SUSY contributions to $\phi_{B_s}$ from hierarchical sfermions

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Abstract. Hierarchical soft terms describe a class of supersymmetric theories in which the first two generations of squarks and sleptons are heavier than the rest of the supersymmetric spectrum. They make well-defined, interesting predictions as there are fewer free parameters than in the ordinary case of degenerate squarks and provide a characteristic correlation between $\Delta F = 1$ and $\Delta F = 2$ transitions. We study the constraints on the flavor-violating parameters and point out that values of the phase of $B_s$ mixing larger than in the case of degenerate soft terms can be obtained.

1. The framework
Let me begin by illustrating the framework. It is well known that the supersymmetry breaking sector of the MSSM introduces new sources of flavour violation. In the squark sector, the latter are encoded in the squark mass terms and trilinear interaction, described by the following terms in the lagrangian

$$\tilde{q} \tilde{L} \tilde{m}_{qL}^2 \tilde{q} \tilde{L} + \tilde{d} \tilde{R} \tilde{m}_{dR}^2 \tilde{d} \tilde{R} + \tilde{u} \tilde{R} \tilde{m}_{uR}^2 \tilde{u} \tilde{R} + \left( \tilde{d} \tilde{R} Y_D A_D \tilde{q} \tilde{L} h_D + \tilde{u} \tilde{R} Y_U A_U \tilde{q} \tilde{L} h_U + \text{h.c.} \right).$$

(1)

In the following we will concentrate on the down squark sector because we will mainly consider gluino mediated down quark transitions. Since the transitions take place among quark mass eigenstates, it is useful to work in a supersymmetric basis in flavor space aligned with them, the super-CKM basis. In this basis the new sources of flavor violation are the off-diagonal elements of the $6 \times 6$ squark mass matrix. The latter can be written in a block form and diagonalized by a $6 \times 6$ unitary matrix $W_D$ as follows

$$(\tilde{d}^\dagger_L, \tilde{d}^\dagger_R) M_D^2 (\tilde{d}_L, \tilde{d}_R) = M_D^2 = \begin{pmatrix} LL & LR \\ RL & RR \end{pmatrix} = W_D M_D^{2 \text{diag}} W_D^\dagger,$$

(2)

where

$$LL = \tilde{m}_{qL}^2 + M_D^1 M_D + M_Z^2 z_D c_{2\beta} 1,$$

$$RR = \tilde{m}_{dR}^2 + M_D^1 M_D + M_Z^2 z_D c_{2\beta} 1,$$

$$RL = -M_D (A_D + \mu \tan \beta),$$

$c_{2\beta} = \cos 2\beta$, $z_D = (-1/2 + 1/3 \sin^2 \theta_W)$, $z_{Dc} = -1/3 \sin^2 \theta_W$, and $M_D$ is the (diagonal) down quark mass matrix.
A few comments are in order. First, it is well known that in a large part of the parameter space large flavor changing neutral current (FCNC) processes arise. If the sfermion masses are all within the TeV range, this requires a peculiar structure of the sfermion mass terms, with a strong degeneracy of the first two sfermion families (barring alignment [3]) and a small mixing between the third and first two families. This can be considered as not completely unexpected, given that the fermion mass terms also have a peculiar structure, with smaller masses for the first two families and again a small mixing between the third and first two families. In fact, it turns out that both the two patterns required by the experiment, in the quark, and squark sectors, correspond to an approximate U(2) symmetry [4, 5]. While such a symmetry is only mildly broken by the small fermion masses of the two first families, we know for sure that its extension to a U(3) symmetry is badly broken by the large top Yukawa coupling. As a consequence, we expect the third squark family masses to be significantly different than the ones of the first two, for example because of radiative effects from the top Yukawa coupling. The size of such non-degeneracy is not known. Two opposite, complementary limits can be then taken to discuss flavor phenomenology:

- Degeneracy: the third family is approximately degenerate with the first two: \( \tilde{m}_b \approx \tilde{m}_s \approx \tilde{m}_d \);
- Hierarchy: the first two families are significantly heavier: \( \tilde{m}_b \ll \tilde{m}_s, \tilde{m}_d \)

It turns out that the second possibility is not a priori incompatible with a natural determination of the electroweak scale, as we will see later on.

A model-independent analysis can be performed in the both the above limits by expanding the squark mass matrix in the small off-diagonal elements: \( \mathcal{M}^2 = \mathcal{M}^2_0 + \mathcal{M}^2_1 \), with \( \mathcal{M}^2_0 \) diagonal.

In the case of degeneracy \( \mathcal{M}_0 \) is universal, \( \mathcal{M}^2_0 = \tilde{m}^2 \mathbf{1} \). The amplitudes of gluino mediated \( \Delta F = 1 \) and \( \Delta F = 2 \) transitions \( i \to j \) can then be written as [6]

\[
A(\Delta F = 1)_{ij} = xf^{(1)}(x) \delta_{ij} \\
A(\Delta F = 2)_{ij} = \frac{x^2}{3!} g^{(3)}(x) \delta^2_{ij} \quad \text{(degenerate case),}
\]

where \( \delta_{ij} = (\mathcal{M}^2_1)_{ij}/\tilde{m}^2 \) is the process-independent source of flavor violation and \( f, g \) are process dependent, flavor conserving loop functions of the ratio of squark and gluino masses \( x = \tilde{m}^2/M^2 \). The factorials and the number of derivatives correspond to the number of identical propagators in the relevant loop diagrams (-1).

In the case of hierarchy \( \mathcal{M}_0 \) has the form

\[
\mathcal{M}^2_0 = \left( \begin{array}{c|c}
\text{heavy} & \tilde{m}^2 \\
\hline
\text{heavy} & \tilde{m}^2 \\
\end{array} \right)
\]

and for chirality conserving flavor transitions we have

\[
A(\Delta F = 1)_{ij} = f(x) \hat{\delta}_{ij} \\
A(\Delta F = 2)_{ij} = g^{(1)}(x) \hat{\delta}^2_{ij} \quad \text{(hierarchical case),}
\]

where now the process-independent source of flavor violation is \( \hat{\delta}_{ij} = \mathcal{W}_{ij} \mathcal{W}_{ij}^\dagger \), or \( \hat{\delta}_{ij} = \mathcal{M}^2_{ij}/\tilde{m}^2 \), for \( a = 1, 2 \), and \( x = \tilde{m}^2/M^2 \). The factorials and the number of derivatives is one less the number of identical propagators in the relevant loop diagrams. Note the absence of the factor 3! in the
\( \Delta F = 2 \) amplitude. In the case of chirality conserving transitions we also have the following interesting relation

\[
\hat{\delta}_{ab} \approx \hat{\delta}_{a3}\hat{\delta}_{3b} \quad (a, b = 1, 2).
\] (7)

Moreover, under mild assumptions on the structure of the heavy mass terms, we have

\[
\hat{\delta}_{a3}^{LR} \approx \hat{\delta}_{a3}^{LL}\hat{\delta}_{33}^{LR}, \quad \text{where} \quad \hat{\delta}_{33}^{LR} = -\frac{m_h(A_{33}^D + \mu \tan \beta)}{\tilde{m}_2} \quad (a = 1, 2).
\] (8)

In the next section we will illustrate the phenomenological analysis of the flavor effects in the case of hierarchy and compare with the case of degeneracy. Before that, let us conclude this section with a few comments on the naturalness of the hierarchical case.

It is well known that the naturalness bound on the first two sfermion family masses is significantly milder than the one on the third family \([7]\), because their radiative effect on the Higgs mass parameter \(m^2_H\) is rather moderate. The leading effect comes from a one-loop renormalization of \(m^2_H\) proportional to an induced hypercharge Fayet-Iliopoulos term. If the Fayet-Iliopoulos term vanishes, the heavy sfermion masses can be as heavy as 10–30 TeV, depending on the scale at which supersymmetry breaking terms are generated. The bound correspond to a fine-tuning similar to the typical necessary fine-tuning in the MSSM.

These upper bounds on \(\tilde{m}_h\) have to be compared with the lower limits coming from flavor-violating effects in the \(K\) system. Assuming that the heavy squark sector is neither degenerate nor aligned, we find the bound

\[
\tilde{m}_h > 35 \text{ TeV}
\] (9)

from the real part of the \(\Delta S = 2\) transition, and

\[
\tilde{m}_h > 800 \text{ TeV}
\] (10)

from \(\epsilon_K\).

This shows that the hypothesis of hierarchical soft terms is not sufficient to solve the flavor problem. We can retain naturalness and rely on a scheme for suppressing the flavor transitions in the heavy sector, as can be achieved by an approximate U(2) symmetry acting on the first two generations. In this respect, the hierarchical structure of soft terms can be a useful way of parametrizing supersymmetric theories which, for model-dependent reasons, have a certain separation of scales in the scalar sector. Moreover, hierarchical soft terms are interesting because they make specific predictions in flavor physics controlled by relatively few parameters related to physical quantities, like the mass hierarchy.

2. Phenomenology

First, we point out that the case of hierarchy leads to different correlations among \(\Delta F = 1\) and \(\Delta F = 2\) processes. From eqs (4,6) we have in fact

\[
\left. \frac{A(\Delta F = 2)}{|A(\Delta F = 1)|^2} \right|_{\text{degeneracy}} = \frac{1}{6} g^{(3)} \left( \frac{f}{f^{(1)}} \right)^2 \left. \frac{A(\Delta F = 2)}{|A(\Delta F = 1)|^2} \right|_{\text{hierarchy}}.
\] (11)

The correlation one obtains in the case of hierarchy differs by a combination of loop functions and their derivatives and by a factor 6. The combination of functions is typically of order one, although it may vary for values of the argument \(x = \tilde{m}_h^2/M^2\) significantly different from one. For example, in the case of the amplitudes for \(\Delta m_B^s\) mixing and \(b \to s\gamma\) corresponding to LL insertions, the combination of functions in eq. (7) gives 25/27 for \(x = 1\). The factor 1/6 gives instead a systematic difference which makes the \(\Delta F = 2\) amplitude larger, compared to the
Table 1. Bounds on the LL insertions in the hierarchical and degenerate cases. The limits on the RR insertions are the same, except the one from BR($B \to X_s\gamma$), which is much weaker.

$$
\begin{align*}
D_0 - \bar{D}_0 &\text{ mixing} \\
|\hat{\delta}_{ul}^a\hat{\delta}_{ct}^a| &< 8.0 \times 10^{-3} \left( \frac{m_t}{350 \text{ GeV}} \right) \\
|\hat{\delta}_{ac}| &< 3.4 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right)
\end{align*}
$$

$$
B \to X_s\gamma
$$

$$
\begin{align*}
|\text{Re} (\hat{\delta}_{sb})| &< 2.2 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right)^2 \left( \frac{10}{\tan \beta} \right) \\
|\text{Im} (\hat{\delta}_{sb})| &< 6.7 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right)^2 \left( \frac{10}{\tan \beta} \right)
\end{align*}
$$

$$
\Delta m_{B_s}
$$

$$
\begin{align*}
|\text{Re} (\hat{\delta}_{sb})| &< 9.4 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right) \\
|\text{Im} (\hat{\delta}_{sb})| &< 7.2 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right)
\end{align*}
$$

$$
B_0^d - \bar{B}_d^0 \text{ mixing}
$$

$$
\begin{align*}
|\text{Re} (\hat{\delta}_{db})| &< 4.3 \times 10^{-3} \left( \frac{m_t}{350 \text{ GeV}} \right) \\
|\text{Im} (\hat{\delta}_{db})| &< 7.3 \times 10^{-3} \left( \frac{m_t}{350 \text{ GeV}} \right)
\end{align*}
$$

$$
\Delta m_K
$$

$$
\begin{align*}
\sqrt{|\text{Re} (\hat{\delta}_{db}^L\hat{\delta}_{sb}^L)^2|} &< 1.0 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right) \\
\sqrt{|\text{Re} (\hat{\delta}_{ds}^L)^2|} &< 4.2 \times 10^{-2} \left( \frac{m_t}{350 \text{ GeV}} \right)
\end{align*}
$$

$$
\epsilon_K
$$

$$
\begin{align*}
\sqrt{|\text{Im} (\hat{\delta}_{db}^L\hat{\delta}_{sb}^L)^2|} &< 4.4 \times 10^{-4} \left( \frac{m_t}{350 \text{ GeV}} \right) \\
\sqrt{|\text{Im} (\hat{\delta}_{ds}^L)^2|} &< 1.8 \times 10^{-3} \left( \frac{m_t}{350 \text{ GeV}} \right)
\end{align*}
$$

$\Delta F = 1$ one, in the case of hierarchy. Note that a factor 6 is huge compared with the accuracy sought in the theoretical computation of the amplitudes in the limit of degeneracy.

The bounds on the flavor-violating parameters $\hat{\delta}$ are summarized in Table 1 and compared with the bounds obtained in the case of degeneracy. An early analysis of the hierarchical case was presented in ref. [1]. For definiteness, here and below we set the $A$-terms to zero and we consider the case $\tilde{m} = M_3 = \mu$, with $\tilde{m}$ normalized to 350 GeV. The bounds have been computed by constructing two-dimensional likelihood functions in the Re $\delta$–Im $\delta$ planes. The bounds on $s \leftrightarrow d$ transitions are obtained using the constraints from the kaon mass difference $\Delta m_K$ and the kaon mixing CP-violation parameter $\epsilon_K$. Because of the large theoretical uncertainty on the long-distance part of $\Delta m_K$, the absolute value of the supersymmetry contribution to $\Delta m_K$ has been allowed to be as large as its experimental value, with a flat probability distribution. The bounds are obtained along the $\sqrt{|\text{Im} (\hat{\delta}^2)|} = 0$ or $\sqrt{|\text{Re} (\hat{\delta}^2)|} = 0$ sections of the two-dimensional likelihood function in the Re $\delta$–Im $\delta$ planes.

The bounds on $b \leftrightarrow d$ transitions are obtained using the constraint from the $B_d - \bar{B}_d$ system.
mass difference $\Delta m_{B_d}$ and on the phase of the corresponding amplitude. Again, a two-dimensional likelihood is constructed. The corresponding 95% CL and 68% CL regions in the Re $\delta$–Im $\delta$ plane are shown in Fig. 1. The bounds in Table 1 are obtained along the Im $\delta = 0$, Re $\delta = 0$ sections of the two-dimensional likelihood. Choosing Im $\delta = 0$ makes the limit on Re $\delta$ in Table 1 much stronger than the size of the allowed region in the Figure. The corresponding constraint in Table 1 should therefore be considered as optimistic.

In the case of $b \leftrightarrow s$ transitions, the constraints we have considered are the mass difference $\Delta m_{B_s}$ and the $B \to X_s \gamma$ branching ratio. We have constructed two separate likelihoods because of the different $\tan \beta$ dependence of the two constraints. In fact, the $\Delta m_{B_s}$ constraint is $\tan \beta$ independent, while the $B \to X_s \gamma$ constraint has a linear dependence on $\tan \beta$ for moderately large $\tan \beta$. The 95% CL contours corresponding to the two constraints are shown in Fig. 2 for $\tan \beta = 10$. As mentioned, the $B \to X_s \gamma$ constraint is relevant for the LL insertions, whose contribution interferes with the SM one, but not for the RR insertions. The bounds on Re $\delta$ and Im $\delta$ in Table 1 are obtained as in the case of $b \leftrightarrow d$ transitions. Because of the “holes” in the two-dimensional likelihood function shown in Fig. 2, the one-dimensional likelihood for Im $\delta$ corresponding to Re $\delta = 0$ has three almost disconnected parts. We calculated the bounds in Table 1 by using the central part of the likelihood only. This “empirically” discards the possibility that the observed agreement with the SM with data be reproduced through an accidental cancellation of SM and NP contributions.

Finally, we show in Fig. 3 the bound on the $c \leftrightarrow u$ transitions obtained from $D^0-\bar{D}^0$ mixing. The theoretical prediction for the SM contribution to the mixing amplitude is affected by a large uncertainty due to long-distance contributions and it is assumed to lie in the interval $(-0.02, 0.02) \text{ ps}^{-1}$ [9], with flat probability distribution. We translate in this case the likelihood in a bound on $|\delta|$ by considering the one-dimensional section of the two-dimensional likelihood along the $|\text{Re}(\delta)| = |\text{Im}(\delta)|$ line.

In the hierarchical case, the bound from the $s \leftrightarrow d$ transitions apply to the product...
Figure 2. 95% CL bounds on the real and imaginary parts of $\delta_{sb}^{LL}$ (left, blue) and $\hat{\delta}_{sb}^{LL}$ (right, red) from the measurements of $\Delta m_{B_s}$ (lighter shading) and $\text{BR}(B \to X_s \gamma)$ (darker shading) for $\tilde{m} = M_3 = \mu = 350$ GeV and $\tan \beta = 10$. Switching the sign of $\mu$ approximately corresponds to switching the sign of $\text{Re}(\delta_{sb}^{LL})$ and $\text{Re}(\hat{\delta}_{sb}^{LL})$ in the two figures. In the background, the contour lines of the phase $\phi_{B_s}$ are shown. The darker regions correspond to the 90% CL range presently favoured by the experiment [8]. The axis of the two figures are chosen in such a way that the contour lines are the same for the degenerate and hierarchical cases.

Figure 3. 95% CL (light shading) and 68% CL (dark shading) bounds on the real and imaginary parts of $\delta_{uc}^{LL}$ (left, blue) and $\hat{\delta}_{uc}^{LL} \equiv \hat{\delta}_{ut}^{LL} \hat{\delta}_{ct}^{LL}$ (right, red) from $D^0 - \bar{D}^0$ oscillations for $\tilde{m} = M_3 = \mu = 350$ GeV.
It is therefore possible to compare that bound with the indirect one obtained from the constraints on $\delta_{s b}^{LL}$ and $\delta_{d b}^{LL}$. It turns out that the combined bound is stronger than the direct one in the case of $\Delta m_K$ but not in the case of $\epsilon_K$.

If the parameters $\delta$ are related to the hierarchy according to the relation $\delta \sim \tilde{m}_t^2/\tilde{m}_h^2$, from the results in Table 1 we obtain a lower bound on the heavy mass scale

$$\tilde{m}_h \gtrsim \left( \frac{\tilde{m}_t}{350 \text{ GeV}} \right)^{1/2} 5 \text{ TeV}. \quad (12)$$

It is plausible to expect that, independently of the value of the hierarchy $\tilde{m}_t/\tilde{m}_h$, the size of the parameters $\delta_{s b}^{LL}$, $\delta_{d b}^{LL}$ cannot be smaller than the corresponding CKM angles, $|V_{td}|$, $|V_{ts}|$, respectively. Thus, it is particularly interesting to probe experimentally flavor processes up to the level of $|\delta_{s b}^{LL}| \approx 8 \times 10^{-3}$, $|\delta_{d b}^{LL}| \approx 4 \times 10^{-2}$ and $|\delta_{d s}^{LL}| = |\delta_{s b}^{LL}\delta_{d b}^{LL}| \approx 3 \times 10^{-4}$. The present constraints on $b \leftrightarrow d$ transitions and on $\epsilon_K$ are at the edge of probing this region. An interesting conclusion is that hierarchical soft terms predict that new-physics effects in $b \leftrightarrow s$ transitions can be expected just beyond the present experimental sensitivity.

Let us now discuss the implications for the phase of the $B_s$ mixing. In the hierarchical scenario, the new-physics effects in $b \leftrightarrow s$ transitions are particularly promising. For most values of $\tan \beta$, the bound on the insertions is mainly due to the $B \rightarrow X_s \gamma$ constraint. One can then derive a bound on $\Delta B = 2$ observables such as $\Delta m_{B_s}$ or the phase $\phi_{B_s}$ of the $B_s \rightarrow B_s$ depending on the scenario we consider. Eq. (11) shows that for $(g(3)/g(1))^2 \sim 1$ the bound on $\Delta B = 2$ observables is expected to be looser in the hierarchical case. Let us consider in particular the phase of $B_s$ mixing, as defined by $\langle B_s|H_{\text{eff}}|B_s \rangle = C_B e^{2i\beta_B} \langle B_s|H_{\text{SM}}|B_s \rangle$, where $H_{\text{eff}} = H_{\text{SM}} + H_{\text{NP}}$, $\langle B_s|H_{\text{SM}}|B_s \rangle = A_{\text{SM}} e^{-2i\beta} \langle B_s|H_{\text{SM}}|B_s \rangle = A_{\text{SM}} e^{-2i(\phi_{B_s} - \beta)}$, and $\beta_B = \arg(-V_{ts} V_{tb}^\dagger/V_{ts} V_{tb}^\dagger) = 0.018 \pm 0.001$. Recent measurements from the CDF [10] and D0 [11] collaborations have shown a mild tension between the experimental value and the SM prediction at the 2.5 $\sigma$ level [12, 13, 8]. In the supersymmetric scenarios under consideration, the value of the phase $\phi_{B_s}$ can be read from the contour lines in Fig. 2. The figure shows that in the region allowed by both the BR($B \rightarrow X_s \gamma$) and $\Delta m_{B_s}$ constraints, the phase reaches larger values in the hierarchical case. This is apparent in Fig. 4, where the expectation for $\phi_{B_s}$ in the two scenarios has been shown in the form of an histogram (for a fixed value of $\tan \beta = 10$). The hierarchical case allows values of the phase $\phi_{B_s}$ about three times larger than in the degenerate case, in agreement with the generic expectation from eq. (11). The range of $\phi_{B_s}$ presently favored by the experiment is shown in Fig. 2.

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Figure 4. Expected distribution of the phase $\phi_{Bs}$, as determined by the BR($B \rightarrow X_s \gamma$) and $\Delta m_{Bs}$ constraints in the degenerate (blue) and hierarchical (red), for $\tan \beta = 10$.

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