Relating seesaw neutrino masses, lepton flavor violation and SUSY breaking

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Abstract. We discuss a GUT realization of the supersymmetric triplet seesaw mechanism (recently proposed by us in hep-ph/0604083 and further analyzed in hep-ph/0607298) where the exchange of the heavy triplet states generates both neutrino masses and soft SUSY breaking terms.

Keywords: Neutrino masses and mixing, Lepton flavor violation, SUSY breaking.

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Recently, we have proposed a novel supersymmetric scenario of the triplet seesaw mechanism where the soft SUSY breaking (SSB) parameters of the minimal supersymmetric standard model (MSSM) are generated at the decoupling of the heavy triplets [1]. The mass scale of such SSB terms is fixed exclusively by the triplet SSB bilinear term $B_T$ and flavor violation (FV) in the SSB MSSM lagrangian can be directly related with the low-energy neutrino parameters. Our scenario is therefore highly predictive since it relates neutrino masses, lepton flavor violation (LFV) in the sfermion sector and electroweak symmetry breaking (EWSB).

We consider an $SU(5)$ grand unified theory (GUT) where the triplet states $T \sim (3,1)$ and $\bar{T} \sim (3, -1)$ fit into the 15 representation $15 = S + T + Z$ transforming as $S \sim (6,1, -\frac{2}{3}), T \sim (1,3,1), Z \sim (3,2, \frac{1}{6})$ under $SU(3) \times SU(2)_W \times U(1)_Y$ (the decomposition is obvious). The SUSY breaking mechanism is triggered by a gauge singlet chiral supermultiplet $X$, whose scalar $S_X$ and auxiliary $F_X$ components are assumed to acquire a vacuum expectation value. Defining the $B - L$ quantum numbers of the various fields as being a combination of their hypercharges and the charges:

$$Q_{10} = \frac{1}{5}, Q_5 = -\frac{3}{5}, Q_{5_H} = -\frac{2}{5}, Q_{\bar{5}_H} = \frac{2}{5}, Q_{15} = \frac{6}{5}, Q_{\overline{15}} = \frac{4}{5}, Q_X = -2,$$

and imposing $B - L$ conservation, the $SU(5)$ superpotential reads

$$W_{SU(5)} = \frac{1}{\sqrt{2}} (Y_{15\bar{5}} 15 \bar{5} + \lambda 5_H 15 \bar{5}_H 5_H) + Y_{\bar{5}_5} 5_H 10 + Y_{10} 10 10 5_H + M_{5} 5_H 5_H + \xi X_{15} \overline{15},$$

where we have used the usual conventions for the $SU(5)$ representations. It is clear from $W_{SU(5)}$ that the $15, \overline{15}$ states act as messengers of both $B - L$ and SUSY breaking to the visible (MSSM) sector due to the coupling with $X$. In particular, while $\langle S_X \rangle$ only breaks $B - L$, $\langle F_X \rangle$ breaks both SUSY and $B - L$. Once $SU(5)$ is broken to the SM group we
find, below the GUT scale $M_G$, $W = W_0 + W_T + W_{S,Z}$ with,

$$
W_0 = Y_e e^c H_1 L + Y_d d^c H_1 Q + Y_u u^c Q H_2 + \mu H_2 H_1 ,
$$

$$
W_T = \frac{1}{\sqrt{2}}(Y_T L T L + \lambda H_2 T H_2) + M_T T T ,
$$

$$
W_{S,Z} = \frac{1}{\sqrt{2}} Y_S d^c S d^c + Y_Z d^c Z L + M_Z Z Z + M_{S S} \bar{S} S .
$$

(3)

Here, $W_0$ denotes the MSSM superpotential, the term $W_T$ contains the triplet Yukawa and mass terms, and $W_{S,Z}$ includes the couplings and masses of the colored fragments $S, Z$. For simplicity, we take $M_T = M_S = M_Z$ and $Y_S, Y_Z \ll Y_T$ at $M_G$ (the general $SU(5)$ has been studied in detail in Ref. [2]). In Eq. (3), $W_T$ is responsible for the realization of the seesaw mechanism. The Majorana neutrino mass matrix reads, at the electroweak scale,

$$
\mathbf{m}_\nu^{ij} = \frac{\lambda \langle H_2 \rangle^2}{M_T} \mathbf{Y}_T^{ij} , \quad i, j = e, \mu, \tau .
$$

(4)

In the basis where $\mathbf{Y}_e$ is diagonal, it is apparent that all LFV is encoded in $\mathbf{Y}_T$. This stems from the fact that the nine independent parameters contained in $\mathbf{m}_\nu$ are directly linked to the neutrino parameters according to $\mathbf{m}_\nu = \mathbf{U}^* \mathbf{m}_\nu^D \mathbf{U}^\dagger$, where $\mathbf{m}_\nu^D = \text{diag}(m_1, m_2, m_3)$ are the mass eigenvalues, and $\mathbf{U}$ is the leptonic mixing matrix.

As for the SSB term one has, in the broken phase, $-B_T M_T (T \bar{T} + \bar{S} S + \bar{Z} Z) + \text{h.c.}$, with $B_T \equiv B_{15}$. These terms lift the tree-level mass degeneracy in the MSSM supermultiplets. Indeed, at the scale $M_T$, all the states $T, \bar{T}, S, \bar{S}$, and $Z, \bar{Z}$ are messengers of SUSY breaking to the MSSM sector via gauge interactions, as it happens in conventional gauge-mediation scenarios. However, in our scenario the states $T, \bar{T}$ also communicate SUSY-breaking through Yukawa interactions. Finite contributions for the trilinear couplings of the superpartners with the Higgs doublets, $A_e, A_u, A_d$, the gaugino masses $M_a$ ($a = 1, 2, 3$) and the Higgs bilinear term $-B_H \mu H_2 H_1$ emerge at the one-loop level:

$$
A_e = \frac{3B_T}{16\pi^2} \mathbf{Y}_e \mathbf{Y}_T^\dagger \mathbf{Y}_T , \quad A_u = \frac{3B_T |\lambda|^2}{16\pi^2} \mathbf{Y}_u , \quad A_d = 0 , \quad M_a = \frac{7B_T g_a^2}{16\pi^2} , \quad B_H = \frac{3B_T |\lambda|^2}{16\pi^2} .
$$

(5)

Instead, the finite contributions to the scalar SSB masses arise at the two-loop level:

$$
\mathbf{m}_L^2 = \frac{B_T^2}{(16\pi^2)^2} \left[ \frac{21}{10} g_1^4 + \frac{21}{2} g_2^4 - \left( \frac{27}{5} g_1^2 + 21g_2^2 \right) \mathbf{Y}_T^\dagger \mathbf{Y}_T + 3\mathbf{Y}_T^\dagger \mathbf{Y}_e^\dagger \mathbf{Y}_e \mathbf{Y}_T + 18(\mathbf{Y}_T^\dagger \mathbf{Y}_T)^2 \right] + 3\text{Tr}(\mathbf{Y}_T^\dagger \mathbf{Y}_T) \mathbf{Y}_T^\dagger \mathbf{Y}_T ,
$$

$$
\mathbf{m}_e^2 = \frac{B_T^2}{(16\pi^2)^2} \left[ \frac{42}{5} g_1^4 - 6\mathbf{Y}_e \mathbf{Y}_T^\dagger \mathbf{Y}_T \mathbf{Y}_e^\dagger \right] ,
$$

$$
\mathbf{m}_{h_2}^2 = \frac{B_T^2}{(16\pi^2)^2} \left[ \frac{21}{10} g_1^4 + \frac{21}{2} g_2^4 - \left( \frac{27}{5} g_1^2 + 21g_2^2 \right) |\lambda|^2 + 9|\lambda|^2 \text{Tr}(\mathbf{Y}_u \mathbf{Y}_u^\dagger) + 21|\lambda|^4 \right] ,
$$

$$
\mathbf{m}_{h_1}^2 = \frac{B_T^2}{(16\pi^2)^2} \left[ \frac{21}{10} g_1^4 + \frac{21}{2} g_2^4 \right] .
$$

(6)

In the above equations we have only shown the result for the slepton and Higgs soft masses $\mathbf{m}_L^2$ and $\mathbf{m}_{h_1,2}^2$, respectively. Since they are not directly relevant for our present
discussion, we do not provide here the results for the squark soft masses $m_{\tilde{u}}$ and $m_{\tilde{Q}}$ which can be found in Ref. [1]. The expressions in Eqs. (5) and (6) hold at the decoupling scale $M_T$ and therefore are meant as boundary conditions for the SSB parameters which then undergo (MSSM) RG running to the low-energy scale $\mu_{SUSY}$. In particular, we observe that the Yukawa couplings $Y_T$ induce LFV to $A_e$, to the scalar masses $m_{\tilde{L}}^2$ and $m_{\tilde{e}}^2$. This makes the present scenario distinct from pure gauge-mediated models where FV comes out naturally suppressed.

The crucial point in our discussion is that the flavor structure of $m_{\tilde{L}}^2$ is proportional to $Y_T^\dagger Y_T$ which can be written by using Eq. (4) in terms of the neutrino parameters (the terms $\propto g^2 Y_T^\dagger Y_T$ are generically the leading ones):

$$
(m_{\tilde{L}}^2)_{ij} \propto B_T^2 (Y_T^\dagger Y_T)_{ij} \sim B_T^2 \left[ U(m_D^\nu)^2 U^\dagger \right]_{ij} \lambda \langle H_2 \rangle^2 \left[ U(m_D^\nu)^2 U^\dagger \right]_{ij}.
$$

Consequently, the relative size of LFV in the different leptonic families can be univocally predicted as:

$$
\frac{(m_{\tilde{L}}^2)_{\tau\mu}}{(m_{\tilde{L}}^2)_{\mu\mu}} \approx \left( \frac{m_3}{m_2} \right)^2 \frac{\sin 2\theta_{23}}{\sin 2\theta_{12} \cos \theta_{23}} \sim 40, \quad \frac{(m_{\tilde{L}}^2)_{\tau\mu}}{(m_{\tilde{L}}^2)_{\mu\mu}} \approx \tan \theta_{23} \sim 1,
$$

where $\theta_{12}$ and $\theta_{23}$ are lepton mixing angles. This aspect renders the present framework much more predictive than the type I seesaw mechanism. Indeed, model-independent relations like the ones shown above cannot be found in the former case without making assumptions about the high-energy flavor structure. From Eqs. (8) the branching ratios (BR) of LFV processes such as the decays $\ell_i \to \ell_j \gamma$ can be predicted

$$
\text{BR}(\tau \to \mu \gamma) / \text{BR}(\mu \to e \gamma) \sim 300, \quad \text{BR}(\tau \to e \gamma) / \text{BR}(\mu \to e \gamma) \sim 10^{-1},
$$

where the estimates have been obtained considering a hierarchical neutrino mass spectrum and the best-fit values for the low-energy neutrino oscillation parameters. Relations like those of Eqs. (8) and (9) are equally obtained if one assumes universal boundary conditions for the soft masses at a scale higher than $M_T$ [3]. It is worth stressing that our scenario constitutes a concrete and simple realization of the so-called minimal lepton flavor violation hypothesis. Other LFV processes and related correlations have been considered in [2]. Without loss of generality we take $B_T$ to be real.$^1$

Following a bottom-up perspective and taking a given ratio $M_T/\lambda$ and $\tan \beta$, $Y_T$ is determined at $M_T$ according to the matching expression by Eq. (4) using the low-energy neutrino parameters. Although the $\mu$-parameter is not predicted by the underlying theory, it is nevertheless determined together with $\tan \beta$ by correct EWSB conditions. Therefore, we end up with only three free parameters, $B_T, M_T$ and $\lambda$.

In the left panel of Fig. [1] we show the $(\lambda, M_T)$ parameter space allowed by the perturbativity (lightest grey region) and EWSB requirements, the experimental lower

\[1\] For discussions on the possible implications of a complex $B_T$ to electric dipole moments and the generation of the baryon asymmetry of the Universe see Refs. [4] and [5], respectively.
bound on the lightest Higgs mass $m_h$ and the upper bound on $BR(\mu \to e\gamma)$, for $B_T = 20$ TeV. The white region shows the portion of the parameter space allowed by the aforementioned constraints (for extensive discussions on the interpretation of this plot see Refs. [1, 2]). In the right-panel, we display the branching ratios $BR(\ell_j \to \ell_i \gamma)$ as a function of $\lambda$ for $B_T = 20$ TeV and $M_T = 10^{13} (10^9)$ GeV in the left (right) plot. The behavior of these branching ratios is in remarkable agreement with the estimates of Eq. (2). Hence, the relative size of LFV does not depend on the detail of the model, such as the values of $\lambda$, $B_T$ or $M_T$.

In conclusion, we have suggested a unified picture of the supersymmetric type-II seesaw where the triplets, besides being responsible for neutrino mass generation, communicate SUSY breaking to the observable sector through gauge and Yukawa interactions. We have performed a phenomenological analysis of the allowed parameter space emphasizing the role of LFV processes in testing our framework. More details can be found in Refs. [1] and [2].

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