

Constraining heavy neutral leptons coupled to the tau-neutrino flavor at the Large Hadron Collider

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Displaced vertex (DV) signatures at colliders offer a powerful probe of new long-lived particles beyond the Standard Model. Among the best-motivated candidates are *heavy neutral leptons* (HNLs)—heavier counterparts of Standard Model neutrinos—which can account for the origin of neutrino masses and potentially produce di-leptonic DV signatures. In this study, we demonstrate how existing DV searches at the LHC can be extended to probe HNLs that couple predominantly to the tau-neutrino flavor. While current search strategies rely on identifying a prompt lepton alongside a displaced vertex, we show that analyzing events *without* a prompt lepton enables sensitivity to the process $pp \rightarrow W \rightarrow \tau N$, where the tau decays hadronically and the HNL subsequently decays to a lepton pair and a neutrino. We perform detailed Monte Carlo simulations of this process with HNLs decaying to $\mu^+\mu^-$ or e^+e^- final states, apply ATLAS-inspired selection criteria, and optimize signal sensitivity. In particular, we demonstrate that appropriate cuts in the plane of dilepton invariant mass and DV radial position significantly enhance signal visibility. We propose several such optimized strategies and show that, even with Run 2 data (139 fb^{-1}), existing bounds can be improved by more than an order of magnitude. Future high-luminosity runs may strengthen sensitivity by up to 3 orders of magnitude compared to current limits.

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I. INTRODUCTION

Right-handed (sterile) neutrinos have long been proposed as an explanation for neutrino oscillations. Over time, it has been understood that the same particles can lead to generation of baryon asymmetry in the Universe [1–3]; provide a dark matter candidate, see, e.g., Ref. [4] for review; or account for all of these phenomena [5–7]. While neutrino oscillations do not constrain the mass of right-handed neutrino, the requirement of successful baryogenesis limits the mass from below at GeV level (see, e.g., Refs. [3,8]). This opens an exciting possibility that particles, responsible for the major beyond-the-Standard-Model (BSM) phenomena, can be searched for in laboratories.

The search for these particles is challenging, as right-handed neutrinos do not participate in the gauge interactions of the Standard Model (SM). They couple to the left-handed lepton doublets through Yukawa interactions

with the Higgs field. Their neutral nature also allows them to acquire a Majorana mass independently of the SM Higgs mechanism. When transitioning from the flavor basis to the mass basis, Yukawa mixing gives rise to both light and heavy mass states. The active neutrinos acquire small masses, consistent with observations, while the heavier states inherit weaklike interactions, albeit with a highly suppressed strength. This suppression is characterized by the matrix of *mixing angles*, $\Theta_{\alpha I}$, proportional to Yukawas $Y_{\alpha I}$ and inversely proportional to masses M_I .¹ The heavy mass states are known as *heavy neutral leptons* (HNLs). Due to their suppressed interactions, HNLs couple only feebly to ordinary matter, making them difficult to detect in experiments.

To account for neutrino oscillations, at least two HNLs are required. Their masses must be nearly degenerate, and their mixing angles must be related by a phase, $\Theta_{\alpha 1} \simeq \pm i\Theta_{\alpha 2}$, in order to keep the light neutrino masses small and suppress large radiative corrections [9–13]. Under these conditions, current neutrino oscillation data constrain the ratio of the mixing angles, restricting the viable regions of HNL parameter space; see Refs. [8,14] for reviews. Phenomenologically, this setup is equivalent to a

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¹Here and below, α denotes the lepton flavor index, while $I = 1, 2, \dots$ labels right-handed (sterile) states.

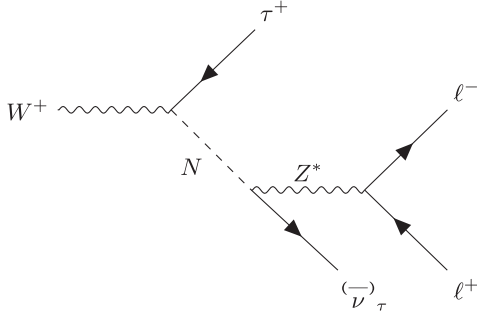


FIG. 1. Main process: Feynman diagram (1) showing the production of the HNL via the mixing with the τ -flavor and its subsequent decay mediated by the neutral current interaction and governed by the same mixing angle.

single HNL with a common mass m_N and total mixing angle $\Theta^2 = \sum_{\alpha, I} |\Theta_{\alpha I}|^2$.

Feeble strength of interaction may result in HNLs being *long-lived particles*, which significantly impacts their search strategies. Depending on their mass and mixing angles, HNLs can travel macroscopic distances before decaying, making them prime candidates for fixed target experiments, such as, e.g., SHiP [15,16] or displaced vertex searches at high-energy colliders [17–24]. In addition to collider experiments, HNLs are also actively searched in wide variety of particle physics experiments, and even through astrophysical observations all of which probe different regions of the HNL parameter space [25].

Unlike other leptons, HNL do not exhibit flavor universality, and therefore each Θ_α should be measured independently, either through direct experimental searches (see below) or indirectly [26,27].

Strategy and sensitivity of the measurements depend on the flavor. Collider searches have been least sensitive to the mixing with the τ -flavor owing to the difficulty of reconstructing τ -leptons in the final state. As a result, the coupling with the τ -flavor has never been directly explored by the LHC Collaborations; only its combinations with other flavors have been studied [22,28] or constraint indirectly, assuming a particular ratio between flavors, cf. Ref. [20], motivated by neutrino oscillations. Other recent searches include Refs. [29–31]; see also Ref. [32] for reinterpretation of the previous experimental results.

In this work, we demonstrate that existing data and analysis pipelines actually allow to probe the mixing of HNLs with the third generation at the LHC. Namely, we consider the process

$$pp \rightarrow \tau^\pm N, \quad N \rightarrow \ell^+ \ell^- \bar{\nu}_\tau, \quad (1)$$

where N is HNL, leptons $\ell \in \{e, \mu\}$, and $\bar{\nu}_\tau$ is neutrino or antineutrino of τ -flavor. The Feynman diagram for the process is shown in Fig. 1. The probability of this process is

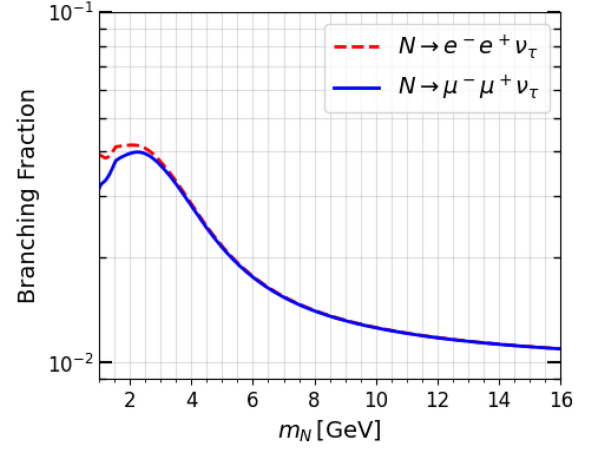


FIG. 2. The branching ratios of an HNL decaying into a lepton pair and ν_τ for the flavor mixing pattern $(\Theta_e^2, \Theta_\mu^2, \Theta_\tau^2) = (0, 0, 1)$. The branching ratios are independent of the specific value of Θ_τ^2 .

proportional to Θ_τ^4 , and therefore the study of this signal gives a direct access to the coupling of the third-generation neutrinos with HNL.

A simple estimate demonstrates the viability of these searches. The HNL production cross section at $\sqrt{s} = 13$ TeV is obtained by rescaling by Θ_τ^2 the measured cross section $\sigma(pp \rightarrow W) \text{Br}(W \rightarrow \ell \nu) = 20.6$ nb [33]. The branching ratio, $\text{Br}(N \rightarrow \mu^+ \mu^- \nu_\tau / \bar{\nu}_\tau)$ [34], is in the range of 1–2% for the masses of interest (see Fig. 2). The number of lepton pairs, produced via HNL decay, is given by

$$N_{\ell\ell} = \mathcal{L} \cdot \Theta_\tau^2 \cdot \sigma(pp \rightarrow \tau_h N) \cdot \text{Br}(N \rightarrow \ell\ell \nu_\tau) \cdot \epsilon_{\text{acc}}, \quad (2)$$

where ϵ_{acc} is the signal acceptance, τ_h refers to τ -leptons decaying either hadronically or to soft leptons (see Sec. III B), and $\mathcal{L}$ is the integrated luminosity. Plugging in the number, this gives

$$N_{\ell\ell} \simeq 10 \left(\frac{\mathcal{L}}{300 \text{ fb}^{-1}} \right) \left(\frac{\text{Br}}{1.2 \times 10^{-2}} \right) \left(\frac{\Theta_\tau^2}{\Theta_{\tau, \text{DELPHI}}^2} \right) \left(\frac{\epsilon_{\text{acc}}}{0.01} \right), \quad (3)$$

where we normalized the result to the DELPHI limit [35] $\Theta_{\tau, \text{DELPHI}}^2 \simeq 1.3 \times 10^{-5}$. For HNL traveling macroscopic distances from the interaction point, the SM background is heavily suppressed, and therefore the searches may be viewed as background free [36,37]. The estimate (3) indicates that with an acceptance rate of around $\epsilon_{\text{acc}} \gtrsim 1\%$ we can probe a previously unexplored region of the HNL parameter space, motivating the current analysis.

The paper is organized as follows. We begin with presenting our results—potential exclusion regions for searches in $\mu\mu$, ee , or combined channels and for different luminosities $\mathcal{L} = 139, 300, 3000 \text{ fb}^{-1}$ (Sec. II). We then move to the description of our method and the assumptions underlying the displaced vertex selection criteria (Sec. III).

TABLE I. Selection criteria for muon and electron channels.

Criteria	Muon channel	Electron channel
No hard prompt leptons	$p_T^{\text{prompt}} < 3 \text{ GeV}$	$p_T^{\text{prompt}} < 4.5 \text{ GeV}$
Minimum transverse momentum p_T^{min}	3 GeV	4.5 GeV
Minimum invariant mass $M_{\text{inv}}^{\text{min}}$	Piecewise function ^a or 5 GeV	Piecewise function ^a or 5 GeV
Minimum angular separation ΔR_{min}	0.05	0.05
Pseudorapidity range $ \eta $	$0 \leq \eta \leq 2.4$	$0 \leq \eta \leq 2.4$
Minimum decay radius r_{min}	120 mm (50 mm for piecewise)	120 mm (50 mm for piecewise)
Maximum transverse decay radius r_{max}	5 m	300 mm
Maximum longitudinal decay radius z_{max}	7 m	500 mm

^aThe piecewise invariant-mass cut is a function in the $m_{\ell\ell} \times r_{\text{dv}}$ plane, dependent on the position of the HNL decay radius r_{dv} , and invariant mass $m_{\ell\ell}$.

We begin by outlining the general event selection (Sec. III A), including the treatment of the decay volume (Sec. III A 1) and the invariant-mass selection (Sec. III A 2). Special care is taken to address the role of prompt τ -leptons in the signal topology (Sec. III B). Background considerations and the strategies employed to suppress them are discussed in Sec. IV. Finally, we summarize our findings and their implications in Sec. VI.

II. RESULTS

We begin by presenting our main results—*signal sensitivity*. Specifically, we identify regions in the parameter space where we expect $N \geq 3$ signal events. This criterion is motivated by the fact that the searches are predominantly background free (as we will argue below), making the $N = 3$ boundaries equivalent to 95% confidence level bounds.

The analysis is performed at generator level—we generate the Monte Carlo signal sample and apply the selection criteria listed in Table I. While our kinematic cuts are similar to the signal selection criteria used in the ATLAS analysis [20], we extend the exploration of cuts in the m_{DV} and r_{DV} plane beyond those considered in the ATLAS study. Specifically, we investigate two approaches (see Sec. III A 2 below):

- (i) *Flat selection*. The invariant-mass criterion is flat, with $m_N \geq 5 \text{ GeV}$ for both muon pairs and electron-positron pairs, across the whole fiducial volume.
- (ii) *Piecewise selection*. The invariant-mass criterion depends on the position inside the fiducial volume. This approach is motivated by the structure of the background observed in Ref. [38]; see also Ref. [39], where a similar background veto was applied.

The analysis is performed for two channels: e^+e^- and $\mu^+\mu^-$. Since an HNL with predominant τ -coupling decays into both channels with approximately equal probability, we also consider a *combined* ($e^+e^- + \mu^+\mu^-$) channel.

Figure 3 illustrates the sensitivity for the combined channel, assuming 3, 10, or 100 signal events at various

luminosities. The cases $N = 10$ and 100 demonstrate how the sensitivity degrades should background contributions be present. One can see that a significant fraction of previously unexplored parameter space can be probed already with data from Run 2 luminosity ($\mathcal{L} = 139 \text{ fb}^{-1}$). The high-luminosity run may allow to probe up to 3 orders of magnitude deep for masses around 10 to 15 GeV, as compared to the current state of the art.

Figure 4 further details how electron and muon channels contribute to the resulting sensitivity at various luminosities for two different choices of m_{DV} , r_{DV} cuts. One can see, in particular, that for $\mathcal{L} = 139 \text{ fb}^{-1}$ and flat cut [Fig. 4(b)] none of the individual channels contribute three signal events, while their combination does. For all other luminosities/cuts combinations, both channels contribute individually and largely overlap, making this a powerful way of rejecting combinatorial backgrounds.

The gray area on the plot represents regions previously explored by experiments with the lowest sensitivity such as DELPHI [35] and BEBC [40].

III. ANALYSIS

The analysis pipeline starts with the Monte Carlo (MC) generation of the process shown in Fig. 1 of proton-proton collisions, $pp \rightarrow N\tau^\pm, N \rightarrow \ell^+\ell^-\bar{\nu}_\tau$. The data generation is performed with MadGraph5_aMC@NLO [41] at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. The MC samples provide the four-momenta for all particles involved in the interaction, covering the specified HNL mass range of $0.5 \leq m_N \leq 20 \text{ GeV}$ with the step of 0.25 GeV. HNL lifetimes and branching ratios are calculated based on the results of Ref. [34] and validated against the SM_HeavyN_NLO model [42,43].

The macroscopic decay of the HNL is handled in postprocessing,² where lifetimes are drawn from a statistical distribution centered around the theoretical values predicted for the given model parameters (m_N, Θ_τ) [34] and

²<https://github.com/edtireli/W2HNL>.

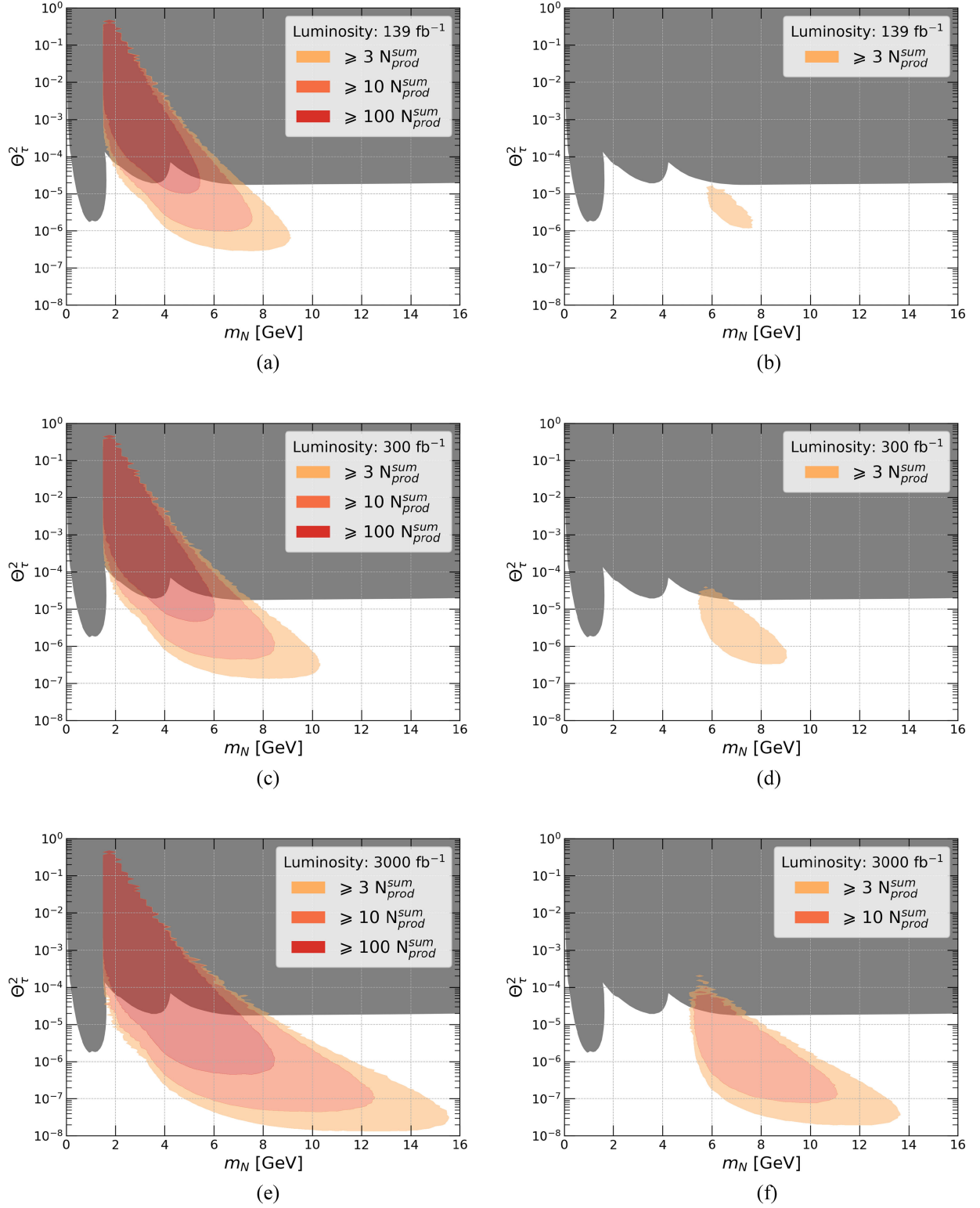


FIG. 3. Sensitivity of the combined channel as a function of the number of observed events. The signal sensitivity (for 3, 10, or 100 expected events) in the combined $e^+e^- + \mu^+\mu^-$ channel at integrated luminosities of 139 fb⁻¹ (top), 300 fb⁻¹ (middle), and 3000 fb⁻¹ (bottom). The left column [panels (a), (c), and (e)] corresponds to the piecewise invariant-mass selection, while the right column (b), (d), and (f) corresponds to the flat invariant-mass selection. Notably, in the flat selection case, no regions with 100 events are observed [panel (f)], and even the 10-event regions disappear in panels (b) and (d), highlighting the critical role of the DV cut choice.

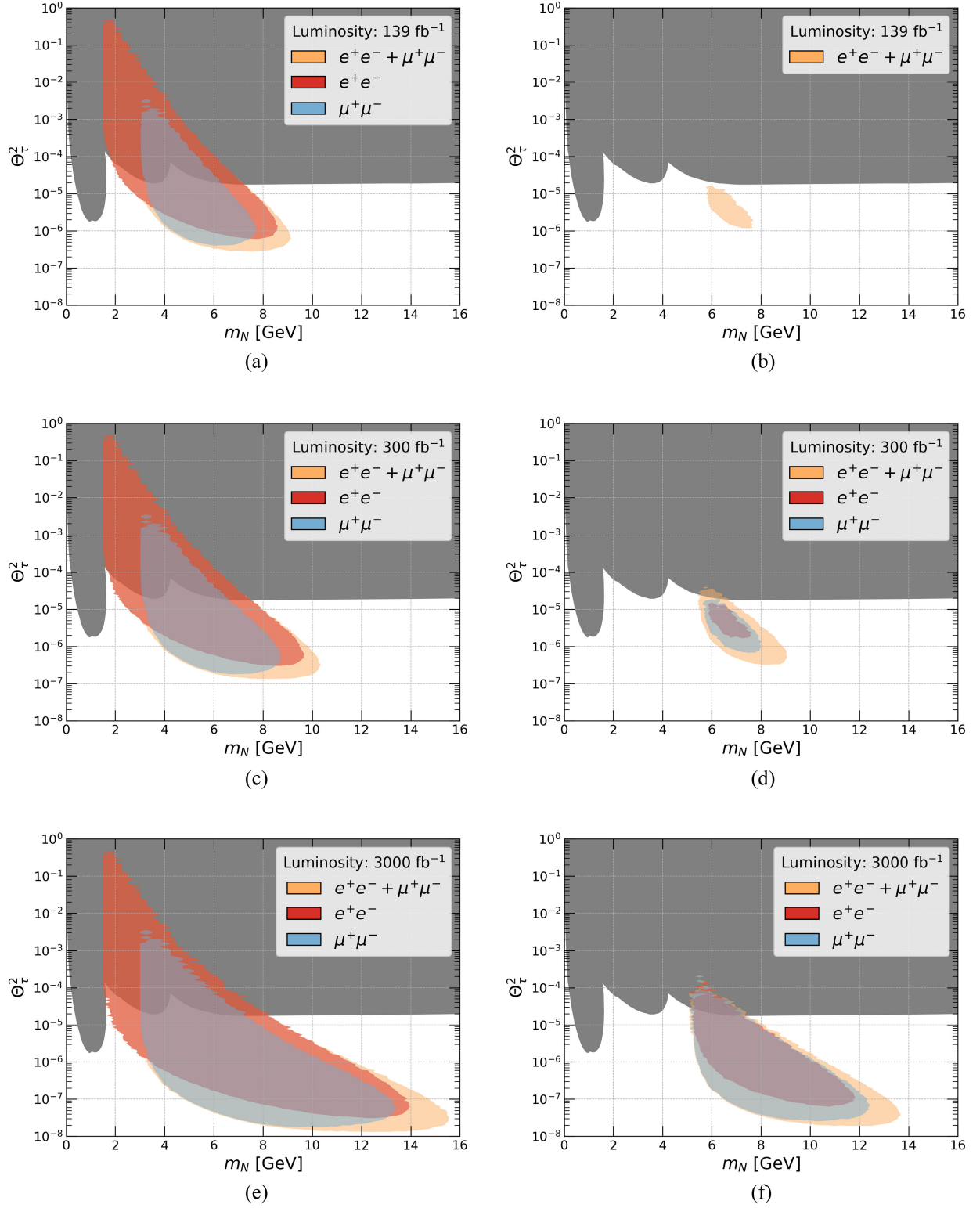


FIG. 4. The signal sensitivity for $N \geq 3$ events of the e^+e^- (red), $\mu^+\mu^-$ (blue), and the combined $e^+e^- + \mu^+\mu^-$ (yellow) channel at 139 (top), 300 (middle) and 3000 fb^{-1} (bottom). The left column (a), (c), and (e) is the piecewise invariant-mass cut, and the right column (b), (d), and (f) is the flat invariant-mass cut.

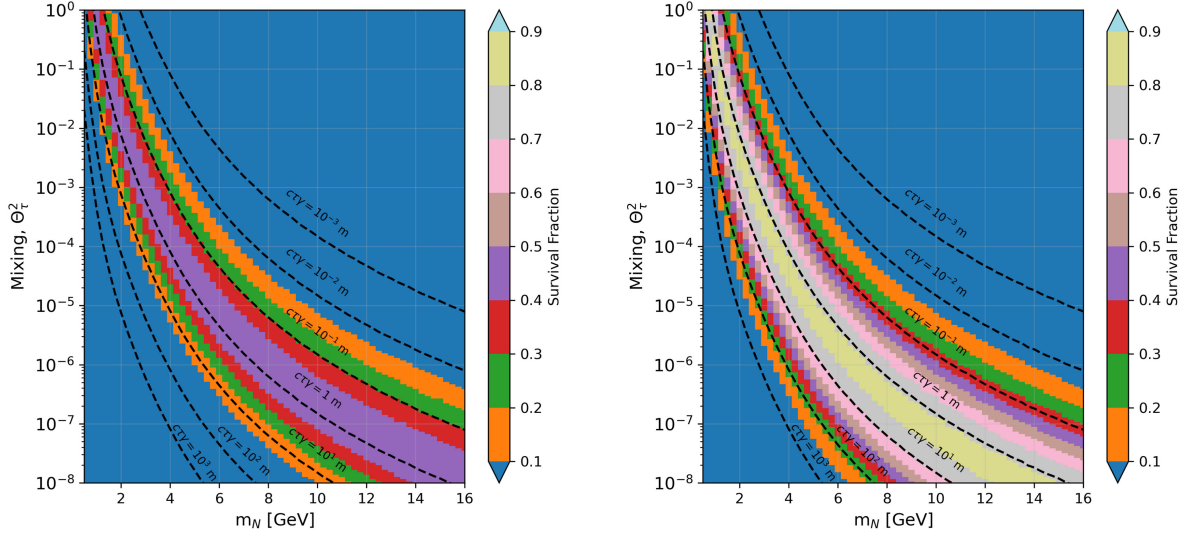


FIG. 5. The fraction of HNLs that decay within the fiducial volume defined by a minimal decay radius, $r_{\min}$, and a cylinder with longitudinal, $z_{\max}$, and transverse, $r_{\max}$, constraints, as specified in Table I. The left panel corresponds to electrons, while the right panel corresponds to muons. The black dashed lines represent lines of constant decay length, $c\tau_N \gamma$ where γ is the average Lorentz-factor for the HNL of a given mass.

taking into account actual γ -factor for each of the HNLs in the sample. Using these sampled lifetimes, the 3D position of the decays is computed in the coordinate system, centered on the interaction point.

The displacement of the decay vertex from the interaction point is determined separately for the transverse and longitudinal directions.

To each dilepton event, we apply the selection criteria listed in Table I and further discussed in Sec. III A. The event selection criteria, listed in Table I, largely follow those of the displaced vertex analysis in Ref. [20]. The kinematic cuts are standard for this type of analysis, with particular attention given to the invariant mass and decay volume selection criteria, which are discussed in detail in the sections below.

The fiducial decay volumes differ for electrons and muons (see Table I). In the muon channel, an extended decay volume is used to leverage the muon spectrometer surrounding the inner detector, whereas in the electron channel, the search is restricted to the inner detector region.

The displaced vertex (DV) reconstruction efficiency is assumed to be 100%, meaning that any particle meeting the selection criteria is equally likely to be detected in all spatial directions and distances within the modeled decay volume. While it is known that vertex reconstruction efficiency decreases with distance [44], properly incorporating this effect outside the ATLAS environment is challenging. Therefore, we have chosen not to include it in our main analysis. In the Appendix, we estimate the size of this effect using the efficiency parameterisations of Ref. [44] and show that it weakens the sensitivity in Θ_τ^2 by less than half an order of magnitude, without changing our qualitative conclusions.

A. Selection criteria

1. Decay volume

The detector environment is modeled as a simplified cylindrical model of the ATLAS environment considering 100% detector acceptance and track reconstruction. The minimal decay volume is defined by a spherical criterion, whereby any decay vertex with a radial position below the threshold $r_{\min}$ is excluded. The outer boundary for the included decay vertices is represented as a cylindrical volume.

These geometric criteria are detailed in Table I, and the survival efficiencies for the displaced vertex cuts listed in Table I are illustrated in Fig. 5, corresponding to the muon and electron channels, respectively.

2. Invariant mass

The invariant-mass selection criteria have been studied using both the *flat* and *piecewise* approaches for the *electron* and *muon* channels. In the flat approach, a constant invariant-mass cut is applied to all events regardless of the HNL decay position, r_{DV} . In contrast, the piecewise approach adjusts the mass selection criterion depending on r_{DV} . This method, inspired by the results of Ref. [39], allows certain events that would otherwise fail the flat cut to be recovered; see the discussion in Sec. IV below.

Figure 8 illustrates how these two strategies affect events at the lowest (m_N, Θ_τ) point in each channel. Green dots indicate events passing the piecewise criteria; red dots indicate those failing. Notably, some events that pass the piecewise cut lie below the flat cut, thereby opening up new regions in parameter space.

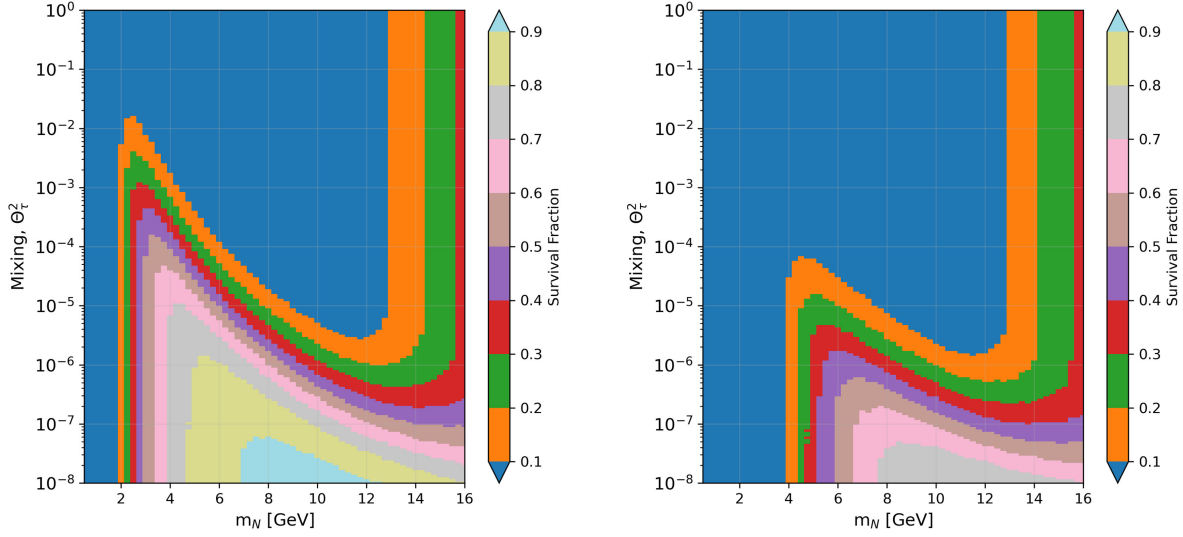


FIG. 6. The survival efficiency of HNLs under the piecewise invariant-mass selection criteria for the electron (left) and muon (right) channels. Note that this represents only the efficiency related to the invariant mass of the dileptons as a function of distance, not the full DV survival probability. To obtain the full radial efficiency, the position of the decay vertices must also be considered, as shown in Fig. 5. For further details, see Fig. 7.

Additionally, to demonstrate the overall efficiency impact, we apply cumulative cuts on transverse momentum (p_T), pseudorapidity (η), invariant mass ($m_{\ell\ell}$), and the displaced-vertex criterion (DV). Figure 9 shows the progressive effect of these cuts for the dielectron and dimuon channels, respectively, and Fig. 10 shows the transverse momentum distributions.

B. τ -lepton analysis

The analysis takes special care to ensure no leptons from the prompt tau may be misidentified as being produced

from the HNL, and as such, any hard leptons must be discarded, leaving only soft leptons of e , μ flavor and hadronic modes. The production is scaled by this branching fraction derived from a PYTHIA [45] simulation of 10^6 events of a 13 TeV center-of-mass proton-proton collision, all τ decay modes enabled using PYTHIA's sophisticated τ decay model (`TauDecays:mode = 1`), as well as enabling τ production from Higgs, $W^\pm$ and Z^0 bosons.

These fractions are computed as the complement of the theoretical branching to leptonic modes multiplied by the

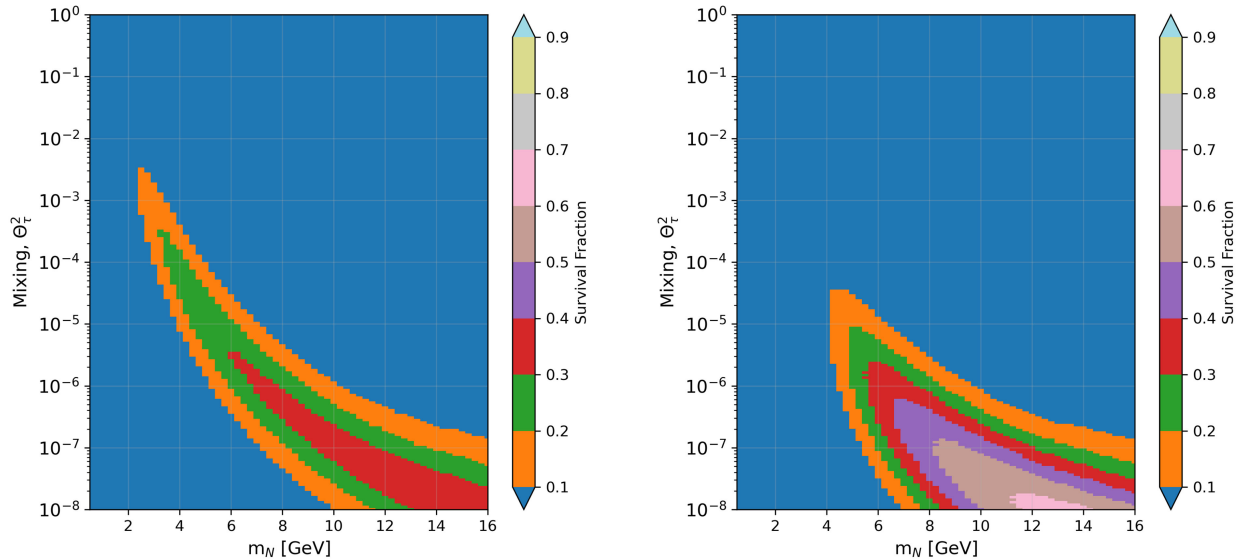


FIG. 7. The survival efficiency of the HNLs from the combined piecewise invariant-mass selection and DV criteria (composition of Figs. 5 and 6) for the electron (left) and muon (right) channel.

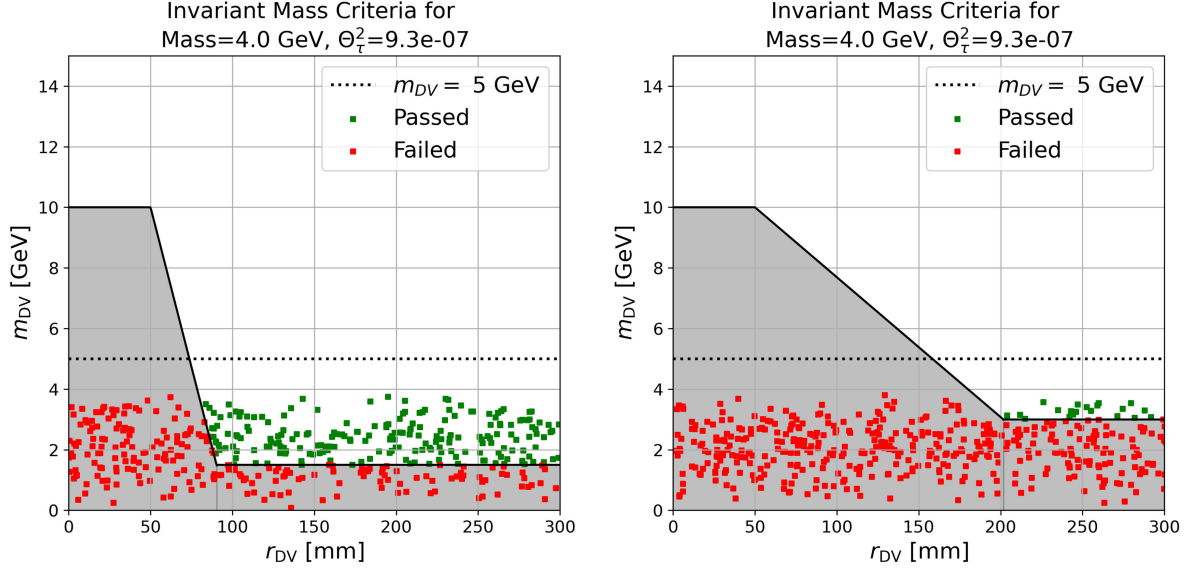


FIG. 8. Efficiency of the flat vs piecewise DV cuts. Invariant mass selection for pairs of electrons (left) and muons (right) for the HNL with parameters specified in the title of the plot. The black line represents the piecewise selection approach, while the dotted line corresponds to the flat selection. Events failing the piecewise cut are shown in red, while those passing are in green. Due to the HNL mass constraints, no events survive under the flat invariant-mass cut.

fraction of hard leptons in the simulated analysis, i.e.,

$$\text{Br}(\tau \rightarrow X) = (1 - \text{Br}[\tau \rightarrow \ell \ell \nu]) \cdot \left(1 - \frac{N_{\ell}^{\text{soft}}}{N_{\ell}}\right). \quad (4)$$

This fraction is 0.895 for the muon channel and 0.912 for the electron channel and is used in the computation of HNL production in Eq. (2) and the branchings taken from literature [46].

IV. BACKGROUND CONSIDERATIONS

Our sensitivity estimates so far have been performed under the background-free assumption, which is only partially justified. To assess the background contamination in our signal region, we exploit the fact that it coincides with the *validation region* used by the ATLAS Collaboration [38], which contains events with a displaced lepton pair but no prompt lepton. The results are presented in detail in Ref. [39], Sec. 5.7.

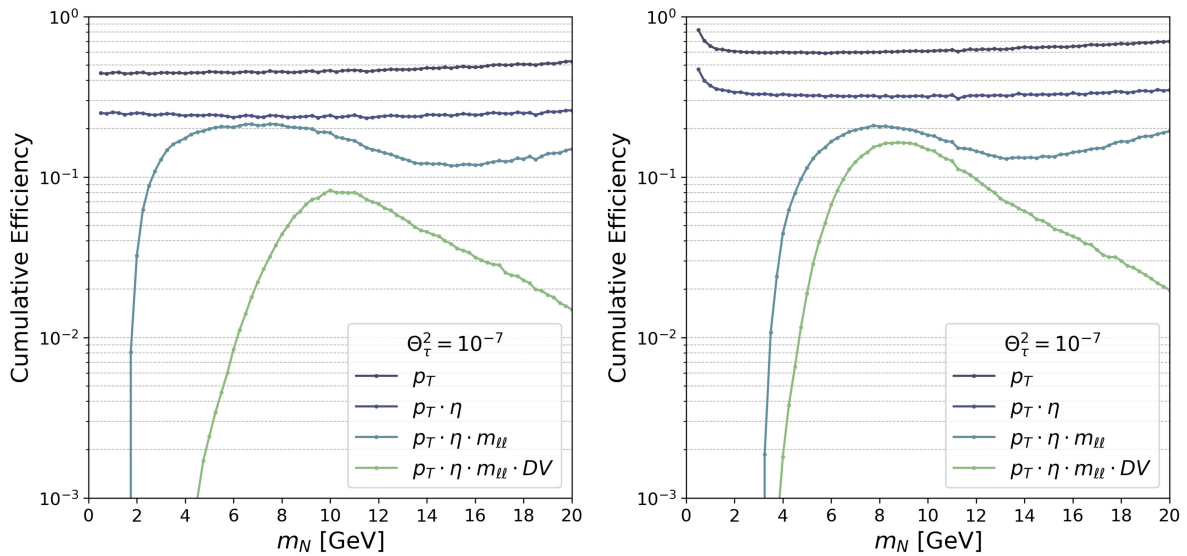


FIG. 9. Cumulative effect of the selection criteria (p_T , η , $m_{\ell\ell}$, DV) applied to daughter leptons: electrons (left) and muons (right) at $\Theta_{\tau}^2 = 10^{-7}$.

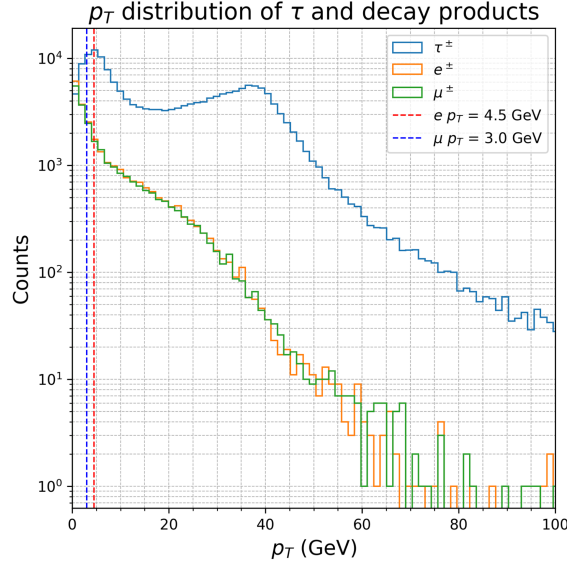


FIG. 10. The transverse momenta of the τ -lepton as well as its decay products from the PYTHIA simulation. The red and blue dashed line indicates the p_T selection criteria for the electron and muon channels, respectively, from Table I.

The dominant sources of background are the decays of metastable particles and accidental track crossings involving cosmic muons. The heavy flavor background in the $\mu\mu$ channel was eliminated in Ref. [38] by imposing the invariant-mass cut $m_{DV} \geq 5.5$ GeV. The accidental track crossing background is largely irreducible but can be assessed by comparing same-sign and opposite-sign muon pairs, which are approximately equal in the case of track crossings. Additionally, in the ee channel, interactions of particles with the detector material and photon conversions can create fake displaced vertices close to high-density regions.

With this background picture in mind, we implemented a piecewise selection in the (m_{DV}, r_{DV}) plane, inspired by the ATLAS ee channel veto and extended in this work to the $\mu\mu$ channel. The shape of the selection region is shown in dark gray in Fig. 8. We compared this selection with a flat selection requiring $M_{inv}^{\min} > 5$ GeV and positions of DV within the fiducial cylinder, following the ATLAS approach [38]. While the flat selection would eliminate the signal entirely, the piecewise selection allows us to preserve part of the signal while efficiently reducing the background.

For the material-induced background in the ee channel, a 3D veto near the high-density regions is imposed in Ref. [38], leading to an approximately 42% reduction of the fiducial volume [38,39]. We do not propagate this reduction in our work, as we cannot properly fold it with the density of DVs without having the detailed map of the detector materials. It should be noted that Fig. 5.28 in Ref. [39] does not exhibit any noticeable increase in ee background around material layers, which further justifies our treatment.

Further background suppression is achieved through additional selection criteria:

- (i) The majority of the explored HNL parameter space satisfies $N \geq 3$ events in *both* electron and muon channels, as shown in Fig. 4. This cross-channel requirement serves as an effective background rejection criterion.
- (ii) We have not yet utilized the presence of a prompt τ -lepton in the signal, which could further suppress background contributions.
- (iii) Figure 3 demonstrates that the piecewise selection criteria allow for regions with $N \gg 1$ events, increasing the robustness of the analysis.

These considerations suggest that searches for HNLs decaying into a displaced lepton pair and a prompt τ -lepton can be made effectively background free.

V. DISCUSSION

The results presented in this work demonstrate that displaced vertex searches in the process $pp \rightarrow W \rightarrow \tau N$, with $N \rightarrow \ell^+ \ell^- \nu_\tau$, can probe previously unexplored regions of the ν_τ -HNL mixing parameter. The adopted radial displacement requirement, $r_{DV} \geq 100$ mm, effectively suppresses backgrounds from heavy flavor decays while preserving signal sensitivity. Moreover, the introduction of a piecewise invariant-mass selection in the (m_{DV}, r_{DV}) plane substantially improves efficiency relative to a flat invariant-mass cut, particularly in regions where the decay topology would otherwise fall below fixed thresholds [38,39].

The explored topology primarily populates decay radii around the first Semiconductor Tracker layers of the ATLAS detector, highlighting the strong physics case for extending the capabilities of large radius tracking to larger displacements and improving reconstruction of displaced electrons [44]. Such detector level improvements would directly enhance the discovery potential of searches targeting long-lived states originating from W -boson decays, including HNLs coupled to the τ -flavor.

A positive signal in this channel would open a new experimental window into the sterile neutrino sector, linking neutrino mass generation, baryogenesis, and possible dark-sector production mechanisms. The absence of a signal will contribute to further exploration of the parameter space for GeV-scale ν_τ -dominated heavy neutral leptons, providing valuable constraints for models that attempt to connect neutrino physics and other BSM phenomena.

VI. CONCLUSION

Heavy neutral leptons remain a compelling extension of the Standard Model, capable of addressing several open questions in fundamental physics, including the origin of neutrino masses, the generation of the baryon asymmetry of

the Universe, and even the nature of dark matter. A particularly promising experimental signature of HNLs is the appearance of displaced vertex events, originating from long-lived particles decaying within the detector. While LHC searches have so far focused on HNLs mixing with electron or muon neutrinos, direct constraints on HNLs coupled to the tau-neutrino flavor remain underexplored.

In this work, we demonstrated that existing DV searches (such as Ref. [20] or [21]) can be naturally extended to probe HNLs with dominant ν_τ mixing. We considered the process $pp \rightarrow \tau^\pm N$, with the HNL decaying via $N \rightarrow \ell^+ \ell^- \nu_\tau$, and studied the final states $\mu^+ \mu^-$, $e^+ e^-$, and their combination. Using Monte Carlo simulations and a simplified ATLAS detector geometry, we estimated the signal acceptances and projected sensitivities for integrated luminosities of 139, 300, and 3000 fb $^{-1}$.

A central feature of such an analysis remains the suppression of Standard Model backgrounds. The dominant background originates from decays of heavy flavor hadrons, populating the region of small invariant mass ($m_{\text{DV}} \lesssim 5.5$ GeV) and short displacement ($r_{\text{DV}} \lesssim 50$ mm). We evaluated two selection strategies in the $m_{\text{DV}} - r_{\text{DV}}$ plane: a simple flat invariant-mass cut and a more refined piecewise cut that adapts the m_{DV} threshold based on the DV radius. The latter, inspired by existing ATLAS strategies in the ee channel, was extended in this work to the $\mu\mu$ channel. We argued that these optimized cut strategies may allow for efficient background suppression while maintaining high signal acceptance.

We found that, even at Run 2 luminosities, parts of parameter space previously untested by experiments such as DELPHI and BEBC become accessible. Future data-taking campaigns, particularly at the High-Luminosity Large Hadron Collider, could improve these bounds by 1 order of magnitude or more. The combined channel notably enhances robustness and offers additional leverage for background rejection. Overall, our study shows that with optimized selection criteria and realistic background modeling DV-based searches can provide meaningful constraints on HNLs mixing with the tau-neutrino flavor, unachievable by other experiments.

Further progress will require full experimental implementation, including detector-specific effects, reconstruction efficiencies, and potential residual backgrounds beyond those visible in validation regions. Nevertheless, we believe that our work provides a clear framework and concrete benchmarks for extending DV searches into this less-explored sector of HNL parameter space. A reinterpretation of existing LHC data along these lines would be both feasible and timely.

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manuscript and providing valuable comments concerning the efficiency of DV detection.

DATA AVAILABILITY

The simulation and postprocessing code used to generate the Monte Carlo samples, apply the selection criteria, and derive the sensitivity contours reported in this work, together with the resulting datasets, are openly available in Ref. [47].

APPENDIX: IMPACT OF THE DV RECONSTRUCTION EFFICIENCY

The headline sensitivity contours in Figs. 3 and 4, as well as the survival efficiencies of Sec. III, were obtained under the assumption that the displaced-vertex reconstruction efficiency is 100% everywhere within the fiducial volume. As discussed at the end of Sec. III and in line with the original ATLAS analysis [20], this is known to be an idealization: vertex- and track-reconstruction efficiency decreases with the distance of the displaced vertex from the interaction point, primarily because tracks with large transverse impact parameter $|d_0|$ and tracks originating beyond the first pixel layers are harder to reconstruct.

In this appendix, we estimate the size of this effect. We use the dedicated ATLAS large-radius tracking performance study of Ref. [44], whose Fig. 7 reports the per-track reconstruction efficiency for the $W \rightarrow N\ell$ topology as a function of the transverse impact parameter $|d_0|$ and the transverse production radius R_{prod} . We digitize both curves and treat the two efficiencies as factorized and independent per track,

$$\epsilon_{\text{track}} = \epsilon_{d_0}(|d_0|) \cdot \epsilon_R(R_{\text{prod}}). \quad (\text{A1})$$

For every displaced lepton in our Monte Carlo sample, we then reject the track stochastically: an independent uniform random variable $u \in [0, 1]$ is drawn, and the track is kept if $u < \epsilon_{\text{track}}$. An event survives only if both displaced tracks pass the per-track draw. In the limit of large statistics, this procedure recovers the factorized acceptance probability of Eq. (A1) while preserving the binary, event-by-event signature used throughout the rest of the analysis.

We stress that Eq. (A1) is an approximation: the ATLAS curves were extracted for one specific BSM topology and detector configuration, the factorization between $|d_0|$ and R_{prod} is not exact, and our analysis is not performed within the ATLAS software environment. We therefore view the results below as a conservative *indication* of the magnitude of the effect rather than a quantitative replacement of the main results.

The resulting impact on the signal acceptance is summarised in Table II, and its effect on the $N \geq 3$ sensitivity contours is shown in Fig. 11, where we overlay the contours

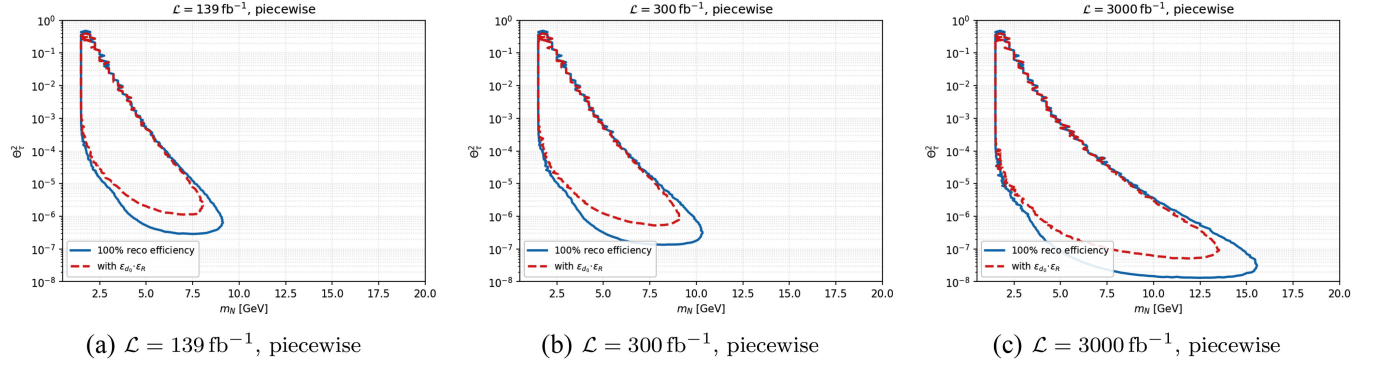


FIG. 11. Effect of the per-track ATLAS reconstruction efficiency on the sensitivity contours, for the three integrated luminosities considered in the main text and the piecewise invariant-mass selection. Solid contours correspond to the 100%-efficiency assumption used in the main analysis; dashed contours show the same selection with the per-track efficiency factor of Eq. (A1) applied. The combined-channel ($ee + \mu\mu$) acceptance is reduced by a factor ~ 0.61 at peak, corresponding to a shift of the $N \geq 3$ contour in Θ_τ^2 by a factor ~ 1.3 , with the largest impact at small mixing angles where the typical decay length pushes the displaced vertices into the low-efficiency region of Ref. [44]. (a) $\mathcal{L} = 139 \text{ fb}^{-1}$, piecewise. (b) $\mathcal{L} = 300 \text{ fb}^{-1}$, piecewise. (c) $\mathcal{L} = 3000 \text{ fb}^{-1}$, piecewise.

TABLE II. Impact of the per-track reconstruction-efficiency factor of Eq. (A1) on the mean signal acceptance. The second column gives the ratio of acceptances with and without the efficiency applied; the third column gives the corresponding shift of the $N \geq 3$ contour in Θ_τ^2 , computed as $1/\sqrt{r}$ (see text).

Channel/selection	Ratio r	Shift in Θ_τ^2
ee , piecewise	0.38	$\approx 1.6\times$
ee , flat	0.30	$\approx 1.8\times$
$\mu\mu$, piecewise	0.20	$\approx 2.3\times$
$\mu\mu$, flat	0.20	$\approx 2.2\times$
Combined ($ee + \mu\mu$), piecewise	0.61	$\approx 1.3\times$
Combined ($ee + \mu\mu$), flat	0.43	$\approx 1.5\times$

of Figs. 3 and 4 with and without the per-track efficiency factor of Eq. (A1). The suppression is stronger in the $\mu\mu$ channel because its extended fiducial volume ($r_{\text{max}} = 5 \text{ m}$, $z_{\text{max}} = 7 \text{ m}$) probes larger displacements, where the ϵ_R digitisation of Ref. [44] drops below ~ 0.6 . Because the

expected event count scales as Θ_τ^4 at short lifetimes, an acceptance ratio r translates into a shift of the $N \geq 3$ contour by a factor $1/\sqrt{r}$ in Θ_τ^2 . In the combined channel, this shift is a factor of ~ 1.3 – 1.5 , i.e., less than half an order of magnitude, and does not change the qualitative conclusions of Sec. II: the parameter space currently constrained only by DELPHI [35] and BEBC [40] remains accessible already at Run 2 luminosities, while the projected high-luminosity reach is reduced but still extends well beyond the present limits.

A more complete treatment would require running our signal samples through the full ATLAS simulation chain, including the dedicated large-radius tracking algorithms described in Refs. [20,44], which is beyond the scope of the present generator-level study. The estimate of this appendix shows, however, that the omission of the radial-dependent reconstruction efficiency in the main analysis introduces a correction at the factor-of-a-few level and motivates a future experimental implementation of the search proposed here.

[1] S. Davidson, E. Nardi, and Y. Nir, Leptogenesis, *Phys. Rep.* **466**, 105 (2008).
 [2] A. Pilaftsis, The little review on leptogenesis, *J. Phys. Conf. Ser.* **171**, 012017 (2009).
 [3] J. Klarić, M. Shaposhnikov, and I. Timiryasov, Reconciling resonant leptogenesis and baryogenesis via neutrino oscillations, *Phys. Rev. D* **104**, 055010 (2021).
 [4] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, and O. Ruchayskiy, Sterile neutrino dark matter, *Prog. Part. Nucl. Phys.* **104**, 1 (2019).

[5] T. Asaka, S. Blanchet, and M. Shaposhnikov, The nuMSM, dark matter and neutrino masses, *Phys. Lett. B* **631**, 151 (2005).
 [6] T. Asaka and M. Shaposhnikov, The ν MSM, dark matter and baryon asymmetry of the universe, *Phys. Lett. B* **620**, 17 (2005).
 [7] A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov, The role of sterile neutrinos in cosmology and astrophysics, *Annu. Rev. Nucl. Part. Sci.* **59**, 191 (2009).
 [8] K. Bondarenko, A. Boyarsky, J. Klarić, O. Mikulenko, O. Ruchayskiy, V. Syvolap, and I. Timiryasov, An allowed

- window for heavy neutral leptons below the kaon mass, *J. High Energy Phys.* **07** (2021) 193.
- [9] A. Pilaftsis, Radiatively induced neutrino masses and large Higgs neutrino couplings in the standard model with Majorana fields, *Z. Phys. C* **55**, 275 (1992).
- [10] M. Shaposhnikov, A possible symmetry of the nuMSM, *Nucl. Phys. B* **763**, 49 (2007).
- [11] J. Kersten and A. Y. Smirnov, Right-handed neutrinos at CERN LHC and the mechanism of neutrino mass generation, *Phys. Rev. D* **76**, 073005 (2007).
- [12] J.-L. Tastet and I. Timiryasov, Dirac vs. Majorana HNLs (and their oscillations) at SHiP, *J. High Energy Phys.* **04** (2020) 005.
- [13] E. Fernández-Martínez, X. Marcano, and D. Naredo-Tuero, HNL mass degeneracy: Implications for low-scale seesaws, LNV at colliders and leptogenesis, *J. High Energy Phys.* **03** (2023) 057.
- [14] J.-L. Tastet, O. Ruchayskiy, and I. Timiryasov, Reinterpreting the ATLAS bounds on heavy neutral leptons in a realistic neutrino oscillation model, *J. High Energy Phys.* **12** (2021) 182.
- [15] S. Alekhin *et al.*, A facility to search for hidden particles at the CERN SPS: The SHiP physics case, *Rep. Prog. Phys.* **79**, 124201 (2016).
- [16] C. Ahdida *et al.* (SHiP Collaboration), Sensitivity of the SHiP experiment to heavy neutral leptons, *J. High Energy Phys.* **04** (2019) 077.
- [17] A. M. Sirunyan *et al.* (CMS Collaboration), Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **120**, 221801 (2018).
- [18] G. Aad *et al.* (ATLAS Collaboration), Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector, *J. High Energy Phys.* **10** (2019) 265.
- [19] R. Aaij *et al.* (LHCb Collaboration), Search for heavy neutral leptons in $W^+ \rightarrow \mu^+ \mu^\pm \text{jet}$ decays, *Eur. Phys. J. C* **81**, 248 (2021).
- [20] G. Aad *et al.* (ATLAS Collaboration), Search for heavy neutral leptons in decays of W bosons using a dilepton displaced vertex in $s = 13$ TeV pp collisions with the ATLAS detector, *Phys. Rev. Lett.* **131**, 061803 (2023).
- [21] A. Tumasyan *et al.* (CMS Collaboration), Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2022) 081.
- [22] A. Hayrapetyan *et al.* (CMS Collaboration), Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **06** (2024) 123.
- [23] A. Hayrapetyan *et al.* (CMS Collaboration), Search for long-lived heavy neutral leptons decaying in the CMS muon detectors in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **110**, 012004 (2024).
- [24] G. Aad *et al.* (ATLAS Collaboration), Search for heavy neutral leptons in decays of W bosons using leptonic and semi-leptonic displaced vertices in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *J. High Energy Phys.* **07** (2025) 196.
- [25] A. M. Abdullahi, P. Barham Alzás, B. Batell, J. Beacham, A. Boyarsky, S. Carbajal *et al.*, The present and future status of heavy neutral leptons, *J. Phys. G* **50**, 020501 (2023).
- [26] K. A. Urquía-Calderón, I. Timiryasov, and O. Ruchayskiy, Heavy neutral leptons—Advancing into the PeV domain, *J. High Energy Phys.* **08** (2023) 167.
- [27] M. Blennow, E. Fernández-Martínez, J. Hernández-García, J. López-Pavón, X. Marcano, and D. Naredo-Tuero, Bounds on lepton non-unitarity and heavy neutrino mixing, *J. High Energy Phys.* **08** (2023) 030.
- [28] A. Moranco Tardà, Search for prompt heavy neutral lepton decays into tau leptons with the atlas detector, Master's thesis, University of Copenhagen, 2022.
- [29] J. P. Lees *et al.* (BABAR Collaboration), Search for heavy neutral leptons using tau lepton decays at BABAR, *Phys. Rev. D* **107**, 052009 (2023).
- [30] M. Nayak *et al.* (Belle Collaboration), Search for a heavy neutral lepton that mixes predominantly with the tau neutrino, *Phys. Rev. D* **109**, L111102 (2024).
- [31] R. Abbasi *et al.* (IceCube Collaboration), Search for heavy neutral leptons with IceCube DeepCore, [arXiv:2502.09454](https://arxiv.org/abs/2502.09454).
- [32] I. Boiarska, A. Boyarsky, O. Mikulenko, and M. Ovchinnikov, Constraints from the CHARM experiment on heavy neutral leptons with tau mixing, *Phys. Rev. D* **104**, 095019 (2021).
- [33] G. Aad *et al.* (ATLAS Collaboration), Measurement of $W^\pm$ and Z -boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* **759**, 601 (2016).
- [34] K. Bondarenko, A. Boyarsky, D. Gorbunov, and O. Ruchayskiy, Phenomenology of GeV-scale heavy neutral leptons, *J. High Energy Phys.* **11** (2018) 032.
- [35] P. Abreu *et al.* (DELPHI Collaboration), Search for neutral heavy leptons produced in Z decays, *Z. Phys. C* **74**, 57 (1997).
- [36] K. Bondarenko, A. Boyarsky, M. Ovchinnikov, O. Ruchayskiy, and L. Shchutska, Probing new physics with displaced vertices: Muon tracker at CMS, *Phys. Rev. D* **100**, 075015 (2019).
- [37] M. Drewes and J. Hajer, Heavy neutrinos in displaced vertex searches at the LHC and HL-LHC, *J. High Energy Phys.* **02** (2020) 070.
- [38] G. Aad *et al.* (ATLAS Collaboration), 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, *Phys. Rev. Lett.* **131**, 061803 (2023).
- [39] C. Appelt, Extending the limits in the hunt for long-lived heavy neutral leptons with the ATLAS experiment at the Large Hadron Collider at CERN, Ph.D. thesis, Humboldt University, Berlin, 2024, [10.18452/28639](https://nbn-resolving.org/urn:nbn:de:hbz:5-65862-p0011-7).
- [40] R. Barouki, G. Marocco, and S. Sarkar, Blast from the past II: Constraints on heavy neutral leptons from the BEBC WA66 beam dump experiment, *SciPost Phys.* **13**, 118 (2022).
- [41] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.

- [42] D. Alva, T. Han, and R. Ruiz, Heavy Majorana neutrinos from $w\gamma$ fusion at hadron colliders, [J. High Energy Phys.](#) **02** (2015) 072.
- [43] C. Degrande, O. Matteleer, R. Ruiz, and J. Turner, Fully-automated precision predictions for heavy neutrino production mechanisms at hadron colliders, [Phys. Rev. D](#) **94**, 053002 (2016).
- [44] ATLAS Collaboration, Performance of the reconstruction of large impact parameter tracks in the inner detector of ATLAS, [Eur. Phys. J. C](#) **83**, 1081 (2023).
- [45] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, [Comput. Phys. Commun.](#) **191**, 159 (2015).
- [46] S. Navas *et al.* (Particle Data Group), Review of particle physics, [Phys. Rev. D](#) **110**, 030001 (2024).
- [47] E. D. Tireli, W2HNL: Simulation and analysis code for displaced-vertex searches for heavy neutral leptons mixing with the tau-neutrino flavor, Zenodo, [10.5281/zenodo.17342798](#) (2025).