J/ψ and $\psi(2S)$ Measurements in PHENIX

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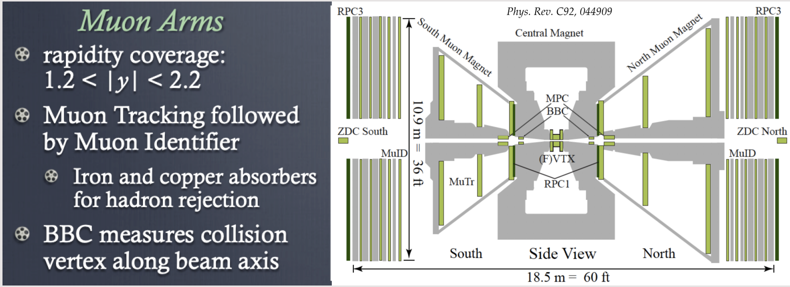
on behalf of the PHENIX Collaboration

CFNS: Physics Opportunities with Heavy Quarkonia at the EIC

October 26, 2021

1. Measurement of Charmonium with PHENIX
2. J/ψ Nuclear Modification Results
3. $\psi(2S)$ Nuclear Modification Results
4. Conclusion

PHENIX Detector: Muon Arms



- MuID dimuon trigger records hits that satisfy trigger logic
- All dimuon hits recorded in coincidence with BBC Minimum Bias trigger

Reconstructed J/ψ Invariant Mass

Los Alamos NATIONAL LABORATORY

PHENIX

- All particles that penetrate the third layer in the MuID are recorded as muons
  - Muon mass assigned to all kinematic calculations

175cm of absorbers

- Conservation of four-momentum q_i is used to reconstruct J/ψ invariant mass
  - Three-momentum measured using bend in magnetic field

$$
\begin{aligned}
q_1 &= q_2 + q_3 \\
q_1^2 &= (q_2 + q_3)^2 \\
&= q_2^2 + 2q_2 \cdot q_3 + q_3^2 \\
&= (q_2^0)^2 - \bar{q}_2^2 + 2q_2 \cdot q_3 + (q_3^0)^2 - \bar{q}_3^2 \\
&= \mathrm{E}_2^2 + E_3^2 + 2(q_2^0 q_3^0 - \bar{q}_2 \cdot \bar{q}_3) - \bar{q}_2^2 - \bar{q}_3^2 \\
&= \mathrm{E}_2^2 + E_3^2 + 2E_2E_3 - 2\bar{q}_2 \cdot \bar{q}_3 - \bar{q}_2^2 - \bar{q}_3^2 \\
&= (\mathrm{E}_2^2 - \bar{q}_2^2) + (E_3^2 - \bar{q}_3^2) + 2E_2E_3 - 2\bar{q}_2 \cdot \bar{q}_3 \\
&= \mathrm{m}_\mu^2 + m_\mu^2 + 2E_2E_3 - 2\bar{p}_2 \cdot \bar{p}_3 \\
&= (\mathrm{m}_{\mu\mu}^{J/\psi})^2
\end{aligned}
$$

$$
\begin{aligned}
|\vec{F}_L| &= |\vec{F}_c| \\
q|\vec{v}||\vec{B}| &= \frac{mv^2}{R} \\
\Rightarrow |\vec{p}| &= q|\vec{B}|R
\end{aligned}
$$

Absorber	Material	South (North) Thickness (cm)	$\lambda_I/cos\theta$
Nose cone	Copper	20(20)	1.8(1.8)
Central Magnet	Steel	60(60)	3.1(3.1)
Stainless steel absorbers	Stainless Steel	35(35)	2.2(2.2)
Sum of pre-MuTr	-	115(115)	7.1(7.1)
Muon Magnet yoke	Steel	20(30)	1.1(1.5)
MuID 1st Layer	Steel	10(10)	0.6(0.6)
MuID 2nd Layer	Steel	10(10)	0.6(0.6)
MuID 3rd Layer	Steel	20(20)	1.2(1.2)
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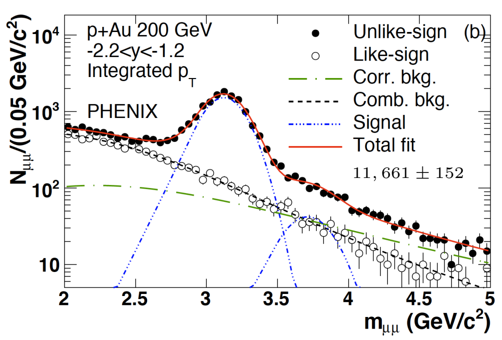
MuID 5th Layer	Steel	20(20)	1.2(1.2)
Sum of post-MuTr	-	100(110)	5.9(6.3)
Total	-	215(225)	13.0(13.4)

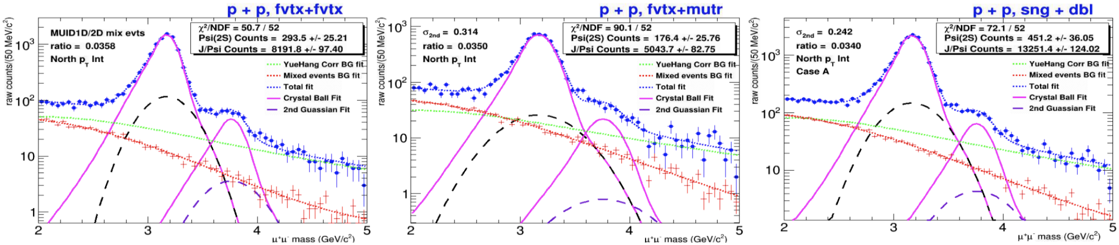
Reconstructed Dimuon Mass Distribution



Phys. Rev. C 102, 014902

- Unlike-sign reconstructed muon pairs
- Like-sign reconstructed muon pairs
  - Estimate of combinatorial background
- Correlated background
  - Open heavy flavor, Drell Yan, etc.
- Fit to the combinatorial background
- J/ψ, $\psi(2S)$ Crystal Ball fits
- Total fit

Dimuon Tracks in PHENIX Muon Arms

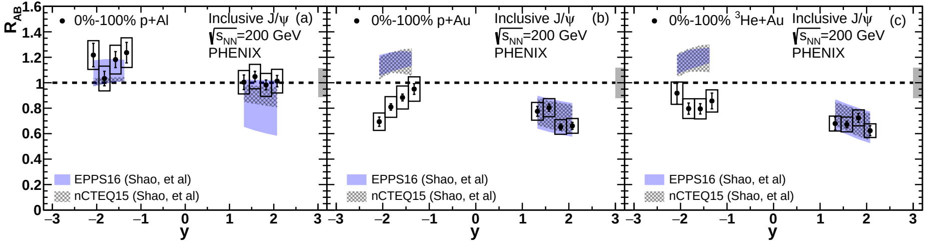


- For the J/ψ measurements:
  - Only the Muon Tracker mass resolution was used (distribution shown on previous slide)
- For the $\psi(2S)$ measurements:
  - The FVTX was used for better mass resolution
  - For better statistics, at least one track associated with the FVTX was required

J/ψ Nuclear Modification Results

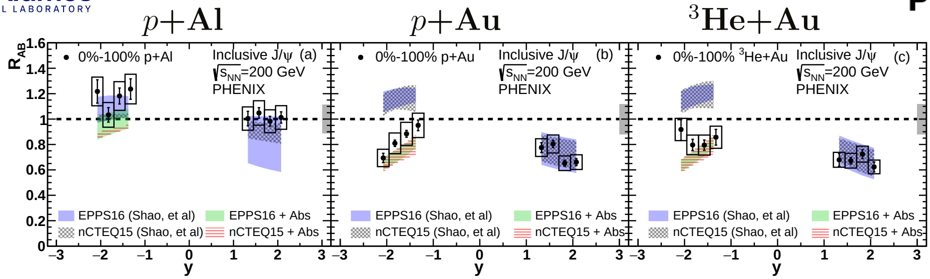
J/ψ Modification vs. Rapidity (0-100%)

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



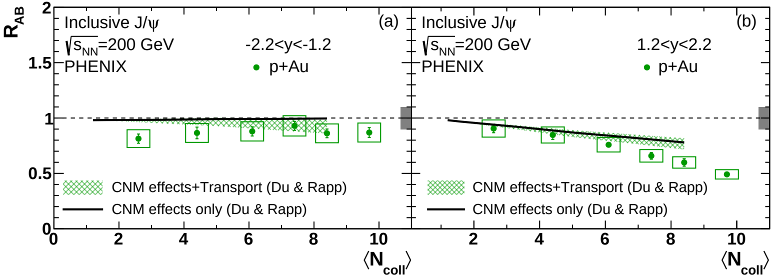
- nPDF nCTEQ15 and EPPS16 predictions reweighted using LHC data [1],[2]
  - Agree well with data at forward rapidity
  - Do not agree at backward rapidity for Au target
- **Shadowing only**

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



- nPDF nCTEQ15 and EPPS16 predictions reweighted using LHC data
  - Added a nuclear absorption estimate at backward rapidity [5]
    - Describe data reasonably well
- **Shadowing + Nuclear Absorption**

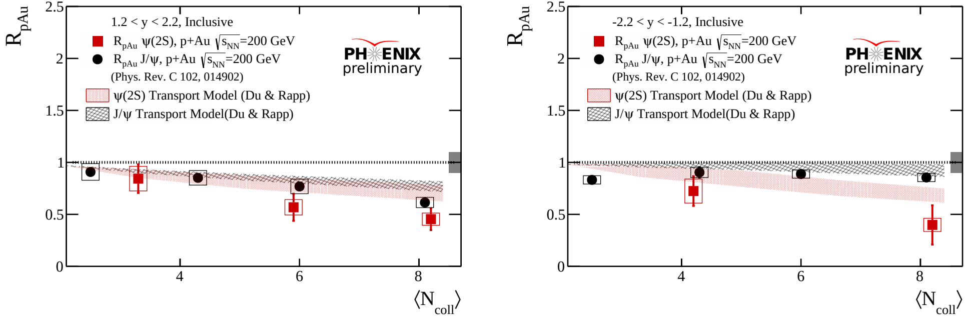
p+Au Dependence on $\langle N_{coll} \rangle$



- CNM effects+Transport Model [3],[4]
  - EPS09NLO with nuclear absorption at backward rapidity
- Little effect from Transport Model at forward rapidity
  - CNM suppression dominant

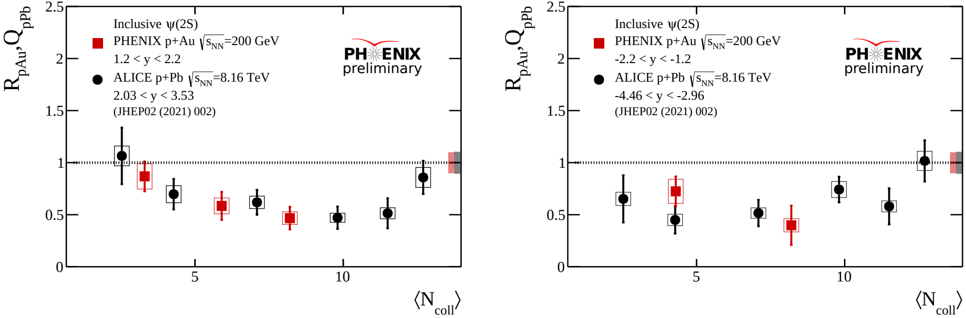
$\psi(2S)$ Nuclear Modification Results

$\psi(2S)$ Nuclear Modification



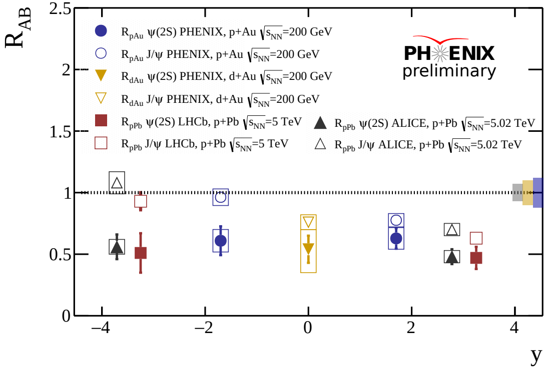
- At forward rapidity, J/ψ and $\psi(2S)$ modification follow similar trend
  - Largest contribution to Transport Model from EPS09 shadowing
- At backward rapidity, clear difference in $\psi(2S)$ modification in most central collisions

$\psi(2S)$ 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

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



- At forward rapidity, J/ψ nuclear modification similar to $\psi(2S)$ nuclear modification
- Stronger suppression observed for $\psi(2S)$ at bkwd rapidity supports final state effects

Conclusion

❶ J/ψ Analysis

- PHENIX J/ψ nuclear modification in small systems best described by nPDFs with a nuclear absorption model included at backward rapidity
- At forward rapidity, J/ψ nuclear modification is consistent with EPPS16 and nCTEQ15 shadowing predictions

❷ $\psi(2S)$ Analysis

- At both RHIC and LHC energies, $\psi(2S)$ nuclear modification as function of $\langle N_{coll} \rangle$ very similar in p+A collisions
- Strong suppression of $\psi(2S)$ nuclear modification at backward rapidity supports final state effects in small systems

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)

Hadron Absorbers

Absorber	Material	South (North) Thickness (cm)	South (North) $\lambda_I / cos\theta$
Nose cone	Copper	20(20)	1.8(1.8)
Central Magnet	Steel	60(60)	3.1(3.1)
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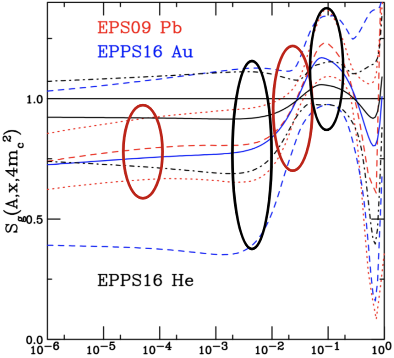
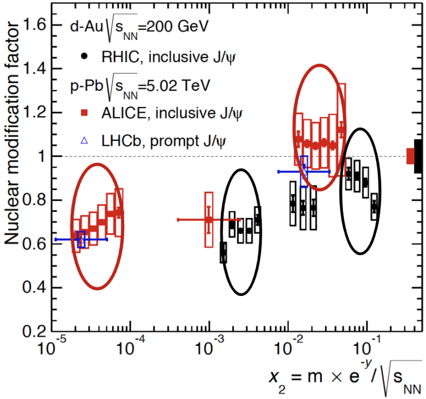
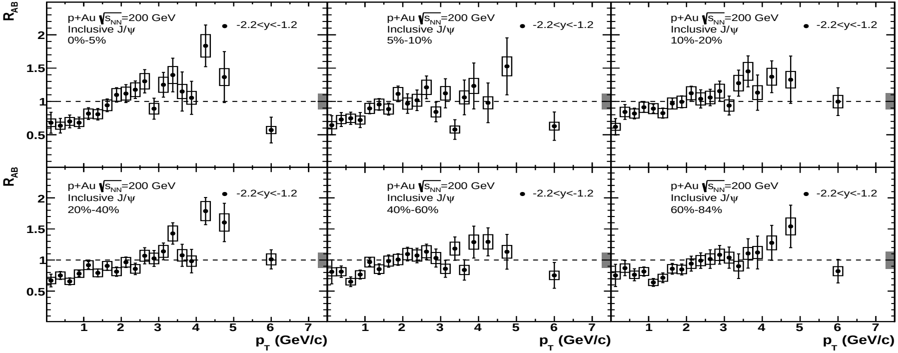
Image Credit: Y. H. Leung





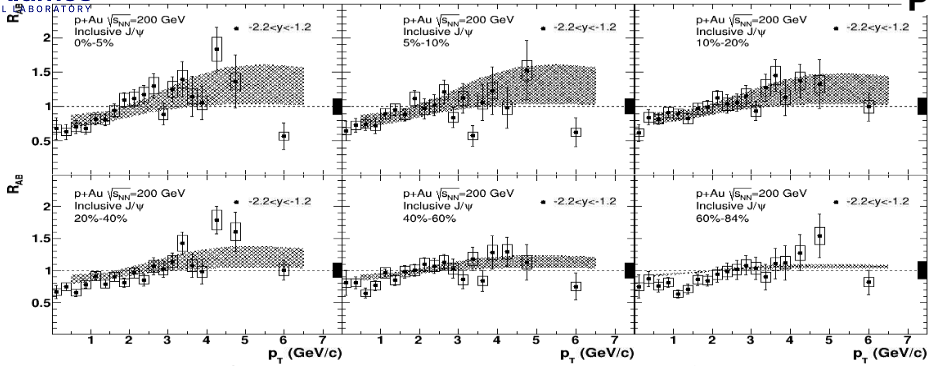
Unmodified plots: Left, R. Vogt. Right, Eur. Phys. J. C (2016) 76: 107

p+Au Centrality Dependence, Bkwd Rapidity



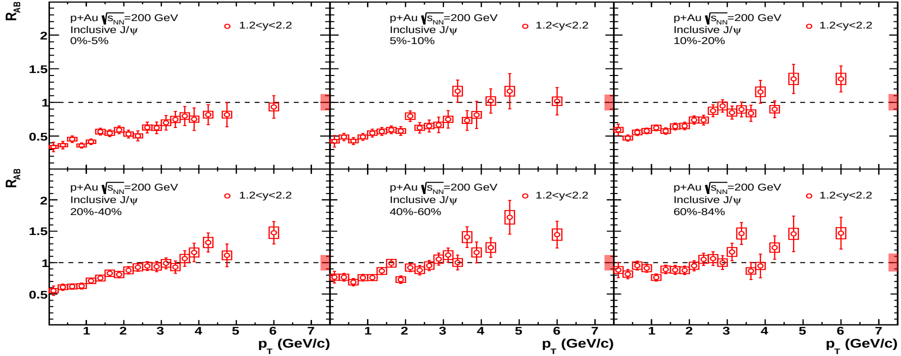
- Suppression at low p_T for most central collisions
  - Competition between nuclear absorption and anti-shadowing

p+Au Centrality Dependence, Bwd Rapidity



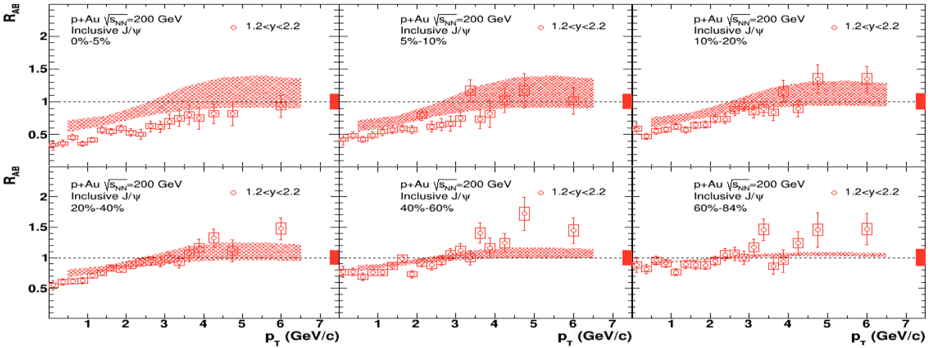
- Transport Model includes nuclear absorption and p_T broadening
- Describes data well across full p_T range

p+Au Centrality Dependence, Fwd Rapidity



- Very strong suppression in most central collisions

p+Au Centrality Dependence, Fwd Rapidity

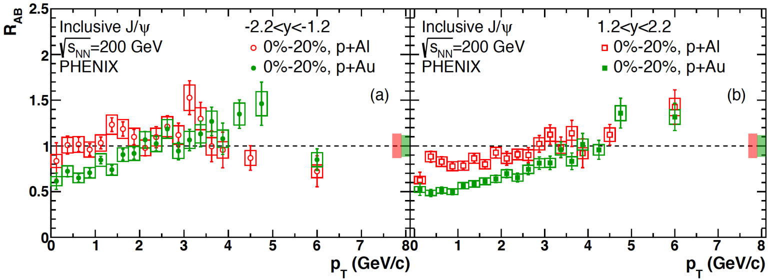


- Transport effects small at forward rapidity
  - EPS09 shadowing dominates → shadowing not strong enough in central collisions

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