Search for Displaced Leptons in $\sqrt{s} = 13$ TeV pp Collisions with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 17 November 2020; revised 3 March 2021; accepted 11 June 2021; published 27 July 2021)

A search for charged leptons with large impact parameters using 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data from the ATLAS detector at the LHC is presented, addressing a long-standing gap in coverage of possible new physics signatures. Results are consistent with the background prediction. This search provides unique sensitivity to long-lived scalar supersymmetric lepton partners (sleptons). For lifetimes of 0.1 ns, selectron, smuon, and stau masses up to 720, 680, and 340 GeV, respectively, are excluded at 95% confidence level, drastically improving on the previous best limits from LEP.

DOI: 10.1103/PhysRevLett.127.051802

Particles with long lifetimes are a feature of the standard model (SM) and many theories beyond the standard model (BSM) including R-parity-conserving supersymmetry (SUSY) [1–7] models like split SUSY [8,9] and gauge-mediated SUSY breaking (GMSB) [10–12], as well as R-parity-violating SUSY models [13,14] and exotic scenarios such as universal extra dimensions [15,16]. However, particle lifetime remains an underexplored parameter of phase space at the Large Hadron Collider (LHC), where detectors and searches for new physics were designed to measure the decay products of short-lived, heavy particles with the assumption that those decay products trace back to the collision point or very close to it [17–21]. BSM particles with lifetimes longer than a few picoseconds produce unconventional signatures, including displaced decay products that do not trace back to the interaction point. This brings technical challenges in almost all aspects of the search; consequently, some models with TeV-scale BSM particles in this lifetime regime remain unexplored. While many dedicated searches for long-lived particles have been performed by the ATLAS [22–34] and CMS [35–46] Collaborations, signatures with displaced leptons with no visible decay vertex would not be identified by any previous ATLAS search. This Letter addresses that gap in coverage.

This signature brings unique sensitivity to GMSB SUSY models [47–49], where the nearly massless gravitino is the lightest SUSY particle (LSP), and the next-to-lightest SUSY particle (NLSP) becomes long-lived due to the small gravitational coupling to the LSP. Well-motivated versions of this model have a stau ($\tilde{\tau}$) as the single NLSP, or a selectron ($\tilde{e}$), smuon ($\tilde{\mu}$), and $\tilde{\tau}$ as co-NLSPs [50]. In these models, pair-produced sleptons ($\tilde{\ell}$) of the same flavor decay into an invisible gravitino and a charged lepton of the same flavor as the parent $\tilde{\ell}$. A combination of results from the LEP experiments excluded the superpartners of the right-handed muons and electrons ($\tilde{\mu}_R$ and $\tilde{e}_R$, respectively) of any lifetime for masses less than 96.3 and 65.8 GeV. The OPAL experiment alone set the best limits for all lifetimes of $\tilde{\tau}_1$, a mixture of the superpartners of the left- and right-handed τ leptons, and excluded masses less than 87.6 GeV [51–55]. A previous search from the CMS experiment [56] selected events with displaced, different-flavor leptons using 19.7 fb^{-1} of 8 TeV data but did not directly target $\tilde{\ell}$ decays. A reinterpretation concluded that OPAL's constraints remained the most stringent [50]. Additionally, Ref. [57] shows that targeting this signature could help improve the coverage of minimal supersymmetric models with a gravitino LSP. The present search provides mass sensitivity beyond the LEP limits.

To evaluate signal sensitivity, Monte Carlo (MC) events in a simplified GMSB SUSY model were simulated with up to two additional partons at leading order using MADGRAPH5_AMC@NLOv2.6.1 [58] with the NNPDF2.3lo parton distribution function (PDF) set [59] and interfaced to PYTHIA8.230 [60] using the A14 set of tuned parameters (tune) [61]. The sparticle decay was simulated using GEANT4 [62], which does not preserve information about the chirality of the $\tilde{\ell}$. The mixed states of the superpartners of the left- and right-handed τ leptons, $\tilde{\tau}_{1,2}$, were generated with mixing angle $\sin\theta_{\tilde{\tau}} = 0.95$. The impact of multiple interactions in the same and neighboring bunch crossings (pileup) was modeled by overlaying each hard-scattering event with simulated minimum-bias events generated with PYTHIA8.210 [60] using the A3 tune [63] and NNPDF2.3lo PDF set [59]. Signal cross sections were calculated at next-to-leading order in α_s, with soft-gluon emission effects

[*]Full author list given at the end of the article.

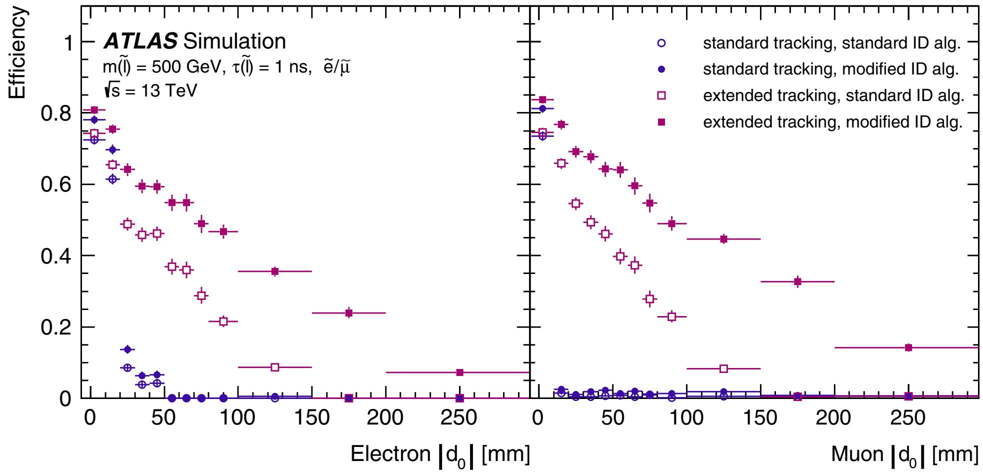

FIG. 1. Electron (left) and muon (right) reconstruction and identification efficiency in signal MC simulation. Leptons result from the decay of a $\tilde{\ell}$ with $m_{\tilde{\ell}} = 500$ GeV and $\tau_{\tilde{\ell}} = 1$ ns. Efficiency is defined as the number of reconstructed leptons divided by the number of generator-level leptons. Both the reconstructed and generator-level leptons are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. The closed purple square markers show the final lepton reconstruction efficiency. Markers are placed at the bin centers.

added at next-to-leading-logarithm accuracy [64–68]. The nominal cross section and uncertainty were taken from an envelope of predictions using different PDF sets and factorization and renormalization scales [69]. The simplified model used for interpretation assumes the superpartners of the left- and right-handed leptons are mass degenerate, yielding a cross section of 0.37 ± 0.01 pb for a single flavor of $\tilde{\ell}$ with mass 100 GeV and 0.059 ± 0.004 fb for a $\tilde{\ell}$ with mass 800 GeV. Simulated events were generated for $\tilde{e}/\tilde{\mu}$ ($\tilde{\tau}$) masses 50–900 GeV (50–400 GeV) and lifetimes 0.01–10 ns (0.1–1 ns).

This search uses 139 fb^{-1} of data collected by the ATLAS experiment from pp collisions at $\sqrt{s} = 13$ TeV. The ATLAS detector consists of concentric subdetectors used together to identify particles [70–73]. Data collection relies on a two-level trigger system, which uses tracking information from the inner detector (ID) along with information from the calorimeters and muon spectrometer (MS) to make fast, event-level decisions [74]. The typical lepton selection algorithms used in the trigger select particles coming from the primary interaction and cannot be used to select displaced leptons. Instead, triggers without tracking information are used: Electrons are identified using only their electromagnetic calorimeter (EM) signature via photon triggers, and muons are identified using MS information only. Single-photon and diphoton triggers select EM signatures with energy greater than 140 and 50 GeV, respectively, and the muon trigger selects MS signatures with transverse momentum (p_T) greater than 60 GeV in the range $|\eta| < 1.05$. These triggers have an acceptance independent of lepton displacement in the range probed by this search. The acceptance ranges from 1% to 80% for all flavors, increasing with $\tilde{\ell}$ mass, and is lower for $\tilde{\tau}$ than $\tilde{e}$ or $\tilde{\mu}$ due to the smaller p_T of the final-state leptons.

After the trigger stage, more complex tracking algorithms are possible, and tracks can be used more extensively for particle identification. Displaced leptons are identified as those with large transverse impact parameter ($|d_0|$), the distance of closest approach of the particle's track to the interaction point in the $x-y$ plane. The $|d_0|$ is measured relative to the vertex with the highest Σp_T^2 of associated tracks. Tracks are reconstructed by fitting a series of ID hits to identify those consistent with a particle's trajectory. For this search, tracking is performed in two stages: First, standard tracking reconstructs tracks with $|d_0| < 10$ mm [75], and then an additional reconstruction step uses hits not matched to tracks in the previous stage, adding tracks with $|d_0| < 300$ mm [76]. The extended track collection is combined with EM energy clusters to reconstruct electrons or with tracks composed of segments measured in the MS to reconstruct muons, both in the range $|\eta| < 2.5$. Standard lepton identification algorithms [77–79] are modified by removing requirements on $|d_0|$ and the number of hits matched to the track. Figure 1 shows the final reconstruction efficiency for displaced electrons and muons.

Signal leptons must have high transverse momentum, $p_T > 65$ GeV, and large transverse impact parameter, 3 mm $< |d_0| <$ 300 mm, to remove SM backgrounds. To reduce the background from out-of-time cosmic-ray muons, a requirement is placed on the MS timing relative to when a standard model particle is expected to arrive in the detector (t_0). The average time measured by the muon's MS track segments, $t_0^{\rm avg}$, must have an absolute value less than 30 ns. In order to reduce the contribution from leptons from decays of heavy-flavor hadrons, signal leptons are required to be isolated from nearby activity in the ID and calorimeters. The sum of the p_T of all tracks near an electron (muon) must be less than 6% (4%) of the lepton

p_T, and the sum of energy deposits near the electron (muon) in the calorimeters must be less than 6% (15%) of the lepton's energy [77,78]. The remaining quality criteria are used to minimize backgrounds and are inverted in the data-driven background estimation. Signal leptons must satisfy these to remove fake leptons originating from the mismatching of ID tracks to MS tracks or to calorimeter signatures. ID tracks associated with leptons are required to have a fit with $\chi^2/n_{\rm d.o.f.} < 2$ and no more than one missing hit after their innermost hit. Consistency between the two components of the reconstructed lepton is required. For electrons, this is ensured by requiring the ID track p_T measurement to be no less than half the electron p_T measured when accounting for the calorimeter energy $[(p_T^{\rm track} - p_T^e)/p_T^e > -0.5]$, and the combined fit of the muon's ID and MS tracks must satisfy $\chi^2/n_{\rm d.o.f.} < 3$. Muons are required to have measurements in at least three precision tracking layers of the MS and at least one high-precision ϕ measurement.

Three orthogonal signal regions are defined with at least two signal leptons and are distinguished by the flavor of the two highest-p_T leptons: SR-ee with two electrons, SR-$\mu\mu$ with two muons, and SR-$e\mu$ with one muon and one electron. No requirements are placed on the charge of the leptons. In order to ensure the broad applicability of this result to other models, event-level requirements beyond the presence of the two signal leptons are minimal. Backgrounds from lepton pairs produced via interactions with detector material are reduced by requiring that the opening angle between the two leptons, $\Delta R_{\ell\ell} \equiv \sqrt{(\Delta\eta_{\ell\ell})^2 + (\Delta\phi_{\ell\ell})^2}$, is greater than 0.2. Additionally, the event must not contain any cosmic-tagged muons. A cosmic-ray muon traversing the detector coincident with an LHC collision leaves a signature that could be reconstructed as two back-to-back muons, one in the top half of the detector, μ_t, and the other in the bottom, μ_b. Each muon is tagged as resulting from a cosmic-ray muon if it has MS segments along its trajectory on the opposite side of the detector or if its trajectory traces back to a gap in detector coverage [23]. A window in η and ϕ is defined relative to the muon's trajectory, and, if an MS segment is found within $|\eta_\mu + \eta_{\rm MS\ segment}| < 0.018$ and $|(\phi_\mu - \phi_{\rm MS\ segment}) - \pi| < 0.25$, the muon is cosmic tagged. This algorithm has a cosmic rejection efficiency of $> 99\%$.

The number of background events remaining after signal selections is estimated from data while keeping the signal regions blinded. In SR-ee and SR-$e\mu$, the dominant background comes from fake leptons, with a smaller contribution from leptons from heavy-flavor hadron decays. Zero events with a cosmic-tagged muon and electron were observed; therefore, the background contribution from untagged cosmic-ray muons in SR-$e\mu$ is expected to be negligible. Fake electrons typically result from the mismatching of a track to a photon. Fake muons result from the mismatching of an ID track to an MS track and are comparatively rare, since there is less activity and better pointing information in the MS than in the calorimeter. Fake leptons tend to fail quality criteria; as a result, they have poor χ^2 or inconsistent track and lepton p_T. Moreover, these requirements also remove heavy-flavor contributions which tend to have extra energy in their clusters compared to their tracks. As a result, the contribution of these backgrounds is estimated together. The quality criteria in this analysis are uncorrelated between the two leptons in an event, which has been verified in inverted regions in data. Since the variables are uncorrelated, they can be used to estimate the background contribution to the signal regions. The background is estimated with an *ABCD* method [80] by calculating the ratio of the number of events where lepton 1 passes inverted quality criteria (not including lepton p_T or $|d_0|$) and lepton 2 passes nominal requirements, and vice versa, divided by the number of events where both leptons fail the quality criteria. To estimate the background in SR-ee, where the two leading leptons are electrons, lepton 1 is the leading electron, and lepton 2 is the subleading electron. To estimate the background in SR-$e\mu$, where the two leading leptons are an electron and a muon, leptons 1 and 2 are the leading electron and muon, respectively. The same algorithm is used for SR-ee and SR-$e\mu$, but, due to statistical limitations in SR-$e\mu$, the p_T and $|d_0|$ requirements on the leptons are relaxed to $p_T > 50$ GeV and $|d_0| > 2$ mm. As the p_T and $|d_0|$ distributions are exponentially falling, this results in a conservative background estimate in SR-$e\mu$.

In the *ABCD* method, the phase space is split into four regions: region A, region B, region C, and region D. Region A is the signal region, where all requirements are satisfied, region B is the region where lepton 1 fails quality criteria but lepton 2 passes all lepton requirements, region C is the region where lepton 2 fails quality criteria but lepton 1 passes all requirements, and region D is the region where both leptons fail quality criteria. For an electron, the inverted quality criteria are ID track $\chi^2/n_{\rm d.o.f.} > 2$, $(p_T^{\rm track} - p_T^e)/p_T^e < -0.5$, and greater than one missing hit after the electron's innermost hit. For a muon, the inverted quality criteria are ID track $\chi^2/n_{\rm d.o.f.} > 2$, combined MS and ID track $\chi^2/n_{\rm d.o.f.} > 3$, measurements in less than three precision tracking layers of the MS, greater than one missing hit after the muon's innermost hit, and no high-precision ϕ measurement. The number of events in the signal region is then estimated by the following calculation:

$$N_A^{\rm predicted} = \frac{N_B \times N_C}{N_D},$$

where $N_A^{\rm predicted}$ is the predicted number of background events in the signal region (region A), N_B is the number of events in region B, N_C is the number of events in region C, and N_D is the number of events in region D.

TABLE I. Validation of the background data-driven estimate for the ee and $e\mu$ channel fake and heavy-flavor backgrounds. Uncertainties are statistical.

	VR-ee-fake	VR-ee-heavy-flavor	VR-$e\mu$-fake	VR-$e\mu$-heavy-flavor
Estimate	1356 ± 49	23.5 ± 1.9	$1.9^{+1.8}_{-1.0}$	$0.38^{+0.37}_{-0.32}$
Observed	1440	26	2	1

Validations of these background estimates are performed, with the heavy-flavor and fake contributions targeted separately. The validation of the heavy-flavor contribution is achieved using the same method as the nominal background estimation but inverting the isolation requirement in all regions. To increase statistics, the requirement on $(p_T^{\rm track} - p_T^e)/p_T^e$ is loosened to be greater than -0.9 instead of -0.5, as this distribution exponentially decreases from -1 to -0.5. The fake-lepton contribution is probed by inverting the most powerful fake discriminators by requiring the electron variable $(p_T^{\rm track} - p_T^e)/p_T^e$ to be less than -0.5 and the muon's combined track's $\chi^2/n_{\rm d.o.f.}$ to be greater than 3 and performing the $ABCD$ estimate with the remaining quality criteria. The validation of both estimates is shown in Table I. Even with the loosened requirements of $p_T > 50$ GeV and $|d_0| > 2$ mm in VR-$e\mu$-fake and VR-$e\mu$-heavy-flavor and $(p_T^{\rm track} - p_T^e)/p_T^e > -0.9$ in VR-$e\mu$-heavy-flavor, the statistics in these validation regions are limited. The background is so small since fake muons are rare, and the requirements on p_T and $|d_0|$ on signal leptons render heavy-flavor backgrounds negligible. Nonetheless, the numbers of estimated and observed events were consistent within statistical uncertainties, and uncertainties were assigned to account for small differences between predictions and observations in each validation. The predicted number of background events from fake and heavy-flavor-decay leptons is 0.46 ± 0.10 in SR-ee and $0.007^{+0.019}_{-0.007}$ in SR-$e\mu$, including all uncertainties.

The dominant background in SR-$\mu\mu$ comes from mismeasured reconstructed muons from cosmic rays. The fake lepton background is found to be negligible due to the rarity of fake muons. The heavy-flavor background is estimated using an $ABCD$ estimate extrapolating from nonisolated muons to isolated muons with loosened p_T and $|d_0|$ requirements to increase statistics ($p_T > 50$ GeV and subleading muon $|d_0| > 0.5$ mm). This results in a heavy-flavor estimate of $< 10^{-4}$ events. For a cosmic event to be a background to this search, both μ_t and μ_b must be reconstructed in the same event, which means their $|t_0^{\rm avg}|$ will be near the edges of the allowed range and are likely to have their MS hits associated with the wrong event. This results in reconstructed muons with good quality ID tracks, but poor quality MS signatures, which could present challenges in cosmic tagging one or both muons. An event with a cosmic-ray muon could meet signal region requirements if both muons have missing MS hits and neither is tagged. Cosmic-tagging failures occur not when the muon in question is mismeasured, but when the muon is in the half of the detector opposite to a poorly reconstructed MS track, and no MS segments are found in the tag window. The estimate of this background relies on the assumption that the quality of a muon and its probability to be cosmic tagged are uncorrelated.

All events considered in this estimate have μ_b passing all signal requirements, while μ_t is either cosmic tagged, fails to satisfy some of the quality criteria, or both. No dimuon events were observed with two muons on the same side of the detector. In events where μ_t is cosmic tagged, the ratio of μ_t which satisfy the quality criteria to those that do not, $R_{\rm good}$, is measured. This ratio is multiplied by the number of events in which μ_t is not cosmic tagged but fails to satisfy at least one of the quality criteria, to estimate the background in SR-$\mu\mu$. The estimate is validated by redefining the cosmic-tag window to leave more muons untagged, providing a larger sample for studying $R_{\rm good}$. An additional uncertainty is assigned to the background estimate from the validation to account for the $|d_0|$ dependence of $R_{\rm good}$, which cannot be directly constrained in the nominal estimate due to statistical limitations. Additional validations test other assumptions by varying the quality criteria and reversing the roles of μ_b and μ_t in the definition of $R_{\rm good}$. Including all uncertainties, $0.11^{+0.20}_{-0.11}$ events are predicted in SR-$\mu\mu$.

Signal systematic uncertainties are evaluated to quantify differences between data and simulation and correct the MC events where possible. Differences in signal lepton selection efficiency cannot be compared between data and MC simulation due to the lack of displaced leptons in data, so a conservative systematic uncertainty is derived in three steps. First, trigger, reconstruction, and selection efficiencies are measured for low-$|d_0|$ leptons resulting from Z boson decays, for which data and simulation can be compared. Scale factors are derived to correct the simulation to match the data. Uncertainties in these scale factors are statistical and less than 5%. Next, the high-$|d_0|$ tracking efficiency is compared between signal simulation and data with cosmic-tagged muons. After corrections to account for the different physical processes, the tracking efficiency as a function of displacement is compared, and an 8% uncertainty is assigned to each lepton. Finally, the $|d_0|$ dependence of the lepton reconstruction and selection efficiency is compared with the $|d_0|$ dependence of the tracking efficiency in simulation only. The variation of the selection efficiency as a function of $|d_0|$ is taken as an uncertainty to

TABLE II. The expected and observed yields in the signal regions. Combined statistical and systematic uncertainties are presented. Estimates are truncated at 0 if the size of measured systematic uncertainties would yield a negative result.

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	$<10^{-4}$	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	...	$0.11^{+0.20}_{-0.11}$	...
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

account for any discrepancies that cannot be studied in data. This uncertainty increases with displacement and is 0.5%–5% (3%–27%) for muons (electrons). It is larger for electrons due to identification challenges introduced by the ambiguity in the detector signatures of electrons, photons, and converted photons. Theoretical uncertainties include cross section uncertainties of 2%–6% and effects of varying the factorization and renormalization scales $< 5\%$. Other uncertainties, including the impact of pileup on signal selection, luminosity uncertainty [81,82], and uncertainty from the filtering selection used for the extended track reconstruction, contribute at $< 2\%$.

Zero events are observed in each of the three signal regions, consistent with the background predictions shown in Table II. As no excess of events is observed, exclusion limits on the $\tilde{\ell}$ masses are derived at 95% confidence level (C.L.) following the C.L.$_s$ prescription [83]. The HistFitter package [84] is used for statistical interpretation, and all systematic uncertainties are treated as Gaussian nuisance parameters during the fitting procedure. SR-ee and SR-$\mu\mu$ are fit individually to calculate limits on GMSB SUSY models with a $\tilde{e}$ or $\tilde{\mu}$ NLSP, while $\tilde{\tau}$ NLSP and co-NLSP limits are obtained using a simultaneous fit of all three signal regions. All uncertainties other than statistical are treated as correlated across the orthogonal regions.

Limits on long-lived $\tilde{\ell}$ production are presented in Fig. 2, where expected and observed exclusion contours as a function of $\tilde{\ell}$ mass and lifetime are shown. For a lifetime of 0.1 ns, $\tilde{e}$ NLSP, $\tilde{\mu}$ NLSP, $\tilde{\tau}$ NLSP, and co-NLSP scenarios are excluded for $\tilde{\ell}$ masses up to 720, 680, 340, and 820 GeV, respectively, for the case where the superpartners of the left- and right-handed leptons are mass degenerate. For a direct comparison with the previous best limits available from LEP, superpartners of right-handed electrons ($\tilde{e}_R$), muons ($\tilde{\mu}_R$), and left-handed τ-leptons ($\tilde{\tau}_L$) are excluded up to 580, 550, and 280 GeV, respectively, for lifetimes of 0.1 ns. This result probes GMSB $\tilde{\ell}$ production for the first time in this lifetime range at the electroweak scale and approaching the TeV scale. Furthermore, as no requirements were made on missing energy, displaced vertices, or jets, this result is model independent and applicable to any BSM model producing high-p_T displaced leptons.

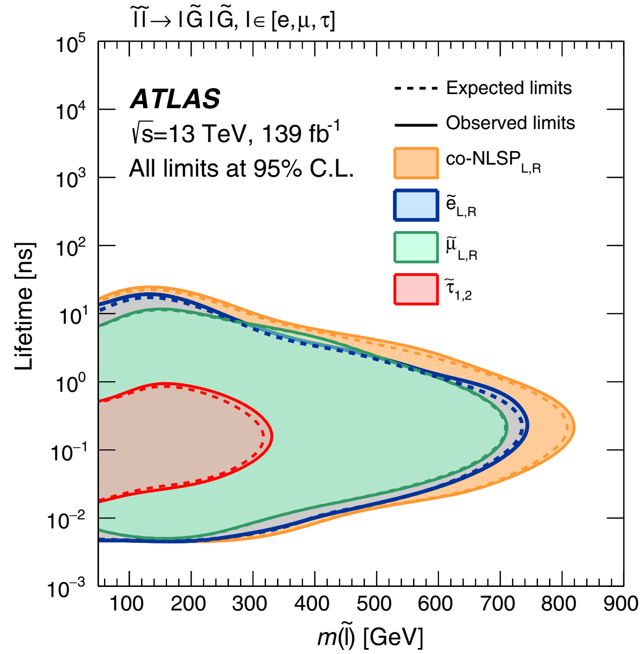

FIG. 2. Expected (dashed lines) and observed (solid lines) exclusion contours for $\tilde{e}$ NLSP, $\tilde{\mu}$ NLSP, $\tilde{\tau}$ NLSP, and co-NLSP production as a function of the slepton $\tilde{\ell}$ mass at 95% C.L. Selectrons $\tilde{e}_{L,R}$ and smuons $\tilde{\mu}_{L,R}$ are the superpartners of the left- and right-handed electrons and muons, respectively. Staus $\tilde{\tau}_{1,2}$ are the mixed states of the superpartners of the left- and right-handed τ leptons, with mixing angle $\sin\theta_{\tilde{\tau}} = 0.95$. The different $\tilde{\ell}$ chiral states are assumed to be mass degenerate.

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; Yerevan Physics Institute, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; Agencia Nacional de Investigación y Desarrollo, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and Committee for Collaboration of the Czech Republic with CERN, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; Shota Rustaveli National Science Foundation of Georgia, Giorgia; 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; Research Council of Norway, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; Ministry of Education and Science of the Russian Federation, Russian Federation and NRC KI, Russian Federation; Ministry of Education, Science and Technological Development, Serbia; Ministry of Education, Science, Research and Sport, Slovakia; ARRS and Ministry of Education, Science and Sport, Slovenia; DST/NRF, South Africa; MICINN, Spain; Ministry of Education, Science and Sport, Slovenia and Wallenberg Foundation, Sweden; Secretariat for Education and Research, Switzerland, SNSF, and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada, CRC, and IVADO, Canada; Beijing Municipal Science and 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 National Strategic Reference Framework, Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Program Generalitat de Catalunya and PROMETEO and GenT Programs Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; and 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 (United Kingdom) and BNL (USA), the Tier-2 facilities worldwide, and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [85].

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(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12a]*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

[12b]*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12c]*Department of Physics, Bogazici University, Istanbul, Turkey*
[12d]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[13]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[14]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[15a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15b]*Physics Department, Tsinghua University, Beijing, China*
[15c]*Department of Physics, Nanjing University, Nanjing, China*
[15d]*University of Chinese Academy of Science (UCAS), Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22a]*Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia*
[22b]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia*
[23a]*INFN Bologna and Universita' di Bologna, Dipartimento di Fisica, Bologna, Italy*
[23b]*INFN Sezione di Bologna, Bologna, Italy*
[24]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[25]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[26]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[27a]*Transilvania University of Brasov, Brasov, Romania*
[27b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[27c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[27d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[27e]*University Politehnica Bucharest, Bucharest, Romania*
[27f]*West University in Timisoara, Timisoara, Romania*
[28a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[28b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[29]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[30]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[31]*California State University, Fresno, California, USA*
[32]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[33a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[33b]*iThemba Labs, Western Cape, South Africa*
[33c]*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
[33d]*University of South Africa, Department of Physics, Pretoria, South Africa*
[33e]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[34]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[35a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
[35b]*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
[35c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[35d]*Moroccan Foundation for Advanced Science Innovation and Research (MAScIR), Rabat, Morocco*
[35e]*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
[35f]*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[36]*CERN, Geneva, Switzerland*
[37]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[38]*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[39]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[40]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[41a]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[41b]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
[42]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[43]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[44]*National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece*
[45a]*Department of Physics, Stockholm University, Stockholm, Sweden*
[45b]*Oskar Klein Centre, Stockholm, Sweden*

[46]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[47]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[48]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[49]Department of Physics, Duke University, Durham, North Carolina, USA
[50]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[51]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[52]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[53]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[54]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[55a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[55b]INFN Sezione di Genova, Genova, Italy
[56]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[57]SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[58]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[59]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[60a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[60b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[60c]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
[60d]Tsung-Dao Lee Institute, Shanghai, China
[61a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[61b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[62a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[62b]Department of Physics, University of Hong Kong, Hong Kong, China
[62c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[63]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[64]IJCLab, Université Paris-Saclay, CNRS/IN2P3, Orsay, France
[65]Department of Physics, Indiana University, Bloomington, Indiana, USA
[66a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[66b]ICTP, Trieste, Italy
[66c]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
[67a]INFN Sezione di Lecce, Lecce, Italy
[67b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[68a]INFN Sezione di Milano, Milano, Italy
[68b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[69a]INFN Sezione di Napoli, Napoli, Italy
[69b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[70a]INFN Sezione di Pavia, Pavia, Italy
[70b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[71a]INFN Sezione di Pisa, Pisa, Italy
[71b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[72a]INFN Sezione di Roma, Pisa, Italy
[72b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[73a]INFN Sezione di c Tor Vergata, Pisa, Italy
[73b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[74a]INFN Sezione di Roma Tre, Roma, Italy
[74b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[75a]INFN-TIFPA, Trento, Italy
[75b]Università degli Studi di Trento, Trento, Italy
[76]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[77]University of Iowa, Iowa City, Iowa, USA
[78]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[79]Joint Institute for Nuclear Research, Dubna, Russia
[80a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[80b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[80c]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[81]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

[82]*Graduate School of Science, Kobe University, Kobe, Japan*
[83a]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[83b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[84]*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[85]*Faculty of Science, Kyoto University, Kyoto, Japan*
[86]*Kyoto University of Education, Kyoto, Japan*
[87]*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[88]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[89]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[90]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[91]*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
[92]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[93]*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
[94]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[95]*Louisiana Tech University, Ruston, Louisiana, USA*
[96]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[97]*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
[98]*Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
[99]*Institut für Physik, Universität Mainz, Mainz, Germany*
[100]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[101]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[102]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[103]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[104]*School of Physics, University of Melbourne, Victoria, Australia*
[105]*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
[106]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[107]*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[108]*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
[109]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[110]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[111]*National Research Nuclear University MEPhI, Moscow, Russia*
[112]*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
[113]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[114]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[115]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[116]*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[117]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[118]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
[119]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[120]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[121a]*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
[121b]*Novosibirsk State University Novosibirsk, Novosibirsk, Russia*
[122]*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
[123]*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, Russia*
[124]*Department of Physics, New York University, New York, New York, USA*
[125]*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
[126]*Ohio State University, Columbus, Ohio, USA*
[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]*LPNHE, 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*

[138a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
[138b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[138c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[138d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[138e]Departamento de Física, Universidade do Minho, Braga, Portugal
[138f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[138g]Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[138h]Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[139]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[140]Czech Technical University in Prague, Prague, Czech Republic
[141]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[142]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[143]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[144]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[145a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[145b]Universidad Andres Bello, Department of Physics, Santiago, Chile
[145c]Instituto de Alta Investigación, Universidad de Tarapacá, Chile
[145d]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[146]Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
[147]Department of Physics, University of Washington, Seattle, Washington, USA
[148]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[149]Department of Physics, Shinshu University, Nagano, Japan
[150]Department Physik, Universität Siegen, Siegen, Germany
[151]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[152]SLAC National Accelerator Laboratory, Stanford, California, USA
[153]Physics Department, Royal Institute of Technology, Stockholm, Sweden
[154]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[155]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[156]School of Physics, University of Sydney, Sydney, Australia
[157]Institute of Physics, Academia Sinica, Taipei, Taiwan
[158a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
[158b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[159]Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
[160]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[161]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[162]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
[163]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[164]Tomsk State University, Tomsk, Russia
[165]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[166a]TRIUMF, Vancouver, British Columbia, Canada
[166b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
[167]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[168]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[169]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[170]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[171]Department of Physics, University of Illinois, Urbana, Illinois, USA
[172]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
[173]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[174]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[175]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[176]Department of Physics, University of Warwick, Coventry, United Kingdom
[177]Waseda University, Tokyo, Japan
[178]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[179]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[180]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[181]Department of Physics, Yale University, New Haven, Connecticut, USA

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.

[c]Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
[d]Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.
[e]Also at TRIUMF, Vancouver, British Columbia, Canada.
[f]Also at Physics Department, An-Najah National University, Nablus, Palestinian Authority.
[g]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[h]Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
[i]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[j]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[k]Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
[l]Also at Universita di Napoli Parthenope, Napoli, Italy.
[m]Also at Institute of Particle Physics (IPP), Victoria, Canada.
[n]Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[o]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[p]Also at Department of Physics, California State University, Fresno, USA.
[q]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[r]Also at Centro Studi e Ricerche Enrico Fermi, Italy.
[s]Also at Department of Physics, California State University, East Bay, USA.
[t]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[u]Also at Graduate School of Science, Osaka University, Osaka, Japan.
[v]Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
[w]Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.
[x]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[y]Also at CERN, Geneva, Switzerland.
[z]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[aa]Also at Hellenic Open University, Patras, Greece.
[bb]Also at Center for High Energy Physics, Peking University, China.
[cc]Also at The City College of New York, New York, New York, USA.
[dd]Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.
[ee]Also at Department of Physics, California State University, Sacramento, USA.
[ff]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[gg]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[hh]Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
[ii]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[jj]Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
[kk]Also at National Research Nuclear University MEPhI, Moscow, Russia.
[ll]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[mm]Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
[nn]Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.