Coherent photoproduction of J/ψ at forward rapidity in Pb–Pb collisions with the ALICE detector

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Abstract. We present the measurement of coherent photoproduction of J/ψ at forward rapidity in Pb–Pb collisions with the ALICE detector at the LHC.

1. The LHC as a photon–ion collider

The interaction of energetic beams of Pb ions at the LHC generates not only hadronic Pb-Pb collisions, but also γ–Pb and γ–γ collisions. This is because an accelerated charge can be viewed as a source of quasi–real photons, as first proposed by Fermi [2,3] with the ultra–relativistic formulation provided by Weizsäcker [4] and Williams [5]. These quasi–real photons may interact either with an ion or with another quasi–real photon.

Since hadronic interactions have short range, hadronic Pb–Pb collisions with an impact parameter larger than the sum of the nuclear radii are strongly suppressed. In contrast, collisions involving quasi real photons occur at very large impact parameters. Such processes are called ultra peripheral collisions (UPC).

The intensity of the photon flux depends on the square of the ion electric charge. The photons are quasi–real and when they are emitted coherently from the whole nucleus, their wavelength is restricted to be larger than the nuclear radius. This implies that in the direction perpendicular to that of the ion beam the transverse momentum is of the order of 30 MeV, while in the longitudinal direction, taking into account the boost, the photon energy, in the laboratory reference system, may reach up to 40 GeV for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The LHC energy during the 2011 ion run.

These quasi–real photons may interact with a full ion, in which case the interaction is called coherent. In the other extreme the interaction may be with a single nucleon in the nuclei, in which case the interaction is called incoherent. The physics of UPC is discussed in a number of reviews [6,7]. In this contribution the measurement of the coherent production of a J/ψ in UPC at large rapidities with the ALICE detector is presented. This measurement was carried out using the ALICE forward muon arm, and was recently published in [1]. A study of the coherent production of ρ^0 vector mesons in UPC can also be found in these proceedings [8].

2. Coherent production of J/ψ in UPC

One of the most interesting processes in UPC is the coherent photoproduction of vector mesons composed of heavy quarks. These processes are expected to probe the nuclear gluon distribution, which is not well constrained by the pre-LHC measurements, especially at low values of Bjorken
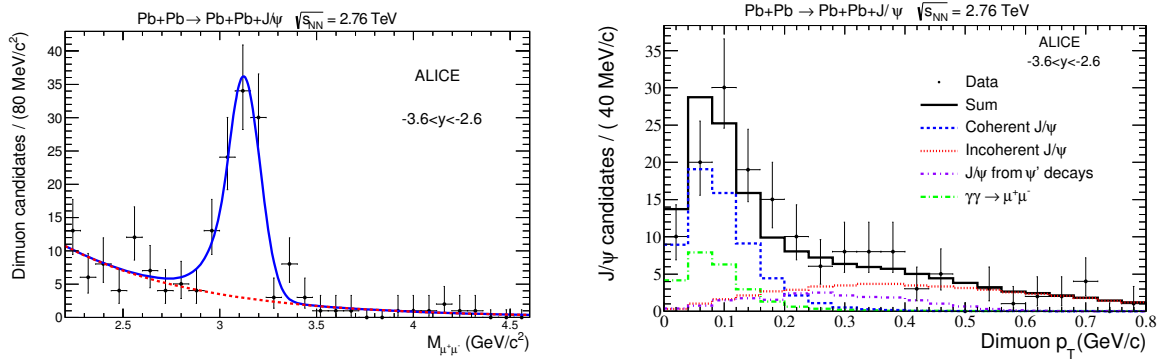
Figure 1. Dimuon invariant mass (left) and transverse momentum (right) distributions for selected events. The transverse momentum distribution is presented only for dimuons in the mass range between 2.8 GeV/c^2 and 3.4 GeV/c^2. For details see the text.

x [9]. Due to the coherent coupling of the photon to the lead ion the transverse momentum of the vector meson is restricted to be ≈ 60 MeV/c for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, while its rapidity depends on the photon energy, k, as $y = \ln(2k/M)$, where M is the mass of the vector meson.

In Pb–Pb collisions there are two possible sources of photons at a given rapidity, because both nuclei could radiate the photon. Since the photon energy spectrum is steep, the contribution from the the low energy photon dominates the cross section. At rapidity $y = -3$ the two contributions correspond to center of mass energy, in the γ–Pb system, of $W_{\gamma Pb} = 20$ GeV and $W_{\gamma Pb} = 400$ GeV respectively. Taking into account the difference in the flux and in the corresponding cross sections, the contribution from the higher energy is approximately 4% of that at the lower energy.

In pQCD models the coherent photoproduction of the J/ψ occurs as follows: the quasi-real photon fluctuates into a quark–antiquark pair which interacts with the nuclei to produce the J/ψ through the exchange of two gluons at the same Bjorken x. The value of the rapidity of the vector meson and the Bjorken x variable are related by $x = Me^{\pm y}/\sqrt{s_{NN}}$, so that at $y = -3$ values of $x \approx 10^{-2}$ and $x \approx 10^{-5}$ are probed, where the dominant contribution to the process comes from the higher x value.

3. The ALICE detector

The ALICE detector [10] consists of a central barrel with a uniform magnetic field of 0.5 T, and a muon spectrometer in the forward direction. The muon spectrometer measures muons with full azimuthal acceptance and within $-4.0 < \eta < -2.5$, where η denotes the pseudorapidity. The muon spectrometer is made of an absorber of ten interaction lengths, followed by five tracking stations made of two planes of cathode pad MWPC. A third MWPC station is situated inside a dipole magnet which has 3 Tm integrated magnetic field. The spectrometer also has a triggering system to select muon candidates with a transverse momentum larger than a programmable threshold, set to 1 GeV/c for the measurement described in this contribution. The trigger system consist of four planes of resistive plate chambers (RPC) placed after the MWPC and behind an iron wall of 7.2 interaction lengths, which absorbs secondary punch–through hadrons from the front absorber and low momentum muons from π and K weak decays.

Other detectors used in the measurement presented here are the VZERO and the ZDC. The VZERO consists of two arrays of 32 scintillator tiles each, covering the ranges $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C). The time resolution of each array is better than

Table 1. Summary of the contributions to the systematic uncertainty for the J/ψ photoproduction cross section measurement.

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	$^{+24}_{-26}$%

1 ns. They contribute to the level–0 trigger of ALICE. In addition two zero degree calorimeters (ZDC) located at $\pm$ 116 m from the interaction point are used to veto hadronic interactions by measuring neutrons in the very forward direction.

4. Cross section for the coherent production of J/ψ in UPC at high rapidities

The J/ψ vector meson has been measured through its decay into a pair of muons. The signature is then two muons with opposite charge from a J/ψ vector meson decay at high rapidities and with low transverse momentum, in an otherwise empty detector. The only irreducible background comes from the continuum production of muon pairs in γ–γ collisions.

This measurement used an integrated luminosity of 55 μb^{-1} of Pb–Pb data recorded by ALICE in 2011. A dedicated UPC trigger selected events with at least one muon track in the muon spectrometer, with transverse momentum larger than 1 GeV/c, at least one hit in the VZERO–C, and no activity on the VZERO-A.

The offline event selection is described in detail in [1]. The selection ensured that muon tracks are not from beam–gas interactions and that they are within the acceptance of both the muon spectrometer and the VZERO–C. Accepted events contained only two muon tracks with opposite charges. These two muon tracks were added to form a dimuon, required to have transverse momentum less than 300 MeV/c and rapidity within $-3.6 < y < -2.6$. Rejection of the remaining beam–gas background and low multiplicity hadronic interactions was performed using VZERO timing and the ZDC respectively. The data set passing these selection criteria contained 117 events within the mass range (2.8,3.4) GeV/c^2.

The mass distribution for the selected dimuons and the transverse momentum distribution for dimuons within the mass range (2.8,3.4) GeV/c^2 are shown in Figure 1. The left panel shows the mass distribution for the selected events. A peak around the J/ψ mass is clearly seen. Also shown is a fit of an exponential plus a Crystal Ball parameterization. The parameters of the minimum likelihood fit are consistent with expectations from the production of J/ψ vector mesons and the di–muon continuum. The right panel shows the distribution of transverse momentum for events in the mass range (2.8,3.4) GeV/c^2. The histograms show the contributions expected from the Starlight MC [11] for coherent and incoherent J/ψ production, feed–down from $\psi(2S)$ and the contribution from the continuum. At low transverse momentum the coherent production dominates. The yield of J/ψ with transverse momentum less than 300 MeV/c is estimated to be 96 ± 12 (stat) ± 6 (sys) with a 11 ± 6 % contribution from feed down and a 12^{+14}_{-4} % contribution from incoherent processes as estimated from a comparison of data with MC expectations.

To normalize the J/ψ cross–section, the cross section for the continuum production of dimuons ($\sigma_{\gamma\gamma}$) was used.
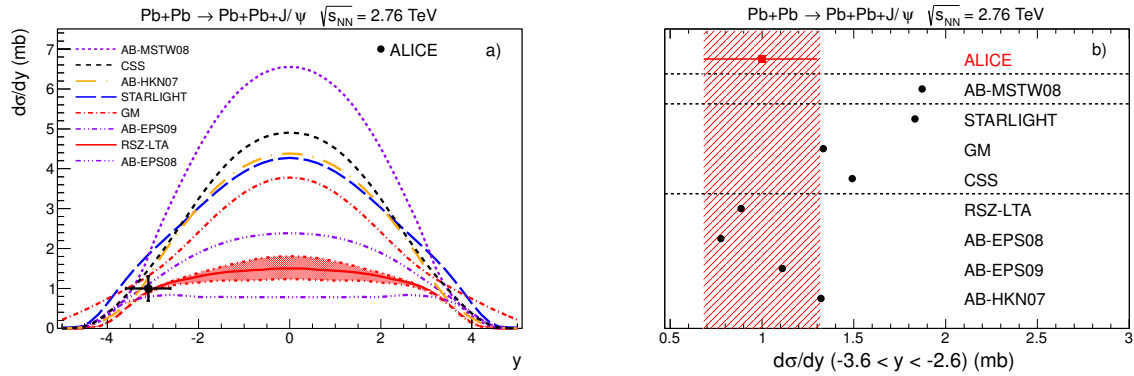
Figure 2. Comparison between the measurement and available theoretical calculations.

$$\frac{d\sigma_{\text{coh}}}{dy} = \frac{1}{\text{BR}} \cdot \frac{N_{\text{coh}}}{N_{\gamma\gamma}} \cdot \frac{(\text{Acc x } \epsilon)_{\gamma\gamma}}{(\text{Acc x } \epsilon)_{\text{coh}}} \frac{\sigma_{\gamma\gamma}}{\Delta y},$$

where BR is the branching ratio of $J/\psi \to \mu^+\mu^-$, (Acc x ϵ) are the factors to correct for the detector efficiency and acceptance of the coherent and continuum samples, Δy is the width of the rapidity range.

The coherent cross section at $\sqrt{s_{NN}} = 2.76$ TeV for $-3.6 < y < -2.6$ was measured to be

$$\frac{d\sigma_{\text{coh}}}{dy} = 1.00 \pm 0.18(\text{stat})^{+0.24}_{-0.26}(\text{sys}) \text{ mb}$$

where the contributions to the systematic error are shown in Table 1. The dominant contribution is the theoretical uncertainty in $\sigma_{\gamma\gamma}$ followed by the extraction of the coherent contribution to the mass and transverse momentum distributions.

5. Comparison to theory predictions

The measured cross section has been compared to five recent theoretical calculations [12–16]. The comparison is shown in Figure 2. STARLIGHT [12], uses a GVDM coupled to a Glauber approach to link the γA to the γp cross section, where the later is obtained from a parameterization of HERA data. GM [13] is based on the color dipole model, where the scattering amplitude depends on the nuclear profile and the dipole nucleon cross section, which is taken from the IIM model which incorporates saturation. The CSS [16] model uses a Glauber approach and the color dipole nucleon amplitude based on the unintegrated gluon distribution of the proton. The AB models [15] use the LO pQCD amplitude scaled to fit $\gamma + p \to J/\psi + p$ data. For the gluon distribution, AB–MSTW08 assumes no nuclear effects. The other AB models incorporate nuclear effects according to the EPS08, EPS09 or HKN07 prescriptions. Finally, RSZ-LTA [14] is based on the LO pQCD amplitude for two gluon exchange where the nuclear gluon density incorporates shadowing computed in the leading twist approximation.

From Figure 2 it can be concluded that models which incorporate shadowing – with the scale fixed near the mass of the J/ψ – are closer to data. This data will help to constraint and improve the theoretical predictions such that the uncertainty on the nuclear gluon distribution can be reduced.

Acknowledgments

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