Coherent $J/\psi$ photoproduction with the ALICE experiment at the LHC

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Abstract. Results from the ALICE experiment on coherent $J/\psi$ photoproduction in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented. The $J/\psi \rightarrow \mu^+\mu^-$ channel has been used to measure the cross section in the rapidity interval $-3.6 < y < -2.6$. The photoproduction cross section has been compared to several theoretical models. The best agreement between data and theoretical predictions is found for models which include nuclear gluon shadowing.

1. Introduction

Heavy vector meson photoproduction is a good probe of the nuclear gluon distribution at low Bjorken-$x$, because the photoproduction cross section is directly related to the gluon distribution. In the case of $J/\psi$ photoproduction at LHC energies in the forward rapidity $-3.6 < y < -2.6$, the Bjorken-$x$ takes values around $x \approx 10^{-2}$ or $x \approx 10^{-5}$, depending on which nucleus emitted the photon. At the gamma-nucleon level, the photonuclear reactions are described via the two-gluon exchange mechanism.

An experimental opportunity to produce such high energy photonuclear reactions are the so called ultra-peripheral heavy-ion collisions (UPC), which are defined as collisions with impact parameter $b$ larger than sum of the nucleus radii. In this case, hadronic interactions are suppressed and the interaction is mediated by the electromagnetic field. The field can be considered as a flux of virtual photons $dN/dk$, where $k$ is the photon energy. Photoproduction cross section is then given by $\sigma_X = f dk (dN/dk) \sigma^\gamma_X(k)$, where $\sigma^\gamma_X(k)$ is the photonuclear cross section [1].

2. Physics of ultra-peripheral collisions

To calculate the spectrum of virtual photons created by the electromagnetic field, the Weizsäcker-Williams method can be used. In this approach, Lorentz contracted electromagnetic field is decomposed into a frequency spectrum of virtual quanta applying the Fourier transformation. Assuming a particle with charge $q$, moving at velocity $\beta$ in minimal distance $b_{\text{min}}$, the virtual photons spectrum is given by the following equation [2]

$$I(\omega) = \frac{2 q^2}{\pi c^2} \beta^2 \left[x K_0(x) K_1(x) - \frac{\beta^2}{2} x^2 (K_1^2(x) - K_0^2(x))\right],$$  

where $K_0$ and $K_1$ are modified Bessel functions and $x = \omega b_{\text{min}}/c \beta \gamma$. 

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The general cross section formula for $J/\psi$ photoproduction in Pb-Pb collisions consists of two contributions with the opposite rapidity sign, because each lead ion can serve either as a photon source or as target. Denoting $N_\gamma$ as the photon flux and $y$ as the $J/\psi$ rapidity in gamma-nucleus center of mass system, the cross section takes the form

$$\frac{d\sigma(PbPb \rightarrow J/\psi PbPb)}{dy} = N_\gamma(y)\sigma_{\gamma Pb \rightarrow J/\psi Pb}(y) + N_\gamma(-y)\sigma_{\gamma Pb \rightarrow J/\psi Pb}(-y).$$

Gamma-nucleus cross section $\sigma_{\gamma Pb \rightarrow J/\psi Pb}$ depends on the square of the gluon PDF.

3. The ALICE experiment

For this analysis, the forward muon spectrometer, the VZERO scintillators and the Zero-Degree calorimeters were used [3].

The VZERO counters consist of scintillator elements and cover the pseudorapidity $2 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for VZERO-A and VZERO-C, respectively. The VZERO detector is used for triggering and for event selection. Two hadronic Zero-Degree Calorimeters (ZDC) are placed at 116 m at both sides of the interaction point. They are used to detect neutrons and protons in the forward direction.

The muon spectrometer covers the pseudorapidity interval $-4.0 < \eta < -2.5$. It consists of five tracking MWPC stations and four RPC trigger plates placed in the magnetic field created by a 3 Tm dipole magnet. Between the interaction point and the spectrometer a 10 interaction length thick composite absorber is placed.

4. Data analysis

The available data sample consists of $3.16 \times 10^6$ events with integrated luminosity 55 $\mu$b$^{-1}$ taken in 2011 Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In order to select UPC events the special trigger was set up, requiring (i) single muon trigger above a 1 GeV/c $p_T$ threshold, (ii) at least one hit in VZERO-C detector and (iii) no hits in the VZERO-A detector (opposite side to the muon arm). The luminosity of data sample was measured using the UPC trigger scalers from the cross section of the reference trigger classes, which was obtained by the van der Meer scan method.

The offline event selection criteria for the $J/\psi \rightarrow \mu^+\mu^-$ analysis required coherent ultra-peripheral processes signatures. In order to ensure an exclusive reaction only two tracks in the muon spectrometer in an otherwise empty detector were required.

The signatures are (i) neutron ZDC signal $< 6$ TeV, (ii) VZERO timing compatible with crossing beams and (iii) two reconstructed tracks in the muon arm with opposite charges. The second group of analysis cuts ensures the muon track quality, this selection consists of (i) momentum dependent DCA (distance between the vertex and the track) to reject multiple scattering in the absorber and (ii) both tracks pseudorapidity $-3.7 < \eta_{1,2} < -2.5$. The last group of analysis requirements select reconstructed candidate having (i) rapidity $-3.6 < y < -2.6$, (ii) transverse momentum $p_T < 0.3$ GeV/c and (iii) invariant mass $2.8 < M_{inv} < 3.4$ GeV/c$^2$.

Following the above criteria, 117 $J/\psi$ candidates remained.

5. Signal extraction

5.1. Dimuon invariant mass

The invariant mass corresponding to dimuon candidates which satisfied the above selection criteria is shown in Figure 1 in the interval $2.2 < M_{inv} < 4.6$ GeV/c$^2$. We can clearly see the $J/\psi$ peak above the background mainly coming from $\gamma\gamma \rightarrow \mu^+\mu^-$ QED process. The fit is performed using the Crystal Ball function [4] for the signal and an exponential function for the background. The $J/\psi$ yield obtained from the corresponding fit is $N_{yield} = 96 \pm 12$(stat) $\pm 6$(syst). The exponential slope parameter is in very good agreement with the STARLIGHT MC expectation ($-1.4 \pm 0.2$ GeV$^{-1}$c$^2$ for data and $-1.39 \pm 0.01$ GeV$^{-1}$c$^2$ for MC) [5].
5.2. Physics processes involved

There are 4 main processes contributing to the exclusive $J/\psi$ production decaying in the $\mu^+\mu^-$ channel.

The coherent $J/\psi$ production is our signal of interest consisting of transverse polarized, low $p_T$ $J/\psi$. In this case the photon couples coherently to all nucleons. The incoherent production occurs when photon couples to a single nucleon. $J/\psi$ produced by this mechanism have higher $p_T$ and are suppressed by the $p_T < 0.3 \text{ GeV/c}$ cut.

The $\psi'$, produced by ultra-peripheral processes, may contribute to the signal by its decay $\psi' \rightarrow J/\psi + X$. The corresponding simulations include a $\psi'$ sample generated with the STARLIGHT MC [5] while the decays were simulated using PYTHIA [6].

The last source of background is the QED $\gamma\gamma \rightarrow \mu^+\mu^-$ interaction.

Figure 2 (right) shows dimuon $p_T$ distribution with the fit performed using MC templates for each of the contributing processes. The number of coherent candidates can be extracted by the equation

$$N_{\text{coh}}^{J/\psi} = N_{\text{yield}}^{J/\psi} \cdot \frac{f_I + f_D}{f_I}$$. 

Using the yield, the incoherent fraction $f_I = 0.12^{+0.14}_{-0.04}$ (incoherent $J/\psi$ contribution) and the feed-down $f_D = 0.11 \pm 0.06$ ($J/\psi$ from $\psi'$ decay), we obtain $N_{\text{coh}}^{J/\psi} = 78 \pm 10\text{(stat)}^{+7}_{-11}\text{(syst)}$ candidates. The contributions $f_I$ and $f_D$ are obtained from the fits on the $p_T$ distribution (Figure 2).

6. Acceptance and efficiency correction

In order to calculate the detection efficiency, the STARLIGHT generator has been used to provide coherent and incoherent $J/\psi$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ samples. The generated events were folded with the detector Monte Carlo simulation using GEANT3.

The correction $(\text{Acc} \times \varepsilon)_{J/\psi}$ is defined as the ratio of accepted over generated candidates and the resulting values are $(\text{Acc} \times \varepsilon)_{J/\psi} = 16.6\%$ and $14.3\%$ for coherent and incoherent productions respectively.

7. Coherent $J/\psi$ differential cross section

The following equation 3 provides cross section calculation using $J/\psi \rightarrow \mu^+\mu^-$ branching ratio $\text{BR}$, number of coherent $J/\psi$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ candidates $N_{\text{coh}}^{J/\psi}$ and $N_{\gamma\gamma}$, the corresponding corrections $\text{Acc} \times \varepsilon$, the $\gamma\gamma \rightarrow \mu^+\mu^-$ QED cross section $\sigma_{\gamma\gamma}$ and rapidity interval $\Delta y = 1$ in present case.

$$\frac{d\sigma_{J/\psi}^{\text{coh}}}{dy} = \frac{1}{\text{BR}(J/\psi \rightarrow \mu^+\mu^-)} \cdot \frac{N_{\text{coh}}^{J/\psi}}{N_{\gamma\gamma}} \cdot \frac{(\text{Acc} \times \varepsilon)_{\gamma\gamma}}{(\text{Acc} \times \varepsilon)_{J/\psi}} \cdot \frac{\sigma_{\gamma\gamma}}{\Delta y}$$ (3)
The QED continuum pair production cross section $\sigma_{\gamma\gamma}$ has been used for normalization, so that the $\sigma_{coh}^{J/\psi}$ formula (3) is independent of luminosity and of trigger efficiency, but the theoretical uncertainty in $\sigma_{\gamma\gamma}$ contributes 20% to the coherent cross section systematic uncertainty.

The coherent $J/\psi$ differential cross section in $-3.6 < y < -2.6$ and $p_T < 0.3$ GeV/c is $d\sigma_{coh}^{J/\psi}/dy = 1.00 \pm 0.18(\text{stat})^{+0.24}_{-0.26}(\text{syst})$ mb.

8. Theoretical predictions
The measured coherent differential cross section of $J/\psi$ photoproduction is shown in Figure 3, together with several model predictions [7]. The uncertainty is given by the quadratic sum of the statistical and systematic errors. Figure 4 provides the ratio of the cross sections between two rapidity bins, taking advantage that some parts of the systematic errors cancel. The ratio of the cross sections is $R = 1.36 \pm 0.36(\text{stat}) \pm 0.19(\text{syst})$.

The best agreement is observed for partonic models AB-EPS08, AB-EPS09 and RST-LTA, which include nuclear gluon shadowing.

Figure 3. Coherent $J/\psi$ cross section. Figure 4. Ratio of the cross sections between two rapidity bins.

9. Conclusions
The ALICE Collaboration made the first LHC measurement on exclusive $J/\psi$ photoproduction in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [7], the cross section in the forward rapidity interval $-3.6 < y < -2.6$ was estimated as $d\sigma_{coh}^{J/\psi}/dy = 1.00 \pm 0.18(\text{stat})^{+0.24}_{-0.26}(\text{syst})$ mb. The value is in agreement with partonic models including nuclear gluon shadowing AB-EPS08, AB-EPS09 and RST-LTA.

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