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Photoproduction of J/ψ in Pb-Pb and p-Pb collisions at the LHC with the ALICE detector

J. G. Contreras (for the ALICE Collaboration)

[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

Abstract. Recent results from the ALICE Collaboration on the photoproduction of J/ψ in Pb-Pb and p-Pb collisions are presented along with results on the production of electron–positron pairs in the collision of two photons.

1 Introduction

The protons and lead nuclei accelerated at the LHC are accompanied by an electromagnetic field. According to a proposal by Fermi [1, 2], extended to the ultra–relativistic case by Weizsäcker [3] and Williams [4], these electromagnetic fields can be viewed as a beam of- quasi–real photons in the laboratory frame.

The virtuality of the emitted photons is restricted by the size of the emitting particle. When the source is a proton the virtuality is smaller than ≈250 MeV, while when the source is a lead nucleus the virtuality is smaller than 30 MeV. On the other hand the energy of the photon is given by the boost of the source in the laboratory frame. For the LHC, during the 2011 Pb-Pb and the 2013 p-Pb runs, the photons emitted by protons reach the 1 TeV energy scale, while those emitted by lead nuclei reach energies up to ≈ 50 GeV.

This means that using Pb-Pb and p-Pb data from the LHC is possible to study γp, γ-Pb and $\gamma\gamma$ collisions at centre of mass energies higher than ever before.

As the strong force has a short range, collisions with an impact parameter larger than the sum of the radii of the colliding particles are strongly suppressed. On the other hand, collisions involving the quasi–real photons can happen even at very large impact parameters. This type of processes are called ultra peripheral collisions (UPC). The physics of UPC is discussed in a number of reviews, among them [5, 6].

An interesting process to study in UPC is the photoproduction of J/ψ vector mesons. This process has some interesting features:

- The mass of the J/ψ is large enough to allow pQCD calculations of this process.
- In the leading order of these calculations, the photoproduction of J/ψ samples the square of the gluon distribution functions in the target, so this process is particularly sensitive to possible non-linear effects involving gluons at low values of the Bjorken-x variable. Key words here are *saturation* and *shadowing*. See for example [7].
- The experimental signature in the leptonic decay channels of the J/ψ is very clean: only two leptons in the detector and in some cases activity in the very forward region. The leptons can be used to trigger this process and from the measured rapidity of the J/ψ the centre of mass energy of the γ+target system can be extracted.

2 The ALICE detector

The ALICE detector [8] consists of a central barrel and a muon spectrometer in the forward direction.

The muon spectrometer covers the pseudorapidity (η) range $-4.0 < \eta < -2.5$. It consists of an absorber of ten interaction lengths, followed by five tracking stations made of two planes of cathode pad MWPC, where the third station is inside a dipole magnet with 3 T·m integrated magnetic field. The spectrometer has a triggering system to select muon candidates with a transverse momentum larger than a programmable threshold. The trigger system consists 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.

The central barrel, placed within a uniform magnetic field of 0.5 T, covers the range $|\eta| < 0.9$. It consists of the inner tracker system (ITS), the time projection chamber (TPC) and the time-of-flight detector (TOF). The ITS has six layers of silicon detectors. From the inside to the outside there are two layers of silicon pixels, two layers of silicon drift and two layers of silicon strip detectors. The TPC is the main tracking device of ALICE and is used for tracking and particle identification using the ionisation energy loss. The TPC is a a cylindrical gaseous detector with a diameter of 500 cm and a length of 510 cm which can provide up to 159 points for the track and PID measurements. The TOF detector, which surrounds the TPC, is composed of multi-gap resistive plate chambers which provide an intrinsic resolution of approximately 80 ps. In the analyses presented here it is used to trigger UPC events at mid-rapidity.

Other detectors relevant for the analyses presented in this contribution are the VZERO and the ZDC, zero degree calorimeter. 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 ≤ 1 ns and they form part of the level–0 trigger. They are also used to veto activity in the detector beyond the two leptons from the decay of the J/ψ. There are two ZDCs located at ±116 m from the interaction point. They can detect neutrons produced in the very forward regions. In the analyses presented in this contribution the neutron ZDCs are used to veto hadronic interactions.

3 ALICE measurement on photoproduction of J/ψ in UPC of Pb-Pb

The ALICE Collaboration has recently published two papers on the photoproduction of J/ψ in UPC of Pb-Pb using data taken during the 2011 run [9, 10]. The first paper covers the measurement performed with the muon spectrometer and the second the measurement performed with the central barrel. J/ψs measured in the muon spectrometer sample values of Bjorken-x in the gluon distribution of the target around 10^{-2}, while those measured in the central barrel sample values around 10^{-3}.

The photoproduction of J/ψ was measured in two regimes. Coherent photoproduction, meaning that the photon couples to the whole nucleus, is characterised by the low transverse momentum of the J/ψ of around 60 MeV/c. Incoherent photoproduction refers to cases where the photon couples to only one nucleon in the nucleus and is characterised by a transverse momentum of the J/ψ around 400 MeV/c.

3.1 Coherent photoproduction of J/ψ

For the measurement of the coherent photoproduction of J/ψ at forward rapidities the events were triggered by the presence of at least one muon in the muon spectrometer with transverse momentum larger than 1 GeV/c and a veto in the activity of VZERO–A. The offline selection required no activity in the detector other than two muon tracks with opposite charges in the muon spectrometer such that the J/ψ candidate had a rapidity in the range $-3.6 < y < -2.6$ and transverse momentum less than 300 MeV/c.

For the measurement at central rapidities the events were triggered requiring no activity in VZERO, at least two hits in the inner layers of ITS and between 2 and 6 hits in the TOF such that at least a pair of them has a separation in azimuth between 150 and 180 degrees. In the offline selection it was required that in the detector there were only two tracks of opposite charges. Using the PID capabilities of the TPC the J/ψ could be measured separately in the electron and muon decay channels. As an example, the mass distribution of di-muons with transverse momentum less than 200 MeV/c and produced at central rapidity is shown in Figure 1 [10].

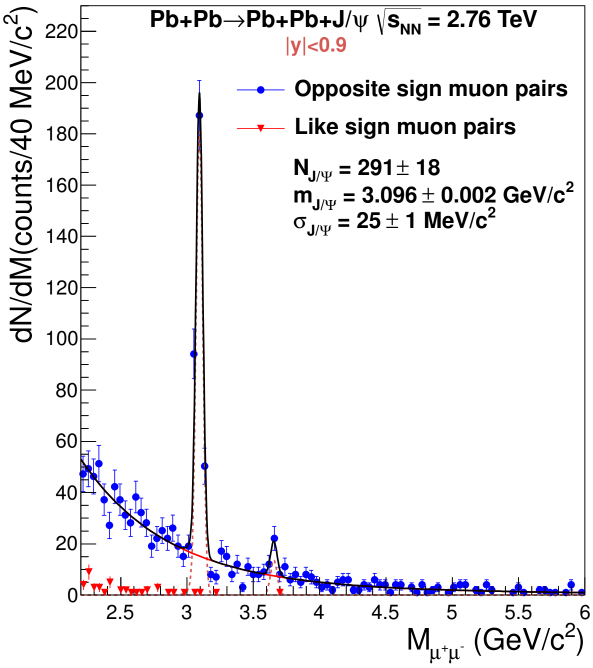

Figure 1. Invariant mass distribution for a coherent enriched sample of di-muons measured in the central barrel. The solid red line describes the background with an exponential and the dotted red line describe the charmonium states with a Crystal-ball for the J/ψ plus a Gaussian for the $\psi(2S)$. The solid black line is the sum of the background and signal functions.

The measured cross section in the forward and in the central rapidity regions has been compared to five recent theoretical calculations [11–15]. The comparison is shown in Figure 2a [10].

STARLIGHT [11], 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 [12] 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 [15] model uses a Glauber approach and the color dipole nucleon amplitude based on the unintegrated gluon distribution of the proton. The AB models [14] 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 [13] 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 2a it can be concluded that models which incorporate nuclear effects like AB–EPS09 and RSZ–LTA

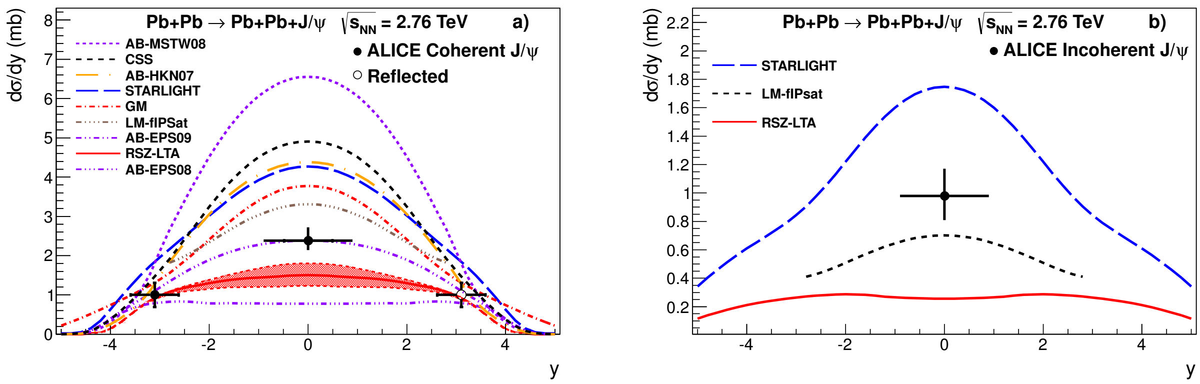

Figure 2. Measured differential cross section for coherent (a) and incoherent (b) photoproduction of J/ψ in UPC of Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV. The different predictions to which the measured data are compared are described in the text.

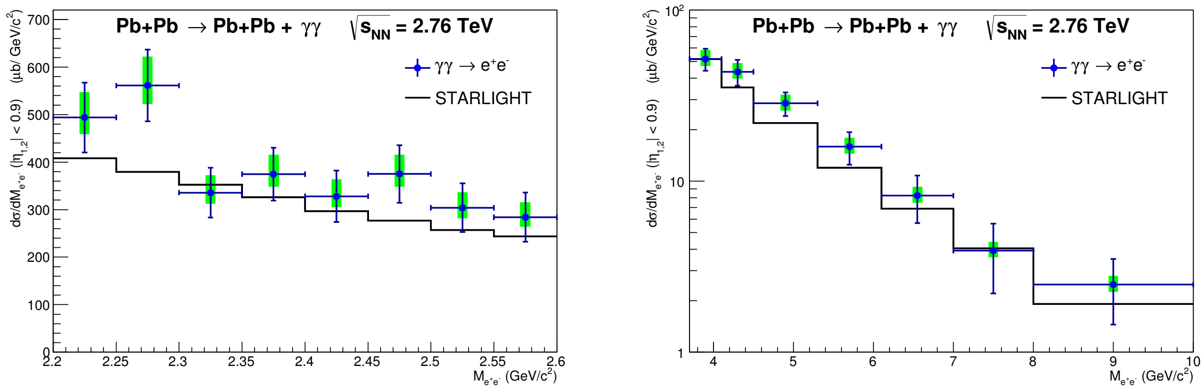

Figure 3. Distribution of the invariant mass of electron–positron pairs in two mass ranges compared to the LO predictions of the STARLIGHT model.

are closer to data. These models fix the perturbative scale near the mass of the J/ψ.

3.2 Incoherent photoproduction of J/ψ

Using the sample of photo produced J/ψ measured in the central barrel it was also possible to measure the incoherent process. For this case there are fewer theoretical predictions. Those made with the STARLIGHT and RSZ-LTA presented in the previous section and the LM-fIPsat prediction based on a colour dipole model with a Glauber approach and a saturation prescription [16].

Figure 2b [10] shows the comparison between the measurement of ALICE and the three predictions. The predictions differ in almost an order of magnitude while the measurement has an uncertainty of the order of 20%.

4 ALICE measurement of $\gamma\gamma \to e^+e^-$ in UPC of Pb-Pb

ALICE has also measured the production of an electron–positron pair in $\gamma\gamma$ UPC collisions of Pb-Pb. Although this is a standard QED process, the coupling constant is enhanced by a factor Z, the electric charge of the nuclei, so that it is not anymore a small number and higher order terms may be important. There are calculations which predict a reduction of the NLO cross section up to 20-30% with respect to the LO calculation [17].

Figure 3 [10] shows the ALICE measurement in two ranges of the invariant mass of the electron–positron pair: [2.2,2.6] GeV/c^2 and [3.7,10] GeV/c^2. Note that the tail from bremsstrahlung is negligible in the first mass range. The measurement is compared to the leading order prediction from STARLIGHT. The LO prediction is slightly below the data, which sets stringent constraints in possible reductions of the predictions due to higher order effects.

5 Preview of photoproduction of J/ψ in UPC of p-Pb

In early 2013 the LHC provided collisions of protons on lead ions in two configurations: p-Pb (the proton travels towards the muon spectrometer) and Pb-p (the lead ion travels towards the muon spectrometer). ALICE took data

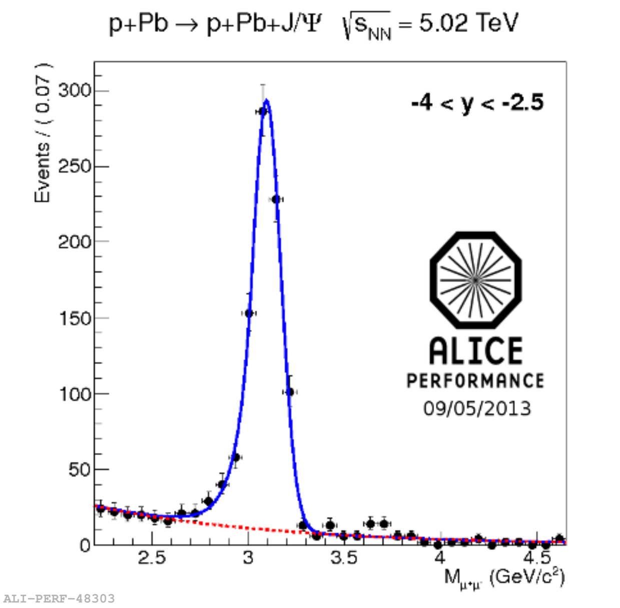

Figure 4. Distribution of the invariant mass of di-muons measured with the muon spectrometer during the p-Pb data taking period of 2013.

in both configurations. There were three types of active triggers: at forward rapidity using the muon spectrometer, at mid rapidity using the central barrel and a semi–forward sample also triggered by the muon spectrometer. In this last sample the second muon is detected in the central barrel. As an example Figure 4 shows the distribution of the invariant mass of di-muon pairs measured in the muon spectrometer during the p-Pb data taking period.

As mentioned before the rapidity of J/ψ is related to the centre of mass energy of the γ+target system. Furthermore, the intensity of the photon flux depends on the square of the charge of the source, so that in p-Pb collisions the photoproduction of J/ψ is dominated by the case where the photon is emitted by the lead ion; that is by γp interactions.

ALICE has collected samples at backward, semi–backward, central, semi-forward and forward rapidities and each sample corresponds to a different range in the centre of mass energy $W_{\gamma p}$ of the γp system:

Backward sample: measured with the muon spectrometer in p-Pb collisions. Corresponds to $20 < W_{\gamma p} < 45$ GeV.

Semi–backward sample: measured with the muon spectrometer and the central barrel in p+Pb collisions. Corresponds to $45 < W_{\gamma p} < 80$ GeV.

Central sample: measured with the central barrel in p-Pb and Pb-p collisions. Corresponds to $100 < W_{\gamma p} < 250$ GeV.

Semi–forward sample: measured with the muon spectrometer and the central barrel in Pb-p collisions. Corresponds to $300 < W_{\gamma p} < 550$ GeV.

Forward sample: measured with the muon spectrometer in Pb-p collisions. Corresponds to $550 < W_{\gamma p} < 1100$ GeV.

It is interesting to note that HERA measurements reached values of $W_{\gamma p}$ up to 300 GeV. So measurements at the LHC open up a new kinematic domain.

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