Implications of the Diboson Excess for Neutrinoless Double Beta Decay and Lepton Flavor Violation in TeV Scale Left Right Symmetric Model

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Overview of the Model— Denoting \( Q \equiv (u \ d)^T \) and \( \psi \equiv (\nu \ell)^T \) as the quark and lepton doublets respectively, \( Q_L \) and \( \psi_L \) are doublets under \( SU(2)_L \) while \( Q_R \) and \( \psi_R \) are \( SU(2)_R \) doublets. The minimal Higgs model of the model consists of an \( SU(2)_L \times SU(2)_R \) bidoublet \( \Phi \) and \( SU(2)_{LR}(R) \)-triplets \( \Delta_{L(R)} \). The generic Yukawa Lagrangian of the model is given by

\[ \mathcal{L}_Y = h_{ij} \bar{Q}_L \Phi Q_R + \bar{h}_i \bar{Q}_L \Phi Q_R + \bar{h}_{ji} \bar{Q}_L \Phi Q_R + \bar{h}_{ij} \bar{\nu}_L \Phi \psi_R + \bar{h}_{ji} \bar{\nu}_L \Phi \psi_R + f_L \bar{\psi}_L \Delta_L \psi_L + f_R \psi_R \Delta_R \psi_R + \text{H.c.,} \]

(1)
where $C$ stands for charge conjugation and $\bar{\Phi} = \tau_2 \Phi^* \tau_2$ ($\tau_2$ being the second Pauli matrix). After electroweak symmetry breaking by the bidoublet vacuum expectation value (VEV) $\langle \Phi \rangle = \text{diag}(\kappa, \kappa')$, Eq. (1) leads to the Dirac mass matrix for neutrinos: $M_D = h_1 \kappa + h_1 \kappa'$. The triplet VEVs $\langle \Delta^\text{T}_{L,R} \rangle = v_{L,R}$ lead to the Majorana neutrino mass terms $m_L = f_L v_L$ and $M_R = f_R v_R$. In the seesaw approximation, the light neutrino mass matrix

$$M_\nu \simeq m_L - M_D M_R^{-1} M_D^T,$$

where the first (second) term on the right-hand side is the Type-II (Type-I) seesaw contribution. An appealing case is when the Type-II contribution dominates in Eq. (2), so that the smallness of the light neutrino masses is guaranteed by the smallness of $v_L \propto v^2/v_R$ (where $v = \sqrt{\kappa^2 + \kappa'^2}$ is the electroweak VEV), independent of the Dirac mass matrix. Moreover, an exact $P$ (or $C$) symmetry implies $f_L = f_R$ (or $f_L = f_R$), so that the light and heavy neutrino mass matrices are proportional to each other, which makes it a very predictive scenario for LNV and LFV observables. Although in our case with $g_R < g_L$, an exact $P$ (or $C$) symmetry may not be realized down to the TeV scale, we will still work with the simple choice $f_L = f_R$, and therefore, $M_\nu = (v_L/v_R) M_R$. Setting $M_{W_L} \approx 2$ TeV and $g_R \approx 0.5$, as required to explain the HIC diboson and dijet anomalies, also fixes the $SU(2)_R$ breaking scale $v_R \approx 6$ TeV. Note that for purely Majorana RH neutrinos as in the minimal LRSM, it is difficult to fit the CMS $eejj$ excess, which requires a suppression of the same-sign dielectron signal and the absence of an $e jj$ peak. For possible alternatives, see e.g. [19, 23, 24].

**Neutrinoless Double Beta Decay** – In the LRSM, there are several new contributions to the $0\nu\beta\beta$ amplitude, apart from the canonical light neutrino exchange diagram. However, in the Type-II seesaw dominance, all the mixed LH-RH contributions are negligible, whereas the scalar triplet contribution can also be neglected for $M_R/M_\Delta \lesssim 0.1$ [17], which is assumed here. Thus, we are only left with the purely LH- and RH-contributions to the $0\nu\beta\beta$ half-life:

$$\frac{1}{T_{0\nu\beta\beta}^{1/2}} = G_{0\nu} |g_A|^4 \left| M_\nu \right|^2 \left| \frac{m_{ee}^N + m_{ee}^N}{m_e} \right|^2,$$

where $G_{0\nu}$ is the phase space factor, $g_A$ is the nucleon axial-vector coupling constant, $m_e$ is the electron mass, $M_{\nu,e,N}$ are the NMEs and $m_{ee}^N$ are the effective neutrino masses corresponding to light and heavy neutrino exchange, respectively. For the light neutrino exchange, $m_{ee} = \sum_i U^2_{ei} m_i$, $U$ being the PMNS mixing matrix which diagonalizes the light neutrino mass matrix $M_\nu$ with eigenvalues $m_i$. Using the standard parametrization for $U$ in terms of three mixing angles $\theta_{ij}$, one Dirac CP phase $\delta$ and two Majorana CP phases $\alpha_{2,3}$, we get

$$m_{ee}^N = m_1^2 c_{12}^2 c_{13}^2 + m_2^2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3^2 s_{13}^2 e^{2i\alpha_3},$$

where $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$ (for $i, j = 1, 2, 3$).

For the heavy neutrino exchange due to RH current,

$$m_{ee}^N = \left| p^2 \right| \left( \frac{g_R}{g_L} \right)^4 \left( \frac{M_{W_L}}{M_{W_R}} \right)^4 \sum_j \frac{V_{ej}^2 M_j}{\left| p^2 \right| + M_j^2},$$

where $\left| p^2 \right| = m_e m_p M_N/M_\nu \sim (100 \text{ MeV})^2$ denotes the typical momentum exchange, $m_p$ is the proton mass, and $V_{ej}$ are the elements of the first row of the unitary matrix diagonalizing the RH neutrino mass matrix $M_R$ with eigenvalues $M_j$. Since $m_i \simeq M_i$ in the Type-II dominance, for normal hierarchy (NH), $M_3$ will be the largest (henceforth denoted as $M_\ell$), and we can express the other two RH neutrino masses as $M_1 = (m_1/m_3) M_\ell$ and $M_2 = (m_2/m_3) M_\ell$. Similarly, for inverted hierarchy (IH), $M_2$ will be the largest and we can write $M_1 = (m_1/m_2) M_\ell$ and $M_3 = (m_3/m_2) M_\ell$.

For the numerical analysis, we consider three relevant isotopes, namely, $^{76}\text{Ge}$, $^{136}\text{Xe}$ and $^{130}\text{Te}$ (see e.g. [20] for the status of experiments with other isotopes), and compare the LRSM predictions for the half-life with the corresponding current experimental limits and future sensitivities. For the phase space factors and NMEs, we use the SRQRPA calculations with $g_A = 1.25$ from [20]. Our results are shown in Fig. 4 as a function of the sum of light neutrino masses for an illustrative value of $M_\ell = 1$ TeV. In each case, we show the LRSM predictions (LR) for both NH and IH, and the corresponding light neutrino contributions alone (Std) for comparison. The kink in the LR contribution is due to a cancellation in the $0\nu\beta\beta$ amplitude when the lightest neutrino mass becomes very small: $m_{\text{lightest}} \lesssim 1 \mu$eV. Here we have used the $3\sigma$ allowed ranges of the neutrino mass and mixing parameters from a recent global fit [21] and have varied the Majorana phases $\alpha_{2,3} \in [0, \pi]$. The lower horizontal lines show the current 90% CL limits on the half-life from GERDA combined with Heidelberg-Moscow and IGEX for $^{76}\text{Ge}$ [22], KamLAND-Zen for $^{136}\text{Xe}$ [23] (see also EXO-200 [24], and Cuore-0 combined with Cuoricino for $^{130}\text{Te}$ [25]. The projected limits from GERDA phase-II [26] as well as the planned ton-scale experiments such as MAJORANA+GERDA [27], nEXO [28], and CUPID [29] are shown by the upper horizontal lines. The rightmost vertical line in each plot represents the future 90% CL sensitivity of KATRIN [30] for the absolute neutrino mass scale, whereas the other two vertical lines show the best 95% CL limit on the sum of light neutrino masses from Planck data [31] and a projected 95% CL limit from Planck+Euclid [32].

From Fig. 4 it is evident that the future sensitivity reach of the ton-scale $0\nu\beta\beta$ experiments can completely probe this LRSM benchmark point, irrespective of the neutrino mass hierarchy and uncertainties due to oscillation parameters and NMEs, except for the cancellation region in the NH case. This can be further constrained by the cosmological limit on the sum of light neutrino...
masses \[^{33}_{33}\]^{34}\). In particular, the precision cosmology with the future Euclid project could provide an indirect measure of the absolute neutrino mass, thus possibly ruling out the cancellation region and enabling more definitive model predictions for \(0\nu\beta\beta\).

The variation of the \(0\nu\beta\beta\) half-life predictions in our LRSM scenario with respect to the heavy neutrino mass parameter \(M_\nu\) is examined in Fig. 2 for both NH and IH. For illustration, we have only shown the results for \(^{76}\text{Ge}\) isotope and have varied the lightest neutrino mass between \(10^{-8}\)–1 eV. Note that in the NH case, there always exists a cancellation region for the LR contribution by itself, which shifts to smaller \(m_{\text{lightest}}\) values as we increase the RH neutrino mass scale \(M_\nu\). This is reminiscent of the NH cancellation region for the canonical light neutrino contribution alone, which occurs between \(m_{\text{lightest}}\) \(\approx 1\)–10 meV. On the other hand, for the IH case, the cancellation in the LR contribution occurs only when at least one of the RH neutrino masses is above \([\nu^2] \sim (100 \text{ MeV})^2\), in contrast with the light neutrino case, where there is no cancellation for IH. We do not show the results for \(m_{\text{lightest}} < 1 \mu\text{eV}\), because in the Type-II seesaw dominance, this will imply the lightest RH neutrino mass close to eV (for some of the benchmark values of \(M_\nu\) shown in Fig. 1), which is already disfavored by cosmology \[^{31}\]. From Fig. 2 we find that the \(M_\nu = 100 \text{ MeV}\) IH case is already ruled out by GERDA phase-I \[^{22}\], and in the NH case, only the cancellation region survives. For higher \(M_\nu\) values with both NH and IH, part of the parameter space is already ruled out by GERDA, and the remaining can be probed in future \[^{20}\]^{27}\), except the cancellation regions. Further information on the absolute light neutrino mass scale could in principle eliminate these cancellation regions.

**Lepton Flavor Violation** – There exist several Feynman diagrams contributing to the LFV observables such as \(\ell \to \ell'\gamma\), \(\ell \to 3\ell'\) and \(\mu - e\) conversion. Focusing on the most promising LFV process \(\mu \to e\gamma\), the purely RH contribution to the branching ratio is given by

\[
\text{Br}(\mu \to e\gamma) \approx \frac{3\alpha_{\text{em}}}{2\pi} \left(\frac{g_R}{g_L}\right)^4 \left(\frac{M_{W_R}}{M_{W_L}}\right)^4 \left|\sum_i V_{\text{ex}} V_{e\gamma} G_\gamma(x_i)\right|^2,
\]

where \(\alpha_{\text{em}} = e^2/4\pi\) is the electromagnetic coupling constant, \(x_i \equiv (M_i/M_{W_R})^2\) and the loop-function

\[
G_\gamma(x) = -\frac{2x^3 + 5x^2 - x}{4(1 - x)^3} - \frac{3x^3}{2(1 - x)^4}\ln x,
\]

which approaches the constant value of 1/2 in the limit \(x \gg 1\). Note that the SM contribution to \(\text{Br}(\mu \to e\gamma)\) due to light neutrino exchange is extremely small \(\lesssim 10^{-55}\) \[^{35}\], and furthermore, the other LH, mixed and scalar contributions can be neglected in our LRSM scenario under the assumptions stated before.

Our predictions for \(\text{Br}(\mu \to e\gamma)\) from Eq. (6) are shown in Fig. 3 for both NH and IH with three benchmark values of \(M_\nu\), where the band in each case is due to the 3\(\sigma\) uncertainties in the neutrino oscillation parameters. The horizontal shaded region is ruled out at 90% CL by the MEG experiment \[^{36}\], while the horizontal dashed and dotted lines show the MEG-II \[^{37}\] and PRISM/PRIME \[^{38}\] sensitivities, respectively. It is evident that the \(\mu \to e\gamma\) searches could be more effective in probing the relatively heavier \(M_\nu\) values, as compared to the \(0\nu\beta\beta\) searches. Also note that the Planck upper limit on the heaviest neutrino mass effectively puts a lower limit on the \(\mu \to e\gamma\) branching ratio in the quasi-degenerate (QD) region; for instance, for \(M_\nu = 1 \text{ TeV}\), this lower limit is \((0.5 - 1.9) \times 10^{-14}\) for NH [IH], as shown in Fig. 3. However, for NH with \(M_\nu/M_{W_R} \gtrsim 1\), there is a destructive interference between the two heaviest neutrino contributions for certain values of the Dirac.
**FIG. 2.** The $0\nu\beta\beta$ half-life of $^{76}$Ge as a function of the lightest neutrino mass for various values of $M_\nu$ in our LRSM scenario.

**FIG. 3.** Branching ratio of $\mu \rightarrow e\gamma$ as a function of the lightest neutrino mass in our LRSM with different values of $M_\nu$.

**FIG. 4.** Correlation between $0\nu\beta\beta$ and $\mu \rightarrow e\gamma$ in our LRSM scenario for $M_\nu = 1$ TeV.

$CP$ phase, which leads to a cancellation region, unless the third RH neutrino contribution is sizable, as demonstrated in Fig. 6 for $M_\nu = 9$ TeV. On the other hand, smaller $M_\nu$ values lead to a suppression in the $\mu \rightarrow e\gamma$ rate, pushing it well below the future sensitivity even for $M_\nu = 100$ GeV, which is however accessible to $0\nu\beta\beta$ experiments. Thus, a combination of the low-energy probes of LNV and LFV is crucial to probe effectively the entire LRSM parameter space in our case. This is complementary to the direct searches at the LHC [5, 39], which can probe RH neutrino masses from about 100 GeV up to $M_W$ [10] using the same-sign dilepton plus dijet channel [13]. Similarly, the GeV-scale RH neutrinos can also be searched for in the proposed SHiP experiment [41].

**Correlation between LNV and LFV**—The synergistic aspects of the low-energy LNV and LFV searches is further illustrated in Fig. 4 via a correlation between the $0\nu\beta\beta$ half-life of $^{76}$Ge and $\mu \rightarrow e\gamma$ branching ratio in our LRSM setup. This plot is obtained for a typical value of $M_\nu = 1$ TeV, while the scattered points are due to the NME uncertainties. The upper horizontal shaded area is ruled out by the MEG experiment [36], whereas the vertical shaded area is excluded by GERDA phase-I [22]. The lower horizontal shaded area corresponds to QD light neutrino masses, which is disfavored by Planck [31], as also shown in Fig. 3 by the vertical shaded area. All the remaining region can in principle be probed by a combination of the future $0\nu\beta\beta$ and LFV experiments, as shown by the dashed/dotted lines in Fig. 4.

**Conclusion**—We have explored the low-energy implications of the recent diboson excess observed at the LHC in the context of a TeV-scale Left-Right Symmetric model with Type-II seesaw dominance. In particular, we analyze the predictions for $0\nu\beta\beta$ and $\mu \rightarrow e\gamma$, and show that a combination of these experiments at the intensity frontier can effectively probe most of the hitherto unknown RH neutrino parameter space of this LRSM scenario. We find that the RH neutrinos with relatively low mass (MeV-GeV) are already ruled out from the existing bound on $0\nu\beta\beta$, apart from some cancellation regions, whereas the future ton-scale $0\nu\beta\beta$ experiments could probe most of the remaining parameter space of this model. On the other hand, the TeV-scale RH neutrinos in this scenario are constrained by the MEG limits on $\mu \rightarrow e\gamma$ decay rate. The synergistic aspects of the future LNV and LFV experiments at the intensity frontier is demonstrated by a novel correlation between the $0\nu\beta\beta$ half-life and the $\mu \rightarrow e\gamma$ branching ratio. Finally, a measurement of the absolute neutrino mass scale from future precision cosmology could render the model predictions for LNV and LFV more definitive.
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