Realizing the supersymmetric inverse seesaw model in the framework of R-parity violation

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A B S T R A C T

If, on one hand, the inverse seesaw is the paradigm of TeV scale seesaw mechanism, on the other it is a challenge to find scenarios capable of realizing it. In this work we propose a scenario, based on the framework of R-parity violation, that realizes minimally the supersymmetric inverse seesaw mechanism. In it the energy scale parameters involved in the mechanism are recognized as the vacuum expectation values of the scalars that compose the singlet superfields $\hat{N}^C$ and $\hat{S}$. We develop also the scalar sector of the model and show that the Higgs mass receives a new tree-level contribution that, when combined with the standard contribution plus loop correction, is capable of attaining 125 GeV without resort to heavy stops.

1. Introduction

A current exciting challenge in particle physics is the explanation of the smallness of the neutrino masses through new physics at TeV scale. In this regard, the inverse seesaw mechanism (ISS) [1] became the paradigm of successful TeV scale seesaw mechanism. Its minimal implementation requires the introduction to the electroweak standard model (SM) of two sets of three neutral fermion singlets, $N = (N_1, N_2, N_3)$ and $S = (S_1, S_2, S_3)$, composing the following mass terms in the flavor basis,

$$\mathcal{L}_{mass} \supset \bar{\nu} M_D N + \bar{N} M_N S + \frac{1}{2} \bar{S}^C \mu_N S + h.c., \quad (1)$$

where $\nu = (\nu_1, \nu_2, \nu_3)$ is the set of standard neutrinos. In the basis (ν, N^C, S) the neutrino mass may be put in the following 9×9 matrix form,

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & \mu_N \end{pmatrix}. \quad (2)$$

In the regime $\mu_N << M_D < M_N$, the mechanism provides $m_\nu = M_D^T M_N^{-1} \mu_N (M_N^T)^{-1} M_D$ for the mass matrix of the standard neutrinos. Taking M_D at electroweak scale, M_N at TeV and μ_N at keV scale, the mechanism provides standard neutrinos at eV scale. The

new set of fermion singlets (N, S) develop mass at M_N scale and may be probed at the LHC.

The challenge concerning the ISS mechanism is to find scenarios that realize it. This means to propose models that generate the mass terms in Eq. (1). In this regard, as the ISS mechanism works in the TeV scale, it seems to be natural to look for realization of the ISS mechanism in the framework of theories that we expect will manifest at TeV scale [2,3], which is the case of supersymmetry (SUSY). Thus it seems to be interesting to look for scenarios that realize the ISS mechanism in the context of SUSY [4–6].

We know already that a natural way of obtaining small neutrino mass in the context of the MSSM is to consider that R-parity, $R \equiv (-1)^{2S+3(B-L)}$, is violated through bilinear terms like $\mu_i \hat{L}_i \hat{H}_u$ in the superpotential [7]. Thus we wonder if R-parity violation (RPV) is an interesting framework for the realization of the SUSYISS mechanism. For this, we implement the SUSYISS mechanism in a framework where R-parity and lepton number are violated explicitly but baryon number is conserved in a way that we call the minimal realization of the SUSYISS mechanism once the necessary set of superfields required to realize it is the original one, $\hat{N}_i^C$ and $\hat{S}_i$, only.

Moreover, it has been extensively discussed that the minimal supersymmetric standard model (MSSM) faces difficulties in accommodating a Higgs of mass of 125 GeV, as discovered by ATLAS and CMS [8] while keeping the principle of naturalness [9]. This is so because, at tree level, the MSSM predicts a Higgs with a mass whose value cannot exceed 91 GeV. Thus robust loop corrections are necessary in order to lift this value to 125 GeV. Consequently

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stops with mass far above 1 TeV are required. To accept this is to put the naturalness principle aside. We show that the SUSYISS mechanism developed here accommodates a 125 GeV Higgs mass without resort to robust loop corrections.

2. The mechanism

The supersymmetric version of the ISS (SUSYISS) mechanism [4] requires the assumption of two sets of three singlet superfields $\hat{N}_i^C$, $\hat{S}_i$ ($i = 1, 2, 3$) composing, with the MSSM superfields, $\hat{L}_i^T = (\hat{v}_i, \hat{e}_i)^T$, $\hat{H}_d^T = (\hat{H}_d^-, \hat{H}_d^0)^T$, $\hat{H}_u^T = (\hat{H}_u^+, \hat{H}_u^0)^T$, the following extra terms in the superpotential, $W \supset \hat{L}\hat{H}_u\hat{N}^C + \hat{S}M_N\hat{N}^C + \frac{1}{2}\hat{S}\mu_N\hat{S}$. A successful extension of the MSSM that realizes the SUSYISS mechanism must generate these terms. This would be an interesting result in particle physics since we would be providing an origin for the energy scales M_N and μ_N [5].

The mechanism we propose here is minimal in the sense that it requires the addition to the MSSM of the two canonical singlet superfields $\hat{N}_i^C$ and $\hat{S}_i$, only. Moreover, we impose that the superpotential be invariant under the following set of discrete symmetries, $Z_3 \otimes Z_2$, according to the following transformation: under Z_3 the transformations are,

$$(\hat{S}_i, \hat{N}_i^C, \hat{e}_i^c) \rightarrow w(\hat{S}_i, N_i^C, \hat{e}_i^C), \quad \hat{L}_i \rightarrow w^2 \hat{L}_i, \tag{3}$$

with $w = \exp^{i2\pi/3}$. Under Z_2 we have, $\hat{S}_i \rightarrow -\hat{S}_i$, with all the remaining superfields transforming trivially by $Z_3 \otimes Z_2$.

Thus the superpotential of the SUSYISS mechanism we propose here involves the following terms,

$$\hat{W} = \mu \hat{H}_u^a \hat{H}_{da} + Y_u^{ij} \epsilon_{ab} \hat{Q}_i^a \hat{H}_u^b \hat{u}_j^c + Y_d^{ij} \hat{Q}_i^a \hat{H}_d^b \hat{d}_j^c + Y_e^{ij} \hat{L}_i^a \hat{H}_d^b \hat{e}_j^c$$
$$+ Y_\nu^{ij} \epsilon_{ab} \hat{L}_i^a \hat{H}_u^b \hat{N}_i^c + \frac{1}{2}\lambda_s^{ijk}\hat{N}_i^c \hat{S}_j \hat{S}_k + \frac{1}{3}\lambda_\nu^{ijk}\hat{N}_i^c \hat{N}_j^c \hat{N}_k^c, \tag{4}$$

where a, b are $SU(2)$ indices and i and j are generation indices. $\hat{Q}_i$, $\hat{u}_i^c$, $\hat{d}_i^c$ and $\hat{e}_i^c$ are the standard superfields of the MSSM. Perceive that the $Z_3 \otimes Z_2$ symmetry permits that lepton number as well as R-parity be explicitly violated in this model by terms in the superpotential that involve the singlet superfields $\hat{N}_i^C$ and $\hat{S}_i$, only.

Now we make an important assumption. We assume that the scalars that compose the superfields $\hat{N}_i^C$ and $\hat{S}_i$ develop nonzero vacuum expectation value (VEV), $\langle \tilde{S} \rangle = v_{S_i}$ and $\langle \tilde{N}_i^C \rangle = v_{N_i}$, respectively. This assumption provides the source of the canonical mass terms M_N and μ_N of the SUSYISS mechanism. Note that, from the last two terms in the superpotential above, we have that the VEV of the scalar $\tilde{S}$ becomes the source of the mass scale M_N while the VEV of the scalar $\tilde{N}^C$ becomes the source of the mass scale μ_N. In other words, the superpotential above together with the assumption that the scalars $\hat{N}_i^C$ and $\hat{S}_i$ develop non zero VEVs has the required ingredients to realize the SUSYISS mechanism.

Another important point of the model is to discuss the possible values v_{S_i} and v_{N_i} may take. For this we have to obtain the potential of the model. The soft breaking sector will play an important role in the form of the potential.

The most general soft breaking sector of our interest involves the following terms,

$$-\mathcal{L}_{\text{soft}} = M_{Q_{ij}}^2 \tilde{Q}_i^{a*}\tilde{Q}_j^a + M_{u_{ij}^c}^2 \tilde{u}_i^{c*}\tilde{u}_j^c + M_{d_{ij}^c}^2 \tilde{d}_i^{c*}\tilde{d}_j^c$$
$$+ M_{L_{ij}}^2 \tilde{L}_i^{a*}\tilde{L}_j^a + M_{e_{ij}^c}^2 \tilde{e}_i^{c*}\tilde{e}_j^c + M_{h_u}^2 H_u^{a*}H_u^a$$
$$+ M_{h_d}^2 H_d^{a*}H_d^a + M_{\tilde{N}_i}^2 \tilde{N}_i^{*C}\tilde{N}_i^C + M_{\tilde{S}_i}^2 \tilde{S}_i^*\tilde{S}_i$$
$$- [(A_u Y_u)_{ij} \epsilon_{ab} \tilde{Q}_i^a H_u^b \tilde{u}_j^c + (A_d Y_d)_{ij} \tilde{Q}_i^a H_d^a \tilde{d}_j^c$$

$$+ (A_e Y_e)_{ij} \tilde{L}_i^a H_d^a \tilde{e}_j^c + h.c.] - [B\mu H_u^a H_d^a + h.c.]$$
$$+ \frac{1}{2}\left(M_3\tilde{\lambda}_3\tilde{\lambda}_3 + M_2\tilde{\lambda}_2\tilde{\lambda}_2 + M_1\tilde{\lambda}_1\tilde{\lambda}_1 + h.c.\right)$$
$$+ (A_y Y_\nu)^{ij}\epsilon_{ab}\tilde{L}_i^a H_u^b \tilde{N}_j^{*C}$$
$$+ [\frac{1}{2}(A_s\lambda_s)^{ijk}\tilde{N}_i^{*C}\tilde{S}_j\tilde{S}_k + \frac{1}{3}(A_\nu\lambda_\nu)^{ijk}\tilde{N}_i^{*C}\tilde{N}_j^{*C}\tilde{N}_k^{*C}$$
$$+ h.c.]. \tag{5}$$

Note that the last two trilinear terms violate explicitly lepton number and the energy scale parameters A_s and A_ν characterize such violation.

A common assumption in developing ISS mechanisms it to assume that the new neutral singlet fermions are degenerated in masses and self-couplings. However, for our case here, it seems to be more convenient, instead of considering the degenerated case, to consider the case of only one generation of superfields. The extension for the case of three generations is straightforward and the results are practically the same.

The potential of the model is composed by the terms $V = V_{soft} + V_D + V_F$. The soft term, V_F, is given above in Eq. (5). The relevant contributions to V_D are,

$$V_D = \frac{1}{8}(g^2 + g'^2)(\tilde{v}\tilde{v}^* + H_d^0 H_d^{0*} - H_u^0 H_u^{0*})^2. \tag{6}$$

In what concerns the F-term, the relevant contributions are given by the following terms,

$$V_F = \left|\frac{\partial \hat{W}}{\partial \hat{H}_u^0}\right|^2_{H_u} + \left|\frac{\partial \hat{W}}{\partial \hat{H}_d^0}\right|^2_{H_d} + \left|\frac{\partial \hat{W}}{\partial \hat{v}}\right|^2_{\tilde{v}} + \left|\frac{\partial \hat{W}}{\partial \hat{N}^C}\right|^2_{\tilde{N}} + \left|\frac{\partial \hat{W}}{\partial \hat{S}_L}\right|^2_{\tilde{S}}$$
$$= \mu^2 \left|H_u^0\right|^2 + \mu^2 \left|H_d^0\right|^2 + Y_\nu^2 \left|\tilde{N}^C\right|^2 \left|\tilde{v}\right|^2 + Y_\nu \mu H_d^{0*}\tilde{N}^{C*}\tilde{v}$$
$$+ Y_\nu^2 \left|H_u^0\right|^2 \left|\tilde{v}\right|^2 + \frac{1}{4}\lambda_s^2 \left|\tilde{S}\right|^4 + 4\lambda_\nu^2 \left|\tilde{N}^C\right|^4 + \lambda_s^2 \left|\tilde{N}^C\right|^2 \left|\tilde{S}\right|^2$$
$$+ \frac{Y_\nu \lambda_s H_u^0 \tilde{v}\tilde{S}^{*2}}{2} + 2Y_\nu\lambda_\nu \left|\tilde{N}^C\right|^2 H_u^0 \tilde{v} + Y_\nu^2 \left|\tilde{N}^C\right|^2 \left|H_u^0\right|^2$$
$$+ \lambda_s\lambda_\nu \left|\tilde{N}^C\right|^2 \tilde{S}^2 + h.c. \tag{7}$$

With the potential of the model in hand, we are ready to obtain the set of constraint equations for the neutral scalars H_u^0, H_d^0, $\tilde{v}$, $\tilde{S}$, $\tilde{N}^C$,

$$v_u\left(M_{h_u}^2 + \mu^2 + \frac{1}{4}(g^2 + g'^2)(v_u^2 - v_d^2 - v_\nu^2) + Y_\nu^2 v_N^2 + Y_\nu^2 v_\nu^2\right)$$
$$-B\mu v_d + \frac{1}{2}Y_\nu\lambda_s v_\nu v_S^2 + Y_\nu A_y v_\nu v_N + 2Y_\nu\lambda_\nu v_\nu v_N^2 = 0,$$
$$v_d\left(M_{h_d}^2 + \mu^2 - \frac{1}{4}(g^2 + g'^2)(v_u^2 - v_d^2 - v_\nu^2)\right)$$
$$-B\mu v_u + Y_\nu\mu v_\nu v_N = 0,$$
$$v_\nu\left(M_{\tilde{v}}^2 + \frac{1}{4}(g^2 + g'^2)(v_\nu^2 + v_d^2 - v_u^2) + Y_\nu^2 v_u^2 + Y_\nu^2 v_N^2\right)$$
$$+\frac{1}{2}\lambda_s Y_\nu v_u v_S^2 + Y_\nu A_y v_u v_N + 2Y_\nu\lambda_\nu v_u v_N^2 + Y_\nu\mu v_d v_N = 0,$$
$$M_{\tilde{S}}^2 + \lambda_s Y_\nu v_u v_\nu + \frac{1}{2}\lambda_s^2 v_S^2 + \lambda_s A_s v_N + \lambda_s^2 v_N^2 + 2\lambda_s\lambda_\nu v_N^2 = 0,$$
$$v_N(M_{\tilde{N}}^2 + Y_\nu^2 v_u^2 + \lambda_s^2 v_S^2 + 3\lambda_\nu A_\nu v_N + 8\lambda_\nu^2 v_N^2 + 4\lambda_\nu Y_\nu v_u v_\nu$$
$$+2\lambda_\nu\lambda_s v_S^2 + Y_\nu^2 v_\nu^2) + Y_\nu v_\nu(A_y v_u + \mu v_d) + \frac{1}{2}A_s\lambda_s v_S^2 = 0. \tag{8}$$

Let us first focus on the third relation in the equation above. Observe that the dominant term inside the parenthesis is $M_{\tilde{\nu}}^2$. Outside the parenthesis, on considering for while that $v_N < v_S$, the dominant term is $\frac{1}{2}\lambda_s Y_\nu v_u v_S^2$. In view of this, from the third relation above we have that,

$$v_\nu \approx -\frac{1}{2}\frac{\lambda_s Y_\nu v_u v_S^2}{M_{\tilde{\nu}}^2}. \tag{9}$$

For $M_{\tilde{\nu}} > v_S$, we have $v_\nu < v_{u,d,S}$, as expected.

Let us now focus on the fifth relation of the Eq. (8). The dominant term inside the parenthesis is $M_{\tilde{N}}^2$, while outside the parenthesis the dominant term is $\frac{1}{2}A_s \lambda_s v_S^2$. Thus the fifth relation provides,

$$v_N \approx -\frac{1}{2}\frac{A_s \lambda_s v_S^2}{M_{\tilde{N}}^2}. \tag{10}$$

This expression for v_N is similar to the v_ν case and suggests that v_N is also small.

Let us now focus on the forth relation. Taking v_ν, $v_N \ll v_S$, we have that the dominant terms in that relation are,

$$M_{\tilde{S}}^2 + \frac{1}{2}\lambda_s^2 v_S^2 = 0. \tag{11}$$

Perceive that M_S dictates the value of v_S. As the neutral singlet scalar $\tilde{S}$ belongs to an extension of the MSSM, then it is reasonable to expect that its soft mass term M_S lies at TeV scale. Consequently v_S must assume values around TeV. In regard to the first and second relations they control the standard VEVs v_u and v_d.

Let us return to the expression to v_N in Eq. (10). As the neutral singlet scalar $\tilde{N}$ also belongs to an extension of the MSSM, then it is reasonable to expect that its soft mass term $M_{\tilde{N}}$ lies at TeV scale, too. In this case perceive that the value of v_N get dictated by the soft trilinear term A_s. Thus a small v_N means a tiny A_s. As A_s is a trilinear soft breaking term, then it must be generated by some spontaneous SUSY breaking scheme. The problem is that we do not know how SUSY is spontaneously broken. Thus there is no way to infer exactly the value of A_s. Moreover, note that A_s is a soft trilinear term involving only neutral scalar singlets by MSSM which turns its estimation even more complex. We argue here that it is somehow natural to expect that such terms be small.

For this we have to think in terms of spontaneous SUSY breaking schemes. For example, in the framework of gauge mediated supersymmetry breaking (GMSB) all soft trilinear terms are naturally suppressed once they arise from loops. In our case the new singlets are sterile by the standard gauge group. The minimal scenario where such soft trilinear terms could arise would be one that involve the GMSM of the B-L gauge extension of the MSSM. To build such extension and evaluate A_s in such a scenario is out of the scope of this paper. However, whatever be the case, in the framework of GMSB scheme A_s must be naturally small and consequently v_N, too. In this point we call the attention to the fact that the idea behind the ISS mechanism is that lepton number is explicitly violated at low energy scale. This suggests that the GMSB seems to be the adequate spontaneous SUSY breaking scheme to be adopted in realizing SUSYISS mechanism.

Let us discuss the case of gravity mediated supersymmetry breaking. As in the ISS mechanism lepton number is assumed to be explicitly violated at low energy scale, it is expected that v_N, v_S, v_ν, A_s, A_ν are all null at GUT scale. Considering this, the authors of Ref. [10] evaluated the running of soft trilinear terms involving scalar singlets from GUT to down scales in a different realization of the SUSYISS model. As a result they obtained that these terms develop small values at electroweak scale. Our case is

somehow similar to the case of Ref. [10] and it seems reasonable to expect that, in the general case of three generations, on doing such evaluation of the running of the soft trilinear terms, our mechanism recover the result of Ref. [10]. As we are just presenting the idea by means of only one generation, such evaluation of the running of A_s is out of the scope of this work.

Thus it seems to be reasonable to expect that, whatever be the spontaneous SUSY breaking scheme adopted, the soft trilinear terms that violate explicitly lepton number involving neutral singlet fields as $\tilde{S}$ and $\tilde{N}$ have the tendency to develop small values. In what follow we assume that A_s and A_ν lies at keV scale.

There is still an issue to consider in respect to the scalar potential. As can be easily verified, the value of the potential at origin of the fields is zero. In order to guarantee that electroweak symmetry will be broken, we need the potential in the minimum to be negative. Taking the constraints in Eq. (8) to eliminate the soft masses in the scalar potential, we have,

$$\begin{aligned}
\langle V \rangle_{mim} =& -\frac{1}{8}\left(g^2 + g'^2\right)\left(v_\nu^2 + v_d^2 - v_u^2\right)^2 \\
& - Y_\nu^2\left(v_\nu^2 v_N^2 + v_\nu^2 v_u^2 + v_u^2 v_N^2\right) - \lambda_s^2 v_S^2 v_N^2 \\
& - \frac{1}{4}\lambda_s^2 v_S^4 - A_y Y_\nu v_\nu v_N v_u \\
& - \frac{1}{2}A_s \lambda_s v_N v_S^2 - A_\nu \lambda_\nu v_N^3 - Y_\nu \lambda_s v_\nu v_u v_S^2 \\
& - 4Y_\nu \lambda_\nu v_\nu v_u v_N^2 - 2\lambda_s \lambda_\nu v_N^2 v_S^2 - 4\lambda_\nu^2 v_N^4 \\
& - Y_\nu \mu v_\nu v_N v_d.
\end{aligned} \tag{12}$$

For the magnitudes of VEVs discussed above, the dominant term is $-\frac{1}{4}\lambda_s^2 v_S^4$, which is negative. For the case of one generation considered here this is a strong evidence of the stability of the potential.

After all these considerations, we are ready to go to the central part of this work that is to develop the neutrino sector. For this we have, first, to obtain the mass matrix that involves the neutrinos. Due to the RPV the gauginos and Higgsinos mix with the neutrinos ν, N and S. Considering the basis $(\lambda_0, \lambda_3, \psi_{h_u^0}, \psi_{h_d^0}, \nu, N^c, S)$, we obtain the following mass matrix for these neutral fermions,

$$\begin{pmatrix}
M_1 & 0 & \frac{g' v_u}{\sqrt{2}} & -\frac{g' v_d}{\sqrt{2}} & -\frac{g' v_\nu}{\sqrt{2}} & 0 & 0 \\
0 & M_2 & -\frac{g v_u}{\sqrt{2}} & \frac{g v_d}{\sqrt{2}} & \frac{g v_\nu}{\sqrt{2}} & 0 & 0 \\
\frac{g' v_u}{\sqrt{2}} & -\frac{g v_u}{\sqrt{2}} & 0 & \mu & Y_\nu v_N & Y_\nu v_\nu & 0 \\
-\frac{g' v_d}{\sqrt{2}} & \frac{g v_d}{\sqrt{2}} & \mu & 0 & 0 & 0 & 0 \\
-\frac{g' v_\nu}{\sqrt{2}} & \frac{g v_\nu}{\sqrt{2}} & Y_\nu v_N & 0 & 0 & Y_\nu v_u & 0 \\
0 & 0 & Y_\nu v_\nu & 0 & Y_\nu v_u & 6\lambda_\nu v_N & \lambda_s v_S \\
0 & 0 & 0 & 0 & 0 & \lambda_s v_S & \lambda_s v_N
\end{pmatrix}, \tag{13}$$

where M_1 e M_2 are the standard soft breaking terms of the gauginos. We remark that on considering the hierarchy $v_N < v_\nu < v_d < v_u < v_S$ the bottom right 3×3 block of this matrix, which involves only the neutrinos, decouples from the gauginos and Higgsinos sector leaving the neutrinos with the following mass matrix in the basis (ν, N^c, S)

$$M_\nu \approx \begin{pmatrix}
0 & Y_\nu v_u & 0 \\
Y_\nu v_u & 2\lambda_\nu v_N & \lambda_s v_S \\
0 & \lambda_s v_S & \lambda_s v_N
\end{pmatrix}. \tag{14}$$

For this decoupling to be effective we must have v_ν of order MeV or less. Diagonalization of this mass matrix implies that the lightest neutrino, which is predominantly the standard one, ν, get the following mass expression,

$$m_\nu \approx \frac{Y_\nu^2}{\lambda_s} \frac{v_u^2}{v_S^2} v_N. \tag{15}$$

This is exactly the mass expression of the ISS mechanism. For v_S around TeV and v_N around keV we obtain neutrinos at eV scale for v_u at electroweak scale. In the case of three generations the pattern of the neutrino masses will be determined by Y_ν^{ij}.

To demonstrate the validity of these approximations we can compute the mass eigenvalues from the full matrix in (13). For typical values of the supersymmetric parameters and $v_S \sim 10$ TeV, $v_N \sim 10$ keV, $v_\nu \sim 1$ MeV and $Y_\nu \sim \lambda_s = 0.21$, we have the following order of magnitude for the mass eigenvalues ($\sim$ TeV, $\sim$ TeV, $\sim 10^2$ GeV, $\sim 10^2$ GeV, $\sim 10^{-1}$ eV, $\sim$ TeV, $\sim$ TeV), where the lightest particle is exclusively the standard neutrino. This result is encouraging and indicates that RPV is an interesting framework to realize the SUSYISS mechanism.

We end this section making a comparison of the SUSYISS developed here with the $\mu\nu$SSM in Ref. [11]. This model resorts to R-parity violation to solve the μ problem. However neutrino masses at sub-eV scale require considerable amount of fine tuning of the Yukawa couplings. We stress that, in spite of the fact that the SUSYISS model contains the particle content of the $\mu\nu$SSM, unfortunately it does not realize the $\mu\nu$SSM. This is so because if we allow a term like $\hat{S}\hat{H}_u\hat{H}_d$ in the superpotential in Eq. (4), as consequence the entries $\psi_{h_d^0}S$ and $\psi_{h_u^0}S$ in the mass matrix in Eq. (13) would develop robust values which jeopardize the realization of the ISS mechanism.

3. The mass of the Higgs

Now, let us focus on the scalar sector of the model. We restrict our interest in checking if the model may accommodates a 125 GeV Higgs mass without resorting to tight loop contributions. For the case of one generation the model involves five neutral scalars whose mass terms compose a 5×5 mass matrix that we consider in the basis $(H_u, H_d, \tilde{\nu}, \tilde{N}, \tilde{S})$. We do not show such a mass matrix here because of the complexity of their entries. Instead of dealing with a 5×5 mass matrix, which is very difficult to handle analytically, we make use of a result that says that an upper bound on the mass of the lightest scalar, which we consider as the Higgs, can be obtained by computing the eigenvalues of the 2×2 submatrix in the upper left corner of this 5×5 mass matrix [12]. This is a common procedure adopted in such cases which give us an idea of the potential of the model to generate the 125 GeV Higgs mass.

The dominant terms of this 2×2 submatrix are given by,

$$M_{2\times 2}^2$$
$$\approx \begin{pmatrix} B\mu\cot(\beta) + M_Z^2\sin^2(\beta) - \frac{Y_\nu\lambda_s v_\nu}{2v_u}v_S^2 & -B\mu - M_Z^2\sin(\beta)\cos(\beta) \\ -B\mu - M_Z^2\sin(\beta)\cos(\beta) & B\mu\tan(\beta) + M_Z^2\cos^2(\beta) \end{pmatrix}. \tag{16}$$

We made use of the hierarchy among the VEVs, as discussed above, to obtain such a 2×2 submatrix. On diagonalizing this 2×2 submatrix we obtain the following upper bound on the mass of the Higgs,

$$m_h^2 \leq M_Z^2\cos^2(2\beta) - \frac{Y_\nu\lambda_s v_\nu}{2v_u}v_S^2. \tag{17}$$

Note also that Eq. (11) imposes that either $M_{\tilde{S}}^2$ or v_S^2 is negative. In order to the second term in Eq. (17) gives a positive contribution to the Higgs mass we take $M_{\tilde{S}}^2$ negative and Y_ν and λ_s with opposite sign.

What is remarkable in the mass expression in Eq. (17) is that the second term provides a robust correction to the Higgs mass
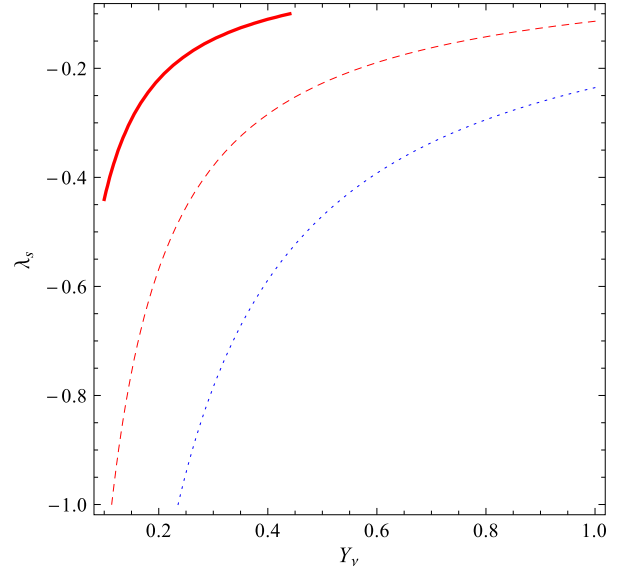
Fig. 1. Contour plot of $m_h = 125$ GeV in the Y_ν versus λ_s plane for $m_s = 800$ GeV and $X_t = 400$ GeV where (blue dotted $tan(\beta) = 5$), (red dashed $tan(\beta) = 7$) and (red solid $tan(\beta) = 10$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

even involving the parameters that dictate the neutrino masses as the couplings Y_ν and λ_s and the VEV v_S. This suggest an interesting connection between neutrino and Higgs mass. For illustrative proposals, perceive that for Y_ν of the same order of λ_s, v_ν around MeV, v_u around 10^2 GeV and v_S of order tens of TeV, the second term provides a contribution of tens of GeV to the Higgs mass. This contribution is enough to alleviate the pressure on the stop masses and their mixing in order to keep valid the principle of naturalness.

In order to check the range of values the stop mass and the A_t term may develop in this model, we add to m_h^2 given above the leading 1-loop corrections coming from the MSSM stop terms [13],

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2} \left(\log\left(\frac{m_s^2}{m_t^2}\right) + \frac{X_t^2}{m_s^2}\left(1 - \frac{X_t^2}{12m_s^2}\right)\right), \tag{18}$$

where $m_t = 173.2$ GeV is the top mass, $v = \sqrt{v_u^2 + v_d^2} = 174$ GeV is the VEV of the standard model, $X_t \equiv A_t - \mu\cot(\beta)$ is the stop mixing parameter and $m_s \equiv (m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2}$ is the SUSY scale (scale of superpartners masses) where $m_{\tilde{t}}$ is the stop mass. In the analysis done below, we work with degenerated stops and, in all plots, we take $v_\nu = 1$ MeV and $v_S = 4 \times 10^4$ GeV.

Fig. 1 shows possible values for the magnitude of Y_ν and λ_s that provide a Higgs with a mass of 125 GeV. Note that the plot tells us that such a mass requires Y_ν and λ_s around 10^{-1}. This range of values for Y_ν and λ_s provides, through Eq. (15), $m_\nu \approx 0.1$ eV for $v_S = 10$ TeV and $v_N = 10$ keV. Thus neutrino at sub-eV scale is compatible with $m_h = 125$ GeV effortlessly.

Fig. 2 tell us that the model yields the desired Higgs mass for stop mass and mixing parameters below the TeV scale. Finally, Fig. 3 shows that a Higgs of mass of 125 GeV is obtained for a broad range of values of $tan(\beta)$.

Let us discuss a little some phenomenological aspects of the SUSYISS mechanism developed here. First of all, observe that the aspects of RPV concerning the mixing among neutralinos and neutrinos, as well as charginos and charged leptons, are dictated by the VEVs v_ν and v_N and the couplings Y_ν and λ_s, which are both small. The squarks sector is practically unaffected. Thus, with
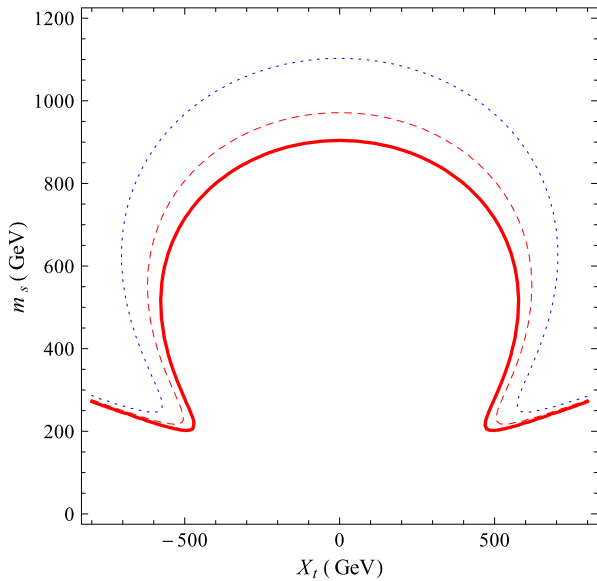
Fig. 2. Contour plot of $m_h = 125$ GeV in the X_t versus m_s plane with $\lambda_s = -0.21$, $Y_\nu = 0.21$ (blue dotted $tan(\beta) = 5$), (red dashed $tan(\beta) = 7$) and (red solid $tan(\beta) = 10$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
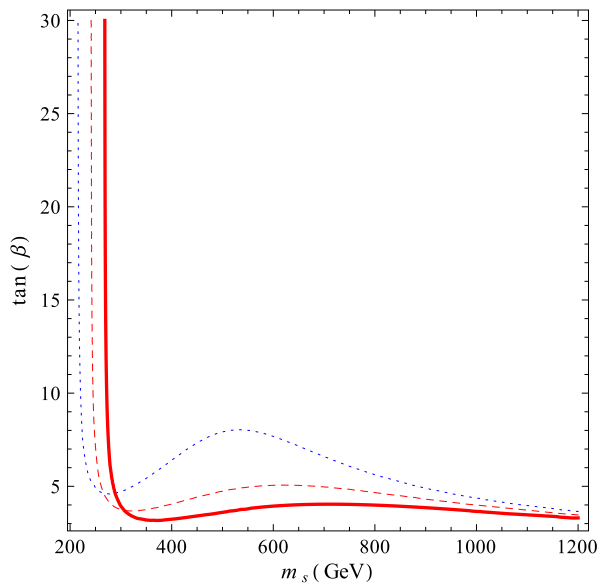
Fig. 3. Contour plot of $m_h = 125$ GeV in the $tan(\beta)$ versus m_s plane with $\lambda_s = -0.21$, $Y_\nu = 0.21$ (blue dotted $X_t = 600$ GeV), (red dashed $X_t = 700$ GeV) and (red solid $X_t = 800$ GeV). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

relation to these sectors, the phenomenology of the SUSYISS mechanism is practically similar to the case of the supersymmetric version of the ISS mechanism [4,14]. The signature of the SUSYISS mechanism developed here should manifest mainly in the scalar sector of the model due to the mixing of the neutral scalars with the sneutrinos which will generate Higgs decay channel with lepton flavor violation $h \to l_i l_j$.

In general, as far as we know, this is the first time the ISS mechanism is developed in the framework of RPV. Thus many theoretical, as well phenomenological aspects of the model proposed here must be addressed such as experimental constraints from RPV, accelerator physics, analysis of the renormalization group equation, spontaneously SUSY breaking schemas, etc., which we

postpone to a future paper [15]. Moreover, needless to say that in SUSY models with RPV the lightest supersymmetric particle is not stable which means that neither the neutralino nor sneutrino are candidates for dark matter [16] any longer. We would like to remark that because of the Z_3 symmetry used in the superpotential above cosmological domain wall problems are expected [17]. However, the solution of this problem in the NMSSM as well in the $\mu\nu$SSM [11] cases may be applied to our case, too [18].

Finally, concerning the stability of the vacuum, we have to impose that the potential be bounded from below when the scalar fields become large in any direction of the space fields and that the potential does not present charge and color breaking minima. Concerning the latter condition, we do not have to worry about this condition here because the new scalar fields associated to the superfield singlets, $\hat{S}$ and $\hat{N}^C$, are neutrals under electric and color charges. Concerning the former issue, the worry arises because at large values of the fields the quartic terms dominate the potential. Thus we have to guarantee that at large values of the fields the potential be positive. Thus we have to worry with the quartic couplings, only. The negative value of λ_s leads to two negative quartic terms. Considering this, on analyzing the potential above, we did not find any direction in the field space in which λ_s negative leads to a negative potential. All direction we find involves a set of condition where it is always possible to guarantee that the potential be positive at large value of the fields [19]. Moreover, we took λ_s negative for convenience. We may arrange the things such that all couplings be positive. For example, on taking λ_s positive, v_ν in Eq. (9) get negative, which guarantee a positive contribution to the Higgs masses and that all quartic couplings be positive. However, a complete analysis of the stability of the potential is necessary. This will be done in [15].

4. Conclusions

In this work we proposed the realization of the SUSYISS model in the framework of RPV. The main advantage of such framework is that it allows the realization of the SUSYISS model with a minimal set of superfield content where the superfields $\hat{S}$ and $\hat{N}^C$ of the minimal implementation are sufficient to realize the model. To grasp the important features of the SUSYISS, we restricted our work to the case of one generation of superfields. As nice result, the canonical mass parameters M_N and μ_N of the SUSYISS mechanism are recognized as the VEVs of the scalars $\tilde{S}$ and $\tilde{N}$ that compose the superfields $\hat{S}$ and $\hat{N}^C$. There is no way to fix the values of the VEVs v_S and v_N. However, it seems plausible that v_S and v_N develop values around TeV and keV scale, respectively. Thus, we conclude that RPV seems to be an interesting framework for the realization of the SUSYISS mechanism. We recognize that in order to establish the model a lot of work have to be done, yet. For example, we have to find the spontaneous SUSY breaking scheme that better accommodates the mechanism, develop the phenomenology of the model and its embedding in GUT schemes. We end by saying that the main results of this work are that the model proposed here realizes minimally the SUSYISS mechanism and provides a 125 GeV Higgs mass respecting the naturalness principle.

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