PROCEEDINGS OF SCIENCE

BSM physics using photon-photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector

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In heavy-ion collisions, the highly relativistic ions act as a strong source of electromagnetic radiation, enhanced by the large proton charge number Z. Ultra-peripheral collisions (UPC) offer a natural environment where one can observe the photon-initiated production of Beyond Standard Model (BSM) processes with QED couplings. One such process sensitive to BSM effects is light-by-light scattering. This process was directly observed for the first time in UPC events at the LHC by ATLAS. In these proceedings, the recent ATLAS measurements of light-by-light scattering are presented. These measurements are performed using the full Run-2 dataset, which results in substantially reduced uncertainties compared to the previous measurements. The new measurements provide a precise and unique opportunity to investigate extensions of the Standard Model, such as the presence of axion-like particles. Measurements of tau-pair production via two-photon scattering that investigate the anomalous magnetic moment of the tau lepton are also presented. This process is also potentially sensitive to BSM effects.

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1. Introduction

The heavy-ion (HI) physics is an important part of the physics programme of the ATLAS experiment [1] at the Large Hadron Collider (LHC). A special class of HI collisions are ultra-peripheral collisions (UPC), which occur when the distance between interacting nuclei is greater than the sum of their radii. The relativistic ions are accompanied by large electromagnetic fields that can also be considered as fluxes of quasi-real photons, as described in the Equivalent Photon Approximation formalism [2, 3]. Since in UPC, one can observe photon-induced interactions, there are many new research opportunities than in typical HI collisions. There are several reasons for using the UPC HI collisions to study rare processes and use them in the Beyond Standard Model (BSM) searches. The photon-induced interactions are also present in *pp* collisions, however, thanks to Z^2 scaling of the photon fluxes (Z is the proton number), the cross-sections for a given process are substantially increased in HI collisions. Additionally, in HI collisions, there is very low hadronic pile-up, which enables the selection of exclusive events and also triggering on low-p_{T} particles. In these proceedings, two results of the ATLAS experiment are discussed: measurement of light-by-light scattering with the search for axion-like particles [4], and the measurement of the τ-lepton anomalous magnetic moment [5]. Both measurements are based on the UPC HI data and are potentially sensitive to BSM effects.

2. Light-by-light scattering and the search for axion-like particles

Light-by-light (LbyL), $\gamma\gamma \to \gamma\gamma$ scattering is a process allowed by the quantum electrodynamics (QED) at the lowest order via loop diagrams involving charged fermions or $W^{\pm}$ bosons. LbyL production can be modified by several BSM phenomena: new particles entering the loop, Born-Infeld extensions of the QED, space-time non-commutativity in QED, extra spatial dimensions, etc. Also, the diphoton mass spectrum measured in the LbyL process offers an opportunity to search for hypothetical new neutral axion-like particles (ALP), which may contribute to the distribution as a narrow diphoton resonance [6].

The event selection of the LbyL measurement required the presence of two identified photons with $E_{\mathrm{T}} > 2.5$ GeV and $|\eta| < 2.37$, diphoton invariant mass, $m_{\gamma\gamma}$, greater than 5 GeV, low diphoton p_{T} (below 1 or 2 GeV, depending on the diphoton mass) and low diphoton acoplanarity: $1 - |\Delta\phi|/\pi < 0.01$. Events having any extra low-p_{T} tracks are vetoed.

The two main background sources for the LbyL scattering are exclusive dielectron production, $\gamma\gamma \to e^+e^-$, and central exclusive production (CEP), $gg \to \gamma\gamma$. The former is estimated using a fully data-driven approach, while the latter is estimated using MC template fitting in the control region defined by the diphoton selected events with reversed acoplanarity requirement (acoplanarity above 0.01). In this approach, the CEP background template is obtained from SuperChic v3.0 [7] MC simulation. The CEP sample is normalised such that the yield in the control region equals the sum of contributions from signal, $\gamma\gamma \to e^+e^-$ and CEP backgrounds. Figure 1 shows good agreement in the shape of the distributions, however with visible data excess.

The cross-section is measured in a fiducial phase space, defined by the requirements reflecting event selection. The measured fiducial cross-section is $\sigma_{fid} = 120 \pm 17$ (stat.) $\pm$ 13 (syst.) $\pm$ 4 (lumi.) nb, which can be compared to the predicted values of 80 ± 8 nb from Ref. [8] and 78 ± 8 nb

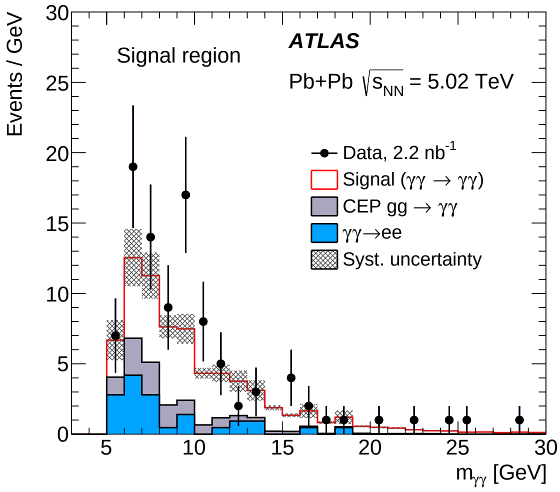

Figure 1: Detector-level diphoton invariant mass distribution for $\gamma\gamma \to \gamma\gamma$ event candidates for the 2015+2018 data. Data (points) are compared to the sum of signal and background expectations (histograms). Systematic uncertainties on the signal and background processes, excluding that on the luminosity, are denoted as shaded bands. [4]

from SuperChic v3.0 MC simulation. The differential fiducial cross-section is unfolded to particle level in the fiducial phase space to correct for bin migrations due to detector resolution effects. The unfolded differential fiducial cross-section is compared with the prediction from SuperChic v3.0, and no significant difference between the prediction and the data is seen.

The $m_{\gamma\gamma}$ distribution, presented in Figure 1, is used for ALP search. The ALPs couple directly to photons, therefore they can be produced in the $\gamma\gamma \to a \to \gamma\gamma$ reaction, where a denotes the ALP field. Their presence can be detected as a narrow resonance in the diphoton invariant mass distribution.

The contributions from the LbyL, exclusive dielectron production, and central exclusive diphoton production are considered as background in the ALP search. The two latter sources of background are estimated using the same data-driven methods as in the LbyL measurement. The contribution from the LbyL process is estimated using events generated by the SuperChic v3.0 MC generator. The diphoton mass distribution from the simulated LbyL sample is normalised to the number of events in data after subtraction of the $\gamma\gamma \to e^+e^-$ and CEP $gg \to \gamma\gamma$ contributions excluding the mass search region. For every bin, the ALP contribution is fitted individually using the maximum-likelihood fit. No significant deviation from the background-only hypothesis is observed. The result is used to estimate the upper limit on the ALP coupling $1/\Lambda_a$ at 95% confidence level, as presented in Figure 2.

3. Exclusive $\tau^+\tau^-$ production and constraints on a_τ

The exclusive production of τ-leptons was observed by the ATLAS experiment using 1.44 nb^{-1} of Pb+Pb collision data at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collected in 2018 [5]. The measurement of the $\gamma\gamma \to \tau^+\tau^-$ process allows to set constraints on the anomalous magnetic moment of the τ-lepton,

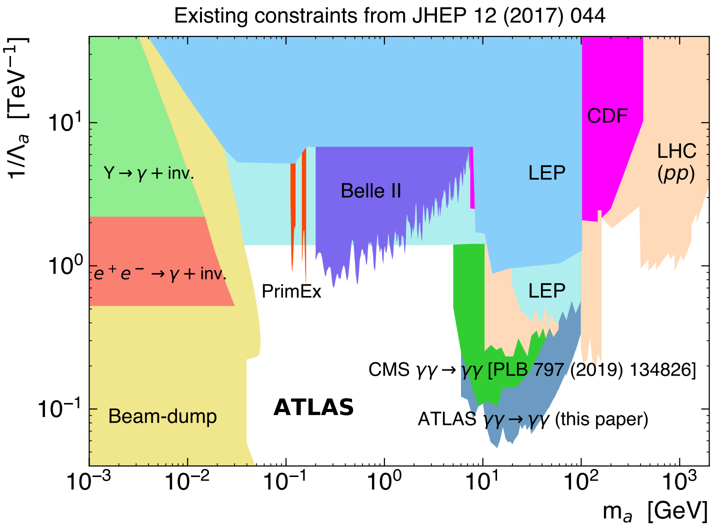

Figure 2: Compilation of exclusion limits at 95% CL in the ALP–photon coupling ($1/\Lambda_a$) versus ALP mass (m_a) plane obtained by different experiments. The existing limits are compared with the limits extracted from this measurement. The exclusion limits labelled "LHC (pp)" are based on pp collision data from ATLAS and CMS. [4]

a_τ. Modifications of the SM value of a_τ are predicted in some BSM theories including leptoquarks, lepton compositeness, supersymmetry, etc. Currently, the best constraints for a_τ are from the DELPHI experiment: $-0.052 < a_\tau < 0.013$ (95% CL) [9].

Due to very low p_T of signal τ-leptons, the identification techniques usually used in ATLAS cannot be applied. Instead, signal events are categorised based on the τ-leptons decay modes as μ + 1 track, μ + 3 tracks, and $\mu + e$ categories. Selected events are triggered with a single muon trigger requiring muon p_T above 4 GeV. Additionally, the event exclusivity is ensured by imposing a requirement of no forward neutrons detected in the ZDC (0n0n category). The selected muons have p_T above 4 GeV and $|\eta| < 2.4$, selected electrons have p_T above 4 GeV and $|\eta| < 2.47$, while selected tracks have p_T above 100 MeV and $|\eta| < 2.5$. Event with additional low-p_T tracks are vetoed. For μ + 1 track and μ + 3 tracks categories also events with additional low-p_T tracks and low-p_T clusters are vetoed. Due to different background processes contributing to each signal category, additional requirements are introduced in μ + 1 track (p_T of the muon and track system above 1 GeV) and μ + 3 tracks (mass of the three track system below 1.7 GeV) categories.

Main background contributions originate from exclusive dimuon production with FSR and diffractive photonuclear interactions. Background from $\gamma\gamma \to \mu\mu(\gamma)$ production is estimated using MC simulation and constrained by a dimuon control region in the data.

Diffractive photonuclear background present in μ + 1 track and μ + 3 tracks signal regions, is estimated with a data-driven technique. Control regions are defined with an additional track with $p_T < 500$ MeV and allowing events from Xn0n category (no neutrons on one side of the ZDC, some neutrons on the other side). Event yields are extrapolated from control to signal region by relaxing the veto on additional (unmatched) clusters from 0 to 8. Normalisation is done to the event yield in the region with 4 to 8 unmatched clusters.

The $\gamma\gamma \to \tau^+\tau^-$ signal strength and a_τ value are extracted using a profile likelihood fit using the muon p_T distribution. The fitting procedure is performed simultaneously, combining all signal regions and dimuon control region. The inclusion of the dimuon control region reduces systematic uncertainty from the photon flux. Calculations are based on the same parameterisation as the one used in the previous LEP measurements [9]. ATLAS results showed clear, exceeding 5σ, observation of the $\gamma\gamma \to \tau^+\tau^-$ process.

The fitted muon p_T distributions for the μ + 1 track signal region and two muon control region are shown in Figure 3. A very good data-to-prediction agreement is seen for the best-fit value of the a_τ.

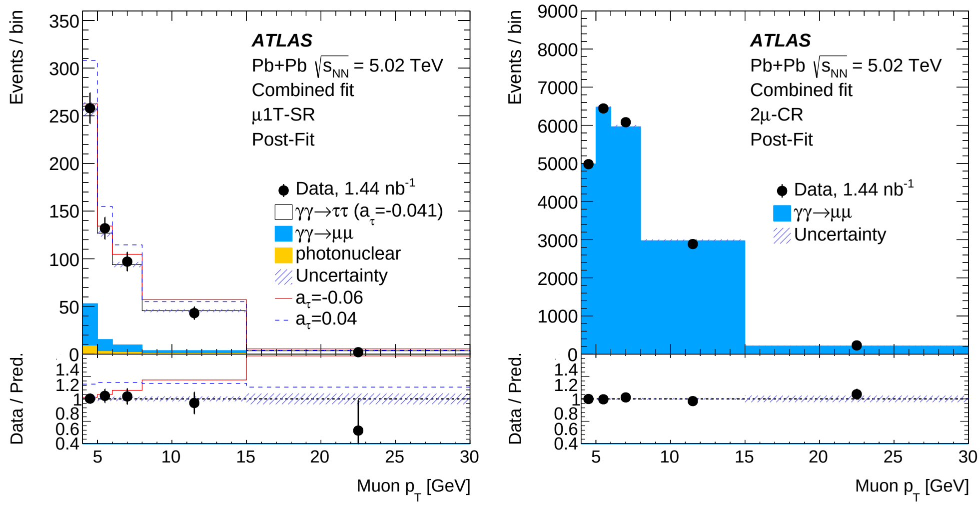

Figure 3: Muon transverse momentum distributions in the μ + 1 track signal region (left) and two muon control region (right). Black markers denote data and stacked histograms indicate the different components contributing to the regions. The signal contribution is corresponding to the best-fit a_τ value (a_τ=-0.041). For comparison, signal contributions with alternative a_τ values are shown as solid red (a_τ=-0.06) or dashed blue (a_τ=0.04) lines. Vertical bars denote uncertainties from the finite number of data events. Hatched bands represent $\pm 1\sigma$ systematic uncertainties of the prediction with the constraints from the fit applied. [5]

The signal strength is consistent with the Standard Model prediction. The best fit value is $a_\tau = -0.041$, with the corresponding 95% CL interval being $(-0.057, 0.024)$. Figure 4 presents the corresponding 95% CL for each of the signal categories including also the combined value along with the expected interval and the comparison with the previous measurements of a_τ. The obtained constraints are similar to currently the best result obtained by DELPHI [9]. The ATLAS result is largely limited by statistical uncertainty, and could therefore be improved with more UPC data collected in Run 3.

4. Conclusions

The $\gamma\gamma \to \gamma\gamma$ process has been measured by the ATLAS experiment with the results consistent with the Standard Model prediction. The exclusion limits for ALP cross-section and coupling were obtained for the mass range of $6 < m_a < 100$ GeV. The $\gamma\gamma \to \tau^+\tau^-$ process has been observed

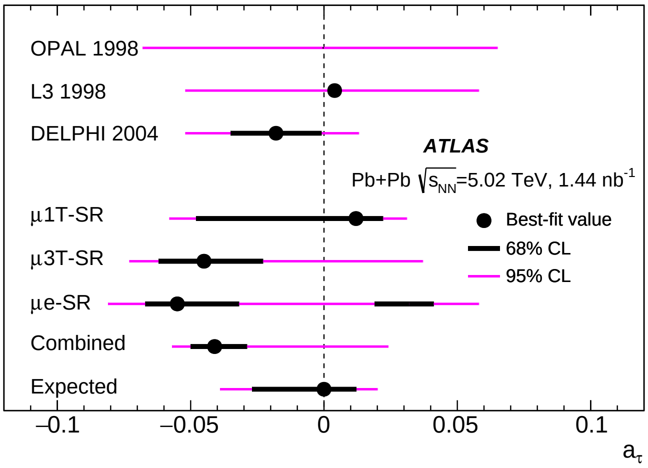

Figure 4: Measurements of a_τ from fits to individual signal regions, and from the combined fit [5]. These are compared with existing measurements from the OPAL, L3 and DELPHI experiments at LEP. The markers denote the best-fit a_τ value for each measurement if available, while thick black (thin magenta) lines show 68% CL (95% CL) intervals. The expected interval from the ATLAS combined fit is also shown. [5]

by the ATLAS experiment. The signal strength is consistent with the Standard Model expectation. The constraints on the τ-lepton anomalous magnetic moment are competitive with the previous measurements at LEP and could be improved with a larger data set collected in the future LHC runs.

Acknowledgements

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