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HIGGS BOSON(S) IN THE MINIMAL LEFT–RIGHT MODEL[*]

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We discuss the scalar sector of the minimal Left–Right model, going through a comprehensive analysis of the relevant theoretical constraints on the parameter space from low energy processes and perturbativity. As a consequence, the anatomy of the Higgs boson(s) is drawn in the parametric space of the model, giving rise to a possible Lepton Number Violating (LNV) channel in the standard-like Higgs boson decay. The process could probe the origin of the neutrino masses and parity restoration at the LHC even beyond other direct searches.

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The discovery of the Higgs boson (h) [1, 2] is the last triumph of the Standard Model (SM), providing the origin of the masses of all charged fermions. The Higgs mechanism manifests directly as $\Gamma_{h\to\bar{f}f} \propto m_f^2$, with f a charged fermion. This is the essence of the Higgs mechanism and can be tested at the LHC [3]. However, the SM leaves the open problem of the origin of the neutral fermion masses, reflecting with no coupling and then no decay rate of h to neutrinos. The latter may be their own antiparticles [4], leading to LNV processes as the well-known neutrino-less double beta decay ($0\nu2\beta$) [5]. A natural key to take into account the origin of neutrino masses is a new gauge symmetry properly broken by a new Higgs boson, implementing what is done for the charged fermions in the SM. Popular theories, where this

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is realized, are the Left–Right symmetric models (LRSM) [6], designed to explain parity violation of weak interactions [7] and then to solve the main aesthetic defect of the SM, namely a complete asymmetry between left and right. The LRSM embeds naturally the seesaw mechanism generating the light neutrino masses [8–12] and offering a complete framework to understand the neutrino nature. Several years after the proposal of the first LNV search through $0\nu 2\beta$, another process was suggested in [13] by Keung and Senjanović (KS) [14] within LRSM. The KS process would probe at the same time the parity restoration and the Majorana nature of neutrino through the LNV. Within the LRSM is then possible to connect it with $0\nu 2\beta$ [15, 16] and predict the Dirac mass [17, 18], testable at the LHC via LNV decays. A number of analyses shows that the lowest right-handed (RH) scale may be at TeV range [19–23], in the reach of the LHC [24]. In this paper, we discuss the scalar sector of the model and how to probe the origin of neutrino masses within LRSM, in the light of the constraints on the theory due to low energy process [25, 26] and perturbativity [27], in the case of a low RH scale.

1. Probing neutrino masses within the minimal LRSM

Since the original work of [7], several studies on the potential of LRSM exist in literature [28–30]. The potential contains all the possible terms allowed by the gauge symmetry $\mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{B-L}$ plus a generalized parity relating left and right sector:

$$
\begin{aligned}
\mathcal{V} = & -\mu_1^2 \mathrm{Tr}\left[\phi^\dagger \phi\right] - \mu_2^2 \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right]\right) - \mu_3^2 \left(\mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \lambda_1 \left(\mathrm{Tr}\left[\phi^\dagger \phi\right]\right)^2 + \lambda_2 \left(\left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right]\right)^2 + \left(\mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right]\right)^2\right) + \lambda_3 \mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \\
& + \lambda_4 \mathrm{Tr}\left[\phi^\dagger \phi\right] \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right]\right) + \rho_1 \left(\left(\mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right]\right)^2 + \left(\mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right)^2\right) \\
& + \rho_2 \left(\mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}\right] \mathrm{Tr}\left[\varDelta_{\mathrm{L}}^\dagger \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}}^\dagger \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \rho_3 \mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right] + \rho_4 \left(\mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}}^\dagger \varDelta_{\mathrm{R}}^\dagger\right]\right. \\
& \left. + \mathrm{Tr}\left[\varDelta_{\mathrm{L}}^\dagger \varDelta_{\mathrm{L}}^\dagger\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}\right]\right) + \alpha_1 \mathrm{Tr}\left[\phi^\dagger \phi\right] \left(\mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \alpha_2 e^{i\varDelta_2} \left(\mathrm{Tr}\left[\tilde{\phi}\phi^\dagger\right] \mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \phi\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \alpha_2 e^{-i\varDelta_2} \left(\mathrm{Tr}\left[\phi\tilde{\phi}^\dagger\right] \mathrm{Tr}\left[\varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \tilde{\phi}\right] \mathrm{Tr}\left[\varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \alpha_3 \left(\mathrm{Tr}\left[\phi\phi^\dagger \varDelta_{\mathrm{L}} \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \phi \varDelta_{\mathrm{R}} \varDelta_{\mathrm{R}}^\dagger\right]\right) + \beta_1 \left(\mathrm{Tr}\left[\phi \varDelta_{\mathrm{R}} \phi^\dagger \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \varDelta_{\mathrm{L}} \phi \varDelta_{\mathrm{R}}^\dagger\right]\right) \\
& + \beta_2 \left(\mathrm{Tr}\left[\tilde{\phi} \varDelta_{\mathrm{R}} \phi^\dagger \varDelta_{\mathrm{L}}^\dagger\right] + \mathrm{Tr}\left[\tilde{\phi}^\dagger \varDelta_{\mathrm{L}} \phi \varDelta_{\mathrm{R}}^\dagger\right]\right) + \beta_3 \left(\mathrm{Tr}\left[\phi \varDelta_{\mathrm{R}} \tilde{\phi}^\dagger \varDelta_{L}^\dagger\right] + \mathrm{Tr}\left[\phi^\dagger \varDelta_{\mathrm{L}} \tilde{\phi} \varDelta_{\mathrm{R}}^\dagger\right]\right) ,
\end{aligned}
\tag{1}
$$

in the notation of [22] for the bi-doublet ϕ and the triplets $\Delta_{\mathrm{L,R}}$. All the physical states come from the diagonalization of the Hessian of (1) [27]. For our discussion here, it is enough to introduce the masses of the SM-like and new Higgs bosons, together with their mixing, and the flavor changing (FC) [31] scalar (pseudo-scalar) masses

$$m_h^2 = \left(4\lambda_1 - \alpha_1^2/\rho_1\right) k^2\,; \quad m_{\Delta_{\mathrm{R}}}^2 = 4\rho_1 v_{\mathrm{R}}^2\,; \quad \theta = \frac{\alpha_1}{2\rho_1}\frac{k}{v_{\mathrm{R}}}\,; \quad m_{\mathrm{FC}}^2 = \alpha_3 v_{\mathrm{R}}^2\,, \tag{2}$$

with k, v_{R} the electro-weak and RH scale vacuum expected values (VEVs) respectively. We neglect the electro-weak corrections to heavy states in (2). The VEVs are parameterized in such a way that the RH gauge boson gets a mass $M_{W_{\mathrm{R}}} = g v_{\mathrm{R}}$. The mixing θ is constrained to be less of 40% at 2-sigma C.L. [32].

1.1. The constraints

The high predictivity of the model reflects directly to several constraints coming from low energy processes as meson oscillations, ϵ' and electric dipole moment of the neutron (nEDM) [22, 23, 25, 26]. As a result, the parameter space is delineated, showing where LNV processes are either favored or disfavored for a given RH scale. In reference [25], a lowest RH scale is estimated from the B-meson oscillations. All the possible tree-level and 1-loop contributions to meson oscillations, involving W_{R} and the FC scalar, lead to a gauge, independent amplitude to be matched with the observable. The authors surprisingly show that the bound coming from the B-meson oscillations is more stringent than the one from kaon oscillations. Quantitatively, this translates to $M_{W_{\mathrm{R}}} \geq 3$ TeV for a $m_{\mathrm{FC}} \geq 20$ TeV. At this purpose, a numerical computation of RH quark mixing, predictable within the model, is performed. Recently, an analytic solution for the RH quark mixing was found in [33]. For a low RH scale order ~ 3 TeV, the CP-violating parameters ϵ, ϵ' can be accommodated for a reasonable choice of the spontaneous phase in the model. Finally, all may be merged with the constraint due to nEDM, as shown in [26]. After a re-evaluation of the chiral loops generating nEDM in a self-consistent power counting scheme, the authors show that no bound emerges on $M_{W_{\mathrm{R}}}$ (without taking into account the strong CP problem [26]). From the previous analyses, however, a possible tension arises in the parameter space of low scale LRSM: the requirement of a heavy m_{FC} from B-oscillations leads to a large α_3, as clear in (2). This in turn could bring to perturbativity problem in the scalar sector. A detailed analysis will be presented in [27]. Here, it is worth to point out that perturbative limits emerge on the coupling constants of the potential, between the masses of the new Higgs boson ($\varDelta_{\rm R}$) with its associate gauge boson $W_{\rm R}$, as well as the Higgs bosons mixing θ in (2). As a consequence, a large mixing between the two Higgs bosons is possible even if the second one (together with $W_{\rm R}$) is fairly large. In that case, such a mixing could rise as the only way to probe the origin of the neutrino masses at the LHC.

1.2. Probing the neutrino masses

The new Higgs boson provides a Majorana mass for the RH neutrino (N) $M_N = 2y_\varDelta v_{\rm R}$, via the Yukawa Lagrangian $\mathcal{L}_{\rm Yukawa} = y_\varDelta \bar{L}_{\rm R} \varDelta_{\rm R}^\dagger \sigma_2 L_{\rm R}^c + ({\rm R} \leftrightarrow {\rm L}) + {\rm h.c.}$, with $L_{\rm L,R}$ the left and right doublet of leptons. By meaning of Higgs mechanism, therefore, we have $\varGamma_{\varDelta_{\rm R}} \to NN \sim y_\varDelta^2$. However, if the mixing θ is non-null, even the SM-like Higgs boson can decay to N, N. The relative decay, normalized to the leading SM channel $h \to \bar{b}b$, is at tree level [34]:

$$\frac{\varGamma_{NN}}{\varGamma_{b\bar{b}}} \simeq \frac{\tan\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_{\rm R}}}\right)^2\left(1-\frac{4m_N^2}{m_h^2}\right)^{\frac{3}{2}} . \tag{3}$$

In turn, N will decay to a lepton plus jets, with a decay length estimable in this portion of parameter space [16] as

$$\left(c\,\tau_N^0\right)^{-1} \simeq \frac{G_{\rm F}^2 m_N^5}{16\pi^3}\left(\frac{M_W}{M_{W_{\rm R}}}\right)^4 \tag{4}$$

providing a displacement of N decay products. Thanks to the Majorana nature of N, 50% of the produced h decay to the same sign di-lepton: $h \to NN \to ll + 4$ jets. This conceptually provides a self-contained picture to probe the origin of neutrino masses: from (3) one can constrain $\theta \times y_\varDelta$; from the displacement vertex in (4) one can constrain $M_{W_{\rm R}}$; from the invariant mass reconstruction of N decay products, one can measure m_N; finally, from a global fit of Higgs data, one can constrain independently θ [34]. As shown in [34] and in [18], the full collider analysis of $h \to \mu\mu + 4$ jets leads to a surprisingly high sensitivity at the LHC, able to probe the parity restoration and the origin of neutrino masses up to 20 TeV. Although surprising, such a result in not completely unexpected since the effectiveness of the displaced vertices in (4), which shows an efficient displacement for a large $M_{W_{\rm R}}$.

2. Summary

We presented the LRSM model as a complete theory for the origin of neutrino masses. After an overview on the theoretical constraints on the model, due to low energy processes and perturbativity, we delineate the parameter space of LRSM, pointing out an intriguing LNV channel in Higgs decay to the same sign leptons. We stress that such a process could probe neutrino masses and parity restoration even beyond complementary direct searches.

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