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Measurement of the centrality dependence of $J/\psi$ yields and observation of $Z$ production in lead–lead collisions with the ATLAS detector at the LHC

ATLAS Collaboration

**A B S T R A C T**

Using the ATLAS detector, a centrality-dependent suppression has been observed in the yield of $J/\psi$ mesons produced in the collisions of lead ions at the Large Hadron Collider. In a sample of minimum-bias lead–lead collisions at a nucleon–nucleon centre of mass energy $\sqrt{s_{NN}} = 2.76$ TeV, corresponding to an integrated luminosity of about 6.7 $\mu$b$^{-1}$, $J/\psi$ mesons are reconstructed via their decays to $\mu^+\mu^-$ pairs. The measured $J/\psi$ yield, normalized to the number of binary nucleon–nucleon collisions, is found to significantly decrease from peripheral to central collisions. The centrality dependence is found to be quantitatively similar to the trends observed at previous, lower energy experiments. The same sample is used to reconstruct $Z$ bosons in the $\mu^+\mu^-$ final state, and a total of 38 candidates are selected in the mass window of 66 to 116 GeV. The relative $Z$ yields as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions, because of limited statistics. This analysis provides the first results on $J/\psi$ and $Z$ production in lead–lead collisions at the LHC.

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1. Introduction

The measurement of quarkonia production in ultra-relativistic heavy ion collisions provides a potentially powerful tool for studying the properties of hot and dense matter created in these collisions. If deconfined matter is indeed formed, then colour screening is expected to prevent the formation of quarkonium states when the screening length becomes shorter than the quarkonium size [1]. Since this length is directly related to the temperature, a measurement of a suppressed quarkonium yield may provide direct experimental sensitivity to the temperature of the medium created in high energy nuclear collisions [2].

The interpretation of $J/\psi$ suppression in terms of colour screening is generally complicated by the quantitative agreement between the overall levels of $J/\psi$ suppression measured by the NA50 experiment at the CERN SPS [3] ($\sqrt{s_{NN}} = 17.3$ GeV) and the PHENIX experiment at RHIC [4] ($\sqrt{s_{NN}} = 200$ GeV). Data from proton–nucleus and deuteron–gold collisions also show decreased rates of $J/\psi$ production [5], indicating that other mechanisms may come into play. Finally, there exist proposals for $J/\psi$ enhancement at high energies from charm quark recombination [6]. Measurements at higher energies, with concomitantly higher temperatures and heavy quark production rates, are clearly needed to address these debates with new experimental input. The production of $Z$ bosons, only available in heavy ion collisions at LHC energies, can serve as a reference process for $J/\psi$ production, since $Z$’s are not expected to be affected by the hot, dense medium, although modifications to the nuclear parton distribution functions must be considered [7].

The LHC heavy ion program, which commenced in November 2010, offers an opportunity to measure $J/\psi$ and $Z$ production in nuclear collisions at the highest energies ever achieved. The ATLAS detector provides excellent muon detection capabilities down to momenta of about 3 GeV, and $J/\psi$ mesons and $Z$ bosons can be readily detected via their decays to $\mu^+\mu^-$ final states. This Letter presents the first measurements of the relative yields of $J/\psi$ meson and $Z$ boson decays in lead–lead collisions at a nucleon–nucleon center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. The yields are measured in four bins of collision centrality, and the variation of the yields with centrality is compared to the dependence expected if hard scattering processes scale according to expectations from nuclear geometry. No attempts are made to account for “normal nuclear suppression” [3], nor for feed-down of $J/\psi$ from higher mass charmonium states or $B$ hadron decay.
Muons are measured by combining independent measurements of the muon trajectories from the Inner Detector (ID) and the Muon Spectrometer (MS). A detailed description of these detectors and their performance in proton–proton collisions can be found in Refs. [8,9]. The ID volume is within the 2 T field of a superconducting solenoid, and measures the trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$.\textsuperscript{1} A charged particle typically traverses three layers of silicon pixel detectors, eight silicon strip sensors (SCT detector) arranged in four layers of double-sided modules, and a transition radiation tracker composed of straw tubes. The MS surrounds the calorimeters and provides tracking for muons with $|\eta| < 2.7$ and triggering in the range $|\eta| < 2.4$. The muon momentum determination is based on three stations of precision drift chambers that measure the trajectory of each muon in a toroidal magnetic field produced by three air-core toroids. In order to reach the MS, muons have to cross the electromagnetic and hadronic calorimeters, losing typically 3 to 5 GeV of energy, depending on the muon pseudorapidity. The calorimeters efficiently absorb the copious charged and neutral hadrons produced in lead–lead collisions.

The trigger system has three stages, the first of which (Level-1) is hardware based. The Level-1 minimum-bias trigger uses either the two sets of Minimum-Bias Trigger Scintillator (MBTS) counters, covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two Zero-Degree Calorimeters (ZDC), each positioned at 140 m from the collision point, detecting neutrons and photons with $|\eta| > 8.3$. No muon-specific triggers were used to select the data presented here. The MBTS trigger was configured to require at least one hit above threshold from each side of the detector. A Level-2 timing requirement on a coincidence of signals from the MBTS was then imposed to remove beam backgrounds. The trigger efficiency was studied using an independent trigger probing random filled bunch crossings at Level-1. For these triggers, empty events were removed by testing for a minimal level of activity in the silicon detectors. The combined trigger and event selection efficiency is discussed in Section 3.2.

In the offline analysis, minimum-bias triggered events are required to have a reconstructed primary vertex, at least one hit in each set of MBTS counters, and a time difference between the sides of less than 3 ns to reject beam-halo and other beam-related background events. Measurements of the muon trajectories from both the ID and MS are combined, resulting in a relative momentum resolution gradually increases from peripheral to central collisions, due primarily to an occupancy-induced inefficiency in the ID tracking, as shown in Table 1. The combined measurement systematic uncertainties on the reconstruction efficiency and signal extraction, as well as the total uncertainty.

### Table 1

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<thead>
<tr>
<th>Centrality</th>
<th>$N_{\text{meas}}(J/\psi)$</th>
<th>$\epsilon(J/\psi) / \epsilon(J/\psi)_{140-80}$</th>
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<tbody>
<tr>
<td>0–10%</td>
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### 2. Di-muon event selection

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The oppositely-charged di-muon invariant mass spectra in the four considered centrality bins from most peripheral (40–80%) to most central (0–10%). The \( J/\psi \) yields in each centrality bin are obtained using a sideband technique. The fits shown here are used as a cross check.

### 3. \( J/\psi \) production as a function of centrality

The oppositely-charged di-muon invariant mass spectra in the \( J/\psi \) region after the selection are shown in Fig. 2. The number of \( J/\psi \rightarrow \mu^+\mu^- \) decays is then found by a simple counting technique. The signal mass window is defined by the range 2.95–3.25 GeV. The background is derived from two mass sidebands, 2.4–2.8 GeV and 3.4–3.8 GeV, with a linear extrapolation. To determine the uncertainties related to the signal extraction, an alternative method based on a maximum likelihood fit with the mass resolution left as a free parameter is used as a cross check, as explained in Section 3.1. Centrality-dependent efficiency corrections, derived from Monte Carlo events, are applied to the resulting signal yields. Table 1 lists the number of \( J/\psi \) decays after background subtraction, but before any other correction. With the chosen transverse momentum cuts on the decay muons, 80% of the reconstructed \( J/\psi \) have \( p_T > 6.5 \) GeV.
The measured $J/\psi$ yields at different centralities are corrected by the reconstruction efficiency $\epsilon$ for $J/\psi \rightarrow \mu^+\mu^-$, derived from MC and parameterized in each centrality bin, and the width of the centrality bin, $W_c$, which represents a well-defined fraction of the minimum bias events. The corrected yield of $J/\psi$ mesons is given by:

$$R_{\text{corr}}(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{\text{meas}}(J/\psi \rightarrow \mu^+\mu^-)\epsilon}{\epsilon(J/\psi)_{\text{MC}} \cdot W_c}.$$  \hspace{1cm} (1)

The "relative yield" is defined by normalizing to the yield found in the most peripheral 40–80% centrality bin: $R_{\text{c}} = R_{\text{corr}}^\text{40–80%}/R_{\text{corr}}^\text{0–10%}$. Note that the uncertainties in the 40–80% bin are not propagated into this ratio for the more central bins. Finally, the "normalized yield" is defined by scaling the relative yield by the ratio $R_{\text{coll}}$ of the mean number of binary collisions $N_{\text{coll,c}}$ detailed in Section 3.2, in each centrality bin to that for the most peripheral (40–80%) bin: $R_{\text{CP}} = R_c / R_{\text{coll}}$.

### 3.1. Experimental systematic uncertainties

Several experimental systematic effects are considered. These are grouped into those affecting the $J/\psi$ reconstruction efficiency, and those from the extraction of the number of signal events from the di-muon mass spectra. Since this measurement only determines the relative yields as a function of centrality, only the centrality dependence of these effects is relevant. Any uncertainty on the absolute value cancels out in the ratio. The variation of the $J/\psi$ reconstruction efficiency with centrality observed in simulation is mainly due to the larger occupancy in the ID. Because of the low occupancy in the MS by the primarily-soft tracks produced in heavy ion collisions, the fraction of muons from $J/\psi$ decays with a reconstructed track in the MS is independent of centrality within the MC statistical uncertainty. On the other hand, to improve the reliability of the ID track reconstruction in the dense environment, rather stringent track quality requirements are made, relative to those defined for proton–proton collisions [15]. In particular, there must be at least nine silicon hits on each track, with no missing pixel hits and not more than one missing SCT hit, in both cases where such hits are expected. In order to evaluate systematic uncertainties, comparisons have been made between the distributions of hits associated with tracks and missing hits between data and MC as a function of centrality. The differences between the fraction of tracks with associated or missing hits close to the track selection cuts have been used to derive the systematic uncertainties on the ID track reconstruction that range between 1 and 3% as a function of the centrality. These uncertainties are fully correlated for both muons from the $J/\psi$ decay, resulting in a systematic uncertainty up to about 7% on the $σ$ section, assumed to be $6 \text{ mb}$ from an extrapolation of lower energy data. Using these parameters, the Glauber calculations give $R_{\text{coll}}$, estimated by separately varying $R_{\text{coll}}^\text{0–10%}$ and $R_{\text{coll}}^\text{40–80%}$, respectively [18], and the nucleon–nucleon inelastic cross section, assumed to be $\sigma_{\text{inel}} = 64 \pm 6 \text{ mb}$ from an extrapolation of lower energy data. Using these parameters, the Glauber calculations give a total inelastic cross section of 7.6 barns, which is defined as the "geometric" cross section below.

Systematic uncertainties on the resulting $R_{\text{coll}}$ values are estimated by separately varying $R$, $a$ and $\sigma_{\text{inel}}$ by one standard deviation. The variations of $R$ and $a$ are found to give results of the same magnitude but opposite sign, indicating that the uncertainties on the two parameters are correlated. However, they are conservatively treated as uncorrelated for the error analysis used in these studies.

Any possible variation in the fraction of the geometric cross section selected by the combination of trigger and event selection criteria, $\epsilon_{\text{mb}}$, as a function of centrality must also be considered in evaluating systematic uncertainties on the lead–lead collision geometry, so that the centrality percentiles correspond to the correct fractions of the efficiency-corrected geometric cross section. The uncertainty is estimated by examining the distribution of $\Sigma E_{\text{FCal}}^\text{out}$ in the independent data sample selected by a random trigger and filtered by requiring a minimal amount of Inner Detector activity. The event selection criteria described above are also applied, with an additional requirement that both ZDCs see energies consistent with the presence of at least one neutron. This combination of vertex, MBTS and ZDC selections efficiently rejects photonuclear interactions [19]. The total selected fraction of the geometric cross section is estimated using a fit to the resulting $\Sigma E_{\text{FCal}}^\text{out}$ distribution, assuming the transverse energy in each event results from a superposition of participating nucleons and binary collisions (a similar assumption to that used in Ref. [20]).
The correction factors $R_{\text{coll}}$, together with the relative systematic uncertainty, stated as a 1σ value.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$R_{\text{coll}}$</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10%</td>
<td>19.5</td>
<td>5.3%</td>
</tr>
<tr>
<td>10–20%</td>
<td>11.9</td>
<td>4.7%</td>
</tr>
<tr>
<td>20–40%</td>
<td>5.7</td>
<td>3.2%</td>
</tr>
<tr>
<td>40–80%</td>
<td>1.0</td>
<td>–</td>
</tr>
</tbody>
</table>

The relative $J/\psi$ yield as a function of centrality normalized to the most peripheral bin (black dots with errors). The expected relative yields from the (normalized) number of binary collisions ($N_{\text{coll}}$) are also shown (boxes, reflecting 1σ systematic uncertainties). (Right) Value of $R_{\text{cp}}$, as described in the text, as a function of centrality. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40–80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

$$\Sigma E_{T}^{\text{FCal}} = E_{T}^{pp} \left(1 - x\right) \frac{N_{\text{part}}}{2} + xN_{\text{coll}}.$$  \hspace{1cm} (2)

In this formula, $E_{T}^{pp}$ is the value of $\Sigma E_{T}^{\text{FCal}}$ when $N_{\text{part}} = 2$ and $N_{\text{coll}} = 1$ (the values for a single proton–proton collision) and $x$ controls the relative contribution of participants and binary collisions in lead–lead events. An additional constant noise term is also included to account for the low energy part of the distribution. Distributions of $\Sigma E_{T}^{\text{FCal}}$ are generated for 500k MC events and fitted to the data for a range of values of $x$ (from 0.09 to 0.15), and also varying $E_{T}^{pp}$ and the noise term. For all cases, the integral of the observed distribution in data accounts for around 98% of the best fit to the simulated distribution, with a variation of around 1%. This provides an estimate of the total event selection efficiency $e_{\text{mb}}$ relative to the geometric cross section. An absolute systematic error of ±2% is assigned to $e_{\text{mb}}$ with the positive range also accounting for the possible leakage of photonuclear events into the event sample used to obtain the $\Sigma E_{T}^{\text{FCal}}$ distribution.

The total systematic uncertainties on the ratios $R_{\text{coll}}$ are evaluated by combining the variations with $R$, $a$, $\sigma_{\text{inel}}$ and $e_{\text{mb}}$, in quadrature. The values of $R_{\text{coll}}$ and their systematic uncertainties are reported in Table 2. It should be noted that the estimate of $e_{\text{mb}}$ leads to correlations between the extracted values of $N_{\text{coll}}$, and thus the uncertainties on $R_{\text{coll}}$ are also correlated bin-to-bin.

3.3. $J/\psi$ yields

The relative $J/\psi$ yields after normalization and efficiency corrections as in Eq. (1), $R_{c}$, are compared to the expected $R_{\text{coll}}$ values in the left panel of Fig. 3. The yield errors are computed by adding the statistical and systematic uncertainties in quadrature. A clear difference is observed as a function of centrality between the measured relative $J/\psi$ yield and the prediction based on $R_{\text{coll}}$, indicating a deviation from the simplest expectation based on QCD factorization. The ratio of these two values, $R_{\text{cp}}$, is shown as a function of centrality in the right panel of Fig. 3. The data points are not consistent with their average, giving a $P(\chi^2, N_{\text{DOF}})$ value of 0.11% with three degrees of freedom, computed conservatively ignoring any correlations among the systematic uncertainties. Instead, a significant decrease of $R_{\text{cp}}$ as a function of centrality is observed.

4. $Z$ production as a function of centrality

$Z$ candidates are selected by requiring a pair of oppositely charged muons with $p_{T} > 20$ GeV and $|\eta| < 2.5$ [21]. An additional cosmic ray rejection cut on the sum of the pseudorapidities of the two muons, $|\eta_{1} + \eta_{2}| > 0.01$, is also applied. The invariant mass distribution of the selected pairs is shown in the left panel of Fig. 4. With this selection, 38 $Z$ candidates are retained in the signal mass window of 66 to 116 GeV. The background after this selection is expected to be below 2%, and is not corrected for in the result. The number of $Z$ events in each centrality bin is given in Table 3. For high transverse momentum tracks, the reconstruction is expected to perform as well as or better than in the low $p_{T}$ regime characteristic of the $J/\psi$ study. For this reason, the same systematic uncertainties as

\[\begin{array}{|c|c|c|}
\hline
\text{Centrality} & \text{$R_{\text{coll}}$} & \text{Uncertainty} \\
\hline
0–10\% & 19.5 & 5.3\% \\
10–20\% & 11.9 & 4.7\% \\
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40–80\% & 1.0 & – \\
\hline
\end{array}\]
The number of $Z$ events per centrality bin and the relative efficiency corrections derived from the simulation.

<table>
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Fig. 4. The di-muon invariant mass (left) after the selection described in the text. The value of $R_{CP}$ (right) computed with the 38 selected $Z$ candidates. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40–80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

for the $J/\psi$ results have been applied to the $Z$ relative yield measurements. Several cross checks have been performed to support this assumption. In addition to the tracks reconstructed with the combined ID and MS information, tracks reconstructed by the MS alone have been checked, and only one additional candidate was found. This candidate has been inspected and an ID track was in fact found but with too few hits to pass the stringent reconstruction requirements. The $Z$ selection was also applied to same charge muon pairs, and no candidates were selected within the 66–116 GeV mass window. To control the residual background from cosmic rays, the distribution of the difference of the transverse impact parameters of the two muons from $Z$ candidates was examined and found to be compatible with that expected for collision muons.

The measured $Z$ yields are displayed in the right panel of Fig. 4, normalized to the yield in the most peripheral bin and to the number of binary collisions ($R_{CP}$). Although, within the large statistical uncertainty, they appear to be compatible with a linear scaling with the number of binary collisions, the low statistics preclude drawing any conclusion.

5. Conclusion

The first results on $J/\psi$ and $Z \to \mu^+\mu^-$ relative yields measured in lead–lead collisions obtained with the ATLAS detector at the LHC, have been presented. In a sample of events with oppositely charged muon pairs with a transverse momentum above 3 GeV and with $|\eta| < 2.5$, a centrality dependent suppression is observed in the normalized $J/\psi$ yield. The relative yields of the 38 observed $Z$ candidates as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions.

Acknowledgements

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References


ATLAS Collaboration
