Decay of Charged Higgs boson in TeV scale supersymmetric seesaw model

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Abstract. We discuss phenomenological consequences of some class of supersymmetric seesaw models in which the right-handed (s)neutrino mass is given to be TeV scale. In this scenario, scalar trilinear interaction of Higgs-slepton-(right-handed) sneutrino is enhanced. We show that the 1-loop correction by sneutrino exchange to the lightest Higgs boson mass destructively interferes with top-stop contributions in the minimal SUSY Standard Model. We find that a decay of charged Higgs boson into sneutrino and charged slepton is sizably enhanced and hence it gives rise to a distinctive signal at future collider experiments in some parameter space.

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1 Introduction

The seesaw mechanism [1] is one of the most attractive explanation of small neutrino masses. The heavy right-handed neutrinos are introduced in the seesaw mechanism, and resulting small neutrino mass eigenvalues is given by $m_\nu \approx (Y_\nu v)^2/m_N$, where $m_N$ and $v$ are the mass of right-handed neutrino and the vacuum expectation value (v.e.v.) of the Higgs boson, respectively. To explain the smallness of $m_\nu$, the right-handed neutrino mass $m_N$ should be much more larger than electroweak scale if the Yukawa coupling $Y_\nu$ is close to order unity. Therefore, we cannot hope to test the seesaw mechanism through searching for the right-handed neutrino at collider experiments. Thus it is reasonable to consider a possibility to lower the scale of seesaw mechanism (scale of right-handed neutrino mass) as low as testable at collider experiments.

It has been discussed such possibilities to explain the small neutrino mass as a consequence of supersymmetry (SUSY) breaking in refs. [2]–[4]. The phenomenological aspects of this class of models can be summarized as follows: (i) light (TeV scale) right-handed sneutrino due to the Giudice-Masiero mechanism [5] and (ii) enhancement of scalar trilinear interaction among the right-handed sneutrino, left-handed slepton and Higgs bosons. In the minimal SUSY SM (MSSM), the scalar three-point vertices are suppressed by small Yukawa couplings for the first two generations of squarks and sleptons. In the models of refs. [2]–[4], however, the scalar trilinear interaction of the right-handed sneutrino is not suppressed by the neutrino Yukawa coupling, as mentioned above.

In this work [6], we investigate phenomenological consequences of a scenario of TeV scale right-handed neutrino inspired by supersymmetric models in refs. [2]–[4], focusing on the unsuppressed coupling $A_\nu$. We first study the 1-loop corrections to the lightest Higgs boson mass through the sneutrino exchange which is proportional to some powers of $A_\nu$. We show that the sneutrino contribution destructively interferes with the MSSM contribution. We next study decay processes of charged Higgs boson [2]. The decay of charged Higgs boson into the sneutrino and selectron could be enhanced as compared to the MSSM because of $A_\nu$. We find that, in some parameter space, the branching ratio of this decay mode can be as large as 10%, and it may be detectable at future linear collider experiments. Although this scenario has a possibility if the neutrino is Majorana or Dirac [3,7], our study is available in both cases if the SUSY breaking $B$-term of sneutrino in the Majorana case is assumed to be small enough so that, in addition to suppress the 1-loop correction to the mass of lighter neutrino, the sneutrino mass matrix has common structure in both cases.

2 Sneutrino mass spectrum

We first show the sneutrino mass spectrum for later convenience. When the SUSY breaking $B$-term of sneutrino is neglected, the mass matrix of sneutrinos in a basis of $(\tilde{\nu}_L, \tilde{\nu}_R)$ is given by

$$M_\tilde{\nu}^2 = \begin{pmatrix} m_{\tilde{\nu}_L}^2 & A_\nu v \sin \beta \\ A_\nu v \sin \beta & m_{\tilde{\nu}_R}^2 \end{pmatrix} ,$$

$$m_{\tilde{\nu}_L}^2 = m_{\tilde{\nu}_L}^2 + \frac{1}{2} \cos 2\beta m_Z^2 ,$$

where $m_{\tilde{\nu}_L}$ and $m_{\tilde{\nu}_R}$ are the mass of left-handed and right-handed sneutrino, respectively.
Fig. 1. The lighter sneutrino mass $m_{\tilde{\nu}}$ as a function of $A_\nu$ for $\tan \beta = 3$. Three lines correspond to $m_{\tilde{\nu}} = 120\, \text{GeV}$ (solid), $150\, \text{GeV}$ (dashed) and $180\, \text{GeV}$ (dotted). The results are obtained by taking $m^2_{\nu_L} = m^2_{\nu_R}$.

Fig. 2. The ratio $R_h$ defined as $R_h \equiv m_h/m_{h_{\text{MSSM}}}$ as a function of $A_\nu$. Each line correspond to combinations of $\tan \beta = 3, 30$ and $m_{\tilde{\chi}} = 300, 500\, \text{GeV}$ as indicated. The 1-loop correction from the top-stop loop is evaluated following ref. [12] using the stop mass $m_{\tilde{\chi}} = 1\, \text{TeV}$. The Higgs mass $m_h$ at $A_\nu = 0$ corresponds to the MSSM prediction.

where $m_L$ is the soft scalar mass for the SU(2)$_L$ doublet slepton while $m_{\tilde{e}_R}$ is for the right-handed sneutrino. We neglect the generation mixings the whole this work. The angle $\beta$ is defined as $\tan \beta \equiv v_u/v_d$, where $v_u$ and $v_d$ are v.e.v. of the Higgs bosons with $Y = 1/2$ and $-1/2$, respectively. A parameter $v$ is normalized as $v \equiv \sqrt{v_u^2 + v_d^2} \approx 246\, \text{GeV}$. The mass matrix \ref{eq:2} can be diagonalized using an unitary matrix $U_{\nu}$.

\begin{equation}
(U_{\nu})^\dagger M^2 U_{\nu} = \text{diag}(m_{\tilde{\nu}_1}, m_{\tilde{\nu}_2}), \quad (m_{\tilde{\nu}_1} < m_{\tilde{\nu}_2}). \quad (3)
\end{equation}

In the MSSM, the sneutrino mass is given by \ref{eq:3}. Note that $m^2_{\nu_L}$ satisfies the following relation with the mass of left-handed selectron $e_L$ due to the SU(2)$_L$ symmetry: $m^2_{\tilde{\nu}_L} - m^2_{\tilde{e}_L} = (-1 + s_W^2) m^2_Z \cos 2\beta$. Since $\cos 2\beta < 1$ for $\tan \beta > 1$, the mass of sneutrino in the MSSM is always smaller than the selectron mass when $\tan \beta > 1$. On the other hand, the lighter sneutrino mass \ref{eq:4} is independent of the mass of the left-handed selectron and can be much lighter than the sneutrino in the MSSM.

In Fig. \ref{fig:1}(a), we show the lighter sneutrino mass $m_{\tilde{\nu}_1}$ as a function of $A_\nu$ for $\tan \beta = 3$. Three lines correspond to $m_{\tilde{\nu}_L} = 120\, \text{GeV}$ (solid), $150\, \text{GeV}$ (dashed) and $180\, \text{GeV}$ (dotted). For the right-handed sneutrino mass, we take $m_{\tilde{\nu}_R} = m_{\tilde{\nu}_L}$ for convenience. Note that the mass $m_{\tilde{\nu}_2}$ at $A_\nu = 0$ corresponds to that in the MSSM. The figure tells us that the large left-right mixing of sneutrino is induced by large $A_\nu$, makes a sneutrino much lighter than that in the MSSM.

3 Sneutrino contribution to the lightest Higgs boson mass

The lightest Higgs boson mass $m_h$ receives large 1-loop corrections mainly from the top quark and the stop exchanging diagram \ref{fig:2}[9][10]. In the scenario of TeV scale $\nu_R$ mass with sizable $A_\nu$, the $\nu_L$-$\nu_R$-h interaction could give a new contribution to the lightest Higgs boson mass at 1-loop level. Using the renormalization group method used in ref. [9], we evaluate the sneutrino contribution to $m_h$.

Let us take the large limit of the SUSY breaking mass scale $m_{\text{SU(2)}}$ so that physics below $m_{\text{SU(2)}}$ is described by the Standard Model. Then the lightest Higgs boson mass $m_h$ is simply parametrized by $m_h^2 = \lambda h^2$, where $\lambda$ is a quartic coupling in the Higgs potential. Note that the quartic coupling at the tree level, $\lambda_{\text{tree}}$, satisfies the SUSY relation $\lambda_{\text{tree}} = (g^2 + g^2) / 2 \beta / 3$, where $g$ and $g$ are the U(1)$_Y$ and SU(2)$_L$ gauge couplings, respectively. The radiative corrections to the quartic coupling $\lambda$ in the MSSM can be found in, for example, ref. [9]. In the scenario of large $A_\nu$, the interaction $\tilde{\nu}_L$-$\tilde{\nu}_R$ gives rise to the sneutrino exchanging box diagram as the 1-loop correction to the quartic coupling $\lambda$. The sneutrino contribution, $\lambda_{\nu}$, can be evaluated as

\begin{equation}
\lambda_{\nu} = -\frac{A^4}{4(4\pi)^2} \sum_{i,j,k=1}^2 |U_{1i}^2| |U_{2j}^2| |U_{1k}^2| |U_{2l}^2|^2 \times D_0(m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\nu}_k}, m_{\tilde{\nu}_l}), \quad (4)
\end{equation}

where $D_0$ is the 1-loop scalar function.

We compare, in Fig. \ref{fig:2} a ratio of the Higgs boson mass in our scenario and in the MSSM which is defined as $R_h \equiv m_h/m_{h_{\text{MSSM}}}$, where $m_h$ and $m_{h_{\text{MSSM}}}$ are the lightest Higgs boson mass in our scenario and the Higgs mass in the MSSM, respectively. In the figure, the 1-loop corrections in the MSSM are estimated following ref. [12] with the stop mass $m_{\tilde{\chi}} = 1\, \text{TeV}$. Solid and dotted lines denote $m_{\tilde{\chi}} = 300\, \text{GeV}$ and $500\, \text{GeV}$, respectively. Thin and thick lines are $\tan \beta = 3$ and $50$.
4 Decay of charged Higgs boson

We next examine a decay $H^- \rightarrow \tilde{\nu}_L + \ell$, where $H^-$ stands for a charged Higgs boson. In particular, a case of $\ell = \tilde{\ell}$ could be a distinctive process of our scenario that such process is strongly suppressed in the MSSM due to the electron Yukawa coupling. So, we consider only the case of $\ell = \tilde{\ell}$ in the following study. In the MSSM, it is known that for $m_{H^-} > 200$GeV, $H^-$ dominantly decays into the top and bottom quarks owing to the sizable Yukawa couplings (for a review of various decay channels of the charged Higgs boson in the supersymmetric models, see ref. [11]). The $\tau + \nu_\tau$ mode is subdominant for large tan $\beta (\gtrsim 10)$ due to the tau-Yukawa coupling. On the other hand, when $\nu_\tau$ is sizable, it is expected that the decay mode $H^- \rightarrow \tilde{\nu}_L + \tilde{\ell}$ is enhanced in small tan $\beta$ region because the decay vertex is proportional to $A_\nu \cos \beta$.

In Fig. 3 we show branching ratios of some decay modes of the charged Higgs boson with $m_{H^-} = 350$GeV as functions of tan $\beta$. We assume that squarks are heavy enough so that the decay modes into squarks are kinematically forbidden. Heavy squarks are also favored to make the lightest Higgs boson heavy through the radiative corrections, against for the negative contribution to $m_h$ from the sneutrino exchange diagrams. The sneutrino and selectron masses are chosen as $m_{\tilde{\nu}_1} = 50$GeV and $m_{\tilde{e}_L} = 200$GeV, respectively. The trilinear coupling of right-handed sneutrino $A_\nu$ is fixed at 500GeV. Then the heavier sneutrino mass ($m_\nu > m_{\tilde{\ell}}$) is about 700GeV. As already mentioned, we assumed the flavor universality of $A_\nu$, so the branching ratio of decay into the sneutrino and smuon, or stau, is same with the sneutrino mode shown in the figure. As an example, the branching ratio of decay into charginos ($\tilde{\chi}_1^\pm$, $i = 1, 2$) and neutralinos ($\tilde{\chi}_j^0$, $j = 1, 4$) is examined for $m_{\tilde{\nu}_1} = 150$GeV with $M_2/\mu = 5$ in Fig. 3(a) and $M_2/\mu = 5$ in Fig. 3(b), where $M_2$ and $\mu$ stand for the $SU(2)_L$ gaugino mass and the higgsino mass, respectively. The $U(1)_Y$ gaugino mass $M_1$ is obtained using the GUT relation, $M_1/\alpha_Y = (5/3)(M_2/\alpha_2)$, where $\alpha_i (i = Y, 2)$ are given as $\alpha_i = g_i^2/(4\pi)$. Then the mass of lightest neutralino is given as $m_{\tilde{\chi}_1^0} \sim 142$GeV in Fig. 3(a) and 93GeV in Fig. 3(b).

The ratio $M_2/\mu$ determines the properties of the lighter chargino and the lightest neutralino. When $M_2/\mu \ll 1$ the lighter chargino is mostly the SU(2)$_L$ gaugino while the relation $M_2/\mu \gg 1$ corresponds to the higgsino dominant case. For $M_2/\mu = 5$, both the lighter chargino and the lightest neutralino are higgsino dominant, so that the decay $H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$ is highly suppressed because there is no Higgs-higgsino-higgsino coupling. This explains the difference of Br($H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$) between Figs. 3(a) and (b).

It can be seen from Fig. 3 that the branching ratio of $H^- \rightarrow \tilde{\nu}_L + \ell$ mode could be as large as 10% for small tan $\beta (\lesssim 3)$. In the MSSM, the charged Higgs boson can decay into $\tilde{\nu}_L$ and $\tilde{e}_R$. For comparison, we fix the mass of $\tilde{e}_R$ as $m_{\tilde{e}_R} = m_{\tilde{e}_L} = 200$GEV. Then the decay mode $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_R$ is kinematically forbidden because the sneutrino $\tilde{\nu}_L$ cannot be much lighter than $\tilde{e}_L$ due to the SU(2)$_L$ relation (note that $m_{\tilde{e}_R} = m_{\tilde{e}_L} = 200$GEV). Therefore, if the charged Higgs boson mass does not differ so much from the masses of charged sleptons, the decay $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_R$ in the MSSM is strongly suppressed.

We next study a signal of the decay $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_L$ in some detail. For our choice of the inputs used in Fig. 3 the selectron $\tilde{e}_L$ dominantly decays into the lightest neutralino and an electron, $\tilde{e}_L \rightarrow \chi_1^0 + e$. Then, since the branching ratio of the $\tilde{\nu}_L + \tilde{e}_L$ mode is roughly 10% for small tan $\beta$ region, a probability which we find an electron from this decay mode can be estimated as $Br(H^- \rightarrow \tilde{\nu}_L + \tilde{e}_L) \times Br(\tilde{e}_L \rightarrow e + \chi_1^0) \approx 10%$. The electron is also coming out from the W boson of the decay $H^- \rightarrow W + h$, and the chargino of the decay $H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$. From Fig. 3 we find that Br($H^- \rightarrow W + h$) $\lesssim 3\%$ and the leptonic decay of the W boson is known as Br($W \rightarrow \nu + e$) $\lesssim 10.8\%$[13]. It leads to $Br(H^- \rightarrow W + h) \times Br(W \rightarrow \nu + e) \lesssim 0.3\%$. In case of Fig. 3(a), therefore, the background from $H^- \rightarrow W + h$ is much suppressed. In case of $H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$, the branching ratio is Br($H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$) is about 1% and Br($\tilde{\chi}_1^- \rightarrow e + \tilde{\nu}$) is roughly 30% per each lepton flavor. Thus Br($H^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0$) $\times Br(\tilde{\chi}_1^- \rightarrow e + \tilde{\nu})$ is about 0.3%.

As shown in Fig. 3(b), however, if the lighter chargino is dominantly gaugino, the branching ratio of the chargino-neutralino mode increases, so that the branching ratio of $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_L$ is relatively decreased. In this case we estimate the probability that the electron is found in the $\tilde{\chi}_1^- + \chi_1^0$ mode of the charged Higgs decay as $Br(H^- \rightarrow \tilde{\chi}_1^- + \chi_1^0) \times Br(\tilde{\chi}_1^- \rightarrow e + \tilde{\nu}) \approx 10\%$. This competes with the probability that an electron is coming out from the $\tilde{\chi}_1^- + \tilde{\nu}_1$ decay. We conclude that, even in our specific choice of parameter set, the $\tilde{\chi}_1^- + \chi_1^0$ mode could be a serious background to search the decay $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_L$ when the chargino and neutralino are almost gauginos.

We would like to discuss the testability of the scenario of light $\tilde{\nu}_R$ with unsuppressed $A_\nu$, at future collider experiments using the decay $H^- \rightarrow \tilde{\nu}_L + \tilde{e}_L \rightarrow e + \tilde{\nu}_R$. An important point is to identify that the observed


5 Summary

In this work, we have studied phenomenology of the scenario of TeV scale right-handed sneutrino inspired by models of SUSY breaking inspired neutrino mass [2,3]. The important prediction of this scenario is that the sneutrino trilinear coupling $A_\nu$ could be sizable and is not suppressed by the neutrino Yukawa coupling. We found that the sneutrino contribution to the lightest Higgs boson mass is destructively interferes with the ordinary MSSM contributions and may be lowered in this model via sneutrino exchange with large $A_\nu$. The large $A_\nu$ also affects the decay of charged Higgs boson. It is shown that the process $H^- \rightarrow \tilde{\nu}_1 + \tilde{e}_L$ could be subdominant decay mode in some parameter region and the branching ratio is roughly $\sim 10\%$ for small $\tan\beta$. In such parameter region, the excess of the electrons in the charged Higgs decay could be a signal of the TeV $\tilde{\nu}_R$ scenario.

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