PHYSICAL REVIEW D **81,** 035002 (2010)

Lepton flavor violation in supersymmetric $B - L$ extension of the standard model

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(Received 16 September 2009; published 1 February 2010)

Supersymmetric $B - L$ extension of the standard model (SM) is one of the best candidates for physics beyond the SM that accounts for the TeV scale seesaw mechanism and provides an attractive solution for the Higgs naturalness problem. We analyze the charged lepton flavor violation (LFV) in this class of models. We show that, due to the smallness of Dirac neutrino Yukawa coupling, the decay rates of $l_i \to l_j \gamma$ and $l_i \to 3l_j$, generated by the renormalization group evolution of soft supersymmetry breaking terms from GUT to seesaw scale, are quite suppressed. Therefore, this model is free from the stringent LFV constraints usually imposed on the supersymmetric seesaw model. We also demonstrate that the right sneutrino is a long-lived particle and can be pair produced at the LHC through the $B - L$ gauge boson. Then, they decay into a same-sign dilepton, with a total cross section of order $\mathcal{O}(1)$ pb. This signal is one of the striking signatures of supersymmetric $B - L$ extension of the SM.

DOI: 10.1103/PhysRevD.81.035002 PACS numbers: 12.60.Jv, 12.60.Cn

I. INTRODUCTION

If neutrinos were massless, the lepton flavor (LF) in the charged sector of the standard model (SM) would be conserved. The observed neutrino oscillations are evidences for neutrino masses, which may entail that lepton flavor is no longer conserved. Nevertheless, lepton flavor violation (LFV) is almost forbidden in the SM with massive neutrinos. The processes of charged LFV are suppressed by a tiny ratio of neutrino masses to the W-boson mass. For instance, the branching ratio of decay $\mu \to e\gamma$ is of order $10^{-43}(m_\nu/1\text{ eV})^4$, which is far from the experimental reach.

In fact, there is no fundamental reason that implies the conservation of LF in the SM. LF is an accidental symmetry at low energy, and it may be violated beyond the SM. Indeed, several SM extensions, like grand unified field theory (GUT), technicolor, and supersymmetry, indicate the possibility of large LFV. Therefore, a signal of LFV in charged lepton sector would be a clear hint for physics beyond the SM. The present experimental limits [1] are

$$\begin{aligned} \mathrm{BR}(\mu \to e\gamma) &< 1.2 \times 10^{-11}, \\ \mathrm{BR}(\tau \to \mu\gamma) &< 6.8 \times 10^{-8}, \\ \mathrm{BR}(\tau \to e\gamma) &< 1.1 \times 10^{-7}, \\ \mathrm{BR}(\mu \to 3e) &< 1.0 \times 10^{-12}. \end{aligned} \tag{1.1}$$

The MEG experiment at PSI [2] is expected to reach the limit of 10^{-13} for the branching ratio of $\mu \to e\gamma$ and $\mu \to 3e$ processes. This will be a very serious test for physics beyond the SM.

Supersymmetry is an attractive candidate for new physics at the TeV scale that provides an elegant solution for the SM gauge hierarchy problem and stabilizes the SM Higgs mass at the electroweak scale. In supersymmetric (SUSY) models, new particles and new interactions are introduced that lead to potentially large LFV rates. Therefore, searches for LFV in the charged sector may probe the pattern of SUSY breaking and constrain its origin [3]. Furthermore, the seesaw mechanism is an interesting solution to the problem of the small neutrino masses. In what is called a type I seesaw mechanism, SM singlets (right-handed neutrinos) with mass of order $\mathcal{O}(10^{14})$ GeV are introduced. It turns out that the combination of these two interesting ideas of SUSY and seesaw implies sizable rates for LFV, even when SUSY breaking terms are assumed to be completely flavor blind. Consequently, the SUSY spectrum should be pushed up to a few TeV's [4]. In this case, there will be no hope to probe SUSY particles at LHC. Also, with a very heavy right-handed neutrino, there is no way to test the seesaw mechanism directly at the LHC. Therefore, the TeV scale seesaw mechanism was well motivated and has been recently considered as an alternative paradigm [5].

The TeV scale right-handed neutrino can be naturally implemented in the supersymmetric $B - L$ extension of the SM (SUSY $B - L$), which is based on the gauge group $G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [6]. In this model, three SM-singlet fermions arise quite naturally due to the $U(1)_{B-L}$ anomaly cancellation conditions. These particles are accounted for right-handed neutrinos, and hence a natural explanation for the seesaw mechanism is obtained [5,7,8]. The masses of these right-handed neutrinos are of the order of the $B - L$ breaking scale. In the SUSY $B - L$ model, the $B - L$ Higgs potential receives large radiative corrections that induce spontaneous $B - L$ symmetry breaking at the TeV scale, in analogy to the electroweak symmetry breaking in minimal supersymmetric standard model (MSSM) [6]. In this case, to fulfill the experimental measurements for the light-neutrino masses, with TeV scale right-handed neutrinos, the Dirac neutrino masses should be of order $\mathcal{O}(10^{-4})$ GeV, i.e., they have to be as light as the electron.

In this paper we analyze the LFV in the SUSY $B-L$ model. We show that, due to the smallness of Dirac neutrino Yukawa couplings, the decay rate of $l_i \to l_j \gamma$ and $l_i \to 3l_j$ are quite suppressed. Hence, the predictions of the SUSY $B-L$ for the branching ratio of these processes remain identical to the MSSM ones. Also, we study the pair production of right sneutrinos at the LHC and show that they are long-lived particles. The decay of these right sneutrinos leads to a very interesting signal of the same-sign dilepton with possible different lepton flavors. We demonstrate that the cross section of this event is of order $\mathcal{O}(1)$ pb. Therefore, it is quite accessible at the LHC and can be considered as indisputable evidence for the SUSY $B-L$ model.

The paper is organized as follows. In Sec. II we present the main features of the SUSY $B-L$ extension of the SM. In particular, we analyze the spontaneous $B-L$ breaking at the TeV scale by large radiative corrections to the $B-L$ Higgs potential. Section III is devoted for the LFV in SUSY $B-L$. We start with the conventional $l_i \to l_j$ transitions, then we study the same-sign dilepton event which is a clean signal for large right-sneutrino mixing. Finally we give our conclusions in Sec. IV.

II. SUPERSYMMETRIC $B-L$ EXTENSION OF THE SM

In this section we analyze the minimal supersymmetric version of the $B-L$ extension of the SM based on the gauge group $G_{B-L} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. This SUSY $B-L$ is a natural extension of the MSSM with three right-handed neutrinos to account for measurements of light-neutrino masses. The particle content of the SUSY $B-L$ is the same content as the MSSM with the following extra particles: three chiral right-handed superfields (N_i), vector superfield necessary to gauge the $U(1)_{B-L}$ (Z_{B-L}), and two chiral SM-singlet Higgs superfields (χ_1, χ_2 with $B-L$ charges $Y_{B-L} = -2$ and $Y_{B-L} = +2$ respectively). As in MSSM, the introduction of a second Higgs singlet (χ_2) is necessary in order to cancel the U_{B-L} anomalies produced by the fermionic member of the first Higgs (χ_1) superfield.

The interactions between Higgs and matter superfields are described by the superpotential

$$W_{B-L} = W_{\rm MSSM} + (Y_\nu)_{ij} L_i H_2 N_j^c + (Y_N)_{ij} N_i^c N_j^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2. \tag{2.1}$$

Note that Y_{B-L} for leptons and Higgs are given by [5]:

$$\begin{aligned} &Y_{B-L}(L) = Y_{B-L}(E) = Y_{B-L}(N) = -1, \\ &Y_{B-L}(H_1) = Y_{B-L}(H_2) = 0. \end{aligned} \tag{2.2}$$

It is also remarkable that, due to the $B-L$ gauge symmetry, the R-parity violating terms are now forbidden. These terms violate baryon and lepton number explicitly and lead to proton decay at unacceptable rates. On the other hand, the relevant soft SUSY breaking terms, assuming certain universality of soft SUSY breaking terms at GUT scale, are in general given by

$$\begin{aligned} -\mathcal{L}_{\rm soft}^{B-L} = &-\mathcal{L}_{\rm soft}^{\rm MSSM} + \tilde{m}^2_{Nij} \tilde{N}_i^{c*} \tilde{N}_j^c + m^2_{\chi_1} |\chi_1|^2 \\ &+ m^2_{\chi_2} |\chi_2|^2 + [Y^A_{\nu ij} \tilde{L}_i \tilde{N}_j^c H_u + Y^A_{Nij} \tilde{N}_i^c \tilde{N}_j^c \chi_1 \\ &+ B\mu' \chi_1 \chi_2 + \tfrac{1}{2} M_{B-L} \tilde{Z}_{B-L} \tilde{Z}_{B-L} + {\rm H.c.}], \end{aligned} \tag{2.3}$$

where $(Y_N^A)_{ij} \equiv (Y_N A_N)_{ij}$ is the trilinear associated with Majorana neutrino Yukawa coupling. We now show how the $B-L$ breaking scale can be related to the scale of SUSY breaking, as emphasized in Ref. [6]. The scalar potential for the Higgs fields $H_{1,2}$ and $\chi_{1,2}$ is given by

$$\begin{aligned} V(H_1, H_2, \chi_1, \chi_2) &= \frac{1}{2} g^2 \left(H_1^* \frac{\tau^a}{2} H_1 + H_2 \frac{\tau^a}{2} H_2 \right)^2 + \frac{1}{8} g'^2 (|H_2|^2 - |H_1|^2)^2 \\ &+ \frac{1}{2} g''^2 (|\chi_2|^2 - |\chi_1|^2)^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 \\ &- m_3^2 (H_1 H_2 + {\rm H.c.}) + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 \\ &- \mu_3^2 (\chi_1 \chi_2 + {\rm H.c.}), \end{aligned} \tag{2.4}$$

where

$$m_i^2 = m_0^2 + \mu^2, \qquad i = 1, 2 \qquad m_3^2 = -B\mu, \tag{2.5}$$

$$\mu_i^2 = m_0^2 + \mu'^2, \qquad i = 1, 2 \qquad \mu_3^2 = -B\mu'. \tag{2.6}$$

As can be seen from Eq. (2.4), the potential $V(H_1, H_2, \chi_1, \chi_2)$ is factorizable. It can be written as $V(H_1, H_2) + V(\chi_1, \chi_2)$, where $V(H_1, H_2)$ is the usual MSSM scalar potential which leads to the radiative electroweak symmetry breaking. As is known, due to the running from GUT to weak scale with large top Yukawa coupling, m_2^2 receives negative contributions that radiatively break the electroweak symmetry. Therefore, we will focus here on the new potential $V(\chi_1, \chi_2)$ to analyze the possibility of breaking $B-L$ at the TeV scale, through the soft SUSY breaking terms. This potential is given by

$$V(\chi_1, \chi_2) = \tfrac{1}{2} g''^2 (|\chi_2|^2 - |\chi_1|^2)^2 + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 - \mu_3^2 (\chi_1 \chi_2 + {\rm H.c.}). \tag{2.7}$$

It should be noted that $V(\chi_1, \chi_2)$ is quite similar to the MSSM Higgs potential which spontaneously breaks the electroweak symmetry. Therefore it is expected that the $B-L$ symmetry breaking approach is going to be the same as the well-known procedure of electroweak symmetry breaking in MSSM. The minimization of $V(\chi_1, \chi_2)$ leads to the following condition:

$$v'^2 = (v_1'^2 + v_2'^2) = \frac{(\mu_1^2 - \mu_2^2) - (\mu_1^2 + \mu_2^2)\cos 2\theta}{2g''^2 \cos 2\theta}, \tag{2.8}$$

where $\langle \chi_1 \rangle = v_1$ and $\langle \chi_2 \rangle = v_2$. The angle θ is defined as $\tan\theta = v_1/v_2$. The minimization conditions also lead to

$$\sin 2\theta = \frac{2\mu_3^2}{\mu_1^2 + \mu_2^2}. \tag{2.9}$$

After $B - L$ breaking, the Z_{B-L} gauge boson acquires a mass [5]: $M_{Z_{B-L}}^2 = 4g''^2 v'^2$. The high energy experimental searches for an extra neutral gauge boson impose lower bounds on this mass. The stringent constraint on $U(1)_{B-L}$, obtained from LEP II [9], implies

$$\frac{M_{Z_{B-L}}}{g''} > 6 \text{ TeV}. \tag{2.10}$$

The discovery potential for Z_{B-L} at the LHC has been analyzed through its decay into an electron-positron pair [10] and into three leptons [11]. It was shown that $\mathcal{O}(1)$ TeV Z_{B-L} can be easily probed at the LHC with an integrated luminosity of order ~ 100 fb^{-1}.

For a given $M_{Z_{B-L}}$, the minimization condition (2.8) can be used to determine the supersymmetric parameter μ'^2, up to a sign. One finds

$$\mu'^2 = \frac{m_{\chi_2}^2 - m_{\chi_1}^2 \tan^2\theta}{\tan^2\theta - 1} - \frac{1}{4} M_{Z_{B-L}}^2. \tag{2.11}$$

In order to ensure that the potential $V(\chi_1, \chi_2)$ is bounded from below, one must require

$$\mu_1^2 + \mu_2^2 > 2|\mu_3^2|. \tag{2.12}$$

This is the stability condition for the potential. Also, to avoid that $\langle \chi_1 \rangle = \langle \chi_2 \rangle = 0$ be a local minimum we have to require

$$\mu_1^2 \mu_2^2 < \mu_3^4. \tag{2.13}$$

It is clear that with positive values of μ_1^2 and μ_2^2, given in Eq. (2.6), one cannot simultaneously fulfill the above conditions. However, as pointed out in Ref. [6], the renormalization group evolutions of the scalar masses $m_{\chi_1}^2$ and $m_{\chi_2}^2$ of Higgs singlets χ_1 and χ_2 are different. Therefore, at TeV scale the mass $m_{\chi_1}^2$ becomes negative, whereas $m_{\chi_2}^2$ remains positive. In this case, both of the electroweak, $B - L$ and SUSY breakings are linked at the scale of $\mathcal{O}$ (TeV).

In this regard, the observed light-neutrino masses can be obtained if the neutrino Yukawa couplings, Y_ν, are of order $\mathcal{O}(10^{-6})$ [5,7], which are close to the order of magnitude of the electron Yukawa coupling. The LHC discovery for the TeV right-handed neutrino in $B - L$ extension of the SM has been studied in Ref. [12]. It was shown 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 four lepton channel, which is a very clean signal at LHC, with a negligibly small SM background.

With the TeV scale right sneutrino, the low-energy sneutrino mass matrix is given by a 12×12 Hermitian matrix [13]. However, the mixing between left and right sneutrinos is quite suppressed since it is proportional to Yukawa coupling $Y_\nu \lesssim \mathcal{O}(10^{-6})$. A large mixing between the right sneutrinos and anti-right sneutrinos is quite plausible, since it is given in terms of the Yukawa $Y_N \sim \mathcal{O}(1)$. Therefore, one can focus on the right-sneutrino sector and study the possible oscillation between sneutrino and anti-sneutrino. The right-sneutrino mass matrix in the $(\tilde{N}^c, \tilde{N}^{c*})$ basis can be written as

$$\mathcal{M}^2 \simeq \begin{pmatrix} \tilde{m}_N^2 + M_N^2 & -v_1'(Y_N^A)^* + v_2' Y_N \mu' \\ -v_1'(Y_N^A) + v_2' Y_N \mu'^* & \tilde{m}_N^2 + M_N^2) \end{pmatrix}. \tag{2.14}$$

As can be seen from the above expression, the off-diagonal elements could be of the same order as the diagonal ones. Therefore, a large mixing can be obtained. In this case, the (6×6) right-sneutrino mass matrix is diagonalized by unitary matrix $X_{\tilde{\nu}}$:

$$X_{\tilde{\nu}} \mathcal{M}^2 X_{\tilde{\nu}}^\dagger = \mathcal{M}_{\text{diag}}^2. \tag{2.15}$$

Hence,

$$\tilde{\nu}_{R_i} = (X_{\tilde{\nu}})_{ij} \tilde{N}_j, \qquad i, j = 1, 2 \ldots, 6. \tag{2.16}$$

Finally, we consider the neutral gaugino and Higgsino sector which is going to be modified by the new $B - L$ gaugino and the fermionic partners of the singlet scalar $\chi_{1,2}$. In the weak interaction basis defined by $\psi^{0^T} = (\tilde{B}^0, \tilde{W}_3^0, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{Z}_{B-L}^0)$, the neutral fermion mass matrix is given by the following 7×7 matrix [14]:

$$\mathcal{M}_n = \begin{pmatrix} \mathcal{M}_4 & \mathcal{O} \\ \mathcal{O} & \mathcal{M}_3 \end{pmatrix}, \tag{2.17}$$

where the $\mathcal{M}_4$ is the MSSM-type neutralino mass matrix and $\mathcal{M}_3$ is the additional neutralino mass matrix with 3×3:

$$\mathcal{M}_3 = \begin{pmatrix} 0 & -\mu' & -2g''v'\sin\theta \\ -\mu' & 0 & 2g''v'\cos\theta \\ -2g''v'\sin\theta & +2g''v'\cos\theta & M_{1/2} \end{pmatrix}. \tag{2.18}$$

In case of the real mass matrix, one diagonalizes the matrix $\mathcal{M}_n$ with a symmetric mixing matrix V such as

$$V\mathcal{M}_n V^T = \text{diag}(m_{\chi_k^0}), \qquad k = 1, \ldots, 7. \tag{2.19}$$

In this aspect, the lightest neutralino (LSP) has the following decomposition:

$$\chi_1^0 = V_{11}\tilde{B} + V_{12}\tilde{W}^3 + V_{13}\tilde{H}_d^0 + V_{14}\tilde{H}_u^0 + V_{15}\tilde{\chi}_1 + V_{16}\tilde{\chi}_2 + V_{17}\tilde{Z}_{B-L}. \tag{2.20}$$

The LSP is called pure $\tilde{Z}_{B-L}$ if $V_{17} \sim 1$ and $V_{1i} \sim 0$, $i = 1, \ldots, 6$ and pure $\tilde{\chi}_{1(2)}$ if $V_{15(6)} \sim 1$ and all the other coefficients are close to zero [14]. It is worth noting that the MSSM chargino mass matrix remains intact in this type of models, since no new charged fermion has been introduced.

III. LFV IN SUSY $B-L$ MODEL

In MSSM, the SUSY contributions to the decay channels of $l_i \to l_j \gamma$ are dominated by one-loop diagrams with neutralino-slepton and chargino-sneutrino exchanges. It turns out that the experimental limit on $\mu \to e\gamma$ induces stringent constraints on the transitions between first and second generations. Applying the $\mu \to e\gamma$ constraints on the neutralino contribution leads to the following upper bounds of the slepton mass insertions:

$$(\delta^l_{LR})_{12} \lesssim 10^{-6}, \qquad (\delta^l_{LL})_{12} \lesssim 10^{-3}. \tag{3.1}$$

Note that, due to the $SU(2)_L$ gauge invariance, one gets the following relation between slepton and sneutrino mass insertions: $(\delta^\nu_{LL})_{ij} \simeq (\delta^l_{LL})_{ij}$. For $(\delta^\nu_{LL})_{12} \simeq 10^{-3}$, the chargino contribution to $\mu \to e\gamma$ is automatically below the current experimental limit. These bounds generally impose very stringent constraints on the soft SUSY breaking terms, known as SUSY flavor problem.

It is also worth mentioning that $\mu \to 3e$ and $\mu \to e$ conversion in nuclei, i.e., $\mu + N \to e + N$ are considered as another source of probing possible SUSY effects. The relation between these two processes and $\mu \to e\gamma$ is, in general, model independent. However, in the SUSY framework, where these processes are generated by the photon penguin, Z-penguin, and box diagrams, one usually finds $\mathrm{BR}(\mu \to 3e) \sim \mathrm{BR}(\mu \to e) \sim \mathcal{O}(10^{-3}) \times \mathrm{BR}(\mu \to e\gamma)$. In this respect, it seems the present limit on $\mu \to 3e$ and $\mu \to e$ conversion is less sensitive than the current bound on $\mu \to e\gamma$. However, future experiments would reach the limit of 10^{-17} for the branching ratio of $\mu \to e$ conversion and 10^{-16} for $\mathrm{BR}(\mu \to 3e)$, while $\mathrm{BR}(\mu \to e\gamma)$ may approach 10^{-14} at most. These search limits will be powerful tools to probe SUSY at a scale of the order of several TeV. Therefore, in the case of negative measurements for all these LFV processes, a very severe constraint is expected to be imposed on the SUSY parameter space.

In the minimal supersymmetric seesaw model (which consists of MSSM and right-handed neutrinos), sizable rates for LFV may be obtained through slepton flavor mixing induced radiatively by the large neutrino mixing during the evolution from the grand unification (GUT) scale down to the right-handed neutrino scale. In this case, even if universal soft SUSY breaking parameters are assumed, one finds that the slepton mass matrix receives flavor dependent radiative corrections and the lepton mass insertions are given by

$$(\delta^l_{LL})_{12} \sim \frac{m_0^2}{\tilde{m}^2}(Y_\nu^+ Y_\nu)_{12}, \qquad (\delta^l_{LR})_{12} \sim \frac{m_e A_0}{\tilde{m}^2}(Y_\nu^+ Y_\nu)_{12}. \tag{3.2}$$

For neutrino Yukawa couplings of order one, the above contribution could enhance the lepton mass insertion significantly. In this case, the upper bound given in Eq. (3.1), in particular $(\delta^l_{LL})_{12} < 10^{-3}$, is violated unless the slepton masses are quite heavy. It has been explicitly checked that if the neutrino Yukawa coupling is of the form $Y_\nu = U_{MNS} Y_\nu^{\rm diag}$, then the predicted SUSY contribution to $\mu \to e\gamma$ is enhanced significantly and exceeds the current experimental limits for most of the parameter space [15].[1] In this respect, the new upper bound $\mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-13}$ from the MEG experiment might impose a lower bound on the SUSY spectrum of the order of a few TeV, which will be unaccessible at LHC. Therefore, LFV is a serious test for the large scale seesaw mechanism within the SUSY framework.

It is therefore of considerable interest to study the TeV scale seesaw, which can easily overcome the LFV problem in SUSY seesaw models. As shown in the previous section, the SUSY $B-L$ extension of the SM is natural framework for implementing the TeV scale seesaw. In this class of models, the severe constraints from charged LFV processes are relaxed.

A. $l_i \to l_j \gamma$ processes

In the SUSY $B-L$, there are two additional one-loop diagrams contributing to the decay $l_i \to l_j \gamma$ with $B-L$ neutralino and chargino exchange, as shown in Fig. 1. In the $\tilde{Z}_{B-L}$ neutralino contribution, the sleptons are running in the loop, while the chargino diagram involves both left and right sneutrinos. It is worth noting that these new contributions are similar to the usual MSSM contribution where neutralino and slepton or chargino and sneutrino are running in the loop. Therefore, the model independent bound on the mass insertions in Eq. (3.1) remains valid for $x = (m_{\tilde{Z}_{B-L}}/m_{\tilde{l}})^2 \simeq 1$. Moreover, since the soft SUSY breaking terms are now evolving from GUT to TeV scale, a factor of order $\mathcal{O}(10)$ is obtained from the $\ln(M_{\rm GUT}/M_R)$ in the slepton/sneutrino mass corrections. However, as one can see from Fig. 1, these contributions are proportional to the square of the Dirac neutrino Yukawa. Therefore, they are expected to be quite small.

In fact, the $\tilde{Z}_{B-L}$ neutralino contribution is proportional to $B-L$ gauge coupling squared times the mass insertion $(\delta^l_{LL})_{ab}$, which is proportional to Y_ν^2. As emphasized above, in the TeV scale seesaw, the Dirac neutrino Yukawa coupling Y_ν is of order $\mathcal{O}(10^{-6})$. Therefore, the new neutralino amplitude is of order $\mathcal{O}(10^{-12})$, which leads to a negligible contribution.

[1] See also Ref. [16]

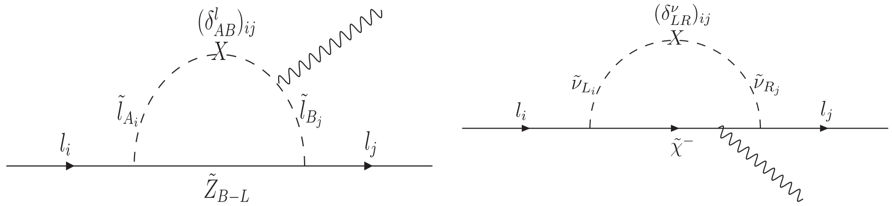

FIG. 1. New contributions to the decay $l_i \to l_j \gamma$ in the SUSY $B - L$ model.

The chargino contribution may be dominated by the mixing between left and right sneutrinos. Note that in the large scale SUSY seesaw, the right-handed (s)neutrinos are decoupled, hence the chargino contribution is associated with the left sneutrino only with mass insertion $(\delta^\nu_{LL})_{ij}$ correlated with the constrained $(\delta^l_{LL})_{ij}$. Thus, in the SUSY $B - L$, the new chargino contribution is given in terms of $SU(2)$ gauge coupling g_2, Dirac neutrino Yukawa coupling Y_ν, and the mass insertion $(\delta^\nu_{LR})_{12}$. Nevertheless $(\delta^\nu_{LR})_{12}$ is given by

$$(\delta^\nu_{LR})_{12} \simeq (Y_\nu)_{12} \frac{v v'}{\tilde{m}^2}. \tag{3.3}$$

For $Y_\nu \sim \mathcal{O}(10^{-6})$, the mass insertion $(\delta^\nu_{LR})_{ab}$ is of order $\mathcal{O}(10^{-7})$, hence the chargino contribution is also quite negligible, of order $\mathcal{O}(10^{-14})$. Thus, one can conclude that the LFV associated to $l_i \to l_j \gamma$ processes, which is generated by renormalization group equations (RGE) from GUT to seesaw scale, is very tiny in the SUSY $B - L$ model.

B. Same-sign and different flavor dilepton signal at the LHC

It is important to note that within the MSSM or the SUSY seesaw model, another test for LFV at the LHC may be provided by generating a final state with different lepton flavors. For example, μ^+ and e^- can be generated at the final state as follows: $q\bar{q} \to \tilde{l}_i^+ \tilde{l}_i^- \to \mu^+ e^- + 2\tilde{\chi}^0$. However, the cross section of this process is proportional to mass insertion $(\delta^l_{LL})_{12}$. Therefore, it is typically less than 1 fb, for slepton mass of order 200 GeV [17]. Note that the dilepton associated with this process has opposite sign of electric charges. In the MSSM or the SUSY seesaw model, a same-sign dilepton may be generated only through the gluino and/or squark production followed by several cascade decays [18].

Now we consider the same-sign and different flavor dilepton production mediated by right-handed neutrino and right sneutrino at the LHC in the SUSY $B - L$ model. In particular, we work out the following two processes, shown in Fig. 2:

$$\text{(i)}\ pp \to \tilde{Z}_{B-L} \to \tilde{\nu}_{R_i}\tilde{\nu}_{R_i} \to l_j^- \chi^+ + l_k^- \chi^+ \to l_j^- l_k^- + \text{jets} + \text{missing energy}.$$

$$\text{(ii)}\ pp \to \tilde{Z}_{B-L} \to \nu_{R_i}\nu_{R_i} \to l_j^- W^+ + l_k^- W^+ \to l_j^- l_k^- + \text{jets}.$$

Here, the following remarks are in order. (i) In the first process the LFV is obtained through the right-sneutrino mixing matrix: $(X_{\tilde{\nu}})_{ij}$. While in the second channel, the neutrino mixing matrix U_{ij} is responsible for such flavor violation. (ii) Both couplings of $\tilde{\nu}_R - l^- - \chi^+$ and $\nu_R - l^- - W^+$ interactions are suppressed by the mixing between left and right neutrino, which is given by $\sim m_D/M_R \simeq \mathcal{O}(10^{-7})$. However, the sneutrino coupling has another suppression factor $\sim\mathcal{O}(0.1)$, due to the chargino diagonalizing matrix, U_χ. (iii) One can show that the decay width of right-sneutrino $\Gamma_{\tilde{\nu}_R}$ and right-handed neutrino Γ_{ν_R} are given by

$$\Gamma_{\tilde{\nu}_R} \sim \frac{1}{8\pi} \frac{|U_\chi Y_\nu|^2}{m_{\tilde{\nu}_R}}, \qquad \Gamma_{\nu_R} \sim \frac{1}{8\pi} \frac{|Y_\nu|^2}{m_{\nu_R}}. \tag{3.4}$$

It is clear that $\Gamma_{\tilde{\nu}_R} < \Gamma_{\nu_R}$, therefore the right sneutrino is a

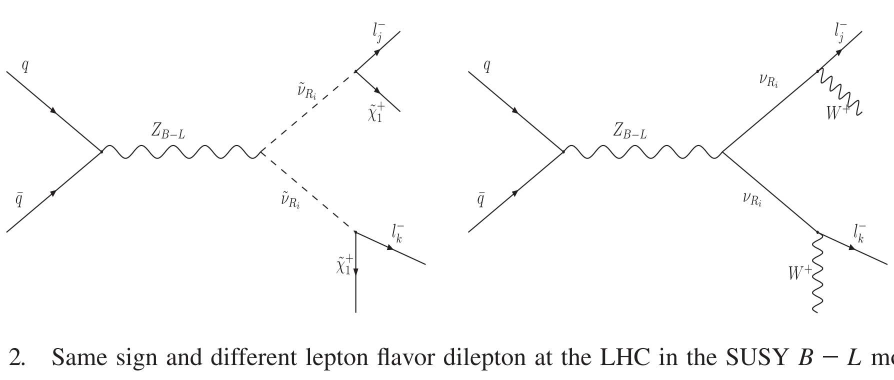

FIG. 2. Same sign and different lepton flavor dilepton at the LHC in the SUSY $B - L$ model.

long-lived particle more than the right-handed neutrino. In this case, it is expected that the right sneutrino will have interesting features at the LHC. Accordingly, we will focus our discussion on the case of right-sneutrino pair production.

From the interaction terms in the SUSY $B-L$ Lagrangian, one finds that the dominant production for the right-sneutrino is through the exchange of Z_{B-L} and its decay is dominated by the chargino channel, so that $\mathrm{BR}(\tilde{\nu}_R \to l^- \chi^+) \simeq 1$. In general, the amplitude of the process $q\bar{q} \to \tilde{Z}_{B-L} \to \tilde{\nu}_{R_k}\tilde{\nu}_{R_k} \to l_i^- \chi^+ + l_j^- \chi^+$, through the s channel, is given by [19]

$$\mathcal{M}_{ij} = \sum_i \mathcal{M}_P \frac{i}{q^2 - \tilde{m}^2_{\tilde{\nu}_{R_k}} + i\tilde{m}_{\tilde{\nu}_{R_k}}\Gamma_{\tilde{\nu}_{R_k}}} (X_{\tilde{\nu}_R})_{ki} \mathcal{M}_D \times \frac{i}{q^2 - \tilde{m}^2_{\tilde{\nu}_{R_k}} + i\tilde{m}_{\tilde{\nu}_{R_k}}\Gamma_{\tilde{\nu}_{R_k}}} (X_{\tilde{\nu}_R})^*_{kj} \mathcal{M}_D, \tag{3.5}$$

where $\mathcal{M}_P$ is the production amplitude for $q\bar{q} \to \tilde{\nu}_{R_k}\tilde{\nu}_{R_k}$ and $\mathcal{M}_D$ is the decay amplitude for $\tilde{\nu}_{R_k}$. As emphasized in Ref. [19], the total cross section $\sigma_{ij} = \sigma(q\bar{q} \to \tilde{\nu}_{R_k}\tilde{\nu}_{R_k} \to l_i^- l_j^- + \text{jets} + \text{missing energy})$ can be written as

$$\sigma_{ij} = \int d^2q \sum_{kl} (X_{\tilde{\nu}_R})_{ki} (X_{\tilde{\nu}_R})^*_{kj} (X_{\tilde{\nu}_R})_{li} (X_{\tilde{\nu}_R})^*_{lj} A_{kl}(q^2) \times [\text{production cross section}] \times [\text{decay branching ratio}], \tag{3.6}$$

where $A_{kl}(q^2)$ is the product of right-sneutrino propagators:

$$A_{kl}(q^2) = \frac{i}{q^2 - \tilde{m}^2_{\nu_{\tilde{R}_k}} + i\tilde{m}_{\nu_{\tilde{R}_k}}\Gamma_{\tilde{\nu}_{R_k}}} \frac{i}{q^2 - \tilde{m}^2_{\tilde{\nu}_{R_l}} + i\tilde{m}_{\tilde{\nu}_{R_l}}\Gamma_{\tilde{\nu}_{R_l}}}. \tag{3.7}$$

Here, we assume the off-diagonal elements of the right-sneutrino mass matrix and the decay width are much smaller than the average right-sneutrino mass. This assumption is quite natural and usually satisfied in standard SUSY models. In this case the right-sneutrino propagator can be approximated as follows [20]:

$$A_{kl}(q^2) = \frac{1}{1 + i\Delta M_{\tilde{\nu}_R}/\Gamma_{\tilde{\nu}_{R_k}}} \frac{\pi}{m_{\tilde{\nu}_R}\Gamma_{\tilde{\nu}_R}} \delta(q^2 - m^2_{\tilde{\nu}_R}). \tag{3.8}$$

Thus, the total cross section σ_{ij} can be written as [20]

$$\sigma_{ij} \approx \frac{|(\Delta m^2_{\tilde{\nu}_R})_{ij}|^2}{\tilde{m}^2_{\tilde{\nu}_R}\Gamma^2_{\tilde{\nu}_R}} \sigma(q\bar{q} \to \tilde{\nu}_R\tilde{\nu}_R). \tag{3.9}$$

From Eq. (3.4), the right-sneutrino decay width is of order $\Gamma_{\tilde{\nu}_R} \lesssim \mathcal{O}(10^{-14})\ \mathrm{GeV}^{-1}$. Therefore, with $m_{\tilde{\nu}_R} \sim \mathcal{O}(1)$ TeV and $\Delta M_{\tilde{\nu}}/m_{\tilde{\nu}_R} \sim \mathcal{O}(10^{-2})$, one finds[2]

$$\sigma_{ij} \approx 10^{10}\sigma(q\bar{q} \to \tilde{\nu}_R\tilde{\nu}_R), \tag{3.10}$$

with

$$\sigma(q\bar{q} \to \tilde{\nu}_R\tilde{\nu}_R) \simeq \frac{g^4_{B-L} m_q^2}{6\pi(s^2 - m^2_{Z_{B-L}})^2} \sqrt{1 - \left(\frac{2m_{\tilde{\nu}_R}}{s}\right)^2} \times \left[1 - \left(\frac{2m_q}{s}\right)^2\right]. \tag{3.11}$$

It is remarkable that for gauge coupling $g'' \sim \mathcal{O}(0.1)$ and $m_{Z_{B-L}} \sim \mathcal{O}(1)$ TeV, one finds that the cross section is given by

$$\sigma(q\bar{q} \to l_i^- l_j^- + \text{jet} + \text{missing energy}) \simeq 10^{-10}\ \mathrm{GeV}^{-2} \simeq \mathcal{O}(1)\ \mathrm{pb}. \tag{3.12}$$

For these values of cross section, the same-sign dilepton signal can be easily probed at the LHC. This event will be a clear hint for sizable LFV at the LHC, which is more significant than the bounds obtained from the rare decays, $l_i \to l_j\gamma$. Since the SM background of the same-sign dilepton is negligibly small, the discovery of this process would be an undoubted signal for the SUSY $B-L$ model.

IV. CONCLUSIONS

We have analyzed the LFV in the supersymmetric $B-L$ extension of the standard model. In this model, $B-L$ symmetry is radiatively broken at the TeV scale. Therefore, it is a natural framework for the TeV scale seesaw mechanism with Dirac neutrino Yukawa coupling of order $\mathcal{O}(10^{-6})$. We have shown that, because of the smallness of Dirac neutrino Yukawa couplings, the decay rates of $l_i \to l_j\gamma$ and $l_i \to 3l_j$, generated by the RGE from GUT to seesaw scale, are quite suppressed. In this case, the LFV constraints imposed on this class of models remain as in the MSSM. Also, we have studied another possibility for LFV at the LHC, which associated with the same-sign dilepton, is produced through the decay of the long-lived pair of right sneutrinos. We have shown that the total cross section of the process $q\bar{q} \to Z_{B-L} \to \tilde{\nu}_{R_i}\tilde{\nu}_{R_i} \to l_j^{\pm} l_k^{\pm} + \text{jets} + \text{missing energy}$ is of order $\mathcal{O}(1)$ pb. Therefore, it is experimentally accessible at the LHC,

[2] A more detailed analysis for these processes at LHC, with specific models of supersymmetry breaking, will be considered elsewhere.

with negligibly small SM background. The probe of this signal will provide indisputable evidence for SUSY $B - L$ extension of the SM and also for right sneutrino-anti-sneutrino oscillation.

ACKNOWLEDGMENTS

I would like to thank H. Okada for fruitful discussions. I am very grateful to the members of the NExT institute at Southampton University and STFC, Rutherford Appleton Laboratory for their kind hospitality, where this work was completed. We also acknowledge financial support through the Centre for Fundamental Physics. This work was partially supported by the Science and Technology Development Fund (STDF) Project ID 437 and the ICTP Project ID 30.

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