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Constraining Right Handed Gauge Boson Mass from Lepton Number Violating Meson Decays in a Low Scale Left Right Model

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We analyze the lepton number violating (LNV) meson decays that arise in a TeV scale Left Right Symmetry model. The right handed Majorana neutrino N along with the right handed or Standard Model gauge bosons mediate the meson decays and provide a resonant enhancement of the rates if the mass of N (M_N) lies in the range $\sim (100\,\mathrm{MeV} - 5\,\mathrm{GeV})$. Using the expected upper limits on the number of events for the LNV decay modes $M_1^+ \to \ell^+\ell^+\pi^-$ ($M_1 = B, D, D_s, K$), we derive constraints plausible on the mass of the right handed charged gauge boson by future searches at the ongoing NA62 and LHCb experiments at CERN, the upcoming Belle II at SuperKEK, as well as at the proposed future experiments, SHiP and FCC-ee. These bounds are complimentary to the limits from same-sign dilepton search at Large Hadron Collider (LHC). The very high intensity of Charmed mesons expected to be produced at SHiP will result in a far more stringent bound, $M_{W_R} > 18.4$ TeV (corresponding to $M_N = 1.46$ GeV), than the other existing bounds from collider and neutrinoless double beta decay searches.

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1. Introduction

One of the most attractive framework to explain the small light neutrino masses is the Minimal Left-Right Symmetry Model (MLRSM) [1]. The light neutrino masses in this model are generated from dimension-five lepton number violating (LNV) operator that violates lepton number by two units and hence their Majorana nature can be confirmed by observing various LNV signal in experiments, such as neutrinoless double beta decay. LNV signature can also be tested through indirect searches from meson decays, $M_1^+ \to \ell^+\ell^+\pi^-$. Right handed Majorana neutrinos with mass in the hundreds of MeV-few GeV range, can be produced as an intermediate on mass shell state, resulting in a resonance enhancement of the LNV meson decay rates. The detailed study of these is the main objective of this paper [2].

In addition to the particle content of the Standard Model (SM), the model contains three right handed Majorana neutrinos N_R, and the additional gauge bosons W_R and Z'. The charged current Lagrangian for the quarks and leptons in this model have the following forms:

$$\mathscr{L}_{CC}^{q} = \frac{g}{\sqrt{2}}\sum_{i,j}\overline{u}_i V_{ij}^{\rm CKM}\, W_{L\mu}^{+}\gamma^{\mu}P_L\, d_j + \frac{g}{\sqrt{2}}\sum_{i,j}\overline{u}_i V_{ij}^{\rm R-CKM'}\, W_{R\mu}^{+}\gamma^{\mu}P_R\, d_j + {\rm H.c.},$$
$$\mathscr{L}_{CC}^{\ell} = \frac{g}{\sqrt{2}}\sum_{i,j}\overline{\ell}_{L_i} W_{L\mu}^{-}\gamma^{\mu}P_L\,(U_{ij}\nu_{L_j} + S_{ij}N_j^c) + \frac{g}{\sqrt{2}}\sum_{i,j}\overline{\ell}_{R_i}\, W_{R\mu}^{-}\gamma^{\mu}P_R\,(V_{ij}^{*}N_j + T_{ij}^{*}\nu_L^c) + {\rm H.c.}, \quad (1.1)$$

where $U = (1-\frac{\theta^2}{2})U_{\rm PMNS}$, $V = (1-\frac{\theta^2}{2})V_R$, $S = \theta V_R$, $T = -\theta U_{\rm PMNS}$, $\theta^2 = \frac{m_\nu}{M_N}$ and we have considered $V_R = I$.

2. Imprint of Majorana Signature in Meson Decays

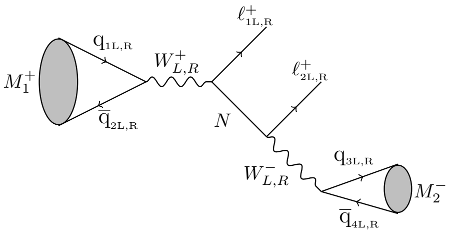
Together with the gauge bosons W_R, or even with W_L, N_i can mediate the lepton number violating meson decays, $M_1^+(p) \to \ell_1^+(k_1)\ell_2^+(k_2)M_2^-(k_3)$, where M_1 is a pseudoscalar, while M_2 can be a pseudoscalar or a vector meson. We assume that there are three RH neutrinos with masses in the $100\,\text{MeV} - 5$ GeV range, that contribute in these meson decays. The Feynman diagrams for these decays are shown in Fig 1. We can write the amplitude for this pseudoscalar meson decay as,

$$\mathscr{M}_{h_1h_2}^{P} = \mathscr{M}_{1h_1h_2}^{P} + \mathscr{M}_{2h_1h_2}^{P}$$

where, h_1h_2 can be of different chiralities LL, RR, LR, RL and the second term is obtained by interchanging the momenta k_1 with k_2 of the 2 leptons, as well as interchanging the leptonic mixing elements.

$$\mathscr{M}_1^P = \mathscr{M}_{1LL}^P + \mathscr{M}_{1RR}^P + \mathscr{M}_{1LR}^P + \mathscr{M}_{1RL}^P$$
$$= A\sum_i \Bigg(M_{N_i}\left(S_{\ell_1N_i}^{*}S_{\ell_2N_i}^{*}\right)\frac{\overline{u}(k_2)\not{k}_3\not{p}(1-\gamma_5)v(k_1)}{(p-k_1)^2 - M_{N_i}^2 + iM_{N_i}\Gamma_{N_i}} + M_{N_i}\left(\frac{M_{W_L}^4}{M_{W_R}^4}\right)(V_{\ell_1N_i}V_{\ell_2N_i})\frac{\overline{u}(k_2)\not{k}_3\not{p}(1+\gamma_5)v(k_1)}{(p-k_1)^2 - M_{N_i}^2 + iM_{N_i}\Gamma_{N_i}}$$
$$+ \left(\frac{M_{W_L}^2}{M_{W_R}^2}\right)(S_{\ell_1N_i}^{*}V_{\ell_2N_i})\frac{\overline{u}(k_2)\not{k}_3(\not{p}-\not{k}_1)\not{p}(1-\gamma_5)v(k_1)}{(p-k_1)^2 - M_{N_i}^2 + iM_{N_i}\Gamma_{N_i}} + \left(\frac{M_{W_L}^2}{M_{W_R}^2}\right)(V_{\ell_1N_i}S_{\ell_2N_i}^{*})\frac{\overline{u}(k_2)\not{k}_3(\not{p}-\not{k}_1)\not{p}(1+\gamma_5)v(k_1)}{(p-k_1)^2 - M_{N_i}^2 + iM_{N_i}\Gamma_{N_i}}\Bigg) \quad (2.1)$$

where, $A = G_F^2 V_{M_1}^{CKM} V_{M_2}^{CKM} f_{M_1} f_{M_2}$. M_{N_i}, Γ_{N_i} are the mass and decay width of the heavy neutrino N_i. The total decay width of heavy majorana neutrino N_i for the considered mass range $(0.1 - 5$ GeV)



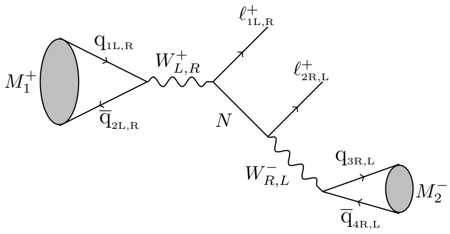


Figure 1: The Feynman diagrams for the lepton number violating meson decays. These processes produce resonance enhancement. See text for details.

is given by,

$$\Gamma_{N_i} = \sum_{\ell,P} 2\Gamma^{\ell P} + \sum_{\ell,P} \Gamma^{\nu_\ell P} + \sum_{\ell,V} 2\Gamma^{\ell V} + \sum_{\ell,V} \Gamma^{\nu_\ell V} + \sum_{\ell_1,\ell_2(\ell_1 \neq \ell_2)} 2\Gamma^{\ell_1 \ell_2 \nu_{\ell_2}} + \sum_{\ell_1,\ell_2} \Gamma^{\nu_{\ell_1} \ell_2 \ell_2} + \sum_{\nu_{\ell_1}} \Gamma^{\nu_{\ell_1} \nu \bar{\nu}}. \quad (2.2)$$

where, $\ell = e, \mu, \tau$, $P^+ = \pi^+, K^+, D^+, D_s^+$, $P^0 = \pi^0, \eta, \eta', \eta_c$, $V^+ = \rho^+, K^{*+}, D^{*+}, D_s^{*+}$, $V^0 = \rho^0, \omega, \phi, J/\psi$, $\ell_1, \ell_2 = e, \mu, \tau$, $\ell_1 \neq \ell_2$. In Fig.2, we have shown the Γ_N as a function of mass M_N for different W_R masses.

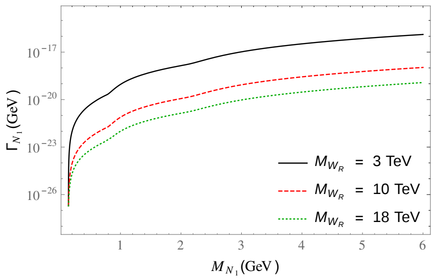


Figure 2: The total decay width of the heavy neutrino N_1.

Table 1: Inputs for various experiments.

Experiments	N_{M_1}	L_D[m]	β_{M_1} [GeV]
NA62	$N_K = 1.35 \times 10^{13}$	170	75
Belle II	$N_{D,D_s,B} = 3.4, 1, 5.5 \times 10^{10}$	1.5	0
LHCb	$N_{D,D_s,B} = 5, 2.3, 0.8 \times 10^{12}$	20	100
FCC-ee	$N_B = 6 \times 10^{11}$	2	$\frac{M_Z}{2}$
SHiP	$N_{D,D_s} = 1.02, 0.27 \times 10^{17}$	60	58

3. Limit on M_{W_R} from ongoing and future experiments

The sensitivity reach for the above LNV decay modes in a particular experiment depends on the number of the parent mesons M_1's produced ($N_{M_1^+}$), their momentum ($\vec{p}_{M_1}$) and the branching ratio for these mesons to the LNV modes. Assuming the parent meson M_1 decays at rest, the expected number of signal events is [3]:

$$N_{event} = 2N_{M_1^+} \text{Br}\left(M_1^+ \to \ell^+\ell^+ M_2^-\right) \mathscr{P}_N \approx 2N_{M_1^+} \text{Br}\left(M_1^+ \to \ell^+ N_i\right) \frac{\Gamma(N_i \to \ell^+ M_2^-)}{\Gamma_{N_i}} \mathscr{P}_N, \quad (3.1)$$

where for $\ell = e$, $N_i = N_1$ and for $\ell = \mu$, N_i=N_2, the factor 2 is due to inclusion of the charge conjugate process $M_1^+ \to \ell^+ N_i$ and $\mathscr{P}_N$, is the probability of the RH neutrino N_i to decay within a detector of the length L_D given by: $\mathscr{P}_N = \left[1 - exp\left(-\frac{M_{N_i}\Gamma_{N_i}L_D}{p^*_{N_i}}\right)\right]$. In the above, $p^*_{N_i} = \frac{m_{M_1}}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_\ell^2}{m_{M_1}^2}, \frac{M_{N_i}^2}{m_{M_1}^2}\right)$ is the momentum of N_i in M_1 rest frame. For the meson M_1 produced with fixed boost $\vec{\beta}$, the energy of N_i is then given by, $E_{N_i} = E^*_{N_i}\left(\gamma + \frac{p^*_{N_i}}{E^*_{N_i}}\sqrt{\gamma^2 - 1}\cos\theta^*_{N_i}\right)$, where $E^*_{N_i}$, $p^*_{N_i}$ are the energy and momentum of N_i in rest frame of M_1 and $\gamma = \frac{E_{M_1}}{m_{M_1}}$. $\theta^*_{N_i}$ is the emission angle of particle N_i in the rest frame of M_1, which is measured from the boost direction $\vec{\beta}$. Hence, the signal event for $M_1^+ \to \ell^+\ell^+M_2^-$ in the lab-frame is:

$$N_{event} \approx 2N_{M_1^+} \int_{E^-_{N_i}}^{E^+_{N_i}} dE_{N_i} \text{Br}\left(M_1^+ \to \ell^+ N_i\right) \frac{m_{M_1}}{2p^*_{N_i}|\vec{p}_{M_1}|} \frac{\Gamma(N_i \to \ell^+ M_2^-)}{\Gamma_{N_i}} \mathscr{P}'_N, \tag{3.2}$$

where $\mathscr{P}'_N = \left[1 - exp\left(-\frac{M_{N_i}\Gamma_{N_i}L_D}{\sqrt{E^2_{N_i} - M^2_{N_i}}}\right)\right]$, is the probability of N_i to decay within the detector length L_D, after taking into account the boost factor.

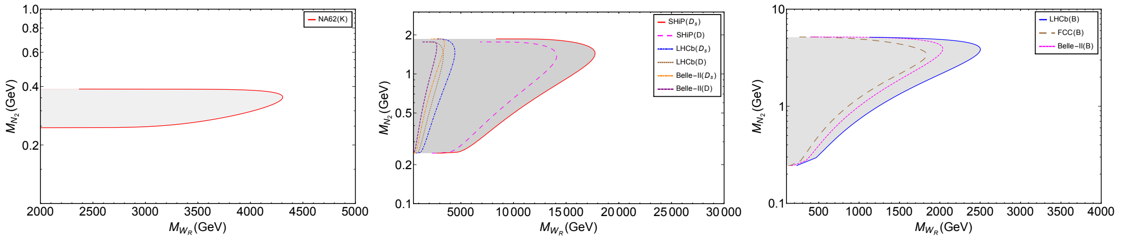


Figure 3: Constraints on the RH gauge boson M_{W_R} mass, corresponding to a heavy neutrino M_N for K, D, D_s and B meson decays.

4. Input for different Experiments

In Table.1, we have listed all the relevant input parameter for different experiments which we have used in our calculation.

5. Results

From Fig. 3 it is evident that the most stringent limit in the $M_N \sim 1$ GeV range will be provided by SHiP with the $D_s/D \to \ell^+\ell^+\pi^-$ decay mode. In the relatively higher mass range $M_N \sim 4$ GeV, stringent limit can be obtained by FCC-ee, Belle-II and LHCb experiments. Besides, the ongoing NA62 can give constraint $M_{W_R} > 4.6$ TeV($M_{N_1} \sim 0.38$ GeV), which is competitive with the collider bounds from LHC.

6. Conclusions

We evaluate the lepton number violating meson decays $M_1 \to \ell^+\ell^+M_2$ within the framework of a Left-Right symmetric model. The meson decays are sensitive for low mass right handed neutrinos (in the few 100 MeV-few GeV range) and are complementary to LHC (sensitive to few hundred GeV to TeV mass neutrinos).

References

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