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New Production Mechanism of Neutral Higgs Bosons with Right scalar tau neutrino as the LSP

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Abstract

Motived by the neutrino oscillation data, we consider the lightest tau sneutrino $\tilde{\nu}_{\tau_1}$ (which is mostly the right tau sneutrino) to be the lightest supersymmetric particle (LSP) in the framework of the minimal supersymmetric Standard Model. Both the standard and the non-standard trilinear scalar coupling terms are included for the right tau sneutrino interactions. The decay branching ratio of $\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0$ can become so large that the production rate of the lightest neutral Higgs boson (h^0) can be largely enhanced at electron or hadron colliders, either from the direct production of $\tilde{\nu}_{\tau_2}$ or from the decay of charginos, neutralinos, sleptons, and the cascade decay of squarks and gluinos, etc. Furthermore, because of the small LSP annihilation rate, $\tilde{\nu}_{\tau_1}$ can be a good candidate for cold dark matter.

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I. INTRODUCTION

Supersymmetry (SUSY) has been largely studied as a possible framework for the theory beyond the Standard Model (SM). It provides a natural solution to the hierarchy problem, the generation of the electroweak symmetry breaking, as well as the grand unification of the gauge coupling constants [1]. Among the various supersymmetric models, the minimal supersymmetric Standard Model (MSSM) is the one studied most extensively in the literature [1]. In addition to the SM particles, it consists of the supersymmetric partners of the SM particles, called sparticles. All renormalizable interactions, including both SUSY conserving and (soft) SUSY breaking terms, are assumed to conserve the $B-L$ global symmetry, which then results in the conservation of the R-parity, $R = (-1)^{3(B-L)+2S}$. (B denotes the baryon number, L the lepton number, and S the spin of the (s)particle.) Accordingly, all the SM particles have even R-parity and the sparticles have odd R-parity. This fact has an important consequence, namely, if the initial particles of a scattering process are the SM particles, then sparticles can only be produced in pairs. R-parity conservation also implies the existence of a stable sparticle, called the lightest supersymmetric particle (LSP). The LSP is absolutely stable and cannot decay.

Recently, the Super-K neutrino experiment presented the high precision neutrino oscillation data which strongly suggests the existence of the neutrino mass [2]. Many SUSY models have been proposed to account for a reasonable set of neutrino masses with bi-maximal mixing among the three family neutrinos [3]. The low energy effective theory of these SUSY models can be summarized in the supersymmetric extension of the see-saw model, in which a right-handed neutrino superfield is added for each family in the framework of the MSSM [4]. As proposed in [3], the observed bi-maximal mixing in neutrino data can be explained by the single right-handed neutrino dominance mechanism, which assumes that the light effective Majorana matrix come predominantly from a single right-handed neutrino which generates some particular textures of the Yukawa couplings in the superpotential of the low energy effective theory. With that example in mind, we assume the bi-maximal mixing among the three family neutrinos does not necessarily imply a large mixing among different flavor sneutrinos because the attendant R-parity conserving soft-supersymmetry breaking terms are not fixed by the generation of neutrino masses or mixings. Furthermore, the trilinear scalar coupling terms introduced by supersymmetry breaking can be large in some SUSY models. For simplicity, we shall only consider a one family model, though its phenomenology is expected to be applicable to three family models after properly including possible mixing factors.

Despited that the conventional supersymmetric see-saw models predict heavy right sneutrinos, we presume the existence of SUSY models, in which the interactions of right sneutrinos with left sneutrinos at the weak scale are described by Eqs.(1), (2) and (3) with R-parity conservation in the framework of MSSM, which may or may not include lepton number violation interactions. We study the scenario that the lightest sneutrino, mostly the right tau sneutrino $\tilde{\nu}_{\tau_R}$, is the LSP. To further simplify our discussion, we also assume that the mixings among the three generation sneutrinos are small enough that the dominant effect to collider phenomenology comes from the interaction of left and right tau sneutrinos. In section II, we give our assumptions and formalism for the $\tilde{\nu}_{\tau_1}$-LSP scenario. In section III, we discuss the possible large production rate of the lightest neutral Higgs boson predicted by this model at electron and hadron colliders. We also show that with a small left-right mixing, a $\tilde{\nu}_{\tau_R}$-like $\tilde{\nu}_{\tau_1}$ can be a good candidate for cold dark matter. In section IV, we consider in details some e^+e^- collider phenomenology for the $\tilde{\nu}_{\tau_1}$-LSP model. Section V contains our conclusion.

II. $\tilde{\nu}_{\tau_1}$-LSP SCENARIO

In our one family model, the scalar tau neutrinos, like scalar quarks and scalar leptons, can mix and form mass eigenstates, and

$$\begin{pmatrix} \tilde{\nu}_{\tau_2} \\ \tilde{\nu}_{\tau_1} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{\nu}} & \sin\theta_{\tilde{\nu}} \\ -\sin\theta_{\tilde{\nu}} & \cos\theta_{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_{\tau_L} \\ \tilde{\nu}^*_{\tau_R} \end{pmatrix}, \tag{1}$$

with

$$\tan 2\theta_{\tilde{\nu}} = \frac{2\Delta m^2}{m^2_{\tilde{\nu}_{\tau_L}} - m^2_{\tilde{\nu}_{\tau_R}}}\,, \tag{2}$$

where $\tilde{\nu}_{\tau_L}$ and $\tilde{\nu}_{\tau_R}$ stand for the left and right tau sneutrinos, and $m^2_{\tilde{\nu}_{\tau_L}}$ and $m^2_{\tilde{\nu}_{\tau_R}}$ are the corresponding soft masses, respectively. We consider the case that the parameter Δm^2 mainly comes from the soft SUSY breaking effect originated from the trilinear scalar couplings in

$$\Delta\mathcal{L} = A_{\rm V} H_2 \tilde{L}_3 \tilde{\nu}_{\tau_R} + C_{\rm V} H_1^* \tilde{L}_3 \tilde{\nu}_{\tau_R} + \text{c.c.} \tag{3}$$

where $A_{\rm V}(C_{\rm V})$ is the standard (non-standard) trilinear scalar coupling, H_1 and H_2 are the two Higgs doublets and $\tilde{L}_3$ is the third generation scalar lepton doublet. (To simplify our discussion, we have assumed that the contribution to Δm^2 from the μ-term in the superpotential is much smaller than that from $\Delta\mathcal{L}$, because of the small Yukawa coupling of tau neutrino.) The parameter Δm^2 arises after the Higgs doublets H_1 and H_2 acquiring their vacuum expectation values v_1 and v_2, and

$$\Delta m^2 \approx v\left(A_{\rm V}\sin\beta - C_{\rm V}\cos\beta\right)\,, \tag{4}$$

with $v = \sqrt{v_1^2 + v_2^2} \approx 176$ GeV and the angle $\beta = \tan^{-1}(v_2/v_1)$. As shown in Eq.(3), we have included the non-standard trilinear scalar coupling $C_{\rm V}$ in the soft-supersymmetry-breaking scalar potential to extend the applicability of our effective model. As to be shown later, a special value of $C_{\rm V}$ can lead to distinct collider signatures. The masses of the mass eigenstates $\tilde{\nu}_{\tau_1}$ and $\tilde{\nu}_{\tau_2}$ are given by $m^2_{\tilde{\nu}_{\tau_1},\tilde{\nu}_{\tau_2}} = (m^2_{\tilde{\nu}_{\tau_L}} + m^2_{\tilde{\nu}_{\tau_R}} \mp \sqrt{(m^2_{\tilde{\nu}_{\tau_L}} - m^2_{\tilde{\nu}_{\tau_R}})^2 + 4(\Delta m^2)^2})/2$, with $m_{\tilde{\nu}_{\tau_1}} < m_{\tilde{\nu}_{\tau_2}}$. In terms of the sneutrino masses, the sneutrino mixing factor $\sin 2\theta_{\tilde{\nu}}$ can be written as:

$$\sin 2\theta_{\tilde{\nu}} = \frac{2\Delta m^2}{m^2_{\tilde{\nu}_{\tau_2}} - m^2_{\tilde{\nu}_{\tau_1}}}\,. \tag{5}$$

Since we require a positive mass for the lightest tau sneutrino $\tilde{\nu}_{\tau_1}$, we must have the mass parameters satisfy the following constraint:

$$m^2_{\tilde{\nu}_{\tau_L}} m^2_{\tilde{\nu}_{\tau_R}} > (\Delta m^2)^2\,. \tag{6}$$

Under the $\tilde{\nu}_{\tau_1}$-LSP scenario, the LSP can be generated either through the direct productions in high energy collision or through the decay of heavy sparticles, such as the next-to-lightest supersymmetric particle (NLSP) and the heavy tau sneutrinos $\tilde{\nu}_{\tau_2}$. It can also be pair-produced through the Z boson decay if the $\tilde{\nu}_{\tau_1}$ mass is smaller than one half of the Z mass. The partial decay width for the Z boson decaying into a $\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}$ pair is given at the tree level as:

$$\Gamma(Z \to \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}) = \frac{\alpha_{em}(\cot\theta_W + \tan\theta_W)^2 \sin^4\theta_{\tilde{\nu}}}{48} m_Z \left[1 - \frac{4m^2_{\tilde{\nu}_{\tau_1}}}{m_Z^2}\right]^{3/2}, \tag{7}$$

where θ_W is the weak mixing angle and α_{em} is the fine structure constant evaluated at the Z-mass scale m_Z. Clearly, the partial decay width $\Gamma(Z \to \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1})$ depends on the $\tilde{\nu}_{\tau_1}$ mass and the mixing angle $\sin\theta_{\tilde{\nu}}$. From the experimental data at LEP and SLC, the invisible decay channel of Z boson is bounded from above, and $\Delta\Gamma(Z \to \text{invisible}) < 2$ MeV [7]. Though this experimental constraint is automatically satisfied for the lightest tau sneutrino mass $m_{\tilde{\nu}_{\tau_1}}$ to be larger than one half of the Z-boson mass, it does not excludes the possibility that $m_{\tilde{\nu}_{\tau_1}}$ can be very small as compared to $m_Z/2$. Indeed, we find that $m_{\tilde{\nu}_{\tau_1}}$ can take any small value as long as the mixing angle $\sin\theta_{\tilde{\nu}}$ is smaller than about 0.39. Because $\tilde{\nu}_{\tau_L}$ carries the electroweak quantum number and $\tilde{\nu}_{\tau_R}$ is a singlet field, a SUSY model usually predicts the soft mass parameter $m_{\tilde{\nu}_{\tau_L}}$ to be larger than $m_{\tilde{\nu}_{\tau_R}}$ at the weak scale, after including the running effect of the renormalization group equations. This case is assumed hereafter. From Eqs.(2) and (6), we conclude that the soft mass parameter Δm should be less than $m_{\tilde{\nu}_{\tau_L}}\sqrt{\tan\theta_{\tilde{\nu}}}$, and $m_{\tilde{\nu}_{\tau_L}} < m_{\tilde{\nu}_{\tau_R}}\cot\theta_{\tilde{\nu}}$. Consequently, as an example, for $m_{\tilde{\nu}_{\tau_L}}$ to be 200 GeV, the upper bound on Δm is about 130 GeV, which imposes a constraint on the values of $A_{\rm V}$ and $C_{\rm V}$ for a fixed $\tan\beta$. (Following the method in Ref. [5], we have checked that in this model, there is no useful bound on the value of $A_{\rm V}$, assuming $C_{\rm V} = 0$, from requiring the absence of dangerous charge and color breaking minima or unbounded from below directions.) For $\sin\theta_{\tilde{\nu}} > 0.39$, a larger $\sin\theta_{\tilde{\nu}}$ requires a larger $m_{\tilde{\nu}_{\tau_1}}$, e.g., when $\sin\theta_{\tilde{\nu}}$ is 0.5, the minimal allowed value for $m_{\tilde{\nu}_{\tau_1}}$ is 32 GeV. Our results are summarized in Fig.1, which shows the allowed parameter space on the $(\sin\theta_{\tilde{\nu}}, m_{\tilde{\nu}_{\tau_1}})$ parameter plane. (Only the allowed range for $m_{\tilde{\nu}_{\tau_1}} < m_Z/2$ is shown. For $m_{\tilde{\nu}_{\tau_1}} > m_Z/2$, $\sin\theta_{\tilde{\nu}}$ can take any value within 1.)

III. NEW PRODUCTION MECHANISM OF HIGGS BOSONS AT COLLIDERS

The trilinear scalar couplings for the neutral Higgs bosons and tau sneutrinos can be derived from Eqs.(1) and (3) as:

$$\begin{aligned}\Delta\mathcal{L} = &\{H^0(A_{\rm V}\sin\alpha - C_{\rm V}\cos\alpha) + h^0(A_{\rm V}\cos\alpha + C_{\rm V}\sin\alpha)\}\{\sin 2\theta_{\tilde{\nu}}(\tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_2} - \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}) \\ &+ \cos 2\theta_{\tilde{\nu}}(\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_2} + \tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_1})\}/\sqrt{2} + iA^0(A_{\rm V}\cos\beta + C_{\rm V}\sin\beta)(\tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_1} - \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_2})/\sqrt{2}\,,\end{aligned} \tag{8}$$

where h^0 is the lightest CP-even neutral Higgs boson, H^0 denotes the other CP-even neutral Higgs boson and A^0 is the CP-odd neutral Higgs particle. The phase angle α defines the mass eigenstates of h^0 and H^0.

When the mixing angle $\theta_{\tilde{\nu}}$ is small, the lightest sneutrino $\tilde{\nu}_{\tau_1}$ (which is almost $\tilde{\nu}_{\tau_R}$-like) predominantly interacts with $\tilde{\nu}_{\tau_2}$ (which is almost $\tilde{\nu}_{\tau_L}$-like) via the scalar interactions, cf.

$\Delta\mathcal{L}$. Hence, to study the production of the LSP $\tilde{\nu}_{\tau_1}$, it is desirable to first examine the decay and the production of $\tilde{\nu}_{\tau_2}$.

When $\tilde{\nu}_{\tau_2}$ is produced at colliders, it may decay into the tau neutrino ν_τ and the neutralino $\tilde{\chi}^0_1$ (or $\tilde{\chi}^0_2$), or into the Higgs particle h^0 and the lightest sneutrino $\tilde{\nu}_{\tau_1}$, assuming the other modes either are forbidden by mass relation or have negligible partial decay widths.) The branching ratios (BR) of these two decay modes depend on the SUSY parameters. For illustration, we give their tree level partial decay widths as follows:

$$\Gamma(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} h^0) = \frac{\cos^2 2\theta_{\tilde{\nu}} |A_{\rm V} \cos\alpha + C_{\rm V} \sin\alpha|^2}{32\pi m_{\tilde{\nu}_{\tau_2}}} \times \sqrt{\left[\left(1 + \frac{m_{h^0}}{m_{\tilde{\nu}_{\tau_2}}}\right)^2 - \frac{m^2_{\tilde{\nu}_{\tau_1}}}{m^2_{\tilde{\nu}_{\tau_2}}}\right]\left[\left(1 - \frac{m_{h^0}}{m_{\tilde{\nu}_{\tau_2}}}\right)^2 - \frac{m^2_{\tilde{\nu}_{\tau_1}}}{m^2_{\tilde{\nu}_{\tau_2}}}\right]}, \tag{9}$$

$$\Gamma(\tilde{\nu}_{\tau_2} \to \nu_\tau \tilde{\chi}^0_j) = \frac{\alpha_{em} m_{\tilde{\nu}_{\tau_2}} \cos^2\theta_{\tilde{\nu}}}{8} \left|\frac{V_{1j}}{\cos\theta_W} - \frac{V_{2j}}{\sin\theta_W}\right|^2 \left(1 - \frac{m^2_{\tilde{\chi}^0_j}}{m^2_{\tilde{\nu}_{\tau_2}}}\right)^2, \tag{10}$$

where V_{1j} and V_{2j}, for $j = 1, 2, 3, 4$, denote the matrix elements of the diagonalizing matrix for the neutralino mass matrix [6]. Based on Eqs.(9) and (10), we plot in Fig.2(a) the branching ratio $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ for $m_{\tilde{\nu}_{\tau_2}} = 200$ GeV, $m_{\tilde{\nu}_{\tau_1}} = 20$ GeV and $m_{h^0} = 130$ GeV, as a function of $A_{\rm V}$, with $C_{\rm V} = 0$ and $\tan\beta = 2$. (The constraint from the invisible decay width of Z boson requires $A_{\rm V} < 96$ GeV, with $\sin\theta_{\tilde{\nu}} < 0.42$, cf. Fig.1 and Eq.(5).) Four curves for different neutralino mixing scenarios are plotted. The first two curves (B1 and B2) are for $\tilde{\chi}^0_1$-NLSP to be Bino-like, in which we have assumed the common soft SUSY breaking masses $m_1 = 100$ GeV, $m_2 = 200$ GeV and $\tan\beta = 2$, but with different μ values: $\mu = 500, -500$ GeV. The third curve (M) is for the mixed-type $\tilde{\chi}^0_1$-NLSP scenario, in which $\mu = -100$ GeV. The last one (H) is for the Higgsino-like $\tilde{\chi}^0_1$-NLSP scenario, in which $m_1 = 200$ GeV, $m_2 = 400$ GeV and $\mu = -100$ GeV. As shown in the figure, the branching ratio increases as $A_{\rm V}$ increases. Furthermore, due to the small Yukawa coupling of the $\tilde{\nu}_{\tau_2}$-higgsino-ν_τ interaction, the branching ratio $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ increases rapidly under the Higgsino-like $\tilde{\chi}^0_1$-NLSP scenario.

The amusing feature of the model is that the lightest neutral Higgs boson h^0 can be largely produced at either electron or hadron colliders from the decay of $\tilde{\nu}_{\tau_2}$, which is mainly $\tilde{\nu}_{\tau_{\rm L}}$ when the left-right mixing angle is small. Since a left sneutrino $\tilde{\nu}_{\tau_{\rm L}}$ carries electroweak quantum number, it can be produced directly in collisions, or indirectly from the decay of charginos, neutralinos, sleptons, and the cascade decay of squarks and gluinos, etc. There are plenty of studies in the literature to show that the production rates of the above mentioned sparticles at the current and future colliders can be very large, depending on the SUSY parameters [8]. In that case, our model would predict a large production rate of events including either single h^0 or multiple h^0's, provided that $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ is large enough. Many of the events including h^0's can also contain single or multiple isolated leptons and/or photons with large transverse momentum, so it will not be difficult to trigger on such events experimentally. Due to the limited space in this short Letter, we cannot explore all the interesting possibilities in details for various colliders. Instead, we shall illustrate the above observation for the future Linear Collider (LC) in the next section.

Before closing this section, we remark that, in contrast to the $\tilde{\nu}_{\tau_{\rm L}}$-LSP scenario, a $\tilde{\nu}_{\tau_{\rm R}}$-

like $\tilde{\nu}_{\tau_1}$ can be a good candidate for the cold dark matter (CDM). The left sneutrino had been suggested in the literature to be the LSP in the MSSM [9]. They can annihilate rapidly in the early universe via s-channel Z-boson and t-channel neutralino and chargino exchanges. To reduce the LSP annihilation and obtain an acceptable relic abundance, it was proposed that the left sneutrinos should be either as light as $m_{\tilde{\nu}} \approx 2$ GeV or as heavy as 550 GeV $< m_{\tilde{\nu}} <$ 2300 GeV [10]. However, both of these proposals have been excluded by experiments. The light $\tilde{\nu}_L$ scenario was excluded by the measurements of Z decay width, and the heavy $\tilde{\nu}_L$ scenario was excluded by the Heidelberg-Moscow direct detection experiment [11]. Since a $\tilde{\nu}_{\tau_\mathrm{R}}$-like $\tilde{\nu}_{\tau_1}$ interacts with other particles mainly through the left-right sneutrino mixing or the trilinear scalar coupling $\tilde{\nu}_{\tau_\mathrm{R}}$-$\tilde{\nu}_{\tau_\mathrm{L}}$-$h^0$, the LSP annihilation cross sections are generically small due to the presence of the small $\sin^4\theta_{\tilde{\nu}}$ or $\sin^2\theta_{\tilde{\nu}}$ factors coming from the mixing effect or the couplings. Comparing to the $\tilde{\nu}_L$-LSP annihilation in the ordinary MSSM [12], the $\tilde{\nu}_{\tau_1}$-LSP annihilation rate via the exchange of Z-boson, neutralinos, or charginos, is suppressed by a factor of $\sin^4\theta_{\tilde{\nu}}$ because the mixing of $\tilde{\nu}_{\tau_\mathrm{R}}$ and $\tilde{\nu}_{\tau_\mathrm{L}}$ yields a factor of $\sin\theta_{\tilde{\nu}}$ in the scattering amplitude. In addition to the usual MSSM processes, $\tilde{\nu}_{\tau_1}$ can also annihilate via an s-channel Higgs boson to produce light fermion pairs, whose scattering amplitude is suppressed by a factor of $\sin\theta_{\tilde{\nu}}$. Notice that the above rate can strongly depend on $\tan\beta$ because of the coupling of Higgs boson and fermions (such as bottom quarks). In lack of a complete SUSY model which gives the mass spectrum of the sparticles, and the $\tilde{\nu}_{\tau_1}$ annihilation rate depends on the details of the MSSM parameters, we only remark that with the additional suppression factor discussed above, a $\tilde{\nu}_{\tau_\mathrm{R}}$-like LSP $\tilde{\nu}_{\tau_1}$ can be a good candidate for CDM.

IV. $\tilde{\nu}_{\tau_1}$-LSP PHENOMENOLOGY AT THE LC

In this section, we consider a simple example to illustrate the interesting phenomenology of our model expected at high energy colliders.

The tree-level cross section for the production of $\tilde{\nu}_{\tau_2}$ pair in e^+e^- collision is

$$\sigma(e^+e^- \to \tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_2}) = \frac{\pi\alpha^2_{em}\cos^2\theta_{\tilde{\nu}}}{6S}\frac{1-4\sin^2\theta_W+8\sin^4\theta_W}{\sin^4 2\theta_W}\left[1-\frac{4m^2_{\tilde{\nu}_{\tau_2}}}{S}\right]^{3/2}\left[1-\frac{m^2_Z}{S}\right]^{-2}, \quad (11)$$

through the s-channel Z-exchange diagram. ($\sqrt{S}$ is the center-of-mass energy of the collider.) As a comparison, the tree-level cross sections for the direct productions of $\tilde{\nu}_{\tau_1}$ in e^+e^- collision associated with $\tilde{\nu}^*_{\tau_2}$ or $\tilde{\nu}^*_{\tau_1}$ are

$$\begin{aligned}\sigma(e^+e^- \to \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_2}) &= \sigma(e^+e^- \to \tilde{\nu}^*_{\tau_1}\tilde{\nu}_{\tau_2}) \\ &= \frac{\pi\alpha^2_{em}\sin^2 2\theta_{\tilde{\nu}}}{24S}\frac{1-4\sin^2\theta_W+8\sin^4\theta_W}{\sin^4 2\theta_W} \\ &\times\left[\left(1-\frac{m^2_{\tilde{\nu}_{\tau_2}}-m^2_{\tilde{\nu}_{\tau_1}}}{S}\right)^2-\frac{4m^2_{\tilde{\nu}_{\tau_1}}}{S}\right]^{3/2}\left[1-\frac{m^2_Z}{S}\right]^{-2}, \quad (12)\\ \sigma(e^+e^- \to \tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}) &= \frac{\pi\alpha^2_{em}\sin^4\theta_{\tilde{\nu}}}{6S}\frac{1-4\sin^2\theta_W+8\sin^4\theta_W}{\sin^4 2\theta_W}\end{aligned}$$

$$\times \left[1 - \frac{4m^2_{\tilde{\nu}_{\tau_1}}}{S}\right]^{3/2} \left[1 - \frac{m_Z^2}{S}\right]^{-2} . \tag{13}$$

Hence, the direct productions of $\tilde{\nu}_{\tau_1}$ could be highly suppressed when the factor $\sin^4\theta_{\tilde{\nu}}$ is much smaller than 1. Apart from a different phase space factor, the direct production of $\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}$ is smaller than the production of $\tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_2}$ by a factor of $\sin^4\theta_{\tilde{\nu}}/\cos^2\theta_{\tilde{\nu}}$.

As mentioned in the previous section, $\tilde{\nu}_{\tau_2}$ could decay into $\tilde{\nu}_{\tau_1}h^0$ or $\nu_\tau\tilde{\chi}^0_j$. With a large $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1}h^0)$, it may be possible to observe the $2h^0 + \not{E}_T$ signal originated from the production of the $\tilde{\nu}_{\tau_2}$ pair. To test this scenario, we need to calculate the SM rate for the process $e^+e^- \to h^0h^0\nu_i\bar{\nu}_i$, where ν_i ($\bar{\nu}_i$) is the left-handed neutrino (anti-neutrino) for the ith family. Since the final state neutrinos, like the LSPs, carry away energy, the above SM process is the intrinsic background to the detection of the signal event $e^+e^- \to \tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_2} \to h^0h^0\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}$, because both processes produce the event signature of $e^+e^- \to 2h^0 + \not{E}_T$. Due to the large suppression factor from the 4-body phase space, the cross section for the SM process is typically small. For example, when the Higgs mass is 130 GeV, the SM rate is about 0.03 fb, for $\sqrt{S} = 500\,\mathrm{GeV}$. On the other hand, for a 200 GeV $\tilde{\nu}_{\tau_2}$, with small left-right tau sneutrino mixing effect (i.e. $\sin\theta_{\tilde{\nu}} \sim 0$), the tree-level cross section for the $\tilde{\nu}_{\tau_2}$-pair production is about 12 fb. This relatively large production rate can lead to an enhancement in the Higgs boson pair signal, provided $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1}h^0)$ is large enough, cf. Fig.2.

It is also interesting to consider a special case with $C_{\mathrm{V}} = A_{\mathrm{V}}\tan\beta$, so that Δm^2 vanishes and $\tilde{\nu}_{\tau_{\mathrm{L}}}$ does not mix with $\tilde{\nu}_{\tau_{\mathrm{R}}}$. Hence, the direct production of $\tilde{\nu}_{\tau_1}$ (now a pure $\tilde{\nu}_{\tau_{\mathrm{R}}}$) vanishes and $\tilde{\nu}_{\tau_1}$ is predominantly produced through the decay of $\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1}h^0$. As shown in Fig.2(b), the branching ratio $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ is generally higher than that in Fig.2(a) because of the inclusion of the non-standard soft SUSY breaking parameter C_{V}. For instance, assuming the same mass parameters as the Higgsino-like $\tilde{\chi}^0_1$-NLSP scenario given above, the $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ is about 0.1 for $A_{\mathrm{V}} = 10$ GeV, and 0.9 for $A_{\mathrm{V}} = 90$ GeV with $\tan\beta = 2$, which results in the production cross section of $e^+e^- \to \tilde{\nu}_{\tau_2}\tilde{\nu}^*_{\tau_2} \to h^0h^0\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1}$ to be about 0.12 fb and 11 fb, respectively. When comparing to the SM rate, the signal rate of our model can be larger by about a factor of 300. With a larger $\tan\beta$, the branching ratio of $\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0$ increases and more $2h^0 + \not{E}_T$ signal events are expected.

Thus far, we have only shown that the $\tilde{\nu}_{\tau_1}$-LSP signal rate of $2h^0 + \not{E}_T$ production can be much larger than the SM rate. However, to distinguish our $\tilde{\nu}_{\tau_1}$-LSP scenario from the ordinary MSSM scenario with $\tilde{\chi}^0$-LSP, we also need to compare our signal rate with that predicted by the ordinary MSSM. When the decay mode $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 + h^0$ is available, the MSSM $2h^0 + \not{E}_T$ signature mainly comes from the pair production of χ^0_2 in e^+e^- collisions. The event rate of $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2 \to h^0h^0\tilde{\chi}^0_1\tilde{\chi}^0_1$ depends on the detail of the MSSM parameters. For example, assuming the usual scenario that $\tilde{\chi}^0_1$ is almost Bino-like, the partial decay width of $\tilde{\chi}^0_2 \to h^0\tilde{\chi}^0_1$ will come from one-loop corrections. Since the difference in the masses of χ^0_2 and χ^0_1 is large enough (greater than m_{h^0}) for the other tree-level decay modes of χ^0_2 to be opened, the branching ratio $\mathrm{BR}(\tilde{\chi}^0_2 \to h^0\tilde{\chi}^0_1)$ is generally small. Furthermore, if $\tilde{\chi}^0_2$ is Higgsino-like, the cross section of $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$ at a 500 GeV collider is expected to be small, at the order of fb or smaller, for MSSM mass parameters to be at the order of a few hundreds of GeV. For a gaugino-like $\tilde{\chi}^0_2$, the above cross section can increase by a factor of 10. A detailed comparison between our model and the ordinary MSSM for the event rate of $e^+e^- \to 2h^0\not{E}_T$ is beyond the scope of this short Letter.

V. CONCLUSION

Motivated by the neutrino oscillation data, we study a low energy effective theory in which the interactions of right sneutrinos with left sneutrinos at the weak scale are described by Eqs.(1), (2) and (3) with R-parity conservation in the framework of MSSM. For simplicity, we assume the mixings among the three generation sneutrinos are small enough that the dominant effect to collider phenomenology comes from the interaction of the left and right tau sneutrinos, which mix via the soft SUSY breaking effect arising from the trilinear scalar couplings of scalar Higgs doublets and sleptons. We find that the mass of the lightest tau sneutrino $\tilde{\nu}_{\tau_1}$ can take any value (even smaller than $m_Z/2$) to agree with the Z decay width measurement, provided that the sneutrino mixing parameter $\sin\theta_{\tilde{\nu}}$ is smaller than 0.39. In that case, $\tilde{\nu}_{\tau_1}$ is almost the right tau sneutrino $\tilde{\nu}_{\tau_R}$, and becomes a good candidate to be the LSP of the model as well as the cold dark matter. Because $\tilde{\nu}_{\tau_R}$ mainly interacts with $\tilde{\nu}_{\tau_L}$ through Higgs boson, the branching ratio $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ can be large. It results in a large production rate of single h^0 or multiple h^0's in electron or hadron collisions via the decay of $\tilde{\nu}_{\tau_2}$, which is $\tilde{\nu}_{\tau_L}$-like and can be copiously produced from the decay of charginos, neutralinos, sleptons, and the cascade decay of squarks and gluinos, etc. Hence, the events including Higgs boson(s) can also contain single or multiple isolated leptons and/or photons with large transverse momentum, which can make it easy to trigger on such events experimentally. Given the possible large production rate of the above mentioned sparticles, the production rate of the lightest neutral Higgs boson is expected to be largely enhanced from its SM rate. For example, with the trilinear couplings $C_{\mathrm{V}} = A_{\mathrm{V}} \tan\beta$, the left and right sneutrino do not mix, and the $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$ is approaching to 1 as A_{V} increases. In that case, the signal rate ($\sim$ 12 fb) of $e^+e^- \to 2h^0 + \not{E}_T$ at a 500 GeV LC is enhanced by a factor of 400, as compared to its SM rate.

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<ins>Note Added:</ins>

After posting this manuscript to the xxx-archives, stamped as hep-ph/0006313, we noticed that in a new paper, hep-ph/0006312, several supersymmetry breaking mechanisms were proposed for generating light sneutrinos. CPY thanks N. Weiner for explaining the SUSY models proposed in Ref. [13], and pointing out an error in the previous version of the manuscript.

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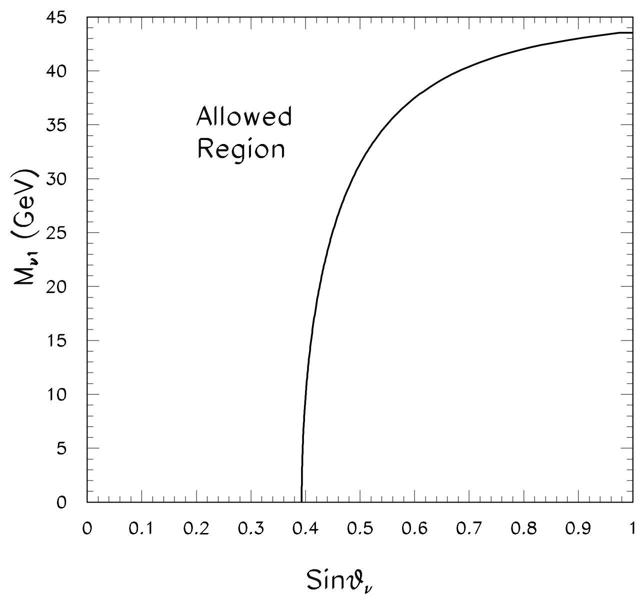

FIG. 1. The allowed parameter space (the left-hand side of the curve) on the $(\sin\theta_{\tilde{\nu}}, m_{\tilde{\nu}_{\tau_1}})$ plane, for $m_{\tilde{\nu}_{\tau_1}} < m_Z/2$.

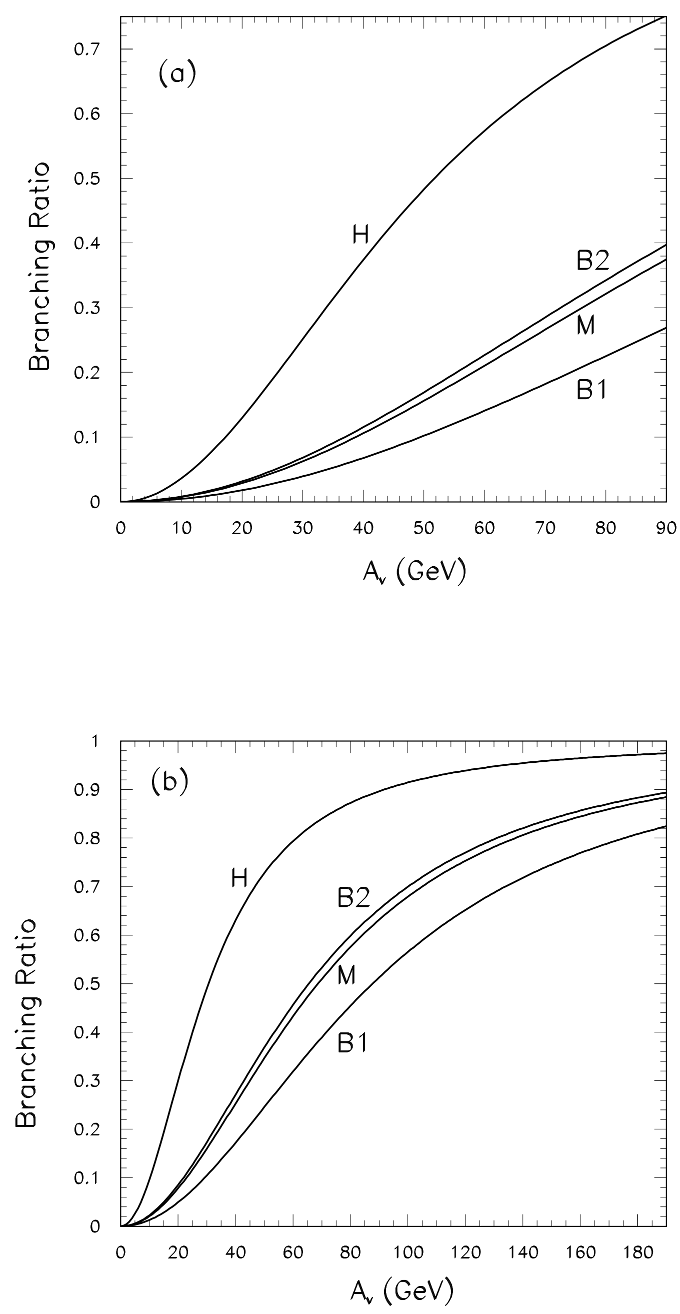

FIG. 2. The decay branching ratio $\mathrm{BR}(\tilde{\nu}_{\tau_2} \to \tilde{\nu}_{\tau_1} + h^0)$, as a function of A_{V}, with (a) $C_{\mathrm{V}} = 0$, $\tan\beta = 2$, and (b) $C_{\mathrm{V}} = A_{\mathrm{V}} \tan\beta$, $\tan\beta = 2$. A detailed explanation is given in the text.