Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

Aad, G.; ATLAS Collaboration

DOI
10.1103/PhysRevLett.125.261801

Publication date
2020

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Citation for published version (APA):
Electromagnetic fields sourced by protons at the Large Hadron Collider (LHC) are sufficiently intense to exceed the Schwinger limit of $10^{18}$ V m$^{-1}$ [1–3] and produce lepton pairs via photon fusion, $\gamma\gamma \rightarrow \ell^+\ell^-$, where $\ell$ denotes electrons or muons [4–7]. This process occurs in a wide range of astrophysical phenomena, such as cosmic gamma rays [8,9] and neutron stars [10,11]. Measurements of $\gamma\gamma \rightarrow \ell^+\ell^-$ at the LHC provide a unique laboratory probe of these natural phenomena and are fundamental tests of quantum electrodynamics [12–17]. These complement lower-energy probes using heavy-ion collisions [18–26] and high-intensity laser beams [27–30]. A hallmark prediction of photon fusion processes at the LHC is the forward scattering of incident protons. Near-beam instruments known as spectrometers can detect the scattered protons, which is a technique referred to as proton tagging. The CMS and TOTEM Collaborations reported proton-tagged dilepton (dimuon) production with 2.6σ(4.3σ) significance, which exceeds 5σ when statistically combined [31], but no cross sections were measured. Previous measurements of $\gamma\gamma \rightarrow \ell^+\ell^-$ by the ATLAS Collaboration were performed without proton tagging [4,5].

Measuring proton-tagged dilepton production, $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p^{(s)}$, where $p^{(s)}$ denotes a proton that remains intact or dissociates following electromagnetic excitation, is important for several reasons. Predictions of photon fusion processes have significant uncertainties associated with modeling strong-force interactions between scattered protons, which suppress cross sections by factors known as soft-survival probabilities [32–35]. This suppression is poorly constrained, especially at high $\gamma\gamma$ invariant masses important for new physics searches, as existing probes indirectly infer dissociation rates using only central-detector information [4–7]. Proton tagging overcomes this longstanding experimental ambiguity by directly detecting the scattered protons. Detecting a proton also directly suppresses background processes and events involving proton dissociation, while providing information on the initial $\gamma\gamma$ system independently of central-detector information. The successful demonstration of proton-tagging techniques for cross-section measurements accomplishes the crucial first step toward a diverse program using proton tagging in measurements of Standard Model processes [36–41] and searches for new phenomena [42–46].

This Letter introduces proton tagging for cross-section measurements of $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p^{(s)}$. The ATLAS Forward Proton (AFP) spectrometer detects one of the intact protons and the central ATLAS detector reconstructs the leptons. The dataset was collected in 2017 and corresponds to 14.6 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton-proton ($pp$) collisions. The average number of interactions per bunch crossing was 36. Several methods specific to proton tagging are introduced: in situ calibration of proton kinematics using the dimuon system, a novel data-mixing background estimation method, and tag-and-probe determination of the AFP reconstruction efficiency.

The ATLAS experiment [47–49] is a general-purpose particle detector with nearly 4π coverage [50] around the interaction point. It comprises an inner detector tracker, calorimeters, and a muon spectrometer. A two-level trigger...
The AFP spectrometer [56,57] consists of four tracking units located along the beam pipe at $z = \pm 205$ and $\pm 217$ m, referred to as near and far stations, respectively. The $+z$ ($-z$) direction is labeled side A (C). Each station houses a silicon tracker comprising four planes of edgeless silicon pixel sensors [58–61]. The sensors have $336 \times 80$ pixels with area $50 \times 250 \, \mu m^2$. The direction normal to each sensor is tilted $14^\circ$ relative to the beam to improve hit efficiency and $x$-position resolution, resulting in an overall spatial resolution of $\sigma_x = 6 \, \mu m$ [62]. Movable near-beam devices at each station, known as Roman pots, insert the tracker along the $x$ direction in the beam pipe. Data taking with the AFP commences once the trackers are at a position where the innermost silicon edge is within 2 mm of the beam center during stable beams. Data quality for this analysis requires that every AFP station has at least three silicon planes operational at high voltage, and the AFP data acquisition system [63] must report no problems.

Simulated events of the exclusive signal $pp \rightarrow p(\gamma \gamma \rightarrow e^+e^-)p$ were produced using the HERWIG7 Monte Carlo (MC) generator [64,65]. The single-dissociative signal $pp \rightarrow p(\gamma \gamma \rightarrow e^+e^-)p^*$ was generated using LPAIR4.0 [66], with proton dissociation modeled using the Brasse et al. [67] and Suri-Yennie [68] structure functions interfaced with JETSET7.408 [69,70]. Simulation of these processes is detailed in Ref. [5]. To model the central-detector response, the exclusive signal sample underwent full detector simulation based on GEANT4 [71], which uses a parametrization of the calorimeter response [73]. The response of the AFP spectrometer is modeled by a fast simulation [72], where a Gaussian smearing is applied to track positions based on the AFP spatial resolution. Simulated samples include the effect on the central detector of multiple $pp$ interactions in the same and neighboring bunch crossing (pileup), as detailed in Ref. [5].

Reconstructed events must contain at least one interaction vertex with two or more associated inner-detector tracks that satisfy $p_T > 500$ MeV, $|\eta| < 2.5$, and the “Loose” criterion [74,75]. Electrons (muons) must satisfy $p_T > 18(15)$ GeV, $|\eta| < 2.47(2.4)$, the “LooseAndBlayer” [76] (“Medium” [77]) identification criterion, and $|z_0 \sin \theta| < 0.5 \, mm$ [78]. Electrons sharing an inner-detector track with a muon are discarded. To suppress fake and/or nonprompt lepton backgrounds, remaining electrons (muons) must satisfy transverse impact parameter significance $|d_0/\sigma_{d_0}| < 5(3)$ and isolation requirements described in Ref. [79] (Ref. [80]). Electrons must also satisfy “Medium” identification [76]. Small corrections are applied to leptons in simulated samples to match reconstruction and trigger efficiencies measured in data, as described in Refs. [76,77].

Selected events must have exactly two same-flavor leptons with opposite electric charge ($e^+e^-$ or $\mu^+\mu^-$) and be matched to the leptons that triggered the event. To suppress quarkonia and $Z$ boson resonances, the dilepton invariant mass must satisfy $m_{\ell\ell} > 20$ and $m_{\ell\ell} \not\in [70,105] \, GeV$. To select events compatible with $pp \rightarrow p(\gamma \gamma \rightarrow e^+e^-)p^*$ processes based on the simulated signals, the dilepton transverse momentum must satisfy $p_{T\ell\ell} < 5 \, GeV$. This set of criteria is referred to as the preselection. Signal event candidates must additionally have small acoplanarity $A_{\ell\ell} = 1/|\Delta \phi_{\ell\ell}|/\pi < 0.01$. These events must have no inner-detector tracks ($N_{tracks}^{innerdet} = 0$) that satisfy $\Delta R (track, \ell) > 0.01$ for both leptons and $|z_{track}^{\ell} - z_{0}^{\ell}| < 0.5 \, mm$, where $z_{track}^{\ell}$ is the track $z_0$ position and $z_{0}^{\ell} = (z_{0}^{\ell_1} + z_{0}^{\ell_2})/2$ with $\ell_{1,2}$ denoting the two leptons. The expected proton energy loss based on lepton kinematics $\xi_{\ell\ell}$ is determined from $m_{\ell\ell}$ and the dilepton rapidity $y_{\ell\ell}$ by momentum conservation $\xi_{\ell\ell} = m_{\ell\ell}/(\sqrt{s} \, e^{2y_{\ell\ell}})$, where $+$ (−) corresponds to the proton on side A (C).

Reconstruction of scattered protons combines information from the AFP tracker and LHC magnet lattice [81]. Protons transported to the AFP leave hits in the silicon tracker, which are processed by clustering and track-finding algorithms detailed in Ref. [59]. Tracks are reconstructed from clusters in at least two planes. Small corrections of around 0.1 mm are applied to ensure the cluster positions between planes are compatible within the spatial resolution. The proton transport function $x_{AFP} = T(\xi_{AFP})$ relates the track $x$ position $x_{AFP}$ to the fractional energy loss of the scattered proton $\xi_{AFP} = 1 - E_{scattered}/E_{beam}$, where $E_{scattered}$ ($E_{beam}$) is the scattered (beam) proton energy. The LHC magnets and beam optics [82] govern the form of $T(\xi_{AFP})$ [83], which is simulated in the MAD-X package [84,85] with further details discussed in Refs. [56,86,87]. Determination of $\xi_{AFP}$ uses both the near and far stations if tracks are within their common acceptance, otherwise only the far station is used.

The absolute scale of $E_{scattered}$ depends on the closest separation $x_0^s$ between each AFP station $s$ and the beam center [87]. The beam positions relative to the detectors were determined in dedicated runs with beam-based alignment procedures [88] using beam loss monitors [89], and cross-checked with beam position monitor measurements [90]. There were three data-taking periods in 2017. In the first data-taking period, the $x_0^s$ values were initially set to $-4.0(-3.0) \, mm$ on side A and $-3.8(-2.9) \, mm$ on side C for the near (far) stations; during a second data-taking period, all stations were moved 0.5 mm closer to the beam to improve acceptance. This first (second) data-taking period corresponds to 5% (17%) of the analyzed dataset. For the remaining dataset, the far stations were moved a further 0.2 mm toward the beam. The initially measured $x_{AFP}$ values relative to $x_0^s$ are calibrated in situ using the dimuon data sample passing the signal event selection. The $x_{AFP}^s - x_{AFP}^i$ distribution is peaked for signal processes due to the kinematical correction between $x_{AFP}^s$ and $x_{AFP}^i$, where
\(x_{\ell\ell} = T(\xi_{\ell\ell})\) is the expected position calculated using the transport function. Additive corrections are applied to \(x_{\text{AFP}}\) in data to center the maximum of the peak at zero. These corrections are found to be \(-0.28(-0.34)\) mm on side A and \(-0.17(-0.36)\) mm on side C for the near (far) stations. Selected dielectron events are used to verify that the signal is centered at zero. After applying these corrections, the lower value of the acceptance corresponds to \(0.028(0.018)\) on side A and \(0.026(0.019)\) on side C for the near (far) stations. The upper value of the acceptance is bounded by \(\xi_{\text{AFP}} < 0.12\) due to the presence of beam collimators [56].

To select events with one or more proton candidates, the \(\xi_{\ell\ell}\) and \(\xi_{\text{AFP}}\) values for at least one AFP side are required to be within the range \([0.02, 0.12]\). If there is more than one proton candidate on the same AFP side, which occurs in 35% of selected events, the proton with the closest \(\xi_{\text{AFP}}\) is chosen. Proton-tagged dilepton candidates, denoted \(\ell\ell + p\), are selected by requiring matching on at least one AFP side, \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005\), which retains more than 95% (85%) of the signal (background).

The dominant source of background after this selection arises from lepton pairs produced in a \(pp\) interaction different from that of the detected proton. In this case, the lepton pairs are produced via the Drell-Yan mechanism, as well as any outgoing protons or are outside the AFP acceptance or not reconstructed in AFP due to detector inefficiency. These events are collectively referred to as combinatorial backgrounds and are estimated using a data-driven method. A mixed-data sample is constructed by randomly pairing each measured \(\xi_{\ell\ell}\) value, passing AFP acceptance \(\xi_{\text{AFP}} \in [0.02, 0.12]\), with 100 values of \(\xi_{\text{AFP}}\) from a large control sample of \(> 10^6\) events. This control sample is constructed from the preselected events and requiring \(A_\phi^p > 0.01\). The 123 selected data events failing kinematic matching, \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| > 0.005\), result mostly from combinatorial background processes, which are used to normalize the mixed-data sample using a background-only profile-likelihood fit [91,92].

Systematic uncertainties in the background normalization arise from the limited size of the data sample satisfying \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| > 0.005\). An uncertainty in the background shape arises from kinematic changes in the control sample of protons due to the acoplanarity requirement. This uncertainty is estimated by replacing the \(A_\phi^p > 0.01\) condition with \(A_\phi^p \geq 1\) and comparing the two background predictions in the region \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005\); they are found to differ by 14%. Further shape uncertainties arise from instrumental effects, which are expected to be dominated by the sensitivity to the number of interactions per bunch crossing \(\mu\). The background predictions for \(\mu < 35\) and \(\mu \geq 35\) are found to differ by 8% in the \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005\) region. These two shape differences are assigned as additional uncertainties.

The background estimation method is validated by applying it to the orthogonal \(m_{\ell\ell} \in [70, 105]\) GeV region. The region \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| > 0.005\) is dominated by Drell-Yan events, which have no correlated protons. In this region, the data and prediction from the mixed-data sample are found to be compatible within the uncertainties across the \(\xi_{\text{AFP}} - \xi_{\ell\ell}\) range for both sides A and C.

After applying the event selection including kinematic matching, \(|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005\), a total of 57 (123) candidates in the \(ee + p (\mu\mu + p)\) final state are observed compared with a background-only expectation of \(6.2 \pm 1.2 (13.4 \pm 2.5)\) events. Using the asymptotic profile-likelihood method [91,92], the background-only hypothesis is rejected with a significance exceeding 5\(\sigma\) in each channel [93]. This provides direct evidence of forward proton scattering in association with electron and muon pairs produced via photon fusion. The \(\xi_{\text{AFP}} - \xi_{\ell\ell}\) distributions of data, signal, and background at detector level before kinematic matching are shown in Fig. 1. To illustrate

![FIG. 1. Distributions of \(\xi_{\text{AFP}} - \xi_{\ell\ell}\) with \(\xi_{\ell\ell}\) and \(\xi_{\text{AFP}}\) satisfying \([0.02, 0.12]\) for side A (left) and side C (right). The total prediction comprises the signal and combinatorial background processes, where \(p^*\) denotes a dissociated proton. The simulated predictions are normalized to data to illustrate the expected signal composition. The first (last) bin includes underflow (overflow). The hatched band indicates the combined statistical and systematic uncertainties of the prediction. Error bars denote statistical uncertainties of the data.](image-url)
detector-level distributions of dilepton acoplanarity, mass, and rapidity after kinematic matching with the signal samples normalized to $N_{\text{obs}} - N_{\text{bkg}}$.

Cross sections are measured in a fiducial region defined at particle level with an event selection similar to that applied at detector level [94]. To reliably estimate AFP reconstruction efficiencies using tag-and-probe techniques, the $\xi_{\text{AFP}}$ and $\xi_{\ell\ell}$ values are restricted to a tighter range [0.035, 0.08] and each proton candidate is required to have an associated track in both near and far stations. The measured cross sections are defined by $\sigma_{\text{fid}} = (N_{\text{obs}} - N_{\text{bkg}})/ (L \cdot C_{\text{cent}} \cdot C_{\text{AFP}})$. Here, $N_{\text{obs}}$ ($N_{\text{bkg}}$) is the number of observed data (expected background) events passing event selection, and $C_{\text{cent}}$ ($C_{\text{AFP}}$) is an overall correction factor accounting for the central-detector (AFP) efficiency. The integrated luminosity, $L = 14.6 \, \text{fb}^{-1}$, is measured using the LUCID-2 detector [95] and the uncertainty is determined to be 2.4% [96]. In this tighter region, $N_{\text{obs}}$ is found to be 19 (23) for the $ee$ ($\mu\mu$) channel and $N_{\text{bkg}} = 1.7 \pm 0.3 (2.3 \pm 0.5)$. The event rate between the two channels differs more for the $\xi \in [0.02, 0.12]$ than $\xi \in [0.035, 0.08]$ region because $\mu\mu$ events with low $m_{\ell\ell}$ and high $|y_{\ell\ell}|$ have greater selection efficiency due to trigger and reconstruction requirements.

The $C_{\text{cent}}$ factor is defined as the ratio of the number of MC events passing detector-level selection to the number passing the particle-level fiducial requirements. Uncertainties in $C_{\text{cent}}$ are estimated by varying the electron (muon) energy (momentum) scale and resolution, and data-to-MC correction factors described in Refs. [76,77], together with corrections applied to account for pileup modeling. The dominant uncertainties for $ee$ events arise from pileup modeling (2%) and identification (1%), while for $\mu\mu$ events, these correspond to pileup modeling (3%), resolution (3%), and scale (2%); other sources such as trigger and isolation efficiencies contribute 1% or less. Using data-driven methods described in Ref. [5], a further correction of $0.89 \pm 0.04$ is applied to $C_{\text{cent}}$ to account for

FIG. 2. The 57 (123) $ee$ ($\mu\mu$) data event candidates in the dilepton rapidity $y_{\ell\ell}$ vs $m_{\ell\ell}$ plane satisfying event selection and kinematic matching, $|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005$, on at least one side. Shaded (hatched) areas denote the acceptance (no acceptance) for the AFP stations indicated in the legend. Areas neither shaded nor hatched correspond to $\xi \in [0, 1]$.

the expected composition of the signal, the simulated samples are normalized to data with sides $A$ and $C$ combined and fit separately in the $ee$ and $\mu\mu$ channels. Figure 2 displays positions in the dilepton rapidity $Shaded (hatched) areas denote the acceptance (no acceptance) for the AFP stations indicated in the legend. Areas neither shaded nor hatched correspond to $\xi \in [0, 1]$.

FIG. 3. Distributions of dilepton acoplanarity $A_{\ell\ell}$ (left), invariant mass $m_{\ell\ell}$ (center), rapidity $y_{\ell\ell}$ (right) satisfying $\xi_{\ell\ell}, \xi_{\text{AFP}} \in [0.02, 0.12]$, and $|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005$ for at least one AFP side. Events with $70 < m_{\ell\ell} < 105 \, \text{GeV}$ are vetoed. The total prediction comprises the signal and combinatorial background processes, where $p^*$ denotes a dissociated proton. The simulated predictions are normalized to data to illustrate the expected signal composition. The rightmost bin of the $m_{\ell\ell}$ distribution includes overflow. The hatched band indicates the combined statistical and systematic uncertainties of the prediction. Error bars denote statistical uncertainties of the data.

261801-4
differences between data and MC when modeling the luminous region at the interaction point. The 5% uncertainty in this correction is evaluated as the difference between either applying this data-driven method to simulated signal samples or imposing the $N_{\text{tracks}}^{\text{tracks}} = 0$ requirement on these samples. Overall, this results in $C_{\text{cent}}^{\text{eff}} = 0.12 \pm 0.01$ ($C_{\text{cent}}^{\text{syst}} = 0.22 \pm 0.02$) for the $ee$ ($\mu\mu$) channel.

The $C_{\text{AFP}}$ factor is defined by the product $e_{\text{track}} \cdot e_{\text{smear}}$. The track reconstruction efficiency $e_{\text{track}}$ is found to be $0.92 \pm 0.02$ for sides A and C. The near-station efficiency is estimated using a tag-and-probe method by first selecting events with exactly one track in the far (tag) station in the acceptance common to both stations, $-12 < x_{\text{AFP}} < -5$ mm. The efficiency is the fraction of these events that also have one or more tracks in the near (probe) station satisfying $|x_{\text{near}} - x_{\text{far}}| < 2$ mm. The tag and probe stations are inverted to measure the far-station efficiency. It is found that $e_{\text{track}}$ varies with $x_{\text{AFP}}$ by 2%, which is assigned as an additional uncertainty. The proton resolution correction $e_{\text{smear}}$ is found to be $0.98 \pm 0.02$ (0.96 ± 0.04) for the $ee$ ($\mu\mu$) channel. This is evaluated as the fraction of simulated signal events passing $\xi_{\text{AFP}} \in [0.035, 0.08]$, and $|\xi_{\text{AFP}} - \xi_{\text{ref}}| < 0.005$ out of those satisfying $\xi_{\text{ref}} \in [0.035, 0.08]$. Uncertainties in $C_{\text{AFP}}$ are dominated by global alignment (6%) evaluated by ±0.3 mm variations of $x_{\text{AFP}}$ and beam optics (5%) evaluated by varying the beam crossing angle by 50 μrad in the MAD-X package. Uncertainties involving track and cluster reconstruction are found to be less than 1%. The overall uncertainty in $C_{\text{AFP}}$ is 9%.

The measured fiducial cross sections in the $ee$ and $\mu\mu$ channels are $\sigma_{ee}^{\text{fid.}} = 11.0 \pm 2.6 \text{(stat)} \pm 1.2 \text{(syst)} \pm 0.3 \text{(lumi)}$ and $\sigma_{\mu\mu}^{\text{fid.}} = 7.2 \pm 1.6 \text{(stat)} \pm 0.9 \text{(syst)} \pm 0.2 \text{(lumi)}$ fb, respectively. Table I compares these with the combined HERWIG and LPAIR predictions assuming unit soft-survival factors $S_{\text{surv}} = 1$. Soft-survival effects are included using an $m_{\ell\ell}$-dependent reweighting of these predictions to $S_{\text{surv}}$ calculated for exclusive processes from Ref. [34]; LPAIR predictions are additionally scaled down by 15% to account for $S_{\text{surv}}$ being lower for single-dissociative processes [33].

<table>
<thead>
<tr>
<th>$S_{\text{surv}}$</th>
<th>$\sigma_{ee}^{\text{fid.}}$ (fb)</th>
<th>$\sigma_{\mu\mu}^{\text{fid.}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{surv}} = 1$</td>
<td>15.5 ± 1.2</td>
<td>13.5 ± 1.1</td>
</tr>
<tr>
<td>$S_{\text{surv}}$, using Refs. [33,34]</td>
<td>10.9 ± 0.8</td>
<td>9.4 ± 0.7</td>
</tr>
<tr>
<td>SUPERCHIC 4 [97]</td>
<td>12.2 ± 0.9</td>
<td>10.4 ± 0.7</td>
</tr>
<tr>
<td>Measurement</td>
<td>11.0 ± 2.9</td>
<td>7.2 ± 1.8</td>
</tr>
</tbody>
</table>

SUPERCHIC 4 [97] predictions include full kinematic dependence on $S_{\text{surv}}$ for exclusive, single-, and double-dissociative processes. The predictions for $ee$ are higher than for $\mu\mu$ due to the looser $\eta(\ell)$ requirement [94].

In summary, forward proton scattering in association with lepton pairs produced via photon fusion, $pp \rightarrow p(\gamma \gamma \rightarrow \ell^+ \ell^-) p(x)$, is observed with a significance exceeding $5\sigma$ in both the $ee + p$ and $\mu\mu + p$ final states using 14.6 fb$^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ collisions at the LHC. These results demonstrate that the ATLAS Forward Proton spectrometer performs well in high-luminosity data taking. Furthermore, proton tagging is introduced for cross-section measurements of photon fusion processes at the electroweak scale.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, U.S. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada, CRC and IVADO, Canada; Beijing Municipal Science & Technology Commission, China; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programs cofinanced by EU-ESF and the Greek NSRF, Greece; BMBF, DFS, and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France),
KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (U.S.), the Tier-2 facilities worldwide, and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [99]. We are grateful to the LHC optics, collimation, machine protection, and operations groups that enabled the use of the ATLAS Forward Proton spectrometer.

[7] CMS Collaboration, Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2012) 052.
[26] M. Dyndal, M. Klusek-Gawenda, M. Schott, and A. Szczyurek, Anomalous electromagnetic moments of $\tau$ lepton in $\gamma\gamma \rightarrow \tau^+\tau^-$ reaction in Pb + Pb collisions at the LHC, Phys. Lett. B 809, 135682 (2020).


[50] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center 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 η = −ln tan(θ/2). The transverse momentum is denoted pT. Angular distances are measured in units of ∆R = √((Δη)2 + (Δφ)2). Rapidity is defined as y = 1/2 ln[(E + pT)/(E − pT)], where E is the energy and pT is the longitudinal component of the momentum of the particle.


[74] ATLAS Collaboration, Early inner detector tracking performance in the 2015 data at √s = 13 TeV, CERN Report


[78] $z_0$ is the longitudinal impact parameter relative to the primary vertex, where the primary vertex is defined as the vertex with the largest $\sum p_T^2$ of associated tracks.


[84] The statistical significance in the $ee + (p\mu + p)$ final state corresponds to 9.7$\sigma$ (13$\sigma$).


[96] Uncertainties on predicted soft-survival factors are estimated in accord with Ref. [33]. For the exclusive process, the uncertainty on $S_{\text{surv}}$ is estimated by the $m_{\ell\ell}$ variations, while for the single-dissociative process, the uncertainty on $S_{\text{surv}}$ is estimated by taking the difference in $S_{\text{surv}}$ between the exclusive and single-dissociative processes.

121 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
122 Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia
123 Institute for High Energy Physics of the National Research Centre "Kurchatov Institute", Moscow, Russia
124 Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Protvino, Russia
125 Department of Physics, New York University, New York, New York, USA
126 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
127 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
128 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
129 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
130 Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
131 Graduate School of Science, Osaka University, Osaka, Japan
132 Department of Physics, University of Oslo, Oslo, Norway
133 Department of Physics, Oxford University, Oxford, United Kingdom
134 LIPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
135 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
136 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
137 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
138 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
139 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
140 Departamento de Física, Universidad de Santiago de Compostela, La Coruña, Spain
141 Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
142 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
143 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
144 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
145 Santa Cruz Institute for Particle Physics, Department of Physics, University of California Santa Cruz, Santa Cruz, California, USA
146 Instituto de Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
147 Instituto de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
148 Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
149 Instituto de Alta Investigación, Universidad de Tarapacá, Chile
150 Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
151 Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
152 Department of Physics, University of Washington, Seattle, Washington, USA
153 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
154 Department of Physics, Shinshu University, Nagano, Japan
155 Department Physik, Universität Siegen, Siegen, Germany
156 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
157 SLAC National Accelerator Laboratory, Stanford, California, USA
158 Physics Department, Royal Institute of Technology, Stockholm, Sweden
159 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
160 Physics Department, Stony Brook University, Stony Brook, New York, USA
161 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
162 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
163 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
164 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
165 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
166 Tomsk State University, Tomsk, Russia
167 Department of Physics, University of Toronto, Toronto, Ontario, Canada

261801-20
Deceased.
\(^{1}\) Also at Department of Physics, King’s College London, London, United Kingdom.
\(^{2}\) Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.
\(^{3}\) Also at TRIUMF, Vancouver, British Columbia, Canada.
\(^{4}\) Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
\(^{5}\) Also at Physics Department, An-Najah National University, Nablus, Palestine.
\(^{6}\) Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
\(^{7}\) Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
\(^{8}\) Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\(^{9}\) Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
\(^{10}\) Also at Universita di Napoli Parthenope, Napoli, Italy.
\(^{11}\) Also at Institute of Particle Physics (IPP), Canada.
\(^{12}\) Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\(^{13}\) Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
\(^{14}\) Also at Department of Physics, California State University, Fresno, USA.
\(^{15}\) Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\(^{16}\) Also at Centro Studi e Ricerche Enrico Fermi, Italy.
\(^{17}\) Also at Department of Physics, California State University, East Bay, USA.
\(^{18}\) Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\(^{19}\) Also at Graduate School of Science, Osaka University, Osaka, Japan.
\(^{20}\) Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
\(^{21}\) Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.
\(^{22}\) Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\(^{23}\) Also at CERN, Geneva, Switzerland.
\(^{24}\) Also at Joint Institute for Nuclear Research, Dubna, Russia.
\(^{25}\) Also at Hellenic Open University, Patras, Greece.
\(^{26}\) Also at Center for High Energy Physics, Peking University, China.
\(^{27}\) Also at The City College of New York, New York, New York, USA.
\(^{28}\) Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.
\(^{29}\) Also at Department of Physics, California State University, Sacramento, USA.
\(^{30}\) Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
\(^{31}\) Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
\(^{32}\) Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
\(^{33}\) Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
\(^{34}\) Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
\(^{35}\) Also at National Research Nuclear University MEPhI, Moscow, Russia.
\(^{36}\) Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
\(^{37}\) Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
\(^{38}\) Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.