J/ψ and $\psi(2S)$ production in small systems with PHENIX

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Introduction

Recent quarkonium analyses in PHENIX have focused on small systems results for J/ψ and ψ(2S).

p+Al, p+Au and ^{3}He+Au data from the 2014 and 2015 RHIC runs have been added to our d+Au data from 2008.

This allows us to address questions about J/ψ and ψ(2S) production:

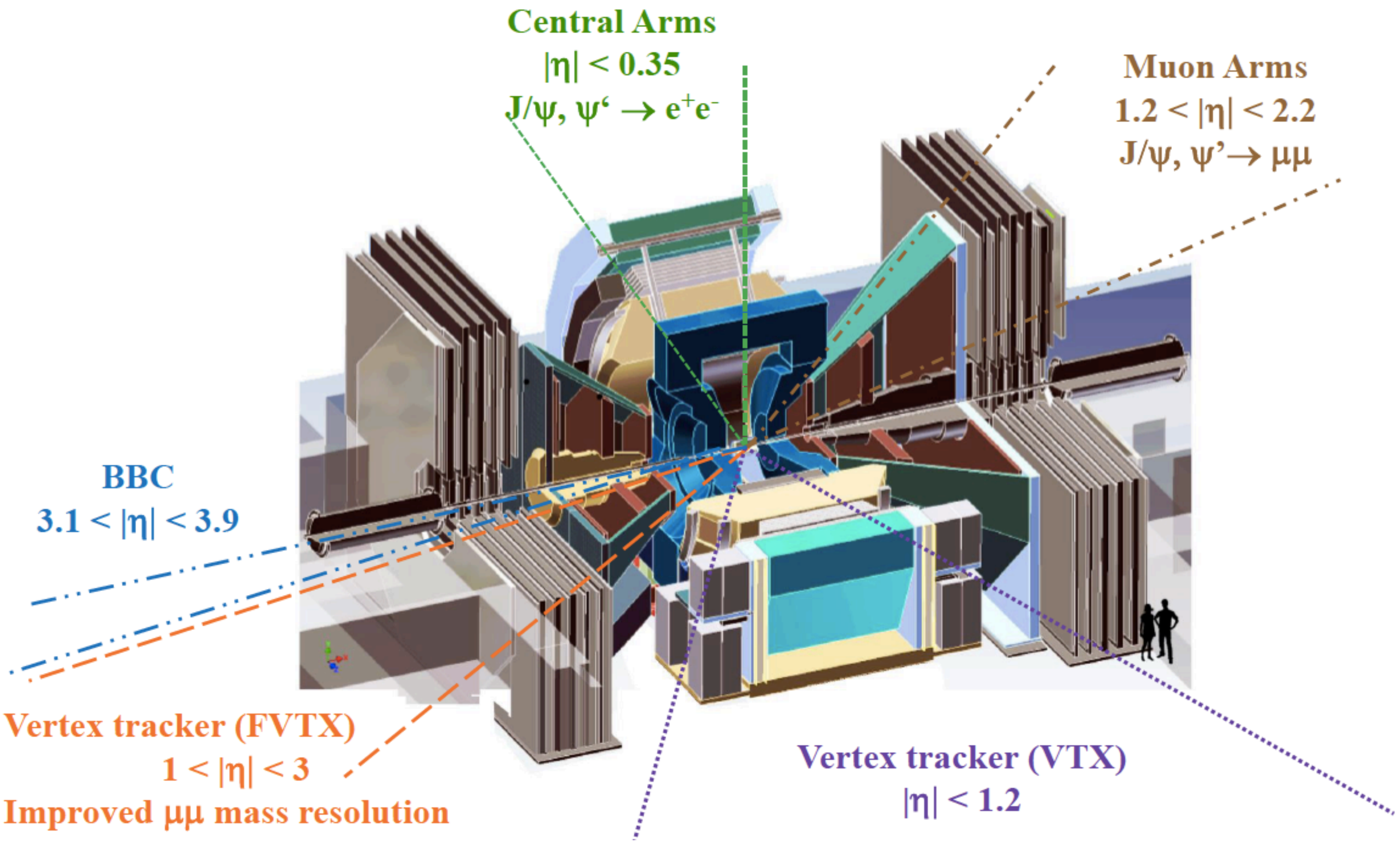
- Do we see evidence of final state effects in light systems?
- How well do we understand quarkonia modification in light systems?

The results shown here are from:

Measurement of ψ(2S) nuclear modification at backward and forward rapidity in p+p, p+Al, and p+Au collisions at √sNN = 200 GeV, PHENIX Collaboration (arXiv:2202.03863)

Measurement of J/ψ at forward and backward rapidity in p + p, p + Al, p + Au, and 3He+Au collisions at √sNN = 200 GeV, PHENIX collaboration, *Phys.Rev.C* 102 (2020) 1, 014902

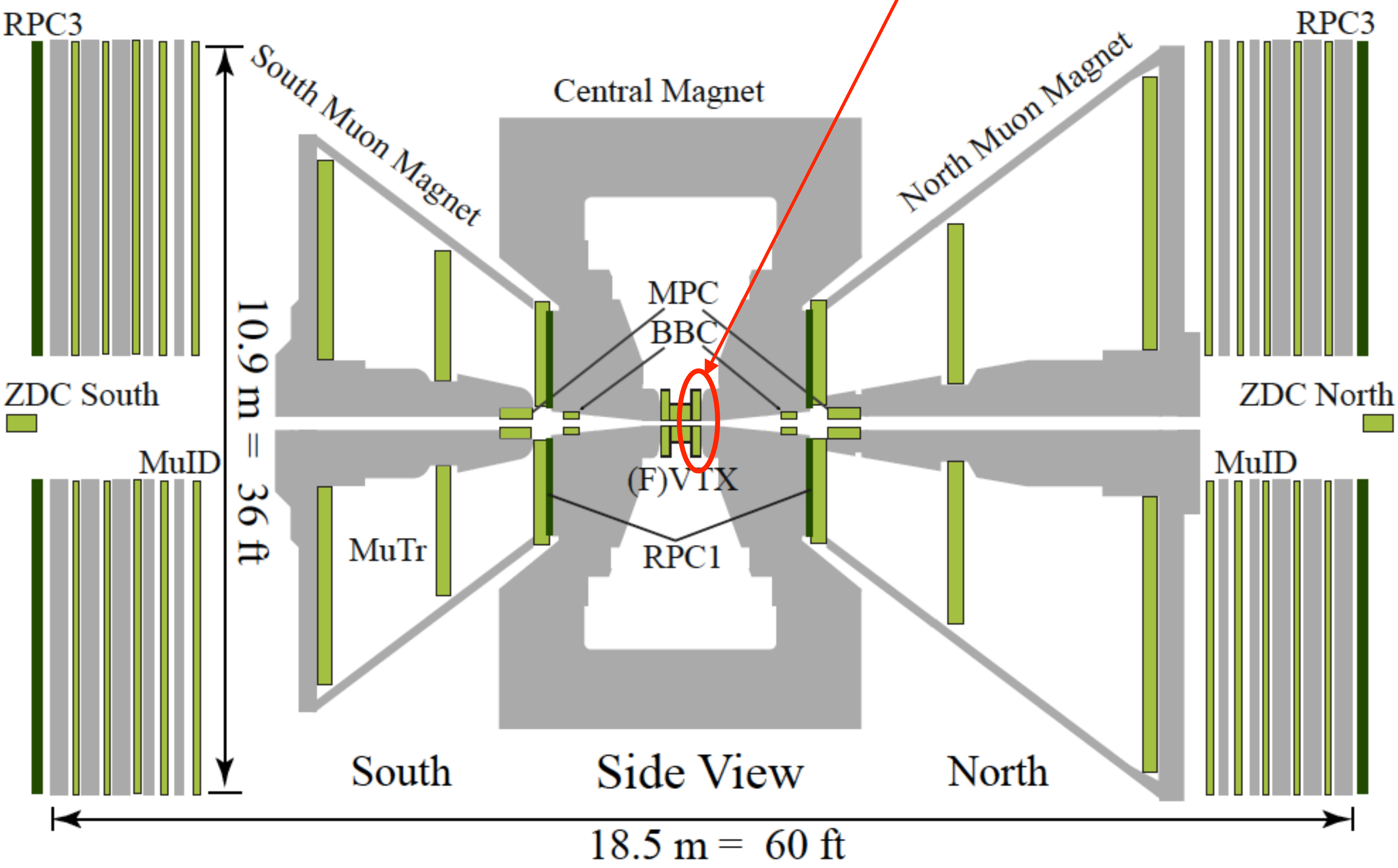
Quarkonia - PHENIX



Di-leptons measured in y = (-2.2, -1.2) (-0.35, 0.35) (1.2, 2.2)

- No triggering required in Au+Au
- Efficient triggers in p+p, (p,d,^{3}He)+A

The muon arms

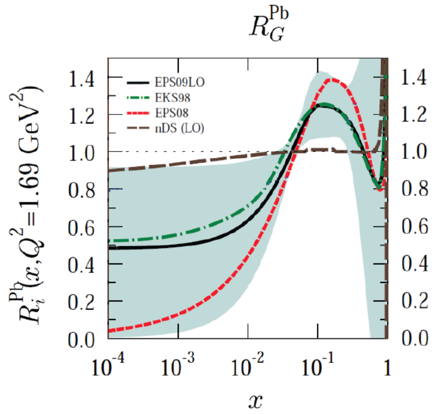


FVTX provides precise space point before passing through magnet

Quarkonia production in a nucleus

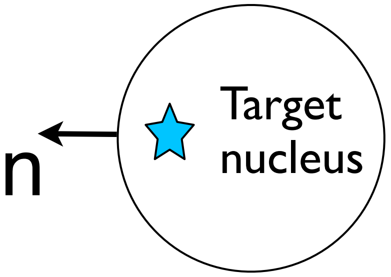
Processes that modify the quarkonia yield in a nuclear target - called cold nuclear matter (CNM) processes.

Gluon shadowing - parton distributions are modified in a nucleus



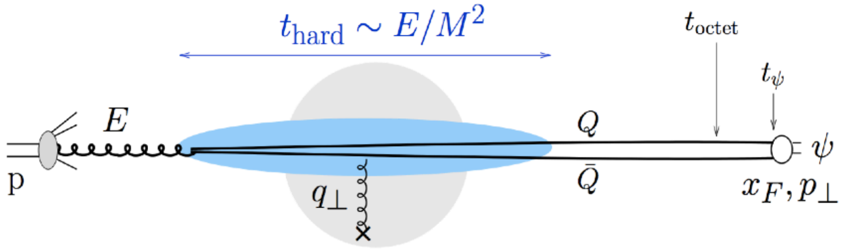
Affects underlying heavy quark yield

Absorption - breakup of the precursor quarkonium by collision with a target nucleon



Breaks up forming mesons

Initial state energy loss of a parton in cold nuclear matter



Changes rapidity distribution

Cronin effect - multiple elastic scattering of partons

Modifies the p_T distribution

There is also a possibility that quarkonium states may be broken up in the final state by interactions with particles produced in the collision.

Breaks up bound mesons

Shadowing

Recent shadowing parameterizations

- EPPS16 (Eskola et. al., Eur. Phys. J. C 77, 163 (2017))
- nCTEQ15 (Kovarik et. al., Phys. Rev. D 93, 085037 (2016))

Bayesian re-weighting of EPPS16 and nCTEQ15 gluon nPDF’s

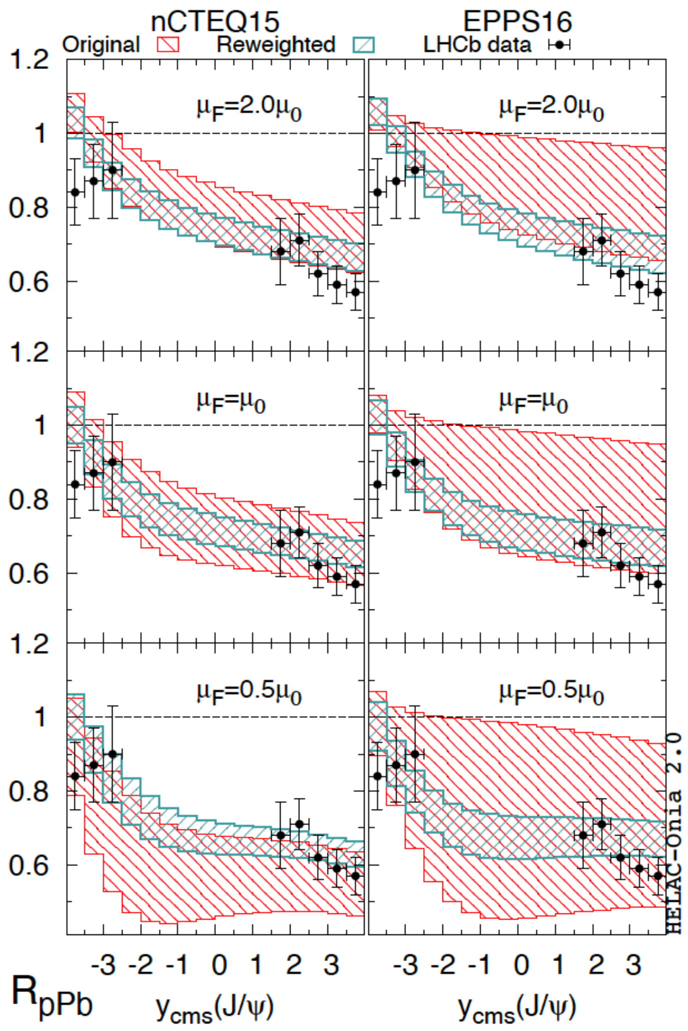
- (Kusina et. al., Phys. Rev. Lett. 121, 052004 (2018))
- Adds LHC pPb data - gluon dominated processes
  - D_0, J/ψ , B →J/ψ, and Y(1S) mesons

See also Eskola et. al. arXiv:1906.03943, and *Nucl.Phys.A* 1005 (2021) 121944.

- Considerably narrows uncertainty band
- Reduces R_g at forward rapidity
- “Absorbs” initial state energy loss into nPDF?

Fitted to centrality integrated data only

- Has no information about centrality dependence
- Centrality dependence has to be invented

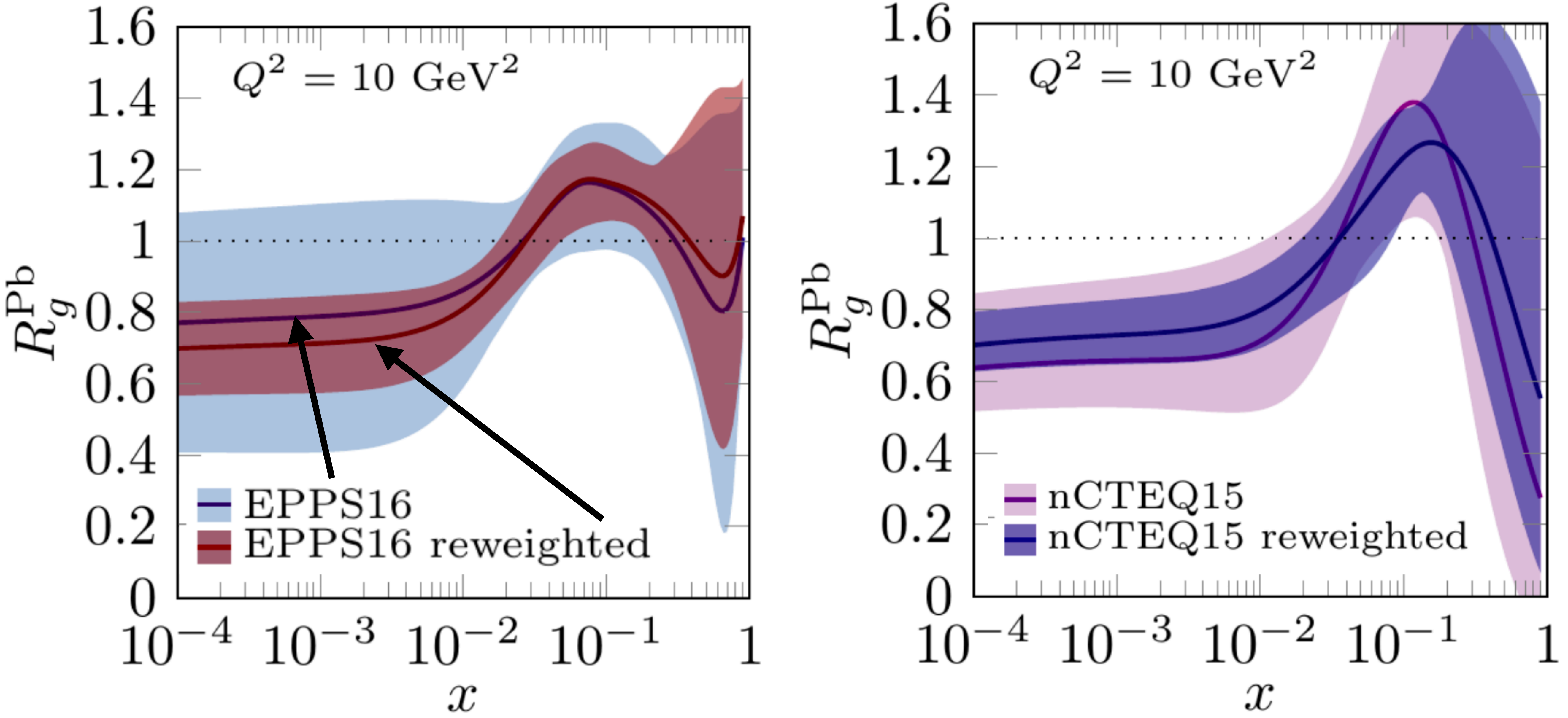


(b) Prompt J/ψ

Impact of re-weighting of gluon nPDF's

Eskola et. al., arXiv:1906.03943, *Nucl.Phys.A* 1005 (2021) 121944

- Hesssian re-weighting of nPDF's using LHCB D^0 data.



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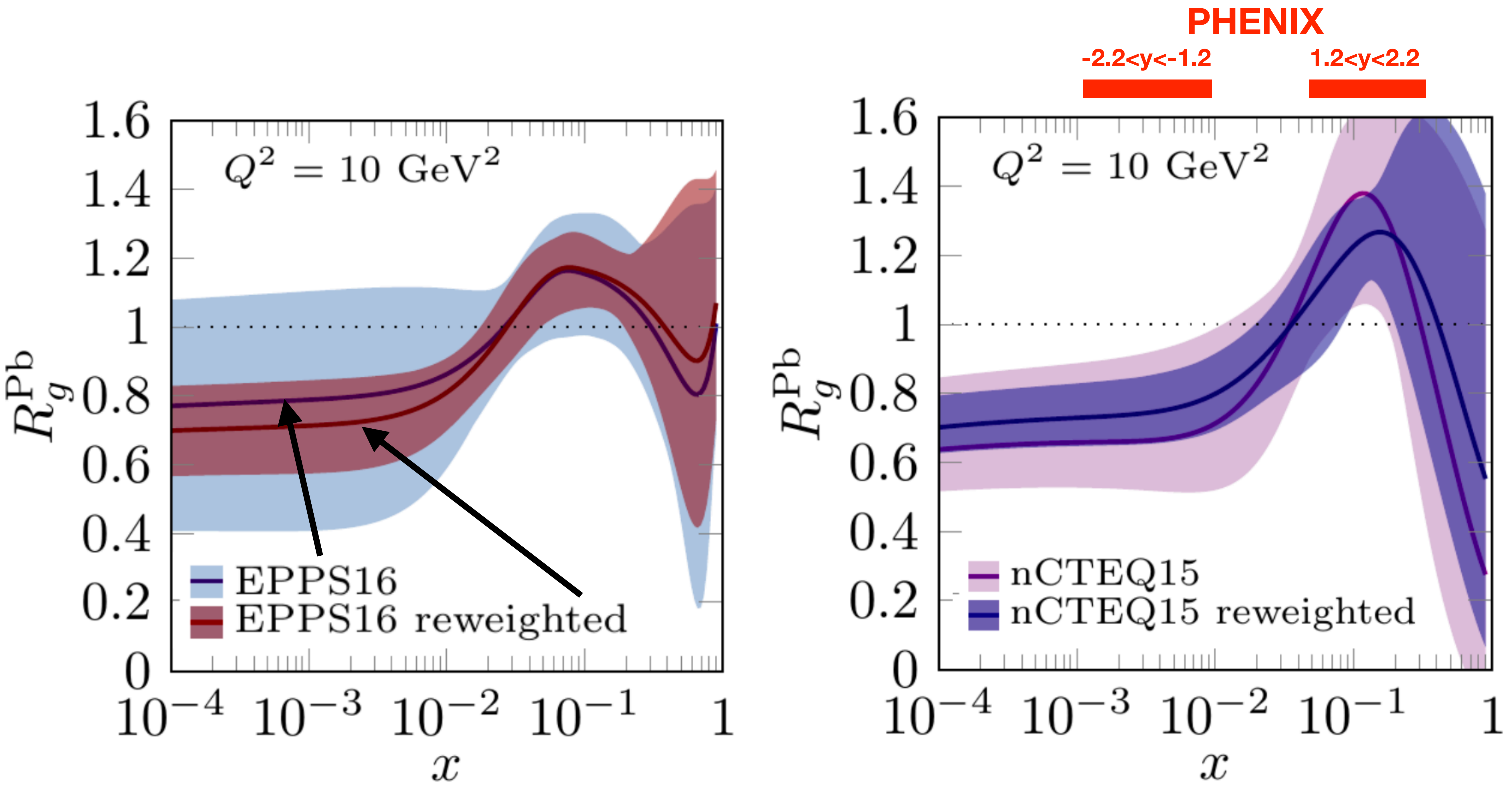


Initial state energy loss

Incoming parton loses energy due to gluon radiation associated with p_T broadening.

Examples:

- Arleo et. al. JHEP 05 (2013) 155.
- Sharma and Vitev, PRC 87 (2013) 044905.
- Kopeliovich et al., Phys.Rev. C95 (2017) 065203.

The Bayesian re-weighted shadowing seems to explain p+A data reasonably well without additional effects from initial state energy loss.

- Absorbs initial state energy loss effects into the shadowing parameterization?

J/ψ absorption

Backward rapidity J/ψ in PHENIX experience a significant “absorption” cross section - in addition to substantial anti-shadowing.

Parameterized using model of expansion of color neutral charmonium precursor as it crosses the target (Arleo et. al., PRC 61, 054906 (2000)).

- Applied in Glauber model of collisions integrated over relevant *y* range.
- Fitted to world’s σ_{abs} data for nuclear crossing time **τ > 0.05 fm/c**
- All data **corrected for shadowing** with EKS98 or EPS09

Provides good description of τ > 0.05 fm/c data from $\sqrt{s_{NN}}$ = 17 to 200 GeV

Anti-shadowing parameterizations have remained stable over several generations.

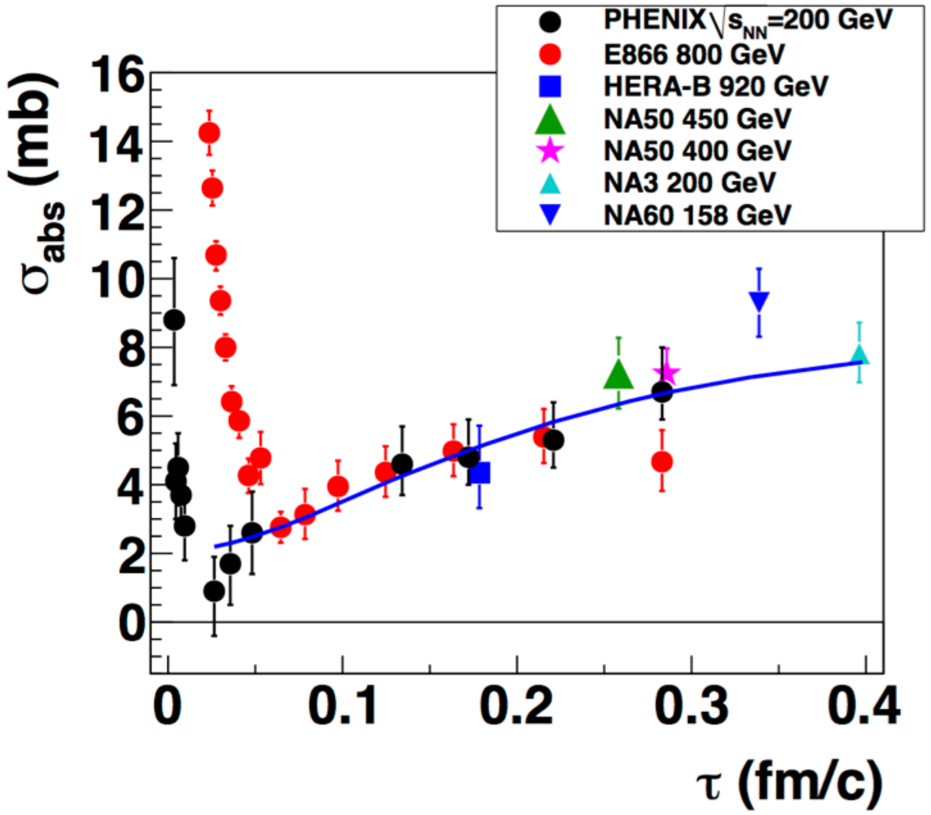
- Well constrained by DIS data.

Not the case for low x shadowing (low τ).

Strong absorption is not expected at LHC

- Nuclear crossing times very short at all y

Phys.Rev. C87 (2013) 5, 054910



Transport model

Du and Rapp (JHEP 1903 (2019) 015) adapted their transport model, used to describe heavy ion collisions, for use in small systems.
They tried to describe available charmonium J/ψ and ψ(2S)

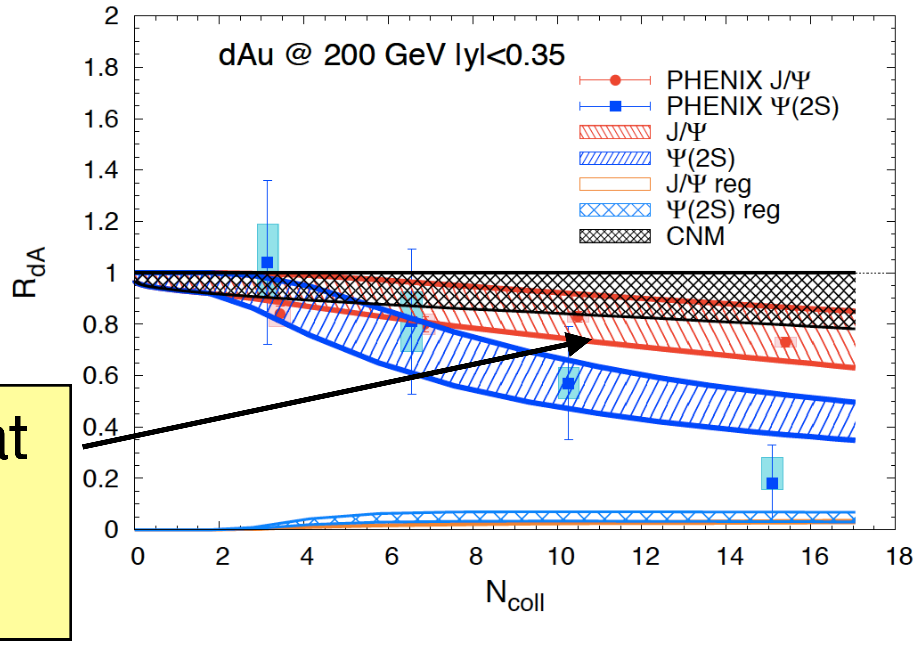
- RHIC: PHENIX J/ψ and ψ(2S) data at midrapidity.
- LHC: ALICE J/ ψ and ψ(2S) data at forward/backward rapidity, including the J/ψ v_2.

The transport model uses

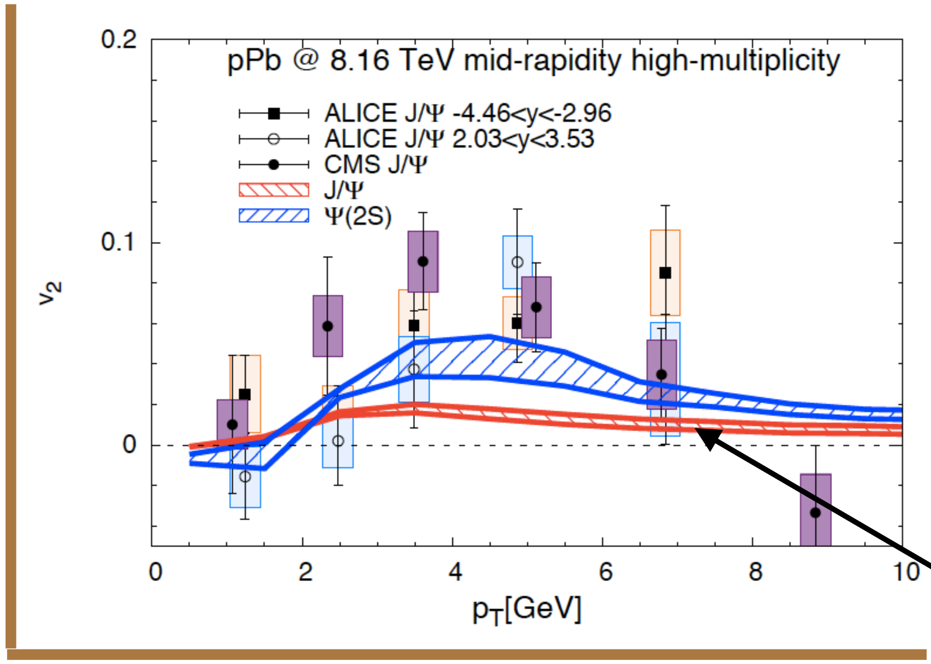
- A rate equation approach within a fireball model
- Initial geometry of the fireball from a Monte-Carlo event generator
- Initial anisotropies are caused by fluctuations
- Includes corrections for CNM effects
  - EPS09 shadowing with assumed linear centrality dependence
  - Assumes constant nuclear absorption at backward rapidity

Some comparisons with data from the paper on the next slide.

200 GeV

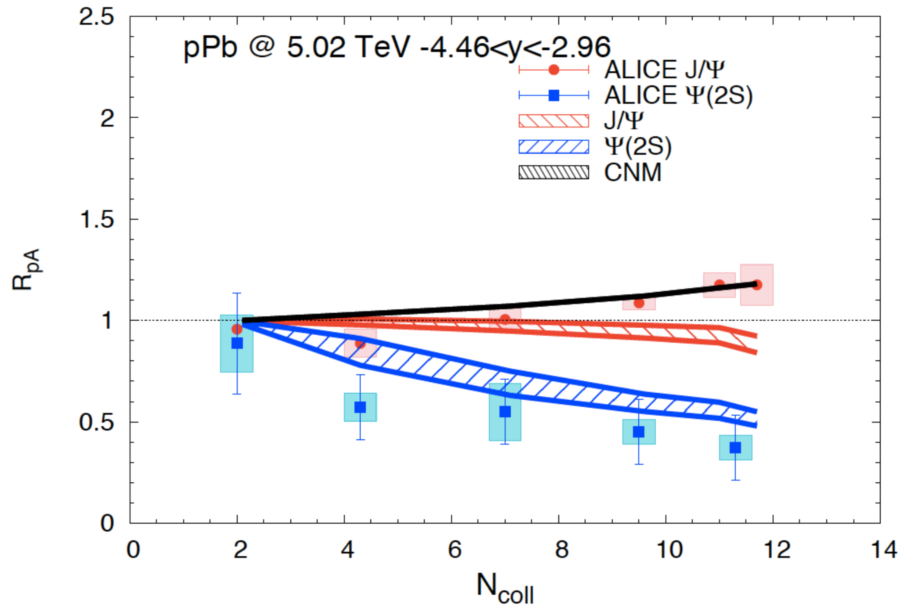


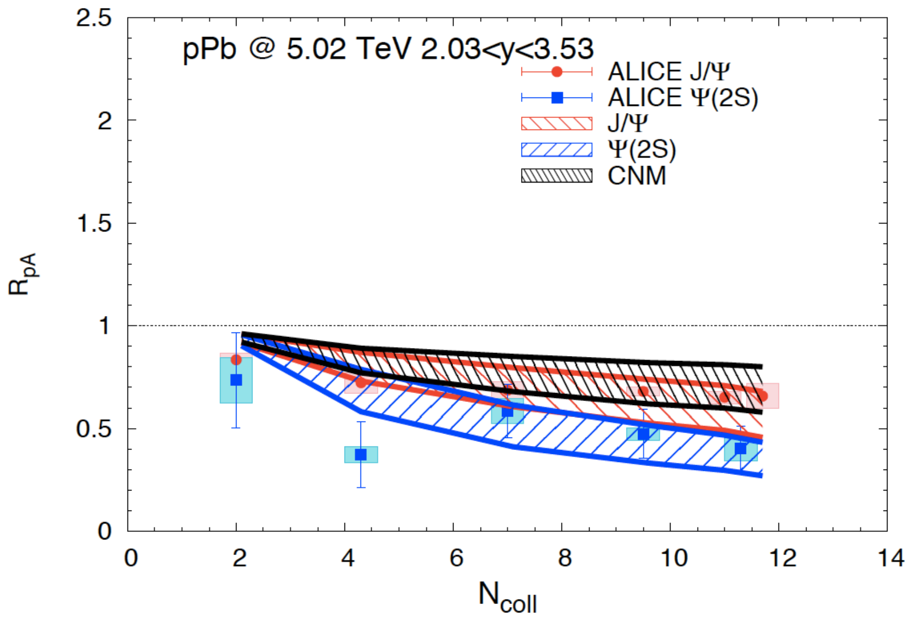
~20% effect at RHIC beyond CNM on J/ψ



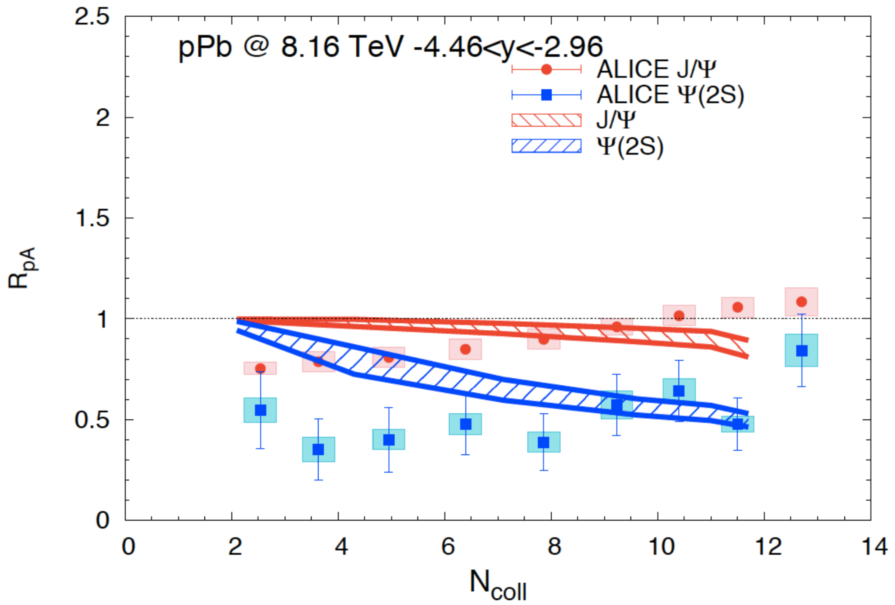
But: J/ψ v_2 not explained

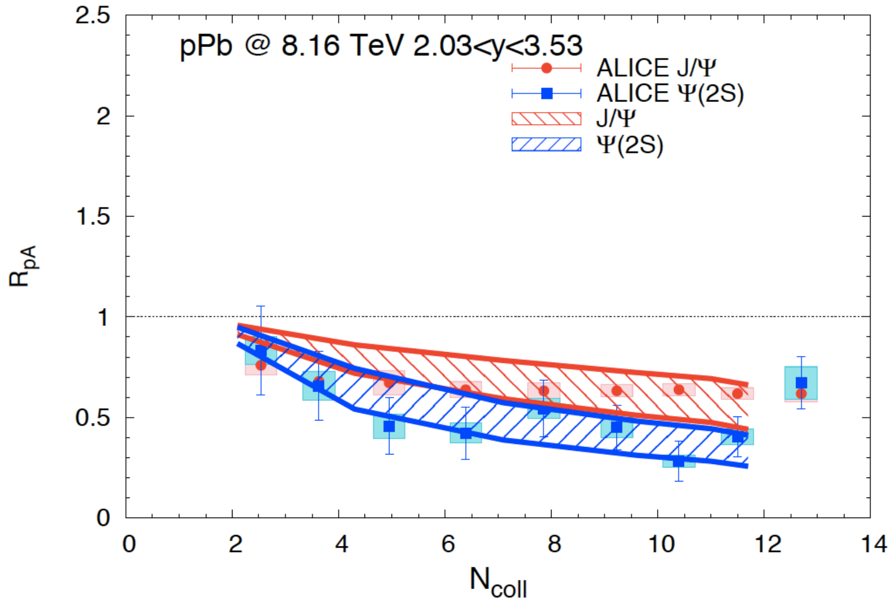
5.02 TeV





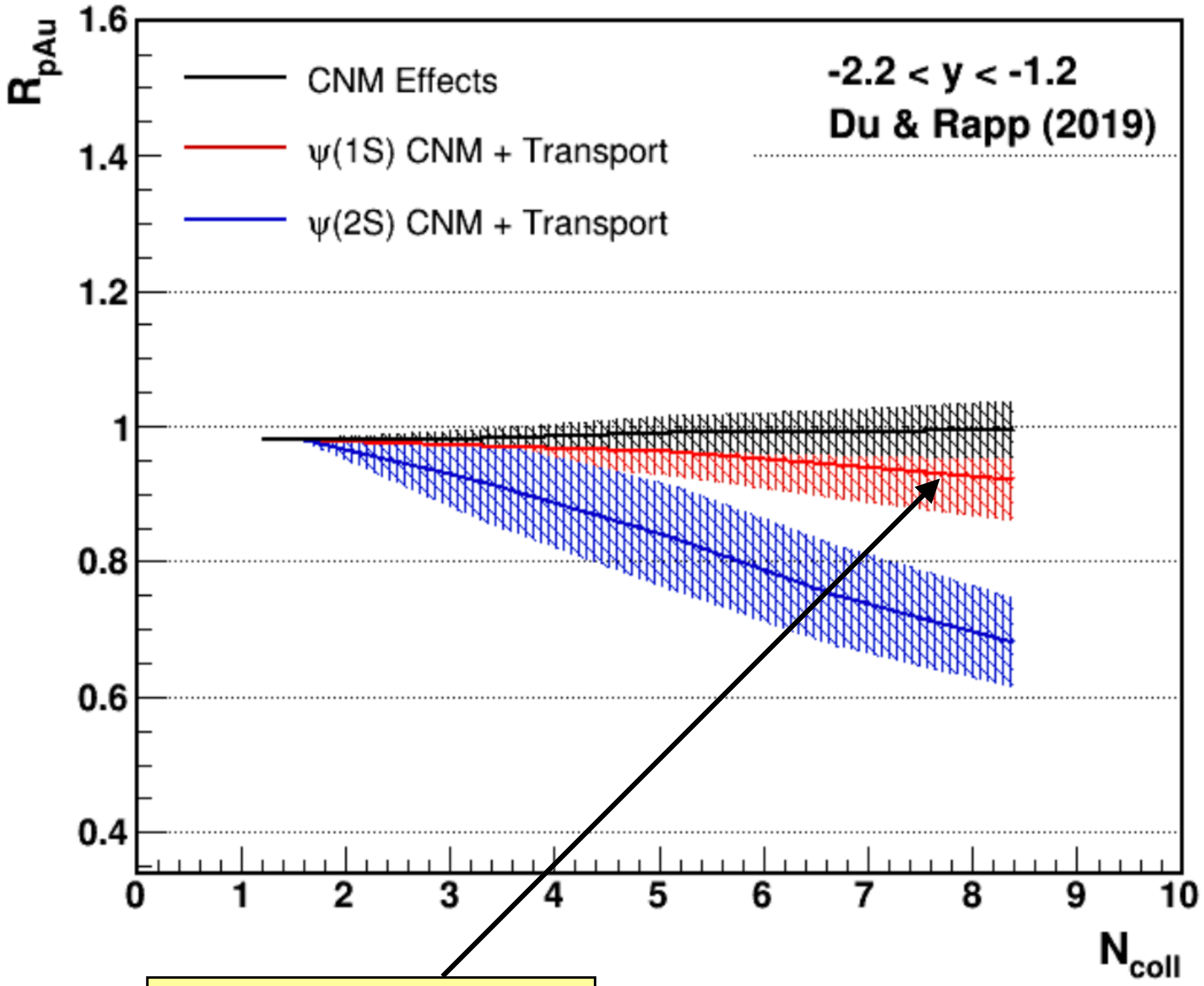
8.16 TeV



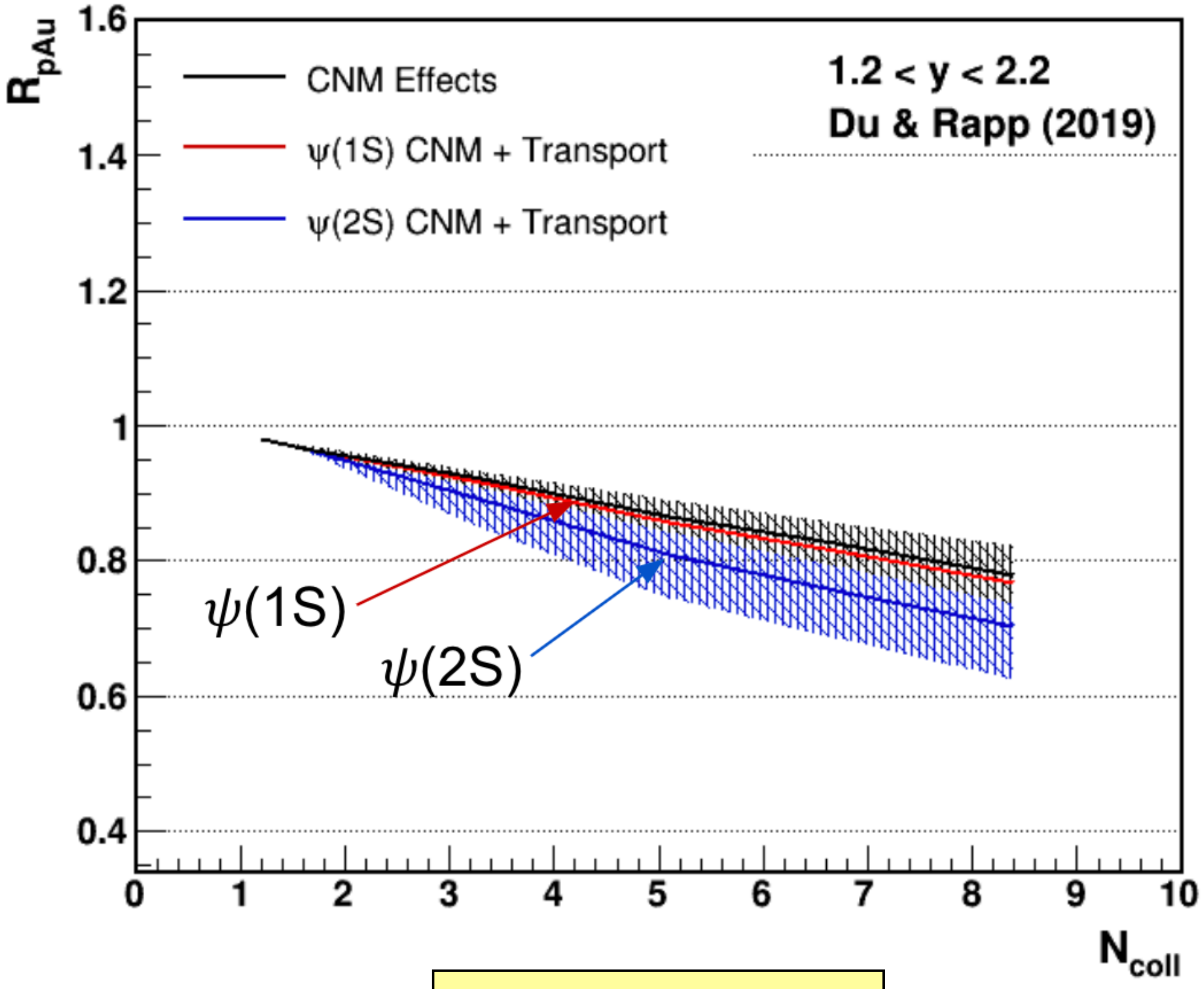


Prediction for p+Au at 200 GeV

Du and Rapp transport model prediction (really!) for 200 GeV p+Au collisions at forward and backward rapidity.



~10% effect in p+Au beyond CNM on J/ψ



Little effect in p+Au beyond CNM on J/ψ

Review of J/ψ results at forward/backward rapidity

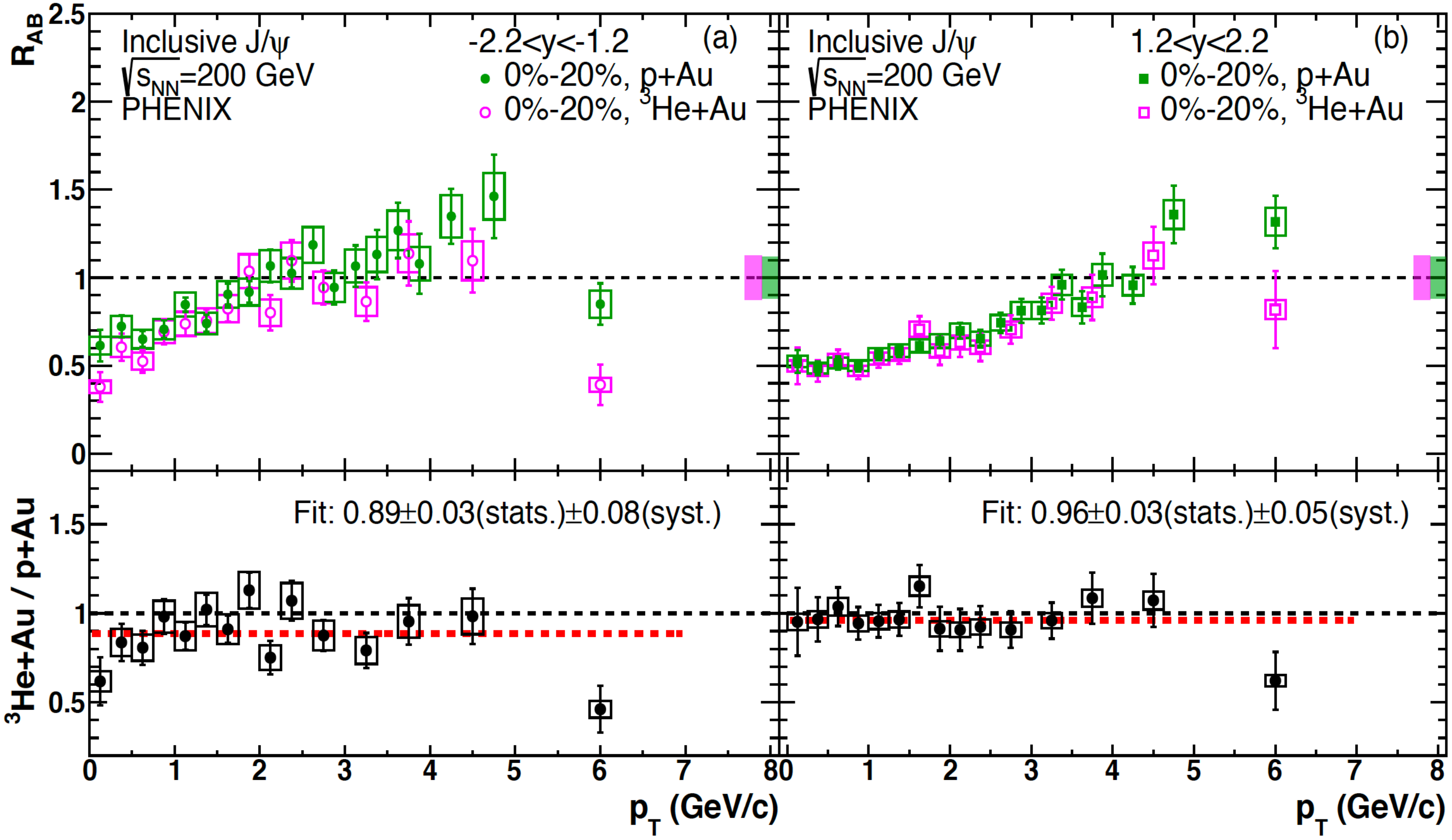
^{3}He+Au to p+Au ratio (0-20%centrality)

Backward rapidity ratio 0.89 ±0.03 ± 0.08

- Consistent with some additional suppression (90% probability).
- But not far outside the systematic uncertainty.

Forward rapidity ratio 0.96 ± 0.03 ± 0.05

- Consistent with 1



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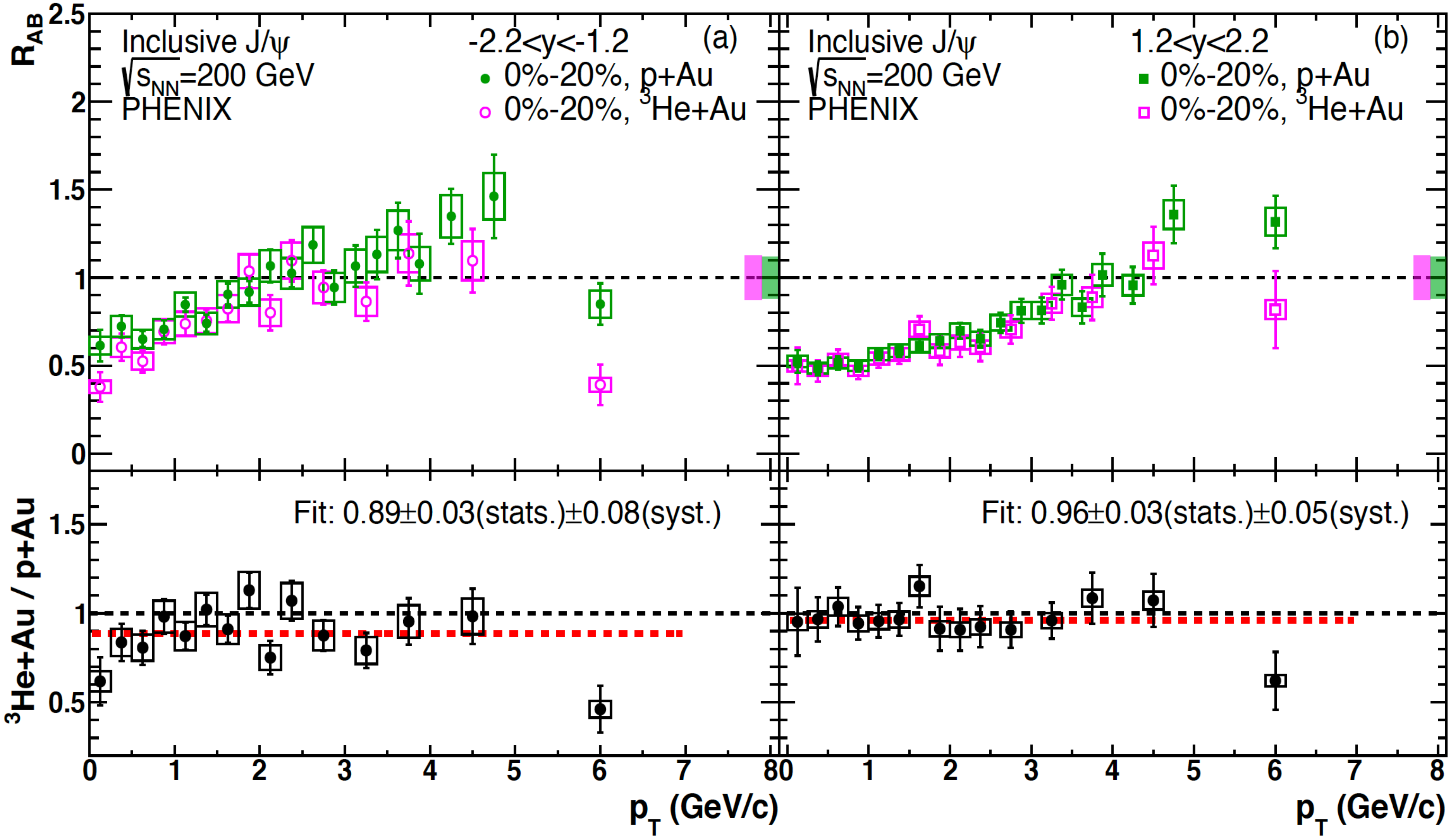
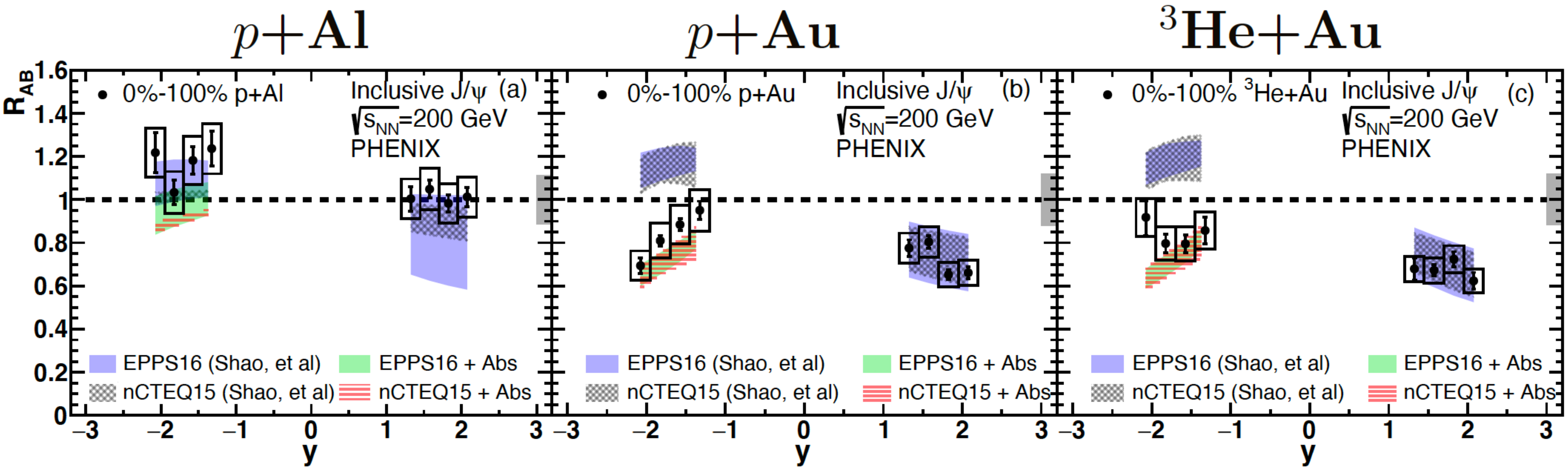
Little evidence for strong suppression of J/ψ in final state



Rapidity dependence, p_T and centrality integrated

0-100% centrality, p_T integrated.

- Add EPPS16 and nCTEQ15 shadowing, with Bayesian re-weighting.
- Fold in absorption prediction with shadowing at backward rapidity.



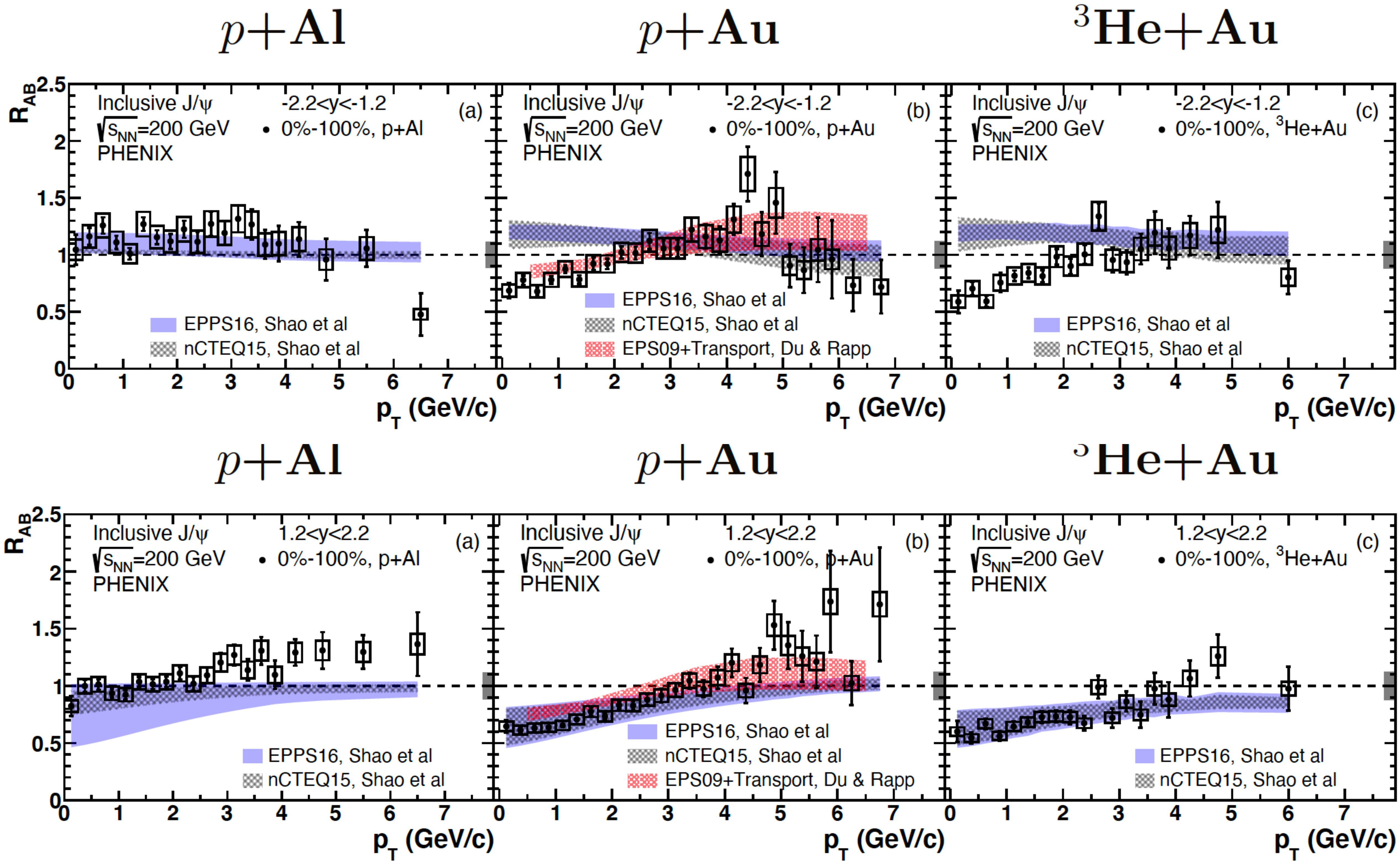
Not so bad!

How about the p_T dependence?

p_T dependence, 0-100% centrality

Blue: Bayesian re-weighted shadowing only

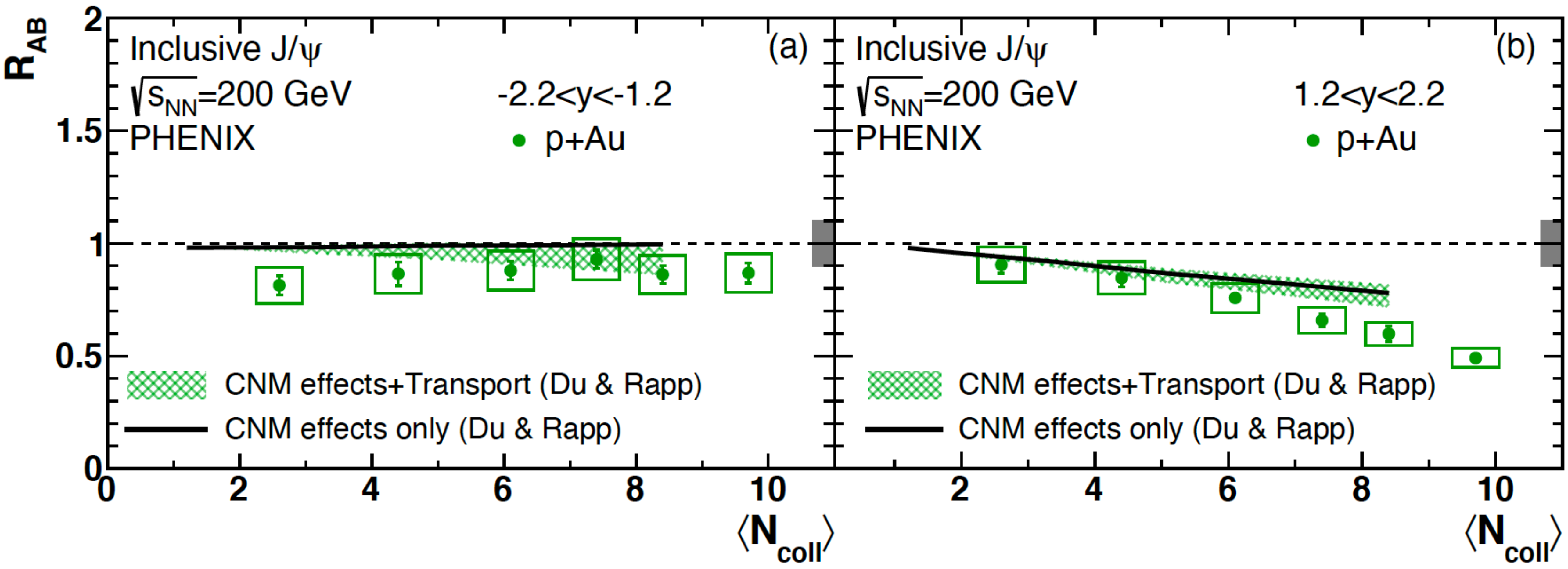
Red: Transport + EPS09 + absorption (-y) + p_T broadening



p+Au N_{coll} dependence for J/ψ

Compare transport calculation with N_{coll} dependence of p_T integrated data.

- At backward rapidity anti-shadowing + absorption + small final state effect.
- At forward rapidity suppression is dominated by EPS09 shadowing.
  - Centrality dependence is assumed to be linear.
  - EPS09 under-predicts suppression considerably!
    - But later parameterizations have stronger low x shadowing.

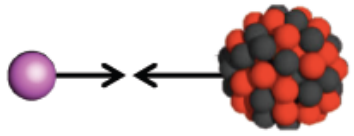


ψ(2S) results at forward/backward rapidity

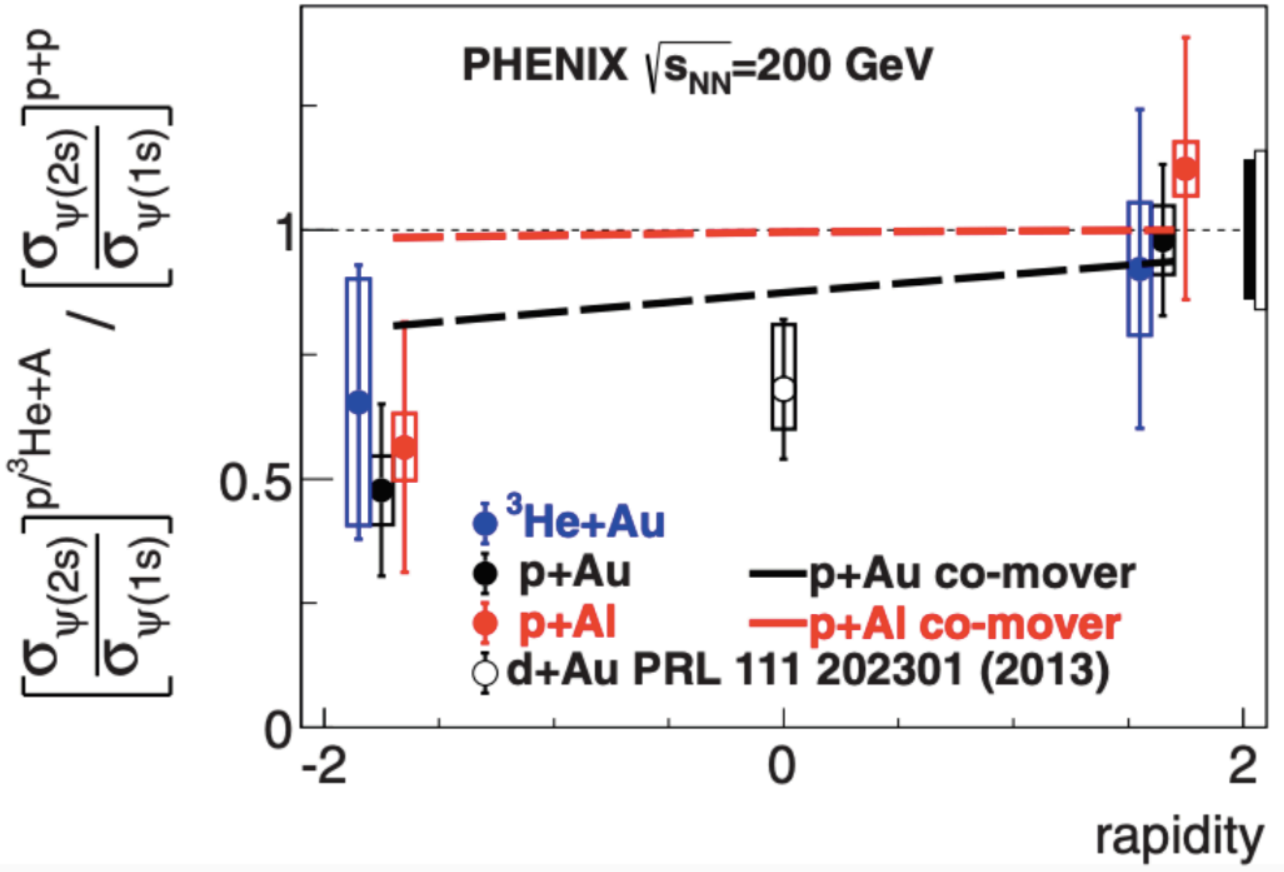
Earlier ψ(2S) results - centrality integrated

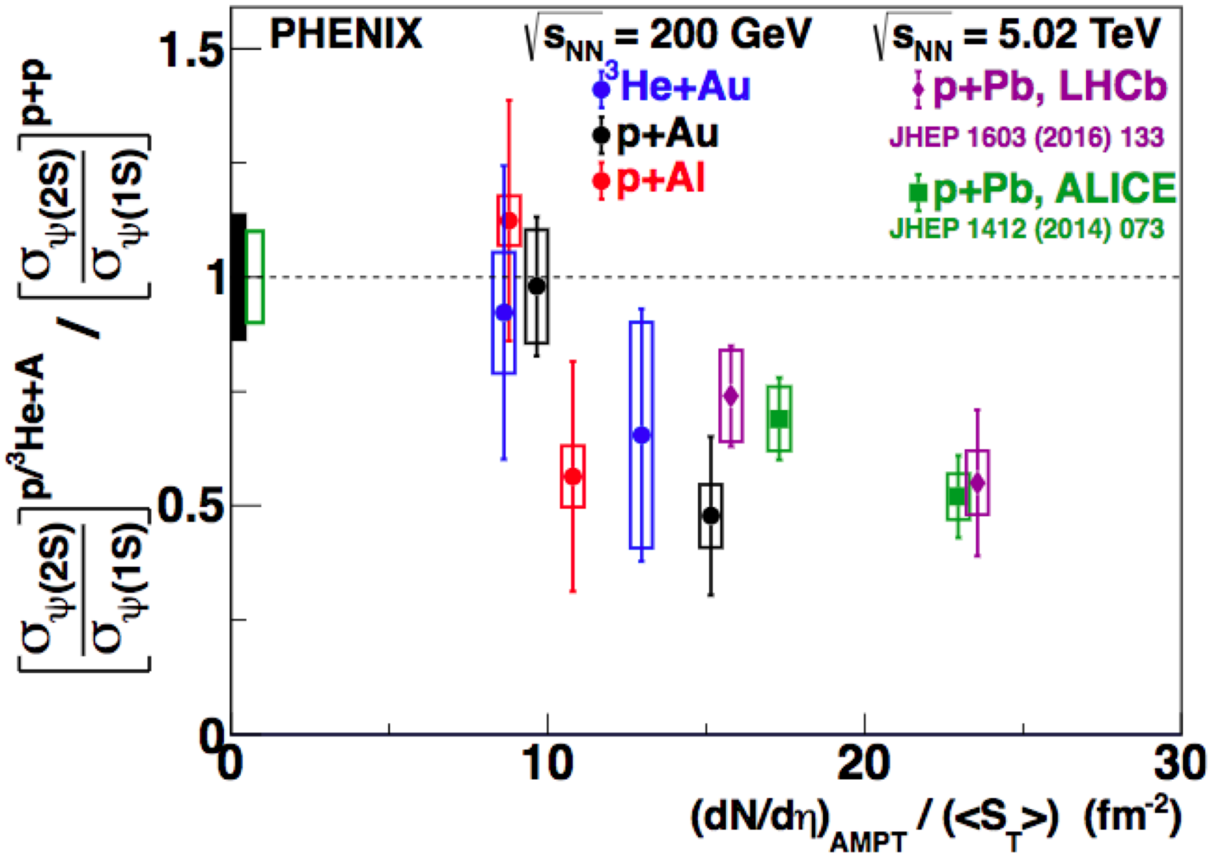
Strong suppression at mid & backward rapidity relative to J/ψ

- Not explained by CNM effects (CNM very similar for both states)



PHENIX, PRC95 034904 (2017)





The differential suppression is correlated with particle multiplicity

- Suggestive of a final state effect
- Would like more yield, and centrality dependence.

New - ψ(2S) production vs centrality

Very statistically challenged measurement!
- Feasible only for the p+Au data set.

Issues:
- Pair acceptance of FVTX/muon arm drops with distance from Z = 0.
- ψ(2S) yield is low when both tracks must pass through FVTX.
- Mass resolution inadequate when neither track passes through FVTX.

Solution:
- Use all muon pairs with **at least one** track passing through FVTX.
- Use pairs with two FVTX associations for systematic estimates

Provides best compromise between mass resolution and yield.

Mass spectrum fitting

Crystal Ball line-shapes used for quarkonia.

- J/ψ mass and width fixed from MB data.
- ψ(2S) mass & width **ratio** to J/ψ from simulations.
- Tail parameters from simulations.

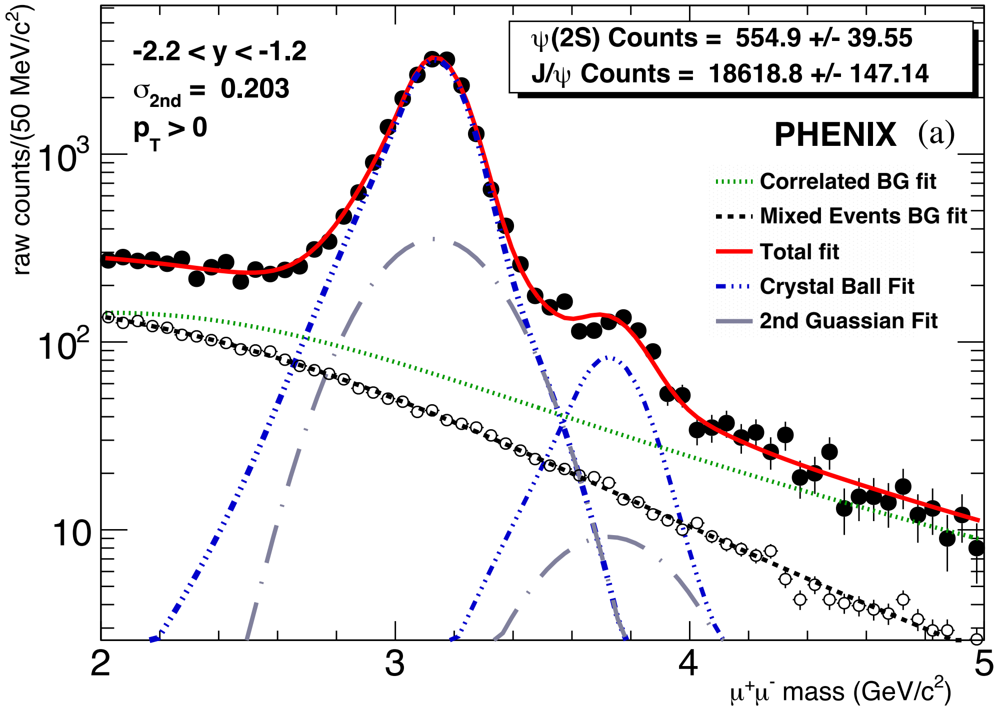
ψ(2S) yield is very sensitive to high mass tail of J/ψ.

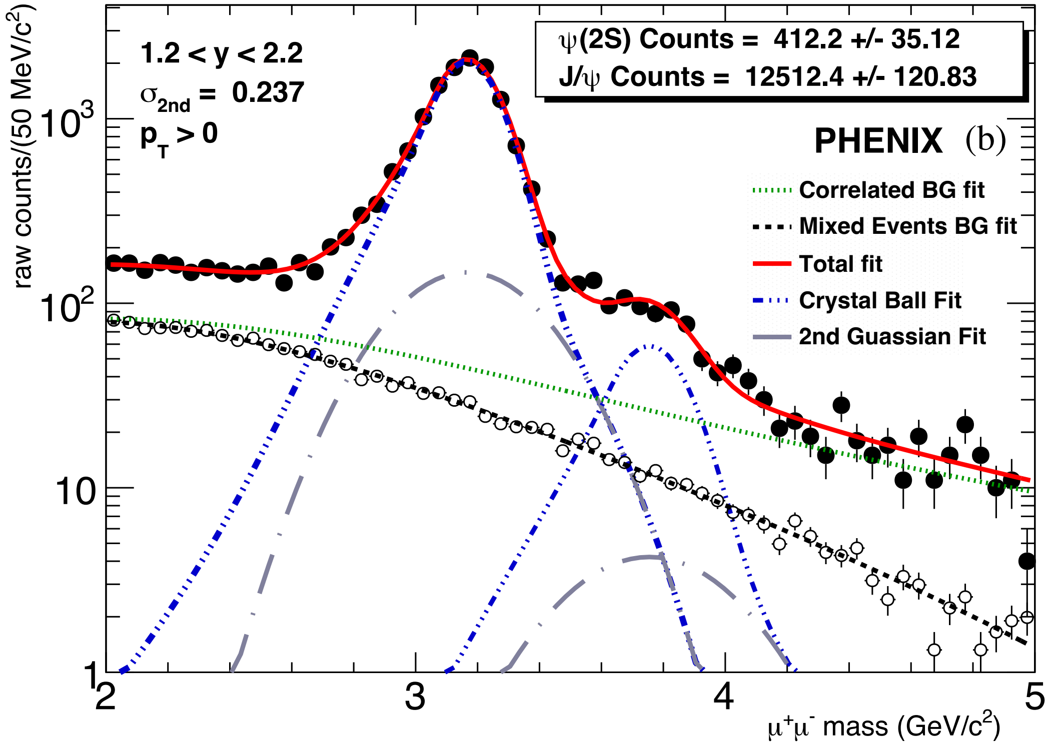
- Caused by mis-association of MuTr and FVTX hits.
- Included in fit using second gaussian.
  - Parameters determined from simulation.

Combinatorial background estimated from event mixing.

Correlated background.

- Open HF, Drell Yan, charged hadron muon decays.
- Poorly constrained by the data.
- Use a modified Hagedorn function, constrained by detailed simulations of all components.

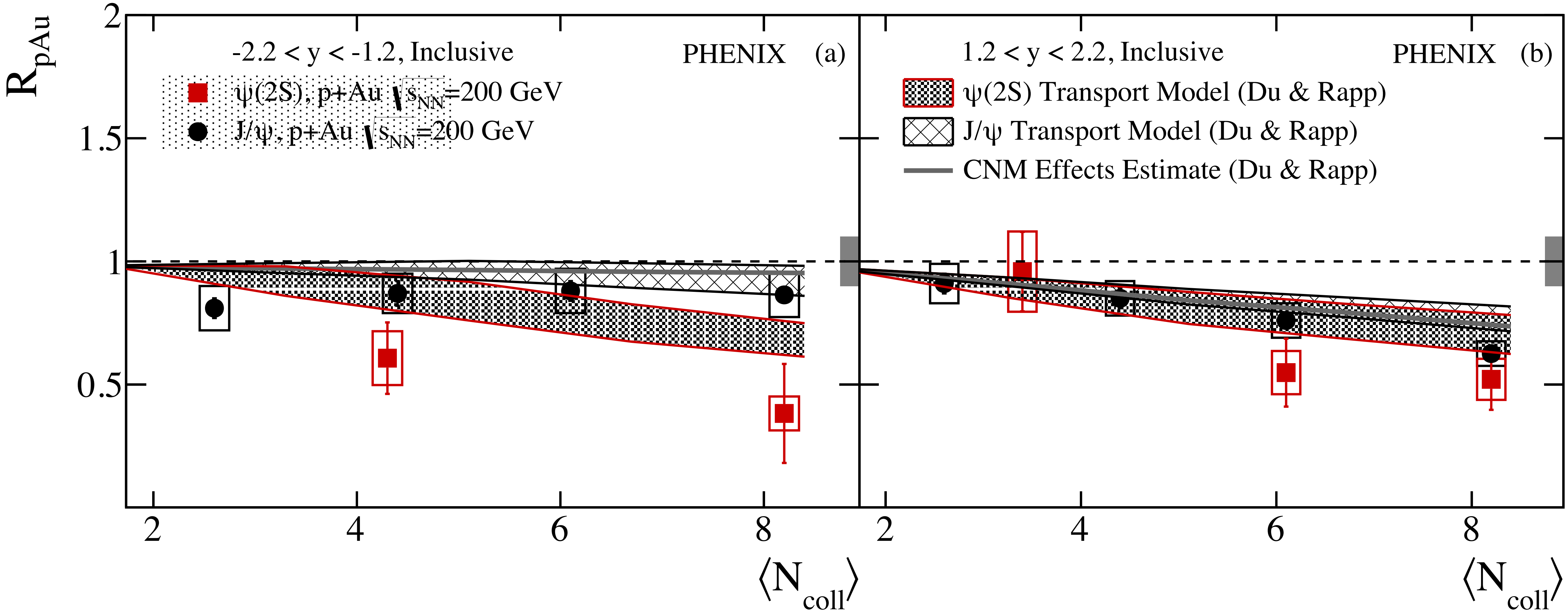




ψ(2S) R_{pAu} - centrality dependence

Nuclear modification in p+Au collisions for J/ψ and ψ(2S) as a function of $<N_{coll}>$.

Du and Rapp transport model somewhat under-predicts the suppression, but gets the suppression **ratios** about right.



ψ(2S) R_{pAu} centrality dependence - compare with shadowing alone

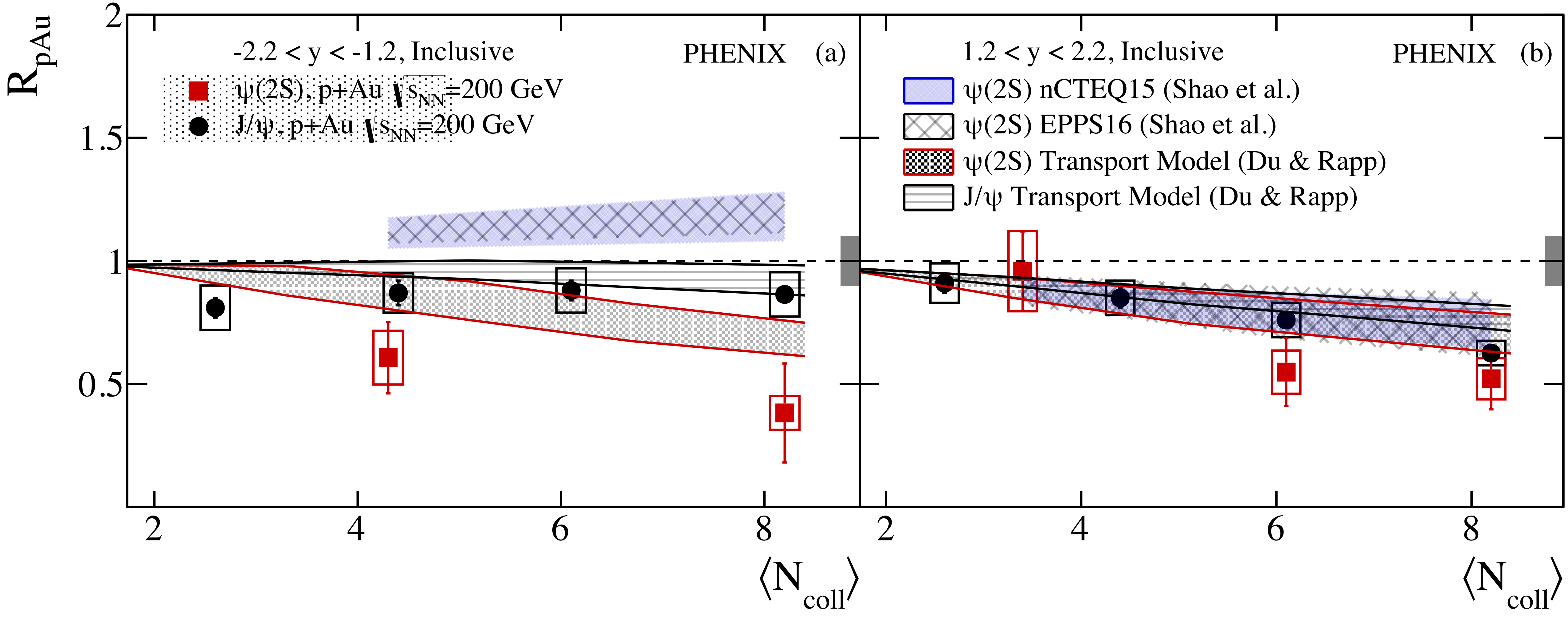
Add re-weighted shadowing comparison to plot.

Forward rapidity:

Modification consistent with shadowing alone.

Backward rapidity:

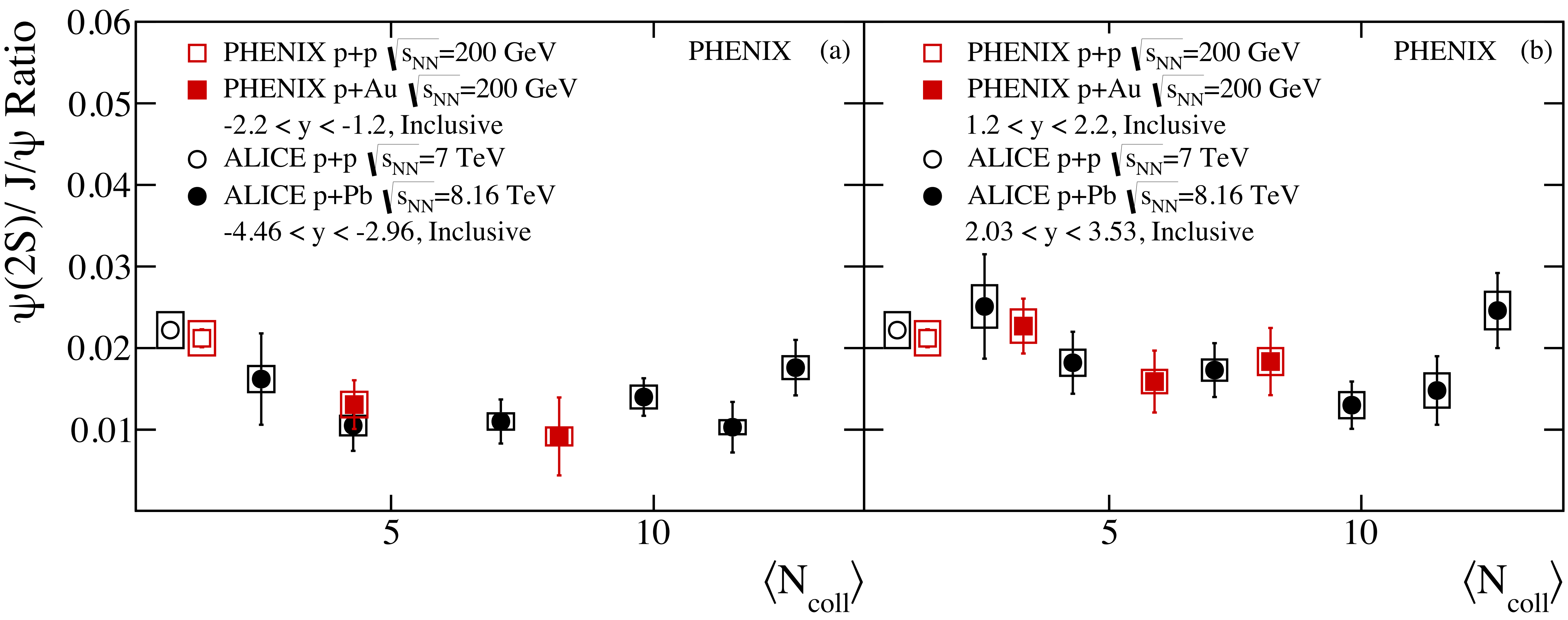
Require addition of strong absorption + differential ψ(2S) suppression.



ψ(2S)/J/ψ ratio vs N_{coll} - PHENIX/ALICE

PHENIX and ALICE ψ(2S) to J/ψ ratio plotted together.

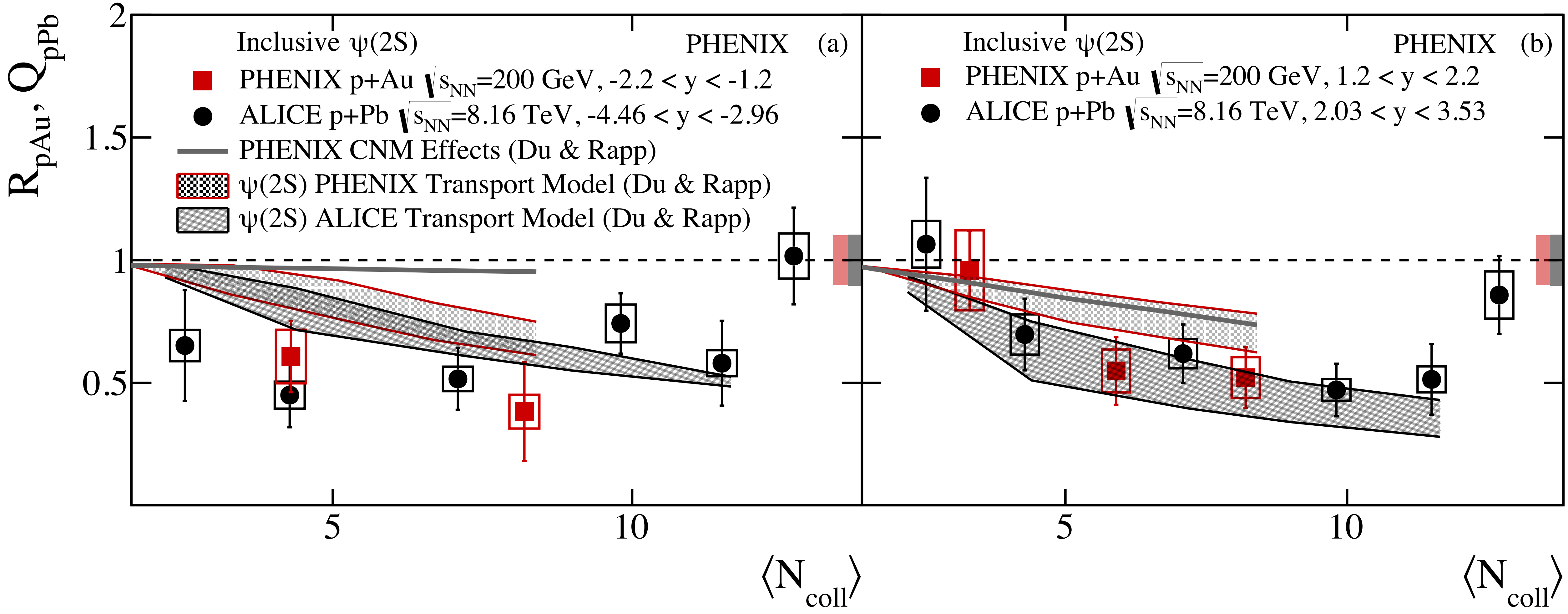
- Behavior is very similar at the two energies.
- The ratio is considerably smaller at backward rapidity.



ψ(2S) R_{pAu} vs N_{coll} - PHENIX/ALICE

Simultaneous comparison of PHENIX and ALICE ψ(2S) modification data with Du & Rapp transport model.

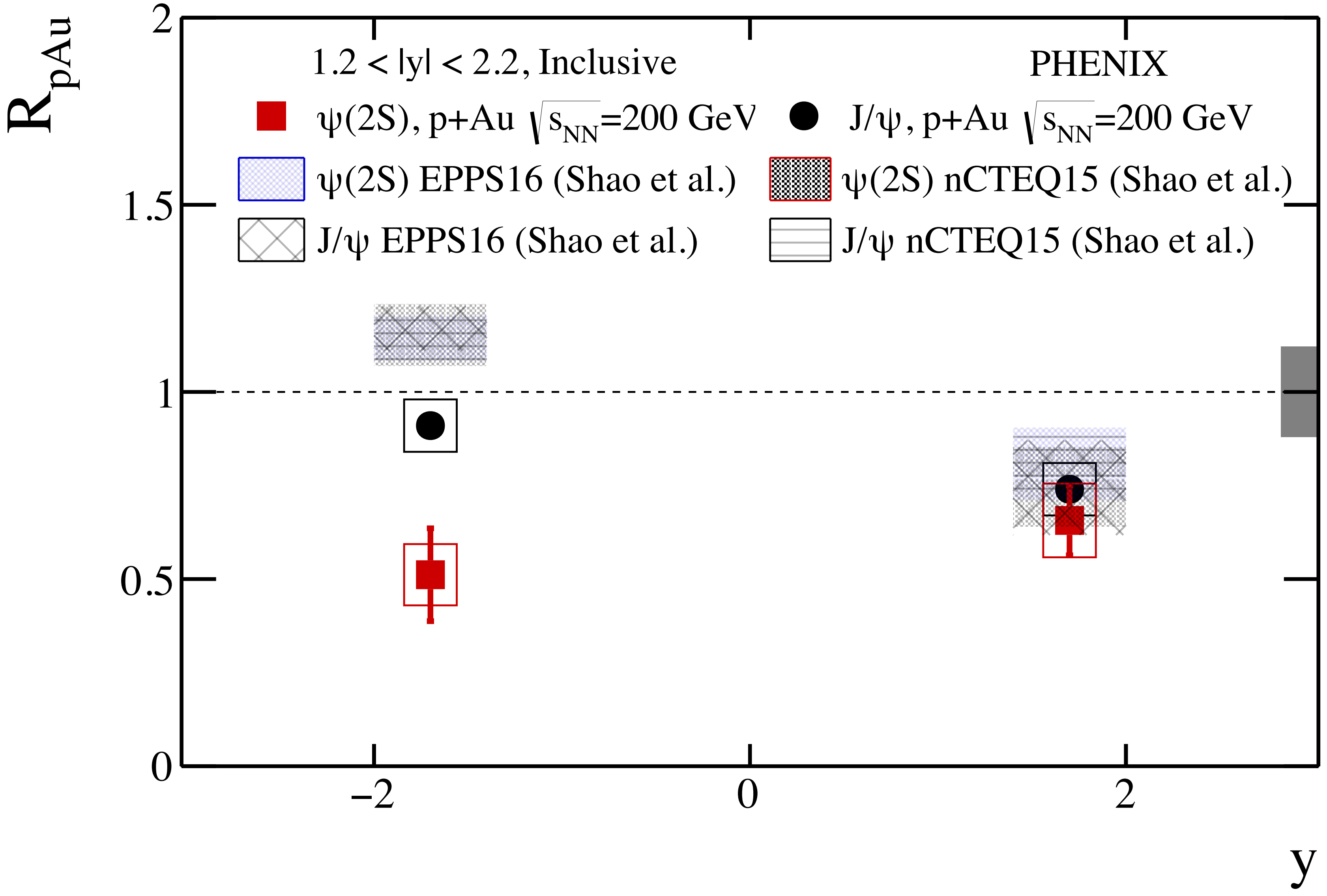
- Similar suppression at backward rapidity
  - **Combination** of anti-shadowing, absorption, final state effects.
- The different model suppression at forward rapidity is due to differences in shadowing.



ψ(2S) R_{pAu} vs rapidity - compare shadowing only

Centrality integrated modification vs rapidity.

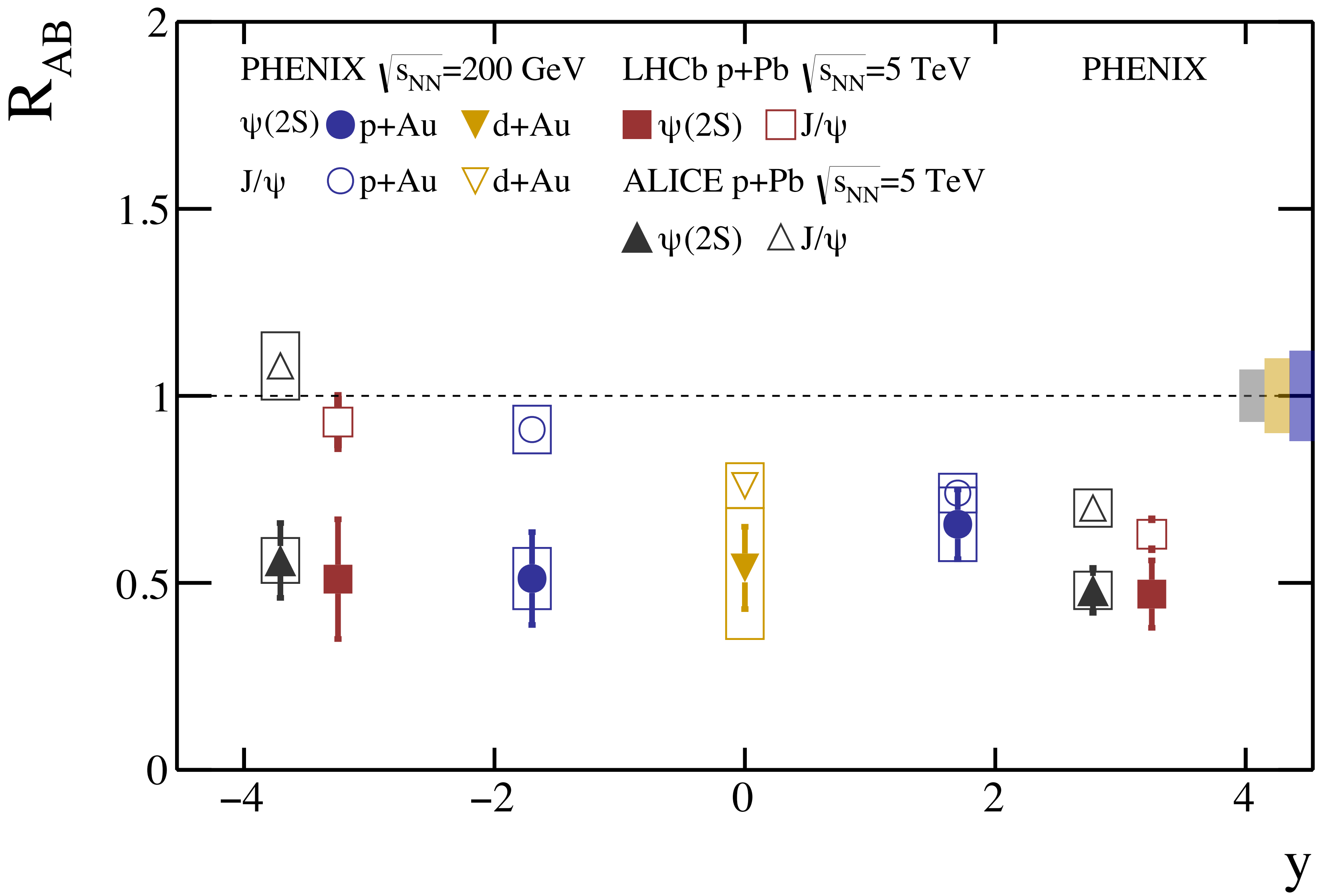
- Forward rapidity: good agreement with data for shadowing alone.
- Backward rapidity: Requires strong absorption + differential ψ(2S) suppression to achieve the measured modification.



ψ(2S) R_{pAu} vs rapidity - trend in world data

PHENIX, ALICE and LHCb modification for J/ψ and ψ(2S) vs rapidity.

Clear trend of increasing differential suppression from forward to backward rapidity.



Conclusions

J/ψ modification in p+Au:

At forward rapidity:

- Described reasonably well by shadowing alone.

At backward rapidity:

- Described reasonably well by anti-shadowing + absorption.
  - There is room for a small (~10%) contribution from final state effects.
    - But there is not strong evidence for it.

ψ(2S) modification in p+Au:

At forward rapidity:

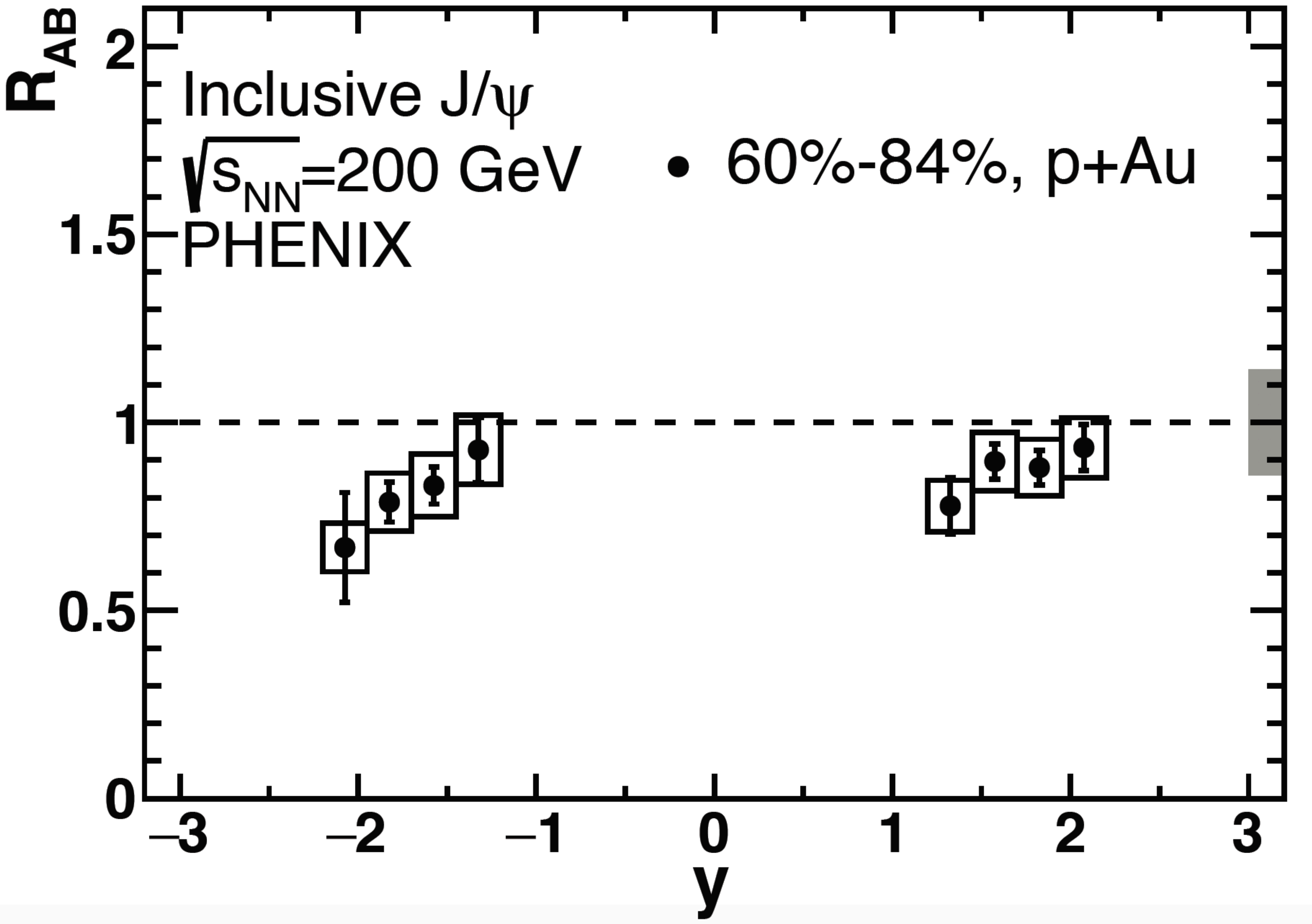
- Described reasonably well by shadowing alone.

At backward rapidity:

- Requires substantial additional suppression from final state effects.
  - Transport model accounts reasonably well for the differential ψ(2S) suppression.

Backup

p+Au centrality dependence



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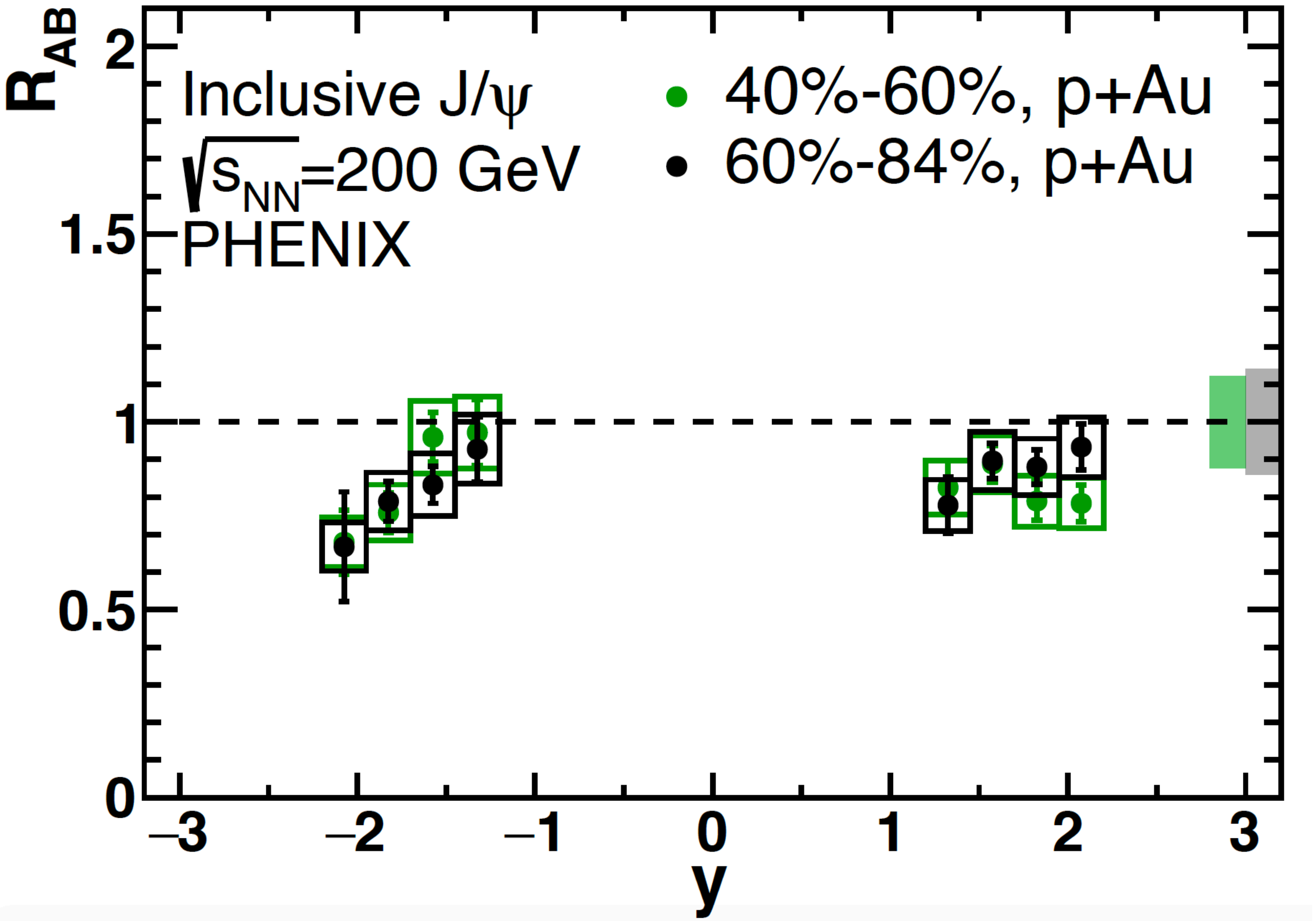
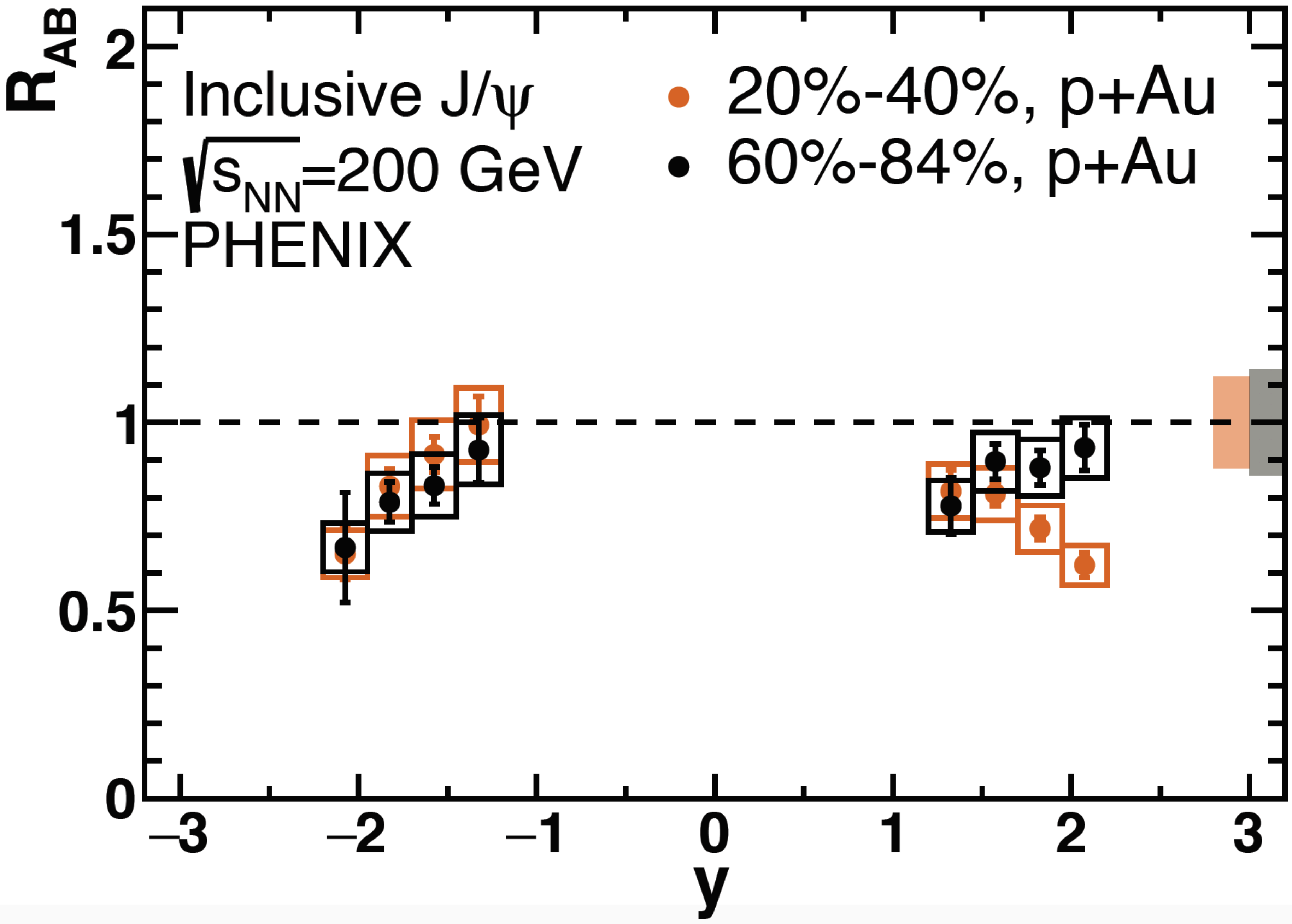


p+Au centrality dependence



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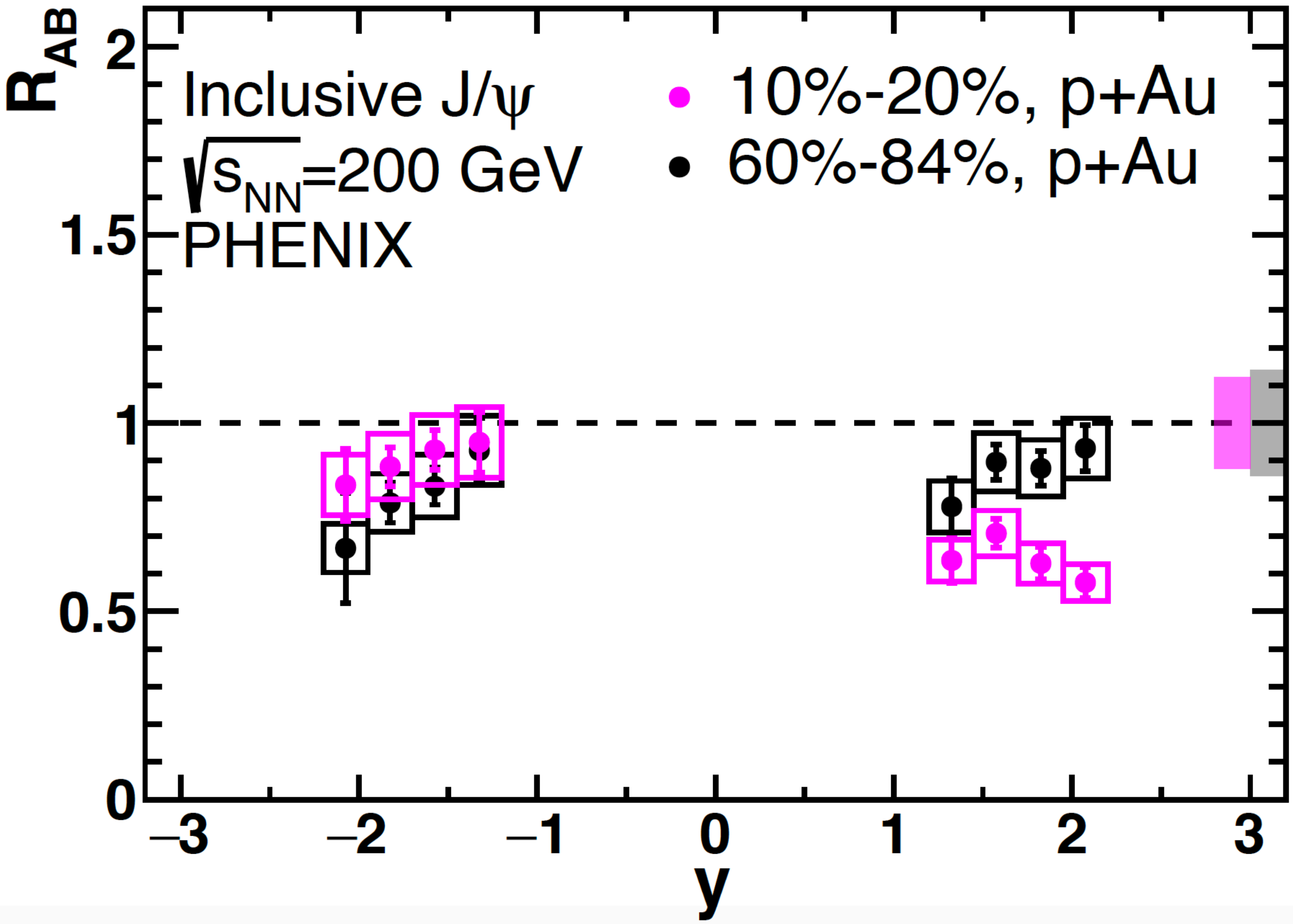
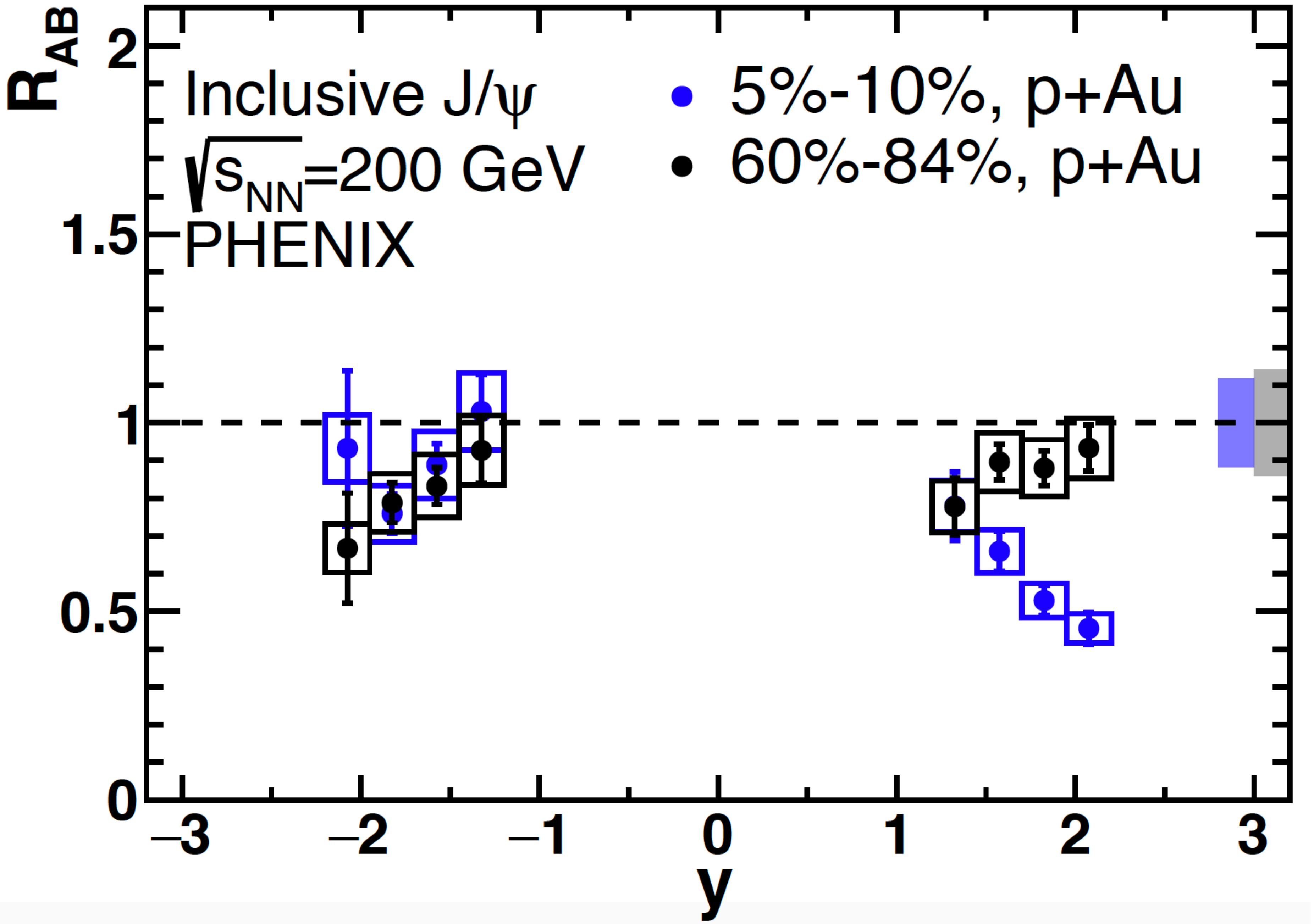


p+Au centrality dependence



p+Au centrality dependence

Trade-off between anti-shadowing and absorption.

Very strong centrality dependence of suppression.