FCNC and non-standard soft-breaking terms in weak-scale Supersymmetry *

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December 23, 2021

Abstract

We study the inclusion of non-standard soft-breaking terms in the minimal SUSY extension of the SM, considering it as a model of weak-scale SUSY. These terms modify the higgs-sfermion interaction and the sfermion mass matrices, which can induce new sources of flavour violation. Bounds on the new soft parameters can be obtained from current data. The results are then applied to evaluate the FCNC top quark decays $t \to c + h_i \ (h_i = h^0, H^0, A^0)$. Implications of complex soft parameters for CP-violation are also addressed.

*Work supported by CONACYT and SNI (México).
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1.- Supersymmetric (SUSY) extensions of the Standard model (SM) have been extensively studied, mainly because of the possibility to solve the hierarchy problem. The minimal SUSY SM (MSSM), has been used as a framework to search for signals of SUSY. The required breaking of SUSY is incorporated in the model through soft-breaking terms, which include gaugino and scalar masses, as well as trilinear interactions. General soft-breaking terms can produce large flavour changing neutral currents (FCNC). Possible solutions to this problem have been proposed within the main theoretical frameworks of SUSY-breaking.

The MSSM reproduces the SM agreement with data, and predicts new signatures associated with the superpartners that are expected to appear in current or future colliders. However, this analysis usually involves some simplifications about the soft-breaking parameters. For instance, one could work within a particular GUT model and incorporate some specific mechanism of SUSY breaking, then use the structure of the soft-terms to study the mass spectrum of superpartners, evaluate production cross-section and decay rates, and search for their signatures at future colliders. Although this approach makes a certain amount of sense, one could question its generality and whether the future colliders will test weak-scale SUSY or only a particular model of SUSY breaking. In order to study, in a general setting, the possible presence of SUSY in nature, we shall define the MSSM at the weak-scale by considering the most general structure of soft-breaking terms, whose values will be constrained by low-energy phenomenology.

Although it is widely stated that the soft-terms included in the definition of the MSSM are the most general ones, there are extra terms that are not usually considered in the literature, which should be included in a model-independent analysis of weak-scale SUSY. In this paper we study how the inclusion of non-standard terms in the MSSM, modify the Higgs-sfermion interactions and the sfermion mass matrices, which in turn can induce new sources of flavour violation. We evaluate then the contribution of the trilinear terms to the the FCNC top quark decays $t \to c + h_i$, with $h_i$ denoting the neutral Higgs bosons of the MSSM. We also comment on the implication of complex trilinear terms for CP-violation phenomena.

2.- The usual trilinear terms included in the MSSM correspond to interactions of the sfermions with the Higgs doublets $(H_{1,2})$, of the form

$$\mathcal{L}_3 = \epsilon_{ij} [A_i \tilde{Q}^i H_1 \tilde{D} - A^a \tilde{Q}^i H_2 \tilde{U} + A^a \tilde{L}^i H_1 \tilde{E}],$$

(1)
where $\tilde{Q}, \tilde{L}$ represent the squark and slepton doublets, whereas the squark and slepton singlets are denoted by $\tilde{U}, \tilde{D}, \tilde{E}$. Equation (1) resembles the Yukawa Lagrangian of the MSSM, provided that the fermion fields are replaced by their scalar superpartners. However, one could write extra soft-breaking terms that resemble the most general two-Higgs doublet model, known as model III [9], by allowing each sfermion flavour to couple to both Higgs doublets, namely,

$$L'_3 = \epsilon_{ij} [C^d \tilde{Q}^i H_2^c \tilde{D} - C^u \tilde{Q}^i H_1^c \tilde{U} + C^l \tilde{L}^i H_2^c \tilde{E}],$$  

(2)

where $H_n^c = i\tau_2 H_n^* \ (n = 1, 2)$; $A^{u,d,l}$ and $C^{u,d,l}$ denote $3 \times 3$ matrices in flavour space. These terms are indeed soft, because each of the scalar fields carries $U(1)_Y$ charges that forbids their appearence in tadpoles graphs, which are the only diagrams that could generate quadratic divergences from these cubic interactions [8]. The resulting squared sfermion mass-matrices ($6 \times 6$) can be written in terms of $3 \times 3$ blocks, as follows

$$M^2_{\tilde{f}} = \begin{pmatrix} (M^2_{\tilde{f}})^{LL} & (M^2_{\tilde{f}})^{LR} \\ (M^2_{\tilde{f}})^{LR} & (M^2_{\tilde{f}})^{RR} \end{pmatrix}$$  

(3)

The mass terms $(M^2_{\tilde{f}})^{LL,RR}$ receive contributions from the F- and D-terms, after the Higgs fields acquire v.e.v.’s $< H_{1,2}^0 >= v_{1,2}$, as well from the chiral-conserving soft-masses. On the other hand, the chirality-changing mass terms $(M^2_{\tilde{f}})^{LR}$, which receive contributions from F-terms and from the $A-$ and $C-$trilinear interactions, are given by

$$(M^2_{\tilde{u}})^{LR} = \mu m^0_u \cot \beta + A^u v \sin \beta + C^u v \cos \beta,$$  

(4)

$$(M^2_{\tilde{d}})^{LR} = \mu m^0_d \tan \beta + A^d v \cos \beta + C^d v \sin \beta,$$  

(5)

$$(M^2_{\tilde{l}})^{LR} = \mu m^0_l \tan \beta + A^l v \cos \beta + C^l v \sin \beta,$$  

(6)

where $m^0_{u,d,l}$ denote the (non-diagonal) fermionic mass matrices and $v^2 = v_1^2 + v_2^2$, $\tan \beta = v_2 / v_1$.

The fermion and sfermion mass matrices must be diagonalized in order to get the mass eigenstates. However, since the general fermion and sfermion mass matrices are not diagonalized by the same rotations, flavour-violating interactions will appear in the MSSM [10]. In our case, since the $C^f$ terms modify the chirality-changing (LR) sfermion mass matrices, they can represent a new source of flavour violation.
3.- To determine the phenomenological predictions of the model, we need to know the values of the parameters $A'$ and $C'$, which requires a complete understanding of the mechanism of SUSY breaking. In supergravity/superstrings [11], these terms are associated to non-holomorphic interactions, whereas in models with horizontal symmetries [12], they will appear as higher-dimensional operators. In gauge-mediated models [13], the non-standard soft-terms will appear as higher-order loops, as the $A$-terms do (two-loop level). Thus, the $C^q$ parameters appear to be small in the minimal realization of the these SUSY-breaking schemes. However, their contribution to low-energy processes may not be negligible when compared with the $A$-terms, for instance when they are proportional to the light fermion masses. Thus, the corresponding $C_{q,l}^q$ parameters should be included in a model independent analysis of FCNC phenomena.

To discuss FCNC bounds, it is convenient to work in the so-called super-KM basis, where fermion mass matrices and fermion-sfermion gaugino vertices are diagonal; flavour violation arises from the off-diagonal components of the sfermion mass matrices, which are treated as mass-insertions in loop-graphs [14]. The FCNC bounds on $M_{LR}^2$ are expressed in terms of dimensionless parameters:

$$\langle \delta_{LR}^q \rangle_{ij} = \frac{1}{m_{\tilde{q}}^2} [V_{Lq}^q(M_{\tilde{q}}^2)_{LR}V_{Rq}^q]_{ij}$$

(7)

where $V_{L,R}^q$ denote the diagonalizing matrices of the fermion masses. Bounds on the off-diagonal elements of $\delta_{LR}^f$ could be obtained, for instance, by requiring that the SUSY contribution to the $K - \bar{K}, D - \bar{D}, B - \bar{B}$ mass differences, saturates the observed values. Similarly, the diagonal elements $(\delta_{LR}^f)_{ii}$ can be bounded using the SUSY correction to the fermion masses. For d-type squarks, the bounds corresponding to $m_{\tilde{d}}^2 = m_{\tilde{\nu}}^2 = 500$ GeV, are [14]:

$$\langle \delta_{LR}^d \rangle \simeq \begin{pmatrix}
1.6 \times 10^{-3} & 4.4 \times 10^{-3} & 3.3 \times 10^{-2} \\
4.4 \times 10^{-3} & 2.4 \times 10^{-2} & 1.6 \times 10^{-2} \\
3.3 \times 10^{-2} & 1.6 \times 10^{-2} & 7.3 \times 10^{-1}
\end{pmatrix}$$

(8)

The C-terms appear in the definition of the $\delta_{LR}$ parameter, namely:

$$\langle \delta_{LR}^\tilde{q} \rangle_{ij} = \frac{1}{m_{\tilde{q}}^2} (a_{q} v A^{q} + b_{q} \mu m_{\tilde{q}} + c_{q} v C^{q})$$

(9)
where $\bar{A}_q = V'^q_{LR} V'^q_{RL}$, $\bar{C}_q = V'^q_{LR} V'^q_{RL}$; $m^2_q$ denotes an average squark mass, and $m_q$ is the quark mass matrix; $a_q, c_q$ can be read from Eqs. (4-6). However, FCNC data constrains the off-diagonal elements of the combination $A^d \cos \beta + C^d \sin \beta$ and $A^u \sin \beta + C^u \cos \beta$, and the constraints are strong only for $A^d$ and $C^d$ associated with first and second families. Moreover, since the analysis of FCNC constraints is not complete for stop/scharm parameters, one can only estimate $A^u$ and $C^u$ to be in the range $100 - 1000$ GeV, for which the $\delta^u_{LR}$ parameters would be one or two orders of magnitude larger than those of the third-family d-type sfermions, still in agreement with present FCNC bounds.

4.- To illustrate the effects of the non-standard soft-breaking terms, we shall consider the FCNC decays of top quark $t \rightarrow c + h_i$ [15], including only the contribution arising from the FCNC Higgs-sfermion interaction, with the gluino and squarks circulating in the loop. The resulting expression for the decay width is

$$\Gamma(t \rightarrow c + h_i) = \frac{m_t}{16\pi} \left(1 - \frac{m_h^2}{m_t^2}\right)\left(|F_L|^2 + |F_R|^2\right), \tag{10}$$

where:

$$F_L = \frac{\sqrt{2} \alpha_s}{3\pi} M_{\tilde{g}} r_{h_i} C_0(m_{\tilde{t}L}, m_{\tilde{g}}, m_{\tilde{c}R}, m_{\tilde{t}L}^2, m_{\tilde{c}R}^2), \tag{11}$$

$$F_R = \frac{\sqrt{2} \alpha_s}{3\pi} M_{\tilde{g}} r_{h_i} C_0(m_{\tilde{t}R}, m_{\tilde{g}}, m_{\tilde{c}L}, m_{\tilde{t}R}^2, m_{\tilde{c}L}^2), \tag{12}$$

$C_0$ denotes the scalar Veltman-Passarino scalar function; $m_{\tilde{t}L}, m_{\tilde{c}R}, m_{\tilde{g}}$ correspond to the stop, scharm and gluino masses, respectively, with

$$r_{h_i} = \begin{cases} 
A^u \cos \alpha - C^u \sin \alpha, & \text{for } h^0, \\
A^u \sin \alpha + C^u \cos \alpha, & \text{for } H^0, \\
A^u \cos \beta + C^u \sin \beta, & \text{for } A^0.
\end{cases} \tag{13}$$

Including only the A-term, the resulting branching ratio has values of order $10^{-5} - 10^{-6}$. On the other hand, if we include $A^u_{tc}$ and $C^u_{tc}$ terms of similar strength ($\simeq 500$ GeV), we find that the branching ratio reaches values of order $10^{-4}$. If we also include the contributions from off-diagonal terms in $M^2_{LL,RR}$ it is possible to obtain branching ratios of order $10^{-3}$, which could be tested at LHC. Some representative values of B.R. are shown in table 1.
5.- Another interesting application of the new soft-breaking terms is in CP-violation phenomena. In a recent paper [16], it has been proposed to use a non-minimal expression for the $A$-terms, in order to explain the recently observed value of $\epsilon'/\epsilon$ as having a SUSY origin. Since the C-terms can also be complex, its contribution to the imaginary part of $(\delta^d_{LR})_{12}$ could enhance the amount of CP-violation due to SUSY, and would help to explain the observed effect within the MSSM.

CP-violating Higgs interactions will also receive a contribution from the $C^f$ terms. For instance, the parameter $\eta^l_{CP}$, which measures CP-violation in the coupling of Higgs bosons with leptons [17], receives a new contributions from the C-terms, with sleptons and gauginos circulating in the loop, it is given by

$$\eta^l_{CP} = -\frac{6\alpha_{em}}{20\sqrt{2}\cos^2\theta_W y_l} |m[C^d M_1 f(M_1, m_{\tilde{l}})]|,$$

where $y_l$ denotes the Yukawa coupling of lepton $l$, $m_{\tilde{l}}, M_1$ corresponds to the slepton and Bino masses, respectively; $f$ is a function that arises from the loop integration. For SUSY masses of order 200 GeV, $\tan\beta = 10$ and $m_A = 100$ GeV, we find that $\eta^l_{CP}$ reaches values of order 0.1, which can be detected at a future muon collider [17].

6.- In conclusion, we have studied the effects of non-standard soft-breaking terms in the MSSM, and found that they modify the chirality-changing (LR) components of the squared sfermion mass matrices, which can induce new sources of flavour violation. Given present FCNC data, we can only estimate the $A$ and $C$ parameters. To probe their strength, we evaluate the decays $t \rightarrow c + h_i$, and find a B.R. that may be detectable at LHC. The C-terms also give the possibility to explain the newly observed CP-violation phenomena as a SUSY effect, and to measure a CP-violating higgs-lepton coupling at a future muon collider.

Acknowledgment.- Discussions with G. Kane and M.A. Perez are acknowledged. This work was supported by CONACYT and SNI (México).

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Table 1. B.R. of top FCNC decay $t \to c + h_i$. Results are shown for $\tan \beta = 2$, $m_{\tilde{q}} = 300 \text{ GeV}$, $m_{\tilde{g}} = A^u = C^u = 500 \text{ GeV}$, and the numbers in paranthesis correspond to $\tan \beta = 10$.

| $m_A \text{ GeV}$ | $B.R.(t \to c + h^0)$ | $B.R.(t \to c + H^0)$ | $B.R.(t \to c + A^0)$ |
|-------------------|----------------------|----------------------|----------------------|
| 100.              | $7.1 \times 10^{-4}$ $(4.8 \times 10^{-4})$ | $1.9 \times 10^{-5}$ $(1.1 \times 10^{-5})$ | $5.8 \times 10^{-4}$ $(3.8 \times 10^{-4})$ |
| 130.              | $7.0 \times 10^{-4}$ $(5.1 \times 10^{-4})$ | $1.2 \times 10^{-6}$ $(1.7 \times 10^{-6})$ | $3.9 \times 10^{-4}$ $(2.6 \times 10^{-4})$ |
| 160.              | $6.8 \times 10^{-4}$ $(3.8 \times 10^{-4})$ | $0$ $(2.5 \times 10^{-5})$ | $1.4 \times 10^{-4}$ $(9.6 \times 10^{-5})$ |
| 190.              | $6.6 \times 10^{-4}$ $(3.3 \times 10^{-4})$ | $0$ $(0)$ | $0$ $(0)$ |

Table 1