Charmonia in p+Al, p+Au and ^{3}He+Au collision systems

Krista Smith

Florida State University

Brookhaven National Lab
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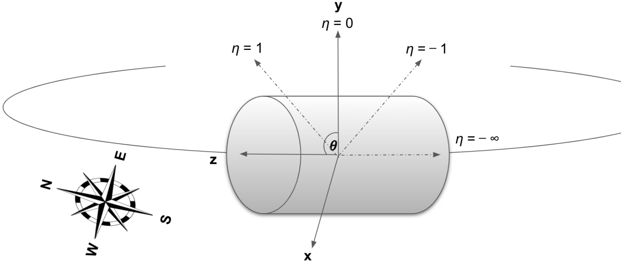
Overview

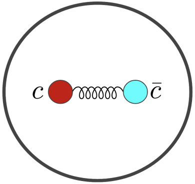
1. Charmonium
2. Motivation for Small Systems
3. Signal Reconstruction
4. Theoretical Predictions
5. J/ψ Nuclear Modification Results
6. Future Analysis: $\psi(2S)$
7. Conclusion

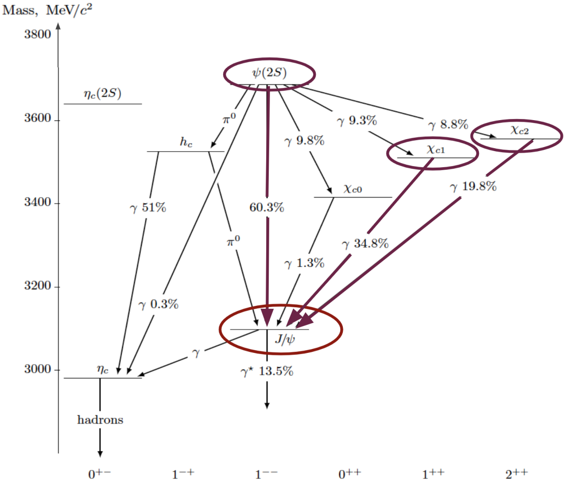


Charmonium

Charmonium Formation at RHIC

- Quarkonia is a short-lived bound state of quark- antiquark pairs $(c\bar{c}, b\bar{b})$
- Charmonium is bound state of charm-anticharm pairs
- Transitions can be made to lower states through photon emission
- Gluon gluon fusion (ggf) produces charm-anticharm quark pairs
  $\sim 2\%$ of all created $c\bar{c}$ pairs at RHIC will form Charmonium states
- $c\bar{c}$ pairs that form Charmonium occur with total energy below the threshold for strong decays
  - $c\bar{c}$ pair has small relative velocity $v/c \ll 1$





Charmonia Level Scheme

- Inclusive J/ψ contributions
  - $\sim$ 60% direct production
  - $\sim$ 30% χ_c states
  - $\sim$ 10% decays from ψ(2S)
- Vector mesons J/ψ and ψ(2S) can decay directly to dileptons via virtual photons
- χ_c states decay to J/ψ via photon emission

Phys. Letters B561 (2003), 61-72. Left: Image Credit M. Teklishyn

Inclusive $J/\psi \rightarrow \mu^+\mu^-$

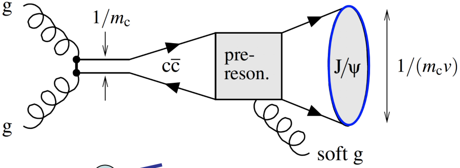
Sources of Signal

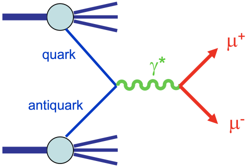
- ggf for Charmonium production
- Feedown from χ_c and $\psi(2s)$
- Contributions from B–meson decays

Sources of Background

- Hadrons misidentified as muons
- Dimuon pairs kinematically unrelated
- Dimuons from Drell Yan
- Open heavy flavor decays
  - Predominantly D–meson decays

B $\longrightarrow$ $J/\psi + X$





D $\longrightarrow$ $\pi + K + X$

$\pi \longrightarrow \mu + X$

$K \longrightarrow \mu + X$

From top: B–meson decays, Gluon gluon fusion, Drell Yan and D-meson decays

Motivation for Small Systems

Inclusive J/ψ Results in Small Systems

- 2003, 2008 d+Au at $\sqrt{s_{NN}} = 200$ GeV

  PHENIX added 3 new small systems data sets

- 2014 ^{3}He+Au at $\sqrt{s_{NN}} = 200$ GeV
- 2015 p+p, p+Al, p+Au at $\sqrt{s_{NN}} = 200$ GeV

PHENIX has measured the inclusive $J/\psi \rightarrow \mu^+\mu^-$ nuclear modification across three collision systems. The systems, which have different projectile and target sizes, are compared at the same collision energy.

*Paper submitted (**arXiv:1910.14487**)*

J/ψ Final State Effects in p+A Collisions?

d+Au and p+Pb

- Strong suppression observed for ψ(2S) with respect to J/ψ
  - Not expected if only CNM effects present
  - Final state interactions with co-movers

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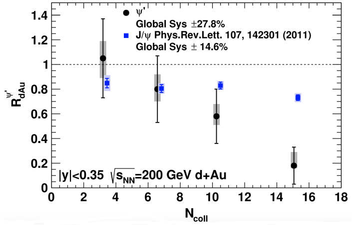
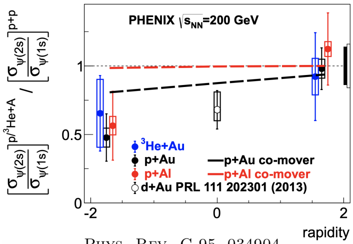


Phys. Rev. Letters 111, 202301



Phys. Rev. C 95, 034904

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Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions

J/ψ Final State Effects in p+A Collisions?

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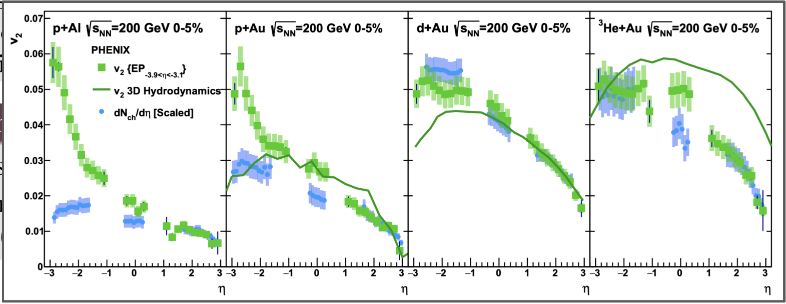


Phys. Rev. Letters 121, 222301

J/ψ Final State Effects in p+A Collisions?

d+Au and p+Pb

- Strong suppression observed for ψ(2S) with respect to J/ψ
  - Would not be expected if only CNM effects are present
  - Final state interactions with co-movers

Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions
  - Transport models extended to small systems and can describe the preferential ψ(2S) suppression

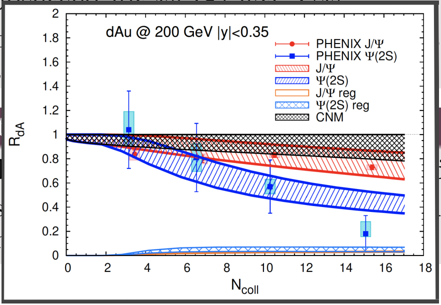
J/ψ Final State Effects in p+A Collisions?

d+Au and p+Pb

- Strong suppression observed for ψ(2S) wrt J/ψ
  - Would not be exp
  - Final state intera

Flow in Small Systems at

- Consistent with QGI ions
  - Transport models escribe the preferential ψ(2S) suppressior



J. High Energy Phys. 03, 015

J/ψ Final State Effects in p+A Collisions?

d+Au and p+Pb

- Strong suppression observed for ψ(2S) wrt J/ψ
  - Would not be expected if only CNM effects are present
  - Final state interactions with co-movers

Flow in Small Systems at LHC and RHIC

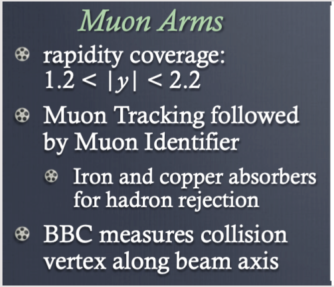
- Consistent with QGP production in most central collisions
  - Transport models can describe the preferential ψ(2S) suppression

Question

- Evidence of final state effects on the J/ψ by comparing p+Au and ^{3}He+Au?

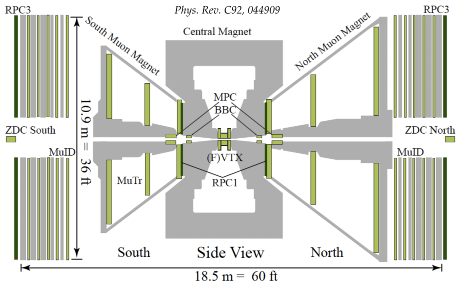
Signal Reconstruction

PHENIX Detector: Muon Arms



Muon Arms

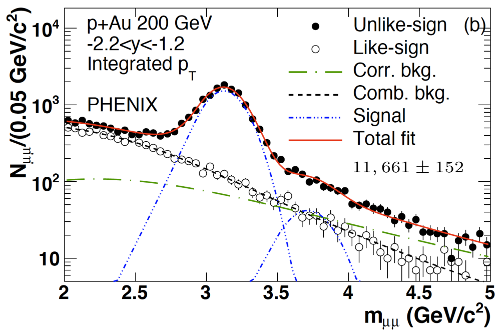
- rapidity coverage: $1.2 < |y| < 2.2$
- Muon Tracking followed by Muon Identifier
  - Iron and copper absorbers for hadron rejection
- BBC measures collision vertex along beam axis



Phys. Rev. C92, 044909

- MUID 2D Trigger records hits that satisfy trigger logic
- Centrality is measured using the BBC detector in the A-going direction

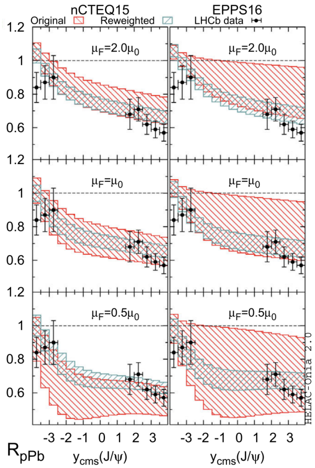
Dimuon Reconstructed Mass Distribution



arXiv:1910.14487

- ● Unlike-sign reconstructed muon pairs
- ○ Like-sign reconstructed muon pairs
- 🟩 Correlated background
- ■ Fit to the combinatorial background
- 🟦 J/ψ, $\psi(2S)$ Crystal Ball fits
- 🟥 Total fit (sum of all fits)

Theoretical Predictions



(b) Prompt J/ψ

Reweighted Shadowing Model

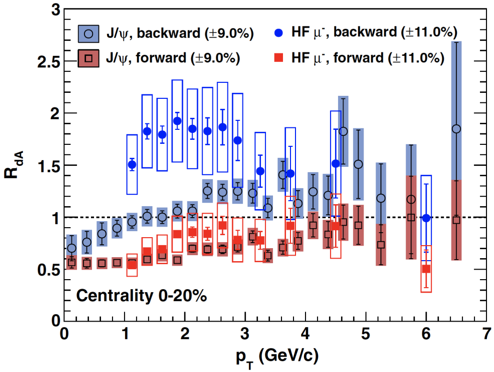
- nCTEQ15 and EPPS16 NLO predictions
- Based on reweighting method which uses tighter J/ψ constraints from LHC data (ALICE and LHCb)
    - Reweighting method is not used for the lighter Helium and Aluminum nuclei
- Include PHENIX $p{+}p$ measurements as baseline
- Dominant uncertainty is the energy scale $\mu_0 = M^2 + p_T^2$
    - Predictions were calculated at three different energy scales: μ_0, $0.5\mu_0$ and $2\mu_0$
- Uncertainty band shown in results is at 68% CL, and is envelope of uncertainty bands at the three energy scales

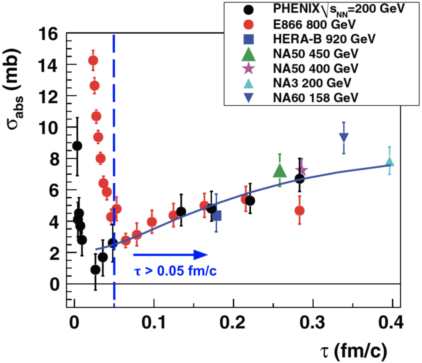
Shao, et al: Phys. Rev. Letters 121, 052004

J/ψ Nuclear Absorption Needed

- Forward rapidity: J/ψ suppression similar to open charm suppression
    - Consistent with shadowing and/or parton energy loss
- Backward rapidity: J/ψ suppressed relative to open charm
    - Expect open charm to be enhanced by anti-shadowing
    - J/ψ suppression consistent with absorption due to collisions with nucleons in the target
    - Possible contribution also from co-movers

Phys. Rev. Letters 112, 252301

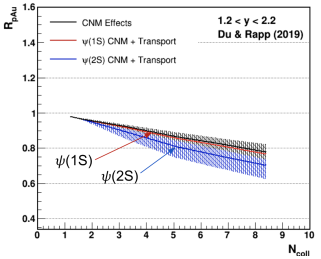


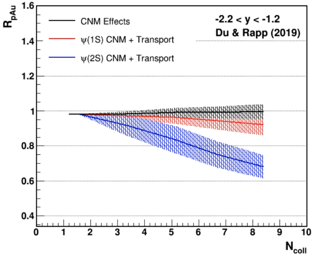


Nuclear Absorption Model

- Parameters estimated from fit to world data
  - Absorption cross sections extracted from gluon shadowing corrected p/d+A data (EPS09, EKS98)
- Absorption cross section is modeled as function of time spent traversing the nucleus
  - Model assumes $c\bar{c}$ pair expands linearly with time
  - Valid for time scales comparable with formation time in nucleus
- Folded into Shao et. al. predictions at backward rapidity only

Phys. Rev. C 87, 054910 2013 Phys. Rev. C 61, 054906 2000





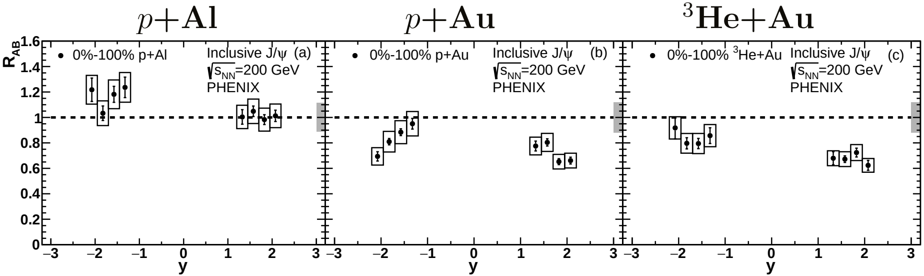
Transport + CNM Effects Model

- EPS09 NLO + Transport Model
- Adapted from original model by Zhao & Rapp for A+A collisions
  - Model previously extended to *d*+Au collisions, now to *p*+A collisions
- Includes fireball, MC Glauber Model for initial conditions
- Shadowing from EPS09 NLO, p_T broadening included
- Nuclear absorption cross section constrained by PHENIX *d*+Au data included at backward rapidity

J/ψ Nuclear Modification Results

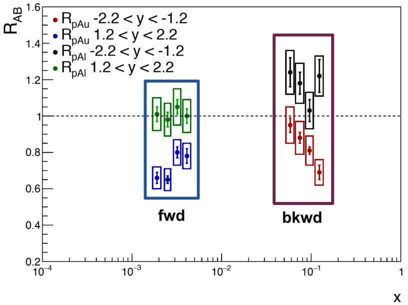
arXiv:1910.14487

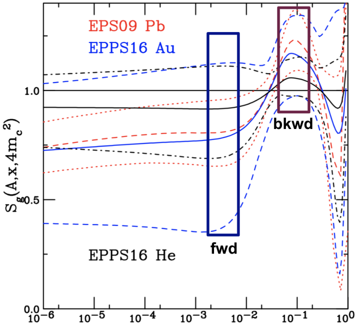
J/ψ Modification vs. Rapidity (0-100%)



- Suppression at forward rapidity for Au target
- Little modification at forward rapidity for Al target, as expected
- At backward rapidity, Al target shows enhancement but Au target does not

J/ψ Modification vs. Bjorken x





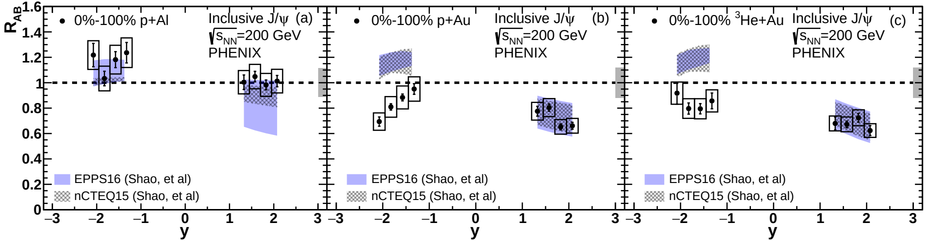
- R_{pAu} backward rapidity inconsistent with gluon modification (anti–shadowing)
  - R_{pAl} does not show same behavior as Au target

$$x = m\, e^{-y}/\sqrt{s_{NN}}$$

Left: Data taken from arXiv:1910.14487. Right, R. Vogt

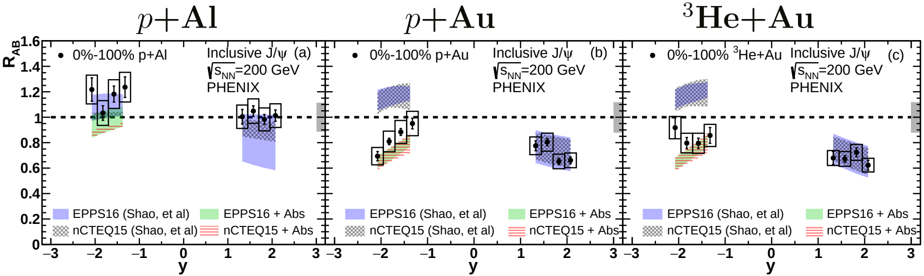
J/ψ Modification vs. Rapidity (0-100%)

p+Al **p+Au** **^{3}He+Au**



- Reweighted nCTEQ15 and EPPS16 predictions (NLO)
  - Agree well with data at forward rapidity
  - Do not agree at backward rapidity for Au target
    - Anti–shadowing only (no nuclear absorption)

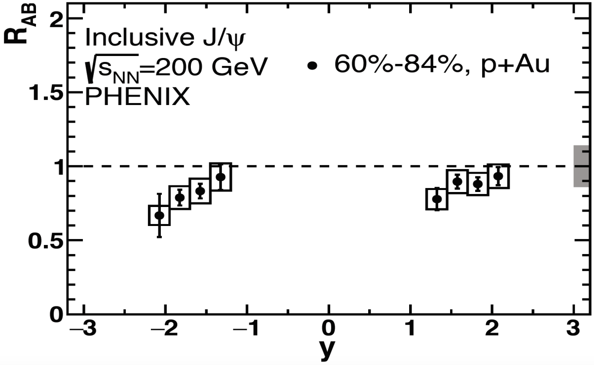
J/ψ Modification vs. Rapidity (0-100%)



- Reweighted nCTEQ15 and EPPS16 predictions
  - Added PHENIX nuclear absorption estimate at backward rapidity
    - Describe data reasonably well

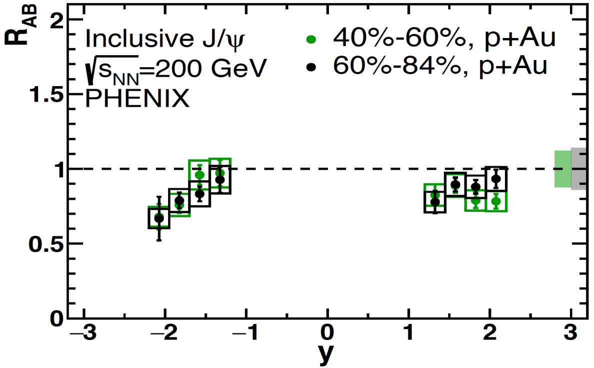
Centrality Dependence

p+**Au**



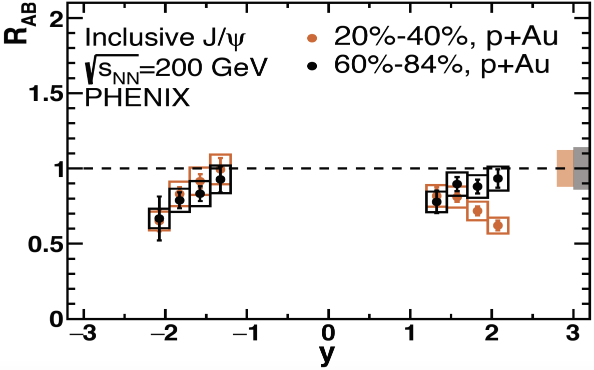
Centrality Dependence

p+**Au**



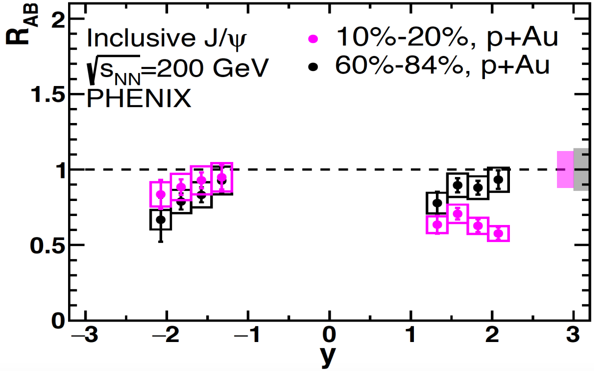
Centrality Dependence

p+Au



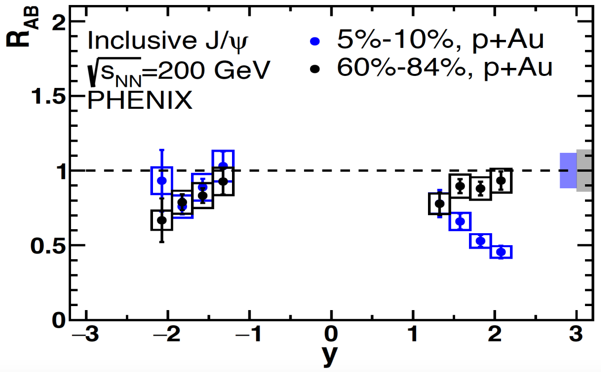
Centrality Dependence

p+Au



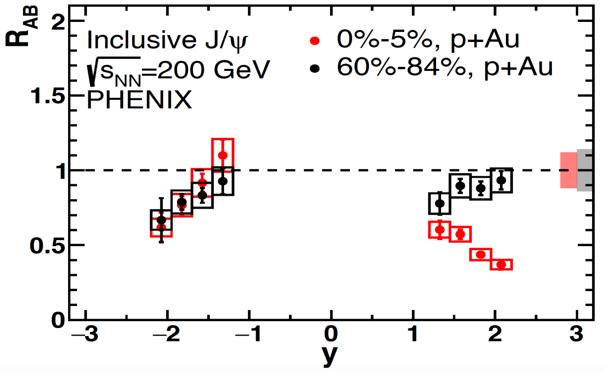
Centrality Dependence

p+Au

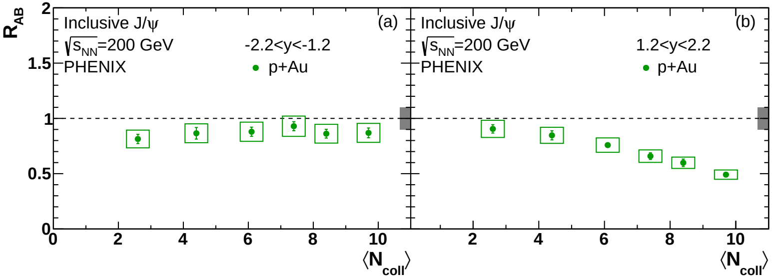


Centrality Dependence

p+Au

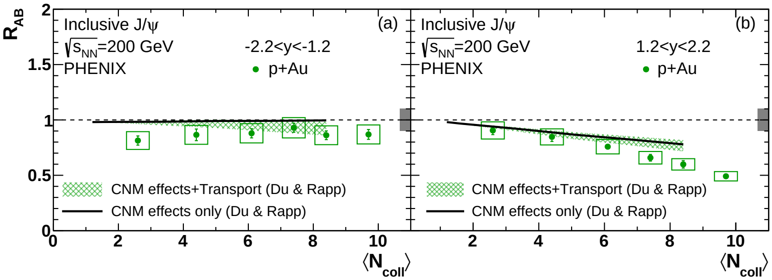


p+Au Dependence on $\langle N_{coll} \rangle$



- Little centrality dependence at backward rapidity
    - Consistent with trade off between anti-shadowing and nuclear absorption
- Strong centrality dependence at forward rapidity

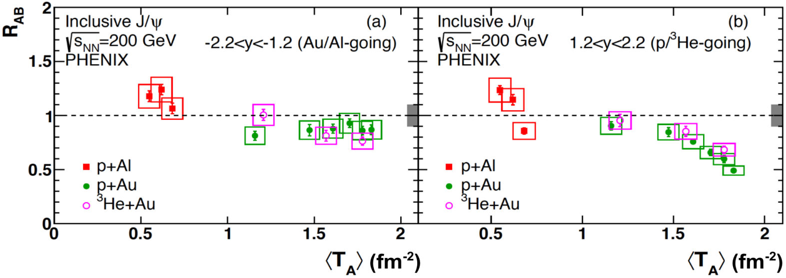
p+Au Dependence on $\langle \mathrm{N}_{\mathrm{coll}} \rangle$



- CNM effects+transport model
  - EPS09NLO with nuclear absorption at backward rapidity
- Little effect from transport model at forward rapidity
  - CNM suppression dominant

$\langle T_{\mathrm{A}} \rangle$ Dependence

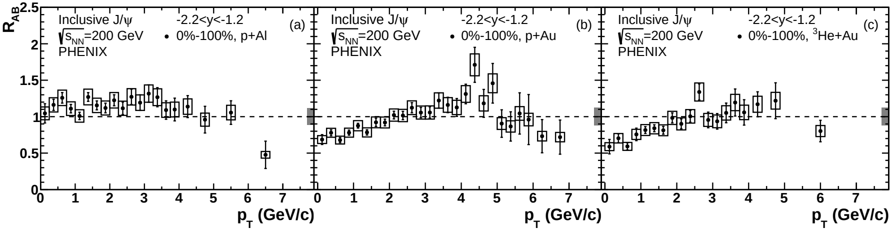
p+**Al** p+**Au** ^{3}**He**+**Au**



- Is modification determined only by target thickness?
  - Plot data vs. mean target thickness for hard processes
  - Data consistent with no projectile dependence

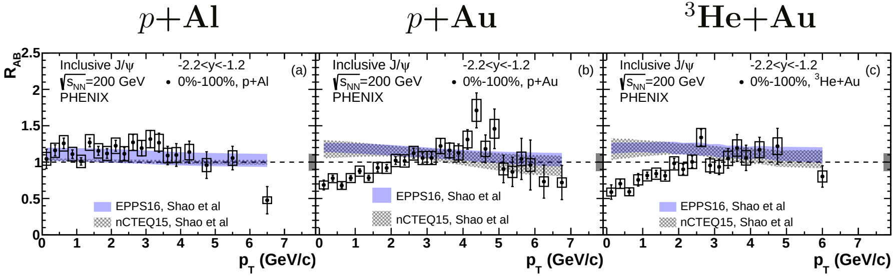
p_T Dependence, Backward Rapidity (0–100%)

p+Al **p+Au** **^{3}He+Au**



- Little modification in p+Al
- Similar modification between p+Au and ^{3}He+Au

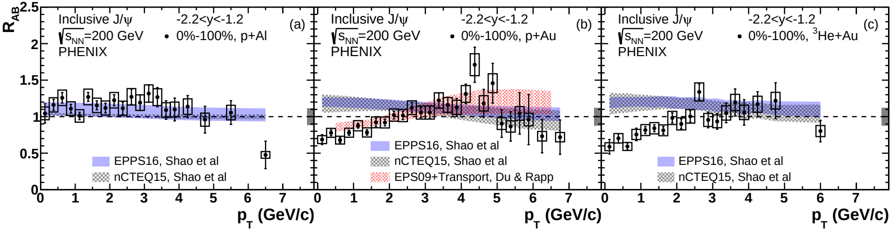
p_T Dependence, Backward Rapidity (0–100%)



- Reweighted shadowing only - no nuclear absorption

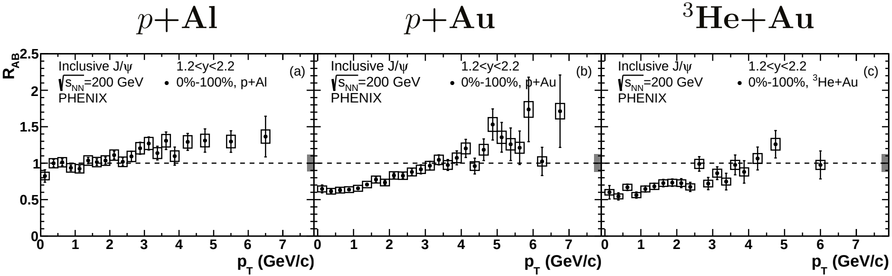
p_T Dependence, Backward Rapidity (0–100%)

p+Al p+Au ^{3}He+Au



- Transport model with nuclear absorption and p_T broadening

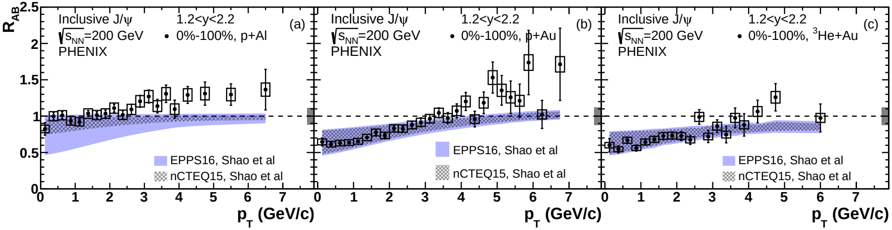
p_T Dependence, Forward Rapidity (0–100%)



- No modification for p+Al
- Similar modification between p+Au and ^{3}He+Au

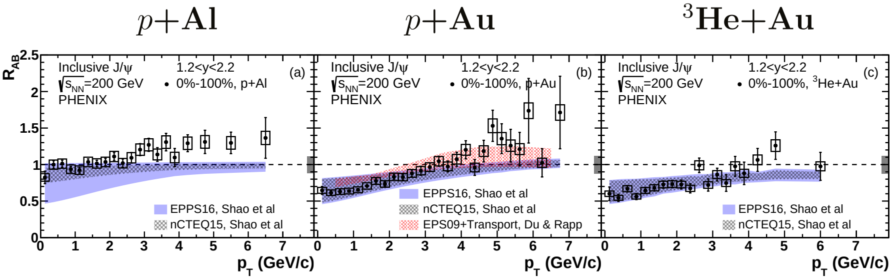
p_T Dependence, Forward Rapidity (0–100%)

p+Al $\quad$ p+Au $\quad$ ^{3}He+Au



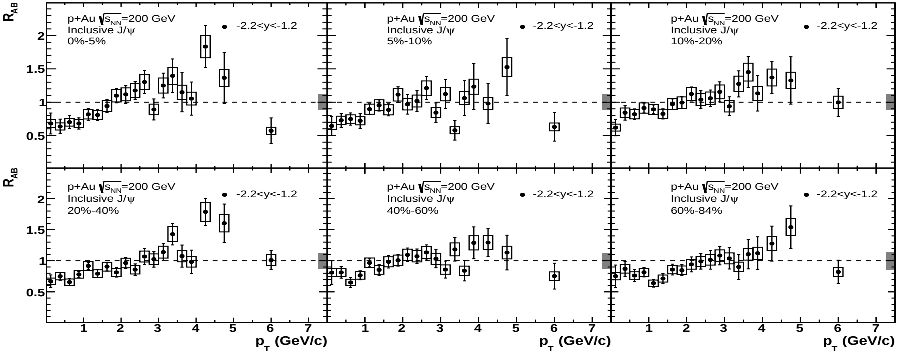
- Reweighted shadowing alone does well at low p_T

p_T Dependence, Forward Rapidity (0–100%)



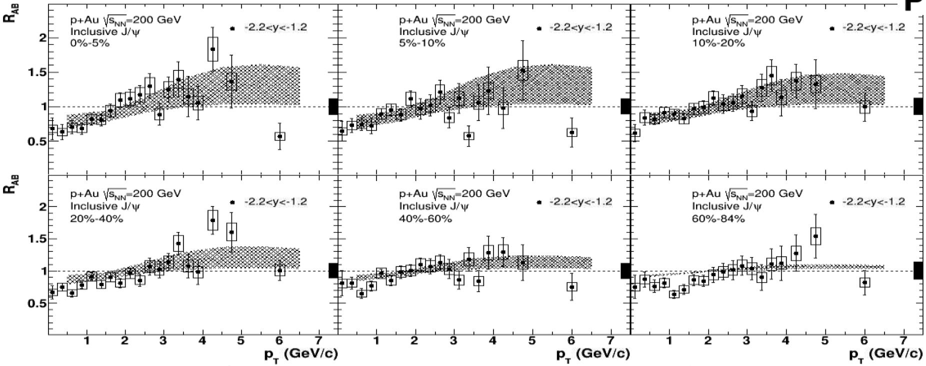
- Transport model with EPS09 + p_T broadening

p+Au Centrality Dependence, Bkwd Rapidity



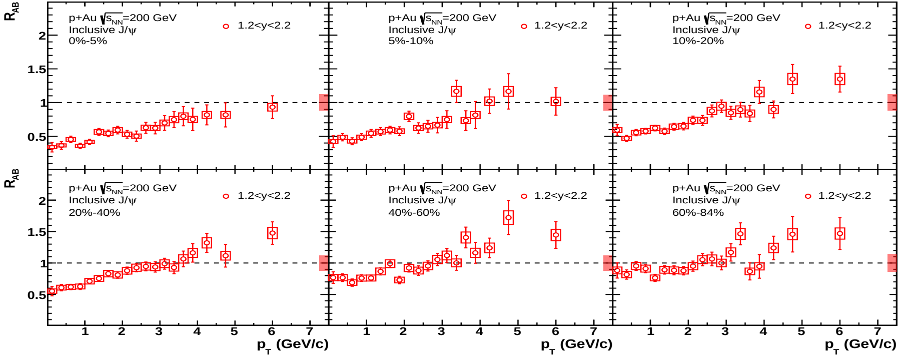
- Suppression at low p_T for most central collisions
  - Competition between nuclear absorption and anti-shadowing

p+Au Centrality Dependence, Bwd Rapidity



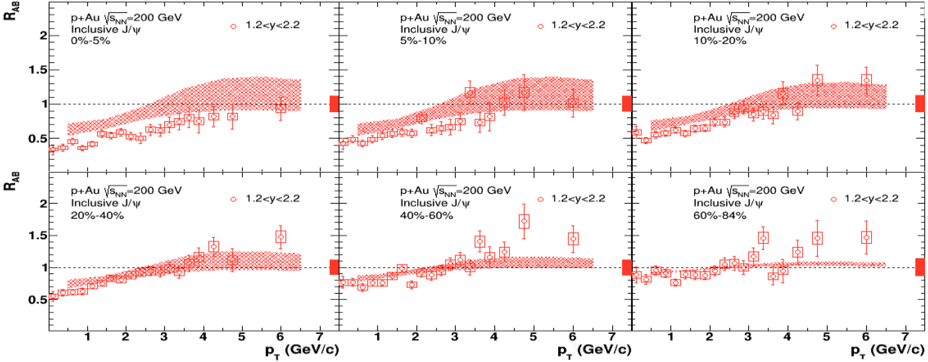
- Transport model includes nuclear absorption and p_T broadening
- Describes data well across full p_T range

p+Au Centrality Dependence, Fwd Rapidity



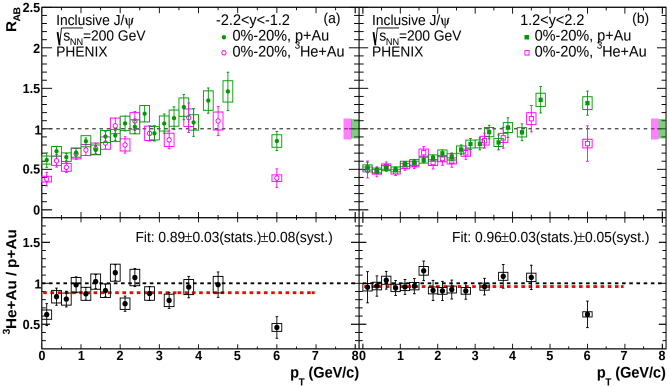
- Very strong suppression in most central collisions

p+Au Centrality Dependence, Fwd Rapidity



- Transport effects small at forward rapidity
  - EPS09 shadowing dominates model calculations
  - Shadowing not strong enough in central collisions

^{3}He+Au to *p*+Au Ratio (0-20%)



- ^{3}He+Au shows 11% stronger suppression than *p*+Au at backward rapidity

Summary of J/ψ Results

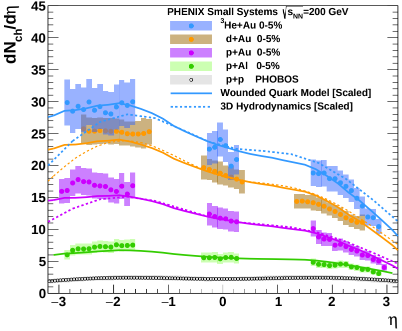
- Very strong forward rapidity suppression for most central collisions
  - Reweighted EPPS16 and nCTEQ15 shadowing describe 0-100% forward rapidity suppression
  - EPS09 centrality dependence (linear) assumed in transport model gives much weaker suppression than observed for most central collisions
- Small increase in suppression for ^{3}He+Au over p+Au
  - Consistent with small final state effect
- Absorption is significant at RHIC energies at backward rapidity
- Data suggest p_T broadening is needed in model calculations

Future Analysis: $\psi(2S)$

Motivation for Future Work

Phys.Rev.Lett. 121 (2018)

- p+Au and ^{3}He+Au CNM effects expected to be similar
- Study $\psi(2S)$ modification in p+Au and ^{3}He+Au
    - Currently, no R_{pA} measurement of $\psi(2S)$ in PHENIX muon arms
    - The $\psi(2S)$ is more loosely bound → more susceptible to final state effects than the J/ψ
    - Different rapidities: different CNM effects, different $dN_{ch}/d\eta$, different final state effects



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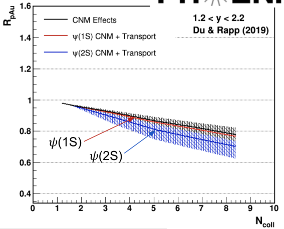
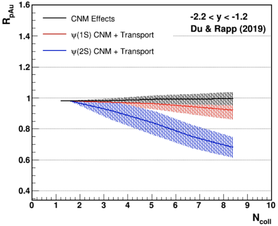
- Study $\psi(2S)$ modification in p+Au and ^{3}He+Au
    - Currently, no R_{pA} measurement of $\psi(2S)$ in PHENIX muon arms
    - The $\psi(2s)$ is more loosely bound → more susceptible to final state effects than the J/ψ
    - Different rapidities: different CNM effects, different $dN_{ch}/d\eta$, different final state effects
- Du & Rapp transport model (hydrodynamic flow) predicts stronger suppression for $\psi(2S)$ than J/ψ in p+Au collisions





ψ(2S) Yield Comparison - NO FVTX

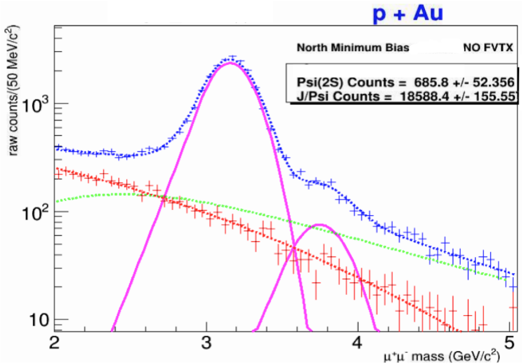
d+Au centrality dependent $\psi(2S)$ raw counts for $|y| < 0.35$ in 5 GeV/c binwidths

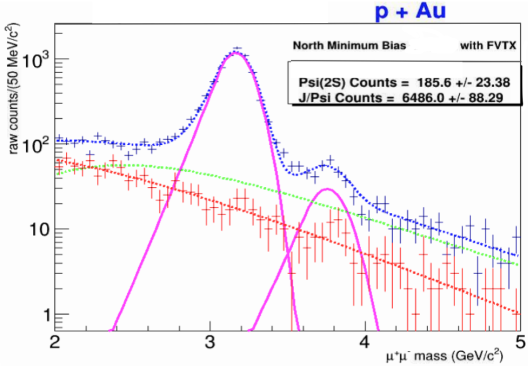
Centrality	d+Au, mid rapidity
0–20%	19 ± 16
20–40%	39 ± 15
40–60%	34 ± 11
60–84%	29 ± 9

- Raw counts in current data look high enough to extract the ψ(2S) in **p+Au(∼1k)** and **p+Al(∼500)** as a function of p_T with centrality
- Challenge will be careful systematic uncertainty study of ψ(2S) yield extraction

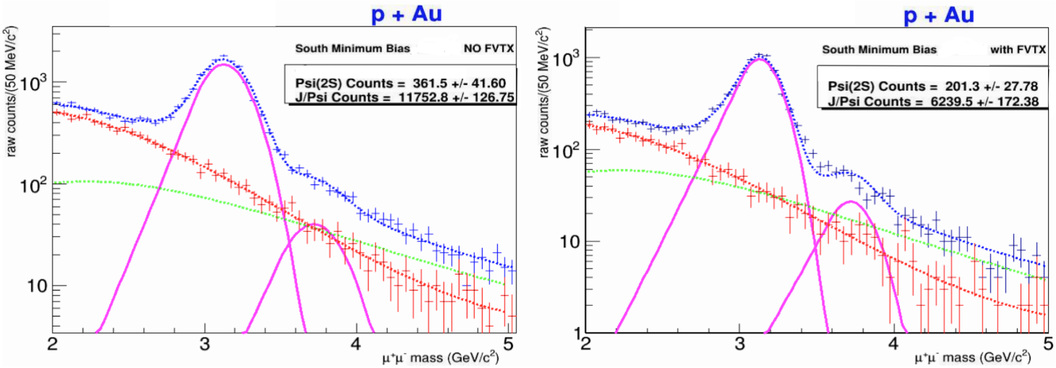
Phys. Rev. Letters 111, 202301

Initial Fits - North Arm





Initial Fits - South Arm



Potential FVTX Track Combinations

- Phys. Rev. C 95, 034904 measured $\psi(2S)/\psi(1S)$ ratio using muons which both had FVTX tracks
  - Best mass resolution (pair efficiency reduced)
- For current analysis, considering using one muon FVTX track and one muon with no FVTX track
  - Acceptance will increase while resolution will decrease
- Also considering using no FVTX track matching
  - Best acceptance
- Planning to measure modification for each case and compare as cross check
- Decision will be based on systematic and statistical uncertainties

Conclusion for Charmonia Analysis

- Measurement of $\psi(2S)$ R_{AB} can provide more information regarding cold nuclear matter (CNM) effects, particularly centrality dependent gluon shadowing
- It can also provide information regarding nuclear absorption, a CNM effect that does not seem as significant at LHC energies

LHC and RHIC have both published results consistent with hydrodynamic flow in small systems

- Suppression in ^{3}He+Au wrt p+Au in most central collisions (0–20% Centrality) at backward rapidity observed for the J/ψ, consistent with small final state effect
- The $\psi(2s)$ is more loosely bound, more susceptible to final state effects than the J/ψ
- Study of the modification of the excited state, $\psi(2S)$, could best indicate if final state effects are due to presence of a QGP

Back-Up

Theory References

[1] Kusina, Aleksander and Lansberg, Jean-Philippe and Schienbein, Ingo and Shao, Hua-Sheng
Gluon Shadowing in Heavy-Flavor Production at the LHC
Phys. Rev. Lett 121, 052004

[2] Lansberg, Jean-Philippe and Shao, Hua-Sheng
Towards an automated tool to evaluate the impact of the nuclear modification of the gluon density on quarkonium, D and B meson production in proton–nucleus collisions
Eur. Phys. J. C77, 2017

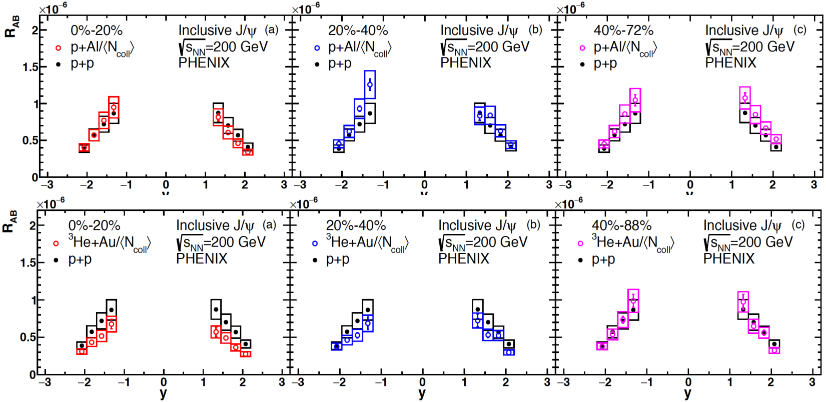
[3] Du, Xiaojian and Rapp, Ralf
In-Medium Charmonium Production in Proton-Nucleus Collisions
J. High Energy Phys. 03, 2015

[4] Du, Xiaojian and Rapp, Ralf
Sequential Regeneration of Charmonia in Heavy-Ion Collisions
Nucl. Phys. A943, 2015

[5] D. McGlinchey, A.D. Frawley and R. Vogt
Impact-parameter dependence of the nuclear modification of J/ψ production in d+Au collisions at $\sqrt{s_{NN}}$ =200 GeV
Phys. Rev. C 87, 054910 (2013)

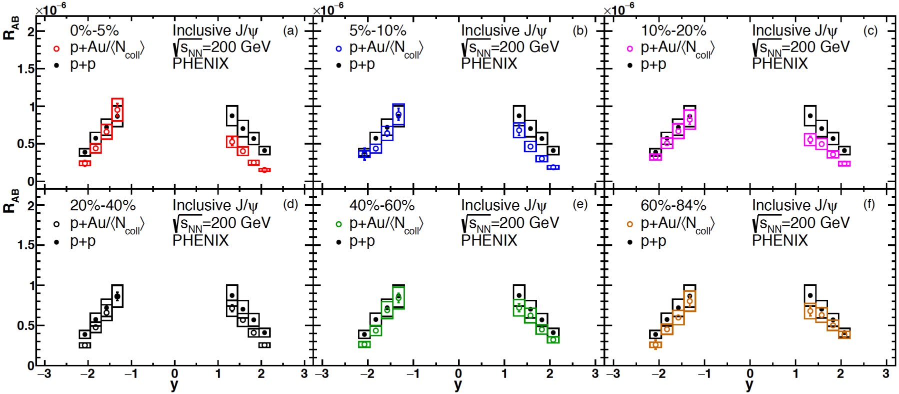
Invariant Yields as a function of y and Centrality

p+Al and ^{3}He+Au

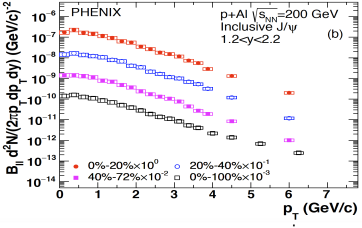


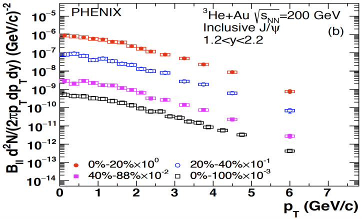
Invariant Yields as a function of y with Centrality

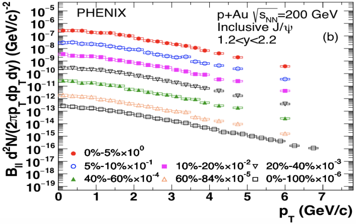
p+Au

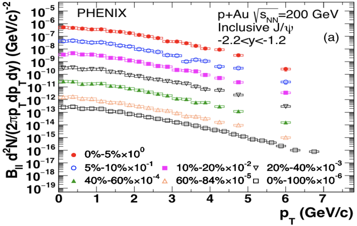


Invariant Yields as a function of p_T





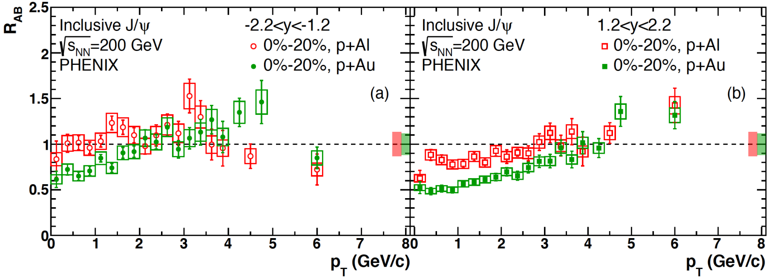




J/ψ Nuclear Modification (0–20% Centrality)

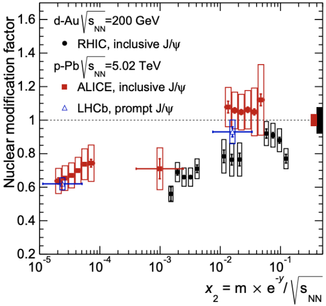
R_{AB} as a function of p_T for 0–20% centrality for p+Al and p+Au

p+Al and p+Au



- At forward rapidity with same projectile, quite different suppression
- At backward rapidity, expect trade off between absorption and shadowing

Comparison of LHC and RHIC



Eur. Phys. J. C (2016) 76: 107