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Higgs mass in the MSSM with flavor mixing soft terms

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Abstract. The Minimal Supersymmetric Standard Model assumes scalar masses universality as a simplification to avoid undesired flavor changing neutral currents (FCNC). In this work, we consider that the trilinear SUSY soft-terms have a hierarchical structure of flavor mixing within generations, leading to a non-degeneration on sfermion masses preserving FCNC under control. We consider this kind of mixing for the u-type squark mass matrix and analyze the consequences on the radiative corrections to the Higgs mass. We work under the consideration of m_h^{max} benchmark scenario, in which the parameter space is set to maximize the radiative contributions to the Higgs mass. Based on recent experimental results on possible Higgs signals, we calculate the mass of the neutral light CP-even Higgs taking into account flavor mixing contributions.

1. Introduction

At present, the Higgs mechanism is an ingredient generally accepted in the Standard Model (SM), or any other theoretical model beyond, as a generator of gauge boson and fermion masses. Full identification of the Higgs particle is close to be proven experimentally. The mass generation problem is intrinsically related to flavor physics, current experimental results on the Higgs boson can set bounds to Flavor Violation (FV) parameters. Namely, it is relevant in order to study non-vanishing flavor violation processes within the experimental current results. Going beyond the SM, through a supersymmetric theory in its minimal structure, the MSSM has a relevant success in stabilizing the EW scale, it unifies three of the interaction couplings, generates candidates for dark matter, and could account for FV couplings through SUSY at one-loop. This last part is what we try to exploit here, as in other works Flavor Violation may phenomenologically bound some parameters of the models. There is much work done in this direction within SUSY models and we mention some diverse examples on flavor violation on leptons and quarks [1, 2, 3], and directly on Higgs sector as [4, 5].

2. Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model (MSSM) contains the least number of Higgs doublets needed to define a supersymmetric structure of the model in order to spontaneously

break EW symmetry and give masses to both u-and d-type fermions [6], *i.e.* two Higgs complex doublets, widening the Higgs particle spectrum as three neutral h^0, H^0, A^0 and two charged $H^\pm$ Higgs bosons. Spontaneous Symmetry Breaking (SSB) is carried out when the scalar fields develop nonzero vacuum expectation values breaking the $SU(2)_L \times U(1)$, and each Higgs doublet couples with one type of fermions. All the fields have canonical kinetic terms with the usual D_μ and field strengths $F_{\mu\nu}$. The only freedom that one has is the choice of the superpotential W, from which the form of the scalar potential and the Yukawa interactions between fermion and scalar fields can be obtained [6, 7]. The expression of W is given by:

$$W_{MSSM} = \frac{1}{2} M^{ij} \phi_i \phi_j + \frac{1}{6} y^{ijk} \phi_i \phi_j \phi_k. \tag{1}$$

By renormalization, only bilinear and trilinear terms are permitted [8]. For the Next-to-MSSM and considering Z_3 invariance, the bilinear terms are present only after the SSB. For this model, also the mixing on the trilinear soft terms is possible and could be implemented as in the MSSM.

2.1. Phenomenological restrictions in pMSSM

One MSSM version which uses the phenomenological restrictions for to reduce the parameters number of the model, is known as pMSSM [9]. This model basically assumes three issues concerning parameters of the MSSM: (*i*) CP-conserving (no extra source), (*ii*) no FCNC, and (*iii*) $m_{\tilde{f}1} \approx m_{\tilde{f}2}$ to accomplish $K^0 - \bar{K}^0$ mixing. Then ending up with 22 input parameters: $\tan\beta$; m_1^2, m_2^2; M_1, M_2, M_3; $\tilde{m}_q$, $\tilde{m}_{uR}$, $\tilde{m}_{dR}$, $\tilde{m}_l$, $\tilde{m}_{eR}$; $\tilde{m}_{Qt}$, $\tilde{m}_{tR}$, $\tilde{m}_{bR}$, $\tilde{m}_{L\tau}$, $\tilde{m}_{\tau R}$; $A_{u,c}$, $A_{d,s}$, $A_{e,\mu}$; A_t, A_b, A_τ. We propose a modification on the trilinear soft terms: instead of decoupling of the first two families from the third, we assume that the second family contribution could be relevant and decouple only the first family to calculate the possible consequences of this assumption on mixing second and third squarks families.

3. Flavor structure ansatz on MSSM soft-SUSY breaking terms

We assume CP-conservation, that is non-complex parameter in squark mass matrix. Then, from the soft mass terms, and F and D-terms coming from the superpotential, the u-type squark mass matrix in the MSSM is given by

$$M_{\tilde{u}}^2 = \begin{pmatrix} m_{\tilde{u}L}^2 + m_u^2 + M_Z^2 \cos 2\beta (I_3^q - Q_q s_w^2) & X_u \\ X_u & m_{\tilde{u}R}^2 + m_u^2 + M_Z^2 \cos 2\beta Q_q s_w^2 \end{pmatrix}, \tag{2}$$

where

$$X_u = A_u - \mu \cot\beta \quad \text{and} \quad m_{\tilde{u}R}^2 \simeq m_{\tilde{u}L}^2 \simeq \tilde{m}_0^2 \mathbf{I}_{3x3}. \tag{3}$$

We consider a flavor ansatz, as it also has been considered in other models [10] as well as in Supersymmetric models at GUT scale in [11]. Here we propose a flavor mixing ansatz for the trilinear *Soft-SUSY Breaking* terms at low energy scale [12], considering a complete mixing within the two SM-heavy families, different from the one presented in [13]. In a general MSSM, the *Soft-SUSY Breaking* terms are expressed in the Lagrangian

$$-\mathcal{L}_{trilinear} = \sum_{i,j=gen} A_{ij}^u \tilde{Q}_i H_2 \tilde{u}_{Rj}^* + A_{ij}^d \tilde{Q}_i H_1 \tilde{d}_{Rj}^* + A_{ij}^l \tilde{L}_i H_1 \tilde{l}_{Rj}^*, \tag{4}$$

where A_{ij}^f is a 6×6 matrix, if we have the three families coupled together in the trilinear terms. Then, we consider that one family is decoupled at first order, that is

$$A_u^{ij} = A_{uLO}^{ij} + \delta A_u^{ij}, \tag{5}$$

$$A_{uLO} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & w & z \\ 0 & y & 1 \end{pmatrix} A_0. \tag{6}$$

Furthermore, the squark u-type mass matrix has the explicit form

$$\tilde{M}^2_{\tilde{u}} = \left(\begin{array}{cc|cccc} \tilde{m}^2_L & 0 & 0 & 0 & 0 & 0 \\ 0 & \tilde{m}^2_R & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & \tilde{m}^2_L & X_2 & 0 & A_z \\ 0 & 0 & X_2 & \tilde{m}^2_R & A_y & 0 \\ 0 & 0 & 0 & A_y & \tilde{m}^2_L & X_t \\ 0 & 0 & A_z & 0 & X_t & \tilde{m}^2_R \end{array} \right), \tag{7}$$

with $X_2 = A_0 w - \mu m_c \cot\beta$ and $X_t = A_0 - \mu m_t \cot\beta$. For simplicity we consider $z = y$, which implies that after rotation the physical masses for u-type squarks are given by

$$\begin{aligned} m^2_{\tilde{c}_1} &= \frac{1}{2}(2\tilde{m}^2_0 + X_2 + X_t - R), \quad m^2_{\tilde{c}_2} = \tfrac{1}{2}(2\tilde{m}^2_0 - X_2 - X_t + R), \\ m^2_{\tilde{t}_1} &= \frac{1}{2}(2\tilde{m}^2_0 - X_2 - X_t - R), \quad m^2_{\tilde{t}_2} = \tfrac{1}{2}(2\tilde{m}^2_0 + X_2 + X_t + R), \end{aligned} \tag{8}$$

where $R = \sqrt{4A_y^2 + (X_2 - X_t)^2}$. So, the rotation matrix for the two mixed heavy SM squarks flavors which diagonalize the 4×4 squark mass matrix is given by

$$\mathcal{O}_{\tilde{u}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Theta & \sigma^1\Theta \\ -\Theta & \sigma^1\Theta \end{pmatrix}, \tag{9}$$

where σ^1 is a Pauli matrix and

$$\Theta = \begin{pmatrix} -\sin\frac{\psi}{2} & \cos\frac{\psi}{2} \\ -\cos\frac{\psi}{2} & -\sin\frac{\psi}{2} \end{pmatrix}, \tag{10}$$

$$\tan\psi = \frac{2A_y}{(X_2 - X_t)}. \tag{11}$$

We get that the six physical states are obtained by rotating the EW states $\tilde{M}^2_{diag} = O^\dagger_{\tilde{u}} M^2_{\tilde{u}} O_{\tilde{u}}$, and we obtain

$$\begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\sin\frac{\psi}{2} & -\cos\frac{\psi}{2} & 0 & \sin\frac{\psi}{2} & \cos\frac{\psi}{2} \\ 0 & \cos\frac{\psi}{2} & -\sin\frac{\psi}{2} & 0 & -\cos\frac{\psi}{2} & \sin\frac{\psi}{2} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -\sin\frac{\psi}{2} & \cos\frac{\psi}{2} & 0 & -\sin\frac{\psi}{2} & \cos\frac{\psi}{2} \\ 0 & \cos\frac{\psi}{2} & \sin\frac{\psi}{2} & 0 & \cos\frac{\psi}{2} & \sin\frac{\psi}{2} \end{pmatrix} \begin{pmatrix} \tilde{u}_1 \\ \tilde{c}_1 \\ \tilde{t}_1 \\ \tilde{u}_2 \\ \tilde{c}_2 \\ \tilde{t}_2 \end{pmatrix}. \tag{12}$$

On the other hand, in order to obtain the non-mixing limit, *i.e.* decoupling between squark families, we only need to consider that $y \to 0$, which implies $A_y \to 0$, $\sin\psi \to 0$, $\cos\psi \to -1$ and $\psi = \pi$.

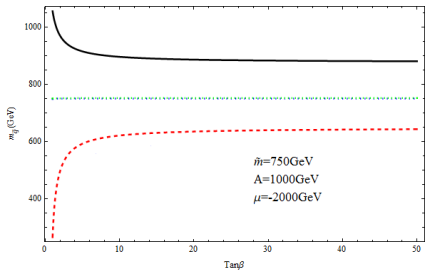

Figure 1. Second and third family u-type squarks masses.

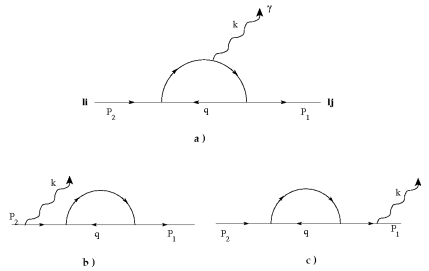

Figure 2. Flavor violating processes in quark sector through squarks-neutralino loops.

3.1. Phenomenological consequences

In addition to the above, now we mention the possible phenomenological consequences of the mixing in the trilinear soft terms, although we only concentrate on the last one.

(i) **Sfermion sector, non degenerate squark masses**, Figure 1.

(ii) **FV in quark sector.** Flavor violation in the u-type quark sector implies SUSY loops with squarks running in it, *i.e.* $BR(B \to X_s\gamma)$ and $BR(t \to c\gamma)$, as in Figure 2.

(iii) **Higgs sector, radiative corrections to Higgs mass**. We focus on this possibility, and we calculate 1-loop self-energy contribution with scharm-stop inside the loop, Figure 3. There has been work which considers mixing in the leptonic sector to achieve neutrino mixing, bounding the mixing parameters using the renormalized Higgs mass as 125 GeV [14].

At leading order, the CP-even neutral Higgs masses are related to the CP-odd mass m_{A^0} which is taken as free parameter [15]:

$$\begin{aligned} m^2_{h,H} &= \frac{1}{2}(m^2_A + m^2_Z) \mp \frac{1}{2}\sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z \cos^2 2\beta}, \\ m^{\pm}_H &= m^2_A + \cos^2\theta_w m^2_Z. \end{aligned} \tag{13}$$

The relations among MSSM parameters impose, at tree level, a strong hierarchical mass spectrum: $m_h < m_Z$, $m_A < m_H$ and $m_W < m_{H^\pm}$, which is broken by radiative corrections. The elements of the mass matrix M^2_h are constructed explicitly from self-energies contributions diagrams: Σ_h.

Using the FeynHiggs code [16] we obtained radiative corrections to m_{h^0} up to 2-loops, Figure 4, for $X_t = 2$ TeV, $\mu = 200$ GeV and a SUSY breaking scale $M_{\rm SUSY} = 1$ TeV. In this figure,

the Higgs mass is calculated in the m_h^{max} benchmark scenario (where parameters of the higher-order corrections are chosen to give the maximum value for m_h). In Figure 4 we set the MSSM parameters and one can see that for this combination of parameters, the 2-loop correction to the Higgs mass yields $M_h \approx 125$ GeV for a value of $\tan\beta \approx 7$ (all uncertainties neglected). In what follows, we will find how much does the FV 1-loop may contribute to the radiative correction. We calculate the self-energy with flavor violation within second and third families of u-type squarks, Figure 3.

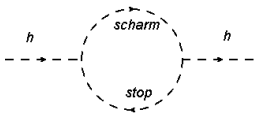

Figure 3. Flavor violating Higgs self-energy diagram in the squark u-type sector.

$$\begin{aligned}\Sigma^{\tilde{ct}}_{h0} &= \frac{\cos^2\frac{\psi}{2}\sin^2\frac{\psi}{2}e^2}{8\pi^2 M_W^2 s_W^2 \sin^2\beta}\times \\ &\Big\{B_0\left[0,\tilde{m}^2_{c1},\tilde{m}^2_{t2}\right](\cos\alpha(m_c+m_t)(A_0+2m_c-2m_t)+\mu\sin(\alpha)(m_c-m_t))^2 \\ &+B_0\left[0,\tilde{m}^2_{c2},\tilde{m}^2_{t1}\right](\cos\alpha(m_c+m_t)(A_0-2m_c+2m_t)+\mu\sin(\alpha)(m_c-m_t))^2\Big\}. \quad (14)\end{aligned}$$

We numerically evaluate this expression, avoiding the divergent part [1], to obtain a quantification of the possible contribution to the mass which is plotted in Figure 5. We can see that the dominant FV contribution could lower the value of the Higgs mass at one-loop level, compared to the MSSM case with no flavor violation. Then the value for $\tan\beta$ could increase for a Higgs mass of ≈ 125 GeV.

4. Conclusions

In this work, we obtained analytical expressions for the mixing angles for squarks considering a possible mixing within the 2nd and 3rd families, this gives a comprehensive and easy manipulation of the parameters. We obtained the flavor violation couplings performing a complete rotation to physical masses instead of the commonly used Mass Insertion Approximation (MIA) [17], in order to achieve flavor violating processes. The MIA method comes from intuitive applications of a Taylor expansion on masses in a non-physical basis, in practice, this results on splitting propagators, and taking the dominat terms in the mass related functions. Once this mass functions are set, it is nevertheless easy to apply and useful to broadly analyze supersymmetric flavor violation processes. For this work, we only focused in the u-type squark sector to obtain the dominant viable contributions to the Higgs mass radiative corrections. We found that the dominant m_t^4 is not finite and would need to be renormalized. Having experimentally set the Higgs mass, this additional contribution to the Higgs mass should be taken into account to properly bound the MSSM parameters.

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[1] A renormalization procedure should be done to cancel the UV divergent part.

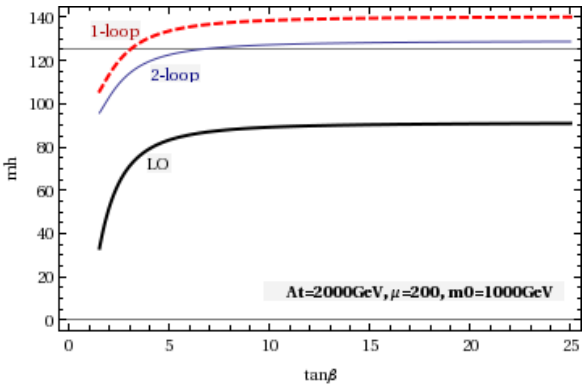

Figure 4. Light neutral MSSM Higgs mass with $\tan\beta$ dependence, complete 1-loop and up to main 2-loops using the FeynHiggs code [16].

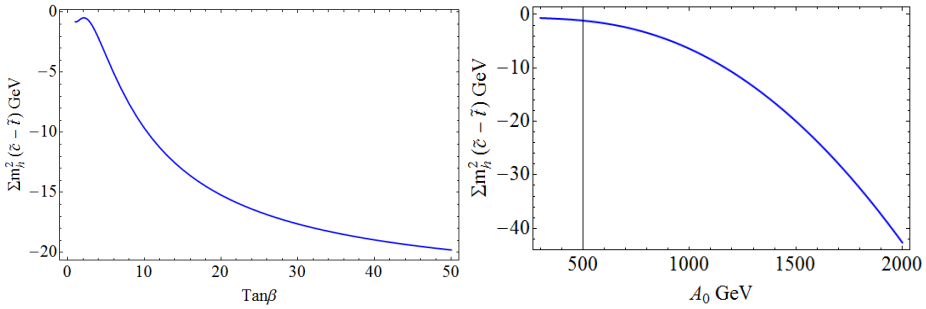

Figure 5. Dominant FV squarks radiative corrections to h^0 mass assuming mixing in second and third families of squarks. Dependence on $\tan\beta$ and in the trilinear term A_0 are shown in the first and second graph, respectively.

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