Quarkonia Results

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PHENIX Quarkonia Overview

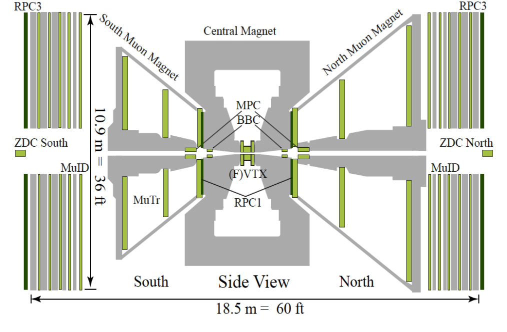
Three recent PHENIX analyses focus on the following collision systems and attempt to answer the following questions:

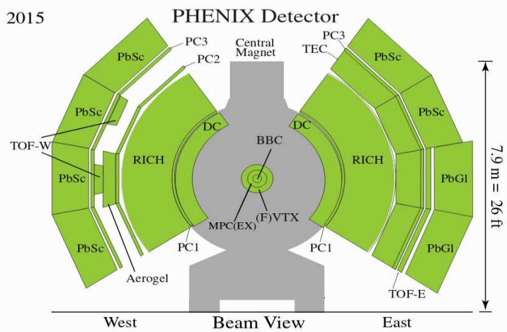
- 2013 $p+p$ at $\sqrt{s} = 510$ GeV
- 2014 ^{3}**He+Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2015 p+p, p+**Al**, p+**Au** at $\sqrt{s_{NN}} = 200$ GeV

1. Is J/ψ polarization in p+p collisions consistent with zero in all frames?
2. Can NRQCD+CGC predictions describe J/ψ production at RHIC?
3. If QGP is present in small systems, does it affect charmonium production?

PRD 102, 072008 (2020) • PRD 101, 052006 (2020) • PRC 102 014902 (2020)

PHENIX Muon and Central Arms



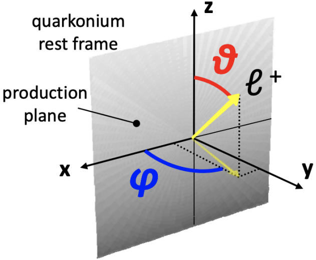


- Muon arms measure muons and inclusive charged hadrons
- Mid-rapidity arms measure electrons, photons, and identified hadrons

J/ψ Polarization

Angular Coefficients

Pedagogical illustration of the decay angular distribution



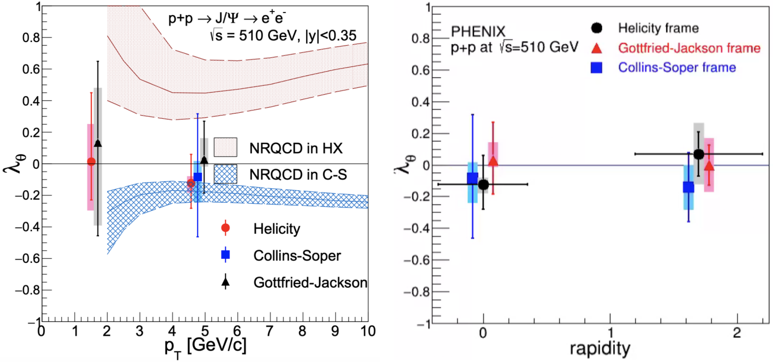
$$W(\cos\theta,\varphi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

P. Faciolli, Quarkonium in Hot Medium (2009) and Eur. Phys. J. C 69, 657 (2010)

- J/ψ polarization characterized by spin alignment of positively charged decay lepton
- $\lambda_\theta, \lambda_\phi$ and $\lambda_{\theta\phi}$ determined using Helicity, Collins-Soper, or Gottfried-Jackson frames
- $\lambda_\theta = \{+1, 0, -1\} \Rightarrow$ fully transverse, fully zero, or fully longitudinal J/ψ polarization
- Frame invariant angular decay coefficient $\tilde{\lambda}$ can be used for consistency check

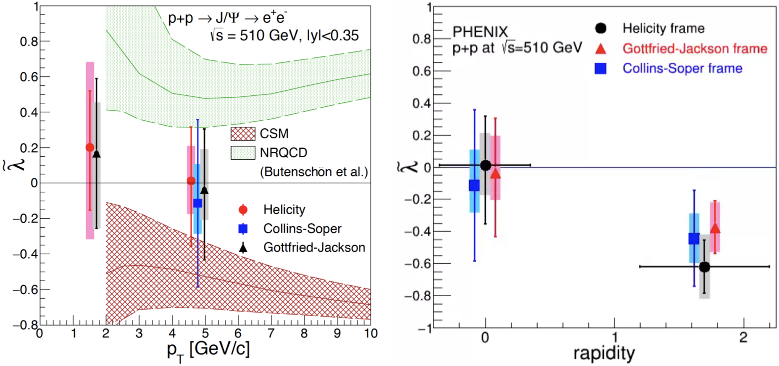
J/ψ Polarization λ_θ



Phys. Rev. D 102, 072008 (2020)

- J/ψ polarization as a function of p_T in all three frames is consistent with zero
  - NRQCD Model[1] in both Helicity and Collins-Soper frames agrees with data
- J/ψ polarization at both mid and forward rapidity consistent with zero

J/ψ Polarization $\tilde{\lambda}$

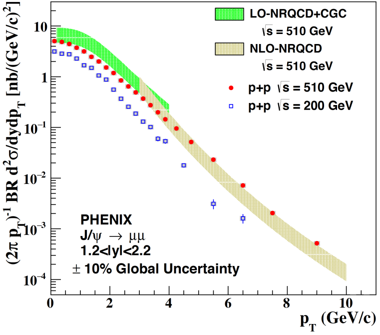


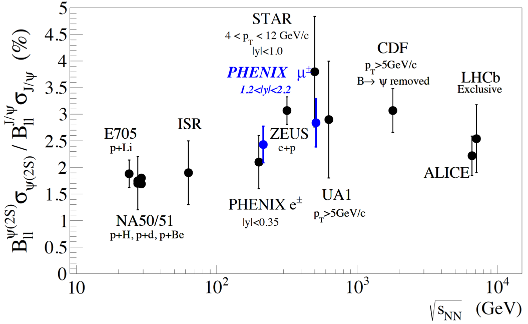
Phys. Rev. D 102, 072008 (2020)

- J/ψ polarization as a function of p_T in all three frames is consistent with zero
  - Neither NRQCD or Color Singlet Model[1] can be ruled out
- At forward rapidity, J/ψ polarization consistent with longitudinal polarization

J/ψ Production & Modification

J/ψ Production, Forward Rapidity

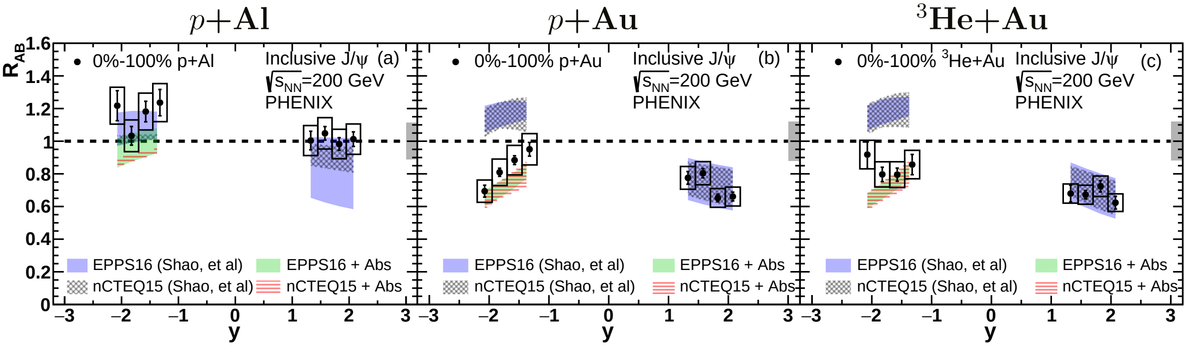




Phys. Rev. D 101, 052006 (2020)

- Inclusive J/ψ differential cross section compared to prompt J/ψ calculations
  - Non-prompt J/ψ contribution more significant at high p_T
  - LO NRQCD+Color Glass Condensate[3] at low p_T overestimates data
- $\psi(2S)/J/\psi$ ratio consistent with world data - no clear energy dependence

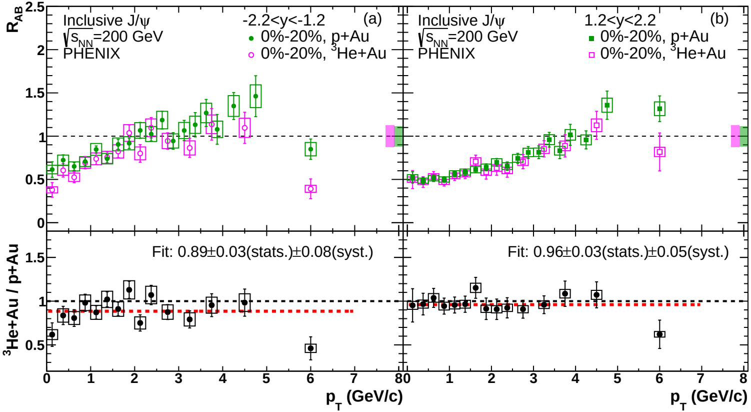
J/ψ Nuclear Modification



Phys. Rev. C 102, 014902 (2020)

- Predictions for $p/^3$He+Au based on Bayesian reweighting method using J/ψ constraints from p+Pb data at the LHC[4]
  - PHENIX nuclear absorption estimate included at backward rapidity[5]

J/ψ Modification Ratio for ^{3}He+Au to p+Au (0-20%)



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- Slightly stronger suppression in ^{3}He+Au at bkwd rapidity with significance 1.3σ
  - No final state effect at fwd rapidity, small final state effect at bkwd rapidity

$\psi(2S)$ Nuclear Modification

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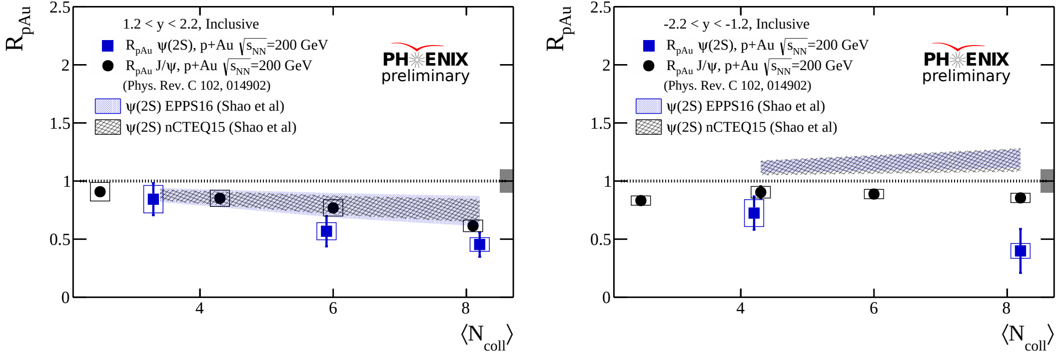
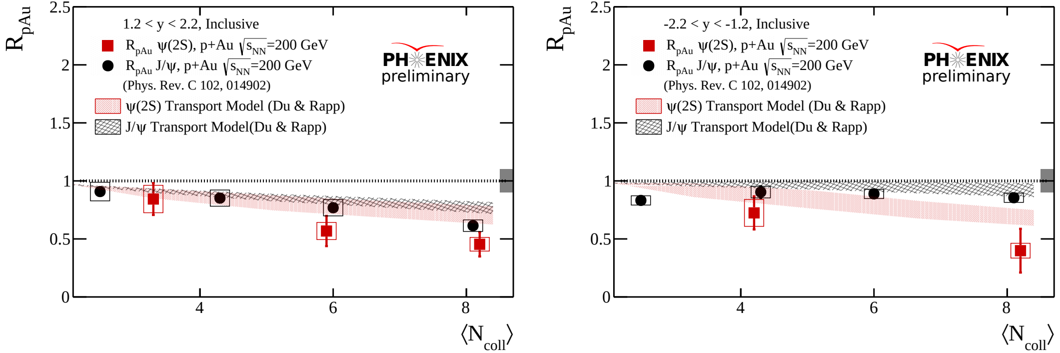


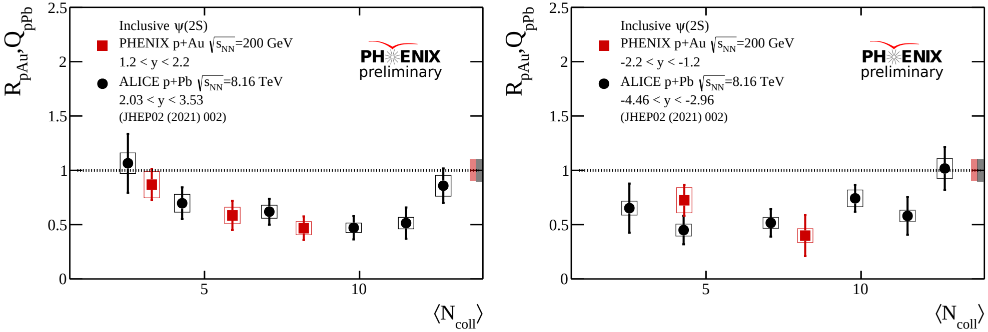
- At forward rapidity, J/ψ and $\psi(2S)$ modification follow similar trend
  - EPPS16 and nCTEQ15 shadowing predictions describe data reasonably well
- At backward rapidity, anti-shadowing predictions alone cannot describe the data

$\psi(2S)$ Nuclear Modification



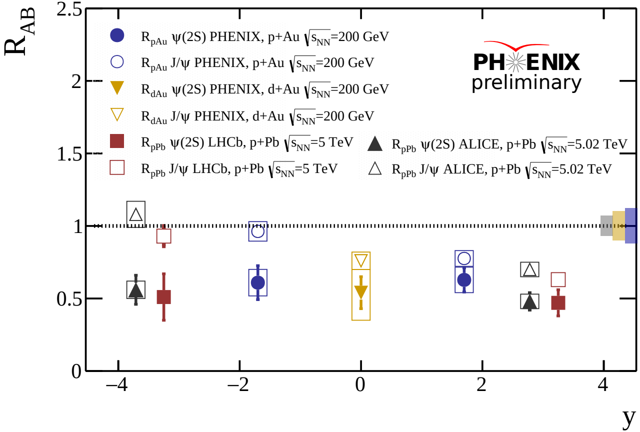
- At forward rapidity, largest contribution to Transport Model EPS09 shadowing [6]
- At backward rapidity, clear difference in $\psi(2S)$ modification in most central collisions
  - Consistent with final state effects in small system collisions

$\psi(2S)$ Modification at RHIC and LHC



- PHENIX and ALICE $\psi(2S)$ modification quite similar at forward rapidity
  - Cold nuclear matter effects appear to be dominant
- PHENIX and ALICE $\psi(2S)$ modification very similar at backward rapidity as well
  - Suggests final state effects in small system collisions

J/ψ, $\psi(2S)$ Modification at RHIC and LHC



- At forward rapidity, J/ψ nuclear modification similar to $\psi(2S)$ nuclear modification
- Much stronger suppression observed for $\psi(2S)$ at backward rapidity

PHENIX Quarkonia Summary

❶ p+p at $\sqrt{s}$ =510 GeV

- J/ψ polarization is consistent with zero at mid-rapidity and with longitudinal polarization at forward rapidity
- At low p_T, J/ψ production at RHIC is not well described by NRQCD+Color Glass Condensate predictions
- World data on the ψ(2S)/J/ψ ratio in small system collisions shows no clear energy dependence

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

- PHENIX J/ψ nuclear modification in small systems best described by nPDFs with a nuclear absorption model included at backward rapidity
- At both RHIC and LHC energies, ψ(2S) nuclear modification as function of $\langle N_{coll} \rangle$ very similar in p+A collisions
- Strong suppression of ψ(2S) nuclear modification at backward rapidity supports final state effects in small systems

Theory References

[1] M. Butenschon and B. A. Kniehl
J/ψ Polarization at the Tevatron and the LHC: Nonrelativistic-QCD Factorization at the Crossroads
Phys. Rev. Lett. 108, 172002 (2012)

[2] M. Butenschon and B. A. Kniehl
Reconciling J/ψ Production at HERA, RHIC, Tevatron, and LHC with Nonrelativistic QCD Factorization at Next-to-Leading Order
Phys. Rev. Lett. 106, 022003 (2011)

[3] Y.-Q Ma, K. Wang, K.-T. Chao
J/$\psi(\psi')$ Production at the Tevatron and LHC at $O(\alpha_s^4 v^4)$ in Nonrelativistic QCD
Phys. Rev. Lett. 106, 042002 (2011)

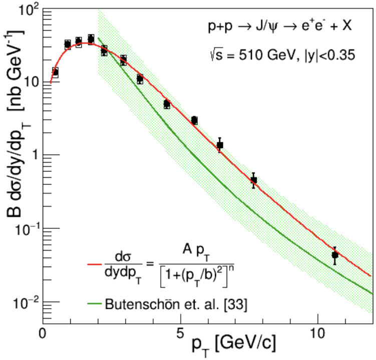
[4] Kusina, Aleksander and Lansberg, Jean-Philippe and Schienbein, Ingo and Shao, Hua-Sheng
Gluon Shadowing in Heavy-Flavor Production at the LHC
Phys. Rev. Lett 121, 052004

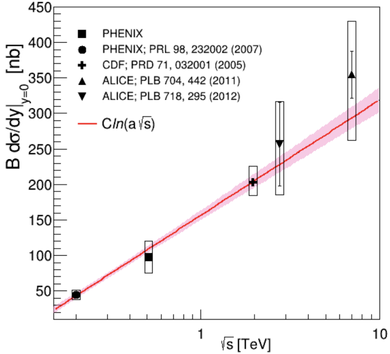
[5] D. McGlinchey, A.D. Frawley and R. Vogt
Impact-parameter dependence of the nuclear modification of J/ψ production in d+Au collisions at $\sqrt{s_{NN}}$ =200 GeV
Phys. Rev. C 87, 054910 (2013)

[6] Du, Xiaojian and Rapp, Ralf
In-Medium Charmonium Production in Proton-Nucleus Collisions
JHEP 03, 015

Back-Up

J/ψ Production, Mid-Rapidity

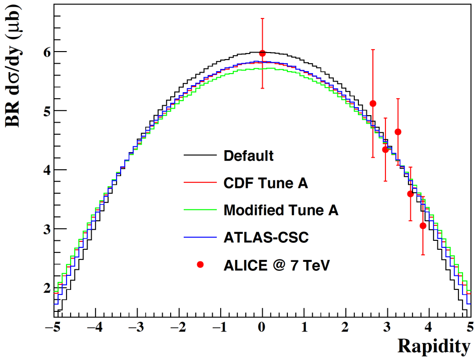


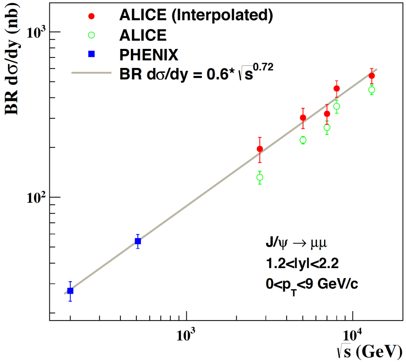


Phys. Rev. D 102, 072008 (2020)

- NLO NRQCD[2] prediction describes J/ψ differential cross section well for p_T>2 GeV/c
- J/ψ production as a function of $\sqrt{s}$ follows simple logarithmic curve $C\ln(a\sqrt{s})$
  - p_T integrated PHENIX results are compared with CDF and ALICE measurements

J/ψ Production, Forward Rapidity





Phys. Rev. D 101, 052006 (2020)

- Here J/ψ production as a function of $\sqrt{s}$ is fit with the power law $C\sqrt{s}^{a}$
  - ALICE data interpolated to PHENIX forward rapidity range $1.2 < y < 2.2$
  - This was done using various PYTHIA tunes and fitting the $d\sigma/dy$ distribution

Polarization Coordinate Frames

PHENIX

The Helicity frame (HX): [9], traditionally used in collider experiments, takes the $\hat{z}$-axis as the spin-1 particle momentum direction.

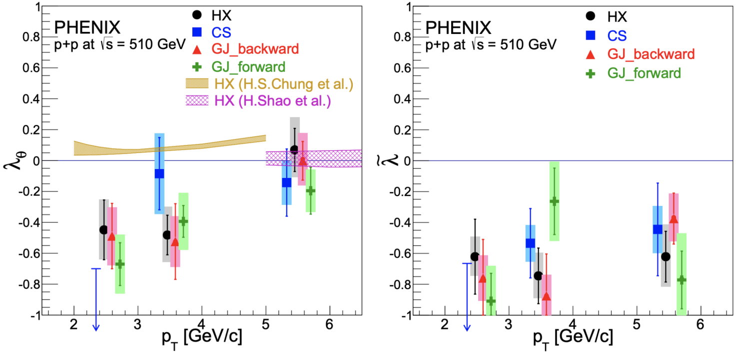
The Collins-Soper frame (CS): [10], widely used in Drell-Yan measurements, chooses the $\hat{z}$-axis as the difference between the momenta of the colliding partons boosted into the spin-1 particle rest frame. Note that while the original paper [10] and subsequent theoretical studies used colliding parton momenta in their calculations, the colliding hadron momenta are used here, because we do not have information about the parton momenta.

The Gottfried-Jackson frame (GJ): [11], typically used in fixed target experiments, takes the $\hat{z}$-axis as the beam momentum boosted into the spin-1 particle rest frame. At forward angles in a collider environment, the definition of the GJ frame depends heavily on which beam is used in the definition. If the beam circulating in the same direction as the J/ψ momentum is chosen (GJ forward), the resulting $\hat{z}$-axis is nearly collinear with the $\hat{z}$-axis of the HX and CS frames and points in the same direction. In GJ backward frame (beam circulating in the direction opposite to J/ψ momentum is chosen) the $\hat{z}$-axis points in the opposite direction.

Phys. Rev. D 95, 092003 (2017)

- Helicity frame is most commonly used for collider experiments
- Definition of $\hat{z}$ is main difference between coordinate frames

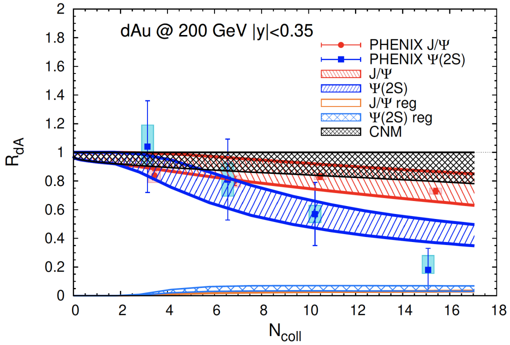
J/ψ Polarization (2017)

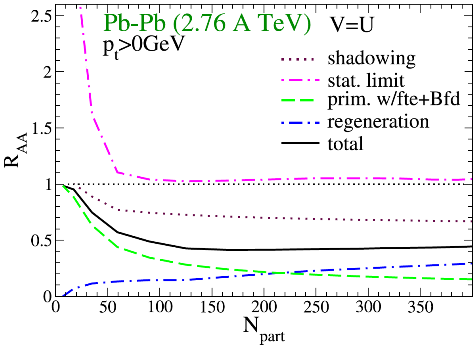


Phys. Rev. D 95, 092003 (2017)

- Previous PHENIX J/ψ polarization results at forward rapidity (2017)
- Also indicates longitudinal polarization at forward rapidity with the frame invariant $\tilde{\lambda}$ angular decay coefficient

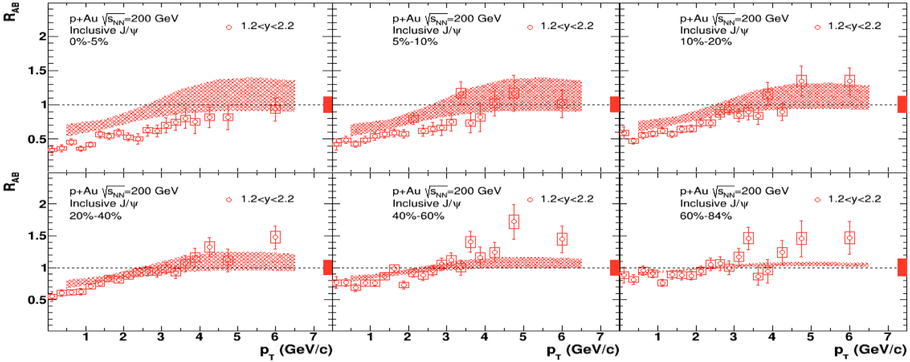
Contributions from Coalescence





- Coalescence predictions for J/ψ, ψ(2S) nuclear modification in d+Au collisions at RHIC
  - Similar expectations at LHC in p+Pb collisions
- Much more significant contribution from coalescence in Pb+Pb collisions

J/ψ Modification in p+Au, Fwd Rapidity



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

Phys. Rev. C 102, 014902 (2020)