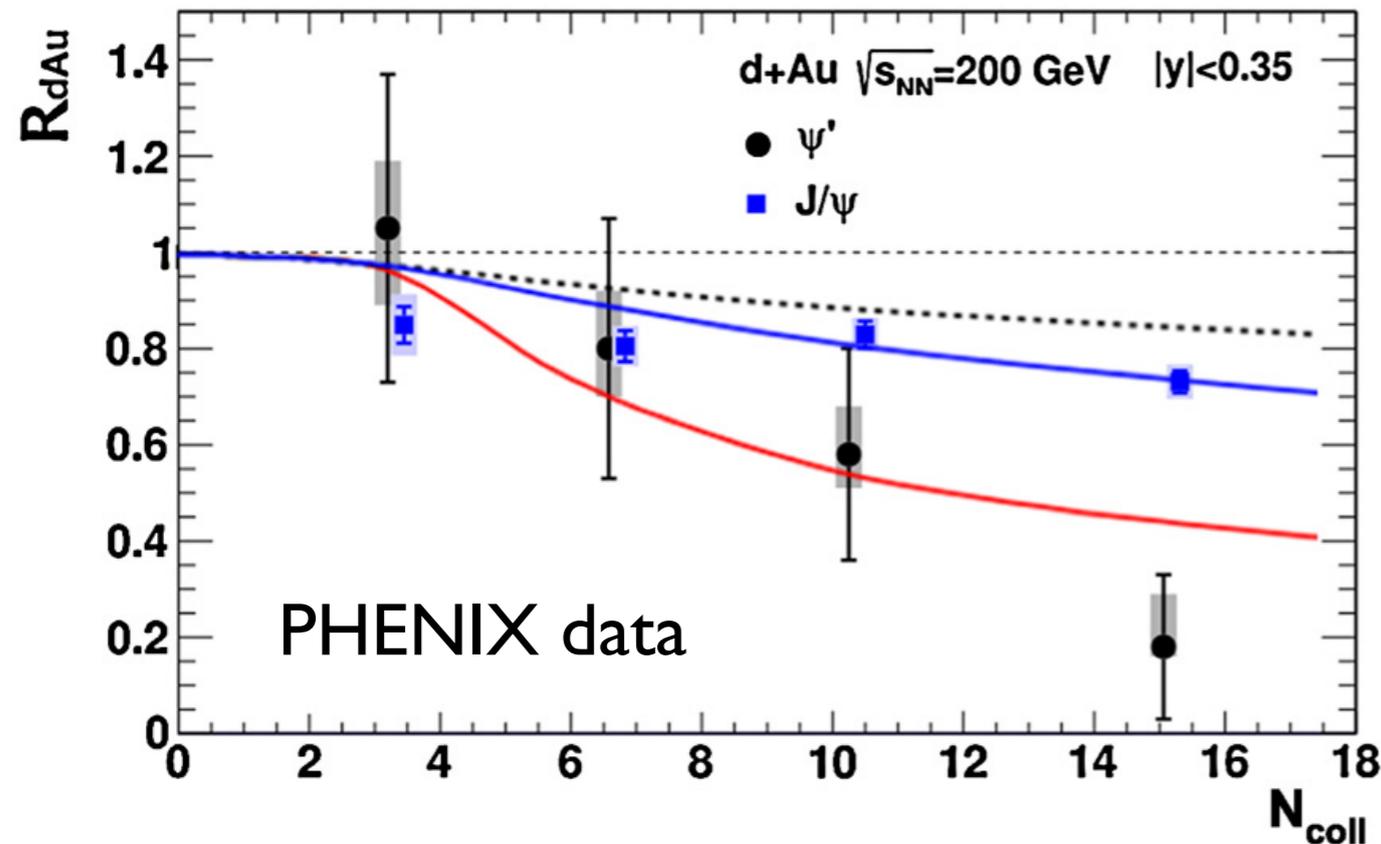
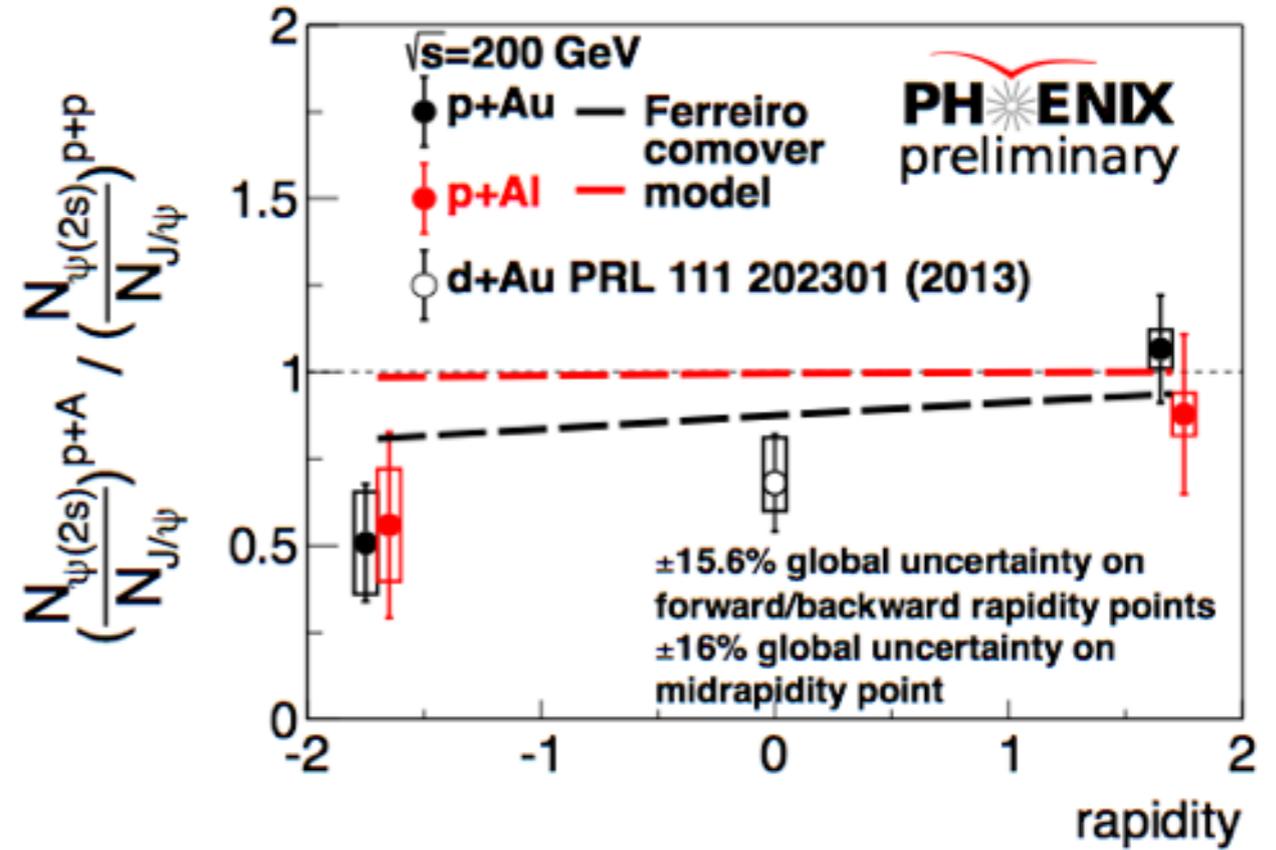
Hadronic gas + QGP in final state



# Adding ALICE data (LHCb very similar)

The **comover model** does a reasonable job of describing available  $\psi(2S)$  and  $J/\psi$  data from both PHENIX and ALICE

But **underestimates** the differential suppression in both cases



# Conclusions

U+U J/ $\psi$  suppression is weaker than that for Au+Au

- Consistent with dominance of coalescence over color screening

Strong indication of **final state** effects in p+Au  $\psi(2S)$  /  $\psi(1S)$  ratio vs rapidity

- Differential suppression of  $\psi(2S)$  - consistent with comover model

To come (all at  $\sqrt{s_{NN}} = 200$  GeV):

- p+Au  $R_{pA}$  analysis vs centrality for  $\psi(2S)$  at forward and backward rapidity
  - Compare with ALICE forward/backward p+Pb data ([arXiv:1603.02816](https://arxiv.org/abs/1603.02816))
- $^3\text{He}+\text{Au}$  data for  $\psi(2S)$  at forward and backward rapidity
- p+Au vs p+Al mass and centrality dependence for J/ $\psi$ 
  - Try to understand  $>$  linear onset of suppression with nuclear thickness for d+Au J/ $\psi$  production at forward rapidity - **centrality measurement issue or physics?**

# Backup

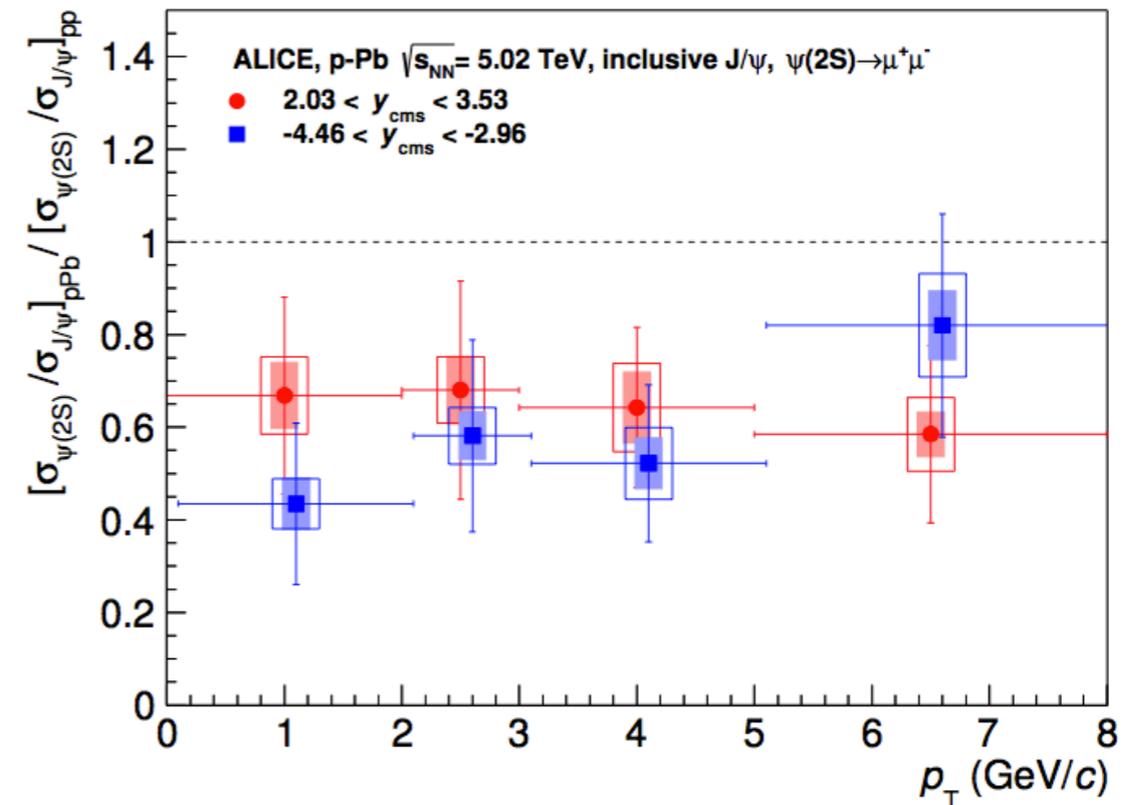
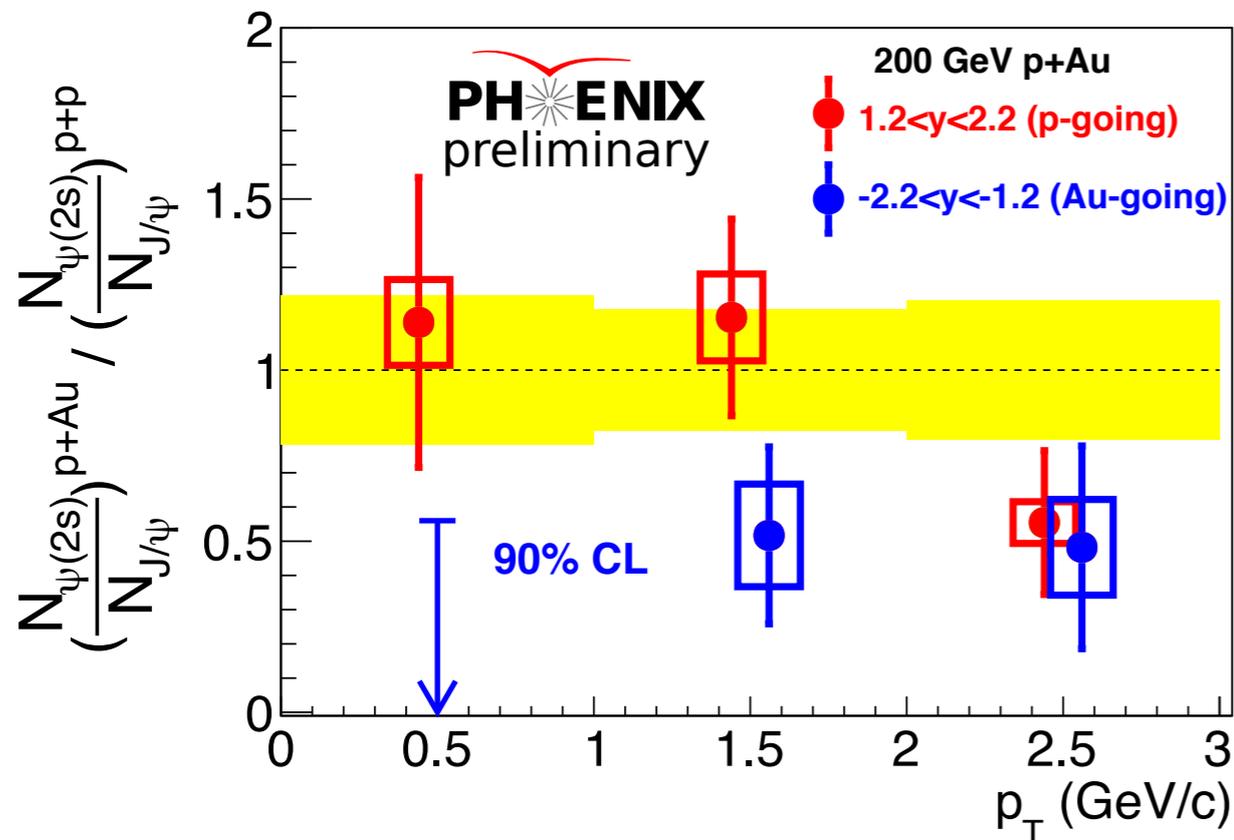
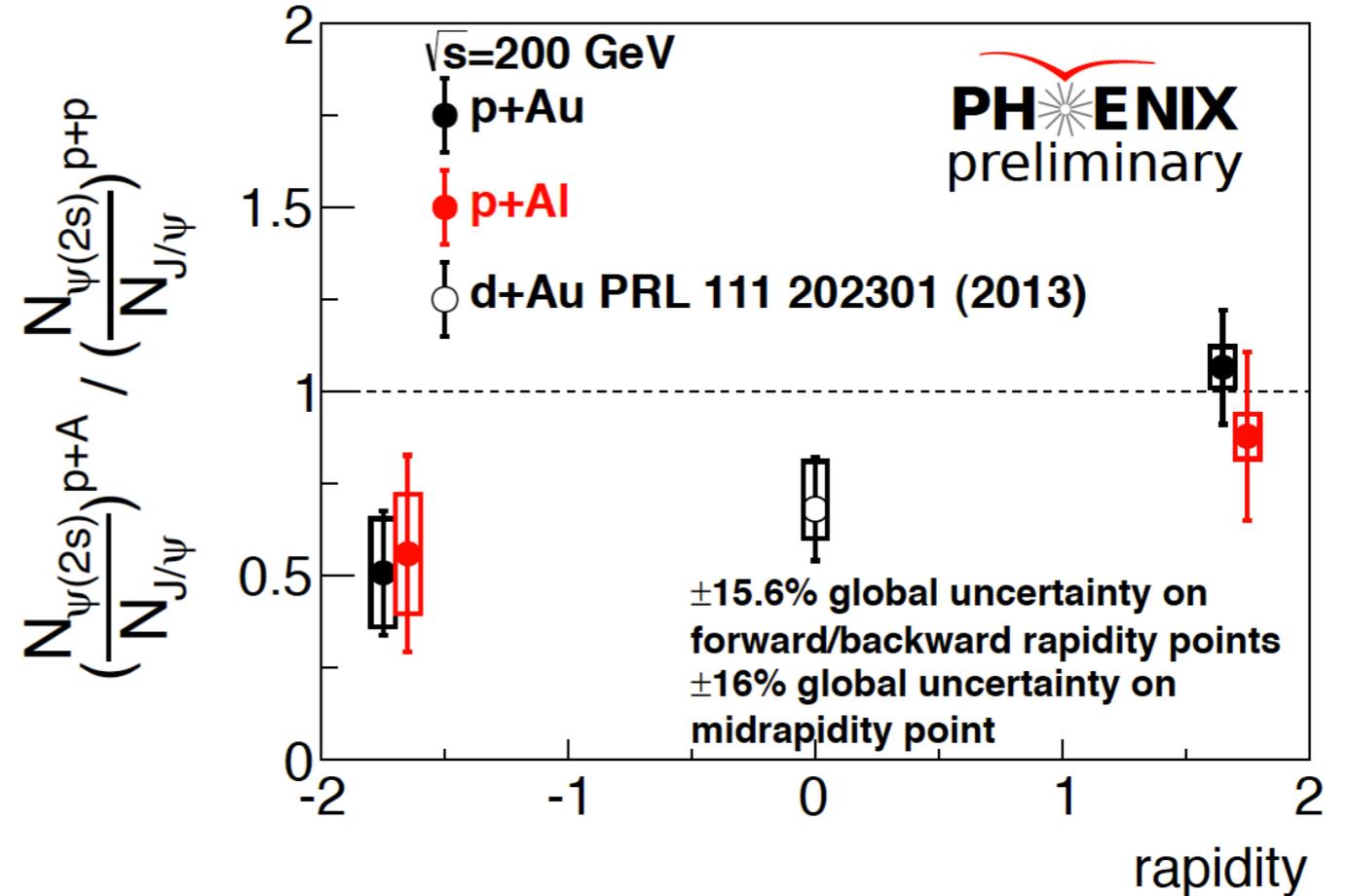
# $\psi' / J/\psi$ ratios in p+Au and p+Al vs rapidity

Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

Midrapidity point is from d+Au

Strong suppression at backward rapidity  
No suppression at forward rapidity

Look also at  $p_T$  dependence for p+Au:



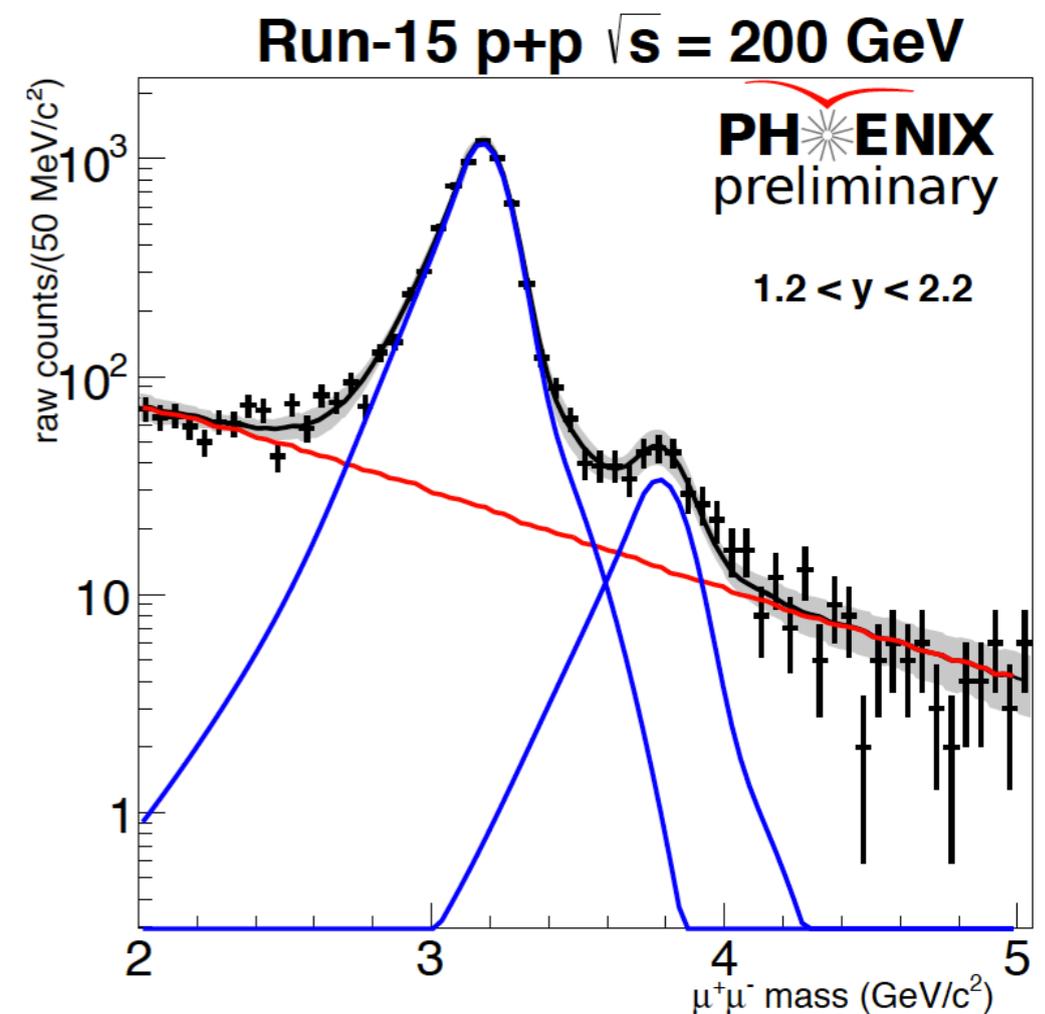
# Fitting the mass spectrum for $p+p$ , $p+Au$ , $p+Al$

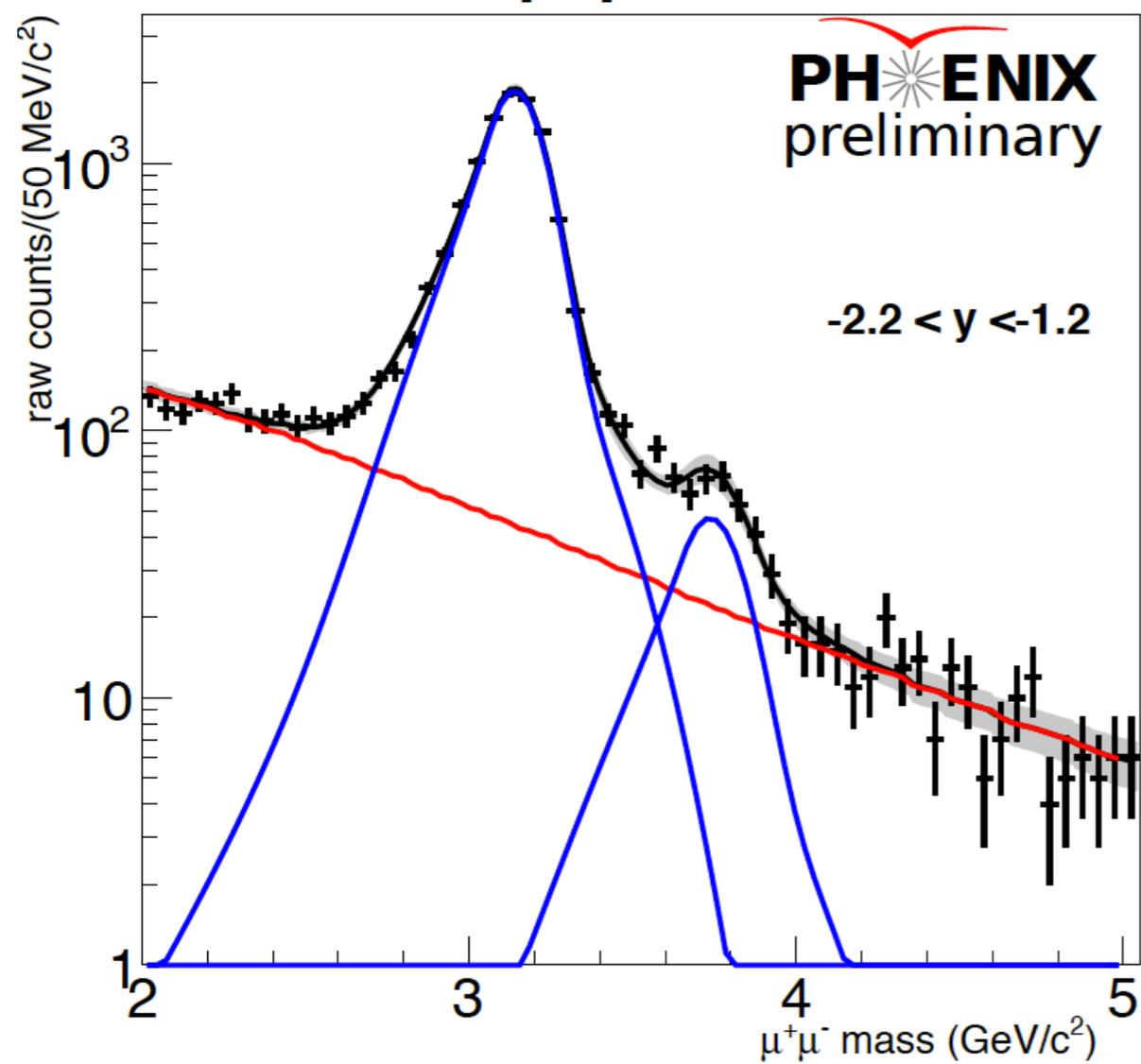
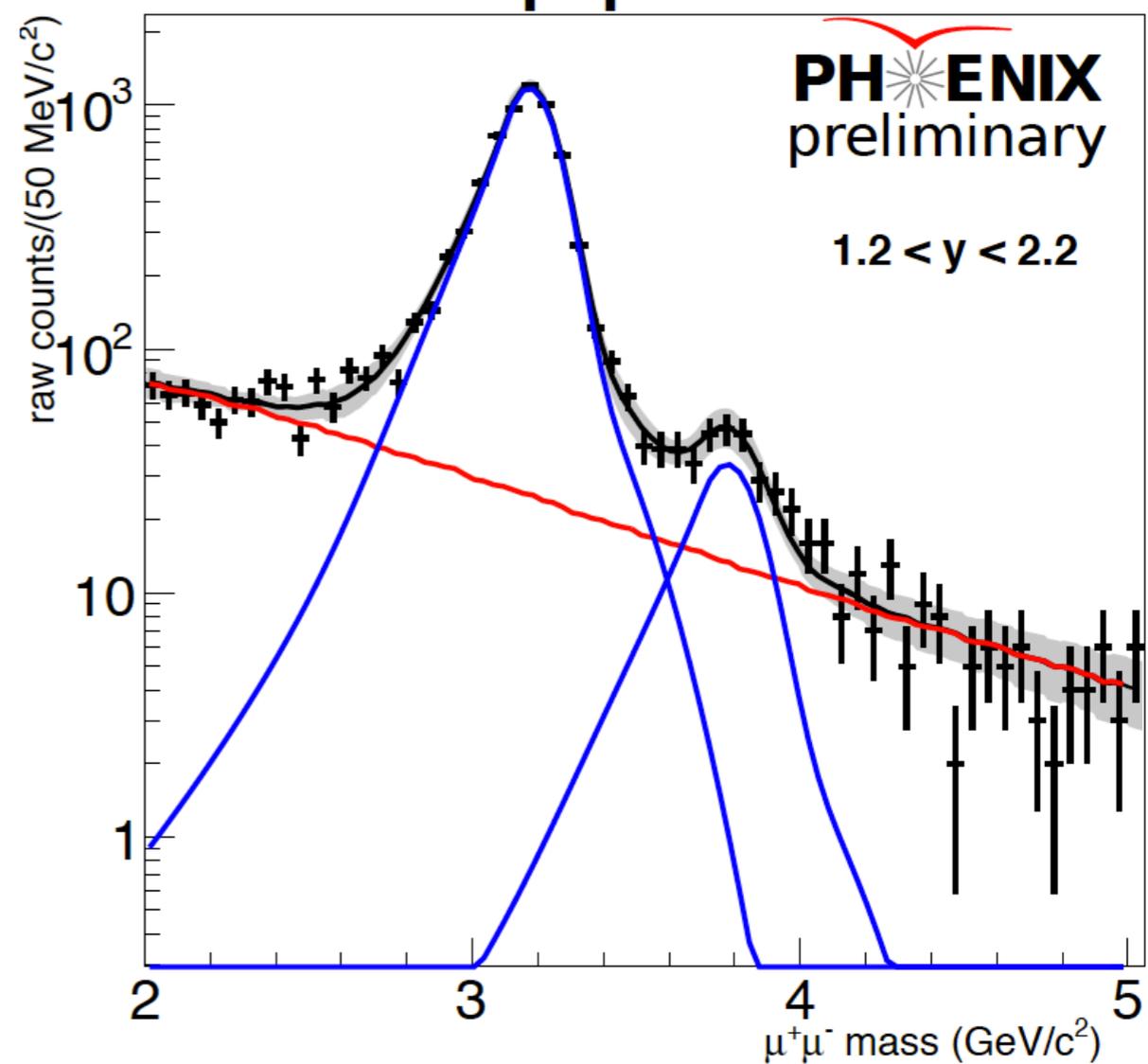
The fit is a log-likelihood fit to raw data with the following components:

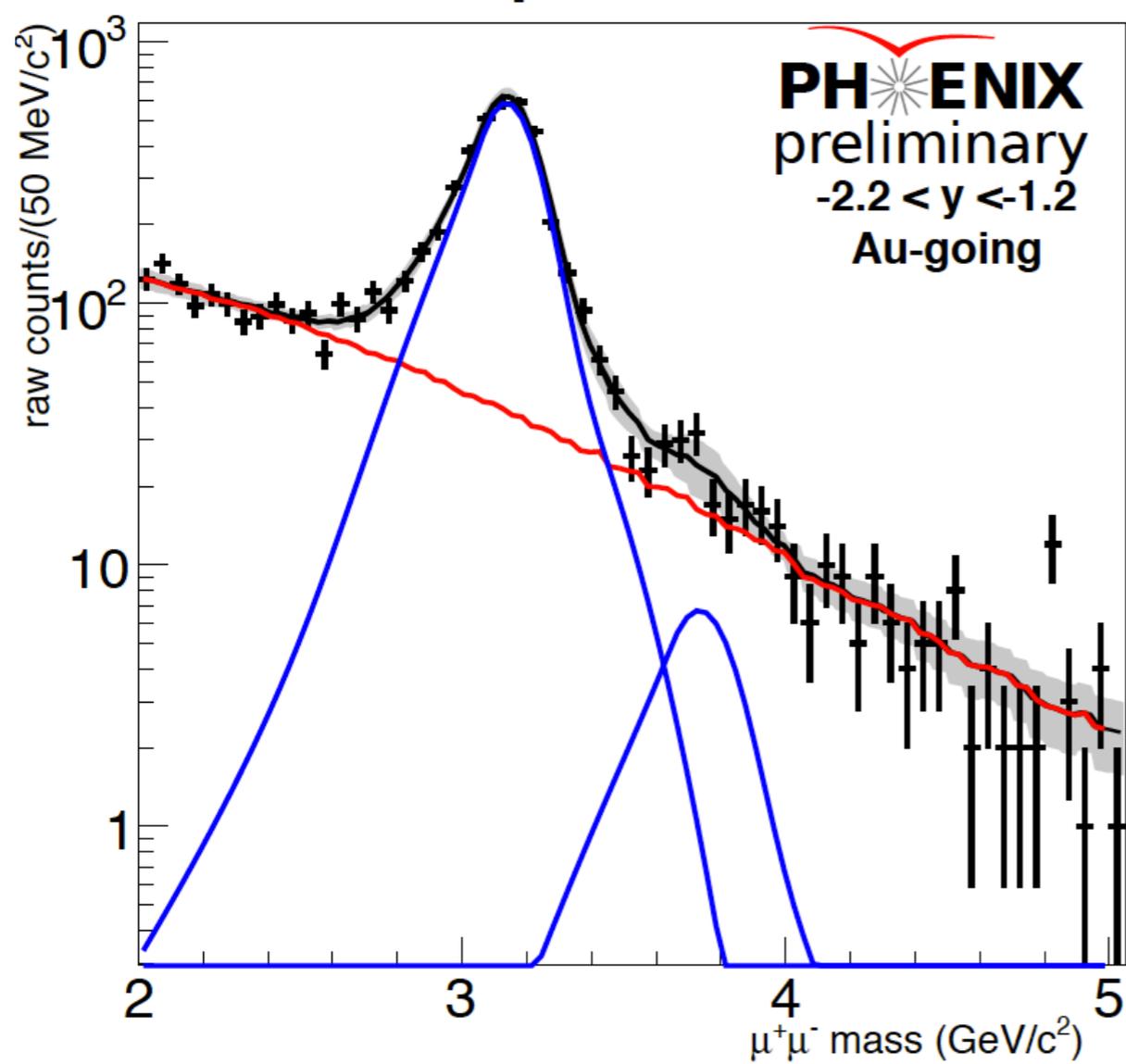
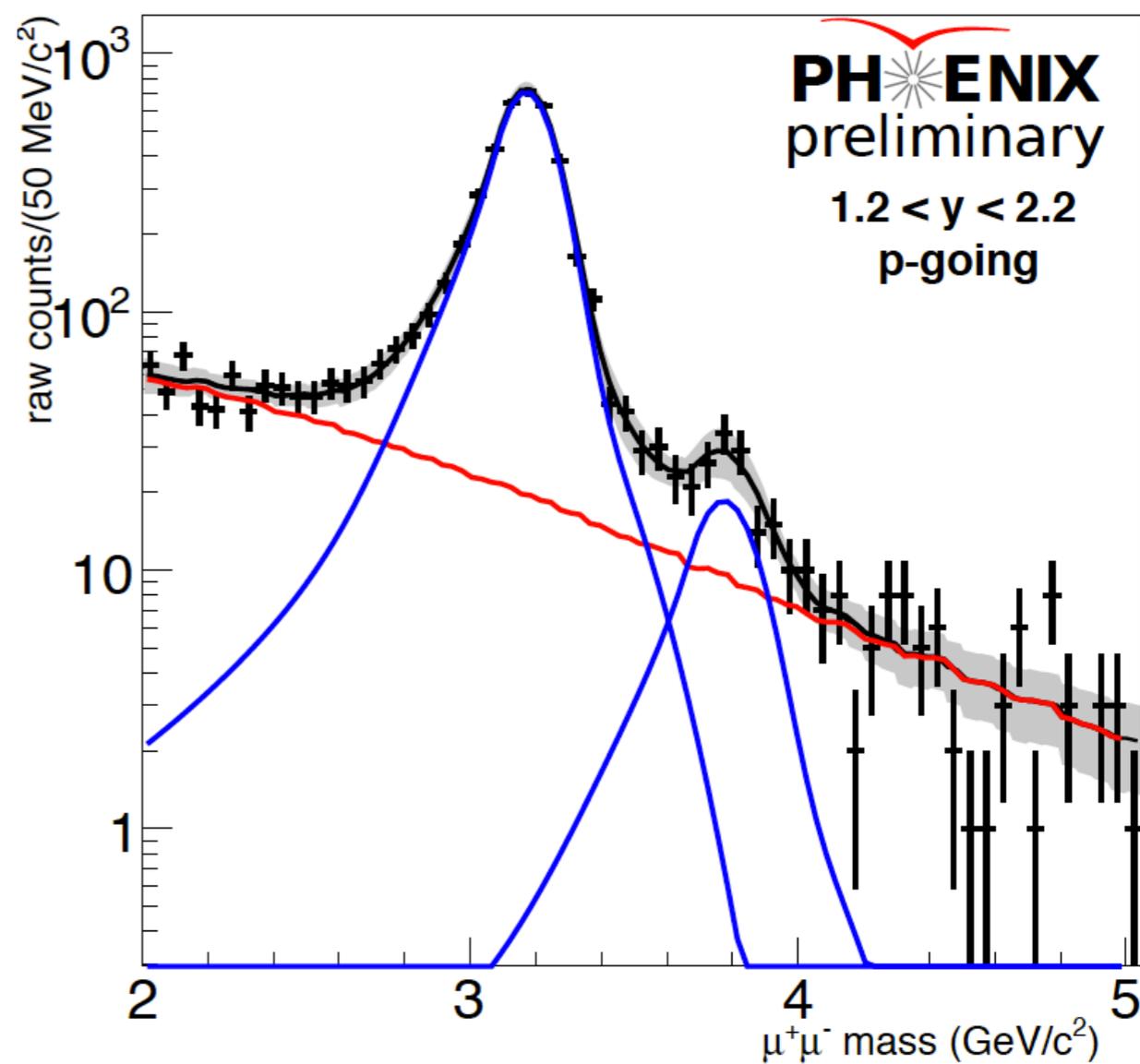
- A properly normalized mixed event combinatorial background
- An exponential function to represent correlated background dimuons
- Peaks to represent the resonances:
  - A Crystal Ball function (mass resolution + range straggling in absorber)
  - An additional Gaussian (valid pairs involving lower quality tracks)
    - Set to 200 MeV in fit, varied to determine systematic

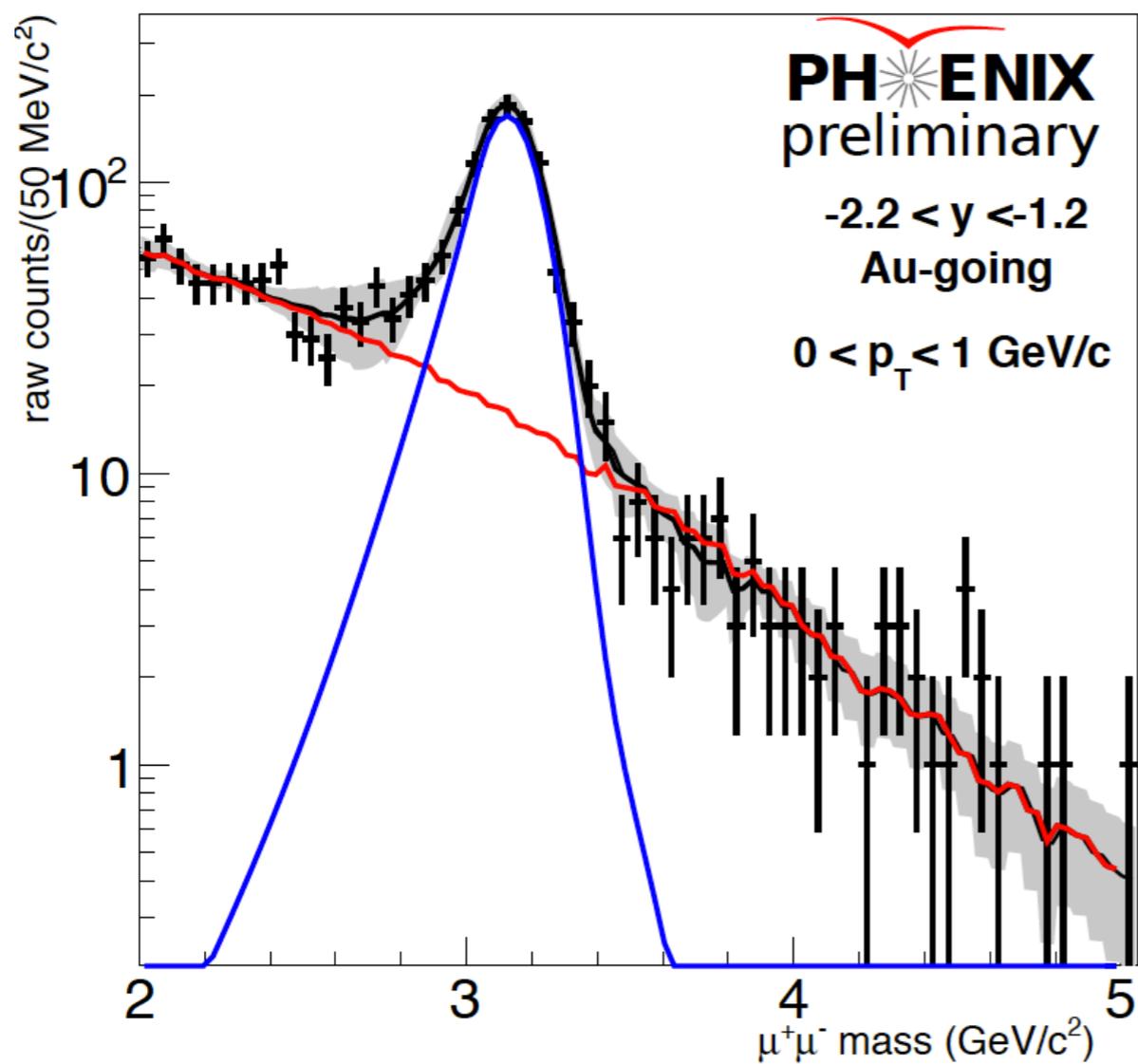
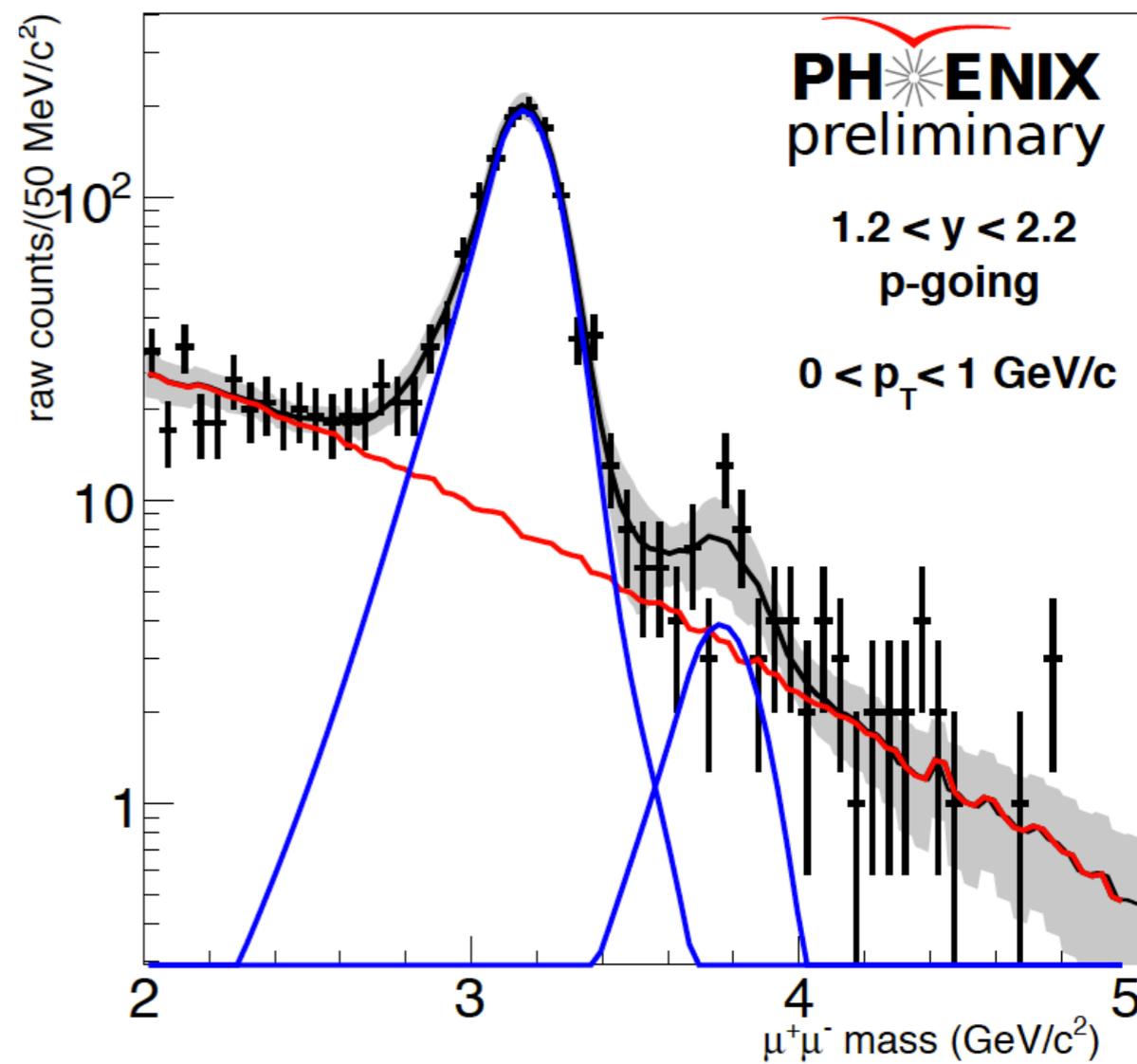
The  $\psi(2S)$  and  $\psi(1S)$  are constrained so:

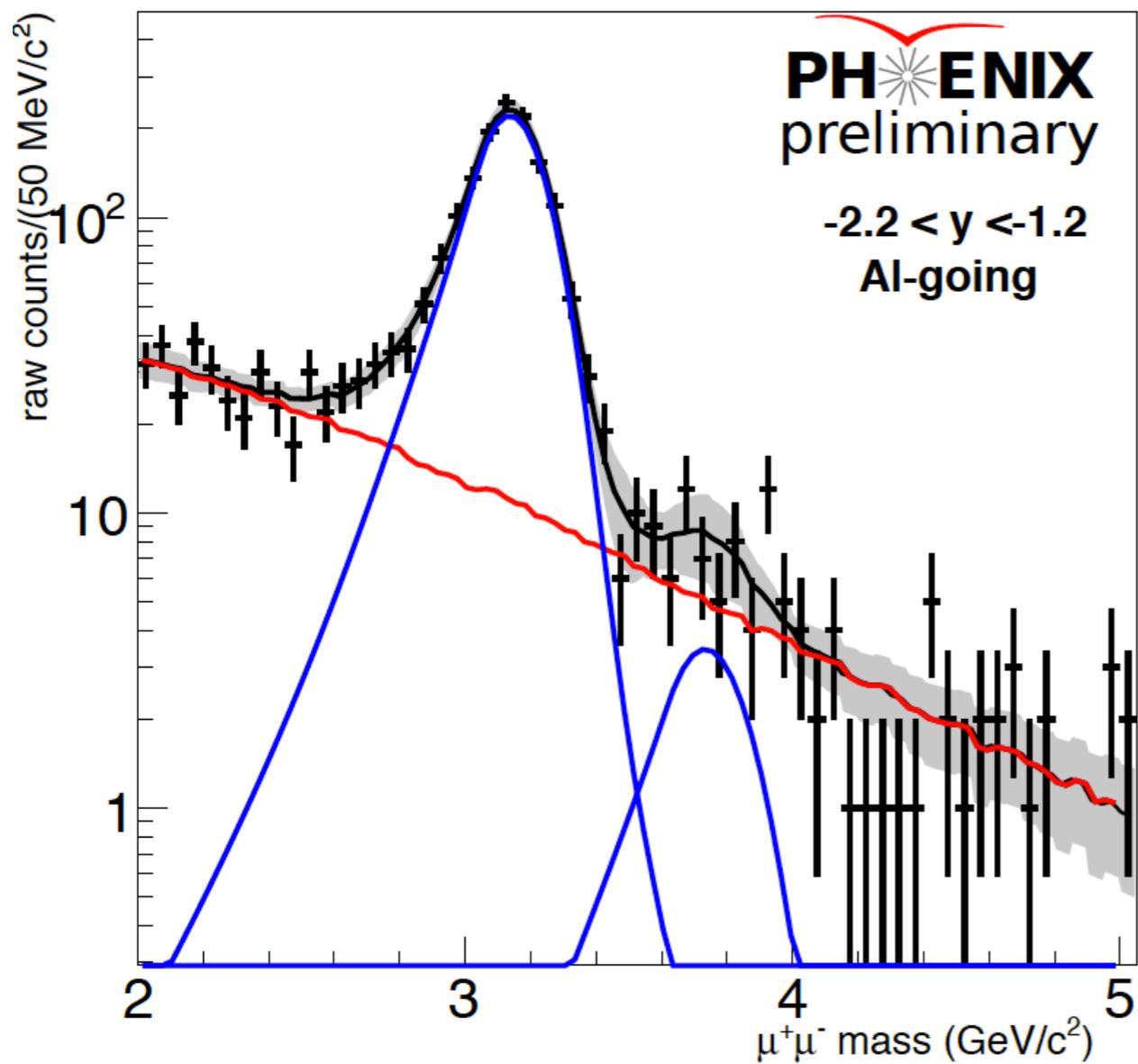
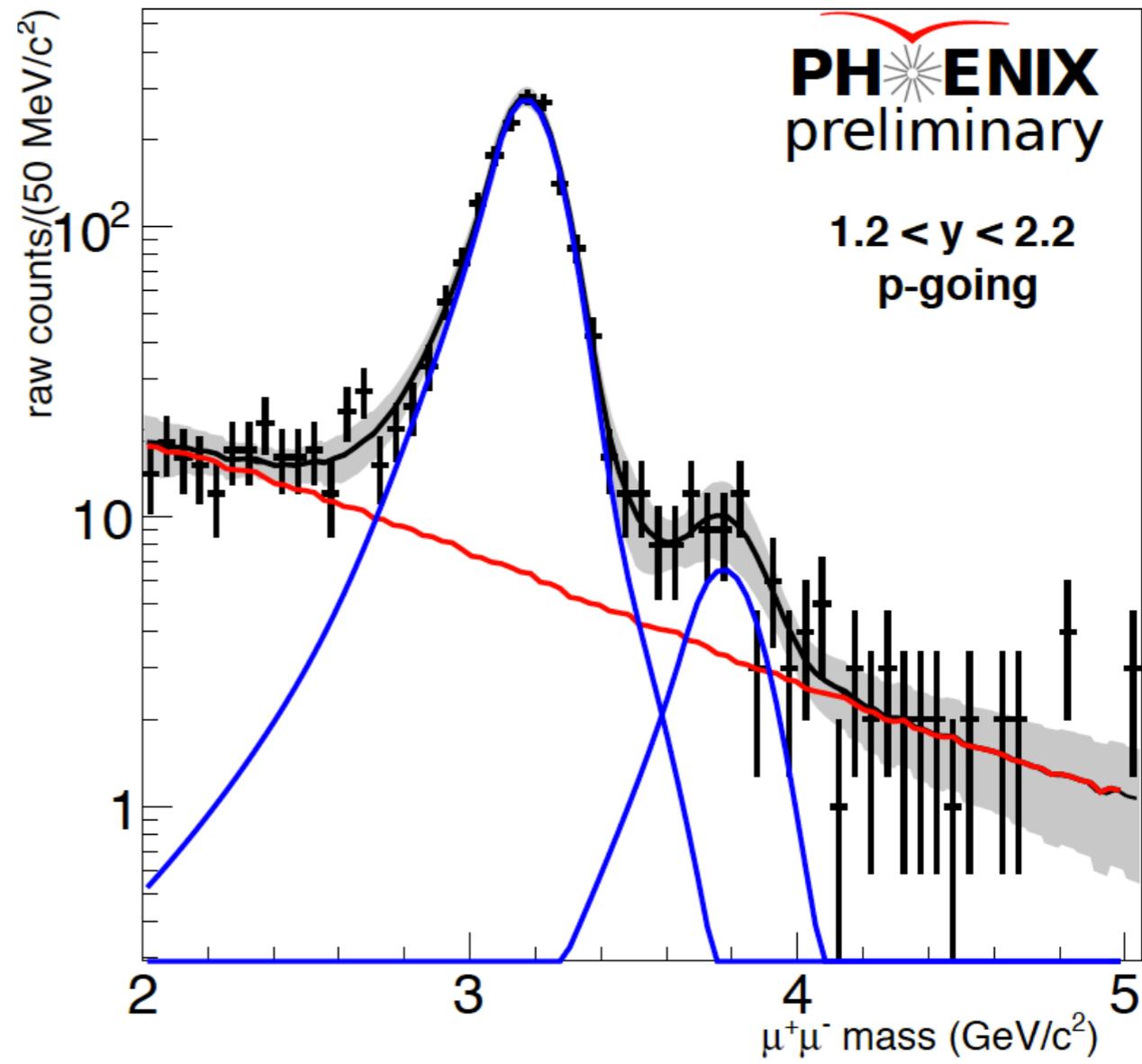
- Crystal Ball tails have the same shape, relative normalization to the peak for  $\psi(1S)$ ,  $\psi(2S)$
- The  $\psi(2S)$  width is 1.15 times the  $\psi(1S)$  width
  - From sims (varied to determine systematic)
- The  $\psi(1S)$  mass floats (moves only 1-2%)
- The  $\psi(2S)$  -  $\psi(1S)$  mass difference fixed:
  - PDG x ratio of  $\psi(1S)$  mass to PDG
- Relative normalization of second gaussian is the same for  $\psi(2S)$  and  $\psi(1S)$



Run-15 p+p  $\sqrt{s} = 200$  GeVRun-15 p+p  $\sqrt{s} = 200$  GeV

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Run-15 p+Al  $\sqrt{s} = 200$  GeVRun-15 p+Al  $\sqrt{s} = 200$  GeV

# The PHENIX muon arms

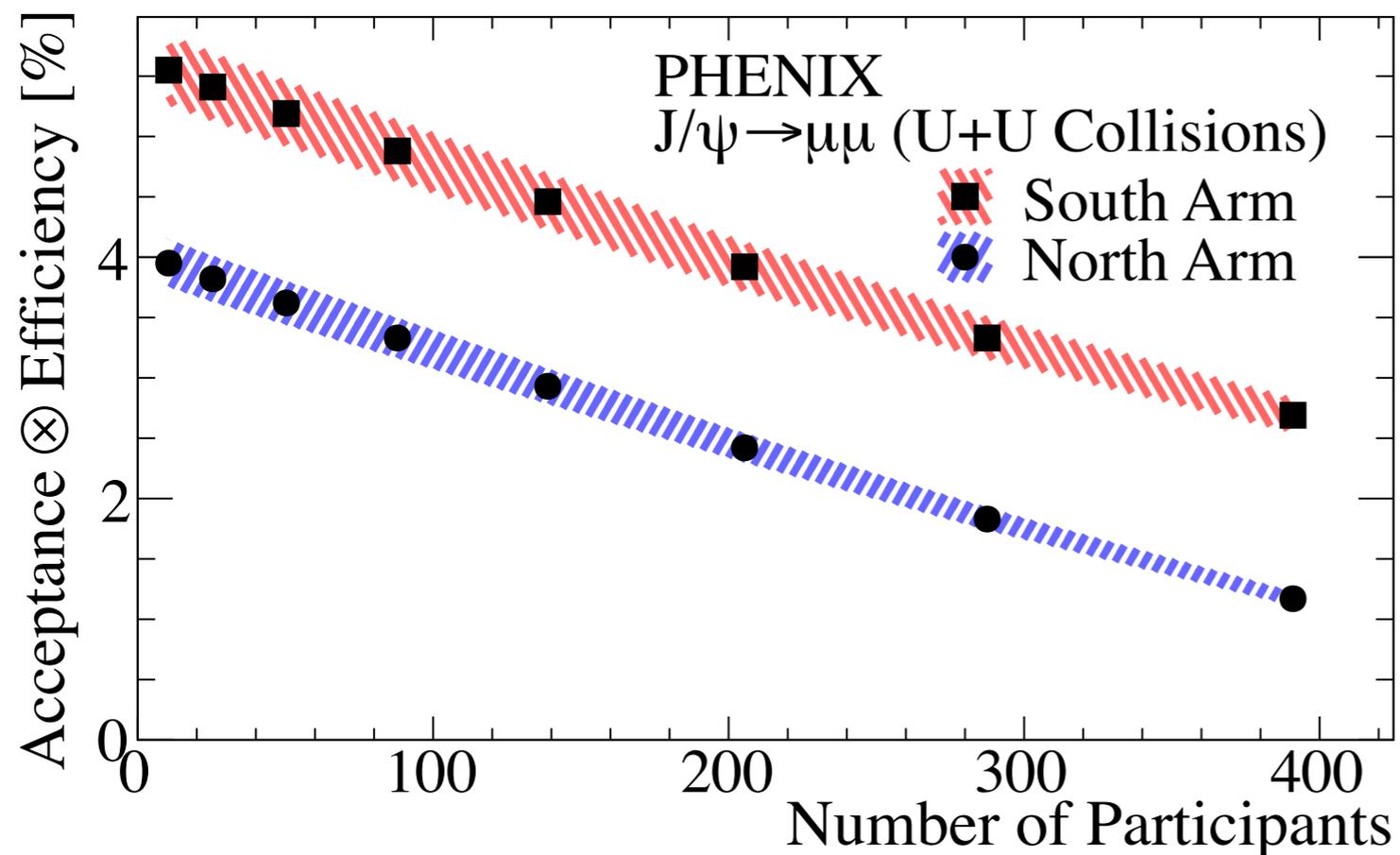
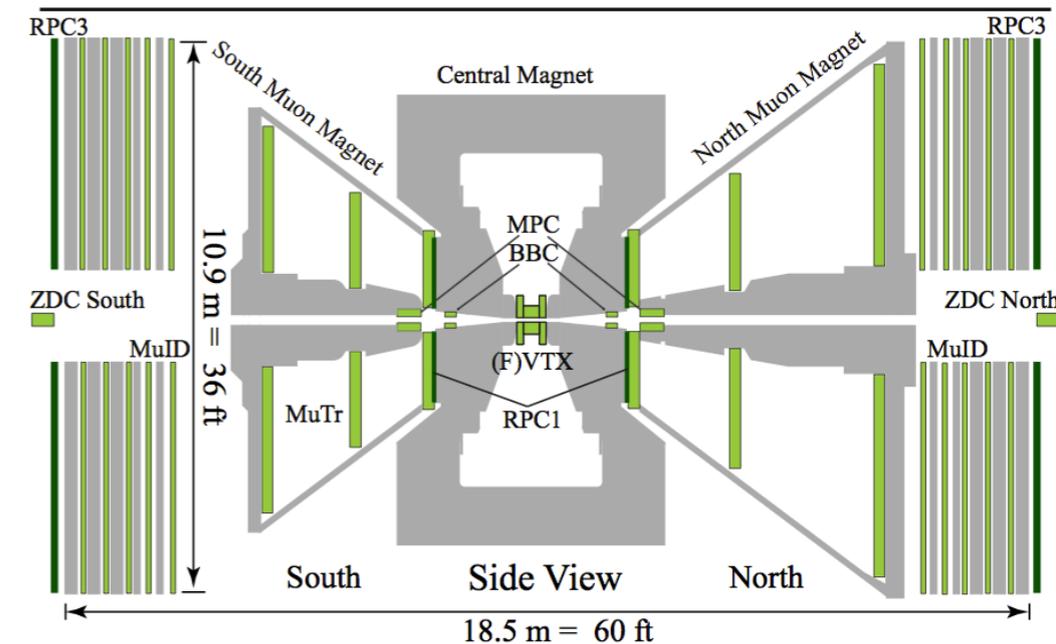
## Experiment:

U+U data at  $\sqrt{s_{NN}} = 193$  GeV from RHIC 2012 run

MB trigger: 96% efficient      1.08 B events recorded

Centrality measured by BBC ( $3.0 < |\eta| < 3.9$ )

$J/\psi \rightarrow \mu^+\mu^-$        $1.2 < |y| < 2.2$



## Acceptance ⊗ Efficiency:

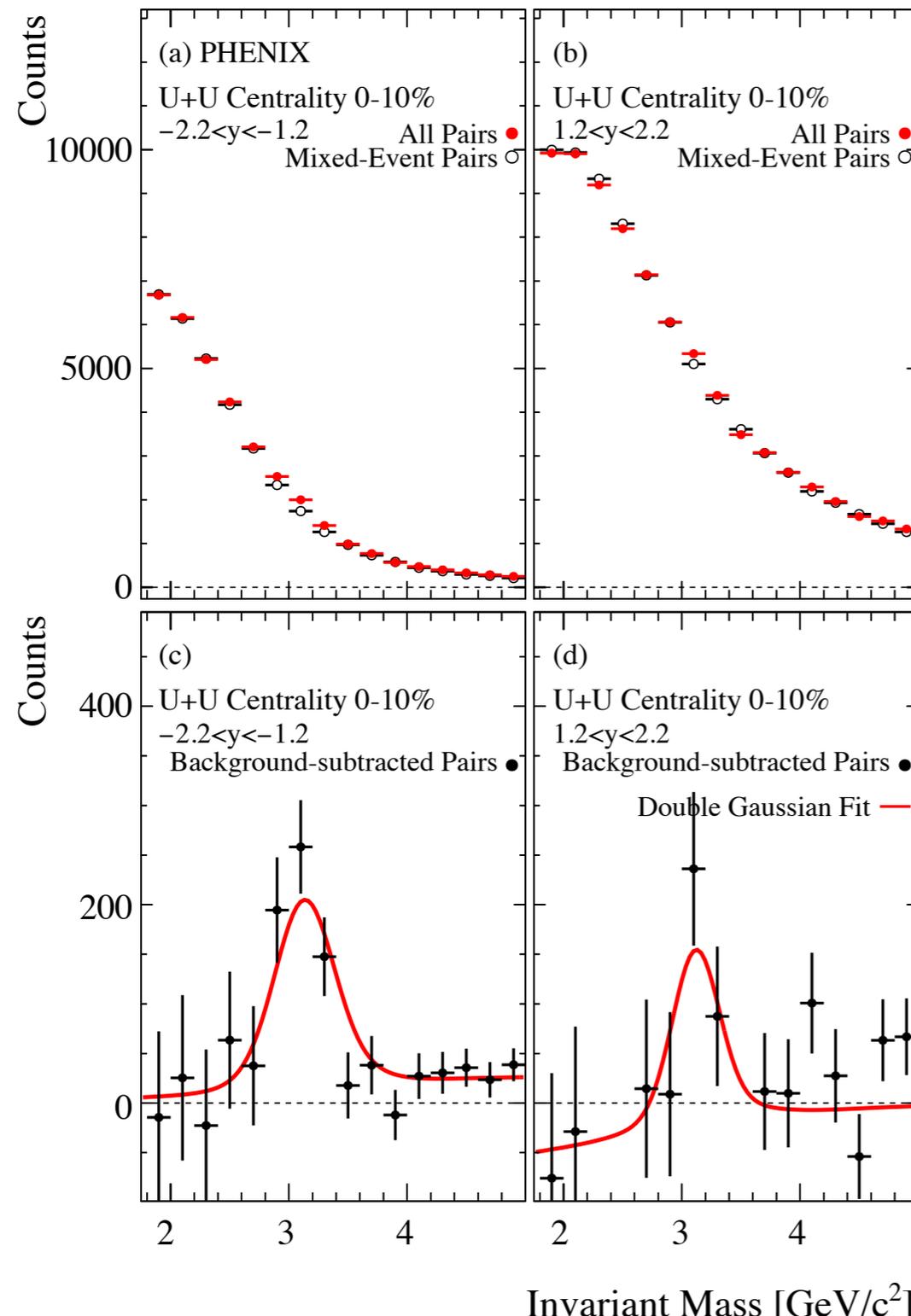
PYTHIA  $J/\psi \rightarrow \mu^+\mu^-$  events through GEANT, embedded in real data and reconstructed

Efficiency includes occupancy effects

Acceptance flat to within 30% from  $p_T = 0 - 8$  GeV/c

# U+U Signal Extraction

## 0-10% (most central)



## 60-70% (most peripheral)

