

Hierarchical Soft Terms and Flavor Physics

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FV in the SM and in the MSSM

- In the SM, flavor violation arises from the Yukawa sector:

$$U_R M U_L^\dagger = \text{diagonal} \quad \longrightarrow \quad V = U_L^u U_L^{d\dagger}$$

- In the MSSM, there are new sources of FV:

$$\mathcal{L}_{\text{sdown masses}} = - (\tilde{\mathbf{d}}_L^\dagger \quad \tilde{\mathbf{d}}_R^\dagger) \mathbf{m}_{\tilde{\mathbf{d}}}^2 \begin{pmatrix} \tilde{\mathbf{d}}_L \\ \tilde{\mathbf{d}}_R \end{pmatrix} \quad \tilde{\mathbf{d}}_L = \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \end{pmatrix} = \begin{pmatrix} \tilde{d}_{L1} \\ \tilde{d}_{L2} \\ \tilde{d}_{L3} \end{pmatrix}$$

$$\mathbf{m}_{\tilde{\mathbf{d}}}^2 = \begin{pmatrix} m_Q^2 + m_d^2 + \Delta_{\tilde{d}_L} & v(a_d^* \cos \beta - \mu y_d \sin \beta) \\ v(a_d \cos \beta - \mu^* y_d \sin \beta) & m_d^2 + m_d^2 + \Delta_{\tilde{d}_R} \end{pmatrix}$$

Diagram illustrating the components contributing to the down quark mass matrix $\mathbf{m}_{\tilde{\mathbf{d}}}^2$:

- Soft** (red text) points to the $\Delta_{\tilde{d}_L}$ and $\Delta_{\tilde{d}_R}$ terms.
- Quark masses** points to the m_Q^2 and m_d^2 terms.
- EWSB** (Electroweak Symmetry Breaking) points to the $v(a_d^* \cos \beta - \mu y_d \sin \beta)$ and $v(a_d \cos \beta - \mu^* y_d \sin \beta)$ terms.
- Trilinear Soft** points to the $v(a_d \cos \beta - \mu^* y_d \sin \beta)$ term.
- Yukawa coupling** points to the y_d terms in the off-diagonal elements.

Model independent analysis

Expand in off-diagonal elements of squark mass matrix: $\mathcal{M}^2 = \mathcal{M}_0^2 + \delta\mathcal{M}^2$

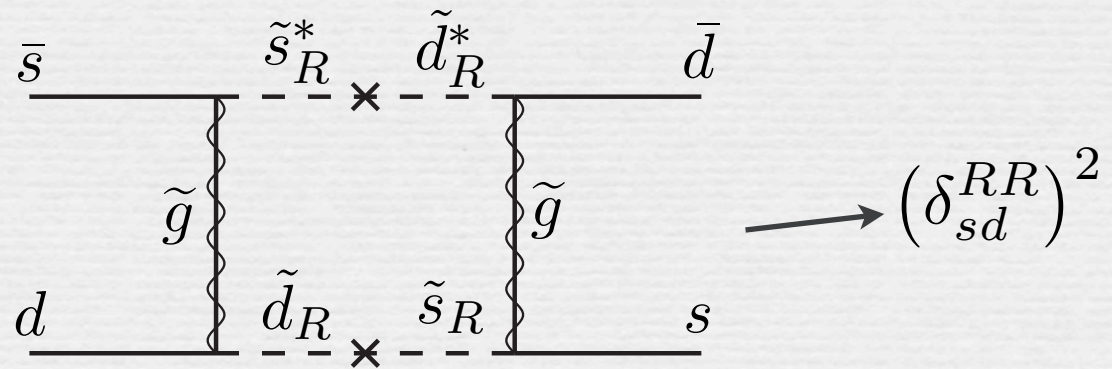
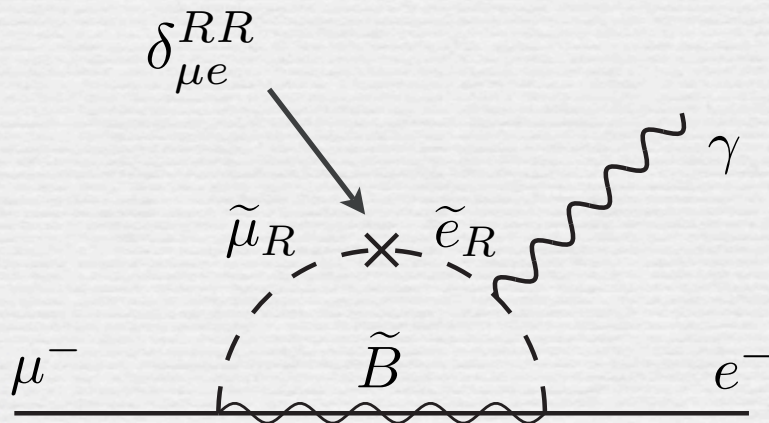
Degeneracy assumption: $\mathcal{M}_0^2 = \tilde{m}^2 I_{6 \times 6}$

$$A(\Delta F = 1) = x f^{(1)}(x) \delta_{ij} \quad \delta_{ij} \equiv \frac{(\delta\mathcal{M}^2)_{ij}}{\tilde{m}^2} \quad x = \frac{\tilde{m}^2}{M^2}$$

$$A(\Delta F = 2) = \frac{x^2}{3!} g^{(3)}(x) \delta_{ij}^2$$

f, g: loop functions (flavor conserving, process dependent)

δ_{ij} : flavor violating parameters (process independent)



Hierarchical Soft Terms

- n In the Hierarchical scenario the LL and RR soft terms have the following structure:

$$\tilde{m}^2 = \begin{pmatrix} h_{11} & h_{12} & a_1 \\ h_{21} & h_{22} & a_2 \\ \bar{a}_1 & \bar{a}_2 & l_3 \end{pmatrix}$$

Where the “h” block is heavy and the remaining entries are much lighter.

The first two families can be **naturally** heavier with respect to the 3rd one.

Motivations:

- n Complementary to degenerate assumption
- n If we start with a degenerate condition at very high energy, we end up to a split situation at low energy because of the Yukawa coupling of the 3rd family
- n Welcome to alleviate SUSY flavor problem

$$A(\Delta F = 1) = f(x) \hat{\delta}_{ij}$$

$$A(\Delta F = 2) = g^{(1)}(x) \hat{\delta}_{ij}^2$$

$$x = \frac{\tilde{m}_3^2}{M^2}$$

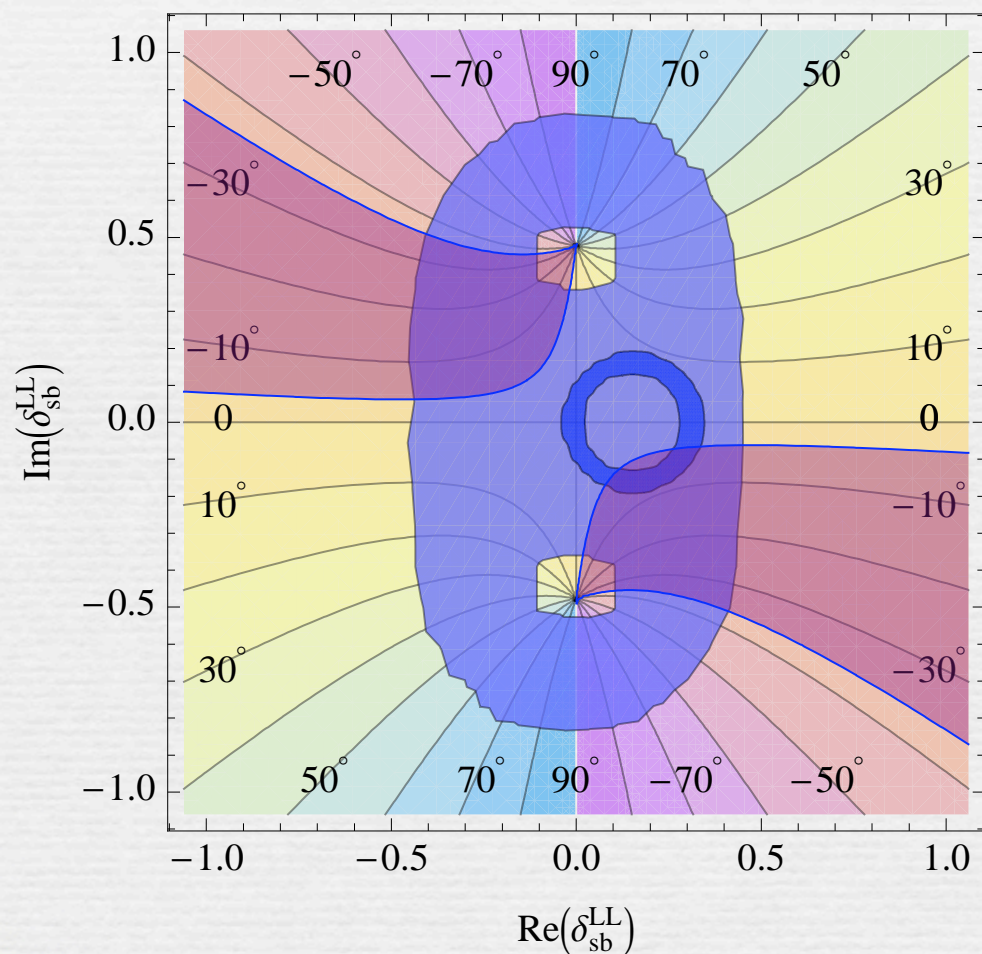
$$\hat{\delta}_{ds}^{LL} \equiv \hat{\delta}_{db}^{LL} \hat{\delta}_{bs}^{LL}$$

Suppression in the 1-2 sector

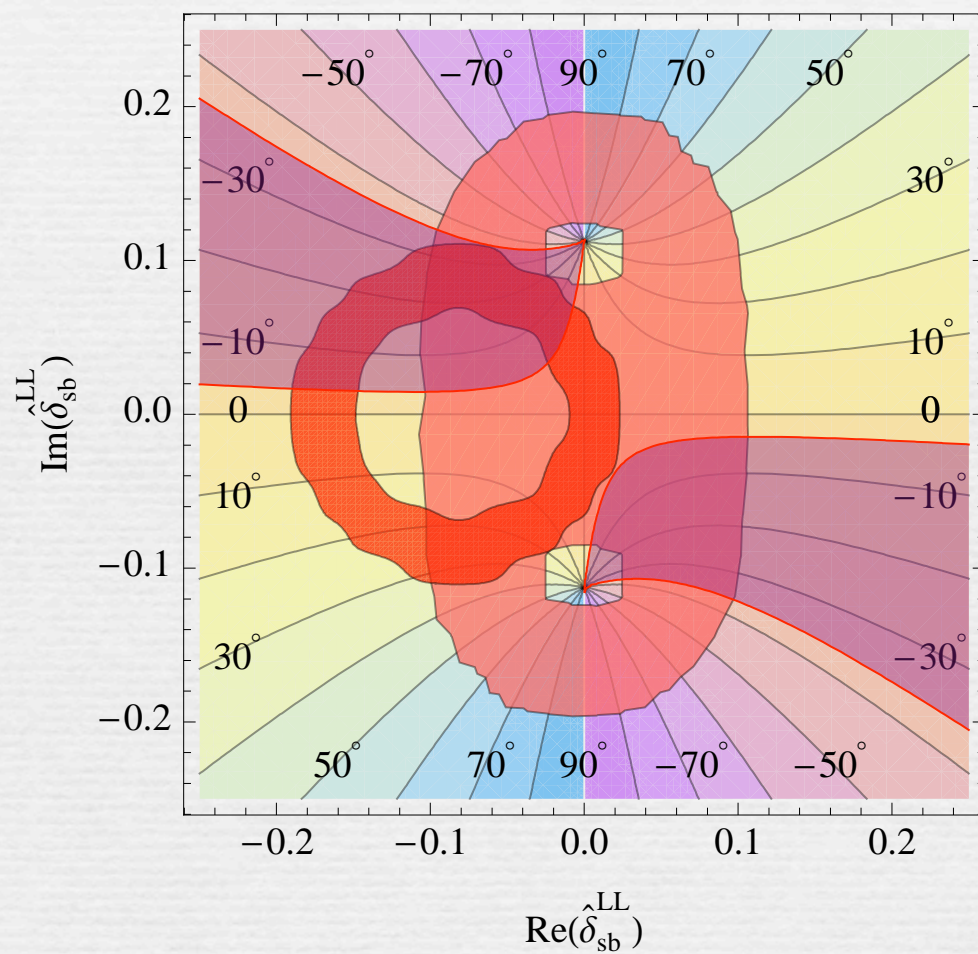
There are only 4 flavor violating insertions: $\hat{\delta}_{bd}^{LL}, \hat{\delta}_{db}^{LL}, \hat{\delta}_{bd}^{RR}, \hat{\delta}_{db}^{RR}$

$$\Delta M_{B_s}, \quad B \rightarrow X_s \gamma, \quad \phi_{B_s}$$

Degenerate Spectrum



Hierarchical Spectrum



Comments and Summary

- n Heavy first two family are not incompatible with naturalness
- n Welcome to alleviate the SUSY flavor problem
- n Useful to describe scenarios where the mass separation is moderate but sufficient to make the degenerate assumption a poor starting point. Which is somewhat expected because of $U(3)$ breaking by Yukawa.
- n Complementary to the degeneracy assumption in a general study of SUSY flavor effects, with prediction different by factor $O(1-10)$
- n Predictions: distinct correlations between different observables.