PROCEEDINGS OF SCIENCE

Ultraperipheral collisions (experiment)

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Ultraperipheral collisions (UPC) of heavy ions and protons offer a highly interesting opportunity to study various aspects of QED and both perturbative and non-perturbative QCD. Photonuclear (γA) and two-photon ($\gamma\gamma$) interactions are measured in various experiments at the LHC. In these proceedings, we discuss recent physics results on topics that can be studied in UPC, including nuclear shadowing, nuclear structure, precision QED and searches for physics beyond the Standard Model.

The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022
16-20 May 2022
online

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PoS(LHCP2022)215

1. Introduction

Ultraperipheral collisions (UPC) involve collisions of relativistic nuclei with impact parameters larger than twice the nuclear radius, where the ions interact electromagnetically (EM): either via photonuclear or two-photon production mechanisms [1]. Such EM interactions between the ions can be described as an exchange of photons with small virtuality of $Q < 1/R \approx 30$ MeV and a maximum energy of approximately $E = \gamma/R \approx 80$ GeV for Pb ions at the LHC.

2. Coherent vector meson photoproduction

A classical example of photonuclear interactions is coherent vector meson photoproduction. The first measurement of the coherent photoproduction of ρ^0 vector mesons in Xe+Xe UPC is performed by the ALICE Collaboration [2]. The dependence on the atomic number A of the $\sigma(\gamma A \rightarrow \rho^0 A)$ cross section at fixed centre-of-mass energy per nucleon of the γA system of 65 GeV is studied. It is found to be consistent with a power-law behaviour $\sigma(\gamma A \rightarrow \rho^0 A) \sim A^{\alpha}$ with a slope $\alpha = 0.96 \pm 0.02$ that confirms the importance of shadowing effects.

The measurement of J/ψ photoproduction off hadrons sheds light onto the initial state of QCD targets and provides important constraints to the initial conditions used in hydrodynamical models of heavy-ion collisions. The coherent photoproduction of J/ψ is studied in Pb+Pb UPC by ALICE and LHCb [3, 4]. The fiducial and differential cross sections are reported. In addition, the cross sections for coherent $\Psi(2S)$ production in Pb+Pb UPC are provided [4].

The J/ψ yield at very low transverse momentum, originating from coherent photoproduction, can be also studied in peripheral and semicentral hadronic Pb+Pb collisions, as reported by LHCb [5] and ALICE [6]. Theoretical calculations, successfully used to describe coherent photoproduction in UPC, are modified to account for geometrical constraints on the photon flux in the selected centrality classes [7, 8], and compared with the measurements.

3. Novel measurements involving photonuclear interactions

The azimuthal anisotropies in particle production have been observed in nearly all hadronic collision systems studied so far, from Pb+Pb collisions to pp collisions. These are often interpreted as resulting from the collective expansion of system reflecting the anistropic pressure gradients from the initial conditions. In order to test if similar effects can be observed in the inclusive photonuclear interactions, ATLAS has studied events triggered on the 0nXn spectator-neutron topology, in coincidence with a large gap in the photon-going direction [9]. These events have been classified by their observed charged particle multiplicity, and analyzed through the template fitting technique, using a peripheral multiplicity bin to subtract non-flow contributions. The measurement extracts v_2 coefficient for charged particles which rises as a function of particle transverse momentum. The photonuclear events show a significant long-range correlation, which is lower than that in pp or p+Pb events. These results could be explained by the vector meson part of the photon wave function, which gives rise to conditions similar as those in pp or p+Pb collisions.

Significant v_2 values are also observed in γp-enriched events from p+Pb collisions by CMS [10]. However, this may be due to the effect of jet correlations within the γp enhanced sample. Due to

the limited charged-particle multiplicity range for the γp events, no low-multiplicity subtraction technique is implemented to remove such non-flow contributions.

Photonuclear interactions are also able to produce dijet pairs. This makes them a useful tool to probe the patonic structure of the nucleus at low-x and high-Q^2. In the updated ATLAS measurement, fully-unfolded triple differential cross sections for photonuclear dijets in Pb+Pb collisions are extracted [11]. The measurement compares well with Pythia 8 photoproduction calculations with nuclear PDF. In a similar study by CMS, the azimuthal angular correlations of exclusively produced events with two jets, predominantly from diffractive photonuclear interactions at large momentum transfer, is measured [12]. Theoretical predictions relate such correlations to the polarization of gluons within nuclei. However, it is found that the soft gluon radiation from final-state jets is the dominant effect of the observed azimuthal anisotropy.

4. Photon–photon interactions in the Standard Model

Photon–photon fusion is an interesting family of processes at ion colliders. It is particularly interesting as a remarkably clean interaction with little (if any) remnant activity from the interacting particles.

ATLAS has measured the cross sections for exclusive dimuon [13] and dielectron [14] production in UPC Pb+Pb collisions for dimuon (dielectron) invariant masses above 10 GeV (5 GeV). The events are categorized with respect to the absence/presence of forward neutrons emitted as a result of Pb ion excitation due to multiple Coulomb interactions accompanying the dilepton production process. The results are compared with calculations from the STARlight 2.0 [15] and SuperChic 3 [16] MC generators, corrected for FSR effects using Pythia 8 [17]. Generally, good agreement is found but some systematic differences are seen.

Using the same process ($\gamma\gamma \to \mu\mu$), CMS has observed the broadening of the core of the dimuon acoplanarity distribution, when comparing the events between various forward-neutron categories [18]. This subtle effect is due to the fact that the average transverse momentum of photons emitted from relativistic ions has an impact parameter dependence.

The measurement of photon-induced dilepton pairs (ee and $\mu\mu$) in peripheral and semiperipheral collisions at low dilepton invariant masses is reported by ALICE [19]. These results are generally reproduced by calculations that contain impact-parameter effects on the shape of the transverse momentum distribution of the quasi-real photons.

Finally, both ATLAS and CMS report the observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC [20, 21]. Both analyses exploit semileptonic $\tau\tau$ decays into a muon and charged-particle track(s). The measurements are found to be compatible with Standard Model predictions.

5. Beyond Standard Model interactions in UPC

The production of τ lepton pairs in UPC provides a highly interesting opportunity to study the EM properties of the τ lepton. Indeed, the presence of $\gamma\tau\tau$ vertex in this reaction gives sensitivity to the anomalous EM couplings of the τ lepton [22, 23]. Both ATLAS and CMS Collaborations provide their first limits on τ anomalous magnetic moment (a_τ) [20, 21]. In case of the ATLAS result, obtained limits on a_τ are competitive with world's best experimental limits from LEP.

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics [24]. The LbyL process has been proposed as a sensitive channel to study physics beyond the Standard Model. For example, new neutral particles, such as axion-like particles (ALP), can contribute to the LbyL cross section in the form of narrow diphoton resonances [25]. Both ATLAS and CMS performed a search for $\gamma\gamma \to a \to \gamma\gamma$ process in UPC data, where a denotes the ALP [26, 27]. Since no significant deviations from the background-only hypothesis are observed, the results are then used to estimate the upper limits on the ALP production. Assuming a 100% ALP decay branching fraction into photons, the derived constraints on the ALP mass and its coupling to photons are compared with those obtained from other experiments. The ALP exclusion limits from ATLAS and CMS analyses are the strongest so far for the mass range of $5 < m_a < 100$ GeV.

Nonperturbative production in the strong fields generated in UPC can be used to search for magnetic monopoles (MM) via the magnetic analogue of the Schwinger effect [29]. Here the main advantage is that the MM production cross section can be calculated semiclassically, evading the breakdown of perturbation theory due to large monopole–photon coupling. The MoEDAL experiment at the LHC has conducted the first search for MMs produced in Pb+Pb collisions via the Schwinger mechanism [28]. Monopoles with Dirac charges $1g_D \leq g \leq 3g_D$ and masses up to 75 GeV are excluded.

6. Summary

There exists a rich physics programme of ultraperipheral collisions at the LHC. New measurements of coherent photoproduction of vector mesons reveal that this process can also occur simulteneusly to hadronic collisions. Photonuclear interactions can be successfully used for other purposes, including tests of the collective phenomena and the exploration of nuclear-PDF effects. UPC events are excellent laboratory for precision QED tests, resulting in first heavy-ion constraints on the anomalous magnetic moment of τ lepton. Finally, various types of searches for beyond the Standard Model particles with EM couplings can be explored in UPC.

Acknowledgments

The project is co-financed by the Polish National Agency for Academic Exchange within Polish Returns Programme, Grant No. PPN/PPO/2020/1/00002/U/00001.

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