Revisiting the LHC reach in the displaced region of the minimal left-right symmetric model

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We revisit discovery prospects for a long-lived sterile neutrino N at the LHC in the context of left-right symmetric theories. We focus on a displaced vertex search strategy sensitive to $\mathcal{O}(\text{GeV})$ neutrino masses produced via a right-handed W_R boson. Both on-shell and off-shell Drell-Yan production of W_R are considered. We estimate the reach as a function of m_N and m_{W_R} . With $\sqrt{s} = 13$ TeV and 300/fb of integrated luminosity, the LHC can probe neutrino masses as high as approximately 30 GeV and m_{W_R} around 6 TeV. The reach goes up to 11.5 TeV with 3000/fb and $m_N \sim 45$ GeV. This represents an improvement of a factor of 2 in sensitivity with respect to earlier work.

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I. INTRODUCTION

The origin of the mechanism responsible for providing mass to the neutrinos in the Standard Model (SM) remains unknown. Left-right symmetric theories [1,2] are popular candidates to explain light neutrino masses via the so-called seesaw mechanism [3], which additionally address the origin of parity violation in the SM weak sector.

In the minimal left-right framework, parity is broken spontaneously together with the new $SU(2)_R$ right-handed weak interaction, generating Majorana masses for both light and right-handed neutrinos N . Production and decay of the right-handed or sterile neutrino N depends mostly on the unknown mass of the new, heavy right-handed gauge boson, W_R . For $m_N \ll m_{W_R}$, the golden channel is the Keung-Sejanović process (KS) [4] in which production proceeds through a W_R via $pp \rightarrow W_R^\pm \rightarrow l^\pm N \rightarrow l^\pm l^\pm jj$.

Recently, the authors in Ref. [5] systematically classified all the signatures resulting from the KS process into four regions, based on the mass of the sterile neutrino N . These regions are *standard*, in which $m_N \gtrsim 200$ GeV, leading to the well-studied same-sign leptons plus jets ($lljj$) signature [4] (for recent reviews, see Refs. [6,7] and references therein); the *merged* region in which the final state is a

prompt lepton and a neutrino jet (lj_N); the *displaced* region where the neutrino appears at a visible distance from the primary vertex leading to a displaced vertex signature; and the *invisible* region where N escapes the detector and leads to events with missing transverse momenta.

Several experimental searches at the LHC target the KS process in the standard region, in a regime where N decays promptly. Most recently, the ATLAS [8] and CMS [9] collaborations provided stringent limits on the mass of W_R , for N masses close to the tera-electron-volt scale. W_R masses below approximately 3.5 TeV are already excluded by dijet resonance searches [10]. Existing searches for a new heavy boson decaying to leptons and missing transverse momenta [11,12] can constrain part of the invisible region [5]. No dedicated experimental searches targeting the merged and displaced regions exists yet when N has a mass below the electroweak scale.¹

For sterile neutrino masses below the electroweak scale, N becomes a long-lived particle that can be detected via its displaced decay to a lepton and jets [14,15]. There is rapidly growing interest in the study of the LHC capabilities to those heavy neutrino signatures and heavy neutral leptons in general [16] (see also Ref. [17] for a community white paper). Long-lived particle signatures in left-right symmetric theories include displaced diphoton jets [18],

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¹Although, we note that the CMS search for right-handed neutrinos in events with three prompt charged leptons in the final state [13] is sensitive to N masses below 40 GeV, where the focus is on a simplified model that extends the SM fermionic sector with only one right-handed neutrino.

displaced jets [5], displaced neutrino jets [19], and displaced vertices [14,20–22].

The purpose of this paper is to revisit the sensitivity estimates we made in Ref. [22] for the displaced KS region. In Ref. [22], we focused on the on-shell production of W_R . The authors in Ref. [5] have demonstrated that for $m_{W_R} > 5$ TeV the KS process is dominated by off-shell production via W_R^* (see Fig. 3 of Ref. [5]). Considering this contribution will give an enhancement in the cross section and therefore in the sensitivity of our displaced strategy. Note that in Ref. [22] we considered a zero background, multitrack displaced vertex search strategy, as opposed to the recognition of displaced jets performed in Ref. [5], which is sensitive to higher neutrino masses. We compare and discuss the complementarity of our strategy and overlap with the other KS regions in the regime $m_N < 100$ GeV.

II. SIMULATIONS OF W_R PRODUCTION AND N DECAY

The minimal left-right symmetric extension of the SM [1,2,23] has gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. This model contains a right-handed gauge boson W_R and three right-handed Majorana neutrinos, with lightest state N . In what follows, we consider only one neutrino in the kinematic region of interest ($m_N \ll m_{W_R}$, and $m_N < 100$ GeV), and we restrict, for simplicity, our discussion to sterile neutrino mixing with the electron sector only.²

Drell-Yan production of W_R proceeds via $pp \rightarrow W_R^\pm \rightarrow l^\pm N$, with N further decaying displaced to $N \rightarrow l^\pm jj$. This production may be dominantly off shell [5,25]. The authors of Ref. [5] have shown that the off-shell enhancement can be significant for light m_N . They also provided a dedicated event generator, the KS Event Generator (KSEG) [26], that considers off-shell W_R production as well as light (or heavy) N . It also appropriately deals with narrow resonances, as is the case of a long-lived N . This is explained in Appendix C of Ref. [5].

We generate parton-level events with KSEG [26] for a grid of masses covering $m_N = (10, 50)$ GeV and $m_{W_R} = (2, 12)$ TeV. The N lifetimes are computed numerically as described in Appendix A of Ref. [5]. The KS event generator takes special care in simulating the case of a long-lived neutrino, and les houches event files events are generated with decay vertex information. The next-to-leading-order (NLO) corrections to the cross section are taken into account by considering a constant k factor of 1.3, as calculated in Ref. [19]. We further hadronize events from

²We do not expect our results to change significantly if flavor mixing in the muon sector is present, as reconstruction efficiencies are rather similar. The sensitivity can be smaller when tau mixing is present due to the difficulties in reconstructing tau leptons [24].

KSEG with PYTHIA8 [27], from where we can retain all the relevant information (including lifetime) for our analysis.

The N charged decay products (i.e., tracks from hadronization) are identified to come from a common displaced vertex. A detailed detector response as a function of the displaced vertex invariant mass and number of tracks is applied to each vertex passing the selection criteria [22], described in the following section.

III. DISPLACED VERTEX REACH

The displaced vertex search strategy used in this article is the same one proposed in our earlier works in Refs. [22,24],³ which was inspired by the ATLAS zero background search in Ref. [29]. Our search is sensitive to decays occurring in the inner trackers of the LHC detectors. Events are triggered by a prompt electron (reconstructed as in Ref. [24]) with $p_T > 25$ GeV, and additional cuts are imposed in the selection of the displaced tracks and vertex.

The displaced vertices are selected by reconstructing tracks with transverse impact parameter $|d_0|$ bigger than 2 mm and with $p_T > 1$ GeV. The vertex position must be within 4 and 300 mm (tracker acceptance) and must have more than three tracks. The invariant mass of the displaced vertex (which is calculated assuming all tracks have the mass of the pion) is required to be greater than or equal to 5 GeV. As in Refs. [22,24], we quantify the detector response to displaced vertices by making use of the ATLAS parametrized efficiencies given in Ref. [29].

Figure 1 shows the 95% C.L. reach at the 13 TeV LHC in the mass plane (m_{W_R}, m_N), based on signal sensitivity to three events in 300 and 3000 fb⁻¹. The green region corresponds to the limit extracted from our past work in Ref. [22].⁴ When considering off-shell W_R production, the reach goes up to $m_{W_R} = 6250$ GeV for $m_N = 21$ GeV and $m_N = 31$ GeV for $m_{W_R} = 3250$ GeV at 300/fb. With 3000/fb, we are able to reach higher than $m_N = 45$ GeV for $m_{W_R} = 4500$ GeV, and $m_{W_R} = 11500$ GeV for $m_N = 37$ GeV.

We also overlay in Fig. 1 (with dashed orange lines) the estimated reach with standard leptons plus missing transverse momenta searches. These were estimated for the invisible region in Ref. [5]. Note that the projection with 3000/fb from Ref. [5] was performed for a center-of-mass energy of 14 TeV, but we still show this for comparison. We see that at high luminosity this displaced search strategy

³With the exception of the “trackless jet cut” defined in Ref. [22]. We originally kept this cut to follow as closely as possible the selections made in the ATLAS search [28,29]. This cut is not necessary and has no effect on the limits presented in this work.

⁴The on-shell production cross sections used in Fig. 4 of Ref. [22] were underestimated by a factor of 3. This was corrected, and a corrected version should appear soon. We thank Goran Popara for hinting that this may come from charge combinations.

FIG. 1. 95% C.L. reach in the (m_{W_R}, m_N) plane at $\sqrt{s} = 13$ TeV of our proposed displaced strategy for $\mathcal{L} = 300/\text{fb}$ (left) and $\mathcal{L} = 3000/\text{fb}$ (right). Comparison of the purely on-shell [22] (green region) and off-shell W_R production (purple) is shown. The projected exclusions in the $e + p_T^{\text{miss}}$ channel from Ref. [5] are also shown (orange dashed lines). Plot generated with MATPLOTLIB [30].

turns out to be in fact more competitive than searches for invisible decays.

IV. CONCLUSIONS

We have revisited LHC prospects with displaced vertices in the search for light, long-lived sterile neutrinos. We focused on the displaced region of the minimal left-right symmetric model, where the long-lived neutrino has a mass below the electroweak scale. By considering that off-shell production of a W_R dominates at $\mathcal{O}(\text{GeV})$ neutrino masses (as shown in Ref. [5]), we show that the high-luminosity LHC is able to probe masses up to approximately 45 GeV and 11.5 TeV for sterile neutrinos and W_R bosons, respectively. This newly calculated reach turns out to be more competitive than the one projected with standard lepton plus missing energy searches. This becomes of great importance when assessing the complementarity of different strategies, as backgrounds for more standard searches will continue to grow at higher center-of-mass energies, while for displaced vertex searches, they will remain low. Further improvements and optimizations of current

displaced searches at the LHC look promising for searches for light sterile neutrinos in the left-right model.

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