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FLAVOUR SYMMETRIES AND SUSY SOFT BREAKING AT THE LHC*

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Supersymmetry is one of the best options among the possible extensions of the SM that can be found at the LHC. However, most of the phenomenological analysis have been done neglecting flavour structures. In this paper, we show that a realistic flavour symmetry can simultaneously explain the flavour structures in the Yukawa matrices and solve the so-called SUSY flavour problem without *ad hoc* modifications of the SUSY model. Furthermore, departures from the SM expectations in these models can be used to discriminate among different possibilities. We find that large contributions can be expected in lepton flavour violating decays, as $\mu \to e\gamma$ and $\tau \to \mu\gamma$, electric dipole moments, d_e and d_n and kaon CP-violating processes as ϵ_K. Thus, these flavoured MSSM realizations are phenomenologically sensitive to the experimental searches in the realm of flavour and CP violation physics.

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1. Introduction

Supersymmetry (SUSY) is still the most popular extension of the Standard Model (SM) for physics above the electroweak scale. SUSY has been extensively analysed as the best bet for the SM extension to be found in the future experiments at the LHC. However, most of the phenomenological analyses have been done neglecting flavour structures, in the so-called Constrained MSSM (CMSSM) where all soft-breaking terms are taken as flavour universal at the Grand Unification scale. Still, it is very hard to believe that the MSSM realization that nature has chosen is completely flavour blind in the soft sector while the Yukawa sector presents a highly non-trivial structure. Thus, before the arrival of the LHC, we must explore "flavoured MSSM" realizations to be able to analyse the host of new results that will arrive from LHC experiments.

In fact, flavour is usually considered a "problem" in supersymmetric theories, but the so-called *supersymmetric flavour problem* cannot be detached from the *Standard Model flavour problem* and as we show, a correct solution to the Standard Model flavour problem will probably pass unscathed all the stringent constraints on flavour changing neutral currents after the inclusion of the MSSM soft sector. The real *flavour problem* is simply our inability to understand the complicated structures in the quark and lepton Yukawa couplings and likewise the soft-breaking flavour structures in the MSSM. At this point we have to emphasise that the presence of new physics, as for instance supersymmetry, is not a problem for flavour but on the contrary a necessary tool to advance in our understanding of the flavour problem. In the framework of the Standard Model all the information we can extract on flavour are the Yukawa eigenvalues (quark and lepton masses) and the left-handed misalignment between up and down quarks (CKM matrix) or leptons (MNS matrix) and this is not enough to determine the full structure of the Yukawa matrices. However, in supersymmetric extensions of the SM, the new interactions can provide additional information on the physics of flavour which will be fundamental to improve our knowledge on flavour. In the following we show that finding a solution to the "SM" flavour problem will also solve the so-called "supersymmetric flavour problem" to a sufficient degree.

2. Flavour symmetries

The flavour structure associated with the SM Yukawa couplings is very special: a strong hierarchy in the couplings and a peculiar structure of the mixing matrices. In a truly fundamental theory we would expect all dimensionless couplings to be O(1) and thus these small couplings must be explained. The basic idea of flavour symmetries is to use a spontaneously broken family symmetry in analogy with the gauge sector to generate these couplings. A ratio of a scalar vacuum expectation value (vev), breaking the flavour symmetry, and a large mediator mass provides a small expansion parameter that enters in different powers in the fermion Yukawa couplings [1]. In the limit of exact symmetry the Yukawa couplings are forbidden and only when the symmetry is broken these couplings appear as functions of small vevs. Similarly, in a supersymmetric theory, the flavour symmetry applies both to the fermion and sfermion sectors and the flavour structures in soft-breaking terms are also generated by the flavon vevs. Therefore, the structures in the soft-breaking matrices and the Yukawa couplings are related. The starting point in our analysis is the texture in the Yukawa couplings. We can deduce the Yukawa flavour structures under some reasonable assumptions [2]. For instance, we assume that the smallness of CKM mixing angles is due to the smallness of the off-diagonal elements in the Yukawa matrices with respect to the corresponding diagonal elements. This fixes the elements above the diagonal (in our convention). However, we do not have any information on the right-handed mixings, and therefore on the elements below the diagonal. We consider also two complementary situations for the Yukawa structures that we call symmetric and asymmetric Yukawa textures. In the former we make the additional simplifying assumption of choosing the matrices to be symmetric. Note that this situation is not unusual in many flavour models [3,4] as well as in GUT theories. Asymmetric textures are also common in simple Abelian flavour symmetries with a single flavon field [5].

The simplest example is provided by a U(1) flavour symmetry. We can assign to the three generations of SM fields the charges: $Q_i = (3,2,0)$, $d_i^c = (0,0,1)$, $u_i^c = (3,2,0)$. These fields couple to a single flavon field of charge -1. The vev of the flavon field normalised to the mass of the heavy mediator fields M_f, is $\epsilon = v/M_f \ll 1$. The superpotential of this model reads

$$W_{\text{Yukawa}} = Q_i d_j^c H_1 \left(\frac{\theta}{M_{\text{fl}}}\right)^{q_i+d_j} + Q_i u_j^c H_2 \left(\frac{\theta}{M_{\text{fl}}}\right)^{q_i+u_j} .$$

It contains unknown O(1) coefficients. The Yukawa couplings are readily obtained as different powers of ϵ. The soft mass terms ($\sim \phi^\dagger \phi$) are clearly invariant under any symmetry, and therefore always allowed and unsuppressed. Assuming that diagonal masses of different generations are equal in the symmetric limit[1], the universality is broken only by the flavon vevs. Any combination of two MSSM scalar fields ϕ_i and an arbitrary number of flavon vevs invariant under the symmetry will contribute to the soft masses: $\mathcal{L}_{m^2} = m_0^2(\phi_1^*\phi_1 + \phi_2^*\phi_2 + \phi_3^*\phi_3 + (\langle\theta\rangle/M_{\text{fl}})^{q_j-q_i}\, \phi_i^*\phi_j + \text{h.c.})$. Thus, the right-handed down squark mass matrix in this model is:

[1] Unlike in the case of non-Abelian symmetries, this is not guaranteed by symmetry, but it is still possible in some cases like dilaton domination in gravity mediation models.

$$M^2_{\tilde{D}_R} \simeq \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} m_0^2 \,. \tag{1}$$

In this case, we expect large mixings in the second and third generations of right-handed down sfermions. Notice however, that this simple model is already ruled-out by the stringent constraints in the 1–2 sector unless sfermions are very heavy.

Symmetric textures are obtained, for instance, from a spontaneously broken SU(3) family symmetry. Within these symmetries, all left-handed fermions (ψ_i and ψ_i^c) are triplets under $\mathrm{SU}(3)_{\mathrm{fl}}$ and we add several new scalar fields which are either triplets ($\overline{\theta}_3$, $\overline{\theta}_{23}$, $\overline{\theta}_2$) or antitriplets (θ_3, θ_{23}). We assume that $\mathrm{SU}(3)_{\mathrm{fl}}$ is broken in two steps. The first step occurs when θ_3 and $\bar{\theta}_3$ get a large vev breaking SU(3) to SU(2). Subsequently a smaller vev of θ_{23} and $\bar{\theta}_{23}$ breaks the remaining symmetry. After this breaking we obtain the effective Yukawa couplings through the Froggatt–Nielsen mechanism [1] integrating out heavy fields. To reproduce measured masses and mixings, the large third generation Yukawa couplings require θ_3 and $\bar{\theta}_3$ vevs of the order of the mediator scale, M_f, while θ_{23}/M_f, $\bar{\theta}_{23}/M_f$ have vevs of the order of $\varepsilon = 0.05$ in the up sector and $\bar{\varepsilon} = 0.15$ in the down sector with different mediator scales in both sectors. Moreover, in the minimisation of the scalar potential the fields θ_{23} and $\bar{\theta}_{23}$ get equal vevs in the second and third components. In this model CP is spontaneously broken by the flavon vevs that are complex and generate the observed CP violation in the CKM matrix. The basic structure of the superpotential is then: $W_{\mathrm{Y}} = H\psi_i\psi_j^c[\theta_3^i\theta_3^j + \theta_{23}^i\theta_{23}^j + \epsilon^{ikl}\overline{\theta}_{23,k}\overline{\theta}_{3,l}\theta_{23}^j\left(\theta_{23}\overline{\theta_3}\right) + \ldots\ ]$. This structure is quite general for various SU(3) models and for additional details we refer the reader to [3, 4]. The Yukawa textures are symmetric and they suppress O(1) coefficients:

$$Y_d \propto \begin{pmatrix} 0 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \end{pmatrix}, \qquad Y_u \propto \begin{pmatrix} 0 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix}. \tag{2}$$

In the same way after SU(3) breaking the scalar soft masses deviate from exact universality. As before, $\psi_i^\dagger\psi_i$ is invariant under any symmetry and hence gives a universal contribution for the family triplet. However, SU(3) breaking terms give rise to important corrections [4, 6]. Including these corrections, the leading contributions to the sfermion mass matrices are:

$$\left(M^2_{\tilde{f}}\right)^{ij} = m_0^2\left(\delta^{ij} + \frac{1}{M_f^2}[\theta_3^{i\dagger}\theta_3^j + \theta_{23}^{i\dagger}\theta_{23}^j] + \frac{1}{M_f^4}(\epsilon^{ikl}\overline{\theta}_{3,k}\overline{\theta}_{23,l})^\dagger(\epsilon^{jmn}\overline{\theta}_{3,m}\overline{\theta}_{23,n})\right),$$

where f represents the SU(2) doublet or the up and down singlets with $M_f = M_L,\ M_{\rm u},\ M_{\rm d}$. For instance, the mass matrices at the electroweak scale in the SCKM basis are

$$M^2_{\tilde{E}_R(\tilde{D}_R)}{}^{\rm SCKM} \simeq C_{E,D}\, M^2_{1/2}\, 1\!\!1 + \begin{pmatrix} 1+\bar{\varepsilon}^3 \frac{\bar{\varepsilon}^3}{\Sigma_{e,d}} e^{i\alpha} \bar{\varepsilon}^3 e^{i\beta} & & \\ \frac{\bar{\varepsilon}^3}{\Sigma_{e,d}} e^{-i\alpha} & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 e^{i\omega} \\ \bar{\varepsilon}^3 e^{-i\beta} & \bar{\varepsilon}^2 e^{-i\omega} & 1+\bar{\varepsilon} \end{pmatrix} m_0^2\,,$$

$$M^2_{\tilde{E}_L(\tilde{Q}_L)} \simeq C_{L,Q}\, M^2_{1/2}\, 1\!\!1 + \begin{pmatrix} 1+\varepsilon^3 & \frac{\varepsilon^2\bar{\varepsilon}}{\Sigma_{e,d}} & c_{\rm run}\ \bar{\varepsilon}^3 \\ \frac{\varepsilon^2\bar{\varepsilon}}{\Sigma_{e,d}} & 1+\varepsilon^2 & c_{\rm run}\bar{\varepsilon}^2 \\ c_{\rm run}\bar{\varepsilon}^3 c_{\rm run}\bar{\varepsilon}^2 1+\bar{\varepsilon} & & \end{pmatrix} m_0^2\,, \tag{3}$$

with $C_E = 0.15$, $C_L = 0.5$, $C_D \simeq C_Q \simeq 6$ and Σ_a is a Georgi–Jarlskog field distinguishing down quarks and charged leptons with $\Sigma_e = 3$, $\Sigma_d = 1$, $c_{\rm run}$ is a factor coming from RGE evolution. In principle it is different in hadron and lepton mass matrices, with values between 0.1 and 1 depending on the up-quark and neutrino Yukawa couplings. Hence, the structures in the symmetric and the asymmetric textures are different and this provides a possibility to distinguish the two Yukawa structures.

As said above, in the discussed SU(3) flavour model CP symmetry is only spontaneously broken by the flavon vevs below the Planck scale. In this way all terms in the Kähler potential, giving rise to the soft masses and the μ terms coming from the Giudice–Masiero mechanism are real before the breaking of the flavour symmetry. After the flavour symmetry breaking, the phases of the order of O(1) appear in the Yukawa matrices and the off-diagonal elements of the soft mass matrices. Consequently, μ is real to a very good approximation and similarly, diagonal elements in the trilinear terms are also real at leading order in the SCKM basis. This way, electric dipole moments (EDMs) are under control and the SUSY CP problem is solved. Nevertheless, off-diagonal phases in the soft mass matrices contribute to the EDMs. For instance we have a contribution to the electron EDM as $d_e \propto m_\tau \mu \tan\beta\, {\rm Im}[\delta^{e_R}_{13} \cdot \delta^{e_L}_{31}]$. In Fig. 1 we show the expected contributions, in the discussed model, to the lepton flavour violation processes and to the electron EDM in the m_0–$M_{1/2}$ plane for $\tan\beta = 10$ and $A_0 = 0$. The plot on the left-hand side shows the expectations for lepton flavour violation processes. The present (future) limits ${\rm BR}(\mu \to e\gamma) \leq 1.2 \times 10^{-11}$ (10^{-13}) and ${\rm BR}(\tau \to \mu\gamma) \leq 1.6\, 10^{-8}$ (10^{-9}) are the dark (light) triangular regions and the dark (light) oval regions, respectively. On the right part of the Fig. 1, we show oval contours, from inside out and darker to lighter, of $|d_e| = 1 \times 10^{-28}$ $e\,$cm (dark), $|d_e| = 5 \times 10^{-29}$ $e\,$cm (medium) and $|d_e| = 1 \times 10^{-29}$ $e\,$cm (light). The Higgs mass bound is shown in thick dashed lines and the area between the thin dashed black lines solves the ϵ_K tension. Thus, within this model, these observables will allow to explore a significant region of the parameter space even for intermediate values of $\tan\beta$ [7,8].

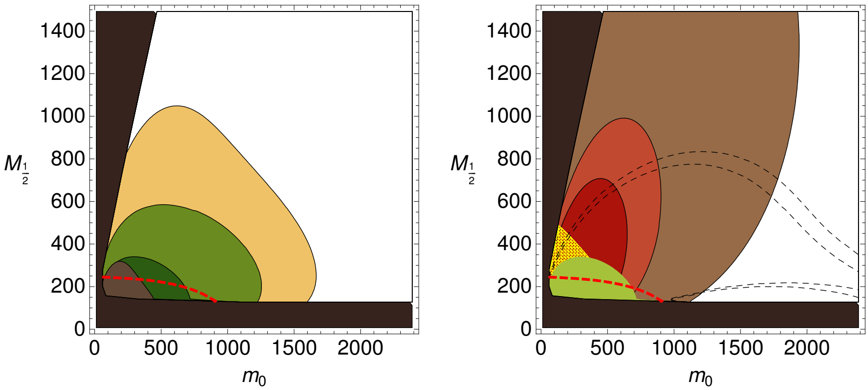

Fig. 1. Expected values for lepton flavour violation processes (left-hand side) and d_e (right-hand side) in the M_0–$M_{1/2}$ plane for $\tan\beta = 10$ and $A_0 = 0$. The meaning of the different regions is explained in the text.

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