Signatures for Right-Handed Neutrinos at the Large Hadron Collider

Katri Huitu,[1] Shaaban Khalil,[2,3] Hiroshi Okada,[2] and Santosh Kumar Rai[1]

[1]*Department of Physics, University of Helsinki and Helsinki Institute of Physics, P.O. Box 64, FIN-00014 University of Helsinki, Finland*

[2]*Centre for Theoretical Physics, The British University in Egypt, El Sherouk City, Postal No, 11837, P.O. Box 43, Egypt*

[3]*Department of Mathematics, Ain Shams University, Faculty of Science, Cairo, 11566, Egypt*

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We explore possible signatures for right-handed neutrinos in a TeV scale $B-L$ extension of the standard model at the Large Hadron Collider. The studied four lepton signal has a tiny standard model background. We find the signal experimentally accessible at the LHC for the considered parameter regions.

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The fact that neutrinos have mass indicates firm evidence of new physics beyond the standard model (SM). The most attractive mechanism that can naturally account for the small neutrino masses is the seesaw mechanism. In this case, three heavy singlet (right-handed) neutrinos ν_{R_i} are invoked. Recently, a low scale $B-L$ symmetry breaking has been considered, based on the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$ [1]. This model provides a natural explanation for the presence of three right-handed neutrinos and can account for the current experimental results of the light neutrino masses and their mixings [2].

In the $B-L$ extension of the SM, the right-handed neutrinos acquire the following masses after the symmetry breaking: $M_{\nu_{R_i}} = (1/\sqrt{2})\lambda_{\nu_{R_i}} v'$, where v' is the scale of $B-L$ breaking. Similar to the electroweak symmetry, the scale of $B-L$ can be linked to the supersymmetry breaking scale at the observed sector, with the $B-L$ symmetry radiatively broken at the TeV scale [3]. Thus, the right-handed neutrino mass can be of order $\mathcal{O}(100)$ GeV, depending on the value of the Yukawa couplings λ_{ν_R} which augurs well for its direct search at the Large Hadron Collider. In addition, one extra neutral gauge boson (Z') corresponding to $B-L$ gauge symmetry is predicted in this type of model. This gauge boson couples to both the SM fermions and the right-handed neutrinos through the nonvanishing $B-L$ quantum numbers and gives the dominant contribution to the production of the right-handed neutrino at the LHC. It is worth noting that, in the SM extended with right-handed neutrinos, this production at the LHC [4], is mainly through the exchange of W boson and is thus suppressed by the small mixing between light and heavy neutrinos.

The aim of this Letter is to analyze the LHC discovery potential for the lightest right-handed neutrino in a TeV scale $B-L$ extension of the SM. We provide a detailed phenomenological analysis for such a neutrino and show that the right-handed neutrinos are accessible via a clean signal at the LHC. Our results indicate that observation of ν_R signals at the LHC would significantly distinguish between a TeV scale $B-L$ extension of the SM and other scenarios for SM extended with right-handed neutrinos.

In the minimal version of the $B-L$-type extension of the SM, the interactions between right-handed neutrino and matter fields are described by the Lagrangian

$$\mathcal{L}_{\nu_R} = i\bar{\nu}_R D_\mu \gamma^\mu \nu_R - (\lambda_\nu \bar{l}\tilde{\phi}\nu_R + \tfrac{1}{2}\lambda_{\nu_R}\bar{\nu}_R^c \chi \nu_R + \text{H.c.}) - V(\phi,\chi), \quad (1)$$

where the covariant derivative D_μ is defined as $D_\mu \nu_R = (\partial_\mu - i g'' Y_{B-L} Z'_\mu)\nu_R$, where g'' is the $U(1)_{B-L}$ gauge coupling constant and Y_{B-L} is the corresponding $B-L$ charge. λ_ν and λ_{ν_R} refer to the 3×3 Yukawa matrices. The scalar potential $V(\phi,\chi)$ for the two scalars ϕ and χ is defined by [1]

$$V(\phi,\chi) = m_1^2 \phi^\dagger\phi + m_2^2 \chi^\dagger\chi + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\chi^\dagger\chi)^2 + \lambda_3(\phi^\dagger\phi)(\chi^\dagger\chi), \quad (2)$$

where $\lambda_3 > -2\sqrt{\lambda_1\lambda_2}$ and $\lambda_1, \lambda_2 \geq 0$ so that the potential is bounded from below. The field ϕ is the usual SM doublet, while χ is a SM singlet complex scalar field, responsible for the spontaneous breaking of the $B-L$ symmetry. After the breakdown of the $B-L$ and electroweak symmetry, mixings between ϕ and χ and also between ν_L and ν_R are generated. These mixings initiate new interactions between the right-handed neutrinos and the SM particles.

The mixing between the neutral scalar components of Higgs multiplets ϕ^0 and χ^0 leads to the following mass eigenstates, which we define as H (SM-like Higgs boson) and H' (heavy Higgs boson):

$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi^0 \\ \chi^0 \end{pmatrix}, \quad (3)$$

where α is the Higgs mixing angle which is given by [5]

$$\tan 2\alpha = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}, \quad (4)$$

while v and v' are the vacuum expectation values given to

ϕ and χ, respectively. On the other hand, the mixing between ν_L and ν_R can be represented by the following 6×6 mass matrix:

$$M(\nu_L, \nu_R) = \begin{pmatrix} \mathbf{0} & m_D^T \\ m_D & M_R \end{pmatrix}, \tag{5}$$

where $m_D \sim \lambda_\nu v$ is the Dirac mass term and $M_R \sim \lambda_{\nu_R} v'$ is the Majorana mass term for neutrinos. Therefore, the mass eigenstates ν_l (light neutrinos) and ν_h (heavy neutrinos) are given by

$$\begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} = \begin{pmatrix} U & -UV \\ V^T & \mathbf{1} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}. \tag{6}$$

Here the matrix U refers to a Maki-Nakagawa-Sakata mixing matrix in the light neutrino sector, and the matrix V is given by $V = m_D^T M_R^{-1}$. It is worth mentioning that the mass eigenstates in Eq. (6) are obtained by applying two successive rotations. The first one transforms the mass matrix $M(\nu_L, \nu_R)$ in Eq. (5) to diag$\{m_\nu^{\rm eff}, M_R\}$, where $m_\nu^{\rm eff} = m_D^T M_R^{-1} m_D$ which is diagonalized by the U matrix. We adopt the Dirac neutrino mass matrix m_D as found in Ref. [2] from the extended mass relations among the quark and lepton masses. In this example, m_D is a nonhierarchical matrix with entries of order 10^{-4} GeV. Since we assume that $M_{\nu_{R_1}} \ll M_{\nu_{R_2}} < M_{\nu_{R_3}}$, the resultant mixing matrix V is characterized by the following feature: $V_{11} \gg V_{1i}$ for $i = 2, 3$. Also the typical value of V_{11} is of order 10^{-6}. Although this mixing is rather small, it generates new coupling among the heavy neutrino, the weak gauge bosons W and Z, and the associated leptons. This new coupling plays an important role in the decays of the lightest heavy neutrino ($\nu_{h_1} \equiv N_1$).

Now we can express the relevant interactions that lead to dominant contributions to the production and decay of the lightest heavy neutrino N_1 at the LHC:

$$\begin{aligned} \mathcal{L}_I \sim & -g'' Z'_\mu [\bar{N}_1 \gamma^\mu N_1 + (UV)_{i1} \overline{(\nu_l)}_i \gamma^\mu N_1 + \text{H.c.}] \\ & + \frac{g_2}{2c_W} Z_\mu (UV)_{i1} \overline{(\nu_l)}_i \gamma^\mu N_1 \\ & + \frac{g_2}{\sqrt{2}} V_{i1} W_\mu^- l_i^+ \gamma^\mu N_1 + \text{H.c.}, \end{aligned} \tag{7}$$

where the family index $i = 1, 2, 3$. From this interaction Lagrangian, one finds that the dominant production mode for the heavy neutrino N_1 is through the exchange of the Z' gauge boson and the main decay channel is through the W gauge boson as shown in Fig. 1.

Some comments are in order: (i) In SM extended with right-handed neutrinos, there is no extra gauge boson, and hence the production of right-handed neutrinos may be obtained via the exchange of Z or W only with a suppression factor due to the mixing between light and heavy neutrinos. (ii) The decay modes for the N_1 depend on the Yukawa strength λ_ν and the mixing parameter V_{11}. Since both are of the order of 10^{-6} as pointed out earlier, we find that the most dominant decay modes are W^+e^- and $Z\nu_e$, with a small fraction into $H\nu_e$. In our analysis, we find that the BR$(N_1 \to W^+e^-)$ is always dominant, ranging between 0.65–0.89 while BR$(N_1 \to Z\nu_e)$ is 0.11–0.33 for $V_{11} \simeq 2 \times (\lambda_\nu = 10^{-6})$, for right-handed neutrino masses $M_N > 100$ GeV.

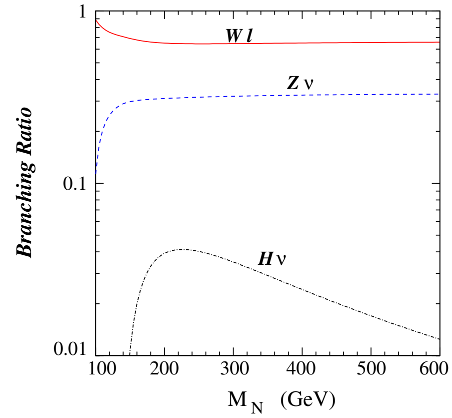

FIG. 1 (color online). The branching ratio for the various decay modes of the right-handed neutrinos.

As mentioned, the dominant production mode for the right-handed neutrinos at the LHC would be through the Drell-Yan mechanism, with Z' in the s channel. The new gauge quantum number associated with the $B - L$ symmetry couples the right-handed neutrinos directly to the gauge boson Z', as seen from the Lagrangian in Eq. (7). Thus the rate for the pair production of the heavy neutrinos would crucially depend on the mass of the Z' and the strength of the $B - L$ coupling g''. In Fig. 2, we plot the pair production cross section for a pair of right-handed neutrinos at the LHC, as a function of the right-handed neutrino mass (M_N) for three different choices of the Z' mass ($M_{Z'}$). The $B - L$ coupling and the Z' mass are chosen in such a way that they always respects the LEP bound [6]. Furthermore, the recent results by CDF II [7] are consistent with the LEP II constraints in the case of a $B - L$ extension of the SM, with a typical lower bound

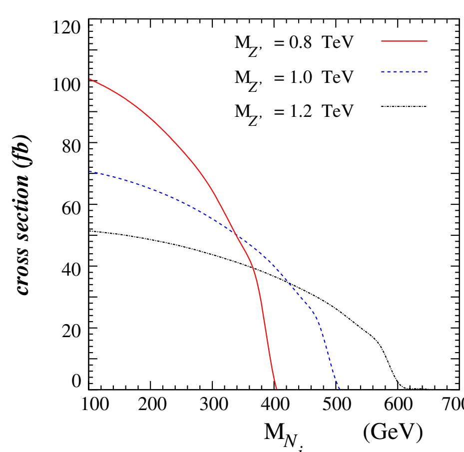

FIG. 2 (color online). Illustrating the pair production cross section for the right-handed neutrinos at the LHC.

$M_{Z'}/g'' > 6$ TeV. We choose benchmark points of the model for our analysis, as given below:

$$\lambda_1 = 0.15, \quad \lambda_2 = 0.02, \quad \lambda_3 = -0.001, \quad v = 246\,\text{GeV},$$
$$v' = 3\,\text{TeV}, \quad \lambda_\nu = 10^{-6}, \quad V_{11} = 2\times 10^{-6},$$
$$(g'', M_{Z'}) = (0.133, 800), (0.167, 1000), (0.2, 1200).$$

The production cross section is enhanced due to the resonant contribution from the Z' exchange in the s channel but falls rapidly with increasing right-handed neutrino mass. We now focus on the event rates for the most promising signal coming from the pair production of the right-handed neutrinos in this model. We choose two points from Fig. 2 to highlight the signal for the right-handed neutrinos at the LHC, viz. ($g'' = 0.133$, $M_{Z'} = 800$ GeV, $M_N = 200$ GeV) and ($g'' = 0.2$, $M_{Z'} = 1200$ GeV, $M_N = 400$ GeV). The right-handed neutrinos dominant decays are to a W boson and a charged lepton and to a left-handed neutrino and the Z boson, through the mixing parameter V_{ij}. These decays are very clean with four hard leptons in the final states and large missing energy due to the associated neutrinos. The SM background for such a final state is negligible at the LHC. The dominant processes in the SM come through $4W$ productions with $\sigma(4W) \sim 6$ fb [8], and the dominant contributions come from the three gauge boson WWZ productions at the LHC, with $\sigma(WWZ) \sim 200$ fb (including QCD corrections) [9]. However, because of the smallness of the pure leptonic branching ratios, the cross sections of the four lepton final states fall to $\mathcal{O}(10^{-4})$ fb and $\mathcal{O}(10^{-2})$ fb for the $4W$ and WWZ modes, respectively. This is rendered negligible once we demand the minimum acceptance cuts on the kinematic variables for our signal.

Depending on the production and decay mechanism, we can have the following final states as our signal:

$$l_i^+ l_j^- l_k^+ l_m^- + \not{E}_T + X,$$

where i, j, k, and m run over the three different lepton flavors. We put the following kinematic cuts when selecting the final states for our analysis: (a) For the charged leptons, $p_T^l > 20$ GeV and $|\eta| < 2.5$. (b) A minimum missing transverse energy (momentum) cut $\not{E}_T > 50$ GeV. (c) For resolving the different leptons in the detector, $\Delta R_{l_i l_j} \geq 0.2$ and a minimum cut on the invariant mass $M_{l_i^+ l_i^-} > 10$ GeV.

To calculate and generate the events, we include the relevant couplings of the model in CALCHEP 2.4.5 [10] and pass the generated events through the CalcHEP + Pythia interface. We have turned on the initial and final state radiation effects using the PYTHIA [11] switches. We use the leading order CTEQ6L [12] parton distribution functions for the protons colliding at the LHC. In Figs. 3 and 4, we plot the various kinematic distributions for the signal arising through

$$pp \to N_1 \bar{N}_1 \to e^+ e^- \mu^+ \mu^- \not{E}_T,$$

satisfying the above selection cuts. We choose an integrated luminosity of $\int \mathcal{L} dt = 300\ \text{fb}^{-1}$. As the dominant decay of N_1 is to the W boson and electron, the μ's would most often come from the Z decay, when one right-handed neutrino decays via the W mode and the other through the Z mode. Thus one expects a clear peak at M_Z, the mass of the Z boson in the $M_{\mu^+\mu^-}$ distribution as seen in Fig. 3(a). The invariant mass of the electrons is more wide as compared to the invariant mass of the muons. With the SM background completely reducible, this gives clear information on which neutrino flavor is produced in the pp collisions. Another interesting feature is seen in Fig. 3(b), where we plot the invariant mass of the different flavor leptons. A distinct kinematic edge is seen at $M_{e\mu} \simeq M_{N_1}$ which is mainly because of the large contributions coming from the dominant decay through the W boson, following the decay chain $N_1 \to eW^* \to e\mu\nu_\mu$. A more efficient way of identifying the edge would come if one selects an invariant mass window for ($M_Z - 10$ GeV $< M_{\mu^+\mu^-} < M_Z + 10$ GeV) and looks at the invariant distribution of $M_{e^+e^-}$. This would correspond to the scenario where the muon pairs always come from Z whereas the electron pairs come from the cascade of N_1. The $M_{e^+e^-}$ distribution would then show a clear sharp edge at M_{N_1} and thus give a very precise determination of the mass of the right-handed neutrino albeit we have a smaller event rate.

Figure 4(a) shows that the electrons coming from the primary decay of the right neutrino are much harder than the muons coming from the lighter weak gauge bosons. The missing p_T distribution in Fig. 4(b) represents the light neutrinos in the final state. With an integrated luminosity of 300 fb^{-1}, the expected number of events for the $4\ell \not{E}_T$ final states is 71 when $M_{N_1} = 200$ GeV and 46 when $M_{N_1} = 400$ GeV. The 4ℓ can be either $4e$, $3e1\mu$, $2e2\mu$, or $1e3\mu$ depending on the decays. However, even with an integrated luminosity of 30 fb^{-1}, we still expect 5–7 events for the above final state. This is quite an encouraging result where we have negligible SM background.

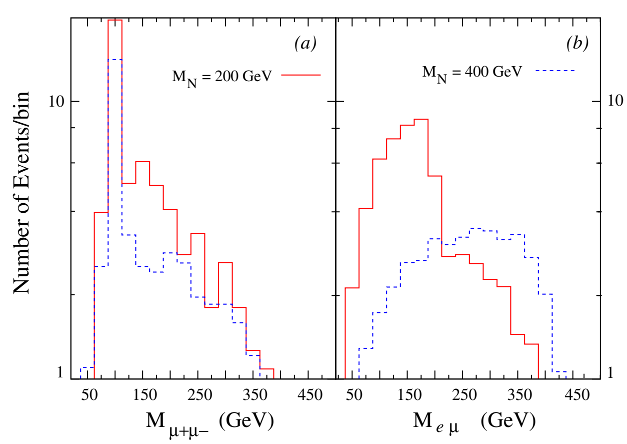

FIG. 3 (color online). Illustrating the binwise distribution in the invariant mass of the charged lepton pairs in the final state for two different N_1 masses: $M_N = 200$ GeV and $M_N = 400$ GeV.

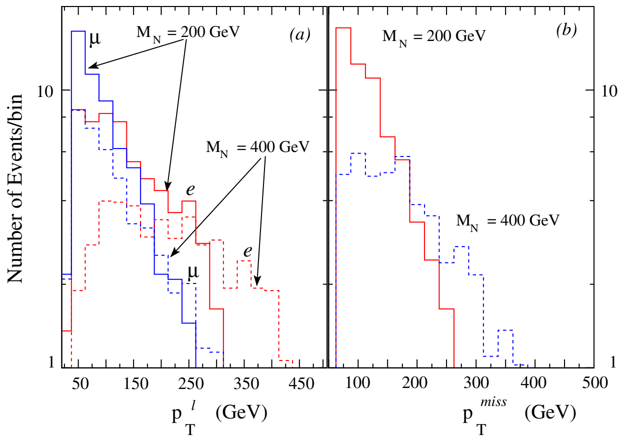

FIG. 4 (color online). Illustrating (a) the transverse momentum distribution for the different charged leptons and (b) the missing transverse momentum, for the $4l + \not{E}_T$ signal at the LHC for two different N_1 masses: $M_N = 200$ GeV and $M_N = 400$ GeV.

The situation gets more complicated if two flavors of the right-handed neutrinos are assumed to be degenerate in mass. Then one has the same final states for both N_1 and N_2 pair production with similar event rates. This would result in a loss of the clear correlation that existed between the different charged lepton flavors as shown in the various kinematic distributions, rendering it difficult to exploit the advantages which were perceivable in the invariant mass distributions. However, one advantage would be the doubling of the total number of events in the final state. Other promising signatures arise from the pair production of right-handed neutrinos in this model at the LHC, if the W and Z bosons were allowed to decay hadronically [13]. This would give $(3\ell + 2j + \not{E}_T)$ or $(2\ell + 4j)$ in the final state. Being a hadron machine, any final state with jets will have a large QCD background. However, with a selection window of 20 GeV around the weak gauge boson masses for the 2-jet invariant mass, one can reduce a large part of the SM background.

Finally, let us note that a $4\ell + \not{E}_T$ final state is possible also in other scenarios beyond the standard model, such as for, e.g., in supersymmetric theories [14]. The signal in supersymmetric theories can come from pair production of heavy neutralinos, heavy Higgs bosons [15] which can give comparable and even larger event rates when compared to our case. However, the invariant mass distribution for the charged lepton pairs can very effectively distinguish our scenario. The distinct kinematic edge seen in the $e - \mu$ distribution and the Z peak in the $\mu^+\mu^-$ distributions shown in Figs. 3(a) and 3(b), respectively, will not appear in the supersymmetric case, where the kinematic edge will be seen in the invariant mass distribution of the oppositely charged leptons of same flavor [14–16].

In this Letter, we have considered the TeV scale $B - L$ extension of the SM. We provided a comprehensive analysis for the phenomenology of the (heavy) right-handed neutrinos with $U(1)_{B-L}$ charge. We find that the production rate of the right-handed neutrinos is quite large over a significant range of parameter space. Searching for the right-handed neutrinos is accessible via a very clean signal at the LHC, with negligibly small SM background. We also find distinct correlations among the final state leptons coming from the decay of the lightest right-handed neutrinos.

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