SUSY\_FLAVOR library and constraints on $B_s^0 \to \mu^+\mu^-$ decay rate

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I present SUSY\_FLAVOR - a Fortran 77 program able to calculate simultaneously 29 low-energy flavor and CP-violating observables in the general $R$-parity conserving MSSM, including the case of large flavor violation in the sfermion sector. SUSY\_FLAVOR v2 performs also the resummation of chirally enhanced corrections, arising in large $\tan \beta$ regime and/or large trilinear soft mixing terms, to all orders of perturbation theory. I discuss an example of application of SUSY\_FLAVOR to analysis of the $B_s^0 \to \mu^+\mu^-$ decay rate in the MSSM.

1 Introduction

Flavor physics was in the recent years one of the most active fields in the high energy physics. New experiments helped to improve the accuracy of various measurements related to rare decays and put strong constraints on the flavor structure of physics beyond the Standard Model (SM), in particular imposing stringent limits on the flavor- and CP-violating parameters of the Minimal Supersymmetric Standard Model (MSSM). It is then increasingly important to have an universal computational tool which helps to compare new data with the predictions of the MSSM. Developing such a tool is a non-trivial task requiring extensive and tedious calculations. Numerous existing analyses usually consider only a few rare decays simultaneously and in most cases they are restricted to the case of so-called Minimal Flavor Violation (MFV) scenario, where the CKM matrix is the only source of CP and flavour violation. Based on a series of papers where many rare processes were analyzed within the general MSSM, a library of relevant computer codes has been published as SUSY\_FLAVOR v1. SUSY\_FLAVOR v2 is in addition capable of resumming leading chirally enhanced corrections, important in the regime of large $\tan \beta$ or large trilinear $A$-terms, to all orders of perturbation theory and for any pattern of sfermion mass matrices - a unique feature not shared by other publicly available programs. In this article I briefly summarize the main features of SUSY\_FLAVOR and present example of its application to estimating the $B_s^0 \to \mu^+\mu^-$ decay rate in the MSSM.

2 SUSY\_FLAVOR structure, input parameters and calculated observables

SUSY\_FLAVOR is capable of calculating physical observables within the most general $R$-parity conserving MSSM, with one exception: currently it assumes massless neutrinos (and no right neutrino/sneutrino fields), so the PMNS mixing matrix does not appear in the couplings. SUSY\_FLAVOR has been in development long before the Les Houches Accord (SLHA) for common MSSM conventions was agreed on. Thus, the internal routines of the library follow the conventions of earlier paper. However, by default SUSY\_FLAVOR can be initialized with a SLHA2 compatible set of parameters - all translations are done internally. Note that in

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Table 1: One loop parton level formfactors implemented in SUSY\_FLAVOR. \(I, J, K, L\) denote flavor indices.

| Box | Penguin | Self energy |
|-----|---------|-------------|
| \(d^i d^j d^K d^L\) | \(Ze^i d^j, \gamma e^j d^i, gd^i d^j\) | \(d^i\)-quark |
| \(u^i u^j u^K u^L\) | \(H_y^i d^j, A_y^i d^j\) | \(u^i\)-quark |
| \(d^i d^j u^K u^L\) | \(H_z^i u^j, A_z^i u^j\) | charged lepton \(l^i\) |
| \(d^i d^j u^K u^L\) | \(\gamma l^i u^j\) | |

SUSY\_FLAVOR one can also use so-called “non-analytic \(A\)-terms” of the form \(A_{I}^{IJ} H_{2}^{LJ} E_{I} + A_{I}^{I2} H_{2}^{QJ} D_{J} + A_{I}^{IJ} H_{11}^{QJ} U_{J}\), which are not included in the standard SLHA2 parametrization.

Calculations in SUSY\_FLAVOR take the following steps:\[8\]

1. **Parameter initialization.** Users can adjust the basic SM parameters and initialize all (or the chosen subset of) Higgs sector parameters and supersymmetric soft masses and couplings (which must be specified at the SUSY scale).

2. **Calculation of the physical masses and the mixing angles.** In the next stage, the eigenvalues of the mass matrices of all MSSM particles and their mixing matrices at tree level are calculated numerically, without any approximations.

3. **Resummation of the chirally enhanced effects.** In the regime of large \(\tan \beta\) and/or large trilinear SUSY breaking terms, large chirally enhanced corrections to Yukawa couplings and CKM matrix elements arise\[9\]. They are resummed to all orders of perturbation theory using the formalism developed in\[10\]. The level of resummation (no resummation, approximate analytical resummation in the decoupling limit, iterative numerical resummation) is a user defined option.

4. **Calculation of the Wilson coefficients at the SUSY scale.** In the current version, SUSY\_FLAVOR calculates Wilson coefficients generated by the diagrams listed in Table 1 (routines for given formfactor accept fermion generation indices as input parameters).

5. **Strong corrections.** After evaluating virtual SUSY contributions, SUSY\_FLAVOR performs the QCD evolution of the Wilson coefficients from the high (SUSY or top quark mass) scale to the low energy scale appropriate for a given decay. Necessary hadronic matrix element estimates and other QCD related quantities are treated as external parameters, initialized to the default values extracted from analyses done within the SM but also directly modifiable by users.

6. **Evaluation of physical observables.** Finally physical observables are calculated and printed out. Current list of processes implemented in SUSY\_FLAVOR v2 is listed in Table 2.

3 **Application of SUSY\_FLAVOR to analysis of the \(B \to \mu^+ \mu^-\) decay rate.**

One of the most promising signals for new physics at the LHC is the rare decay \(B_s^0 \to \mu^+ \mu^-\). It is suppressed as a loop-level flavour-changing neutral current and by a lepton mass insertion required for the final state muon helicities. The LHC will be the first experiment able to probe this decay channel down to its SM-predicted branching ratio. The winter 2012 experimental 95\% CL bound\[14\] and the SM prediction\[15\] for \(B_s^0 \to \mu^+ \mu^-\) decay rate can be summarized as:

- CMS: \(< 7.7 \times 10^{-9}\)
- LHCb: \(< 4.5 \times 10^{-9}\)
- SM Prediction: \((3.35 \pm 0.32) \times 10^{-9}\)

ATLAS, CMS and LHCb will be able soon to reconstruct the SM-like \(B_s^0 \to \mu^+ \mu^-\) signal with significance of 3\(\sigma\), so that this very rare decay could be finally discovered and measured.

SUSY\_FLAVOR is an efficient tool allowing to estimate the size of possible SUSY contributions to the \(B_s^0 \to \mu^+ \mu^-\) channel. In the MSSM, even in the restricted MFV case, for large values of \(\tan \beta\) the \(B(B_s^0 \to \mu^+ \mu^-)\) can be strongly enhanced\[4\] (\(M_A\) is the \(CP\)-odd Higgs boson mass):

\[
B(B_s^0 \to \mu^+ \mu^-) \approx 5 \cdot 10^{-7} \left( \frac{\tan \beta}{50} \right)^6 \left( \frac{300 \text{ GeV}}{M_A} \right)^4 ,
\]
This result can be further significantly modified by non-vanishing flavor-violating terms in the sfermion mass matrices, leading to large contributions from box and Z-penguin diagrams. Apart from enhancing the decay rate, the interference of these terms could also conceivably lead to a cancellation that would suppress the branching ratio even below the SM prediction.

To quantitatively study the size of possible effects, one needs to perform a scan over the MSSM parameter space. The ranges of variation over MSSM parameters are shown in left panel of Table\(^2\) (all parameters in scan are real; “SUSY scale” refers to the common mass parameter for the first two squark generations; the trilinear soft breaking terms are set to \(A_t = A_b = M_{\tilde{Q}_L}\) and \(A_{\tilde{g}} = M_{\tilde{g}}\)). Flavour violation is parametrized by the “mass insertions”\(^2\), where \(I, J\) denote quark flavours, \(X, Y\) denote superfield chirality, and \(Q\) indicates the sfermion field:

\[
\delta_{QXY}^{IJ} = \frac{(M_Q^2)^{IJ}}{(M_Q)^{XX} (M_Q)^{YY}}. \tag{2}
\]

Realistic estimate of the allowed range for \(\mathcal{B}(B_s^0 \to \mu^+\mu^-)\) requires taking into account the experimental constraints from measurements of other rare decays. For that, all \(\Delta F = 2\) observables, \(\mathcal{B}(B \to X_s\gamma), \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}), \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})\) decay rates and the neutron and electron electric dipole moments have been used out of quantities listed in Table\(^2\). In addition, bounds on SUSY particle masses listed in right panel of Table\(^3\) have been used.

For the chosen bounds from Table\(^2\) for which the experimental result and its error are known, parameter point in scan was accepted if

\[
|Q^{exp} - Q^{th}| \leq 3\Delta Q^{exp} + q|Q^{th}|. \tag{3}
\]

For the quantities for which only the upper bound is known,

\[
(1 + q)|Q^{th}| \leq Q^{exp} \tag{4}
\]

was required. The first and second terms on the right-hand side of Eq.\(^8\) represent the 3σ experimental error and the theoretical error respectively. The latter differs from quantity to
Table 3: The range of input parameters and experimental constraints used for the numerical scan. All mass parameters are in GeV.

| Parameter           | Min  | Max  | Step |
|---------------------|------|------|------|
| \( \tan \beta \)    | 2    | 30   | varied |
| CKM phase \( \gamma \) | 0    | \( \pi \) | \( \pi/25 \) |
| CP-odd Higgs \( M_A \) | 100  | 500  | 200  |
| Higgs mixing \( \mu \) | -450 | 450  | 300  |
| SU(2) wino mass \( M_2 \) | 100  | 500  | 200  |
| Gluino mass \( M_3 \) | \( 3M_2 \) | \( 3M_2 \) | 0 |
| SUSY scale \( M_{\text{SUSY}} \) | 500  | 1000 | 500  |
| Left stop \( M_{\tilde{Q}_L} \) | 200  | 500  | 300  |
| Right stop \( M_{\tilde{b}_R} \) | 150  | 300  | 150  |
| \( \delta_{d_{d_{LL}}}^{13} \) | -1   | 1    | 0.1  |
| \( \delta_{d_{d_{LR}}}^{23} \) | -0.1 | 0.1  | 0.01 |

The quantity and is usually smaller than the value \( q = 50\% \) which was assume generically to account for the limited density of a numerical scan (see ref. 6 for details).

Fig. 1 shows the predictions for \( B(B_s^0 \to \mu^+ \mu^-) \) over a general scan of 20 million points according to Table 3. \( \delta_{d_{d_{LL}}}^{23} \) (left panel) and \( \delta_{d_{d_{LR}}}^{23} \) (right panel) were varied one at a time while setting the other to zero, e.g. all \( \delta_{XY}^{ij} = 0 \) and only \( \delta_{d_{LL}}^{23} \neq 0 \) in the left panel. When \( \delta_{d_{LL}}^{23} \) is varied in the range \([-1, 1]\), one finds \( B(B_s^0 \to \mu^+ \mu^-)_{\text{min}} \approx 10^{-9} \). This minimum is almost independent of \( \tan \beta \). \( \delta_{d_{LL}}^{23} \) can take on values up to \( \approx 0.9 \) and still pass all imposed constraints, though points beyond 0.3 are less dense. More interesting is the case when \( \delta_{d_{LR}}^{23} \) is varied in the range \([-0.1, 0.1]\]. One can find a narrow cancellation region around \( \delta_{d_{LR}}^{23} \approx -0.01 \) and \( \tan \beta \lesssim 10 \) where \( B(B_s^0 \to \mu^+ \mu^-)_{\text{min}} \approx 10^{-12} \). This is three orders of magnitude lower than the SM prediction, making it effectively unobservable at the LHC.

![Figure 1: Predictions for \( B(B_s \to \mu^+ \mu^-) \) vs \( \tan \beta \) from the scan of MSSM parameters in Table 3. Left(right) panel: \( \delta_{d_{LL}}^{23} \) (\( \delta_{d_{LR}}^{23} \)) varied. The dashed line shows the SM expectation.](image)

4 Conclusions

I have presented SUSY\_FLAVOR, a tool capable of calculating simultaneously 29 important flavor observables in the general \( R \)-parity conserving MSSM. The calculation of the SUSY tree-level particle spectrum and flavor mixing matrices are performed exactly. SUSY\_FLAVOR v2 implements also the resummation of chirally enhanced corrections, stemming from large values of \( \tan \beta \) and/or large trilinear \( A \)-terms. Thus SUSY\_FLAVOR v2 is valid for the whole parameter space.
of the general $R$-parity conserving MSSM, without restrictions on the size of the off-diagonal elements in the sfermion mass matrices - a unique feature currently not shared by other publicly available programs calculating FCNC and CP violation in supersymmetric models. I hope that SUSY\_FLAVOR becomes an important tool useful both for theorists and experimentalists who need to perform multi-process flavor analyses within the MSSM.

As an example of such analysis, SUSY\_FLAVOR has been used to perform a numerical exploration of the MSSM parameter space and estimate of the $B_s^0 \rightarrow \mu^+\mu^-$ decay rate. Scan shows that there exist cancellation regions where the contribution of diagrams with supersymmetric particles interferes destructively with SM diagrams, thus allowing the branching ratio to be significantly smaller than the SM prediction. Such effects may effectively hide the dimuon $B_s^0$ decay mode from the LHCb even though it is supposed to be one of the experiment’s benchmark modes. Barring such cancellations, supersymmetric contributions typically tend to enhance the branching ratio for $B_s^0 \rightarrow \mu^+\mu^-$ even for moderate values of $\tan\beta < \sim 10$ so that an experimental measurement close to the SM prediction puts strong bounds on the size of allowed flavour violation in the squark sector.

SUSY\_FLAVOR can be downloaded from the address\texttt{http://www.fuw.edu.pl/susy\_flavor}.

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