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

Aad, G.; ATLAS Collaboration

DOI
10.1103/PhysRevLett.127.051802

Publication date
2021

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
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 (\(\tilde{l}\)) of the same flavor decay into an invisible gravitino and a charged lepton of the same flavor as the parent \(\tilde{l}\). 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 \(\tilde{l}\), a mixture of the superpartners of the left- and right-handed \(\tau\) 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 \(\tilde{l}\) 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 \(\tilde{l}\). The mixed states of the superpartners of the left- and right-handed \(\tau\) leptons, \(\tilde{l}_{1,2}\), 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 \(\alpha_s\), with soft-gluon emission effects

**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
trigger selects MS signatures with transverse momentum greater than 140 and 50 GeV, respectively, and the muon and diphoton triggers select EM signatures with energy identified using MS information only. Single-photon (EM) signature via photon triggers, and muons are identified using only their electromagnetic calorimeter without tracking information are used: Electrons are used to select displaced leptons. Instead, triggers 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 \( \hat{\ell} \) mass, and is lower for \( \tilde{\tau} \) 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 \( \Sigma p_T^2 \) 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, \( p_T > 65 \text{ GeV} \), and large transverse impact parameter, \( 3 \text{ mm} < |d_0| < 300 \) 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 \( (\eta_0) \). The average time measured by the muon’s MS track segments, \( \tau_0^{\text{avg}} \), 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 $\chi^2/n_{d.o.f.} < 2$ 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 $[(p_T^{\text{track}} - p_T^{\gamma})/p_T^{\gamma} > -0.5]$, and the combined fit of the muon’s ID and MS tracks must satisfy $\chi^2/n_{d.o.f.} < 3$. Muons are required to have measurements in at least three precision tracking layers of the MS and at least one high-precision $\phi$ 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-μμ with two muons, and SR-μe 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, $\Delta R_{ll} \equiv \sqrt{(\Delta \eta_{ll})^2 + (\Delta \phi_{ll})^2}$, 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, $\mu_t$, and the other in the bottom, $\mu_b$. 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 $\eta$ and $\phi$ is defined relative to the muon’s trajectory, and, if an MS segment is found within $|\eta_{\mu} - \eta_{\text{MS segment}}| < 0.018$ and $|\phi_{\mu} - \phi_{\text{MS segment}}| < 0.25$, 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-μeμ, 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-μeμ 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 $\chi^2$ 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-μeμ, 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-μeμ, but, due to statistical limitations in SR-μeμ, 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-μeμ.

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 $\chi^2/n_{d.o.f.} > 2$, $(p_T^{\text{track}} - p_T^{\gamma})/p_T^{\gamma} < -0.5$, and greater than one missing hit after the electron’s innermost hit. For a muon, the inverted quality criteria are ID track $\chi^2/n_{d.o.f.} > 2$, combined MS and ID track $\chi^2/n_{d.o.f.} > 3$, 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 $\phi$ measurement. The number of events in the signal region is then estimated by the following calculation:

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

where $N_A^{\text{predicted}}$ 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 $D$. 

051802-3
TABLE I. Validation of the background data-driven estimate for the $ee$ and $e\mu$ channel fake and heavy-flavor backgrounds. Uncertainties are statistical.

<table>
<thead>
<tr>
<th></th>
<th>VR-$ee$-fake</th>
<th>VR-$ee$-heavy-flavor</th>
<th>VR-$e\mu$-fake</th>
<th>VR-$e\mu$-heavy-flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate</td>
<td>1356 ± 49</td>
<td>23.5 ± 1.9</td>
<td>1.9$^{+1.8}_{-1.0}$</td>
<td>0.38$^{+0.37}_{-0.32}$</td>
</tr>
<tr>
<td>Observed</td>
<td>1440</td>
<td>26</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

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 $(p_T^{\text{track}} - p_T^{\mu})/p_T^{\mu}$ 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 $(p_T^{\text{track}} - p_T^{e})/p_T^{e}$ to be less than $-0.5$ and the muon’s combined track’s $\chi^2/n_{\text{d.o.f.}}$ 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 $(p_T^{\text{track}} - p_T^{\mu})/p_T^{\mu} > -0.9$ 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 $0.46 \pm 0.10$ in SR-$ee$ and $0.007^{+0.019}_{-0.007}$ in SR-$e\mu$, including all uncertainties.

The dominant background in SR-$e\mu$ 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 $\mu_t$ and $\mu_b$ must be reconstructed in the same event, which means their $|r_3^{\text{QV}}|$ 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 $\mu_t$ passing all signal requirements, while $\mu_t$ 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 $\mu_t$ is cosmic tagged, the ratio of $\mu_t$ which satisfy the quality criteria to those that do not, $R^{\text{good}}$, is measured. This ratio is multiplied by the number of events in which $\mu_t$ is not cosmic tagged but fails to satisfy at least one of the quality criteria, to estimate the background in SR-$e\mu$. The estimate is validated by redefining the cosmic-tag window to leave more muons untagged, providing a larger sample for studying $R^{\text{good}}$. An additional uncertainty is assigned to the background estimate from the validation to account for the $|d_0|$ dependence of $R^{\text{good}}$ 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 $\mu_b$ and $\mu_t$ in the definition of $R^{\text{good}}$. Including all uncertainties, $0.11^{+0.20}_{-0.11}$ events are predicted in SR-$e\mu$.

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
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%.

Limits on long-lived \( \tilde{\ell} \) leptons, with mixing angle \( \sin \theta_L = 0.95 \). 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; BMWF and FWF, Austria; ANAS, Azerbaijan; SfTC, 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,
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].


[34] ATLAS Collaboration, Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton–proton collisions at \( \sqrt{s} = 8 \) TeV with the ATLAS detector, Phys. Rev. D 92, 012010 (2015).


[38] CMS Collaboration, Searches for physics beyond the standard model with the \( M_{12} \) variable in hadronic final states with and without disappearing tracks in proton–proton collisions at \( \sqrt{s} = 13 \) TeV, Eur. Phys. J. C 80, 3 (2020).


[46] CMS Collaboration, Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at \( \sqrt{s} = 8 \) TeV, Phys. Rev. D 91, 052012 (2015).


051802-7


[70] 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).


Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN e Laboratori Nazionali di Frascati, Frascati, Italy
Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
Dipartimento di Fisica, Università di Genova, Genova, Italy
INFN Sezione di Genova, Genova, Italy
II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
Tsung-Dao Lee Institute, Shanghai, China
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, University of Hong Kong, Hong Kong, China
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
IJJCLab, Université Paris-Saclay, CNRS/IN2P3, Orsay, France
Department of Physics, Indiana University, Bloomington, Indiana, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Fisica, Università del Salento, Lecce, Italy
INFN Sezione di Milano, Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Pavia, Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pisa, Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma, Pisa, Italy
Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di c’Tor Vergata, Pisa, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Roma, Italy
Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
INFN-TIFPA, Trento, Italy
Università degli Studi di Trento, Trento, Italy
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
Joint Institute for Nuclear Research, Dubna, Russia
Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Physics Department, An-Najah National University, Nablus, Palestinian Authority.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
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), Victoria, 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 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.