ATLAS results on charmonium production in Pb-Pb and pp collisions at the LHC

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Introduction

Outline of this talk:

pp collisions at 7 TeV
  ▪ Motivation
  ▪ Inclusive, prompt and non-prompt J/ψ production
  ▪ Upsilon(1S) production

PbPb collisions at 2.76 TeV
  ▪ Motivation
  ▪ J/ψ suppression as a function of centrality
  ▪ Studies of Z

Conclusions
Motivations

- No unified mechanism exists to consistently explain the heavy quarkonium production and spin-alignment in \( e^+e^- \), hadron and heavy-ion colliders
- \( J/\psi \) & \( \Upsilon \) production measurements provide constraint to physics models
Measuring $J/\psi$ in pp: candidate selection

Muons associated to $J/\psi$ candidate may be:

- **Combined** (full Muon Spectrometer & Inner Detector track measurement with fit between the two)
- **Tagged** (Inner Detector measurement associated to at least one hit in Muon Spectrometer)

- Tagged increases chance of fake muon signature, so require at least one of muons in pair to be combined
- At least one muon in pair must have been the object that fired the trigger:
  - ~0 GeV, 4 GeV and 6 GeV $p_T$ thresholds as instantaneous luminosity increased.
  - Dimuon triggers in late 2010, 2011 data

- Muons must have $p>3$ GeV, $p_T>1$ GeV, $|\eta|<2.5$, pixel hits $>0$, silicon hits $>5$
J/ψ candidate selection

ATLAS

2.2 pb⁻¹

σ = 46 MeV

σ = 111 MeV

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Basic strategy of inclusive cross-section analysis method is:
Reconstruct $J/\psi$ candidates in $p_T$-$y$ bins
Correct candidate-by-candidate for efficiency, bin migrations, acceptances

$$N_{\text{corr}} = \sum w^{-1} \cdot N_{\text{reco}}$$

Fit resultant weighted yields to derive signal component $N_{\text{corr}} \rightarrow N_{J/\psi \text{corr}}$
Extract resultant cross-section from $N_{J/\psi \text{corr}}$ in given analysis bin

$$\frac{d^2\sigma(J/\psi)}{dp_Tdy} \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{J/\psi \text{corr}}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$
Spin-alignment and acceptance corrections

Model-dependent on spin-alignment state
Possible differences between prompt and non-prompt J/ψ spin-alignment
**J/ψ efficiency corrections**

**Single muon trigger efficiency**
- Evaluated with Monte Carlo to obtain fine granularity, corrected with Tag & Probe data measurement
- Efficiencies reach plateau of 80—100% at around 6—8 GeV (pseudo-rapidity dependent)

**Offline reconstruction efficiency**
- Evaluated with data (Tag & Probe) using J/ψ→μμ at low p_T supported by Z→μμ measurements at higher p_T for improved plateau precision
- Regions with efficiency < 20% excluded from analysis

**ID track reconstruction efficiency**
- Essentially constant (within uncertainties) at 99.5%±0.5% for muon tracks
Weighted fits and cross-section extraction

For inclusive cross-section measurement, a binned $\chi^2$ fit was used

- Was found to give stable unbiased weighted fit results w.r.t unbinned maximum likelihood fits once restricted to fine $p_T$–$y$ slices as in this analysis
- $\psi(2S)$ included in fit, but yields not extracted at this time
Systematic uncertainties

- Muon Reconstruction
- Muon/ID efficiency
- Acceptance
  - Bin Migration
  - Vertexing
  - Trigger
  - Fit uncertainty
- Total
  - Above
  - Luminosity (3.4%) 
  - MC model dependence
  - Final State Radiation
  - Spin-alignment envelopes are separate uncertainties (5~200%)
Sources of systematic uncertainty, and total uncertainties in each analysis bin.
Measurement of non-prompt fraction

Simultaneous unbinned maximum likelihood fit on invariant mass and pseudo-proper time distribution (used as discriminant for prompt/non-prompt J/ψ) to determine fraction in $p_T$-$y$ bins

Further combine inclusive cross-section and corrected non-prompt fraction to extract prompt and non-prompt differential cross-sections
Simultaneous mass/lifetime fit projections

\[ \sqrt{s} = 7 \text{ TeV}, \quad L dt = 2.3 \text{ pb}^{-1} \]

\[ 9.5 < p_T < 10 \text{ GeV}, \quad |y| < 0.75 \]

\[ 9.5 < p_T < 10 \text{ GeV}, \quad 2.0 < |y| < 2.4 \]
Comparisons include $J/\psi$ feed-down from higher states

Theoretical predictions have issues to describe both shapes and normalization


Upsilon fiducial cross-section

Measurement of differential production cross-section of Upsilon(1S) in $p_T$ & $\gamma$

Similar procedure as for $J/\psi$ for weight correction

Candidate selection: 4 GeV $p_T$ on both muons ($|\eta|<2.5$)

Likelihood fit to $\Upsilon(1,2,3S)$ and background templates

Backgrounds more significant than in $J/\psi$, larger and more complex!

Use OS/SS $\mu$+trk data and HF MC to model
Upsilon cross-section

Measurement based on 1.13 pb\(^{-1}\) of data, using a single muon trigger

Every event is reweighted by the inverse of the event efficiency: weight\(^{-1}\) = \(\varepsilon_{\text{total}} = \varepsilon_{\text{trigger}} \times \varepsilon_{\text{muon reco}} \times \varepsilon_{\text{tracking}}\)

Efficiencies are derived from data-driven methods (e.g. \(J/\psi\) tag and probe)
Background modeling

Muon $p_T$ cuts are only slightly less than $M_{\Upsilon(1S)}/2$

BG is strongly sculpted and varies rapidly as a function of $\mu^+\mu^-$ mass

We model the BG shape by selecting on

- **opposite sign (OS) $\mu+$track in data**
- SS $\mu+$track in data
- $\mu^+\mu^-$ in heavy flavor MC

\[ \int L \, dt = 1.13 \text{ pb}^{-1} \]

\[ 2 \text{ GeV} < p_T^{\mu\mu} < 4 \text{ GeV} \]

\[ |y^{\mu\mu}| < 1.2 \]

\[ 14 \text{ GeV} < p_T^{\mu\mu} < 18 \text{ GeV} \]

\[ |y^{\mu\mu}| < 1.2 \]
Upsilon cross-section: fit of di-muon invariant mass

- Unbinned extended maximum likelihood fit for 4 parameters: \( N_{1S}, N_{2S}, N_{3S}, N_{BG} \)
- Background PDF from OS \( \mu + \)track templates
- Signal PDF from simulation templates
- Resolution determined from studies of \( J/\psi \) and \( Z \) peaks as well as cosmics and fixed in fit.
**Upsilon cross-section results**

Results are not corrected for acceptance step: defined within muon kinematics (4 GeV $p_T$, $|\eta|<2.5$) – removes spin-alignment uncertainty!

- Systematic uncertainties in central bins dominated by BG shape; 2-6%
- In forward bins, BG and signal shape uncertainties each about ~8%
- Upsilon(1,2,3S) fiducial/inclusive differential cross-sections coming soon…

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The 2010 ATLAS Heavy Ions run

• **LHC 2010 Pb-Pb collisions**
  • Luminosity in Pb-Pb Collisions Center-of-mass energy: $\sqrt{s} = 2.76$ TeV per nucleon
  • 9.17 μb⁻¹ of Pb-Pb data collected by ATLAS → data taking efficiency > 95%

• **Samples used**
  • Measurements use ~5 μb⁻¹
  • Trigger used: Minimum Bias Trigger Scintillators ~100% efficiency
  • MC sample: Pythia J/ψ (W, Z) p-p @2.76 TeV overlaid with Hijing MC

Luminosity integrated in 2010 by ATLAS for Pb-Pb collisions

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ATLAS Online Luminosity $\sqrt{s_{NN}} = 2.76$ TeV

- **LHC Delivered (Pb+Pb)**
- **ATLAS Recorded**

Total Delivered: 9.69 ub⁻¹
Total Recorded: 9.17 ub⁻¹

Day in 2010

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**J/ψ (and Z, and W) in heavy ion collisions**

**ATLAS** has performed studies on J/ψ, W and Z with 2010 PbPb data

In each heavy ion collision, have $N_{\text{coll}}$ binary collisions between $N_{\text{part}}$ particles. Any yield measurement in heavy ions must be normalised to $N_{\text{coll}}$.

**Centrality:** characterized by percentage of total cross-section using the forward calorimeter transverse energy sum: $\Sigma E_T (3.2 < |\eta| < 4.9)$

- Estimate of $N_{\text{coll}}$ is performed using Glauber MC simulation
- Exclude 80-100% range due to uncertainty in determination of $N_{\text{coll}}$
$J/\psi$ in HI: analysis approach

$$R_c = \frac{N_c^{corr}(J/\Psi \rightarrow \mu^+\mu^-)}{N_c^{40-80\%}(J/\Psi \rightarrow \mu^+\mu^-) \cdot R_{col}}$$

$N_c^{corr} = \frac{N_c^{meas}}{\varepsilon(J/\psi)_c \times W_c}$

- No attempt to compare with $p$-$p$ results
- Normalization on most peripheral bin
**J/ψ reconstruction in heavy ions**

J/ψ candidates identified from two combined muons; $p_T > 3$ GeV, $|\eta| < 2.5$
(reduces centrality dependence of track reconstruction to ~4%)

- Sideband subtraction method to extract signal yield, cross-check with UBML fit
- Systematic uncertainties assigned from reconstruction efficiency & signal extraction
Systematics: efficiency vs centrality

- Trigger+reconstruction efficiency $\varepsilon = 98\%$

- Small centrality dependence for Combined Muons
  - $\sim 3-4\%$ drop from inner detector tracks reconstruction

- As expected: central events have higher occupancy in the ID but not in the muon chambers

- We use this efficiency variation to correct our raw yield

Efficiency correction in centrality bins:
- 0-10%: $0.93 \pm 0.01$
- 10-20%: $0.91 \pm 0.02$
- 20-40%: $0.97 \pm 0.01$
- 40-80%: 1

All normalized on peripheral bin
Systematics: MC reliability

Largest efficiency dependence on centrality comes from ID occupancy effects
Systematic effects studied comparing basic track quantities in MC and data versus centrality bins

Fraction of tracks with :
• less than 2 hits in Pixel detector,
• less than 6 hits in Semi-Conductor Tracker (SCT),

• with hole in SCT,
• with hole in innermost Pixel layer

Uncertainty ranges from ~2% in peripheral collisions to ~7% in central
**J/\(\psi\) suppression**

Experimental acceptance: \(p_T > 3\) GeV, \(|\eta| < 2.5\) [includes both prompt/non-prompt J/\(\psi\)]

- Significant decrease of the ratio is observed as a function of centrality
- Qualitatively same effect as the one seen by NA50 and PHENIX at very different center-of-mass energies
- Main systematics: J/\(\psi\) reconstruction efficiency \(\sim 2.3\text{-}6.8\%\), signal extraction \(\sim 5.2\text{-}6.8\%\), Rcoll estimate \(\sim 3.2\text{-}5.3\%\)

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Comparison with RHIC

Attempt to replot PHENIX data vs Centrality [P.Steinberg, J.Jia] suggests suppression is energy-independent
**R_{CP} analysis: Z → μμ**

Analysis repeated with Z→μμ decays (p_T(μ)>20 GeV)

Relative Z boson yield found to be compatible with a linear scaling with binary collisions

Low statistics (38 Z candidates) precludes any definite conclusions

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**Graphs and Plots:**

- **Left Graph:**
  - **Axes:** 
    - x-axis: μ⁺μ⁻ invariant mass [GeV]
    - y-axis: Entries / 4 GeV
  - **Legend:**
    - Data
    - MC
  - **Label:**
    - ATLAS Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
    - arXiv:1012.5419 [hep-ex]

- **Right Graph:**
  - **Axes:**
    - x-axis: 1-Centrality %
    - y-axis: Normalized Z yield
  - **Legend:**
    - Pb Pb
  - **Label:**
    - ATLAS Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
Have presented a variety of measurements from ATLAS in pp/PbPb:

**Quarkonia and heavy flavour production in pp collisions @ 7 TeV**
- Prompt quarkonia continue to provoke questions in pp collisions
  - and how does effect of spin-alignment impact PbPb results?
- Non-prompt J/ψ in good agreement with FONLL, within scale uncertainties
- Have 2.76 TeV pp results for various observables as benchmarks for PbPb runs

**Studies of suppression of J/ψ, Z in PbPb collisions @ 2.76 TeV/nucleon**
- We observe an anomalous suppression of the J/ψ yield that increases with centrality
- Centrality suppression is consistent with PHENIX Au+Au collision

Expect many more results in quarkonia/electroweak results in pp/PbPb from ATLAS in the near future!
Additional slides
Di-muon invariant mass distribution (40 pb$^{-1}$)

Combined + combined di-muon pair, 15-2.5 GeV

\[ \int L \approx 40 \text{ pb}^{-1} \]

ATLAS Preliminary

Data 2010, $\sqrt{s} = 7$ TeV
Muons in barrel (|η|<1.05) only

\[ N_{\mu\nu} = (2.208 \pm 0.002) \times 10^6 \]
\[ m_{\mu\nu} = 3.094 \pm 0.003 \text{ GeV} \]
\[ \sigma_{m_{\mu\nu}} = 60 \pm 1 \text{ MeV} \]

At least one combined muon in muon pair

\( J/\psi: \) 4, 2.5 GeV muon p\(_T\) thresholds
\( U(nS): \) 4, 4 GeV muon p\(_T\) thresholds
Muon trigger efficiencies for quarkonia

Trigger efficiency maps derived from hybrid scheme of finely-binned Monte Carlo (needed to remove biases) reweighted using Tag & Probe data from $J/\psi$ (low $p_T$) and $Z$ (high $p_T$) decays

$$\mathcal{E}_{\text{trig}} = 1 - \left(1 - \mathcal{E}_{\text{trig}}^+(p_T^+, \eta^+)\right) \cdot \left(1 - \mathcal{E}_{\text{trig}}^-(p_T^-, \eta^-)\right)$$

- Significant charge dependence observed (and corrected for)
- Muon turn-on thresholds needed accurate handling
- Fine granularity needed to properly model features (even at high $p_T$)

Efficiencies plateau at around 80-100% dependent on pseudorapidity
Reconstruction efficiency maps derived from Tag & Probe data from J/ψ supported by Z→μμ derived data at higher p_T for improved precision in plateau region: exclude areas of low efficiency (<20%)
Due to the toroidal magnetic field of the ATLAS Muon Spectrometer, muons with positive (negative) charge are bent towards larger (smaller) $\eta$.

Introduces a charge dependence of the muon reconstruction/trigger efficiencies, particularly relevant at very large $|\eta|$, where muons of one charge may be bent outside the detector geometrical acceptance, and at low $p_T$, where muons of one charge may be bent back before reaching spectrometer stations.
Reconstruction efficiency of Combined (CB) + Tagged (ST) muons as a function of charge*pseudorapidity in MC and data.
We know acceptance can vary with spin-alignment. State has generalised angular decay distribution:

\[ |\psi\rangle = a_{-1} |1, -1\rangle + a_0 |1, 0\rangle + a_{+1} |1, +1\rangle \]

\[
\frac{dN}{d\Omega} = 1 + \lambda_{\theta^*} \cos^2 \theta^* + \lambda_{\phi^*} \sin^2 \theta^* \cos 2\phi^* + \lambda_{\theta^* \phi^*} \sin 2\theta^* \cos \phi^* \\
\frac{1 - 3|a_0|^2}{1 + |a_0|^2} + \frac{2Re a_{+1}^* a_{-1}}{1 + |a_0|^2} + \frac{\sqrt{2}Re [a_0^* (a_{+1} - a_{-1})]}{1 + |a_0|^2}
\]

Before measure spin-alignment, we work with five specific working points that provide a maximal envelope for expectation →

**FLAT** (unphysical, but default in Pythia MC)
\[ \lambda_{\theta^*} = \lambda_{\phi^*} = \lambda_{\theta^* \phi^*} = 0 \]

**TRPM**
\[ a_0 = 0, \quad a_{+1} = -a_{-1} \]

**LONG**
\[ \lambda_{\theta^*} = -1 \]

**TRP0**
\[ \lambda_{\theta^*} = +1 \]

**TRPP**
\[ \lambda_{\theta^*} = a_0 = 0, \quad a_{+1} = +a_{-1} \]

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Acceptance in azimuthal angle dependent on angle between J/ψ production and decay plane

Non-trivial influence of $\phi^*$ acceptance on produced J/ψ, particularly at low $p_T$

Integrating over $\phi^*$ (as was/is done at e.g. Tevatron) safe only if have flat acceptance in that variable, else $\cos \theta^*$ dependence and average acceptance in given bin will be incorrect!
Upsilon cross-section reported within fiducial cuts on muons of $p_T > 4 \text{ GeV}$, $|\eta| < 2.5$, in two bins of Upsilon rapidity and eight bins of $p_T$. 

<table>
<thead>
<tr>
<th>$p_T^{(1S)}$ (GeV)</th>
<th>$N_{1S}$</th>
<th>$d^2\sigma / dp_T dy$ (pb/GeV)</th>
<th>$\delta_{\text{stat}}$ (%)</th>
<th>$\delta_{\text{ryst}}$ (%)</th>
<th>$\delta_{\text{tot}}$ (%)</th>
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<tbody>
<tr>
<td>$</td>
<td>y^{(1S)}</td>
<td>&lt; 1.2$</td>
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<td></td>
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</tr>
<tr>
<td>0 – 2</td>
<td>213</td>
<td>39.3</td>
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<td>5</td>
<td>13</td>
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<td>11 – 14</td>
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<td>33</td>
<td>9</td>
<td>34</td>
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<tr>
<td>$1.2 &lt;</td>
<td>y^{(1S)}</td>
<td>&lt; 2.4$</td>
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<td>4 – 6</td>
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<td>6 – 8</td>
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<td>17</td>
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<td>8 – 11</td>
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<td>11 – 14</td>
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<tr>
<td>14 – 18</td>
<td>71</td>
<td>6.5</td>
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<td>10</td>
<td>20</td>
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<tr>
<td>18 – 26</td>
<td>28</td>
<td>1.3</td>
<td>29</td>
<td>15</td>
<td>33</td>
</tr>
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</table>
The decay $D^{*\pm} \rightarrow D^0 \pi^\pm_s$ relies on ID track reconstruction and vertexing of the $D^0 \rightarrow K^-\pi^+$

Uses MBTS trigger > 99.5% efficient; track multiplicity independent

Combine two oppositely-charged tracks assign $K/\pi$ mass hypothesis to each, and $p_T(K,\pi)>1.0$ GeV

Third (soft) track added with pion mass, and $p_T(\pi)>0.25$ GeV

Build $D^0$ signal from $M(K\pi)$ for $D^{*\pm}$ candidates

Additional discrimination from mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$

Use presence of secondary vertex and properties of hard process to guide cut selection to enhance signal
Approx. 2000 \( D^{*\pm} \) in both \( M \) and \( \Delta M \) peaks
Mass of \( D^0 \) compatible with PDG value
Not corrected for efficiency or detector effects

Secondary vertex fit \( \chi^2 < 5 \)
Transverse decay length > 0 mm
\( p_T(D^*)/\Sigma E_T > 0.02 \)
\( p_T(D^*) > 3.5 \) GeV, \( p_T(K,\pi) > 1.0 \) GeV
\( |\eta(D^*)| < 2.1 \)
Similar strategy to D*:
combine two oppositely charged tracks,
assign pion mass, \( p_T(\pi_1) > 1.0 \text{ GeV}, \ p_T(\pi_2) > 0.8 \text{ GeV} \)

Combine with third track with kaon mass
\( p_T(K) > 1.0 \text{ GeV} \)

Combinatorial background reduced
with cut on angle between kaon in
\( D^+ \) rest frame and \( D^+ \) momentum
direction in lab frame

Suppression of \( D^{*+} \):
require \( M(K\pi\pi) - M(K\pi) > 150 \text{ MeV} \)

Suppression of \( D^+_s \rightarrow \phi(K^+K^-)\pi^+ \):
require \( |M(K^+K^-) - M(\phi)_{PDG}| > 8 \text{ MeV} \)

\(~1550\) candidates seen in clear peak
Mass in good agreement with PDG

\[ 1870.4 \pm 0.9 \text{ MeV} \]

\[ M_{PDG} = 1869.5 \text{ MeV} \]
\( D^\pm_s \rightarrow \phi \pi^+ \rightarrow K^+K^- \)

Secondary vertex fit \( \chi^2 < 6 \)
Transverse decay length \( > 0.4 \text{ mm} \)
\( p_T(D^+_s)/\Sigma E_T > 0.04 \)
\( p_T(D^+_s) > 3.5 \text{ GeV} \)
\( |\eta(D^+_s)| < 2.1 \)
\( \cos^2(\pi) < 0.4, |\cos^3\theta'(K)| > 0.2 \)

Again combine two oppositely charged tracks, assign kaon mass, \( p_T(K) > 0.7 \text{ GeV} \)

Consider good \( \phi \) candidate if
\( |M(KK)| < 6 \text{ MeV} \) of PDG \( \phi \) mass
\( \phi \) peak clearly visible on \( M(KK) \) plot

Combine with third track (\( \pi \) hypothesis)
\( p_T(\pi) > 0.8 \text{ GeV} \)

326 \( D^\pm_s \) candidates seen in \( M(KK\pi) \) peak
**ATLAS now able to reconstruct $B^\pm \rightarrow J/\psi(\mu\mu)K^\pm$**

Candidates built from $J/\psi$ candidate with 4, 2.5 GeV muon $p_T$ cuts
Constrained vertex fit of $\mu\mu K$ system, $p_T(\mu\mu K) > 10$ GeV

**Exploit displaced vertex of decay to improve signal/background:**
B transverse decay length cut $> 300$ $\mu$m
Signal reduction 13%, consistent with MC, background reduced by factor of **six**
Nuclear modification factor

- PHENIX, Au+Au, |y|<1.2, ±7% syst.
- PHENIX, Au+Au, |y|<1.2, ±12% syst.
- NA50, Pb+Pb, 0<y<1, ±11% syst.
- NA60, In+In, 0<y<1, ±11% syst.
- NA38, S+U, 0<y<1, ±11% syst.

Attempt to replot PHENIX data vs Centrality [P. Steinberg, J. Jia] suggest suppression is energy-independent.
Corrected efficiency ratios for $J/\psi$ and $Z$ candidates from MC
Relative yields in all cases – normalise to most peripheral bin

Candidate acceptance on $J/\psi$: two muons have $p_T>3$ GeV in $|\eta|<2.5$

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$N^{\text{meas}}(J/\psi)$</th>
<th>$\epsilon(J/\psi)<em>c/\epsilon(J/\psi)</em>{40-80}$</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>190 ± 20</td>
<td>0.93 ± 0.01</td>
<td>6.8 % 5.2 % 8.6 %</td>
</tr>
<tr>
<td>10-20%</td>
<td>152 ± 16</td>
<td>0.91 ± 0.02</td>
<td>5.3 % 6.5 % 8.4 %</td>
</tr>
<tr>
<td>20-40%</td>
<td>180 ± 16</td>
<td>0.97 ± 0.01</td>
<td>3.3 % 6.8 % 7.5 %</td>
</tr>
<tr>
<td>40-80%</td>
<td>91 ± 10</td>
<td>1</td>
<td>2.3 % 5.6 % 6.1 %</td>
</tr>
</tbody>
</table>

Candidate acceptance on $Z$: two muons have $p_T>20$ GeV in $|\eta|<2.5$

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$N(Z)$</th>
<th>$\epsilon(Z)<em>c/\epsilon(Z)</em>{40-80}$</th>
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<tbody>
<tr>
<td>0-10%</td>
<td>19</td>
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