



ATLAS CONF Note

ATLAS-CONF-2019-002

16th March 2019



Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

The ATLAS Collaboration

This note describes the observation of the light-by-light scattering process, $\gamma\gamma \rightarrow \gamma\gamma$, in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The analysis is conducted using a data sample corresponding to an integrated luminosity of 1.73 nb^{-1} , collected in November 2018 by the ATLAS experiment at the LHC. Light-by-light scattering event candidates are selected in events with two photons produced exclusively, each with transverse energy $E_T^\gamma > 3 \text{ GeV}$ and pseudorapidity $|\eta_\gamma| < 2.37$, diphoton invariant mass above 6 GeV, and small diphoton transverse momentum and acoplanarity. After applying all selection criteria, 59 candidate events are observed for a background expectation of 12 ± 3 events. An excess of events over the expected background is found with an observed significance of 8.2 standard deviations. The measured fiducial cross section is $78 \pm 13 \text{ (stat.)} \pm 7 \text{ (syst.)} \pm 3 \text{ (lumi.) nb}$.

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Light-by-light scattering, $\gamma\gamma \rightarrow \gamma\gamma$, is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics [1, 2]. In the Standard Model (SM), the $\gamma\gamma \rightarrow \gamma\gamma$ reaction proceeds at one-loop level at order α_{em}^4 (where α_{em} is the fine structure constant) via virtual box diagrams involving electrically charged fermions (leptons and quarks) or $W^\pm$ bosons. However, in various extensions of the SM, extra contributions are possible, making the measurement of $\gamma\gamma \rightarrow \gamma\gamma$ scattering sensitive to new physics [3–7]. Light-by-light scattering graphs with electron loops also contribute to the anomalous magnetic moment of the electron and muon [8, 9].

The $\gamma\gamma \rightarrow \gamma\gamma$ reaction has been measured in photon scattering in the Coulomb field of a nucleus (Delbrück scattering) [10–13] and in the photon-splitting process [14]. A related process, in which initial photons fuse to form a pseudoscalar meson that subsequently decays to a pair of photons, has been studied at electron–positron colliders [15–17].

Light-by-light scattering can occur in relativistic heavy-ion collisions at impact parameters larger than about twice the radius of the ions. The strong interaction becomes less significant and the electromagnetic (EM) interaction becomes more important in these ultra-peripheral collision (UPC) events. The EM fields produced by the colliding Pb nuclei can be described as a beam of quasi-real photons with a small virtuality of $Q^2 < 1/R^2$, where R is the radius of the charge distribution and so $Q^2 < 10^{-3} \text{ GeV}^2$ [18, 19]. The cross section for the reaction $\text{Pb}+\text{Pb}(\gamma\gamma) \rightarrow \text{Pb}+\text{Pb}\gamma\gamma$ can then be calculated by convoluting the appropriate photon flux with the elementary cross section for the process $\gamma\gamma \rightarrow \gamma\gamma$. Since the photon flux associated with each nucleus scales as Z^2 , the cross section is strongly enhanced as compared to proton–proton (pp) collisions.

Strong evidence for this process in Pb+Pb UPC at the Large Hadron Collider (LHC) has been reported by the ATLAS [2] and CMS [20] collaborations, based on the Pb+Pb dataset of 0.4 nb^{-1} recorded in 2015 at a centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The present note describes a new measurement exploiting 1.73 nb^{-1} of Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$, recorded in November 2018 with the ATLAS detector at the LHC. The analysis follows the approach proposed in Ref. [21] and the methodology used in the previous ATLAS measurement.

The ATLAS detector [22] is a multipurpose particle detector that covers nearly the entire solid angle around the interaction point (IP).¹ It consists of an inner detector (ID) for charged-particle tracking in the pseudorapidity region $|\eta| < 2.5$, EM and hadronic calorimeters that provide energy measurements up to $|\eta| = 4.9$, and a muon spectrometer that covers $|\eta| < 2.7$. Forward calorimeters (FCal) cover the range of $3.2 < |\eta| < 4.9$. The zero-degree calorimeters (ZDC), located along the beam axis at 140 m from the IP on both sides, detect neutral particles, including neutrons emitted from the nucleus.

The final-state signature of interest is the exclusive production of two photons, $\text{Pb}+\text{Pb}(\gamma\gamma) \rightarrow \text{Pb}^{(*)}+\text{Pb}^{(*)}\gamma\gamma$, where the diphoton final-state is measured in the central detector, and the incoming Pb ions survive the EM interaction, with a possible EM excitation [23], denoted by (*). Hence, the final state consists of two low-energy photons and no further activity in the detector, and in particular no reconstructed charged-particle tracks originating from the IP.

A two-level trigger system was used to select events online [24]. It consists of a Level-1 trigger implemented using a combination of custom electronics and programmable logic, and a software-based high-level

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. The distance between two objects in $\eta - \phi$ space is $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse momentum is defined by $p_T = p \sin \theta$.

trigger (HLT). Candidate diphoton events were recorded using a dedicated trigger for events with moderate activity in the calorimeter but little additional activity in the detector. At Level-1 a logical OR of two conditions was required: at least one EM cluster [25] with $E_T > 1$ GeV in coincidence with total E_T measured in the calorimeter between 4–200 GeV, or at least two EM clusters with $E_T > 1$ GeV with total E_T measured in the calorimeter below 50 GeV. The upper bound on total E_T was optimised to be fully efficient on signal events, while allowing to reject events from non-peripheral Pb+Pb collisions. At HLT, the total FCal E_T on each side of the IP was required to be consistent with noise (FCal veto), and the number of hits in the pixel detector (part of the ID) was required to be at most 15.

Simulated $\gamma\gamma \rightarrow \gamma\gamma$ signal events were generated using SuperChic v3.0 [26]. This program takes into account box diagrams with charged leptons, quarks and $W^\pm$ bosons. An alternative signal sample was generated using calculations from Ref. [27]. These calculations were then folded with the Pb+Pb photon flux taken from the Starlight 2.0 Monte Carlo (MC) generator [28]. The theoretical uncertainty on the cross section is mainly due to the limited knowledge of nuclear form factors and initial photon fluxes. This is extensively studied in Ref. [20], and the relevant uncertainty is estimated to be 10% within the fiducial phase space of the measurement. Higher-order corrections, which are not included in the calculations, are also part of the theoretical uncertainty and amount to 1–3% in the fiducial phase space [29, 30].

The exclusive diphoton final state can also be produced via the strong interaction through a quark loop in the exchange of two gluons in a colour-singlet state. This central exclusive production (CEP) process, $gg \rightarrow \gamma\gamma$, is also modelled using SuperChic v3.0. The $\gamma\gamma \rightarrow e^+e^-$ process is a potential background, when both leptons are reconstructed as photons, but is also valuable for various calibration studies in the analysis. The process was modelled with the Starlight 2.0 generator. Its production cross section is computed by combining the Pb+Pb photon flux with the leading-order formula for $\gamma\gamma \rightarrow e^+e^-$. Two-photon production of quark–antiquark pairs, with their subsequent decay to multiple hadrons, is estimated using HERWIG++ 2.7.1 [31], where the initial photon fluxes from pp collisions are implemented. The sample was then normalised to cover the differences in the photon fluxes between Pb+Pb and pp collisions. All simulated events make use of a detector simulation [32] based on GEANT4 [33] and are reconstructed with the standard ATLAS reconstruction software.

Photons are reconstructed from EM clusters in the calorimeter and tracking information provided by the ID, which allows the identification of photon conversions [34]. An energy calibration specifically optimised for photons [35] is applied to the candidates to account for energy loss before the calorimeter and both lateral and longitudinal shower leakage. Dedicated corrections [34] are applied to photons in MC samples to correct for known mismodelling of quantities that describe the properties (“shapes”) of the associated EM showers.

The photon particle identification (PID) in this analysis is based on a selection of these shower-shape variables, optimised for the signal events. Only photons with $E_T > 3$ GeV and $|\eta| < 2.37$, excluding the calorimeter transition region $1.37 < |\eta| < 1.52$, are considered. This allows for good separation between prompt photons and fake signatures due to calorimeter noise, cosmic-ray muons, or non-prompt photons originating from the decay of neutral hadrons. The photon PID is based on a dedicated neural network trained on background photons extracted from data and photons from the signal MC. The selection of background photons follows the procedure established in Ref. [2].

Selected events are required to have exactly two photons satisfying the above selection criteria, with a diphoton invariant mass ($m_{\gamma\gamma}$) greater than 6 GeV. In order to suppress the $\gamma\gamma \rightarrow e^+e^-$ background, a veto on a “standard” charged-particle track with $p_T > 100$ MeV, $|\eta| < 2.5$, and a minimal number of hits in the pixel and silicon detectors is imposed. To further suppress $\gamma\gamma \rightarrow e^+e^-$ events with poorly reconstructed

charged-particle tracks, candidate events are required to have no “pixel tracks”, which are reconstructed using information from the pixel detector only. Candidate pixel tracks are required to have $p_T > 50$ MeV, $|\eta| < 2.5$, and a minimal number of hits in the pixel detector. Events with pixel tracks matched to photon candidates with $|\Delta\eta| < 0.5$ are rejected. According to MC simulation, these requirements reduce the fake photon background from the dielectron final state by a factor of 10^4 , whilst they have only minor impact (7%) on $\gamma\gamma \rightarrow \gamma\gamma$ signal events.

To reduce other fake-photon backgrounds, such as cosmic-ray muons, the transverse momentum of the diphoton system ($p_T^{\gamma\gamma}$) is required to be below 1 GeV for $m_{\gamma\gamma} < 12$ GeV and below 2 GeV for $m_{\gamma\gamma} > 12$ GeV. To reduce prompt-photon background from CEP $gg \rightarrow \gamma\gamma$ reactions, an additional requirement on the reduced acoplanarity, $\text{Aco} = (1 - |\Delta\phi_{\gamma\gamma}|/\pi) < 0.01$, is used. The above requirements define the fiducial region for the signal measurement.

Exclusive dielectron pairs from the reaction $\text{Pb+Pb}(\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)} e^+ e^-$ are used for various aspects of the analysis, in particular to validate the EM calorimeter energy scale and resolution [35]. To select $\gamma\gamma \rightarrow e^+ e^-$ candidates, events are required to pass the same trigger as in the diphoton selection. Each electron is reconstructed from an EM energy cluster in the calorimeter matched to a track in the ID [36]. The $\gamma\gamma \rightarrow e^+ e^-$ events are selected by requiring exactly two oppositely charged electrons, no further charged-particle tracks coming from the interaction region, and dielectron reduced acoplanarity, $\text{Aco} < 0.01$. The observed $\gamma\gamma \rightarrow e^+ e^-$ event yield in data is compatible with that expected from simulation.

The Level-1 trigger efficiency is estimated with $\gamma\gamma \rightarrow e^+ e^-$ events passing an independent trigger. The Level-1 trigger efficiency as a function of the electron EM cluster energy sum, ($E_T^{\text{cluster1}} + E_T^{\text{cluster2}}$), reaches 60% for $E_T^{\text{cluster1}} + E_T^{\text{cluster2}} = 5$ GeV and 75% for $E_T^{\text{cluster1}} + E_T^{\text{cluster2}} = 6$ GeV. The efficiency plateau is reached at around $E_T^{\text{cluster1}} + E_T^{\text{cluster2}} = 10$ GeV, as shown in Figure 1(a). The measured efficiency is parameterised and used to correct the trigger response in the simulation. To test the stability of the results, the analysis is repeated using tighter or looser dielectron event selection criteria, and the resulting differences are taken as a systematic uncertainty. The FCal veto efficiency is estimated using $\gamma\gamma \rightarrow e^+ e^-$ events selected with a dedicated control trigger without involving the FCal requirement. It is estimated to be $(99.1 \pm 0.6)\%$. Due to the high hit-reconstruction efficiency and relatively low conversion probability of signal photons in the pixel detector, the inefficiency of the pixel veto requirement at the trigger level is found to be negligible.

The photon reconstruction efficiency is extracted from data using $\gamma\gamma \rightarrow e^+ e^-$ events, where one of the electrons emits a hard bremsstrahlung photon due to interaction with the material of the detector. The analysis is performed for events with exactly one identified electron and exactly two reconstructed charged-particle tracks, and a tag-and-probe method is used as described in Ref. [2]. The resulting photon reconstruction efficiency is shown in Figure 1(b). It rises from about 60% at $E_T = 2.5$ GeV to 90% at $E_T = 6$ GeV and is used to derive simulation-to-data correction factors.

High- p_T exclusive dilepton production ($\gamma\gamma \rightarrow \ell^+ \ell^-$, where $\ell = e, \mu$) with final-state radiation (FSR) is used to measure the photon PID efficiency, defined as the probability for a reconstructed photon to pass the identification criteria. Events with exactly two oppositely charged tracks with $p_T > 0.5$ GeV are selected from UPC triggered events. In addition, a requirement to reconstruct a photon candidate with $E_T > 2.5$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$ is imposed. A photon candidate is required to be separated from each track by fulfilling $\Delta R > 0.3$ to avoid leakage between the photon and the electron clusters. The FSR event candidates are identified using a $p_T^{\ell\ell\gamma} < 1$ GeV requirement, where $p_T^{\ell\ell\gamma}$ is the transverse momentum of the three-body system consisting of the two tracks and the photon candidate. Figure 1(c) shows the photon PID efficiency as a function of reconstructed photon E_T , where

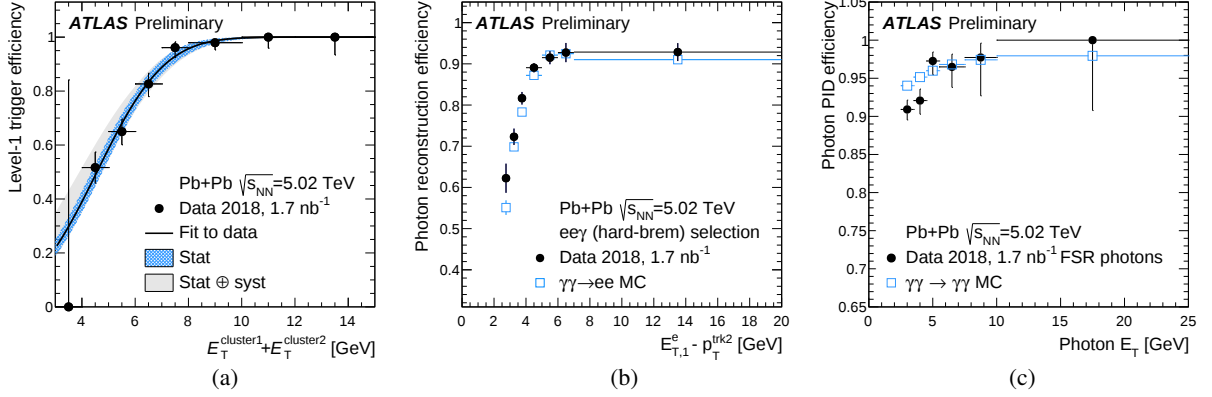


Figure 1: Measured Level-1 trigger efficiency as a function of the reconstructed energy in $\gamma\gamma \rightarrow e^+e^-$ events (a), photon reconstruction efficiency as a function of the photon E_T (approximated with $E_{T,1}^e - p_{T,1}^{\text{trk2}}$, where trk2 denotes the track of the second leading electron) (b) and photon particle-identification efficiency as a function of the photon E_T (c).

the measurement from data is compared to the one extracted from the signal MC sample. Based on these studies, MC events are corrected using photon E_T -dependent simulation-to-data correction factors.

The two electrons exhibit balanced transverse momentum with an asymmetry, $|p_T^{e^+} - p_T^{e^-}|$, expected to be below 30 MeV. This is much smaller than the EM calorimeter energy resolution, which can thus be measured by the difference $E_T^{\text{cluster1}} - E_T^{\text{cluster2}}$. Below 10 GeV electron E_T the relative energy resolution is found to be between 8 and 10% and is well reproduced by the MC simulation. The EM energy scale is validated using the ratio of the electron cluster E_T^e and the electron track p_T^{trk} .

The $\gamma\gamma \rightarrow e^+e^-$ process can be a source of fake diphoton events, since misidentification of electrons as photons can occur when the electron track is not reconstructed or the electron emits a hard bremsstrahlung photon. The $\gamma\gamma \rightarrow e^+e^-$ yield in the signal region is estimated using a data-driven method. Two control regions (CRs) are defined with exactly two photons passing the signal selection, but requiring also one or two pixel tracks. The event yield observed in these two CRs is extrapolated to the signal region using the probability to miss the electron pixel track if the standard track is not reconstructed (p_{mistag}^e). It is measured in data in a region with exactly one standard track and two photons with $\text{Aco} < 0.01$. In order to verify the stability of the p_{mistag}^e estimation method, the Aco requirement is dropped and the difference with the nominal selection is taken as a systematic uncertainty. This leads to $p_{\text{mistag}}^e = (47 \pm 9)\%$. The number of $\gamma\gamma \rightarrow e^+e^-$ events in the signal region is estimated to be 7 ± 3 , where the uncertainty accounts for the p_{mistag}^e uncertainty, the CR statistical uncertainty, and the difference found between the CRs defined by requiring exactly one or two pixel tracks, respectively.

The $\text{Aco} < 0.01$ requirement significantly reduces the CEP $gg \rightarrow \gamma\gamma$ background. Its remaining contribution is estimated from a control region defined by applying the same selection as for the signal region, but inverting the Aco requirement to $\text{Aco} > 0.01$ (see Figure 2), and correcting the measured event yield for the expected signal and $\gamma\gamma \rightarrow e^+e^-$ contributions. The CEP and $\gamma\gamma \rightarrow e^+e^-$ processes exhibit a significantly broader Aco distribution than the $\gamma\gamma \rightarrow \gamma\gamma$ process. In the CEP process gluons recoil against the Pb nucleus, which then dissociates. The shape of the Aco distribution for $\gamma\gamma \rightarrow e^+e^-$ events is mainly due to the curvature of the trajectory of the electrons in the detector magnetic field, before they emit hard photons in their collisions with the ID material.

The uncertainty on the CEP $gg \rightarrow \gamma\gamma$ background process takes into account the statistical uncertainty due to the limited number of events in the $A_{\text{co}} > 0.01$ control region (17%), as well as experimental and modelling uncertainties. It is found that all experimental uncertainties have negligible impact on the normalisation of the CEP $gg \rightarrow \gamma\gamma$ background. The impact of the MC modelling of the A_{co} shape is estimated using an alternative SuperChic MC sample with no absorptive effects [37]. These effects reflect the absence of secondary particle emissions, which can take place in addition to the $gg \rightarrow \gamma\gamma$ process. After applying the data-driven normalisation procedure, this leads to a 25% change in the CEP background yield in the signal region, which is taken as systematic uncertainty. An additional check is done by varying the gluon parton distribution function (PDF). The differences between the MMHT 2014 [38], CT14 [39] and NNPDF3.1 [40] PDF sets have negligible impact on the shape of the CEP diphoton A_{co} distribution. The background due to the CEP process in the signal region is estimated to be 5 ± 1 events. In addition, the energy deposition in the ZDC, which is sensitive to dissociation of Pb nuclei, is studied for events before the A_{co} selection is imposed. Good agreement is observed between the normalised CEP expectation from MC simulation and the observed events with a signal corresponding to at least one neutron in the ZDC.

The background contribution from $\gamma\gamma \rightarrow q\bar{q}$ production is estimated using MC simulation and is found to be negligible. Exclusive two-meson production can be a potential source of background for light-by-light scattering events, mainly due to their similar back-to-back topology. Mesons can fake photons either by their intermediate decay to photons (neutral mesons: π^0, η, η') or by mis-reconstructed charged-particle tracks (charged mesons: for example π^+, π^- states). Estimates for such contributions are reported in Refs. [21, 41–44] and are considered to have a negligible contribution to the signal region.

The background from other fake diphoton events (mainly those induced by cosmic-ray muons) is estimated using a control region with at least one track reconstructed in the muon system and further studied using the reconstructed photon-cluster time distribution. After imposing $p_{\text{T}}^{\gamma\gamma}$ requirements, this background is found to be negligible. Background from the $\gamma\gamma \rightarrow e^+e^-\gamma\gamma$ reaction is evaluated using the MADGRAPH5_AMC@NLO MC generator [45] and the Pb+Pb photon flux from Starlight. This contribution is estimated to be below 1% of the expected signal and has therefore negligible impact on the results. The contribution from bottomonia production (for example, $\gamma\gamma \rightarrow \eta_b \rightarrow \gamma\gamma$ or $\gamma\text{Pb} \rightarrow \Upsilon \rightarrow \gamma\eta_b \rightarrow 3\gamma$) is calculated using parameters from Refs. [46, 47] and considered to be negligible. The contribution from UPC events where both nuclei emit a bremsstrahlung photon is estimated using calculations from Ref. [48]. The cross section for single-bremsstrahlung photon production of the Pb ion in the fiducial region of the measurement is calculated to be below 10^{-4} pb so that the coincidence of two such occurrences is considered to be negligible.

After applying the signal selection, 59 events are observed in the data where 30 ± 4 signal events and 12 ± 3 background events are expected. The compatibility of the data with the background-only hypothesis has been evaluated in a narrower $0 < A_{\text{co}} < 0.005$ range, which in studies using simulated data was found to be most sensitive. In this region, 42 events are observed in the data where 25 ± 3 signal events and 6 ± 2 background events are expected. The data excess is quantified by calculating the p -value using a profile likelihood-ratio test statistic [49], resulting in an observed (expected) statistical significance of 8.2 (6.2) standard deviations. Photon kinematic distributions for events satisfying all selection criteria are shown in Figure 3. A further cross-check of energy deposits in ZDC for events in the signal region is performed. The activity in the ZDC agrees with the signal-plus-background expectation. The analysis is also repeated with a lower minimal photon E_{T} requirement of 2.5 GeV, yielding an increase of signal statistics but also an increased relative background contribution. Consistent results have been found using this relaxed signal selection.

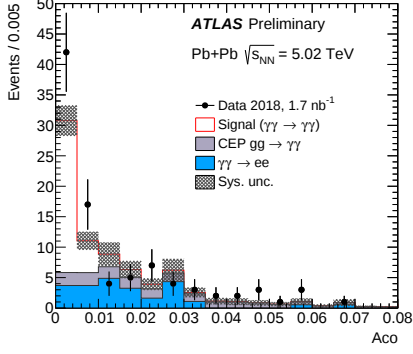


Figure 2: The diphoton Aco distribution for events satisfying signal region selection, but before the $A_{\text{co}} < 0.01$ requirement. Data are shown as points, while the histograms represent the expected signal and background levels.

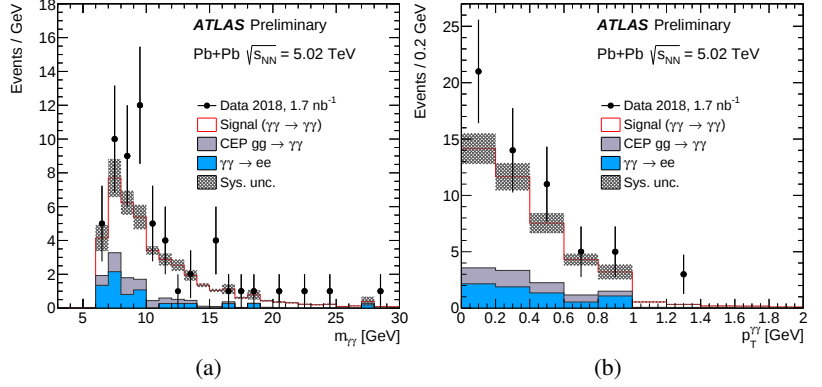


Figure 3: Kinematic distributions for $\gamma\gamma \rightarrow \gamma\gamma$ event candidates: diphoton invariant mass (a), diphoton transverse momentum (b). Data (points) are compared to the sum of signal and background expectations (histograms). Systematic uncertainties on the signal and background processes, excluding that on the luminosity, are denoted as shaded bands.

The cross section for the $\gamma\gamma \rightarrow \gamma\gamma$ process is measured in a fiducial phase space, defined by a set of requirements on the diphoton final state, reflecting the selection at reconstruction level.² Experimentally, the fiducial cross section is given by $\sigma_{\text{fid}} = (N_{\text{data}} - N_{\text{bkg}}) / (C \times \int L dt)$, where N_{data} is the number of selected events in data, N_{bkg} is the number of background events, $\int L dt = 1.73 \pm 0.07 \text{ nb}^{-1}$ is the integrated luminosity of the data sample and C is the overall correction factor that accounts for efficiencies and resolution effects. The C factor is defined as the ratio of the number of selected MC signal events passing the selection and after applying data/MC correction factors to the number of generated MC signal events satisfying the fiducial requirements. The value of C is found to be 0.350 ± 0.024 . The uncertainty on C is estimated by varying the data/MC correction factors within their uncertainties, as well as using a different choice of signal MC. The overall uncertainty is dominated by uncertainties on the photon reconstruction efficiency (4%) and on the trigger efficiency (2%).

The measured fiducial cross section is $78 \pm 13 \text{ (stat.)} \pm 7 \text{ (syst.)} \pm 3 \text{ (lumi.) nb}$, which can be compared to the predicted values of $49 \pm 5 \text{ nb}$ from Ref. [27] and $48 \pm 5 \text{ nb}$ from SuperChic3 MC [26]. The experiment-to-theory ratio using the former theory prediction is 1.59 ± 0.33 .

In summary, this note reports the observation of light-by-light scattering in quasi-real photon interactions from ultra-peripheral Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ recorded in 2018 by the ATLAS experiment. After applying all selection criteria, 59 data events are observed in the signal region, while 12 ± 3 background events are expected. The dominant background processes, i.e. $\text{CEP } gg \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow e^+e^-$ as well as other fake-photon backgrounds, are estimated from data. The statistical significance against the background-only hypothesis is found to be 8.2 standard deviations.

References

- [1] W. Heisenberg and H. Euler, *Folgerungen aus der Diracschen Theorie des Positrons*, [Z. Phys. **98** \(1936\) 714](#), arXiv: [physics/0605038](#).

² Two photons at particle level with $|\eta^\gamma| < 2.4$, $E_T^\gamma > 3 \text{ GeV}$, $m_{\gamma\gamma} > 6 \text{ GeV}$, $p_T^{\gamma\gamma} < 1 \text{ GeV}$ and $A_{\text{co}} < 0.01$.

- [2] ATLAS Collaboration, *Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC*, [*Nature Phys.* **13** \(2017\) 852](#), arXiv: [1702.01625 \[hep-ex\]](#).
- [3] S. Knapen, T. Lin, H. K. Lou and T. Melia, *Searching for Axionlike Particles with Ultraperipheral Heavy-Ion Collisions*, [*Phys. Rev. Lett.* **118** \(2017\) 171801](#), arXiv: [1607.06083 \[hep-ph\]](#).
- [4] M. Bauer, M. Neubert and A. Thamm, *Collider Probes of Axion-Like Particles*, [*JHEP* **12** \(2017\) 044](#), arXiv: [1708.00443 \[hep-ph\]](#).
- [5] J. Ellis, N. E. Mavromatos and T. You, *Light-by-Light Scattering Constraint on Born-Infeld Theory*, [*Phys. Rev. Lett.* **118** \(2017\) 261802](#), arXiv: [1703.08450 \[hep-ph\]](#).
- [6] P. N. Akmansoy and L. G. Medeiros, *Constraining nonlinear corrections to Maxwell electrodynamics using $\gamma\gamma$ scattering*, (2018), arXiv: [1809.01296 \[hep-ph\]](#).
- [7] A. Kostelecky and Z. Li, *Gauge field theories with Lorentz-violating operators of arbitrary dimension*, (2018), arXiv: [1812.11672 \[hep-ph\]](#).
- [8] S. Laporta and E. Remiddi, *The analytical value of the electron light-light graphs contribution to the muon $(g - 2)$ in QED*, [*Phys. Lett. B* **301** \(1993\) 440](#).
- [9] F. Jegerlehner and A. Nyffeler, *The Muon $g-2$* , [*Phys. Rept.* **477** \(2009\) 1](#), arXiv: [0902.3360 \[hep-ph\]](#).
- [10] R. R. Wilson, *Scattering of 1.33 MeV Gamma-Rays by an Electric Field*, [*Phys. Rev.* **90** \(1953\) 720](#).
- [11] G. Jarlskog et al., *Measurement of Delbrück Scattering and Observation of Photon Splitting at High Energies*, [*Phys. Rev. D* **8** \(1973\) 3813](#).
- [12] M. Schumacher, I. Borchert, F. Smend and P. Rullhusen, *Delbrück scattering of 2.75 MeV photons by lead*, [*Phys. Lett. B* **59** \(1975\) 134](#).
- [13] S. Z. Akhmalaliev et al., *Delbrück scattering at energies of 140-450 MeV*, [*Phys. Rev. C* **58** \(1998\) 2844](#).
- [14] S. Z. Akhmalaliev et al., *Experimental investigation of high-energy photon splitting in atomic fields*, [*Phys. Rev. Lett.* **89** \(2002\) 061802](#), arXiv: [hep-ex/0111084](#).
- [15] JADE Collaboration, W. Bartel et al., *A measurement of the η radiative width $\Gamma_{\eta \rightarrow \gamma\gamma}$* , [*Phys. Lett. B* **158** \(1985\) 511](#).
- [16] TPC/Two-Gamma Collaboration, H. Aihara et al., *Study of η formation in photon-photon collisions*, [*Phys. Rev. D* **33** \(1986\) 844](#).
- [17] Crystal Ball Collaboration, D. Williams et al., *Formation of the Pseudoscalars π^0 , η and η' in the Reaction $\gamma\gamma \rightarrow \gamma\gamma$* , [*Phys. Rev. D* **38** \(1988\) 1365](#).
- [18] E. Fermi, *On the theory of collisions between atoms and electrically charged particles*, [*Nuovo Cim.* **2** \(1925\) 143](#), arXiv: [hep-th/0205086](#).
- [19] E. J. Williams, *Nature of the High Energy Particles of Penetrating Radiation and Status of Ionization and Radiation Formulae*, [*Phys. Rev.* **45** \(1934\) 729](#).
- [20] CMS Collaboration, *Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, (2018), arXiv: [1810.04602 \[hep-ex\]](#).
- [21] D. d'Enterria and G. G. Silveira, *Observing light-by-light scattering at the Large Hadron Collider*, [*Phys. Rev. Lett.* **111** \(2013\) 080405](#), [Erratum: *Phys. Rev. Lett.* **116**, 129901 (2016)], arXiv: [1305.7142 \[hep-ph\]](#).

- [22] ATLAS Collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, [JINST **3** \(2008\) S08003](#).
- [23] ALICE Collaboration, *Measurement of the Cross Section for Electromagnetic Dissociation with Neutron Emission in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, [Phys. Rev. Lett. **109** \(2012\) 252302](#), arXiv: [1203.2436 \[nucl-ex\]](#).
- [24] ATLAS Collaboration, *Performance of the ATLAS Trigger System in 2015*, [Eur. Phys. J. C **77** \(2017\) 317](#), arXiv: [1611.09661 \[hep-ex\]](#).
- [25] ATLAS Collaboration, *Calorimeter Clustering Algorithms: Description and Performance*, ATL-LARG-PUB-2008-002, 2008, URL: <https://cds.cern.ch/record/1099735>.
- [26] L. A. Harland-Lang, V. A. Khoze and M. G. Ryskin, *Exclusive LHC physics with heavy ions: SuperChic 3*, [Eur. Phys. J. C **79** \(2019\) 39](#), arXiv: [1810.06567 \[hep-ph\]](#).
- [27] M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, *Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collider*, [Phys. Rev. C **93** \(2016\) 044907](#), arXiv: [1601.07001 \[nucl-th\]](#).
- [28] S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov and J. Butterworth, *STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions*, [Comput. Phys. Commun. **212** \(2017\) 258](#), arXiv: [1607.03838 \[hep-ph\]](#).
- [29] Z. Bern, A. De Freitas, L. J. Dixon, A. Ghinculov and H. L. Wong, *QCD and QED corrections to light-by-light scattering*, [JHEP **11** \(2001\) 031](#), arXiv: [hep-ph/0109079](#).
- [30] M. Kłusek-Gawenda, W. Schaefer and A. Szczurek, *Two-gluon exchange contribution to elastic $\gamma\gamma \rightarrow \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions*, [Phys. Lett. B **761** \(2016\) 399](#), arXiv: [1606.01058](#).
- [31] M. Bähr et al., *Herwig++ Physics and Manual*, [Eur. Phys. J. C **58** \(2008\) 639](#), arXiv: [0803.0883 \[hep-ph\]](#).
- [32] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, [Eur. Phys. J. C **70** \(2010\) 823](#), arXiv: [1005.4568 \[physics.ins-det\]](#).
- [33] GEANT4 Collaboration, S. Agostinelli et al., *GEANT4: A Simulation toolkit*, [Nucl. Instrum. Meth. A **506** \(2003\) 250](#).
- [34] ATLAS Collaboration, *Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016*, Submitted to: *Eur. Phys. J. C* (2018), arXiv: [1810.05087 \[hep-ex\]](#).
- [35] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector using 2015-2016 LHC proton-proton collision data*, Submitted to: *JINST* (2018), arXiv: [1812.03848 \[hep-ex\]](#).
- [36] ATLAS Collaboration, *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV*, Submitted to: *Eur. Phys. J. C* (2019), arXiv: [1902.04655 \[physics.ins-det\]](#).
- [37] L. A. Harland-Lang, V. A. Khoze and M. G. Ryskin, *Exclusive physics at the LHC with SuperChic 2*, [Eur. Phys. J. C **76** \(2016\) 9](#), arXiv: [1508.02718 \[hep-ph\]](#).
- [38] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, [Eur. Phys. J. C **75** \(2015\) 204](#), arXiv: [1412.3989 \[hep-ph\]](#).

- [39] S. Dulat et al., *New parton distribution functions from a global analysis of quantum chromodynamics*, *Phys. Rev. D* **93** (2016) 033006, arXiv: [1506.07443 \[hep-ph\]](#).
- [40] R. D. Ball et al., *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663, arXiv: [1706.00428 \[hep-ph\]](#).
- [41] M. Klusek-Gawenda and A. Szczurek, *Exclusive production of large invariant mass pion pairs in ultraperipheral ultrarelativistic heavy ion collisions*, *Phys. Lett. B* **700** (2011) 322, arXiv: [1104.0571 \[nucl-th\]](#).
- [42] M. Klusek-Gawenda, *Importance of mesons in light-by-light scattering in ultraperipheral lead-lead collisions at the LHC*, *EPJ Web Conf.* **199** (2019) 05004, arXiv: [1809.03823 \[hep-ph\]](#).
- [43] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin and W. J. Stirling, *Central exclusive meson pair production in the perturbative regime at hadron colliders*, *Eur. Phys. J. C* **71** (2011) 1714, arXiv: [1105.1626 \[hep-ph\]](#).
- [44] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin and W. J. Stirling, *Central exclusive production as a probe of the gluonic component of the η' and η mesons*, *Eur. Phys. J. C* **73** (2013) 2429, arXiv: [1302.2004 \[hep-ph\]](#).
- [45] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, arXiv: [1405.0301 \[hep-ph\]](#).
- [46] D. Ebert, R. N. Faustov and V. O. Galkin, *Properties of heavy quarkonia and B_c mesons in the relativistic quark model*, *Phys. Rev. D* **67** (2003) 014027, arXiv: [hep-ph/0210381](#).
- [47] J. Segovia, P. G. Ortega, D. R. Entem and F. Fernández, *Bottomonium spectrum revisited*, *Phys. Rev. D* **93** (2016) 074027, arXiv: [1601.05093 \[hep-ph\]](#).
- [48] C. A. Bertulani and G. Baur, *Electromagnetic Processes in Relativistic Heavy Ion Collisions*, *Phys. Rept.* **163** (1988) 299.
- [49] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554, [Erratum: *Eur. Phys. J. C* **73**, 2501 (2013)], arXiv: [1007.1727 \[physics.data-an\]](#).

Appendix

This appendix contains several plots that complement the information given in the main part of the note.

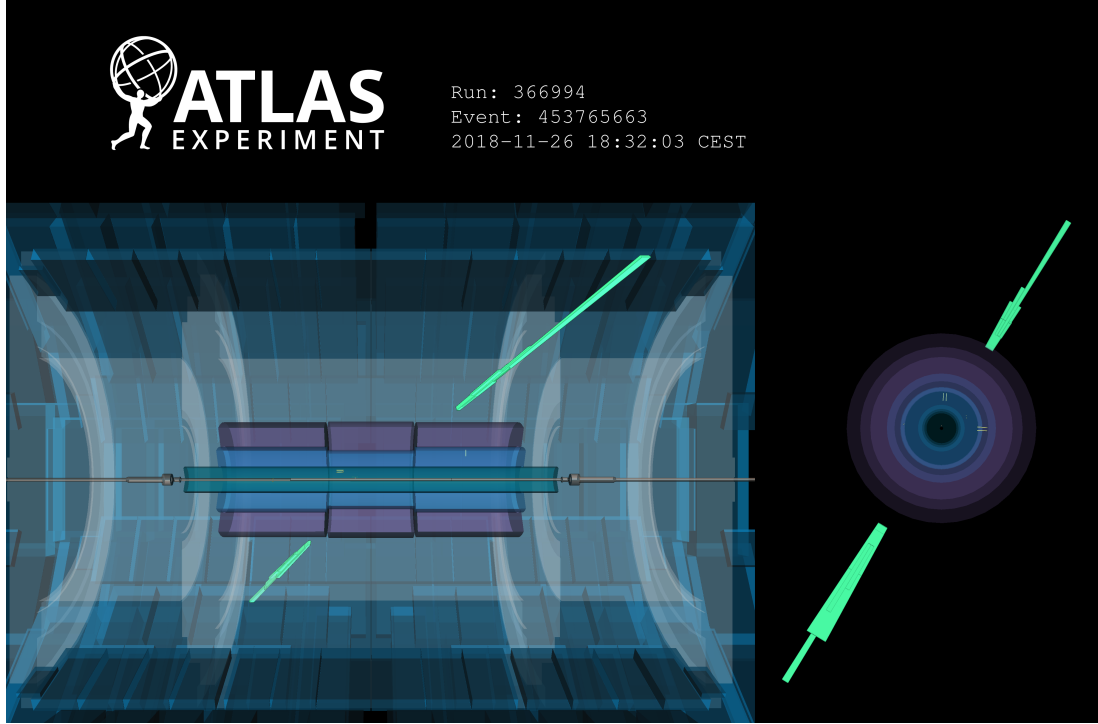


Figure 4: Event display for an exclusive $\gamma\gamma \rightarrow \gamma\gamma$ candidate. Event 453765663 from run 366994 recorded on 2018.11.26 at 18:32:03 is shown. Two back-to-back photons ($E_T^{\gamma^1} = 11$ GeV and $E_T^{\gamma^2} = 10$ GeV) with an invariant mass of 29 GeV, Aco of 0.002, diphoton transverse momentum of 1.2 GeV and no additional activity in the detector are presented. All calorimeter cells with various E_T thresholds are shown: $E_T > 250$ MeV for EMB, EMEC and Tile, $E_T > 800$ MeV for HEC, and $E_T > 1000$ MeV for FCal.

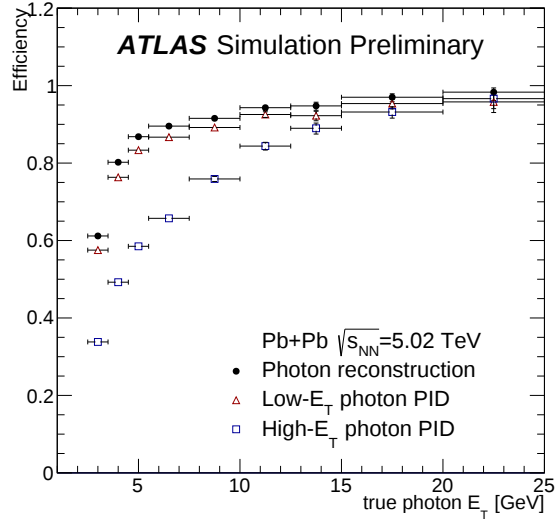


Figure 5: Photon reconstruction (full markers), and identification efficiencies for low- E_T photon PID (open triangles) and high- E_T photon PID (open squares) extracted from the signal MC simulation. The low- E_T working point is used in this analysis, whereas the high- E_T working point corresponds to the “loose” identification criteria from Ref. [34].

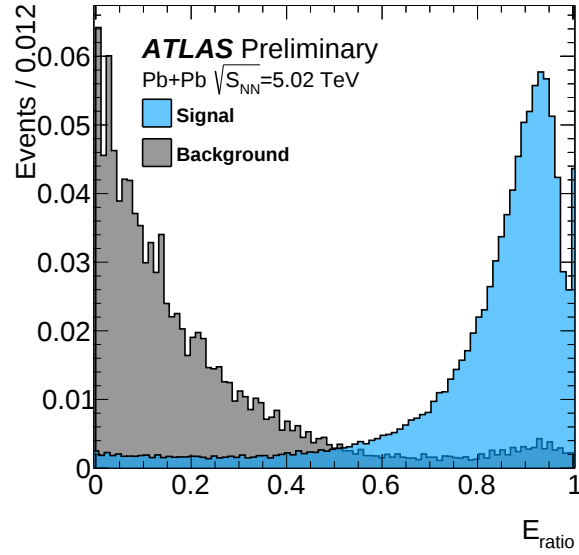


Figure 6: Distribution of the E_{ratio} shower-shape variable, defined as the fraction of energy reconstructed in the first layer of the EM calorimeter relative to the total energy of the cluster, for photons in the signal MC (blue), and fake photons in data (gray). This shower shape variable is one of the most discriminating variables in the photon PID selection used in this analysis.

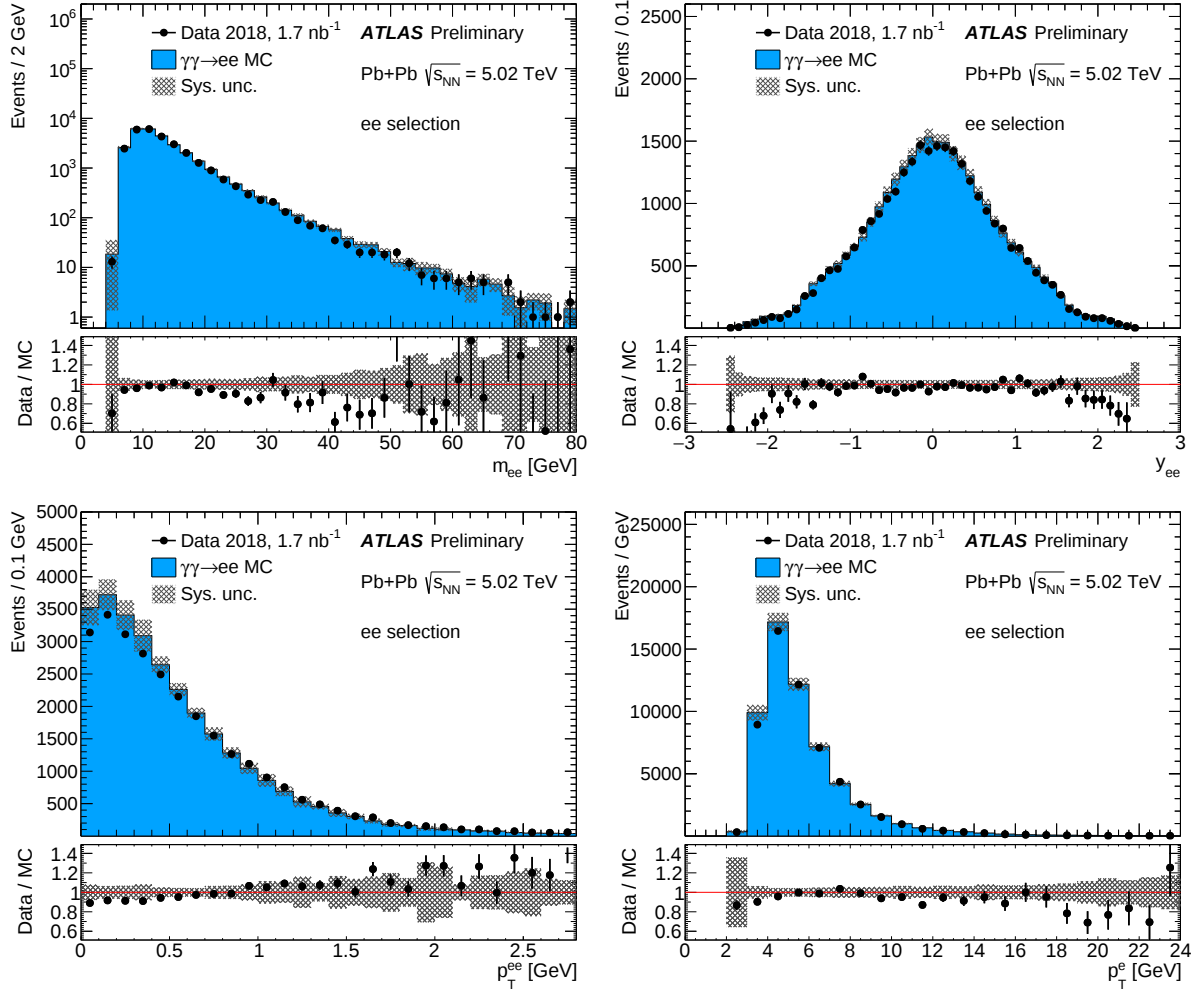


Figure 7: Kinematic distributions for $\text{Pb+Pb } (\gamma\gamma) \rightarrow \text{Pb}^{(*)}+\text{Pb}^{(*)} e^+e^-$ event candidates: dielectron mass (top left), dielectron rapidity (top right), dielectron p_T (bottom left) and electron transverse momentum (bottom right). Data (points) are compared to MC expectations (histograms). Electrons with $E_T > 2.5$ GeV and $|\eta| < 2.47$ excluding the calorimeter transition region $1.37 < |\eta| < 1.52$, and with dielectron reduced acoplanarity, $\text{Aco} < 0.01$, are considered. The shaded bands represent the systematic uncertainties.

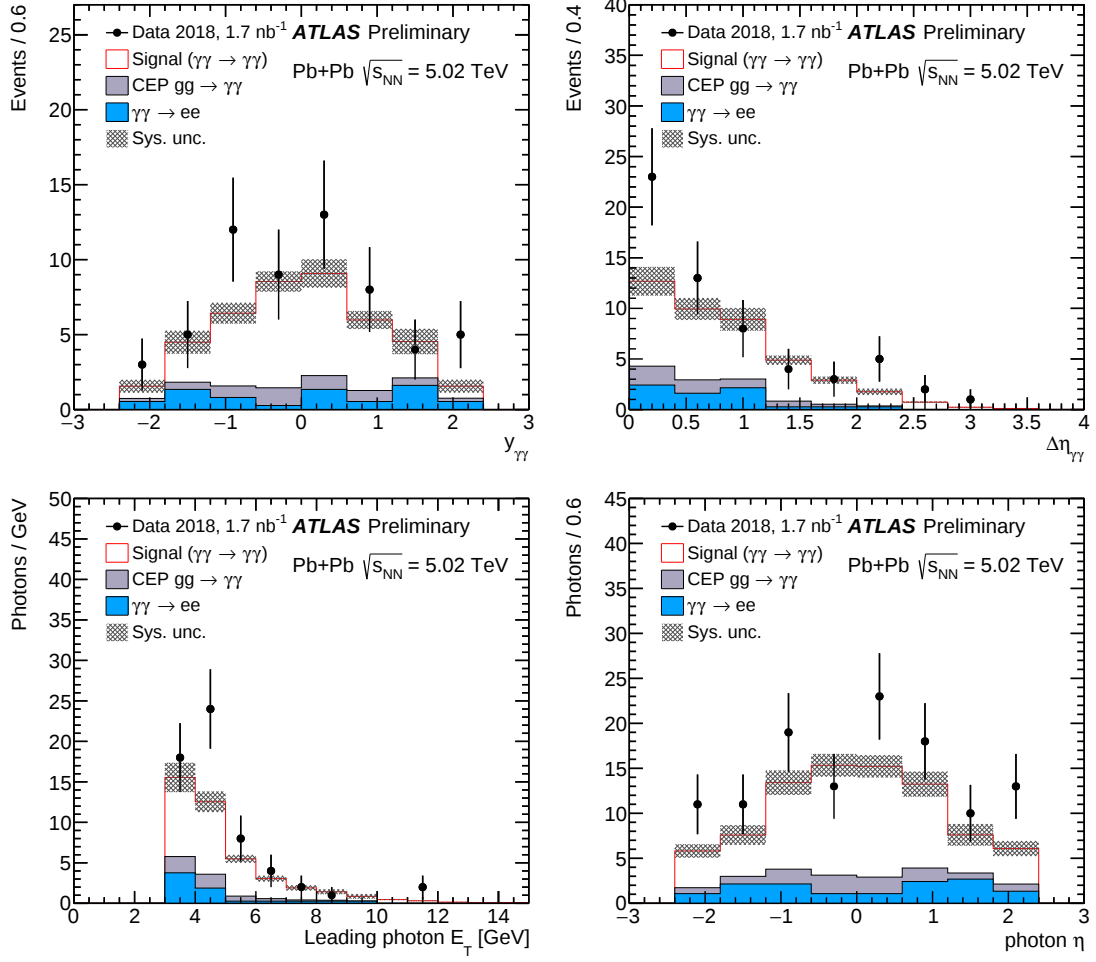


Figure 8: Kinematic distributions for $\gamma\gamma \rightarrow \gamma\gamma$ event candidates: rapidity of the diphoton system (top left), diphoton pseudorapidity difference (top right), leading photon transverse energy (bottom left), and photon pseudorapidity (bottom right). Data (points) are compared 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.

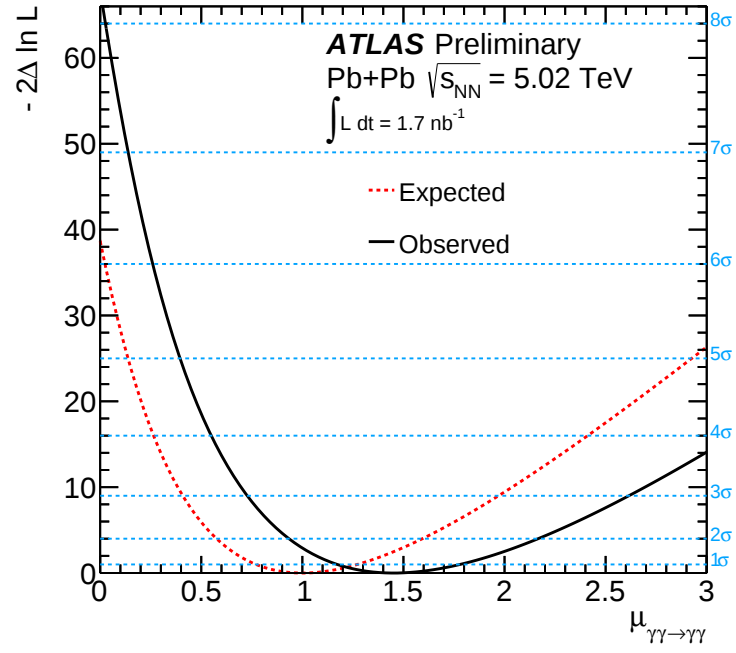


Figure 9: Scan of the profile likelihood as a function of the signal strength, μ , relative to the expectation for the process $\gamma\gamma \rightarrow \gamma\gamma$. The observed (expected) significance for the background only hypothesis ($\mu = 0$) is 8.2σ (6.2σ).