Lepton Flavor Violations in High-Scale SUSY with Right-Handed Neutrinos

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Abstract

Motivated by the recent discovery of the Higgs boson at $m_h \simeq 126$ GeV and also by the non-observation of superparticles at the LHC, high-scale SUSY, where the superparticles are as heavy as $O(10)$ TeV, has been recently proposed. We study lepton-flavor violations (LFVs) in the high-scale SUSY with right-handed neutrinos. Even if the slepton masses are of $O(10)$ TeV, the renormalization group (RG) effects on the slepton mass-squared matrix may induce large enough LFVs which are within the reach of future LFV experiments. We also discuss the implication of the right-handed neutrinos on the electroweak symmetry breaking in such a model, and show that the parameter region with the successful electroweak symmetry breaking is enlarged by the RG effects due to the right-handed neutrinos.
The recent results of the LHC experiments have provided important information about the physics at the TeV scale. Given the fact that supersymmetry is a prominent candidate of the physics beyond the standard model, the observed Higgs boson mass about 126 GeV\cite{1,2} together with the lack of any observation of superparticles \cite{3,4} strongly suggests that the SUSY-breaking scale is likely higher than $O(10)$ TeV \cite{5,6,7,8} in the minimal SUSY standard model (MSSM). If this is the case, it may be very difficult to discover directly superparticles at the LHC.

The purpose of this letter is to show that, with the seesaw mechanism \cite{9,10,11}, the rates of lepton-flavor-violation (LFV) processes may be within the testable ranges even if the mass scale of the superparticles is very high as suggested by the observed Higgs mass. Indeed, for the case where the off-diagonal elements of the slepton mass-squared matrices are sizable compared to the diagonal elements, two of the authors have pointed out that the rates of the LFV processes may be within the reach of future experiments if the masses of superparticles are $O(10)$ TeV \cite{12}. Here, we show that such a size of the off-diagonal elements can be naturally generated by the renormalization group (RG) effects if there exist heavy right-handed neutrinos \cite{13,14,15}. For a demonstration of our point, we assume the universal SUSY-breaking soft masses for all chiral multiplets at the GUT scale. Such an assumption is also advantageous to avoid serious SUSY FCNC problems \cite{16}; in particular, the SUSY contribution to the $\epsilon_K$ parameter can be sufficiently suppressed in this assumption. We will see that, in the parameter region of our interest (i.e., the region with the sfermion masses of $\sim 10$ TeV, where the lightest Higgs mass becomes about 126 GeV), $Br(\mu \rightarrow e\gamma)$ can be as large as $\sim 10^{-13} - 10^{-14}$, which may be tested in future experiments.

We also show that the presence of the heavy right-handed neutrinos enlarge the parameter space for the successful electroweak symmetry breaking. It is often the case that the electroweak symmetry breaking becomes unsuccessful if the scalar masses are much larger than the gaugino masses. In particular, this is the case in the pure gravity mediation model \cite{17,18,19} with the universal SUSY-breaking soft masses at the GUT scale; in such a model, only a very narrow region of the gravitino mass, $m_{3/2} \simeq (300 - 1500)$ TeV, can induce the correct electroweak symmetry breaking if the right-handed neutrinos do not exist \cite{20}. Here, we find that the electroweak symmetry breaking becomes possible with smaller value of $m_{3/2}$.

Let us first introduce the model of our interest. As we have mentioned, we consider SUSY model with right-handed (s)neutrinos. Denoting the up-type Higgs, lepton doublet, and right-handed neutrino as $H_u$, $l$, and $N^c$, respectively, the relevant part of the superpotential for our analysis is

\begin{equation}
W = W_{\text{MSSM}} + y_{\nu,Ij}N^c_I l_j H_u + \frac{1}{2} M_{N,IJ}N^c_I N^c_J,
\end{equation}

where $W_{\text{MSSM}}$ is the superpotential of the MSSM, and the indices $I$ and $j$ are flavor indices which run $1 - 3$. With the above superpotential, the active neutrinos become massive in the seesaw mechanism \cite{9,10,11}; the mass matrix of the active neutrinos is given by

\begin{equation}
M_{\nu,ij} = [U_{\text{MNS}}^T \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) U_{\text{MNS}}]_{ij} = \frac{1}{2} y_{\nu,Ii} y_{\nu,Jj} v^2 \sin^2 \beta (M_N^{-1})_{IJ},
\end{equation}
where \( v \approx 246 \text{ GeV} \) is the vacuum expectation value (VEV) of the Higgs boson, and \( \beta \) is the angle parametrizing the Higgs VEVs (with \( \tan \beta \) being the ratio of the VEVs of up- and down-type Higgs bosons). Here, \( m_{\nu_{L,i}} \) are mass eigenvalues of active neutrinos. From neutrino-oscillation experiments, we have information about the mass-squared differences. In our analysis, concentrating on the case of hierarchical mass matrix for active neutrinos, we adopt the following as canonical values \cite{21}:

\[
\begin{align*}
    m_{\nu_{L,3}} &= \sqrt{\Delta m^2_{\text{atom}}} = 0.048 \text{ eV}, \\
    m_{\nu_{L,2}} &= \sqrt{\Delta m^2_{\text{solar}}} = 0.0087 \text{ eV}, \\
    m_{\nu_{L,1}} &\approx 0.
\end{align*}
\]

In addition, \( U_{\text{MNS}} \) is the so-called Maki-Nakagawa-Sakata (MNS) matrix, which we parametrize

\[
U_{\text{MNS}} = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}e^{i\delta} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}e^{i\delta}
\end{pmatrix} \times \text{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2}),
\]

where \( c_{ij} \equiv \cos \theta_{ij} \), \( s_{ij} \equiv \sin \theta_{ij} \). In our numerical calculation, we take \cite{21}

\[
s_{12} = 0.46, \quad s_{23} = 0.5, \quad s_{13} = 0.16,
\]

and

\[
\delta = 0.
\]

In addition, in order to capture the most important features of the present model, we consider the case that the Majorana mass matrix of right-handed neutrinos has universal structure as\footnote{As long as \( M_{N_3} \) is large enough (\( M_{N_3} \sim O(10^{15}) \text{ GeV} \)), the following discussion is almost unchanged even if we choose hierarchical right-handed neutrino masses, \( M_{N_1,2} \ll M_{N_3} \). Thus, the present discussion is applicable to the case compatible with the leptogenesis \cite{22}, which requires \( M_{N_1} \sim O(10^9-10) \text{ GeV} \).}

\[
M_{N,IJ} = M_N \delta_{IJ},
\]

and that the neutrino Yukawa matrix is given in the following form:

\[
y_{\nu,Ij} = \sqrt{2M_N m_{\nu_{L,I}}[U_{\text{MNS}}]_{IJ}} \frac{1}{v \sin \beta}.
\]

Notice that, with the above assumptions, the parameters \( \alpha_{21} \) and \( \alpha_{31} \) are irrelevant for the following analysis.
The soft SUSY breaking terms relevant for our following discussion are given by

\[ L^{(\text{soft})} = L^{(\text{soft})}_{\text{MSSM}} + m^2_{\tilde{N}^c_{e,IJ}} \tilde{N}^c_{I} \tilde{N}^c_{J} + (A_{\nu, IJ} \tilde{N}^c_{I} H_u + \text{h.c.}), \]

(11)

where \( L^{(\text{soft})}_{\text{MSSM}} \) contains the SUSY breaking terms of the MSSM. As we have mentioned, we consider the case where the SUSY FCNC problems are solved by the assumption of the universal scalar mass. In addition, we assume that the tri-linear scalar coupling constant is proportional to the corresponding Yukawa coupling constant, like in the case of mSUGRA, at the scale where the boundary condition is imposed. Thus, with \( \tan \beta \) being fixed, the soft SUSY breaking parameters related to the scalars are parametrized by the following parameters:

\[ m_0, \quad a_0, \]

(12)

where \( m_0 \) is the universal scalar mass and \( a_0 \) is the coefficient of the tri-linear scalar coupling (normalized by \( m_0 \) as well as by the corresponding Yukawa coupling constant). In our analysis, we impose the boundary condition at the GUT scale \( M_{\text{GUT}} \), which is taken to be \( 2 \times 10^{16} \) GeV.

The neutrino Yukawa coupling constants \( y_{\nu} \) change the RG runnings of soft SUSY breaking parameters, which may affect the low-energy phenomenology. In particular, above the mass scale of the right-handed neutrinos, the soft SUSY breaking mass-squared parameters of left-handed leptons \( m^2_{\tilde{l},ij} \) may be significantly affected. To see this, it is instructive to see the RG equations (RGEs) of those parameters; at the one-loop level, the RGEs above the scale of the right-handed neutrinos are given by

\[
\frac{d m^2_{\tilde{l},ij}}{d \ln Q} = \left[ \frac{d m^2_{\tilde{l},ij}}{d \ln Q} \right]_{\text{MSSM}} + \frac{1}{16\pi^2} \left[ (m^2_{\tilde{l},ij} y^*_\nu y_{\nu} + y^*_\nu y_{\nu} m^2_{\tilde{l},ij}) + 2(y^*_\nu y_{\nu} m^2_{\tilde{N}^c_{I} H_u} + A^{\dagger}_{\nu} A_{\nu}) \right]_{ij},
\]

(13)

where \( [d m^2_{\tilde{l},ij}/d \ln Q]_{\text{MSSM}} \) denotes the MSSM contribution to the RGE, \( m_{H_u}^2 \) is the soft SUSY breaking mass-squared parameter of up-type Higgs, and \( Q \) is the renormalization scale. Then, we can easily see that the off-diagonal elements \( m^2_{\tilde{l},ij} \) become non-vanishing at low energy even if the universality assumption is adopted at the GUT scale. Indeed, with the scalar masses being universal at the GUT scale, the low-energy values of \( m^2_{\tilde{l},ij} \) are estimated as

\[ m^2_{\tilde{l},ij} \simeq m_0^2 \left[ \delta_{ij} - \frac{(y^*_\nu y_{\nu})_{ij}}{16\pi^2} (6 + 2a_0^2) \ln \frac{M_{\text{GUT}}}{M_N} \right], \]

(14)

where we have used the leading-log approximation. As one can see, the off-diagonal elements of \( m^2_{\tilde{l},ij} \), which become the origin of the LFV processes, are generated through the RG effects.
Another important effect is on the evolution of $m_{H_u}^2$; the RGE of $m_{H_u}^2$ above the mass scale of the right-handed neutrinos is

$$\frac{d m_{H_u}^2}{d \ln Q} = \left[ \frac{d m_{H_u}^2}{d \ln Q} \right]_{\text{MSSM}} + \frac{2}{16\pi^2} \text{tr} \left[ y^\dagger \nu y_\nu m_{H_u}^2 + y^\dagger \nu y_\nu m^2 + y_\nu y^\dagger \nu m^2_{\tilde{N}e} + A^\dagger \nu A_\nu \right].$$

The change of the RGE may affect the condition of the electroweak symmetry breaking, as we discuss below.

In order to discuss the phenomenology at the electroweak scale (and below), we evaluate the low-energy values of the soft SUSY breaking parameters by solving the RGEs numerically. The value of the SUSY invariant Higgs mass (so-called $\mu$ parameter) is determined by solving the condition of electroweak symmetry breaking.

Let us first consider the LFVs mainly induced by the off-diagonal elements of $m_{i,j}^2$. The values of $m_{i,j}^2$ (with $i \neq j$) are sensitive to model parameters; in particular, they are approximately linearly dependent on the mass scale of the right-handed neutrinos with the masses of active neutrinos being fixed. (See Eq. (20).) For the case where the gaugino masses are equal to $m_0$ at the GUT scale, for example, $(m_{i,12}^2/m_0^2, m_{i,23}^2/m_0^2, m_{i,13}^2/m_0^2)$ is about $(-5.0 \times 10^{-4}, -1.3 \times 10^{-3}, -1.5 \times 10^{-4}), (-3.5 \times 10^{-3}, -9.1 \times 10^{-3}, -1.0 \times 10^{-3}),$ and $(-1.9 \times 10^{-2}, -5.0 \times 10^{-2}, -5.5 \times 10^{-3})$ for $M_N = 10^{13}$ GeV, $10^{14}$ GeV, and $10^{15}$ GeV, respectively; if all the gaugino masses are much smaller than $m_0$, we obtain $(-6.8 \times 10^{-4}, -1.8 \times 10^{-3}, -2.0 \times 10^{-4}), (-4.7 \times 10^{-3}, -1.2 \times 10^{-2}, -1.4 \times 10^{-3}),$ and $(-2.6 \times 10^{-2}, -7.9 \times 10^{-2}, -7.7 \times 10^{-3})$ for $M_N = 10^{13}$ GeV, $10^{14}$ GeV, and $10^{15}$ GeV, respectively. One can see that the off-diagonal elements become sizable in particular when $M_N$ is close to $\sim 10^{15}$ GeV, with which the largest Yukawa coupling constant is $\sim 1$.

To see how large the LFV rates can be, we calculate $Br(\mu \rightarrow e\gamma)$ in the present setup. Here, to make our discussion concrete, we concentrate on two typical models for the choice of the gaugino masses.

1. mSUGRA model: If there exists a singlet field in the SUSY breaking sector, gaugino masses can dominantly originate from the direct interaction between the singlet field and the gaugino. Then, assuming that the interaction respects the GUT symmetry, we parametrize

$$M_A^{(\text{mSUGRA})}(Q = M_{\text{GUT}}) = M_{1/2}.$$  \hfill (16)

The low-energy values of the gaugino masses are determined by solving the RGEs with the above boundary condition.

2. Pure gravity mediation model [17, 18, 19]: If there is no singlet field in the SUSY breaking sector, gaugino masses may be dominantly from the effect of anomaly-mediated SUSY breaking (AMSB) [23, 24]; if the pure anomaly-mediation contribution domi-
The ratio \( \frac{\text{effective BR}}{\text{MSSM case}} \) improves the sensitivity up to \( \mu \). Here, we take the parameter space. For example, the Mu3e experiment may cover the future, however, several experiments may improve the bound on these processes. In the present model, \( \mu \to 3e \) and \( \mu-e \) conversion processes can be significant. If the LFV processes are dominated by the dipole-type operator, which is the case when \( \tan \beta \) is relatively large, \( \text{Br}(\mu \to 3e) \) and the rate of the \( \mu-e \) conversion \( R_{\mu e} \) are both approximately proportional to \( \text{Br}(\mu \to e\gamma) \). For the \( \mu \to 3e \) process, we obtain \( \text{Br}(\mu \to 3e) \approx 6.6 \times 10^{-3} \times \text{Br}(\mu \to e\gamma) \). The ratio \( R_{\mu e}/\text{Br}(\mu \to e\gamma) \) depends on the nucleus \( N \) used for the conversion process; the ratio \( R_{\mu e}/\text{Br}(\mu \to e\gamma) \) is approximately given by \( 2.5 \times 10^{-3} \) for \( N \) being \( ^{27}_{13}\text{Al} \). With the proportionality factor given above, the current bounds on \( \mu \to 3e \) and the \( \mu-e \) conversion processes give less severe constraints compared to the \( \mu \to e\gamma \) process. In the future, however, several experiments may improve the bound on these processes. For example, the Mu3e experiment may cover \( \text{Br}(\mu \to 3e) \approx 10^{-15} - 10^{-16} \). For the \( \mu-e \) conversion process, Mu2e and COMET experiments may reach \( R_{\mu e} \approx 10^{-17} \) with \( N = ^{27}_{13}\text{Al} \), while PRISM/PRIME project may have a sensitivity up to \( R_{\mu e} \approx 10^{-19} \). Thus, these experiments may provide more stringent constraint on the model of our interest. In other words, even if all the superparticles are at the scale of \( O(10) \) TeV, the LFV processes may have large enough rates to be detected at future experiments.

Next, we consider the situation with smaller gaugino masses; for this purpose, we adopt the pure gravity mediation model where the gaugino masses is given by the AMSB and \( m_0 = m_{3/2} \). The branching ratio for the \( \mu \to e\gamma \) process is shown in Fig. 2. Even in this case, we can see that \( \text{Br}(\mu \to e\gamma) \) can be as large as \( O(10^{-13}) \) or larger even if we require that \( m_A \approx 126 \text{ GeV} \).

\[ M_A^{(\text{AMS})} = -\frac{b_A g_A^2}{16 \pi^2} m_{3/2} \]  

(17)

where \( b_A \) denote coefficients of the RGEs of \( g_A \), i.e., \( b_A = (-11, -1, 3) \).

In both cases, the scalar masses are assumed to be universal at the GUT scale. Requiring successful electroweak symmetry breaking, other MSSM parameters (i.e., \( \mu \)- and \( B_\mu \)-parameters) are determined. Thus, with \( \tan \beta \) being fixed, the low-energy values of the MSSM parameters are given as functions of \( m_0 \), \( a_0 \), \( \text{sign}(\mu) \), and \( M_{1/2} \) or \( m_{3/2} \).

In Fig. 1, we show the contours of constant \( \text{Br}(\mu \to e\gamma) \) on \( m_0 \) vs. \( \tan \beta \) plane for the mSUGRA case. Here, we take \( M_{1/2} = m_0 \). We can see that \( \text{Br}(\mu \to e\gamma) \) can be as large as \( O(10^{-13}) \) or larger in the parameter region where the Higgs mass becomes about 126 GeV. With the experimental bound of \( \text{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13} \) recently reported by the MEG experiment, some of the parameter region (with large \( \tan \beta \)) is already excluded even if \( m_0 \) is as large as \( \sim 10 \text{ TeV} \). In the future, the MEG upgrade experiment is expected to improve the sensitivity up to \( \text{Br}(\mu \to e\gamma) < 6 \times 10^{-14} \), which gives better converge of the parameter space.

As well as the \( \mu \to e\gamma \) process, other LFV reactions may also occur. In particular, in the present model, \( \mu \to 3e \) and \( \mu-e \) conversion processes can be significant. If the LFV processes are dominated by the dipole-type operator, which is the case when \( \tan \beta \) is relatively large, \( \text{Br}(\mu \to 3e) \) and the rate of the \( \mu-e \) conversion \( R_{\mu e} \) are both approximately proportional to \( \text{Br}(\mu \to e\gamma) \). For the \( \mu \to 3e \) process, we obtain \( \text{Br}(\mu \to 3e) \approx 6.6 \times 10^{-3} \times \text{Br}(\mu \to e\gamma) \). The ratio \( R_{\mu e}/\text{Br}(\mu \to e\gamma) \) depends on the nucleus \( N \) used for the conversion process; the ratio \( R_{\mu e}/\text{Br}(\mu \to e\gamma) \) is approximately given by \( 2.5 \times 10^{-3} \) for \( N \) being \( ^{27}_{13}\text{Al} \). With the proportionality factor given above, the current bounds on \( \mu \to 3e \) and the \( \mu-e \) conversion processes give less severe constraints compared to the \( \mu \to e\gamma \) process. In the future, however, several experiments may improve the bound on these processes. For example, the Mu3e experiment may cover \( \text{Br}(\mu \to 3e) \approx 10^{-15} - 10^{-16} \). For the \( \mu-e \) conversion process, Mu2e and COMET experiments may reach \( R_{\mu e} \approx 10^{-17} \) with \( N = ^{27}_{13}\text{Al} \), while PRISM/PRIME project may have a sensitivity up to \( R_{\mu e} \approx 10^{-19} \). Thus, these experiments may provide more stringent constraint on the model of our interest. In other words, even if all the superparticles are at the scale of \( O(10) \) TeV, the LFV processes may have large enough rates to be detected at future experiments.

Next, we consider the situation with smaller gaugino masses; for this purpose, we adopt the pure gravity mediation model where the gaugino masses is given by the AMSB and \( m_0 = m_{3/2} \). The branching ratio for the \( \mu \to e\gamma \) process is shown in Fig. 2. Even in this case, we can see that \( \text{Br}(\mu \to e\gamma) \) can be as large as \( O(10^{-13}) \) or larger even if we require that \( m_A \approx 126 \text{ GeV} \).

\(^2\)If the \( \mu \) parameter is as large as \( m_0 \), there may exist a sizable contribution to the gaugino masses via the Higgs-Higgsino loop. We neglect such a contribution in the present analysis.
Figure 1: $Br(\mu \rightarrow e\gamma)$ as functions of the universal scalar mass $m_0$ and $\tan \beta$ for $M_N = 3 \times 10^{15}$ GeV, $M_{1/2} = m_0$, $a_0 = 0$ and $\text{sign}(\mu) > 0$ in the mSUGRA model. Numbers in the figure are the values of $Br(\mu \rightarrow e\gamma)$. Dark (light) green region satisfies $125 \text{ GeV} < m_h < 127 \text{ GeV}$ ($124 \text{ GeV} < m_h < 128 \text{ GeV}$) and dashed two green lines show $m_h = 120 \text{ GeV}, 130 \text{ GeV}$. For small $\tan \beta$, gray region is excluded by the non-perturbativity of the top Yukawa coupling constant.

In the case of AMSB-type gaugino masses, it should be noted that the negative searches for the gluino signals at the LHC impose significant constraint on $m_{3/2}$; $M_3 \gtrsim 1.1 - 1.2 \text{ TeV}$ requires $m_{3/2} \gtrsim 40 \text{ TeV}$. If $m_0 = m_{3/2}$, $\tan \beta$ is required to be smaller than $\sim 5$ to realize $m_h \simeq 126 \text{ GeV}$; if so, as we can see in Fig. 2, LFV rates are so small that experimental confirmation of the LFV processes becomes really challenging even in future experiments. For non-minimal Kahler potential, we do not have to adopt the relation $m_0 = m_{3/2}$; if so we may have a chance to observe the LFV processes at future experiments even in the case with AMSB-type gaugino masses.

Next, we discuss the electroweak symmetry breaking in the present model, because the existence of right-handed neutrinos may have important effect on it. In Fig. 2 we can see that the successful electroweak symmetry breaking can be realized in the region with large...
Figure 2: $\text{Br}(\mu \rightarrow e\gamma)$ as functions of $m_0$ and $\tan\beta$ for $M_N = 3 \times 10^{15}$ GeV and $m_0 = m_{3/2}$ in the pure gravity mediation model. Numbers in the figure are the values of $\text{Br}(\mu \rightarrow e\gamma)$. Dark (light) green region satisfies $125 \text{ GeV} < m_h < 127 \text{ GeV}$ ($124 \text{ GeV} < m_h < 128 \text{ GeV}$) and dashed two green lines show $m_h = 120 \text{ GeV}, 130 \text{ GeV}$. For small $\tan\beta$, gray region is excluded by the non-perturbativity of the top Yukawa coupling constant. For large $\tan\beta$, there is no correct EWSB minimum in the gray region. The upper (lower) dotted lines show the upperbounds on $\tan\beta$ by correct EWSB conditions for $M_N = 10^{15}$ GeV ($10^{10}$ GeV).

In fact, it is a generic feature that, with too large universal scalar mass compared to the gaugino masses, electroweak symmetry breaking does not occur unless $\tan\beta$ is $\mathcal{O}(1)$. This is due to the fact that, with large $m_0$ and small $M_{1/2}$, it becomes difficult to realize negative $m_{H_u}^2$, which is essential for the electroweak symmetry breaking. Because $m_{H_u}^2 > 0$ at high scale and also because the RG running of $m_{H_u}^2$ terminates at the scale of scalar fermions (which is of the order of $m_0$), $m_0$ should be small enough to make $m_{H_u}^2$ negative by the RG effect. In the present case, $m_{H_u}^2$ is driven to negative by the Yukawa interactions. If right-handed neutrinos do not exist, $m_{H_u}^2 < 0$ is realized by the top Yukawa interaction whose effect is more enhanced for smaller $\tan\beta$ because the top Yukawa coupling constant is proportional to $\sim 1/\sin\beta$ (above the mass scale of superparticles). As a result, for large $m_0$, $\tan\beta$; such a region does not exist in the case without right-handed neutrinos [20].
Figure 3: $\text{Br}(\mu \rightarrow e\gamma)$ as functions of $M_N$ and $M_{1/2}/m_0$ for $m_0 = 20\text{ TeV}$, $\tan \beta = 10, a_0 = 0$ and $\text{sun}(\mu) > 0$ in the mSUGRA model. Numbers in the figure are the values of $\text{Br}(\mu \rightarrow e\gamma)$. Dark (light) green region satisfies $125 \text{ GeV} < m_h < 127 \text{ GeV}$ ($124 \text{ GeV} < m_h < 128 \text{ GeV}$) and dashed green line shows $m_h = 130 \text{ GeV}$. For small $M_N$, there is no correct EWSB minimum in the gray region.

A smaller value of $\tan \beta$ is required to have successful electroweak symmetry breaking if $M_{1/2}$ is relatively small. (If $M_{1/2}$ is comparable to $m_0$, the RG effect enhances the stop masses because of the large gluino mass. In such a case, the enhanced stop masses make it easier to realize $m_{H_u}^2 < 0$.) If there exist right-handed neutrinos, the neutrino Yukawa interactions also reduce the low-energy value of $m_{H_u}^2$, as indicated by Eq. (15); with the high-scale (like the GUT-scale) value of $m_{H_u}^2$ being fixed, the low-scale value of $m_{H_u}^2$ becomes smaller compared to the case without right-handed neutrinos. Thus, in models with large scalar masses, the existence of right-handed neutrinos significantly changes the condition of the electroweak symmetry breaking.

To see the effect of right-handed neutrinos, in Fig. 3 we show the parameter region where electroweak symmetry breaking successfully occurs in the case of mSUGRA-type boundary condition on $M_N$ vs. $M_{1/2}/m_0$ plane. (Here, we take $\tan \beta = 10$ and $m_0 = 20 \text{ TeV}$.) We can see that, with larger value of $M_N$ (corresponding to larger neutrino Yukawa coupling
constant), successful electroweak symmetry breaking becomes possible in the parameter region with the gaugino masses much smaller than $m_0$. This fact indicates that lighter gluino mass becomes allowed in models with right-handed neutrinos, which makes LHC searches for superparticles easier. In the same figure, we also show the contours of constant $Br(\mu \to e\gamma)$. We can see that, in the region of successful electroweak symmetry breaking newly allowed by the effect of right-handed neutrinos, the LFV rates can be sizable and may be within the reach of future experiments.

In summary, we have discussed the LFV rates in SUSY model in which superparticles (in particular, sfermions) are as heavy as $O(10^{-100})$ TeV. The observed Higgs boson mass of 126 GeV suggests the relatively high scale SUSY breaking with such a mass spectrum. In this letter, we show that lepton flavor violating processes such as $\mu \to e\gamma$ can be in a region accessible to future experiments if the gaugino masses are of order of gravitino mass and the right-handed neutrino mass is $O(10^{15})$ GeV suggested by the GUT-like seesaw mechanism. On the other hand, they are more suppressed in the pure gravity mediation model and it may be very challenging to observe the lepton flavor violation in near future experiments. However, the gluino mass can be as small as a few TeV in this model which can be testable at future LHC experiments [33, 34].

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