Higgs boson mass in NMSSM with right-handed neutrino: Postprint

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Abstract

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Full Text

Preamble

Higgs boson mass in NMSSM with right-handed neutrino

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Abstract

In order to generate neutrino masses, right-handed neutrino/sneutrino superfield(s) (N) must be introduced in supersymmetry. In the framework of NMSSM (the MSSM extended by a singlet S), such an extension dynamically generates a TeV-scale Majorana mass for the right-handed neutrino through the SNN coupling when S develops a vev (the free Majorana mass term is forbidden by an assumed Z_3 symmetry). Furthermore, through the couplings SNN and $SH_{uH}d$, the SM-like Higgs boson (a mixture of H_u, H_d and S) can naturally couple to the right-handed neutrino/sneutrino. As a result, TeV-scale right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass. Through explicit calculation, we find that the Higgs boson mass can indeed be sizably altered by the right-handed neutrino/sneutrino. Such new contributions can help push up the SM-like Higgs boson mass and thus make the NMSSM more natural.

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Introduction

Supersymmetry (SUSY) [?, ?] provides a natural solution to the hierarchy problem suffered by the Standard Model (SM). It also provides a good dark matter candidate and realizes gauge coupling unification. Among SUSY models, the Minimal Supersymmetric Standard Model (MSSM) [?] has been intensively studied. However, the recently discovered Higgs-like boson around 125 GeV has caused a problem for this model: a 125 GeV Higgs boson requires a heavy stop or large trilinear coupling A_t, thus incurring the little hierarchy problem. Additionally, the MSSM suffers from the μ-problem [?].

Remarkably, both the little hierarchy problem and the μ-problem can be solved in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [?], in which an additional gauge singlet S is introduced (in fact, the NMSSM was proposed even earlier than the MSSM [?]). In this model, the μ-problem is solved by the dynamical generation of the μ-term through the coupling $SH_{uH}d$ when S develops a vev, while the little hierarchy problem is solved by the generation of an extra tree-level mass term for the SM-like Higgs boson (thus the stop mass or A_t is no longer required to be unnaturally large).

Note that to generate neutrino masses, right-handed neutrino/sneutrino superfield(s) (N) must be introduced in SUSY models. For the NMSSM with such right-handed neutrino/sneutrino field(s) [?], some intriguing features emerge. Due to the assumed Z_3 symmetry, the free Majorana mass term for the right-handed neutrino is forbidden in the superpotential. Instead, a TeV-scale Majorana mass for the right-handed neutrino is dynamically generated through the SNN coupling when S develops a non-zero vev (v_s). Note that such a TeV-scale Majorana mass is too low for the conventional see-saw mechanism, and thus the neutrino Yukawa couplings H_{uLN} must be very small. In the same way, a TeV-scale mass for the right-handed sneutrino can also be generated, which can serve as a good dark matter candidate [?]. Furthermore, through the couplings SNN and $SH_{uH}d$, the SM-like Higgs boson (a mixture of H_u, H_d and S) can naturally couple with the right-handed neutrino/sneutrino.

As a result, TeV-scale right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass (in the MSSM with split SUSY, the right-handed neutrino/sneutrino can also make sizable contributions to the Higgs mass, as studied in [?]). In this paper we perform an explicit calculation of such contributions.

This work is organized as follows. In Sec. II we present the spectrum and couplings for the Higgs boson and right-handed neutrino/sneutrino. In Sec. III the renormalization scheme is described. Numerical results and discussions are given in Sec. IV. Finally, we give a summary in Sec. V.

II. Higgs and Right-handed Neutrino/Sneutrino in NMSSM

A. Model Description

The NMSSM with a right-handed neutrino superfield N has a superpotential given by

$$W = W_{\text{NMSSM}} + \lambda_N SNN + y_N H_u \cdot LN$$

where W_{NMSSM} contains the usual Yukawa and Higgs terms, flavor indices are omitted, and the dot denotes the $SU(2)_L$ antisymmetric product.

Since a global Z_3 symmetry is imposed, there are no supersymmetric mass terms (like $H_{uH}d$, NN or SS) in the superpotential. Note that in this model we impose R-parity, and thus the terms NNN and SSN are forbidden. As a result, sneutrino-Higgs mixing is avoided and there is no vev for the right-handed sneutrino (we will show how to obtain the global minimum in the following). Although a bare Majorana mass term NN is forbidden in the superpotential, a TeV-scale Majorana mass can be generated through the coupling SNN when S develops a non-zero vev (v_s). Such a TeV-scale Majorana mass is too small for the conventional see-saw mechanism, and thus the Yukawa coupling $y_N H_u LN$ should be very small ($y_N \ll 1$). Note that here we introduce only one right-handed neutrino superfield to illustrate its effects on the Higgs mass. To explain neutrino masses and mixings, more right-handed neutrino superfields need to be introduced, each of which will contribute to the Higgs mass. In that case, the calculation method is the same as in our calculation, but the total effects may be more sizable due to more free parameters.

The soft SUSY breaking terms for Higgs and right-handed sneutrino are given by (hereafter we use N and $\tilde{N}$ to denote respectively the right-handed neutrino and sneutrino)

$$-\mathcal{L}_{\text{soft}} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + m_{\tilde{N}}^2|\tilde{N}|^2 + (\lambda_N A_N S\tilde{N}\tilde{N} + \text{h.c.}) + (\lambda A_\lambda H_u H_d S + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.})$$

Here we neglect the mixing between left-handed and right-handed sneutrinos because the mixing is assumed to be suppressed by y_N. In the following we briefly discuss the neutral Higgs and neutrino sectors.

B. The Neutral Higgs Sector

From Eq. (1) and Eq. (2) we obtain the Higgs potential V, which includes F-term, D-term, and soft-breaking contributions. Assuming H_u, H_d and S develop vevs such that

$$H_u^0 = v_u + \text{Re}(H_u^0) + i\text{Im}(H_u^0), \quad H_d^0 = v_d + \text{Re}(H_d^0) + i\text{Im}(H_d^0), \quad S = v_s + S_R + iS_I$$

we can extract the mass terms for the Higgs fields, which are presented in [?]. Here we only show the conventions and give some brief comments:

1. The mass matrix for the CP-even neutral Higgs is obtained from the real components of the Higgs fields. In the basis $h^{\text{bare}} = [\text{Re}(H_u^0), \text{Re}(H_d^0), S_R]$ and using the minimization equations to eliminate the soft masses, one obtains three CP-even states (ordered in mass) with an orthogonal rotation S_{ij}:

$$h_i = S_{ij} h_j^{\text{bare}}$$

2. The mass matrix for the CP-odd neutral Higgs is obtained from the imaginary components of the Higgs fields $[\text{Im}(H_u^0), \text{Im}(H_d^0), S_I]$. Its diagonalization is performed in two steps. First, one rotates it into a basis (A, S_I, G) where $G = \cos\beta \text{Im}(H_d^0) + \sin\beta \text{Im}(H_u^0)$ is a massless Goldstone mode ($\tan\beta = v_u/v_d$ is the ratio of the vevs of the two Higgs doublets). Dropping the Goldstone mode, the remaining 2×2 mass matrix $\mathcal{M}_P^2$ in the basis (A, S_I) can be diagonalized by an orthogonal matrix P_{ij} into two physical CP-odd states a_i (ordered in mass):

$$a_1 = P_{11} A + P_{12} S_I, \quad a_2 = P_{21} A + P_{22} S_I$$

3. The neutralino mass matrix $\mathcal{M}_\chi^0$ in the basis $\psi^0 = (i\lambda_1, i\lambda_2, \psi_u^0, \psi_d^0, \psi_s)$ can be diagonalized by a rotation matrix N_{ij}. One then obtains five eigenstates (ordered in mass) $\chi_i^0 = N_{ij} \psi_j^0$.

C. Right-handed Neutrino/Sneutrino Sector

Since there is no Dirac mass term here, the mass spectrum of the right-handed neutrino sector is very simple. Denoting $\tilde{N} = \tilde{N}_R + i\tilde{N}_I$, there is only one CP-even right-handed sneutrino (denoted as $\tilde{N}_R$) and one CP-odd right-handed sneutrino (denoted as $\tilde{N}_I$). The right-handed neutrino is denoted as N. From Eq. (1) and Eq. (2) we obtain the spectrum:

$$m_{\tilde{N}R}^2 = 4\lambda_N^2 v_s^2 + 2\lambda_N v_s A_N + 2\lambda_N(\kappa v_s^2 - \lambda v_u v_d)$$

$$m_{\tilde{N}I}^2 = 4\lambda_N^2 v_s^2 + 2\lambda_N v_s A_N - 2\lambda_N(\kappa v_s^2 - \lambda v_u v_d)$$

$$m_N = 2\lambda_N v_s$$

With this spectrum we can derive the couplings between the Higgs and the right-handed neutrino/sneutrino. Note that in our numerical study we require $m^2_{\tilde{N}R}$ and $m^2_{\tilde{N}I}$ to be positive, and as a result, the global minimum of the scalar potential is located at the zero point of the right-handed sneutrino field (the right-handed sneutrino has no vev and thus R-parity is preserved). In the following we list the couplings used in our calculations:

$$V_{h_i\tilde{N}R\tilde{N}_R} = \sqrt{2}\lambda_N\lambda(v_uS_{i2} + v_dS_{i1}) - 2\lambda_N\kappa v_s + 4\lambda_N^2 v_s + \lambda_N A_N$$

$$V_{h_i\tilde{N}I\tilde{N}_I} = \sqrt{2}\lambda_N\lambda(v_uS_{i2} + v_dS_{i1}) + 2\lambda_N\kappa v_s + \lambda_N A_N$$

$$V_{h_ih_j\tilde{N}R\tilde{N}_R} = \lambda_N[2\kappa S_{i3}S_{j3} - \lambda(S_{i1}S_{j2} + S_{i2}S_{j1})]$$

$$V_{h_ih_j\tilde{N}I\tilde{N}_I} = \lambda_N[2\kappa S_{i3}S_{j3} - \lambda(S_{i1}S_{j2} + S_{i2}S_{j1})]$$

$$V_{a_i\tilde{N}R\tilde{N}_I} = \lambda v \cos 2\beta P_{i1}/\sqrt{2} + \sqrt{2}\kappa v_s P_{i2} + \sqrt{2}\lambda_N A_N P_{i2}$$

$$V_{a_ia_j\tilde{N}R\tilde{N}_R} = 2\lambda_N(\lambda \sin\beta\cos\beta P_{i1}P_{j1} + \kappa P_{i2}P_{j2})$$

$$V_{a_ia_j\tilde{N}I\tilde{N}_I} = 2\lambda_N(\lambda \sin\beta\cos\beta P_{i1}P_{j1} + \kappa P_{i2}P_{j2})$$

$$V_{h_iNN} = \sqrt{2}\lambda_N S_{i3}$$

$$V_{a_iNN} = \sqrt{2}i\lambda_N P_{i2}\gamma_5$$

$$V_{\chi_i^0\tilde{N}RN} = \lambda_N\tilde{N}_R\bar{N}\chi_i^0$$

$$V_{\chi_i^0\tilde{N}IN} = \lambda_N i\tilde{N}_I\bar{N}\gamma_5\chi_i^0$$

III. Renormalization Scheme

To calculate the neutrino/sneutrino contribution to the Higgs mass, we must compute the one-loop Higgs propagator and choose a renormalization scheme. Here we follow [?] and choose the mixed renormalization scheme (other schemes give similar results). We choose the following parameter set:

$$M_Z, M_W, M_{H^\pm}, e, t_{H_u}, t_{H_d}, t_{H_s}, \tan\beta, \lambda, v_s, \kappa, A_\kappa$$

in the on-shell scheme, where $t_{H_u}, t_{H_d}, t_{H_s}$ are the tadpoles of the CP-even Higgs fields. Since we concentrate on the $\overline{\mathrm{DR}}$ scheme for the right-handed neutrino/sneutrino contributions, the input parameters from the gauge interaction part need not be renormalized. For parameters requiring renormalization, we replace them by renormalized ones plus corresponding counterterms:

$$t_{H_u} \to t_{H_u} + \delta t_{H_u}, \quad t_{H_d} \to t_{H_d} + \delta t_{H_d}, \quad t_{H_s} \to t_{H_s} + \delta t_{H_s}$$

$$v_s \to v_s + \delta v_s, \quad \tan\beta \to \tan\beta + \delta\tan\beta, \quad \lambda \to \lambda + \delta\lambda$$

$$\kappa \to \kappa + \delta\kappa, \quad A_\kappa \to A_\kappa + \delta A_\kappa$$

In the following we show how to determine the counterterms in the mixed renormalization scheme.

First, the Higgs doublet and singlet fields are replaced by renormalized ones:

$$H_u = Z_{H_u}^{1/2} H_u^{\mathrm{ren}}, \quad H_d = Z_{H_d}^{1/2} H_d^{\mathrm{ren}}, \quad S = Z_S^{1/2} S^{\mathrm{ren}}$$

with

$$Z_{H_u} = 1 + \delta Z_{H_u}, \quad Z_{H_d} = 1 + \delta Z_{H_d}, \quad Z_S = 1 + \delta Z_S$$

The renormalized two-point functions can be obtained from the Feynman diagrams shown in Fig. 1:

$$\hat{\Sigma}_{H_i H_j}(k^2) = S_{ik} S_{jl} \hat{\Sigma}_{kl}^{\mathrm{bare}}(k^2) \quad (i,j,k,l = 1,2,3)$$

$$\hat{\Sigma}_{A_i A_j}(k^2) = P_{ik} P_{jl} \hat{\Sigma}_{kl}^{\mathrm{pseudo}}(k^2) \quad (i,j,k,l = 1,2)$$

where S_{ij} and P_{ij} are matrix elements defined in Eqs. (5) and (6). The renormalization condition is set as

$$\delta Z_{H_iH_i} = \frac{\partial \Sigma_{H_iH_i}(k^2)}{\partial k^2}\bigg|^{\text{div}}_{k^2=(M^{(0)}_{H_i})^2} \qquad (i = 1, 2, 3)$$

where $M^{(0)}_{H_i}$ denotes the corresponding tree-level Higgs mass, and 'div' indicates that we choose the $\overline{\text{DR}}$ renormalization scheme, meaning that in field renormalization only the divergent part $\Delta = 2/(4-D) - \gamma_E + \ln(4\pi)$ (where γ_E is the Euler constant) is kept. The field renormalization constants $\delta Z_{H_u}, \delta Z_{H_d}, \delta Z_S$ are obtained by solving the equations:

$$\delta Z_{H_iH_i} = 2\delta Z_{H_d} + 2\delta Z_{H_u} + \cdots \quad (i = 1, 2, 3)$$

We use these field renormalization constants to determine the counterterms listed above. The detailed calculations are lengthy. In the following we present the final results and give necessary comments.

1. Tadpole Parameters The tadpole parameters are determined by the condition that they vanish after renormalization. The Feynman diagrams are shown in Fig. 2 and the counterterms are determined by

$$\delta t_{H_i} = S_{ji} t^{(1)}_{h_j} \quad (i = u, d, s; j = 1, 2, 3)$$

where $t^{(1)}_{h_j}$ denote the one-loop Higgs tadpoles.

2. The Coupling λ The coupling λ is renormalized through the CP-odd Higgs element $\mathcal{M}^2_{P,11}$ and is given by

$$\delta\lambda = \frac{4\lambda M_Z^2 \Sigma_{P,11}(M^2_{P,11})}{v^2(M^2_{P,11} - M^2_{P,22})}$$

The self-energy $\Sigma_{P,11}$ is obtained from the self-energies in the mass eigenstate basis $\Sigma_{A_iA_j}$ $(i, j = 1, 2, 3)$ through

$$\Sigma_{P,11} = P_{i1}\Sigma_{A_iA_j}P_{j1}$$

3. The Parameter $\tan\beta$

$$\delta \tan\beta = \tan\beta \frac{(\delta Z_{H_u} - \delta Z_{H_d})}{2}$$

4. The vev v_s δv_s is determined by the neutralino renormalization whose diagrams are shown in Fig. 3. Note that we have different conventions for the vev and thus the formula differs slightly from Ref. [**?**].

5. The Coupling κ κ is renormalized through the neutralino renormalization and is given by

$$\delta\kappa = \frac{\Sigma^{55}_{\chi^0_i\chi^0_i}}{2v_s}$$

6. The Trilinear Coupling A_κ A_κ is renormalized by the CP-odd Higgs element $\mathcal{M}^2_{P,22}$ and is given by

$$\delta A_\kappa = \frac{3\kappa v_s}{2}\left[\Sigma_{P,22}(M^2_{P,22}) - \frac{f(M^2_{P,22})}{v_s}\right]^{\text{div}}$$

where the function f can be found in Ref. [**?**].

After determining the counterterms, we insert them into the Higgs mass matrix shown in the Appendix. By adding the loop contribution to the Higgs mass matrix, we obtain the mass correction for the Higgs boson.

IV. Numerical Results

A. The Right-handed Neutrino/Sneutrino Correction to the Higgs Boson Mass

In our numerical calculation we concentrate on the SM-like Higgs boson, which is the lightest CP-even Higgs boson dominated by the Higgs doublets. From the superpotential in Eq. (1) we see that the right-handed neutrino/sneutrino interacts with the doublets only through the F-term of the singlet Higgs S, and thus the parameter λ plays an important role in the correction to the Higgs boson mass. Also, from the superpotential we see that the right-handed neutrino/sneutrino couples to the Higgs sector through the parameter λ_N. Therefore, as λ_N approaches zero, the right-handed neutrino/sneutrino should decouple from the NMSSM sector. To check this numerically, we scan the parameter space in the range:

$$0 < \lambda, \kappa, \lambda_N < 1, \quad 2 < \tan\beta < 50, \quad 0 < \mu, M_{\tilde{N}} < 1 \text{ TeV},$$

$$-1 \text{ TeV} < A_\lambda, A_\kappa, A_N < 1 \text{ TeV}.$$

Note that in calculating the Higgs mass spectrum we choose to use μ $(= \lambda v_s)$ as an input parameter because it is commonly used in NMSSM phenomenology studies and relevant numerical packages. Also, λ and λ_N may be rather constrained (e.g., λ at weak scale must be below 0.7) if we require perturbativity of the theory up to the grand unification scale [?]. Of course, if we treat NMSSM as a low-energy effective theory, such stringent perturbativity constraints are much relaxed.

The correction to the Higgs boson mass versus the product $\lambda\lambda_N$ is shown in Fig. 4. The figure shows that when the product $\lambda\lambda_N$ approaches zero, the correction approaches zero; when $\lambda\lambda_N$ is of order 1, the right-handed neutrino/sneutrino alters the mass significantly. Thus, if λ and λ_N are not small, the right-handed neutrino/sneutrino contribution to the Higgs boson mass must be taken into account.

Now we check the SUSY limit in the right-handed neutrino/sneutrino sector. From Eq. (7) we see that with $M_{\tilde{N}}$ and A_N approaching zero, the right-handed neutrino/sneutrino sector has a SUSY limit for $\kappa v_s^2 = \lambda v_u v_d$. In our second scan, we assume this relation and let the parameters $\lambda, \kappa, \tan\beta, A_\lambda, A_\kappa, M_{\tilde{N}}$ and A_N vary randomly in the ranges as in Eqs. (30, 31), only fixing $\lambda_N = 0.9$. The results are shown in Fig. 5. The results show that as $M_{\tilde{N}}^2 + A_N^2$ approaches zero, the Higgs mass correction approaches zero, which confirms the SUSY limit.

[Figure 5: see original paper]: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus $M_{\tilde{N}}^2 + A_N^2$ (in GeV^2).

It is well known that the Higgs mass can be enhanced by the hierarchy between SM particles and their SUSY partners. In the right-handed neutrino/sneutrino sector, the mass hierarchy between sneutrino and neutrino is controlled by the soft parameters $M_{\tilde{N}}$ and A_N. To show the dependence on the mass splitting, we choose a benchmark point:

$$\lambda = 0.2, \quad \lambda_N = 0.35, \quad \kappa = 0.4, \quad \tan\beta = 10, \quad \mu = 200 \text{ GeV},$$

$$A_\lambda = 300 \text{ GeV}, \quad A_\kappa = 500 \text{ GeV},$$

and scan the other two parameters in the range $0 < M_{\tilde{N}} < 1$ TeV and -1 TeV $< A_N < 1$ TeV. The results are shown in Fig. 6, where the left panel shows δm_h versus $M_{\tilde{N}}$ and the right panel shows δm_h versus $m_{\tilde{N}R}^2/m_N^2$. From this figure we see that as $M_{\tilde{N}}$ increases (the mass splitting between sneutrino and neutrino also increases as shown in Eq. (7)), the mass correction increases.

[Figure 6: see original paper]: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus the sneutrino soft mass $M_{\tilde{N}}$ and the ratio $m_{\tilde{N}R}^2/m_N^2$ (for $m_{\tilde{N}R}$ and m_N, see Eq. (7)).

From the above results we see that the right-handed neutrino/sneutrino can either enhance or reduce the Higgs boson mass. Since the parameter space is multi-dimensional (9 input parameters), we perform an intensive scan to determine what parameter(s) govern the sign of the correction. We scan the parameter set $(\lambda, \lambda_N, M_{\tilde{N}}, A_N)$ while fixing other parameters as listed in Eq. (32). The results are shown in Fig. 7. We see that the parameter λ plays the most important role in this aspect, although it cannot solely determine the sign. For large values of λ, the sign of the correction tends to be negative. Clearly, the sign is not sensitive to λ_N. We also checked that the sign is not sensitive to other parameters.

[Figure 7: see original paper]: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass shown in the plane of λ_N versus λ. Here we scan the parameter set $(\lambda, \lambda_N, M_{\tilde{N}}, A_N)$ while fixing other parameters as listed in Eq. (32). The red '×' are for $\delta m_h < -1$ GeV, the green '+' for -1 GeV $< \delta m_h < 0$, the blue ' ' for $0 < \delta m_h < 1$ GeV, and the magenta ' ' for $\delta m_h > 1$ GeV.

B. Higgs Mass with All Loop Corrections under Current Experimental Constraints

In the preceding section we only considered loop corrections from the right-handed neutrino/sneutrino. Of course, loop corrections from other particles (especially the top and stop) should also be taken into account. In our following numerical study, we include all available loop corrections using the package NMSSMTools [?]. Since the right-handed neutrino/sneutrino is a gauge singlet, it will not change Higgs decays or dark matter annihilation. Therefore, we simply add the right-handed neutrino/sneutrino correction to the Higgs boson mass in NMSSMTools. Then we scan the NMSSM parameter space in the range:

$$0 < \lambda, \kappa < 1, \quad 2 < \tan\beta < 50, \quad 0 < (\mu, M_1 = M_2/2 = M_3/6, m_{\tilde{Q}}, m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{\tau}} = m_{\tilde{\mu}}) < 1 \text{ TeV},$$

$$-1 \text{ TeV} < (A_\lambda, A_\kappa, A_t = A_b = A_\tau = A_\mu) < 1 \text{ TeV}.$$

For the neutrino/sneutrino sector, we set $\lambda_N = 0.5$ and scan $M_{\tilde{N}}, A_N$ in the range:

$$0 < M_{\tilde{N}} < 1 \text{ TeV}, \quad -1 \text{ TeV} < A_N < 1 \text{ TeV}.$$

In our scan we consider the following experimental constraints [?]:

1. We require the lightest neutralino $\tilde{\chi}_1^0$ to account for the dark matter relic density $0.105 < \Omega h^2 < 0.119$;
2. We require the SUSY contribution to explain the deviation of the muon a_μ, i.e., $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.5 \pm 8.0) \times 10^{-10}$ at 2σ level;

3. The LEP-I bound on the invisible Z-decay, $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 1.76$ MeV, and the LEP-II upper bound on $\sigma(e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0) < 10^{-2}$ pb for $i, j > 1$, as well as lower mass bounds on sparticles from direct searches at LEP and the Tevatron;
4. Constraints from direct searches for Higgs bosons at LEP-II, including decay modes $h \to h_1 h_1, a_1 a_1 \to 4f$, which limit all possible production channels for Higgs bosons;
5. Constraints from B-physics observables like $B \to X_s \gamma$, $B_s \to \mu^+\mu^-$, $B^+ \to \tau^+\nu$, $\Upsilon \to \gamma a_1$, a_1-η_b mixing, and mass differences ΔM_d and ΔM_s;
6. The newest results for Higgs, top, and stop from the LHC.

These constraints are encoded in the package NMSSMTools [**?**]. In addition to the above experimental limits, we also consider the constraint from the stability of the Higgs potential, which requires that the physical vacuum with non-vanishing Higgs vevs should be lower than any local minima.

[Figure 8: see original paper]: The left panel shows the loop-corrected mass of the SM-like Higgs with or without the right-handed neutrino/sneutrino contribution, while the right panel shows the ratio $m_{\text{NMSSM+RHN}}/m_{\text{NMSSM}}$, where $m_{\text{NMSSM+RHN}}$ (m_{NMSSM}) denotes the SM-like Higgs mass with (without) the right-handed neutrino/sneutrino contribution.

The numerical results of our scan are shown in Fig. 8, where we plot the SM-like Higgs mass versus the trilinear parameter A_t in the left panel, and the ratio $m_{\text{NMSSM+RHN}}/m_{\text{NMSSM}}$ in the right panel. Again we see that the contribution of the right-handed neutrino/sneutrino is sizable, which helps push up the SM-like Higgs boson mass and thus makes the NMSSM more natural.

Note that from Figs. 6 and 7 we see that the correction to the Higgs mass can be positive or negative, depending on the parameter space (with λ being the most sensitive parameter). However, under current experimental constraints, the results in Fig. 8 show that in the majority of the surviving parameter space the correction is positive. The reason is that parameter samples giving negative corrections are difficult to satisfy current experimental constraints (especially the Higgs mass lower bound from LEP-II).

V. Summary

To generate neutrino masses, right-handed neutrino/sneutrino superfield(s) must be introduced in SUSY. In the NMSSM framework, such an extension dynamically leads to a TeV-scale Majorana mass for the right-handed neutrino. Furthermore, through the couplings SNN and $SH_{uH}d$, the SM-like Higgs boson can naturally couple to such TeV-scale right-handed neutrino/sneutrino. As a result, the right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass.

In this work we performed an explicit calculation and found that the Higgs boson mass can indeed be sizably altered by the right-handed neutrino/sneutrino.

Such new contributions can help push up the SM-like Higgs boson mass and thus make the NMSSM more natural.

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Appendix

Here we list the analytical renormalized formulas for the elements of the Higgs mass matrix. Although they can be found in Ref. [?], we have checked them and modified them according to our conventions. Note that β_B denotes the tree-level β and c_X, s_X, t_X denote respectively $\cos X, \sin X$ and $\tan X$.

The scalar 3×3 mass matrix $\mathcal{M}_S^2$ in the basis $h_S = (H_u, H_d, S)^T$ is given by entries $\mathcal{M}_{Sij}^2 = \mathcal{M}_{Sji}^2$ $(i, j = 1, 2, 3)$ with:

$$\mathcal{M}_{S11}^2 = m_{H_u}^2 + \lambda^2 v_d^2 + \frac{g^2 + {g'}^2}{4}(3v_u^2 - v_d^2) + \lambda\kappa v_d^2$$

$$\mathcal{M}_{S12}^2 = (\lambda^2 + \frac{g^2 + {g'}^2}{4} - \lambda\kappa)v_u v_d - \lambda A_\lambda v_s$$

$$\mathcal{M}_{S13}^2 = 2\lambda^2 v_u v_s - \lambda\kappa v_u v_d - \lambda A_\lambda v_d$$

$$\mathcal{M}_{S22}^2 = m_{H_d}^2 + \lambda^2 v_u^2 + \frac{g^2 + {g'}^2}{4}(3v_d^2 - v_u^2) + \lambda\kappa v_u^2$$

$$\mathcal{M}_{S23}^2 = 2\lambda^2 v_d v_s - \lambda\kappa v_u v_d - \lambda A_\lambda v_u$$

$$\mathcal{M}_{S33}^2 = m_S^2 + 4\kappa^2 v_s^2 - \kappa A_\kappa v_s + \lambda^2(v_u^2 + v_d^2) - \lambda\kappa v_u v_d$$

The entries $\mathcal{M}_{Pij}^2 = \mathcal{M}_{Pji}^2$ $(i, j = 1, 2, 3)$ of the pseudoscalar 3×3 mass matrix $\mathcal{M}_P^2$ in the basis $h_P = (a, a_s, G)^T$ read:

$$\mathcal{M}_{P11}^2 = \lambda A_\lambda \frac{v_s}{\sin\beta\cos\beta} + \lambda\kappa v_s^2$$

$$\mathcal{M}_{P12}^2 = \lambda A_\lambda v - 2\lambda\kappa v_s v$$

$$\mathcal{M}^2_{P13} = 0$$

$$\mathcal{M}^2_{P22} = \lambda A_\lambda \frac{v_u v_d}{v_s} + 3\kappa A_\kappa v_s - 3\lambda\kappa v_u v_d$$

$$\mathcal{M}^2_{P23} = 0$$

$$\mathcal{M}^2_{P33} = 0$$

where $v^2 = v_u^2 + v_d^2$ and the Goldstone mode has been separated.

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Note: Figure translations are in progress. See original paper for figures.