Flavor issues in the Higgs Sector

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Abstract

We discuss the conditions under which the flavor structure of SUSY model induces, either radiatively or through mixing, new flavor-violating interactions in the Higgs sector. The *radiative* flavor mediation mechanism is illustrated using the minimal SUSY extension of the SM (MSSM) with generic trilinear A-terms, and applied to evaluate the corrections to Lepton Flavor-Violating (LFV) and Flavor-Conserving (LFC) Higgs vertices. Flavor mediation through *mixing* is discussed within the context of an E_6-inspired multi-Higgs model, supplemented with an Abelian flavor symmetry. Tevatron and LHC can probe the flavor structure of these models through the detection of the LFV Higgs mode $h \to \tau\mu$, while NLC can perform high-precision tests of the LFC mode $h \to \tau^+\tau^-$.

1. Introduction. The discovery of atmospheric neutrino oscillations [1], as well as the new measurements of CP-violation [2], can be considered some of the most important recent results in particle physics, and together with the reported bounds on the Higgs boson mass [3], are helping us to shape our understanding of flavor physics and electroweak symmetry breaking. The Higgs boson mass is constrained by radiative corrections to lay in the range 110-185 GeV at 95 % c.l. [3]; such a light Higgs boson is consistent with the predictions from weak-scale supersymmetry (SUSY), which has become one of the leading candidates for physics beyond the standard model. The Higgs sector of the MSSM includes two Higgs doublets, and the light Higgs boson (with mass bound $m_h \lesssim 125$ GeV), is perhaps the strongest prediction of the model.

However, after a Higgs signal will be seen, probably at the Tevatron and/or LHC, it will become crucial to measure its mass, spin and couplings, to elucidate its nature. In particular, the Higgs coupling to light fermions ($b\bar{b}, c\bar{c}, \tau^+\tau^-$) could be measured at next-linear collider (NLC) with a precision of a few percent, which can be used to constrain physics beyond the SM. For instance, higher-dimensional operators of the type $\Phi^\dagger\Phi\bar{Q}_L\Phi b_R$ involving the third family, will generate corrections to the coupling $h\bar{b}b$, which in turn will modify the dominant decay of the light Higgs, as well as the associated production of the Higgs with b-quark pairs [4, 5].

The most widely studied scenarios for Higgs searches, assume that the Flavor-Conserving (FC) Higgs-fermion couplings only depend on the diagonalized fermion mass matrices, while flavor-violating (FV) Higgs transitions are absent or highly suppressed. Indeed, within the SM the Higgs boson-fermion couplings are only sensitive to the fermion mass eigenvalues. However, if one considers extensions of the SM, which either present a significant source of flavor-changing transition or are aimed precisely to explain the pattern of masses and mixing angles of the quarks and leptons, then it is quite possible that such physics will include new flavored interactions. Namely, when additional fields that have non-aligned couplings to the SM fermions, i.e. which are not diagonalized by the same rotations that diagonalize the fermion mass matrices, also couple to the Higgs boson, then such fields could be responsible for transmitting the structure of the flavor sector to the Higgs bosons, thereby producing a *a more flavored Higgs boson*.

As a consequence of the presence of Lepton Flavor Violating (LFV) Higgs interactions, the decay $h \to \tau\mu$ can be induced at rates that could be detected at future colliders, which could be the manifestation of a deeper link between the Higgs and flavor sectors. In fact, a large coupling $h\tau\mu$ is suggested by the large $\nu_\mu - \nu_\tau$ mixing observed with atmospheric neutrinos. The importance of LFV Higgs modes has been discussed in refs. [6, 7], and it is also the main focus of this work. Depending on the nature of such new physics, we can identify two possibilities for flavor-Higgs mediation, namely:

1. *RADIATIVE MEDIATION.* In this case the Higgs sector has diagonal couplings to the fermions at tree-level. However, in the presence of new particles associated with extended flavor physics, which couple both to the Higgs and to the SM fermions, these flavor-mediating fields will induce corrections to the Yukawa couplings and/or new FCNC process at loop levels. This case will be discussed within the context of the MSSM with general trilinear soft-breaking terms.

2. *MIXING MEDIATION.* Modifications to the Higgs-flavor structure can also arise when additional particles (bosons or fermions) mix with the SM ones. These new interactions could then be transmitted to the Higgs sector, either through scalar-Higgs mixing or through mixing of SM fermions with exotic ones. A multi-Higgs E_6-inspired model, supplemented with an Abelian-flavor symmetry, will be used as an example of this mechanism.

Other models where flavor-Higgs mediation could occur through mixing include: i) the general two-Higgs doublet model (THDM-III) [8, 9] , ii) A model where the SM fermions mix with mirror fermions [6] , as well as the models with: iii) Higgs-flavon mixing, and iv) R-parity breaking scenarios.

2. Flavor-mediation in the MSSM. Within the MSSM, it can be shown that flavor-Higgs mediation is of radiative type, and it communicates the non-trivial flavor structure of the soft-breaking sector to the Higgs bosons through gaugino-sfermion loops. As an illustration of this case, we have evaluated the SUSY contributions to the Higgs-lepton vertices, arising from the slepton mixing that originates from the trilinear A_l-terms. The slepton mixing is constrained by the low-energy data, but it mainly suppress the FV's associated with the first two family sleptons, and still allows the flavor-mixings between the second- and third-family sleptons, to be as large as $O(1)$. Thus, one can neglect the mixing involving the selectrons, and the general 6×6 slepton-mass-matrix reduces down to a 4×4 matrix, involving only the smuon ($\tilde{\mu}$) and stau ($\tilde{\tau}$) sectors, similarly to the squarks case discussed in ref. [10]. Such pattern of large slepton mixing, can also be motivated by considering GUT models that incorporate the large neutrino mixing observed with atmospheric neutrinos.

To evaluate the loop corrections both to the the lepton-flavor conserving (LFC) ($h \to l_i l_i$) and the flavor violating (LFV) Higgs modes ($h \to l_i l_j$), we have performed the diagonalization of the slepton mass matrices, and expressed the gaugino-lepton-slepton and Higgs-slepton-slepton interactions in the mass eigenstate basis, thus without relying on the mass-insertion approximation. The results for the radiative corrections to the LFC modes are in general small, and can be neglected here [11]. While the decay width for $h \to l_i l_j$ (adding both final states $l_i^+ l_j^-$ and $l_i^- l_j^+$) is written as:

$$\Gamma(h \to l_i l_j) \;=\; \frac{m_h}{8\pi}(|F_L|^2 + |F_R|^2) \tag{1}$$

Including only the vertex corrections, $F_{L,R}$ are given by:

$$\begin{aligned} F_L^V &= \frac{g_1^2 m_{\tilde{B}}}{32\pi^2}\sum_{\alpha\beta}\lambda_{jk}^L C_0(m_h^2, m_\tau^2, 0; m_{\tilde{l}_\alpha}, m_{\tilde{B}}, m_{\tilde{l}_\beta})\,, \\ F_R^V &= \frac{g_1^2 m_{\tilde{B}}}{32\pi^2}\sum_{\alpha\beta}\lambda_{\alpha\beta}^R C_0(m_h^2, m_t^2, 0; m_{\tilde{l}_\alpha}, m_{\tilde{B}}, m_{\tilde{l}_\beta})\,, \end{aligned} \tag{2}$$

where $\tilde{l}_{\alpha,\beta} \in (\tilde{\mu}_1, \tilde{\mu}_2, \tilde{\tau}_1.\tilde{\tau}_2)$, C_0 denotes the 3-point C-function of Passarino-Veltman. $\lambda_{\alpha k}^{L,R}$ is the product of the relevant $h\tilde{l}_\alpha\tilde{l}_\beta$ and $\tilde{l}_\alpha\tilde{B}\tau(\mu)$ couplings, (For details see Ref. [11]). As shown in table 1, the LFV mode $h \to \tau\mu$ has a branching ratio that may reach the 4×10^{-4}; this result may be at the reach of LHC (as one can conclude by comparing with the minimum detectable B.r. [6, 7]).

Table 1. Br[$h \to \tau\mu$] is shown for a sample set of SUSY inputs with $(\mu, m_A) = (0.2, 0.3)$ TeV, $A = \frac{\widetilde{m}_0}{2}$ and $\tan\beta = 5(10)$. The numbers in each entry are obtained using the maximum value $x_{max} (\simeq 1.2 - 3.0)$ allowed for the given set of SUSY parameters.

$m_{\tilde{B}}$	$\widetilde{m}_0 = 450$ GeV	$\widetilde{m}_0 = 600$ GeV
150 GeV	1.1×10^{-7} (3.0×10^{-8})	5.0×10^{-5} (1.2×10^{-5})
300 GeV	3.1×10^{-7} (8.0×10^{-8})	8.0×10^{-5} (2.1×10^{-5})
600 GeV	5.3×10^{-5} (1.4×10^{-5})	4.4×10^{-4} (1.2×10^{-4})

3. An E_6-inspired multi-Higgs model. On the other hand, flavor-Higgs mediation through mixing occurs within an E_6-inspired multi-Higgs model [12], supplemented with an Abelian flavor symmetry. Large Higgs-FV effects are also found to arise, though in this case at the tree-level; in this model there is a Higgs pair associated with each family. Then, to generate a realistic flavor structure for both leptons and sleptons we include a horizontal $U(1)_H$ symmetry, which at the same time helps to keep under control the FCNC problem, via proper powers of a single suppression factor $\epsilon = \langle S \rangle / \Lambda$ [13], which has a similar size as the Wolfenstein-parameter λ in the CKM matrix, i.e.,

$\epsilon \simeq \lambda \simeq 0.22$ [13]. Here, $\langle S \rangle$ denotes the vacuum expectation value of a singlet scalar S, responsible for spontaneous $U(1)_H$ breaking, and Λ is the scale at which the $U(1)_H$ breaking is mediated to light fermions. The Yukawa Lagrangian is written as:

$$\mathcal{L}_Y = \bar{U}_i Y^u_{ij} H^u_\alpha Q_j - \bar{D}_i Y^d_{ij} H^d_\alpha Q_j - \bar{E}_i Y^l_{ij} H^d_\alpha L_j \tag{3}$$

where $H^{u,d}_\alpha$ $(\alpha = 1, 2, 3)$ denote the three Higgs pairs of the model. Then, assuming that all Higgs pairs have vanishing charges under the flavor symmetry $U(1)_F$, we can induce Yukawa couplings that satisfy current data on quark and lepton masses, as well as CKM angles. Working in the basis where only $H^{u,d}_3 = H_{u,d}$ aquires a v.e.v. $(< H^0_{u,d} >= v_{u,d})$, and considering only the two-flavor tau-mu case, we can write the charged lepton mass matrix $(M_l = \frac{v_d}{\sqrt{2}} Y^l)$, by assigning the flavor-charges: $(h_2, h_3) = (2, 2)$ and $(\beta_2, \beta_3) = (3, 1)$, to the lepton doublet and singlet, respectively, then:

$$M_l \sim \frac{v_d}{\sqrt{2}} \begin{pmatrix} \lambda^5 & \lambda^5 \\ \lambda^3 & \lambda^3 \end{pmatrix}, \tag{4}$$

which gives the correct order of magnitude for the charged lepton masses, namely $m_\mu \simeq m_\tau \lambda^2 \simeq \lambda^5 v_d$. Then, the "Yukawa matrices" that describe the interactions for the remaining Higgs doublets $H^d_{1,2}$, induce LFV and LFC interactions through the mixing of heavy states with the light MSSM-like Higgs, and can be described as follows:

$$\mathcal{L}_{int} = \frac{g m_\tau \sin\alpha}{\sqrt{2} m_W \cos\beta} [-\epsilon_l \frac{(1-z_1)}{\sin\alpha} \bar{\tau}\mu + (1 - \epsilon_l \frac{(1+z_1)}{\sin\alpha}) \bar{\tau}\tau + h.c.] h^0 \tag{5}$$

where $z_{1,2}$ correspond to the $O(1)$ coefficients left undetermined by the FN approach, and ϵ_l is used to parametrize the mixing between the light MSSM-like Higgs and the heavier Higgs states.

Then, to evaluate the Higgs-FV interactions for tau-mu and the corrections to the FC Higgs-tau vertex, we have considered the values $z_1 = 0.75, 0.9$ and $\epsilon_l = 0.1, .05$. From table 2, we can see that the decay branching ratio Br$[h \to \tau\mu]$ can be of the order $10^{-2} - 10^{-3}$, over the part of the SUSY parameter space with large values of $\tan\beta$, and when the mass of the lightest Higgs boson h^0 is around $115 - 120$ GeV, which can be detected at future colliders. In fact, the rates obtained in this model for $z_1 = 0.75$ and $\tan\beta \geq 20$ are at the reach of Tevatron Run-2, while LHC can have a larger sensitivity to discover this LFV mode $h \to \tau\mu$ in largest portions of parameter space.

On the other hand, this model also predicts corrections to the Higgs-tau couplings, which can be tested at NLC. Table 2 shows the resulting deviation of the Higgs width $(h \to \tau^+\tau^-)$ from the MSSM value, defined as: $\Delta\Gamma_{h\tau\tau} = \frac{\Gamma_{h_{E_6}\tau\tau}}{\Gamma_{h_{MSSM}\tau\tau}}$ This table shows that $\Delta\Gamma_{h\tau\tau}$ can easily be above 0.08, which according to current studies, could be measurable at the NLC.

Table 3. Values of $B.R.(h \to \tau\mu)$ and $\Delta\Gamma_{h\tau\tau}$ that arise for $z_1 = 0.75, 0.9$ and $\epsilon_l = 0.1$. Results in each parenthesis correspond to $\tan\beta = 5, 10, 20$

m_A	z_1	$B.R.(h \to \tau\mu) \times 10^3$	$\Delta\Gamma_{h\tau\tau}$
100 GeV	0.75	(0.19, 0.16, 0.15)	(0.69, 0.72, 0.74)
	0.90	(0.03, 0.027, 0.024)	(0.66, 0.69, 0.71)
150 GeV	0.75	(0.64, 0.17, 0.56)	(0.44, 0.29, 0.04)
	0.90	(0.10, 0.27, 0.90)	(0.40, 0.15, 0.01)
200 GeV	0.75	(1.40, 4.80, 17.0)	(0.23, 0.03, 0.95)
	0.90	(0.22, 0.76, 2.70)	(0.19, 0.07, 1.30)
250 GeV	0.75	(1.90, 7.20, 15.0)	(0.13, 0.06, 2.0)
	0.90	(0.31, 1.10, 3.90)	(0.10, 0.13, 2.60)
300 GeV	0.75	(2.40, 8.80, 29.0)	(0.09, 0.16, 2.80)
	0.90	(0.38, 1.40, 4.60)	(0.05, 0.27, 3.50)

4. Conclusions. We have discussed the conditions under which the flavor structure of SUSY model induces, either radiatively or through mixing, new flavor-violating interactions in the Higgs sector, which can be probed at future high-energy colliders. It is found that the Higgs-FV couplings are induced at rates that can be significant enough to provide new discovery signals at the on-going Run-2 at the Fermilab Tevatron Collider and the CERN Large Hadron Collider (LHC), which can detect the LFV mode $h \to \tau\mu$, and give information on the flavor structure of the model, while NLC high-precision measurements can bound the deviations from the SM for the LFC mode $h \to \tau^+\tau^-$. Implications for rare top quark decays [14] are under current investigation.

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