Photonuclear production of vector mesons in ultra-peripheral Pb-Pb collisions at the LHC

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Abstract

Vector mesons are copiously produced in ultra-peripheral nucleus-nucleus collisions. In these collisions, the nuclei are separated by impact parameters larger than the sum of the nuclear radii, and the interaction is mediated by the electromagnetic field. The interaction effectively corresponds to a photonuclear interaction between a photon, generated from the electromagnetic field of one of the nuclei, and the target nucleus. The ALICE Collaboration has previously published results on exclusive $J/\psi$ photoproduction at mid and forward rapidities in Pb-Pb collisions. The cross section for this process is a particularly good measure of the nuclear gluon distribution. In this talk, the latest results on exclusive production of light and heavy vector mesons from ALICE in Pb-Pb collisions will be presented.

Keywords: photoproduction, vector mesons, ultra-peripheral collisions

1 Introduction

The strong electromagnetic fields accompanying heavy-ions accelerated at the LHC may lead to particle production in ultra-peripheral collisions where there is no overlap between the colliding nuclei. This has been exploited by the ALICE Collaboration to constrain the nuclear and proton gluon distributions through exclusive photoproduction of $J/\psi$ mesons [1,2,3]. This presentation extends these studies to exclusive photoproduction of $\rho^0$ and $\psi(2S)$. It also contains results on two-photon production of $e^+e^-$ pairs in a novel invariant mass range.

During the heavy-ion runs in 2010 and 2011, ALICE used dedicated triggers for collecting vector mesons produced in ultra-peripheral collisions. The ALICE detector and the triggers used during the 2011 run are described in [1,2]. The midrapidity triggers were based on input from the ALICE Time-of-Flight (TOF), Silicon Pixel (SPD), and VZERO detectors. At least two hits were required in TOF and SPD, while the VZERO detectors, covering $2.8 < \eta < 5.2$ and $-3.7 < \eta < -1.7$, were used as veto detectors and were required to be empty. In 2011, a cut on azimuthal angle was applied which required the hits in TOF to be back-to-back, thereby restricting the final states to have invariant masses $\geq 2$ GeV/$c^2$. The ultra-peripheral trigger used in 2010 was similar to the one in 2011 but without the angular cut. During the early part of the 2010 run a trigger using input only from the TOF was also used. The integrated luminosities for the analyses presented below were about 260 mb$^{-1}$ ($\rho^0$ and $e^+e^-$ pairs, 2010 data) and 22 mb$^{-1}$ ($\psi(2S)$, 2011 data).
2 Coherent $\rho^0$ production

The events used for the analysis were required to satisfy the ultra-peripheral trigger, to have exactly two reconstructed tracks identified as pions from the dE/dx in the Time Projection Chamber (TPC), and to have a reconstructed primary vertex within ±10 cm from the center of the interaction region along the beam axis. To select coherent production the pair-$p_T$ was required to be $< 0.15$ GeV/c. The rapidity of the pair was required to be within $|y| < 0.5$ to avoid edge effects. The data were corrected for acceptance and efficiency bin-by-bin in invariant mass using simulated events processed through the detector response simulation and reconstructed back using the same selection as for real data. The simulated events consisted of two pions of opposite charge with a flat distribution in invariant mass $(2m_\pi \leq M_{\pi\pi} \leq 1.5$ GeV/$c^2$), rapidity $(|y| < 0.5)$, and transverse momentum $(p_T < 0.15$ GeV/c). The decay angle distribution was not measured. In the simulation, it was, as expected for the decay from a spin-1 state, assumed to be $dn/d\cos(\theta) \propto \sin^2(\theta)$ in the $\pi\pi$ center of mass. The systematic error is estimated and includes the errors in signal extraction, track selection, luminosity, trigger efficiency, incoherent contribution, and particle identification.

The corrected invariant mass distribution is shown in Fig. 1 (left). The distribution has been fitted to a relativistic Breit-Wigner function plus a continuum term:

$$\frac{d\sigma}{dM_{\pi\pi}} = A \left( \frac{\sqrt{M_{\pi\pi}^2 - M_{\rho}^2 + iM_{\rho}\Gamma(M_{\pi\pi})}}{M_{\pi\pi}^2 - M_{\rho}^2 + iM_{\rho}\Gamma(M_{\pi\pi})} \right) + B^2 \text{ with } \Gamma(M_{\pi\pi}) = \frac{M_\rho}{M_{\pi\pi}} \left[ \frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2} \right]^{3/2},$$

where $A$ and $B$ are the amplitudes for the resonant and continuum contributions, respectively. $M_\rho$ and $\Gamma_\rho$ are the mass and width of the $\rho^0$ meson, and $m_\pi$ is the mass of the pion. Although other parameterizations of the $\rho^0$ shape are possible, the above is chosen to be consistent with the most recent $\rho^0$ photoproduction measurements by ZEUS [8] and STAR [5]. The fit gives $M_\rho = 761.6 \pm 2.3(\text{stat.})^{+6.1}_{-3.0}(\text{sys.})$ MeV/c$^2$ and $\Gamma_\rho = 150.2 \pm 5.5(\text{stat.})^{+12.0}_{-9.6}(\text{sys.})$ MeV/c$^2$, in good agreement with the PDG values. The ratio of the non-resonant to resonant amplitudes is $|B/A| = 0.50 \pm 0.04(\text{stat.})^{+0.10}_{-0.04}(\text{sys.})$ (GeV/c$^2$)$^{-1/2}$.

The cross section for coherent $\rho^0$ production is obtained by integrating the resonant part of the $d\sigma/dM_{\pi\pi}$ (dashed curve in Fig.1 (left)) from $2m_\pi$ to 1.5 GeV/c$^2$. The contribution from incoherent photoproduction below $p_T < 0.15$ GeV/c is estimated to be 5% and is subtracted. The result is $d\sigma/dy = 420 \pm 10(\text{stat.})^{+39}_{-55}(\text{sys.})$ mb, which is shown and compared with model predictions in Fig.1 (right).

The measured cross section is in agreement with STARLIGHT [8] and the calculation by Goncalves and Machado (GM) [7] while the GDL (Glauber-Donnachie-Landshoff) prediction [5] is about a factor of 2 higher than data. The calculation by GM is based on the Color Dipole model, while STARLIGHT and GDL use the photon-proton cross section $\sigma(\gamma + p \rightarrow \rho^0 + p)$ constrained from data as input. All calculations use the Glauber model to scale the cross section from $\gamma$-nucleon to $\gamma$-nucleus. The agreement with STARLIGHT is a bit surprising since the calculation does not include the elastic part of the total cross section, which is included in the GDL model, but a similar trend was observed by STAR at RHIC [5].
3 Coherent ψ(2S) production

Photoproduced ψ(2S) mesons can be studied in the dilepton decay channel using the ALICE triggers for ultra-peripheral collisions [2]. The trigger at midrapidity is, however, also sensitive to the decay channel \( \psi(2S) \rightarrow J/\psi + \pi^+ \pi^- \), which has a more advantageous branching ratio of 34%. These events are characterized by two hard tracks with \( p_T > 1 \text{ GeV}/c \) from the decay of the \( J/\psi \) and two soft tracks with \( p_T < 0.4 \text{ GeV}/c \) from the two pions.

The triggered events were required to have exactly 2 or 4 reconstructed tracks and a reconstructed primary vertex. The dileptons can be separated into \( e^+e^- \) or \( \mu^+\mu^- \) using the TPC dE/dx. To select coherently produced \( \psi(2S) \) a requirement \( p_T < 0.15 \) (0.30) GeV/c was applied for the decay channels containing muons (electrons).

The yield in the direct dilepton channel (\( e^+e^- \) and \( \mu^+\mu^- \) combined) was obtained by fitting the invariant mass distribution to the sum of a Crystal Ball function for the signal and an exponential for the background. The 4 track samples have a very high purity and the yield is obtained by counting the number of events within selected intervals in phase space determined from Monte Carlo simulations. The invariant mass of the dileptons are required to be within \( 3.0 \lesssim M_{inv} \lesssim 3.2 \) (2.6 \( \lesssim M_{inv} \lesssim 3.2 \)) GeV/c\(^2\) for \( \mu^+\mu^- \) (\( e^+e^- \)) to select pairs coming from a \( J/\psi \) decay. The \( \mu^+\mu^- \pi^+ \pi^- (e^+e^- \pi^+\pi^-) \) final state is required to have an invariant mass \( 3.6 \lesssim M_{inv} \lesssim 3.8 \) (3.1 \( \lesssim M_{inv} \lesssim 3.8 \)) GeV/c\(^2\) to count as a \( \psi(2S) \). This gives a total of 17 (11) events for the \( \mu^+\mu^- \pi^+ \pi^- (e^+e^- \pi^+\pi^-) \) decay channel, with a like-sign background of 1 (0) event.

The extracted yield is corrected for acceptance and efficiency using STARLIGHT events processed through the detector response simulation and reconstructed back using the same selection as for real data. The cross section is obtained from a weighted mean of the dilepton and 4-track decay channels, giving \( d\sigma/dy = 0.83 \pm 0.19(\text{stat.} + \text{sys.}) \) mb. This is compared to model predictions [6, 9, 10, 11] in Fig. 2.

The \( \psi(2S) \) is a hard probe, the scale being set by its mass, and is therefore expected to be sensitive to the nuclear gluon distribution in the same way as the \( J/\psi \). The experimental error is, however, larger for the \( \psi(2S) \) than for the \( J/\psi \) measurement, mainly because of the limited statistics. It is also important to note that the underlying \( \gamma + p \rightarrow V + p \) cross section has a considerably larger uncertainty for \( \psi(2S) \) than for \( J/\psi \). This is illustrated by the large discrepancy between the AN [9] and STARLIGHT predictions without nuclear effects in the figure. One can nevertheless conclude that the measured cross section disfavors models with no nuclear effects and models with strong gluon shadowing.

4 Two-photon production of \( e^+e^- \) pairs

Two-photon production of \( e^+e^- \) pairs has a topology similar to that of exclusive vector mesons production followed by decay into a pair of dileptons or pions. This process is of interest since the coupling between the photon and the emitting nucleus is enhanced by a factor \( Z \) (the nuclear charge). One can therefore expect higher order terms to be important. The results from ALICE on \( \gamma\gamma \rightarrow e^+e^- \) from the 2011 Pb-Pb run were, however, found to be in good agreement with STARLIGHT, which includes only the leading order QED terms [2]. Because of the requirement on azimuthal angle in
the trigger, the results from 2011 were restricted to high invariant masses, $M_{ee} > 2.2 \text{ GeV}/c^2$. The 2010 data allow to go down to $M_{ee} = 0.6 \text{ GeV}/c^2$.

The event selection was similar to that for coherent $\rho^0$ production, with the selection on the TPC $dE/dx$ modified to accept electrons rather than pions. The raw data were corrected for acceptance and efficiency using events generated by STARLIGHT. Figure 3 (left) shows the $pT$ distribution of the selected $e^+e^-$ pairs. The distribution is well described by STARLIGHT, indicating that there is no background not accounted for in the sample. The measured cross section for the selection $0.6 \leq M_{ee} \leq 2.0 \text{ GeV}/c^2$ and $|\eta_{1,2}| < 0.9$ ($\eta_{1,2}$ are the pseudorapidities of the two tracks) is $9.8 \pm 0.6(\text{stat.})^{+0.9}_{-1.3}(\text{sys.}) \text{ mb}$. The STARLIGHT prediction for the same selection is $\sigma = 9.7 \text{ mb}$. The differential cross section, $d\sigma/dM_{ee}$, is shown in Fig. 3 (right) together with the previous ALICE measurement for $M_{ee} > 2.2 \text{ GeV}/c^2$ and the cross section from STARLIGHT. The variation of $d\sigma/dM_{ee}$ with $M_{ee}$ is well described by STARLIGHT.

5 Conclusions

The ALICE Collaboration has made the first measurements of coherent $\rho^0$ and $\psi(2S)$ photoproduction in Pb-Pb collisions at the LHC. The measured cross section for the $\psi(2S)$ disfavors models with no nuclear effects and models with strong gluon shadowing. This is thus consistent with the conclusions from the $J/\psi$ measurements [1, 2] but less strong because of the larger uncertainties for $\psi(2S)$ discussed above. The results on $\rho^0$ show that a straightforward scaling of the $\gamma$-$p$ cross section using the Glauber model [3] overpredicts the cross section. This confirms what was observed in Au-Au collisions at RHIC energies. The cross section for two-photon production of $e^+e^-$ pairs at midrapidity in Pb-Pb collisions is in good agreement with leading order QED as implemented in STARLIGHT in the invariant mass range $0.6 \leq M_{ee} \leq 10.0 \text{ GeV}/c^2$.

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