PHENIX measurements of the collision system dependence of heavy quarkonia production

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On behalf of the PHENIX Collaboration

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New data from PHENIX:

U+U J/ψ suppression from RHIC 2012 Run (arXiv:1509.05380)

ψ(2S) / ψ(1S) ratios in p+p, p+Au, p+Al from 2015 Run
  • Tracks measured with muon arms + FVTX detector
  • Improved opening angle resolution separates J/ψ from ψ’ in mass spectrum
LHC energy brings strong charm coalescence

$J/\psi$ suppression much stronger at 200 GeV than 2.76 TeV for similar energy density - strong coalescence

At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression - perhaps strongest at 200 GeV

In the model (PRC82, (2010) 064905) this similarity is due to a balance between color screening and coalescence
Where does coalescence start to dominate?

U+U collisions allow us to go to higher energy density at RHIC

Central U+U collisions should have:
• 15-20% higher energy density than Au+Au collisions
• stronger color screening
• Increased charm production from ~ 25% larger $N_{\text{coll}}$ values
• stronger coalescence

$J/\psi$ production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production
U+U measurements

In RHIC Run 12 we recorded 1.08 B minbias $\sqrt{s_{NN}} = 193$ GeV U+U events

The p+p reference for $R_{AA}$ is from the RHIC 2008 run
  • Phys. Rev. Lett. 107, 142301 (2011)

The p+p cross section was reduced by 0.964
  • Accounts for 200 → 193 GeV energy difference between p+p and U+U data
  • derived from PYTHIA p+p simulations

Final J/ψ data from the muon arms (1.2 < |y| < 2.2) are now available
  • arXiv:1509.05380
U deformation

Need $N_{\text{coll}}$ to get $R_{AA}$ for U+U. Requires a deformed Woods Saxon distribution of the nucleons in the U nucleus

$$\rho = \frac{\rho_0}{1 + \exp([r - R']/a)}$$

where

$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

We considered two parameterizations of the deformation of the U nucleus:

**Set 1** (Phys. Lett. B 679, 440 (2009)) - “conventional” description of the U deformation
  - The mean radius and diffuseness are taken from electron scattering

**Set 2** (Phys. Lett. B 749, 215 (2015)) differs in 2 ways:
  - Takes into account the finite radius of the nucleon
  - Averages over all orientations of axis-of-symmetry
    - match average radius and diffuseness to values reported from electron scattering
The U+U $R_{AA}$

Start with the latest parameter set (2) to calculate $R_{AA}$

The U+U $R_{AA}$ is noticeably larger than that for Au+Au

PHENIX  
$J/\psi \rightarrow \mu \mu$

$1.2 < |y| < 2.2$

- U+U $\sqrt{s_{NN}}=193$ GeV (gl. sys. 8.1%)
  - pp reference: $\sqrt{s}=200$ GeV $\times$ 0.964
  - Deformed Woods-Saxon parameter set 2
- Au+Au $\sqrt{s_{NN}}=200$ GeV (gl. sys. 9.2%)

arXiv:1509.05380

Number of Participants

The U+U $R_{AA}$ is noticeably larger than that for Au+Au
Effect of U deformation model

The parameters for set 1 are significantly different in their surface diffuseness:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>set 1</th>
<th>set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (fm)</td>
<td>6.81</td>
<td>6.86</td>
</tr>
<tr>
<td>$a$ (fm)</td>
<td>0.6</td>
<td>0.42</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>0.28</td>
<td>0.265</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>0.093</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Larger surface diffuseness for set 1 results in a less compact nucleus, a larger reaction cross section by 12%, and $N_{coll}$ values that are smaller by 6 - 15%
Ratio of dN/dy for U+U and Au+Au

Make the experimental ratio of dN/dy values.
• Has the advantage that it does not rely on $N_{\text{coll}}$
• However our expectation for its behavior is determined by $N_{\text{coll}}$

Compare with curves showing how the ratio would depend on centrality if J/$\psi$ production scaled with
• $N_{\text{coll}}$ (dashed)
• $N_{\text{coll}}^2$ (solid)

Curves shown for sets 1 and 2

For set 2, for central collisions the ratios tend to favor the $N_{\text{coll}}^2$ curve

For set 1, the ratios are consistent with both curves across centrality, slightly favoring $N_{\text{coll}}^2$ for most central collisions
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Consistent with a picture in which the increase in charm coalescence becomes more important than the increased color screening when going from Au+Au to U+U
Preliminary $\psi' / J/\psi$ ratios in $p+p$, $p+Al$ and $p+Au$
Preliminary $\psi'$ / $J/\psi$ ratios in $p+p$ & $p+Au$

$p+p$, collisions
$\psi'$ and $J/\psi \rightarrow \mu^+\mu^-$  \hspace{0.5cm} 1.2 < |y| < 2.2
Preliminary $\psi'$ / $J/\psi$ ratios in $p+p$ & $p+Au$

$p+Au$, collisions
$\psi'$ and $J/\psi \to \mu^+\mu^-$  $1.2 < |y| < 2.2$

Fit method and cuts in $p+Au$ identical to $p+p$ analysis
Preliminary $\psi' / J/\psi$ ratios in $p+p$ & $p+Au$

$p+Au$, collisions
$\psi'$ and $J/\psi \rightarrow \mu^+\mu^- \quad 1.2 < |y| < 2.2$

Fit method and cuts in $p+Au$ identical to $p+p$ analysis

Stronger suppression evident in Au going direction
ψ' / J/ψ ratios in p+Au and p+Al vs rapidity

Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

Midrapidity point is from d+Au

Strong suppression at backward rapidity, no suppression at forward rapidity
What causes the differential suppression?

Can **breakup** in collisions with nucleons explain the differential suppression at \( y = -1.7 \)?

**No** - the effect is much too small!

From PRC 87 (2013) 054910 - model of \( \tau \) dependence fitted to world’s data

Get \( \sim 1\% - 7\% \) effect in \(-1.2 < y < -2.2\)
What causes the differential suppression?

Since we have eliminated breakup, there is no CNM mechanism that could explain the strong suppression at backward rapidity

- That leaves final state effects

**Final state effects:**

- Suppression is caused by interactions with **produced** particles
- So it can occur **after the charmonium leaves the target**
- i.e. when the meson is fully formed

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**Graphs and Data:**

- PHENIX data
- Ferreiro (PLB 749 (2015) 98)

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"Comovers" in final state

- PHENIX preliminary
- ±15.6% global uncertainty on forward/backward rapidity points
- ±16% global uncertainty on midrapidity point

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$d+Au \sqrt{s_{NN}}=200 \text{ GeV} \ |y|<0.35$

- $N_{\psi}^{(2s)}(p+p)/N_{J/\psi}$
- $R_{dAu}$

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**Figure:**

- $N_{\psi}(p+p)/N_{J/\psi}$
- $N_{J/\psi}(d+Au)$
- $p+Au$
- $p+Al$
- $d+Au$ PRL 111 202301 (2013)

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What causes the differential suppression?

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Final state effects:

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- So it can occur after the charmonium leaves the target
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![Graph showing suppression as a function of rapidity and N_{coll}]

**Differential Suppression**

- $N_{\psi(2s)}^{p+p} / N_{J/\psi}^{p+p}$
- $N_{\psi(2s)}^{p+A} / N_{J/\psi}^{p+A}$

**Uncertainty**

- ±15.6% global uncertainty on forward/backward rapidity points
- ±16% global uncertainty on midrapidity point

**Model Comparison**

- PHENIX data
- PRL 111 202301 (2013)

**References**

- Du & Rapp arXiv:1504.00670
- Hadronic gas + QGP in final state
Adding ALICE data

The comover model does a reasonable job of describing available $\psi(2S)$ and $J/\psi$ data from both PHENIX and ALICE.

But underestimates the differential suppression in both cases.

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**Diagram Description**

- The diagram shows the ratio of yields $N_{\psi(2S)}$ to $N_{J/\psi}$ for different reactions: $p+p$, $p+Au$, $p+Al$, and $d+Au$.
- The data points are compared to the comover model predictions.
- The graph is labeled with PHENIX preliminary and ALICE data.
- The $y$-axis represents the rapidity range from $-2$ to $2$.
- The $x$-axis represents the number of collisions $N_{\text{coll}}$ for PHENIX data and the rapidity $y_{\text{cms}}$ for ALICE data.

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**References**

- d+Au PRL 111 202301 (2013)
- PHENIX data
- ALICE data

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Conclusions

U+U J/ψ suppression is weaker than that for Au+Au
  • Consistent with dominance of coalescence over color screening

Strong indication of final state effects in p+Au $\psi(2S) / \psi(1S)$ ratio vs rapidity
  • Differential suppression of $\psi(2S)$ - consistent with comover model

p+Au $R_{pA}$ analysis vs centrality to come ....
Backup
ψ' / J/ψ ratios in p+Au and p+Al vs rapidity

Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

Midrapidity point is from d+Au

Strong suppression at backward rapidity
No suppression at forward rapidity

Look also at p_T dependence for p+Au:
Fitting the mass spectrum for p+p, p+Au, p+Al

The fit is a log-likelihood fit to raw data with the following components:

- A properly normalized mixed event combinatorial background
- An exponential function to represent correlated background dimuons
- Peaks to represent the resonances:
  - A Crystal Ball function (mass resolution + range straggling in absorber)
  - An additional Gaussian (valid pairs involving lower quality tracks)
    - Set to 200 MeV in fit, varied to determine systematic

The $\psi(2S)$ and $\psi(1S)$ are constrained so:

- Crystal Ball tails have the same shape, relative normalization to the peak for $\psi(1S)$, $\psi(2S)$
- The $\psi(2S)$ width is 1.15 times the $\psi(1S)$ width
  - From sims (varied to determine systematic)
- The $\psi(1S)$ mass floats (moves only 1-2%)
- The $\psi(2S) - \psi(1S)$ mass difference fixed:
  - PDG $\times$ ratio of $\psi(1S)$ mass to PDG
- Relative normalization of second gaussian is the same for $\psi(2S)$ and $\psi(1S)$
The PHENIX muon arms

Experiment:
U+U data at $\sqrt{s_{NN}} = 193$ GeV from RHIC 2012 run

MB trigger: 96% efficient 1.08 B events recorded

Centrality measured by BBC ($3.0 < |\eta| < 3.9$)

$J/\psi \rightarrow \mu^+\mu^- \quad 1.2 < |y| < 2.2$

Acceptance $\otimes$ Efficiency:
PYTHIA $J/\psi \rightarrow \mu^+\mu^-$ events through GEANT, embedded in real data and reconstructed

Efficiency includes occupancy effects

Acceptance flat to within 30% from $p_T = 0 - 8$ GeV/c
U+U Signal Extraction

0-10% (most central)

(a) PHENIX
U+U Centrality 0-10%
-2.2<\eta<-1.2 All Pairs
Mixed-Event Pairs

(b) PHENIX
U+U Centrality 0-10%
1.2<\eta<2.2 All Pairs
Mixed-Event Pairs

(c) PHENIX
U+U Centrality 0-10%
-2.2<\eta<-1.2 Background-subtracted Pairs

(d) PHENIX
U+U Centrality 0-10%
1.2<\eta<2.2 Background-subtracted Pairs

60-70% (most peripheral)

(e) PHENIX
U+U Centrality 60-70%
-2.2<\eta<-1.2 All Pairs
Mixed-Event Pairs

(f) PHENIX
U+U Centrality 60-70%
1.2<\eta<2.2 All Pairs
Mixed-Event Pairs

(g) PHENIX
U+U Centrality 60-70%
-2.2<\eta<-1.2 Background-subtracted Pairs

(h) PHENIX
U+U Centrality 60-70%
1.2<\eta<2.2 Background-subtracted Pairs

Double Gaussian Fit