ψ(2S) production in small systems

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Heavy Flavor Production in Heavy Ion and Elementary Collisions

Institute for Nuclear Theory
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Introduction

The talk title refers to ψ(2S) production in small systems.

- However it is most useful to consider ψ(2S) and J/ψ together.

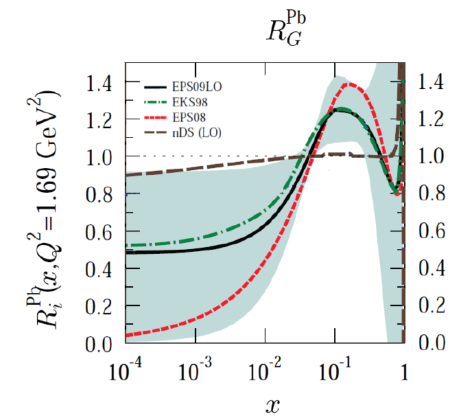
We now have data on J/ψ and ψ(2S) modification in p+A collisions

- At both RHIC and LHC energies.
- Across a broad rapidity range in both cases.

This talk is an experimentalist’s view of what the data tell us about the sources of the nuclear modification.

Quarkonia production in a nucleus

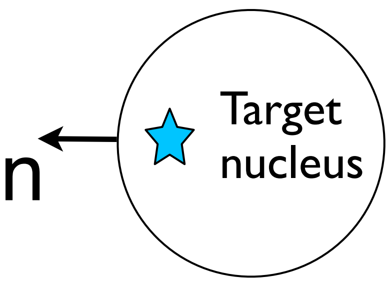
Processes that modify the quarkonia yield in a nuclear target - called cold nuclear matter (CNM) processes.



Gluon shadowing - parton distributions are modified in a nucleus

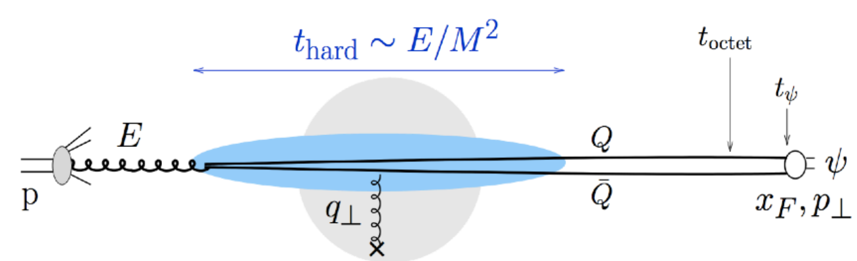
Affects underlying heavy quark yield

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

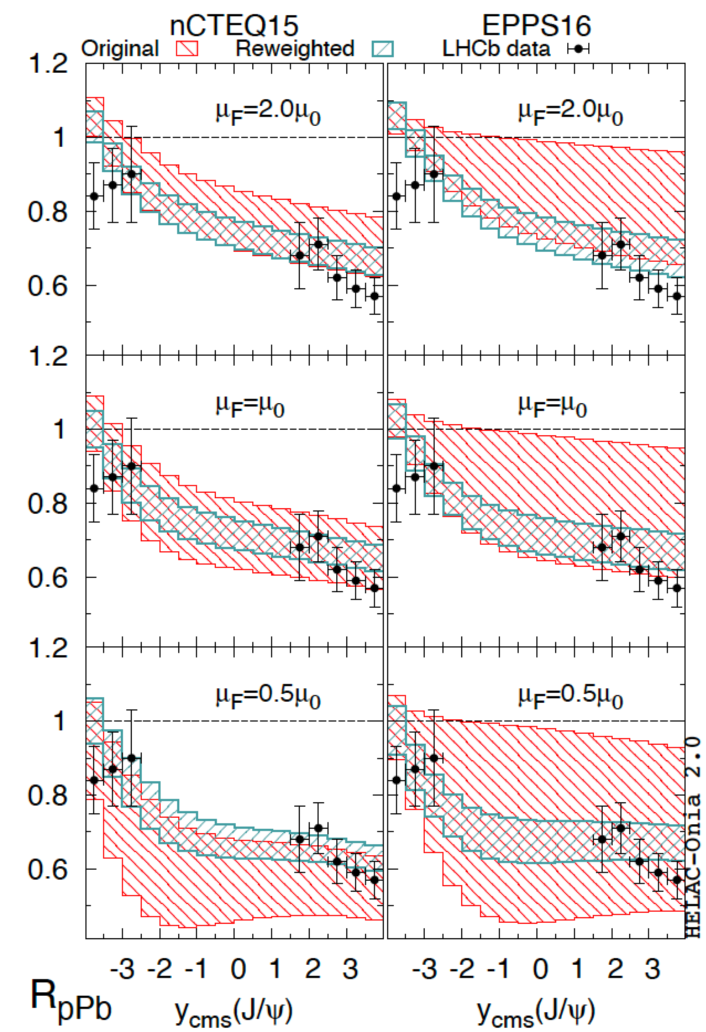
- (Kusina et. al., Phys. Rev. Lett. 121, 052004 (2018))
- Adds LHC pPb data - gluon dominated processes
  - D_0, J/ψ , B →J/ψ, and Υ(1S) mesons

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

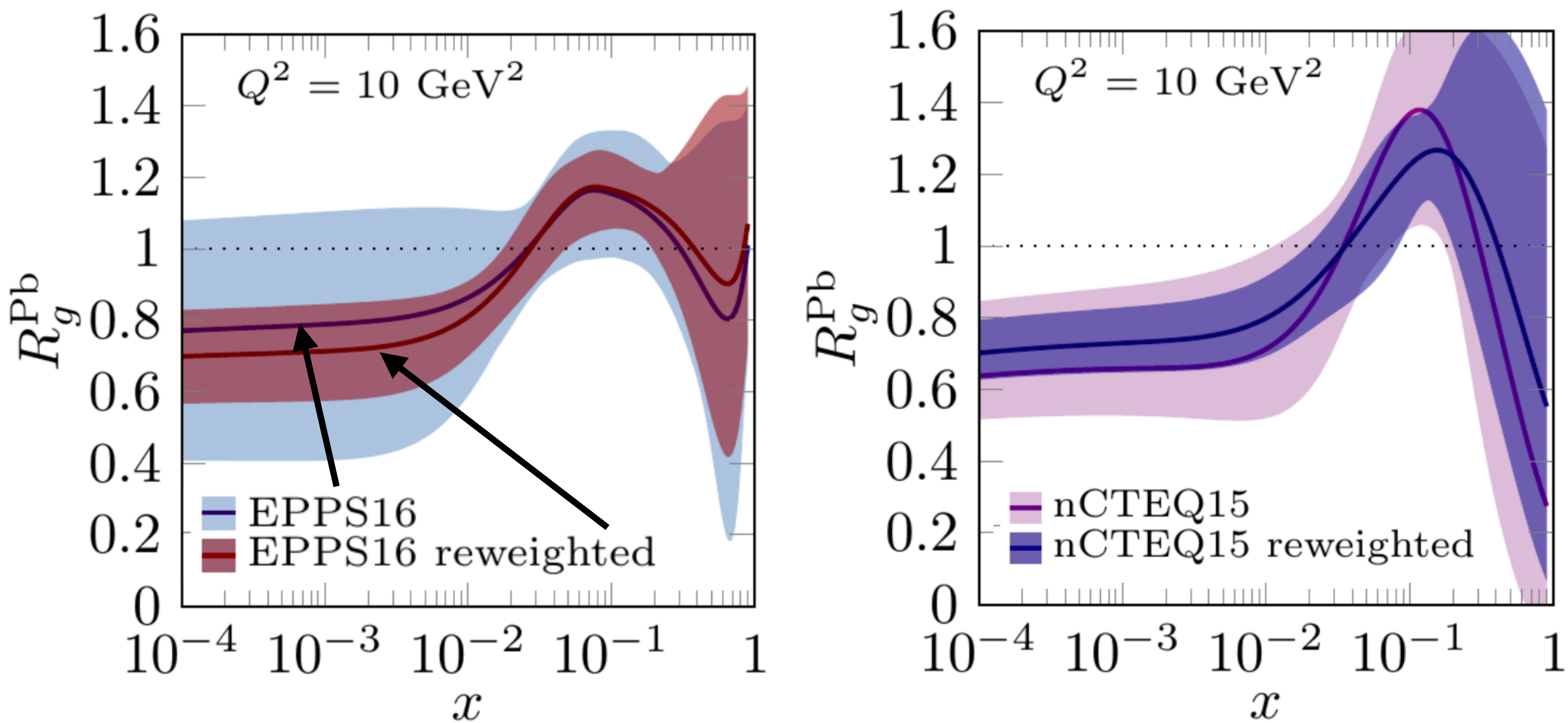


(b) Prompt J/ψ

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.



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 (Arleo et. al., PRC 61, 054906 (2000)) of cross section for colliding with a nucleon of an expanding color neutral charmonium precursor as it crosses the target.

- 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

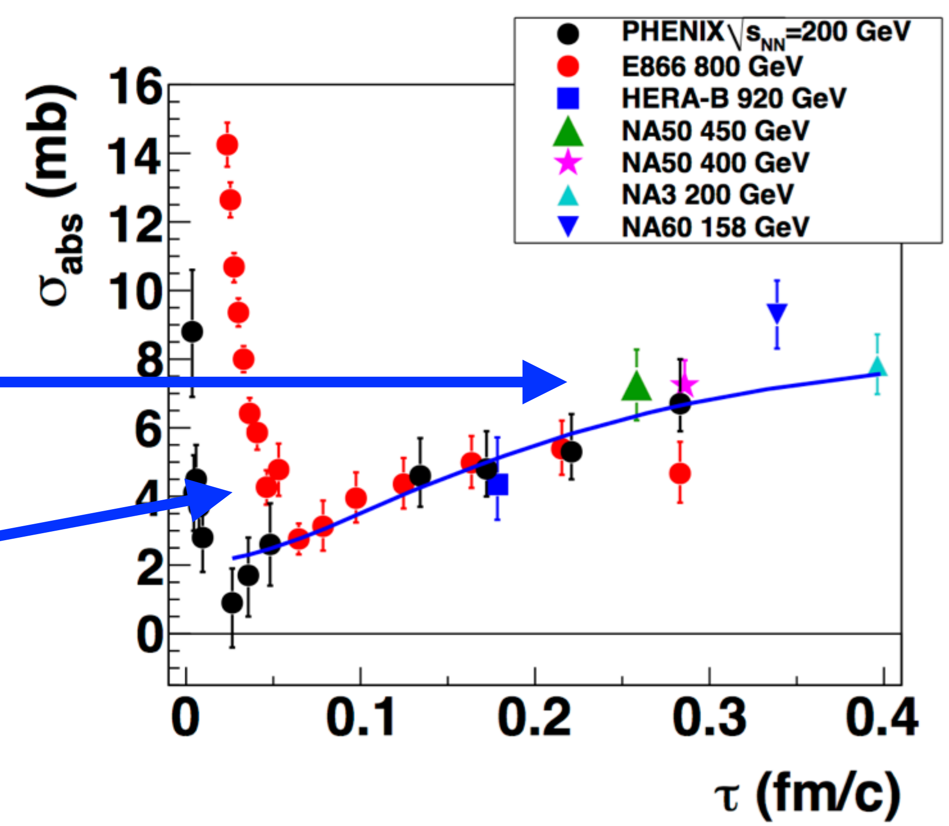
Provides good description of τ > 0.05 fm/c data from $\sqrt{s_{NN}}$ = 17 to 200 GeV

Anti-shadowing parameterizations have remained stable over several generations.

- Well constrained by DIS data.

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

Phys.Rev. C87 (2013) 5, 054910



Strong absorption is not expected at LHC

- Nuclear crossing times are very short at all y

RHIC J/ψ results at forward/backward rapidity

Do we see evidence of final state effects on J/ψ production?

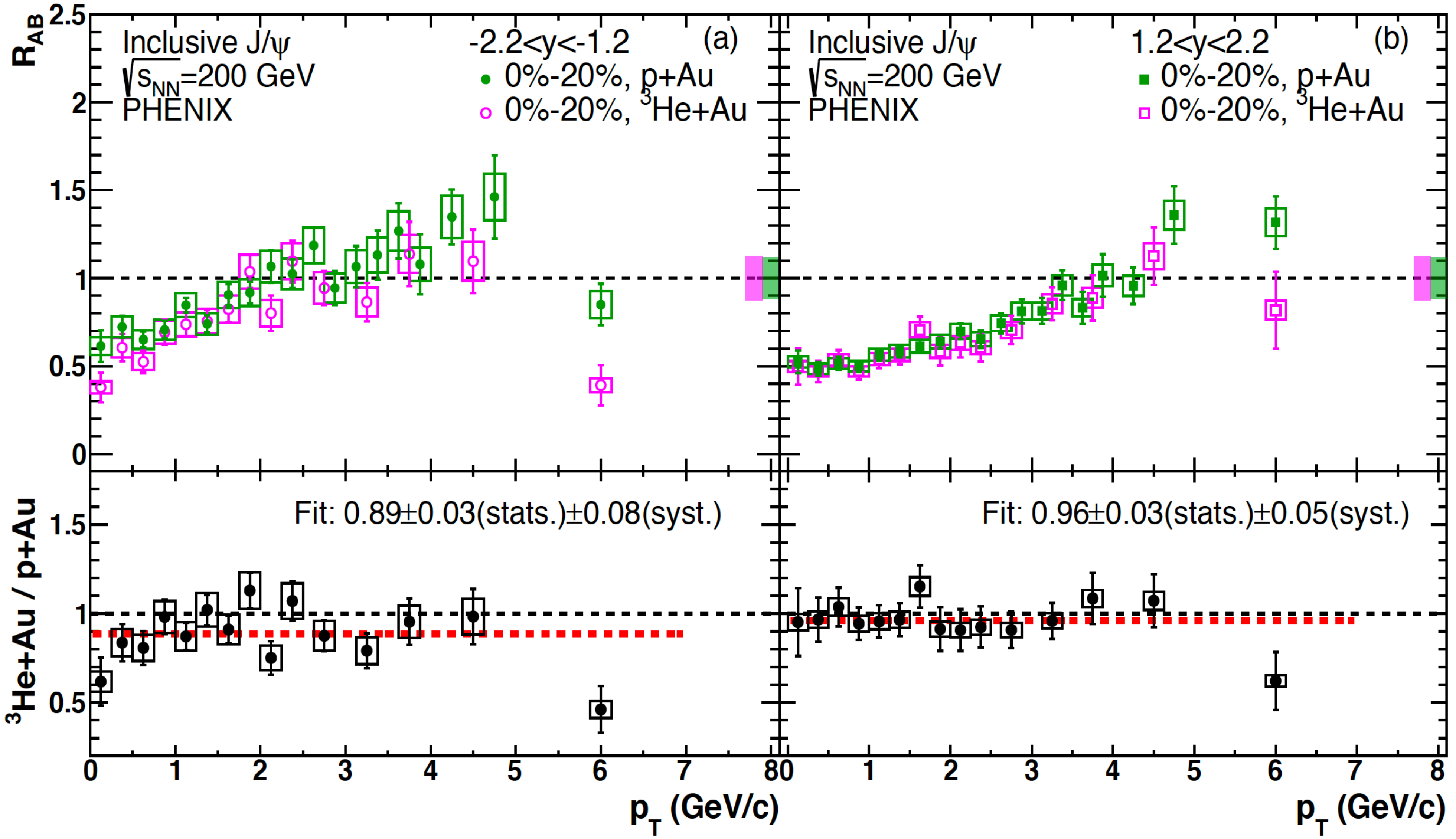
^{3}He+Au to p+Au ratio (0-20%centrality)

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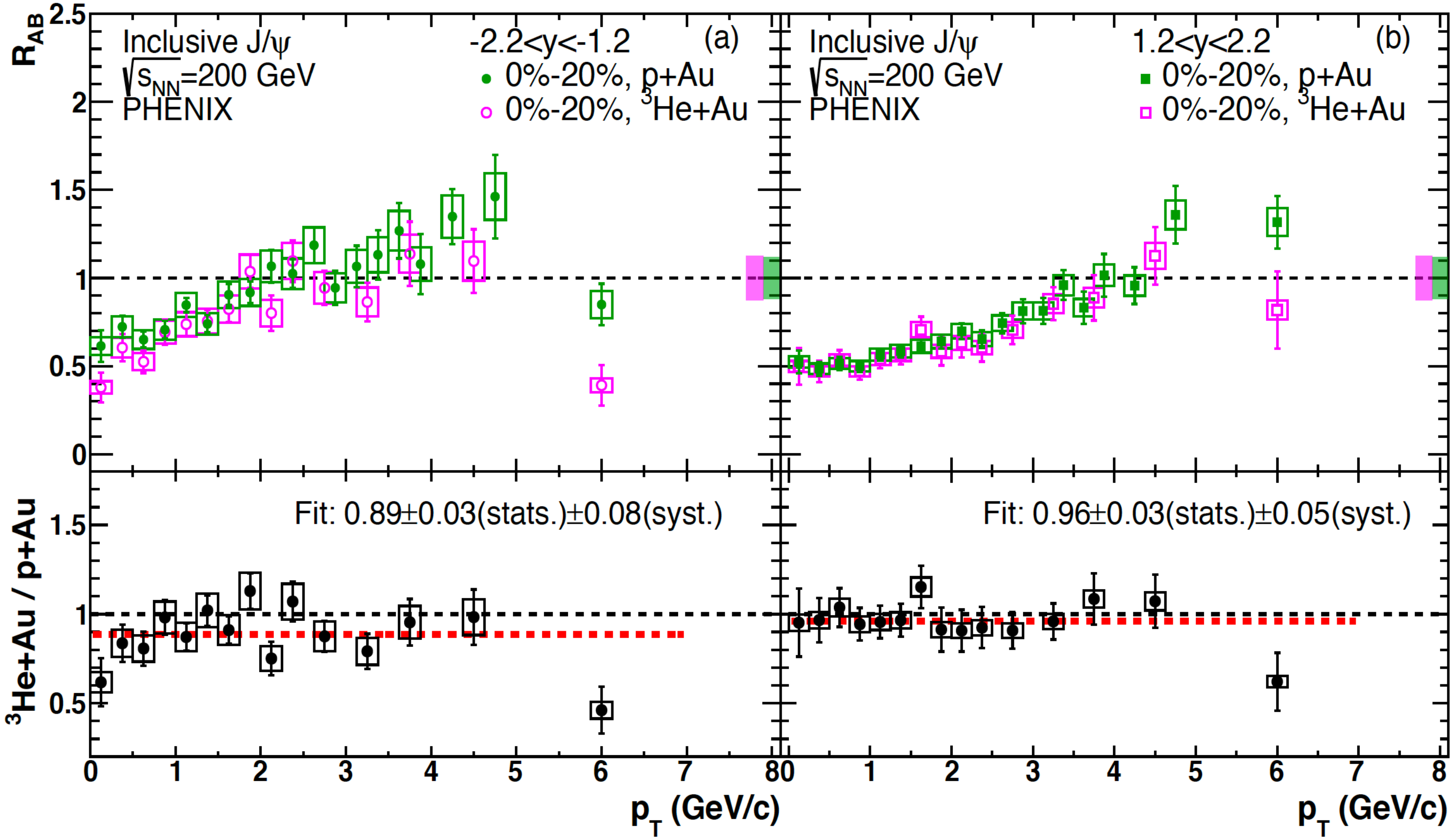
Little evidence for strong suppression of J/ψ in final state



RHIC J/ψ results at forward/backward rapidity

How well can cold nuclear matter effects explain what we see?

First

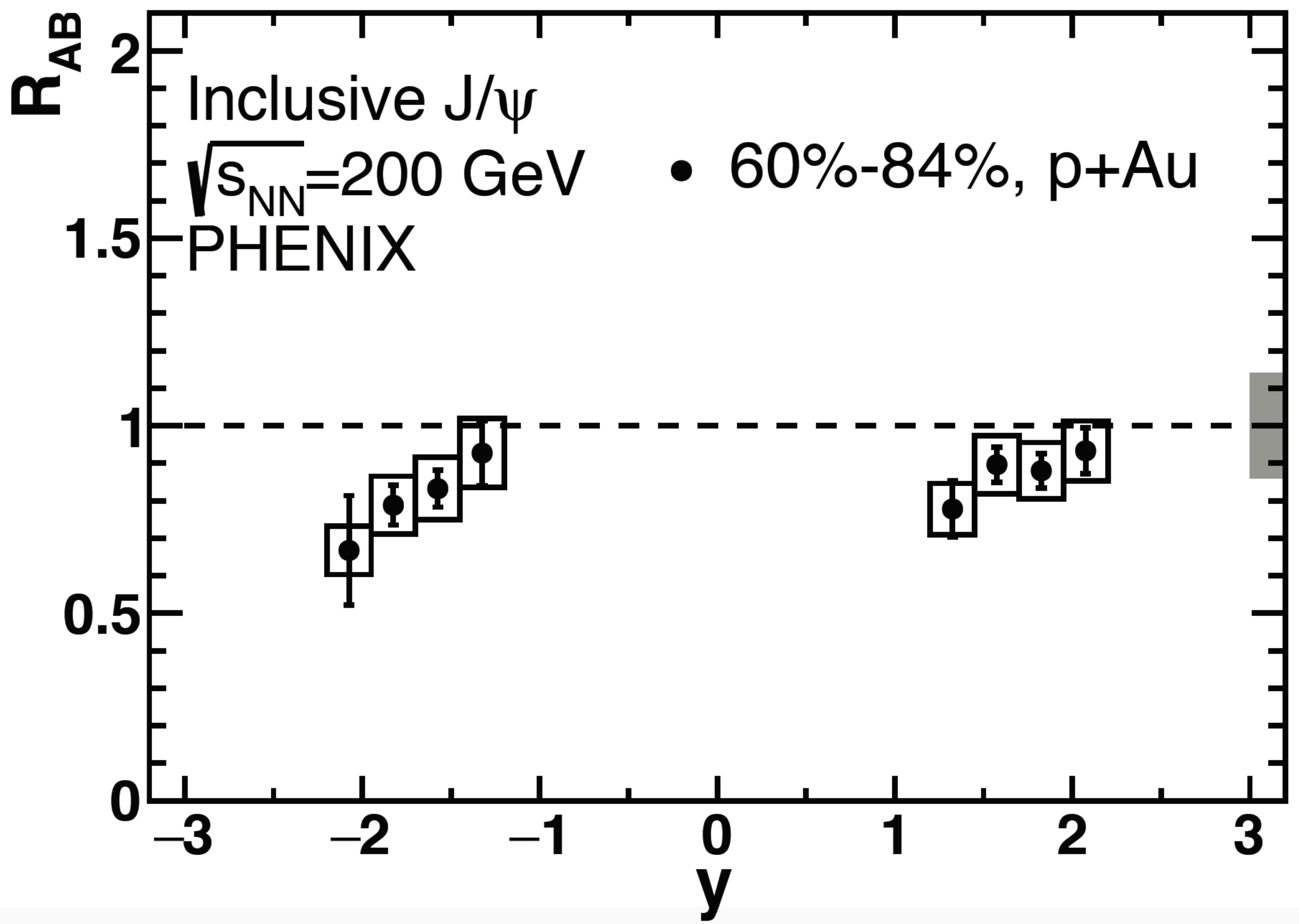
The importance of nuclear absorption at backward rapidity at RHIC.

The measured nuclear modification at backward rapidity is almost independent of the collision centrality.

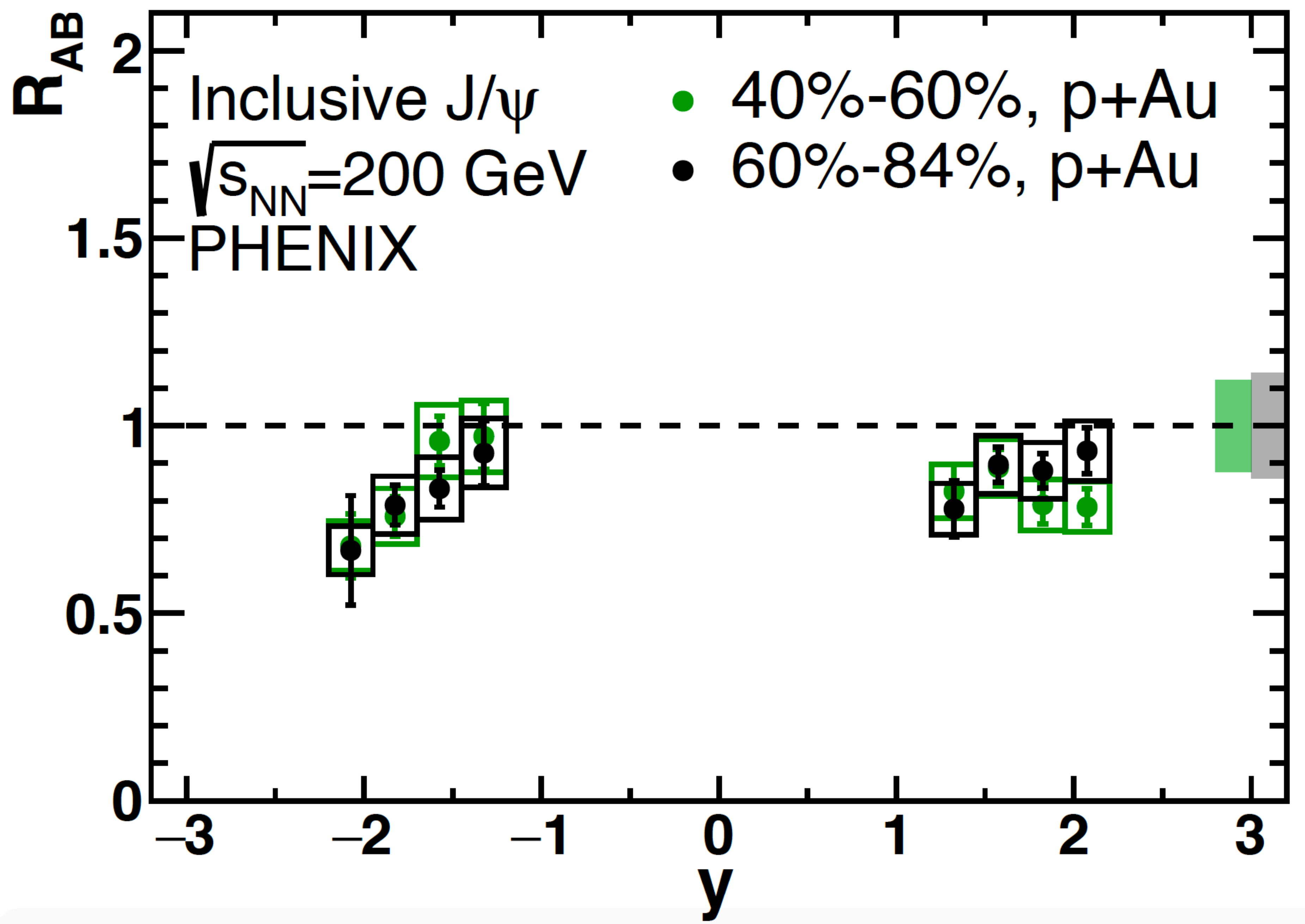
This appears to be an almost almost perfect cancellation of anti-shadowing and nuclear absorption effects.

— See the following slides ….

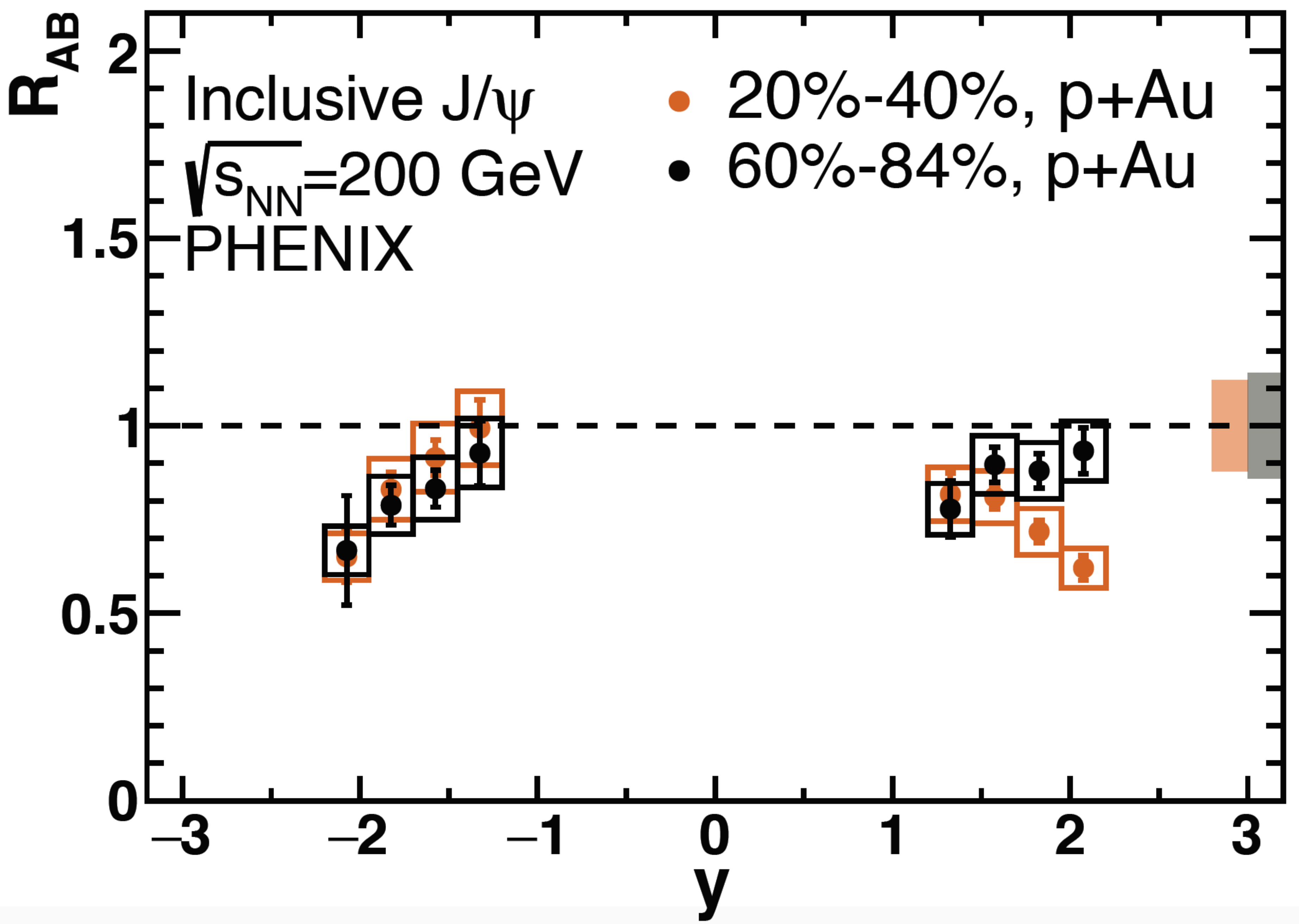
p+Au centrality dependence



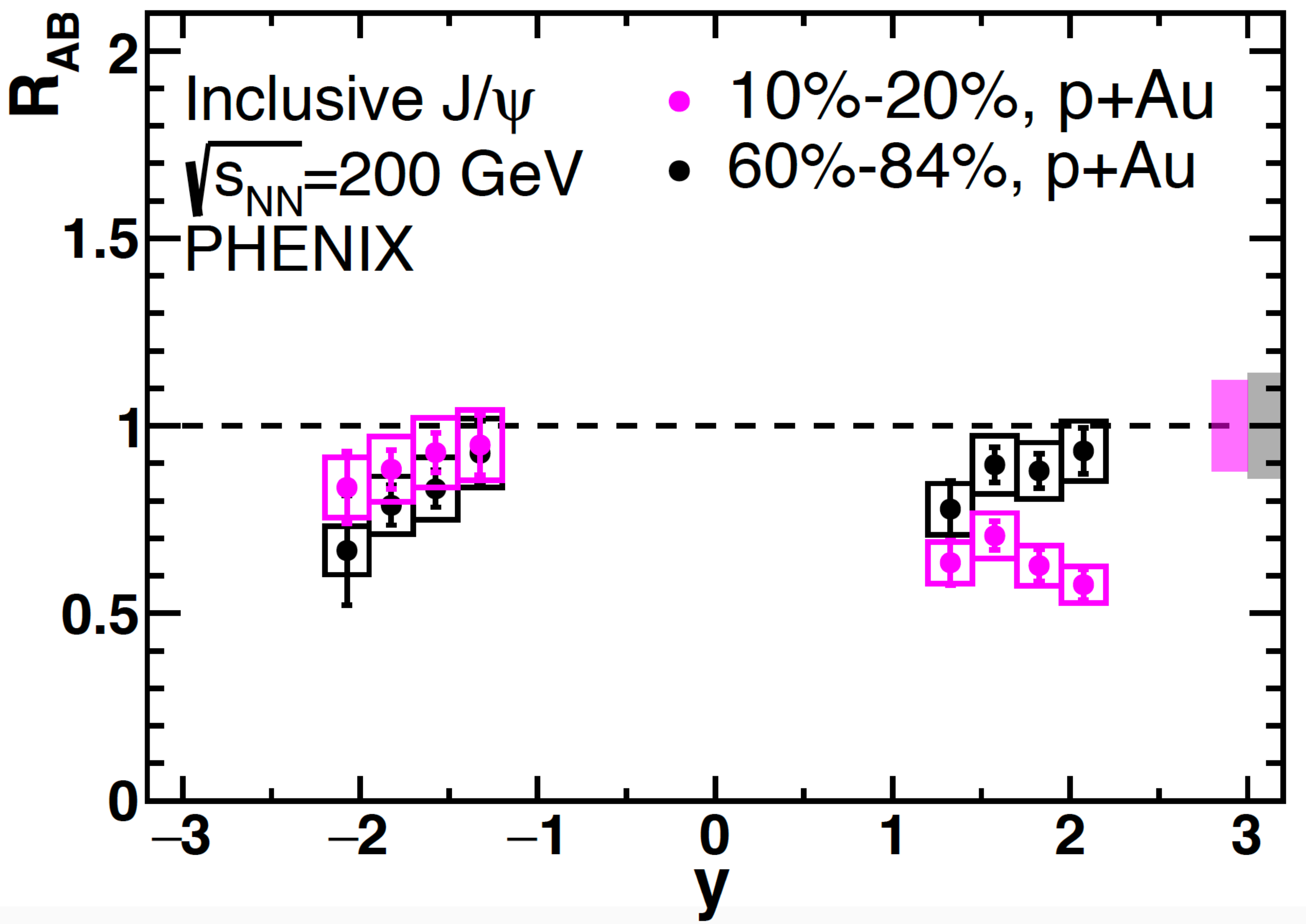
p+Au centrality dependence



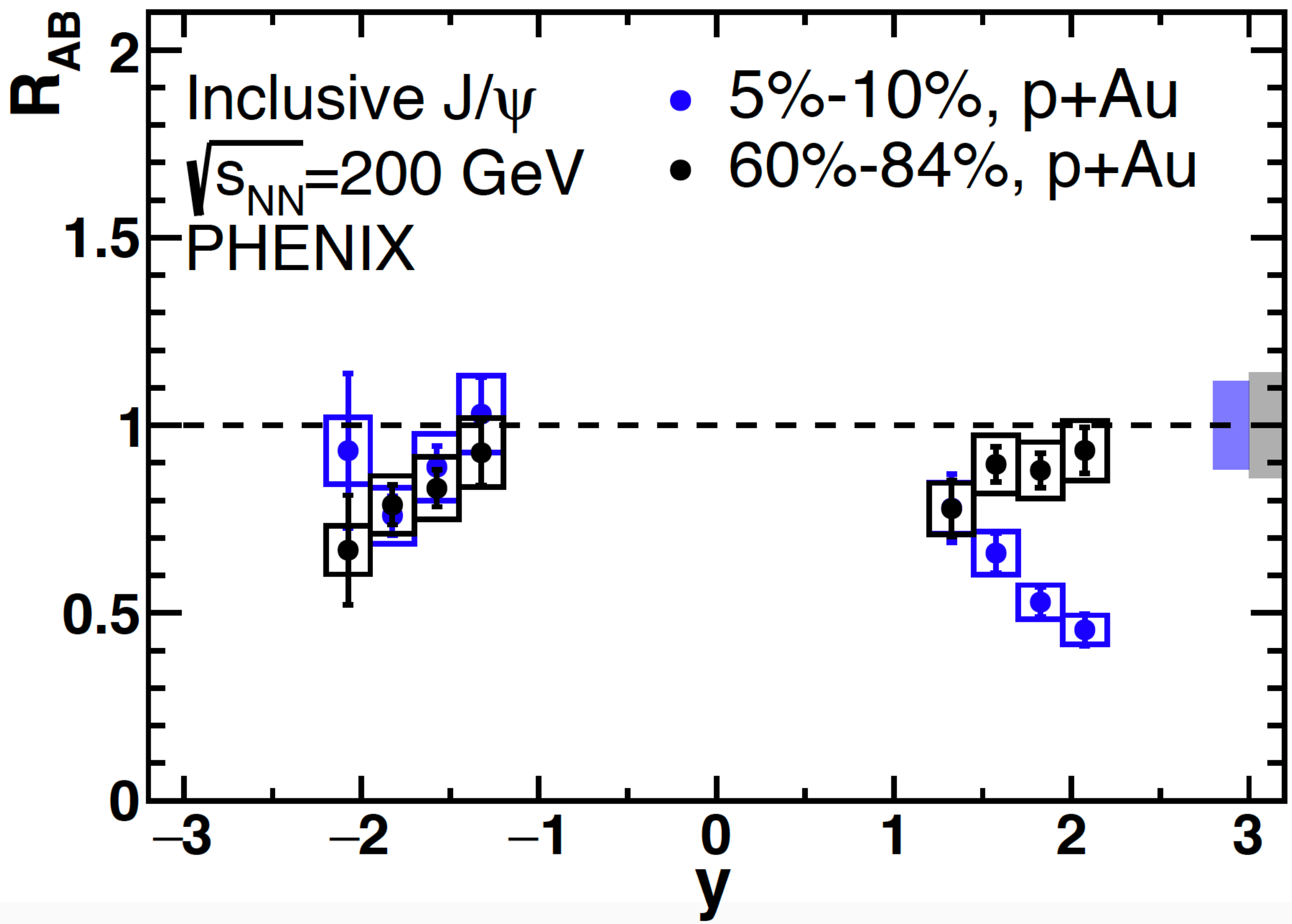
p+Au centrality dependence



p+Au centrality dependence



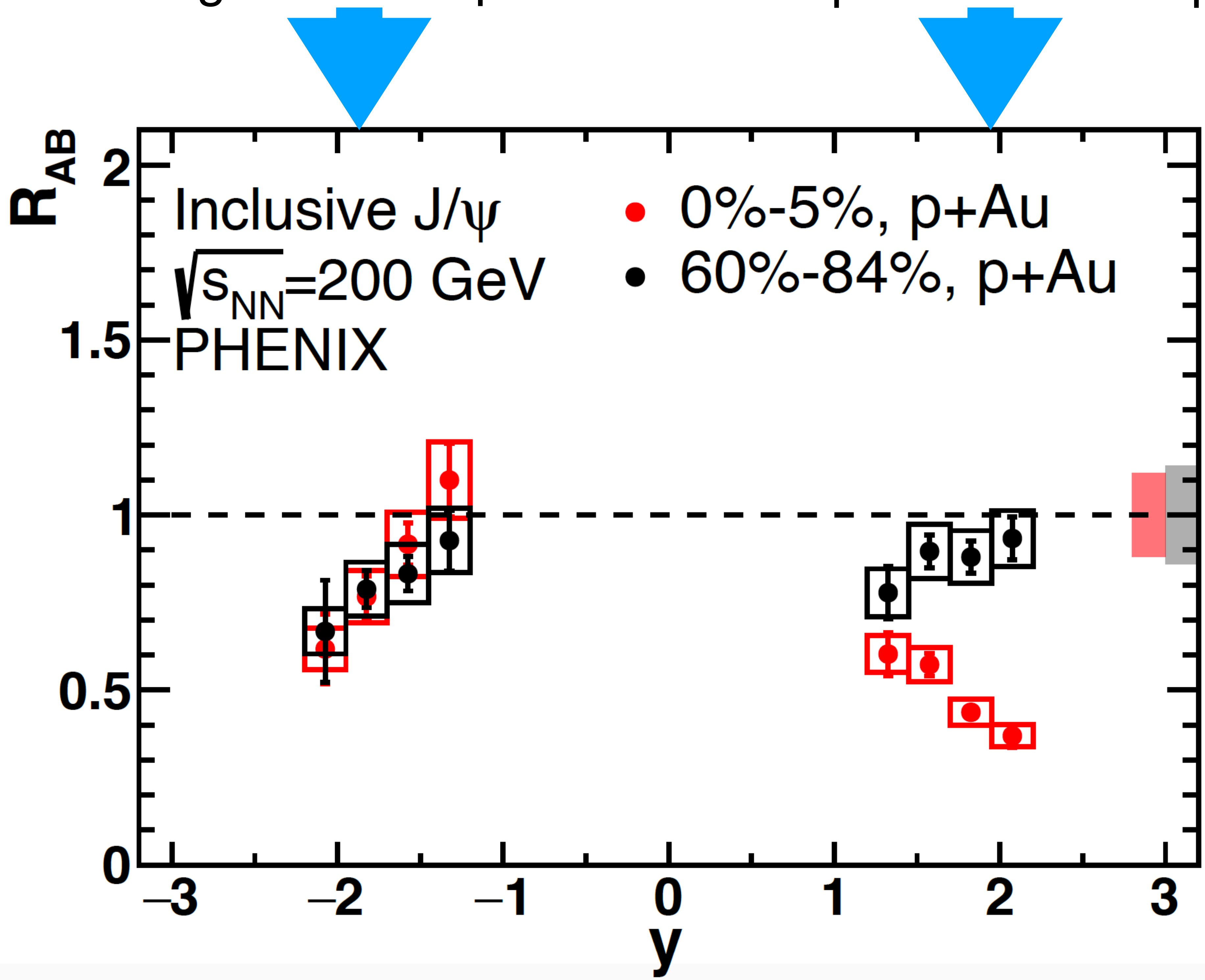
p+Au centrality dependence



p+Au centrality dependence

Trade-off between anti-shadowing and absorption.

Very strong centrality dependence of suppression.

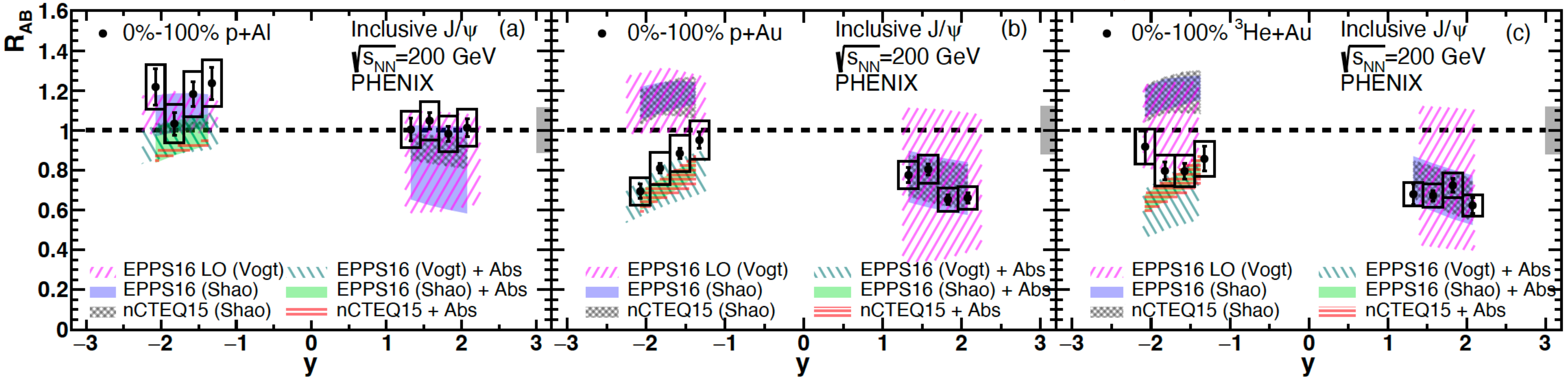


Rapidity dependence, p_T and centrality integrated

0-100% centrality, p_T integrated.

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

Phys.Rev.C 102 (2020) 1, 014902



Not so bad!

How about the p_T dependence?

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)

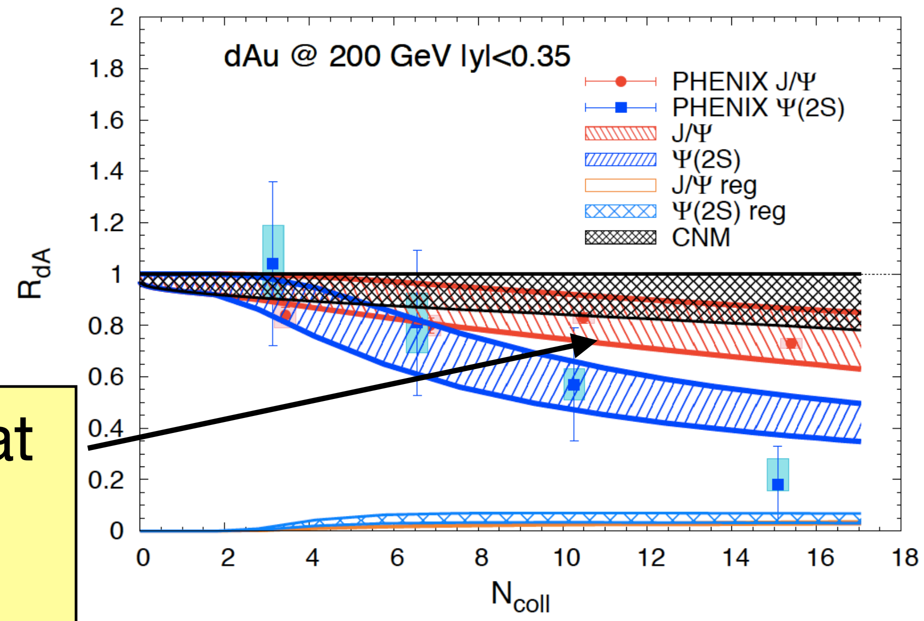
- RHIC: PHENIX J/ψ and ψ(2S) data were available only at midrapidity
- LHC: ALICE J/ ψ and ψ(2S) data at forward/backward rapidity, including the J/ψ v_2.

The transport model uses

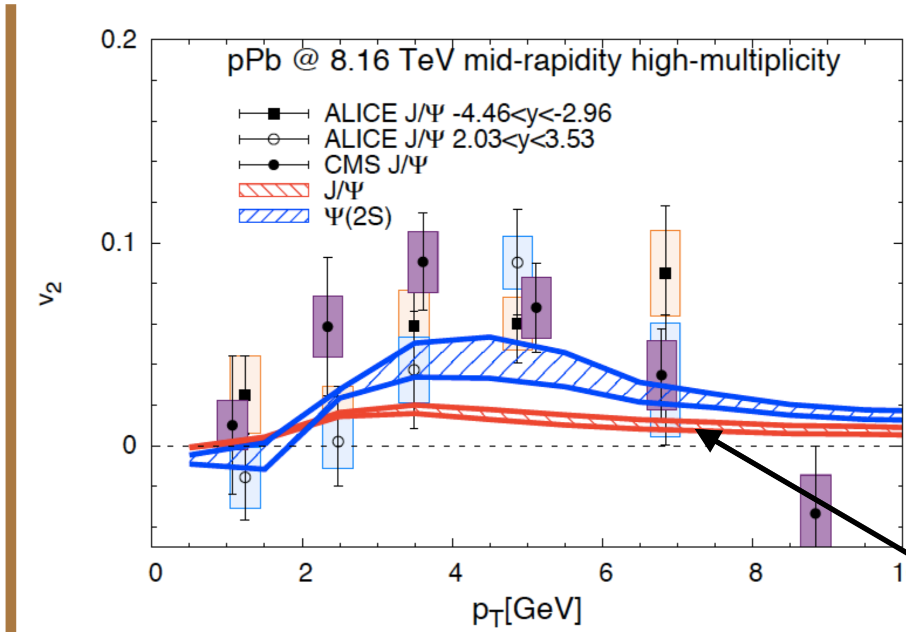
- A rate equation approach within a fireball model
- Initial geometry of the fireball from a Monte-Carlo event generator
- Initial anisotropies are caused by fluctuations
- Includes corrections for CNM effects
  - EPS09 shadowing with assumed linear centrality dependence
  - Assumes constant nuclear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

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

200 GeV

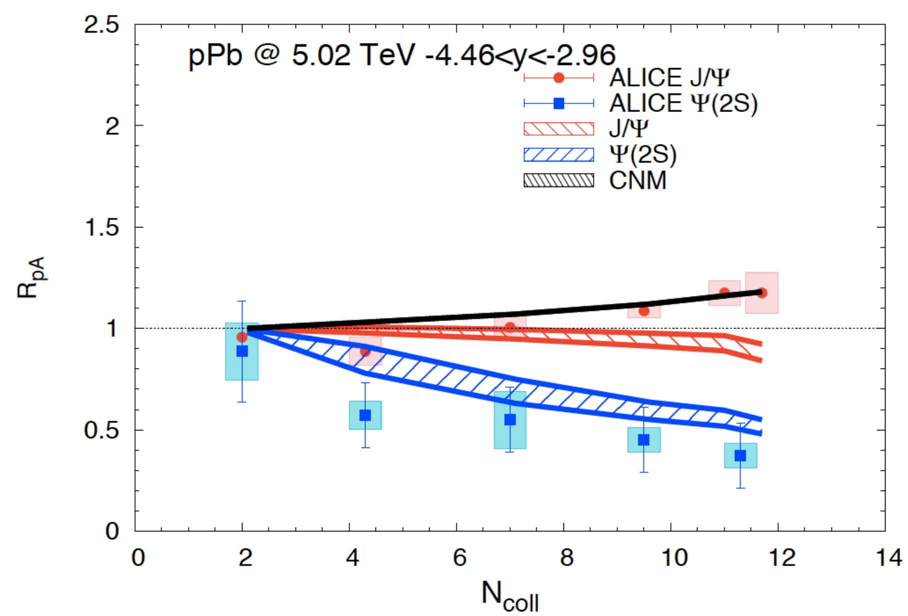


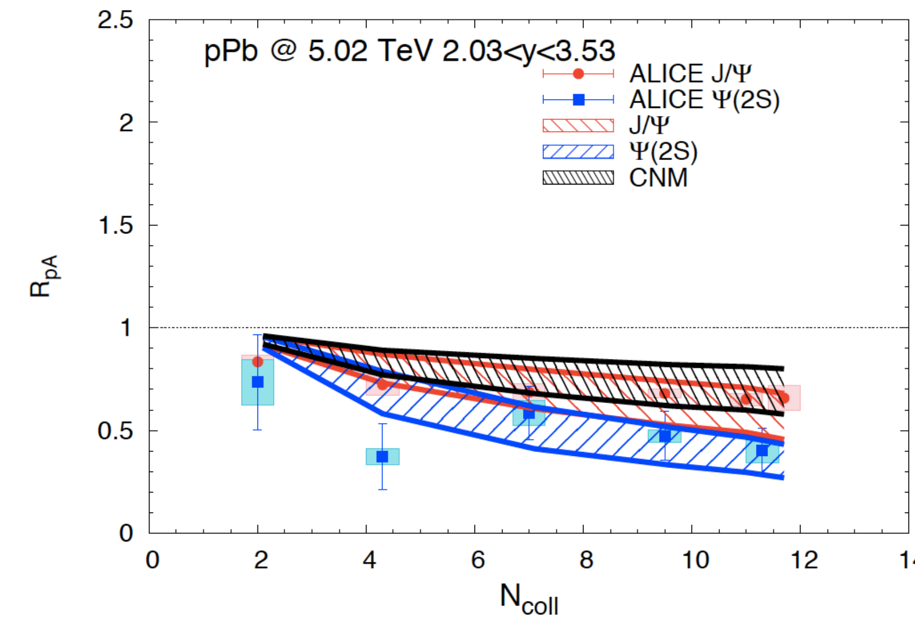
~20% effect at RHIC beyond CNM on J/ψ



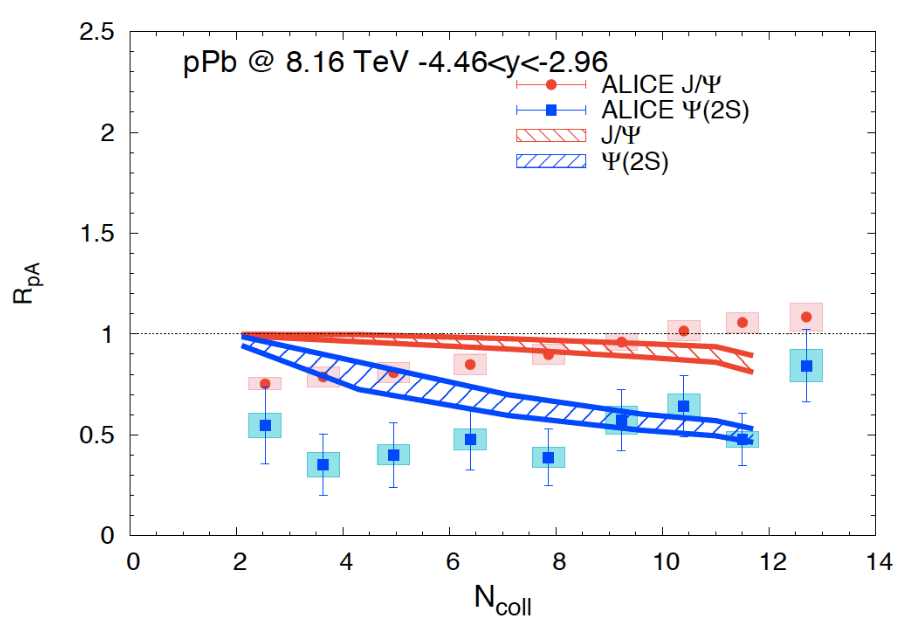
But: J/ψ v_2 not explained

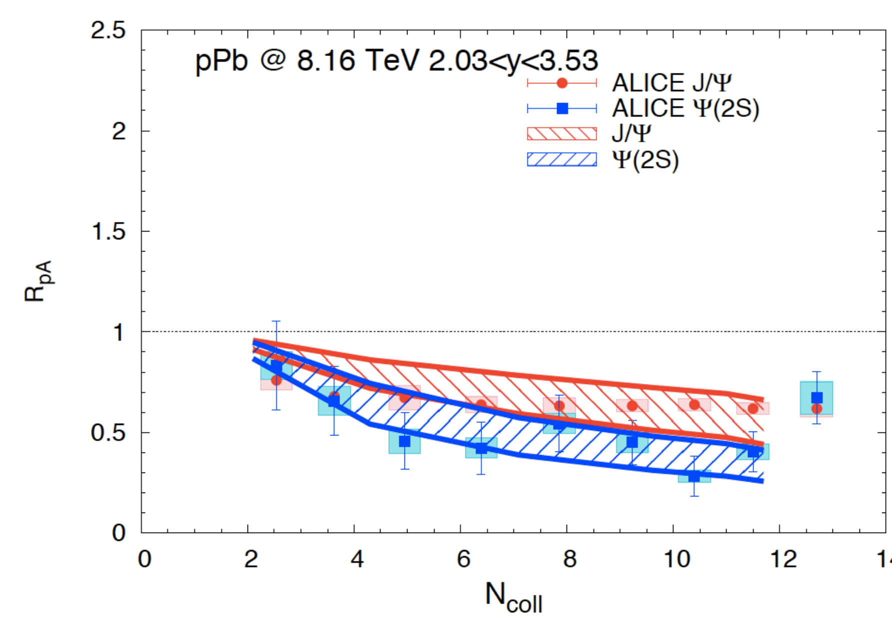
5.02 TeV





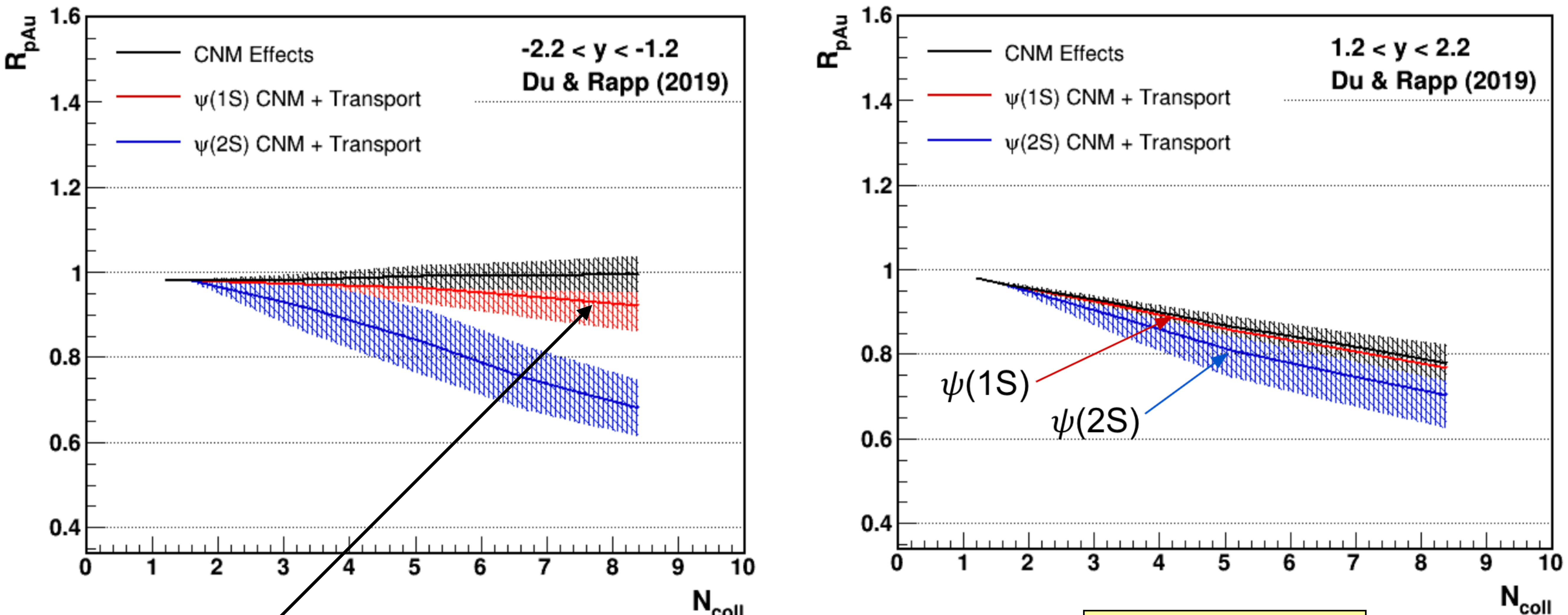
8.16 TeV





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.



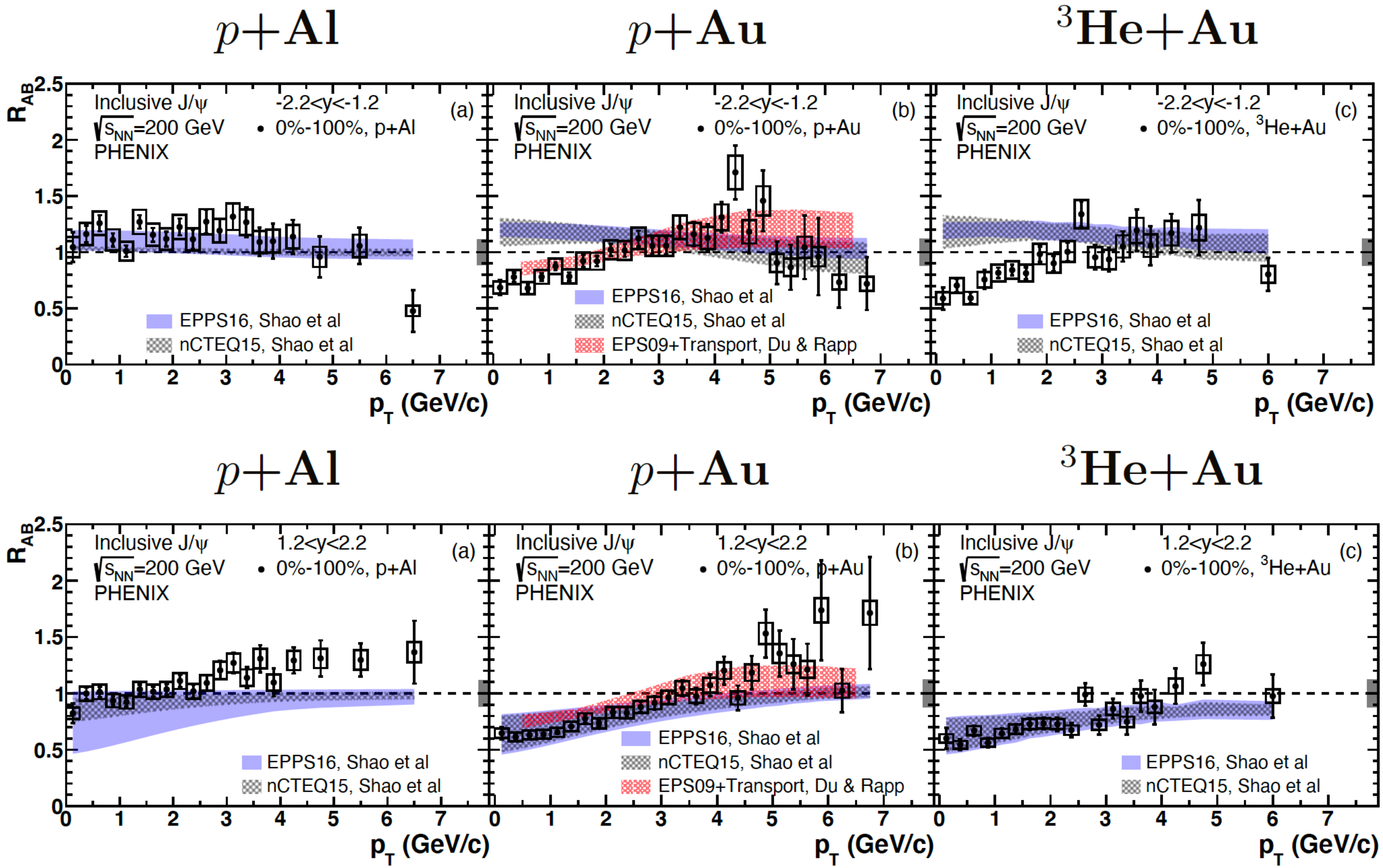
~10% effect in p+Au beyond CNM on J/ψ

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

p_T dependence, 0-100% centrality

Blue: Bayesian re-weighted shadowing only

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



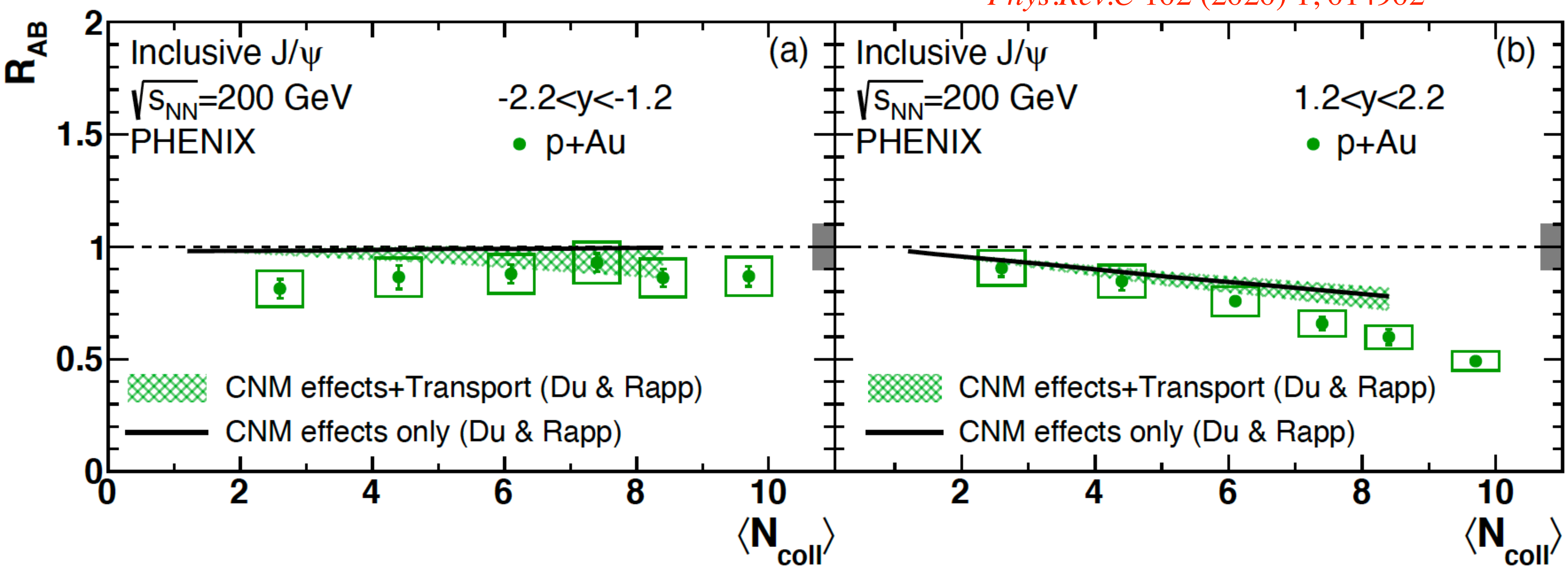
Phys.Rev.C 102 (2020) 1, 014902

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 with nuclear thickness.
  - EPS09 under-predicts suppression considerably!
    - But later parameterizations have stronger low x shadowing.

Phys.Rev.C 102 (2020) 1, 014902



LHC J/ψ results at forward/backward rapidity

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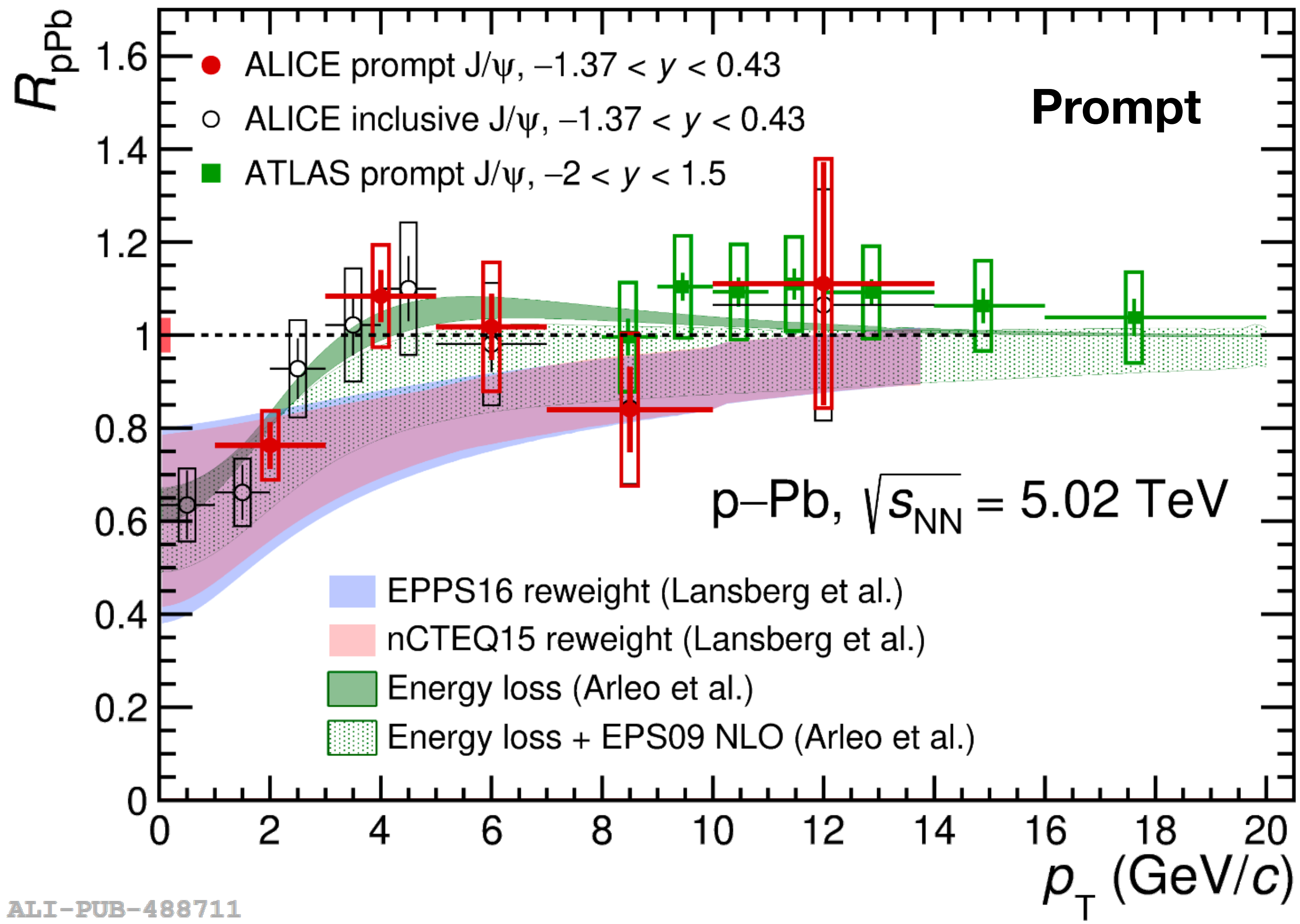
J/ψ R_{pPb} from ALICE midrapidity

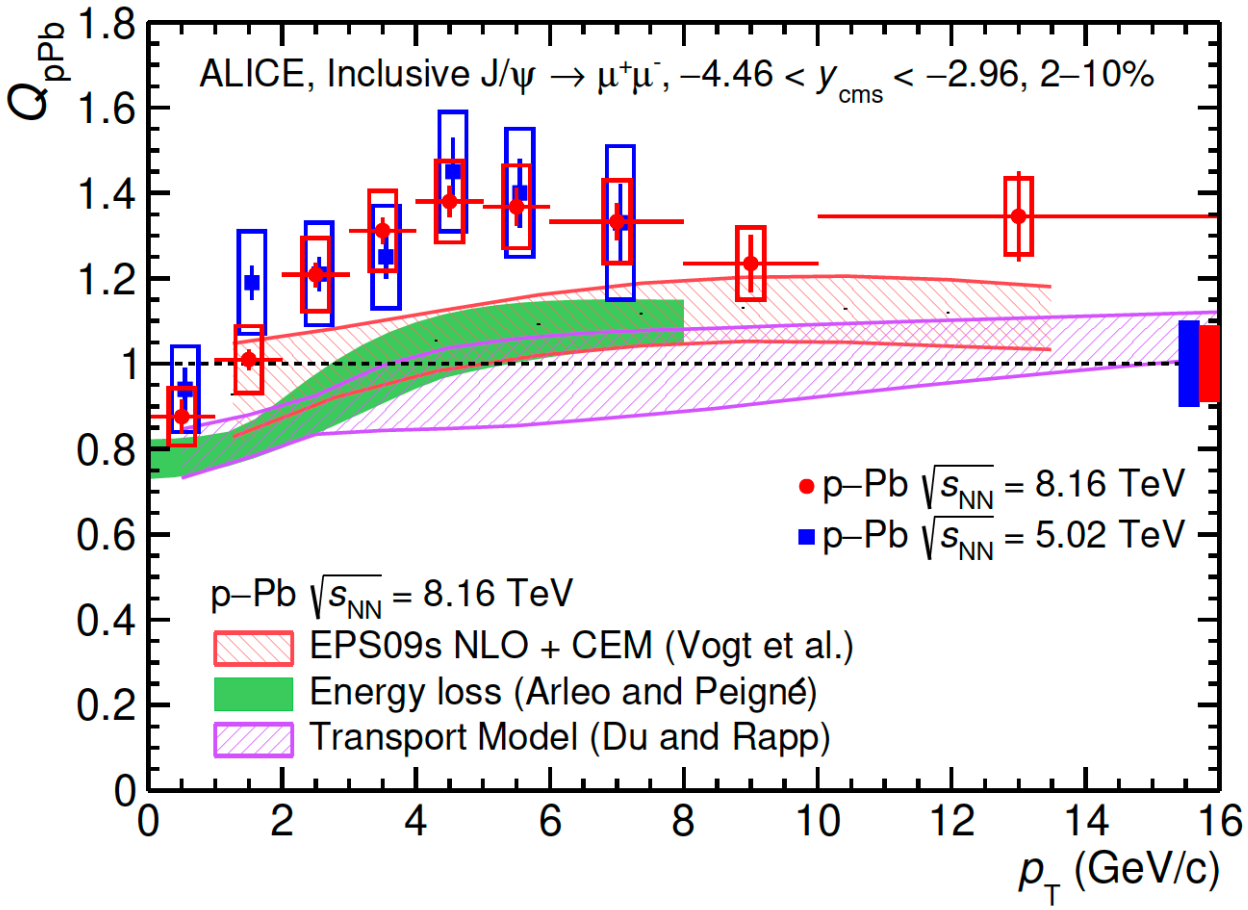
Interesting that the reweighted shadowing does not do well here.

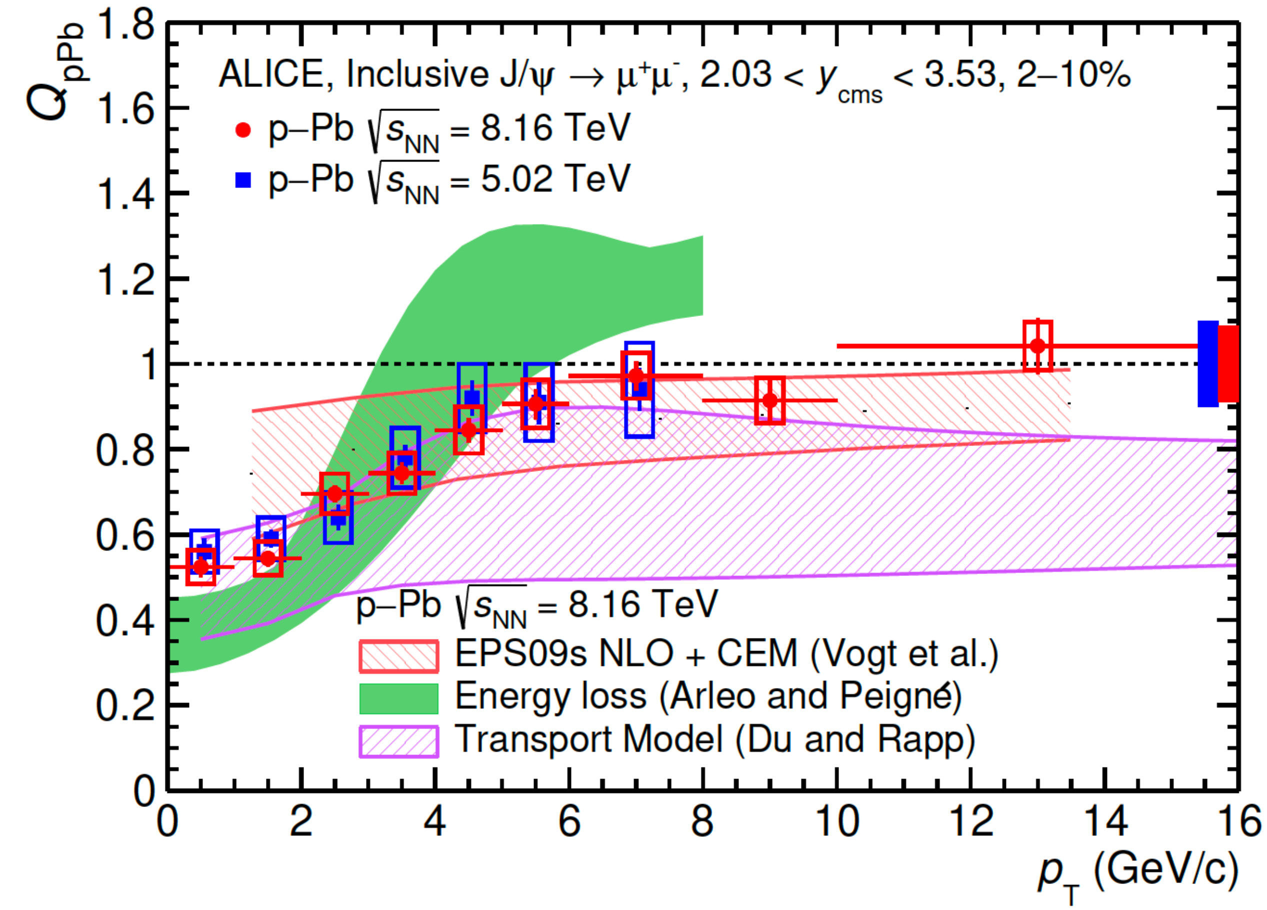


J/ψ R_{pPb} from ALICE forward/backward rapidity - central collisions

At backward rapidity the models all under-predict the modification. Forward rapidity not so bad.

ALICE, JHEP 02 (2021) 2

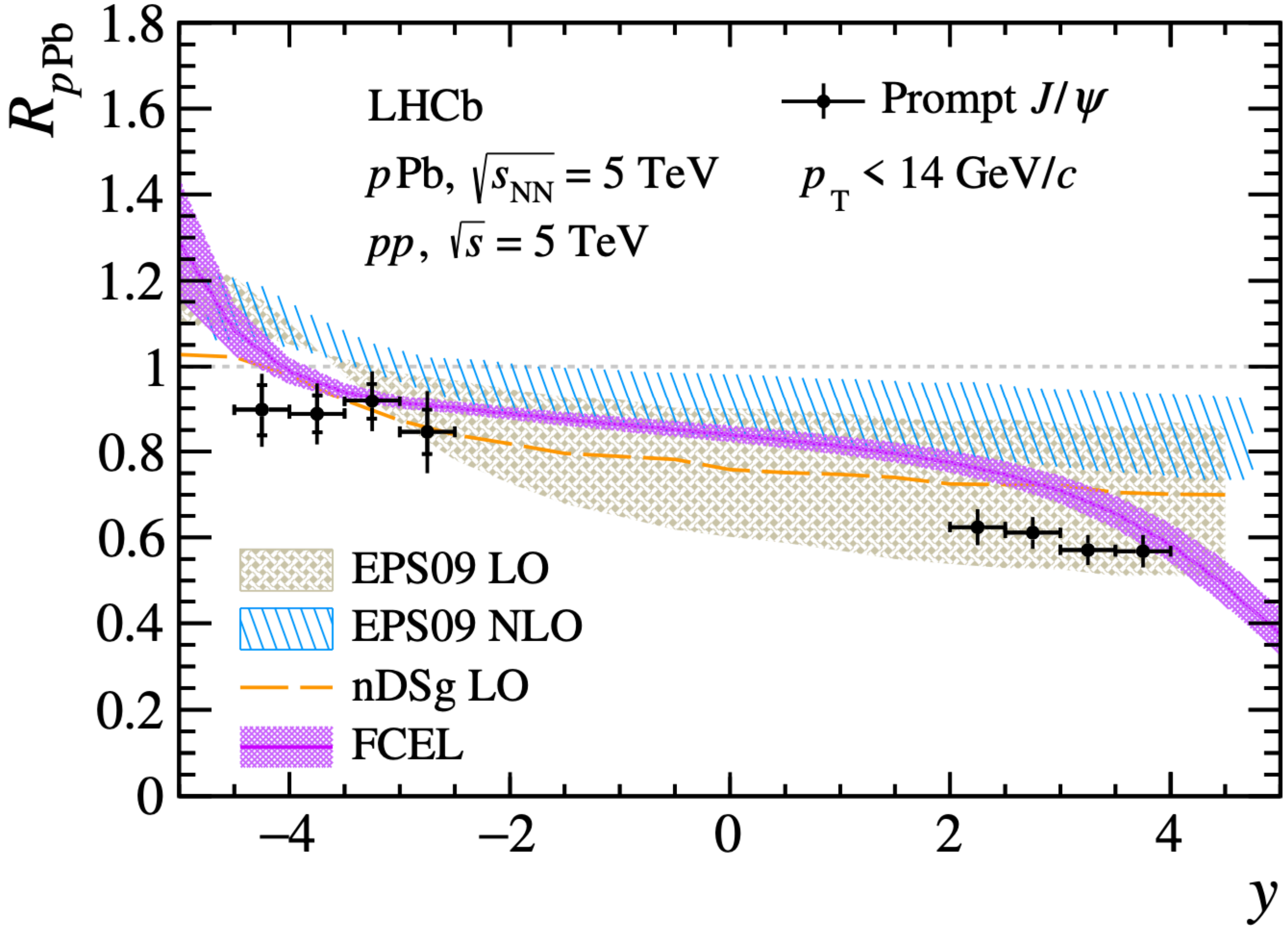




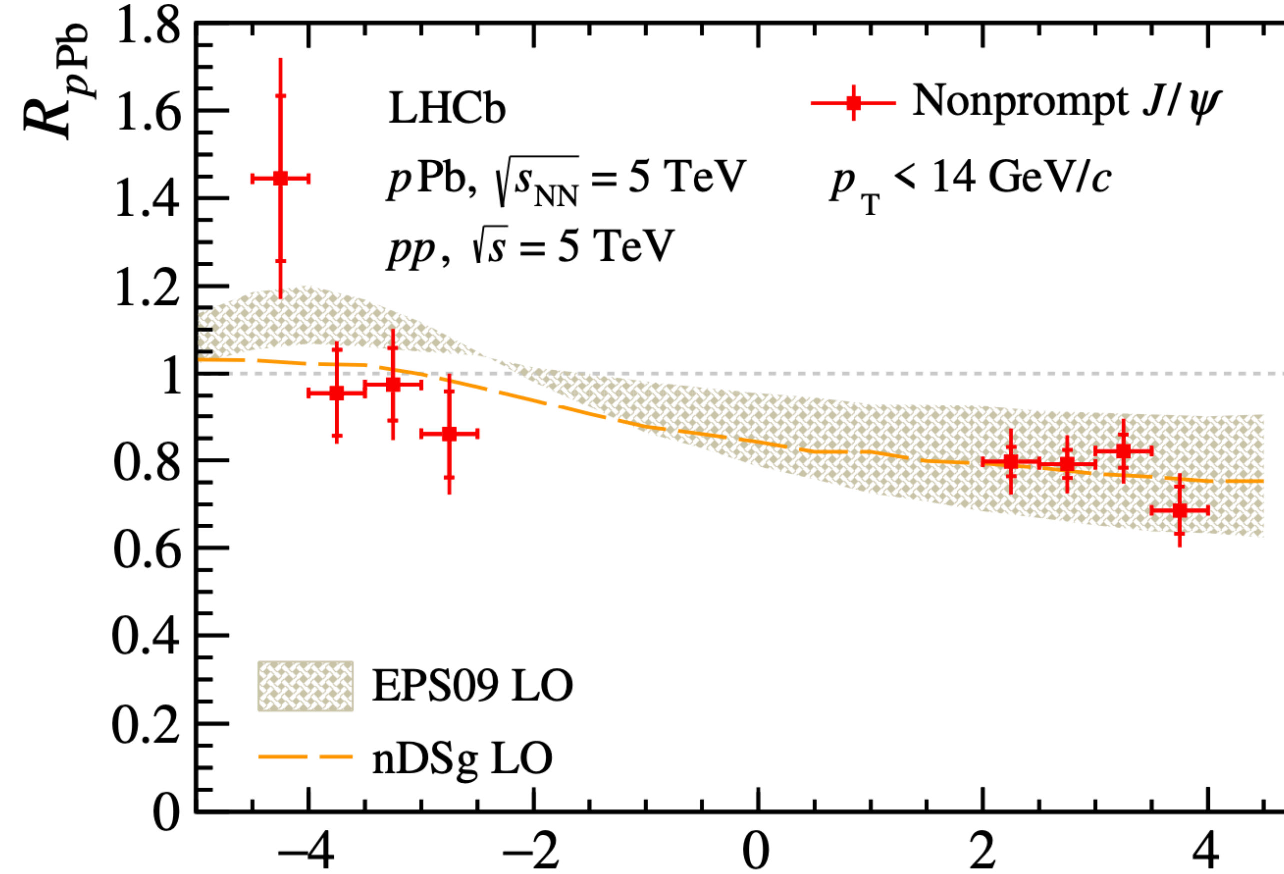
J/ψ R_{pPb} from LHCb
Centrality and p_T integrated

Data are consistent with shadowing at all rapidities.

Prompt



Nonprompt



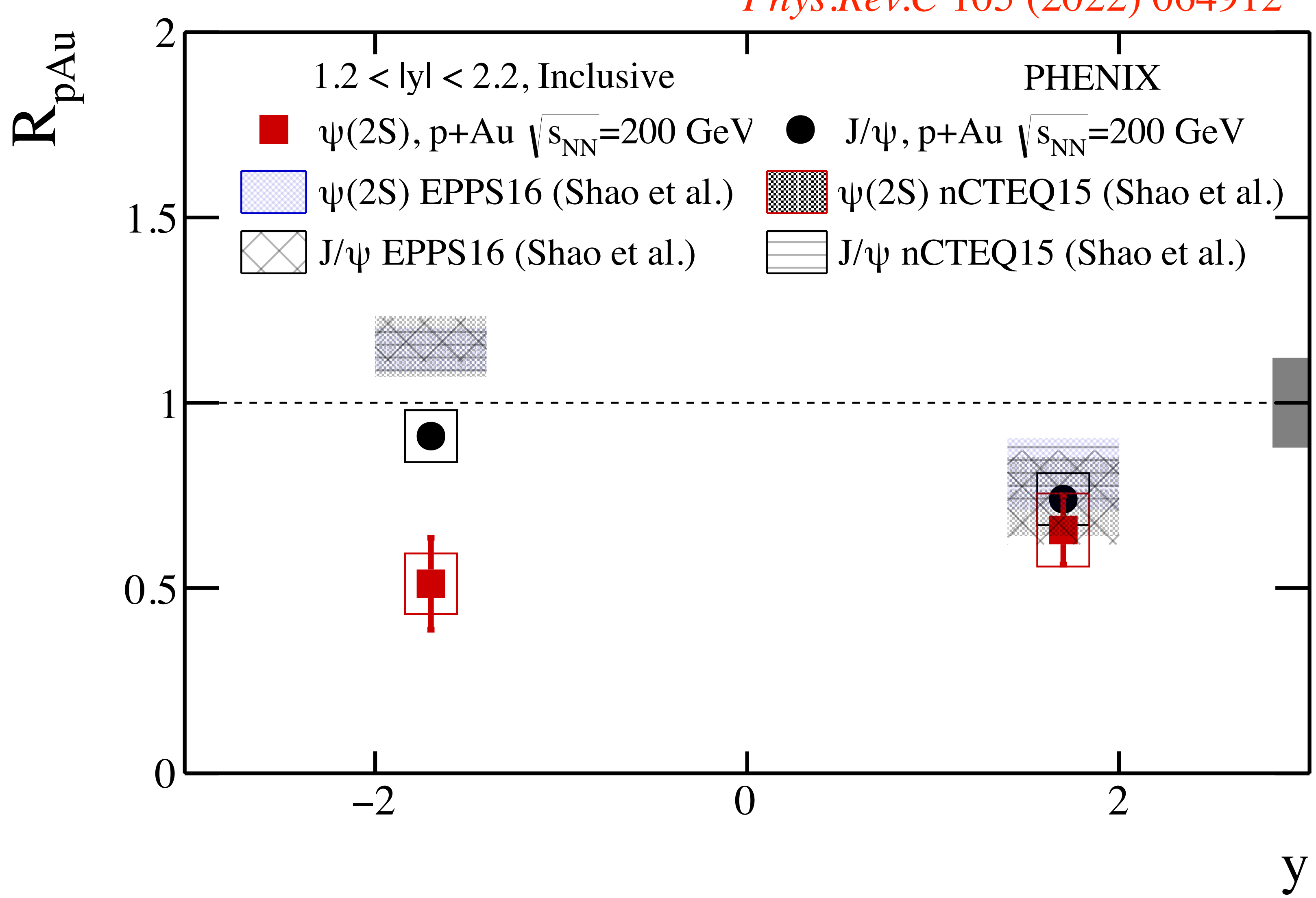
RHIC ψ(2S) results at forward/backward rapidity

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.

Phys.Rev.C 105 (2022) 064912

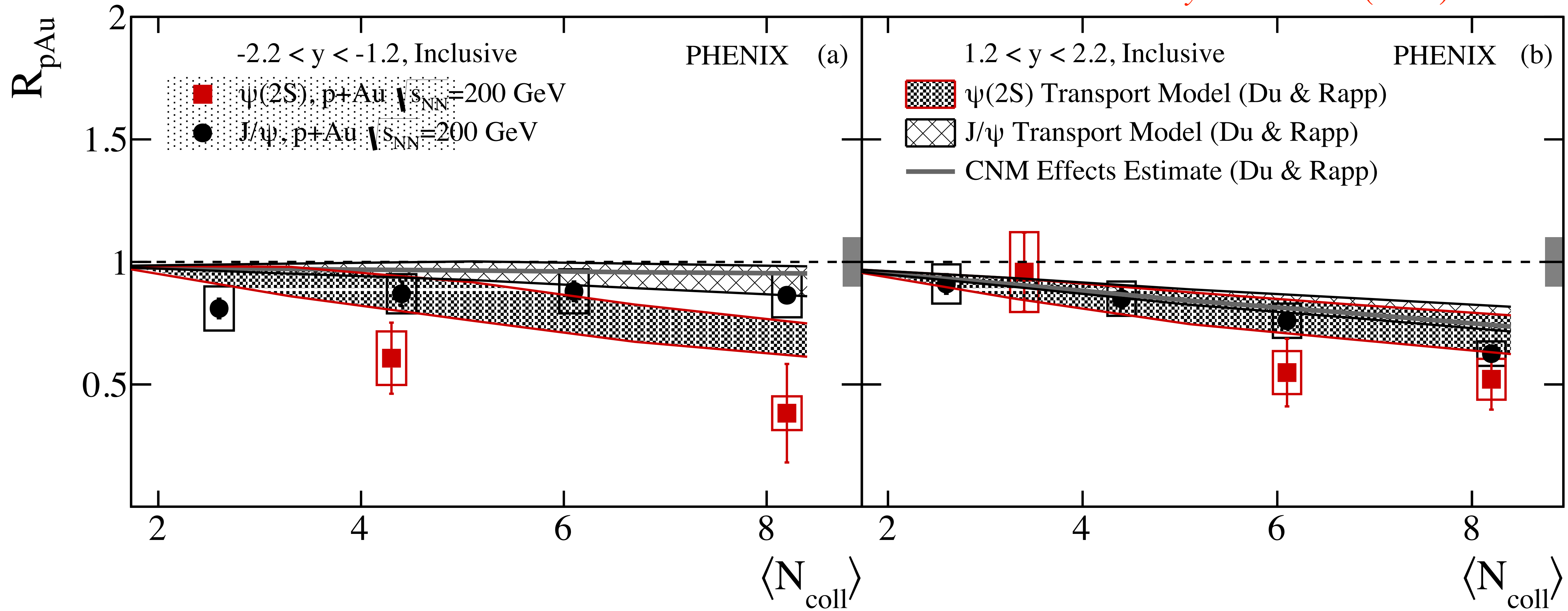


ψ(2S) R_{pAu} - centrality dependence

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.

Phys.Rev.C 105 (2022) 064912



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

Add re-weighted shadowing comparison to plot.

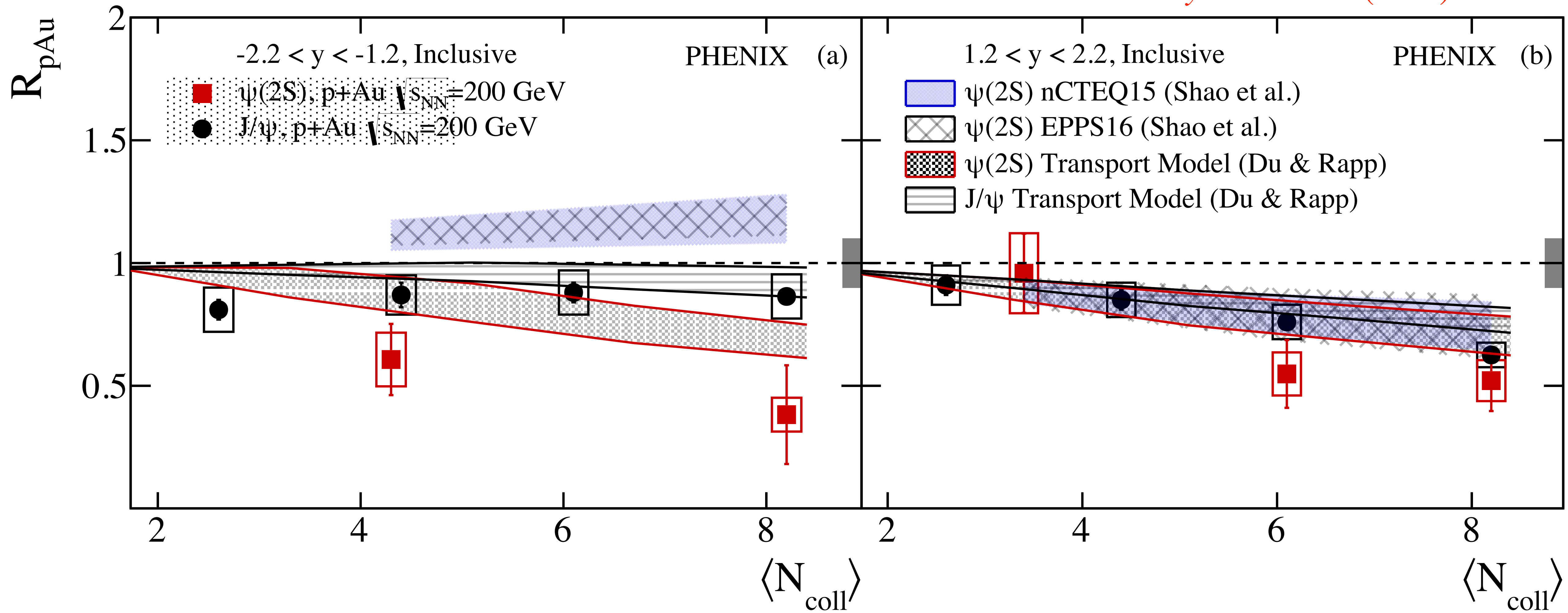
Forward rapidity:

Modification consistent with shadowing alone.

Backward rapidity:

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

Phys.Rev.C 105 (2022) 064912



LHC $\psi(2S)$ results at forward/backward rapidity

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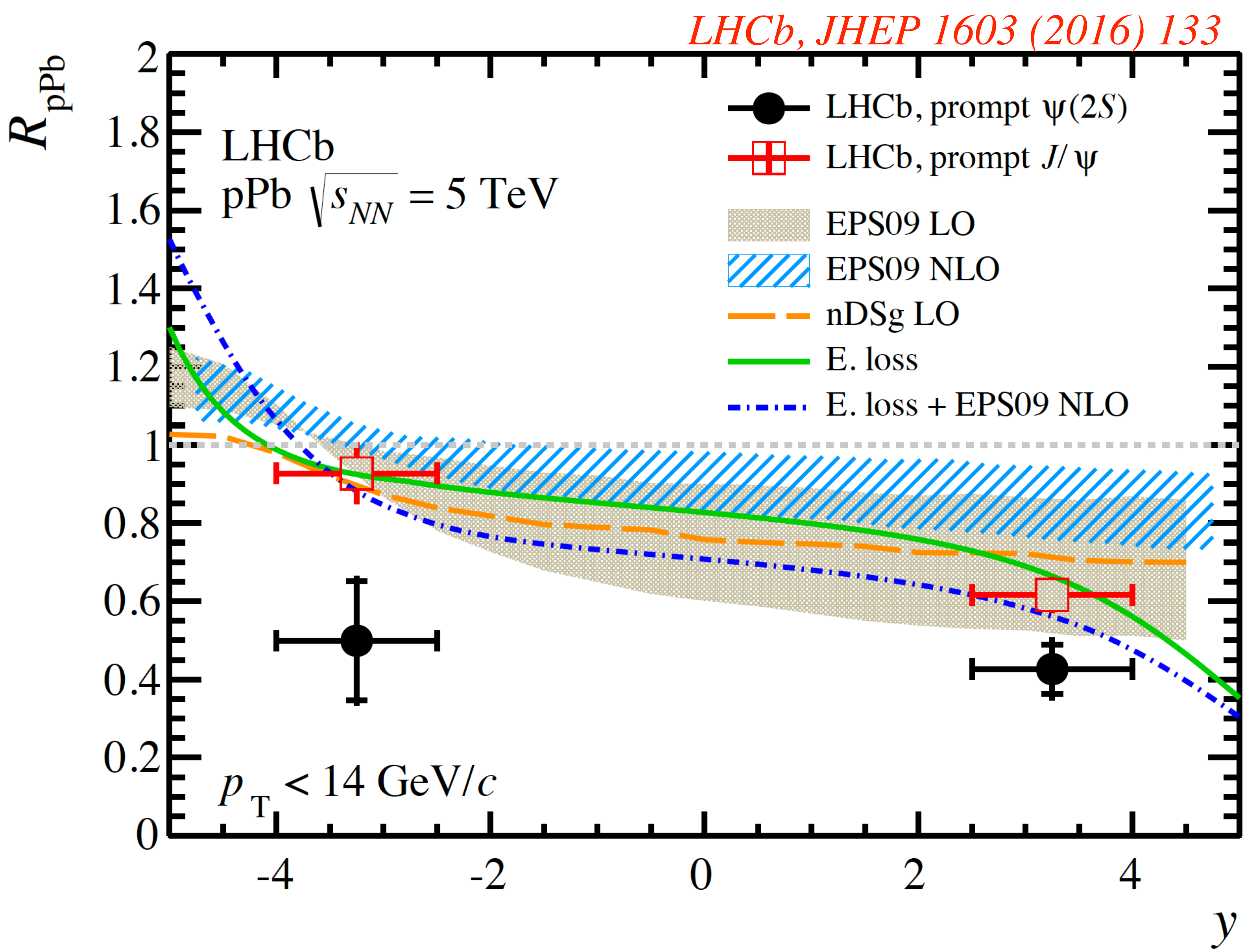
$\psi(2S)$ R_{pPb} from LHCb
Centrality and p_T integrated

J/ψ described well by CNM effects
ψ(2S) not described at all at backward rapidity.



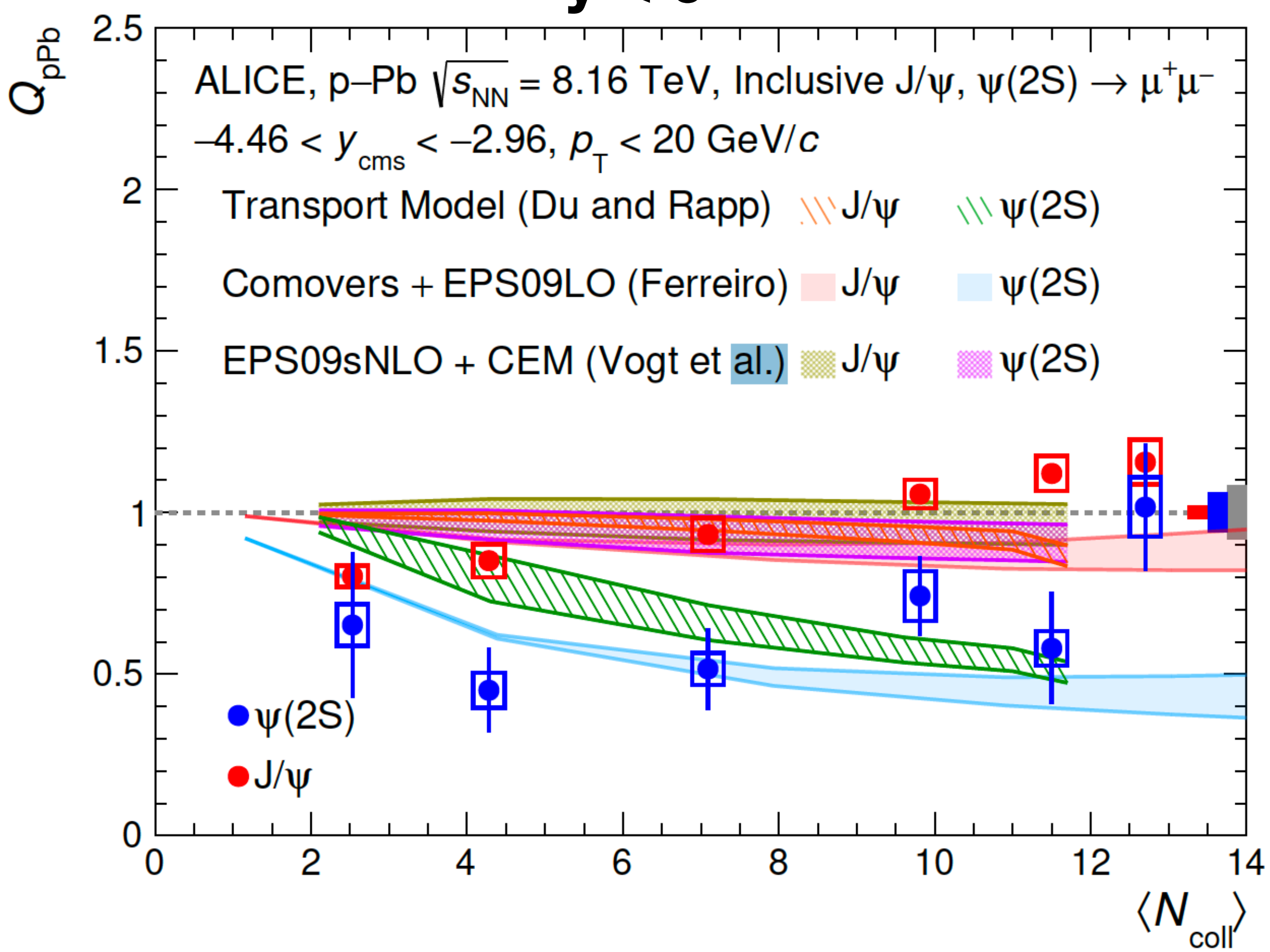
ψ(2S) R_{pPb} from ALICE
Centrality dependence

Not bad, except for the most central collisions at backward rapidity.

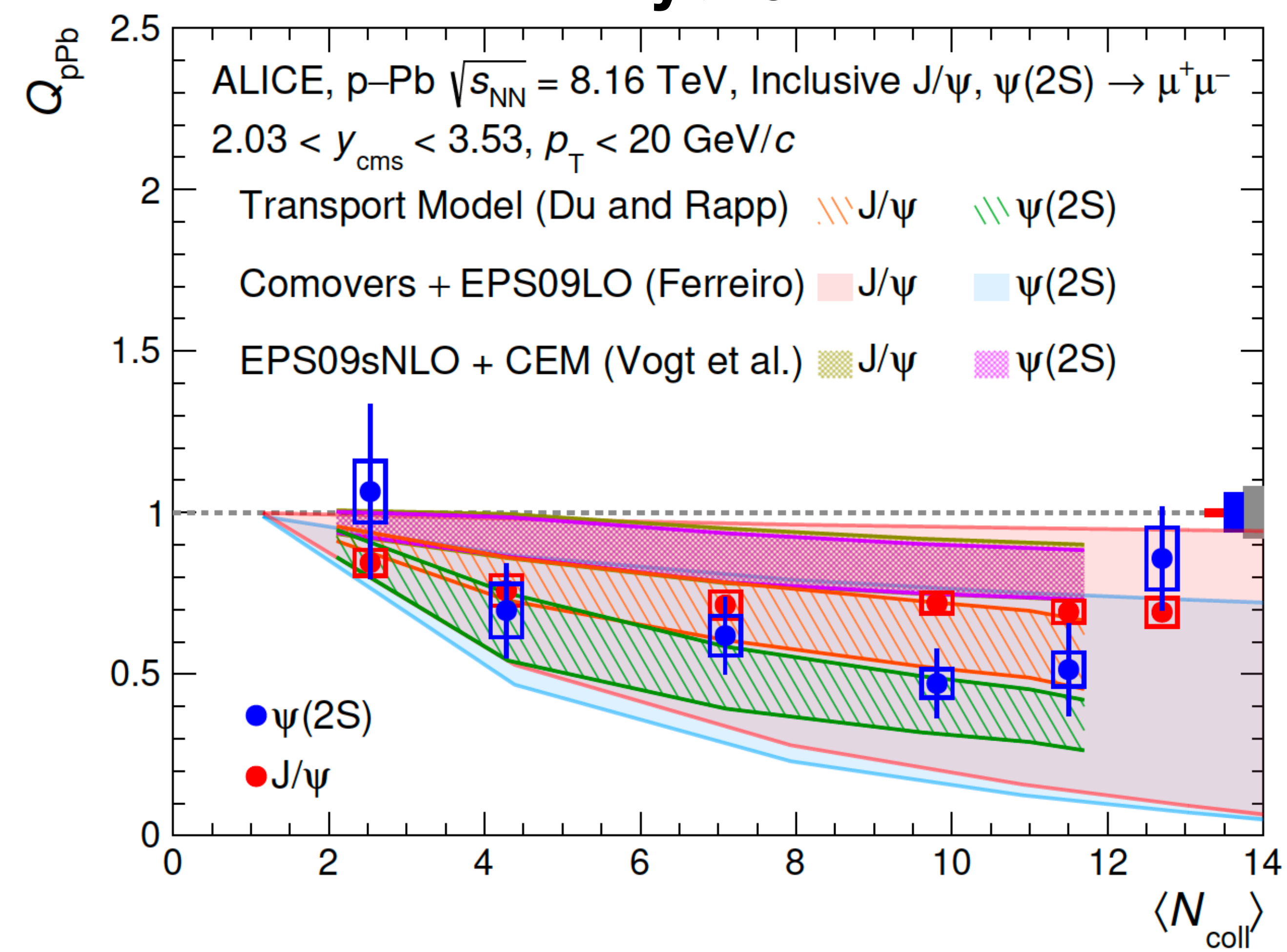
At forward rapidity the transport model differential suppression of the ψ(2S) is greater at the LHC than at RHIC

ALICE, JHEP 02 (2021) 2

y < 0



y > 0



RHIC and LHC ψ(2S) results compared

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.

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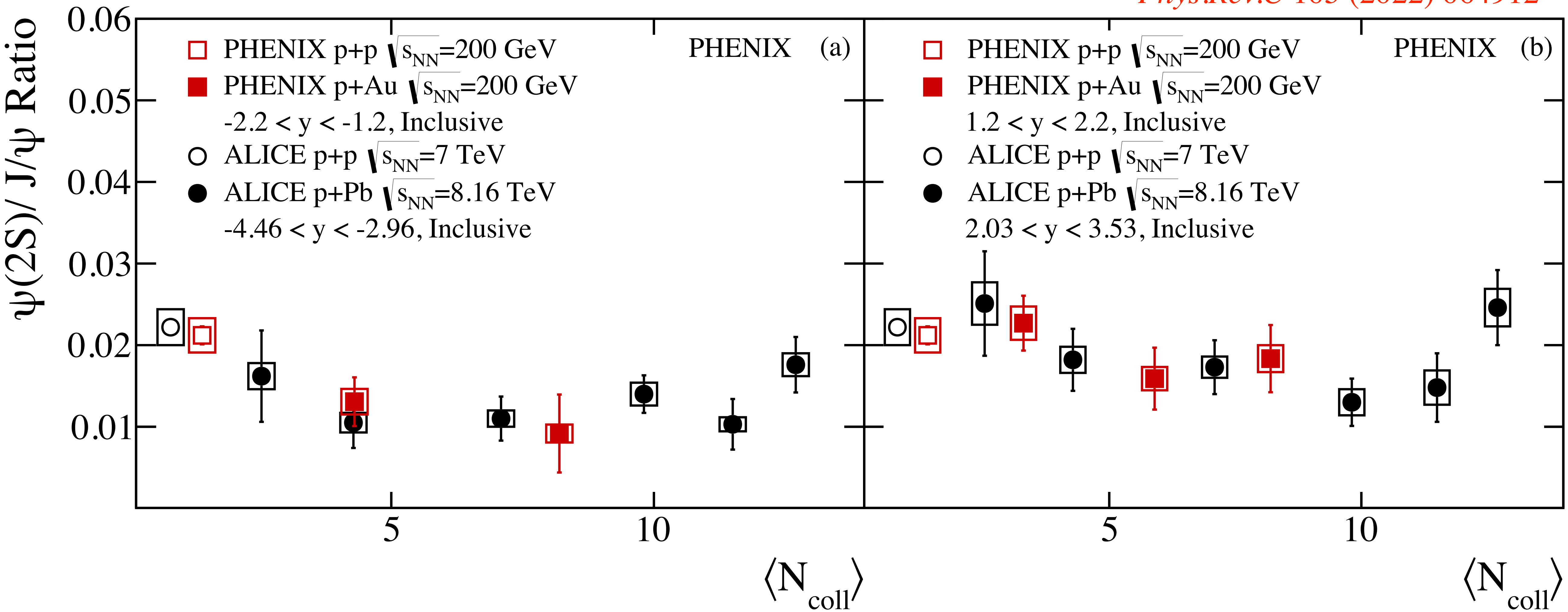

ψ(2S) R_{pAu} vs N_{coll} - PHENIX/ALICE

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 assumptions.

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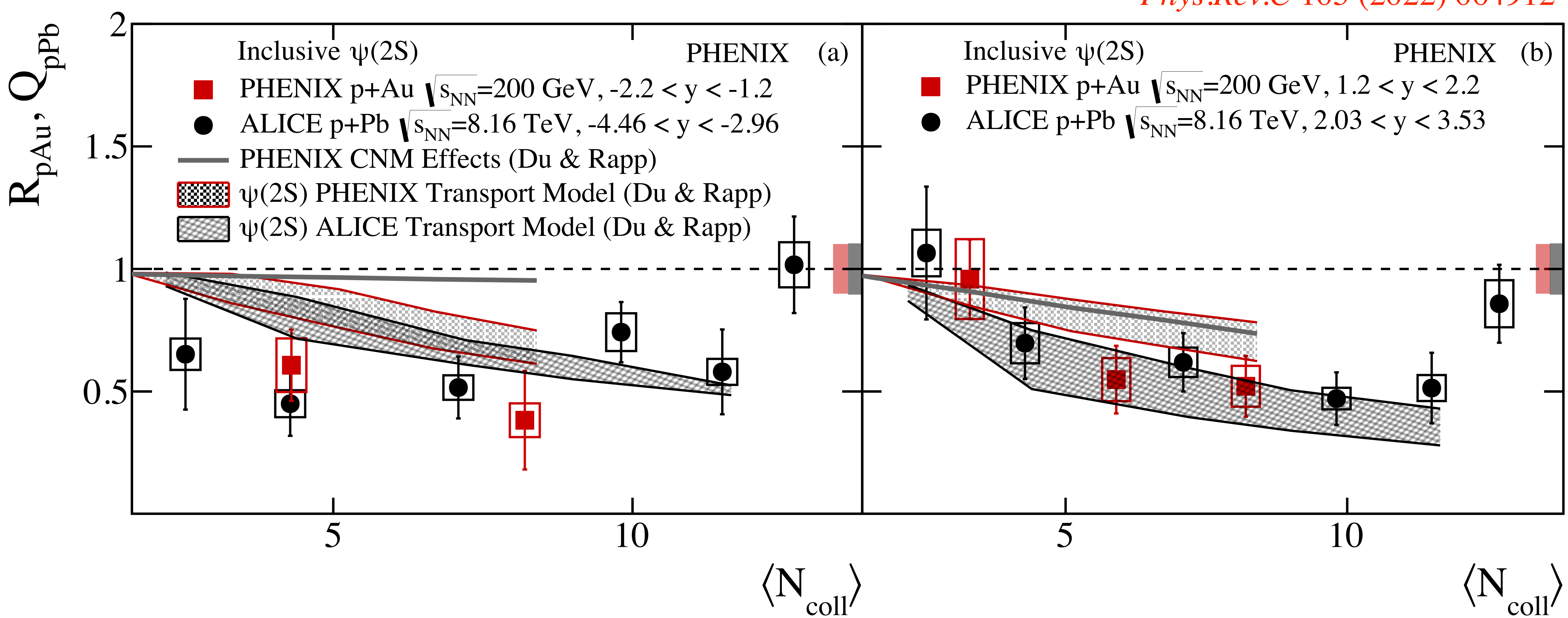

ψ(2S) R_{pAu} vs rapidity - trend in world data

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

Clear trend of increasing differential suppression from forward to backward rapidity - i.e. relative rapidity of charmonioum and target.

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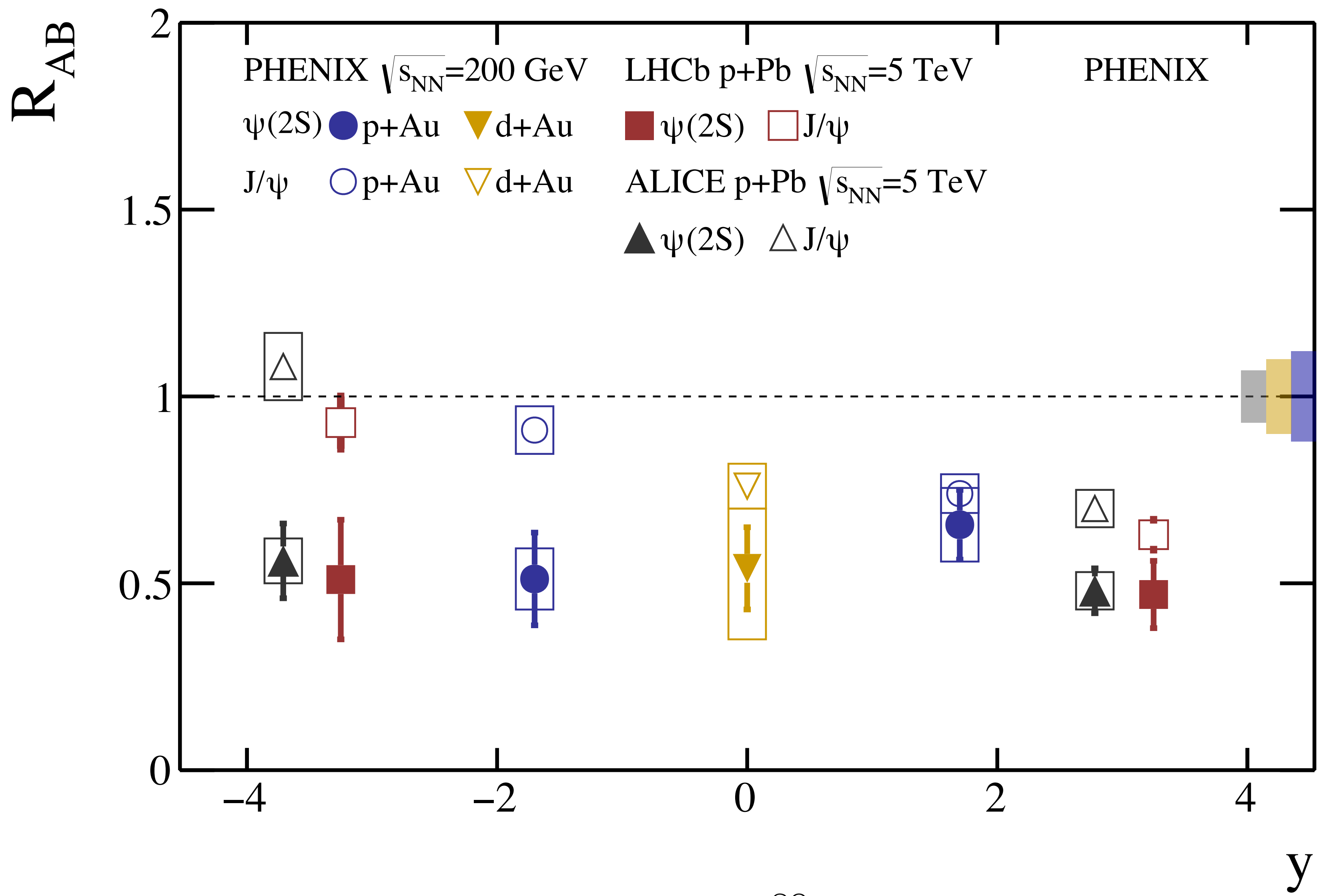


Conclusions

J/ψ modification in p+A:

At forward rapidity:

- Described reasonably well by shadowing alone at RHIC and LHC.

At backward rapidity:

- RHIC: 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.
- LHC: Not bad description by CNM effects, except that most central collision data are under-predicted.

ψ(2S) modification in p+Au:

At forward rapidity:

- Differential suppression relative to J/ψ is small at RHIC.
- Needs stronger additional suppression at LHC.

At backward rapidity:

- Requires a lot of additional suppression from final state effects.
  - Transport model accounts reasonably well for the differential ψ(2S) suppression at both RHIC and LHC.

Following up on the discussion yesterday on J/ψ multiplicity dependence

J/ψ event multiplicity dependence in p+p

Study event multiplicity dependence of J/ψ production in p+p collisions using PHENIX forward / backward muon arms

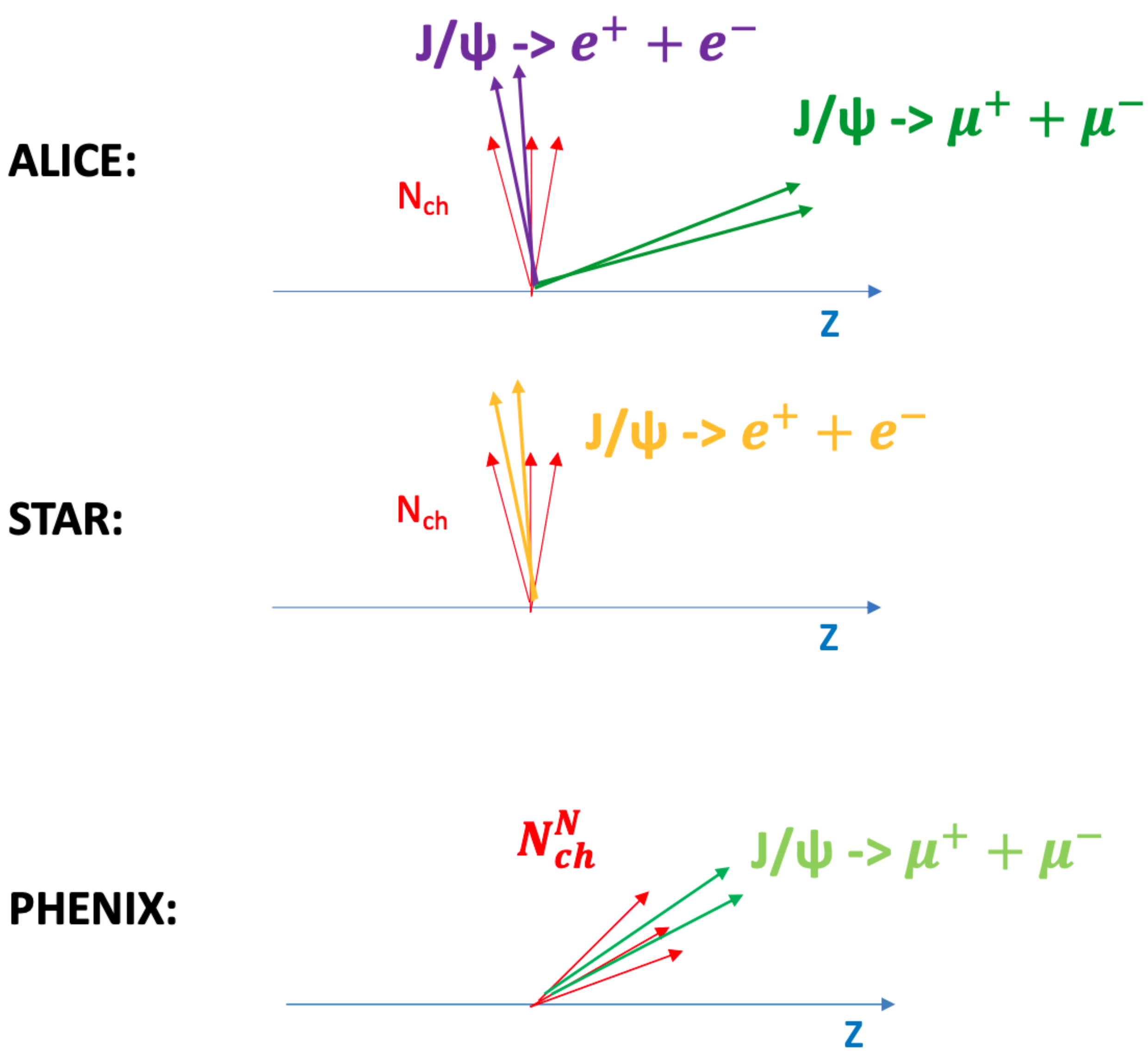
Data from 2015 RHIC run

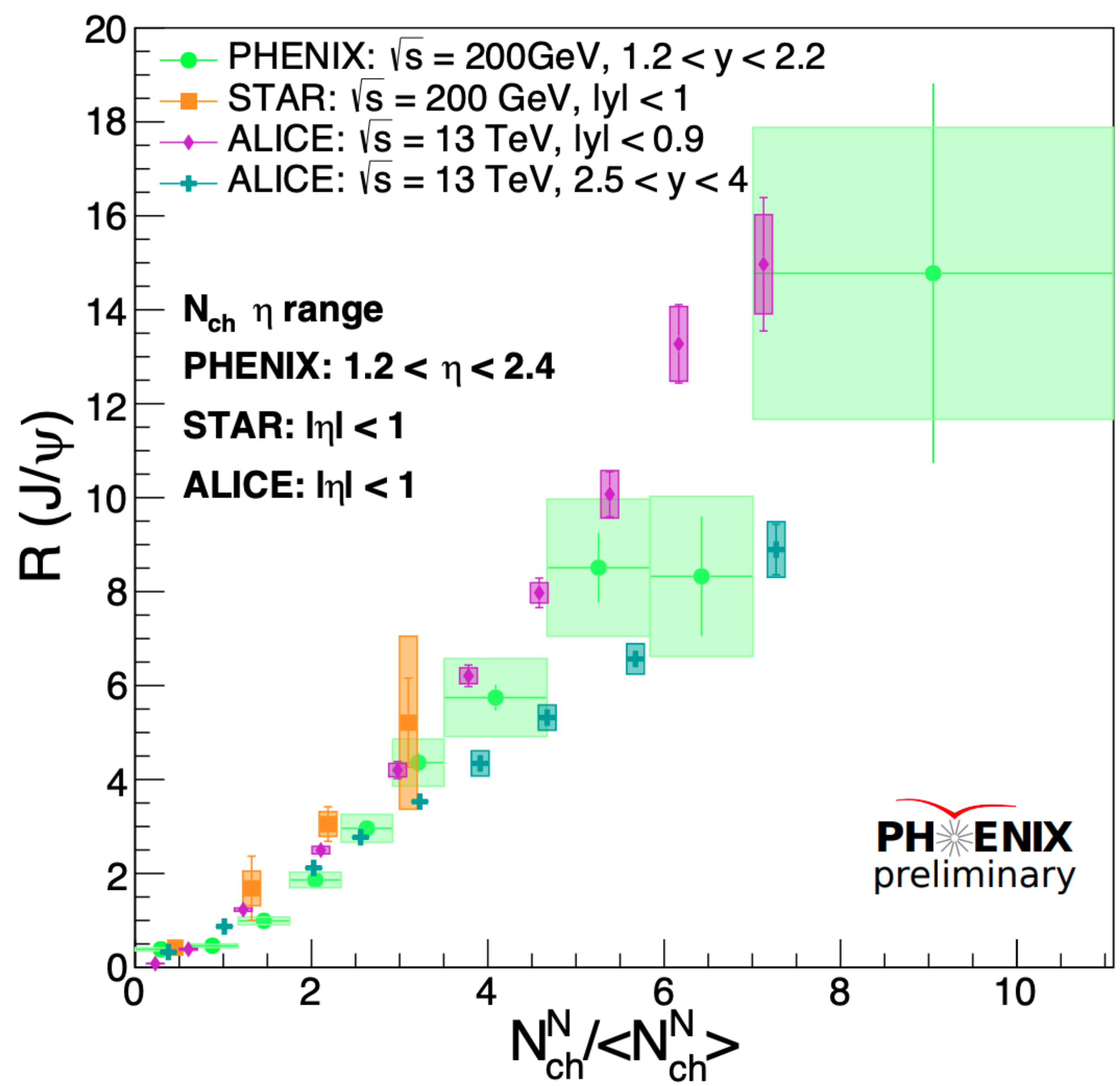
The muon arms can also detect unidentified hadrons

- Measure charged particle yields at $1.2 < \eta < 2.2$
- Measure J/ψ in same event at $1.2 < \eta < 2.2$ **or** $-1.2 < \eta < -2.2$

J/ψ production vs event multiplicity in p+p collisions

- Strong dependence on local track multiplicity
- PHENIX result consistent with observations at ALICE and STAR
- Large slope attributed to multi-parton interactions in p+p collisions





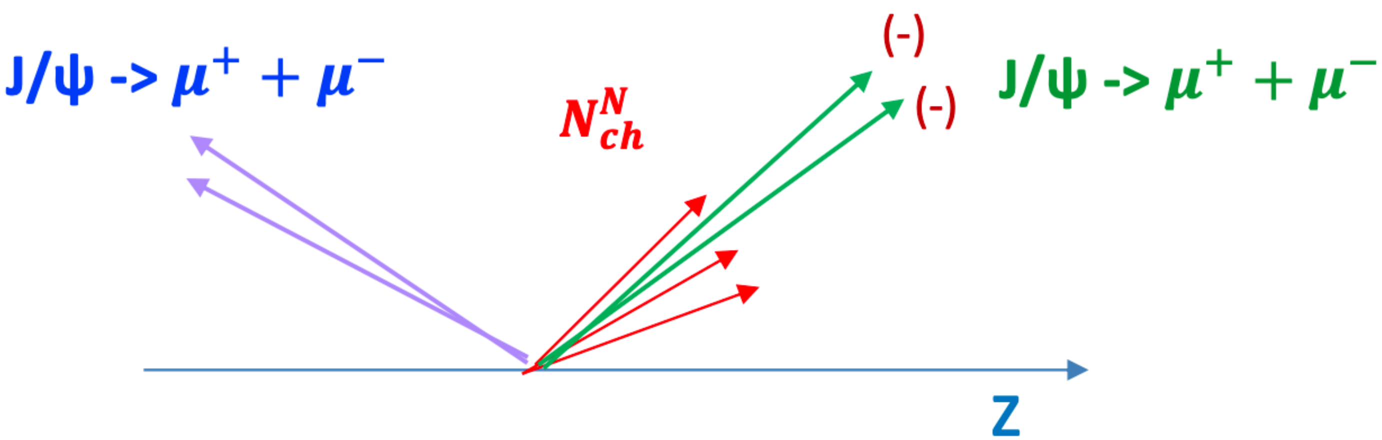
J/ψ production vs event multiplicity in p+p collisions

- Large dependence significantly reduced when
  - Removing tracks belonging to J/ψ or
  - Using non-local track multiplicity
- Is there still room for Multi-Parton Interactions ?

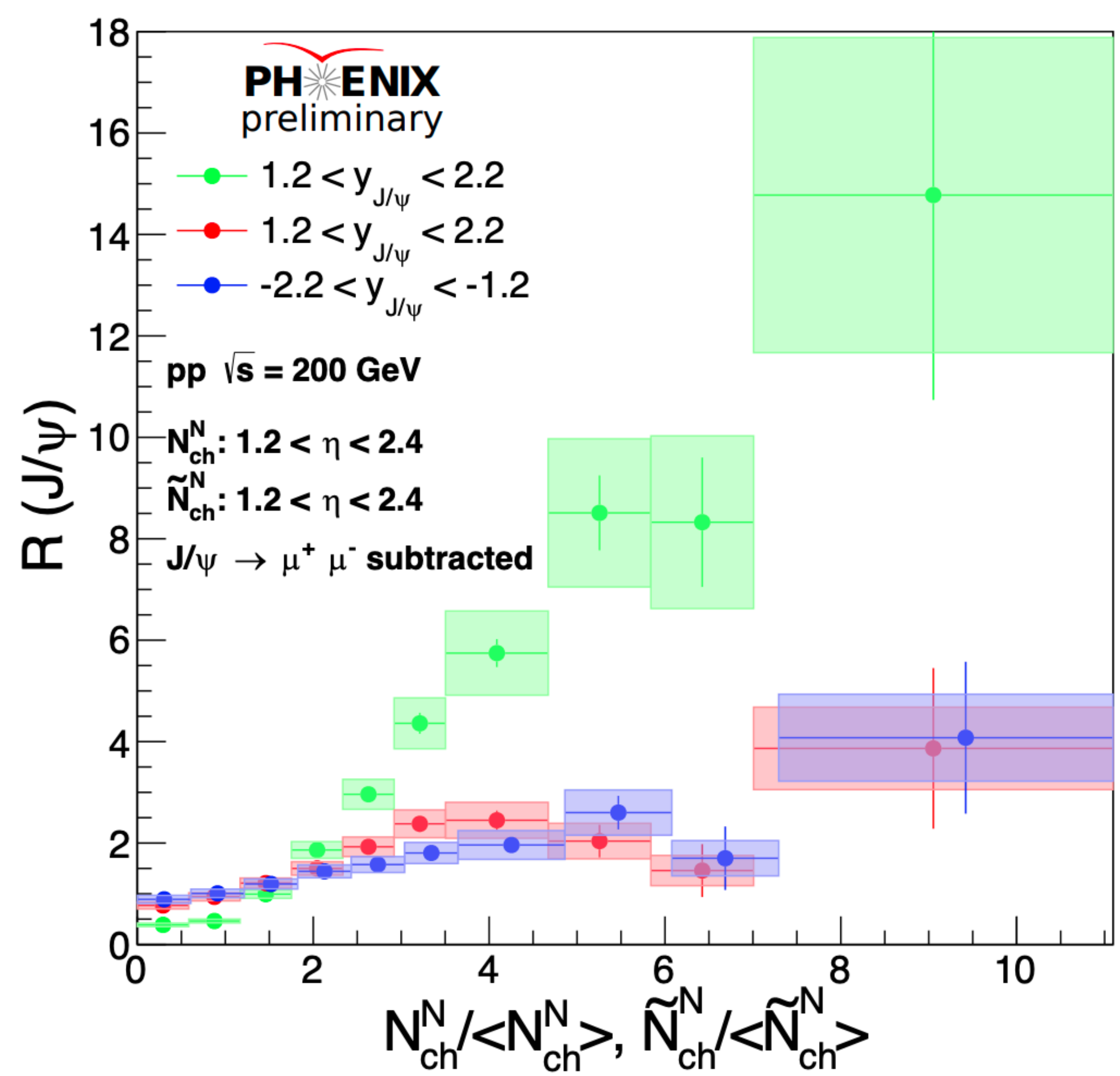
RED = Tracklets $N_{ch}^{N}(1.2 < \eta < 2.4)$ [inclusive, dimuon subtracted]

Green = J/ψ (1.2 < y < 2.2)

Blue = J/ψ (-2.2 < y < -1.2)



- Less MPI contribution to the forward J/ψ production?



Backup