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Higgs effective Hl_il_j vertex from heavy ν_R and applications to LFV phenomenology

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We present a new computation of the Lepton Flavor Violating effective vertex involving the Higgs boson and two leptons with different flavors. This vertex is generated from the integration to one-loop level of the heavy right handed neutrinos which are considered here within the context of the Low Scale Seesaw Models and with masses close to the TeV scale. We apply the Mass Insertion Approximation technique to compute the loop contributions from these heavy ν_R and derive a symple analytical formula for the Hl_il_j effective vertex in terms of the input Y_ν Yukawa coupling matrix and right handed M_R neutrino masses. Some interesting phenomenological applications of this Hl_il_j effective vertex are also included.

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1. Introduction

Physical processes involving Lepton Flavor Violation (LFV) in the charged leptonic sector have not been found yet in Nature, but they are intensely searched for at present experiments. The great interest for these searches is obvious: A positive signal of any of these kind of LFV processes would indicate undoubtly the existence of new physics beyond the Standard Model (SM), and most probably would point towards a connection with the origin of neutrino masses and neutrino flavor mixings. Understanding this connection is precisely our major motivation.

Our main focus here will be on the practical computation of the Hl_il_j effective vertex that is generated from the integration to one-loop of the heavy right handed neutrinos, within the context of the Low Scale Seesaw Models. Concretely, we will choose to work in the particular realization of these models provided by the Inverse Seesaw Model (ISS), and will assume that the mass scale associated to the right-handed neutrinos M_R is close to the TeV scale, therefore potentially reacheable at the LHC. The other important assumption here is that the charged LFV does not happen at the tree level, but it is radiatively induced to one-loop level from exclusively the heavy ν_R, due to the existence of non-vanishing entries in the neutrino Yukawa coupling matrix, Y^{ν}_{ij}, with $i \neq j$. These represent the interactions between the Higgs boson H, a ν_{L_i} with a given flavor i and a ν_{R_j} with a different flavor j. An schematic view of this radiatively induced effective Hl_il_j vertex and its role in the LFV Higgs decays and in some Higgs mediated processes is shown in fig.1. For this new computation we apply the Mass Insertion Approximation (MIA) technique and derive symple analytical formulas for this Hl_il_j effective vertex in the two most important cases: 1) the LFV Higgs decays where the Higgs is on-shell, and 2) the LFV Higgs mediated processes where the Higgs is off-shell. Here we just outline the main results and address the reader to our full paper [1] where all the details and technicalities of this study are presented.

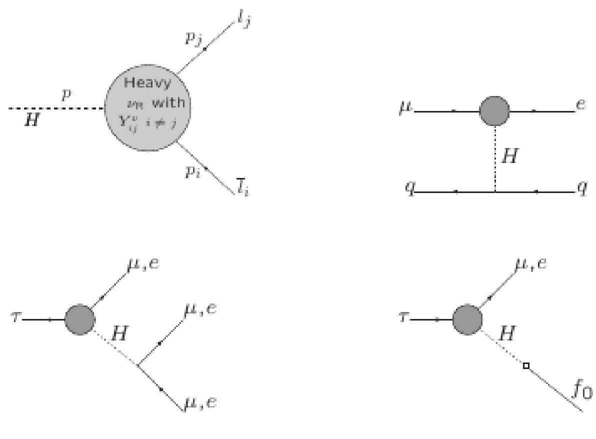

Figure 1: Schematic LFV effective vertex Hl_il_j generated from the integration of heavy ν_R in the loops (shadowed blob), and examples of this vertex participating in Higgs mediated processes: 1) LFV Higgs decays (upper left panel), 2) $\mu - e$ conversion in heavy nuclei (upper right panel), 3) LFV tau leptonic decays (lower left panel), 4) LFV tau semileptonic decays (lower right panel)

2. Theoretical framework: The ISS and the MIA

We work within the framework of Low Scale Sessaw Models, and more concretely we choose the ISS. The SM particle content is extended with 3 pairs of fermionic singlets with opposite lepton numbers, $\nu_{Ri}(L=+1)$ and $X_j(L=-1)$ with $i,j=1,2,3$. The basic assumption of the ISS, in contrast to other Seesaw Models, is that the Lepton Number global symmetry is only violated by the small μ_X Majorana mass for the singlets X, whereas the mass term for the ν_R singlets, given by the M_R mass scale, is Lepton Number preserving. The ISS Lagrangian includes as well the Yukawa interactions among the left-handed neutrinos, ν_L, the right-handed neutrinos, ν_R, and the Higgs boson particle, H, and is given by:

$$\mathscr{L}_{\rm ISS} = -Y_\nu^{ij}\overline{L_i}\widetilde{\Phi}\nu_{Rj} - M_R^{ij}\overline{\nu_{Ri}^c}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^c}X_j + h.c.\,, \tag{2.1}$$

where L is the SM lepton doublet, $L=(\nu_L\; l_L)^T$, $\widetilde{\Phi}=i\sigma_2\Phi^*$ with Φ the SM Higgs doublet containing the Higgs particle H, and i,j are indices in flavor space that run from 1 to 3. Correspondingly, Y_ν, μ_X and M_R are 3×3 matrices. Without loss of generality, one can choose a basis where M_R is flavor diagonal. The neutrino mass matrix and its diagonalization are given by:

$$M_{\rm ISS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}\,,\;\; U_\nu^T M_{\rm ISS} U_\nu = {\rm diag}(m_{n_1},\ldots,m_{n_9}). \tag{2.2}$$

It involves the three relevant mass scales, M_R, μ_X and the Dirac mass, $m_D = vY_\nu$, with $v=174\,{\rm GeV}$, and leads to 9 physical neutrino mass eigenstates n_i, $i=1,.,9$, which are Majorana fermions, i.e. they are their own antiparticles. The three lightest ones are identified with the experimentaly detected neutrinos, ν, and the six remaining ones are the new heavy neutrinos, N. For the range of our interest, with $\mu_X \ll m_D \ll M_R$, the masses of the light neutrinos are typically of the order of $m_\nu \sim (m_D^2/M_R^2)\mu_X$, and the masses of the heavy neutrinos are of the order of $m_N \sim M_R$. The six heavy neutrinos indeed come into 3 pseudo-Dirac pairs with small mass splittings between the two components in each pair of the order of μ_X, hence, they are considered as quasi-degenerate.

For the present computation, we use the MIA and we do not work with the neutrino physical basis, n_i, but instead with the Electroweak (EW) basis. Therefore, we use ν_L, ν_R and X and their corresponding Feynman rules derived from $\mathscr{L}_{\rm ISS}$ in terms of Y_ν, M_R and μ_X. Furthermore, we choose as our input neutrino parameters: Y_ν and M_R. For this purpose, we use the μ_X parametrization proposed in [2], where μ_X is not an input but it is derived from m_D (i.e. from Y_ν), M_R and the physical light neutrino masses, m_ν, and mixings in $U_{\rm PMNS}$, in order to accommodate the low energy neutrino data,

$$\mu_X = M_R^T m_D^{-1} U_{\rm PMNS}^* m_\nu U_{\rm PMNS}^\dagger m_D^{T^{-1}} M_R. \tag{2.3}$$

The use of the MIA has the advantage of organizing the computation of the one-loop effective vertex Hl_il_j as a series expansion in powers of Y_ν. This is an important point here since, as we have said, the existence of non-diagonal entries $(Y_\nu)_{ij}$ with $i\neq j$ acts as the only seed for the radiative generation of charged LFV. Concretely, the LFV decay $H(p_1)\to l_k(-p_2)\bar{l}_m(p_3)$ can be written in terms of lepton flavor changing form factors $F_{L,R}$ (we omit the km flavor indices in these form

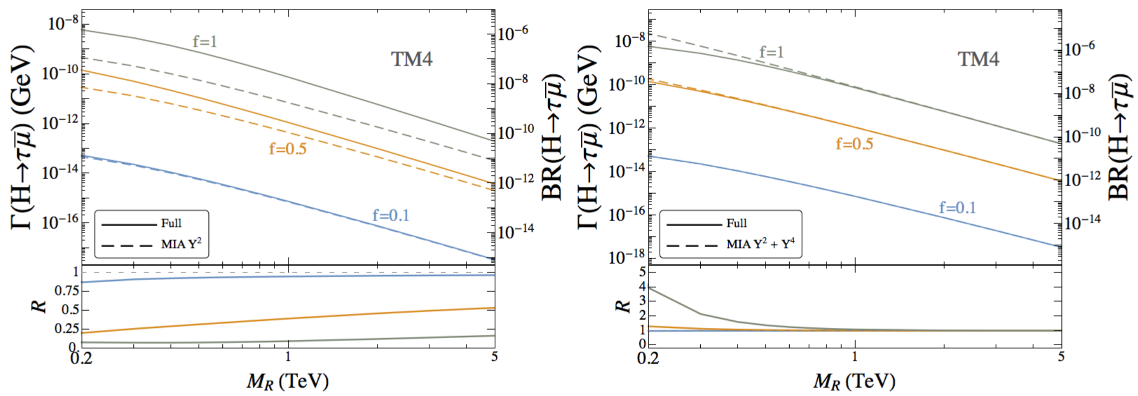

Figure 2: Predictions for $H \to \tau\bar{\mu}$ with the MIA (dashed lines) to leading order, $O(Y_\nu^2)$ (left panel), and to next to leading order, $O(Y_\nu^2 + Y_\nu^4)$ (right panel), and comparison with the full one-loop result (solid lines). R depicted in the lower part of the plot is the ratio between the MIA and the full results. The input neutrino Yukawa matrix in this plot is (in rows): $Y_\nu^{\rm TM4} = f\{(0.1\ 0\ 0),\ (0\ 1\ 0),\ (0\ 1\ 0.014)\}$.

factors, for shortness) as:

$$i\mathcal{M} = -ig\bar{u}_{l_k}(-p_2)(F_L P_L + F_R P_R)v_{l_m}(p_3) \tag{2.4}$$

which then are expressed in the MIA as:

$$F_{L,R}^{\rm MIA} = \left(Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^2)} + \left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^4)} + \ldots. \tag{2.5}$$

Here, $P_{L,R}$ refer to the usual Left and Right chiral proyectors, respectively. The leading order (LO) terms are of $\mathcal{O}(Y_\nu Y_\nu^\dagger)$, or $\mathcal{O}(Y_\nu^2)$ in short, the Next to Leading Order (NLO) terms are of $\mathcal{O}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)$, or $\mathcal{O}(Y_\nu^4)$ in short, etc.The counting of Y_ν factors in each diagram can be easily tracked since by using the EW basis they just come from either the neutrino couplings to the Higgs boson, $(H\nu_{L_i}\nu_{R_j}) = -(i/\sqrt{2})(Y_\nu)_{ij}P_R$, the neutrino couplings to the charged Goldstone boson, $(G^- l_i \nu_{R_j}) = i(Y_\nu)_{ij}P_R$, or the Left-Right neutrino mass insertion $(\nu_{R_j} - \nu_{L_i}) = -iv(Y_\nu)_{ij}P_R$. In addition, we have used what we call the *fat propagators* for the ν_R's, where the full series with internal insertions of X singlets into the propagation of the ν_R's (each $X - \nu_R$ mass insertion given by M_R) are added up, leading to $P_R\ (ip_\mu\gamma^\mu/(p^2 - M_R^2))\ P_L$. These propagators turn out to be very convenient since M_R appears effectively in the denominator. More details can be found in [1].

3. Results

To derive the analytical formulas for the MIA form factors $F_{L,R}^{\rm MIA}$ above we have performed the explicit diagrammatic computation of all the relevant one-loop diagrams in terms of the standard Veltman-Passarino scalar one-loop functions. In order to show the gauge invariance of our results we have done this computation in: 1) the Feynman-'t Hooft gauge, 2) the unitary gauge and 3) the generic R_ξ covariant gauges; and we found the same result in the three cases. Specificaly, in the Feynman-'t Hooft gauge the relevant one-loop diagrams are: 25 diagrams of $\mathcal{O}(Y_\nu^2)$ and 14 diagrams of $\mathcal{O}(Y_\nu^4)$) whose drawings and full analytical results can be found in [1].

Some selected examples of our numerical results with the MIA for the LFVHD partial widths and their corresponding branching ratios are shown in fig.2. For comparison with the MIA results, we have also included in these plots the predictions from the full one-loop computation in the physical neutrino mass basis taken from [2]. For the numerical evaluation we use the kind of TM and TE scenarios defined in [2] which are designed as to get the needed suppression of $\mu - e$ transitions and, correspondingly, the agreement with the most restrictive bounds on these transitions are automaticaly guaranteed. Particularly, this plot is for the scenario TM4, with suppressed μe and τe but non-suppressed $\tau\mu$ transitions. The results shown in this figure clearly demonstrate that keeping just the LO terms, i.e. $\mathcal{O}(Y_\nu^2)$, in the MIA expansion, is not sufficient to find a good agreement with the full result, unless the global size of the Yukawa coupling is small, $f \leq 0.1$. Going to the NLO, i.e. $\mathcal{O}(Y_\nu^2 + Y_\nu^4)$, the agreement of the MIA with the full result is very good for $M_R > 500$ GeV. This figure also shows clearly the decoupling behaviour of the right handed neutrinos in LFVHD at large M_R.

In order to get the final formula for the effective vertex, Hl_il_j, we performed a systematic expansion of the loop integrals in inverse powers of the large mass M_R. Our analytical results for the previous functions, LO $f_{L,R}^{(Y^2)}$ and NLO $f_{L,R}^{(Y^4)}$, show explicitly that they are both of order $(v/M_R)^2$, whereas the NNLO terms of $\mathcal{O}(Y_\nu^6)$ were found to be suppresed as $(v/M_R)^4$, therefore negligible. Assuming heavy ν_R and $m_{l_m} \ll m_{l_k} \ll m_W, m_H, m_D \ll M_R$, we found that the dominant contribution goes to the left handed form factor:

$$i\mathcal{M} = -ig\bar{u}_{l_k} V_{Hl_kl_m}^{\text{eff}} P_L v_{l_m}\,, \tag{3.1}$$

and the simple analytical result for the Higgs on-shell LFV effective vertex reads:

$$V_{Hl_kl_m}^{\text{eff}} = \frac{1}{64\pi^2}\frac{m_{l_k}}{m_W}\left[\frac{m_H^2}{M_R^2}\left(r(\frac{m_W^2}{m_H^2}) + \log(\frac{m_W^2}{M_R^2})\right)\left(Y_\nu Y_\nu^\dagger\right)^{km} - \frac{3v^2}{M_R^2}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km}\right] \tag{3.2}$$

where,

$$\begin{aligned} r(\lambda) \,=\, & -\frac{1}{2} - \lambda - 8\lambda^2 + 2(1-2\lambda+8\lambda^2)\sqrt{4\lambda-1}\,\arctan\left(\frac{1}{\sqrt{4\lambda-1}}\right) \\ & +\, 16\lambda^2(1-2\lambda)\arctan^2\left(\frac{1}{\sqrt{4\lambda-1}}\right)\;;\; r(m_W^2/m_H^2) \simeq 0.3\,. \end{aligned} \tag{3.3}$$

We also obtained the proper off-shell vertex for Higgs-mediated LFV processes, like those in fig.1, where to take zero external momenta in the effective vertex is a good approximation. We found the simple formula:

$$V_{Hl_kl_m}^{\text{eff}\,(p^{\text{ext}}=0)} = -\frac{1}{32\pi^2}\frac{m_{l_k}}{m_W}\left(\frac{3m_W^2}{2M_R^2}\right)\left[\left(Y_\nu Y_\nu^\dagger\right)^{km} + v^2\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km}\right]. \tag{3.4}$$

Finally, we have studied several phenomenological applications of these simple formulas which allow us for very fast and quite accurate estimates of the LFV rates. In particular, the numerical results shown in fig.3 are for $H \to \tau\bar{\mu}$ and $H \to \tau\bar{e}$ and assume an input neutrino Yukawa coupling matrix Y_ν^{GF} which is derived by the 'maximum allowed by data' $\eta = (v^2/(2M_R^2))(Y_\nu Y_\nu^\dagger)$ matrix, saturated at the 3σ level, as extracted from the 'Global Fits' constraints of [3]. Again, the agreement of the MIA and the full predictions is excellent, and we can easily conclude on the maximum LFVHD rates that are allowed by present Global Fits constraints, specifically, $\text{BR}(H \to \tau\bar{\mu}) \sim 3\times10^{-8}$ and $\text{BR}(H \to \tau\bar{e}) \sim 2\times10^{-7}$ in these shown examples.

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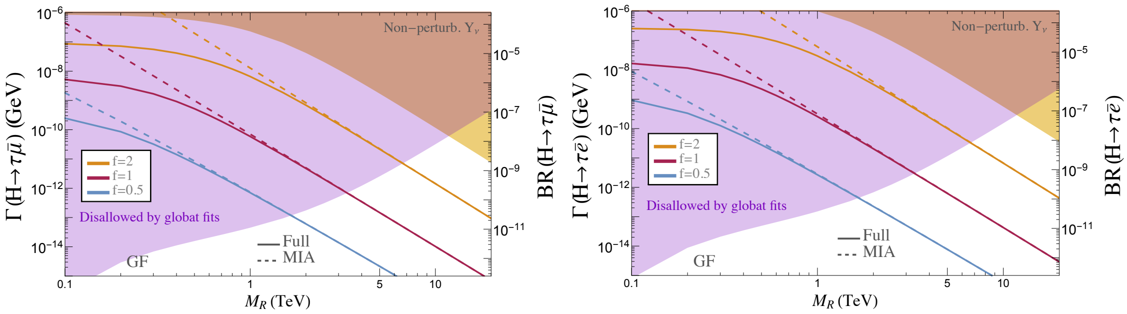

Figure 3: Predictions for $H \to \tau\bar{\mu}$ (left panel) and $H \to \tau\bar{e}$ (right panel) with the effective vertex computed with the MIA (dashed lines). Solid lines are the corresponding predictions from the full one-loop computation in the mass basis. Shadowed areas to the left part of these plots (in purple) are disallowed by global fits. Shadowed areas to the right part of these plots (in yellow) give a nonperturbative Yukawa coupling. The input neutrino Yukawa matrix in this plot is (in rows): $Y_\nu^{\rm GF} = f\{(0.33\ 0.83\ 0.6),\ (-0.5\ 0.13\ 0.1),\ (-0.85\ 1\ 1)\}$.

4. Conclusions

We have found very simple and useful formulas for the LFV effective vertex, Hl_il_j in terms of the most relevant neutrino input parameters of Low Scale Seesaw Models, Y_ν and M_R. This vertex collects the main effects from the integration to one-loop level of the heavy right-handed neutrinos and has very interesting applications for LFV phenomenology. In particular, this could also be used by other researchers with their favourite input Y_ν and M_R settings to get a rapid estimate of the induced LFV rates.

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