Displaced vertices as probes of sterile neutrino mixing at the LHC

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We investigate the reach at the LHC to probe light sterile neutrinos with displaced vertices. We focus on sterile neutrinos N with masses $m_N \sim (5\text{--}30)$ GeV that are produced in rare decays of the standard model gauge bosons and decay inside the inner trackers of the LHC detectors. With a strategy that triggers on the prompt lepton accompanying the N displaced vertex and considers charged tracks associated with it, we show that the 13 TeV LHC with 3000/fb is able to probe active-sterile neutrino mixings down to $|V_{lN}|^2 \approx 10^{-9}$, with $l = e, \mu$, which is an improvement of up to 4 orders of magnitude when comparing with current experimental limits from trileptons and proposed lepton-jets searches. In the case when τ mixing is present, mixing angles as low as $|V_{\tau N}|^2 \approx 10^{-8}$ can be accessed.

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I. INTRODUCTION

Searches for new physics responsible for the lightness of neutrino masses [1] have been in the program of the LHC experiments for decades [2]. This new physics beyond the standard model (SM) may be explained by the so-called see-saw mechanism [3] that introduces the existence of heavy right-handed (sterile) neutrinos that mix with the neutrinos in the standard model [4,5]. For low-enough mixing angles and sterile neutrino masses below the electroweak scale, the sterile neutrino N can be long-lived and may decay with a characteristic displaced vertex (DV) signature inside particle detectors.

Experimental efforts to search for these states at hadron colliders normally focus on promptly decaying sterile neutrinos with masses $m_N \sim \mathcal{O}(100)$ GeV. Earlier searches by ATLAS [6] and CMS [7,8] focus on the Majorana signature of same-sign dileptons and jets [9]. Only recently, the CMS experiment has provided limits for N masses below

40 GeV in the search for three prompt charged leptons [10]. For current bounds on sterile neutrino mixing, see [11,12]. Attention to displaced vertex signatures, which can probe masses in the GeV range, is rapidly growing. Recent phenomenological studies assessing the LHC sensitivity with displaced vertices to light sterile neutrinos in various models are studied in [13–18]. Despite the technical challenges in the reconstruction and modeling of the detector response to displaced vertices, this is an important signal of new physics as it is scarce in the standard model and has to be explored further in order to ensure the successful exploration of new physics at the LHC and across all mass ranges.

In this work, we use a strategy motivated by the ATLAS multitrack displaced vertex search [19,20], recently validated in our previous work [21] in the context of a left-right symmetric model. Here we focus on a simplified model in which the standard model field content is extended by one heavy sterile neutrino, briefly described in Sec. II. We consider three cases for active-sterile neutrino mixing V_{lN} , for each of the active flavors $l = e, \mu, \tau$. The displaced vertex strategy implemented in each case is described in Sec. III. Discovery prospects and reach at the LHC are discussed in Sec. IV. We close the paper and summarize in Sec. V.

II. STERILE NEUTRINO SIMPLIFIED MODEL

We consider a simplified see-saw model of neutrinos based on the standard model gauge group, in which only

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FIG. 1. Contours of fixed sterile neutrino proper decay distance $c\tau_N$ as a function of mass and active-sterile neutrino mixing angle. The shaded region represents roughly the region that can be accessed with current displaced vertex searches in the ATLAS inner tracker [19,20].

one massive sterile neutrino N is present in the kinematic range of our interest. In this generic framework, N couples to the SM leptons via a small mixing in the electroweak currents. The charged and neutral current interactions of this model are described in [22].

We consider one neutrino flavor at a time, e , μ or τ , produced in W boson decays in association with the respective lepton flavor: $W^\pm \rightarrow Nl^\pm$. The N decays proceed via $N \rightarrow l^\pm q\bar{q}$, $N \rightarrow l'^\mp l^\pm \nu_l$ and $N \rightarrow \nu_l q\bar{q}$. The N proper lifetime is given by [22]

$$c\tau_N \sim 3.7 \left(\frac{1 \text{ GeV}}{m_N} \right)^5 \left(\frac{0.1}{|V_{IN}|^2} \right) [\text{mm}]. \quad (1)$$

The relevant parameters are the sterile neutrino mass m_N and active-sterile neutrino mixing $|V_{IN}|^2$, which we treat as independent. In general, small neutrino masses and mixing lead to macroscopic lifetimes. In principle one can have a large N lifetime by making the mixing very small (instead of the sterile neutrino mass). However, for smaller values of the mixing, the production rate of N also becomes smaller. We are interested in masses in the GeV range to access lifetimes of the order of picoseconds while scanning over mixings as low as $|V_{IN}|^2 = 10^{-12}$.

In Fig. 1 we show different values of the proper lifetime in the $(m_N, |V_{IN}|^2)$ plane. We highlight the approximated region where vertices can efficiently be reconstructed inside the tracker region of ATLAS, for proper decay distances between 4 and 300 mm. We are interested in sterile neutrino mass between $5 \text{ GeV} < m_N < 30 \text{ GeV}$, which can be probed with a multitrack displaced vertex search at ATLAS or CMS.

III. SIMULATIONS AND SELECTION OF DISPLACED EVENTS

We generate a UFO [23] model with SARAH [24] and use SPHENO [25,26] for the spectrum calculation of the sterile neutrino simplified model. We simulate events at $\sqrt{s} = 13 \text{ TeV}$ for the process $pp \rightarrow W^\pm \rightarrow Nl^\pm$. Generation is performed with MADGRAPH5_AMC@NLOv2.4.3 [27] at leading order. We normalize the corresponding value to match the experimental cross section in Ref. [28]. The generated events are then interfaced to PYTHIA8 v2.3 [29] for showering, hadronization and computation of the N decays. Plots are generated with matplotlib [30].

The promising decay channels for the sterile neutrino are semileptonically $N \rightarrow l^\pm q\bar{q}$ and leptonically $N \rightarrow l'^\mp l^\pm \nu_l$. Decays via a neutral current such that $N \rightarrow \nu_l q\bar{q}$ are also possible [22]. All these modes will lead to displaced vertices with charged tracks associated with them. For the case when only τ mixing is present, both semileptonic and leptonic decays lead to the presence of a τ lepton coming from the displaced vertex.

We propose a search inspired by the ATLAS multitrack displaced vertex analysis [19,20], which is sensitive to lifetimes of the order of picoseconds to about a nanosecond, so particle decays can be reconstructed with a displaced vertex signature inside the inner tracker. This strategy was developed in our recent work in Ref. [21], where we trigger on the prompt lepton coming from the W boson decay, impose cuts on the neutrino displaced vertex and its decay products, and apply vertex-level efficiencies (made public by ATLAS in [19]) to DVs that pass the required particle-level acceptance cuts. Since the parametrized selection efficiencies provided by ATLAS assumes all decay products are prompt from the DV, they are not directly applicable to the case when there is a τ lepton coming from the displaced vertex,¹ so we consider decays to $N \rightarrow \nu_l q\bar{q}$ only when τ mixing is present.

Prompt leptons are reconstructed considering the following:

For electrons: We require an isolated electron within $|\eta| < 2.5$. We smear their momenta with a resolution of 2% at 10 GeV, falling linearly to 1% at 100 GeV, and then 1% flat.

For muons: We require an isolated muon within $|\eta| < 2.5$. We smear their momenta with a resolution between $|\eta|$ of 2 and 0, linearly falling from 4% to 1.5%.

¹The further displacement of τ 's inside the vertex will affect the vertex reconstruction efficiency from the subsequent displacement of taus (and from any heavy flavor quark in general). This was addressed for example in Ref. [31], when there are two b 's coming from the displaced vertex. By allowing a bigger merging distance of 5 mm (instead of 1 mm) when forming a vertex, some efficiency is recovered. Since we do not implement a vertex reconstruction algorithm in this work, the loss in efficiency can not be estimated.

For taus: We implement a basic reconstruction following Ref. [32]. We start by reconstructing jets with FASTJET 3.1.3 [33] using the anti- k_t algorithm with distance parameter $R = 0.4$. Only jets with $p_T > 10$ GeV and $|\eta| < 2.5$ are taken as seeds for τ reconstruction. Charged constituents inside the jet must have $p_T > 1$ GeV. If a truth τ candidate falls within a cone $\Delta R < 0.2$ centered on the jet axis, it is selected.

The following selections are then imposed:

- (1) One prompt lepton (as reconstructed above) with $p_T > 25$ GeV.
- (2) Decay position of the DV contained within transverse distance $r_{DV} < 300$ mm, and $|z_{DV}| < 300$ mm. The distance between the interaction point and the decay position must be bigger than > 4 mm.
- (3) Decay products must be charged (i.e., tracks) with $p_T > 1$ GeV and transverse impact parameter $|d_0| > 2$ mm. d_0 is defined as $d_0 = r_{DV} \times \sin \Delta\phi$, with $\Delta\phi$ being the azimuthal angle between the decay product and the trajectory of the long-lived N .
- (4) The number of selected tracks N_{trk} must be at least 3. The invariant mass of the DV m_{DV} must be ≥ 5 GeV, and assumes all tracks have the mass of the pion.
- (5) Parametrized selection efficiencies are applied depending on the displaced vertex distance (within 4 and 300 mm, between the pixel and the SCT), number of tracks and mass.

As pointed out in [21], with these selections we are still in a zero background region, where background comes mostly from instrumental sources.

IV. SENSITIVITY REACH

We analyze the region where a displaced search with the above selections can have sensitivity. The relevant parameters in the sterile neutrino model are the neutrino mass m_N and active-sterile neutrino mixing $|V_{IN}|^2$.

We first chose a representative benchmark point with $m_N = 15$ GeV, $|V_{IN}|^2 = 10^{-8}$ and proper neutrino decay distance $c\tau_N \approx 50$ mm to illustrate the effect of all analysis cuts from the previous section. We combine the second and third cuts in the “DV fiducial” entry in Table I. Events are generated at 13 TeV which corresponds to a production cross section of 0.09 fb. Cut-flows in the case of electron, muon and tau mixing are shown.

As already noted in the context of a left-right symmetric model in [21], for sterile neutrinos with masses below the electroweak scale this search strategy loses sensitivity, as lower masses will lead to softer decay products with limited amount of tracks available to make up a vertex. However, given the low background nature of this signature, the discovery of a displaced vertex signal in the sterile neutrino model is possible at the high-luminosity LHC.

Figures 2–4 show the estimated reach in the $(m_N, |V_{IN}|^2)$ plane, in the case of electron, muon and tau mixing,

TABLE I. Numbers of simulated events at $\sqrt{s} = 13$ TeV for a benchmark with $m_N = 15$ GeV, $|V_{IN}|^2 = 10^{-8}$, and $c\tau_N \approx 50$ mm, in the three cases considered where $l = e, \mu$ or τ . Overall efficiencies ϵ after all cuts are also shown.

	e mixing	μ mixing	τ mixing
	$\epsilon = 4.88\%$	$\epsilon = 4.21\%$	$\epsilon = 0.7\%$
All events	10 000	10 000	10 000
Prompt l	4004	3321	764
DV fiducial	2266	2058	433
N_{trk}	814	712	177
m_{DV}	645	579	72
DV efficiency	488	421	70

respectively. We also show for comparison the projected sensitivities from the proposed SHiP [34] and MATHUSLA [35,36] experiments. For projected sensitivities for other proposals for heavy neutral leptons within $m_N < 5$ GeV, see FASER [14,37,38] and CODEX-b [14,39].

In Fig. 2, we see that mixings as low as $|V_{eN}|^2 \approx 1.5 \times 10^{-9}$ for 3000/fb and 13 TeV can be probed for $m_N = 20$ GeV. Current neutrinoless double beta decay ($0\nu\beta\beta$) experiments and searches for tripletons at the LHC are also sensitive to $\mathcal{O}(10)$ GeV sterile neutrino masses. We show an update of the limits calculated in [22] using the latest limit on $0\nu\beta\beta$ from the GERDA experiment [43]. LHC limits for sterile neutrino masses

FIG. 2. 95% CL reach in the $(|V_{eN}|^2, m_N)$ plane at $\sqrt{s} = 13$ TeV of our proposed multitrack displaced strategy for $\mathcal{L} = 300 \text{ fb}^{-1}$ (blue) and $\mathcal{L} = 3000 \text{ fb}^{-1}$ (red). Projected sensitivities for the MATHUSLA (dashed green) and SHiP (dashed purple) experiments are also shown for comparison (taken from Refs. [14,40], respectively). The DELPHI limit, taken from [2], is also shown. A limit derived from $0\nu\beta\beta$ experiments is also shown (see text for more details). The 95% CL exclusion of the CMS 13 TeV tripletons search [10] is given by the filled grey region.

FIG. 3. 95% CL reach in the $(|V_{\mu N}|^2, m_N)$ plane at $\sqrt{s} = 13$ TeV of our proposed multitrack displaced strategy for $\mathcal{L} = 300 \text{ fb}^{-1}$ (blue) and $\mathcal{L} = 3000 \text{ fb}^{-1}$ (red). Projected sensitivities for the MATHUSLA (dashed green) and SHiP (dashed purple) experiments are also shown for comparison (taken from Refs. [14,40], respectively). The DELPHI limit, taken from [2], is also shown. The 13 TeV limit from proposed lepton-jets searches are shown in dashed brown, taken from Ref. [41] (“lepton-jets1”) and Ref. [42] (“lepton-jets2”). See the text for more details. The 95% CL exclusion of the CMS 13 TeV tripletons search [10] is given by the filled grey region.

FIG. 4. 95% CL reach in the $(|V_{\tau N}|^2, m_N)$ plane at $\sqrt{s} = 13$ TeV of our proposed multitrack displaced strategy for $\mathcal{L} = 300 \text{ fb}^{-1}$ (blue) and $\mathcal{L} = 3000 \text{ fb}^{-1}$ (red). Projected sensitivity the MATHUSLA (dashed green) and for the SHiP (dashed purple) experiment is also shown for comparison (taken from Ref. [35]). The DELPHI limit, taken from [2], is also shown for comparison.

below 40 GeV are presented for the first time in the CMS 13 TeV search for three prompt charged leptons in the final state [10]. Other significant constrain in our mass region of interest comes from LEP data, where the DELPHI collaboration provides limits on sterile states produced in decays of the Z boson [44].

In Fig. 3, mixings as low as $|V_{\mu N}|^2 \approx 2.2 \times 10^{-9}$ for 3000/fb and 13 TeV can be probed for $m_N = 20$ GeV. We also show limits from proposals with lepton-jets searches, which is a complementary strategy. The curve labeled “lepton-jets-1” shows the exclusion form Ref. [41] at 13 TeV and 300/fb, where zero background is assumed. The curve labeled “lepton-jets-2” shows the 13 TeV limit in [42] and 300/fb, and considers additional background sources to the ones in [41]. An improvement of roughly 2 orders of magnitude in sensitivity is achieved with our strategy with 300/fb for masses $5 < m_N < 25$ GeV. The 95% CL exclusion of the CMS 13 TeV prompt tripletons search [10] is also shown, proving to be competitive with DELPHI [44].

Finally, we show in Fig. 4 the reach when there is τ mixing. Experimental limits for τ mixing have not been addressed yet at the LHC. We show the DELPHI limit [44] from Z decays for comparison. For taus, a large luminosity sample will be needed for obtaining meaningful constraints. As the figure shows, there is only a very narrow region testable with 300/fb. Mixings as low as $|V_{\tau N}|^2 \approx 8 \times 10^{-9}$ for $m_N = 16$ GeV at 3000/fb can be probed with this strategy.

V. SUMMARY AND CONCLUSIONS

We study the potential of the LHC to probe light sterile neutrinos, and active-sterile neutrino mixing angles, with a displaced vertex strategy motivated by current multitrack DV searches at the 13 TeV LHC. We focus on a simplified model where the standard model is extended with one sterile neutrino N . Mixing with the three flavors e, μ and τ , are treated separately. In all cases, to our knowledge, we see that this strategy probes to be the most sensitive to date in the mass region of interest ($5 \text{ GeV} < m_N < 30 \text{ GeV}$).

For e mixing, we show that this DV search is more sensitive than current neutrinoless double beta decay experiments. In the case of μ mixing, parts of the parameter space not accessible with other LHC searches (such as lepton-jets or tripletons) is possible. In both cases, with 3000/fb, an improvement of up to 4 orders of magnitude ($|V_{IN}|^2 \approx \times 10^{-9}$ for sterile neutrino masses between 5 and 20 GeV) in sensitivity is gained when comparing with the current experimental limits from tripletons searches at CMS [10].

Accessing τ mixing is less straightforward due to the difficulty in reconstructing τ leptons, and also since the presence of a subsequently displaced τ coming from the displaced vertex affects the vertex reconstruction efficiency in a way that is not trivial to quantify. We access

τ mixing by considering sterile neutrino decays via a neutral current only, which still leads to a displaced vertex formed from hadronized tracks, to which publicly available DV efficiencies can be applied, thus avoiding the problematic τ in the DV. This may be an advantage of a multitrack based strategy, as opposed to tagging leptons coming from the DV, in constraining τ mixing.

We briefly comment on prospects for testing sterile neutrinos at LHCb. The authors in [45] discuss limits for a different model than the one presented in this work. They show that sterile neutrino masses around 9 GeV and mixings down to $\approx 10^{-6}$ can be constrained in semileptonic sterile neutrino decays ($\mu q \bar{q}$) at the 95% CL with current LHCb data [46]. Mixings up to $\approx 10^{-8}$ (for masses between 15–25 GeV) can be further probed at higher luminosity, suggesting limits for μ mixing from LHCb could be competitive in this mass region to the ones we derived here in the context of ATLAS.

Finally, the sensitivity of this displaced strategy at the LHC is complementary to that of future fixed-target experiments, such as SHiP, or the MATHUSLA surface detector, which can probe sterile neutrino masses below 5 GeV. This makes a tracker based DV search for light sterile neutrinos unique, as it has no competition from other experiments within $5 \text{ GeV} < m_N < 30 \text{ GeV}$.

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