Recent Charmonium Measurements from PHENIX

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RHIC versatility

√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

PHENIX

- 16 years of operation
- 9 collision species
- 9 collision energies

RHIC versatility

This talk →

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PHENIX

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PHENIX

Outline

- J/ψ production in pp collisions at $\sqrt{s}=510$ GeV: looking at polarization *Phys.Rev.D 102 (2020), 072008*
  Phys. Rev. D 101(2020), 052006

- J/ψ production at $\sqrt{s}=200$ GeV in p+Al, p+Au, ^{3}He+Au *Phys.Rev.C 102 (2020) , 014902*

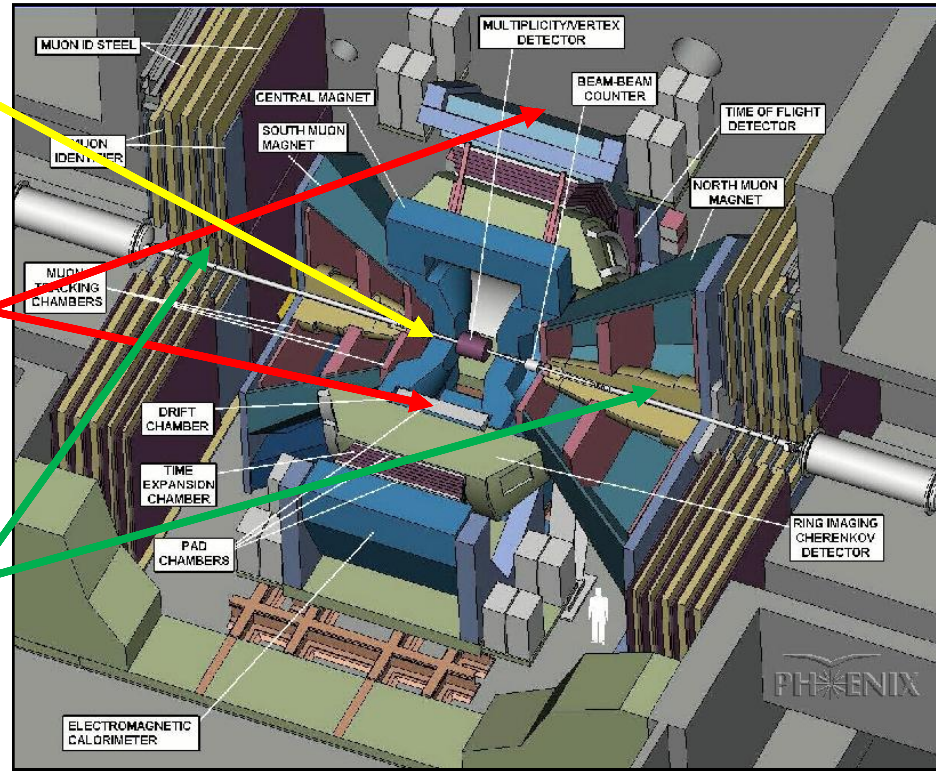
- $\psi(2S)$ production in p+Au NEW!

PHENIX Detector

Event characterization detectors in middle

Two central arms for measuring hadrons, photons and electrons

Two forward arms for measuring muons



$J/\psi \rightarrow ee$ $\psi(2S) \rightarrow ee$ in central arms

electron measurement:

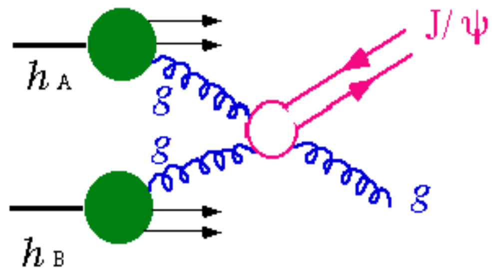
$|\eta| \leq 0.35$ $p_e \geq 0.2$ GeV/c

$J/\psi \rightarrow \mu\mu$ $\psi(2S) \rightarrow \mu\mu$ in forward arms

muon measurement:

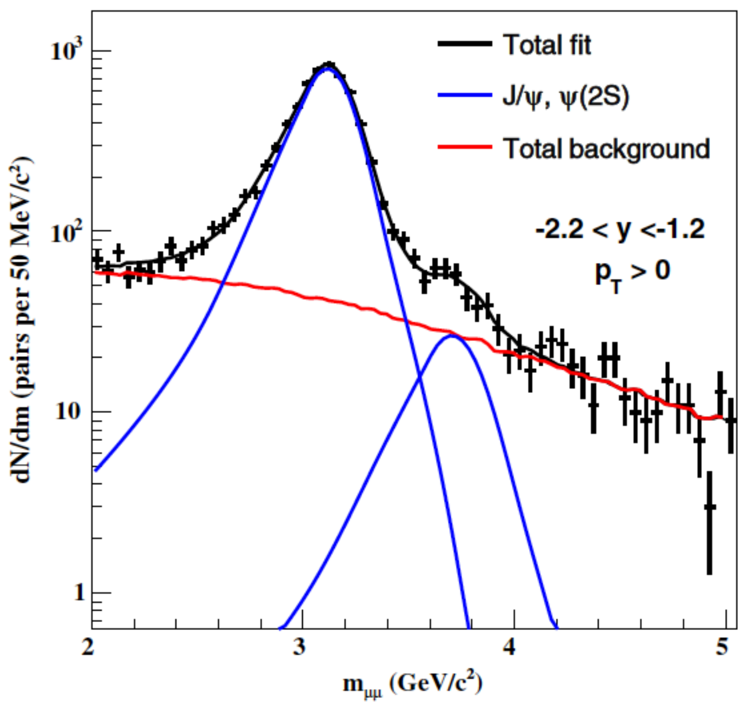
$1.2 < |\eta| < 2.4$ $p_\mu \geq 2$ GeV/c

Do we understand the basic production mechanism?



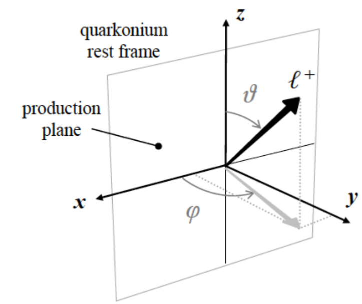
- The production mechanism of charmonium in p-p collisions is not yet completely understood.
  - Color evaporation model, Color singlet model, Color octet model
  - Polarization, Rapidity dependence (electron and muon channels)
  - Production of J/Ψ, Ψ(2S),.. states

Dimuon Invariant mass



- Yield is extracted as a function of p_T, rapidity, in $\cos\theta$, φ bins

Eur. Phys. J. C 69, 657 (2010)



J/ψ Polarization

- We measure the angular distribution of a positively charged decay lepton relative to a "polarization axis" in quarkonium rest frame and extract the **λ** coefficients

$$\frac{dN}{d\Omega} \sim 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin^2\theta\cos 2\phi + \lambda_\phi \sin 2\theta \cos\phi$$

- We use three definition of the z axis: helicity (HX) frame, Collins-Soper (C-S) frame, and Gottfried-Jackson (G-J) frame
- We can also define a frame invariant quantity

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

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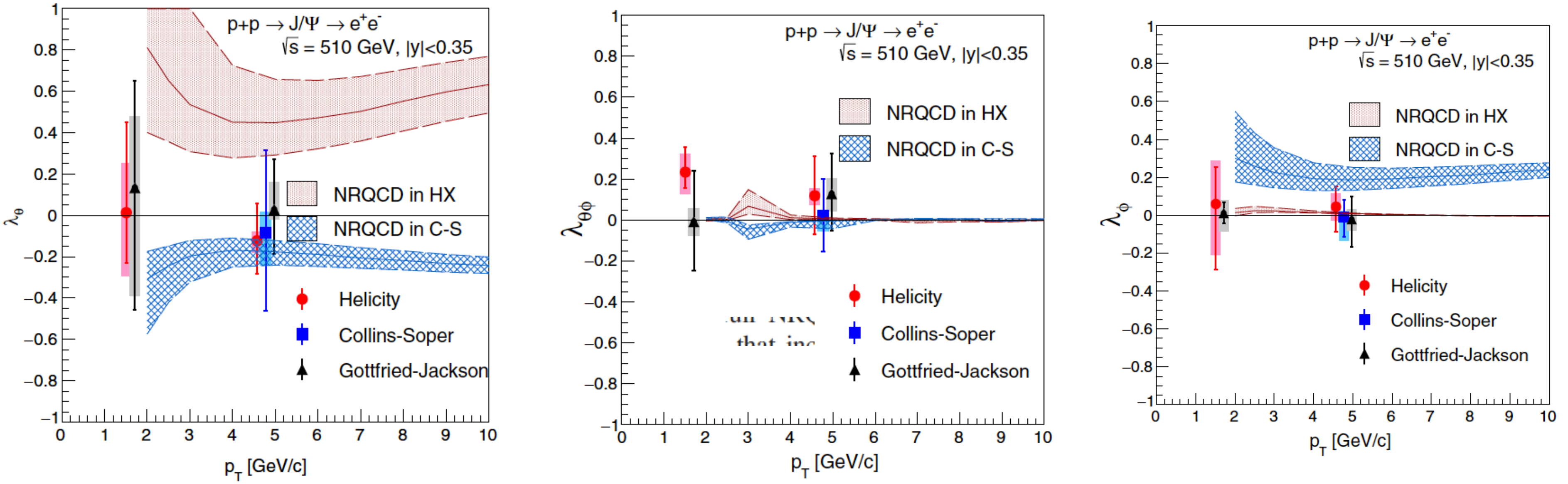
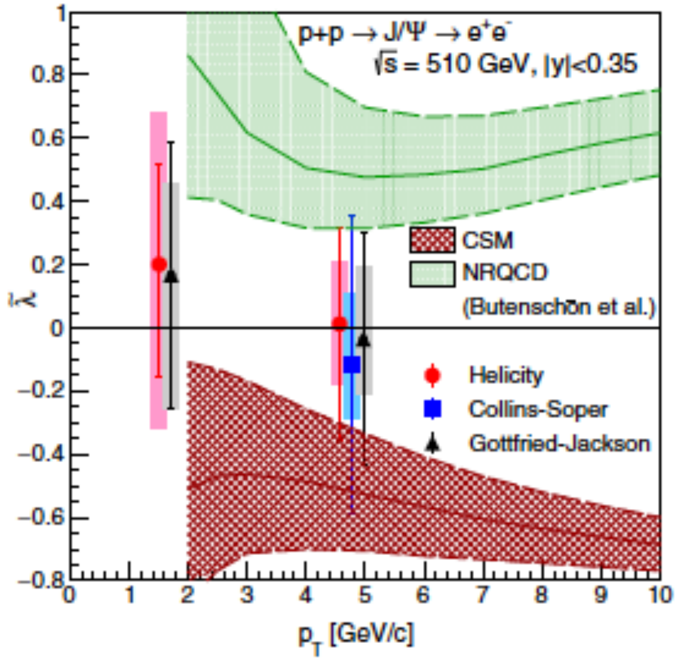
J/ψ Polarization at midrapidity



- Consistent with NLO NRQCD calculations with relativistic corrections that include both color singlet and octet contributions

J/ψ Polarization vs p_T

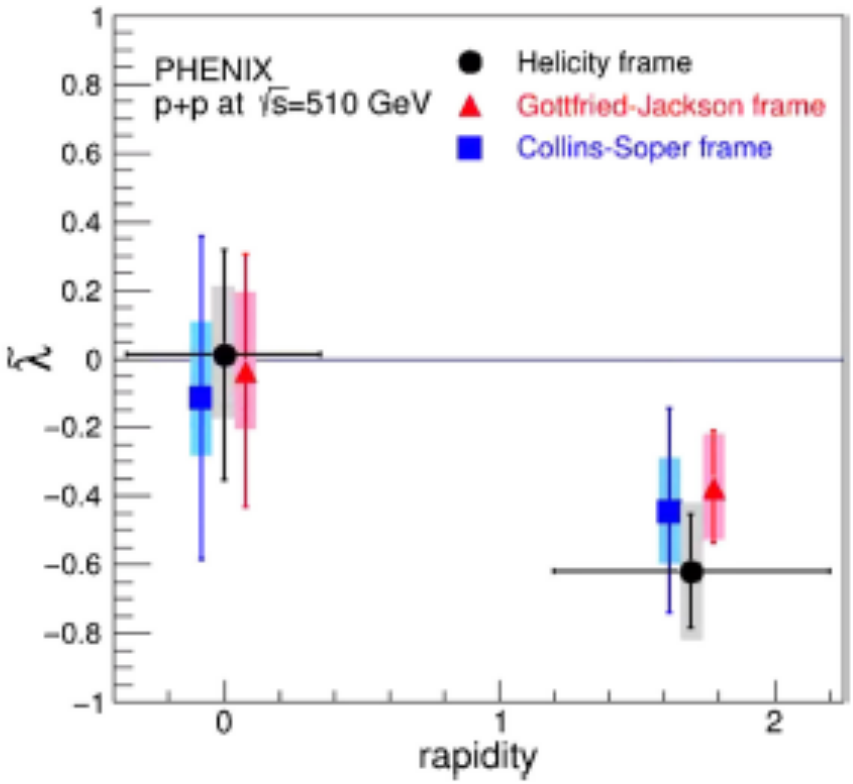
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$



- Neither NRQCD or Color Singlet Model can be ruled out
- At mid rapidity J/ψ polarization consistent with zero

J/ψ Polarization vs rapidity

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



- ➢ At mid rapidity J/ψ polarization consistent with zero
- ➢ At forward rapidity, J/ψ polarization consistent with longitudinal polarization

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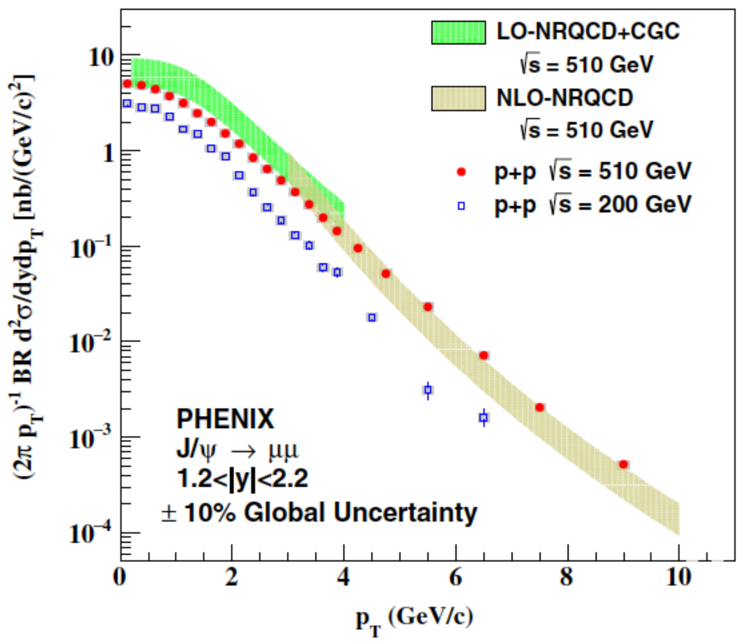
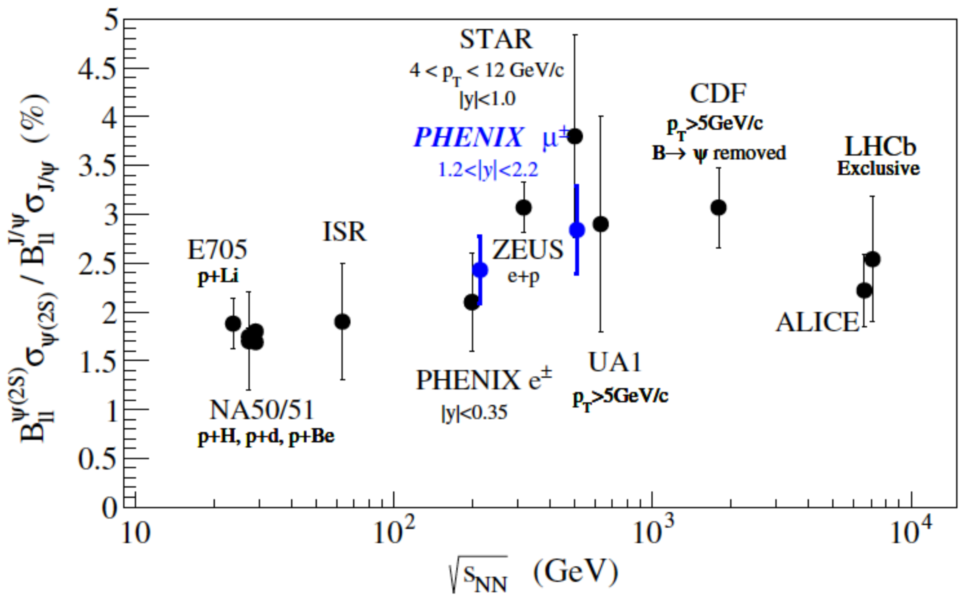
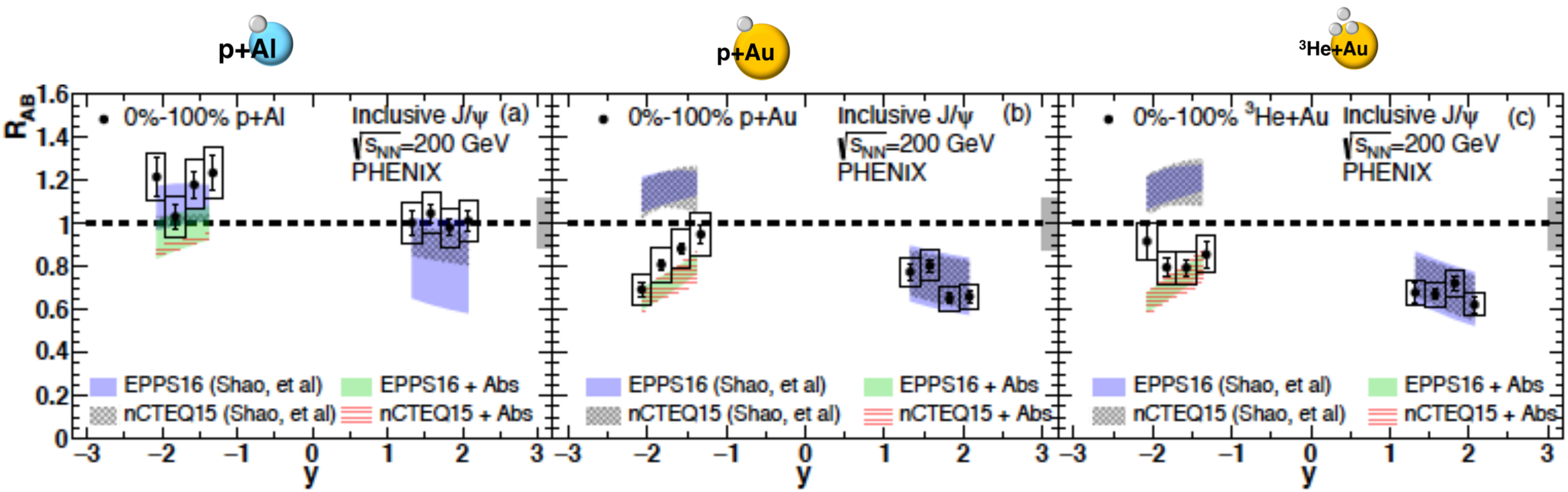
Inclusive J/ψ at forward rapidity





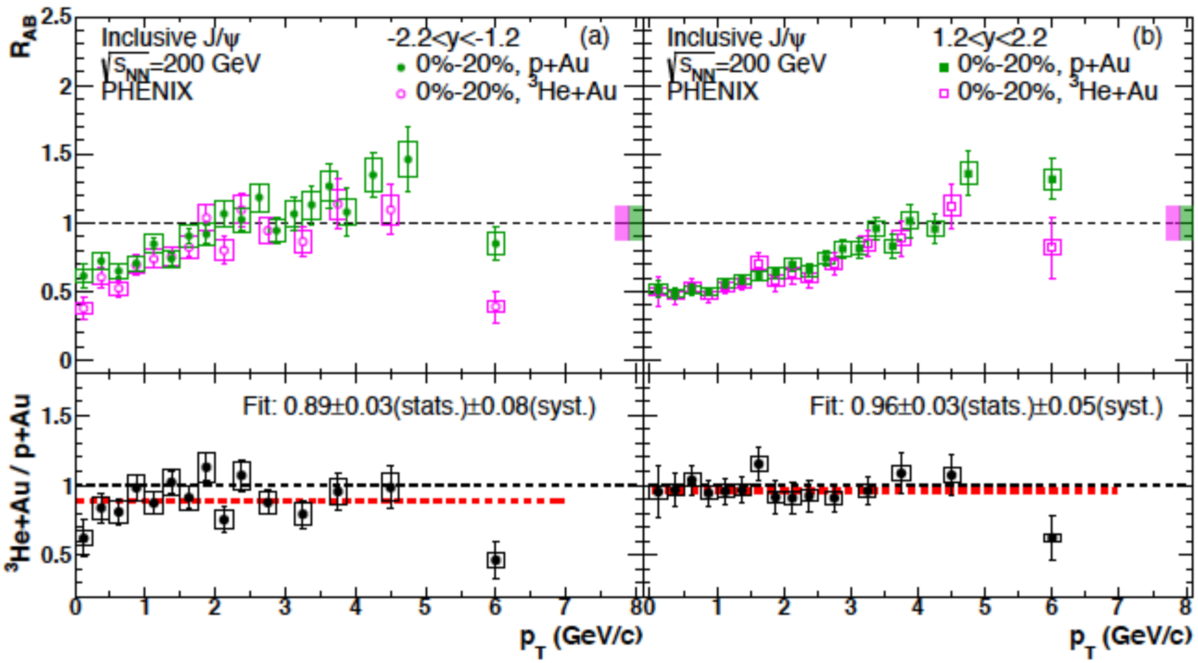
- LO NRQCD+Color Glass Condensate at low p_T overestimates data
- ψ(2S)/J/ψ ratio consistent with world data; no clear energy dependence

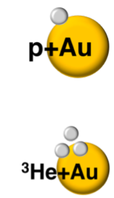
Inclusive J/ψ in small systems



- Only weak modification for p + Al collisions
- p + Au and 3He +Au significant suppression is seen at forward rapidity, with less suppression at backward rapidity.
- Theory calculations include nuclear absorption at backward rapidity

J/ψ in Central p+Au and ^{3}He+Au

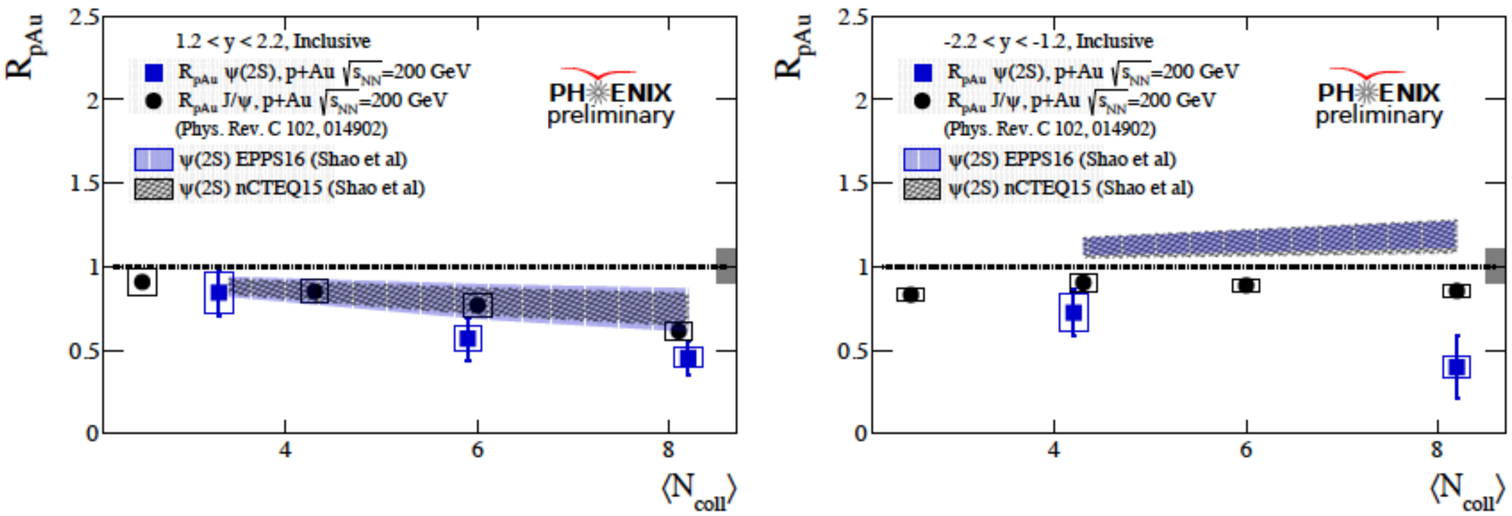




- Slightly stronger suppression in ^{3}He+Au at backward rapidity with significance 1.3σ
- No final state effect at forward rapidity, small final state effect at backward rapidity

Ψ(2S) Nuclear Modification

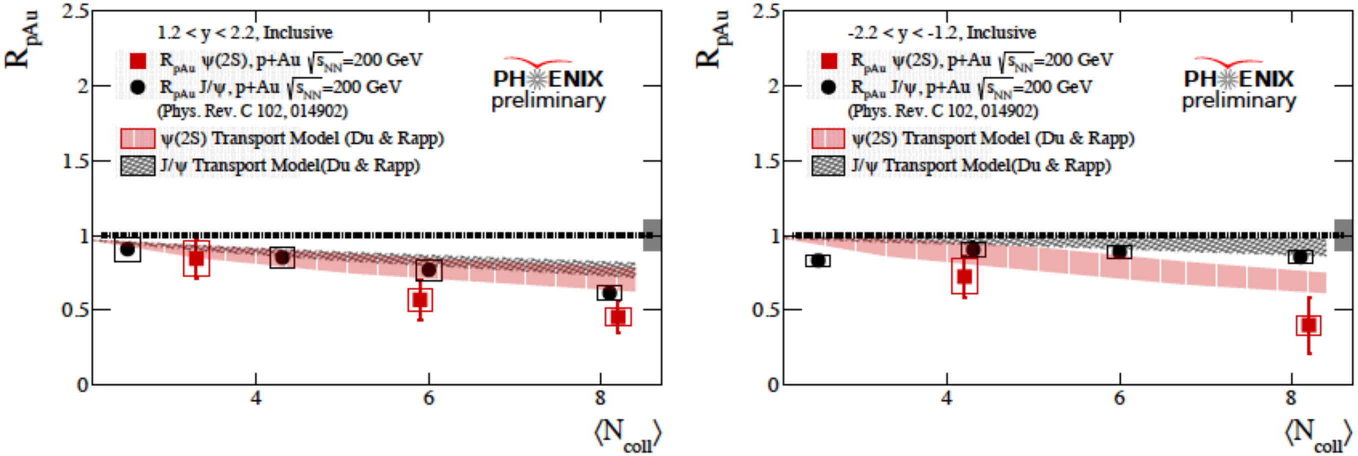
NEW!



- At forward rapidity, J/ψ and ψ(2S) modification follow similar trend and well described by theory
- At backward rapidity, clear difference in ψ(2S) modification in most central collisions, anti-shadowing predictions alone cannot describe the data

Ψ(2S) Nuclear Modification

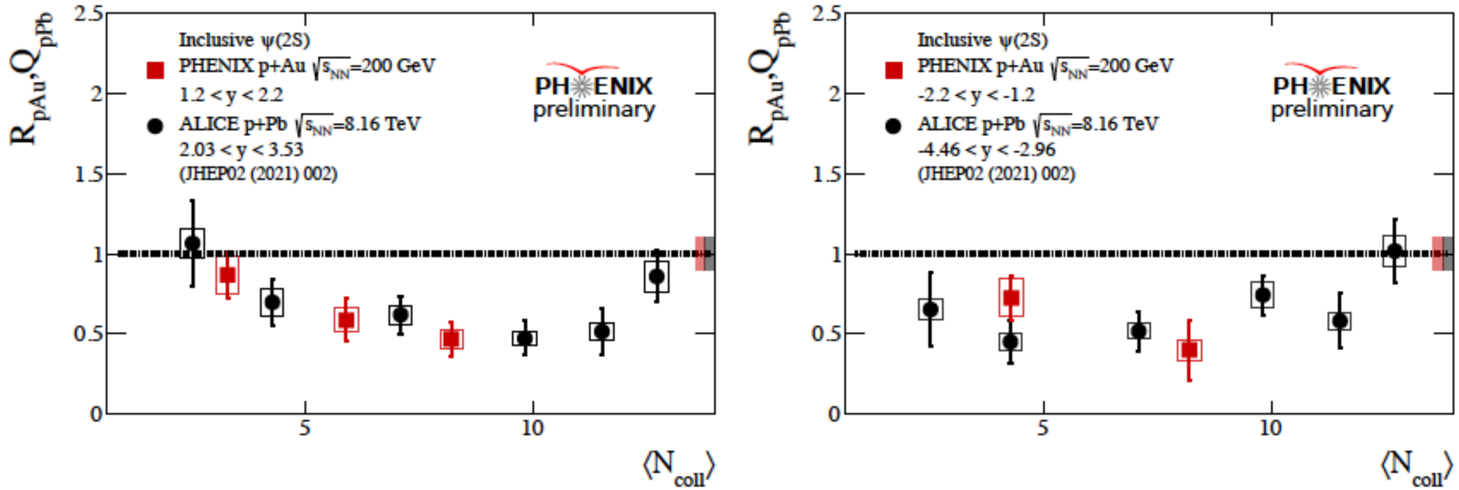
NEW!



- At backward rapidity, clear difference in ψ(2S) modification in most central collisions, consistent with final state effects in small system collisions

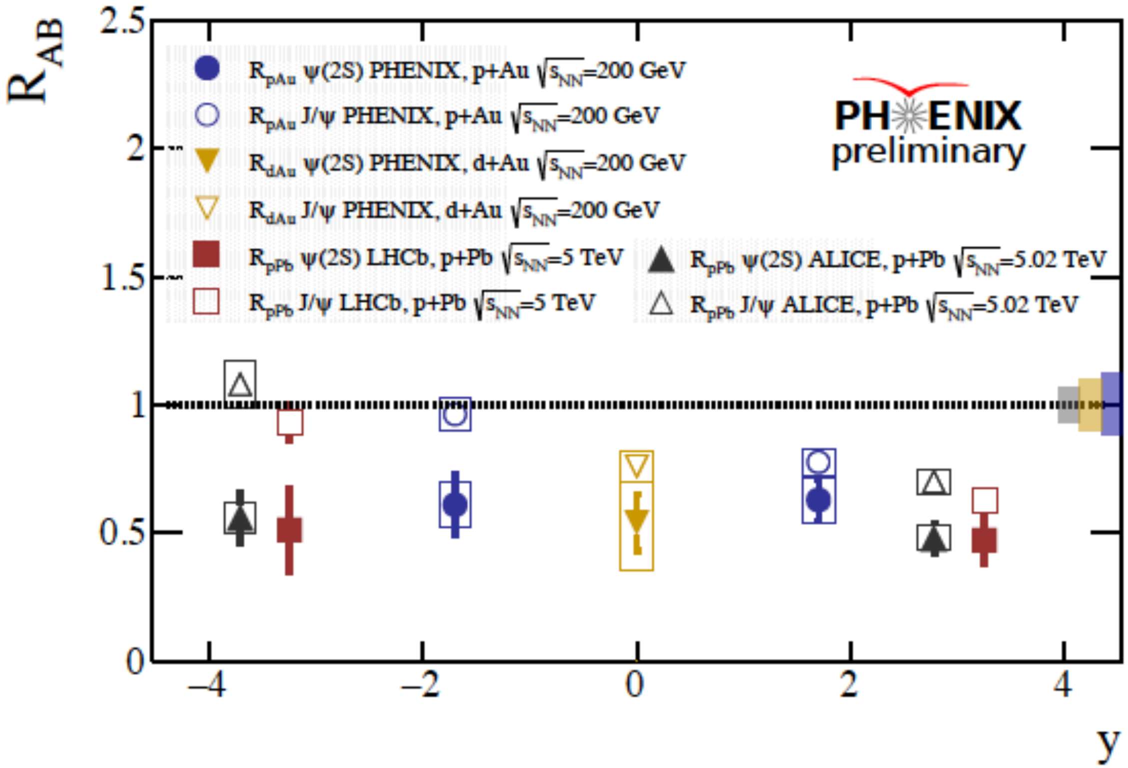
Ψ(2S) Nuclear Modification at RHIC and LHC

NEW!



- At forward rapidity PHENIX and ALICE ψ(2S) modification quite similar ➞ cold nuclear matter effects appear to be dominant
- PHENIX and ALICE ψ(2S) modification very similar at backward rapidity as well ➞ final state effects are important in small system collisions

J/Ψ and Ψ(2S) at RHIC and LHC



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

Summary

- J/ Ψ polarization is consistent with zero at mid-rapidity and with longitudinal polarization at forward rapidity
- J/ Ψ production at RHIC is better described by NRQCD rather than NRQCD+CGC
- World data on the Ψ(2S)/J/Ψ ratio shows no clear energy dependence
- 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, J/Ψ and Ψ (2S) nuclear modification as function of Ncoll very similar in p+A collisions
- Strong suppression of Ψ(2S) nuclear modification at backward rapidity supports final state effects in small systems

BACKUP

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Polarization frames: choosing Z-axis

- Helicity (HX): J/ψ momentum in lab frame, explores final state effects
- Gottfried-Jackson (GJ): beam particle momentum, fixed target experiments.
- Collins-Soper (CS): bisector of two colliding beams.
  - *Note the difference between parton momentum used in theory and proton momentum used in experiment*
  - *Inclusive vs. direct production is also an important consideration*