Phys. Proc. Ultra-Peripheral Collisions **2**, 017 (2026) 1-8

EXPERIMENTAL OVERVIEW ON UPCs RESULTS FROM ALICE

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The ALICE Collaboration has extensively studied neutron and proton emission in various electromagnetic dissociation classes of Pb ions, coherent and incoherent J/ψ photoproduction, as well as coherent ρ^0 photoproduction using the Run 2 data set, including results from the $|t|$-dependence of (in)coherent J/ψ. These measurements, which studied exclusive charmonia photoproduction as a function of e.g. energy, Bjorken-x, rapidity, and neutron emission, provide unique insights into the initial state of protons and ions, with great sensitivity for both gluon saturation and shadowing. The ALICE Collaboration has also carried out various measurements of different final state systems, such as exclusive four pion photoproduction as well as the measurement of the impact-parameter dependence of coherent production. Run 3 data opened a new area for inclusive measurements in UPCs, where π, $K^{\pm}$, K^0_S, D^0 meson and p, Λ baryon fully corrected spectra are extensively studied. On top of that, rare processes like τ pair production are shown. Finally, the prospects for these and new measurements using the Run 3 and Run 4 data are discussed.

DOI: https://doi.org/10.17161/wrvgtb51
Keywords: photoproduction, UPCs, gluon shadowing, gluon saturation, BSM

1 Introduction

There is a very broad program of heavy ion collision at the ALICE experiment [1] at the LHC. Among various classes of collisions, there are ultraperipheral collisions (UPCs) where the impact parameter (IP) is larger than the sum of radii of colliding ions. When IP is large hadronic processes are suppressed. An charged ion which is moving is surrounded by a cloud of photons. The photon cloud can be interpreted as photon flux and described by Weitzsacker-Williams approximation [2]. Due to that fact the cross section of photon induced processes in heavy-ion collisions is enhanced (by factor Z^2 for each ion which emits a photon, and $Z_{\mathrm{Pb}} = 82$ for lead) when compared to proton-proton collisions. There are several classes of processes with interacting photons. Processes with no color exchange (a single or mutual dissociation, an (in)coherent photoproduction, a double photon exchange, etc.) are so called exclusive processes. Processes with a color exchange (a direct or a resolved production) are inclusive processes.

A couple of variables which are used in further studies need to be defined. There is photon-target centre-of-mass energy $W^2_{\gamma^*\mathrm{Pb}} = 2E_{\mathrm{Pb}}M_{\mathrm{VM}}e^{\pm y}$, where E_{Pb} is a Pb ion energy, M_{VM} is a vector meson (VM) mass and y is a VM rapidity. The reason behind two solutions ($\pm y$) comes from the fact that there are two indistinguishable ions which act as photon emitters and targets. The two-fold ambiguity between high- ($+y$) and low- ($-y$) energy of the photon-target interaction arises with a rapidity different from zero. There is $x_{\mathrm{B}} = M_{\mathrm{VM}}/\sqrt{s_{\mathrm{NN}}}e^{\mp y}$, the fraction of longitudinal momentum of a proton, and finally Mandelstam $|t|$ proportional to VM p^2_{T}.

The coherent photoproduction cross section of J/ψ meson is sensitive to gluon density evolution and constrains gluon shadowing [3]. The Mandelstam-$|t|$ dependence of cross section allows for constraining transverse gluonic structure and is sensitive to the gluon saturation [4]. Additionally, the clean environment which is provided in UPCs gives a possibility to study new resonances, like excited ρ states.

The inclusive measurements give the possibility to study collective behavior in a small system (γ-Pb). Collectivity used to be one of signatures of the quark-gluon plasma (QGP) in very central heavy ion collisions. The recent discoveries show the collective behavior in smaller systems, like in p-Pb collisions or high multiplicity pp. The possibility to measure different particle spectra will allow us to extract mean particle transverse momentum $\langle p_{\mathrm{T}} \rangle$ which can be transformed to the speed of sound in the medium, which drives the collective expansion. Having spectra of a composite particles one can calculate particle yield ratios which lead to meson-to-baryon anomaly, yet an other observable used in QGP searches. Finally, the strangeness enhancement was investigated as the next QGP observable.

The inclusive measurements of heavy quarks, like open charm, give besides an access to a broad range of probed Q^2, an access to searches of saturation scale and probe gluon PDFs in a broad range.

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The electroweak sector, accessible via τ lepton pair production, gives the access to the new physics searches, due to the quantum corrections to the vertex.

2 ALICE Detector

The ALICE detector [1] provides excellent tracking. Charged particles like $e^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$, $p^{\pm}$, $K^{\pm}$ can be reconstructed in the the central region ($|\eta| < 0.9$) in the Inner Tracking System (ITS)[b], the Time Projection Chamber (TPC)[c] and the Time of Flight (TOF). Additionally, the Muon Arm allows for the muon identification in the forward region ($-4 < \eta < -2.5$). The two arrays of quartz Cherenkov counters which T0 detector is made of are responsible for event timing and luminosity measurement, and covered $4.6 < \eta < 4.9$ and $-3.3 < \eta < -3.0$. The detector emptiness is assured by the V0 and AD diffractive detectors. The V0 detector covered $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, while the AD one covered $4.8 < \eta < 6.3$ and $-7.0 < \eta < -4.9$ in Run 2. V0, AD and T0 detectors were integrated into the Fast Interaction Trigger (FIT) and upgraded for the Run 3. In Run 3, FV0 covers $2.2 < \eta < 5.1$, FT0 covers $3.5 < \eta < 4.9$ and $-3.3 < \eta < -2.1$. The Zero Degree Calorimeter (ZDC) provides an information about any neutron detected in the forward direction ($|\eta| > 8.8$). Both exclusive VM and inclusive particle photoproduction cross section measurements may be done for different nuclear breakup class (0n0n - no neutron detected on either side, XnXn - at least one neutron detected on each side, 0nXn or Xn0n - at least one neutron detected on one side while none detected on the other side). Besides the detector and electronics upgrades, ALICE has changed the Data Acquisition System from triggered to streaming readout, which allows for much larger data collection in terms of available statistics.

3 Results

In the following section both published analyses from Run 2 and preliminary results from Run 3 are presented.

Proton emission in EMD of ^{208}Pb

A dominant process in relativistic heavy ion collisions is caused by interaction of low energy photons. The exchanged photon can excite the nuclei and cause its electromagnetic dissociation (EMD) as described in the RELDIS model [5]. The EMD leads to the emission of one or two neutrons from heavy nuclei. When a higher energy photon is exchanged besides neutrons a proton may be emitted. The ALICE experiment can measure EMD neutrons and protons thanks to the excellent performance of ZDC. The ALICE collaboration has measured the cross sections for one, two, and three protons emission (1p, 2p, and 3p) accompanied by at least one neutron in EMD in ultraperipheral Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [6]. These cross sections are associated with the production of Tl, Hg, and Au nuclei, respectively. The measured cross sections are shown in Fig. 1.

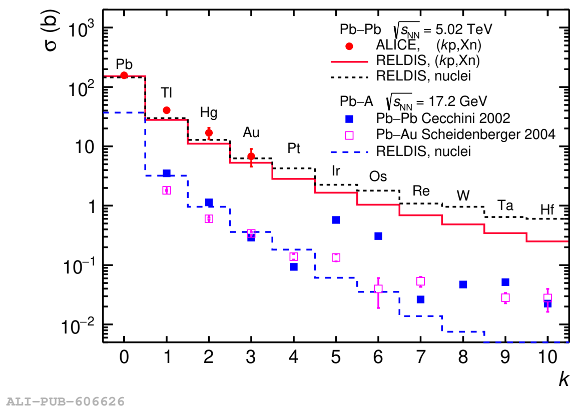

Figure 1 – The cross section of the emission of a given number of protons k accompanied by at least one neutron in UPCs of Pb-Pb nuclei at $\sqrt{s_{\rm NN}} = 5.02$ TeV compared to the RELDIS model and lower energy collisions [6].

[b] During Run 2 ITS consisted of two pixel, two drift and two strip layers of silicon. It was replaced by a brand new ITS2, which consists of seven silicon pixel layers for Run 3.

[c] The TPC has been upgraded from the Multi Wire Proportional Chamber readout in Run 2 to the GEM readout in Run 3.

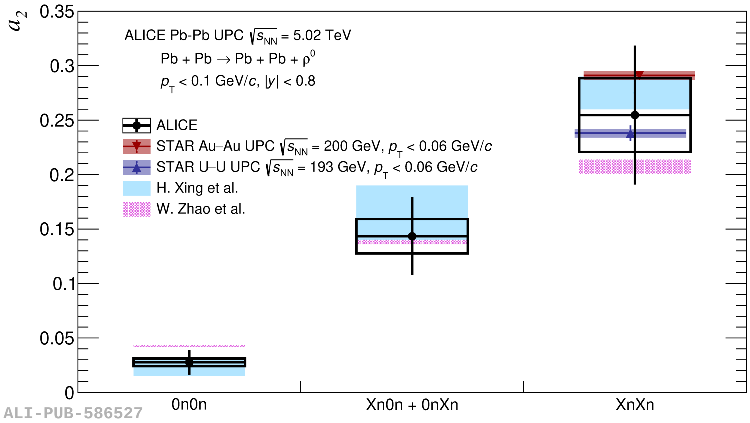

Figure 2 – Amplitudes of $\cos(2\phi)$ modulations of ρ^0 meson yield in UPCs of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV in 0n0n, Xn0n+0nXn and XnXn EMD classes compared to model predictions and RHIC data [10].

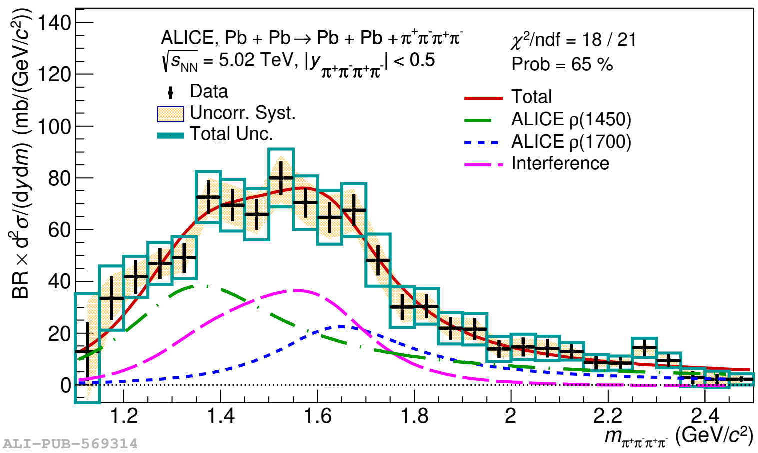

Figure 3 – The corrected coherently produced four pion invariant mass in UPCs of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV fitted with two resonance with an interference models [11].

Angular anisotropy of coherently photoproduced ρ^0 mesons
The ALICE experiment has studied ρ^0 meson photoproduction in ultraperipheral Pb-Pb collisions during Run 1 [7] and Run2 [8] and in Xe-Xe collisions [9]. The available statistics allowed for the first measurement of azimuthal anisotropy of coherently produced ρ^0 mesons in neutron break-up classes [10]. The ρ^0 mesons were reconstructed from oppositely charged pion pairs. The anisotropy refers to the $\cos(2\phi)$ amplitude modulation, where ϕ is the angle bethween a sum and a difference of vector transverse momentum of two pions. Amplitudes of $\cos(2\phi)$ modulations of ρ^0 meson yield in UPCs of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV in 0n0n, Xn0n+0nXn and XnXn EMD classes are shown in Fig. 2. There is a clear magnitude increase as the impact parameter decreases (0n0n means the largest average IP, XnXn - the smallest one). The comparisons with models confirms that anisotropy comes from linearly polarized photons and the quantum interference effect. However, the current statistical uncertainties prevent scientists from constraining models. There is a good agreement with RHIC data.

Exclusive four pion photoproduction
Due to the very clean environment in UPCs, the ALICE collaboration studied coherent photoproduction of four pions [11]. Among many possible scenarios, two of them were seriously considered. The invariant mass of four pions was parameterized by a single resonance $\rho(1450)$ and by two resonances $\rho(1450)$ and $\rho(1700)$ with the interference term (see Fig. 3). The single resonance scenario is disfavored by fit, while double resonance one is favored.

Coherent J/ψ polarization
The ALICE collaboration has measured coherently and incoherently photoproduced J/ψ mesons in a central and forward region, and at various center-of-mass energies, and in several variables [12,13,14,15,16,17].

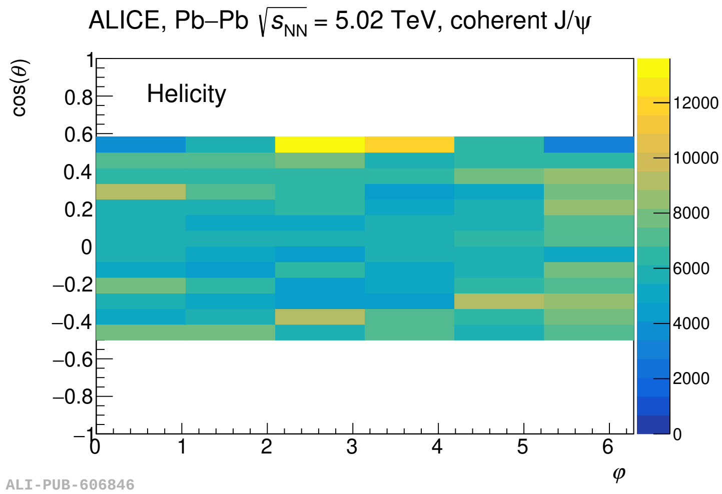

Figure 4 – Two-dimensional angular distribution of coherent J/ψ candidates in the helicity frame, after being unfolded in ϕ and corrected for acceptance and efficiency in $\cos\theta$ [19].

The method of J/ψ meson polarization measurement, exploited in pp collisions (see i.e. [18]) allowed for the first polarization measurement in UPCs at the LHC [19]. The coherently photoproduced J/ψ mesons were reconstructed in a forward region from a pair of oppositely charged muons. Two-dimensional angular distribution of J/ψ candidates in the helicity frame, after being unfolded in ϕ and corrected for acceptance and efficiency in $\cos\theta$ (see Fig. 4) has been fitted with a function

$$W(\cos\theta,\phi) = \frac{1}{3+\lambda_\theta}[1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi], \tag{1}$$

where λ_ϕ, λ_θ and $\lambda_{\theta\phi}$ are polarization parameters. The measured parameters $\lambda_\theta = 0.93 \pm 0.05 \pm 0.22$, $\lambda_\phi = 0.03 \pm 0.04 \pm 0.02$ and $\lambda_{\theta\phi} = 0.10 \pm 0.09 \pm 0.06$ are consistent with transversely polarized J/ψ. It can be further stated that vector meson keeps the polarization of the photon, so polarization parameters are consistent with the s-channel helicity conservation hypothesis.

Incoherent J/ψ suppression

Single differential t-dependent coherent [16] and incoherent [17] J/ψ photoproduction cross section spectra show the importance of subnucleon fluctuations. While the energy dependent coherent J/ψ photoproduction nuclear suppression factor shows suppression of order ~ 0.5 at high energy (~ 800 GeV) [20], and shows the importance of the gluon shadowing and the saturation. Recently, ALICE has shown the evidence for J/ψ suppression in incoherent photonuclear production [21] in a double differential measurement in y and t bins (see Fig. 5). There is a flattening in the energy dependence of the cross section observed with a rising t interval. The ratio of cross section for lowest and highest t interval shows a significant suppression ($> 3\sigma$) of ~ 0.52 for the highest energy bin. The shadowing based model is disfavored by data (gluon shadowing is energy independent in this model), while gluon saturation plays a significant role as smaller spatial scales are probed.

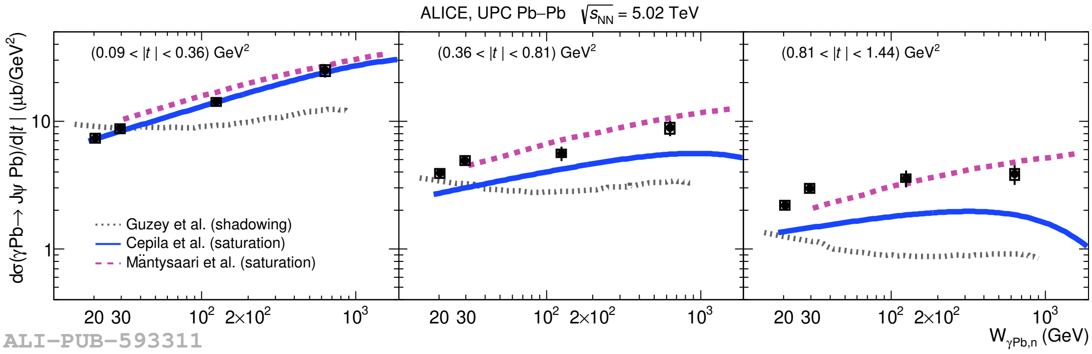

Figure 5 – The energy dependence of the cross section of incoherent J/ψ photonuclear production off lead nuclei shown for three ranges of the Mandelstam-t variable and compared with model predictions [21].

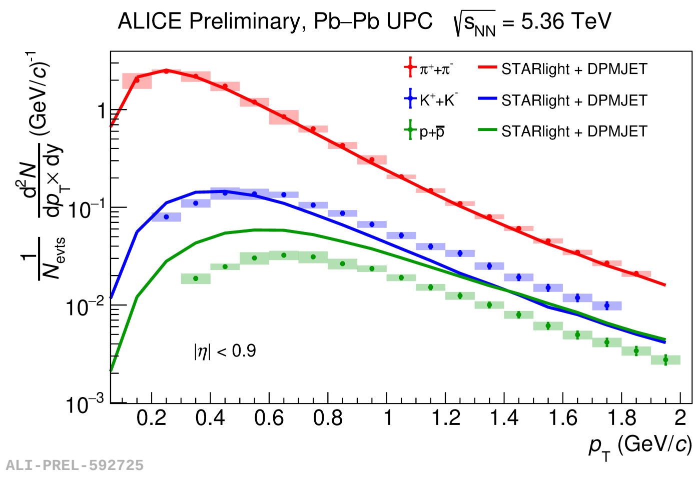

Figure 6 – Fully corrected π, K, p spectra measured in the inclusive photonuclear reactions in UPCs of Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV compared to STARlight and DPMJET Monte Carlo predictions.

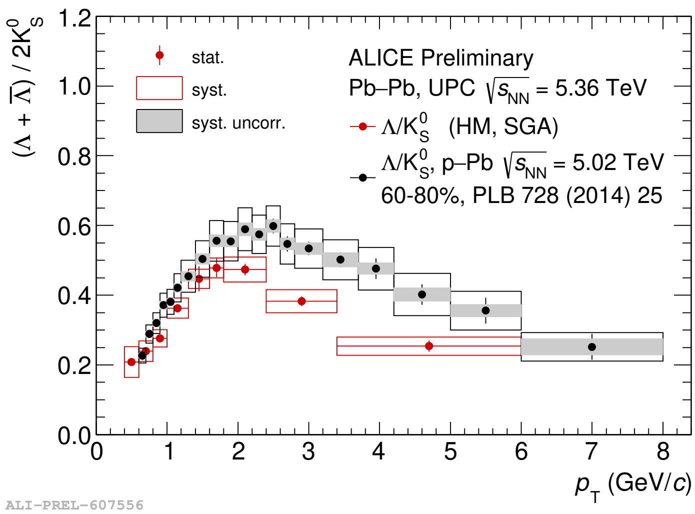

Figure 7 – The baryon-to-meson ratio p_{T} spectrum measured in the inclusive photonuclear reactions in UPCs of Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV compared to the similar spectrum measured in low multiplicity p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [24].

Inclusive π, K, p spectra
Based on Run 3 data from 2023 ALICE has started to explore the new area of inclusive photonuclear measurements. The ALICE collaboration has measured for the first time fully corrected π, K, p yields in the inclusive photonuclear reactions thanks to the excellent capabilities of TPC and TOF detectors which allowed for a particle identification in the range up to $p_{\mathrm{T}} = 2$ GeV/c. The π, K, p spectra are shown in Fig. 6. The results are compared to STARlight [22] (provides photon flux) and DPMJET [23] (provides nuclear breakup) MC predictions. The predictions for charged pions agree with data, while kaons are under-predicted, and baryons are over-predicted.

Inclusive strangeness photoproduction
The ALICE collaboration has measured Λ baryon and K^0_{S} meson spectra in a broad range $0.6 < p_{\mathrm{T}} < 8$ GeV/c in inclusive photonuclear reactions in UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV. The measured particle spectra allowed for the extraction of the yield ratio spectrum, $(\Lambda + \bar{\Lambda})/2K^0_{\mathrm{S}}$, which is shown in Fig. 7. The baryon-to-meson ratio shows an enhancement around $p_{\mathrm{T}} = 2$ GeV/c. Both the shape and the position of maximum are similar to the ones in the ratio in low multiplicity p-Pb collisions [24]. The result can bring a new insight into the collective phenomena observed in $\gamma - Pb$ reactions. There is a caveat, that photon can fluctuate into a vector meson, so effectively reaction remains as hadron-Pb and is governed as described by the Vector Meson Dominance model.

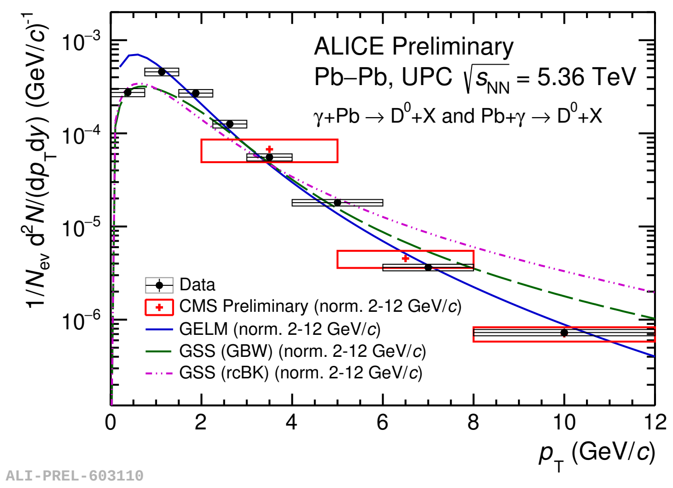

Figure 8 – The D^0 meson spectrum measured in inclusive photonuclear reactions in UPCs of Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV compared to CMS result [25] and CGC based model predictions, GELM [26] and GSS [27].

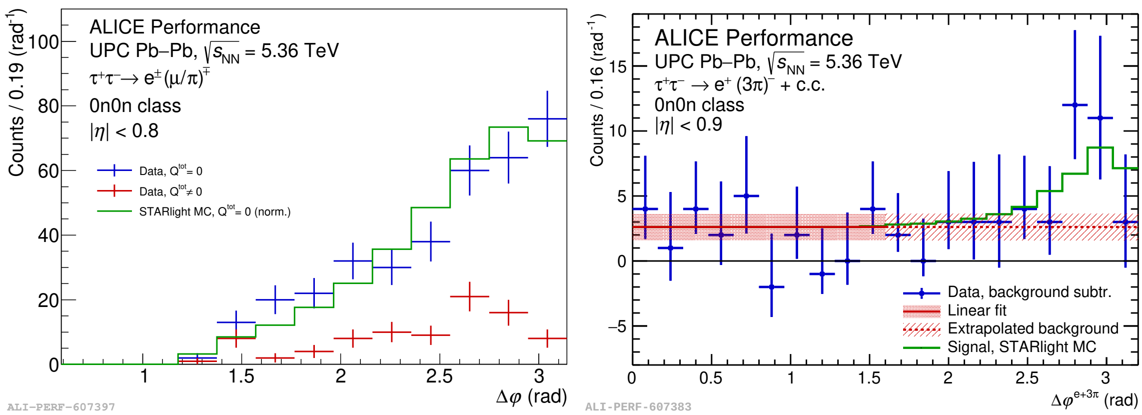

Figure 9 – The angle between systems of charged particles coming from decay of two τ leptons in $e + \mu/\pi$ topology (left hand-side) and $e + 3\pi$ topology (right hand-side). Results are compared to STARlight MC predictions.

Inclusive open charm photoproduction

The ALICE Collaboration has measured D^0 mesons in inclusive photonuclear reactions in UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV. The $D^0 \to K\pi$ p_{T} spectrum has been measured down to $p_{\mathrm{T}} = 0$, which allowed for mean p_{T} extraction. The D^0 meson spectrum is shown in Fig. 8. It agrees with CMS results [25] and extends them. The result is compared to CGC based models: GELM [26] and GSS [27]. GELM model reproduces the shape of spectrum above $p_{\mathrm{T}} = 1$ GeV/c, but no model reproduces the mean p_{T}.

Exclusive τ pair production

The ALICE experiment benefited from streaming readout and accumulated large statistics of Pb–Pb UPCs. For the first time ALICE was able to reconstruct τ pair production events in Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV. The following event topologies have been studied: $1+1$ prong (both τs decay to $e^{\pm}$ or one τ decays to $e^{\pm}$ and the other to $\mu^{\pm}$ or $\pi^{\pm}$) and $1+3$ prongs (one τ decays to $e^{\pm}$ and other to 3π). Both electrons ($e^{\pm}$) and μ/π candidates have been identified in TPC and TOF detectors. The charged descendants of τ leptons should be roughly in back-to-back topology and have total charge, Q_{tot} equal to zero. The events with $Q_{\mathrm{tot}} \neq 0$ have sign of a combinatorial background and should be subtracted from events selected with $Q_{\mathrm{tot}} = 0$. The coherent component and other lepton pair production are reduced by imposing a requirement on p_{T} of system. In 1+3 topology additional requirement on invariant mass of 3π system, $M^{3\pi} < 1.8$ GeV/c^2 reduces combinatorial background. Additional requirement of 0n0n class reduces hadronic contamination. The results of τ lepton pair production analysis in e+μ/π and $e + 3\pi$ topologies are shown in Fig. 9.

4 Summary and outlook

ALICE has extensively studied UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV during Run 2. ALICE has measured cross sections of one, two and three proton emission in EMD of ^{208}Pb, which was associated with production of Tl, Hg, and Au nuclei, respectively. The data on the angular anisotropy of coherently photoproduced ρ^0 mesons shows increase of the amplitude with decreasing impact parameter. The behavior is well described by models containing the quantum interference effect and linearly polarized photons. The clean UPCs environment allowed for deep studies of coherent photoproduction of four charged pions in a final state. The ALICE collaboration has measured polarization of coherently photoproduced J/ψ and confirmed its transverse polarization, which is inherited after the photon. The incoherent J/ψ photoproduction shows a significant suppression of the cross section for the largest photonuclear energy at the largest Mandelstam-t interval, and signals the huge importance of the gluon saturation. Although, results were conclusive the more statistics gathered in Run 3 will allow for more precise measurements with decreased uncertainties.

Thanks to the streaming and mainly trigger-less readout in Run 3 ALICE opened a new area for inclusive measurements. The inclusively photoproduced spectra of π, K, p, Λ, K^0_{S} and D^0 have been shown. Besides the constraints on the gluon distribution function, the collectivity phenomena was probed in γ-Pb reactions. The Λ to K^0_{S} yields ratio shows the baryon-to-meson anomaly like in quark gluon plasma searches in Pb-Pb collisions. The D^0 spectrum allowed for mean p_{T} extraction and constraints on CGC models.

The large statistics in Run 3 allows for studies of two-photon processes like τ lepton pair production. Currently, 1+1 ($e+e$, $e+\mu/\pi$) and 1+3 ($e+3\pi$) prong τ leptons decay topologies are considered. The excess over combinatorial background is visible in the azimuth angle between τ lepton decay products, and is consistent with signal MC. It will help with constraints on the τ anomalous magnetic moment.

During Long Shutdown 3 ALICE detector will be upgraded. ALICE plans to install the electromagnetic and hadron Forward Calorimeter, FoCal [28]. It will be located 7 m away from the interaction point, and covers pseudorapidity range $3.2 < \eta < 5.8$. FoCal will be able to measure direct photons at forward rapidities, which probes the gluon distribution in protons and nuclei at small Bjorken-x. Additionally, the exclusive measurements of J/ψ in UPC of Pb-Pb and p-Pb may explore the dynamics of hadronic matter and the nature of QCD evolution down to $x_{\mathrm{B}} \sim 10^{-6}$.

Acknowledgments

The authors would like to thank the Ministry of Science and Higher Education, Poland for the supporting grant 2022/WK/01.

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