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Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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ABSTRACT

The ALICE Collaboration has made the first measurement at the LHC of J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The J/ψ is identified via its dimuon decay in the forward rapidity region with the muon spectrometer for events where the hadronic activity is required to be minimal. The analysis is based on an event sample corresponding to an integrated luminosity of about 55 μb^{-1}. The cross section for coherent J/ψ production in the rapidity interval $-3.6 < y < -2.6$ is measured to be $d\sigma^{coh}_{J/\psi}/dy = 1.00 \pm 0.18(stat)^{+0.24}_{-0.26}(syst)$ mb. The result is compared to theoretical models for coherent J/ψ production and found to be in good agreement with those models which include nuclear gluon shadowing.

Two-photon and photonuclear interactions at unprecedentedly high energies can be studied in ultra-peripheral heavy-ion collisions (UPC) at the LHC. In such collisions the nuclei are separated by impact parameters larger than the sum of their radii and therefore hadronic interactions are strongly suppressed. The cross sections for photon induced reactions remain large because the strong electromagnetic field of the nucleus enhances the intensity of the virtual photon flux, which grows as Z^2, where Z is the charge of the nucleus. The virtuality of the photons is restricted by the nuclear form factor to be of the order $1/R \approx 30$ MeV/c (R is the radius of the nucleus). The physics of ultra-peripheral collisions is reviewed in [1,2].

Exclusive photoproduction of vector mesons, where a vector meson but no other particles are produced in the event, is of particular interest. Exclusive production of J/ψ in photon–proton interactions, $\gamma + p \to J/\psi + p$, has been successfully modelled in perturbative QCD in terms of the exchange of two gluons with no net-colour transfer [3]. Experimental data on this process from HERA have been used to constrain the proton gluon-distribution at low Bjorken-x [4]. Exclusive vector meson production in heavy-ion interactions is expected to probe the nuclear gluon-distribution [5], for which there is considerable uncertainty in the low-x region [6]. A J/ψ produced at rapidity y is sensitive to the gluon distribution at $x = (M_{J/\psi}/\sqrt{s_{NN}})\exp(\pm y)$ at hard scales $Q^2 \approx M^2_{J/\psi}/4$ [7]. The two-fold ambiguity in x is due to the fact that either nucleus can serve as photon emitter or photon target. At the forward rapidities studied here ($-3.6 < y < -2.6$), the relevant values of x are $\approx 10^{-2}$ and $\approx 10^{-5}$, respectively.

Exclusive ρ^0 [8] and J/ψ [9] production have been studied in Au–Au collisions at RHIC. The ρ^0 is too light to provide a hard scale, and the J/ψ analysis suffered from very low statistics, so no conclusions concerning nuclear shadowing were made from these studies. Exclusive J/ψ production has also been studied by the CDF Collaboration in proton–antiproton collisions at the Tevatron [10]. The availability of such measurements has led to an increase in interest in ultra-peripheral collisions, stimulating several new model calculations.

In this Letter, the first LHC results on exclusive photoproduction of J/ψ vector mesons are presented. J/ψ mesons produced in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been measured at forward rapidities through their dimuon decay. Exclusive photoproduction can be either coherent, where the photon couples coherently to all nucleons, or incoherent, where the photon couples to a single nucleon. Coherent production is characterized by low vector meson transverse momentum ($\langle p_T \rangle \simeq 60$ MeV/c) and the target nucleus normally does not break up. Incoherent production, corresponding to quasi-elastic scattering off a single nucleon, is characterized by a somewhat higher transverse momentum ($\langle p_T \rangle \simeq 500$ MeV/c) and the target nucleus normally breaks up, but except for single nucleons or nuclear fragments in the very forward region no other particles are produced. This analysis is focussed on coherently produced J/ψ mesons. The experimental definition of coherent production, which must also take into consideration the finite detector resolution, is here $p_T < 0.3$ GeV/c. The measured cross section is compared to model predictions [5,11–14].

The ALICE detector consists of a central barrel placed inside a large solenoid magnet ($B = 0.5$ T), covering the pseudorapidity region $|\eta| < 0.9$ [15], and a muon spectrometer covering the range $-4.0 < \eta < -2.5$. The spectrometer consists of a ten interaction length (λ_I) thick absorber filtering the muons, in front of

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five tracking stations containing two planes of cathode pad multiwire proportional chambers (MWPC) each, with the third station placed inside a dipole magnet with a $\int Bdl = 3$ Tm integrated field. The forward muon spectrometer includes a triggering system, used to select muon candidates with a transverse momentum larger than a given programmable threshold. It has four planes of resistive plate chambers (RPC) downstream of a 1.2 m thick iron wall (7.2 λ_I), which absorbs secondary punch-through hadrons from the front absorber and low momentum muons from π and K weak decays. This analysis uses the VZERO counters for triggering and event selection. These consist of two arrays of 32 scintillator tiles each, covering the range $2.8 < \eta < 5.1$ (VZERO-A, on the opposite side of the muon arm) and $-3.7 < \eta < -1.7$ (VZERO-C) and positioned at $z = 329$ cm and $z = -87$ cm from the interaction point, respectively. Finally, two sets of hadronic Zero-Degree Calorimeters (ZDCs) are located at 116 m on either side of the Interaction Point. These detect neutrons emitted in the very forward region, for example neutrons emitted following electromagnetic dissociation [16].

The analysis presented in this publication is based on a sample of events collected during the 2011 Pb–Pb run, selected with a special trigger (FUPC) set up to select UPC events in which a dimuon pair is produced within the acceptance of the detector. The integrated luminosity corresponds to about 55 μb^{-1}.

The purpose of the FUPC trigger is to select events containing two muons from two-photon production ($\gamma\gamma \to \mu^+\mu^-$) or from J/$\psi$ decay, and it requires the following event characteristics:

(i) a single muon trigger above a 1 GeV/c p_T-threshold;
(ii) at least one hit in the VZERO-C detector since the muon spectrometer covers most of its pseudorapidity acceptance. In addition, VZERO-C vetoes the remaining upstream beam-gas events which could produce a trigger in the muon arm;
(iii) no hits in the VZERO-A detector to reject hadronic collisions.

A total of 3.16×10^6 events were selected by the FUPC trigger.

The offline event selection used in a previous J/ψ analysis [17] was modified to account for the typical experimental signatures of ultra-peripheral processes, *i.e.* only two tracks in the spectrometer and very low J/ψ transverse momentum. The following selection criteria were applied (number of remaining events after the selection):

(i) two reconstructed tracks in the muon arm (432,422 events);
(ii) owing to the multiple scattering in the front absorber, the DCA (distance between the vertex and the track extrapolated to the vertex transverse plane) distribution of the tracks coming from the interaction vertex can be described by a Gaussian function, whose width depends on the absorber material and is proportional to $1/p$, where p is the muon momentum. The beam induced background does not follow this trend, and was rejected by applying a cut on the product $p \times$ DCA, at 6 times the standard deviation of the dispersion due to multiple scattering and detector resolution. The additional dispersion due to the uncertainty on the vertex position (not measurable in UPC events) is negligible in comparison and does not affect the value of the cut (26,958 events);
(iii) at least one of the muon track candidates were required to match a trigger track above the 1 GeV/c p_T-threshold in the spectrometer trigger chambers (10,172 events);
(iv) both tracks pseudorapidities within the range $-3.7 < \eta_{1,2} < -2.5$, to match the VZERO-C acceptance (5100 events);
(v) the tracks exit from the absorber in the range 17.5 cm $< R_{abs} <$ 89.5 cm, delimiting the two homogeneous parts of the absorber covering the angular acceptance of the spectrometer (R_{abs} is the radial coordinate of the track at the end of the front absorber) (5095 events);
(vi) dimuon rapidity to be in the range $-3.6 < y < -2.6$, which ensured that the edges of the spectrometer acceptance were avoided (4919 events);
(vii) two tracks with opposite charges (3209 events);
(viii) only events with a neutron ZDC signal below 6 TeV on each side were kept. In the present data sample, this cut does not remove any events with a J/ψ produced with a transverse momentum below 0.3 GeV/c, but reduces hadronic contamination at higher p_T (817 events);
(ix) dimuons to have $p_T < 0.3$ GeV/c and invariant mass $2.8 < M_{inv} < 3.4$ GeV/c^2 (122 events);
(x) VZERO offline timing compatible with crossing beams (117 events).

Table 1
Summary of the contributions to the systematic uncertainty for the integrated J/ψ cross section measurement. The error for the coherent signal extraction includes the systematic error in the fit of the invariant mass spectrum and the systematic errors on f_D and f_I, as described in the text.

Source	Value
Theoretical uncertainty in $\sigma_{\gamma\gamma}$	20%
Coherent signal extraction	$^{+9}_{-14}$%
Reconstruction efficiency	6%
RPC trigger efficiency	5%
J/ψ acceptance calculation	3%
Two-photon e^+e^- background	2%
Branching ratio	1%
Total	$^{+24}_{-26}$%

The acceptance and efficiency of J/ψ-reconstruction were calculated using a large sample of coherent and incoherent J/ψ events generated by STARLIGHT [18] and folded with the detector Monte Carlo simulation. STARLIGHT simulates photonuclear and two-photon interactions at hadron colliders. The simulations for exclusive vector meson production and two-photon interactions are based on the models in [11] and [19], respectively.

The residual misalignment and the time-dependent conditions of the tracking and trigger chamber components were taken into account in these simulations. The trigger chamber efficiencies were computed from the data and used in the global efficiency calculation. A separate simulation was performed for each run, in order to take into account the slight variations in run conditions during the data taking. The product of the acceptance and efficiency corrections $(\text{Acc} \times \varepsilon)_{J/\psi}$ was calculated as the ratio of the number of the simulated events that satisfy the event selection in Table 1 to the number of generated events within $-3.6 < y < -2.6$. The final values for the combined acceptance and efficiency were found to be 16.6% and 14.3% for coherent and incoherent J/ψ, respectively. The relative systematic error coming from the uncertainties on the trigger chamber efficiencies used in these simulations amounts to 4%. In addition, the muon reconstruction efficiency has been evaluated both in data and simulations, in a way similar to that described in [17], and a 6% relative systematic uncertainty on the $(\text{Acc} \times \varepsilon)_{J/\psi}$ corrections was assigned to account for the observed differences.

In order to evaluate the systematic error on the acceptance coming from the generator choice, the acceptance was computed from a parameterization of the results on coherent J/ψ production in [5]. It was also calculated by modifying the rapidity distribution in STARLIGHT and letting it vary between a flat distribution and a distribution consistent with the model with the steepest slope

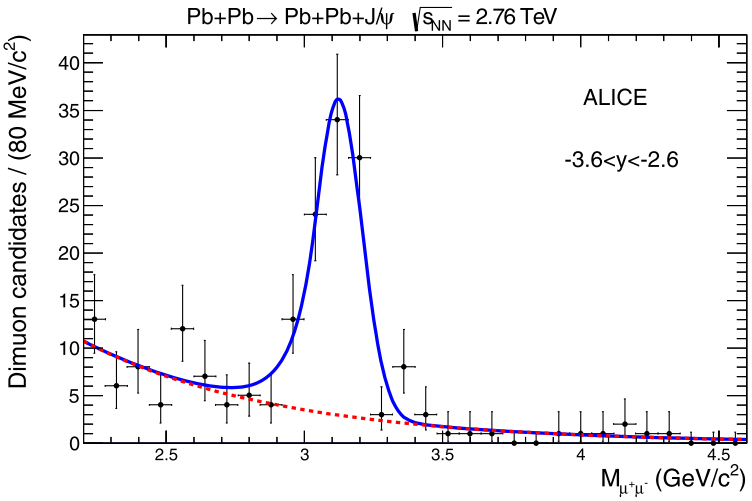

Fig. 1. Invariant mass distribution for events with exactly two oppositely charged muons satisfying the event selection described in the text.

(AB-MSTW08, see below for definition) over the range $-3.6 < y < -2.6$. The differences in acceptance between the methods were below 3%, which was taken into account in the systematic error calculation. It is assumed in these calculations that the J/ψ is transversely polarized. Transverse polarization is expected for a quasi-real photon from s-channel helicity conservation. This has been confirmed experimentally for exclusive J/ψ production in $\gamma + p \to J/\psi + p$ interactions [20,21] and for exclusive ρ^0 photoproduction in heavy-ion collisions [8]. Owing to the low p_T of the J/ψ, the calculations are insensitive to the choice of reference frame (here the helicity frame was used), and the polarization axis effectively coincides with the beam axis.

Activity in the central barrel was checked for events with invariant mass in the range $2.8 < M_{inv} < 3.4$ GeV/c^2. No events with more than one tracklet in the Si-Pixel (SPD) detector were found. The events with one tracklet (6 out of 117) were not removed, as this level of activity is consistent with the background from random combinations of noise hits.

The invariant mass distribution for opposite sign (OS) muon pairs with $2.2 < M_{inv} < 4.6$ GeV/c^2 is shown in Fig. 1. A J/ψ peak is clearly visible in the spectrum, on top of a continuum coming from $\gamma\gamma \to \mu^+\mu^-$. Only two like-sign dimuon pairs are in the invariant mass range $2.2 < M_{inv} < 4.6$ GeV/c^2, at 2.3 GeV/c^2 and 2.8 GeV/c^2. The combinatorial background is therefore estimated to be $\leqslant 2\%$ at 90% confidence level in the invariant mass range $2.8 < M_{inv} < 3.4$ GeV/c^2.

The J/ψ yield was obtained by fitting the dimuon invariant mass spectrum in the range $2.2 < M_{inv} < 4.6$ GeV/c^2 with an exponential function to describe the underlying continuum, and a Crystal Ball function [22] to extract the J/ψ signal. The Crystal Ball tail parameters (α_{CB} and n) were fixed to values obtained from simulations. The central mass value from the fit is 3.123 ± 0.011 GeV/c^2, which is within 2.4σ (0.8%) of the known value of the J/ψ mass and compatible with the absolute calibration accuracy of the muon spectrometer. The width, 84 ± 14 MeV/c^2, is in agreement with the Monte Carlo simulations. The extracted number of J/ψs is $N_{yield} = 96 \pm 12(stat) \pm 6(syst)$. The systematic error on the yield (6%) was obtained by varying the Crystal Ball tail parameters. The exponential slope parameter of the continuum is -1.4 ± 0.2 GeV/c^2 in good agreement with the corresponding Monte Carlo expectation (-1.39 ± 0.01 GeV/c^2). This, together with the fact that the p_T distribution is consistent with the expectations from STARLIGHT, is an additional indication that there is no unexpected background in the invariant mass range considered.

The fraction f_D of the J/ψ mesons coming from the decay of $\psi' \to J/\psi +$ anything was estimated by simulating a sample of coherently produced ψ's with STARLIGHT, using PYTHIA [23] to simulate their decay into J/ψ. The detector response was simulated as described above. The contribution from incoherently produced ψ' is expected to give a negligible contribution for $p_T < 0.3$ GeV/c and was not considered. Unlike the directly produced J/ψ discussed above, the polarization of J/ψs coming from ψ' decays cannot easily be predicted, since the polarization of the original ψ' can be shared between the J/ψ and the other daughters in different ways. The ψ' decay was therefore simulated by assuming the following J/ψ polarizations: (i) no polarization (NP), (ii) full transverse (T), and (iii) full longitudinal (L). The J/ψ fraction coming from ψ' decay for a given polarization P, f_D^P can be written as:

$$f_D^P = \frac{\sigma_{\psi'} \cdot BR(\psi' \to J/\psi + \text{anything}) \cdot (\text{Acc} \times \varepsilon)^P_{\psi' \to J/\psi}}{\sigma_{J/\psi} \cdot (\text{Acc} \times \varepsilon)_{J/\psi}}, \qquad (1)$$

where the $(\text{Acc} \times \varepsilon)_{J/\psi}$ and $(\text{Acc} \times \varepsilon)^P_{\psi' \to J/\psi}$ were computed for $p_T < 0.3$ GeV/c.

According to STARLIGHT, the ratio between the ψ' and J/ψ coherent photoproduction cross sections is 0.19 giving $f_D^{NP} = 11.9\%$, $f_D^T = 9.3\%$, $f_D^L = 16.8\%$. The cross sections ratio is significantly lower in the pQCD inspired model [5], 0.087. This changes the above fraction, giving $f_D^{NP} = 5.5\%$, $f_D^T = 4.3\%$, $f_D^L = 7.9\%$. The estimates for f_D thus range from 4.3% to 16.8%. The best estimate was taken as the middle of this range with the extremes providing the lower and upper limits, giving $f_D = (11 \pm 6)\%$.

The dimuon p_T distribution integrated over $2.8 < M_{inv} < 3.4$ GeV/c^2 is presented in Fig. 2. The clear peak at low p_T is mainly due to coherent interactions, while the tail extending out to 0.8 GeV/c comes from incoherent production. In addition, the high-p_T region may still contain a few hadronic events, which makes it difficult to extract the incoherent photoproduction cross section from these data. To estimate the fraction (f_I) of incoherent over coherent events in the region $p_T < 0.3$ GeV/c, the ratio $\sigma_{inc}/\sigma_{coh}$, weighted by the detector acceptance and efficiency for the two processes, was calculated, giving $f_I = 0.12$ when $\sigma_{inc}/\sigma_{coh}$ was taken from STARLIGHT, and $f_I = 0.08$ when the model in [5] was used. Four different functions were used to describe the p_T spectrum: coherent and incoherent photoproduction of J/ψ, J/ψ from ψ' decay, and two-photon production of continuum pairs. The shapes for the fitting functions (Monte Carlo templates)

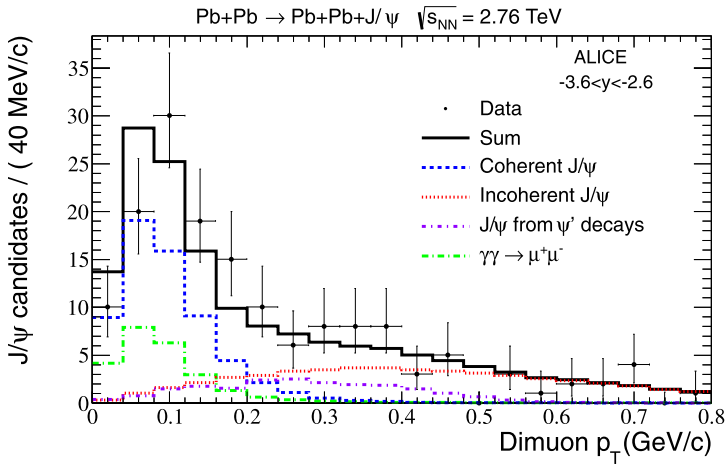

Fig. 2. Dimuon p_{T} distribution for events satisfying the event selection described in the text. The data points are fitted summing four different Monte Carlo templates: coherent J/ψ production (dashed – blue), incoherent J/ψ production (dotted – red), J/ψs from ψ' decay (dash-dotted – violet), and $\gamma\gamma \to \mu^+\mu^-$ (dash-dotted – green). The solid histogram (black) is the sum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

were provided by STARLIGHT events folded with the detector simulation. The relative normalization was left free for coherent and incoherent photoproduction. The contribution from the ψ' was constrained from estimate above ($f_D = (11 \pm 6)\%$), and the two-photon contribution was determined from the fit of the continuum in Fig. 1. In the fit, the incoherent process is constrained mainly in the region $0.5 < p_{\mathrm{T}} < 0.8$ GeV/c, where the other three processes are negligible. As this p_{T} region (not used in the J/ψ signal extraction) is likely to suffer from some hadronic background, the fit can only provide an upper limit on f_I. The result is $f_I = 0.26 \pm 0.05$, about a factor 2 larger than the estimate from the theoretical models quoted above. We conclude by taking the middle value of the two calculations and the fit as the best estimate of f_I, and the other two results as lower and upper limits, respectively, giving $f_I = 0.12^{+0.14}_{-0.04}$.

The fact that the Monte Carlo templates describe the p_{T} distribution well in the range $0.0 < p_{\mathrm{T}} < 0.8$ GeV/c confirms that there is no strong contamination from hadronic production in the event sample. An upper limit on the contribution from hadronic interactions can be obtained by considering events with $p_{\mathrm{T}} > 1.0$ GeV/c, where the contribution from incoherent photoproduction is very small. For hadronic J/ψ production it is known from the parameterization in Ref. [24] that (including the acceptance and efficiency corrections) 82% of the yield is above $p_{\mathrm{T}} > 1.0$ GeV/c, while only 2% is below $p_{\mathrm{T}} < 0.3$ GeV/c. If one conservatively assumes that the 32 events in the data sample with $p_{\mathrm{T}} > 1.0$ GeV/c are all from hadronic production, the expected yield from hadronic interactions below $p_{\mathrm{T}} < 0.3$ GeV/c can be estimated to be $(0.02/0.83) \cdot 32 = 0.8$ events. This is thus less than a 1% contamination. A similar estimate can be obtained by scaling the measured cross section for J/ψ production in Pb–Pb collisions [17] with the number of binary collisions assuming that all events with 80–100% centrality survive the event selection (a very conservative assumption). The conclusion is thus that the contamination from hadronic interactions is negligible and no correction need be applied for it.

Finally, the total number of coherent J/ψs is calculated from the yield extracted from the fit to the invariant mass distribution by

$$N^{\mathrm{coh}}_{\mathrm{J}/\psi} = \frac{N_{\mathrm{yield}}}{1 + f_I + f_D}, \tag{2}$$

resulting in $N^{\mathrm{coh}}_{\mathrm{J}/\psi} = 78 \pm 10(\mathrm{stat})^{+7}_{-11}(\mathrm{syst})$.

The coherent J/ψ differential cross section is given by:

$$\frac{\mathrm{d}\sigma^{\mathrm{coh}}_{\mathrm{J}/\psi}}{\mathrm{d}y} = \frac{N^{\mathrm{coh}}_{\mathrm{J}/\psi}}{(\mathrm{Acc} \times \varepsilon)_{\mathrm{J}/\psi} \cdot \epsilon_{\mathrm{trig}} \cdot BR(\mathrm{J}/\psi \to \mu^+\mu^-) \cdot \mathcal{L}_{\mathrm{int}} \cdot \Delta y}, \tag{3}$$

where $N^{\mathrm{coh}}_{\mathrm{J}/\psi}$ is the number of J/ψ candidates from Eq. (2), $(\mathrm{Acc} \times \varepsilon)_{\mathrm{J}/\psi}$ corresponds to the acceptance and efficiency of the muon spectrometer, as discussed above, and ϵ_{trig} is the VZERO trigger efficiency. $BR(\mathrm{J}/\psi \to \mu^+\mu^-) = 5.93\%$ is the branching ratio for J/ψ decay into muons [25], $\Delta y = 1$ the rapidity interval bin size, and $\mathcal{L}_{\mathrm{int}}$ the total integrated luminosity. During the 2011 Pb–Pb run the VZERO detector was optimized for the selection of hadronic Pb–Pb collisions, with a threshold corresponding to an energy deposit above that from a single minimum ionizing particle (MIP). The distribution of the signal produced by a MIP crossing the 2 cm thick VZERO scintillator has a Landau shape. To get an accurate simulation of the efficiency for low multiplicity events with this threshold setting, would require an almost perfect reproduction of the Landau by the MC simulation. Therefore we used the QED continuum pair production for the normalization and not Eq. (3).

In addition to exclusive J/ψ, the FUPC trigger selected $\gamma\gamma \to \mu^+\mu^-$ events, which are very similar to coherent J/ψ decays in terms of kinematics and associated event characteristics. This reaction is a standard QED process, which in principle can be calculated with high accuracy. The fact that the photon coupling to the nuclei is $Z\sqrt{\alpha}$ (with $Z = 82$ here) rather than just $\sqrt{\alpha}$ increases the uncertainty of the contribution from higher order terms. Predictions exist where this effect is negligible [26]. However, other studies obtained a 16% reduction in the cross section from higher order terms in Pb–Pb collisions at the LHC [27]. There is also an uncertainty associated with the minimum momentum transfer and the nuclear form factor [28]. Two-photon production of $\mu^+\mu^-$-pairs from STARLIGHT was used to determine the trigger efficiency [19]. The cross sections from STARLIGHT for two-photon production of e^+e^- and $\mu^+\mu^-$ pairs have previously been compared with results from STAR [29] and PHENIX [9], respectively. The predictions from STARLIGHT have been found to be in good agreement with the experimental results. These results, however, have uncertainties of about 25 to 30%. In the absence of high precision measurements constraining the model, and taking into account the outstanding theoretical issues mentioned above, the

uncertainty in the STARLIGHT two-photon cross section is estimated to be 20%.

The cross section for $\gamma\gamma \to \mu^+\mu^-$ can be written in a similar way to Eq. (3) and the ratio of the two is independent of luminosity and of the trigger efficiency:

$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{1}{BR(J/\psi \to \mu^+\mu^-)} \cdot \frac{N^{coh}_{J/\psi}}{N_{\gamma\gamma}} \cdot \frac{(Acc \times \varepsilon)_{\gamma\gamma}}{(Acc \times \varepsilon)_{J/\psi}} \cdot \frac{\sigma_{\gamma\gamma}}{\Delta y}, \quad (4)$$

where $N_{\gamma\gamma}$ was obtained by counting the number of events in the invariant mass intervals $2.2 < M_{inv} < 2.6$ GeV/c^2 ($N_{\gamma\gamma} = 43 \pm 7$(stat)) and $3.5 < M_{inv} < 6$ GeV/c^2 ($N_{\gamma\gamma} = 15 \pm 4$(stat)), to avoid contamination from the J/ψ peak. To determine $\sigma_{\gamma\gamma}$ STARLIGHT [19] was used. The cross section for dimuon invariant mass between $2.2 < M_{inv} < 2.6$ GeV/c^2 or $3.5 < M_{inv} < 6$ GeV/c^2, dimuon rapidity in the interval $-3.6 < y < -2.6$, and each muon satisfying $-3.7 < \eta_{1,2} < -2.5$ is $\sigma_{\gamma\gamma} = 17.4$ μb ($\sigma_{\gamma\gamma} = 13.7$ μb and $\sigma_{\gamma\gamma} = 3.7$ μb for the low and high invariant mass intervals, respectively). The $(Acc \times \varepsilon)_{\gamma\gamma}$ for events satisfying the same selection was calculated using events from STARLIGHT folded with the detector simulation as described above. The data cuts applied to the Monte Carlo sample were the same as those applied for the J/ψ data analysis, resulting in a $(Acc \times \varepsilon)_{\gamma\gamma}$ of 42.1% (37.9% for $2.2 < M_{inv} < 2.6$ GeV/c^2 and 57.5% for $3.5 < M_{inv} < 6$ GeV/c^2).

A possible source of inefficiency comes from correlated QED pair production, *i.e.* interactions which produce both a J/ψ and a low mass e^+e^--pair (the latter has a very large cross section), with one of the electrons hitting the VZERO-A detector and thus vetoing the event. This effect was studied with data, in a sample collected with comparable luminosity by a control trigger, requiring a coincidence of at least two muons in the muon arm trigger with hits in both the VZERO-A and VZERO-C. Two J/ψ events were found in this sample, giving an upper limit on the inefficiency smaller than 2%.

Since the kinematic distributions of the muons from J/ψ decays and $\gamma\gamma$ processes are different, the systematic uncertainties on the corresponding $(Acc \times \varepsilon)$ corrections coming from the uncertainties on the muon trigger and reconstruction efficiencies do not exactly cancel out in Eq. (4). In order to account for this effect, a 50% correlation factor has been estimated, conservatively, when computing the systematic uncertainty on the ratio. The sources of the systematic error are summarized in Table 1. The final result is a differential cross section for coherent J/ψ production of $d\sigma^{coh}_{J/\psi}/dy = 1.00 \pm 0.18(stat)^{+0.24}_{-0.26}(syst)$ mb.

The cross section is compared with calculations from various models [5,11–14] in Fig. 3. The differences between the models come mainly from the way the photonuclear interaction is treated. The predictions can be divided into three categories:

i) those that include no nuclear effects (AB-MSTW08, see below for definition). In this approach, all nucleons contribute to the scattering, and the forward scattering differential cross section, $d\sigma/dt$ at $t = 0$ (t is the momentum transfer from the target nucleus squared), scales with the number of nucleons squared, A^2;
ii) models that use a Glauber approach to calculate the number of nucleons contributing to the scattering (STARLIGHT, GM, and CSS). The reduction in the calculated cross section depends on the total J/ψ-nucleon cross section;
iii) partonic models, where the cross section is proportional to the nuclear gluon distribution squared (AB-EPS08, AB-EPS09, AB-HKN07, and RSZ-LTA).

STARLIGHT uses the latest HERA data on exclusive J/ψ production in photon–proton interactions [20,21] as input to calculate the corresponding photon-nucleus cross section. The model by Goncalves and Machado (GM) [13] calculates the J/ψ-nucleon cross section from the Color Dipole model, whereas Cisek, Szczurek,

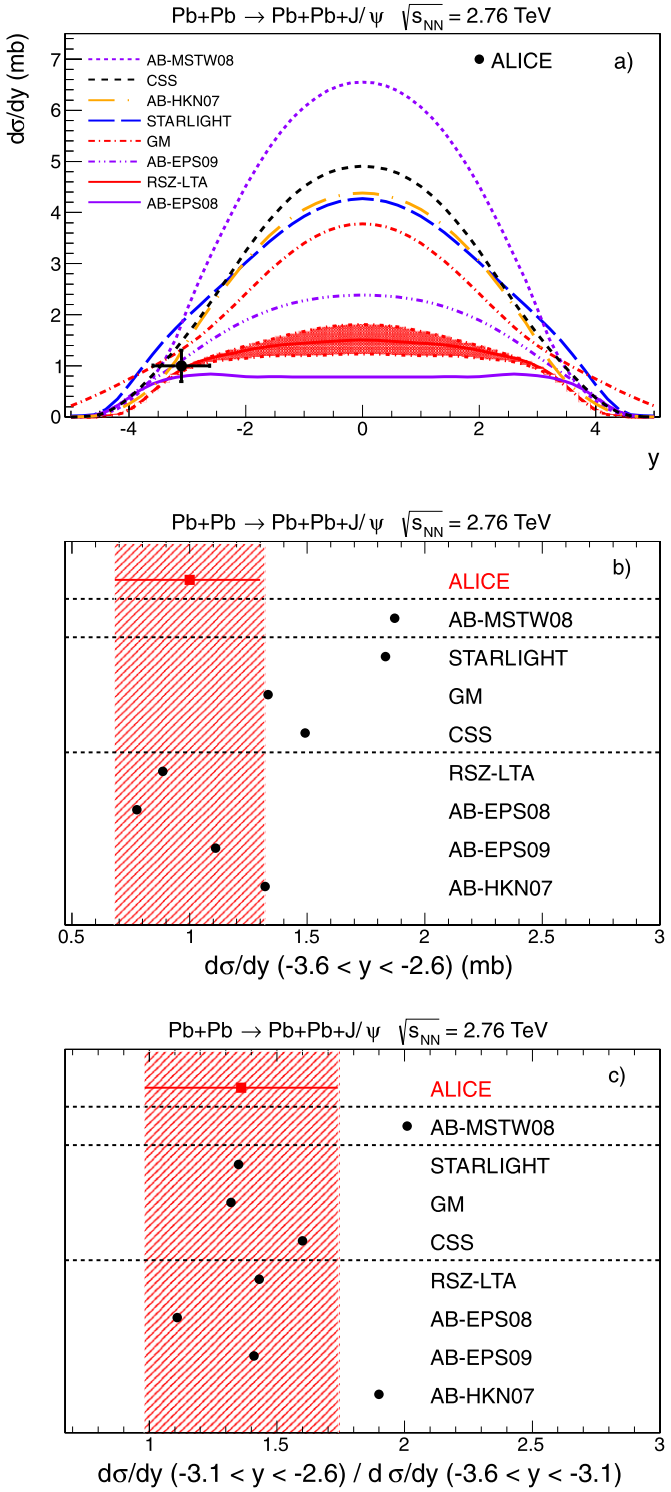

Fig. 3. Measured coherent differential cross section of J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The error is the quadratic sum of the statistical and systematic errors. The theoretical calculations described in the text are also shown. The rapidity distributions are shown in a), b) shows the cross section integrated over $-3.6 < y < -2.6$, and c) shows the ratio of the cross sections in the rapidity intervals $-3.1 < y < -2.6$ and $-3.6 < y < -3.1$. The dashed lines in the lower two plots indicate the three model categories discussed in the text.

and Schäfer (CSS) [14] use the essentially equivalent $k_\perp$-factorization approach. The difference of about 25% between the two calculations is due to different treatment of the nucleon gluon distribution at low x (gluon saturation), and the way in which it affects the dipole-nucleon cross section.

Calculations by Adeluyi and Bertulani (AB) [12] and by Rebyakova, Strikman, and Zhalov (RSZ) [5] are based on perturbative QCD. The calculations by Rebyakova *et al.* use a cross section for exclusive J/ψ photoproduction on a proton target calculated from leading order perturbative QCD within the leading log approximation. The calculations use the integrated gluon density distribution in the proton determined by the Durham-PNPI group from data on exclusive J/ψ production at HERA [4]. The modification to the nuclear gluon distribution has been calculated in the Leading Twist Approximation [30] and is based on using the DGLAP evolution equations and the HERA diffractive parton density distributions.

Adeluyi and Bertulani constrain the nucleon parton distributions to be consistent with data on exclusive vector meson production in photon–proton interactions. The photonuclear cross section is then calculated using different standard parameterizations of the nuclear gluon distribution functions (EPS08, EPS09, and HKN07). For comparison, they also performed calculations where the constrained nucleon gluon distribution function is scaled with the number of nucleons without shadowing or other nuclear effects (AB-MSTW08).

In the region of interest here, $-3.6 < y < -2.6$, the sensitivity to shadowing is reduced compared with that at mid-rapidity. Away from mid-rapidity, there is a two-fold ambiguity in the photon energy and the momentum transfer from the nucleus acting as photon target. For example, a J/ψ produced at $y = 3$ corresponds to a photon–proton centre-of-mass energy of either $W_{\gamma p} = 414$ GeV or $W_{\gamma p} = 21$ GeV. These two energies in turn correspond to values of x of about 5×10^{-5} and 2×10^{-2}, respectively. According to STARLIGHT interactions with $W_{\gamma p} = 21$ GeV contribute 94% of the cross section, while events with $W_{\gamma p} = 414$ GeV contribute only 6%. The total $\mathrm{d}\sigma^{\mathrm{coh}}_{J/\psi}/\mathrm{d}y$ at $y = 3$ is therefore mainly sensitive to the gluon distribution around $x = 2 \times 10^{-2}$.

The measured cross section, $\mathrm{d}\sigma^{\mathrm{coh}}_{J/\psi}/\mathrm{d}y = 1.00 \pm 0.18(\mathrm{stat})^{+0.24}_{-0.26}(\mathrm{syst})$ mb, is compared with the model predictions in Fig. 3 a). Fig. 3 b) shows a comparison of the cross section integrated over the range $-3.6 < y < -2.6$. The models with largest deviations from the measured value are STARLIGHT and AB-MSTW08, which both deviate by about 3 standard deviations if the statistical and systematic errors are added in quadrature. Best agreement (within one standard deviation) is seen for the models RSZ-LTA, AB-EPS09, and AB-EPS08, which include nuclear gluon shadowing. A further check can be performed by dividing the rapidity interval in two and determining the ratio of the cross sections in each interval. This has the advantage that some parts of the systematic errors cancel, and the dominant remaining error is the statistical error. The result is $R = \sigma(-3.1 < y < -2.6)/\sigma(-3.6 < y < -3.1) = 1.36 \pm 0.36(\mathrm{stat}) \pm 0.19(\mathrm{syst})$. The systematic error includes the uncertainties in the signal extraction and in the trigger and reconstruction efficiency. The measured ratio is compared with that from the models in Fig. 3 c). The only models which deviate by more than one standard deviation are AB-MSTW08 and AB-HKN07 (1.7 and 1.5 standard deviations, respectively).

In summary, the first LHC measurement on exclusive photoproduction of J/ψ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV has been presented and compared with model calculations. The AB-MSTW08 model, which assumes that the forward scattering cross section scales with the number of nucleons squared, disagrees with the measurement, both for the value of the cross section and for the ratio of the two rapidity intervals, and is strongly disfavoured. STARLIGHT deviates by nearly three standard deviations in the cross section and is also disfavoured. Best agreement is found with models which include nuclear gluon shadowing consistent with the EPS09 or EPS08 parameterizations (RSZ-LTA, AB-EPS09, and AB-EPS08).

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