Study of coherent $J/\psi$ production in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 5$ TeV with the LHCb experiment

Abstract

Coherent production of $J/\psi$ mesons is studied in lead-lead collision data at a nucleon-nucleon centre-of-mass energy of 5 TeV collected by the LHCb experiment. The data set corresponds to an integrated luminosity of about $10^{\mu b}$. The $J/\psi$ mesons are reconstructed in the dimuon final state, where the muons are detected within the pseudorapidity region $2.0 < \eta < 4.5$. The $J/\psi$ mesons are required to have transverse momentum $p_T < 1$ GeV and rapidity $2.0 < y < 4.5$. The cross-section times branching fraction within this fiducial region is measured to be $\sigma = 5.3 \pm 0.2$ (stat) $\pm 0.5$ (syst) $\pm 0.7$ (lumi) mb. The cross-section is also measured in five bins of $J/\psi$ rapidity. The results are compared to predictions from phenomenological models.
1 Introduction

In ultra-relativistic heavy-nuclei collisions at the LHC, two-photon and photonuclear interactions are enhanced in ultraperipheral collisions (UPC) when the impact parameters of the two nuclei are larger than the sum of their radii. The cross-sections for photon-induced reactions remain large because the intensity of the photon flux is enhanced by the strong electromagnetic field of the nucleus, which grows as \( Z^2 \), where \( Z \) is the charge of the nucleus. The collisions are either coherent, where the photon couples coherently to all nucleons, or incoherent, where the photon couples to a single nucleon.

In the case of coherent \( J/\psi \) production in UPC, \( \text{PbPb} \rightarrow \text{Pb} + J/\psi + \text{Pb} \), the photon-lead interaction can be modelled by the exchange of two gluons, identified as a single object called a pomeron \([1-5]\). This interaction is expected to probe the nuclear gluon-distribution at hard scales of about \( m_{J/\psi}^2/4 \), where \( m_{J/\psi} \) is the \( J/\psi \) mass \([6,7]\). The \( J/\psi \) mesons are reconstructed in the rapidity range \( 2.0 < y < 4.5 \). This corresponds to values of the Bjorken variable \( x = (m_{J/\psi}/s)e^{\pm y} \) between \( \sim 10^{-5} \) and \( 10^{-2} \), where \( s \) is the centre-of-mass energy of the photon-pomeron system and \( y \) is the \( J/\psi \) rapidity. At these values of \( x \), the uncertainties on the gluon distributions are still sizable \([8,9]\) and a measurement in the LHCb acceptance can be used to reduce them.

In this note, a measurement of coherent \( J/\psi \) production is reported, in lead-lead collisions at a nucleon-nucleon centre of mass energy \( \sqrt{s_{\text{NN}}} = 5 \text{ TeV} \) collected with the LHCb detector in late 2015. Results of UPC studies have been reported by RHIC and LHC experiments \([10-16]\). This work is a step towards higher experimental precision.

The note is organised as follows. The LHCb detector and the event selection are described in Sect. 2. The analysis strategy and the systematic uncertainties are discussed in Sects. 3 and 4 respectively. The differential cross-section results for \( J/\psi \) production in UPC are detailed in Section 5. Conclusions and prospects are given in Section 6.

2 Detector and candidate selection

The LHCb detector \([17,18]\) is a single-arm forward spectrometer covering the pseudorapidity range \( 2 < \eta < 5 \), designed for the study of particles containing \( b \) or \( c \) quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the interaction region, a silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet.

The tracking system provides a measurement of momentum, \( p \), of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad (SPD) and preshower (PRS) detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The real-time event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

\footnote{In this note natural units where \( c = 1 \) are used.}
In this analysis, $J/\psi \rightarrow \mu^+ \mu^-$ candidates are selected by the trigger system, requiring at least one muon with a transverse momentum $p_T > 900$ MeV, at the hardware level, and the invariant mass of the two muons to be greater than 2.7 GeV, at the software level. In the offline selection, candidates are identified by requiring both muons to have $p_T > 500$ MeV within the pseudorapidity region $2.0 < \eta < 4.5$ and the dimuon invariant mass to be within 65 MeV of the known $J/\psi$ mass [19]. In addition, only $J/\psi$ candidates with reconstructed $p_T < 1$ GeV, $2.0 < y < 4.5$ and that form a good-quality vertex are used. In order to suppress background from central collisions, events with more than 20 deposits in the SPD or VELO tracks in addition to those of the muon candidates are vetoed. Only VELO tracks that have a minimum distance of 1 mm to the $J/\psi$ vertex are considered covering the regions of $-3.5 < \eta < -1.5$ and $1.5 < \eta < 5.0$.

The number of selected $J/\psi$ candidates is 1044 and the distribution of the dimuon invariant mass is shown in Fig. 1.

3 Cross-section measurement

The cross-section times branching fraction of coherent $J/\psi$ production is defined within a $J/\psi$ rapidity interval $\Delta y$ as

$$\frac{d\sigma(PbPb \rightarrow Pb + J/\psi + Pb)}{dy} = \frac{n_{coh}}{\varepsilon_y \cdot \Delta y \cdot L \cdot B}$$

where $\varepsilon_y$ is the total efficiency in each rapidity bin, $n_{coh}$ is signal yield, $\Delta y$ is the rapidity bin width, $L$ is the integrated luminosity and $B$ is the branching fraction $B(J/\psi \rightarrow \mu^+ \mu^-) = (5.961 \pm 0.033)\%$ [19].

The integrated luminosity of the data set, $L$, is determined to be $10.1 \pm 1.3 \mu b^{-1}$. The luminosity has been determined using a subset of the data where a beam profile imaging and a van der Meer scan [20] has been be performed. An extrapolation method is applied to calculate $L$ for the whole data set.

3.1 Efficiency determination

The total efficiency, $\varepsilon_y$, is the product of the reconstruction and selection efficiencies. The reconstruction efficiency includes effects of triggering, track reconstruction and muon identification. The selection efficiency includes effects of imposing requirements on the SPD deposits, VELO track multiplicities, muon $p_T$ and dimuon mass.

The hardware trigger efficiency is determined using simulated events, calibrated with data selected by an independent hardware trigger which requires at least two SPD deposits. The software trigger efficiency is measured in data, using $J/\psi$ candidates by requiring at least one VELO track.

The efficiencies due to the muon pseudorapidity requirement, the tracking reconstruction and the muon identification are described in the measurement of central exclusive $J/\psi$ production in $pp$ collisions at $\sqrt{s} = 13$ TeV [21]. These efficiencies are determined from simulated events generated with SuperCHIC [22] and scaled using data calibrations in $pp$ collisions. Although these studies have been done in a different collision system, the final state and kinematic region are similar. It has been checked in simulation that there
are no significant differences in these efficiencies between final state muons in this dataset and the PbPb dataset.

The dimuon mass requirement efficiency is determined using the integral of the double-sided Crystal Ball function described below outside the mass window. The efficiency due to the muon $p_T$ requirement is obtained by considering that half of the number of events that fail this requirement is signal. A similar method is used to determine the VELO track and SPD deposits multiplicities requirement efficiencies.

3.2 Signal yield determination

The signal yield, $n_{coh}$, is determined in two steps. First, a fit to the dimuon invariant mass spectrum is performed to obtain the number of $J/\psi$ candidates, which includes coherent and incoherent $J/\psi$, and $\psi(2S)$ feed-down components. A fit to the $J/\psi$ transverse momentum, $p_T$, is used to estimate the number of signal candidates where the nonresonant UPC background is constrained from the first fit.

The number of $J/\psi$ mesons is estimated by fitting the invariant dimuon mass distribution to signal and background components. The $J/\psi$ and $\psi(2S)$ masses are modelled by double-sided Crystal Ball functions, and the nonresonant background by an exponential multiplied by a first-order polynomial. The $\psi(2S)$ parameters, aside from the mean, are constrained in the fit to follow those of the $J/\psi$. Figure 1 shows the fitted dimuon mass spectrum. The fit returns a $J/\psi$ yield of 1003 $\pm$ 30.

Two resonant background sources are considered: incoherent production of $J/\psi$ and feed-down of photoproduction of $\psi(2S)$ mesons. In order to determine the signal yield in the presence of these backgrounds, a maximum likelihood fit to the natural logarithm of the $J/\psi$ transverse momentum squared, $\log(p_T^2)$, is performed. In this fit, the background and signal are modelled by templates taken from the STARlight event generator [2]. An ad-hoc track momentum smearing is used in order to obtain a similar momentum resolution to the one described in Ref. [18]. In this fit, the amount of nonresonant background is constrained by the dimuon invariant mass fit. The feed-down background is assumed to have the same $\log(p_T^2)$ distribution as the incoherent background and the sum of these two background yields corresponds to a single parameter in the fit.

Fig. 2 shows the fit to the $\log(p_T^2)$ distribution. The number of coherently produced $J/\psi$ mesons is found to be 713 $\pm$ 28, while the background due to the incoherent $J/\psi$ production and feed-down from $\psi(2S)$ photoproduction is determined to be 304 $\pm$ 18.

4 Systematic uncertainties

Systematic uncertainties in the measured cross-section are related to the determination of the muon reconstruction and selection efficiencies, the trigger efficiency, the muon momentum smearing, the mass fit signal model and the modelling of the feed-down background. They are described below and summarised in table 1.

The largest uncertainty comes from the integrated luminosity determination due to the small data set and the extrapolation method employed. The branching fraction uncertainty is taken from Ref. [19].

The systematic uncertainties related to the $J/\psi$ reconstruction efficiency are taken from Ref. [21]. They include uncertainties on the track reconstruction, muon identification
Figure 1: Dimuon invariant mass spectrum in the range between 2.7 and 4.0 GeV. The contribution of (solid blue line) $J/\psi$, (solid green line) $\psi(2S)$ and (black dashed line) nonresonant are shown individually and the sum of all contributions is represented by the orange curve.

Figure 2: Distribution of $\log(p_T^2)$ of dimuon candidates after all requirements have been applied. The orange line represents the fit to the data points; the blue line shows the coherent contribution and the green (black) line shows the incoherent and feed-down (nonresonant) component. A fit is performed to data using three different templates obtained from the STARlight event generator.

The efficiency of the hardware trigger is determined from simulated events. It is compared to the efficiency obtained with a data-driven method on a smaller data sample selected by independent triggers, and the difference taken as systematic uncertainty.

The efficiency of the software stage trigger is cross-checked by an independent estimation in data. Here, events are selected with a different trigger requirement. The efficiencies are
Table 1: Relative systematic uncertainties considered for the cross-section measurement of coherent $J/\psi$ production. The first two contributions are taken from Ref. [21].

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction efficiency</td>
<td>2.1–4.5</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>3.2</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>Software trigger efficiency</td>
<td>1.6–5.3</td>
</tr>
<tr>
<td>Momentum smearing</td>
<td>3.3</td>
</tr>
<tr>
<td>Mass fit model</td>
<td>3.9</td>
</tr>
<tr>
<td>Feed-down background</td>
<td>5.8</td>
</tr>
<tr>
<td>Branching Fraction</td>
<td>0.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>13.0</td>
</tr>
</tbody>
</table>

consistent, and the statistical uncertainty of this test is assigned as systematic uncertainty.

The systematic uncertainties related to the efficiencies of the requirement on the multiplicity of SPD deposits and on the muon $p_T$ are estimated by assuming that all events failing these requirements can be either background or signal. The systematic uncertainty related to the dimuon mass efficiency is taken from the error of the integral of the double-sided Crystal Ball function. The VELO track multiplicity requirement is found to be 100% efficient and no uncertainty is assigned.

The signal and background templates used in the $\log(p_T^2)$ fit are affected by the ad-hoc momentum smearing. An alternative smearing model is performed varying the smearing factor with the muon $p_T$ instead of the muon momentum. A difference of 3.3% in the signal yield is observed and assigned as systematic uncertainty.

The systematic uncertainty associated to the signal model in the fit to the dimuon mass spectrum is assessed using an alternative model. A single-sided Crystal Ball function is used for the signal and the difference in the signal yields with respect to the nominal fit is assigned as systematic uncertainty.

Since there is no dedicated template distribution for the feed-down background in the $\log(p_T^2)$ fit, a systematic uncertainty is evaluated. The $J/\psi$ candidate selection is modified in order to allow for two additional opposite-sign tracks that are consistent with originating from a mixture of coherent and incoherent production of $\psi(2S) \rightarrow J/\psi \pi^+\pi^−$ decays. After requiring the reconstructed mass of the $\psi(2S)$ candidates to be within 65 MeV of the known $\psi(2S)$ mass, 22 candidates are observed. Using the ratio between 22 and the number of observed $\psi(2S) \rightarrow \mu^+\mu^−$ decays, $78.5 \pm 3.1 \text{ J/}\psi \text{ mesons are expected to come from } \psi(2S) \rightarrow J/\psi X$ feed-down. Assuming that half of these candidates may be included in the signal yield, a systematic uncertainty of 5.8% is assigned.

5 Results

The cross-section for coherent $J/\psi$ production within the fiducial region is calculated using Eq. [1] and found to be $\sigma = 5.3 \pm 0.2 \text{ (stat) } \pm 0.5 \text{ (syst) } \pm 0.7 \text{ (lumi) mb}$, where the first uncertainty is statistical and the second is systematic and the third is due to the
Table 2: Cross-section measured differentially in J/ψ rapidity. The first quoted uncertainty is statistical and the second systematic, where the luminosity component (correlated across all bins) has been removed.

<table>
<thead>
<tr>
<th>J/ψ rapidity</th>
<th>dσ/dy (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00-2.50</td>
<td>3.0 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>2.50-3.00</td>
<td>2.60 ± 0.19 ± 0.25</td>
</tr>
<tr>
<td>3.00-3.50</td>
<td>2.28 ± 0.15 ± 0.21</td>
</tr>
<tr>
<td>3.50-4.00</td>
<td>1.73 ± 0.15 ± 0.17</td>
</tr>
<tr>
<td>4.00-4.50</td>
<td>1.10 ± 0.22 ± 0.13</td>
</tr>
</tbody>
</table>

uncertainty on the luminosity. The J/ψ mesons are reconstructed from dimuon final states, where the muons are detected within the pseudorapidity region 2.0 < η < 4.5 and the J/ψ meson is required to have p_T < 1 GeV and 2.0 < y < 4.5. The coherent differential J/ψ production cross-section, measured in bins of J/ψ rapidity, is given in table 2. A comparison of the measurement with theoretical predictions discussed below is shown in Fig. 3.

In the model of Gonçalves et al. [4, 23], the cross-section is calculated within the framework of the Colour-Dipole model. Three different parametrisations of the dipole-proton cross-section (IIM, IP-SAT, bCGC), based on saturation physics, are combined to two different models of vector-meson wave functions, namely boosted Gaussian (BG) and Gauss-LC (GLC). All the parameters are tuned using the latest HERA data. The solid (dashed) curves in Fig. 3 correspond to the IP-SAT+GLC (IIM+BG) model and they are compared to LHCb data. Both predictions can describe this measurement.

The model from Cepila et al. [24] is a variation of the Colour-Dipole model. The main differences with respect to Ref. [4, 23] come from the parametrisation of the dipole-proton cross-section and the prescription used to propagate it to the dipole-nucleus scattering amplitudes. In this model, the Glauber-Gribov methodology (GG) or a geometric scaling between the nuclear saturation scale and the saturation scale in the proton (GS) prescriptions are used. Both prescriptions are able to describe the data.

In the model proposed by Mäntysaari et al. [25], the cross-section is also calculated using the Colour-Dipole model including subnucleon scale fluctuations. Predictions with and without subnucleonic fluctuations using the IP-SAT parametrisation for the dipole-proton cross-section and the GLC for the vector-meson wave function are compared to this measurement. Assuming the GLC wave function, the prediction with subnucleonic fluctuation is favoured by the LHCb data.

The model provided by Guzey et al. [1] is based on a perturbative QCD (pQCD) calculation. The coherent J/ψ production cross-section on a proton target is calculated at leading order pQCD within the leading-log approximation. Three prescriptions for the nuclear structure are then used to compute the final cross-section: weaker (LTA_W) and two stronger (LTA_S) scenarios using leading twist nuclear shadowing model [26], and EPS09 [8] nuclear parton distribution function. The measurement can be described by the three prescriptions.
6 Conclusions and prospects

The coherent $J/\psi$ production cross-section times branching fraction in PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV, corresponding to an integrated luminosity of about $10 \mu b^{-1}$, is measured to be $\sigma = 5.3 \pm 0.2$ (stat) $\pm 0.5$ (syst) $\pm 0.7$ (lumi) mb. The measurement uses $J/\psi$ mesons reconstructed in the dimuon final state with reconstructed $p_T < 1$ GeV and $2.0 < y < 4.5$, where muons are detected within the pseudorapidity region $2.0 < \eta < 4.5$. The cross-section is also measured in five bins of $J/\psi$ rapidity and the results are compared to predictions from different phenomenological models.

There are ongoing studies to increase the pseudorapidity coverage by using the HeRSCHEL forward shower counters [27]. The HeRSCHEL counters were used in Ref. [21], resulting in lower backgrounds. A reduction of the incoherent background is expected after vetoing significant energy detected in HeRSCHEL, as shown in Fig 4.

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References


