PHENIX Results on J/ψ Production in p+Al, p+Au and ^{3}He+Au Collisions

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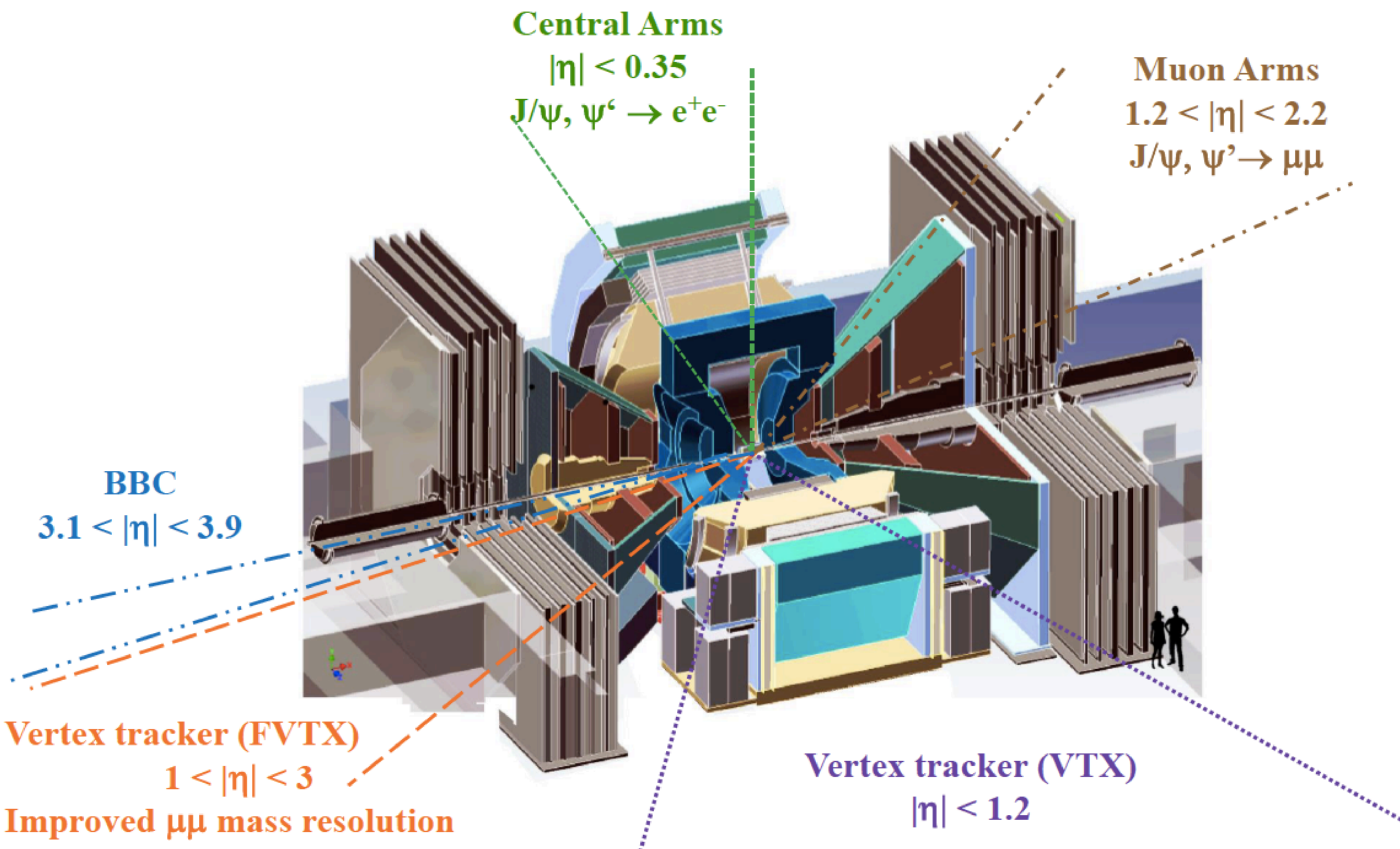
Quarkonia - PHENIX



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

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 two questions about J/ψ production:

- Do we see evidence of differences between p+Au and ^{3}He+Au
  - i.e. evidence of final state effects?
- How well do we understand J/ψ modification in light systems?

See PHENIX, arXiv:1910.14487 for a description of the measurement.

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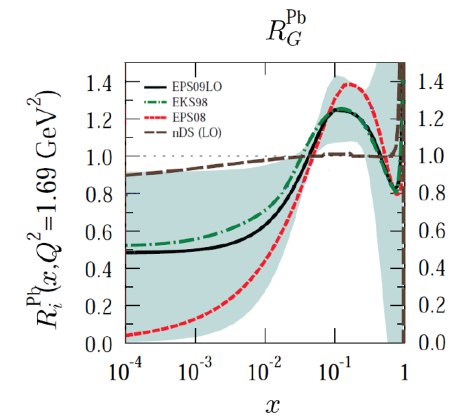
We need to start by briefly reviewing effects that modify quarkonia production in a nuclear target.

Quarkonia production in a nucleus

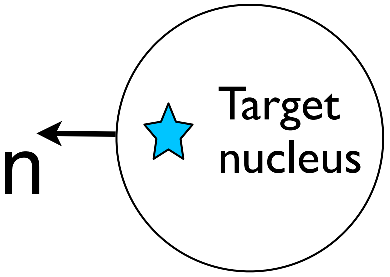
Processes that modify the quarkonia yield in a nuclear target - called cold nuclear matter (CNM) processes.

Gluon shadowing - parton distributions are modified in a nucleus



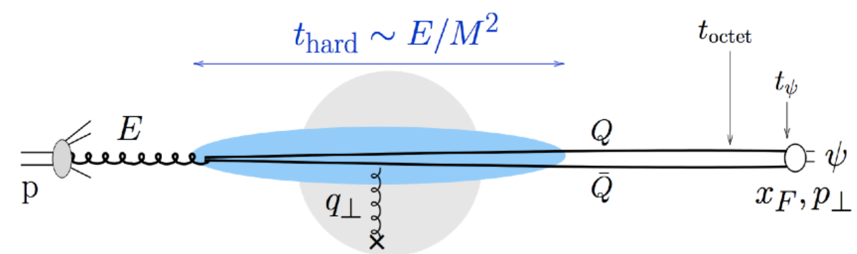
Affects underlying heavy quark yield

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

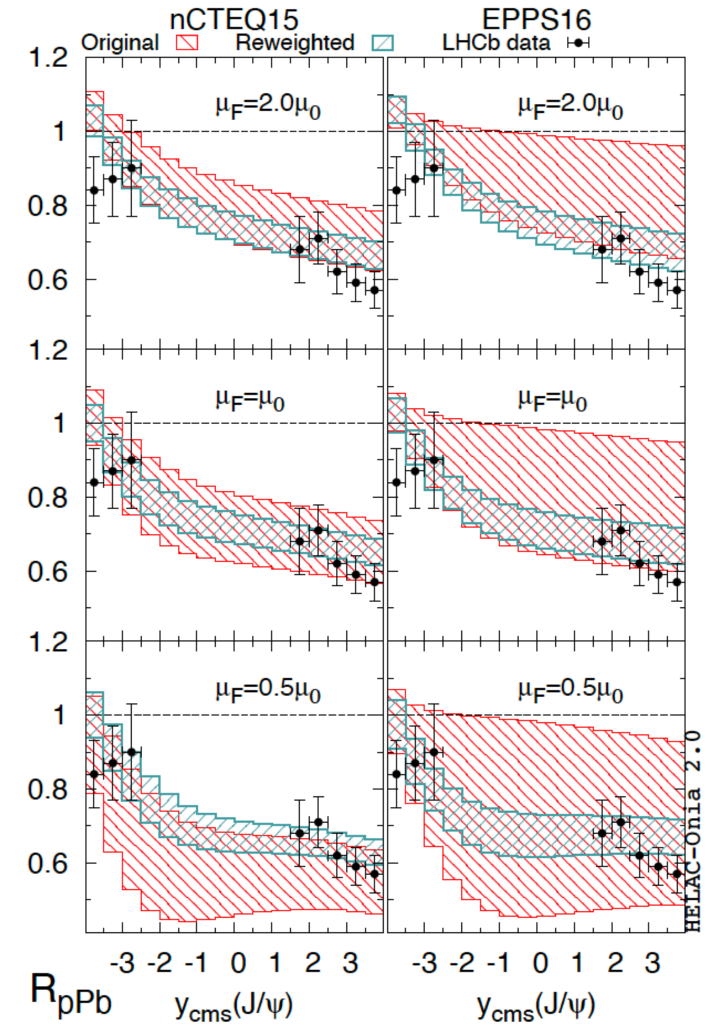
- (Kusina et. al., Phys. Rev. Lett. 121, 052004 (2018))
- Adds LHC pPb data - gluon dominated processes
  - D_0, J/ψ , B →J/ψ, and Y(1S) mesons

See also Eskola et. al. arXiv:1906.03943

- 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

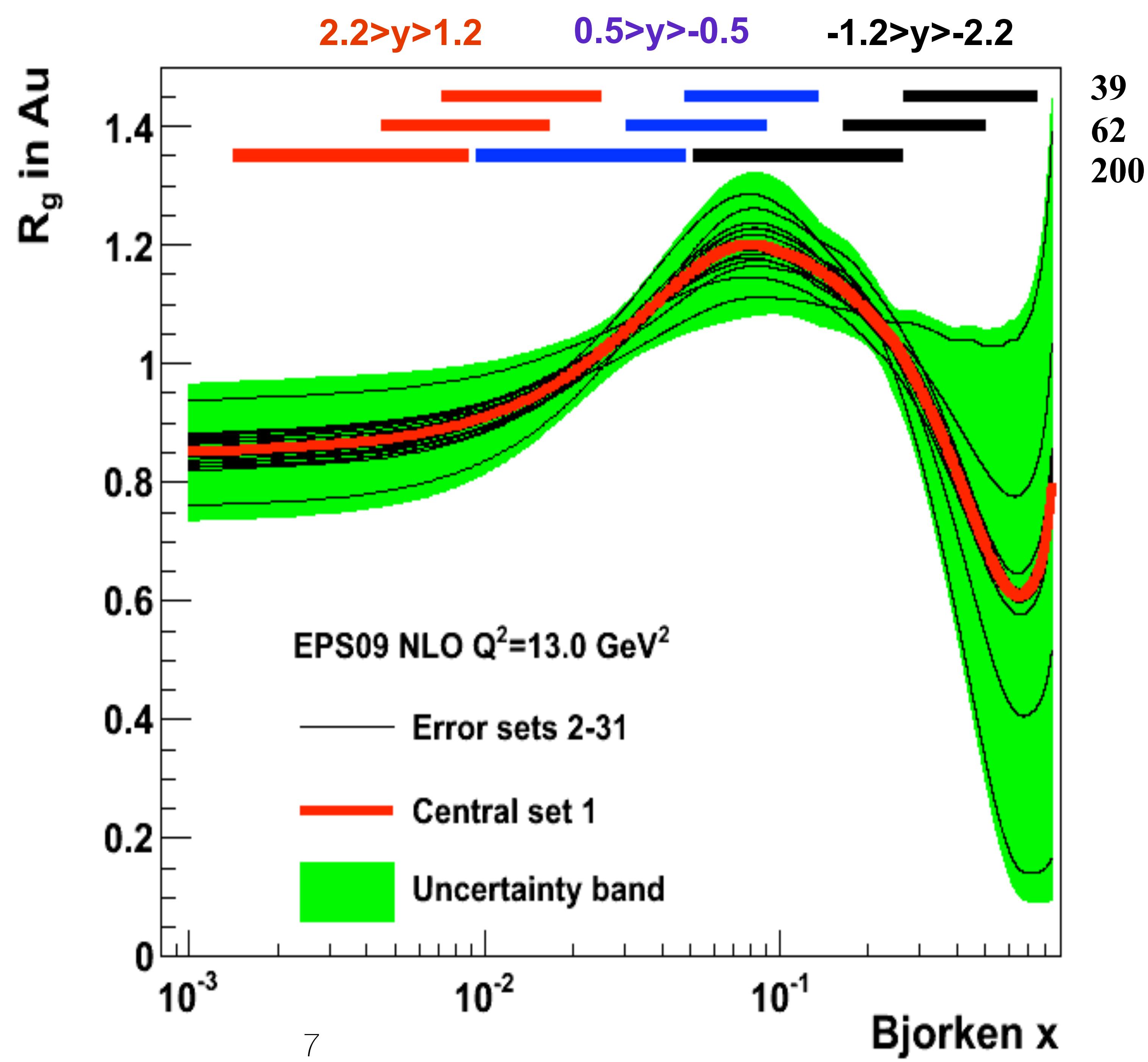


(b) Prompt J/ψ

x versus rapidity in PHENIX for J/ψ

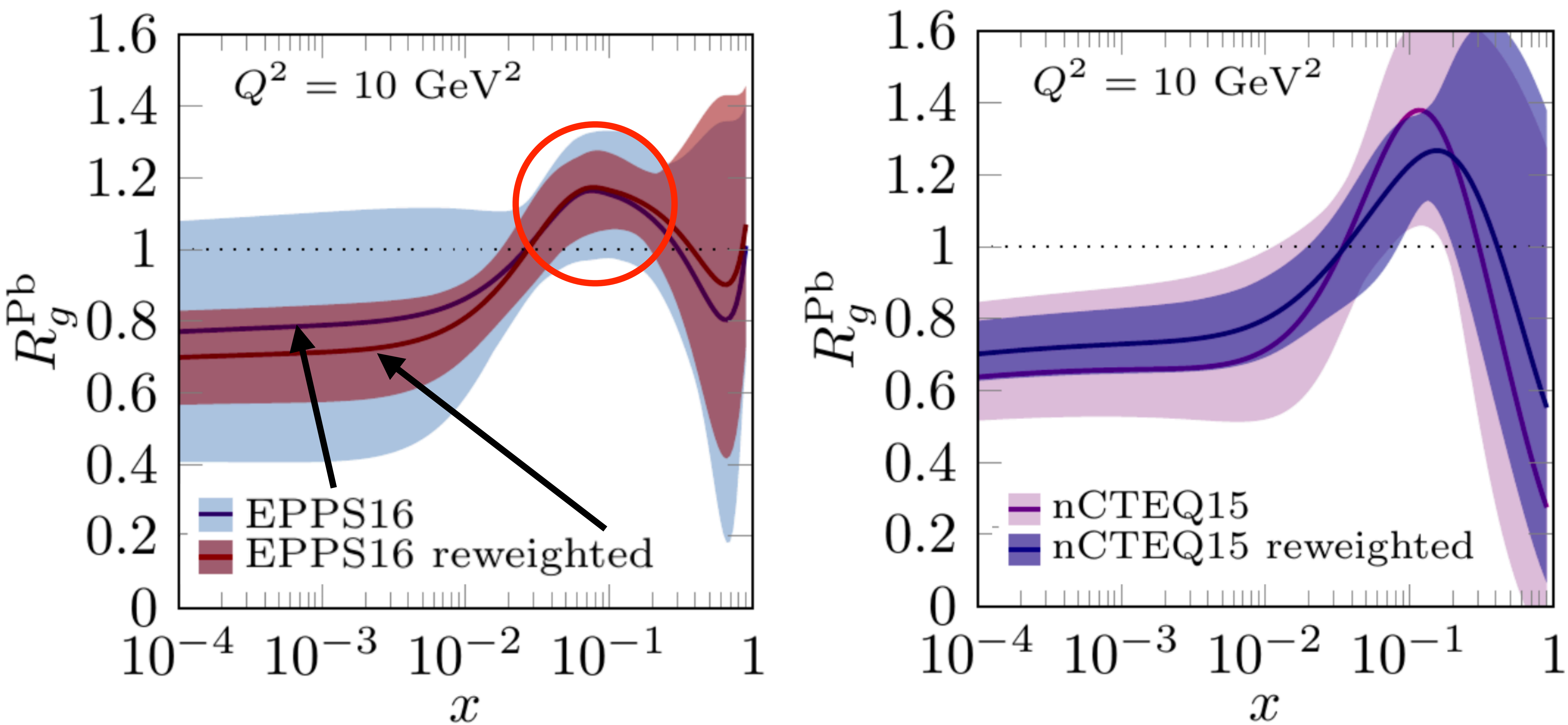
$$x_2 = \frac{\sqrt{M^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y} \ , \quad Q^2 = M^2 + p_T^2$$

Ranges of x values sampled by J/ψ production in PHENIX.



Re-weighting of gluon nPDF's

Eskola et. al., arXiv:1906.03943.
Hesssian re-weighting of nPDF's using LHCB D^0 data.



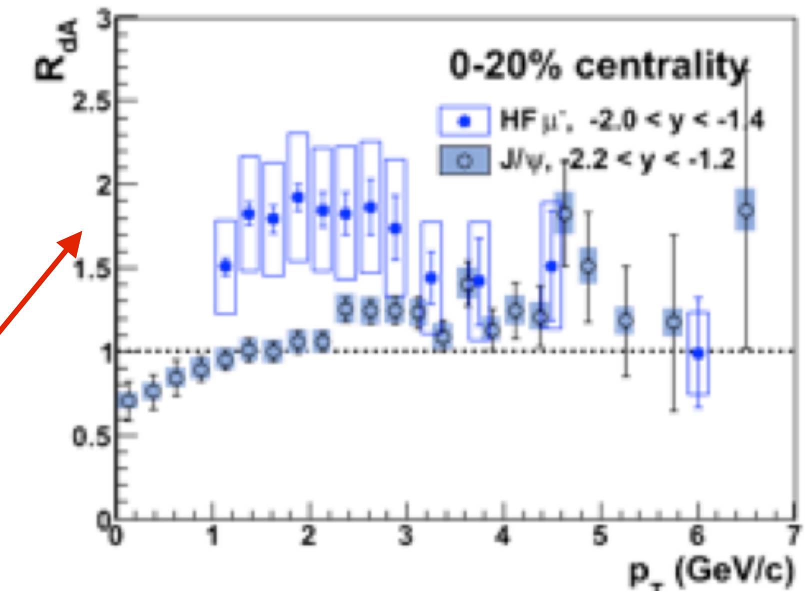
d+Au J/ψ and open HF results vs rapidity

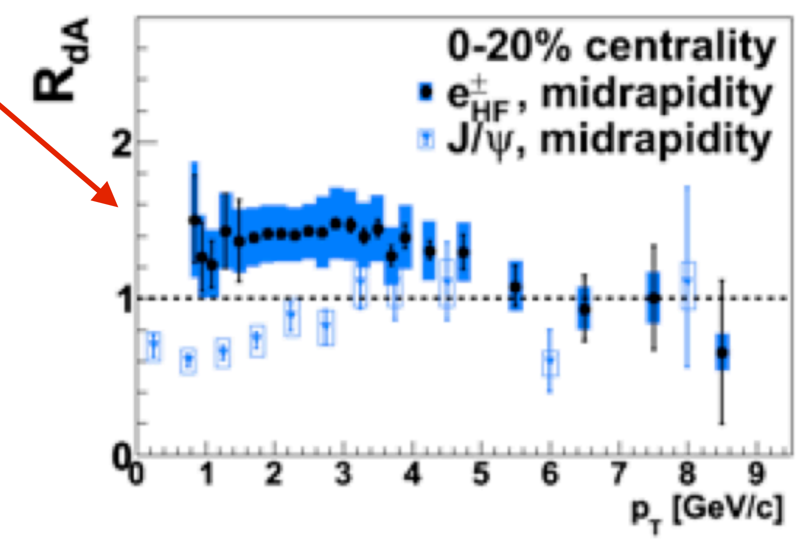
PHENIX, PRL 112 252301 (2014)

Caveat: Different kinematics!

The J/ψ suppression at **backward & mid rapidity** is much stronger than for HF.

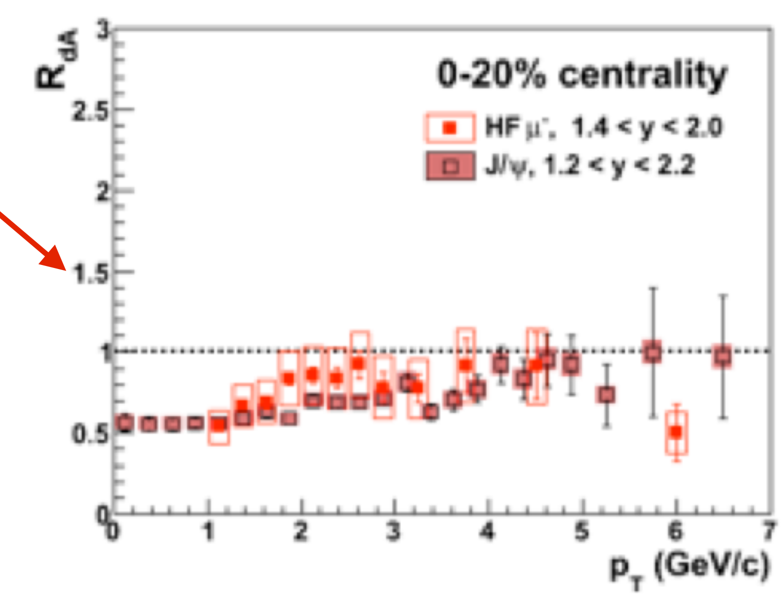
- Implies J/ψ is suppressed **beyond** the underlying HF production.





At **forward rapidity** they are similar.

- Implies J/ψ suppressed at forward rapidity **because** the underlying HF is suppressed.



J/ψ absorption

Backward rapidity J/ψ in PHENIX experience a significant "absorption" cross section from breakup due to collisions with target nucleons

- 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)).

- 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 data from $\sqrt{s_{NN}}$ = 17 to 200 GeV

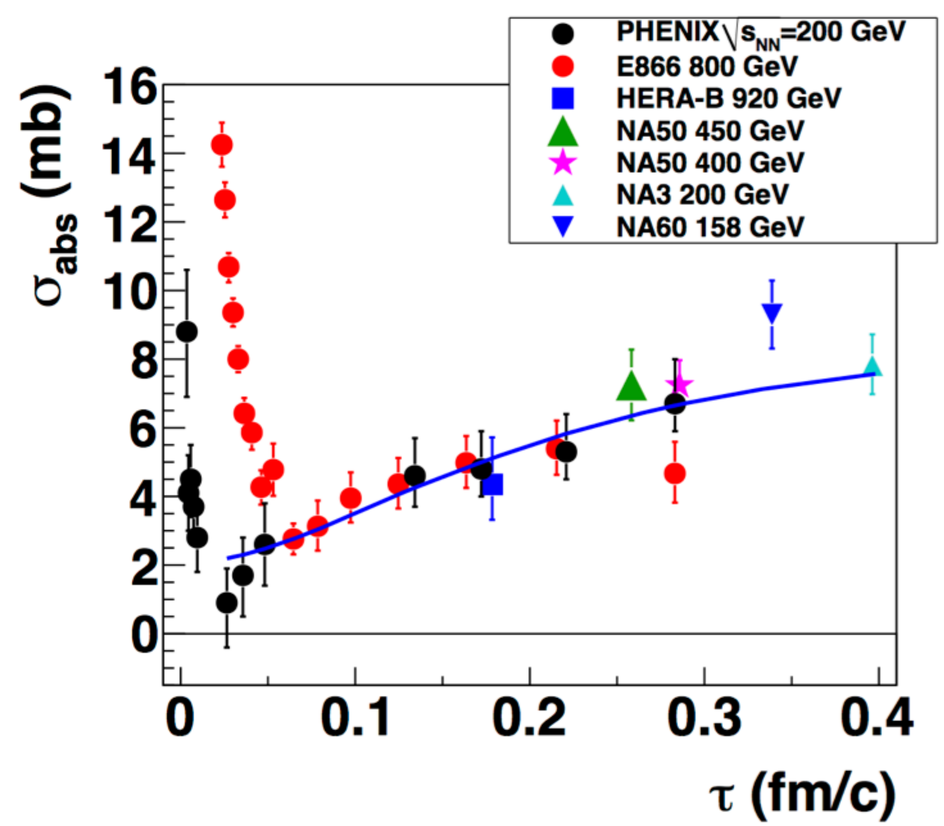
Anti-shadowing parameterizations have remained stable over several generations.

- Well constrained by DIS data.

Not expected to be important at LHC

- Nuclear crossing times very short at all y

Phys.Rev. C87 (2013) 5, 054910



Initial state energy loss

Incoming parton energy 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.

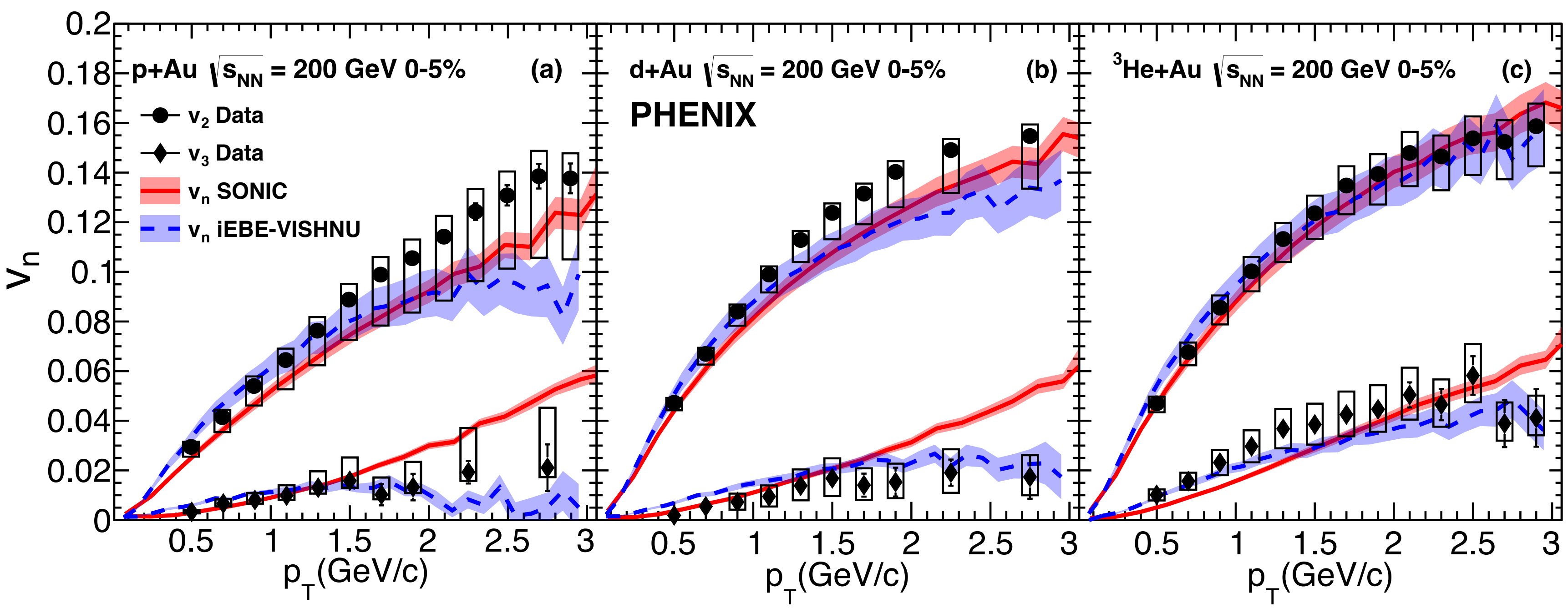
The Bayesian re-weighted shadowing seems to explain p+A data reasonably well without additional effects from initial state energy loss.

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

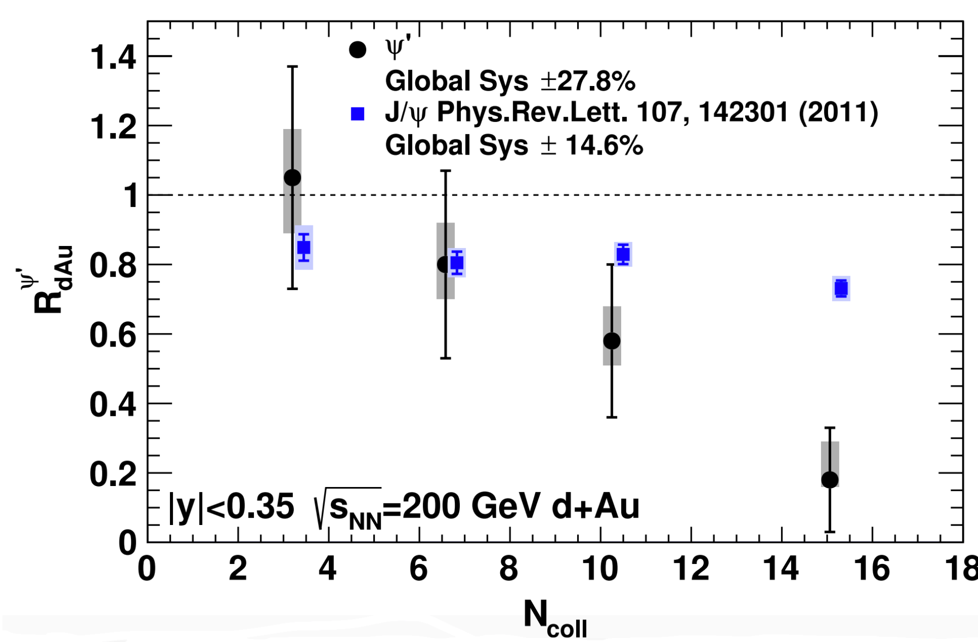
Motivation for studying multiple light systems

- Interest in p+A partly motivated by the A+A program
  - p+A is sensitive to initial state effects that are not theoretically well understood.
  - Assumed for a long time only initial state effects important in p+A.
- **But:**
  - Unexpectedly strong suppression of the ψ(2S) observed in d+Au collisions at RHIC, and then in p+Pb collisions at LHC.
  - Evidence of flow in small systems observed, first at LHC and then at RHIC.
  - Final state effects on quarkonia production in p+A?

Nature Physics 15, 214-220 (2019)



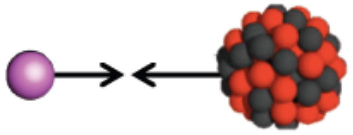
PHENIX, PRL 111 202301 (2013)



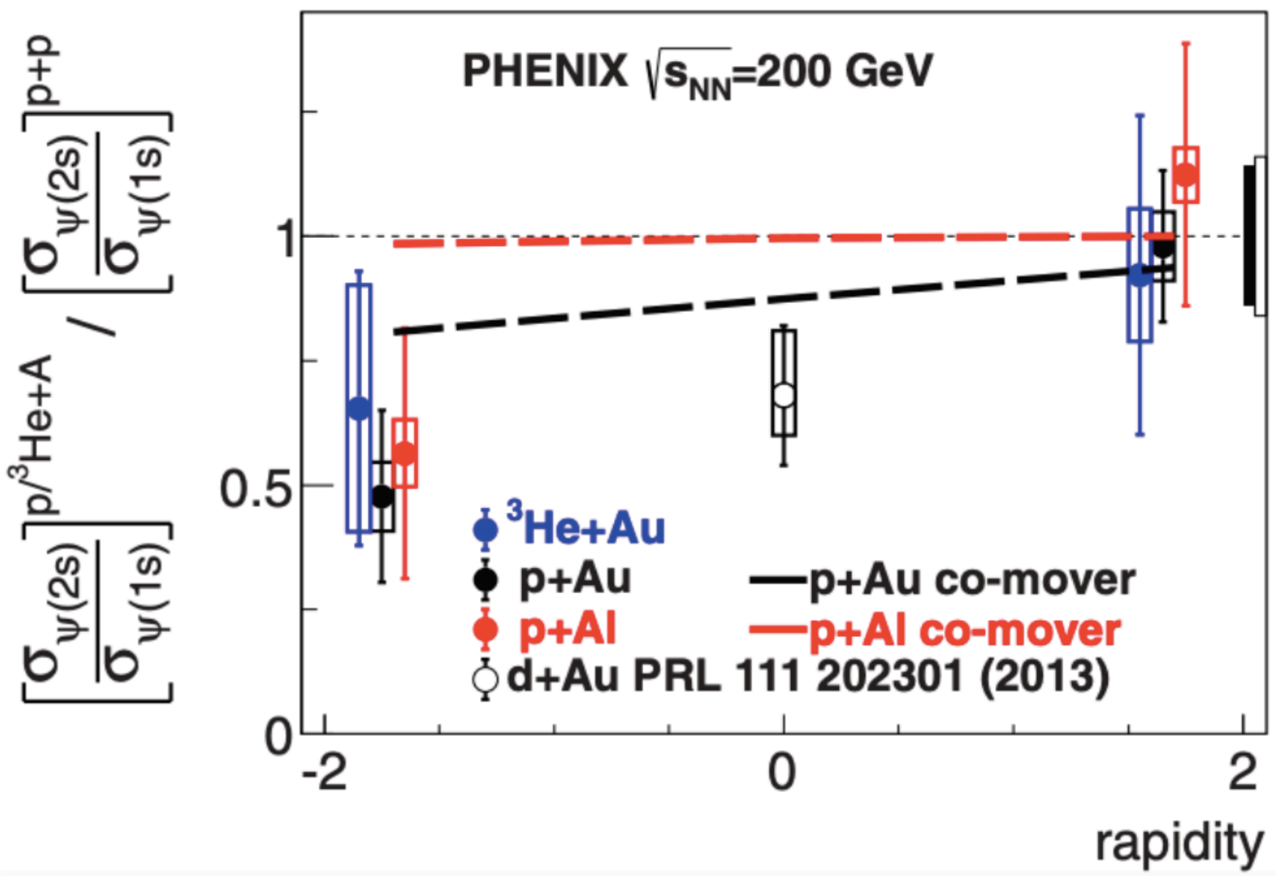
ψ(2S) results

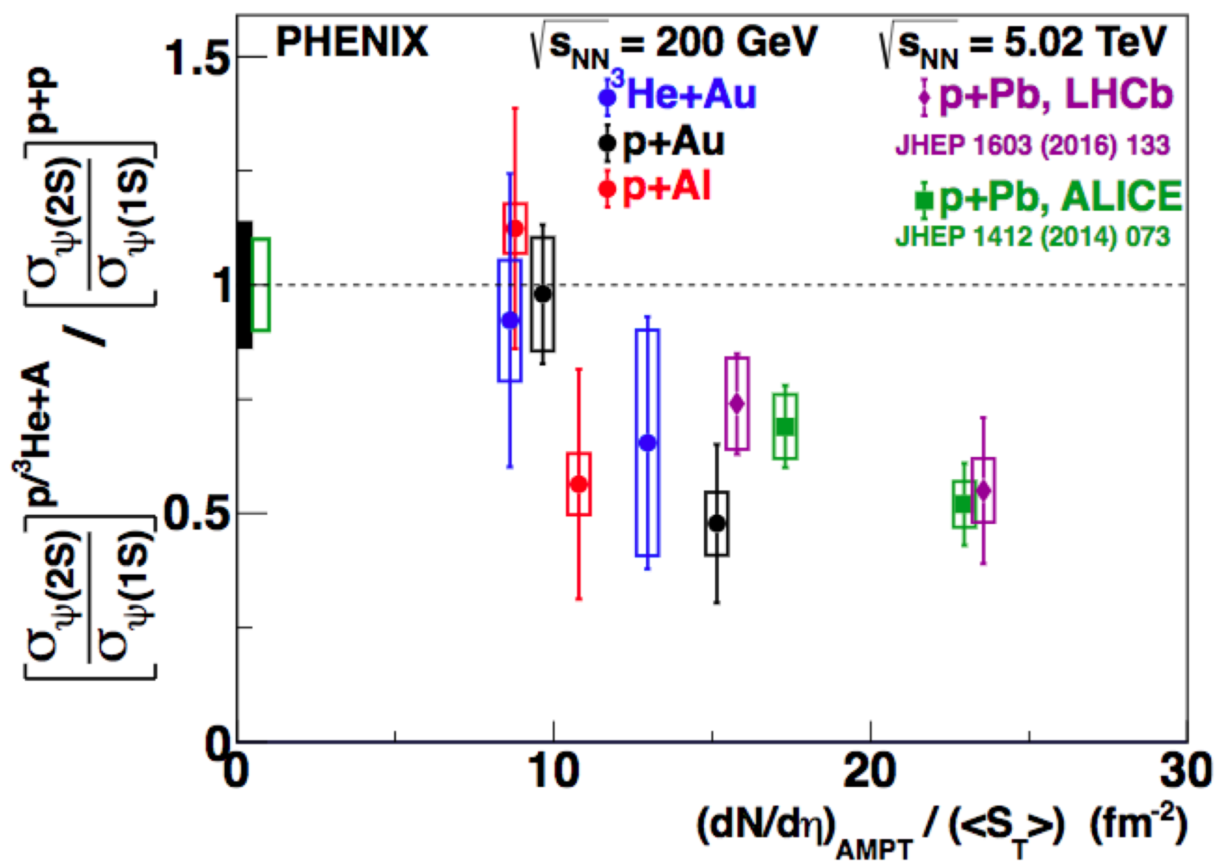
Strong suppression at mid & backward rapidity relative to J/ψ

- 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

Transport model

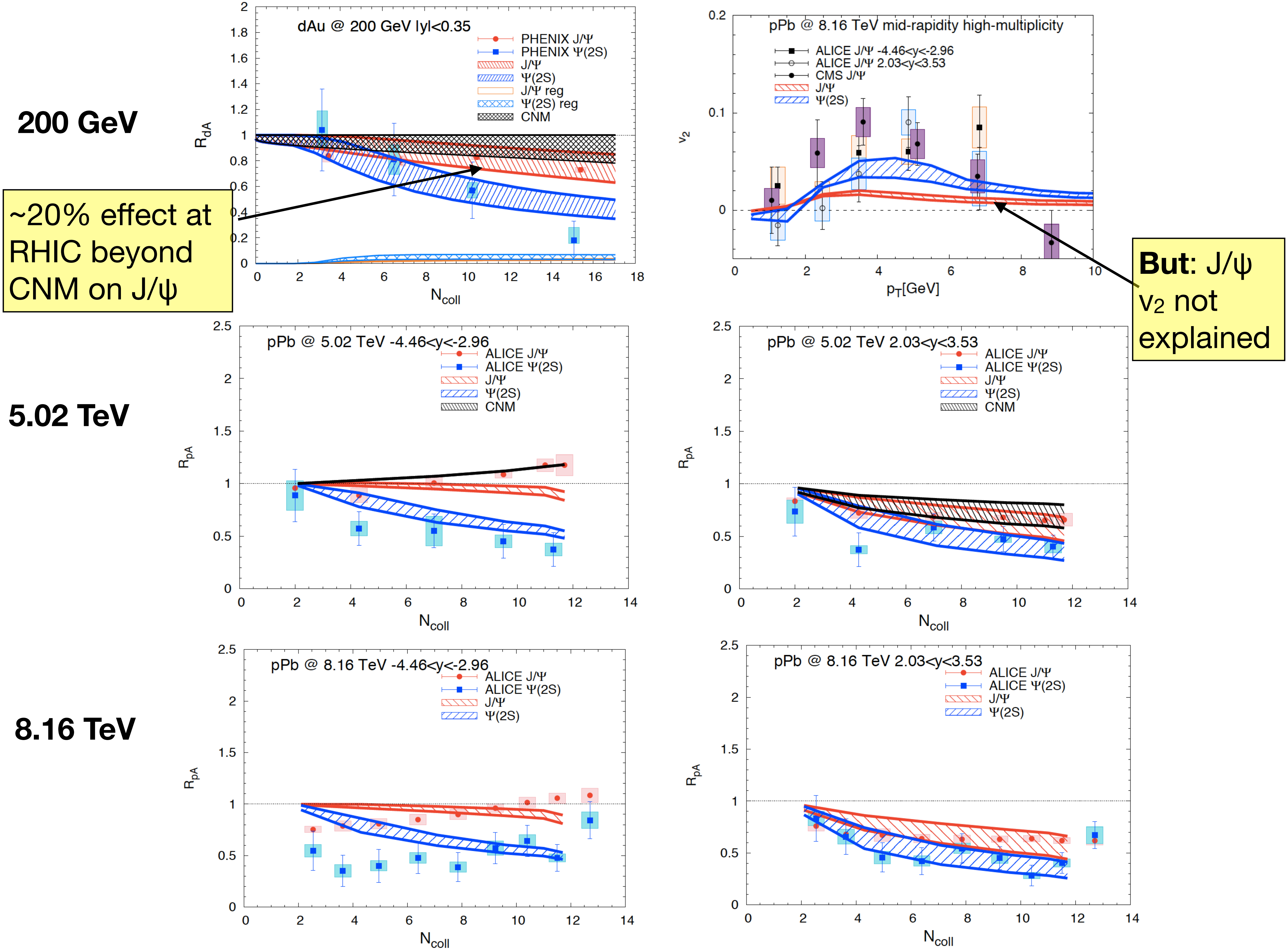
Du and Rapp (JHEP 1903 (2019) 015) have adapted their transport model, used to describe heavy ion collisions, for use in small systems.
They try to describe all available charmonium J/ψ and ψ(2S) data from RHIC and LHC, including the J/ψ v_2.

The transport model uses

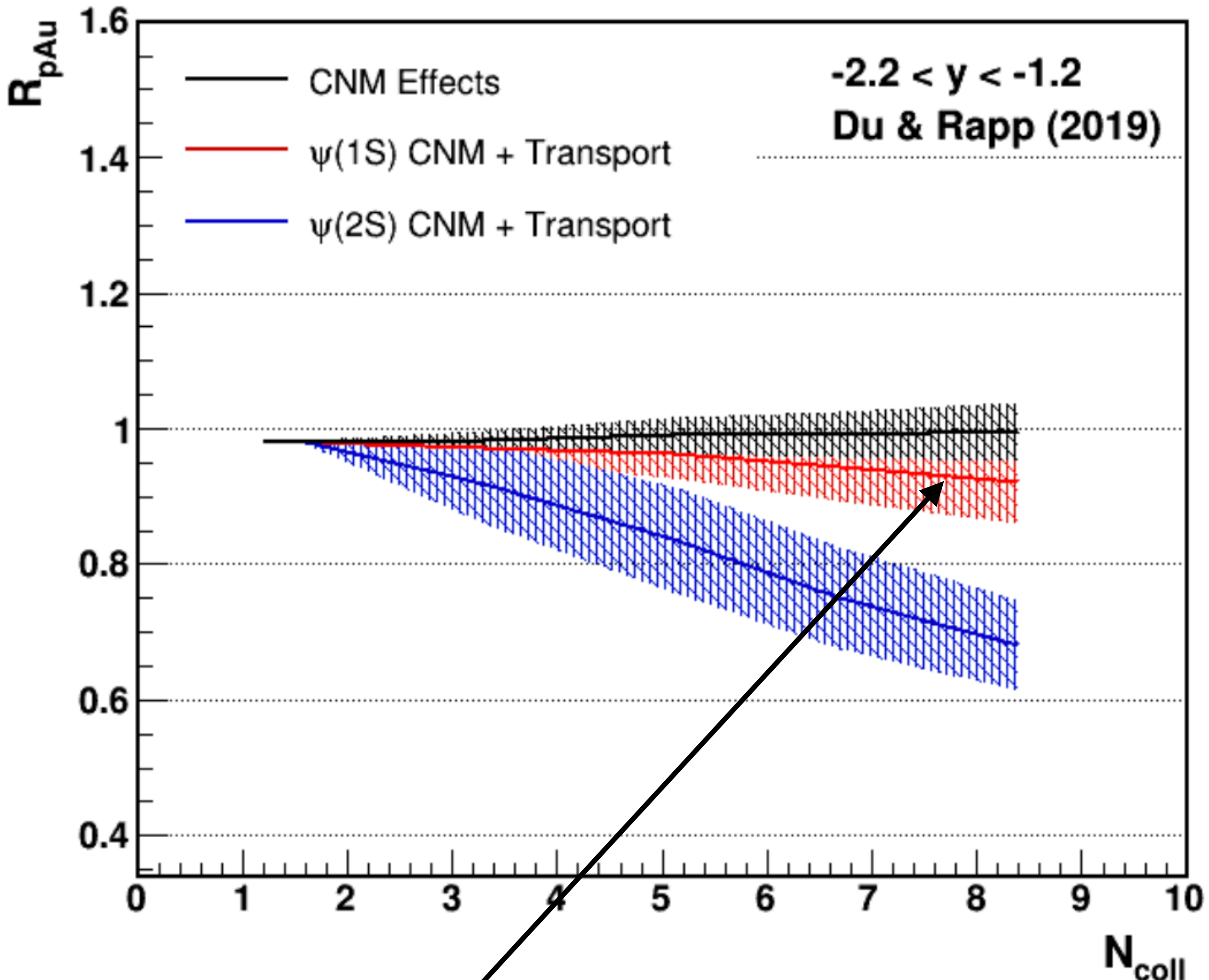
- A rate equation approach within a fireball model
- Initial geometry of the fireball from a Monte-Carlo event generator
- Initial anisotropies are caused by fluctuations
- Includes corrections for CNM effects
  - EPS09 shadowing with assumed linear centrality dependence
  - Constant nuclear absorption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

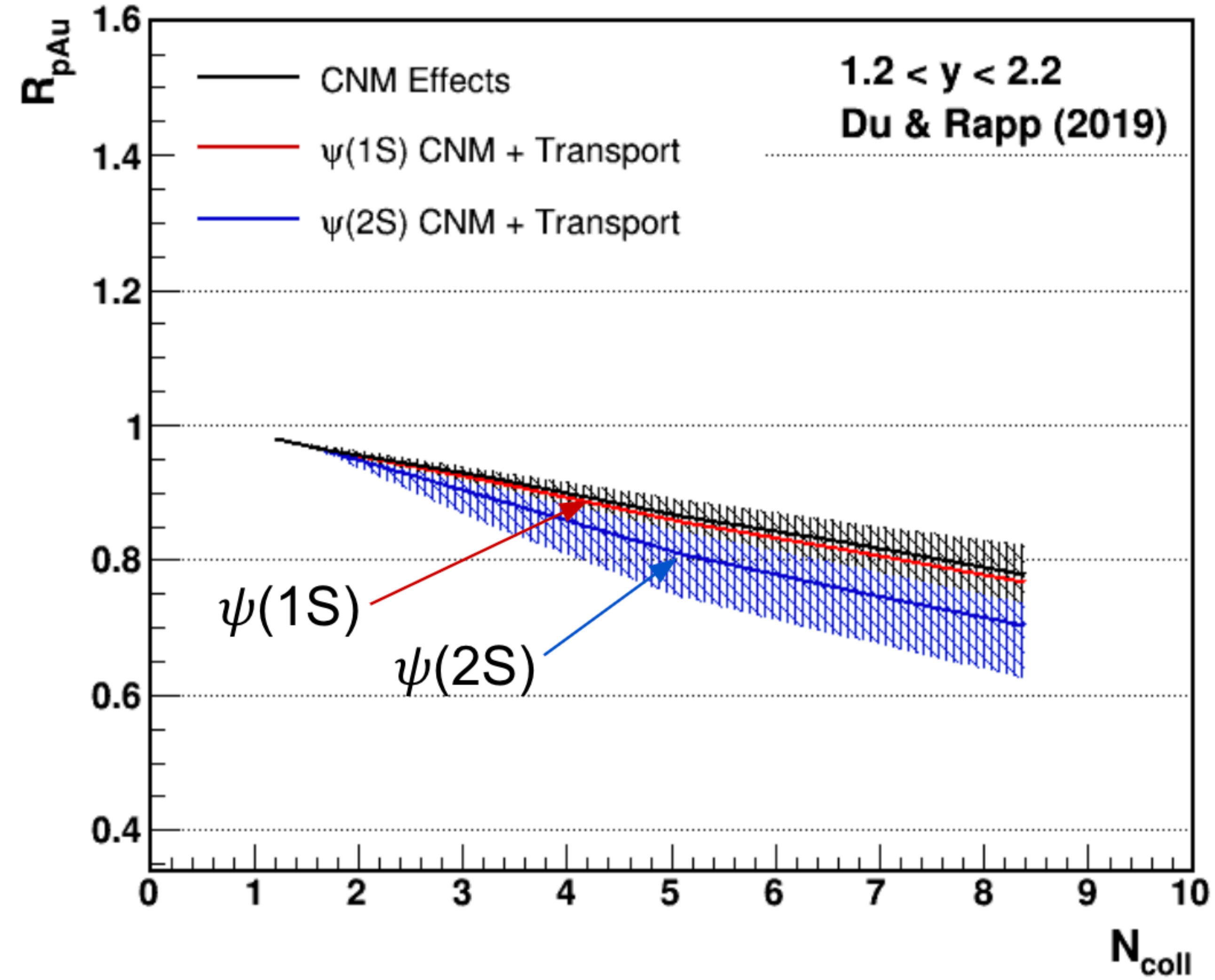
Some results for J/ψ, ψ(2S) centrality dependence and J/ψ v_2 are shown on the next slide.

- The calculations also provide a good description of the p_T dependence — not shown here.


200 GeV
5.02 TeV
8.16 TeV
dAu @ 200 GeV |y|<0.35
PHENIX J/Ψ
PHENIX Ψ(2S)
J/Ψ
Ψ(2S)
J/Ψ reg
Ψ(2S) reg
CNM
~20% effect at RHIC beyond CNM on J/ψ
pPb @ 8.16 TeV mid-rapidity high-multiplicity
ALICE J/Ψ -4.46<y<-2.96
ALICE J/Ψ 2.03<y<3.53
CMS J/Ψ
But: J/ψ v2 not explained
pPb @ 5.02 TeV -4.46<y<-2.96
ALICE J/Ψ
ALICE Ψ(2S)
pPb @ 5.02 TeV 2.03<y<3.53
pPb @ 8.16 TeV -4.46<y<-2.96
pPb @ 8.16 TeV 2.03<y<3.53
R_{dA}
R_{pA}
v_2
N_{coll}
p_T[GeV]

Perspective: transport model prediction for p+Au





~10% effect in p+Au beyond CNM on J/ψ

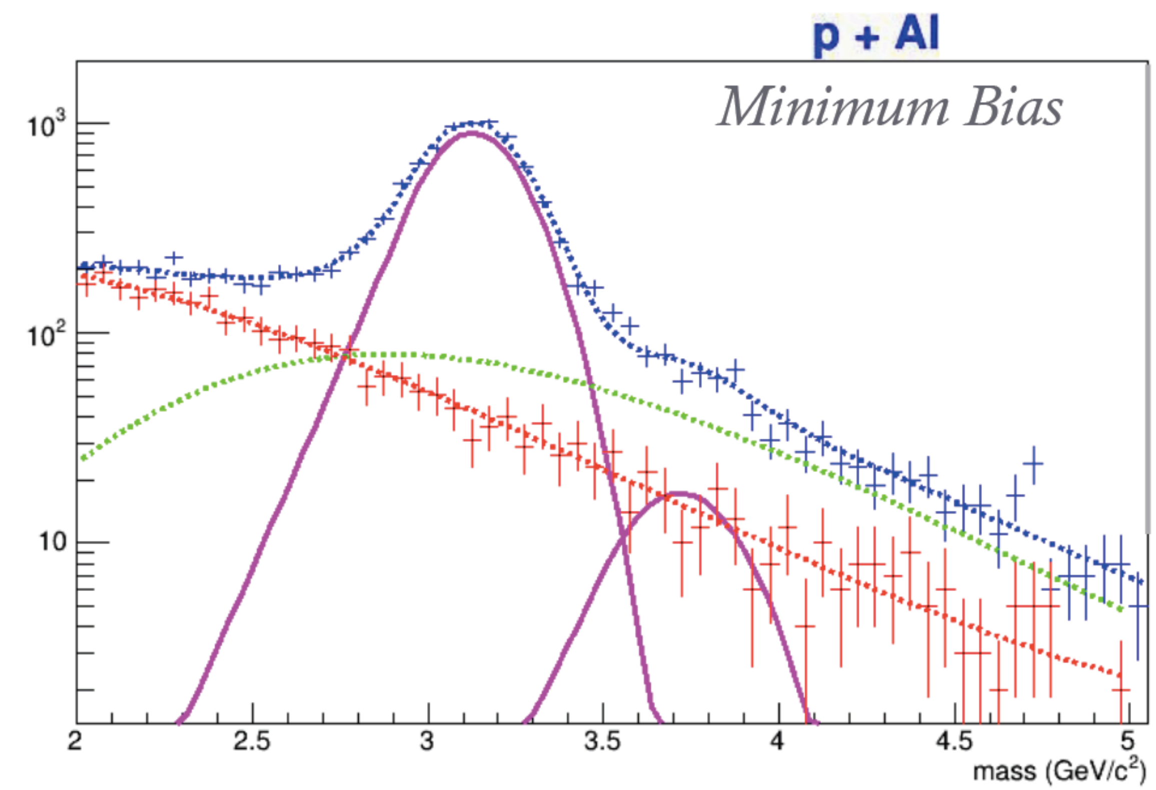
Little effect in p+Au beyond CNM on J/ψ

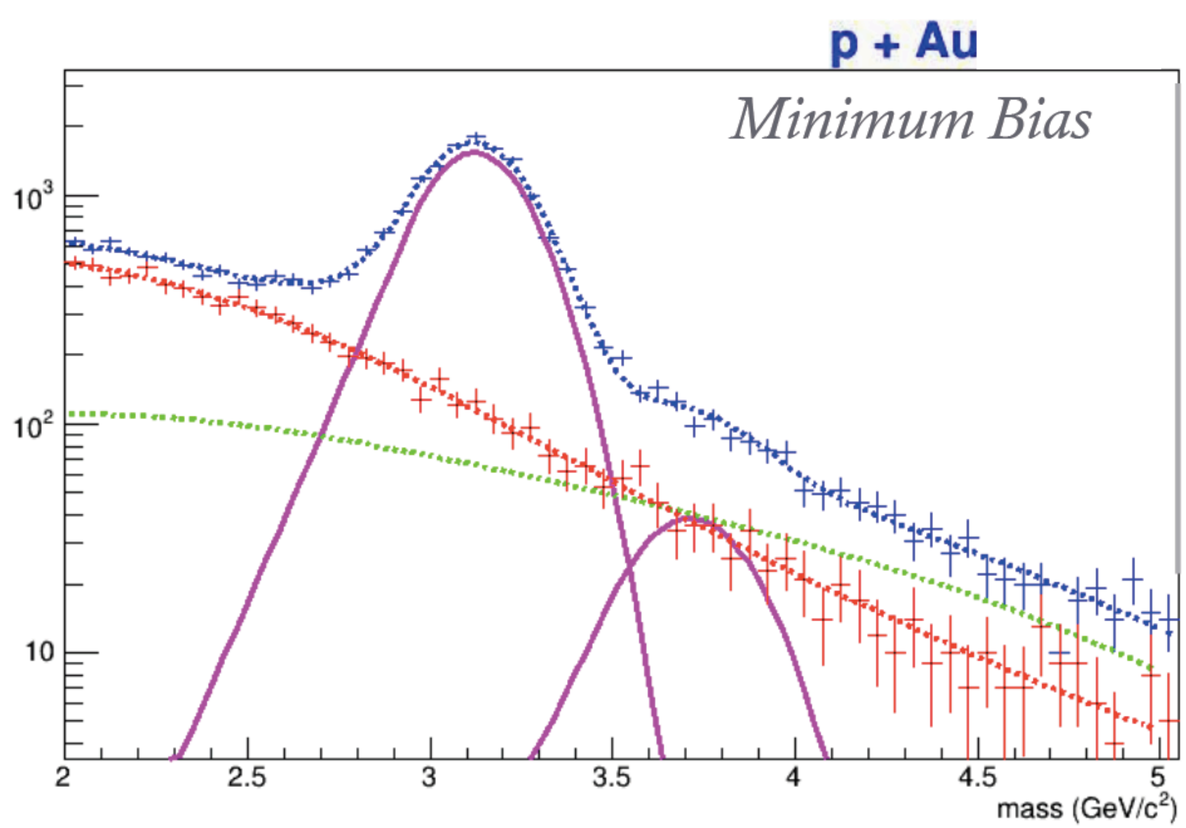
J/ψ Measurement

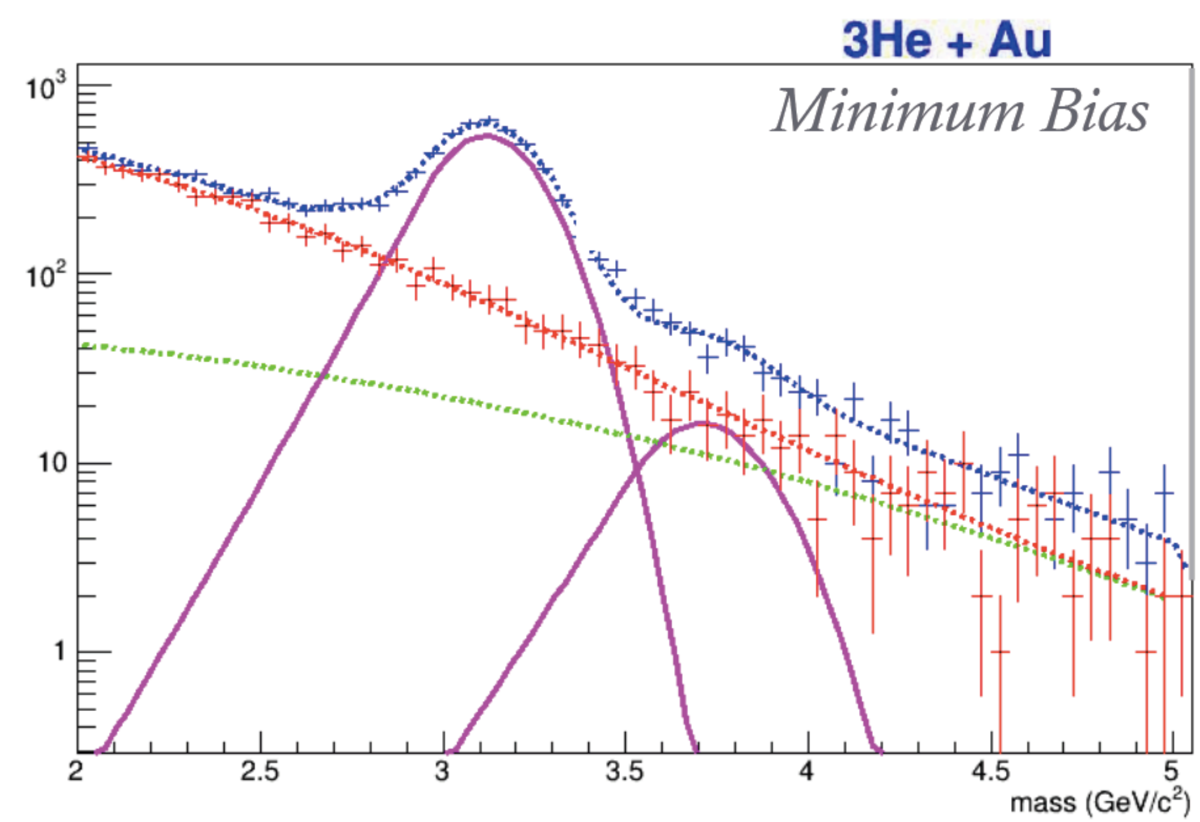
Dimuon invariant mass spectra for p+Al, p+Au and ^{3}He+Au

With fitted J/ψ peak and various background sources shown

- Red : combinatoric from like-sign.
- Green: non- combinatoric (physics) background estimate.



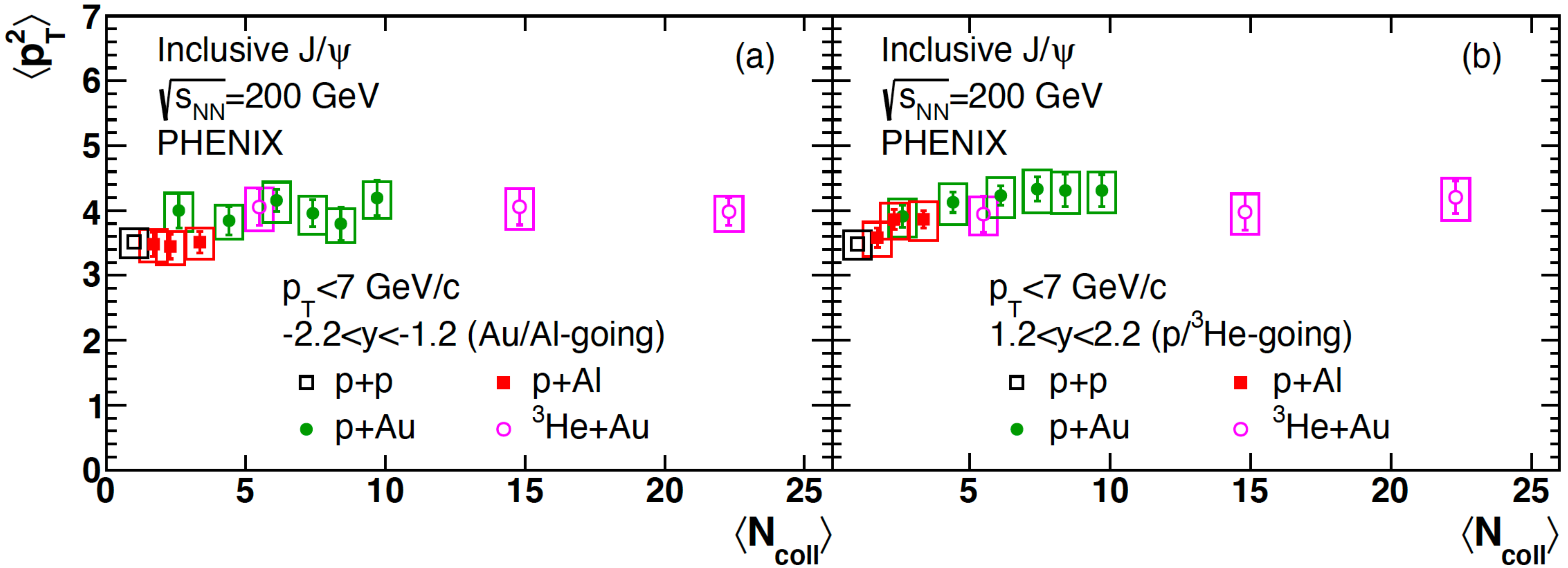




p+Al, p+Au, ^{3}He+Au < p_T^2 > vs N_{coll}

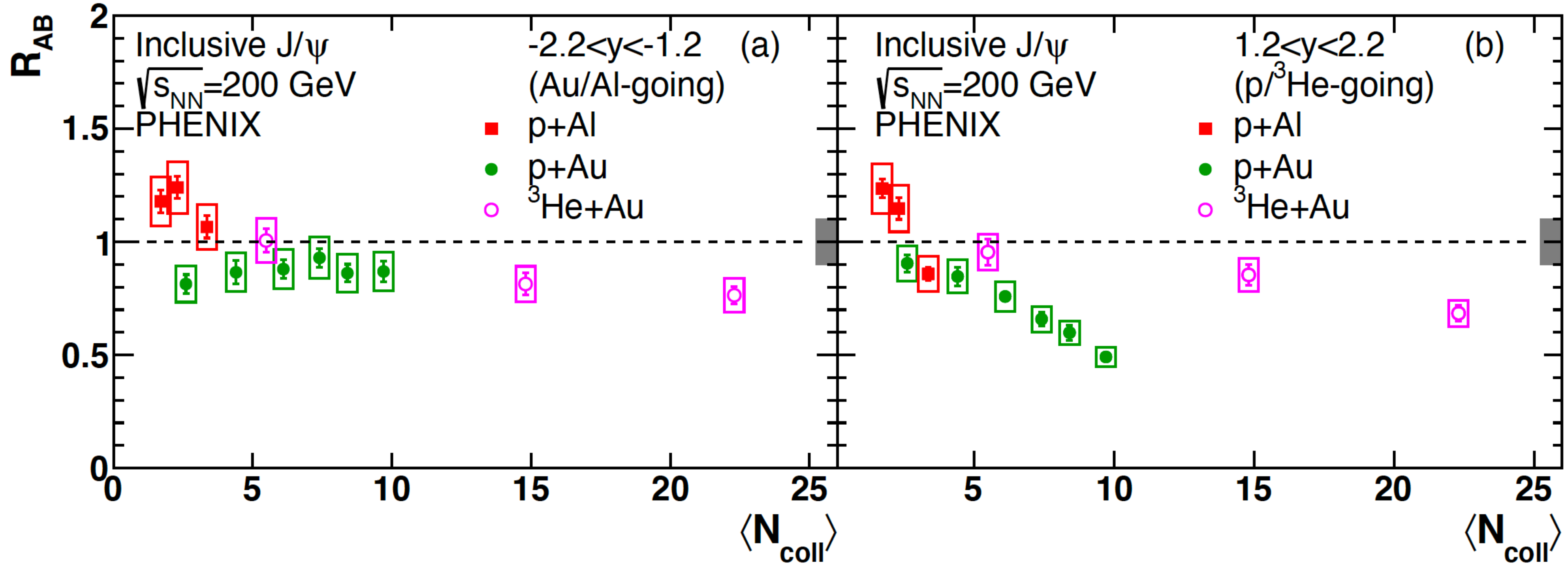
Compare $\langle p_T^2 \rangle$ for the three collision systems.

- Limited to **p_T < 7 GeV/c** because of statistics.
- Slight enhancement for larger N_{coll}
- No evidence of any effects due to projectile size.

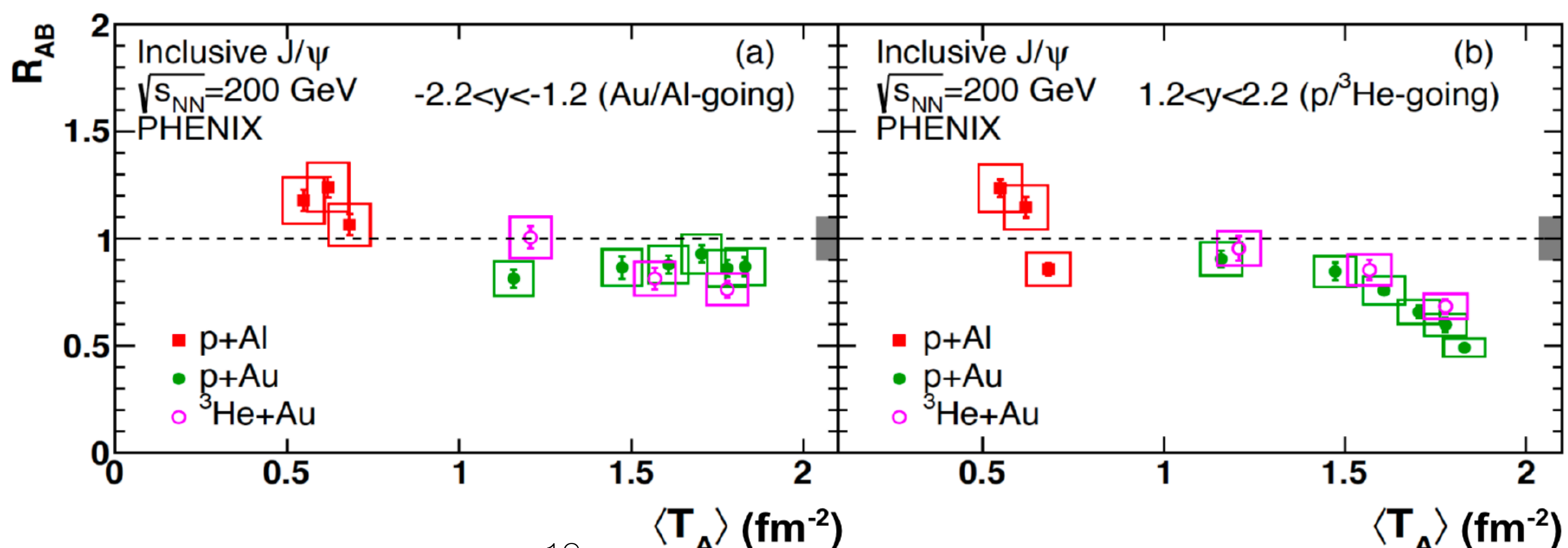


N_{coll} and T_A dependence

No N_{coll} scaling expected between p+Au and ^{3}He+Au.



Plot modification versus nuclear thickness of target (T_A) instead.



Final state effects on J/ψ production?

To look for evidence of final state effects on J/ψ in light systems we can compare Run 14 ^{3}He+Au and Run 15 p+Au data.

Systematic uncertainties reduced because:

- The runs are close in time.
- There were no detector upgrades in between.
- The same simulations model was used for analysis.

The particle multiplicity in 3He+Au is ~ twice that in p+Au (Phys. Rev. Lett. 121, 222301 (2018)).

Make the ratio of ^{3}He+Au to p+Au modifications.

- Should be < 1 if greater energy produced in ^{3}He+Au is important.
- Expect the greatest effect at backward rapidity

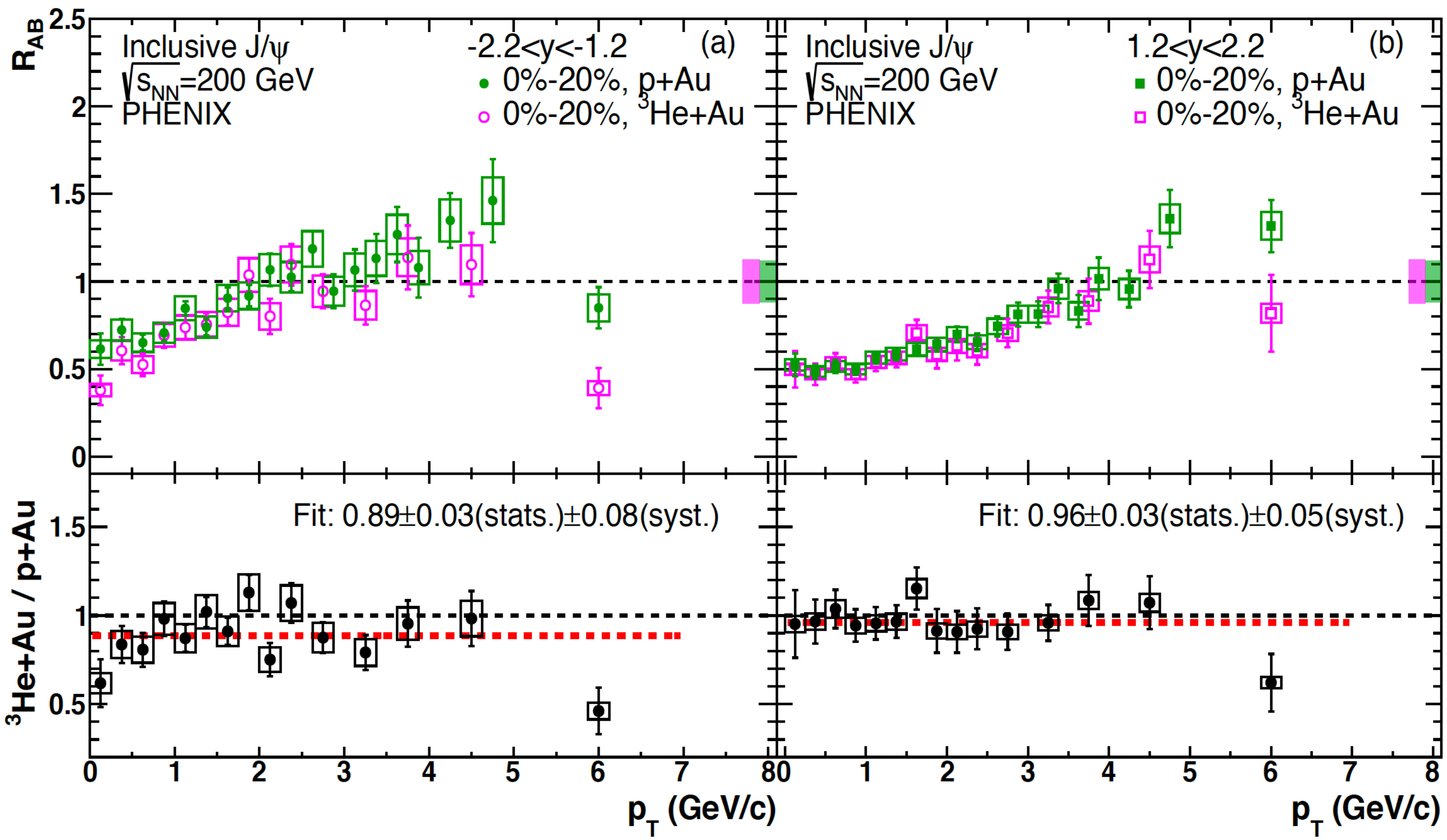
^{3}He+Au to p+Au ratio (0-20%centrality)

Backward rapidity ratio 0.89 ±0.03 ± 0.08

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

Forward rapidity ratio 9.96 ± 0.03 ± 0.05

- Consistent with 1



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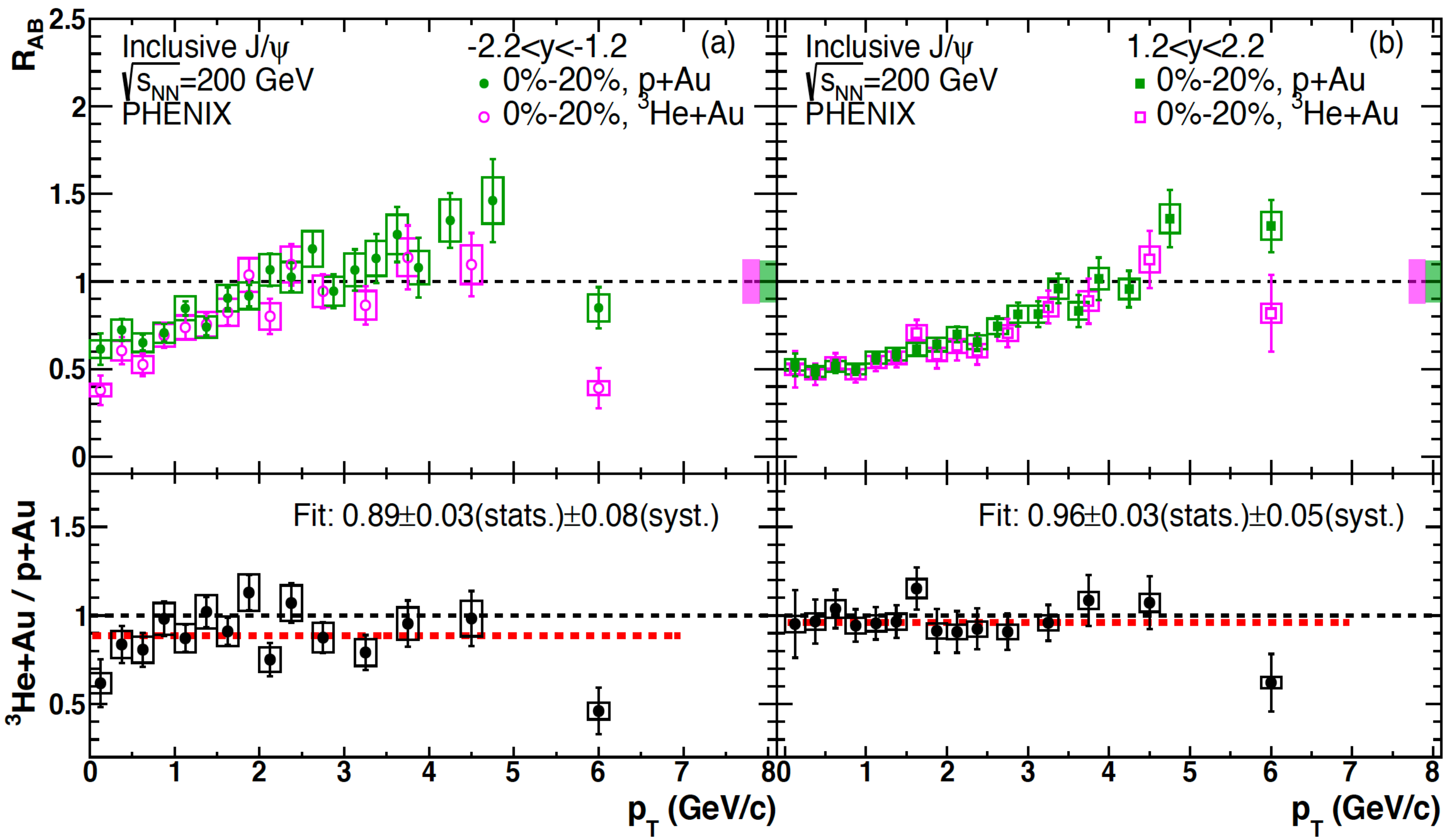
Both are consistent with the transport model



How well do we understand J/ψ modification?

We have a new p+Au J/ψ data set with high integrated luminosity.

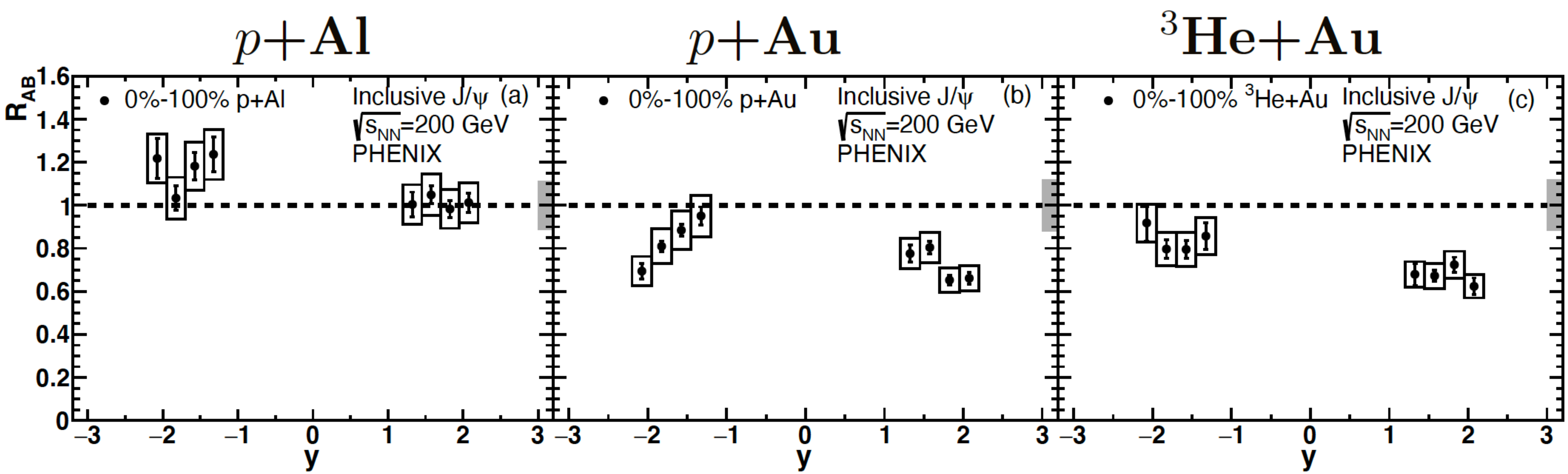
We can use it test our understanding of the effects that contribute to J/ψ modification.

We look at the

- Rapidity dependence
- p_T dependence
- Centrality dependence

Rapidity dependence, p_T and centrality integrated

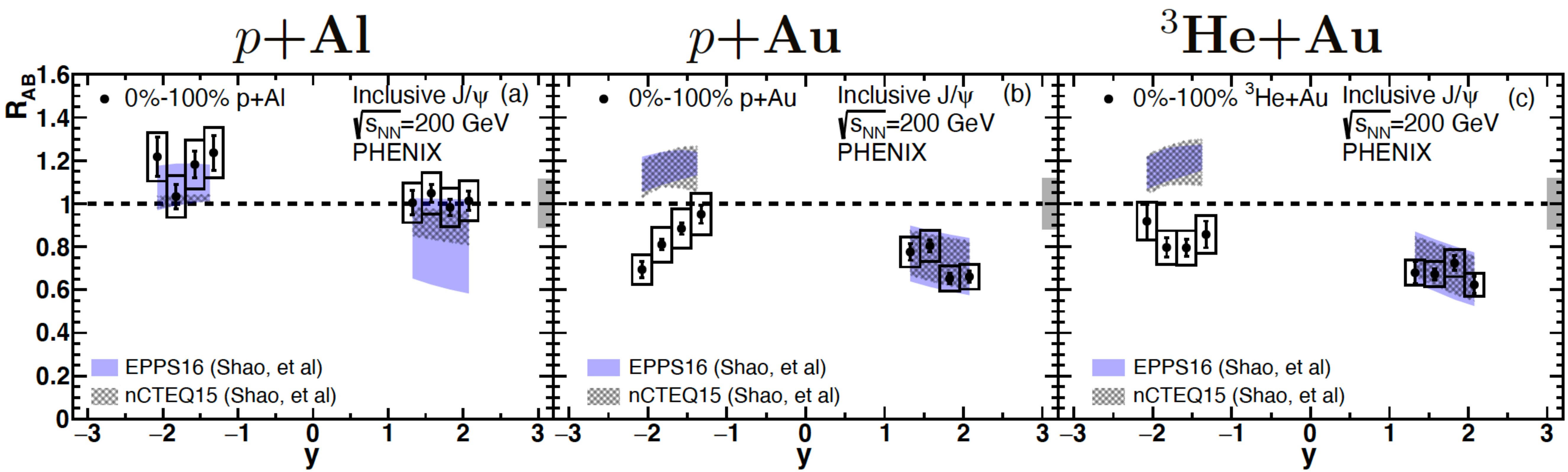
0-100% centrality, p_T integrated.



Rapidity dependence, p_T and centrality integrated

0-100% centrality, p_T integrated.

- Add EPPS16 and nCTEQ15 shadowing, with Bayesian re-weighting.



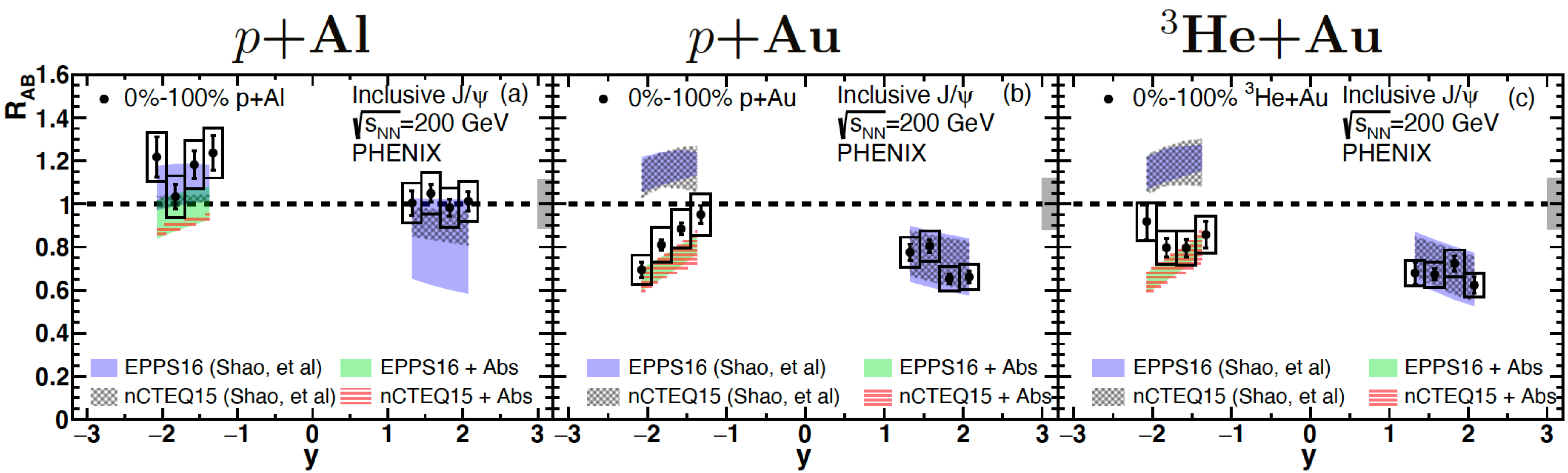
Nice agreement at forward rapidity.

Anti-shadowing alone at backward rapidity does not describe the data.

Rapidity dependence, p_T and centrality integrated

0-100% centrality, p_T integrated.

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

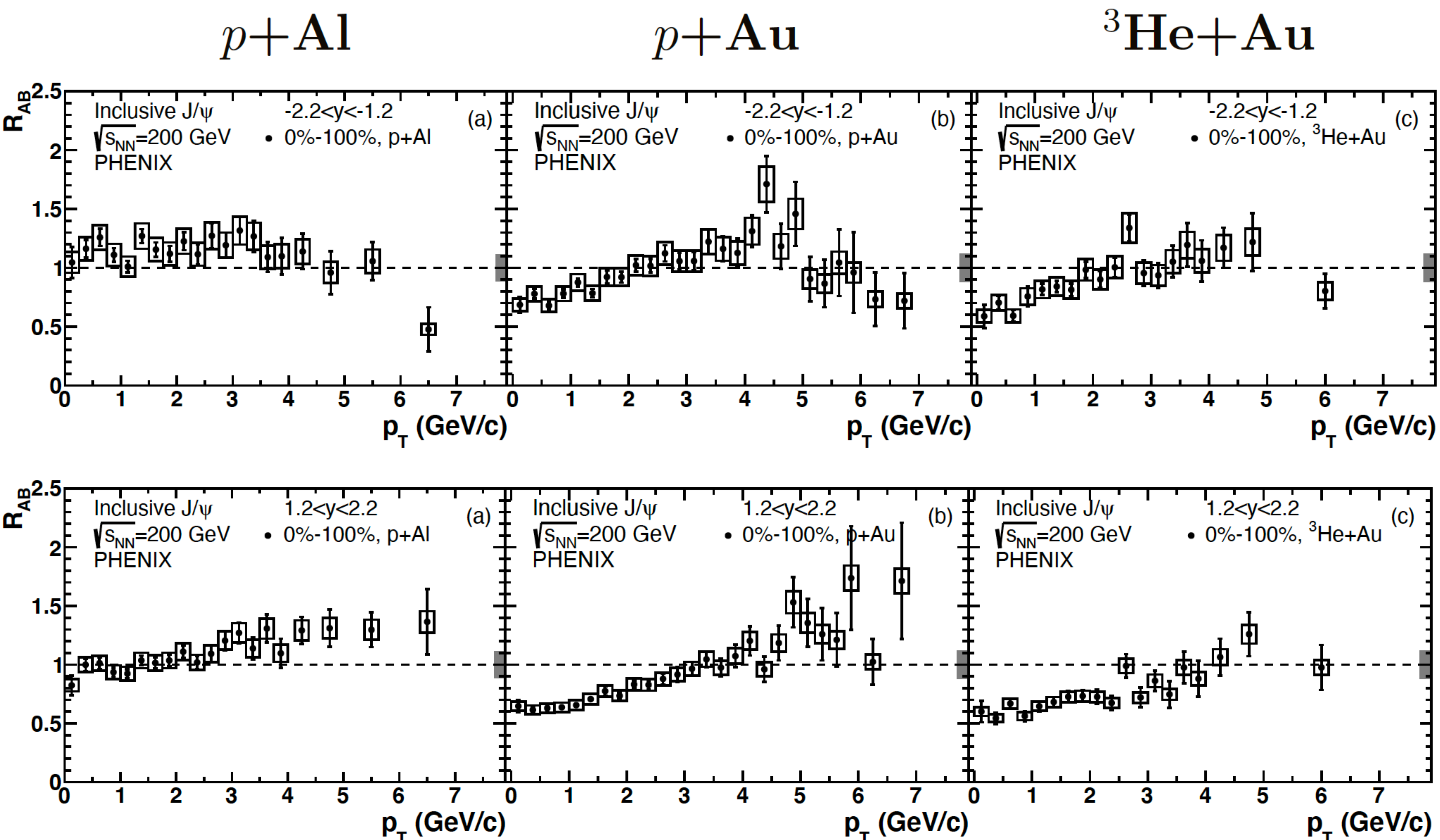


Not so bad!

How about the p_T dependence?

p_T dependence, 0-100% centrality

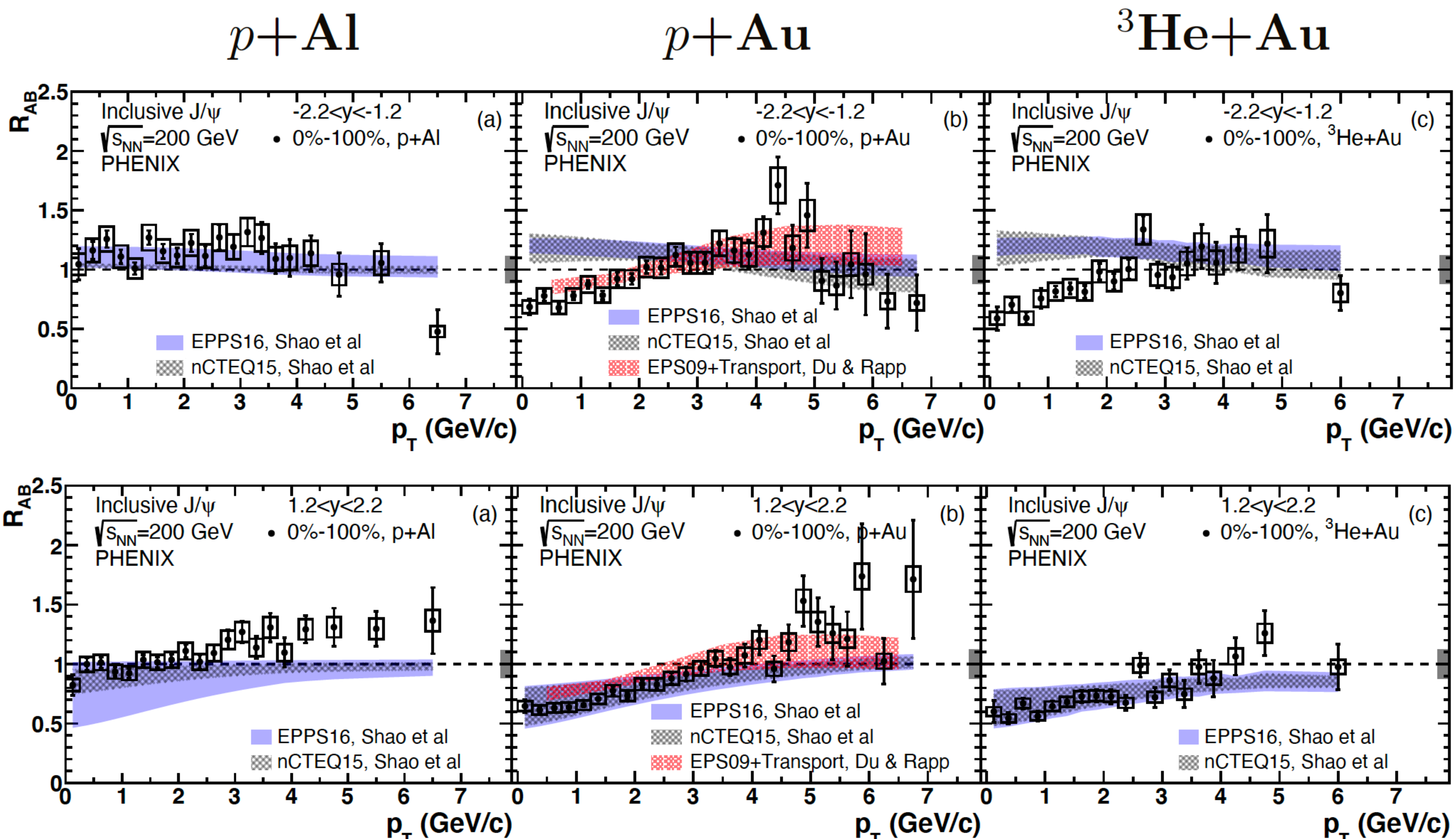
Top row: Backward rapidity
Bottom row: Forward rapidity



p_T dependence, 0-100% centrality

Blue: Bayesian re-weighted shadowing only

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



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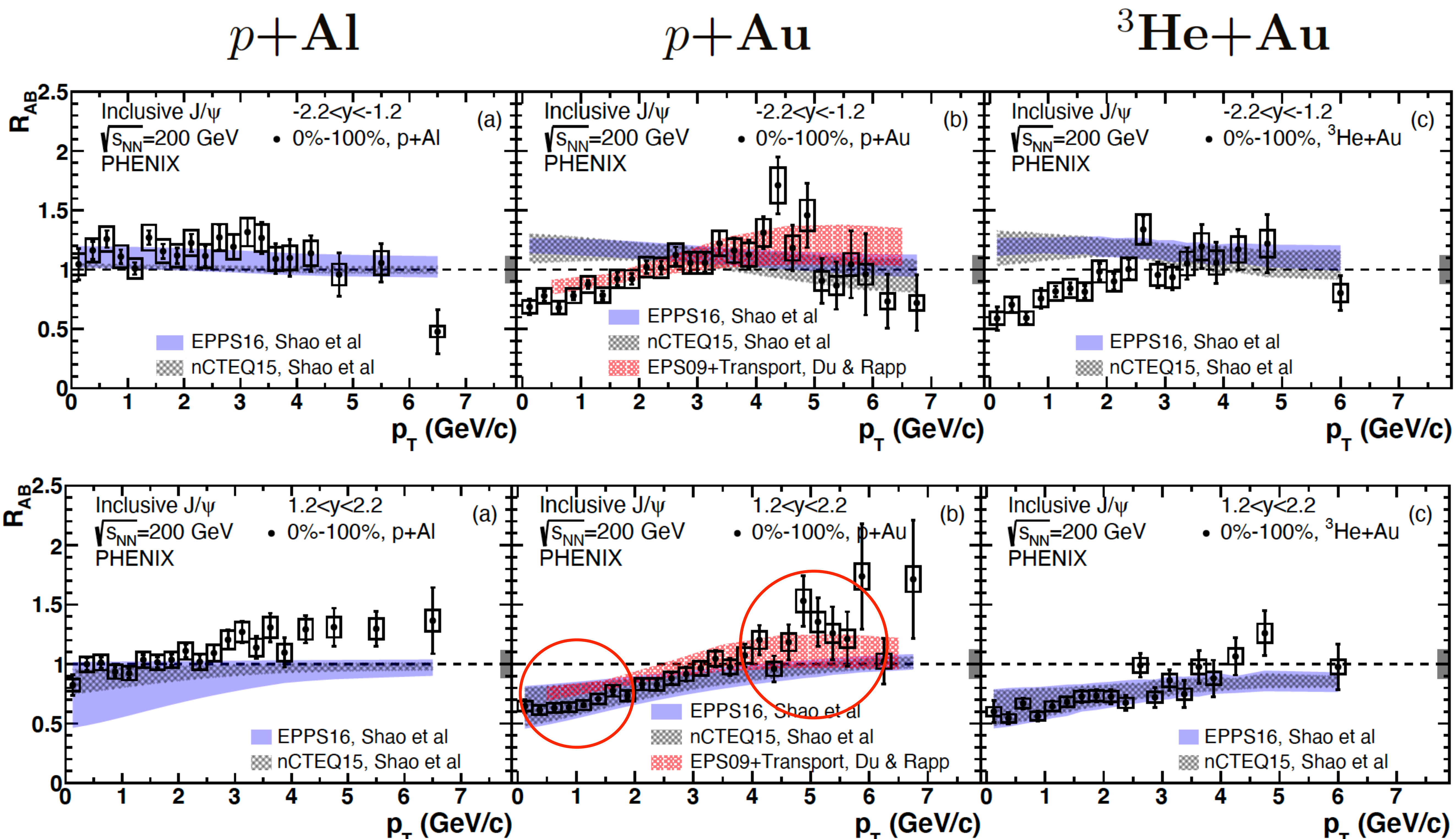
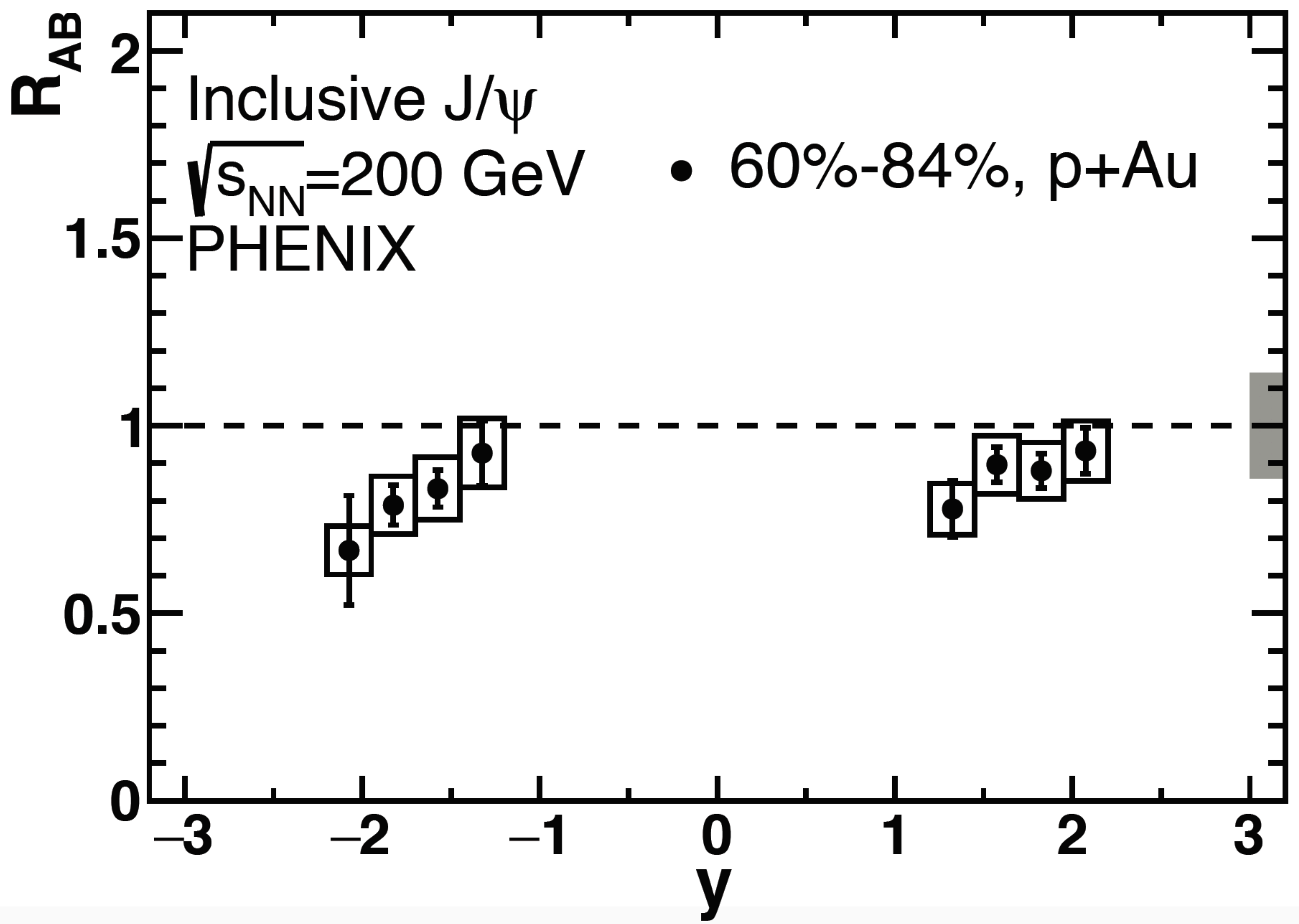
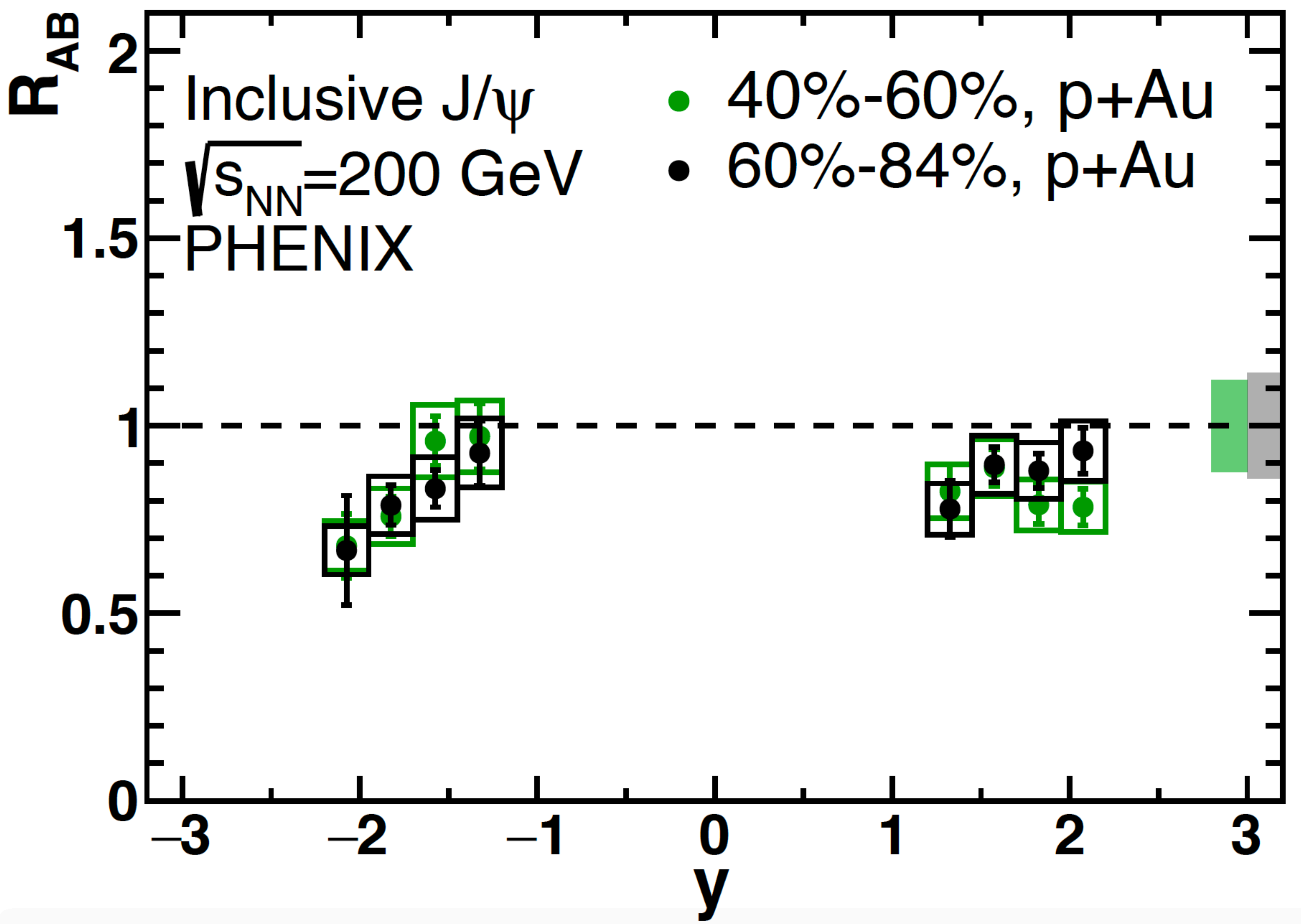


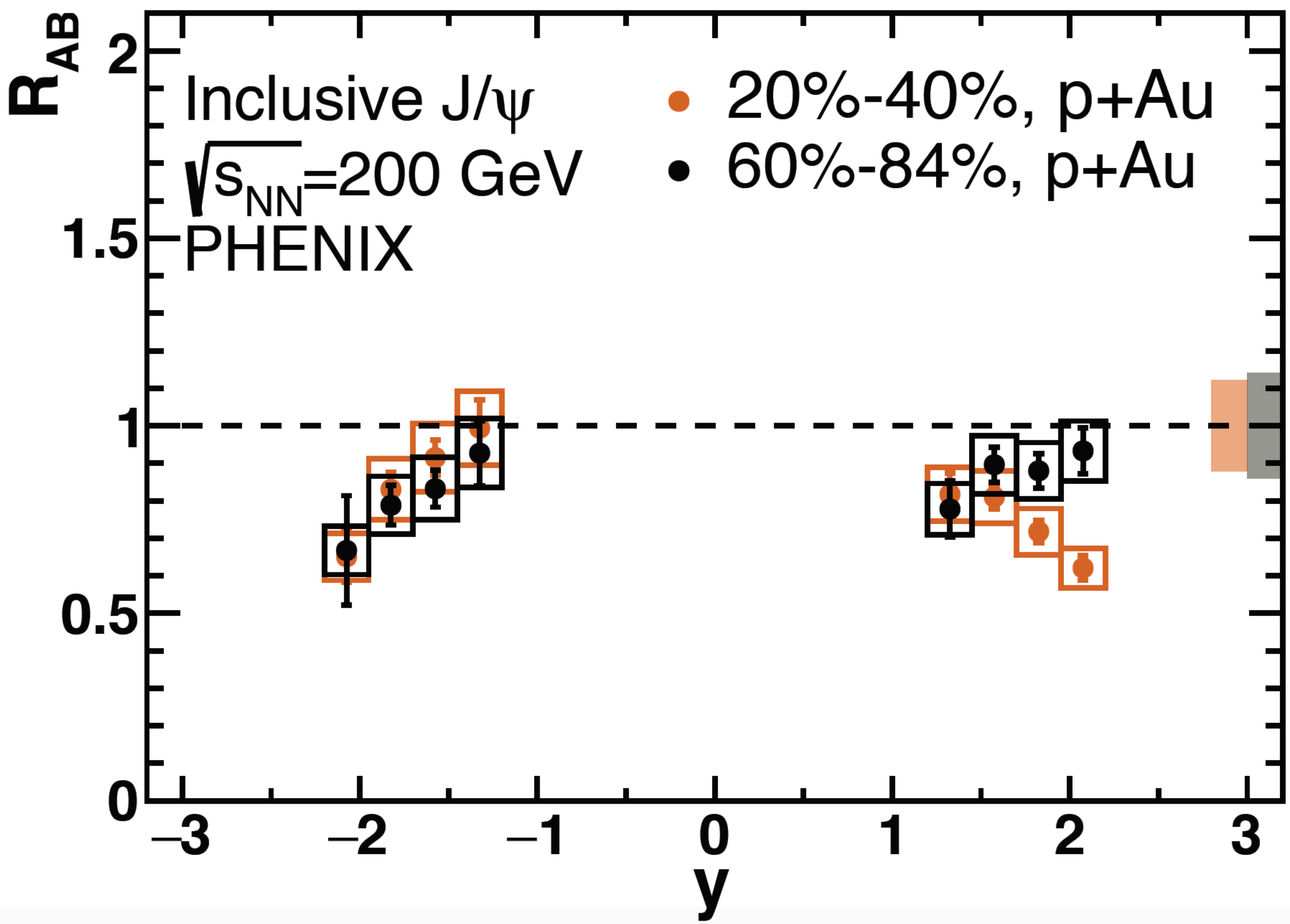
p+Au centrality dependence



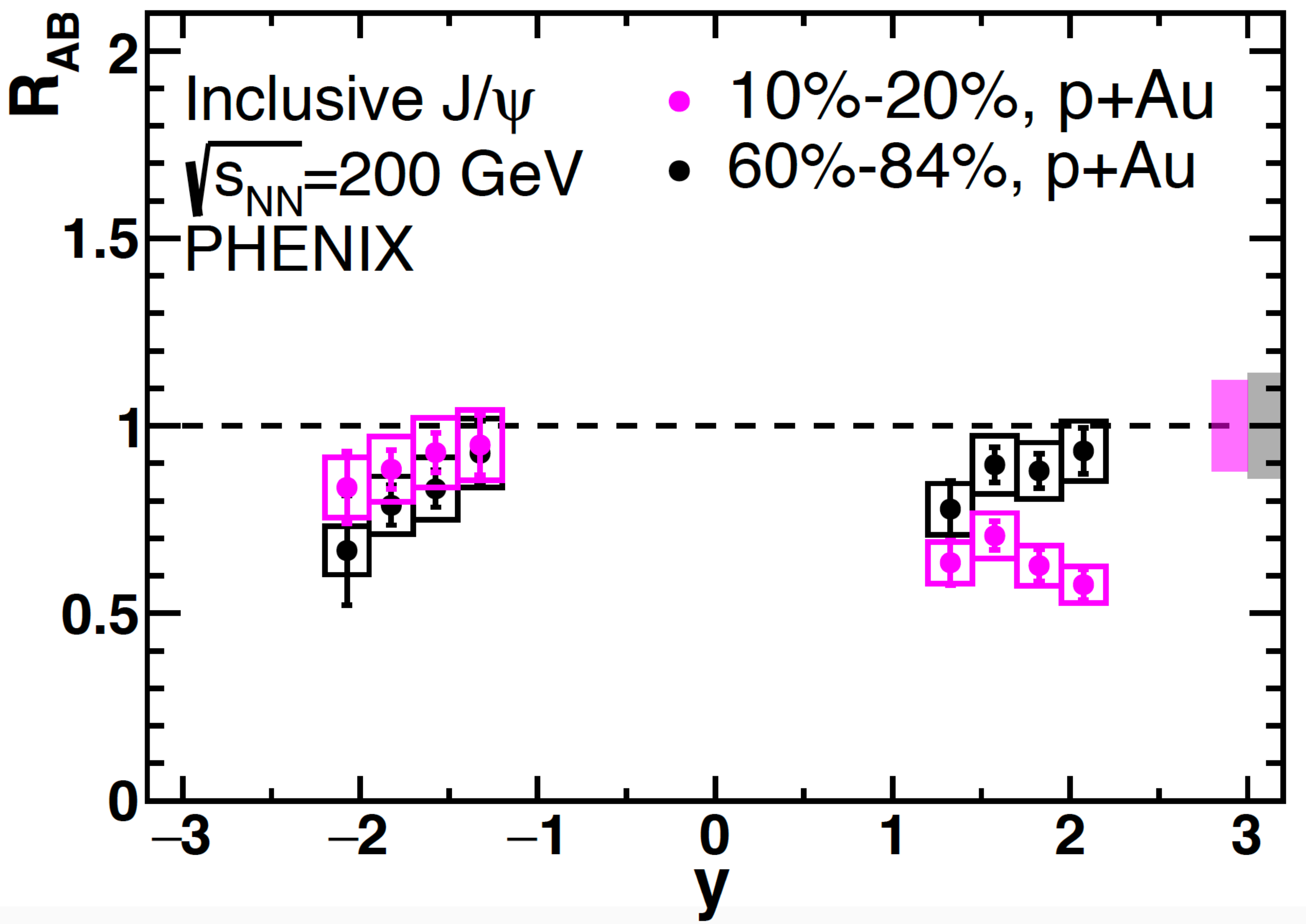
p+Au centrality dependence



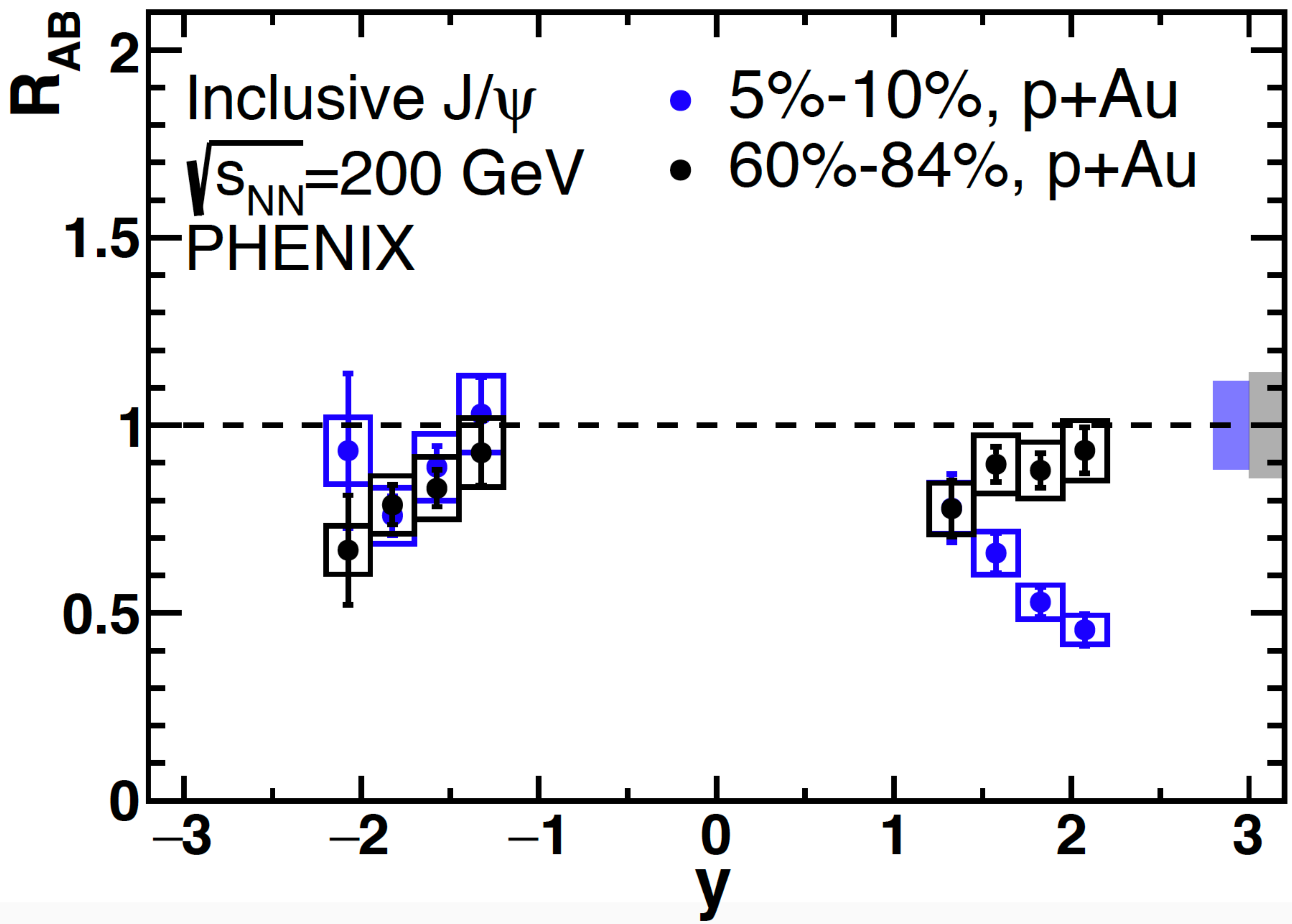
p+Au centrality dependence



p+Au centrality dependence



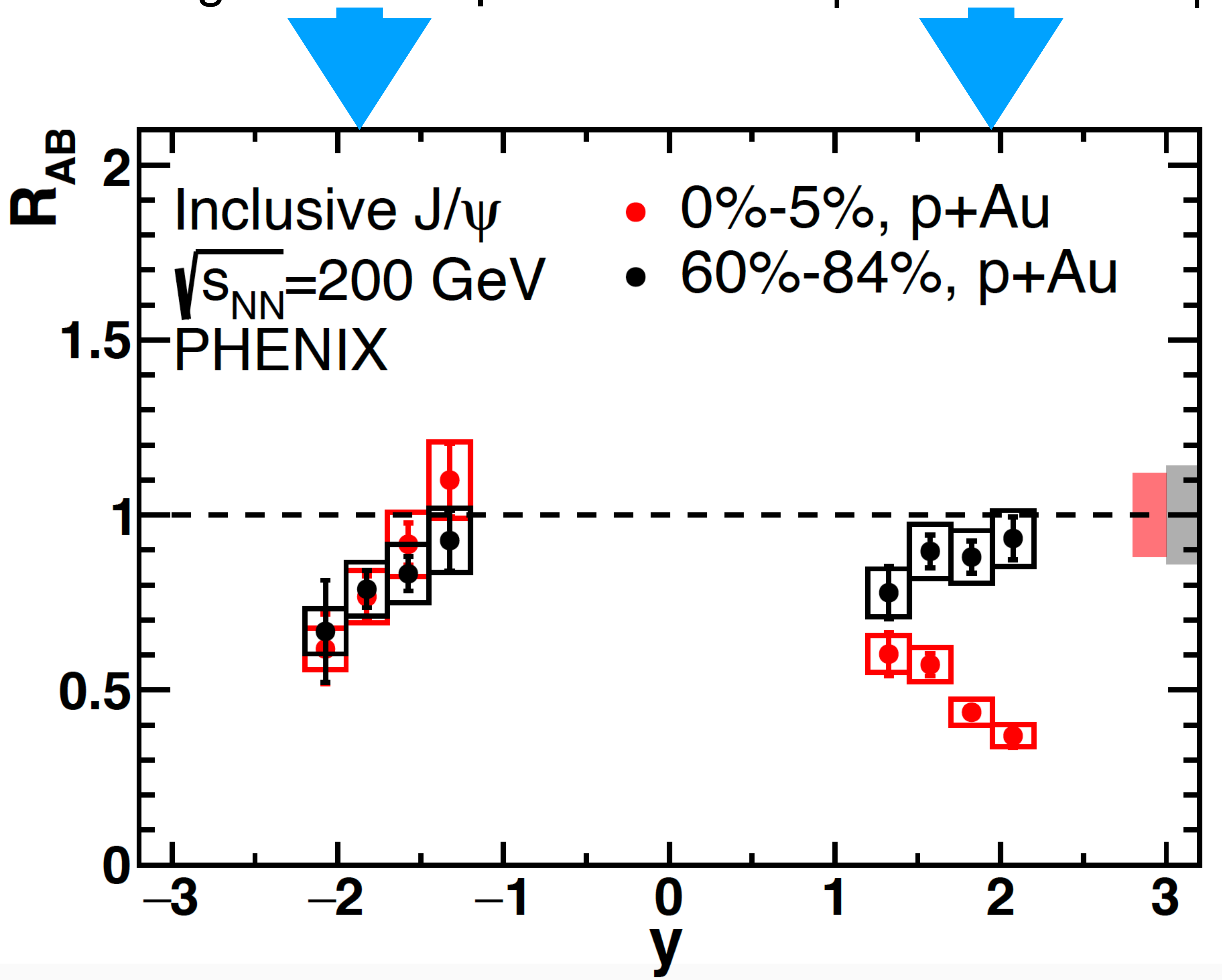
p+Au centrality dependence



p+Au centrality dependence

Trade-off between anti-shadowing and absorption.

Very strong centrality dependence of suppression.

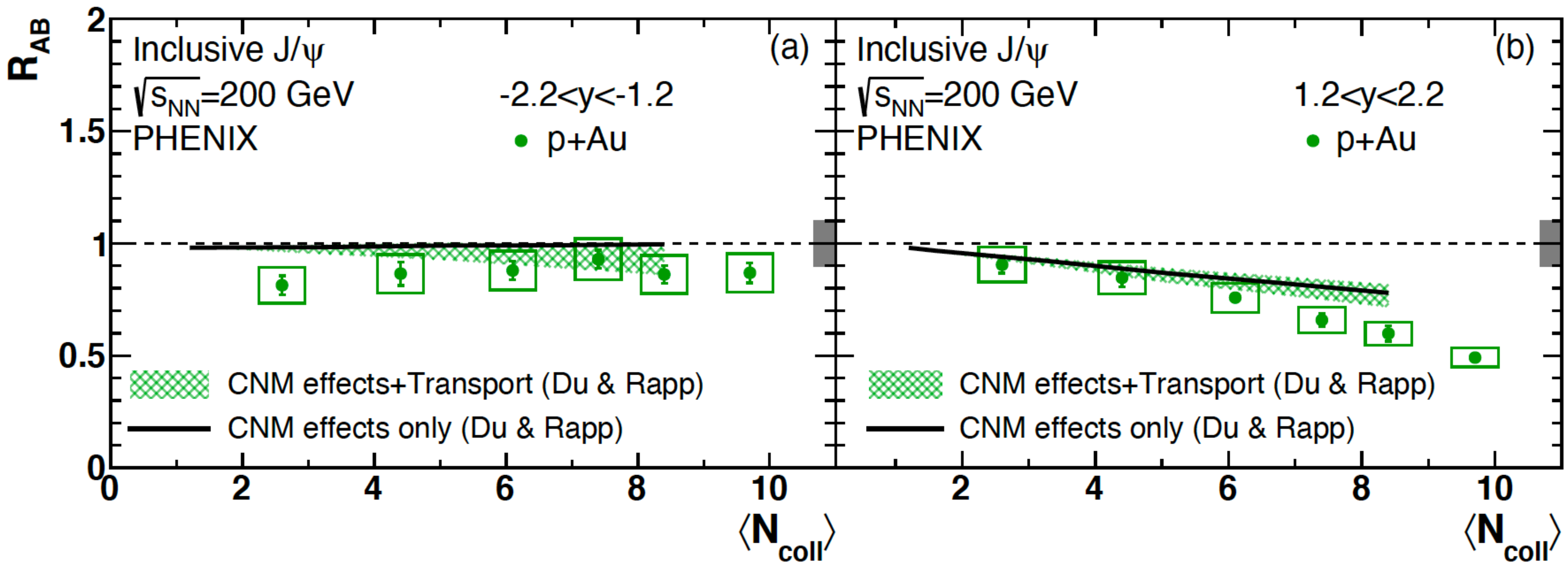


p+Au N_{coll} dependence

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

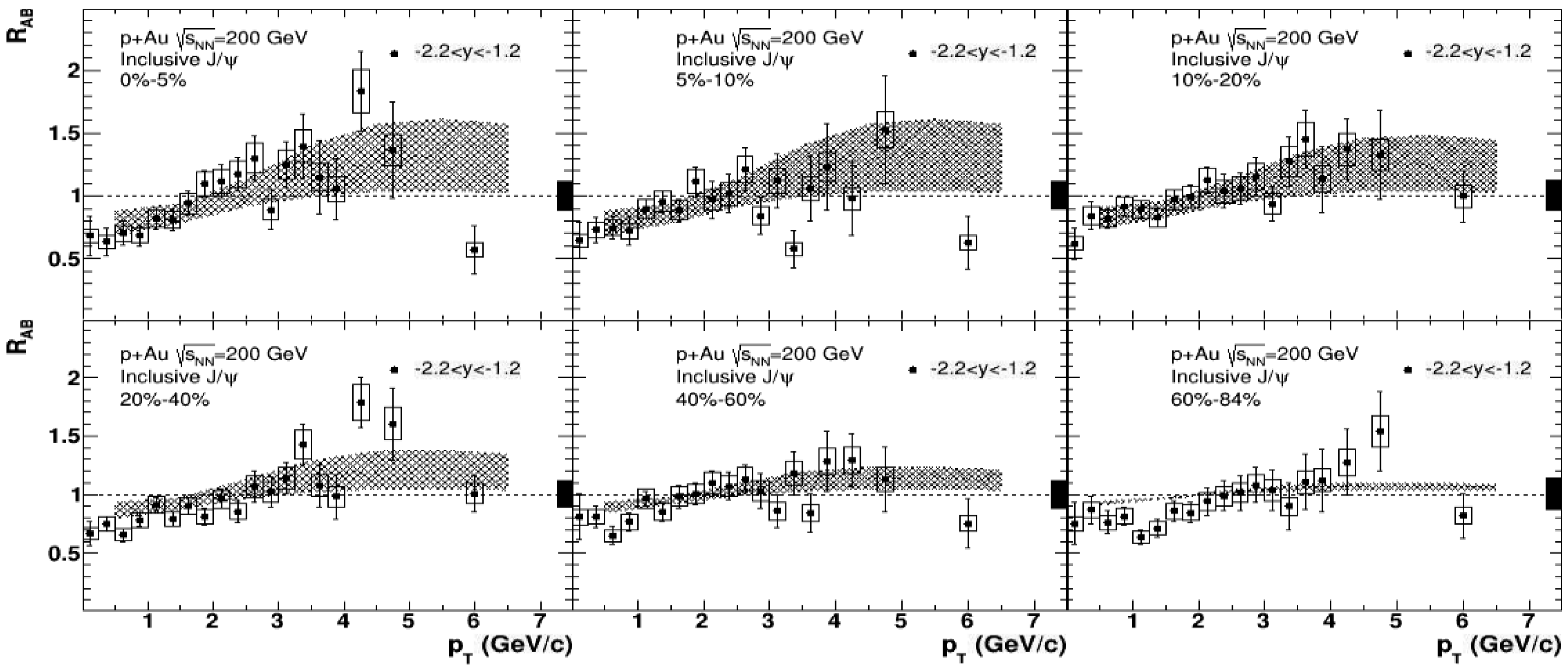
Forward rapidity suppression is dominated by EPS09 shadowing.

- Centrality dependence is assumed to be linear.
- Underpredicts suppression considerably!



p+Au p_T dependence, binned in centrality

Backward rapidity -2.2 < y < -1.2
Compared with transport model

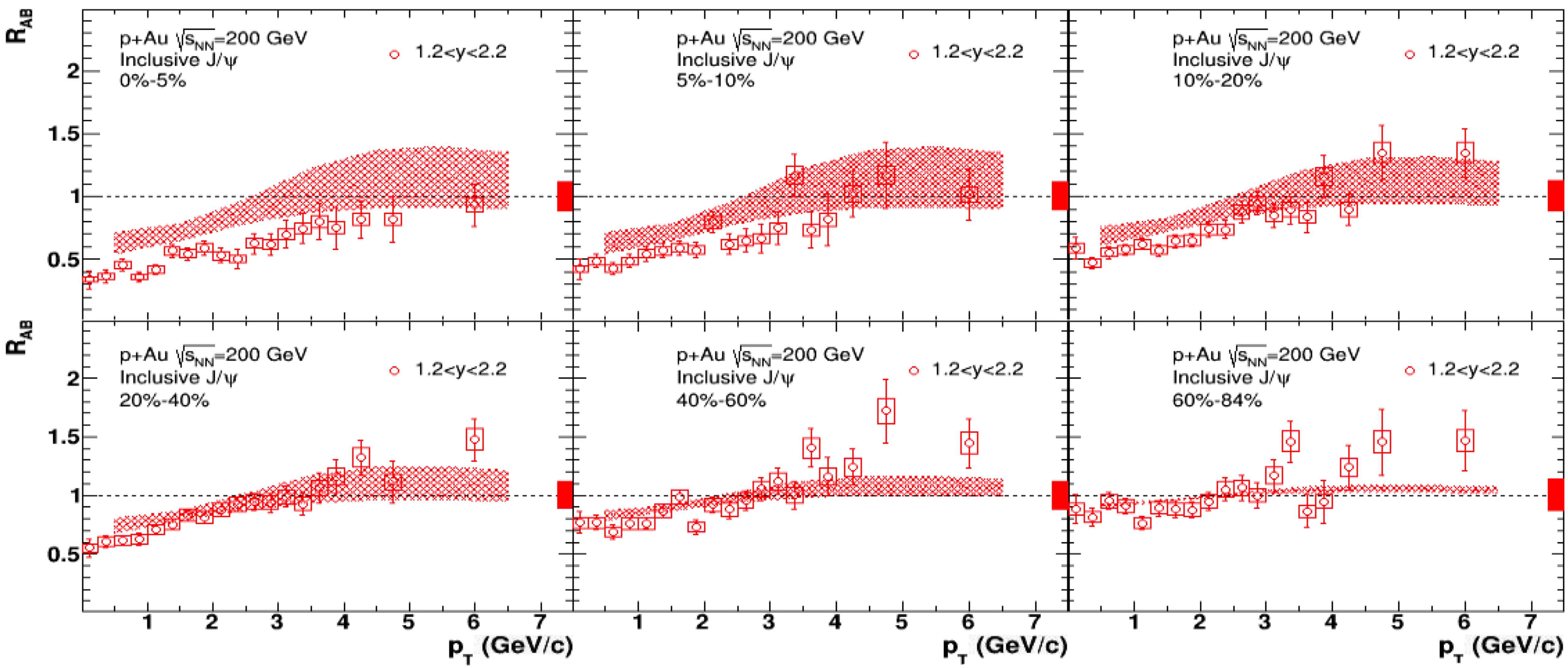


Transport model does a good job at backward rapidity.

p+Au p_T dependence, binned in centrality

Forward rapidity 1.2 < y < 2.2

Compared with transport model



Remember: Transport model has very small effect from medium at forward y.

So: EPS09 shadowing does not have a strong enough centrality dependence.

Bayesian re-weighted shadowing describes 0-100% data well

- But has no centrality prediction.

Comments

The centrality and p_T integrated data are described well by the Bayesian re-weighted shadowing parameterizations.

- Requires the addition of nuclear absorption at backward rapidity.

The p_T dependence of the centrality integrated data at forward rapidity is well described.

- Shadowing alone needs some p_T broadening added, but does pretty well.

The centrality dependence at forward rapidity is not understood.

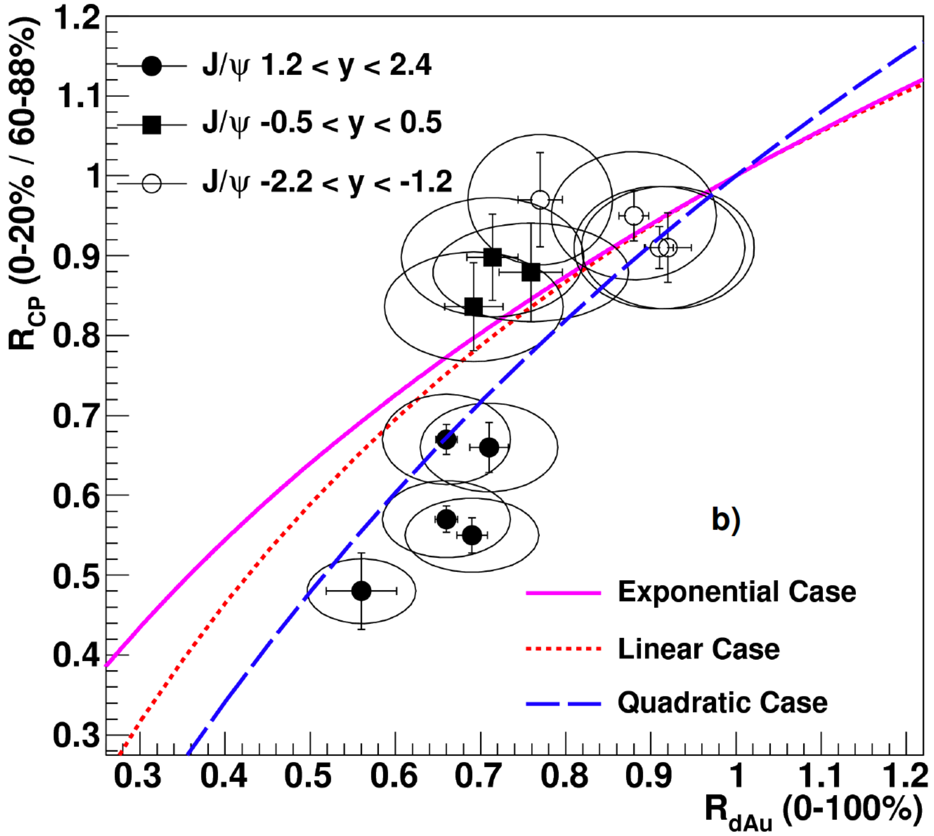
- The shadowing parameterizations are fitted to centrality integrated data.
- An attempt to determine centrality dependence from the target mass dependence of data (EPS09s: Helenius et. al., JHEP 1207 (2012) 073) does not describe data.
- So you have to make up your own centrality dependence of shadowing.

Shadowing centrality dependence

The centrality dependence of shadowing is an unsolved problem.

This plot from PHENIX d+Au J/ψ data indicates that the forward rapidity shadowing needs a **stronger than quadratic** dependence on nuclear thickness to match the rapidity dependence of the data.

PHENIX, PRL 107 (2011) 142301



A later study (McGlinchey et.al. PRC 87 (2013) 5, 054910) concluded that shadowing was **heavily concentrated at small impact parameter** for d+Au.

Our new p+Au data set has advantages for studying this.

- The connection of impact parameter to centrality is more direct in p+Au.
- High statistical precision allows fine binning for central collisions.

Summary

Measured J/ψ modification in p+Al, p+Au and ^{3}He+Au.

Increased modification in ^{3}He+Au over p+Au is small
- Consistent with Du and Rapp transport model
- Future work: try to extract ψ(2S) in p+Au (and maybe ^{3}He+Au).

0-100% centrality, p_T integrated data well described:
- $1.2<y<2.2$: by Bayesian re-weighted shadowing alone
- $-2.2<y<-1.2$: needs addition of absorption prediction from model

p_T dependence of 0-100% centrality data
- $1.2<y<2.2$: Bayesian re-weighted shadowing, needs p_T broadening
- $-2.2<y<-1.2$: Bayesian re-weighted shadowing needs absorption
- Transport model does well at both rapidities

Centrality dependence of p+Au data compared with transport model
1.2<y<2.2: **very** strong increase with centrality, not described by EPS09
-2.2<y_-1.2: Does well

Backup

J/ψ in p+Pb at 5.02 TeV

ALICE, JHEP 1511 (2015) 127

Left: Negative rapidity

Right: Positive rapidity

Compared with calculations using EPS09 shadowing (blue)

Energy loss in cold matter (red)

No absorption cross section at LHC energy (crossing time).

- EPS09 shadowing works OK at backward rapidity.
- But underpredicts suppression at forward rapidity.