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Hierarchical soft terms and flavor physics

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Abstract

We study the framework of hierarchical soft terms, in which the first two generations of squarks and sleptons are heavier than the rest of the supersymmetric spectrum. This scheme gives distinctive predictions for the pattern of flavor violations, which we compare to the case of nearly degenerate squarks. Experiments in flavor physics have started to probe the most interesting parameter region, especially in $b \leftrightarrow s$ transitions, where hierarchical soft terms can predict a phase of B_s mixing much larger than in the Standard Model.

1. Introduction

The softly-broken supersymmetric Standard Model introduces new terms in the Lagrangian with non-trivial transformation properties under the flavor symmetry group. These terms appear in the squark mass matrices and the trilinear interactions

$$\begin{aligned}&\tilde{Q}_L^\dagger \mathcal{M}^2_{Q_L} \tilde{Q}_L + \tilde{D}_R^\dagger \mathcal{M}^2_{D_R} \tilde{D}_R + \tilde{U}_R^\dagger \mathcal{M}^2_{U_R} \tilde{U}_R \\ &\quad + \big(\tilde{D}_R^\dagger Y_D A_D \tilde{Q}_L H_D + \tilde{U}_R^\dagger Y_U A_U \tilde{Q}_L H_U + \text{h.c.}\big).\end{aligned} \tag{1}$$

Here $Y_{D,U}$ are the Yukawa couplings and generation indices have been suppressed. We concentrate on the quark sector, but the extension to leptons is straightforward.

Fully generic flavor-breaking structures in the soft terms are ruled out by experimental constraints. However, these constraints can be used to identify the restricted class of allowed soft terms, providing useful guidelines for model building. A broad class of theories is singled out

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by the hypothesis of Minimal Flavor Violation (MFV) [1], which states that any flavor violation originates from Yukawa couplings. The MFV hypothesis effectively suppresses new-physics contributions to most of the flavor-violating processes. However, in the search for new effects in K, D and B physics it is useful to consider departures from exact MFV. Usually such departures are described in terms of a small expansion parameter that measures the breaking of the flavor group or of one of its subgroups. Three especially interesting examples have been studied in the literature.

(1) *Degeneracy*. The starting point is the universality assumption [2], which states that $\mathcal{M}^2$ and A in Eq. (1) behave as flavor singlets. A distortion from exact universality comes from additional contributions to $\mathcal{M}^2$ and A which are fully generic in flavor space, but their size is characterized by a smaller mass scale, $\delta\tilde{m}$. The small expansion parameter is given by the ratio of these two scales, $\delta\tilde{m}^2/\tilde{m}^2$, i.e. the ratio between the flavor-violating and flavor-symmetric terms. The rotation angles that diagonalize the squark mass matrices are generally large, because they are neither suppressed by the expansion parameter nor related to CKM angles. The suppression of flavor-violating amplitudes arises from the near degeneracy of the quark mass eigenstates.

(2) *Alignment*. The assumption is that quark and squark mass matrices are nearly simultaneously diagonalized by a supersymmetric field rotation, either in the down or in the up sector [3]. The bounds from the kaon system severely constrain the case in which $\mathcal{M}^2_{Q_L}$ is aligned along the up direction. The bounds on D^0–$\bar{D}^0$ mixing give important constraints on the alignment along the down direction [4]. Correlations between quark and squark mass matrices leading to alignment are possible in models where some approximate flavor symmetry determines the form of Yukawa couplings and soft terms [3,5]. Flavor alignment does not imply mass degeneracy of squarks. Thus, in this case the situation is exactly reversed with respect to the case of degeneracy. The suppression of flavor violating processes is due to the small squark mixing angles, while squark masses can be widely different.

(3) *Hierarchy*. The flavor structure of the first and second generation squarks is tightly constrained by K physics. On the other hand, the upper bounds on the masses of the first two generations of squarks are much looser than for the other supersymmetric particles. Therefore one can relax the flavor constraints, without compromising naturalness, by taking the first two generations of squarks much heavier than the third [6–9]. As discussed in more detail in Section 2, this procedure alleviates, but does not completely solve, the flavor problem and a further suppression mechanism for the first two generations must be present. However, it is not difficult to conceive the existence of such a mechanism which operates if, for instance, the soft terms respect an approximate U(2) symmetry acting on the first two generations [8,10]. In the case of hierarchy, the small expansion parameter describing the flavor violation is the mismatch between the third-generation quarks identified by the Yukawa coupling and the third-generation squarks identified by the light eigenstates of the soft-term mass matrix. This small mismatch can be related to the hierarchy of scales present in the squark mass matrix and to CKM angles. However, for the phenomenological implications we are interested in, we do not have to specify any such relation and we can work in an effective theory where the first two generations of squarks have been integrated out. Their only remnant in the effective theory is the small mismatch between third-generation quarks and squarks.

In this paper, we will revisit the properties of hierarchical soft terms, concentrating especially on their implications in flavor physics. We will show how the hypothesis of hierarchy predicts correlations between $\Delta F = 1$ and $\Delta F = 2$ processes which are different from the correlations found in scenarios with degeneracy. We will present the bounds on the expansion parameters of the hierarchy case and compare them with the case of degeneracy. As a particularly interesting