

# Heavy neutrino searches at the LHC with displaced vertices

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Sterile neutrinos with masses in the range (1-100) GeV, have been searched for in a variety of experiments. Here, we discuss the prospects to search for sterile neutrinos at the LHC using displaced vertices. Two different cases are discussed: (i) the standard model extended with sterile neutrinos and (ii) right-handed neutrinos in a left-right symmetric extension of the standard model. A dedicated displaced vertex search will allow to probe parts of the parameter space not accessible to other searches, but will require large luminosity in both cases.

Keywords: neutrino masses and mixing; LHC

## I. INTRODUCTION

Searches for heavy neutral leptons have been carried out in a variety of experiments [1]. Lacking any positive evidence so far, upper limits on the mixing of these “sterile neutrinos” with the ordinary, light, active neutrinos have been derived as function of the neutrino mass, with the most stringent limits for the mass range  $m_N = [3, 80]$  GeV on  $|V_{\mu 4}|^2 \lesssim 2 \times 10^{-5}$  coming still from the DELPHI experiment at LEP [2], while  $|V_{e 4}|^2 \lesssim 10^{-7} \times \frac{m_N}{\text{GeV}}$  has been calculated from the absence of neutrinoless double beta decay [3]. In the mass range  $m_N = [0.1, 3]$  GeV meson decays give the most stringent limits, due to a resonant enhancement of the decay rate, if the sterile neutrino mass  $m_N$  is close to its mass-shell [4]. For a complete list of limits on heavy sterile (Majorana) neutrino searches see [5].

In this paper, we discuss possible searches for sterile Majorana neutrinos with masses  $m_N = [3, 80]$  GeV at the LHC. The classical signal for lepton number violation at a hadron collider is like-sign di-leptons with (two) jets and no missing energy [6], although also tri-lepton final states as possible signal have been suggested [7]. We instead discuss displaced vertices as a possibility to search for sterile neutrinos at the LHC. The advantage of a displaced vertex search is that for decay lengths of the order of very roughly  $L = [10^{-3}, 1]$  m there is little

(or no) standard model background. Thus, in principle, a discovery could be claimed with as few as (3-5) events.

Below, we will consider two different setups in which heavy neutral leptons could occur. (i) Motivated by the seesaw mechanism, the standard model extended by the addition of a sterile Majorana neutrino. And, (ii) the (minimal) left-right symmetric extension of the standard model.

Neutrino oscillation experiments have shown that neutrinos have non-zero masses. For the current status of oscillation data see, for example [8]. In the classical seesaw mechanism [9–12] the smallness of the neutrino mass is due to the large mass of the right-handed neutrinos, expressed in the famous seesaw relation as  $m_\nu \propto \frac{m_D^2}{M_M}$ . For Yukawa couplings of order  $Y \sim (10^{-2} - 1)$  current neutrino data then put  $M_M$  in the range  $M_M \simeq (10^{11} - 10^{15})$  GeV, forever in the realm of theoretical speculation. However, for smaller Yukawa couplings, say of the order  $Y \sim (10^{-7} - 10^{-6})$ , sterile neutrinos with masses  $m_N = (10 - 1000)$  GeV could exist. Note that the naive expectation for heavy-light neutrino mixing in the seesaw is  $V \propto \sqrt{m_\nu/M_N}$ , i.e.  $|V_{i4}|^2 \simeq 5 \times 10^{-14} \left(\frac{m_\nu}{0.05\text{eV}}\right) \left(\frac{1\text{TeV}}{M_N}\right)$ . Obviously, none of the limits on heavy lepton mixing discussed above comes even close to this expectation.

Expectations for a discovery are much higher for left-right (L-R) symmetric extensions of the standard model [13, 14]. If the right-handed neutrinos, necessarily present in L-R models, have a Majorana mass [15], they appear in accelerators as “sterile” heavy objects and their Majorana nature can be probed by searching for like-sign di-leptons [6]. For  $m_{W_R} \gg m_{W_L}$ , but  $m_N \ll m_{W_R}$  the sterile neutrino  $N$  can be produced via an effective

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operator  $pp \rightarrow e^\pm + N$ , with  $N$  decaying to  $N \rightarrow e^\pm jj$ . Different from the case of the standard model plus sterile neutrino, here the production cross section and the decay length are not suppressed by the small mixing  $|V_{i4}|^2$ , but depend mostly on the unknown mass of the heavy  $W_R$ .

The rest of this paper is organized as follows. In the next section we briefly summarize the main formulas for production and decay of sterile neutrinos for our two models. Section III then discusses numerical results for displaced vertex searches, first in section III A for SM + sterile neutrino and in section III B for the case of LR symmetry. We then close the paper with a short discussion.

## II. THEORETICAL SETUP

Here we consider two setups with sterile neutrinos: (i) an extension of the SM field contents with a non-fixed number  $i$  of the SM singlet fermions  $\nu_{Ri}$  of unspecified origin and (ii) the Left-Right (L-R) symmetric model having three right-handed neutrinos  $\nu_{Ri}$  the L-R partners of the usual left-handed neutrinos  $\nu_{e,\mu,\tau}$ .

### A. A generic sterile neutrino scenario.

Adding  $n$  species of SM singlet right-handed neutrinos  $\nu'_{R\alpha} = (\nu'_{R1}, \dots, \nu'_{Rn})$  allows together with the three left-handed weak doublet neutrinos  $\nu'_{L\beta} = (\nu'_{Le}, \nu'_{L\mu}, \nu'_{L\tau})$  one to construct a mass term

$$\begin{aligned} & -\frac{1}{2}\overline{\nu'}^T \mathcal{M}^{(\nu)} \nu'^c + \text{h.c.} = \\ & -\frac{1}{2}(\overline{\nu'}^T_L, \overline{\nu'}^c_R) \begin{pmatrix} \mathcal{M}_L & \mathcal{M}_D \\ \mathcal{M}_D^T & \mathcal{M}_R \end{pmatrix} \begin{pmatrix} \nu'^c_L \\ \nu'_R \end{pmatrix} + \text{h.c.} \\ & = -\frac{1}{2} \left( \sum_{i=1}^3 m_{\nu_i} \overline{\nu}_i^c \nu_i + \sum_{j=1}^n m_{\nu_j} \overline{\nu}_j^c \nu_j \right) + \text{h.c.} \end{aligned} \quad (1)$$

where  $\mathcal{M}_L, \mathcal{M}_R$  are  $3 \times 3$  and  $n \times n$  symmetric Majorana mass matrices, and  $\mathcal{M}_D$  is a  $3 \times n$  Dirac type matrix. In the seesaw language the entry  $\mathcal{M}_L \neq 0$  is due to the seesaw type-II mechanism. Below we study a generic scenario without specifying concrete mechanism generating the mass matrix in Eq. (1).

A unitary rotation

$$V^T \mathcal{M}^{(\nu)} V = \text{Diag}\{m_{\nu_1}, \dots, m_{\nu_{3+n}}\} \quad (2)$$

leads to  $3 + n$  Majorana neutrinos with masses  $m_{\nu_1}, \dots, m_{\nu_{3+n}}$ . The matrix  $V_{\alpha k}$  is the neutrino mixing matrix. This spectrum must contain the three very

light neutrinos with different masses and dominated by the active flavors  $\nu_\alpha$  ( $\alpha = e, \mu, \tau$ ) and  $n$  heavy states  $N_{Ri}$  with the masses  $M_{N_{Ri}}$  and the active neutrino admixtures  $V_{\alpha N_{Ri}}$  subject to the experimental constraints discussed in the introduction (see, for instance [1, 5]). In what follows we consider the case of only one heavy sterile neutrino  $N$ . Thus there are four parameters characterizing the scenario in question: the neutrino mass  $m_N$  and its mixing  $V_{\alpha N}$  with the active flavors  $\alpha = e, \mu, \tau$ .

The heavy sterile neutrino Charged (CC) and Neutral Current (NC) interactions are

$$\begin{aligned} \mathcal{L} = & \frac{g_L}{\sqrt{2}} (V_{li}^L \bar{l} \gamma^\mu P_L \nu_i + V_{lN} \bar{l} \gamma^\mu P_L N) W_{L\mu}^- + \\ & + \frac{g}{2 \cos \theta_W} \sum_{\alpha, i, j} V_{\alpha i}^L V_{\alpha N}^* \bar{N} \gamma^\mu P_L \nu_i Z_\mu, \end{aligned} \quad (3)$$

where  $i = 1, 2, 3$ . The left-handed sector neutrino mixing matrix  $V^L$ , that appears in neutrino oscillations, coincides with the PMNS matrix. The matrix  $V_{\alpha N}$  describes the mixing between heavy and light neutrino sectors. The heavy neutrino  $N$  total decay rate  $\Gamma_N$  in the mass range  $m_N \subset [1, 80]$  GeV, used in the next section, is given in Appendix.

The half-life  $T_{1/2}$  for neutrinoless double beta ( $0\nu\beta\beta$ ) decay in this framework is

$$T_{1/2}^{-1} = G_{01} |\mathcal{M}_N|^2 \left| \frac{V_{eN}^2}{m_N} \right|^2 \quad (4)$$

where  $G_{01}$  and  $\mathcal{M}_N$  are the phase space factor and nuclear matrix element. Their values can be found in, for instance, the recent review [16].

### B. Minimal left-right symmetric extension of the standard model.

This is a significantly more restrictive framework [13–15] based on the gauge group  $SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$  with the gauge couplings  $g_L, g_R, g_1$  and the LR symmetric assignment of the quarks and leptons:  $Q_{L,R} = (u, d)_{L,R}$  and  $L_{L,R} = (\nu, l)_{L,R}$ . The gauge symmetry is broken to the SM symmetry at some scale  $M_R$ , at least somewhat larger than the electroweak symmetry breaking scale. Now there are three heavy neutrino mass eigenstates  $N$  one per family.

The CC and NC interactions relevant for our analysis are

$$\begin{aligned} \mathcal{L} = & \frac{g_R}{\sqrt{2}} (\bar{d} \gamma^\mu P_R u + V_{lN}^R \bar{l} \gamma^\mu P_R N) W_{R\mu}^- + \\ & + \frac{g_R}{\sqrt{1 - \tan^2 \theta_W (g_L/g_R)^2}} \times \\ & Z_{LR}^\mu \bar{f} \gamma_\mu [T_{3R} + \tan^2 \theta_W (g_L/g_R)^2 (T_{3L} - Q)] f \end{aligned} \quad (5)$$

where  $V^R$  is the right-handed sector neutrino mixing matrix. The charged  $W_{L,R}$ -boson states are expressed in terms of the mass eigenstates as:

$$\begin{aligned} W_L^- &= \cos \zeta \cdot W_1^- - \sin \zeta \cdot W_2^-, \\ W_R^- &= \sin \zeta \cdot W_1^- + \cos \zeta \cdot W_2^-, \end{aligned} \quad (6)$$

where the  $W_L - W_R$  mixing angle in a good approximation [17] is

$$\begin{aligned} \tan 2\zeta &= \frac{2g_L g_R M_{W_L}^2 \cdot \sin 2\beta}{g_R^2 M_{W_L}^2 + g_L^2 (M_{W_R}^2 - M_{W_L}^2)} \\ &\approx 2 \frac{g_R}{g_L} \frac{M_{W_L}^2}{M_{W_R}^2} \sin 2\beta. \end{aligned} \quad (7)$$

Here  $\tan \beta = \kappa'/\kappa$  is the ratio of the two vev's of the bidoublet Higgs  $\Phi$ . In the last step we used  $M_{W_R} \gg M_{W_L}$ . For convenience we denoted the masses of  $W_{1,2}^-$  as  $M_{W_L}$  and  $M_{W_R}$  respectively. Maximal  $W_L - W_R$  mixing is reached for  $\kappa = \kappa'$  when  $\sin 2\beta = 1$ . Imposing the perturbativity condition  $g_R^2/4\pi \leq 1$  and using  $g_L = g(M_Z) \approx 0.64935$  [1] we find the upper bound

$$\tan 2\zeta \leq \frac{4\sqrt{\pi}}{g(M_Z)} \frac{M_{W_L}^2}{M_{W_R}^2}. \quad (8)$$

For the total decay of each of the three heavy neutrinos of the L-R models in the mass range  $m_N \in [3, 80]$  GeV the neutral current contribution is negligible and we approximately have:

$$\Gamma_N \approx \frac{3G_F^2}{32\pi^3} m_N^5 \left( \frac{M_{W_L}}{M_{W_R}} \frac{g_R}{g_L} \right)^4 [1 + \sin^2 2\beta] \sum_l |V_{lN}^R|^2, \quad (9)$$

where we neglected the masses of all the final state particles.

The half-life  $T_{1/2}$  for neutrinoless double beta ( $0\nu\beta\beta$ ) decay via heavy  $W_R$  and heavy  $N$  exchange is given by:

$$T_{1/2}^{-1} = G_{01} |\mathcal{M}_N|^2 \left| (V_{eN}^R)^2 \frac{m_p}{m_N} \frac{M_{W_L}^4}{M_{W_R}^4} \frac{g_R^4}{g_L^4} \right|^2 \quad (10)$$

In the numerical section we will consider a simplified case with only one heavy neutrino in the relevant mass range.

### III. DISPLACED VERTEX SEARCHES

We have implemented the two models discussed above in CALCHEP [18] for the calculation of the cross section. We have compared our calculation for the sterile neutrino with cross sections available in the literature [5, 7] and found good agreement. We will first discuss the theoretically simpler case of SM plus sterile neutrino.

#### A. Sterile neutrino case

In the SM plus sterile neutrino scenario, the decay length of the heavy neutrino can be written as a function of two unknown parameters:

$$L = c\bar{\gamma}\tau_N \simeq 3.7\bar{\gamma} \left( \frac{\text{GeV}}{m_N} \right)^5 \left( \frac{10^{-4}}{|V_{l4}|^2} \right) [m] \quad (11)$$

Here,  $l = e, \mu$  and  $\bar{\gamma} = \bar{E}_N/m_N$ , where  $\bar{E}_N$  is the average energy of the heavy neutrino  $N$  which we calculated numerically. The heavy neutrino half-life is denoted by  $\tau_N$ . Decay lengths testable at the LHC are roughly of the order of  $L \simeq (10^{-3} - 1)$  m and thus, sterile neutrino masses between  $m_N \simeq [1, 30]$  GeV could lead to measurable displaced vertices.

The cross section for sterile neutrino production at 14 TeV can be separated into a bare cross sections times a factor containing the neutrino mixing [5]. The bare cross section is huge, reaching several nb for neutrino masses below  $m_W$ . This allows, in principle, to constrain heavy neutrino mixing to impressively small values. However, the resulting events from production and decay of sterile neutrino produced by an off-shell W-boson are relatively soft. Correspondingly we have found that our results do very sensitively depend on the cuts used in the analysis.

The lepton-based triggers used by the ATLAS collaboration in the 2012 run were [19]: For two electrons (muons), either both electrons (muons) have to have a  $p_T \geq 12$  GeV ( $p_T \geq 13$  GeV) or the leading electron (muon) has to have  $p_T \geq 24$  GeV ( $p_T \geq 18$  GeV) with the second electron required to have  $p_T \geq 7$  GeV ( $p_T \geq 8$  GeV). We have then calculated possible constraints on  $|V_{l4}|^2$  as function of the heavy neutrino mass  $m_N$  for a variety of cuts, motivated by these experimental cuts, but with variations as given below to check the future reach that could be obtained under different assumptions. The results are shown in fig. (1).

Fig. (1) shows constraints on  $|V_{l4}|^2$  obtained by the DELPHI collaboration [2], together with two limits from non-observation of neutrinoless double beta decay ( $0\nu\beta\beta$ ): The weaker limit shown is derived from the latest search result by the GERDA collaboration ( $T_{1/2} \geq 2.0 \times 10^{25}$  ys for  $^{76}\text{Ge}$  [20]), while the line at smaller values of  $|V_{l4}|^2$  is the expected sensitivity for  $T_{1/2} \geq 10^{27}$  ys. Note that the limit from DELPHI applies to both  $l = e, \mu$ , while the limit from double beta decay applies only to  $l = e$ . The coloured bands show the region that can be probed at the LHC in a 14 TeV run by a displaced vertex search. The three bands correspond to decay lengths of order  $L = 1$  mm,  $L = 0.01, 0.1$  and  $L = 1$  m, with the smallest length for largest values of

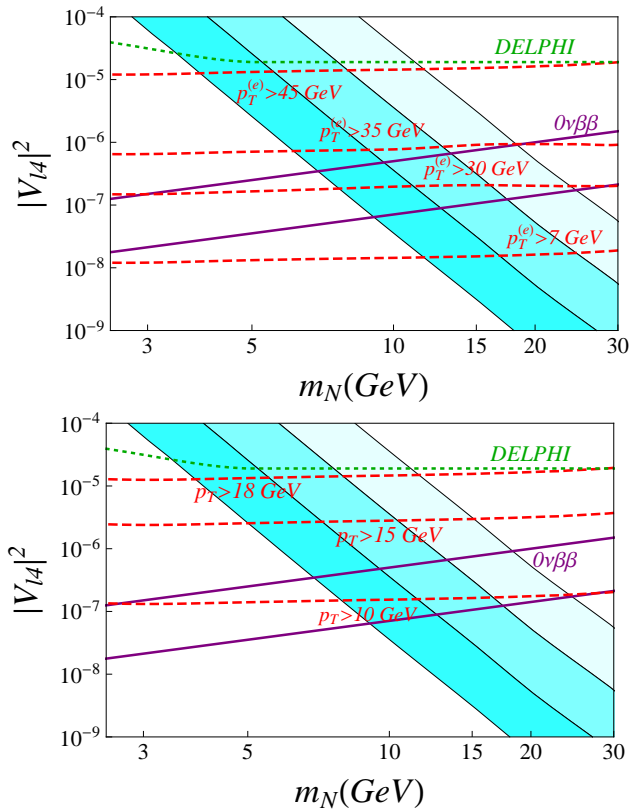


FIG. 1: Constraints on sterile neutrinos from DELPHI [2], compared with double beta decay and the region in parameter space where a displaced vertex search at LHC will be sensitive. (a) top, cuts:  $p_T^{e1} > 30$  GeV,  $p_T^{e2} > 7$  GeV, 30 GeV, 35 GeV, 45 GeV and  $|\eta^e| < 2.5$ . Luminosity:  $\mathcal{L} = 300$  fb $^{-1}$ . (b) bottom using  $p_T^{e2} > 7$  GeV,  $p_T^j > 10, 15$  and 20 GeV,  $p_T^{e1} > 30$  GeV and  $|\eta^{e,j}| < 2.5$ . The limit from double beta decay applies only to  $l = e$ , see text.

$|V_{l4}|^2$ . In this plot we assume a luminosity of  $\mathcal{L} = 300$  fb $^{-1}$ .

The red dashed lines are the expected sensitivity for the LHC assuming less than five signal events as the experimental upper limit. Different cuts on energies and  $p_T$  have then be used to estimate the sensitivity of the LHC. Consider the top panel first. Here,  $|\eta^e| < 2.5$  and the  $p_T$  of the first electron is required to be  $p_T^{e1} > 30$  GeV, while for the second electron (the one coming from the displaced vertex, not necessarily the softer of the two electrons) we require different values of  $p_T > 7, 30, 35$  and 45 GeV. It is clear that lowering the cut on the displaced vertex electron as much as possible is absolutely essential in this search. However, the plot shown in the top of fig. (1) does not show a (completely) realistic situation, since no cut on the jet energy was applied. Thus, while these events would show clearly two electrons, with

one coming from the displaced vertex, the hadronic activity at the displaced vertex might be too soft to allow for jet reconstruction. For a more realistic estimate we thus show in the same figure in the bottom panel the reach of the LHC, requiring  $p_T^{e2} > 7$  GeV,  $p_T^j > 10, 15$  and 20 GeV,  $p_T^{e1} > 30$  GeV and  $|\eta^{e,j}| < 2.5$ . The additional cut on the jet  $p_T$  again leads to a rapid loss of sensitivity, thus for this search to be effective, experimentalists will have to lower the threshold for jet search in displaced vertices as much as possible.

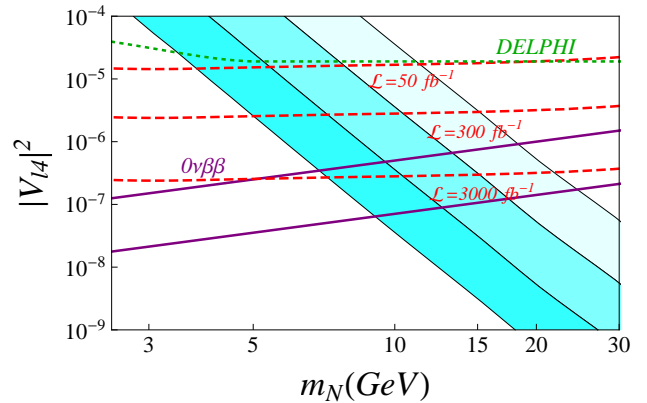


FIG. 2: Constraints on sterile neutrinos from DELPHI [2], compared with double beta decay and the region in parameter space where displaced vertex search at LHC will be sensitive. Cuts:  $p_T^{e1} > 30$  GeV,  $p_T^{e2} > 7$  GeV,  $p_T^j > 15$  GeV and  $|\eta| < 2.5$ . Lines for different values for luminosity:  $\mathcal{L} = 50, 300$  and 3000 fb $^{-1}$ . The limit from double beta decay applies only to  $l = e$ , see text.

In fig. (2) we then show the sensitivity of the LHC in the same plane as fig. (1), but now for fixed values of the cuts and for different assumed values of the luminosity:  $\mathcal{L} = 50, 300$  and 3000 fb $^{-1}$ . LHC could probe for  $l = \mu$  so far unexplored ranges of  $|V_{l4}|^2$  for luminosities as small as  $\mathcal{L} = 50$  fb $^{-1}$ . To do better than the current limit from  $0\nu\beta\beta$  on  $|V_{e4}|^2$ , very large luminosities or significantly lower  $p_T$  cuts will be necessary.

## B. Left-right symmetric model

Now we will discuss the results for the left-right symmetric model. For the sake of simplicity we will start our discussion assuming “manifest” L-R symmetry, i.e.  $g_R = g_L$ . In the LRSM the decay length can be written as function of the two masses  $m_N$  and  $m_{W_R}$ :

$$L = c\bar{\gamma}\tau_N \simeq 0.12 \bar{\gamma} \left(\frac{10\text{GeV}}{m_N}\right)^5 \left(\frac{m_{W_R}}{1\text{TeV}}\right)^4 [mm] \quad (12)$$

Here  $\bar{\gamma} = \bar{E}_N/m_N$  which we calculated numerically. Here and in the following plots, we have neglected effects of  $W_L - W_R$  mixing, since  $\sin 2\beta \leq 1$ . For the extreme case of  $\sin 2\beta$  approaching one, decay lengths will be a factor of two smaller than shown in the figures, compare eq. (9).

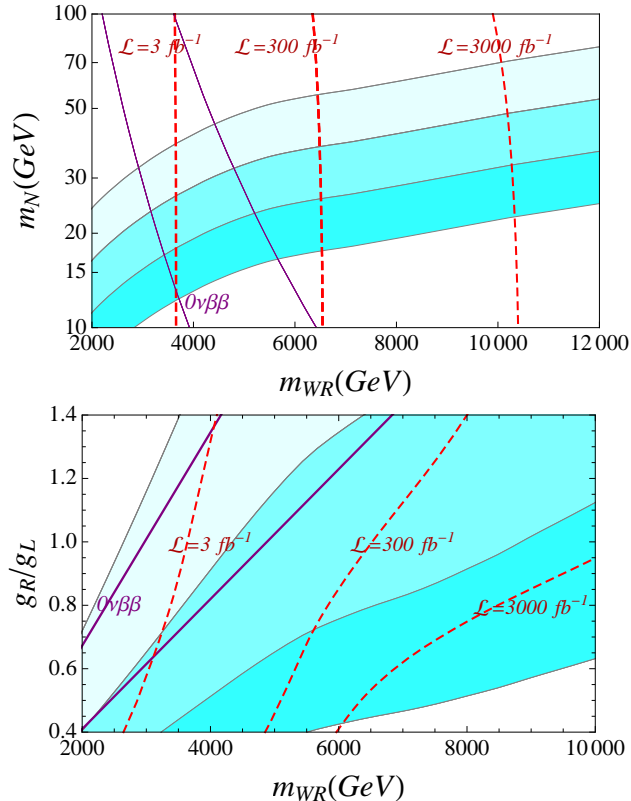


FIG. 3: Constraints on LR model from double beta decay compared with parameter space where displaced vertex search at LHC will be sensitive. (a) top:  $m_{W_R}$  vs  $m_N$  for fixed  $g_R = g_L$ . (b) bottom:  $g_R/g_L$  vs  $m_{W_R}$  for fixed  $m_N = 30 \text{ GeV}$ .

Unlike the sterile neutrino case, displaced vertex searches of a heavy neutrino produced via a  $W_R$  boson are not that sensitive on the cuts used in the analysis. This can be understood from the fact that the  $W_R$  is much heavier than the  $W_L$ , and as a result, the  $p_T$  distribution of the events extends to much higher  $p_T$  than for the sterile neutrino case. Fig. (3) shows two limits from non-observation of  $0\nu\beta\beta$ . The weaker limit correspond to  $T_{1/2} > 2.0 \times 10^{25}$  ys, while the line for larger values of  $m_{W_R}$  is a expected sensitivity of  $10^{27}$  ys. Again coloured bands show the region that can be probed at the LHC in a 14 TeV run by a displaced vertex search for decay lengths of order  $L = 1 \text{ mm}$ ,  $L = 0.01$ ,  $0.1$  and  $1 \text{ m}$ , with the largest lengths for largest values of  $m_{W_R}$ . In this plot we have used the cuts  $p_T > 40 \text{ GeV}$  and  $|\eta| < 2.5$  for lep-

tons and jets. Lines for different assumed luminosities:  $\mathcal{L} = 3, 300$  and  $3000 \text{ fb}^{-1}$  are shown. As demonstrated, LHC could probe so far unexplored ranges of  $m_N - m_{W_R}$  parameter space for luminosities as small as  $\mathcal{L} = 3 \text{ fb}^{-1}$  and for higher luminosities could be much more sensitive than even (optimistic) future  $0\nu\beta\beta$  results. Recall that current direct search limits for  $W_R$  at the LHC are of the order of  $(2 - 2.5) \text{ TeV}$  for  $m_{W_R}$ , depending on luminosity used and search channel [21, 22]. The future 14 TeV run might be able to improve this limit to roughly  $(4 - 4.5) \text{ TeV}$  [23]. For  $m_{W_R}$  much larger than this value, the  $W_R$  will not be produced on-shell at the LHC.

Up to now, we have made the assumption that  $g_R = g_L$  which is assumed to be true in the minimal LRSM, but need not be so in general. In Fig. (3b) we thus plot, as in Fig. (3a) a comparison of  $0\nu\beta\beta$  and LHC sensitivities but now in the plane  $g_R/g_L - m_{W_R}$  fixing  $m_N = 30 \text{ GeV}$ . As is shown, especially for small values of  $g_R/g_L$  and large luminosity, the LHC can probe much larger parts of the parameter space than even future  $0\nu\beta\beta$  experiments.

#### IV. SUMMARY

We have discussed a possible displaced vertex search at the LHC to constrain (or discover!) signals of heavy neutral leptons. We have worked in the SM, extended by a sterile neutrino, and have also discussed the case of a left-right symmetric extension of the standard model.

Limits from non-observation of double beta decay are very stringent and LHC will need at least  $300 \text{ fb}^{-1}$  to be competitive in the search for  $|V_{e4}|^2$ . However, the best limits on  $|V_{\mu 4}|^2$ , due to LEP, could be surpassed with order  $(10 - 50) \text{ fb}^{-1}$  already, although strongly depending on cuts as we have discussed in some detail.

The prospects for discovery of a signal look much brighter in the left-right symmetric model. So far unexplored regions of parameter space may become accessible with as little as  $3 \text{ fb}^{-1}$  and very large values of  $m_{W_R}$  can be probed by our displaced vertex search for large luminosities.

Finally, we would like to close mentioning that we have assumed there is no significant generation mixing in the heavy neutrino sector, i.e. events are always  $e^\pm e^\pm$ - or  $\mu^\pm \mu^\pm$ -like. Obviously, and given the experience with the large mixing angles in the active neutrino sector, this does not have to be true at all. Particularly if there is one heavy neutrino which mixes significantly in the  $\mu - \tau$  sector, limits from LHC will be much worse than our estimates for  $e^\pm e^\pm$ - or  $\mu^\pm \mu^\pm$ -like events, due to the rather poor  $\tau$  reconstruction efficiencies of the LHC ex-

periments.

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### Appendix A: Heavy neutrino decay rates

Here we summarize the partial decay rates of the heavy sterile neutrino  $N$  in the mass range  $1 \text{ GeV} \leq m_N \leq 80 \text{ GeV}$  analyzed in the present paper. In this range the semileptonic decays can be approximated by the decays into quark-antiquark pairs  $N \rightarrow l(\nu)q_1\bar{q}_2$ . For more details see Ref. [4].

The partial decay rates are:

$$\Gamma(N \rightarrow l_1^- l_2^+ \nu_{l_2}) = \quad (\text{A1})$$

$$= |V_{l_1 N}|^2 \frac{G_F^2}{192\pi^3} m_N^5 I_1(y_{l_1}, y_{\nu_{l_2}}, y_{l_2})(1 - \delta_{l_1 l_2}),$$

$$\Gamma(N \rightarrow \nu_{l_1} l_2^- l_2^+) = \quad (\text{A2})$$

$$= |V_{l_1 N}|^2 \frac{G_F^2}{96\pi^3} m_N^5 [(g_L^l g_R^l + \delta_{l_1 l_2} g_R^l) I_2(y_{\nu_{l_1}}, y_{l_2}, y_{l_2}) + ((g_L^l)^2 + (g_R^l)^2 + \delta_{l_1 l_2}(1 + 2g_L^l)) I_1(y_{\nu_{l_1}}, y_{l_2}, y_{l_2})],$$

$$\sum_{l_2=e,\mu,\tau} \Gamma(N \rightarrow \nu_{l_1} \nu_{l_2} \bar{\nu}_{l_2}) = |V_{l_1 N}|^2 \frac{G_F^2}{96\pi^3} m_N^5, \quad (\text{A3})$$

$$\Gamma(N \rightarrow l_1^- u \bar{d}) = \quad (\text{A4})$$

$$= |V_{l_1 N}|^2 |V_{ud}|^2 \frac{G_F^2}{64\pi^3} m_N^5 I_1(y_{l_1}, y_u, y_d),$$

$$\Gamma(N \rightarrow \nu_{l_1} q \bar{q}) = \quad (\text{A5})$$

$$= |V_{l_1 N}|^2 \frac{G_F^2}{32\pi^3} m_N^5 [g_L^q g_R^q I_2(y_{\nu_{l_1}}, y_q, y_q) + ((g_L^q)^2 + (g_R^q)^2) I_1(y_{\nu_{l_1}}, y_q, y_q)].$$

Here we denoted  $y_i = m_i/m_N$  with  $m_i = m_l, m_q$  being the lepton and quark masses, respectively. For the quark masses we use the values  $m_u \approx m_d = 3.5 \text{ MeV}$ ,  $m_s = 105 \text{ MeV}$ ,  $m_c = 1.27 \text{ GeV}$ ,  $m_b = 4.2 \text{ GeV}$ . In Eqs. (A4), (A5) we denoted  $u = u, c, t$ ;  $d = d, s, b$  and  $q = u, d, c, s, b, t$ . The SM neutral current couplings of leptons and quarks are

$$\begin{aligned} g_L^l &= -1/2 + \sin^2 \theta_W, & g_R^l &= \sin^2 \theta_W, & (\text{A6}) \\ g_L^u &= 1/2 - (2/3) \sin^2 \theta_W, & g_R^u &= -(2/3) \sin^2 \theta_W, \\ g_L^d &= -1/2 + (1/3) \sin^2 \theta_W, & g_R^d &= (1/3) \sin^2 \theta_W. \end{aligned}$$

The kinematical functions are:

$$I_1(x, y, z) = \quad (\text{A7})$$

$$= 12 \int_{(x+y)^2}^{(1-z)^2} \frac{ds}{s} (s - x^2 - y^2)(1 + z^2 - s) \times \\ \times \lambda^{1/2}(s, x^2, y^2) \lambda^{1/2}(1, s, z^2),$$

$$I_2(x, y, z) = \quad (\text{A8})$$

$$= 24yz \int_{(y+z)^2}^{(1-x)^2} \frac{ds}{s} (1 + x^2 - s) \lambda^{1/2}(s, y^2, z^2) \lambda^{1/2}(1, s, x^2).$$

The total decay rate  $\Gamma_N$  of the heavy neutrino  $N$  is:

$$\begin{aligned} \Gamma_N &= \sum_{l_1, l_2, \mathcal{H}} [2\Gamma(N \rightarrow l_1^- \mathcal{H}^+) + 2\Gamma(N \rightarrow l_1^- l_2^+ \nu_{l_2}) + \\ &+ \Gamma(N \rightarrow \nu_{l_1} \mathcal{H}^0) + \Gamma(N \rightarrow l_2^- l_2^+ \nu_{l_1}) + \\ &+ \Gamma(N \rightarrow \nu_{l_1} \nu_{l_2} \bar{\nu}_{l_2})], \end{aligned} \quad (\text{A9})$$

where we denoted  $\mathcal{H}^+ = \bar{d}u, \bar{s}u, \bar{d}c, \bar{s}c$  and  $\mathcal{H}^0 = \bar{q}q$ . The factor 2 of the first two terms is due to Majorana nature of heavy sterile neutrino  $N$  studied in the present paper. This factor is related with the fact that both charge conjugate final states are allowed:  $N \rightarrow l_1^- l_2^+ \nu_{l_2}, l_1^+ l_2^- \bar{\nu}_{l_2}$  and  $N \rightarrow l^\mp \mathcal{H}^\pm$ .

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