Left-Right Symmetric Models at the High-Intensity Frontier

Oscar Castillo-Felisola, Claudio O. Dib, Juan C. Helo, Sergey G. Kovalenko, and Sebastian E. Ortiz

Univ. Tecnica Federico Santa Maria, Casilla 110-V, Valparaiso, Chile, and Centro Cientifico Tecnologico de Valparaiso, Casilla 110-V, Valparaiso, Chile.

We study constraints on Left-Right Symmetric models from searches of semileptonic decays of $D$, $D_s$, $B$ mesons, mediated by heavy neutrinos $N$ with masses $m_N \sim$ GeV that go on their mass shell leading to a resonant enhancement of the rates. Using these processes we examine, as a function of $m_N$ and $M_{WR}$, the physics reach of the recently proposed high-intensity beam dump experiment SHiP, which is expected to produce a large sample of $D_s$ mesons. We compare these results with the corresponding reach of neutrinoless double beta decay experiments, as well as like-sign dilepton searches with displaced vertices at the LHC. We conclude that the SHiP experiment has clear advantages in probing the Left-Right Symmetric models for heavy neutrinos in the GeV mass range.

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I. INTRODUCTION

One of the current avenues to search for new physics has been opened with the discovery of neutrino oscillations. Oscillations indicate that neutrinos necessarily must be massive, while the standard model (SM) of electroweak interactions considers neutrinos as massless particles. Even if one tries to include the neutrino masses within the SM by means of Yukawa interactions — the mechanism that gives mass to all other fermions —, the scenario does not come out natural because one needs to introduce right-handed neutrino fields, which in turn lead to the possible inclusion of Majorana mass terms for these extra neutrino components, thus breaking lepton number, and so on [2]. In summary, the scenario opens into a wide range of possibilities, all of which indicate the existence of extra particles, mainly extra neutrinos, in a very broad range of energy scales [3]. While each extension of the SM proposes extra neutrinos in a specific mass range, in general the possibilities are from a few eV all the way to grand unification scales of order $10^{15}$ GeV. On the other hand, the experiments can put bounds on specific combinations of neutrino masses and mixings, each one covering a different range of masses [5].

In a typical seesaw model of neutrinos based on the SM gauge group, the heavy neutrinos are coupled to the standard sector through a small mixing with the standard leptons in the electroweak currents. In contrast, in a Left-Right symmetric gauge theory, the heavy neutrinos connect to the standard sector primarily through the right-handed currents. In the first case, the couplings are suppressed by the mixing, while in the second case they are suppressed by the large mass of the $W_R$ bosons. In the present paper we study the latter scenario, applied to rare decays of heavy mesons that are induced by massive neutrinos that go on mass shell in the intermediate state. Depending on the mass of the heavy neutrinos and the $W_R$ bosons, experiments could either discover the effect or establish new bounds, restricted to neutrino masses below the mass of a decaying particle, i.e., below 5 GeV for $B$ mesons, or below 1.8 GeV for $D$, $D_s$ mesons, so that the resonant effect can occur.

A particularly attractive feature of Left-Right symmetric (LR) models of electroweak interactions is that the appearance of right-handed neutrino components are not accidental but required in order to complete the right-handed lepton doublets [6–8]. In these models, the heavy neutrinos are mainly the right-handed fields with small admixtures of the standard neutrinos. Consequently, they couple sizeably to the SM sector through the gauge fields of the right-handed sector, $W_R$, but the latter induce very weak interactions on the SM particles due to the large scale of $M_{WR}$. The neutrino mass range of interest here is appropriate for searches in $B$ factories such as BaBar [9] and BELLE [10], and future high-intensity beam experiments such as SHiP [11].

This article is organized as follows. In Section II we briefly summarize the main formulas for production and decay of heavy neutrinos in Left-Right symmetric models. In Section III we discuss the sensitivity of heavy neutrinos searches driven by meson decays $D$, $D_s$, $B$ in LR models as could be observed in the SHiP experiment, comparing them with current and future limits coming from neutrinoless double beta decay ($\nu\beta\beta$) experiments and equal sign dilepton searches with displaced vertices at the LHC. We leave the last section for a short discussion and summary.

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1 For the current status of oscillation data see, for example, [1].
2 The role of heavy neutrinos in astrophysics and cosmology has been studied in Refs. [4].
II. THEORETICAL SETUP

Left-Right symmetric models are well motivated and popular extensions of the standard model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with gauge couplings $g_L, g_R$ and $g_t$, respectively, and a LR symmetric assignment of quarks and leptons, $Q_{L,R} = (u,d)_{L,R}$ and $L_{L,R} = (\nu,l)_{L,R}$ [6–8]. These theories have two particularly interesting features: Firstly, LR symmetric models can be accommodated in broader groups such as the Pati–Salam or $SO(10)$; and secondly, these models contain three right-handed neutrinos, which are required to complete the right-handed lepton doublets, making it a natural framework to justify the Type I seesaw mechanism. Thus in a three-family scenario, there are three light (or standard) and three heavy neutrino mass eigenstates, which we call $N_1$.

At some mass scale $M_R$, larger than the scale of the electroweak symmetry breaking, the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken down to the SM group $SU(2)_L \times U(1)_Y$. The charged current (CC) interactions relevant for the present analysis are

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} \left( \bar{\nu}_L \gamma^\mu P_R u + V_{1N} \cdot \bar{\nu}_R \gamma^\mu P_L N \right) W_{R\mu}^c + \frac{M_R}{\sqrt{2}} \left( \bar{\nu}_R \gamma^\mu P_L u + U_{1N} \cdot \bar{\nu}_L \gamma^\mu P_R N \right) W_{L\mu}^c,$$

where $U_{1N}$ and $V_{1N}$ are the neutrino mixing matrices of the left- and right-handed sectors, respectively. The charged boson states, $W_L^\pm$ and $W_R^\pm$, are linear combinations of mass eigenstates, denoted as $W_L^\pm$ and $W_R^\pm$:

$$W_L^\pm = W_1^\pm \cos \zeta - W_2^\pm \sin \zeta, \quad W_R^\pm = W_1^\pm \sin \zeta + W_2^\pm \cos \zeta,$$

where the $W_L$-$W_R$ mixing angle $\zeta$, to a good approximation [12], is given by

$$\tan 2\zeta = \frac{2g_L g_R M_{W_L}^2 \sin 2\beta}{g_R^2 M_{W_R}^2 + g_L^2 (M_{W_R}^2 - M_{W_L}^2)} \approx \frac{2g_R M_{W_L}^2}{g_L M_{W_R}^2} \sin 2\beta,$$

with $\tan \beta = \kappa'/\kappa$ being the ratio of the two vev’s of the $SU(2)$ bidoublet Higgs $\Phi$. Here the approximate expression refers to $M_{W_R} \gg M_{W_L}$. The masses of $W_{1,2}$ are denoted as $M_{W_L}$ and $M_{W_R}$, respectively. The maximal value of the $W_L$-$W_R$ mixing corresponds to $\kappa = \kappa'$ when $\sin 2\beta = 1$. The perturbativity condition $g_R^2/4\pi \leq 1$ together with $g_L = g(M_Z) \approx 0.64935$ [13] sets the upper bound

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

The total decay width of each of the three heavy neutrinos of the L-R models receives a negligible contribution from the neutral current interactions and can be written in the mass range of $m_N \sim 1$–80 GeV, to a good approximation, as [12, 14, 15]

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

Here the masses of all final state particles are neglected. For completeness we give the expression for the half-life $T_{1/2}$ of a neutrinoless double beta $(0\nu\beta\beta)$ decay mediated by $W_R$ and heavy $N$ exchange [12, 14, 16]

$$T_{1/2}^{-1} = G_{01} |M_N|^2 \left( V_{eN} \right)^2 \frac{m_p M_{W_L}^4}{m_N M_{W_R}^4 g_R^4} \frac{1}{g^2},$$

where $G_{01}$ is the phase space factor and $M_N$ is the nuclear matrix element.

III. PHENOMENOLOGY OF LR SYMMETRIC MODELS

For simplicity we will first restrict our discussion to heavy neutrino mixing with the electron sector only. We assume that the production of a heavy Majorana neutrino in a meson decay, $M \to eN$ (with $M$ either $D$, $D_s$ or $B$), and its subsequent decay as $N \to e\pi$, is dominated by the $W_R$ boson exchange, as it is shown in Fig. 1.

![FIG. 1. Heavy neutrino production (a) and decay (b) in the LR symmetric model.](image)

Consider a beam of heavy neutrinos $N$ with average energy $\bar{E}$, produced in a fixed target experiment. In the manifestly left-right symmetric scenario, i.e. $g_R = g_L$, the decay length of such neutrinos can be written according to Eq. (5) as a function of the masses $m_N$ and $m_{W_R}$ [16] in the form:

$$L = c\bar{\tau}_N \approx 12 \bar{\tau} \left( \frac{1\text{ GeV}}{m_N} \right) \left( \frac{m_{W_R}}{1\text{ TeV}} \right)^4 [\text{m}],$$

with $\bar{\tau} = \bar{E}/m_N$. Therefore, for $m_{W_R} \sim \text{TeV}$ and $m_N \sim \text{GeV}$ this decay length is rather large, and one can expect that only a fraction of the heavy neutrinos will decay inside a given detector.

In a LR symmetric model, the number of signal events in the form of meson decays $M \to eN$ followed by the heavy neutrino decay $N \to e\pi$ are suppressed by a factor of $(m_{W_L}/m_{W_R})^8$. This suppression comes from the production of heavy neutrinos $M \to eN$, which is suppressed
by \((m_{W_L}/m_{W_R})^4\), and from the fraction of heavy neutrinos decaying inside the detector, which is proportional to \(\tau_N^{-1}\), also suppressed by a factor of \((m_{W_L}/m_{W_R})^4\).

From the experimental point of view, this signal can not distinguish a LR symmetric model from a seesaw model based on the SM gauge group, where the number of signal events is suppressed by the small heavy-to-light neutrino mixing \(|U_{eN}|^2 \times |U_{\tau N}|^2\) [11, 15, 17, 18] (see also [19–28]). However, for the same reason, if limits on \(|U_{eN}|^2\) are known experimentally, we can extract limits on \(m_{W_R}\) by doing the simple conversion of \(|U_{eN}|^2 \rightarrow (m_{W_L}/m_{W_R})^4\).

The BELLE experiment, using B meson decays \(B \rightarrow XIN\) followed by \(N \rightarrow e\pi\), has set limits on \(|U_{eN}|^2 \sim 10^{-4}\) in the heavy neutrino mass range \(0.5–5\) GeV [10, 3]. In addition, the proposed high-intensity beam dump experiment SHiP [11], which should produce a very large

In the same way, these BELLE searches on heavy neutrinos correspond to lower limits on \(m_{W_R}\) near 800 GeV, which are not better than the current limit \(m_{W_R} > 2.5\) TeV coming from \(K_0 – \bar{K}_0\) mixing [30–32]. On the other hand, the future SHiP experiments will be sensitive to larger \(W_R^+\) masses, up to \(m_{W_R} \sim 8–18\) TeV, for heavy neutrino masses \(m_N \sim 1–2\) GeV, as shown in Fig. 2.

The LHC can also constrain LR symmetric models by searching for like-sign leptons plus two jets [33–37]. Currently the LHC has imposed a lower limit for \(m_{W_R}\) at 3.0 TeV [37] in a neutrino mass range \(m_N \sim 0.2–2.0\) TeV. These limits are expected to be extended up to \(m_{W_R} \gtrsim 6\) TeV [35] in future searches. Although the current searches at the LHC are not sensitive to heavy neutrinos with masses \(m_N\) as low as a few GeV, it has been proposed in Ref. [16] to search for heavy neutrinos with masses \(m_N \lesssim 80\) GeV using displaced vertices.5 These heavy neutrinos could be produced via a \(W_R\) boson as it is shown in Fig. 3. The advantage of a displaced vertex search is that for vertex separation roughly between \(10^{-3}–1\) m, there is little or no background [16].

Using the narrow width approximation for the intermediate \(N\) propagator, we can express the number of events of this type at the LHC decaying in the range from \(d_1 = 1\) mm to \(d_2 = 1\) m as:

\[
\#(eejj) = \mathcal{L} \times \sigma(pp \rightarrow eN) \times Br(N \rightarrow ejj) \times P_N. \tag{8}
\]

Here \(P_N = [\exp(-d_1/L) - \exp(-d_2/L)]\) is the probability for a heavy neutrino to decay within a distance between \(d_1 = 1\) mm and \(d_2 = 1\) m from its production point. Following the analysis of Ref. [16] we have used Eq. (8) to estimate the parametrical region that would produce at least five events with vertex separation between 1 mm to 1 m, for an integrated luminosity of \(L = 300\) fb\(^{-1}\) and collision energy \(\sqrt{s} = 13\) TeV, and using the kinematical cuts in transverse momentum and rapidity \(p_T > 40\) GeV and \(\eta < 2.5\), respectively, for both leptons and jets.

In Fig. 2(a) we show two limits from the non-observation of \(0\nu\beta\beta\), assuming that the contribution via the \(W_R\) boson and heavy neutrino exchange shown in Fig. 3 dominates. The weaker limit (solid line) [14, 45–47] corresponds to the current bounds on the half life of neutrinoless double beta decay, \(T_{1/2} > 2 \times 10^{25}\) yr [48, 49], while the stronger limit (dashed line) corresponds to an expected future sensitivity of \(T_{1/2} > 10^{27}\) yr. The grey band bordered by the solid line shows the region in parameter space where a displaced vertex search at the LHC could yield at least 5 events. The solid line near the bottom of Fig. 2(a) shows the region in the parameter space, which can be probed by the heavy neutrino search at SHiP. This is so far an unexplored domain of the \(m_N - m_{W_R}\) parameter space below \(m_N \sim 5\) GeV where, as seen from Fig. 2(a), the SHiP searches are much more sensitive than the LHC, and even more sensitive than optimistic future \(0\nu\beta\beta\) results for heavy neutrino masses \(m_N \sim 1–2\) GeV.

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3 The LHCb experiment has searched for heavy neutrinos using the B meson decay mode \(B \rightarrow \mu N\) followed by \(\mu \rightarrow e\pi\) in a mass range \(m_N \approx 0.5–5\) GeV, setting limits on \(|U_{\mu N}|^2 \sim 10^{-3}–10^{-2}\) [29].

4 Generic processes of this kind have been discussed in [38–40] (see also [41–43]) as tree-level high-energy completions of lepton number violation operators that generate neutrinoless double beta decay.

5 Recently, the authors of Ref. [44] have proposed to search for heavy neutrinos induced by Higgs decays at the LHC.
Up to here, we have made the assumption that $g_R = g_L$, which corresponds to the manifestly left-right symmetric scenario, a case that may not necessarily be so in general [50]. In Fig. 2(b) we show, just as in Fig. 2(a), a comparison between the $0\nu\beta\beta$, LHC and SHiP sensitivities, but for a fixed heavy neutrino mass $m_N = 1$ GeV and in the plane $g_R/g_L - m_{W_R}$. As shown, and in agreement with the previous analysis, the LHC is not competitive to $0\nu\beta\beta$ or SHiP for $m_N = 1$ GeV. It is clear that the SHiP experiment is capable to probe a much larger area of this parameter space than even future neutrinoless double beta decay experiments.

The lepton flavor violating (LFV) muon decays $\mu \rightarrow e \gamma$, $\mu \rightarrow eee$ and $\mu \rightarrow e$ conversion in nuclei\(^6\) also impose constraints on LR symmetric models [51]. However for masses $m_N \sim$ GeV these bounds are very weak and not comparable to those coming from $0\nu\beta\beta$ [56, 57].

Finally we would like to close by mentioning that so far we have considered heavy neutrino mixing only in the electron sector. For heavy neutrino mixing in the $\mu$-sector, the LHC and SHiP limits shown in Fig. 2 will remain the same but the limits coming from $0\nu\beta\beta$ are not applicable. This is so because the $0\nu\beta\beta$ amplitude is only sensitive to the $U_{eN}$ mixing matrix elements. For heavy neutrino mixing predominantly in the $\tau$-lepton sector, the situation is also different. On the one hand, the limits from the LHC will be much worse than the limits shown in Fig. 2, due to the relatively poorer $\tau$ reconstruction efficiencies at the LHC. On the other hand, the SHiP experiment could be sensitive to $|U_{eN}|^2 \sim 10^{-8} - 10^{-9}$ for heavy neutrino masses of the order of $m_N \sim 1$ GeV [5], which correspond to strong limits on the $W_R$ boson mass up to $m_{W_R} \sim 9$ TeV for heavy neutrino masses $m_N \sim 1$ GeV and $g_R = g_L$.

IV. SUMMARY AND CONCLUSIONS

We have analysed the scenario of heavy neutrinos within Left-Right symmetric models of electroweak interactions. We considered both a manifestly left-right symmetric case, as well as cases where the right and left gauge couplings are different. Concerning the heavy neutrino sector, we studied the cases where one neutrino is in the mass range $m_N$ from 1 to 80 GeV, and the rest are assumed to be heavier or not to interfere with the processes we consider. In LR symmetric models of neutrinos, the heavy neutrinos couple to the standard sector mainly through the right handed currents, so their suppression is due to the large mass of the $W_R$ bosons. We studied the sensitivity of $0\nu\beta\beta$, LHC and SHiP experiments to the mass of the heavy neutrinos and $W_R$ bosons. In the case of LHC, we considered signals of equal sign dileptons with displaced vertices, which are free of backgrounds, and in the case of SHiP, we considered the production of heavy neutrinos through charmed meson decays. We find that in the range of masses where SHiP is relevant, its sensitivity could be much stronger than the other two kinds of experiments, with the potential of discovery or considerable improvements on current $m_{W_R}$ and $m_N$ bounds.

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\[^6\] The authors of Ref. [51] have been studied the contribution of Majorana neutrinos in $\mu \rightarrow e$ conversion in nuclei. See also Refs. [52–55].
