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):
Aad, G., & ATLAS Collaboration (2020). Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS. Physical Review Letters, 125(26), [261801].
https://doi.org/10.1103/PhysRevLett.125.261801
Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS

G. Aad et al.*
(ATLAS Collaboration)

(Received 2 October 2020; revised 30 October 2020; accepted 23 November 2020; published 23 December 2020)

The observation of forward proton scattering in association with lepton pairs \((e^+e^- + p\) or \(\mu^+\mu^- + p\)) produced via photon fusion is presented. The scattered proton is detected by the ATLAS Forward Proton spectrometer, while the leptons are reconstructed by the central ATLAS detector. Proton-proton collision data recorded in 2017 at a center-of-mass energy of \(\sqrt{s} = 13\) TeV are analyzed, corresponding to an integrated luminosity of 14.6 fb\(^{-1}\). A total of 57 (123) candidates in the \(ee + p\) (\(\mu\mu + p\)) final state are selected, allowing the background-only hypothesis to be rejected with a significance exceeding 5 standard deviations in each channel. Proton-tagging techniques are introduced for cross-section measurements in the fiducial detector acceptance, corresponding to \(\sigma_{ee+p} = 11.0 \pm 2.6\) (stat) \(\pm 1.2\) (syst) \(\pm 0.3\) (lumi) and \(\sigma_{\mu\mu+p} = 7.2 \pm 1.6\) (stat) \(\pm 0.9\) (syst) \(\pm 0.2\) (lumi) fb in the dielectron and dimuon channel, respectively.

DOI: 10.1103/PhysRevLett.125.261801

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, \(\gamma\gamma \to \ell^+\ell^-\), 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 \(\gamma\gamma \to \ell^+\ell^-\) 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 proton spectrometers can detect the scattered protons, which is a technique referred to as proton tagging.

The CMS and TOTEM Collaborations reported proton-tagged dielectron (dimuon) production with 2.6\sigma(4.3\sigma) significance, which exceeds 5\sigma when statistically combined [31], but no cross sections were measured. Previous measurements of \(\gamma\gamma \to \ell^+\ell^-\) by the ATLAS Collaboration were performed without proton tagging [4,5].

Measuring proton-tagged dilepton production, \(pp \to p(\gamma\gamma \to \ell^+\ell^-)p^{(*)}\), where \(p^{(*)}\) 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 \(pp \to p(\gamma\gamma \to \ell^+\ell^-)p^{(*)}\). 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 4\pi coverage [50] around the interaction point. It comprises an inner detector tracker, calorimeters, and a muon spectrometer. A two-level trigger
system [51] is employed to select events containing same-flavor lepton pairs, each lepton with $p_{T}\ell > 17(14)$ GeV [52–54], after which standard data-quality requirements are applied [55].

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 x 80 pixels with area 50 x 250 $\mu$m$^2$. The direction normal to each sensor is tilted 14° 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 $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p$ were produced using the HERWIG7 Monte Carlo (MC) generator [64,65]. The single-dissociative signal $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p^*$ 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]. The single-dissociative samples employed a fast simulation [72], which uses a parametrization of the calorimeter response [73]. The response of the AFP spectrometer is modeled by a fast simulation, 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 $|d_0/\sigma_d| < 5(3)$ 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 $m_{\ell\ell} \ell [70,105]$ GeV. To select events compatible with $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p^*$ 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 ($N_{\text{tracks}} = 0$) that satisfy $\Delta R(\text{track},\ell) > 0.01$ for both leptons and $|z_0^{\text{track}} - z_0^\ell| < 0.5$ mm, where $z_0^{\text{track}}$ is the track $z_0$ position and $z_0^\ell = (z_0^1 + z_0^2)/2$ 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 $\xi_{\ell\ell} = m_{\ell\ell}/(\sqrt{s}E_{\text{AFP}}\ell)$, 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 $x_{\text{AFP}} = T(\xi_{\text{AFP}})$ relates the track $x$ position $x_{\text{AFP}}$ to the fractional energy loss of the scattered proton $\xi_{\text{AFP}} = 1 - E_{\text{scattered}}/E_{\text{beam}}$, where $E_{\text{scattered}}$ ($E_{\text{beam}}$) is the scattered (beam) proton energy. The LHC magnets and beam optics [82] govern the form of $T(\xi_{\text{AFP}})$ [83], which is simulated in the MAD-X package [84,85] with further details discussed in Refs. [56,86,87]. Determination of $\xi_{\text{AFP}}$ 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 $E_{\text{scattered}}$ 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 $-4.0(\pm 3.0)$ mm on side $A$ and $-3.8(\pm 2.9)$ 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 $x_{\text{AFP}}$ values relative to $x_0^s$ were calibrated in situ using the dimuon data sample passing the signal event selection. The $x_{\text{AFP}}^\ell - x_{\text{AFP}}$ distribution is peaked for signal processes due to the kinematic correlation between $x_{\text{AFP}}^\ell$ and $x_{\text{AFP}}$, where
$x_{\ell\ell} = T(\xi_{\ell\ell})$ is the expected position calculated using the transport function. Additive corrections are applied to $x_{\text{AFP}}^A$ 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 $\xi_{\text{AFP}}^A > 0.028 (0.018)$ on side $A$ and $\xi_{\text{AFP}}^C > 0.026 (0.019)$ 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 $\xi_{\text{AFP}}$ 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 $\xi_{\text{AFP}}^A$ closest to $\xi_{\ell\ell}$ is chosen. Proton-tagged dilepton candidates, denoted $\ell^+\ell^- + p$, are selected by requiring kinematic matching on at least one AFP side, $|\xi_{\text{AFP}} − \xi_{\ell\ell}| < 0.005$, which retains (rejects) 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 $\gamma\gamma \rightarrow \ell^+\ell^-$ processes, in which any outgoing protons are either 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 $A_{\ell\ell}^2 > 0.01$. 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 $A_{\ell\ell}^2 > 0.01$ condition with $A_{\text{tracks}}^0 \geq 1$ 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 $m_\ell\ell \in [70, 105] \text{ GeV}$ 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

![Diagram](261801-3)
FIG. 2. The 57 (123) ee (μμ) data event candidates in the dilepton rapidity $y_{ll}$ vs $m_{ll}$ plane satisfying event selection and kinematic matching, $|\xi_{\text{AFP}} - \xi_{ll}| < 0.005$, 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 $\xi \notin [0, 1]$.

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 μμ channels. Figure 2 displays in the $y_{ll} - m_{ll}$ plane of data candidates satisfying $|\xi_{\text{AFP}} - \xi_{ll}| < 0.005$ on at least one side and the corresponding acceptance regions of the four AFP stations. The highest-mass ee candidate has an invariant mass $m_{ll} = 717$ GeV and rapidity $y_{ll} = 0.252$, so the scattered protons would be within the acceptance of both AFP sides if this were an exclusive process. However, it is found that the proton on side A fails kinematic matching $|\xi_{\text{AFP}} - \xi_{ll}| < 0.005$, so this event is likely a single-dissociative process where the side A proton candidate originates from a pileup interaction. The corresponding quantities for the highest-mass μμ candidate are $m_{ll} = 319$ GeV and $y_{ll} = 0.255$. Figure 3 illustrates 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 $\xi_{ll}$ 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, $L = 14.6$ 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 (μμ) 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 μμ events with low $m_{ll}$ and high $|\xi_{ll}|$ 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 μμ 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 ± 0.04 is applied to $C_{\text{cent}}$ to account for
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 $N_{\text{tracks}}^\text{cuts} = 0$ requirement on these samples. Overall, this results in $C_{\text{cent}}^\mu = 0.12 \pm 0.01$ ($C_{\text{cent}}^\mu = 0.22 \pm 0.02$) for the $ee$ ($\mu\mu$) channel.

The $C_{\text{AFP}}$ factor is defined by the product $\epsilon_{\text{track}} \cdot \epsilon_{\text{smear}}$. The track reconstruction efficiency $\epsilon_{\text{track}}$ 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 $|x_{\text{near}} - x_{\text{true}}| < 2$ mm. The tag and probe stations are inverted to measure the far-station efficiency. It is found that $\epsilon_{\text{track}}$ varies with $\xi_{\text{AFP}}$ by 2%, which is assigned as an additional uncertainty. The proton resolution correction $\epsilon_{\text{smear}}$ is found to be $0.98 \pm 0.02$ (0.96 $\pm$ 0.04) for the $ee$ ($\mu\mu$) channel. This is evaluated as the fraction of simulated signal events passing $\xi_{\text{AFP}} < 2$, $\xi_{\ell_1} \in [0.035, 0.08]$, and $|\xi_{\ell_2} - \xi_{\ell_1}| < 0.005$ out of those satisfying $\xi_{\ell_1} \in [0.035, 0.08]$. 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 $\mu$rad 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 $\sigma_{\text{fid, }ee+p}^{\text{surv}} = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi})$ and $\sigma_{\mu\mu+p}^{\text{surv}} = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi})$ 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 a $m_{\gamma^*}$-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>$S_{\text{surv}} = 1$</th>
<th>$\sigma_{\text{fid, }ee+p}^{\text{surv}}$ (fb)</th>
<th>$\sigma_{\text{fid, }\mu\mu+p}^{\text{surv}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPAIR</td>
<td>$15.5 \pm 1.2$</td>
<td>$13.5 \pm 1.1$</td>
</tr>
<tr>
<td>HERWIG+LPAIR</td>
<td>$10.9 \pm 0.8$</td>
<td>$9.4 \pm 0.7$</td>
</tr>
<tr>
<td>SUPERCHIC 4</td>
<td>$12.2 \pm 0.9$</td>
<td>$10.4 \pm 0.7$</td>
</tr>
<tr>
<td>Measurement</td>
<td>$11.0 \pm 2.9$</td>
<td>$7.2 \pm 1.8$</td>
</tr>
</tbody>
</table>

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; BMWFFW and FWF, Austria; ANAS, Azerbaijan; STC, 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; IFs and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; NWO, Netherlands; RCT, Norway; MNIW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZSI, 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; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafsson’s 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

[52x685]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 $\gamma\gamma \to \mu^+\mu^-$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2012) 052.


[74] ATLAS Collaboration, Early inner detector tracking performance in the 2015 data at √s = 13 TeV, CERN Report
<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Physics, Northern Illinois University</td>
<td>DeKalb, Illinois, USA</td>
</tr>
<tr>
<td>Budker Institute of Nuclear Physics and NSU, SB RAS</td>
<td>Novosibirsk, Russia</td>
</tr>
<tr>
<td>Novosibirsk State University</td>
<td>Novosibirsk, Russia</td>
</tr>
<tr>
<td>Institute for High Energy Physics of the National Research Centre Kurchatov Institute</td>
<td>Protvino, Russia</td>
</tr>
<tr>
<td>Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”</td>
<td>Moscow, Russia</td>
</tr>
<tr>
<td>Department of Physics, New York University</td>
<td>New York, New York, USA</td>
</tr>
<tr>
<td>Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan</td>
<td></td>
</tr>
<tr>
<td>Ohio State University, Columbus, Ohio, USA</td>
<td></td>
</tr>
<tr>
<td>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma</td>
<td>Norman, Oklahoma, USA</td>
</tr>
<tr>
<td>Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA</td>
<td></td>
</tr>
<tr>
<td>Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic</td>
<td></td>
</tr>
<tr>
<td>Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA</td>
<td></td>
</tr>
<tr>
<td>Graduate School of Science, Osaka University, Osaka, Japan</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Oslo, Oslo, Norway</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Oxford University, Oxford, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA</td>
<td></td>
</tr>
<tr>
<td>Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia</td>
<td></td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA</td>
<td></td>
</tr>
<tr>
<td>Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física, Universidade de Coimbra, Coimbra, Portugal</td>
<td></td>
</tr>
<tr>
<td>Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física, Universidade do Minho, Braga, Portugal</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain</td>
<td></td>
</tr>
<tr>
<td>Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal</td>
<td></td>
</tr>
<tr>
<td>Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal</td>
<td></td>
</tr>
<tr>
<td>Institute of the Czech Academy of Sciences, Prague, Czech Republic</td>
<td></td>
</tr>
<tr>
<td>Czech Technical University in Prague, Prague, Czech Republic</td>
<td></td>
</tr>
<tr>
<td>Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic</td>
<td></td>
</tr>
<tr>
<td>Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France</td>
<td></td>
</tr>
<tr>
<td>Santa Cruz Institute for Particle Physics, University of California</td>
<td>Santa Cruz, California, USA</td>
</tr>
<tr>
<td>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile</td>
<td></td>
</tr>
<tr>
<td>Universidad Andres Bello, Department of Physics, Santiago, Chile</td>
<td></td>
</tr>
<tr>
<td>Instituto de Alta Investigación, Universidad de Tarapacá, Chile</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile</td>
<td></td>
</tr>
<tr>
<td>Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Washington, Seattle, Washington, USA</td>
<td></td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Shinshu University, Nagano, Japan</td>
<td></td>
</tr>
<tr>
<td>Department Physik, Universität Siegen, Siegen, Germany</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada</td>
<td></td>
</tr>
<tr>
<td>SLAC National Accelerator Laboratory, Stanford, California, USA</td>
<td></td>
</tr>
<tr>
<td>Physics Department, Royal Institute of Technology, Stockholm, Sweden</td>
<td></td>
</tr>
<tr>
<td>Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA</td>
<td></td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>School of Physics, University of Sydney, Sydney, Australia</td>
<td></td>
</tr>
<tr>
<td>Institute of Physics, Academia Sinica, Taipei, Taiwan</td>
<td></td>
</tr>
<tr>
<td>E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia</td>
<td></td>
</tr>
<tr>
<td>High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel</td>
<td></td>
</tr>
<tr>
<td>Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece</td>
<td></td>
</tr>
<tr>
<td>International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan</td>
<td></td>
</tr>
<tr>
<td>Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Tokyo Institute of Technology, Tokyo, Japan</td>
<td></td>
</tr>
<tr>
<td>Tomsk State University, Tomsk, Russia</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Toronto, Toronto, Ontario, Canada</td>
<td></td>
</tr>
</tbody>
</table>
PHYSICAL REVIEW LETTERS 125, 261801 (2020)

TRIUMF, Vancouver, British Columbia, Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana, Illinois, USA

Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Deceased.

Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.

Also at TRIUMF, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

Also at Physics Department, An-Najah National University, Nablus, Palestine.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.

Also at Department of Physics, California State University, Fresno, USA.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Centro Studi e Ricerche Enrico Fermi, Italy.

Also at Department of Physics, California State University, East Bay, USA.

Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at CERN, Geneva, Switzerland.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Hellenic Open University, Patras, Greece.

Also at Center for High Energy Physics, Peking University, China.

Also at The City College of New York, New York, New York, USA.

Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.

Also at Department of Physics, California State University, Sacramento, USA.

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.