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Azimuthal anisotropy from quantum interference in ρ^0 photoproduction in ultra-peripheral collisions with ALICE

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Ultra-peripheral heavy-ion collisions (UPCs) occur when the impact parameter of the collision is greater than the sum of the radii of the colliding nuclei. UPCs allow one to study photon-induced reactions, such as the photoproduction of a vector meson, which is a well-established tool to probe the gluon structure of the colliding nuclei.
We will focus on the measurement of the impact-parameter dependence of the azimuthal anisotropy in the ρ^0 meson photoproduction. The interference originates from the linear polarization of the exchanged virtual photons and from quantum interference between amplitudes contributing to the photoproduction process.
We present the results of the first measurement of this kind at the LHC, using Pb–Pb UPCs and the ALICE detectors. The anisotropy is studied via the distribution of a variable, ϕ, that is, approximately, the angle between the transverse momentum of the ρ^0 and that of one of its two decay pions. Models predict a $\cos(2\phi)$ modulation of the ρ^0 yield. The amplitude of such a modulation was measured in three impact parameter ranges, defined by event classes with different neutron emission requirements. The amplitude of the modulation is found to increase by about one order of magnitude from large to small impact parameters, in agreement with the available theoretical predictions.

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1. Introduction

Ultra-peripheral collisions (UPCs) occur when the impact parameter b of the collision is greater than the sum of the radii of the colliding nuclei. In UPCs, purely hadronic interactions are highly suppressed, allowing one to study photon-induced processes, such as vector meson photoproduction, that is a well established tool to probe the gluon structure of the colliding nuclei. In this process one of the nuclei emits a photon that fluctuates into a quark–antiquark color dipole, which interacts strongly with the other nucleus and appears as a real vector meson. The photo-nuclear interaction is coherent (incoherent), if the photon couples with the nucleus as a whole (only one nucleon).

In the coherent case, it is not known which of the nuclei emits the photon and which acts as the target in the interaction, opening up the possibility to study, at femtometer scales, the fundamental quantum mechanical interference between the amplitudes [1]. The strong force restricts the production site within one of the two nuclei, therefore this process can be seen as a double slit experiment at fm scale, where b acts as the distance between the openings of the interferometer.

The strong electromagnetic fields in UPCs of heavy ions can cause multiple photon exchanges in a single collision. These additional photons usually lead to independent electromagnetic dissociation (EMD) processes accompanying the vector meson photoproduction. EMD allows one to select different impact parameter ranges [2] by means of neutrons emitted at beam rapidity and detected using Zero Degree Calorimeters (ZDCs). UPCs can be classified as: (*i*) 0n0n, if no neutrons are detected in the ZDCs, (*ii*) Xn0n if only one of the ZDCs has neutron signal, and (*iii*) XnXn, if both ZDCs have neutron signal. The intensity of the electromagnetic field decreases with increasing impact parameter, implying that XnXn events, where at least three photons are exchanged, are dominated by relatively small impact parameters, while 0n0n by higher impact parameters.

Since the electromagnetic fields of the colliding nuclei are highly Lorentz-contracted, the exchanged photons are fully linearly polarized [3]. In Ref. [3] it has been proposed that due to the polarization the interference effect can give rise to an azimuthal anisotropy in the di-lepton production from photon-photon fusion. This effect has also been studied as a function of the impact parameter in Ref. [4], and measured for XnXn events by the STAR Collaboration [5].

These studies were later extended to the photoproduction of a ρ^0 vector meson, where the ρ^0 inherits the linear polarization of the photon. The interference correlates momentum and polarization, ensuring that the anisotropy of the decay of a spin-1 particle into two spin-less products is preserved when averaging over events with random impact parameters. This anisotropy is predicted to manifest as a $\cos(2\phi)$ asymmetry [6, 7], where ϕ is defined as the angle between the sum and the difference of the p_{T} of the pions produced in the decay $\rho^0 \to \pi^+\pi^-$. This asymmetry has been measured by the STAR Collaboration, for coherent ρ^0 photoproduction in XnXn events [8].

Here, we report the first measurement of the impact-parameter dependence of the azimuthal asymmetry in Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using the coherent photoproduction of a ρ^0 meson. The ρ^0 meson is detected through its decay into a pion pair at midrapidity.

2. Data analysis

The analyzed data were collected by ALICE in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV during the Run 2 of the LHC, using a trigger that selects events with two tracks that are almost back-to-back in

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the transverse plane [9]. The integrated luminosity of the sample is about 485 mb^{-1}. The particles were tracked using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Pions were identified using the specific energy loss in the TPC. Furthermore, V0 and AD, scintillator detectors at forward rapidity, provided veto signals to suppress hadronic interactions and the ZDCs were used to detect neutrons at beam rapidity.

The events selected for the analysis were required to have exactly two pion tracks that pass the selection criteria on TPC clusters, ITS-TPC matching and distance of closest approach to the event primary vertex reported in Ref. [9]. Kinematic selections were also applied: (*i*) the pion pair rapidity must lie in the range $|y| < 0.8$, (*ii*) the invariant mass of the pion pair must be inside the range 0.6 GeV/c^2 $< m_{\pi\pi} <$ 0.95 GeV/c^2, and (*iii*) the transverse momentum of the ρ^0 candidate must be $p_{\mathrm{T}} < 0.1$ GeV/c to select coherent processes with high purity. Using these selection criteria, the contamination from incoherent events is found to be lower than 4% [9]. More details about event and track selections can be found in Ref. [9].

The observable used to measure the azimuthal anisotropy described in Sec. 1 is the azimuth angle ϕ. It can be defined in two different ways, indicated, respectively, as *average* and *charge*. In both cases ϕ is the angle between the transverse components of $\vec{p}_+$ and $\vec{p}_-$, where $\vec{p}_\pm = \vec{\pi}_1 \pm \vec{\pi}_2$. Using the *charge* definition, $\vec{\pi}_1$ ($\vec{\pi}_2$) is the momentum of the positive (negative) track. Using the *average* definition, $\vec{\pi}_{1,2}$ are randomly associated to the positive or to the negative track.

A Monte Carlo (MC) simulation, using the STARlight [10] MC generator and a realistic description of the ALICE detector, has been used to estimate the correction for acceptance and efficiency (Acc $\times\,\epsilon$) to detect the pion pairs. This simulation describes the raw data kinematics well, except for the transverse momentum distribution. The agreement between MC and data has been improved by applying the re-weighting procedure explained in Ref. [11] to the generated p_{T}^2 spectrum. The raw invariant mass spectra of pion pairs, for each invariant mass and ϕ interval, was then corrected by the Acc $\times\,\epsilon$, evaluated using the re-weighted MC.

The corrected mass spectra, in each neutron class and in each ϕ bin, were fitted using a modified Söding model, plus a term to account for the background contribution of the $\gamma\gamma \rightarrow \mu^+\mu^-$ process. The fits were performed by fixing the pole mass and the pole width of the ρ^0 to the values reported for a ρ^0 formed in a photoproduction reaction [12]. A default strategy was chosen to extract the central value of the asymmetry parameter. In this strategy, the *average* definition of ϕ is used, and the background contribution is fixed to zero. To check the robustness of the fit procedure, the fit of the invariant mass distribution were repeated 100 times, using different binning and varying the lower (upper) limit of the fit range from 0.6 to 0.65 GeV/c^2 (0.9 to 0.95 GeV/c^2).

The extraction of the amplitude of the modulation is affected by the migration of events between neutron classes, due to detector efficiency and pile-up effects, as discussed in Ref. [9]. To take this into account, a simultaneous fit to the ρ^0 yield as a function of ϕ in all three classes (0n0n, Xn0n, XnXn) was performed, using the following expression:

$$\begin{pmatrix} n_{\rho\,\mathrm{0n0n}(\phi)} \\ n_{\rho\,\mathrm{Xn0n}(\phi)} \\ n_{\rho\,\mathrm{XnXn}(\phi)} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} w_{\,\mathrm{0n0n}\to\mathrm{0n0n}} & w_{\,\mathrm{Xn0n}\to\mathrm{0n0n}} & w_{\,\mathrm{XnXn}\to\mathrm{0n0n}} \\ w_{\,\mathrm{0n0n}\to\mathrm{Xn0n}} & w_{\,\mathrm{Xn0n}\to\mathrm{Xn0n}} & w_{\,\mathrm{XnXn}\to\mathrm{Xn0n}} \\ w_{\,\mathrm{0n0n}\to\mathrm{XnXn}} & w_{\,\mathrm{Xn0n}\to\mathrm{XnXn}} & w_{\,\mathrm{XnXn}\to\mathrm{XnXn}} \end{pmatrix} \begin{pmatrix} a_{2\,\mathrm{0n0n}} \\ a_{2\,\mathrm{Xn0n}} \\ a_{2\,\mathrm{XnXn}} \end{pmatrix} \cos(2\phi), \quad (1)$$

where $n_{\rho\,\mathrm{0n0n}}$ is the normalized ρ^0 yield in a given ϕ range for the 0n0n class, and similarly for other

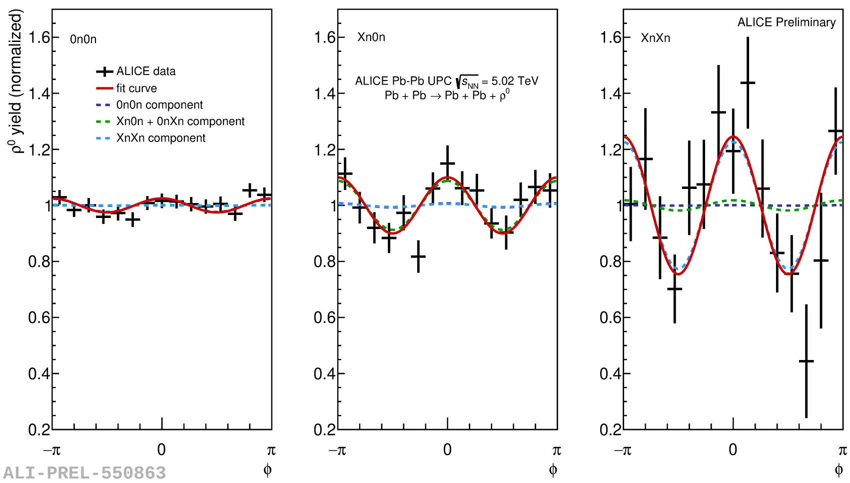

Figure 1: Example of a simultaneous fit used to extract the amplitude of the $\cos(2\phi)$ modulation in all neutron classes. The contribution of each physical class to the yield in all experimental classes is shown.

classes, and the fitting parameters $a_{2\,\mathrm{0n0n}}$, $a_{2\,\mathrm{Xn0n}}$ and $a_{2\,\mathrm{XnXn}}$ are the amplitudes of the $\cos(2\phi)$ modulation in the three classes. The coefficients $w_{\mathrm{Y}\rightarrow\mathrm{Z}}$ represent the contribution of the physical neutron class Y to the yield in the experimental neutron class Z, computed using the measured cross sections and migration probabilities [9]. The constant term is fixed to unity by normalization. This fitting procedure is repeated 100 times, on the different distributions of the ρ^0 as a function of ϕ provided by the signal extraction procedure. In each class, the central value of modulation and the statistical uncertainty have been evaluated, respectively, as the mean value of the distribution of the amplitude, and as the mean value of the distribution of the uncertainties from the fit.

The systematic uncertainties affecting the results presented here can be grouped in two categories: signal extraction and Acc $\times\,\epsilon$. The systematic uncertainty related to the signal extraction has three contributions. The first has been evaluated as the standard deviation of the distribution of the $\cos(2\phi)$ amplitudes over the 100 trials mentioned above. The second comes from using the model by Ross and Stodolsky to fit the invariant mass distributions. The third was estimated using six different strategies for the measurement of the ρ^0 yield as a function of ϕ, that consisted in using *charge* or *average* definition of ϕ, setting or not the muon background to zero in the mass fits, and, for the average mode, including or not a $\cos(\phi)$ component in Eq. 1 (such a component is mandatory for the charge mode). The systematic uncertainty on the Acc $\times\,\epsilon$ mainly arises from the re-weighting procedure.

3. Results

Figure 2 shows the extracted amplitude of the $\cos(2\phi)$ modulation as a function of the neutron class. The measured anisotropy shows a clear trend, with a significant increase, by approximately one order of magnitude, from 0n0n to XnXn, which according to the $\mathbf{n_O^On}$ event generator [13] corresponds to a variation of the median impact parameter between, approximately, 49 and 18 fm.

As discussed in Sec. 1, the $\cos(2\phi)$ anisotropy in the model emerges from the presence of two elements: (*i*) the photon is linearly polarized along the impact parameter and this polarization is

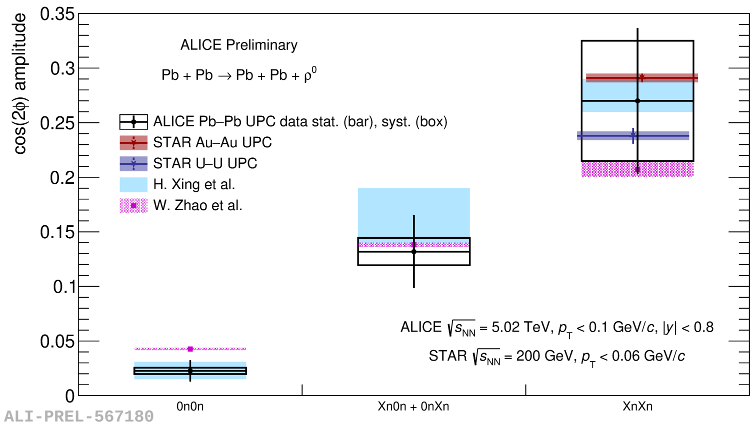

Figure 2: Amplitudes of the $\cos(2\phi)$ modulation of the ρ^0 yield as a function of the neutron class, compared with the Xing *et al.* [6] and W. Zhao *et al.* [7] model predictions and, for XnXn, with the STAR results [8].

transferred to the produced vector meson, (*ii*) the two amplitudes that contribute to the cross section of the vector meson photoproduction process interfere.

The results are compared with the models by H. Xing *et al.* [6] and by W. Zhao *et al.* [7]. In both models, the quasi-real photon exchanged by the nuclei is treated as a color quark–antiquark dipole, that recombines to produce a ρ^0 after scattering off the color glass condensate state inside the nuclei, although this is implemented differently in the two models. Both models describe the data well, with the possible exception of the 0n0n class for the model by W. Zhao *et al.*.

For the XnXn class, the ALICE result is also compared with the ones from the STAR Collaboration [8], for Au–Au and U–U collisions at a lower center-of-mass energy of $\sqrt{s_{\rm NN}} = 200$ GeV and $\sqrt{s_{\rm NN}} = 193$ GeV, respectively. The amplitude measured by ALICE is compatible with both STAR results. This is consistent with the models, which predict the $\cos(2\phi)$ modulation amplitude to vary with the colliding nuclei and the center-of-mass energy by less than the current experimental uncertainties.

4. Conclusions and outlook

The first measurement of the impact-parameter dependence of the modulation of the ρ^0 yield with the ϕ angle in coherent photoproduction processes from Pb–Pb ultraperipheral collisions at a center-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV has been presented. A significant impact-parameter dependence of the anisotropy strength was observed, with the amplitude of the $\cos(2\phi)$ modulation increasing by about one order of magnitude from large to small median impact parameters. This trend is well reproduced by the theoretical models [6, 7]. The results for the XnXn class are compatible with those, by the STAR Collaboration, for Au–Au and U–U collisions at RHIC [8].

The large amount of data that will be collected by ALICE during Run 3 and 4 of the LHC will allow one to constrain the models and will enable a more detailed characterization of the quantum interference effects, by means of more differential studies. It will be also possible to study similar effects in other processes, such as in the coherent photoproduction of the J/ψ, and in other colliding systems.

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