Mirror matter, inverse seesaw neutrino masses and the Higgs mass spectrum

M. M. Candido, Y. A. Coutinho, P. C. Malta, J. A. Martins Simões, A. J. Ramalho∗
Instituto de Física–Universidade Federal do Rio de Janeiro
Av. Athos da Silveira Ramos 149
Rio de Janeiro - RJ, 21941-972, Brazil

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In this work we study a mirror model with inverse seesaw neutrino masses in which symmetry breaking scales are fixed from bounds in the neutrino sector. The Higgs sector of the model has two doublets and neutral singlets. The mirror model can be tested at the LHC energies in several aspects. Two very distinctive signatures of the mirror model are a new neutral gauge boson $Z'$, with a high invisible branching ratio, and a heavy Majorana neutrino production through the decay $Z' \rightarrow N + \bar{\nu}$. This result is compared with heavy Majorana production through heavy pair production and the consequent same-sign dilepton production. The other important consequence of the mirror model is the prediction of the Higgs mass. A particular solution leads to a Higgs in the same region as in the standard model. There is, however, another natural solution where the Higgs mass is above 400 GeV.

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I. INTRODUCTION

Progress in neutrino oscillation experiments gradually confirms that neutrinos are massive and oscillate [1]. However, the theoretical understanding of the origin of the mixing pattern and the smallness of neutrino masses has not yet been settled. Many suggestions on possible models for neutrino mixing and masses have been made. For example, the T2K data [2] on $\sin^2 2\theta_{13} > 0$ has motivated models on discrete flavor groups and corrections to the original tri-bimaximal mixing [3]. The MiniBooNE antineutrino data [4] has renewed the interest on sterile neutrinos [5] and extra Higgs doublets can also be a source of new neutrino properties [6].

Neutrino masses and oscillations seem to require new physical scales that are not present in the standard model (SM). There are at least three new scales involved: the neutrino mass scale, the lepton number violation scale and the parity breaking scale. All these scales enter in one of the most appealing extensions of the SM, the left-right symmetric models [7]. These models start from the simple gauge structure of $SU(2)_L \otimes SU(2)_R \otimes U(1)$ and can, hopefully, be tested at the LHC energies. Parity can be broken at the $SU(2)_R$ scale. But it can also be broken by a neutral singlet sector, as in the D-parity mechanism developed by Chang, Mohapatra and Parida [8]. Small neutrino masses can be generated by the seesaw mechanism. In this case, lepton number violation is introduced by Majorana terms at very high (GUT) energies. An alternative is the inverse seesaw mechanism [9].

In the original version of the inverse seesaw mechanism, a new left-handed neutrino singlet is introduced. If one imposes lepton number conservation in this sector, there are no Majorana mass terms. A new right-handed neutral fermion singlet is also present and it is allowed to violate lepton number at a very small scale. This small scale is responsible for the small neutrino mass. In this scenario no ultrahigh breaking scale is introduced.

From another point of view, mirror models have recently [10] been studied and it was shown that three additional mirror families are consistent with the standard model if one additional inert Higgs doublet is included.

This paper is organized as follows: in Section II we summarize the scalar content of the model. In Section III we present the fundamental fermionic representation of the model. In Section IV we discuss the gauge interactions and identify the neutrino fields and new $Z'$ interactions. In Section V we present the model predictions for the LHC energies. Finally we summarize the model and its phenomenological consequences in Section VI.

II. THE HIGGS SCALARS

The fundamental scalar representation in our mirror model contains the following Higgs scalars: two doublets $\Phi_L$ and $\Phi_R$, which develop the vacuum expectation values $v_L$ and $v_R$ respectively,

$$
\Phi_L = \begin{pmatrix} \phi^+_L \\ \phi^0_L \end{pmatrix}, \quad \Phi_R = \begin{pmatrix} \phi^+_R \\ \phi^0_R \end{pmatrix},
$$

(1)
where

$$
\Phi_R \overset{D}{\leftrightarrow} \Phi_L
$$

with transformation properties under $SU(2)_L \times SU(2)_R \times U(1)_Y$ given by $(1/2,0,1)_{\phi_L}, (0,1/2,1)_{\phi_R}$. The singlet fields of the model are $S_M$, which develops a v.e.v. at a very small scale and is coupled with Majorana mass terms, and $M_{NL}, M_{NR}$, which must couple to lepton number conserving terms (Dirac) at a TeV scale.

For the lepton number violating singlet we impose the symmetry,

$$
S_M \overset{D}{\leftrightarrow} S_M
$$

and for the lepton number conserving singlets,

$$
M_{NL} \overset{D}{\leftrightarrow} -M_{NR}.
$$

These scalar fields will develop vacuum expectation

values according to

$$
\phi_L, \phi_R, S_M, M_{NL}, M_{NR} \overset{v.e.v.}{\leftrightarrow} v_L, v_R, s, v_{ML}, v_{MR}.
$$

The motivation behind these symmetries is to generate a simple spectrum for the neutrino sector (see section III). The $\phi_L$ field will be broken at the same scale of the SM Higgs field $v_L = v_{\text{Fermi}}$. The new $v_R$ scale can be searched for at the LHC energies in the $1-10$ TeV range. The bound from neutrinoless double beta decay will imply (see section IV) that $v_{ML} > 1$ TeV and $v_{MR} > 10^5$ TeV. The $S_M$ singlet field will break lepton number at a small scale $s \simeq 1$ eV and will give small neutrino masses.

The most prominent feature of these expressions is the prediction for the squared-mass value that corresponds to the standard model Higgs. This result for the Higgs mass shows that mirror models have a clear difference with the standard model Higgs. The recent LHC experimental searches for the standard model Higgs have detected no positive signal. There are increasing data constraining some regions for the Higgs mass value [11]. According to the recent data from ATLAS [12] and CMS [13] collaborations, there still remains a first open window for the Higgs mass in the 116 – 145 GeV region.

The $\phi_{L,R}$ doublets will give masses to the gauge bosons of $SU(2)_{L,R}$ respectively. There will remain five neutral scalar Higgs fields in the model. It is straightforward, although lengthy, to find the constraint equations and Hessian matrix that guarantee the minimum conditions. They are explicitly given in the Appendix.

The approximate eigenvalues of the squared-mass matrix are given by

$$
M_1^2 = 8\lambda_1 s^2
$$
$$
M_2^2 \simeq 4 \left[ \lambda_4 (v_R^2 + v_L^2) - \sqrt{\lambda_3^2 (v_R^2 - v_L^2)^2 + \lambda_5^2 v_R^2 v_L^2} \right]
$$
$$
M_3^2 \simeq 4 \left[ \lambda_4 (v_R^2 + v_L^2) + \sqrt{\lambda_3^2 (v_R^2 - v_L^2)^2 + \lambda_5^2 v_R^2 v_L^2} \right]
$$
$$
M_4^2 \simeq \lambda_2 - |\lambda_3 - 6\lambda_2| |v_{3M_R}^2|
$$
$$
M_5^2 \simeq \lambda_2 - |\lambda_3 - 6\lambda_2| |v_{2M_R}^2|
$$

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III. NEUTRINOS IN THE MIRROR MODEL

The fundamental fermion representation for the first lepton family and its transformation under the discrete parity symmetry ($D$ parity) in the mirror model is given by

$$
\left( \begin{array}{c} \nu_L \\ e \end{array} \right)_L, \nu_R, e_R \overset{D}{\leftrightarrow} \left( \begin{array}{c} N \\ E \end{array} \right)_R, N_L, E_L,
$$

where the doublets transform under $SU(2)_L \times SU(2)_R \times U(1)_Y$ as $(1/2,0,-1)_L$, $(0,1/2,-1)_R$. The ATLAS and CMS collaborations also exclude with 95% C.L. the existence of a Higgs over most of the mass range from 145 to 466 GeV. A second open mass window $M_{Higgs} > 466$ GeV would imply the same values for $\lambda_i$, except for $\lambda_4 > 0.8$. 

This limits the free parameters of our invariant potential to the following region in parameter space:

$$
0 < \lambda_1 < 1 \\
0 < \lambda_2 < 1/2 \\
0 < \lambda_3 < 1 \\
0.05 < \lambda_4 < 0.56 \\
-1 < \lambda_5 < 1
$$

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where the doublets transform under $SU(2)_L \times SU(2)_R \times U(1)_Y$ as $(1/2,0,-1)_L$, $(0,1/2,-1)_R$.
In order to discuss the mass for the neutral fermion fields we start by considering the following Majorana fields coming from the fundamental mirror representation:

\[
\begin{align*}
\Psi_\nu & \equiv \nu_L + \nu_L^c & \Psi_N & \equiv N_L + N_L^c \\
\omega_\nu & \equiv \nu_R + \nu_R^c & \omega_N & \equiv N_R + N_R^c.
\end{align*}
\]

The doublets transform as \((1/2, 0, -1)_L, (0, 1/2, -1)_R\). Let us discuss the mass Lagrangian by showing explicitly the physical content of each term. The mirror mass Lagrangian coupled with the Higgs doublets is given by

\[
L_M^{(\text{mirror})} = \frac{1}{2} v_L [\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L^c + \overline{\nu}_L^c \nu_R^c + \overline{\nu}_R^c \nu_L] + \frac{1}{2} v_R [\overline{N}_L N_R + \overline{N}_R N_L^c + \overline{N}_L^c N_R^c + \overline{N}_R^c N_L].
\]

(6)

In this expression we have no Majorana mass terms that violate lepton number. In the Majorana field basis we have

\[
L_M^{(\text{mirror})} = \frac{1}{2} v_L [\overline{\nu}_L \omega_\nu + \overline{\omega}_\nu \Psi_\nu] + \frac{1}{2} v_R [\overline{\Psi}_N \omega_N + \overline{\omega}_N \Psi_N].
\]

(7)

As required by the inverse seesaw mechanism we must introduce a new neutral fermionic singlet (called "\(P^c\)).

As we are considering a parity conserving model both left and right handed components of this field must be present. We have a new Lagrangian mass term given by:

\[
L'_M = \frac{s}{2} [\overline{P}_L P_L^c + \overline{P}_R P_R^c + \overline{P}_L^c P_L + \overline{P}_R^c P_R] + v_{ML} \overline{\nu}_R \nu_L + \overline{\nu}_L \nu_R + v_{MR} \overline{N}_R N_L + \overline{N}_L N_R + v_{M} N_L^c N_R + v_{M}^c N_R^c N_L.
\]

(9)

We have now new Majorana fields,

\[
\epsilon \equiv P_L + P_L^c \quad \sigma = P_R + P_R^c,
\]

and these terms give a new contribution to the mass Lagrangian,

\[
L'_M = \frac{s}{2} [\epsilon \sigma + \overline{\epsilon} \overline{\sigma} + \overline{\epsilon} \overline{\sigma} + \epsilon \sigma] + v_{ML} [\overline{\omega}_\nu \epsilon + \overline{\epsilon} \omega_\nu] - v_{MR} [\overline{\Psi}_N \epsilon + \overline{\epsilon} \Psi_N].
\]

(11)

Returning now to the Majorana basis, the full mass Lagrangian can be written as

\[
\mathcal{L}_{\text{mass}} = \left( \begin{array}{cccc}
0 & v_L/2 & 0 & 0 \\
v_L/2 & 0 & v_{ML} & 0 \\
0 & v_{ML} & s/2 & 0 \\
0 & v_{ML} & 0 & 0
\end{array} \right) \left( \begin{array}{c}
\overline{\Psi}_\nu \\
\tilde{\omega}_\nu \\
\epsilon \\
\Psi_N
\end{array} \right).
\]

This last matrix has two blocks in the inverse seesaw form,

\[
M = \left( \begin{array}{ccc}
0 & v & 0 \\
v & 0 & M \\
0 & M & s
\end{array} \right).
\]

As \(s\) will be responsible for the very small neutrino masses, it must have a very small value. Then the general mass matrix, to first order, has two independent inverse seesaw blocks.

The diagonalization of the mass matrix, to first order,
From equation (18), the neutral gauge bosons general gauge structure of our model was developed in ref. [14]. From equation (18) of ref. [14], the neutral current interactions. The relevant combination for the $Z^0$ interaction comes from equation (19) of ref. [14], all other neutrino states have no gauge interactions as they are neutral singlets.

\[
\mathcal{L}_{NC} = -\frac{g_L}{2 \cos \theta_W} [\bar{\Psi}_\nu \gamma^\mu (1 - \gamma^5) \Psi_\nu] Z_\mu - \frac{g_Z}{2} \tan \theta_W \tan \beta [\bar{\Psi}_\nu \gamma^\mu (1 - \gamma^5) \Psi_\nu + \frac{1}{\sin^2 \beta} \omega \gamma^\mu (1 + \gamma^5) \omega] Z'_\mu.
\]

As the $\Psi_\nu$ field is given by

\[
\Psi_\nu = \sqrt{2} \left[ s_L \Psi_1 + c_L \Psi_5 \right],
\]

the relevant combination for the $Z$ interaction comes from

\[
\bar{\Psi}_\nu \Psi_\nu = \frac{1}{2} [s_L^2 \bar{\Psi}_1 \Psi_1 + \bar{\Psi}_3 \Psi_3 + c_L^2 \bar{\Psi}_5 \Psi_5 + s_L \bar{\Psi}_1 \Psi_3 - s_L c_L \bar{\Psi}_1 \Psi_5 - c_L \bar{\Psi}_3 \Psi_5].
\]

IV. THE GAUGE INTERACTIONS

In order to proceed to the neutrino identification we must look at the neutral current interactions. The general gauge structure of our model was developed in ref. [14]. From equation (18), the neutral gauge bosons $Z$ and $Z'$ interact only with $\nu_L$ and $N_R$. All other neutrino states have no gauge interactions as they are neutral singlets.

Neglecting $\omega^2$ terms, in the Majorana basis this is given by equation (19) of ref. [14],

\[
\Psi_1 = \begin{pmatrix} \sqrt{s_L} & 0 & -\sqrt{s_L} & 0 \\ 0 & \sqrt{s_L} & 0 & -\sqrt{s_L} \\ -\sqrt{s_L} & 0 & \sqrt{s_L} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

\[
\Psi_2 = \begin{pmatrix} \sqrt{s_L} & 0 & -\sqrt{s_L} & 0 \\ 0 & \sqrt{s_L} & 0 & -\sqrt{s_L} \\ -\sqrt{s_L} & 0 & \sqrt{s_L} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

\[
\Psi_3 = \begin{pmatrix} c_L & 0 & -s_L c_L \frac{R_L}{R_R} & 0 \\ 0 & c_R & 0 & -s_R \frac{R_L}{R_R} \\ -s_L c_L \frac{R_L}{R_R} & 0 & -s_R \frac{R_L}{R_R} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

\[
\Psi_4 = \begin{pmatrix} \sqrt{s_R} & 0 & -\sqrt{s_R} & 0 \\ 0 & \sqrt{s_R} & 0 & -\sqrt{s_R} \\ -\sqrt{s_R} & 0 & \sqrt{s_R} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

\[
\Psi_5 = \begin{pmatrix} \sqrt{s_R} & 0 & -\sqrt{s_R} & 0 \\ 0 & \sqrt{s_R} & 0 & -\sqrt{s_R} \\ -\sqrt{s_R} & 0 & \sqrt{s_R} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

\[
\Psi_6 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ -c_R & 0 & 0 & 0 \\ -s_R & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},
\]

The diagonalization matrix can be written as:

\[
U = \begin{pmatrix} \sqrt{s_L} & \sqrt{s_L} & -c_L & 0 \\ 0 & 0 & 0 & 0 \\ \sqrt{s_L} & -\sqrt{s_L} & -s_L c_L \frac{R_L}{R_R} & 0 \\ 0 & 0 & 0 & 0 \\ -\sqrt{s_L} c_L & 0 & s_L & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\sqrt{s_L} c_L & 0 & s_L & 0 \end{pmatrix}.
\]
Hence, the $Z$ full coupling is given by the light $Ψ_3$ state. This state is to be identified with the SM neutrino. There is no (light-light) $Ψ_3 - Ψ_6$ mixing and the $Z$ width is the same as in the SM. As $Ψ_5$ is the heaviest state, we will have the leading terms:

$$\bar{Ψ}_L Ψ_ν \simeq \frac{1}{2} [\bar{Ψ}_3 Ψ_3 + s_L \bar{Ψ}_1 Ψ_3].$$

The $Z'$ interaction involves the $ω_N$ state as

$$ω_N = \frac{\sqrt{2}}{2} [Ψ_1 s_L - Ψ_3 - c_L Ψ_5],$$

and we have

$$\bar{ω}_N ω_N \rightarrow \frac{1}{2} [s_L^2 Ψ_1 Ψ_1 + Ψ_3 Ψ_3 + c_L^2 Ψ_5 Ψ_5] - s_L Ψ_1 Ψ_3 - s_L c_L Ψ_1 Ψ_5 + c_L Ψ_3 Ψ_5].$$

The leading terms are

$$\bar{ω}_N ω_N \simeq \frac{1}{2} [Ψ_3 Ψ_3 - s_L \bar{Ψ}_1 Ψ_3].$$

So the new $Z'$ will decay in the light state $Z' \rightarrow \bar{ν}_3 ν_3$ but with a coupling much larger than that of SM case. The $Z'ν_3 ν_3$ vertex is given by

$$Z'ν_3 ν_3 \simeq \frac{g_L}{2} \tan θ_W \tan β (1 + \frac{1}{\sin^2 β}).$$

We also have the interaction vertex

$$Z'ν_1 ν_3 \simeq \frac{g_L}{2} \tan θ_W \tan β (1 - \frac{1}{\sin^2 β}),$$

and this term can also be quite large.

The charged current interaction is given by

$$L_{c,NW} = \frac{g}{2\sqrt{2}} \bar{ν}_μ ν_μ W_μ = \frac{g}{2\sqrt{2}} \bar{Ψ}_L ν_μ [Ψ_1 + Ψ_3 + c_L Ψ_5] W_μ, \quad (16)$$

where $Ψ_3$ is the SM neutrino state.

From neutrinoless double $β$ decay ($0νββ$) we have the experimental bound $^{17}$

$$\frac{\sin^2 θ_{c,NW}}{M_N} < 5 \times 10^{-8} \text{ GeV}^{-1}.$$

For the first heavy neutrino ($Ψ_1$) we obtain the bound

$$\frac{v_L^2}{v_L^2 + v_{M_L}^2} \frac{1}{\sqrt{v_L^2 + v_{M_L}^2}} \simeq \frac{v_L^2}{v_{M_L}^2} < 5 \times 10^{-8} \text{ GeV}^{-1},$$

which implies $v_{M_L} > 1 - 10 \text{ TeV}$. This uncertainty comes from the absorption of coupling constants in the definition of our $v_i$. If we let the corresponding couplings vary in the range $g_i \simeq 0.1 - 1$, then the preceding result follows.

For the second heavy neutrino ($Ψ_5$) we have

$$\frac{v_{M_6}^2}{v_L^2 + v_{M_r}^2} \frac{1}{\sqrt{v_L^2 + v_{M_r}^2}} \simeq \frac{1}{v_{M_r}} < 5 \times 10^{-8} \text{ GeV}^{-1},$$

so that $v_{M_r} \simeq 10^5 \text{ TeV}$.

It is a remarkable result that from neutrino bounds we have recovered the Peccei-Quinn scale related to the strong CP problem $^{10}$. With the identification $Ψ_3 \rightarrow Ψ_ν$ and $Ψ_1 \rightarrow Ψ_N$, the leading new $Z'$ interaction with neutrinos is

$$L_{NC} = - \frac{g_L \tan θ_W \tan β}{4} \{ \bar{Ψ}_ν γ^μ [g_ν - g_ν γ^5] Ψ_ν + s_L \bar{Ψ}_ν γ^μ [g_ν - g_ν γ^5] Ψ_N + h.c. \} Z_μ \quad (17)$$

where

$$g_ν = 1 - \frac{1}{\sin^2 β} \quad \text{and} \quad g_A = 1 + \frac{1}{\sin^2 β}.$$

From the preceding relations the $Z'N N$ vertex is suppressed by an $s_L^2$ factor.

**V. RESULTS**

In this section we present the main phenomenological consequences of our model for the LHC. Although many extended models predict a new $Z'$, it is a very distinctive property of mirror models that the invisible $Z'$ channel will be very high. In Table I we show the branching ratios for the $M_{Z'} = 1.5 \text{ TeV}$ with $Γ_{Z'} \simeq 25 \text{ GeV}$ considering $v_{M_L} = 1 - 10 \text{ TeV}$. The heavy neutrino channels are strongly dependent on the choice of $v_{M_L}$.

The clearest signal for a new $Z'$ will be the leptonic channel $p + p \rightarrow t^- + l^- + X$. The recent LHC searches for this process have not detected any evidence of a new $Z'$ boson. For instance, the ATLAS Collaboration $^{17}$ with a luminosity around 1 fb$^{-1}$ sets a lower bound $M_{Z'} > 1.83 \text{ TeV}$ on the mass of a new sequential heavy $Z'$. Using the package CompHep $^{18}$ with CTEQL1 parton distribution functions, we have estimated the corresponding bound on the mass of the mirror $Z'$ boson. Applying a set of cuts on the final leptons, namely, $|y| < 2.5$, $M_{Z'} - 5Γ_{Z'} < M_{t^-} < M_{Z'} + 5Γ_{Z'}$, and an energy cut of $E_T > 25 \text{ GeV}$, we display in Figure 1a the total cross section and number of events for $√s = 7 \text{ TeV}$ and an integrated luminosity of 10 fb$^{-1}$. The negative result of the ATLAS search leads, therefore, to a bound $M_{Z'} > 1.5 \text{ TeV}$ on the $Z'$ mass in our model. The forthcoming luminosity of 10 fb$^{-1}$ will allow the search for this $Z'$ to be extended up to $M_{Z'} = 2.0 \text{ TeV}$. In Figure 1b we show our results for a center of mass energy of 14 TeV and an
FIG. 1: Total cross section and number of events versus $M_{Z'}$ in the process $p + p \rightarrow l^+ + l^- + X$ at $\sqrt{s} = 7$ TeV considering $\mathcal{L} = 10$ fb$^{-1}$ (up) and at $\sqrt{s} = 14$ TeV considering $\mathcal{L} = 100$ fb$^{-1}$ (down).

FIG. 2: Total cross section and number of events versus $M_N$ in the process $p + p \rightarrow N + \bar{\nu}_i + X$ at $\sqrt{s} = 7$ TeV considering $\mathcal{L} = 10$ fb$^{-1}$ (up) and at $\sqrt{s} = 14$ TeV considering $\mathcal{L} = 100$ fb$^{-1}$ (down).

For higher masses the dominant mechanism is via $Z'$ exchange. From Figure 2 we can estimate the heavy neutrino mass dependence at the energy of $\sqrt{s} = 7$ TeV produced via $Z'$ with mass equal to 2.0 TeV. The scenario of $\sqrt{s} = 14$ TeV allows us to estimate the $M_N$ behavior from 500 GeV to 2 TeV, with $Z'$ masses varying from 1.5 TeV to 3.0 TeV.

VI. CONCLUSIONS

In this paper we have presented a mirror model that restores parity at high energies. Neutrino masses are generated by the inverse seesaw mechanism. Besides new mirror fermions, the model also predicts new gauge vector bosons. Our choice of a scalar sector with Higgs doublets and singlets and no Higgs bidoublets means that the new charged vector bosons will not be coupled with ordinary matter in the mirror model at tree level. This points to a significant difference between the present model and
other left-right models with new \( \nu_R \) neutrinos in new \( SU(2)_R \) doublets. But mixing in the neutral vector boson sector is present and the first important phenomenological consequence of the model is a new neutral current. As the new v.e.v. \( v_R \) is not known, we cannot determine exactly the new \( Z' \) mass. But the LHC can test the hypothesis that \( v_R \) is of the order of a few TeV. The new \( Z' \) mixing with the other neutral gauge bosons can be calculated \cite{21} and we can determine both the main decay channels and production rates for this new \( Z' \).

The heavy Majorana neutrino production can be used as a test for the basic neutrino mass generation mechanism. In the double seesaw mechanism we have the dominant channel \( Z' \to N + \bar{N} \) and the consequent same-sign dilepton production, whereas for the inverse seesaw mechanism the dominant channel is \( Z' \to N + \nu \).

The other important prediction of our mirror model comes from the fact that we have fixed the symmetry breaking scales only from the neutrino sector; therefore, the Higgs spectrum can be fixed according to the recent LHC bounds. The two main mass windows for the SM Higgs mass in the \( 116 - 145 \) GeV and above \( 466 \) GeV can be fixed by natural choices of the coupling constants of the scalar potential, in the range \((-1, 1)\).

### Appendix A: Mass Matrix

The following five relations correspond to the necessary potential minimum conditions:

\[
\begin{align*}
4s^3\lambda_1 - 2s\mu_1^2 &= 0 \\
2v_L(v_{ML} - v_{MR})\mu_5 - 2v_Lv_R^2\lambda_3 + 4v_R^2\lambda_4 &= 0 \\
-2(v_{ML} - v_{MR}v_H \mu_5 - 2v_Rv_L^2\lambda_5 + 4v_T^2\lambda_4 &= 0 \\
(v_R^2 - v_L^2)\mu_5 + v_{ML}^2\mu_3^2 - 2v_{ML}v_{MR}^2\lambda_3 + 4v_{ML}^2\lambda_2 &= 0 \\
-(v_R^2 - v_L^2)\mu_5 + v_{ML}^2\mu_3^2 - 2v_{MR}v_{ML}^2\lambda_3 + 4v_{ML}^2\lambda_2 &= 0
\end{align*}
\]

In the basis \( \{S_M, \phi_L, \phi_R, M_{NL}, M_{NR}\} \) the squared-mass matrix is given by

\[
M_{a,\beta}^2 = \frac{\partial^2 V}{\partial \Phi_a \partial \Phi_\beta}.
\]

By using the constraints above to express the \( \mu_i \) parameters in terms of the v.e.v \( v_i \), we arrive at the following matrix:

\[
M^2 = \begin{pmatrix}
4s_3^2\lambda_1 & 0 & 0 & 0 & 0 \\
0 & 8s_3^2\lambda_4 & 4v_Lv_R\lambda_4 & -v_L\Delta_1 & -v_R\Delta_1 \\
0 & 4v_Lv_R\lambda_4 & 8s_3^2\lambda_4 & 0 & -v_R\Delta_1 \\
0 & v_L\Delta_1 & -v_R\Delta_1 & \Delta_2 + 2\Delta_2^\prime (2\lambda_2 - \lambda_3) - 8s_3^2\lambda_2 & \Delta_2 + 2\Delta_2^\prime (2\lambda_2 - \lambda_3) - 8s_3^2\lambda_2 \\
0 & -v_L\Delta_1 & v_R\Delta_1 & \Delta_2 + 2\Delta_2^\prime (2\lambda_2 - \lambda_3) - 8s_3^2\lambda_2 & \Delta_2 + 2\Delta_2^\prime (2\lambda_2 - \lambda_3) - 8s_3^2\lambda_2
\end{pmatrix},
\]

with the definitions,

\[
\Delta_1 = \frac{(v_R^2 - v_L^2)(\lambda_5 - 2\lambda_4)}{(v_{MR} - v_{ML})} \quad \text{and} \quad \Delta_2 = \frac{(v_R^2 - v_L^2)^2(\lambda_5 - 2\lambda_4)}{2(v_{MR} - v_{ML})^2}.
\]

The previous results can be approximated in the limits \( \Delta_1 \to 0 \) and \( \Delta_2 \to 0 \). In all our results, no fine-tuning conditions are imposed on the scalar potential.

| \( v_{ML} \) (TeV) | \( Z' \to \sum_{i=1}^3 \bar{\nu}_i \nu_i \) | \( Z' \to \sum_{i=1}^3 \bar{l}_i l_i \) | \( Z' \to \bar{N}N \) | \( Z' \to \sum_{i=1}^6 \bar{q}_i q_i \) | \( Z' \to \sum_{i=1}^3 (\bar{\nu}_i N + \bar{N}\nu_i) \) |
|---|---|---|---|---|---|
| 1 | 60% | 15.9% | < 10^{-3}\% | 23.2% | 1.9% |
| 10 | 60% | 16.2% | < 10^{-6}\% | 23.6% | 0.02% |

**TABLE I:** The \( Z' \) branching-ratios for \( M_{Z'} = 1.5 \) TeV for \( v_{ML} = 1 \) TeV and 10 TeV.

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