7 Higgs Mediated Lepton Flavour Violation in the Supersymmetric Inverse Seesaw Model

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Abstract We have investigated Higgs mediated lepton flavor violating observables in the inverse seesaw framework of Minimal Supersymmetric Standard Model. We have shown that, lightness of the sterile (s)neutrinos can enhance the effective coupling $H/A - l_i - l_j$. As a consequence, all Higgs mediated flavor violating observables are enhanced by as much as two orders of magnitude.

7.1 Introduction

Neutrino oscillations have provided one of the most intriguing experimental evidence towards the beyond Standard Model (SM) physics. Minimal Supersymmetric Standard Model (MSSM), one of the most popular extension of the Standard Model can also accommodate neutral flavor oscillation when it is extended to include the right handed neutrino superfields. The additional supersymmetric (SUSY) states with masses in the TeV scale can provide contributions to charged lepton flavor violations (cLFV), such as $l_i \to l_j \gamma$ or three body decays $l_i \to 3l_j$. Thus, any cLFV signal, if observed, would clearly convey the indirect evidence for new physics.

The introduction of the right handed neutrino superfields in the SUSY theories naturally invites seesaw mechanism to embed with it. In the SUSY-seesaw theories, neutrino Yukawa couplings can induce mixing term in the SUSY soft-breaking slepton mass matrices through renormalisation group evolution (RGE) of the aforementioned parameters. This in turn generates observable effects in the charged lepton flavor violation through the mixings in the slepton mass matrices. However, in this seesaw scheme, requirement of $O(1)$ neutrino Yukawa couplings leads the right handed neutrino mass scale or seesaw scale very close to the gauge coupling unification scale which is impossible to probe experimentally.

On the contrary, inverse seesaw scenarios [1] offers an appealing alternative, where one can retain $O(1)$ neutrino Yukawa couplings while the right handed neutrino mass scale can reside near the TeV scale. This at one hand offers testability by directly producing the sterile neutrinos at the Large Hadron Collider, while on the other hand, can enhance the charged lepton flavor violating processes through the unsuppressed lepton number *conserving* dimension-6 operator $\left(Y_\nu^\dagger \frac{1}{|M|^2} Y_\nu\right)$ (M represents right handed neutrino mass scale). Indeed, in view of this strong potential, several phenomenological studies have been carried out in the recent past.

The singlet neutrinos with masses at the TeV scale may significantly contribute to cLFV observables, irrespective of the supersymmetric states . Supersymmetric realisations of the inverse seesaw may enhance these cLFV rates even further [2, 3]. This particular work is devoted to the Higgs mediated charged lepton flavor violation processes in the supersymmetric inverse seesaw framework [4]. We have shown that the effective coupling $H/A - l_i - l_j$ can be enhanced significantly, thanks to the comparatively light right-handed neutrinos and sneutrinos (which provide negligible contribution in the framework of a type I SUSY-seesaw). We find that this new contribution, in particular leads to a significant enhancement of the several cLFV observables.

7.2 Inverse Seesaw Mechanism in the MSSM

Here, the MSSM field contents is augmented by three pairs of singlet superfields, $\widehat{\nu}^c_i$ and $\widehat{X}_i$ ($i = 1, 2, 3$) with lepton numbers -1 and $+1$, respectively. Consequently, the superpotential for the supersymmetric inverse seesaw model can be defined by

$$\begin{aligned} \mathcal{W} &= \varepsilon_{ab}\Big[Y_d^{ij}\widehat{D}_i\widehat{Q}_j^b\widehat{H}_d^a + Y_u^{ij}\widehat{U}_i\widehat{Q}_j^a\widehat{H}_u^b + Y_e^{ij}\widehat{E}_i\widehat{L}_j^b\widehat{H}_d^a \\ &+ Y_\nu^{ij}\widehat{\nu}_i^c\widehat{L}_j^a\widehat{H}_u^b - \mu\widehat{H}_d^a\widehat{H}_u^b\Big] + M_{R_i}\widehat{\nu}_i^c\widehat{X}_i + \frac{1}{2}\mu_{X_i}\widehat{X}_i\widehat{X}_i\,, \end{aligned} \tag{7.1}$$

The information of inverse seesaw are encoded in the last two terms in Eq: 7.1. Here, M_{R_i} represents the right-handed neutrino mass term that conserves lepton number while μ_{X_i} violates the same by two units. The terms $\widehat{\nu}_i^c\widehat{X}_i$ and $\widehat{X}_i\widehat{X}_i$ are assumed to be diagonal in generation space.
The soft SUSY breaking Lagrangian can be written as

$$\begin{aligned} -\mathcal{L}_{\text{soft}} = -\mathcal{L}_{\text{soft}}^{\text{MSSM}} + m^2_{\widetilde{\nu}^c}\widetilde{\nu}_i^{c\dagger}\widetilde{\nu}_i^c + m_X^2\widetilde{X}_i^\dagger\widetilde{X}_i \\ + \left(A_\nu Y_\nu^{ij}\varepsilon_{ab}\widetilde{\nu}_i^c\widetilde{L}_j^a H_u^b + B_{M_{R_i}}\widetilde{\nu}_i^c\widetilde{X}_i + \frac{1}{2}B_{\mu_{X_i}}\widetilde{X}_i\widetilde{X}_i + \text{h.c.}\right), \end{aligned} \tag{7.2}$$

where $\mathcal{L}_{\text{soft}}^{\text{MSSM}}$ denotes the soft SUSY breaking terms of the MSSM. In the above, for the singlet scalar states we assume $m^2_{X_i} = m^2_X$ and $m^2_{\widetilde{\nu}^c_i} = m^2_{\widetilde{\nu}^c}$. The parameters $B_{M_{R_i}}$ and $B_{\mu_{X_i}}$ represent the bilinear couplings for the sterile neutrino states. Note that while the former conserves lepton number, the latter generates the lepton number violating $\Delta L = 2$ term.

Now we illustrate the pattern of light neutrino masses in the inverse seesaw model considering only one-generation case. In the $\{\nu, \nu^c, X\}$ basis the (3×3) neutrino mass matrix can be written as

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix}, \tag{7.3}$$

with $m_D = Y_\nu v_u$, yielding the mass eigenvalues ($m_1 \ll m_{2,3}$):

$$m_1 = \frac{m_D^2\mu_X}{m_D^2 + M_R^2}, \quad m_{2,3} = \mp\sqrt{M_R^2 + m_D^2} + \frac{M_R^2\mu_X}{2(m_D^2 + M_R^2)}. \tag{7.4}$$

The advantage of the inverse seesaw is that, here the lightness of the smallest eigenvalue m_1 can be attributed to the smallness of μ_X ($\mu_X \simeq m_1$). Technically, such small value of μ_X is natural in the sense of 't Hooft since in the limit $\mu_X \to 0$, the total lepton number symmetry is restored. Thus the lepton number conserving mass parameters (m_D and M_R) are completely unconstrained in this model.

Finally, the effective right-handed sneutrino mass term (Dirac-like) can be expressed as $M^2_{\tilde{\nu}^c_i} = m^2_{\tilde{\nu}^c} + M^2_{R_i} + \sum_j |Y^{ij}_\nu|^2 v_u^2$. Assuming $M_R \sim \mathcal{O}$(TeV), the effective sneutrino mass term also assumes $O(1)$ TeV, in clear contrast to what occurs in the standard (type I) SUSY seesaw where it takes masses $O(M_R)$. Such a light sneutrino (i.e. $M^2_{\tilde{\nu}^c} \sim M^2_{\rm SUSY}$) leads to the enhancement of Higgs mediated contributions to lepton flavour violating observables.

7.3 Lepton flavour violation: Higgs-mediated contributions

In the SUSY seesaw framework, the neutrino Yukawa couplings, which are non-diagonal to accommodate the neutrino oscillation data are the only sources for flavour violation. The presence of right handed neutrino would drive the soft SUSY breaking slepton mass parameter $m^2_{\tilde{L}_{ij}}$ (for $i \neq j$) to acquire non vanishing contribution at the weak scale. Considering cMSSM/mSUGRA like boundary condition at the GUT scale, in the leading logarithmic approximation this radiative effect is proportional to Y_ν [5, 6] and can be expressed as

$$\begin{aligned}(\Delta m^2_{\tilde{L}})_{ij} &\simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu)_{ij}\,, \quad L = \ln\frac{M_{GUT}}{M_R} \\ &= \xi (Y_\nu^\dagger Y_\nu)_{ij}, \end{aligned} \tag{7.5}$$

where for simplicity, we assume degenerate right-handed neutrino spectrum, $M_{R_i} = M_R$. As can be guessed from Eq:7.5, the factor ξ would be enhanced in the inverse seesaw framework compared to the standard (type I) SUSY seesaw, thanks to smallness of the right handed neutrino mass term.

On the other hand, Higgs-mediated flavor violating processes are induced by the non-holomorphic Yukawa interactions $\bar{D}_R Q_L H_u^*$ at the one-loop level. This was first pointed out in the context of quark families in [7]. On a similar note, in the lepton sector, the Higgs-mediated flavour violating couplings are also induced at the one loop level by the non-holomorphic Yukawa term $\bar{E}_R L H_u^*$ [8]. Consequently, its role has been studied in the context of several lepton flavor violating processes like $\tau \to 3\mu$ [8], $B_s \to \mu\tau$, $B_s \to e\tau$ [9], $\tau \to \mu\eta$ [10]. A detailed analyses of the several $\mu - \tau$ lepton flavour violating observables $\tau \to \mu X$ ($X = \gamma, e^+e^-, \mu^+\mu^-, \rho, \pi, \eta, \eta'$) can be found in [11].

The effective Lagrangian that describes the coupling of the neutral Higgs fields to the charged leptons can be expressed as

$$-\mathcal{L}^{\rm eff} = \bar{E}^i_R Y_e^{ii}\left[\delta_{ij} H_d^0 + \left(\epsilon_1 \delta_{ij} + \epsilon_{2ij}(Y_\nu^\dagger Y_\nu)_{ij}\right) H_u^{0\,*}\right] E^j_L + \text{h.c.}\,. \tag{7.6}$$

The first term represents the usual Yukawa interaction, while the coefficient ϵ_1 encodes the corrections to the charged lepton Yukawa couplings. In the basis for diagonal charged lepton

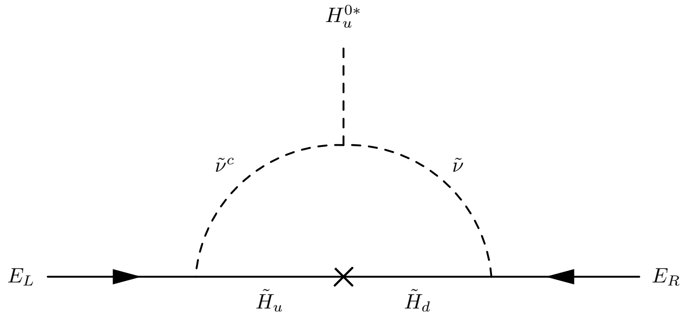

Figure 7.1: Right-handed sneutrino contribution to ϵ'_2.

Yukawa couplings, the last term in Eq. (7.6), i.e. $\epsilon_{2ij}(Y_\nu^\dagger Y_\nu)_{ij}$, is in general non-diagonal which introduces the flavor violating Higgs coupling $H/A - l_i - l_j$.

In the standard seesaw mechanism, the co-efficient ϵ_{2ij} encodes the sole contribution to the cLFV processes where LFV is introduced via a radiatively induced non-diagonal terms in the slepton masses $(\Delta m^2_{\tilde{L}})_{ij}$ (see Eq. (7.5)) (For details see ref: [4]).

Now, in the framework of the inverse SUSY seesaw, there is an additional diagram: the sneutrino-chargino mediated loop [1], depicted in Fig. 7.1 which provides the leading contribution. This new contribution can be computed from

$$\epsilon'_{2ij} = \frac{1}{16\pi^2}\mu A_\nu F_1(\mu^2, m^2_{\tilde{\nu}_i}, M^2_{\tilde{\nu}^c_j}), \tag{7.7}$$

with

$$F_1(x,y,z) \;=\; -\frac{xy\ln(x/y) + yz\ln(y/z) + zx\ln(z/x)}{(x-y)(y-z)(z-x)}. \tag{7.8}$$

Here, we have parametrized the soft trilinear term for the neutral leptons as $A_\nu Y_\nu$, and A_ν is a flavour independent real mass term. Consequently, the effective Lagrangian is modified as

$$-\mathcal{L}^{\text{LFV}} = \bar{E}^i_R Y_e^{ii} \epsilon^{\text{tot}}_{2ij} (Y_\nu^\dagger Y_\nu)_{ij} H_u^{0*} E^j_L + \text{h.c.}, \tag{7.9}$$

with $\epsilon_2^{\text{tot}} = \epsilon_2 + \epsilon'_2$.

Note that ϵ'_{2ij} does not require any LFV mass insertions, thus naturally dominate over ϵ_{2ij}. This can easily be understood from a simple analysis where we have assumed all dimensionful parameters as m_{SUSY} and $M_R \sim 1$TeV. In this limit, the loop functions are given by $F_2(x,x,x,x) = \frac{1}{6x^2}$ and $F_1(x,x,x) = \frac{1}{2x}$. This leads to

$$\epsilon_2 \simeq -0.0007\,, \;\; and \;\; \epsilon'_2 \simeq 0.003\,.$$

In the above, we have further assumed that at M_{GUT}, one has $A_0 = 0$, taking for the gauge couplings $\alpha_2 = 0.03$ and $\alpha' = 0.008$. Thus, at the leading order in the inverse seesaw, the lepton flavour violation coefficient becomes $|\epsilon_2^{\text{tot}}| = |\epsilon_2 + \epsilon'_2| \simeq 2 \times 10^{-3}$.

[1] Note that the large masses of $\tilde{\nu}^c$ in the standard (type I) seesaw makes this effect negligible, thus has not been taken into account in the literature.

On the contrary, in the standard seesaw model ($M_R \sim 10^{14}$ GeV), the coefficient ξ would be small, thus one finds $|\epsilon_2^{\text{tot}}| = |\epsilon_2| \simeq 2 \times 10^{-4}$. This shows how in the inverse SUSY seesaw, ϵ_2^{tot} is enhanced by a factor of order ~ 10 compared to the standard seesaw.

The effective Lagrangian describing $\bar{E}_R^i E_L^j H_k$ (where $H_k = h, H, A$) can be derived from Eq. (7.6), and reads [8, 9] as

$$-\mathcal{L}^{\text{eff}}_{i\neq j} = (2G_F^2)^{1/4} \frac{m_{E_i}\kappa^E_{ij}}{\cos^2\beta} \left(\bar{E}_R^i E_L^j\right) [\cos(\alpha-\beta)h + \sin(\alpha-\beta)H - iA] + \text{h.c.}, \tag{7.10}$$

where α is the CP-even Higgs mixing angle and $\tan\beta = v_u/v_d$, and

$$\kappa^E_{ij} \;=\; \frac{\epsilon^{\text{tot}}_{2ij}(Y_\nu^\dagger Y_\nu)_{ij}}{\left[1 + \left(\epsilon_1 + \epsilon^{\text{tot}}_{2ii}(Y_\nu^\dagger Y_\nu)_{ii}\right)\tan\beta\right]^2}\,. \tag{7.11}$$

As clear from the above equation, large values of ϵ_2^{tot} lead to large values of κ^E_{ij}. Since the cLFV branching ratios are proportional to $(\kappa^E_{ij})^2$, a sizeable enhancement, as large as two orders of magnitude, is expected for all Higgs-mediated LFV observables.

7.4 Results and Discussion

As can be seen from Eq:7.10, Higgs mediation would be more pronounced for large values of $\tan\beta$ and small values Higgs boson masses. Similarly, the corresponding amplitude strongly depends on the chirality of the lepton. The cLFV observables would be maximized if the right-handed particle is the heaviest lepton τ. In view of this we particularly focus on the following observables:

1. Br($\tau \to 3\mu$)
2. Br($B_s \to \ell_i \ell_j$)
3. $\tau \to \mu P$ ($P = \pi, \eta, \eta'$).

Analytical results for these observables can be found in ref: [4](also see the references therein). Here, we numerically evaluate the LFV observables where the benchmark points are selected from Ref: [12]. Moreover, we also consider scenarios of Non-Universal Higgs Masses (NUHM), as this allows to explore the impact of the lightness of the CP-odd Higgs boson. In Table 7.1, we list the chosen points: CMSSM-A and CMSSM-B respectively correspond to the 10.2.2 and 40.1.1 benchmark points in [12], while NUHM-C is an example of a non-universal scenario. For these points, the low-energy SUSY parameters were obtained using SuSpect [13]. The flavour-violating slepton mass term $(\Delta m^2_{\tilde{L}})_{ij}$ or ξ, are calculated at the leading order using Eq. (7.5). (For NUHM, we also use the same value of ξ as for CMSSM-A.) In addition, the (physical) right-handed sneutrino masses are assumed $M_{\tilde{\nu}^c} \approx 3$ TeV and $\left(Y_\nu^\dagger Y_\nu\right) = 0.7$, particularly in agreement with the Non-Standard Neutrino Interactions bounds [14]. Moreover, in our numerical analysis, we have fixed the trilinear soft breaking parameter $A_\nu = -500$ GeV (at the SUSY scale). As can be seen (From Table 7.2) $\tau \to \mu\eta$ is the most promising

Point	$\tan\beta$	$m_{1/2}$	m_0	$m^2_{H_U}$	$m^2_{H_D}$	A_0	μ	m_A
CMSSM-A	10	550	225	$(225)^2$	$(225)^2$	0	690	782
CMSSM-B	40	500	330	$(330)^2$	$(330)^2$	-500	698	604
NUHM-C	15	550	225	$(652)^2$	$-(570)^2$	0	478	150

Table 7.1: Benchmark points used in the numerical analysis (dimensionful parameters in GeV).

LFV Process	Present Bound	Future Sensitivity	CMSSM-A	CMSSM-B	NUHM-C
$\tau \to \mu\mu\mu$	2.1×10^{-8} (Belle)	8.2×10^{-10} (SuperB)	1.4×10^{-15}	3.9×10^{-11}	8.0×10^{-12}
$\tau \to \mu\eta$	2.3×10^{-8} (Belle)	$\sim 10^{-10}$ (SuperB)	8.0×10^{-15}	3.3×10^{-10}	4.6×10^{-11}
$B^0_s \to \mu\tau$			7.7×10^{-14}	2.5×10^{-8}	7.8×10^{-10}
$B^0_s \to e\mu$	2.0×10^{-7} (CDF)	6.5×10^{-8}(LHCB)	3.4×10^{-16}	8.9×10^{-11}	3.4×10^{-12}

Table 7.2: Higgs-mediated contributions to the branching ratios of several lepton flavour violating processes, for the different benchmark points of Table 7.1. We also present the current experimental bounds and future sensitivities for the LFV observables.

concerning the next generation of B factories. The $B^0_{d,s} \to \mu\tau$ decay is also interesting, but there is not much hope concerning the future sensitivities.

7.5 Conclusion

Lepton flavor violation, if observed in the charged lepton sector would (i) manifest the presence of new physics and (ii) could provide a hint for the origin of neutrino masses and mixings. Assuming inverse seesaw framework in the Minimal Supersymmetric Standard Model we have studied the impact of the Higgs mediation to the cLFV observables. We have argued that TeV scale right-handed (s)neutrinos offer the possibility to enhance the Higgs-mediated contributions. Consequently, different LFV branching ratios can be enhanced by as much as two orders of magnitude when compared to the standard (type I) SUSY seesaw

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