EXPERIMENTAL AND PHENOMENOLOGICAL DEVELOPMENTS IN ULTRAPERIPHERAL COLLISIONS*

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Ultraperipheral collisions (UPC) of heavy ions and protons offer a highly interesting opportunity to study various aspects of QED and (non-) perturbative QCD. Both photonuclear (γA) and two-photon ($\gamma\gamma$) interactions are measured in the experiments at RHIC and 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.

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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+Pb collisions at the LHC or ≈ 3 GeV for Au+Au collisions at RHIC.

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 $\sigma(\gamma A \to \rho^0 A)$ cross section at a fixed centre-of-mass energy per nucleon of the γA system

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of 65 GeV is studied. It is found to be consistent with a power-law behaviour $\sigma(\gamma A \to \rho^0 A) \sim A^{\alpha}$ with a slope $\alpha = 0.96 \pm 0.02$ that confirms important shadowing effects.

The measurement of coherent ρ^0 photoproduction in Au+Au and U+U collisions at the STAR experiment constitutes the first utilization of the interacting photon's transverse linear polarization [3]. The effects of photon transverse momentum and two-source interference are removed to extract the nuclear radius of gold and uranium. The resulting radii are found to be systematically larger than the measured nuclear charge radii at lower energies.

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 at the LHC with the ALICE detector in p+Pb and Pb+Pb UPC, where the Pb ion acts as a source of quasi-real photons [4, 5]. The fiducial cross sections (p+Pb) and differential cross section as a function of J/ψ transverse momentum (Pb+Pb) are reported. On the theoretical side, the first next-to-leading-order (NLO) perturbative QCD study of rapidity-differential cross sections of coherent photoproduction of J/ψ mesons in Pb+Pb UPC at LHC energies is provided [6].

The J/ψ yield at very low transverse momentum, originating from coherent photoproduction, can be also studied in peripheral and semi-central hadronic Pb+Pb collisions, as reported by LHCb [7] and ALICE [8]. The measured differential cross sections for this process are shown in figure 1. Theoretical calculations successfully used to describe coherent photoproduction in UPC and, modified to account for geometrical constraints on the photon flux in the selected centrality classes, are compared with the measurements. In particular, the cross section as a function of centrality is

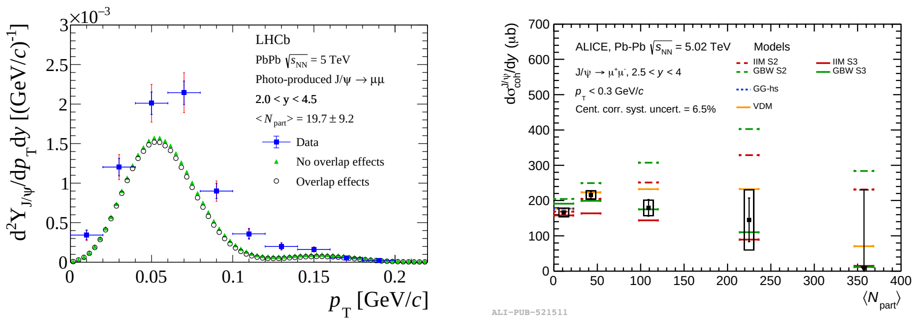

Fig. 1. Left: Double-differential yields of photoproduced J/ψ candidates as a function of J/ψ transverse momentum in peripheral Pb+Pb collisions, as measured by LHCb [7]. Right: Coherent J/ψ photoproduction cross section as a function of centrality at forward rapidity in Pb+Pb collisions with ALICE [8].

well described by two models, one implementing a modification of the photon flux only [9], and the other requiring an additional modification of the photonuclear cross section [10].

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 interpreted as resulting from the collective expansion of the system reflecting the anisotropic 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 [11]. These events have been classified by their observed charged particle multiplicity, and analysed 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 collision conditions similar to those in pp or p+Pb.

Significant v_2 values are also observed in γp-enriched events from p+Pb collisions by CMS [12]. 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.

At lower collision energies, long-range di-hadron correlations in inclusive γAu-rich events are studied by STAR [13]. No sign of collectivity is observed, and the future measurements will focus on the exploration of higher-energy and higher-multiplicity events, also with the help of the upcoming STAR Forward Upgrade [14]. In addition, STAR presented the measurement of identified $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ spectra in photonuclear Au+Au collisions [17]. Significant baryon stopping and rapidity asymmetry are observed at low transverse momentum, which could indicate the existence of a baryon junction within the nucleon, a non-perturbative configuration of gluons which carries the baryon number.

Photonuclear interactions are also able to produce dijet pairs. This makes them useful tools to probe the partonic 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 [15]. The measurement compares well with PYTHIA 8 photoproduction calculations with nuclear PDF [16] (figure 2).

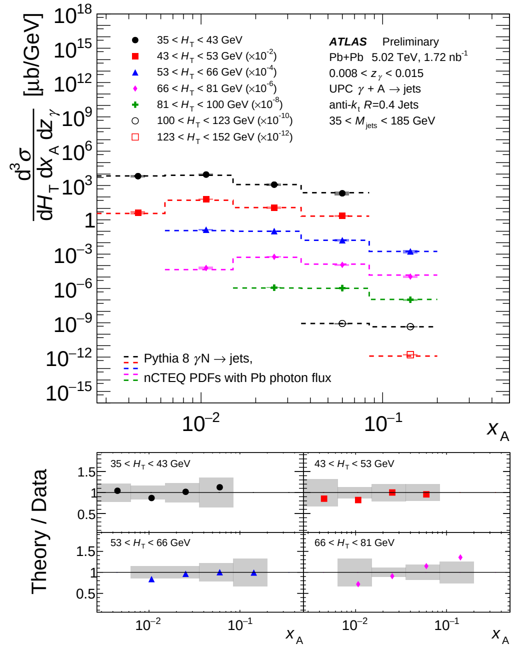

Fig. 2. Triple-differential cross-sections for photonuclear dijet production in Pb+Pb collisions measured by ATLAS [15].

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 [18] and dielectron [19] 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 [20] and SuperChic 3 [21] MC generators, corrected for FSR effects using PYTHIA 8 [22], as shown in figure 3 (left). 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 [23]. This subtle effect is due to the fact that the average transverse momentum of photons emitted from relativistic ions has an impact-parameter dependence.

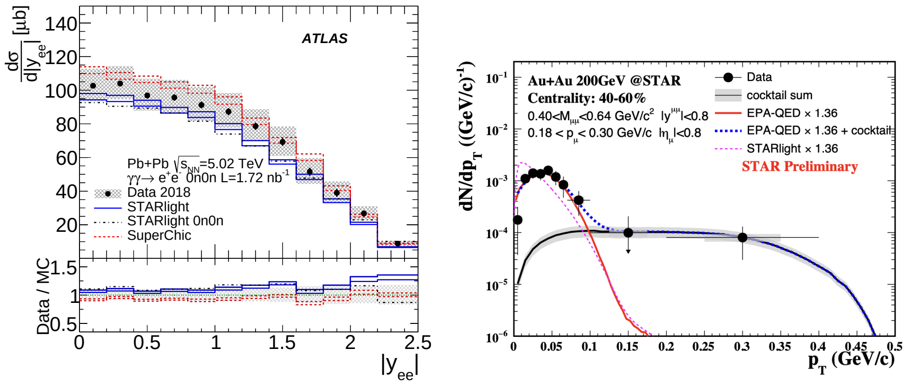

Fig. 3. Left: Differential cross sections for $\gamma\gamma \to ee$ production in Pb+Pb UPC measured by ATLAS for events in the absence of forward neutrons ($0n0n$) as a function of absolute dielectron rapidity [19]. Right: Differential event yield for a dimuon production as a function of system transverse momentum, as measured by STAR in semiperipheral Au+Au collisions [25].

The measurement of photon-induced dilepton pairs (ee and $\mu\mu$) in peripheral and semiperipheral collisions at low dilepton invariant masses is reported by the ALICE [24] and STAR [25] experiments. 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 (figure 3 (right)).

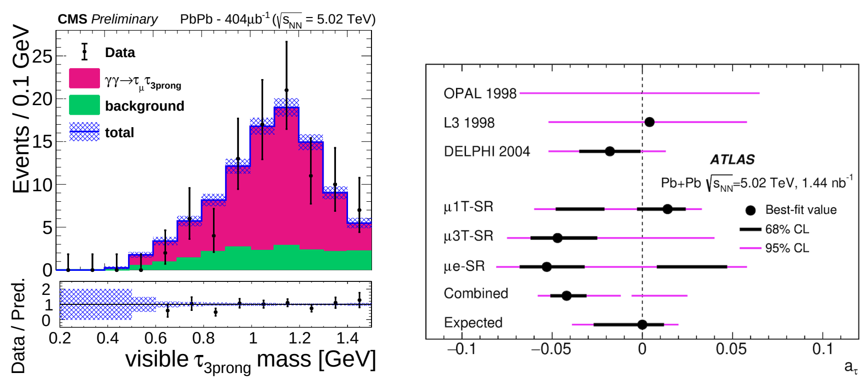

Fig. 4. Left: Visible 3-prong invariant mass distribution for hadronic τ decays in $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC measured by CMS [29]. Right: Measurements of a_τ from ATLAS, compared with previous measurements from the experiments at LEP [28].

Finally, both ATLAS and CMS report the observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC [28, 29]. Both analyses exploit semileptonic $\tau\tau$ decays into a muon and charged-particle track(s), see figure 4 (left). The measurements are found to be compatible with the 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 [26, 27]. Both the ATLAS and CMS collaborations provide their first limits on τ anomalous magnetic moment (a_τ) [28, 29]. In the case of the ATLAS result, obtained limits on a_τ are competitive with world's best experimental limits from LEP (figure 4 (right)).

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. Recent measurements of the fiducial cross section for this process by ATLAS and CMS are combined in a common phase space [30]. 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 [31]. Both ATLAS and CMS performed a search for $\gamma\gamma \to a \to \gamma\gamma$ process in UPC data, where a denotes the ALP [32, 33]. 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 in figure 5 (left) with those obtained from other experiments. The ALP exclusion limits from the ATLAS and CMS analyses are the strongest so far for the mass range of $5 < m_a < 100$ GeV.

Non-perturbative 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 [35]. 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 [34]. Monopoles with Dirac charges $1g_{\mathrm{D}} \leq g \leq 3g_{\mathrm{D}}$ and masses up to 75 GeV are excluded, as seen in figure 5 (right).

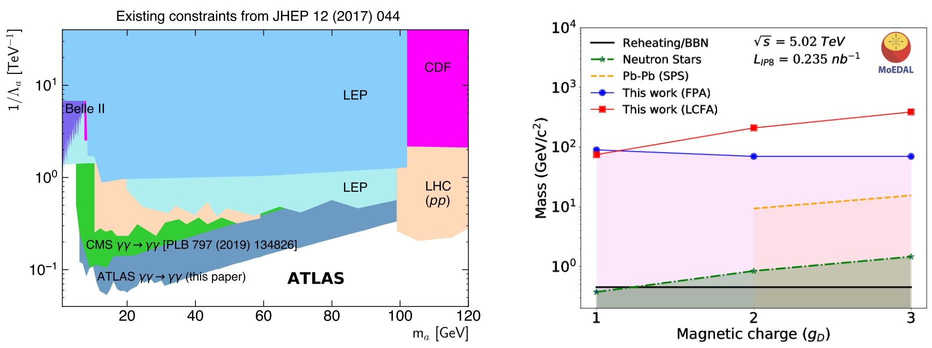

Fig. 5. Left: Compilation of exclusion limits at 95% C.L. in the ALP–photon coupling ($1/\Lambda_a$) *versus* ALP mass (m_a) plane obtained by different experiments [33]. Right: 95% C.L. magnetic-monopole exclusion region in monopole mass and magnetic charge obtained using two different calculations of the Schwinger production mechanism for Pb+Pb collisions [34].

6. Summary

There exists a rich physics programme of the UPC collisions at ion colliders (RHIC and LHC). New measurements of coherent photoproduction of vector mesons reveal that this process can occur down to the most central (hadronic) collisions. Photonuclear interactions can be successfully used for other purposes, including tests of the collective phenomena and baryon stopping in small systems, and the exploration of nuclear-PDF effects. UPC events are an excellent laboratory for precision QED tests, resulting in the 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.

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