PROCEEDINGS OF SCIENCE

First study of initial gluonic fluctuations using UPCs with ALICE

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Incoherent photoproduction is sensitive to fluctuations in the gluon structure of the target. Thus, the photoproduction measurement off colliding hadrons sheds light on QCD at high energies and provides important constraints on the initial conditions used in hydrodynamical models of heavy-ion collisions. In this contribution, the first measurement of the transverse momentum dependence of both coherent and incoherent photoproduction in ultra-peripheral collisions (UPCs) of lead ions at mid-rapidity is presented. These new results provide, for the first time, an indication of subnucleonic fluctuations in the color structure of lead ions. Recent results on the energy dependence of photoproduction with proton dissociation in proton–lead UPCs are also shown, measured for the first time at a hadron collider.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

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PoS(DIS2024)103

1. Introduction

In quantum chromodynamics (QCD), the quark and gluon content of hadrons is expressed in terms of parton distribution functions (PDFs), which evolve with the energy of the probe. This energy is inversely proportional to the Bjorken-x of the colliding parton. In high-energy QCD [1], the gluon PDF in particular exhibits a rapid increase with decreasing x and is predicted to become so large that gluon splitting is balanced by recombination, thus creating a dynamic equilibrium known as gluon saturation. For protons and neutrons bound in nuclei, saturation is expected to set in at higher x due to the influence of the nuclear environment on the PDFs, making heavy-ion colliders a promising experimental facility for studying the onset of gluon saturation.

2. Diffractive vector meson photoproduction in ultra-peripheral collisions

Ultra-peripheral collisions (UPCs) of heavy ions at hadron colliders such as the LHC provide a unique opportunity to measure cross sections of processes sensitive to hadron structure [2]. In UPCs, nuclei collide with an impact parameter b larger than the sum of their radii, $b > R_1 + R_2$. This condition ensures that hadronic interactions are suppressed, so the physics processes are mainly induced by photons emitted by at least one of the participating nuclei. An example of a prominent UPC process is diffractive photoproduction of vector mesons, which is often depicted in the color dipole picture. In this framework, the emitted photon fluctuates into a quark–antiquark pair, which scatters off the target nucleus and a vector meson is produced as a result of the interaction. The photonuclear cross section $\sigma_{\gamma A}$, which describes the strong interaction between the dipole and the target nucleus A, is then sensitive to gluon PDF in the target.

Many recent UPC measurements with the ALICE experiment [3] have focused on J/ψ photoproduction, since this meson can be reconstructed with high precision with the ALICE detectors and its large mass guarantees the applicability of perturbative QCD in theoretical calculations. While the Bjorken-x of the colliding parton is related to the J/ψ rapidity y, the four-momentum transferred in the target vertex, the Mandelstam t, is linked to the square of the J/ψ transverse momentum, $t \approx -p_{\mathrm{T}}^2$. The relation is only approximate due to the photon momentum contribution, which may be negligible under certain conditions.

In coherent photoproduction, the photon couples coherently with all nucleons in the target nucleus and the four-momentum transfer is rather small, for Pb nuclei typically $|t| \lesssim 0.01$ GeV^2. On the other hand, if the photon interacts with a single nucleon, called incoherent production, it is about an order of magnitude larger, $|t| \sim 0.1$ GeV^2. Such an interaction leaves the nucleus excited and is often followed by nuclear breakup. A larger value of $|t|$ is reached when the photon scatters from smaller, subnucleon-sized objects, then the target nucleon dissociates and $|t| \sim 1$ GeV^2. Since the impact parameter b and the J/ψ transverse momentum p_{T} are Fourier conjugates, the measured dependence of the photonuclear cross section $\sigma_{\gamma\mathrm{Pb}}$ on $|t|$ is related to the color distribution in the transverse plane via a Fourier transform. Within the Good–Walker approach [4], the $|t|$-dependence of the coherent photonuclear cross section is sensitive to the mean of the transverse spatial gluon distribution in the target, while the incoherent process is sensitive to its variance [5].

3. Dependence of J/ψ photoproduction at mid-rapidity on Mandelstam $|t|$

Using data from Pb–Pb UPCs at $\sqrt{s_{\rm NN}}$ = 5.02 TeV collected during Run 2 (2015–2018) of the LHC, ALICE performed the first measurement of the dependence of the coherent and incoherent cross sections for J/ψ photonuclear production on $|t|$ [6, 7]. In both analyses, J/ψ mesons were reconstructed in the mid-rapidity range $|y| < 0.8$, which corresponds to the Bjorken-x interval of $(0.3, 1.4) \times 10^{-3}$.

J/ψ decays into muon pairs were analyzed. Tracking and vertex reconstruction were performed by the main central-barrel detectors: the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). The TPC was also responsible for particle identification by measuring specific energy losses. In addition, the Time-Of-Flight (TOF) detector and the two innermost layers of the ITS provided inputs to a central UPC trigger. The trigger also relies on inputs from the V0 and ALICE Diffractive (AD) detectors, which are pairs of forward scintillation counters. In UPC studies, these detectors are used to reject hadronic activity, thereby ensuring that the two lepton tracks resulting from the J/ψ decay are the only tracks present in an otherwise empty detector.

The cross section for coherent J/ψ production was measured in six $p_{\rm T}$ intervals in the range $p_{\rm T} < 0.11$ GeV/c. A fit to the invariant mass distribution was performed in each interval to extract the yields of J/ψ candidates; in total about 3000 J/ψ candidates were found. The raw yields were corrected for feed-down from photoproduction of the excited charmonium state, ψ', as well as for contamination from incoherent production by a fit to the transverse momentum distribution of muon pairs with invariant mass $3.0 < m_{\mu\mu} < 3.2$ GeV/c^2. An analogous strategy was applied to the measurement of incoherent J/ψ production, where a total of about 500 J/ψ candidates were found in five intervals in the range $0.2 < p_{\rm T} < 1$ GeV/c; the sample was corrected for contamination from feed-down and coherent production. In the analysis of coherent J/ψ, the measured distribution was unfolded to account for detector resolution effects ($p_{\rm T}$ migration) and photon transverse momentum $k_{\rm T}$, while in the study of incoherent production these effects were found to be negligible.

The measured $|t|$-dependence of both processes and a comparison with the predictions of several models are shown in Fig. 1 (left). The cross section for coherent production is similarly well described by two models that include dynamic QCD effects: the leading twist approximation of nuclear shadowing (LTA) [8] or saturation effects through solutions of the b-dependent BK equation (b-BK) [9]. STARlight [10] (not shown, see Fig. 2 of Ref. [6]), a hadronic model based on a Glauber calculation where the $p_{\rm T}$ spectrum is determined solely from the nuclear form factor, predicts a cross section that is too large and a slope that deviates from the measurement. The cross section for incoherent production was compared with the models of three groups [11–13], each providing either a prediction where the process is represented as elastic scattering of a photon from a full nucleon (MS-p, MSS, and GSZ-el), or a prediction where subnucleonic degrees of freedom and their fluctuations were included (MS-hs, MSS-fl, and GSZ-el+diss). It is observed that the models from the first group predict steeper slopes than in the data, while the models with subfemtometer fluctuations are favored by the data at larger $|t|$. The models generally fail to describe the normalization, which is mainly related to the scaling from proton to nuclear targets.

The measured $|t|$-dependences in Fig. 1 (left) constitute the first study of the subnucleonic structure in lead ions using UPCs. The ALICE data cover three orders of magnitude in $|t|$ with a precision comparable to that at HERA.

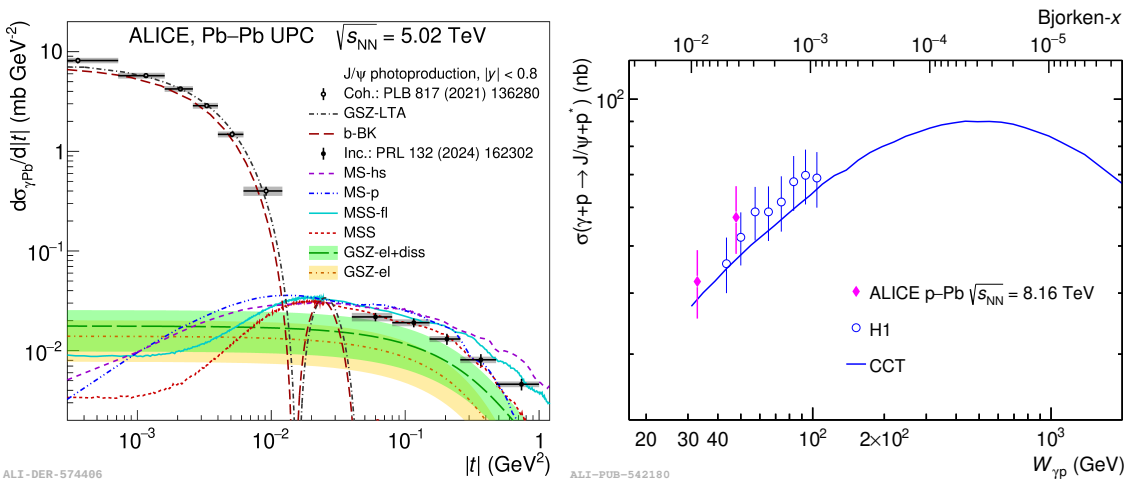

Figure 1: Left: The measured dependence of coherent and incoherent J/ψ photoproduction on $|t|$ in Pb–Pb UPCs at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [6, 7] and the comparison with the models. The uncorrelated uncertainties are indicated with vertical bars, while the gray bands denote the correlated ones. Right: The energy dependence of dissociative J/ψ photoproduction measured in p–Pb UPCs at $\sqrt{s_{\rm NN}}$ = 8.16 TeV [14]. The vertical bars represent the quadratic sum of the statistical and systematic uncertainties.

4. Energy dependence of dissociative J/ψ photoproduction off protons

ALICE also measured the energy dependence of J/ψ photoproduction off protons accompanied by proton dissociation using Run 2 data from p–Pb UPCs at $\sqrt{s_{\rm NN}}$ = 8.16 TeV collected with the forward muon arm [14]. J/ψ were reconstructed from decays into muon pairs in the rapidity range $-4 < y < -2.5$.

The energy dependence shown in Fig. 1 (right) was determined in the range $27 < W_{\gamma p} < 57$ GeV, where $W_{\gamma p}$ is the photon-proton center-of-mass energy. The measurement is compatible with results from the H1 experiment at HERA and represents the first probe of fluctuations of subnucleonic structures inside the proton using UPCs. The data were compared with the prediction of the CCT model [15], which is based on the hot-spot framework. The model describes the available data reasonably well and predicts a maximum of the cross section at $W_{\gamma p} \simeq 500$ GeV. Such energies should be achievable during Run 4 of the LHC.

5. Conclusions

For the first time, ALICE measured the dependence of the cross section for coherent and incoherent J/ψ photoproduction on Mandelstam $|t|$ using Pb–Pb UPCs at 5.02 TeV. These processes probe the mean and fluctuations of the gluon distribution in the lead nucleus and, at LHC energies, the associated high-energy QCD effects. The data on coherent production are consistent with models based on saturation or nuclear shadowing, while the data on incoherent production favor models implementing subnucleonic fluctuations of the gluon fields. ALICE also used p–Pb UPCs at 8.16 TeV to measure the energy dependence of dissociative J/ψ photoproduction off protons, thus using UPCs to probe subnucleonic structures inside the proton.

Acknowledgments

This work was co-funded by the European Union and supported by the Czech Ministry of Education, Youth and Sports (Project No. FORTE – CZ.02.01.01/00/22_008/0004632).

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