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Dilepton production and BSM physics from photon fusion processes in UPC and non-UPC Pb+Pb collisions with the ATLAS detector

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Relativistic heavy-ion beams at the LHC are accompanied by a large flux of equivalent photons, leading to multiple photon-induced processes. This talk presents a series of measurements of dilepton production from photon fusion performed by the ATLAS Collaboration, which provide strong constraints on the nuclear photon flux, its dependence on the impact parameter and photon energy, and can also probe physics beyond the standard model (BSM) using tau leptons. Recent measurements of exclusive dielectron production in ultra-peripheral collisions (UPC) are presented. Comparisons of the measured cross-sections to QED predictions from the STARlight and SuperChic models are also presented. Furthermore, measurements of muon pairs produced via two-photon scattering processes in hadronic (i.e. non-UPC) Pb+Pb collisions are discussed. These non-UPC measurements provide a novel test of strong-field QED and may be a potentially sensitive electromagnetic probe of the quark-gluon plasma. These measurements include the dependence of the cross-section and angular correlation on the mean-p_{T} of the dimuon pair, the rapidity separation between the muons, and the pair angle relative to the second-order event-plane, all measured differentially as a function of the Pb+Pb collision centrality. The presented results are compared with recent theory calculations. Tau-pair production measurements can constrain the tau lepton's anomalous magnetic dipole moment (g-2), and a recent ATLAS measurement using muonic decays of tau leptons in association with electrons and tracks provides one of the most stringent limits available to date.

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1. Introduction

Heavy-ion collisions at ultra-relativistic energies are typically examined in processes in which nuclear beams interact hadronically at impact parameters less than twice the nuclear radius. In the overlap region of two colliding nuclei a dense quark–gluon plasma is expected to be produced. On the other hand, the strong electromagnetic (EM) fields associated with the nuclei can also lead to interactions in ultra-peripheral collisions (UPC), events with impact parameters well beyond twice the nuclear radius, where any contributions from strong processes are suppressed.

At high energies of the Large Hadron Collider (LHC), UPC can induce a wide variety of exclusive final states – dileptons, dijets, and diphotons being the most commonly measured – for which no other activity in the detectors is observed, except for nucleons emitted at very small angles relative to the beam direction. The photons are also characterised by small transverse momenta, such that high-energy decay products in these exclusive final states are almost perfectly balanced in the transverse direction. UPC processes have also been proposed to be utilised as a competitive tool to search for beyond Standard Model (BSM) physics [1].

In this report the most recent results on photon-photon ($\gamma\gamma$) induced processes in UPC physics from the ATLAS experiment [2] are discussed. Also a measurement of the $\gamma\gamma \to \mu^+\mu^-$ process occurring simultaneously to hadronic Pb+Pb collisions is studied.

2. Exclusive $\gamma\gamma \to \ell^+\ell^-$ production with muons and electrons

ATLAS measured exclusive $\gamma\gamma \to \mu^+\mu^-$ production [3] in UPC Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collisions in the data set with an integrated luminosity of 0.49 nb^{-1}. The fiducial region of the measurement was defined by single muon $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.4$. Furthermore, requirements on invariant mass of the dimuon system, $m_{\mu\mu} > 10$ GeV, and its transverse momentum, $p_{\mathrm{T}}^{\mu\mu} < 2$ GeV, were imposed. The event selection allowed exactly two opposite-charge muons per event. It resulted in about 12k event candidates from the $\gamma\gamma \to \mu^+\mu^-$ process. After the evaluation and subtraction of dissociative background, which amounts to 3%, the integrated and differential cross-sections were measured in $m_{\mu\mu}$, dimuon rapidity $y_{\mu\mu}$, scattering angle in the dimuon rest frame $\cos\theta^*$, initial-photon momenta k_{min}, k_{max} and acoplanarity, $\alpha = 1 - |\Delta\phi|/\pi$. The latter quantifies how two muons are aligned in the azimuthal angle.

The left panel of Figure 1 presents differential cross-sections for exclusive $\gamma\gamma \to \mu^+\mu^-$ production as a function of α. STARLIGHT fails in describing a tail of the differential cross-section as a function of α. For $\alpha > 5 \times 10^{-3}$ a contribution of signal events is suppressed and the excess of data is visible. It is caused by a contribution from the final state radiation (FSR) which is not accounted for in the STARLIGHT calculation. A better description of the full α distribution is obtained by interfacing STARLIGHT with PYTHIA which accounts for the FSR contribution.

A measurement of exclusive $\gamma\gamma \to e^+e^-$ production was performed [5] by ATLAS in the Pb+Pb data set with an integrated luminosity of 1.72 nb^{-1}. The fiducial region of the measurement was defined by single electron $p_{\mathrm{T}} > 2.5$ GeV and $|\eta| < 2.5$. Furthermore, requirements on invariant mass of the dielectron system, $m_{ee} > 5$ GeV, and its transverse momentum, $p_{\mathrm{T}}^{ee} < 2$ GeV, were imposed. The event selection required exactly two opposite-charge electrons per event. In

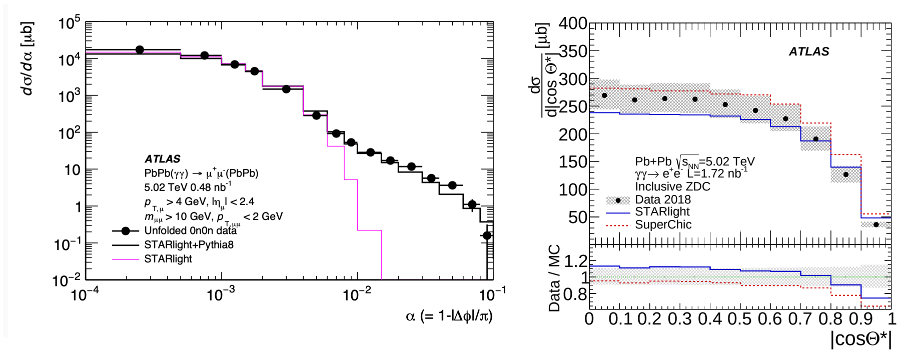

Figure 1: (Left) Differential cross-section as a function of acoplanarity (right) for exclusive $\gamma\gamma \to \mu^+\mu^-$ production in UPC Pb+Pb collisions [3]. Data points are compared with predictions from STARLIGHT or STARLIGHT+PYTHIA to account for the FSR contribution. (Right) Differential cross-section as a function of $|\cos\theta^*|$ for exclusive $\gamma\gamma \to e^+e^-$ production in UPC Pb+Pb collisions [5]. In the bottom panel, data is compared with predictions from STARLIGHT and SUPERCHIC.

comparison to the $\gamma\gamma \to \mu^+\mu^-$ measurement, the dielectron analysis features a factor of three larger statistics, the extended fiducial coverage, and advancement in the background evaluation techniques.

The right panel of Figure 1 shows differential cross-sections for exclusive $\gamma\gamma \to e^+e^-$ production as a function of $|\cos\theta^*|$ where θ^* is scattering angle in the dielectron rest frame. The data was corrected to the Born level i.e. before the FSR. The measurements are compared with two MC predictions for the $\gamma\gamma \to e^+e^-$ process: STARLIGHT v3.13 and SUPERCHIC v3.05, which are systematically about 10% lower or higher than the data, respectively. SUPERCHIC tends to better describe the shapes of the distributions in both cases.

3. Forward neutron activity

An inclusive sample of $\gamma\gamma \to \ell^+\ell^-$ events with $\ell = \mu^\pm, e^\pm$ can be inspected using information from the Zero Degree Calorimeters (ZDC) which are located in the forward region ±140 m away from the ATLAS interaction point (IP). The ZDC detectors are designed to detect neutral particles originating from IP. In particular in hadronic Pb+Pb collisions they detect spectator neutrons. On the other hand, in UPC events the probability of exchanging one or more photons between the two incoming ions is sizeable. These additional photons may dissociate one or both nuclei and cause emission of single neutrons in ZDC. Because of the radial dependence of the photon flux [6], the presence of these additional photons can preferentially select certain impact parameter ranges, and so can influence the photon spectrum of the other photons.

ATLAS measured forward neutron activity in exclusive $\gamma\gamma \to \mu^+\mu^-$ [3] and $\gamma\gamma \to e^+e^-$ [5] processes. In both cases, all $\gamma\gamma \to \ell^+\ell^-$ event candidates were divided into three categories: 0n0n - without activity on either side of ZDC, Xn0n - with activity on one side of ZDC, and XnXn - with activity on each side of ZDC. After subtracting the dissociative background contribution and accounting for simultaneous EM interactions in the same bunch crossing, fractions of events falling into each category were measured.

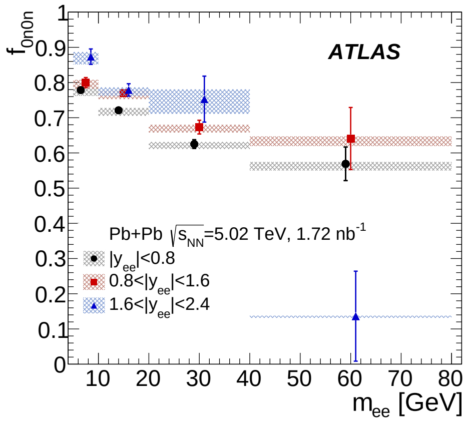

Figure 2: Fractions of events in the 0n0n category evaluated from $\gamma\gamma \to e^+e^-$ data in three bins of the dielectron rapidity, $|y_{ee}|$, corrected for the presence of additional neutrons [5]. Error bars represent statistical uncertainties, while shaded boxes represent systematic uncertainties. Points for $|y_{ee}| < 0.8$ and $1.6 < |y_{ee}| < 2.4$ are displaced horizontally for better visibility.

Figure 2 shows corrected fractions of events in the 0n0n category evaluated from $\gamma\gamma \to e^+e^-$ data as a function of m_{ee} in three bins of $|y_{ee}|$. These fractions tend to drop with increasing m_{ee}, and are in general larger for higher $|y_{ee}|$ values. These observations are consistent with the conclusions for forward neutron activity measured in the $\gamma\gamma \to \mu^+\mu^-$ process [3].

4. Exclusive $\gamma\gamma \to \tau^+\tau^-$ production and anomalous magnetic moment of τ lepton

ATLAS made the observation of exclusive $\gamma\gamma \to \tau^+\tau^-$ production [7] in 2018 Pb+Pb collisions with an integrated luminosity of 1.44 nb^{-1}. Selected events contained one muon from a τ-lepton decay, an electron or charged-particle track(s) from the other τ-lepton decay, little additional central-detector activity, and no forward neutrons (0n0n category). After applying the event selection, a total of 656 data events were observed in three signal regions (SR) in which the analysis was performed.

The $\gamma\gamma \to \tau^+\tau^-$ process is observed with a significance exceeding 5 standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ assuming the Standard Model value for the anomalous magnetic moment of the τ lepton, a_τ. The left panel of Figure 3 shows $\mu_{\tau\tau}$ extracted from the fit, based on the individual SRs. The combined $\mu_{\tau\tau}$ is also shown which is in agreement with the prediction from the Standard Model.

The measurement of $\gamma\gamma \to \tau^+\tau^-$ production from ATLAS provided also constraints on a_τ [7]. To measure a_τ, a fit to the muon p_{T} distribution was performed in the three SRs with a_τ being the only free parameter. Also a control region with events from the $\gamma\gamma \to \mu^+\mu^-$ process were used in the fit to constrain initial-photon fluxes. The right panel of Figure 3 depicts the a_τ measurement alongside previous results obtained at LEP. The precision of this measurement is similar to the most precise single-experiment measurement by the DELPHI Collaboration [8].

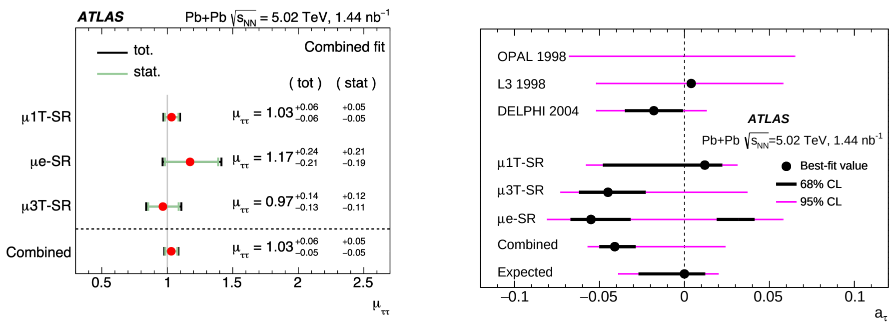

Figure 3: (Left) Best-fit values of the signal strength parameter, $\mu_{\tau\tau}$, under the Standard Model a_τ value assumption, extracted from the fit based on the individual SRs [7]. (Right) Anomalous magnetic moment of tau a_τ from fits to individual SRs, and from the combined fit [7]. These are compared with existing measurements from the OPAL, L3 and DELPHI experiments at LEP.

5. Non-UPC dimuon production

Dimuon production induced by $\gamma\gamma$ fusion was also measured by ATLAS using non-UPC Pb+Pb collisions spanning $0 - 100\%$ centralities with an integrated luminosity of 1.94 nb^{-1} [9]. The $\gamma\gamma \to \mu^+\mu^-$ pairs were identified using selections on pair momentum asymmetry and acoplanarity, α. Backgrounds, dominated by heavy-flavour decays, were evaluated using template fits to the distribution of muon-pair transverse impact parameter.

The STARLIGHT model, which was recently augmented to allow evaluation of cross-sections for $\gamma\gamma \to \mu^+\mu^-$ production within restricted impact parameter intervals, was found to substantially underestimate the measured cross-sections. Measurements of α and the associated transverse momentum scale, $k_\perp$, distributions confirmed a significant centrality dependence in mean, RMS and standard deviations which are shown for α in Figure 4.

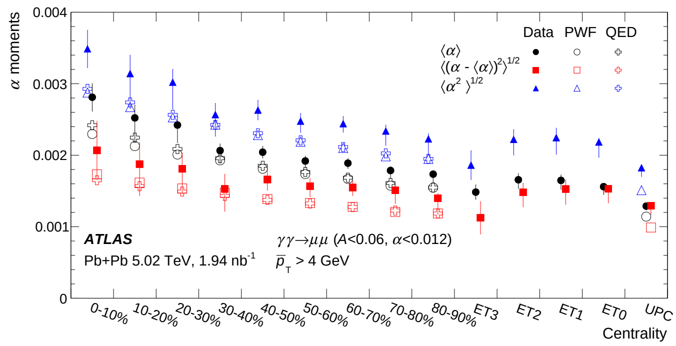

Figure 4: Moments of the $\gamma\gamma \to \mu^+\mu^-$ acoplanarity distributions as a function of centrality compared with the QED and PWF predictions [9]. The error bars on the data points indicate combined statistical and systematic uncertainties.

The moments calculated for the initial-state QED and PWF predictions are in excellent agreement except for the most central collisions where the QED results are slightly higher. Both calculations show a systematic difference from the data.

With the improved statistical precision of this measurement, an additional depletion is observed in the α and $k_\perp$ distributions near zero values of the corresponding quantities. In more peripheral intervals, both calculations show weaker suppression near $\alpha = 0$ than is observed in the data. Moreover, the predicted trends associated with effects of magnetic fields on the dimuons are not observed in the ATLAS data.

6. Summary

In this report, the latest results for $\gamma\gamma$ fusion processes from the ATLAS Collaboration were discussed. The UPC physics programme focused on precise measurements of exclusive $\gamma\gamma \to \mu^+\mu^-$ and $\gamma\gamma \to e^+e^-$ production including also forward neutron emission. Thanks to a large integrated luminosity of Pb+Pb collisions collected by ATLAS, rare processes such light-by-light scattering [10] (not discussed in the report due to the page limit) and $\gamma\gamma \to \tau^+\tau^-$ could be measured at the LHC for the first time. Also UPC collisions proved to be a competitive tool for BSM searches. In particular, they provided constraints on anomalous magnetic moment of τ lepton with the precision comparable to the best world-limits from the LEP experiments. The latest precision results for $\gamma\gamma \to \mu^+\mu^-$ measured in non-UPC Pb+Pb collisions in all $0-100\%$ centralities revealed new features and made progress on the interpretation using the latest initial-state calculations.

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