


# Search for Heavy Neutral Leptons in Decays of $W$ Bosons Using a Dilepton Displaced Vertex in $\sqrt{s} = 13$ TeV $pp$ Collisions with the ATLAS Detector

G. Aad *et al.*\*  
(ATLAS Collaboration)

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A search for a long-lived, heavy neutral lepton ( $\mathcal{N}$ ) in  $139 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV  $pp$  collision data collected by the ATLAS detector at the Large Hadron Collider is reported. The  $\mathcal{N}$  is produced via  $W \rightarrow \mathcal{N}\mu$  or  $W \rightarrow \mathcal{N}e$  and decays into two charged leptons and a neutrino, forming a displaced vertex. The  $\mathcal{N}$  mass is used to discriminate between signal and background. No signal is observed, and limits are set on the squared mixing parameters of the  $\mathcal{N}$  with the left-handed neutrino states for the  $\mathcal{N}$  mass range  $3 \text{ GeV} < m_{\mathcal{N}} < 15 \text{ GeV}$ . For the first time, limits are given for both single-flavor and multiflavor mixing scenarios motivated by neutrino flavor oscillation results for both the normal and inverted neutrino-mass hierarchies.

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The observations of neutrino flavor oscillations [1,2] can be explained by postulating the existence of right-handed neutrino states that carry no standard model (SM) gauge charges, allowing them to have Majorana masses. The resulting “type-I seesaw” model [3–9] explains the light neutrino masses and predicts heavy mass eigenstates, referred to as “heavy neutral leptons” (HNLs) and denoted by  $\mathcal{N}$  henceforth. The existence of HNLs can also explain the baryon asymmetry of the Universe via leptogenesis [10–12], which is efficient for HNL masses down to the sub-GeV range [13–17]. Moreover, a model with three HNLs can incorporate a dark matter candidate [14,18–21].

Each HNL state carries a small admixture of the left-handed neutrino of flavor  $\alpha = \{e, \mu, \tau\}$ . It can therefore participate in weak interactions, controlled by dimensionless mixing coefficients  $U_\alpha$ , where  $|U_\alpha| \ll 1$ . Previous searches were interpreted only in terms of a one-HNL model with single-flavor mixing (1SFH) [22–32]. This model is a useful benchmark but is not phenomenologically viable as it predicts neutrino masses that are too large and does not account for two neutrino mass splittings or neutrino flavor oscillations [33–35]. The simplest viable model is that of two quasidegenerate HNLs (2QDH), with close masses and couplings, where all  $U_\alpha$  are nonzero. A reinterpretation of ATLAS HNL searches in such HNL scenarios has been performed [35]. However, no experiment has directly explored 2QDH models yet.

The search reported here considers the production of HNLs via  $W \rightarrow \mathcal{N}\ell_\alpha$ , where  $\alpha = \{e, \mu\}$  indicates the flavor of the “prompt” lepton  $\ell_\alpha$ . The HNL decays into two oppositely charged leptons and a neutrino:  $\mathcal{N} \rightarrow \ell_\beta \ell_\gamma \nu_\gamma$  via an intermediate  $W^*$  boson, or  $\mathcal{N} \rightarrow \nu_\beta \ell_\gamma \ell_\gamma$  via a  $Z^*$  boson, where  $\beta, \gamma = e$  or  $\mu$ , as shown in Fig. 1 (the lepton-number-violating processes are shown in Fig. 1 of the Supplemental Material [36]).

The search focuses on the mixing and mass range (up to 20 GeV) in which the HNL is long-lived. The resulting HNL lifetime can be approximated by  $\tau_{\mathcal{N}} \approx (4.3 \times 10^{-12} \text{ s}) |U|^{-2} (m_{\mathcal{N}}/1 \text{ GeV})^{-5}$  [37], where  $|U|^2 \equiv \sum_\beta |U_\beta|^2$  is taken from Ref. [38]. The HNL decay occurs at a significantly displaced position from the proton-proton ( $pp$ ) collision point, forming a displaced vertex (DV) of two charged leptons,  $\ell_\beta \ell_\gamma$  or  $\ell_\gamma \ell_\gamma$ . The measured final states are labeled according to the prompt and displaced

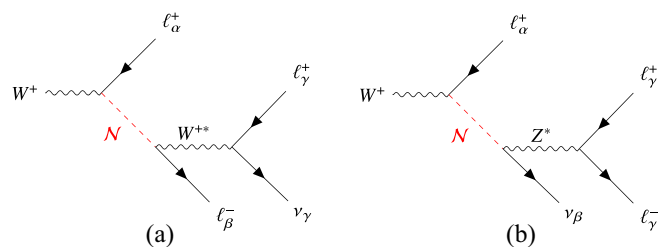


FIG. 1. Feynman diagrams for the HNL production and decay modes targeted in this analysis. Only lepton-number-conserving processes are shown. The flavors of the leptons in the diagrams, labeled by  $\alpha$ ,  $\beta$ , and  $\gamma$ , are either muons or electrons. If the charged leptons in the HNL decay have the same flavor, then both the diagrams with the virtual  $W$  (a) and virtual  $Z$  (b) contribute to the process. Equivalent processes are also valid for an initial state  $W^-$  boson.

\*Full author list given at the end of the article.

charged leptons therein, denoted by “ $\ell_\alpha\text{-}\ell_\beta\ell_\gamma$ ” (explicitly listed in Table I). Decays of the  $W$  or  $\mathcal{N}$  to  $\tau$  leptons were determined to have negligible contribution to the analysis, since the leptonic branching fractions of the  $\tau$  and the soft lepton spectrum make their selection highly inefficient. In 1SFH scenarios, the analysis is sensitive to the squared mixing parameter  $|U_\mu|^2$  via the final states  $\mu\text{-}\mu\mu$ ,  $\mu\text{-}\mu e$ , and  $\mu\text{-}ee$ , while  $|U_e|^2$  is accessible via  $e\text{-}ee$ ,  $e\text{-}e\mu$ , and  $e\text{-}\mu\mu$ . In 2QDH scenarios, the combination of the six final states provides sensitivity to  $|U_e|^2$ ,  $|U_\mu|^2$ , and  $|U_\tau|^2$ . For both scenarios, bounds on the mixing parameters are extracted in the “Dirac limit” of lepton-number-conserving (LNC) HNL interactions, where the  $W^*$ -mediated final state is  $\ell_\alpha^\pm\text{-}\ell_\beta^\mp\ell_\gamma^\pm$ , and in the “Majorana limit” of equal branching fractions for LNC and lepton-number-violating (LNV,  $\ell_\alpha^\pm\text{-}\ell_\beta^\pm\ell_\gamma^\mp$ ) decays [36]. The analysis can separate LNC and LNV decays only by using an explicit charge requirement for the 1SFH model in the  $\mu\text{-}\mu e$  and  $e\text{-}e\mu$  channels, where the displaced leptons are experimentally distinguishable by their different flavors. The bounds are tighter than and supersede those of Ref. [22], where only the final states  $\mu\text{-}\mu\mu$  and  $\mu\text{-}\mu e$  were studied.

This search is performed with  $139\text{ fb}^{-1}$  of 13 TeV  $pp$  collision data collected by the ATLAS experiment at the LHC from 2015 to 2018. To study the signal sensitivity, Monte Carlo (MC) signal samples were generated using PYTHIA8.212 [39] with the A14 set of tuned parameters [40] and the NNPDF2.3LO PDF set [41]. The impact of multiple  $pp$  interactions per bunch crossing was modeled by adding simulated minimum-bias events generated with PYTHIA 8.210 using the A3 tune [42] and NNPDF2.3LO PDF set. Particles were propagated through a detector simulation [43] based on GEANT4 [44]. To properly simulate spin correlations between  $W$ -boson decay products [35,45,46], which are not accounted for in PYTHIA8, events are weighted to reproduce the angular distributions obtained with MADGRAPH5\_AMC@NLO2.9.3 [47] using the HEAVYN model [48,49]. The weighting procedure is validated by comparing the momentum spectra of each of the charged-lepton flavors and the neutrino between the weighted PYTHIA8 and MADGRAPH5\_AMC@NLO samples. For each  $\ell_\alpha\text{-}\ell_\beta\ell_\gamma$  final state, signal samples were generated with HNL masses in the range  $3\text{ GeV} < m_{\mathcal{N}} < 20\text{ GeV}$  and proper decay lengths  $c\tau_{\mathcal{N}} = 1, 10, 100\text{ mm}$ .

The ATLAS detector [50–52] is a cylindrical detector with forward-backward symmetry and nearly  $4\pi$  solid-angle coverage [53]. It is composed of three major subsystems: the inner detector (ID) closest to the  $pp$  interaction point (IP), the electromagnetic and hadronic calorimeters, and the muon spectrometer farthest from the IP. The ID is used to reconstruct the trajectories of charged particles (tracks) in an almost uniform 2 T magnetic field, and comprises three subsystems: pixel, silicon microstrip tracker (SCT), and transition radiation tracker. An extensive software suite [54]

is used in the reconstruction and analysis of data and MC events, in detector operations, and in the trigger and data acquisition systems of the experiment.

Events in the signal region (SR) of this analysis were selected with triggers [55] that require a single isolated electron [56] or muon [57] with a minimum transverse momentum ( $p_T$ ) of 20–26 GeV, depending on the lepton flavor and year. Events passing the trigger are required by a filter algorithm to contain at least one lepton [58,59] with  $p_T > 28\text{ GeV}$  and  $|\eta| < 2.5$ .

To ensure isolation of this lepton from hadronic activity, the scalar sum of the  $p_T$  of other tracks within a cone of size  $\Delta R = 0.3$  around the lepton momentum ( $\Sigma p_T^{(0.3)}$ ) is required to be less than 5% of the lepton  $p_T$ . The filter also requires at least one additional lepton with  $p_T > 5\text{ GeV}$ ,  $|\eta| < 2.5$ , and  $\Sigma p_T^{(0.3)}/p_T < 1.0$ . To reduce the number of events with prompt decays while maintaining efficiency for displaced leptons, the second lepton must have a transverse impact parameter ( $d_0$ ) with respect to the IP of  $|d_0| > 0.1\text{ mm}$  ( $|d_0| > 1\text{ mm}$ ) for muons (electrons). Events that pass the filter are then processed with a large-radius tracking (LRT) algorithm [60], that is efficient for tracks with  $|d_0| < 300\text{ mm}$ . The LRT is run using hits leftover after the standard tracking [61], which is efficient only for  $|d_0| < 10\text{ mm}$ . Standard and large-radius tracks are combined with muon-spectrometer tracks (electromagnetic energy clusters) to reconstruct muons (electrons). Events are required to contain a reconstructed primary vertex (PV) with at least two tracks, each having  $p_T > 500\text{ MeV}$ . When more than one PV is reconstructed, the one with the highest  $\Sigma p_T^2$  is used, where the sum is over the tracks associated with the PV.

Event selection relies on the reconstruction of two physics objects: a prompt lepton and a DV. The prompt-lepton candidate,  $\ell_\alpha$ , is taken to be the highest- $p_T$  muon (electron) that satisfies  $p_T > 3$  (4.5) GeV,  $|d_0| < 3\text{ mm}$ , and  $|(z_0 - z_{\text{PV}}) \sin \theta| < 0.5\text{ mm}$ , where  $z_0$  is the track’s longitudinal impact parameter and  $z_{\text{PV}}$  is the  $z$  coordinate of the PV. If a prompt muon and a prompt electron have an angular separation  $\Delta R < 0.05$ , the event is rejected. Reconstruction of DVs is performed with an optimized version of the secondary vertexing algorithm described in Ref. [62]. First, “seed” DVs are formed from pairs of tracks from both the standard tracking and LRT algorithms. Subsequently, tracks are added to the DVs, and closely spaced DVs are merged. The secondary vertexing is run with the following configuration changes relative to Ref. [62]: seed DVs are formed from leptons only, with at least one lepton satisfying  $|d_0| > 1\text{ mm}$ , and each having at least eight pixel plus SCT hits; leptonic and hadronic tracks are subsequently attached to the DVs, but selected DVs must have exactly two leptons and no additional tracks.

Events must contain a prompt lepton and a DV comprising a pair of leptons with opposite-sign (OS) electric charge, although same-sign (SS) DVs are retained and

used for background studies. If a displaced track is identified as both a muon and an electron, the track is taken to be a muon (electron) if the muon- (electron-) identification quality is stricter. The displaced muons (electrons) must have  $p_T > 3$  (4.5) GeV. If a displaced track in the DV is within  $\Delta R = 0.05$  of the prompt lepton, the event is rejected. The DV radial position ( $r_{\text{DV}}$ ) must satisfy  $4 \text{ mm} < r_{\text{DV}} < 300 \text{ mm}$ . The invariant mass of the DV and the prompt lepton, which is generally smaller than the  $W$  mass, must satisfy  $40 \text{ GeV} < m_{\text{DV}+\ell} < 90 \text{ GeV}$ .

Background arises from five sources: DVs from particle interactions with detector material; decays of metastable SM particles;  $Z \rightarrow \ell\ell$  decays; cosmic-ray muons; and DVs from random crossings of lepton tracks. The following SR selection is designed to retain high signal efficiency and suppress the first four types of background to negligible levels, with random-crossing remaining the dominant background. Cosmic-ray muons, which can be reconstructed as two back-to-back muons in a DV, are rejected by requiring the two displaced tracks to satisfy  $\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$  [63]. Dielectron ( $ee$ ) DVs have the most background from particle interactions with detector material, so those selected must be in regions without detector material, determined from a three-dimensional map of the ID [64]. The displaced dilepton's invariant mass ( $m_{\text{DV}}$ ), which is generally smaller than  $m_{\mathcal{N}}$  due to the unobserved final-state neutrino, is used to suppress background from  $J/\psi$  and other heavy-flavor decays. For  $\mu\mu$  DVs,  $m_{\text{DV}} > 5.5 \text{ GeV}$  is required. For  $e\mu$  and  $ee$  DVs, the selection efficiency is smaller, motivating looser requirements that exploit correlations between  $r_{\text{DV}}$  and  $m_{\text{DV}}$ . These requirements are:  $m_{\text{DV}} > 5.5 \text{ GeV}$  for  $r_{\text{DV}} < (225/7) \text{ mm}$ ;  $m_{\text{DV}} > 2 \text{ GeV}$  for  $r_{\text{DV}} > (750/7) \text{ mm}$ ; and  $m_{\text{DV}} > 7 \text{ GeV} \times [1 - r_{\text{DV}}/(150 \text{ mm})]$  between these  $r_{\text{DV}}$  regions [36].

Background from  $Z \rightarrow \ell\ell$  decays, in which one of the leptons forms a DV with a third lepton, is suppressed by vetoing events where the invariant mass of the prompt lepton and the displaced lepton with the same flavor (i.e.,  $\alpha = \beta$ ) and opposite charge satisfies  $80 \text{ GeV} < m(\ell_\alpha^\pm \ell_\beta^\mp) < 100 \text{ GeV}$ . In channels with  $e\mu$  DVs, the random crossing background is reduced by roughly 50% for 1SFH, LNC interpretations, by requiring the prompt and displaced lepton with the same flavor to have opposite charges:  $\mu^\pm - \mu^\mp e^\pm$  or  $e^\pm - e^\mp \mu^\pm$ .

The four-momentum of the HNL is obtained by applying four-momentum conservation in the  $W$  and  $\mathcal{N}$  decays, using the kinematics of the charged leptons, the known  $W$  mass, an approximation where the leptons and neutrino are massless, and the flight direction of the  $\mathcal{N}$ , given by the vector connecting the PV and DV (see the Appendix). This calculation yields a quadratic equation with two solutions. The positive-radical solution is used to define the invariant mass ( $m_{\text{HNL}}$ ) of the HNL candidate. In MC signal events, the distribution of  $m_{\text{HNL}}$  peaks at the generated value  $m_{\mathcal{N}}$ , as shown in Fig. 2(a).

The final SR selection is  $m_{\text{HNL}} < 20 \text{ GeV}$ . The maximum signal selection efficiency is approximately 4%. A control region (CR) is defined as events with  $20 \text{ GeV} < m_{\text{HNL}} < 50 \text{ GeV}$ . Since HNLs with  $m_{\mathcal{N}} > 20 \text{ GeV}$  and  $|U_\alpha|^2$  values that the search is sensitive to are short-lived, they fail the  $r_{\text{DV}}$  requirements, resulting in negligible signal contamination in the CR.

A validation region (VR) is used for data-driven background modeling and evaluation of systematic uncertainties. The VR comprises events that passed a variety of triggers, underwent LRT reconstruction, and do not contain a prompt lepton. The DVs in the VR must satisfy the  $r_{\text{DV}}$  requirements and pass the cosmic-ray muon veto. For  $ee$  DVs, the detector material veto is also applied. The expected signal contamination in the VR is less than two events for a 100% HNL branching fraction into the channel of interest. Since the VR contains more than 100 events in each DV channel, the signal contamination is negligible.

Background from random track crossings is expected to yield equal numbers of OS and SS DVs, given the large number of tracks produced in each event. By contrast, background from  $Z \rightarrow \ell\ell$  or cosmic-ray muons yields only OS DVs, and backgrounds from particle interactions with detector material or from decays of metastable hadrons preferentially yield OS DVs. Figure 2(b) shows the  $m_{\text{DV}}$  distributions for SS and OS DVs in the VR. Good agreement is seen between the yield and shape of the distributions, shown for  $e\mu$  DVs. This indicates that the dominant source of background in the SR is random lepton crossings. Therefore, the background model described next focuses on this background type. A systematic uncertainty related to this assumption is described below.

The signal and background yields are obtained with the following fit. The fit uses a data-driven background model obtained from a sample of “shuffled events.” This sample is created by combining each OS DV in the VR with each prompt lepton found in a non-VR event that contains an SS DV satisfying loose requirements:  $m_{\text{DV}} > 1 \text{ GeV}$ , with no lepton identification criteria imposed on its displaced leptons. For each channel, the shuffled sample has at least  $2 \times 10^3$  times the number of events in the “unshuffled” data sample, in which the DV and the prompt lepton are from the same event. As with an unshuffled event, a shuffled event may have  $m_{\text{HNL}} < 20 \text{ GeV}$  (SR) or  $20 \text{ GeV} < m_{\text{HNL}} < 50 \text{ GeV}$  (CR). The background model in the SR and CR is given by the shuffled events [shown in Fig. 2(a)] with an independent floating normalization factor for each channel. The signal model for the fit is taken from simulation and is assigned a single floating signal strength for all channels. The input to the fit is the OS event yields observed in the SR and CR. Inclusion of the CR in the fit directly constrains the predicted background yield in the SR.

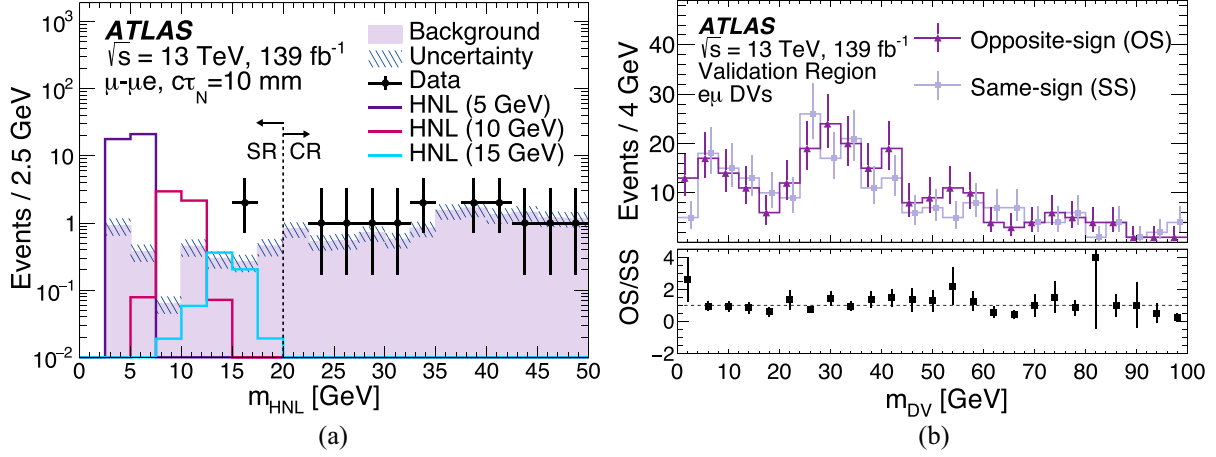


FIG. 2. (a) The  $m_{\text{HNL}}$  distribution in the signal (SR) and control (CR) regions for the observed data, the shuffled-event-model background normalized by the fit described in the text with its uncertainty, and simulated signal for three different mass hypotheses. (b) The  $m_{\text{DV}}$  distributions for the OS and SS  $e\mu$  DVs in the validation region. The marker is offset from the central position for visualization purposes.

The shuffled-event background model relies on the assumption that the absence of correlation between the randomly crossing tracks results in an absence of correlation between the DV and the prompt lepton. The validity of this assumption is checked by comparing the  $m_{\text{HNL}}$  distributions and the  $m_{\text{DV}+\ell}$  distributions of shuffled events with the distributions of unshuffled events. Only SS DVs are used in this test. In order to have a sufficient number of unshuffled events, the requirements on  $m_{\text{HNL}}$ ,  $m(\ell_{\alpha}^{\pm}\ell_{\beta}^{\mp})$ , and  $m_{\text{DV}+\ell}$  are removed, and that on  $m_{\text{DV}}$  is loosened to  $m_{\text{DV}} > 2$  GeV. The unshuffled-event samples have between 36 and 187 events in each channel, and the shuffled-event samples are more than 50 times larger. The comparison based on a Kolmogorov-Smirnov test yields probabilities ranging from 20% to 99% for the

TABLE I. Numbers (yields) of estimated postfit background events and of observed events in the signal and control regions. The background yields shown are from the 2QDH, inverted-hierarchy, Majorana-limit fit described in the text, and include both systematic and statistical uncertainties. The observed yields are shown for all final states. The last two rows show the 1SFH Dirac-limit, LNC configuration  $\ell_{\alpha}^{\pm}-\ell_{\alpha}^{\mp}\ell_{\gamma}^{\pm}$ .

Channel	Signal region		Control region	
	Background	Observed	Background	Observed
$e-ee$	$0.4 \pm 0.3$	2	$3.6 \pm 1.8$	2
$\mu-ee$	$0.2 \pm 0.1$	1	$1.8 \pm 1.3$	1
$e-e\mu$	$0.9 \pm 0.4$	0	$4.1 \pm 1.9$	5
$\mu-\mu e$	$2.8 \pm 0.8$	2	$12.2 \pm 3.2$	13
$e-\mu\mu$	$1.2 \pm 0.9$	1	$2.8 \pm 1.6$	3
$\mu-\mu\mu$	$2.2 \pm 1.4$	2	$8.7 \pm 2.9$	9
$e^{\pm}-e^{\mp}\mu^{\pm}$	$0.6 \pm 0.3$	0	$2.4 \pm 1.4$	3
$\mu^{\pm}-\mu^{\mp}e^{\pm}$	$1.9 \pm 0.6$	0	$8.1 \pm 2.6$	10

different channels, indicating the validity of the no-correlation assumption.

Systematic uncertainties in the background model, taken to be 100% correlated between the CR and the SR, are evaluated for two sources. The first estimates the uncertainty from the assumption that nonrandom backgrounds are negligible and is estimated from differences between the  $m_{\text{HNL}}$  distributions of shuffled events created from SS and OS DVs. This uncertainty varies between 5% for the  $e-e\mu$  channel and 79% for the  $\mu-\mu\mu$  channel. The second uncertainty accounts for statistical fluctuations in the  $m_{\text{HNL}}$  distribution of the shuffled sample due to the finite number of prompt leptons used therein. It is estimated from the differences between the  $m_{\text{HNL}}$  distributions for shuffled events of two types: in type 1 (2), the combined DV and prompt lepton originate from events in identical (different) DV channels ( $ee, \mu\mu, e\mu$ ). This uncertainty is largest for the  $\mu-\mu e$  channel, reaching 5%.

The total systematic uncertainty of the signal efficiency varies between 8% and 42% depending on the channel,  $m_{\mathcal{N}}$ , and  $c\tau_{\mathcal{N}}$ . Its largest contribution (up to 28%) arises from the reconstruction of displaced tracks and vertices. This is evaluated by comparing  $K_S^0 \rightarrow \pi^+\pi^-$  event yields in the VR with those in MC samples produced with PYTHIA8.186 in bins of  $p_T$  and  $r_{\text{DV}}$ , as in Ref. [65]. An additional uncertainty of 3% in the track reconstruction efficiency is calculated by randomly removing tracks from each signal MC event with a  $p_T$ - and  $\eta$ -dependent probability [66].

Uncertainties due to data-MC differences in the trigger efficiency [56,57] range up to 1%, and those due to lepton reconstruction, identification, and impact parameter resolution are between 2% and 17% [59,67] for the different channels. As in Ref. [68], an uncertainty in lepton-identification is estimated as the difference in selection efficiency between large and small  $|d_0|$  tracks. Its maximal

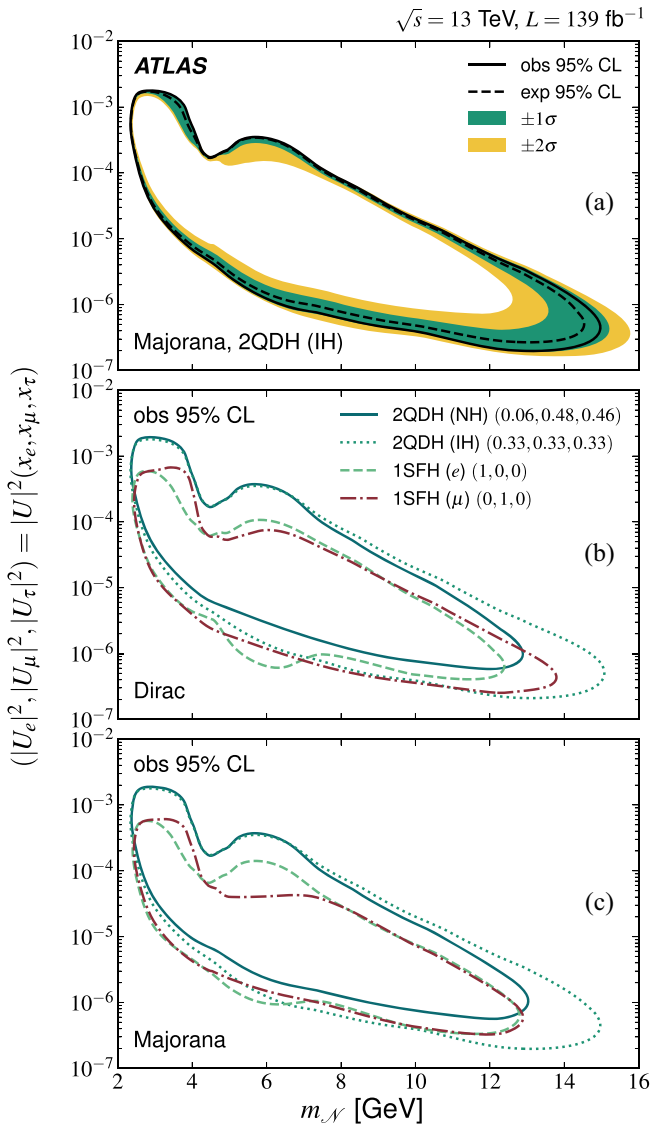


FIG. 3. (a) The observed and expected 95% CL limits on  $|U_\alpha|^2$  vs.  $m_{\mathcal{N}}$  in the Majorana-limit case, with green and yellow bands showing the one and two standard deviation ( $\sigma$ ) spreads for the expected limits. (b),(c) The observed limits in the 2QDH scenario with inverted (IH) and normal (NH) mass hierarchy, and in 1SFH scenarios where the HNL mixes with only  $\nu_\mu$  or  $\nu_e$ .

value is 7%. The uncertainty in the  $W$ -boson production cross section and modeling is 3% [69], and that in the HNL branching fractions and decay modeling is 5%, arising mainly from the QCD corrections to the HNL hadronic decay width [38,70]. Other uncertainties, including the impact of pileup on signal selection, luminosity uncertainty [71,72], and uncertainty from the filtering selection used for the extended track reconstruction, each contribute at  $<3\%$ .

Table I shows the postfit estimated and observed yields in the SR and CR for all channels (including the 1SFH, LNC scenario with the requirement  $\ell_\alpha^\pm - \ell_\alpha^\mp \ell_\beta^\pm$ ); a signal plus background hypothesis is used (postfit signal is compatible with zero). The SR contains two OS events

in each of the  $e-ee$ ,  $\mu-\mu e$ , and  $\mu-\mu\mu$  channels and one OS event in each of the  $\mu-ee$  and  $e-\mu\mu$  channels. No OS  $e-e\mu$  events are observed. These yields are consistent with the estimated backgrounds shown. The observed yields in the CR are consistent with the CR background estimates.

Limits are set at 95% confidence level (CL) on  $|U_\alpha|^2$  vs.  $m_{\mathcal{N}}$  for each HNL scenario, using the  $\text{CL}_s$  prescription [73] implemented in TRExFitter [74–76]. All systematic uncertainties are included in the fit by using nuisance parameters, whose postfit values do not show any significant pull or constraint. Each MC signal sample corresponds to specific values of  $|U_\alpha|^2$  vs.  $m_{\mathcal{N}}$ , for which the efficiency is evaluated and a hypothesis test is performed with  $10^4$  pseudoexperiments.

Figure 3 shows the excluded parameter space in the 1SFH and 2QDH scenarios for both the Dirac limit and the Majorana limit. In the 2QDH scenarios, exclusion limits are shown for the two neutrino-mass hierarchy scenarios. In the inverted-hierarchy case, the relative mixing coefficients are taken to be  $x_\alpha \equiv |U_\alpha|^2/|U|^2 = 1/3$  ( $\alpha = e, \mu, \tau$ ); for the normal-hierarchy case, the values  $x_e = 0.06$ ,  $x_\mu = 0.48$ , and  $x_\tau = 0.46$  are used [35,77]. These values are at the centers of the regions consistent with the neutrino flavor oscillation data. The observed limits are consistent with the expected limits. The feature visible near  $m_{\mathcal{N}} = 5$  GeV is due to the  $r_{\text{DV}}$ -dependent  $m_{\text{DV}}$  selection, which limits the sensitivity at low mass.

In conclusion, a search for long-lived heavy neutral leptons is conducted in a  $139 \text{ fb}^{-1}$  data sample of  $\sqrt{s} = 13$  TeV  $pp$  collisions collected with the ATLAS detector at the LHC. No excess is observed, and limits are set at 95% CL on the squared mixing coefficient  $|U_\alpha|^2$  in different HNL scenarios for HNL masses in the approximate range  $3 \text{ GeV} < m_{\mathcal{N}} < 15 \text{ GeV}$ . The observed limits exclude a region with wider ranges of  $|U_\mu|^2$  and  $m_{\mathcal{N}}$  than previously excluded by ATLAS, and the limits on  $|U_e|^2$  are novel in ATLAS. For the first time, limits are evaluated for the case of multiflavor mixing scenarios that agree with the neutrino flavor oscillation data, for both the normal and inverted neutrino-mass hierarchies. The strongest limits are observed for multiflavor mixing with the inverted hierarchy.

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*Appendix: A HNL mass.*—The HNL mass ( $m_{\text{HNL}}$ ) can be obtained using energy–momentum conservation in the HNL production ( $W \rightarrow \mathcal{N}\ell_1$ ) and decay ( $\mathcal{N} \rightarrow \ell_2\ell_3\nu$ ), where  $\ell_1$  is the prompt lepton and  $\ell_2$  and  $\ell_3$  are the charged leptons in the DV. The problem can be summarized with the following equations. Four-momentum conservation in the  $\mathcal{N}$  decay gives

$$p_{\mathcal{N}}^{\mu} = p_2^{\mu} + p_3^{\mu} + p_{\nu}^{\mu} \equiv p_{23}^{\mu} + p_{\nu}^{\mu}. \quad (\text{A1})$$

Four-momentum conservation in the  $W$  decay gives

$$p_W^{\mu} = p_1^{\mu} + p_{\mathcal{N}}^{\mu} = p_1^{\mu} + p_{23}^{\mu} + p_{\nu}^{\mu}. \quad (\text{A2})$$

The following are defined:

$$\begin{aligned} p_{23}^2 &= E_{23}^2 - |\vec{p}_{23}|^2 \equiv m_{23}^2, \\ p_{23}^{\parallel} &\equiv \vec{p}_{23} \cdot \hat{\nu}, \\ p_{23}^{\perp} &\equiv |\vec{p}_{23} - p_{23}^{\parallel}\hat{\nu}|, \end{aligned}$$

where  $m$ ,  $E$ , and  $|\vec{p}|$  are the mass, energy, and momentum-vector magnitude of the particles indicated

by their subscript and  $\hat{\nu}$  is the flight direction of the HNL given by the vector connecting the PV and DV.

The solution to the HNL mass is presented in the coordinate system  $k = (\hat{x}', \hat{y}', \hat{z}')$ , which is rotated relative to the ATLAS coordinate system, such that the origin of the  $k$  frame is at the PV and the  $z'$  axis points along the flight direction of the HNL. The definition of this coordinate system is

$$\hat{z}' = \hat{\nu}, \quad \hat{x}' = \frac{\vec{p}_{23} \times \hat{z}'}{|\vec{p}_{23} \times \hat{z}'|}, \quad \hat{y}' = \hat{z}' \times \hat{x}'.$$

The momenta of  $\ell_2$  and  $\ell_3$  constrain the components of the neutrino momentum orthogonal to  $\vec{p}_{\mathcal{N}}$ . This means that energy-momentum conservation in the  $W$  and  $\mathcal{N}$  decays can be expressed in terms of one unknown variable  $\alpha$ , which is the component of neutrino momentum in the  $\hat{z}'$  direction. To express Eqs. (A1) and (A2) in terms of  $\alpha$ , the following quantities are defined:

$$\vec{p}'_{23} \equiv \vec{q}, \quad (\text{A3})$$

$$\vec{q} = (0, |\vec{p}_{23} \times \hat{z}'| \equiv q_{\perp}, \vec{p}_{23} \cdot \hat{z}' \equiv q_z), \quad (\text{A4})$$

$$\vec{p}'_{\nu} = (0, -q_{\perp}, \alpha), \quad (\text{A5})$$

$$E'_{\nu} = \sqrt{q_{\perp}^2 + \alpha^2}. \quad (\text{A6})$$

Squaring Eq. (A2) gives

$$p_W'^2 = m_W^2 = m_1^2 + m_{\nu}^2 + m_{23}^2 + 2p'_1 \cdot (p'_{23} + p'_{\nu}) + 2p'_{23} \cdot p'_{\nu}, \quad (\text{A7})$$

where

$$\begin{aligned} p'_1 \cdot (p'_{23} + p'_{\nu}) &= E'_1(E'_{23} + E'_{\nu}) - p'_{1,z}(q_z + \alpha), \\ p'_{23} \cdot p'_{\nu} &= E'_{23}E'_{\nu} + q_{\perp}^2 - q_z\alpha. \end{aligned}$$

In the energy regime of interest, the charged leptons and neutrino can be treated as massless particles, such that  $m_1 = m_{\nu} = 0$ . Rearranging Eq. (A7) to solve for  $E_{\nu}$  gives

$$E'_{\nu} = A + B\alpha, \quad (\text{A8})$$

where

$$A = \frac{(m_W^2 - m_{23}^2)/2 - E'_1 E'_{23} + p'_{1,z} q_z - q_{\perp}^2}{E'_1 + E'_{23}}, \quad B = \frac{p'_{1,z} + q_z}{E'_1 + E'_{23}}.$$

Subtracting Eq. (A8) from Eq. (A6) gives the following quadratic expression in  $\alpha$

$$(B^2 - 1)\alpha^2 + 2AB\alpha + A^2 - q_\perp^2 = 0.$$

The solution for  $\alpha$  is therefore

$$\alpha = \frac{-AB \pm \sqrt{(B^2 - 1)q_\perp^2 + A^2}}{(B^2 - 1)}. \quad (\text{A9})$$

Both solutions for  $\alpha$  were studied using simulated HNL events and it was noted that the solution that led to a smaller  $|\vec{p}_{\mathcal{N}}|$  typically led to a value for  $m_{\text{HNL}}$  that was closer to the simulated  $m_{\mathcal{N}}$ . This solution often corresponded to forward emission of the neutrino with respect to the HNL decay. Therefore, the definition of  $m_{\text{HNL}}$  in the analysis uses the solution with the positive radical.

The expression for  $\alpha$  in Eq. (A9) depends on  $m_W$ . ATLAS has measured the  $W$ -boson pole mass to be  $M_W = 80.370 \pm 0.019$  GeV [79]. This measurement is combined in Ref. [2] with results from other collider experiments to provide a measurement of the  $W$ -boson width,  $\Gamma_W = 2.195 \pm 0.083$  GeV. Since the  $W$  mass has a width, then if  $m_W = M_W$  in Eq. (A9) it is possible that there is no real solution for  $\alpha$ . Instead of rejecting these events,  $m_W$  is set equal to the median  $W$  mass in the kinematically allowed region ( $m_{W,\text{med}}$ ). This ensures that  $\alpha$  (and correspondingly  $m_{\text{HNL}}$ ) always has a real solution.

To define the kinematically allowed region, the minimum  $W$  mass that is consistent with the charged-lepton decay products ( $m_{W,\text{min}}$ ) is computed. From Eq. (A7), the mass of the  $W$  boson is given by

$$m_W^2 = m_{23}^2 + 2(E'_1 E'_{23} + E'_\nu(E'_1 + E'_{23}) - p'_{1,z} q_z + q_\perp^2 - \alpha(p'_{1,z} + q_z)) \quad (\text{A10})$$

and  $m_{W,\text{min}}$  occurs where

$$\frac{d(m_W^2/2)}{d\alpha} = (E'_1 + E'_{23}) \frac{dE'_\nu}{d\alpha} - (p'_{1,z} + q_z) = 0. \quad (\text{A11})$$

Using

$$\frac{dE'_\nu}{d\alpha} = \frac{d\sqrt{q_\perp^2 + \alpha^2}}{d\alpha} = \frac{\alpha}{E'_\nu}$$

in Eq. (A11), the chosen value of  $\alpha$  that gives the minimum  $m_W$  is

$$\alpha = \frac{q_\perp B}{\sqrt{1 - B^2}}. \quad (\text{A12})$$

Substituting Eq. (A12) into Eq. (A10), the minimum  $W$  boson mass is

$$m_{W,\text{min}}^2 = m_{23}^2 + 2 \left( E'_1 E'_{23} + (E'_1 + E'_{23}) \sqrt{q_\perp^2 + \frac{q_\perp^2 B^2}{1 - B^2}} - p'_{1,z} q_z + q_\perp^2 - (p'_{1,z} + q_z) \frac{q_\perp B}{\sqrt{1 - B^2}} \right).$$

The cumulative probability for the  $W$  boson to have a mass greater than  $m_{W,\text{min}}$  is used to find the median of the remaining distribution. The probability density function ( $f$ ) for  $m_W^2$  satisfies

$$f(m_W^2) \propto \frac{1}{(m_W^2 - M_W^2)^2 + M_W^2 \Gamma_W^2}.$$

Therefore, the cumulative distribution function ( $F$ ) is

$$F(m_W^2) = \frac{1}{\pi} \arctan \left( \frac{m_W^2 - M_W^2}{M_W \Gamma_W} \right) + \frac{1}{2}. \quad (\text{A13})$$

The midpoint of the allowed kinematic region has a value of

$$F_{\text{med}} = \frac{1 + F(m_{W,\text{min}}^2)}{2}.$$

Rearranging Eq. (A13) for  $m_W^2$  gives

$$m_W^2 = M_W^2 + \Gamma_W M_W \tan \left( \pi \left[ F - \frac{1}{2} \right] \right). \quad (\text{A14})$$

Substituting  $F = F_{\text{med}}$  in Eq. (A14) gives an expression for the median  $W$  mass in the kinematically allowed region

$$m_{W,\text{med}}^2 = M_W^2 + \Gamma_W M_W \tan \left( \pi \left[ \frac{1 + F(m_{W,\text{min}}^2)}{2} - \frac{1}{2} \right] \right).$$

This value of  $m_{W,\text{med}}$  is used in Eq. (A9) to solve for  $\alpha$ .

From Eq. (A1) and the definitions in Eq. (A3) to (A6), the expression for the HNL mass in terms of  $\alpha$  is

$$\begin{aligned} m_{\text{HNL}}^2 &= m_{23}^2 + 2p'_\nu \cdot p'_{23} \\ &= m_{23}^2 + 2E'_{23} \sqrt{q_\perp^2 + \alpha^2} + 2q_\perp^2 - 2q_z \alpha. \end{aligned} \quad (\text{A15})$$

Substituting the expression for  $\alpha$  in Eq. (A9) into Eq. (A15) gives the solution for the HNL mass.

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G. Aad<sup>101</sup>, B. Abbott<sup>119</sup>, D. C. Abbott<sup>102</sup>, A. Abed Abud<sup>36</sup>, K. Abeling<sup>55</sup>, D. K. Abhayasinghe<sup>94</sup>, S. H. Abidi<sup>29</sup>,  
A. Aboulhorma<sup>35e</sup>, H. Abramowicz<sup>150</sup>, H. Abreu<sup>149</sup>, Y. Abulaiti<sup>116</sup>, A. C. Abusleme Hoffman<sup>136a</sup>,  
B. S. Acharya<sup>68a,68b,b</sup>, B. Achkar<sup>55</sup>, L. Adam<sup>99</sup>, C. Adam Bourdarios<sup>4</sup>, L. Adamczyk<sup>84a</sup>, L. Adamek<sup>154</sup>,  
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(ATLAS Collaboration)

<sup>1</sup>Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup>Department of Physics, University of Alberta, Edmonton Alberta, Canada

<sup>3a</sup>Department of Physics, Ankara University, Ankara, Türkiye

<sup>3b</sup>Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye

<sup>4</sup>LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>5</sup>APC, Université Paris Cité, CNRS/IN2P3, Paris, France

<sup>6</sup>High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

<sup>7</sup>Department of Physics, University of Arizona, Tucson, Arizona, USA

<sup>8</sup>Department of Physics, University of Texas at Arlington, Arlington, Texas, USA

<sup>9</sup>Physics Department, National and Kapodistrian University of Athens, Athens, Greece

- <sup>10</sup>*Physics Department, National Technical University of Athens, Zografou, Greece*
- <sup>11</sup>*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
- <sup>12</sup>*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- <sup>13</sup>*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
- <sup>14a</sup>*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
- <sup>14b</sup>*Physics Department, Tsinghua University, Beijing, China*
- <sup>14c</sup>*Department of Physics, Nanjing University, Nanjing, China*
- <sup>14d</sup>*University of Chinese Academy of Science (UCAS), Beijing, China*
- <sup>15</sup>*Institute of Physics, University of Belgrade, Belgrade, Serbia*
- <sup>16</sup>*Department for Physics and Technology, University of Bergen, Bergen, Norway*
- <sup>17a</sup>*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
- <sup>17b</sup>*University of California, Berkeley, California, USA*
- <sup>18</sup>*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- <sup>19</sup>*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- <sup>20</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- <sup>21a</sup>*Department of Physics, Bogazici University, Istanbul, Türkiye*
- <sup>21b</sup>*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
- <sup>21c</sup>*Department of Physics, Istanbul University, Istanbul, Türkiye*
- <sup>21d</sup>*Istinye University, Sariyer, Istanbul, Türkiye*
- <sup>22a</sup>*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia*
- <sup>22b</sup>*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
- <sup>23a</sup>*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
- <sup>23b</sup>*INFN Sezione di Bologna, Italy*
- <sup>24</sup>*Physikalisches Institut, Universität Bonn, Bonn, Germany*
- <sup>25</sup>*Department of Physics, Boston University, Boston, Massachusetts, USA*
- <sup>26</sup>*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
- <sup>27a</sup>*Transilvania University of Brasov, Brasov, Romania*
- <sup>27b</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- <sup>27c</sup>*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- <sup>27d</sup>*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
- <sup>27e</sup>*University Politehnica Bucharest, Bucharest, Romania*
- <sup>27f</sup>*West University in Timisoara, Timisoara, Romania*
- <sup>28a</sup>*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- <sup>28b</sup>*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- <sup>29</sup>*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- <sup>30</sup>*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
- <sup>31</sup>*California State University, California, USA*
- <sup>32</sup>*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>33a</sup>*Department of Physics, University of Cape Town, Cape Town, South Africa*
- <sup>33b</sup>*iThemba Labs, Western Cape, South Africa*
- <sup>33c</sup>*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- <sup>33d</sup>*National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines*
- <sup>33e</sup>*University of South Africa, Department of Physics, Pretoria, South Africa*
- <sup>33f</sup>*University of Zululand, KwaDlangezwa, South Africa*
- <sup>33g</sup>*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- <sup>34</sup>*Department of Physics, Carleton University, Ottawa ON, Canada*
- <sup>35a</sup>*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- <sup>35b</sup>*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
- <sup>35c</sup>*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- <sup>35d</sup>*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
- <sup>35e</sup>*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- <sup>35f</sup>*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
- <sup>36</sup>*CERN, Geneva, Switzerland*
- <sup>37</sup>*Affiliated with an institute covered by a cooperation agreement with CERN*
- <sup>38</sup>*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
- <sup>39</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- <sup>40</sup>*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*

- <sup>41</sup>*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- <sup>42</sup>*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- <sup>43a</sup>*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- <sup>43b</sup>*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- <sup>44</sup>*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- <sup>45</sup>*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- <sup>46</sup>*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- <sup>47a</sup>*Department of Physics, Stockholm University, Sweden*
- <sup>47b</sup>*Oskar Klein Centre, Stockholm, Sweden*
- <sup>48</sup>*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- <sup>49</sup>*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
- <sup>50</sup>*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- <sup>51</sup>*Department of Physics, Duke University, Durham, North Carolina, USA*
- <sup>52</sup>*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- <sup>53</sup>*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- <sup>54</sup>*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- <sup>55</sup>*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- <sup>56</sup>*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- <sup>57a</sup>*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- <sup>57b</sup>*INFN Sezione di Genova, Italy*
- <sup>58</sup>*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- <sup>59</sup>*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- <sup>60</sup>*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- <sup>61</sup>*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- <sup>62a</sup>*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- <sup>62b</sup>*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- <sup>62c</sup>*School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
- <sup>62d</sup>*Tsung-Dao Lee Institute, Shanghai, China*
- <sup>63a</sup>*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- <sup>63b</sup>*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- <sup>64a</sup>*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- <sup>64b</sup>*Department of Physics, University of Hong Kong, Hong Kong, China*
- <sup>64c</sup>*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- <sup>65</sup>*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- <sup>66</sup>*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
- <sup>67</sup>*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- <sup>68a</sup>*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- <sup>68b</sup>*ICTP, Trieste, Italy*
- <sup>68c</sup>*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- <sup>69a</sup>*INFN Sezione di Lecce, Italy*
- <sup>69b</sup>*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- <sup>70a</sup>*INFN Sezione di Milano, Italy*
- <sup>70b</sup>*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- <sup>71a</sup>*INFN Sezione di Napoli, Italy*
- <sup>71b</sup>*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- <sup>72a</sup>*INFN Sezione di Pavia, Italy*
- <sup>72b</sup>*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- <sup>73a</sup>*INFN Sezione di Pisa, Italy*
- <sup>73b</sup>*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- <sup>74a</sup>*INFN Sezione di Roma, Italy*
- <sup>74b</sup>*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- <sup>75a</sup>*INFN Sezione di Roma Tor Vergata, Italy*
- <sup>75b</sup>*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- <sup>76a</sup>*INFN Sezione di Roma Tre, Italy*
- <sup>76b</sup>*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- <sup>77a</sup>*INFN-TIFPA, Italy*

- <sup>77b</sup>*Università degli Studi di Trento, Trento, Italy*
- <sup>78</sup>*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
- <sup>79</sup>*University of Iowa, Iowa City, Iowa, USA*
- <sup>80</sup>*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
- <sup>81a</sup>*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
- <sup>81b</sup>*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- <sup>81c</sup>*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- <sup>81d</sup>*Rio de Janeiro State University, Rio de Janeiro, Brazil*
- <sup>82</sup>*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- <sup>83</sup>*Graduate School of Science, Kobe University, Kobe, Japan*
- <sup>84a</sup>*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- <sup>84b</sup>*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- <sup>85</sup>*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- <sup>86</sup>*Faculty of Science, Kyoto University, Kyoto, Japan*
- <sup>87</sup>*Kyoto University of Education, Kyoto, Japan*
- <sup>88</sup>*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- <sup>89</sup>*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- <sup>90</sup>*Physics Department, Lancaster University, Lancaster, United Kingdom*
- <sup>91</sup>*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- <sup>92</sup>*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- <sup>93</sup>*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- <sup>94</sup>*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- <sup>95</sup>*Department of Physics and Astronomy, University College London, London, United Kingdom*
- <sup>96</sup>*Louisiana Tech University, Ruston, Los Angeles, USA*
- <sup>97</sup>*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- <sup>98</sup>*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- <sup>99</sup>*Institut für Physik, Universität Mainz, Mainz, Germany*
- <sup>100</sup>*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- <sup>101</sup>*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- <sup>102</sup>*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- <sup>103</sup>*Department of Physics, McGill University, Montreal QC, Canada*
- <sup>104</sup>*School of Physics, University of Melbourne, Victoria, Australia*
- <sup>105</sup>*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
- <sup>106</sup>*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- <sup>107</sup>*Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- <sup>108</sup>*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- <sup>109</sup>*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- <sup>110</sup>*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- <sup>111</sup>*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- <sup>112</sup>*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
- <sup>113</sup>*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- <sup>114</sup>*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- <sup>115a</sup>*New York University Abu Dhabi, Abu Dhabi, United Arab Emirates*
- <sup>115b</sup>*United Arab Emirates University, Al Ain, United Arab Emirates*
- <sup>115c</sup>*University of Sharjah, Sharjah, United Arab Emirates*
- <sup>116</sup>*Department of Physics, New York University, New York, New York, USA*
- <sup>117</sup>*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- <sup>118</sup>*Ohio State University, Columbus, Ohio, USA*
- <sup>119</sup>*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- <sup>120</sup>*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- <sup>121</sup>*Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
- <sup>122</sup>*Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA*
- <sup>123</sup>*Graduate School of Science, Osaka University, Osaka, Japan*
- <sup>124</sup>*Department of Physics, University of Oslo, Oslo, Norway*
- <sup>125</sup>*Department of Physics, Oxford University, Oxford, United Kingdom*
- <sup>126</sup>*LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
- <sup>127</sup>*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- <sup>128</sup>*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- <sup>129a</sup>*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*

- <sup>129b</sup>*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- <sup>129c</sup>*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- <sup>129d</sup>*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- <sup>129e</sup>*Departamento de Física, Universidade do Minho, Braga, Portugal*
- <sup>129f</sup>*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- <sup>129g</sup>*Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- <sup>130</sup>*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- <sup>131</sup>*Czech Technical University in Prague, Prague, Czech Republic*
- <sup>132</sup>*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- <sup>133</sup>*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>134</sup>*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>135</sup>*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- <sup>136a</sup>*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- <sup>136b</sup>*Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile*
- <sup>136c</sup>*Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile*
- <sup>136d</sup>*Universidad Andres Bello, Department of Physics, Santiago, Chile*
- <sup>136e</sup>*Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
- <sup>136f</sup>*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- <sup>137</sup>*Department of Physics, University of Washington, Seattle, Washington, USA*
- <sup>138</sup>*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- <sup>139</sup>*Department of Physics, Shinshu University, Nagano, Japan*
- <sup>140</sup>*Department Physik, Universität Siegen, Siegen, Germany*
- <sup>141</sup>*Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- <sup>142</sup>*SLAC National Accelerator Laboratory, Stanford, California, USA*
- <sup>143</sup>*Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
- <sup>144</sup>*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- <sup>145</sup>*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- <sup>146</sup>*School of Physics, University of Sydney, Sydney, Australia*
- <sup>147</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- <sup>148a</sup>*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- <sup>148b</sup>*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- <sup>148c</sup>*University of Georgia, Tbilisi, Georgia*
- <sup>149</sup>*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- <sup>150</sup>*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- <sup>151</sup>*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- <sup>152</sup>*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- <sup>153</sup>*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- <sup>154</sup>*Department of Physics, University of Toronto, Toronto ON, Canada*
- <sup>155a</sup>*TRIUMF, Vancouver BC, Canada*
- <sup>155b</sup>*Department of Physics and Astronomy, York University, Toronto ON, Canada*
- <sup>156</sup>*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- <sup>157</sup>*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- <sup>158</sup>*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- <sup>159</sup>*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- <sup>160</sup>*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- <sup>161</sup>*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
- <sup>162</sup>*Department of Physics, University of British Columbia, Vancouver BC, Canada*
- <sup>163</sup>*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
- <sup>164</sup>*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
- <sup>165</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*
- <sup>166</sup>*Waseda University, Tokyo, Japan*
- <sup>167</sup>*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
- <sup>168</sup>*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- <sup>169</sup>*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- <sup>170</sup>*Department of Physics, Yale University, New Haven, Connecticut, USA*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Department of Physics, King's College London, London, United Kingdom.

<sup>c</sup>Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.

<sup>d</sup>Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

<sup>e</sup>Also at TRIUMF, Vancouver BC, Canada.

<sup>f</sup>Also at Physics Department, An-Najah National University, Nablus, Palestine.

<sup>g</sup>Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

<sup>h</sup>Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

<sup>i</sup>Also at Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona, Spain.

<sup>j</sup>Also at Affiliated with an institute covered by a cooperation agreement with CERN.

<sup>k</sup>Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

<sup>l</sup>Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

<sup>m</sup>Also at Università di Napoli Parthenope, Napoli, Italy.

<sup>n</sup>Also at Institute of Particle Physics (IPP), Canada.

<sup>o</sup>Also at Bruno Kessler Foundation, Trento, Italy.

<sup>p</sup>Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.

<sup>q</sup>Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

<sup>r</sup>Also at Centro Studi e Ricerche Enrico Fermi, Italy.

<sup>s</sup>Also at Department of Physics, California State University, East Bay, USA.

<sup>t</sup>Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

<sup>u</sup>Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

<sup>v</sup>Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.

<sup>w</sup>Also at Yeditepe University, Physics Department, Istanbul, Türkiye.

<sup>x</sup>Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

<sup>y</sup>Also at CERN, Geneva, Switzerland.

<sup>z</sup>Also at Hellenic Open University, Patras, Greece.

<sup>aa</sup>Also at Center for High Energy Physics, Peking University, China.

<sup>bb</sup>Also at The City College of New York, New York, New York, USA.

<sup>cc</sup>Also at Department of Physics, California State University, Sacramento, USA.

<sup>dd</sup>Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

<sup>ee</sup>Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

<sup>ff</sup>Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.

<sup>gg</sup>Associated with Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark.

<sup>hh</sup>Also at Department of Physics, Stanford University, Stanford, California, USA.

<sup>ii</sup>Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France.

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

<sup>kk</sup>Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.