Quarkonia Results from PHENIX

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PHENIX

Motivation

- Measurements of quarkonia provide an excellent opportunity to explore QCD.
  - In the case of J/ψ , the charm quark mass is larger than the hadronization scale ⇒ NRQCD techniques can be used to provide access to hadronization.
  - J/ψ is copiously produced and decays to lepton pairs with high branching ratio
- Many J/ψ production models describe general features well, like p_T or rapidity distributions at mid-rapidity, but not as well at forward rapidity.
- Measuring finer details, like angular distribution (spin alignment) can provide an additional handle on studying production and hadronization mechanisms.
- Quarkonia are very valuable probe in heavy-ion collisions to study the properties of the QGP.
  - In small collision systems, quarkonia allow studying cold nuclear matter effects, which are also present in large collision systems

J/ψ Polarization

The decay angular distribution of the positive lepton in the J/ψ rest frame is often parametrized as:

$$\frac{d\sigma}{d(\cos\theta)d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi$$

λ_θ, $\lambda_{\theta\phi}$ and λ_ϕ are related to the density matrix elements and depend on kinematical variables and the definition of coordinate system.

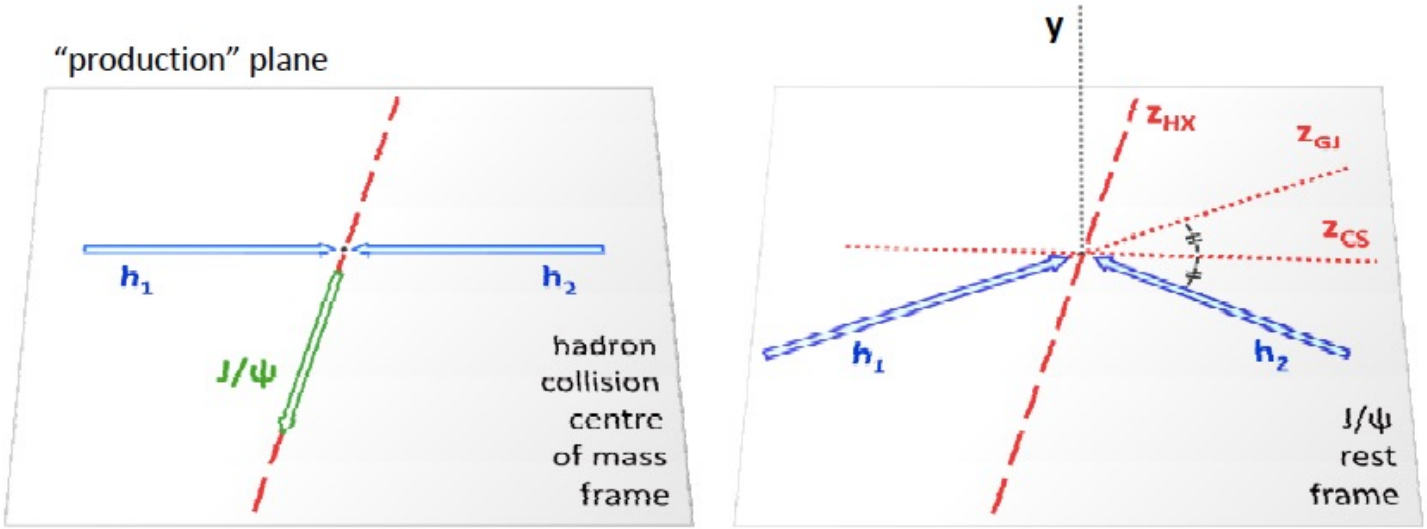
- Frame-invariant angular decay coefficient

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

  - It is sensitive to the maximum angular asymmetry, or polarization.

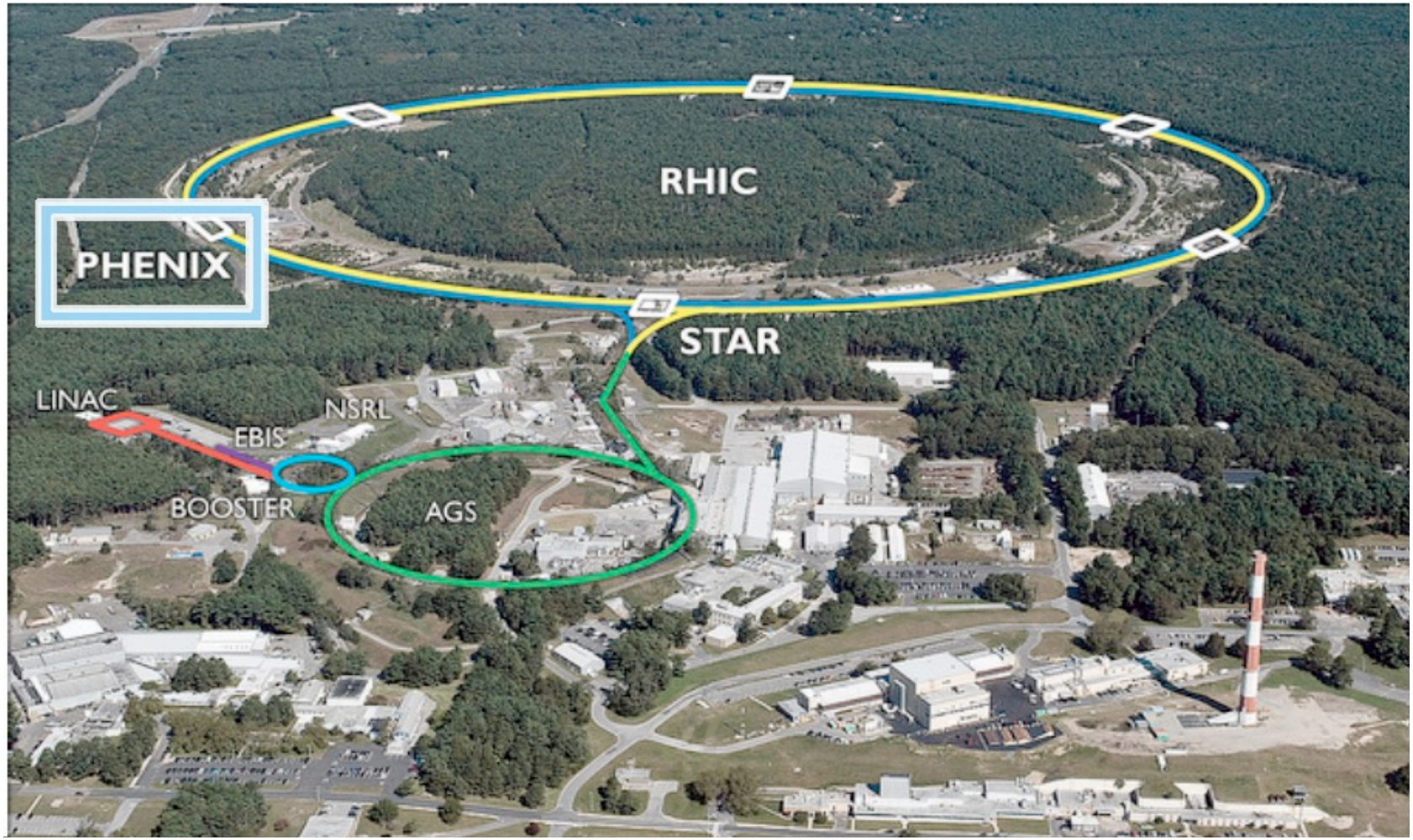
Reference Systems

- The decay angular distribution is usually reported in one of 3 systems of axes, differing in the definition of the polarization axis ($\hat{z}$):
  - **Helicity** (HX): J/ψ momentum in lab frame (traditionally used in collider experiments)
  - **Gottfried-Jackson** (GJ): direction of h_1 or h_2 in J/ψ rest frame (typically used in fixed target experiments)
  - **Collins-Soper** (CS): bisector between h_1 and (-) h_2 directions in J/ψ rest frame (widely used in Drell-Yan measurements)



❖ $\tilde{\lambda}$ is sensitive to the maximum angular asymmetry, or polarization, independent of the $\hat{z}$-axis orientation of the reference frame.

The Relativistic Heavy Ion Collider (RHIC)



- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that has collided a variety of collision species at various energies
- PHENIX finished its last run in 2016.

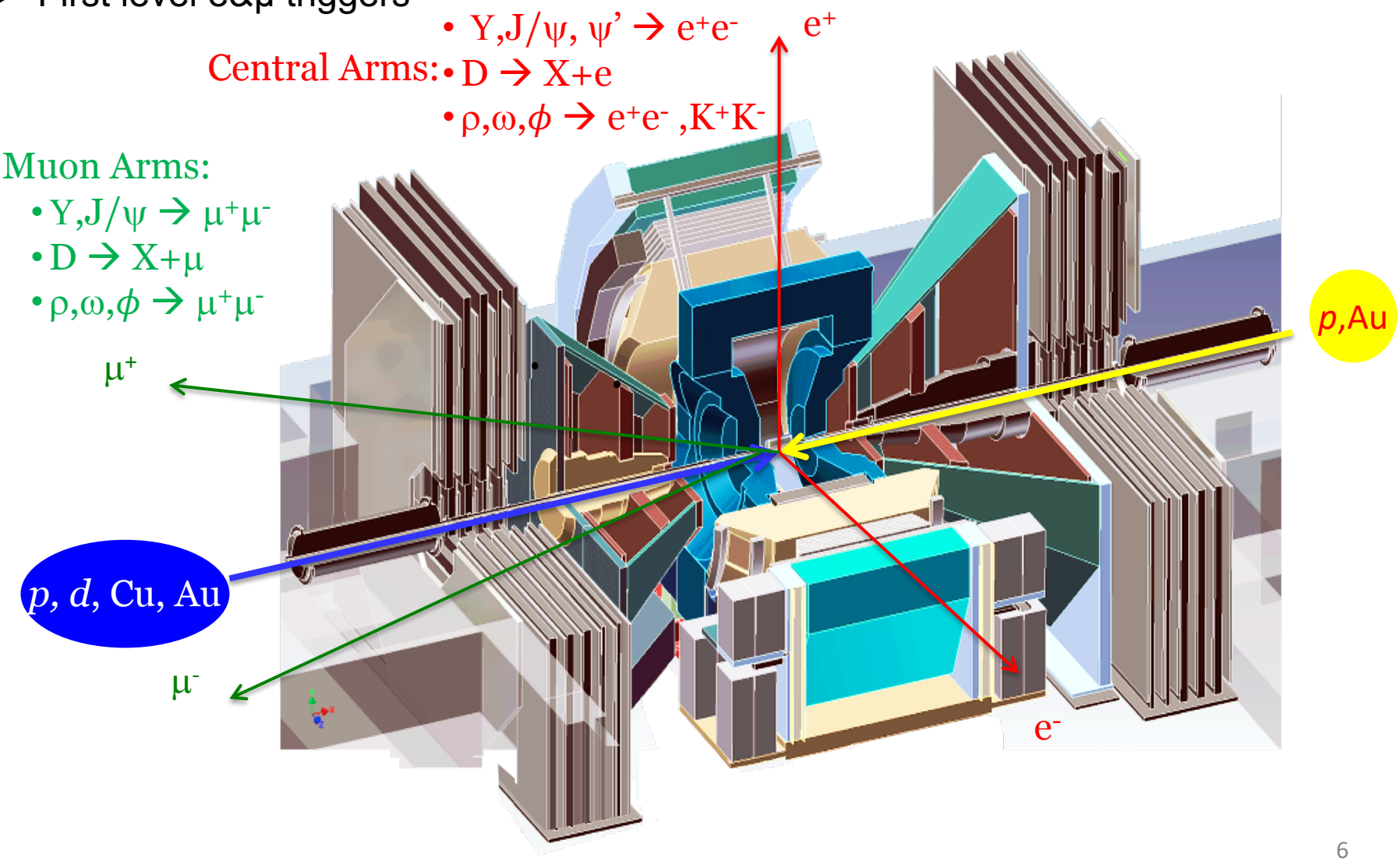
The PHENIX Detector

PHENIX: optimized to measure leptons: rapidity coverage: 1.2<|y|<2.2 & |y|<0.35

- High-rate capability with emphasis on mass resolution & particle ID
- First level e&μ triggers

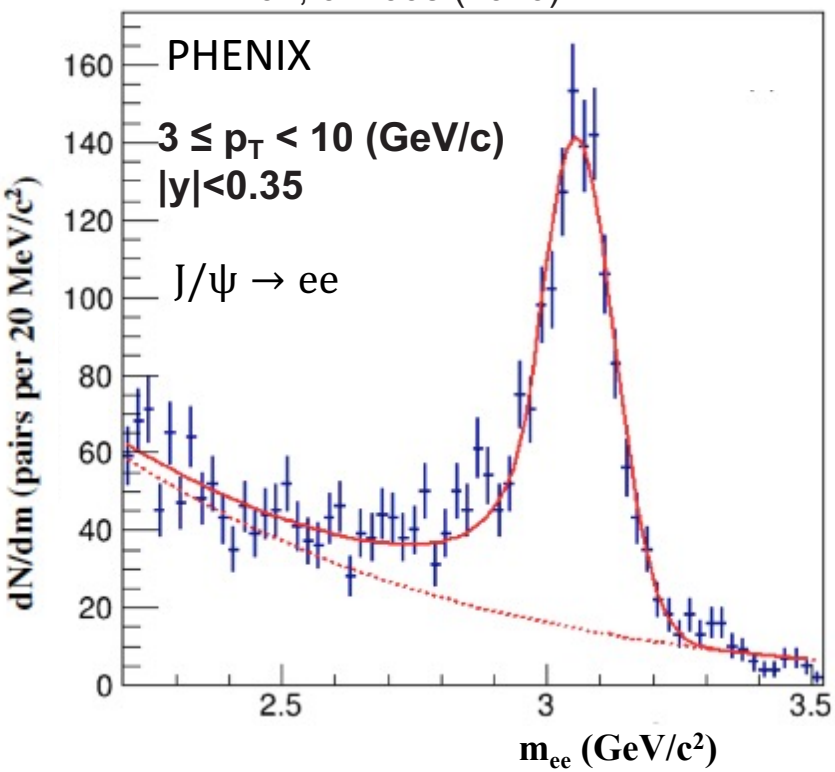
Central Arms:
- $\Upsilon, J/\psi, \psi' \rightarrow e^+e^-$
- $D \rightarrow X+e$
- $\rho,\omega,\phi \rightarrow e^+e^-, K^+K^-$

Muon Arms:
- $\Upsilon, J/\psi \rightarrow \mu^+\mu^-$
- $D \rightarrow X+\mu$
- $\rho,\omega,\phi \rightarrow \mu^+\mu^-$



Dilepton Mass Spectra at PHENIX

PRD **102**, 072008 (2020)



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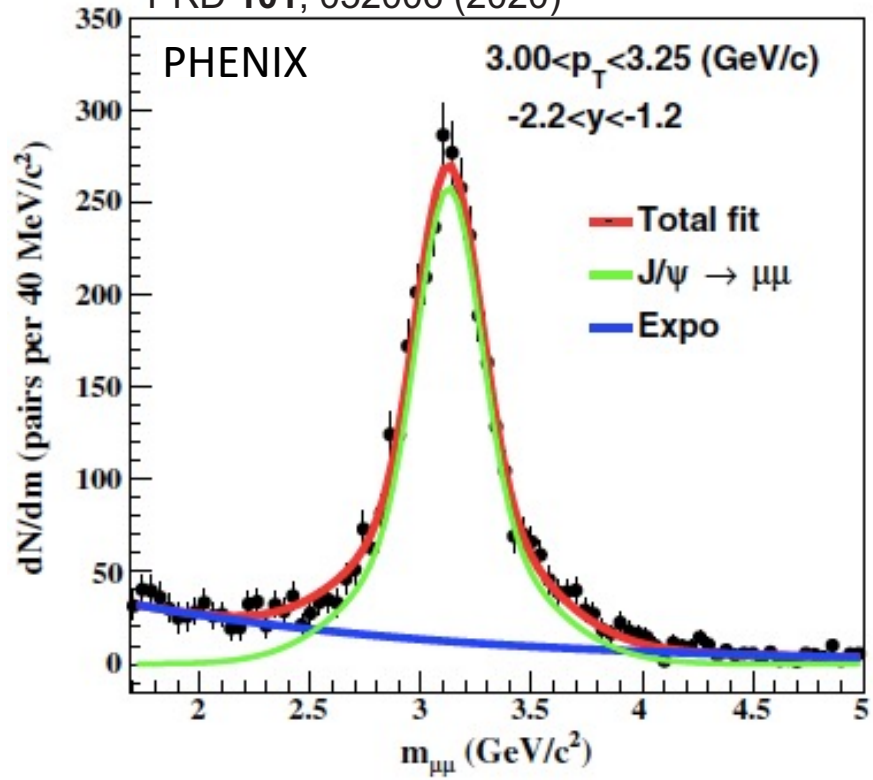
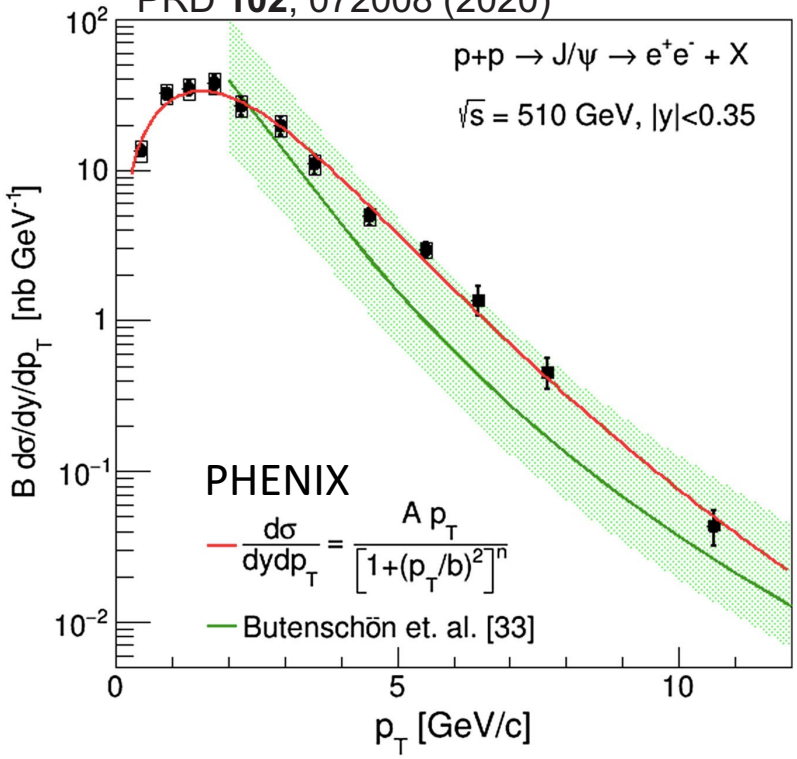


- Uncorrelated background is calculated using the mixed-event method and subtracted before fitting
- Exponential function is used to fit the correlated background

J/ψ Production at $\sqrt{s} = 510$ GeV

PRD **102**, 072008 (2020)



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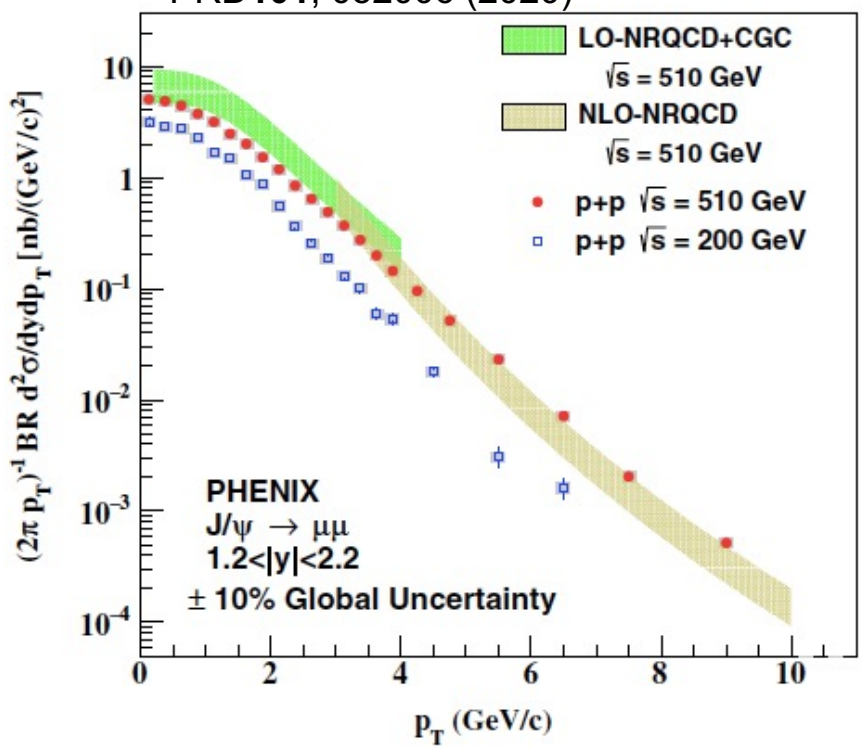
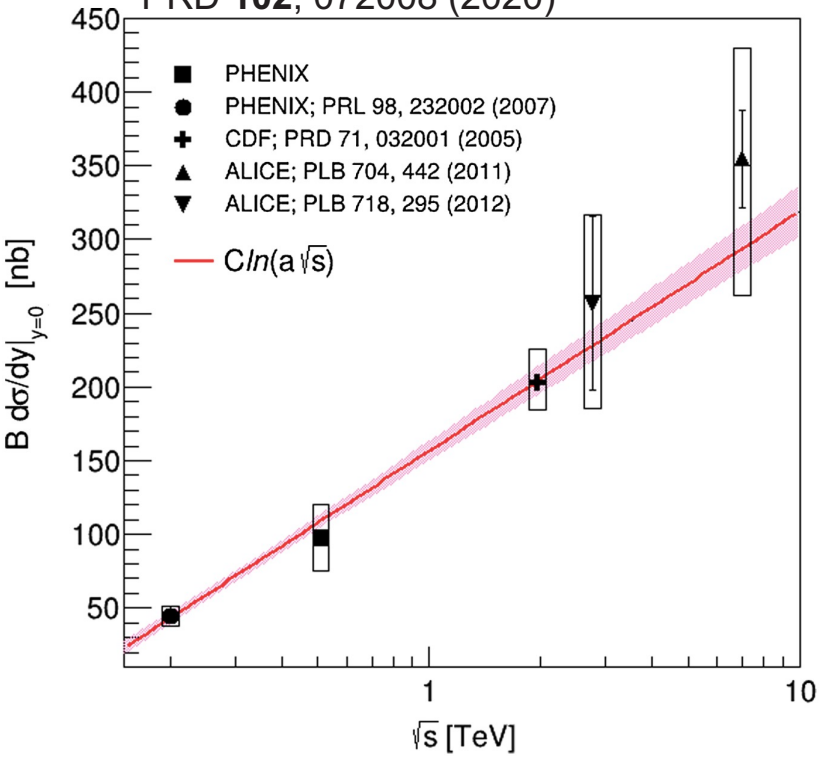


- LO-NRQCD+CGC calculations overestimate the data at low p_T
- NLO-NRQCD calculations underestimate the data at high p_T while to some extent, are consistent with the data at intermediate p_T, 3–5 GeV/c.
  - Nonprompt J/ψ contribution is not included in NLO-NRQCD calculations

J/ψ Production vs. $\sqrt{s}$

PRD **102**, 072008 (2020)



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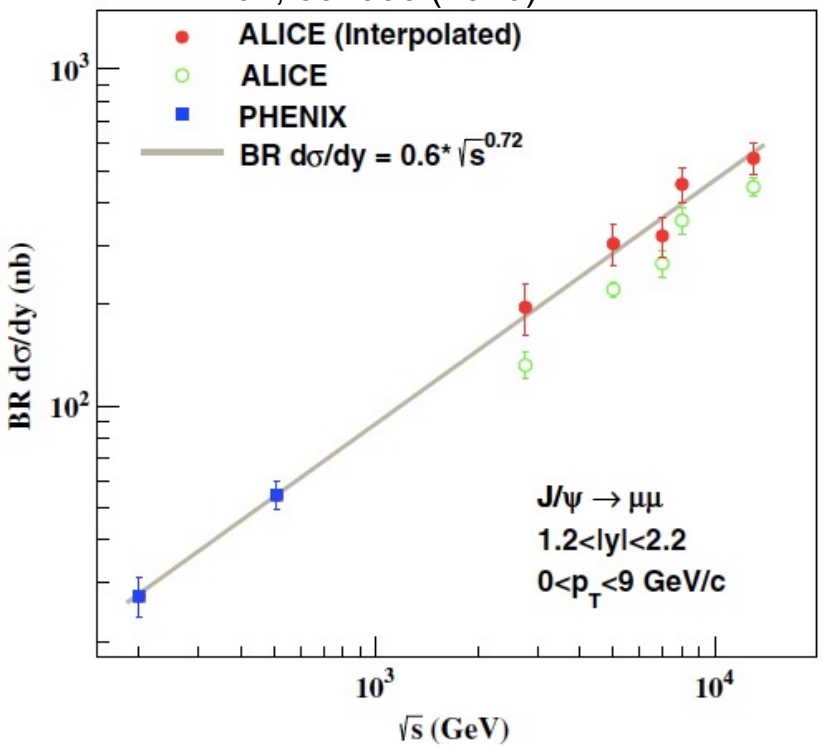
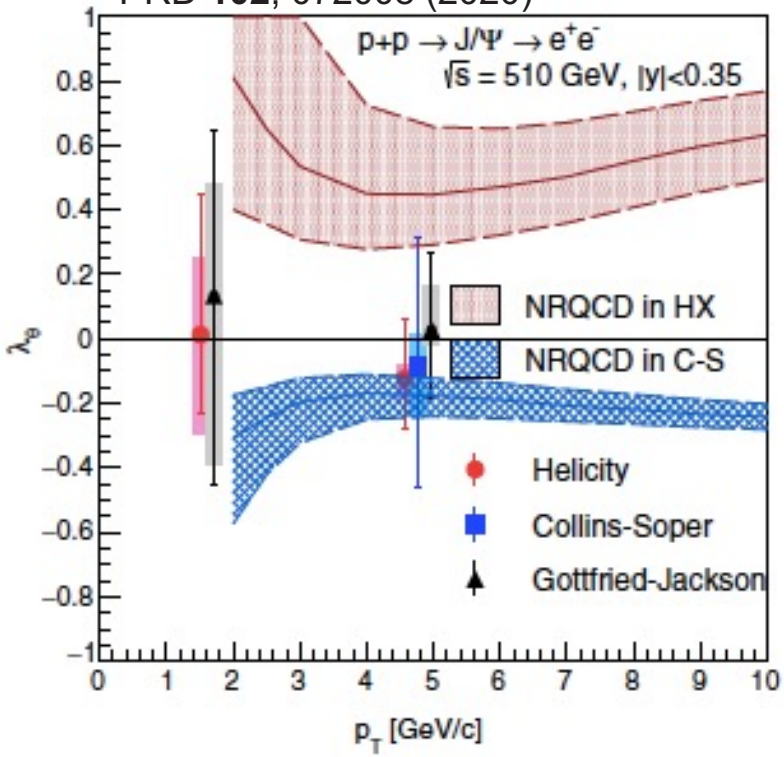
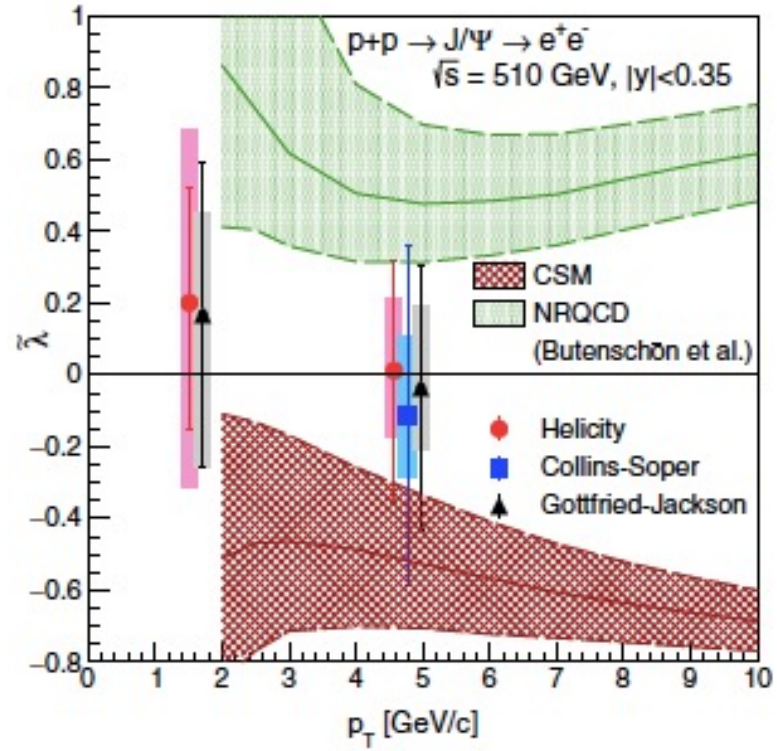


- PHENIX's $BR\ {}^{d\sigma}/_{dy}\ (1.2 < |y| < 2.2)$ is consistent with interpolated ALICE's data

J/ψ Polarization vs p_T at Mid-Rapidity

PRD **102**, 072008 (2020)

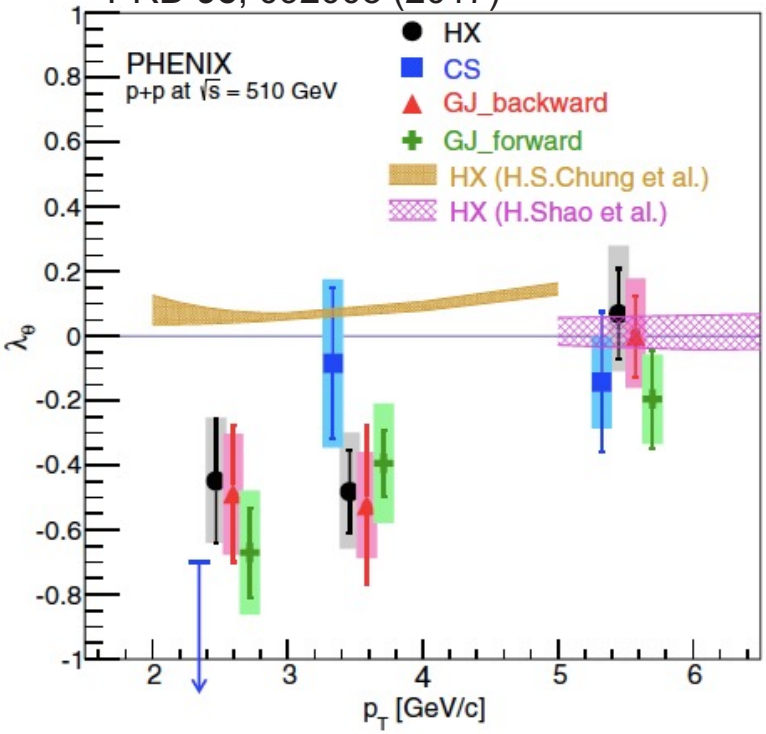


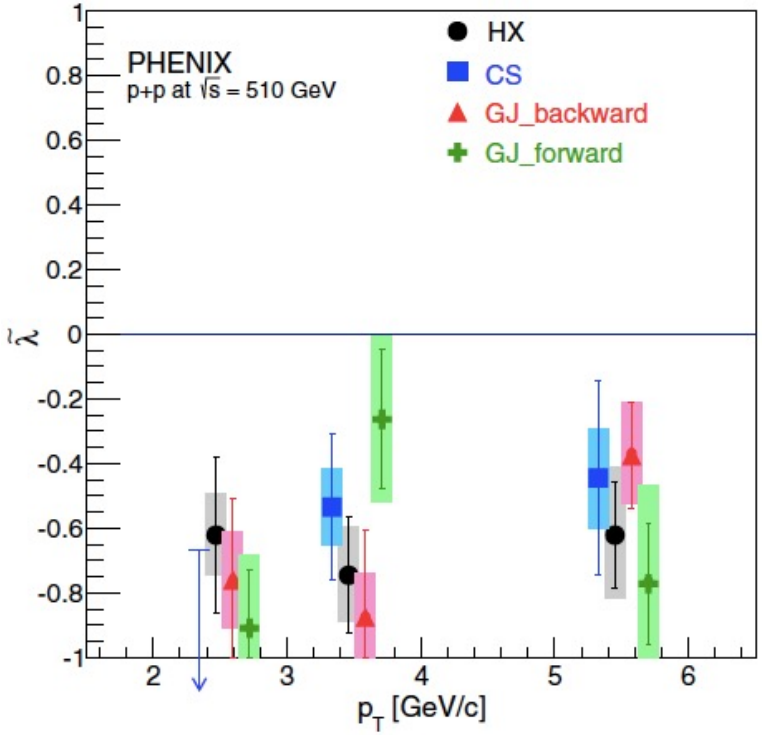


- C-S frame measurement at low p_T not possible due poor acceptance
- Data consistent with no J/ψ polarization
- NRQCD and CSM ($\nu \to 0$ limit of NRQCD) predict qualitatively different strong polarization

J/ψ Polarization vs p_T at Forward Rapidity

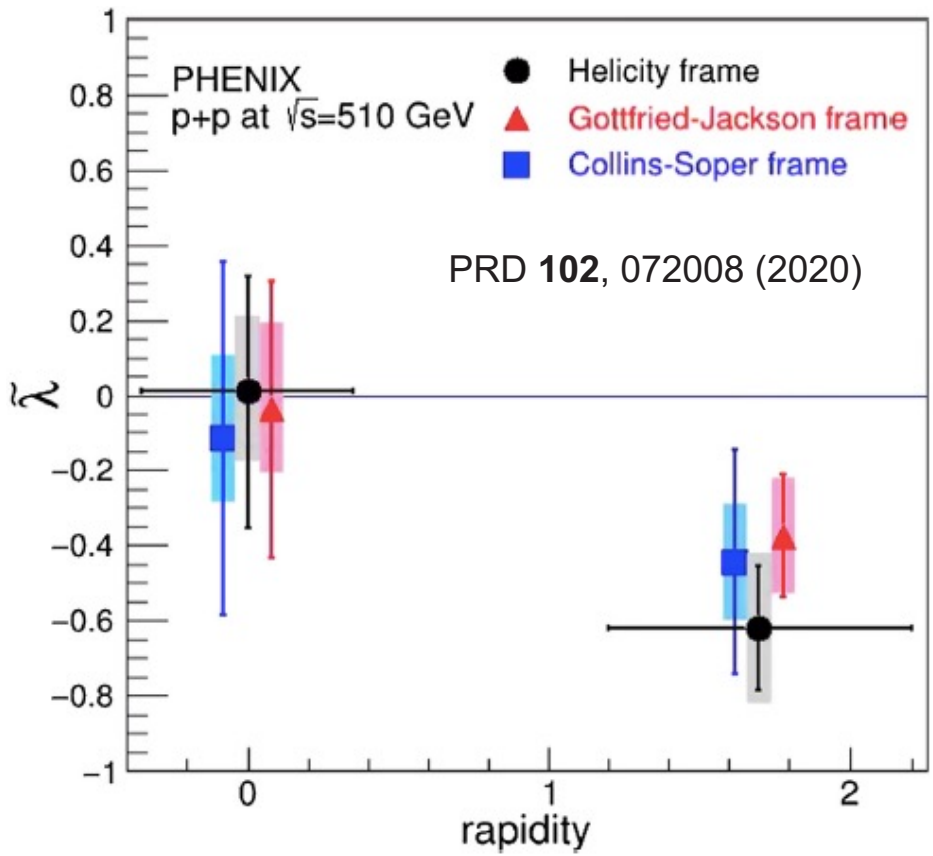
PRD **95**, 092003 (2017)





- $\tilde{\lambda}$ is consistent among all frames and show strong polarization across all p_T
- NRQCD calculations consistent with λ_θ results at high p_T while show strong deviation at low p_T

J/ψ Polarization vs Rapidity

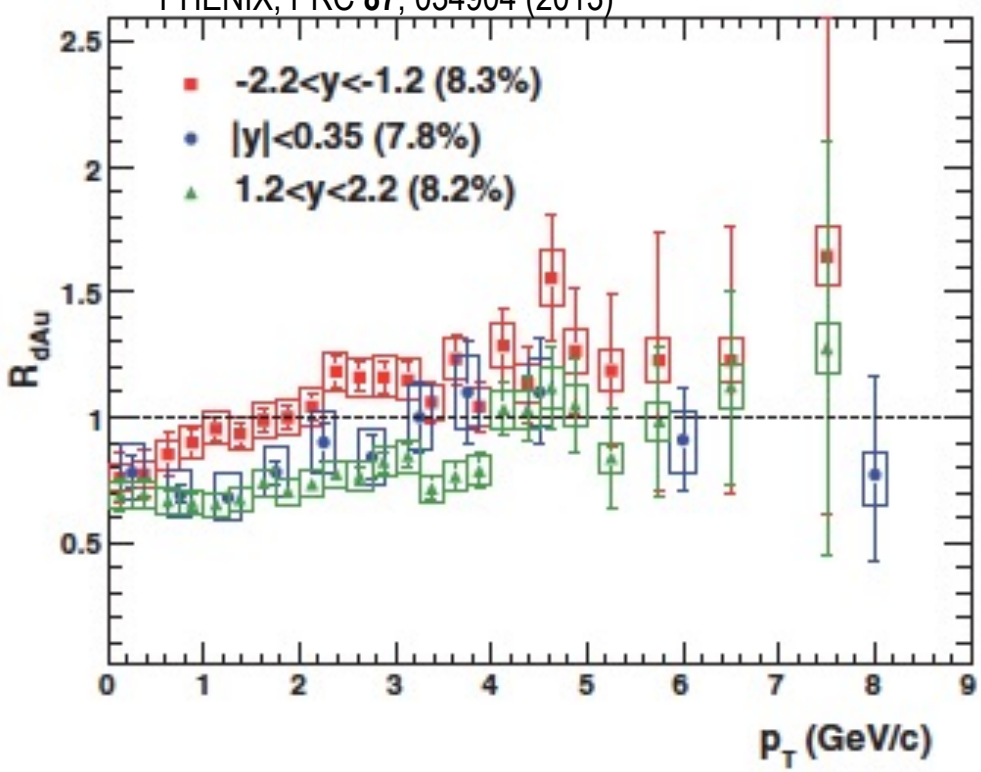


- $\tilde{\lambda}$ shows strong J/ψ polarization at forward rapidity
- $\tilde{\lambda}$ is largely negative at forward rapidity indicating longitudinal polarization

J/ψ Production in Small System (CNM?)

- J/ψ is a valuable probe in heavy-ion collisions to study the properties of QGP.
- Use small collision systems to study cold nuclear matter effects (CNM), which are also present in large collision systems.

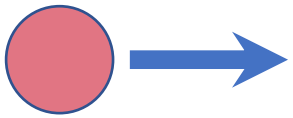
PHENIX, PRC **87**, 034904 (2013)

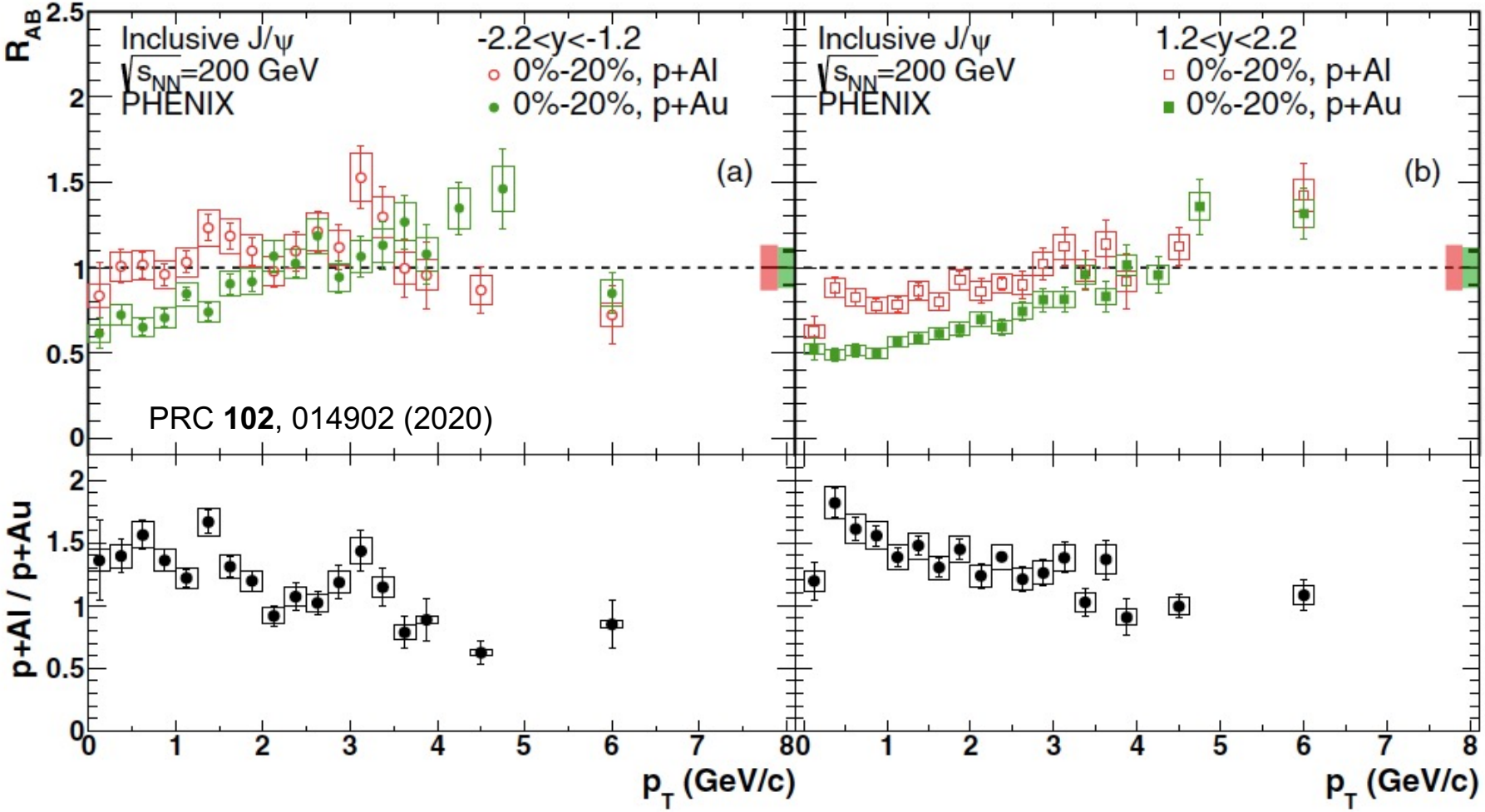


- Significant rapidity and p_T dependent modifications were seen in d+Au collisions: Cold Nuclear Matter effects?
- However, more recently the question arose whether the QGP is also being formed in small systems!

➠Study several small systems (p+Al, p+Au, ^{3}He+Au)

p+Al vs. *p*+Au

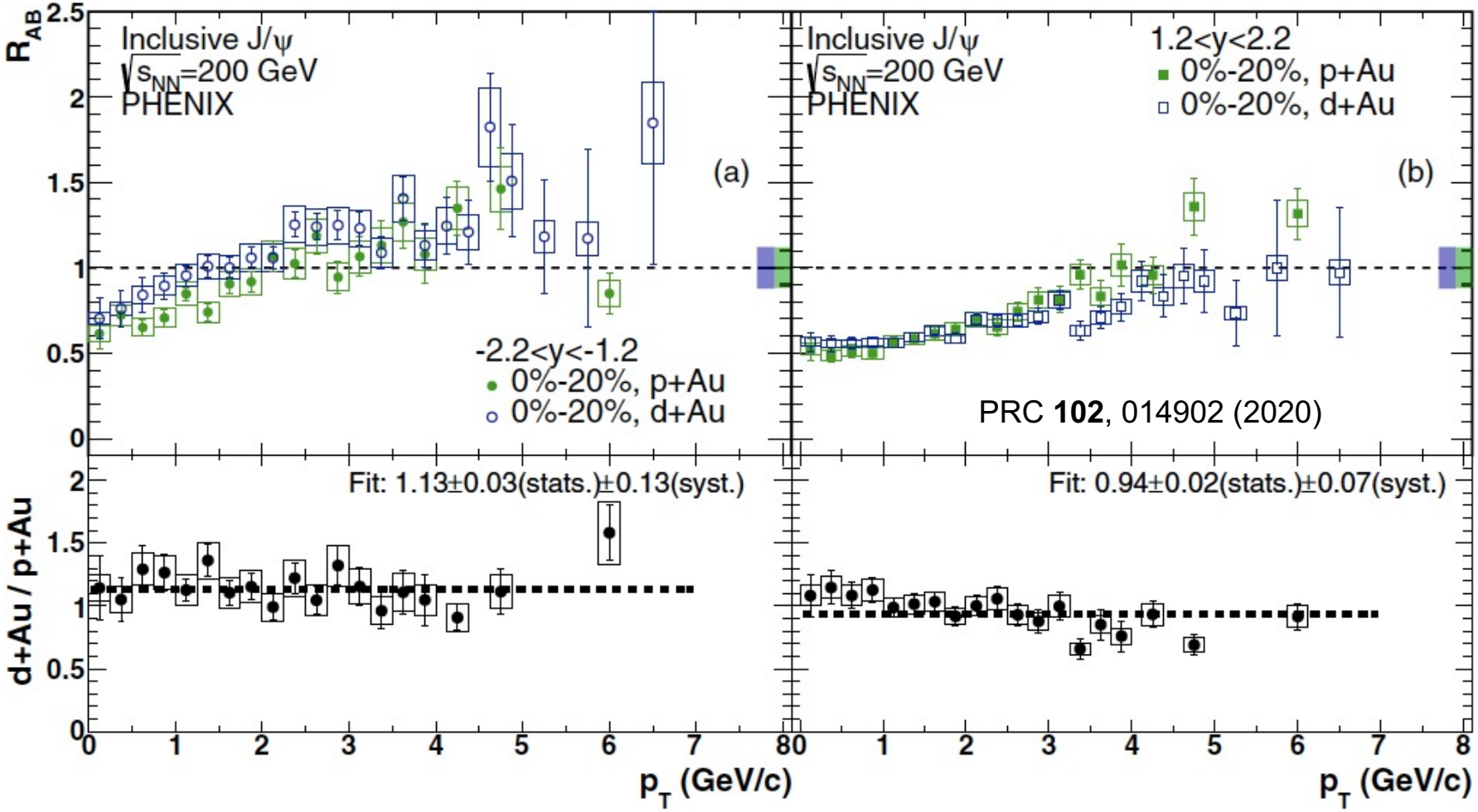




PRC **102**, 014902 (2020)

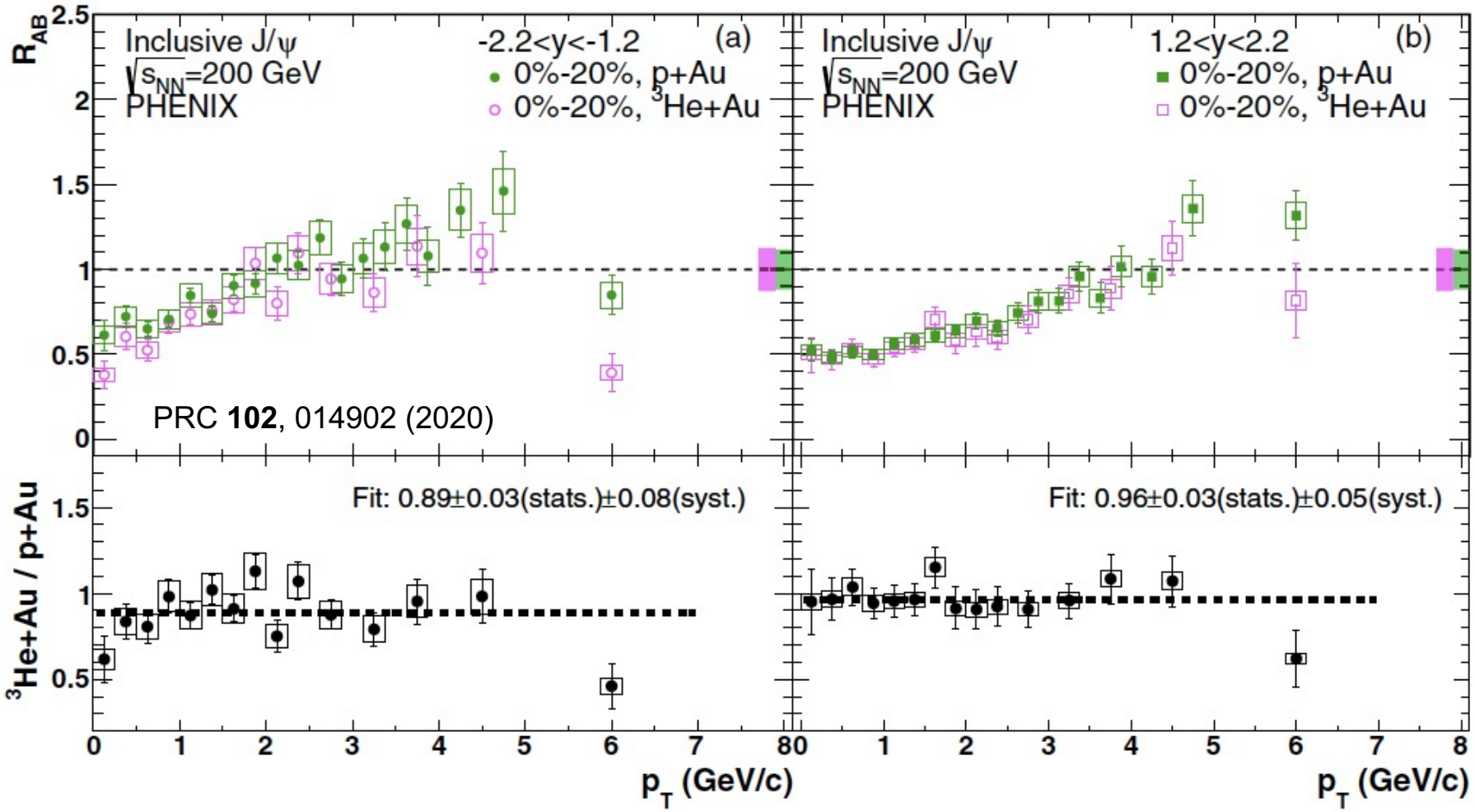
- *p*+Al shows little modification
- J/ψ modification in *p*+Au shows suppression at low p_T in both directions

p+Au vs. d+Au



- *Similar* modification at forward rapidity and less modification at backward rapidity
- J/ψ modification in *p/d*+Au shows suppression at low p_T in both directions

p+Au vs. ^{3}He+Au



- *p*/^{3}He+Au show essentially no difference in the modifications
- No obvious effect from increased energy density or increased particle production … Would be expected if CNM effects dominate J/ψ production

Summary & Conclusions

- PHENIX measured J/ψ production vs p_T, rapidity and p_T-integrated cross-section in p+p collisions at 200 and 510 GeV both at mid- and forward rapidities.
  - Cross-section's $\sqrt{s}$ dependence follows simple logarithmic trend from different measurements.
  - NRQCD calculations do not describe the data very well especially at forward-rapidity
- PHENIX measured J/ψ polarization in p+p collisions at 200 and 510 GeV both at mid- and forward rapidities.
  - The data are consistent with no polarization at mid-rapidity
  - Indication of negative polarization at forward rapidity with p_T dep.
  - Various NRQCD-based predictions can not describe the data.
- PHENIX measured R_{AB} in p/d/^{3}He+Au➔ Centrality integrated R_{AB} for p/d/^{3}He+Au are very similar
  - No obvious effect from increased energy density or increased particle production
  - Would be expected if CNM effects dominate J/ψ production

Backup

Quarkonium results from PHENIX

Friday, 21 May 2021 10:30 (20 minutes)

Quarkonia are among the most important tools for studying Quantum Chromodynamics (QCD) in high energy hadronic collisions. Despite decades of extensive studies, we still have a limited knowledge of their production mechanism and hadronization; and carrying out as many measurements as possible in p+p collisions over a broad kinematic region at different energies is essential to understanding their production mechanisms. Quarkonia are very valuable probe in heavy-ion collisions to study the properties of the quark gluon plasma, and also an important probe in small collision systems to study cold nuclear matter effects, which are also present in large collision systems.
The PHENIX experiment has measured inclusive J/ψ production as well as its angular decay coefficients at mid ($|y| < 0.35$) and forward ($1.2 < |y| < 2.2$) rapidities in p+p collisions at 200 GeV and 510 GeV; and at forward ($1.2 < |y| < 2.2$) rapidity in a variety of small collision systems (p+Al, p+Au and ^{3}He+Au) at 200 GeV. Results from these measurements will be presented.

Collaboration

PHENIX

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Presenter: SARSOUR, Murad (Georgia State University)

Session Classification: Heavy Flavor (Charmonia)