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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. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead ions. Using $480 \mu b^{-1}$ of lead-lead collision data recorded at a centre-of-mass energy per nucleon pair of $5.02$ TeV by the ATLAS detector, here we report evidence for light-by-light scattering. A total of 13 candidate events were observed with an expected background of $2.6 \pm 0.7$ events. After background subtraction and analysis corrections, the fiducial cross-section of the process Pb + Pb ($\gamma\gamma \rightarrow \gamma\gamma$), for photon transverse energy $E_T > 3$ GeV, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, is measured to be $70 \pm 24$ (stat.) $\pm 17$ (syst.) nb, which is in agreement with the standard model predictions.

One of the key features of Maxwell's equations is their linearity in both the sources and the fields, from which follows the superposition principle. This forbids effects such as light-by-light (LbLY scattering, $\gamma\gamma \rightarrow \gamma\gamma$, which is a purely quantum-mechanical process. It was realized in the early history of quantum electrodynamics (QED) that LbLY scattering is related to the polarization of the vacuum. In the standard model of particle physics, the virtual particles that mediate the LbLY coupling are electrically charged fermions or $W^\pm$ bosons. In QED, the $\gamma\gamma \rightarrow \gamma\gamma$ reaction proceeds at lowest order in the fine-structure constant ($\alpha_{\text{em}}$) via virtual one-loop box diagrams involving fermions (Fig. 1a), which is an $O(\alpha_{\text{em}}^4 \approx 3 \times 10^{-5})$ process, making it challenging to test experimentally. Indeed, the elastic LbLY scattering has remained unobserved: even the ultra-intense laser experiments are not yet powerful enough to probe this phenomenon.

LbLY scattering via an electron loop has been precisely, albeit indirectly, tested in measurements of the anomalous magnetic moment of the electron and muon where it is predicted to contribute substantially, as one of the QED corrections. The $\gamma\gamma \rightarrow \gamma\gamma$ reaction has been measured in photon scattering in the Coulomb field of a nucleus (Delbrück scattering) at fixed photon energies below 7 GeV (refs 6–9). The analogous process, where a photon splits into two photons by interaction with external fields (photon splitting), has been observed in the energy region of 0.1–0.5 GeV (ref. 10). A related process involving only real photons, in which several photons fuse to form an electron–positron pair ($e^+ e^-$), has been measured in ref. 11. Similarly, the multiphoton Compton scattering, in which up to four laser photons interact with an electron, has been observed.

An alternative way by which LbLY interactions can be studied is by using relativistic heavy-ion collisions. In ‘ultra-peripheral collisions’ (UPC) events, with impact parameters larger than twice the radius of the nucleus, the strong interaction does not play a role. The electromagnetic (EM) field strengths of relativistic ions scale with the proton number (Z). For example, for a lead (Pb) nucleus with $Z = 82$ the field can be up to $10^{16} \text{ V m}^{-1}$ (ref. 15), much larger than the Schwinger limit above which QED corrections become important. In the 1930s it was found that highly relativistic charged particles can be described by the equivalent photon approximation (EPA)17–19, which is schematically shown in Fig. 1b. The EM fields produced by the colliding Pb nuclei can be treated 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 $Q^2 < 10^{-2}$ GeV$^2$. Then, the cross-section for the reaction Pb + Pb ($\gamma\gamma \rightarrow \gamma\gamma$) to Pb + Pb $\gamma\gamma$ can be calculated by convolving the respective photon flux with the elementary cross-section for the process $\gamma\gamma \rightarrow \gamma\gamma$. Since the photon flux associated with each nucleon scales as $Z^2$, the cross-section is extremely enhanced as compared with proton–proton (pp) collisions.

In this article, a measurement of LbLY scattering in Pb + Pb collisions at the Large Hadron Collider (LHC) is reported, following the approach recently proposed in ref. 20. The final-state signature of interest is the exclusive production of two photons, Pb + Pb ($\gamma\gamma \rightarrow \gamma\gamma$) to Pb$^{90+}$ + Pb$^{90-}\gamma\gamma$, where a possible EM excitation of the outgoing ions21,22 is denoted by (*). Hence, the expected signature is two photons and no further activity in the central detector, since the Pb$^{90+}$ ions escape into the LHC beam pipe. Moreover, it is predicted that the background is relatively low in heavy-ion collisions and is dominated by exclusive dielectron ($\gamma\gamma \rightarrow e^+ e^-$) production20,22. The misidentification of electrons as photons can occur when the electron track is not reconstructed or the electron emits a hard-bremsstrahlung photon. The fiducial cross-section of the process $\gamma\gamma \rightarrow \gamma\gamma$ in Pb + Pb collisions is measured, using a data set recorded at a nucleon–nucleon centre-of-mass energy (sqrt(s)) of 5.02 TeV. This data set was recorded with the ATLAS detector at the LHC in 2015 and corresponds to an integrated luminosity of $480 \pm 30 \mu b^{-1}$. In addition to the measured fiducial cross-section, the significance of the observed number of signal candidate events is given, assuming the background-only hypothesis.

Experimental set-up

ATLAS is a cylindrical particle detector composed of several subdetectors. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the centre of the LHC ring, and the y

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axis points upwards. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, with \(\phi\) being the azimuthal angle around the \(z\) axis. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln(\tan(\theta/2))\).

Angular distance is measured in units of \(\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}\). The photon or electron transverse energy is \(E_T = E \sin(\theta)\), where \(E\) is its energy. The inner tracking detector (ITD) consists of a silicon pixel system, a silicon microstrip detector and a straw-tube tracker immersed in a 2T magnetic field provided by a superconducting solenoid. The ITD track reconstruction efficiency is estimated in its energy. The photon or electron transverse energy is

\[
\gamma \gamma \rightarrow e^+ e^-\, , \text{ central exclusive production (CEP) of photon pairs,}
\]

exclusive production of quark–antiquark pairs \((\gamma \gamma \rightarrow q\bar{q})\) and other backgrounds that could mimic the diphoton event signatures. The diphoton final state can be also produced via the strong interaction through a quark loop in the exchange of photons that can couple to form a given final state \(X\). The flux of photons is determined from the Fourier transform of the electromagnetic field of the ion, taking into account the nuclear electromagnetic form factors.

Monte Carlo simulation and theoretical predictions

Several Monte Carlo (MC) samples are produced to estimate background contributions and corrections to the fiducial measurement. The detector response is modelled using a simulation based on GEANT4 (refs 26,27). The data and MC simulated events are passed through the same reconstruction and analysis procedures.

LbyL signal events are generated taking into account box diagrams with charged leptons and quarks in the loops, as detailed in ref. 28. The contributions from \(W\)-boson loops are omitted in the calculations since they are mostly important for diphoton masses \(m_{\gamma\gamma} > 2m_W\) (ref. 29). The calculations are then convolved with the Pb + Pb EPA spectrum from the STARlight 1.1 MC generator\(^{30}\).

Next, various diphoton kinematic distributions are cross-checked with predictions from ref. 20 and good agreement is found. The theoretical uncertainty on the cross-section is mainly due to limited knowledge of the nuclear electromagnetic form factors and the related initial photon fluxes. This is studied in ref. 20 and the relevant uncertainty is conservatively estimated to be 20%. Higher-order corrections (not included in the calculations) are also part of the theoretical uncertainty and are of the order of a few per cent for diphoton invariant masses below 100 GeV (refs 31,32).

The sources of background considered in this analysis are:

\[
\gamma \gamma \rightarrow e^+ e^-\, , \text{ central exclusive production (CEP) of photon pairs,}
\]

exclusive production of quark–antiquark pairs \((\gamma \gamma \rightarrow q\bar{q})\) and other backgrounds that could mimic the diphoton event signatures. The diphoton final state can be also produced via the strong interaction through a quark loop in the exchange of photons that can couple to form a given final state \(X\). The flux of photons is determined from the Fourier transform of the electromagnetic field of the ion, taking into account the nuclear electromagnetic form factors.

**Event selection**

Candidate diphoton events were recorded in the Pb + Pb run in 2015 using a dedicated trigger for events with moderate activity in the calorimeter but little additional activity in the entire detector. At Level-1 the total \(E_T\) registered in the calorimeter after noise suppression was required to be between 5 and 200 GeV. Then at the high-level trigger, events were rejected if more than one hit was found in the inner ring of the MBTS (MBTS veto) or if more than ten hits were found in the pixel detector.

The efficiency of the Level-1 trigger is estimated with \(\gamma \gamma \rightarrow e^+ e^-\) events passing an independent supporting trigger. This trigger is designed to select events with mutual dissociation of Pb nuclei and small activity in the ITD. It is based on a coincidence of signals in both ZDC sides and a requirement on the total \(E_T\) in the calorimeter below 50 GeV. Event candidates are required to have only two reconstructed tracks and two EM energy clusters. Furthermore, to reduce possible backgrounds, each pair of clusters (cl1, cl2) is required to have a small acoplanarity \((1 - \Delta P_{cl1,cl2}/\pi < 0.2)\).

The extracted Level-1 trigger efficiency is provided as a function of the
sum of cluster transverse energies \((E_T^{cl1} + E_T^{cl2})\). The efficiency grows from about 70% at \((E_T^{cl1} + E_T^{cl2}) = 6\,\text{GeV}\) to 100% at \((E_T^{cl1} + E_T^{cl2}) > 9\,\text{GeV}\). The efficiency is parameterized using an error function fit, which is then used to reweight the simulation. Due to the extremely low noise, very high hit reconstruction efficiency and low conversion probability of signal photons in the pixel detector (around 10%), the uncertainty due to the requirement for minimal activity in the ITD is negligible. The MBTS veto efficiency was applied to remove EM clusters with a large amount of energy from poor functioning calorimeter cells, and a timing requirement applied to remove EM clusters with a large amount of energy from muons are rejected with 95% efficiency.

Performance and validation of photon reconstruction

Since the analysis requires the presence of low-energy photons, which are not typically used in ATLAS analyses, detailed studies of photon reconstruction and calibration are performed.

High-\(p_T\) \(\gamma\gamma \rightarrow e^+e^-\) production with a final-state radiation (FSR) photon is used for the measurement of the photon PID efficiency. Events with a photon and two tracks corresponding to oppositely charged particles with \(p_T > 1\,\text{GeV}\) are required to pass the same trigger as in the diphoton selection or the supporting trigger. The \(\Delta R\) between a photon candidate and a track is required to be greater than 0.2 to avoid leakage of the electron clusters from the \(\gamma\gamma \rightarrow e^+e^-\) process to the photon cluster. The FSR event candidates are identified using a \(p_T^{\gamma}\) requirement, where \(p_T^{\gamma}\) is the transverse momentum of the three-body system consisting of two charged-particle tracks and a photon. The FSR photons are then used to extract the photon PID efficiency, which is defined as the probability for a reconstructed photon to satisfy the identification criteria. Figure 2a shows the photon PID efficiencies in data and simulation as a function of reconstructed photon \(E_T\). Within their statistical precision the two results agree.

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. Events with exactly one identified electron, two reconstructed charged-particle tracks and exactly one photon are studied. The electron \(E_T\) is required to be above 5 GeV and the \(p_T\)
Due to its relatively high rate, the exclusive production of electron pairs ($\gamma \gamma \rightarrow e^+e^-$) can be a source of fake diphoton events. The contribution from the dielectron background is estimated using $\gamma \gamma \rightarrow e^+e^-$ MC simulation (which gives 1.3 events) and is verified using the following data-driven technique. Two control regions are identified in which the first control region is defined by requiring events with exactly one reconstructed charged-particle track and two identified photons that satisfy the same preselection criteria as for the signal definition. The second control region is defined similarly to the first one, except exactly two tracks are required ($N_{\text{trk}} = 2$). Good agreement is observed between data and MC simulation in both control regions, but the precision is limited by the number of events in data. A conservative uncertainty of 25% is therefore assigned to the $\gamma \gamma \rightarrow e^+e^-$ background estimation, which reflects the statistical uncertainty of data in the $N_{\text{trk}} = 1$ control region. The contribution from a related QED process, $\gamma \gamma \rightarrow e^+e^-\gamma\gamma$, is evaluated using the MadGraph5_aMC@NLO MC generator and is found to be negligible.

The $A_{\cos}$ requirement significantly reduces the CEP $gg \rightarrow \gamma\gamma$ background. However, the MC prediction for this process has a large theoretical uncertainty, hence, an additional data-driven normalization is performed in the region $A_{\cos} > b$, where $b$ is a value greater than 0.01 which can be varied. Three values of $b$ (0.01, 0.02, 0.03) are used, where the central value $b=0.02$ is chosen to derive the nominal background prediction and the values $b=0.01$ and $b=0.03$ to define the systematic uncertainty. The normalization is performed using the condition:

$$f_{\text{norm}}^{\gamma\gamma} = \left( \frac{N_{\text{data}}(A_{\cos} > b) - N_{\text{bg}}(A_{\cos} > b)}{N_{\text{MC}}(A_{\cos} > b)} \right) \times \frac{N_{\text{data}}(A_{\cos} > b)}{N_{\text{MC}}(A_{\cos} > b)}$$

for each value of $b$, where $N_{\text{data}}$ is the number of observed events, $N_{\text{bg}}$ is the expected number of signal events, $N_{\text{MC}}$ is the MC estimate of the expected background from CEP $gg \rightarrow \gamma\gamma$ events. The normalization factor is found to be $f_{\text{norm}}^{\gamma\gamma} = 0.5 \pm 0.3$ and the background due to CEP $gg \rightarrow \gamma\gamma$ is estimated to be $f_{\text{norm}}^{\gamma\gamma} \times N_{\text{MC}}(A_{\cos} < 0.01) = 0.9 \pm 0.5$ events. To verify the CEP $gg \rightarrow \gamma\gamma$ background estimation method, energy deposits in the ZDC are studied for events before the $A_{\cos}$ selection. It is expected that the outgoing ions in CEP events predominantly dissociate, which results in the emission of neutrons detectable in the ZDC. Good agreement between the normalized CEP $gg \rightarrow \gamma\gamma$ MC expectation and the observed events with a ZDC signal corresponding to at least 1 neutron is observed in the full $A_{\cos}$ range (see Supplementary Information for details).

Low-$p_T$ dijet events can produce multiple $n\pi$ mesons, which could potentially mimic diphoton events. The event selection requirements are efficient in rejecting such events, and based on studies performed with a supporting trigger, the background from hadronic processes is estimated to be $0.3 \pm 0.3$ events. MC studies show that the background from $\gamma\gamma \rightarrow q\bar{q}$ production is negligible.

Exclusive neutral two-meson production can be a potential source of background for $b$-by$b$ events, mainly due to their back-to-back topology being similar to that of the CEP $gg \rightarrow \gamma\gamma$ process. The cross-section for this process is calculated to be below 10% of the CEP $gg \rightarrow \gamma\gamma$ cross-section and it is therefore considered to
give a negligible contribution to the signal region. The contribution from bottomonia production (for example, \( \gamma \gamma \rightarrow \eta_b \rightarrow \gamma \gamma \) or \( \gamma \text{Pb} \rightarrow \gamma \rightarrow \gamma \eta_b \rightarrow 3\gamma \)) is calculated using parameters from refs 46, 47 and is found to be negligible.

The contribution from other fake diphoton events (for example those induced by cosmic-ray muons) is estimated using photons that fail to satisfy the longitudinal shower-shape requirement. The total background due to other fake photons is found to be 0.1 ± 0.1 events. As a further cross-check, additional activity in the muon spectrometer is studied. It is observed that out of 18 events satisfying the inverted \( p_T^\gamma < 2 \text{ GeV} \) requirement, 13 have at least one additional reconstructed muon. In the region \( p_T^\gamma < 2 \text{ GeV} \), no events with muon activity are found, which is compatible with the above-mentioned estimate of 0.1 ± 0.1.

The contribution from UPC events where both nuclei emit a bremsstrahlung photon is estimated using calculations from ref. 13 and is found to be negligible for photons with \( |\eta| < 2.4 \) and \( E_T > 3 \text{ GeV} \).

### Results

Photon kinematic distributions for events satisfying the selection criteria are shown in Fig. 3. The shape of the diphoton acoplanarity distribution for \( \gamma \gamma \rightarrow e^+e^- \) events in Fig. 3a reflects the trajectories of the electron and positron in the detector magnetic field, before they emit hard photons in their collisions with the ITD material. In total, 13 events are observed in data whereas 7.3 signal events and 2.6 background events are expected. In general, good agreement between data and MC simulation is observed. The effect of sequential selection requirements on the number of events selected is shown in Table 1, for each of the data, signal and background samples.

To quantify an excess of events over the background expectation, a test statistic based on the profile likelihood ratio \( \lambda \) is used. The \( p \) value for the background-only hypothesis, defined as the probability for the background to fluctuate and give an excess of events as large or larger than that observed in the data, is found to be 5 × 10^{-4}. The \( p \) value can be expressed in terms of Gaussian tail probabilities, which, given in units of standard deviation (\( \sigma \)), corresponds to a significance of 4.4\( \sigma \). The expected \( p \) value and significance (obtained before the fit of the signal-plus-background hypothesis to the data and using standard model predictions from ref. 28) are 8 × 10^{-5} and 3.8\( \sigma \), respectively.

The cross-section for the \( \gamma \gamma \rightarrow e^+e^- \) process is measured in a fiducial phase space defined by the photon transverse energy \( E_T > 3 \text{ GeV} \), photon absolute pseudorapidity \( |\eta| < 2.4 \), diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01. Experimentally, the fiducial cross-section is given by

\[
\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}
\]

where \( N_{\text{data}} \) is the number of selected events in data, \( N_{\text{bkg}} \) is the expected number of background events and \( \int L dt \) is the integrated luminosity. The factor \( C \) is used to correct for the net effect of the trigger efficiency, the diphoton reconstruction and PID efficiencies, as well as the impact of photon energy and angular resolution. It is defined as the ratio of the number of generated signal events satisfying the selection criteria after particle reconstruction and detector simulation to the number of generated events satisfying the fiducial criteria before reconstruction. The value of \( C \) and its total uncertainty is determined to be 0.31 ± 0.07. The dominant systematic uncertainties come from the uncertainties on the photon reconstruction and identification efficiencies. Other minor sources of uncertainty are the photon energy scale and resolution uncertainties and trigger efficiency uncertainty. To check for a potential model dependence, calculations from ref. 28 are compared with predictions from ref. 20, and a negligible impact on the \( C \)-factor uncertainty is found. Table 2 lists the separate contributions to the systematic uncertainty. The uncertainty on the integrated luminosity is 6%. It is derived following a methodology similar to that detailed in refs 49,50, from a calibration of the luminosity scale using x–y beam-separation scans performed in December 2015.

The measured fiducial cross-section is \( \sigma_{\text{fid}} = 70 ± 24 \) (stat.) ±17 (syst.) nb, which is in agreement with the predicted values of 45 ± 9 nb (ref. 20) and 49 ± 10 nb (ref. 28) within uncertainties.

### Conclusion

In summary, this article presents evidence for the scattering of LbyL in quasi-real photon interactions from 480 \( \mu \text{b}^{-1} \) of ultra Peripheral Pb + Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV by the ATLAS experiment at the LHC. The statistical significance against the background-only hypothesis is found to be 4.4 standard deviations. After background subtraction and analysis corrections, the fiducial cross-section for the \( \gamma \gamma \rightarrow e^+e^- \) process was measured and is compatible with standard model predictions. The analysis is mostly limited by the amount of data available and the lower limit on transverse energy for reconstructed photons (\( E_T = 3 \text{ GeV} \)), below which more signal is expected. Advancements on these two points would also allow for reconstruction of low-mass mesons decaying into two photons, which in turn could be used to improve detector calibration. The heavy-ion data yield is expected to double at the end of 2018 (and again increase tenfold after
LHC Run 4, scheduled to start in 2026), which would significantly reduce the statistical uncertainty. Future upgrades of ATLAS, such as extended tracking acceptance from $|\eta|<2.5$ to $|\eta|<4.0$, will further improve this.

**Data availability.** The experimental data that support the findings of this study are available in HEPData with the identifier http://dx.doi.org/10.17182/hepdata.77761.

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Author contributions
All authors have contributed to the publication, being variously involved in the design and the construction of the detectors, in writing software, calibrating subsystems, operating the detectors and acquiring data, and finally analysing the processed data. The ATLAS Collaboration members discussed and approved the scientific results. The manuscript was prepared by a subgroup of authors appointed by the collaboration and subject to an internal collaboration-wide review process. All authors reviewed and approved the final version of the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.

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