Preliminary Physics Summary:
Centrality dependence of inclusive $J/\psi$ production in p-Pb collisions at $\sqrt{s_{_{\text{NN}}}} = 8.16$ TeV

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Abstract

The inclusive $J/\psi$ production in p-Pb interactions at the centre-of-mass energy per nucleon-nucleon collision $\sqrt{s_{_{\text{NN}}}} = 8.16$ TeV is studied with the ALICE detector at the CERN LHC. The measurement has been performed reconstructing $J/\psi$ mesons via their dimuon decay channel, in the centre-of-mass rapidities $2.03 < y_{_{\text{cms}}} < 3.53$ and $-4.46 < y_{_{\text{cms}}} < -2.96$, down to zero transverse momentum. Preliminary results on the $J/\psi$ nuclear modification factor will be presented as a function of the centrality of the collisions, estimated through the energy deposited in forward-rapidity calorimeters. Results will be compared with those obtained by ALICE in p-Pb collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02$ TeV.

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1 Introduction

Quarkonium production in nucleus-nucleus collisions is sensitive to the formation of a plasma of quarks and gluons (QGP). The high colour-density reached in such a medium might, in fact, induce a screening of the force among the $q$ and $\bar{q}$ quarks, which leads to a temperature-depending melting of the various quarkonium states, according to their binding energy [1]. In parallel to this suppression mechanism, quarkonium might also be produced by regeneration processes during the QGP evolution or at the phase boundary [2, 3]. This additional mechanism becomes relevant in very high-energy collisions, in particular for charmonium (i.e. the quarkonium state formed by $c$ and $\bar{c}$ quarks), due to the large abundance of charm quarks in the medium.

ALICE has measured $J/\psi$ production in Pb-Pb interactions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, for both central and forward rapidities [4–8]. A suppression of the $J/\psi$ production, with respect to the corresponding pp reference, has been observed at both energies. The size of the suppression turns out to be significantly smaller than the one observed at RHIC at $\sqrt{s_{NN}} = 0.2$ TeV. This behaviour may be explained assuming that, at LHC energies, a large fraction of $J/\psi$ is produced by recombination of charm quarks.

However, quarkonium production might be modified also by other mechanisms, not related to QGP formation. Cold nuclear matter effects (CNM), as the modification of the parton distribution functions, or the formation of a Colour Glass Condensate in the nuclei, or the coherent energy loss of the $c\bar{c}$ pair during its path through the medium, are examples of mechanisms which can influence quarkonium production. The size of these effects is usually investigated in proton-nucleus collisions. ALICE results from the 2013 p-Pb data taking at $\sqrt{s_{NN}} = 5.02$ TeV have shown a considerable modification of the $J/\psi$ production yields as a function of rapidity ($y_{\text{cm}}$), transverse momentum ($p_T$) and centrality of the collisions [9–11]. Effects are more sizeable at forward rapidities and at low $p_T$ and, when investigated as a function of centrality, their role is more prominent in central collisions. Theoretical calculations based on the aforementioned mechanisms fairly describe the observed modification of the $J/\psi$ yields. Preliminary results based on a high luminosity p-Pb data taking in 2016, at $\sqrt{s_{NN}} = 8.16$ TeV, confirm, with an increased precision, the features already observed at $\sqrt{s_{NN}} = 5.02$ TeV [12].

The results on the rapidity and transverse momentum dependence of the $J/\psi$ production in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are complemented in this note by results on the measurement of the $J/\psi$ nuclear modification factor ($Q_{\text{mult}}^{p\text{Pb}}$) as a function of the event centrality, both at forward and backward rapidities.

2 Experimental apparatus, data sample and event selection

A detailed description of the ALICE set-up can be found in [13, 14]. The main detector used in this analysis is the Muon Spectrometer [15], which tracks muons in the pseudo-rapidity range $-4 < \eta < -2.5$. The Muon Spectrometer provides also a dimuon trigger based on the simultaneous detection of two unlike-sign muons in a dedicated trigger detector system. Both muons must have $p_T > 0.5$ GeV/c. Two scintillator hodoscopes (V0) [16], covering $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, are used to remove beam-induced background and a coincidence or their signals provides the minimum bias (MB) trigger. The trigger condition used in this analysis ($\mu\mu-MB$) is based on the coincidence of the MB trigger and the dimuon one. The primary interaction vertex is reconstructed with the two innermost layers of the Inner Tracking System (Silicon Pixel Detector, SPD) [17], covering the pseudo-rapidity intervals $|\eta| < 2$ and $|\eta| < 1.4$, respectively. Finally, two sets of Zero Degree Calorimeters (ZDC) [18], each one including a neutron (ZN) and a proton (ZP) calorimeter, placed 112.5 m from the interaction point, are used for the centrality estimate and to reject events where interactions occurred out of the nominal bunches. Events where two or more interactions occur in the same colliding bunch (in-bunch pile-up) or during the readout time of the SPD (out-of-bunch pile-up) are removed using the information from SPD and V0.
Further selection cuts, commonly adopted in the ALICE analyses on J/ψ production at forward rapidity, have also been applied, namely:

- to reject tracks at the edges of the Muon Spectrometer acceptance, both muons forming the dimuon should have a pseudo-rapidity value in the range $-4 < \eta_\mu < -2.5$;
- the radial transverse position of each muon track at the end of the absorber ($R_{abs}$) has to be within $17.6 < R_{abs} < 89.5$ cm, to remove muons crossing the thicker part of the absorber;
- tracks reconstructed in the Muon Spectrometer tracking chambers should match the track reconstructed in the trigger system;
- the dimuon transverse momentum should be in the range $p_T < 20$ GeV/c.

By taking data in two beam configurations, corresponding to the proton or to the Pb going towards the Muon Spectrometer, it has been possible to access forward ($2.03 < y_{cms} < 3.53$) and backward ($-4.46 < y_{cms} < -2.96$) dimuon rapidity ranges. The corresponding data samples are referred to as p-Pb and Pb-p in the following.

The data sample used in this analysis corresponds to an integrated luminosity $L_{pPb}^{int} \sim 7.3$ nb$^{-1}$ for p-Pb and $L_{Pbp}^{int} \sim 10.2$ nb$^{-1}$ for Pb-p.

3 Data Analysis

The results presented in this writeup are based on an analysis procedure very similar to the one described in [11] and [12] for former studies of J/ψ production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 8.16$ TeV. The same approach is followed for both p-Pb and Pb-p data samples.

The J/ψ production in p-Pb collisions is compared to the one measured in pp interactions, through the so-called nuclear modification factor $Q_{pPb}^{mult}$, expressed as:

$$Q_{pPb}^{mult,i} = \frac{N_{J/\psi}^{i}}{BR_{J/\psi \rightarrow \mu^+ \mu^-} \cdot N_{MB}^{i} \cdot \langle A \cdot \varepsilon \rangle \cdot \langle T_{pPb}^{mult,i} \rangle \cdot \sigma_{pp}^{J/\psi}}$$

(1)

where $i$ refers to the centrality bin under study. The quantities which enter in Eq. (1) are explained in the following.

The centrality selection is based on a hybrid approach, as discussed in [19]. Events are selected according to the energy released in the ZN calorimeter positioned in the Pb-going direction. ZN mainly detects slow neutrons emitted by the Pb nucleus in the interaction, whose emission is monotonically related to the number of collisions. The average number of collisions $\langle N_{mult}^{coll} \rangle$, for each ZN-selected centrality class, is then obtained assuming that the charged particle multiplicity measured at mid-rapidity is proportional to the number of participant nucleons $N_{part} = N_{coll} + 1$. Other assumptions to derive $N_{coll}$ are considered in the determination of the associated systematic uncertainty, as discussed in [19]. The average number of participants is evaluated via the Glauber model [20], which is commonly used to compute such geometrical quantities, and the variation of the model parameters also contributes to the systematic uncertainty on the centrality variables.

Two different choices for the centrality binning have been adopted. The first one matches the binning of the J/ψ results in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, to ease the comparison with the lower energy results, i.e. 2-10%, 10-20%, 20-40%, 40-60%, 60-80% and 80-90% (it should however be noted that the most peripheral bin, in the $\sqrt{s_{NN}} = 5.02$ TeV analysis, was covering the range 80-100%). Given the large luminosity collected in the p-Pb data taking at $\sqrt{s_{NN}} = 8.16$ TeV, a finer binning has also
been investigated, resulting in a higher precision measurement of the centrality dependence of the J/ψ production. The adopted binning corresponds to classes having 10%-centrality width, apart from the most central bin, which corresponds to 2-10%. The most central events corresponding to 0-2% centrality are removed because they might still be sensitive to residual pile-up contamination, whose contribution is elsewhere negligible.

In Eq. 1, \( N_{J/\psi} \) is the number of detected J/ψ obtained by fitting the unlike-sign invariant mass spectra, in each centrality class, as shown in Fig. 1. Fits are performed adopting various choices of signal functions for the J/ψ and ψ(2S) resonances and empirical shapes for the background [21]. It has to be remarked that the influence of the ψ(2S) contribution on the evaluation of \( N_{J/\psi} \) is negligible. More in detail, the background is described with an exponential function times a fourth-order polynomial or with a Gaussian function with a mass-dependent width. For the resonance shapes an extended Crystal Ball function, with non Gaussian tails on the right and left side of the resonance peak is used. Alternatively, a pseudo-Gaussian function, with a mass-dependent width is also adopted. The systematic uncertainties on the signal extraction are evaluated from the RMS of the \( N_{J/\psi} \) distribution, obtained varying the signal and background functions and the fitting ranges. The dominant contribution comes from the choice of the non-Gaussian tails used to describe the J/ψ signal shapes. The number of J/ψ in each centrality class varies from \( \sim 6400 \) and \( \sim 6000 \) in the most peripheral bin to \( \sim 21000 \) and \( \sim 34000 \) in the most central bin, for p-Pb and Pb-p respectively, and the signal over background ratios range from 1.4 to 2.5 (1.2 to 3) from central to peripheral collisions, for p-Pb (Pb-p).

\( N_{iMB} \) is the number of equivalent minimum bias events, in each centrality class, corresponding to the sample of \( \mu \mu - MB \) triggers (\( N_{i\mu\mu-MB} \)) used in the analysis. It is evaluated, for both the p-Pb and Pb-p samples, as \( N_{iMB} = N_{i\mu\mu-MB} \cdot F_{i\mu\mu-MB}^{\text{norm}} \), where \( F_{i\mu\mu-MB}^{\text{norm}} \) represents the inverse of the probability of having a triggered dimuon in a MB event. This quantity is computed from the trigger input information and the level-0 trigger mask. In each centrality bin \( F_{i\mu\mu-MB}^{\text{norm}} \) is obtained from the corresponding centrality integrated value scaled by \( (N_{iMB}/N_{MB})/(N_{i\mu\mu-MB}/N_{i\mu\mu-MB}) \). Alternatively, \( F_{i\mu\mu-MB}^{\text{norm}} \) has been computed directly for each centrality class and the 1% difference between the two approaches is included in the systematic uncer-
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A further 1% uncertainty comes by comparing these results with another independent evaluation based on the information from the trigger scalers. $F_{\text{norm}}^i$ varies as a function of centrality, from $\sim 2700$ ($\sim 3300$) in peripheral events to $\sim 380$ ($\sim 160$) in the most central events for p-Pb (Pb-p) respectively. The statistical uncertainty on $F_{\text{norm}}^i$ is negligible.

The acceptance times detection efficiency ($A \cdot \varepsilon$) is calculated in Monte Carlo (MC) simulations, performed on a run-by-run basis, to closely follow the evolution of the performances of the detectors during the data taking. $J/\psi$ are generated using, as input shapes, rapidity and transverse momentum distributions directly tuned on p-Pb or Pb-p data at $\sqrt{s_{\text{NN}}} = 8.16$ TeV [12], through an iterative procedure. The transverse momentum and rapidity integrated $A \cdot \varepsilon$ shows a negligible centrality dependence, therefore the centrality-integrated values, $0.264 \pm 0.009$ (syst) and $0.240 \pm 0.010$ (syst), are used in the following for the p-Pb and Pb-p data samples, respectively. The quoted systematic uncertainties account for contributions related to the uncertainty on the MC input distributions (1.5% for both p-Pb and Pb-p), on the tracking and trigger efficiencies ($\sim 3\%$ and $\sim 4\%$ for p-Pb and Pb-p respectively) and on the matching efficiency between the tracking and triggering systems (1% for both data taking configurations) [12]. No significant centrality dependence has been observed for such systematic uncertainties. The statistical uncertainties on $A \cdot \varepsilon$ are negligible.

As described earlier, the pile-up contribution has been removed. A toy MC simulation reproducing the LHC filling scheme indicates that a 2% effect due to residual pile-up may affect the measured $Q_{\text{pPb}}^{\text{mult}}$. The effect is concentrated on central events, but has been conservatively assigned, as systematic uncertainty, to all the analysed centrality ranges.

Finally, $BR_{J/\psi \rightarrow \mu^+\mu^-} = 5.96\%$ is the branching ratio for $J/\psi$ decaying to a muon pair [22], while $\langle T_{\text{pPb}}^{\text{mult},i} \rangle$ represents the average nuclear overlap function. $\langle T_{\text{pPb}}^{\text{mult},i} \rangle$ is computed in each centrality class as $T_{\text{pPb}}^{i} = N_{\text{coll}}^{i}/\sigma_{\text{NN}}$, where $\sigma_{\text{NN}}$ is the nucleon-nucleon inelastic cross section. The systematic uncertainties on $\langle T_{\text{pPb}}^{\text{mult},i} \rangle$ vary between $\sim 3\%$ and $\sim 7\%$ from peripheral to central collisions.

As discussed in [12], the reference pp cross section has been obtained starting from the ALICE [23] and LHCb [24] measurements at $\sqrt{s_{\text{NN}}} = 8$ TeV. The resulting cross section has been corrected to account for the slightly different centre-of-mass energy of the collisions. A further correction has been included since the pp data cover a $y_{\text{cms}}$ interval ($2.5 < y_{\text{cms}} < 4$) shifted by 0.465 units, with respect to the p-Pb and Pb-p ranges, in opposite directions. The reference cross sections $\sigma_{\text{pp}}^{J/\psi}$ used in this analysis are $9.79 \pm 0.75 \mu b$ in the range $2.03 < y_{\text{cms}} < 3.53$ and $7.09 \pm 0.55 \mu b$ in the range $-4.46 < y_{\text{cms}} < -2.96$.

In Table 1 the values of the systematic uncertainties entering the $Q_{\text{pPb}}^{\text{mult}}$ evaluation are summarised. The uncertainties on signal extraction and on $\langle T_{\text{pPb}}^{\text{mult},i} \rangle$ have a dependence on the centrality of the collisions, while the others are common to all centralities and, therefore, considered as global uncertainties. All uncertainties are considered as uncorrelated between the results at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

### 4 Results

The nuclear modification factor for inclusive $J/\psi$, as a function of the ZN centrality percentiles, is shown in Fig. 2. At forward rapidity, $Q_{\text{pPb}}^{\text{mult}}$ shows a suppression which is slightly increasing from the peripheral bin (80-100% at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and 80-90% at $\sqrt{s_{\text{NN}}} = 8.16$ TeV) to the most central one (2-10%). At backward rapidity, the $Q_{\text{pPb}}^{\text{mult}}$ has an opposite pattern, showing a suppression in the most peripheral bins, with a tendency to a rise towards the most central events.

This pattern is rather similar at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and $\sqrt{s_{\text{NN}}} = 5.02$ TeV [11], confirming the consistency already observed in the transverse momentum and rapidity dependence of $R_{\text{pPb}}$ [12]. The observed difference between the $Q_{\text{pPb}}^{\text{mult}}$ values at the two energies ($\sim 20\%$ and $\sim 10\%$ for p-Pb and Pb-p in the most
Table 1: Systematic uncertainties on $Q_{\text{pp}}^{\text{mult}}$ for both p-Pb and Pb-p collisions. Ranges refer to the variation as a function of centrality. All uncertainties except those on signal extraction and $\langle T_{\text{pp}}^{\text{mult}} \rangle$ are correlated versus centrality.

<table>
<thead>
<tr>
<th>Source</th>
<th>p-Pb (%)</th>
<th>Pb-p (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extr.</td>
<td>2.8-3.1</td>
<td>3.0-3.3</td>
</tr>
<tr>
<td>Trigger</td>
<td>2.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Tracking</td>
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<td>2</td>
</tr>
<tr>
<td>Matching</td>
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<td>1</td>
</tr>
<tr>
<td>MC inputs</td>
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<td>1.5</td>
</tr>
<tr>
<td>pp reference</td>
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<td>8</td>
</tr>
<tr>
<td>$F_{\text{norm}}$</td>
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<td>2</td>
</tr>
<tr>
<td>Pile-up</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\langle T_{\text{pp}}^{\text{mult}} \rangle$</td>
<td>3.6-7</td>
<td>3.6-7</td>
</tr>
<tr>
<td>$BR$</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

peripheral bin, $\sim$8% and $\sim$6% in the central one) is within the uncertainties of the measurements.

The larger luminosity of the data samples at $\sqrt{s_{\text{NN}}} = 8.16$ TeV has allowed us to study $Q_{\text{pp}}^{\text{mult}}$ in narrow centrality classes. Results, presented as a function of $N_{\text{coll}}^{\text{mult}}$, are compared to the $Q_{\text{pp}}^{\text{mult}}$ measured at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, as shown in Fig. [3]. The trends observed in Fig. [2] are confirmed, with a higher precision. It can be noted that, as expected, the higher energy of the 2016 data taking has slightly extended the reach in $N_{\text{coll}}^{\text{mult}}$.

5 Conclusions

The ALICE measurement of the centrality dependence of the inclusive $J/\psi$ production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV has been presented. At forward rapidity, preliminary results show a suppression which slightly increases towards central collisions. At backward rapidity a different trend is observed, with the nuclear modification factor increasing from peripheral to central collisions. Results obtained

Fig. 2: Inclusive $J/\psi$ $Q_{\text{pp}}^{\text{mult}}$ shown as a function of the ZN centrality percentiles in p-Pb (left) and Pb-p (right). The $Q_{\text{pp}}^{\text{mult}}$ values at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (red circles) are compared to those obtained at $\sqrt{s_{\text{NN}}} = 5.02$ TeV (blue squares) in the same centrality classes $\llbracket \Pi \rrbracket$, except for the most peripheral bin, which corresponds to 80-90% for the results at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and 80-100% for those at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity. The $Q_{\text{pp}}^{\text{mult}}$ values at the two energies are slightly shifted to improve visibility.
Centrality dependence of inclusive $J/\psi$ production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

Fig. 3: Inclusive $J/\psi$ $Q_{\text{mult}}^{\text{pPb}}$ shown as a function of $\langle N_{\text{coll}}^{\text{mult}} \rangle$ in p-Pb (left) and Pb-p (right). The $Q_{\text{mult}}^{\text{pPb}}$ at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (red circles) are compared to those obtained at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [11] (blue squares). Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity.

At $\sqrt{s_{\text{NN}}} = 8.16$ TeV are compatible with those measured by ALICE in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

References


