# OVERVIEW OF THE LATEST ALICE UPC AND PHOTONUCLEAR RESULTS*

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Ultra-peripheral collisions (UPC) are events characterised by large impact parameters between the two projectiles, larger than the sum of their radii. In UPCs, the protons and ions accelerated by the LHC do not interact via strong interaction and can be regarded as sources of quasi-real photons. Using the Run 2 data, the ALICE Collaboration has carried out various measurements of different final-state systems, such as exclusive four-pion photoproduction as well as photoproduction of $K^+K^-$ pairs, measured for the first time in ultra-peripheral collisions. In addition, vector-meson production in Pb–Pb provides the unique opportunity to carry out an analogy of the double-slit experiment at femtometre scales, owing to the interference between the production sources of the two lead nuclei. These results and prospects for UPC measurements using Run 3 data will be presented.

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## 1. Introduction

Vector-meson photoproduction in $p$–Pb and Pb–Pb ultra-peripheral collisions (UPCs) [1] is being actively studied at the CERN LHC. In these events, a photon from one of the two nuclei interacts with the other nucleus through the exchange of a colourless object, resulting in the production of a vector meson. The ALICE Collaboration has studied $J/\psi$ [2, 3], $\psi'$, $\rho^0$ [4], $K^+K^-$ [5], and more light vector-meson photoproduction. The interest in these processes is growing since they shed light on nuclear shadowing, gluon saturation, and more recently gluonic hotspots, and their dependence on energy [6, 7].

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## 2. ALICE results using Run 2 (2015–2018) data

ALICE has recently presented results for exclusive charged $4\pi$ photoproduction [8]. The $4\pi$ invariant mass distribution is fitted using either a single Breit–Wigner or a combination of contributions representing excited $\rho^0$ states, *i.e.* $\rho(1450)$ and $\rho(1700)$. The cross sections are compared to theoretical models [9] and are shown in Fig. 1. The computation for the combination of $\rho(1450)$ and $\rho(1700)$ (upper panel) is in better agreement with the data. The exclusive $K^+K^-$ photoproduction results [5] show

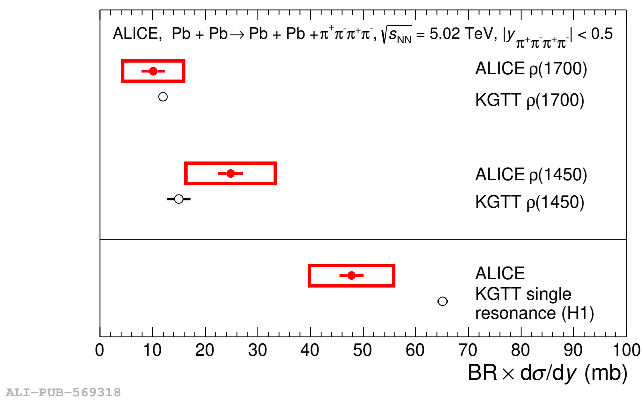


Fig. 1. Comparison of the $\rho(1450)$ and $\rho(1700)$ cross sections (upper panel), and single-resonance cross section (lower panel), as extracted from the fits to the invariant-mass distribution of exclusive $4\pi$ production [8] and comparison with the theoretical predictions for a one- and two-resonance model [9].

that the sample is a cocktail of resonant and non-resonant contributions, as shown in Fig. 2. The $K^+K^-$ invariant mass distribution is measured for states above 1.1 GeV$/c^2$, away from the $\phi(1020)$ peak — a clear sign that the energy loss in the tracking material is too significant for the decay kaons from the $\phi(1020)$ to be able to reach the Time Projection Chamber (TPC) using the Inner Tracking System (ITS) that was installed in ALICE during Runs 1 and 2. A new ITS was installed during the Long Shutdown 2 [10], with reduced material budget and higher precision.

The ALICE Collaboration has also recently provided new results concerning the impact-parameter-dependent azimuthal anisotropy in UPCs, which was measured in coherent $\rho^0$ production [11]. The results are shown in Fig. 3. The amplitude $a_2$ of the modulation increases as the impact parameter becomes smaller, which is achieved in UPCs by separating the data set in neutron emission classes [12]. From the $0n0n$ to the $XnXn$ class, the impact parameters lower from a median of about 49 fm to about 18 fm [11, 13].

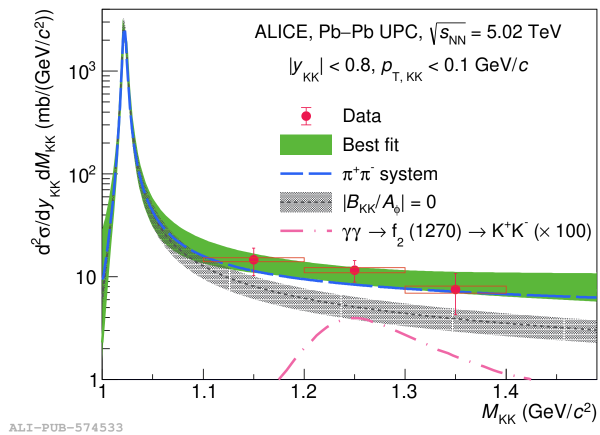


Fig. 2. Cross sections for $K^+K^-$ photoproduction as a function of the $K^+K^-$ invariant mass as measured by ALICE [5]. The data are compatible with a cocktail of resonant and non-resonant contributions.

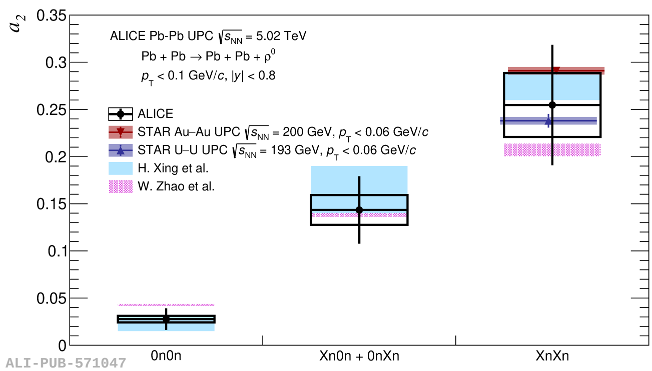


Fig. 3. Impact-parameter-dependent azimuthal anisotropy measured in coherent $\rho^0$ photoproduction [11]. The amplitude $a_2$ of the modulation increases as the impact parameter becomes smaller.

## 3. ALICE future opportunities using Run 3 and Run 4 data

In Run 3 (2022–2026) and Run 4 (starting in 2030), ALICE will collect significantly higher amounts of data [14], also in previously inaccessible rapidity regions, owing to the installation of new detectors, *i.e.* Muon Forward Tracker (MFT) in Run 3 and Forward Calorimeter (FoCal) in Run 4. The effects of the introduction of a continuous readout are particularly evident using UPC selections. While in Run 2 the sample contained about fifty thousand $\pi^+\pi^-$ candidates in the invariant-mass region of the $\rho^0$, as shown in Fig. 4 (a), which were used in [4] and [11], the data set collected in Run 3 is already an order of magnitude larger in a similar invariant-mass region with UPC selections, as shown in Fig. 4 (b). More precise and even more (multi-)differential measurements are expected with the new data sample. In

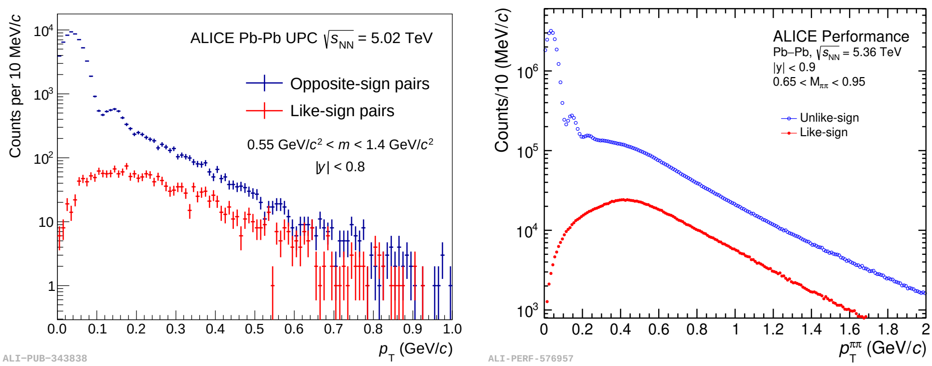


Fig. 4. Transverse-momentum distribution of $\pi\pi$ pairs selected in Run 2 (left panel) [4] and Run 3 (right panel) for UPC measurements in ALICE.

addition, the increased acceptance brought by the addition of MFT and FoCal will allow for the access to observables that are expected to significantly contribute to the observation of the onset of the gluon saturation regime, as described in [15]. FoCal, which will be installed during Long Shutdown 3, will provide sensitivity to charmonia through their decay to dielectrons, as shown in Fig. 5. This figure is an ALICE simulation produced using events

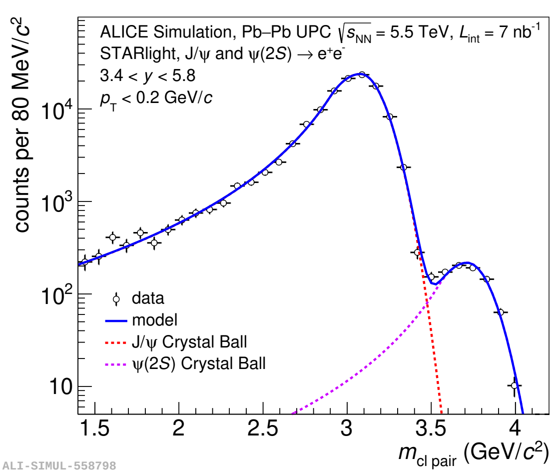


Fig. 5. ALICE simulations using STARlight [16] showing the potential of FoCal to measure photoproduced charmonia decaying into dielectrons.

from STARlight [16], where the $J/\psi$ and $\psi'$ peaks are clearly visible. Finally, the ALICE detector in Runs 3 and 4 should be able to collect enough statistics to measure *e.g.* light-by-light scattering [17, 18], $\gamma\gamma \to \gamma\gamma$, and the anomalous magnetic moment in the tau sector [19], $\gamma\gamma \to \tau\tau$, allowing for measurements beyond the Standard Model with implications for axion-like particles (ALPs) [17] and SUSY [19]. New opportunities will also arise through the usage of machine learning in UPCs, such as anomaly detection through autoencoders for the detection of exotic hadrons such as tetraquarks [20] and pentaquarks, as described in [21].

## 4. Conclusions

The UPC program in ALICE brought about interesting new results, which cover a large range of phenomena, such as nuclear shadowing, gluon saturation, and gluonic hotspots. The most recent measurements were however limited by their statistical uncertainty. The new incoming Runs 3 and 4 data sets will provide abundant amounts of high-quality data, allowing for more differential measurements. These large data sets will also permit the measurement of the $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to \tau\tau$ processes in ALICE, giving prospects for investigation of theories beyond the Standard Model. The new detectors, *i.e.* MFT and FoCal in Runs 3 and 4, respectively, will in addition allow for the access to new and exciting rapidity regions.

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