PROCEEDINGS OF SCIENCE

Light-by-light scattering and high mass dilepton production in UPC

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The presence of a large flux of photons accompanying relativistic heavy ion beams leads to a significant number of photon-induced processes, including photon-photon fusion. These processes are remarkably clean with little or no remnant activity from the interacting particles. This document presents the status of photon-photon fusion measurements resulting in either two photons ($\gamma\gamma \rightarrow \gamma\gamma$) or two charged leptons ($\gamma\gamma \rightarrow l^+l^-$) in the final state, as measured by the ATLAS and CMS experiments in ultra-peripheral heavy-ion collisions.

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1. Photon-induced processes in heavy ions

Photon-induced events arise from the interactions between the electromagnetic fields surrounding the charged beam particles at colliders. Ultra-peripheral collisions (UPC) of nuclei, where impact parameter is larger than the sum of the nuclei radii, provide an extremely clean environment to study various photon-induced processes [1]. The particular interest lies in the processes resulting in two photons or two opposite-charge leptons in the final state:

- Light-by-light (LbyL) scattering, $\gamma\gamma \rightarrow \gamma\gamma$, is a process in the Standard Model that proceeds at lowest order in quantum electrodynamics via virtual one-loop box diagrams involving charged fermions and $W^{\pm}$ bosons.
- Dilepton production, $\gamma\gamma \rightarrow l^+l^-$ (with $l = e, \mu, \tau$), non-resonant exclusive two-photon scattering to dileptons. It is produced at an abundant rate and can be used for a precise test of QED and initial photon flux modelling. It is considered a background process for many other processes.

2. ATLAS and CMS experiments

The ATLAS [2] and CMS [3] experiments are general-purpose particle detectors at the Large Hadron Collider [4]. The ATLAS detector consists of the Inner Detector, immersed in 2 T axial magnetic field and providing charged-particle tracking in pseudorapidity range $|\eta| < 2.5$, electromagnetic and hadronic calorimeters, covering pseudorapidity range $|\eta| < 4.9$, and a muon spectrometers, allows measuring the deflection of muons in a magnetic field of the superconducting air-core toroid magnet. The central feature of the CMS detector is a superconducting solenoid, providing a magnetic field of nearly 4 T. Immersed in this field are the all-silicon inner tracker, and crystal electromagnetic and the brass and scintillator hadronic calorimeters. The outermost subsystems are the gas-ionization muon detectors. Both ATLAS and CMS are equipped with zero-degree calorimeters (ZDC) [5, 6], located at approximately 140 m from the interaction point, detecting forward neutral particles, such as neutrons, originating from the interacting nuclei.

3. Light-by-light scattering and axion-like particle search

The first evidence of the LbyL scattering in lead-lead (Pb+Pb) UPC at the LHC comes from the ATLAS measurement [7], with a signal significance of 4.4 standard deviations (3.8σ expected). The evidence was obtained from data recorded in 2015, at the centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosity of 0.48 nb^{-1}. The general approach to the analysis of LbyL scattering in heavy-ion collisions is described in Ref. [8]. The main background for LbyL scattering process originates from misidentified electrons from dielectron production, $\gamma\gamma \rightarrow e^+e^-$, and central exclusive production of the diphoton system, $gg \rightarrow \gamma\gamma$.

The CMS result [9], conducted using 390 $\mu\mathrm{b}^{-1}$ of data collected in 2015, reports evidence of 14 LbyL events and corresponding significance of 3.7 standard deviations. The LbyL scattering events were selected with two photons exclusively produced, each with transverse energy $E_{\mathrm{T}}^{\gamma} > 2$ GeV, pseudorapidity $|\eta_{\gamma}| < 2.4$, diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV, diphoton transverse momentum

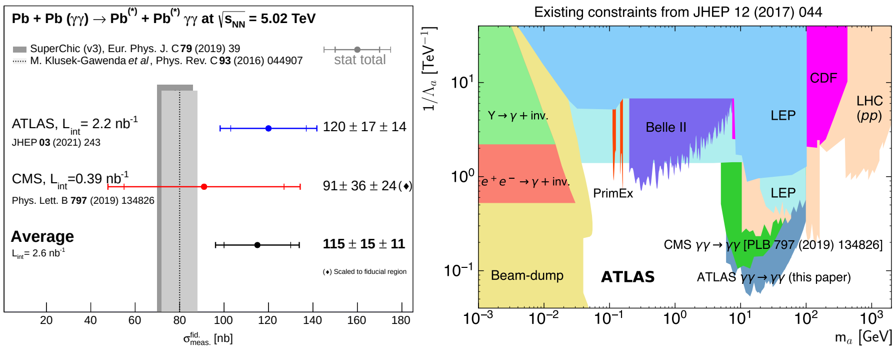

Figure 1: Left: The averaged Pb+Pb $(\gamma\gamma) \to \mathrm{Pb}^{(*)}$+$\mathrm{Pb}^{(*)}$ $\gamma\gamma$ cross-section value along with the individual cross-section measurements at 5.02 TeV from ATLAS and CMS. The theoretical predictions [11, 12] are computed at LO accuracy [14]. **Right**: Compilation of exclusion limits at 95% CL in the ALP-photon coupling $(1/\Lambda_a)$ versus ALP mass (m_a) plane obtained by different experiments. The existing limits are compared with the limits extracted from CMS (green) and ATLAS (dark blue) measurements. The exclusion limits labelled "LHC (pp)" are based on pp collision data from ATLAS and CMS [10].

$p_{\mathrm{T}}^{\gamma\gamma} < 1$ GeV, and diphoton acoplanarity below 0.01. The measured fiducial LbyL scattering cross-section, $\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46$ (stat) $\pm$ 28 (syst) $\pm$ 12 (theo) nb, is consistent with the Standard Model predictions [8].

The most recent ATLAS paper [10] presents a measurement based on 2.2 nb^{-1} integrated luminosity of the full Run-2 Pb+Pb data set. The LbyL process candidates were selected in events with two photons produced exclusively, each with transverse energy $E_{\mathrm{T}}^{\gamma} > 2.5$ GeV, pseudorapidity $|\eta_\gamma| < 2.37$, diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV, and with small diphoton transverse momentum and diphoton acoplanarity, resulting in 97 LbyL events with 27 ± 5 background events expected. The measured integrated fiducial cross-section, $\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 17$ (stat) $\pm$ 13 (syst) $\pm$ 4 (lumi) nb, is in agreement with SuperChic v3.0 MC generator [11] predictions, 78 ± 8 nb, within 2 standard deviations.

Figure 1 (left) shows cross-sections from most recent ATLAS and CMS results, and combination of both in the common fiducial phase-space, compared to the theoretical predictions [11, 12].

The $\gamma\gamma \to \gamma\gamma$ process has also been proposed as a sensitive channel to search for the physics beyond the Standard Model [13]. The example of such is axion-like particle production, $\gamma\gamma \to a \to \gamma\gamma$, with upper production limits calculated by the both experiments presented in Figure 1 (right).

4. Dilepton production

The first observation of $\gamma\gamma \to \tau^+\tau^-$ process was reported by ATLAS [15] and CMS [16]. Both analyses target μ + 3 prong decay – one tau lepton decays into a muon, while the other decays into three charged pions. ATLAS extends the search by considering also μ + 1 prong and μ + e decays. CMS reports fiducial cross-section, $\sigma_{\mathrm{fid}} = 4.8 \pm 0.6$ (stat) $\pm$ 0.5 (syst) mb, while ATLAS reports the signal strength, $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$.

The highlight of both measurements is setting constraints on τ anomalous magnetic moment, a_τ. CMS estimated a model-dependent value of $a_\tau = 0.001^{+0.055}_{-0.089}$ at 68% confidence-level, while

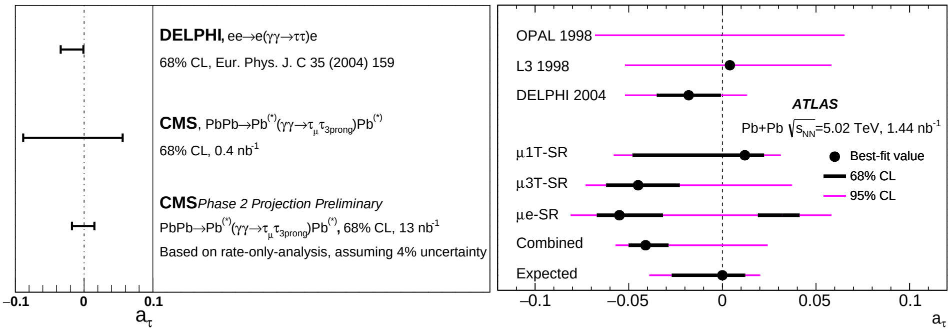

Figure 2: Constraints on τ lepton anomalous magnetic moment a_τ from CMS [16] (left) and ATLAS [15] (right) measurements. These are compared to the existing best measurements from the LEP experiments.

ATLAS at 95% confidence-level reports a_τ of -0.057 < a_τ < 0.024 (Figure 2).

The measurement of $\gamma\gamma \to \mu^+\mu^-$ process was performed by both experiments, with ATLAS focusing on the cross-section measurement [17], and CMS concentrating on measuring the dependency between forward neutron multiplicity and dimuon acoplanarity [18]. ATLAS measured the fiducial cross-section, σ_{fid} = 34.1 ± 0.3 (stat) ± 0.7 (syst) μb, which is in agreement with STARLIGHT [19] (STARLIGHT+PYTHIA [20]) predictions of 32.1(30.8) μb. An excess in differential cross-section of around 20% at higher rapidity values for data was observed, which may hint larger initial photon fluxes. CMS performed the first measurement of the dependence of dimuon acoplanarity on the multiplicity of forward neutrons, analysing events with zero, one, or two and more forward neutrons. The results show clear dependence between these two observables, which is not grasped by the STARLIGHT generator.

Finally, ATLAS reports the cross-section measurement of $\gamma\gamma \to e^+e^-$ process [21]. The analysis technique closely follows ATLAS $\gamma\gamma \to \mu^+\mu^-$ UPC measurement [17], but with two notable advances: the higher statistics from 2018 Pb+Pb data and the extended fiducial region in lepton p_{T} and invariant mass. Measured fiducial cross-section, σ_{fid} = 215 ± 1 (stat) $^{+23}_{-20}$ (syst) ± 4 (lumi) μb is, within experimental uncertainties, in agreement with STARLIGHT (SUPERCHIC) predictions of 196.9(235.1) μb. A similar excess at higher rapidities as in the ATLAS $\gamma\gamma \to \mu^+\mu^-$ measurement was observed.

5. Summary

A rich physics programme of ultra-peripheral collisions is realised at the LHC. The measurements of photon-induced processes can be used to test the Standard Model predictions: observation of light-by-light scattering, dilepton production, and constraints on anomalous magnetic moment of tau lepton, and also to search for BSM effects, e.g. axion-like particle search. Existing Run-2 results show very good prospects for Run-3 and beyond.

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