Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at √sNN=5.02 TeV

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Coherent $J/\psi$ photoproduction at forward rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration*

1. Introduction

Ultra-peripheral collisions (UPC) between two Pb nuclei, in which the impact parameter is larger than the sum of their radii, provide a useful way to study photonuclear reactions [1–4]. Photoproduction of vector mesons in these collisions has an easily identifiable experimental signature: the decay products of the vector meson, in the case of this analysis a $\mu^+\mu^-$ pair, are the only signals in an otherwise empty detector. This process is akin to exclusive vector meson production in electron-proton collisions, already studied extensively at HERA [5]. The exchange photon, which carries a momentum transfer squared $Q^2$, is typified by very small values of $Q^2$, and may be described as quasi-real. The intensity of the photon flux scales as the square of nuclear charge resulting in large cross sections for the photoproduction of vector mesons in Pb–Pb collisions at the CERN Large Hadron Collider (LHC), where the measurement presented in this Letter was performed.

Photoproduction of vector mesons on nuclei can be either coherent, where the photon couples coherently to the nucleus as a whole, or incoherent, where the photon couples to a single nucleon [2]. Coherent production is characterized by low vector meson transverse momentum ($p_T \approx 60$ MeV/c) and by the target nucleus not breaking up. Incoherent production, corresponding to quasi-elastic scattering off a single nucleon, is characterized by a somewhat higher average transverse momentum ($p_T \approx 500$ MeV/c). The target nucleus normally breaks up in the incoherent production, but, except for single nucleons or nuclear fragments in the very forward region, no other particles are produced. The incoherent production can be accompanied by the excitation and dissociation of the target nucleus resulting in even higher transverse momenta of the produced vector mesons, extending well above 1 GeV/c [6].

Coherent photoproduction of the $J/\psi$ meson, a charm-anticharm bound state, is of particular interest since, for a leading order QCD calculation [7], its cross section is expected to scale as the square of the gluon parton density function (PDF) in the target hadron. The mass of the charm quark provides an energy scale large enough to allow for perturbative QCD calculations. For this process, a variable corresponding to Bjorken-$x$ can be defined using the mass of the vector meson ($m_{J/\psi}$) and its rapidity ($y$) as $x = (m_{J/\psi}/\sqrt{s_{NN}}) \exp(\pm y)$. Though next-to-leading order effects and scale uncertainties complicate extraction of gluon PDFs from $J/\psi$ photoproduction data [8], the related uncertainties are expected to largely cancel in the ratio of coherent photoproduction cross sections off nuclei and off protons [9]. Thus, coherent $J/\psi$ photoproduction off lead nuclei ($\gamma + \text{Pb} \rightarrow J/\psi + \text{Pb}$) provides a powerful tool to study poorly known gluon shadowing effects at low Bjorken-$x$ values ranging from $x \sim 10^{-5}$ to $x \sim 10^{-2}$ at LHC energies [10,11].

The ALICE collaboration has pioneered the study of charmonium photoproduction in ultra-peripheral Pb–Pb collisions at the LHC at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV [12–14]. Coherent $J/\psi$ photoproduction was studied both at forward rapidity ($-3.6 < y < -2.6$) with the ALICE muon spectrometer and at mid-rapidity ($|y| < 0.9$) with the central barrel. The CMS collaboration studied coherent $J/\psi$ photoproduction accom-
panied by neutron emission in the semi-forward rapidity range $1.8 < |y| < 2.3$ [15]. The ALICE and CMS results on $J/\psi$ photoproduction were compared with predictions from models available at that time, and suggested that moderate shadowing in the nucleus was necessary to describe the measurements. In particular, the nuclear gluon shadowing factor $R_g$, i.e. the ratio of the nuclear gluon density distribution to the proton gluon distribution, was extracted from the ALICE measurements [10], and found to be, at the scale of the charm quark mass, $R_g(x \sim 10^{-2}) = 0.81_{-0.04}^{+0.06}$ and $R_g(x \sim 10^{-2}) = 0.74_{-0.12}^{+0.11}$. The ALICE collaboration also measured the coherent cross section for $\psi'$ photoproduction at mid-rapidity, and the results supported, within the experimental uncertainties, the moderate-shadowing scenario [14].

In this Letter, we present the first measurement of the coherent $J/\psi$ photoproduction in ultra-peripheral Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV. The measurement was performed with the ALICE muon spectrometer covering the rapidity range $-4.0 < \eta < -2.5$. The results presented here are based on data taken in 2015 and in 2018, during Run 2 of the LHC. The recorded data sample is some 200 times larger than the data used in the $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb analysis [12]. The new result is based on the absolute luminosity normalization in contrast to the previous measurement based on the normalization relative to the continuum $\gamma\gamma \rightarrow \mu^+\mu^-$ cross section predicted by STARlight [16]. These two improvements imply a considerable reduction in the statistical and systematic uncertainties and the possibility to study the rapidity dependence in the forward region.

2. Detector description

The ALICE detector and its performance are described in [17,18]. Muons from $J/\psi$ decays are measured in the single-arm muon spectrometer, while other activity is vetoed using the Silicon Pixel Detector (SPD), the V0 and ALICE Diffractive (AD) detectors. The muon spectrometer covers the pseudorapidity interval $-4.0 < \eta < -2.5$. It consists of a ten interaction length absorber followed by five tracking stations, the third of which is placed inside a dipole magnet with a 3 T m integrated magnetic field, a 7.2 interaction length iron wall, and a trigger system located downstream of the iron wall. Each tracking station is made of two planes of cathode pad chambers, while the trigger system consists of four planes of resistive plate chambers arranged in two stations. Muon tracks are reconstructed using the tracking algorithm described in [19]. The central region $|\eta| < 1.4$ is covered by the SPD consisting of two cylindrical layers of silicon pixel sensors. The V0 detector is composed of the V0A and VOC sub-detectors, consisting of 32 cells each and covering the pseudorapidity interval $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The newly installed AD detector is composed of the ADC and ADA sub-detectors located at $-19.5 +16.9$ m from the interaction point covering the pseudorapidity ranges $-7.0 < \eta < -4.9$ and $4.7 < \eta < 6.3$, respectively [20]. The V0 and AD detectors are scintillator tile arrays with a time resolution better than 1 ns, allowing one to distinguish between beam-beam and beam-gas interactions.

3. Data analysis

The analysis presented in this publication is based on a sample of events collected during the 2015 and 2018 Pb–Pb data taking periods at $\sqrt{s_{NN}} = 5.02$ TeV, characterized by similar beam conditions and interaction rates. The muon spectrometer performance was stable during the whole Run 2 thus allowing for the merging of the two data sets. The trigger required two oppositely charged tracks in the muon spectrometer, and vetoes on V0A, ADA and ADC beam-beam interactions. The single muon trigger threshold was set to a transverse momentum $p_T = 1$ GeV/c [21]. The integrated luminosities of 216 $\mu b^{-1}$ in 2015 and 538 $\mu b^{-1}$ in 2018, with relative systematic uncertainty of 5%, were estimated from the counts of a reference trigger, based on multiplicity selection in the V0 detector. The reference trigger cross section was derived from Glauber-model-based estimates of the inelastic Pb–Pb cross section [22].

Events with only two tracks with opposite electric charge (unlike-sign) in the muon spectrometer were selected offline. The pseudorapidity of each track was required to be within the range $-4.0 < \eta < -2.5$. The tracks had to fulfill the requirements, described in [12], on the radial coordinate of the track at the end of the absorber and on the extrapolation to the nominal vertex. Track segments in the tracking chambers had to be matched with corresponding segments in the trigger chambers.

Additional offline vetoes on the V0A, ADA and ADC detector signals were applied to ensure the exclusive production of the muon pair. Exclusivity in the muon spectrometer region was ensured by requiring a maximum of 2 fired cells in VOC. Online and offline veto requirements may result in significant inefficiencies (denoted as veto inefficiencies) in the exclusive $J/\psi$ cross section measurements due to additional V0 and AD detector activity induced by independent hadronic or electromagnetic pile-up processes accompanying the coherent $J/\psi$ photoproduction. The probability of hadronic pile-up did not exceed 0.2%, however there was a significant pile-up contribution from the electromagnetic electron pair production process $\gamma\gamma \rightarrow e^+e^-$. The veto inefficiency induced by these pile-up effects in the V0A, VOC, ADA and ADC detectors, was estimated using the events selected with an unbiased trigger based only on the timing of bunches crossing the interaction region. The veto rejection probability, defined as the probability to detect activity in these sub-detectors, was found to scale linearly with the expected number of collisions per bunch crossing reaching 10% in V0A. The veto inefficiency correction factors were determined by weighting the corresponding veto rejection probabilities over periods with different pile-up conditions, taking the luminosity of each period as a weight. The veto inefficiency of the V0A online and offline selection was found to be $p_{V0A} = \{4.6 \pm 0.2\}$%, where the uncertainty is related to the limited statistics in the unbiased trigger sample. The veto inefficiencies in ADA ($p_{ADA}$) and ADC ($p_{ADC}$) were found to be about 0.2%, because these detectors are far away from the interaction point and are thus much less affected by soft $e^+e^-$ pairs. The veto inefficiency in VOC, associated with the requirement of maximum 2 fired cells, was found to be negligible. The average veto efficiency correction factor $\epsilon_{\text{Veto}} = 95.0\%$, and this is applied to raw $J/\psi$ yields to account for hadronic and electromagnetic pile-up processes, was calculated as a product of individual veto inefficiencies $\epsilon_{\text{Veto}} = (1 - p_{V0A})(1 - p_{ADA})(1 - p_{ADC})$.

The acceptance and efficiency of $J/\psi$ and $\psi'$ reconstruction were evaluated using a large sample of coherent and incoherent $J/\psi$ and $\psi'$ events generated by STARlight 2.2.0 [23] with decay muons tracked in a model of the apparatus implemented in GEANT 3.21 [24]. The model includes a realistic description of the detector performance during data taking as well as its variation with time. The acceptance and efficiency of feed-down $\psi' \rightarrow J/\psi + \pi\pi$ decays were also evaluated using the STARlight generator under the assumption that feed-down $J/\psi$ mesons inherit the transverse polarization of their $\psi'$ parents, as indicated by previous measurements [25]. The same samples were also used for modeling the signal shape and different background contributions.

A sample enriched in coherent candidates was obtained by selecting dimuons with transverse momentum $p_T < 0.25$ GeV/c. The invariant mass distributions for selected unlike-sign muon pairs are shown in Fig. 1, left, in the full dimuon rapidity range
order to describe the high-$p_T$ tail, the incoherent $J/\psi$ photoproduction accompanied by nucleon dissociation was also taken into account in the fits with the template based on the H1 parametrization of the dissociative $J/\psi$ photoproduction [28] (denoted as dissociative $J/\psi$ in the following):

$$\frac{dN}{dp_T} \sim \rho_T \left( 1 + \frac{b_{pd} p_T^2}{n_{pd}} \right)^{-n_{pd}}.$$

The H1 collaboration provided two sets of measurements corresponding to different photon–proton center-of-mass energy ranges: $25$ GeV < $W_{\gamma p}$ < $80$ GeV (low-energy data set) and $40$ GeV < $W_{\gamma p}$ < $110$ GeV (high-energy data set). The fit parameters $b_{pd} = 1.79 \pm 0.12$ (GeV/c)$^{-2}$ and $n_{pd} = 3.58 \pm 0.15$ from the high-energy data set were used by default, while the corresponding uncertainties and the low-energy values $b_{pd} = 1.6 \pm 0.2$ (GeV/c)$^{-2}$ and $n_{pd} = 3.58$ (fixed) were used for systematic checks.

The templates were fitted to the data leaving the normalization free for coherent $J/\psi$, incoherent $J/\psi$ and dissociative $J/\psi$ production. The normalization of the $\gamma'\gamma \rightarrow \mu^+\mu^-$ spectrum was fixed to the one obtained from the invaraint mass fits. The normalization of the coherent and incoherent feed-down $J/\psi$ templates was constrained to the normalization of primary coherent and incoherent $J/\psi$ templates, according to the feed-down fractions extracted from the measurement of raw inclusive $J/\psi$ and $\psi'$ yields, as described below. The extracted incoherent $J/\psi$ fraction $f_1 = \frac{N_{(incoh)J/\psi}}{N_{(total)J/\psi}}$ for $p_T < 0.25$ GeV/c ranges from $(4.9 \pm 0.6)\%$ to $(6.4 \pm 0.8)\%$ depending on the rapidity interval and is consistent with being constant within the uncertainties of the fits. The contribution of incoherent $J/\psi$ with nucleon dissociation was also taken into account in this fraction.

4. Results and discussion

4.1. Ratio of coherent $\psi'$ and $J/\psi$ cross sections

The obtained dimuon invariant mass spectra can be used to extract the ratio of coherent $\psi'$ and $J/\psi$ cross sections $R = \frac{\sigma(\psi')}{\sigma(J/\psi)}$ and the fraction of feed-down $J/\psi$ from $\psi'$ decays in the raw $J/\psi$ yields. The fits to the invariant mass distributions for dimuons with pair $p_T < 0.25$ GeV/c in the full rapidity range $-4.0 < y < -2.5$ result in the following ratio of the measured raw inclusive $\psi'$ and $J/\psi$ yields:
The raw $\psi'$ and $J/\psi$ yields in this ratio contain contributions both from coherent and incoherent $\psi'$ and $J/\psi$ photoproduction. However, according to the dimuon $p_T$ fits, the fraction $f_I$ of incoherent $J/\psi$ in the raw $J/\psi$ yields does not exceed 6% and, according to STARlight [23] and calculations within the color dipole approach [29], the fraction of incoherent $\psi'$ in the raw $\psi'$ yields is expected to be similar. The $R_N$ ratio can therefore be considered as a good estimate of the ratio of coherent $J/\psi$ and $\psi'$ yields, since the incoherent fractions of $\psi'$ and $J/\psi$ yields largely cancel in the ratio. Besides, the raw $J/\psi$ yields contain significant feed-down contribution coming from $\psi' \rightarrow J/\psi +$ anything decays. Taking into account this feed-down contribution, one can express the $R_N$ ratio in terms of primary coherent $\psi'$ and $J/\psi$ photoproduction cross sections $\sigma(\psi')$ and $\sigma(J/\psi)$ integrated over all transverse momenta in the rapidity range $-4.0 < y < -2.5$:

$$
R_N = \frac{N(\psi')}{N(J/\psi)} = 0.0250 \pm 0.0030 \text{ (stat.)},
$$

(2)

$$
R_N = \frac{\sigma(\psi') R_{BR}(\psi' \rightarrow \mu\mu) \epsilon(\psi')}{\sigma(J/\psi) R_{BR}(J/\psi \rightarrow \mu\mu) \epsilon(J/\psi) + \sigma(\psi') R_{BR}(\psi' \rightarrow J/\psi) \epsilon(\psi' \rightarrow J/\psi) R_{BR}(J/\psi \rightarrow \mu\mu)}
$$

(3)
Fig. 3. Transverse momentum distributions in six rapidity intervals for muon pairs satisfying the event selection described in the text.

where \( \epsilon(J/\psi) = 12.0\% \), \( \epsilon(\psi') = 15.8\% \) and \( \epsilon(\psi' \rightarrow J/\psi) = 7.2\% \) are the efficiency corrections for primary coherent \( J/\psi, \psi' \) and feed-down \( J/\psi \) from coherent \( \psi' \) decays estimated with STARlight, while \( BR(J/\psi \rightarrow \mu\mu) = (5.961 \pm 0.033)\% \), \( BR(\psi' \rightarrow \mu\mu) = (0.80 \pm 0.06)\% \), \( BR(\psi' \rightarrow J/\psi + \text{anything}) = (61.4 \pm 0.6)\% \) are the corresponding branching ratios [27].

Equation (3) can be used to express the ratio of primary coherent \( \psi' \) and \( J/\psi \) photoproduction cross sections, \( R \), in terms of the measured yield ratio \( R_N \):

\[
R = \frac{R_N \times BR(J/\psi \rightarrow \mu\mu) \times \epsilon(J/\psi)}{BR(\psi' \rightarrow J/\psi) \times \epsilon(\psi') - R_N \times BR(\psi' \rightarrow J/\psi) \times \epsilon(\psi' \rightarrow J/\psi) \times BR(J/\psi \rightarrow \mu\mu)}
\]

Substituting the measured \( R_N \) value from Eq. (2) and the corresponding efficiency values and branching ratios, one gets:

\[
R = 0.150 \pm 0.018 \text{ (stat.)} \pm 0.021 \text{ (syst.)} \pm 0.007 \text{ (BR)},
\]

where the uncertainties on branching ratios \( BR(J/\psi \rightarrow \mu\mu) \) and \( BR(\psi' \rightarrow \mu\mu) \) were added in quadrature, while the main sources of systematic uncertainties are the variation of the fit range, of the signal and background shapes, and of the dimuon transverse momentum cut.

The measured ratio of the \( \psi' \) and \( J/\psi \) cross sections is compatible with the exclusive photoproduction cross section ratio \( R = 0.166 \pm 0.007 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \pm 0.007 \text{ (BR)} \) measured by the
H1 collaboration in ep collisions [30] and with the ratio $R \approx 0.19$ measured by the LHCB collaboration in pp collisions [31]. The measured ratio also agrees with predictions based on the Leading Twist Approximation [32] for Pb–Pb UPC ranging from 0.13 to 0.18 depending on the model parameters. The $\psi'$-to-$J/\psi$ coherent cross section ratio is expected to have a mild dependence on the collision energy and vector meson rapidity [32] (at most a few percent). Therefore the measured ratio can be directly compared to the unexpectedly large $\psi'$-to-$J/\psi$ coherent cross section ratio 0.34$^{+0.08}_{-0.07}$ measured by ALICE in the $\psi' \to l^+l^-$ and $\psi' \to l^+l^-\pi^+\pi^-$ channels at central rapidity in Pb–Pb UPC at $\sqrt{s_{NN}} = 2.76\text{ TeV}$ [14]. The ratio at central rapidity is more than a factor two larger but still stays compatible within 2.5 standard deviations with the forward rapidity measurement, owing mainly to the large uncertainties of the central rapidity measurement that will be improved by the analysis of the much larger UPC data sample collected with the ALICE central barrel in Run 2.

The measured cross section ratio $R$ was used to extract the fraction of feed-down $J/\psi$ from $\psi'$ relative to the primary $J/\psi$ yield:

$$f_D = \frac{N(\text{feed-down} J/\psi)}{N(\text{primary} J/\psi)} = \frac{R \epsilon(\psi' \to J/\psi)}{\epsilon(J/\psi)} BR(\psi' \to J/\psi).$$

(6)

The fraction $f_D = 8.5\% \pm 1.5\%$ was obtained for the full rapidity range without any $p_T$ cut, where statistical, systematic and branching ratio uncertainties were added in quadrature. The fraction reduces to $f_D = 5.5\% \pm 1.0\%$ for $p_T < 0.25\text{ GeV/c}$ because feed-down $J/\psi$ is characterized by wider transverse momentum distributions compared to primary $J/\psi$.

4.2. Coherent $J/\psi$ cross section

The coherent $J/\psi$ differential cross section is given by:

$$d\sigma^{coh}_{J/\psi} = \frac{N(J/\psi)}{(1 + f_1 + f_0) \epsilon(J/\psi) BR(J/\psi \to \mu^+\mu^-) \epsilon_{\text{det}} \Delta y}$$

(7)

The raw $J/\psi$ yield values, efficiencies, $f_1$ and $f_0$ fractions and coherent $J/\psi$ cross sections with relevant statistical and systematic uncertainties are summarized in Table 1. The associated systematic uncertainties are briefly described in the following.

The first source of systematic uncertainty is related to the separation of peripheral and ultra-peripheral collisions. Coherent-like $J/\psi$ photoproduction, observed in peripheral collisions of heavy ions [33], may contribute a few percent to the raw $J/\psi$ yields in case hadronic activity is not detected by the V0 and AD detectors. In order to reduce a possible contamination from $J/\psi$ produced in peripheral hadronic events, the analysis was repeated with an additional requirement that there be no tracklets detected at mid-rapidity in the SPD (where a tracklet is a segment formed by at least one hit in each of the two detector layers), resulting in 12.6% to 15.0% lower $J/\psi$ yields depending on the rapidity range. The veto inefficiency associated with this additional SPD requirement was estimated with unbiased triggers similar to what was done for the V0 and AD veto inefficiencies. The average fraction of events with at least one SPD tracklet was found to be $\beta_{\text{SPD}} = 9.4 \pm 0.2\%$. The yields corrected for the additional SPD veto inefficiency of 9.4% result in cross sections 3.6% to 6.0% lower than the ones obtained without the SPD veto. This cross section difference is taken into account in the systematic uncertainty.

The systematic uncertainties on the efficiencies obtained by variation of the generated rapidity shapes range from 0.1% to 0.8%, depending on the rapidity interval. The tracking efficiency uncertainty of 3% was estimated by comparing the single-muon tracking efficiency values obtained in MC and data, with a procedure that exploits the redundancy of the tracking-chamber information [34]. The systematic uncertainty on the dimuon trigger efficiency has two origins: the intrinsic efficiencies of the muon trigger chambers and the response of the trigger algorithm. The first one was determined by varying the trigger chamber efficiencies in the MC by an amount equal to the statistical uncertainty on their measurement with a data-driven method and amounts to 1.5%. The second one was estimated by comparing the trigger response function between data and MC, resulting in efficiency differences ranging from 5% to 6% depending on the rapidity interval. Finally, there is a 1% contribution related to the precision required to match track segments reconstructed in the tracking and trigger chambers.

Several tests were performed to estimate the uncertainty on the raw $J/\psi$ signal extraction. These include the uncertainty on the $J/\psi$ signal shape estimated by fitting the Crystal Ball slope parameters instead of fixing them from Monte-Carlo templates and by replacing the single-sided Crystal Ball with a double-sided Crystal Ball function. The variation of the continuum background shape due to the uncertainty on the trigger response function, variation of the invariant mass intervals by $\pm 0.1\text{ GeV/c}^2$ and of the dimuon $p_T$ selection by $\pm 0.05\text{ GeV/c}$ were also considered. The systematic uncertainty on the raw $J/\psi$ yield, estimated as root mean square of the results obtained from all tests, is about 2% with a slight rapidity dependence.

Several sources of systematic uncertainties are associated with different contributions to the $p_T$ spectrum: the fraction of feed-down $J/\psi$, the shape and contribution of the $\gamma\gamma \to \mu^+\mu^-$ template, the shape for the coherent $J/\psi$ and the shape for the incoherent $J/\psi$ with nucleon dissociation. These contributions are shortly detailed in the following. First, the fraction $f_0$ of feed-down $J/\psi$ with $p_T$ below 0.25 GeV/c was varied in the range from 4.4 to 6.4% corresponding to the total systematic uncertainty of the measured $\psi'$-to-$J/\psi$ cross section ratio. Second, the shape of the $\gamma\gamma \to \mu^+\mu^-$ $p_T$ template from STARlight does not include possible contributions from incoherent emission of photons, characterized by much wider transverse momentum distributions extending well above 1 GeV/c. In order to account for these contributions, the shape of the $\gamma\gamma \to \mu^+\mu^-$ $p_T$ template was changed from STARlight to that obtained from the side-bands surrounding the $J/\psi$ peak in the invariant mass spectra, resulting in 1% systematic uncertainty.

| Rapidity range | $N(\psi')$ | $\epsilon$ | $f_D$ | $f_1$ | $\epsilon_{\text{det}}$ | $d\sigma^{coh}_{J/\psi}$ |
|---------------|-------------|------------|-------|------|-----------------|------------------|
| $(-4.00, -2.50)$ | 21747 ± 190 | 0.120 | 0.055 | 0.055 ± 0.001 | 2.549 ± 0.022 (stat) ± 0.29 (syst.) |
| $(-4.00, -3.75)$ | 974 ± 36 | 0.051 | 0.055 | 0.064 ± 0.008 | 1.615 ± 0.060 (stat) ± 0.15 (syst.) |
| $(-3.75, -3.50)$ | 3217 ± 70 | 0.140 | 0.055 | 0.058 ± 0.004 | 1.938 ± 0.042 (stat) ± 0.16 (syst.) |
| $(-3.50, -3.25)$ | 5769 ± 98 | 0.204 | 0.055 | 0.060 ± 0.003 | 2.377 ± 0.040 (stat) ± 0.22 (syst.) |
| $(-3.25, -3.00)$ | 6387 ± 105 | 0.191 | 0.055 | 0.052 ± 0.002 | 2.831 ± 0.047 (stat) ± 0.25 (syst.) |
| $(-3.00, -2.75)$ | 4229 ± 85 | 0.119 | 0.055 | 0.049 ± 0.003 | 3.018 ± 0.061 (stat) ± 0.26 (syst.) |
| $(-2.75, -2.50)$ | 1190 ± 47 | 0.029 | 0.054 | 0.049 ± 0.006 | 3.531 ± 0.139 (stat) ± 0.34 (syst.) |
uncertainty on the measured coherent cross section. Third, a 0.2% systematic uncertainty was determined via the variation of the $\gamma_\gamma$ contribution according to the statistical uncertainty in the background term calculated from the invariant mass fits. A modification of the transverse momentum spectra for the coherent $J/\psi$ according to the model [35], results in a 0.1% systematic uncertainty. Finally, the template shape for the incoherent $J/\psi$ with nucleon dissociation was varied by exchanging the H1 high-energy run parameters for those determined from the low-energy run resulting in a 0.1% systematic uncertainty on the coherent cross section.

The systematic uncertainties are summarized in Table 2. The total systematic uncertainty is the quadratic sum of all the sources listed in the table. Luminosity normalization, veto efficiency and branching ratio uncertainties are fully correlated. The uncertainty on the signal extraction is considered as uncorrelated as a function of rapidity. Finally, all other sources of uncertainty are considered as partially correlated across different rapidity intervals.

### 4.3. Discussion

The measured differential cross section of coherent $J/\psi$ photoproduction in the rapidity range $-4.0 < y < -2.5$ is shown in Fig. 4 and compared with various models. The covered rapidity range corresponds to a Bjorken-x of gluons either in the range $1.1 \times 10^{-5} < x < 5.1 \times 10^{-5}$ or $0.7 \times 10^{-2} < x < 3.3 \times 10^{-2}$ depending on which nucleus emitted the photon. According to models [32], the fraction of high-Bjorken-x gluons ($x \sim 10^{-2}$) is dominant at forward rapidities and ranges from $\sim 60\%$ at $y = -2.5$ to $\sim 95\%$ at $y = -4$.

The Impulse Approximation, taken from STARlight [16], is based on the data from the exclusive $J/\psi$ photoproduction off protons and neglects all nuclear effects except for coherence. The square root of the ratio of experimental points and the Impulse Approximation cross section is about 0.8, reflecting the magnitude of the nuclear gluon shadowing factor at typical Bjorken-x values around $10^{-2}$, under the assumption that the contribution from low Bjorken-x $\sim 10^{-3}$ can be neglected [10].

STARlight is based on the Vector Meson Dominance model and a parametrization of the existing data on $J/\psi$ photoproduction off protons [23]. A Glauber-like formalism is used to calculate the $J/\psi$ photoproduction cross section in Pb–Pb UPC accounting for multiple interactions within the nucleus but not accounting for gluon shadowing corrections. The STARlight model overpredicts the data, indicating the importance of gluon shadowing effects, but the discrepancy is much lower than for the Impulse Approximation.

Guzey, Kryshen and Zhalov [32] provide two calculations (GKZ), one based on the EPS09 LO parametrization of the available nuclear shadowing data [42] and the other on the Leading Twist Approximation. The GKZ calculations are based on the nuclear shadowing model of the EPS09 LO framework. Approximation (LTA) of nuclear shadowing based on the combination of the Gribov-Glauber theory and the diffractive PDFs from HERA [43]. Both the LTA model and the EPS09 curve, corresponding to the EPS09 LO central set, underpredict the data but remain compatible with it at the most forward rapidities. The data tends to follow the upper limit of uncertainties of the EPS09 calculation corresponding to the upper bound of uncertainties on the gluon shadowing factor in the EPS09 LO framework.

Several theoretical groups provided predictions within the color dipole approach coupled to the Color Glass Condensate (CGC) formalism with different assumptions on the dipole–proton scattering amplitude. Predictions by Gonçalves, Machado et al. (GM) based on IIM and b-CGC models for the scattering amplitude underpredict the data [35,57]. Predictions by Lappi and Mäntysaari (LM) based on the IPsat model [38,39] give reasonable agreement though the range of predictions does not span all the experimental points. Recent predictions by Luszczak and Schafer (LS BKG-I) within the color-dipole formulation of the Glauber-Gribov theory [44] are in agreement with data at semi-forward rapidities, $|y| < 3$, but slightly underpredict the data at more forward rapidities.

Cepila, Contreras and Kreлина (CKK) provided two predictions based on the extension of the energy-dependent hot-spot model [40] to the nuclear case: using the standard Glauber-Gribov formalism (GG-HS) and using geometric scaling (GS-HS) to obtain the nuclear saturation scale [41]. The GG-HS model agrees with data at most forward rapidities but underpredicts it at semi-forward rapidities. The GS-HS model (not shown) strongly underpredicts the data.

### 5. Conclusions

The first rapidity-differential measurement on the coherent photoproduction of $J/\psi$ in the rapidity interval $-4 < y < -2.5$ in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been presented and compared with model calculations. The Impulse Approximation and STARlight models overpredict the data, indicating the importance of gluon shadowing effects. The model based on the central set of the EPS09 gluon shadowing parametrization, the Leading Twist Approximation, and the hot-spot model coupled to
the Glauber-Gribov formalism underpredict the data but remain compatible with it at most forward rapidities. The majority of color dipole models underpredict the data.

The nuclear gluon shadowing factor of about 0.8 at Bjorken-x values around $10^{-2}$ and a hard scale around the charm quark mass was estimated from the comparison of the measured coherent $1/\psi$ cross section with the Impulse Approximation under the assumption that the contribution from low Bjorken $x \sim 10^{-5}$ can be neglected. Future studies on coherent heavy vector meson photoproduction accompanied by neutron emission may help to decouple low-x and high-x contributions and provide valuable constraints on poorly known gluon shadowing effects at Bjorken $x \sim 10^{-5}$ [45].

The ratio of the $\psi'$ and $J/\psi$ cross sections is in reasonable agreement both with the ratio of photoproduction cross sections off protons measured by the H1 and LHCb collaborations and with LTA predictions for Pb-Pb UPC.

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ALICE Collaboration

S. Acharya 141, D. Adamová 93, S.P. Adhya 141, A. Adler 74, J. Adolfsson 80, M.M. Aggarwal 98, A. Aglieri Rinella 34, M. Agrillo 31, N. Agrawal 10, Z. Ahammed 141, S. Ahmad 17, S.U. Ahn 76, S. Aiola 146, A. Akindinov 84, M. Al-Turany 105, S.N. Alam 141, D.S.D. Albuquerque 122, D. Aleksandrov 87, B. Alessandri 58, H.M. Alfanda 6, R. Alfaro Molina 72, B. Ali 17, Y. Ali 15, A. Alici 10,53,27, A. Alkin 2, J. Alme 22, T. Alt 69, L. Altenkamper 22, I. Alsbyeev 112, M.N. Anaam 6, C. Andrei 47, D. Andreou 34, H.A. Andrews 109, A. Andronic 144, M. Angeletti 144, V. Anguevol 102, C. Anson 16, T. Antičić 106, F. Antonino 90, P. Antoniol 52, R. Anwar 126, N. Apadula 79, L. Aphescuthe 114, H. Appelhæsler 69, S. Arcelli 27, R. Arnaldi 58, M. Arratia 79, I.C. Arsene 21, M. Arslanbek 102, A. Augustinus 34, R. Averbeck 105, S. Aziz 61, M.D. Azmi 17, A. Badalà 55, Y.W. Baek 40, S. Bagnasco 58, X. Bai 105, R. Baille 69, R. Bala 69, A. Baldissyer 143, M. Ball 42, R.C. Barr 85, L. Barbera 28, L. Barbi 85, G.G. Barnaföldi 45, L.S. Barnby 92, V. Barret 134, P. Bartalini 6, K. Barth 34, E. Bartsch 69, F. Baruffaldi 29, N. Bastid 134, S. Bastu 143, G. Batigné 114, B. Batyunya 75, P.C. Batzing 21, D. Baur 48, J.L. Bazó Alba 115, I.G. Bearden 88, C. Bedda 63, N.K. Behera 60, I. Belikov 136, F. Bellini 34, R. Bellwied 126, V. Belyaev 91, G. Bencedi 145, S. Behle 26, A. Bercuci 47, Y. Berdnikov 69, D. Berényi 145, R.A. Bertens 130, D. Benzaou 58, L. Betev 34, A. Basini 99, I.R. Bhat 99, H. Bhattacharjee 41, A. Bianchi 26, L. Bianchi 126, N. Bianchi 51, J. Bielicki 37, J. Bielicková 93, A. Bizlandic 103, G. Bini 145, R. Biswas 3, S. Biswas 3, J.T. Blair 119, D. Blaug 72, C. Blume 59, G. Boca 139, F. Bock 34,94, A. Bogdanov 91, L. Boldizsár 145, A. Bozoldyna 91, M. Bombara 38, G. Bonomi 140, M. Bonora 34, H. Borel 137, A. Borisssov 144,91, M. Borri 108, H. Boss 146, E. Botta 26, C. Bourjault 88, L. Bratrad 69, P. Braun-Munzinger 105, M. Bregant 121, T.A. Broker 69, M. Broz 37, E.J. Brucken 43, E. Bruna 58, G.E. Bruno 33,104, M.D. Buckland 128, D. Budnikov 107, H. Buesching 69,
A.R. Schmier 130, J. Schukraft 34,88, Y. Schutz 34,136, K. Schwarz 105, K. Schweda 105, G. Scioli 27, 
E. Scomparin 58, M. Šefčík 38, J.E. Seger 16, Y. Sekiguchi 132, D. Sekihata 45, I. Selyuzhenkov 105,91, 
S. Senyukov 136, E. Serradilla 22, P. Sett 48, A. Sevcenco 68, A. Shabanov 62, A. Shabetai 114, R. Shahoyan 34, 
W. Shaikov 108, A. Shangaraev 80, A. Sharma 98, A. Sharma 99, M. Sharma 99, N. Sharma 98, A.I. Sheik 141, 
K. Shigaki 45, M. Shimomura 92, S. Shirinkin 64, Q. Shou 111, Y. Sibiriak 87, S. Siddhanta 54, 
T. Siemiarczuk 84, D. Silvermyer 80, G. Simatovic 69, G. Simonetti 103,34, R. Singh 85, R. Singh 99, 
V.K. Singh 141, V. Singhal 141, T. Sinha 108, B. Sitar 14, M. Sitta 32, T.B. Skaal 21, M. Slupecki 127, 
N. Smirnov 146, R.J.M. Snellings 63, T.W. Snellman 127, J. Sochan 116, C. Soncco 110, J. Song 60,126, 
A. Songmoolnak 115, F. Soramel 29, S. Sorensen 130, I. Sputowska 118, I. Stachel 102, I. Stan 68, P. Stankus 94, 
P.J. Steffanic 130, E. Stenlund 80, D. Stocco 114, M.M. Storetvedt 36, P. Strmen 14, A.A.P. Suade 121, 
T. Sugitate 45, C. Sui 61, M. Suleymanov 15, M. Suljic 34, R. Sultano 64, M. Šumbera 93, 
S. Sumowidagdo 50, K. Suzuki 113, S. Swain 66, A. Szabo 14, I. Szarka 14, U. Tabassam 15, G. Taillepied 134, 
J. Takahashi 122, G.J. Tambave 22, S. Tang 134,6, M. Tarchini 114, M.G. Tarzila 47, A. Tauro 34, 
G. Tejeida Muñoz 44, A. Telesca 64, C. Terrevoli 126,29, D. Thakur 49, S. Thakur 141, D. Thomas 119, 
F. Thoresen 88, R. Treilevant 135, A. Tikhonov 62, A.R. Timmins 126, A. Toia 69, N. Topilskaya 62, M. Toppi 51, 
F. Torales-Acosta 20, S.R. Torres 120, S. Tripathy 49, T. Tripathy 48, S. Trogolo 26,29, G. Trombetta 33, 
L. Tropp 38, V. Trubnikov 2, W.H. Trzaska 127, T.P. Trzcinski 142, B.A. Trzeciak 63, T. Tsuji 132, A. Tumkin 107, 
R. Turrisi 56, T.S. Tveter 21, K. Ullaland 22, E.N. Umaka 126, A. Uras 135, G.L. Usai 24, A. Utrobovic 97, 
M. Vala 116,38, N. Valle 139, S. Valiero 58, N. van der Kolk 63, L.V.R. van Doremalen 63, M. van Leeuwen 63, 
P. Vande Vyvre 34, D. Varga 145, M. Varga-Kofarago 145, A. Vargas 44, M. Vargyas 127, R. Varma 48, 
M. Vasileiou 83, A. Vasileii 87, O. Vázquez 105, V. Vechernin 112, A.M. Veen 63, E. Vercellin 26, 
S. Vergara Limón 44, L. Vertmunt 63, R. Vernet 7, R. Vértesi 145, L. Vickovic 35, J. Viinikainen 127, 
Z. Vilakazi 131, O. Villalobos Baillie 109, A. Villatoro Tello 44, G. Vino 52, A. Vinogradov 87, T. Virgili 30, 
V. Vislavicius 88, A. Vodopianov 175, B. Volk 34, M.A. Volkl 101, K. Voloshin 64, S.A. Voloshin 143, 
G. Volpe 33, B. von Haller 34, I. Vorobyev 103,117, D. Voscek 116, J. Vrláková 38, B. Wagner 22, 
Y. Watanabe 133, M. Weber 113, S.G. Weber 105, A. Wegrynzyk 34, D.F. Weisser 102, S.C. Wenzel 34, 
J.P. Wessels 144, U. Westerhoff 144, A.M. Whitehead 125, E. Widmann 113, J. Wiechula 69, J. Wikne 21, 
G. Wilk 84, J. Wilkinson 53, G.A. Willems 34, E. Willsher 109, B. Windelband 102, W.E. Witt 130, Y. Wu 129, 
R. Xu 6, S. Yalcin 77, K. Yamakawa 45, S. Yang 22, S. Yano 137, Z. Yin 6, H. Yokoyama 63, I.-K. Yoo 18, 
J.H. Yoon 60, S. Yuan 22, A. Yuncu 102, V. Yurchenko 2, V. Zaccolo 58,25, A. Zaman 15, C. Zampolli 34, 
H.J.C. Zanoli 121, N. Zardoshti 34,109, A. Zarochnetsভ 112, P. Závada 67, N. Zaviyalov 107, H. Zbroszczuk 142, 
M. Zhalov 96, X. Zhang 6, Z. Zhang 6,134, C. Zhao 21, V. Zherebchevskii 112, N. Zhigareva 84, D. Zhou 1, 
Y. Zhou 88, Z. Zhou 22, J. Zhu 6, Y. Zhu 6, A. Zichichi 27,10, M.B. Zimmermann 34, G. Zinovjev 2, N. Zurlo 140 

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