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SUSY_FLAVOR : a computational tool for FCNC and CP-violating processes in the MSSM

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ABSTRACT

We present SUSY_FLAVOR — a Fortran 77 program that calculates important leptonic and semi-leptonic low-energy observables in the general R -parity conserving MSSM. For a set of input MSSM parameters, the code gives predictions for the $\bar{K}^0 K^0$, $\bar{D} D$, $\bar{B}_d B_d$ and $\bar{B}_s B_s$ mixing parameters; $B \rightarrow X_s \gamma$, $B_{s,d} \rightarrow l^+ l^-$, $K_L^0 \rightarrow \pi^0 \bar{\nu} \nu$ and $K^+ \rightarrow \pi^+ \bar{\nu} \nu$ decay branching ratios; and the electric dipole moments of the leptons and the neutron. All these quantities are calculated at one-loop level (with some higher-order QCD corrections included) in the exact sfermion mass eigenbasis, without resorting to mass insertion approximations. The program can be obtained from http://www.fuw.edu.pl/susy_flavor.

1 Introduction

Flavor changing neutral currents (FCNCs) in the Minimal Supersymmetric Standard Model (MSSM) [1] originate from the fact that one cannot, in general, simultaneously diagonalize the mass matrices of fermions and their supersymmetric partners. The misalignment between these mass matrices leads to FCNCs at tree level. Moreover a large number of the MSSM parameters which can take complex values is a potential source of CP violation. Thus supersymmetric contributions to amplitudes of processes violating flavor and to quantities measuring CP violation, like Electric Dipole Moments (EDMs), can exceed by orders of magnitudes the ones of the SM particles. Such large effects are ruled out by experimental measurements which generally agree with the SM predictions and thus provide strong bounds on the amount of flavor and CP violation in the MSSM. For instance, measurements of the kaon system properties prohibit FCNC couplings between the first and second generation of down-type squarks larger than 10^{-3} . These strong limits are often called the “SUSY flavor problem”. However, there are also areas where current experiments still leave room for large SUSY contributions. For example, constraints from B -meson experiments allow an $\mathcal{O}(1)$ mixing between the second and third generation down-type squarks. Such a large mixing could produce FCNC effects that could be observed in the future at B -factories and/or hadron colliders, like the Tevatron and LHC [2].

Even assuming the so-called Minimal Flavor Violation (MFV) scenario in which *all* FCNC effects originate from the superpotential Yukawa couplings, the flavor conserving soft SUSY breaking parameters can still contain complex phases that cannot be absorbed by a redefinition of fields and can, for example, give large contributions to the electron and neutron EDMs.

As the accuracy of rare decay experiments improves, it is important to have a universal computational tool which would help compare new data with the predictions of the MSSM. Constructing such a tool is a non-trivial task because finding SUSY contribution to each rare decay requires tedious calculations, especially when one wishes to have fully general formulae that do not rely on the restrictive assumptions of the MFV scenario. Numerous analyses have been published in the literature, but because of the complexity of the problem, they mostly take into account one, or at most few, rare decays simultaneously. Furthermore, most analyses done for general flavor violation in the MSSM soft terms use the mass insertion approximation (MIA) (see e.g. [3]) which significantly simplifies calculations but does not produce correct results when flavor violation in the superpartner sector becomes strong.

In a series of papers since 1997 [3–13], many supersymmetric FCNC and CP-violating observables were analyzed with loop-level accuracy within the setup of the fully general R -parity conserving MSSM without resorting to any MIA-type expansions. A FORTRAN 77 computer programs based on the common set of Feynman rules of Ref. [14] were developed for each process. Because these programs use the same conventions, input parameters, and

Observable	Experiment
$\Delta F = 0$	
$ d_e (\text{ecm})$	$< 1.6 \times 10^{-27}$ [16]
$ d_\mu (\text{ecm})$	$< 2.8 \times 10^{-19}$ [17]
$ d_\tau (\text{ecm})$	$< 1.1 \times 10^{-17}$ [18]
$ d_n (\text{ecm})$	$< 2.9 \times 10^{-26}$ [19]
$\Delta F = 1$	
$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	$< 6.7 \times 10^{-8}$ [20]
$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$17.3_{-10.5}^{+11.5} \times 10^{-11}$ [21]
$\text{Br}(B_d \rightarrow ee)$	$< 1.13 \times 10^{-7}$ [22]
$\text{Br}(B_d \rightarrow \mu\mu)$	$< 1.8 \times 10^{-8}$ [23]
$\text{Br}(B_d \rightarrow \tau\tau)$	$< 4.1 \times 10^{-3}$ [24]
$\text{Br}(B_s \rightarrow ee)$	$< 7.0 \times 10^{-5}$ [25]
$\text{Br}(B_s \rightarrow \mu\mu)$	$< 5.8 \times 10^{-8}$ [23]
$\text{Br}(B_s \rightarrow \tau\tau)$	---
$\text{Br}(B \rightarrow X_s \gamma)$	$(3.52 \pm 0.25) \times 10^{-4}$ [26]
$\Delta F = 2$	
$ \epsilon_K $	$(2.229 \pm 0.010) \times 10^{-3}$ [18]
ΔM_K	$(5.292 \pm 0.009) \times 10^{-3} \text{ ps}^{-1}$ [18]
ΔM_D	$(2.37_{-0.71}^{+0.66}) \times 10^{-2} \text{ ps}^{-1}$ [18]
ΔM_{B_d}	$(0.507 \pm 0.005) \text{ ps}^{-1}$ [26]
ΔM_{B_s}	$(17.77 \pm 0.12) \text{ ps}^{-1}$ [27]

Table 1: List of observables calculated by **SUSY_FLAVOR** and their currently measured values or 95% C.L bounds (except for $\text{Br}(B_d \rightarrow ee)$ and $\text{Br}(B_d \rightarrow \tau\tau)$ for which the 90% C.L bounds are given.).

internal data structures, they can naturally interface with one another. Combining these works, we present in this article **SUSY_FLAVOR** - a publicly available computer code that simultaneously calculates the set of important $\Delta F = 0, 1, 2$ FCNC and CPV observables in the framework of the general MSSM. The current version (1.0) of the program takes a set of MSSM parameters and calculates the processes¹ listed in Table 1.

Several programs allowing to analyze various aspects of the MSSM flavor phenomenology have been published. The most relevant to **SUSY_FLAVOR** are: **CPsuperH** [28], **SusyBSG** [29] and **SuperIso** [30]. **SusyBSG** is dedicated to high-precision predictions for $B \rightarrow s\gamma$ while **CPsuperH** and **SuperIso** calculate processes similar to the ones computed by **SUSY_FLAVOR**.

¹In the current version **SUSY_FLAVOR** calculates also the full one-loop corrections to lepton flavor violating B -meson decays such as $B \rightarrow \mu\tau$. However, it is known that contributions to the amplitudes of these processes are greatly enhanced at large $\tan\beta$ by formally two loop double penguin diagrams [15] which currently are not included in the code. Thus, **SUSY_FLAVOR** can be used to estimate such decay rates only at low $\tan\beta \lesssim 10$.

However, these existing codes are restricted to the Minimal Flavor Violation scenario. Thus, to the best of the authors' knowledge, **SUSY_FLAVOR** is the first program which can simultaneously calculate the set of rare decays listed in Table 1 without any (apart from the R -parity conservation) restrictions on the choice of MSSM parameters. Other publicly available codes that are relevant to **SUSY_FLAVOR** (which can e.g. calculate the MSSM soft parameters used as input to **SUSY_FLAVOR**, or for the same set of input parameters calculate non-FCNC related observables) are **FeynHiggs** [31], **SoftSUSY** [32], **SuSpect** [33], **SPheno** [34], **MicrOMEGAs** [35], **DarkSUSY** [36] and **NMHDECAY** [37].

In summary, the basic features of **SUSY_FLAVOR** are:

- The program utilizes the most general R -parity conserving Lagrangian for the MSSM. In addition to standard soft breaking terms, it can even accommodate additional non-holomorphic terms, such as

$$A_d'^{IJ} H_i^{2\star} Q_i^I D^J + A_u'^{IJ} H_i^{1\star} Q_i^I U^J + \text{H.c.}, \quad (1)$$

that, for example, do not appear in the minimal supergravity scenario but are present in the most general softly broken supersymmetric effective Lagrangian [38].

- There is no limit on the size of flavor violating parameters because the calculation does not rely on the MIA expansion. Complex “mass insertions” of the form

$$\delta_{QXY}^{IJ} = \frac{(M_Q^2)^{IJ}_{XY}}{\sqrt{(M_Q^2)^{II}_{XX}(M_Q^2)^{JJ}_{YY}}}, \quad (2)$$

(I, J denote quark flavors, X, Y denote superfield chirality, and Q indicates either the up or down quark superfield sector, similarly for slepton superfields) are taken as inputs, but they only serve to conveniently parametrize the sfermion mass matrices. **SUSY_FLAVOR** numerically calculates the exact tree-level spectrum and mixing matrices, which are later used in loop calculations.

- As an intermediate step, parton-level form factors for quark and lepton 2-, 3- and 4-point Green functions are calculated. They are later dressed in hadronic matrix elements (see Table 3 in Section 3) to obtain predictions for the physical quantities listed in Table 1. The set of Green's functions computed by **SUSY_FLAVOR** as intermediate “building blocks” is quite universal and can be used by other authors to calculate other processes.
- The program runs fairly quickly. On a Mac PowerBook G4 with GNU FORTRAN g77 it returns the output for a single parameter set run within a second.

We note that the current **SUSY_FLAVOR** version does not resum higher-order corrections in the limit of large $\tan\beta$. Such corrections in the MFV scenario can easily dominate the SM result for $\tan\beta \gtrsim 30 - 40$. However, even in that case new sources of flavor violation often give comparable or more significant contributions than the MFV-type $\tan\beta$ -enhanced

corrections. Thus, for large $\tan\beta$ one should perform the resummation of leading higher-order terms in the presence of the non-vanishing flavor violation in the sfermion mass matrices. Unfortunately, such resummation is not yet fully understood, i.e., although there are theoretical ideas [10, 39–41] on how to resum these contributions beyond MFV, it is quite difficult to implement them into **SUSY_FLAVOR** without losing numerical stability for large mass insertions. Thus, even though some parts of **SUSY_FLAVOR** (e.g. $\bar{B}B$ mixing and the $B \rightarrow l^+l^-$ decays) were originally devised to perform a large $\tan\beta$ resummation for the MSSM parameter choice restricted to the MFV case, in the present version this option has been deactivated for consistency. We hope to improve this in future versions of the code. The current version of **SUSY_FLAVOR** should be used for low to moderate values of $\tan\beta$ ($\tan\beta \lesssim 30$), however even in the case of significant supersymmetric flavor violation it should still produce reasonably accurate results even for $\tan\beta$ beyond this range.

The rest of the paper is organized as follows. In Section 2 we define the general structure of the MSSM Lagrangian following Ref. [14] to facilitate comparison of the conventions used in **SUSY_FLAVOR** with others used in the literature and to connect the variables used in the code with physical quantities. Section 3 describes the internal structure of **SUSY_FLAVOR**, the most important steps of calculations, and the file structure of the library. In Section 4 we carefully present the initialization sequence for **SUSY_FLAVOR**, defining input parameters and how they are used. Routines for calculating the FCNC and CPV observables collected in Table 1 are described in Section 5. We conclude with a summary of the presentation. Appendix A contains brief instructions on how to install and run the **SUSY_FLAVOR** package. In Appendices B and C we provide templates for initializing **SUSY_FLAVOR** from within the program and using an external file in the SLHA2 format [42], respectively. Both of these templates produce the set of test results listed in Appendix D.

SUSY_FLAVOR can be downloaded from the following address:

http://www.fuw.edu.pl/susy_flavor

2 Lagrangian, conventions and the tree level masses

2.1 Lagrangian parameters

SUSY_FLAVOR follows the conventions for the MSSM Lagrangian and Feynman rules for the most general R -parity conserving version of the MSSM Lagrangian given in [14]. Over 100 Lagrangian parameters are taken as input to **SUSY_FLAVOR** and can be initialized independently.

For completeness and for easier comparison with conventions used in other sources, we present here the full list of the general MSSM couplings. They can be classified by sectors of the theory:

1. Gauge sector. g_1, g_2, g_3 denote the coupling constants of gauge groups $U(1)_Y, SU(2)_L, SU(3)_c$, respectively.

2. Superpotential and Yukawa couplings. The superpotential and the soft breaking sfermion couplings are written after the rotations of superfields to the super-KM basis in which the Yukawa couplings are diagonal and the soft parameters are redefined accordingly to account for accommodate these flavor rotations (see e.g. [3]).

We do not assume the existence of the heavy right-handed neutrino/sneutrino supermultiplet and neglect related terms in the Lagrangian.² Then the most general form of the R -parity conserving MSSM superpotential takes the form:

$$W = \mu \epsilon_{ij} H_i^1 H_j^2 + \epsilon_{ij} Y_l^I H_i^1 L_j^I R^I + \epsilon_{ij} Y_d^I H_i^1 Q_j^I D^I + \epsilon_{ij} Y_u^I H_i^2 Q_j^I U^I. \quad (3)$$

Capital indices ($I, J, K \dots$) label matter field generations and run from 1 to 3. Lower-case indices (i, j, \dots) are $SU(2)_L$ indices (we use $\epsilon_{12} = -1$). $SU(3)_c$ indices are not written explicitly; we assume that the Q supermultiplets are QCD triplets and the D and U supermultiplets are anti-triplets. At tree level, quark and lepton masses are related to Yukawa couplings by (note that Y_l^I, Y_d^I are negative in our convention):

$$m_e^I = -\frac{v_1 Y_l^I}{\sqrt{2}}, \quad m_d^I = -\frac{v_1 Y_d^I}{\sqrt{2}}, \quad m_u^I = \frac{v_2 Y_u^I}{\sqrt{2}}. \quad (4)$$

It follows that in **SUSY_FLAVOR** the fermion masses and the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, rather than the Yukawa couplings, are used as input parameters.

3. Soft gaugino mass terms for the $U(1)_Y, SU(2)_L$ and $SU(3)_c$ gauge groups

$$\frac{1}{2} M_1 \lambda_B \lambda_B + \frac{1}{2} M_2 \lambda_A^i \lambda_A^i + \frac{1}{2} M_3 \lambda_G^a \lambda_G^a + \text{h.c.} \quad (5)$$

4. Soft-breaking mass terms for the scalar fields.

$$\begin{aligned} & -m_{H_1}^2 H_i^{1*} H_i^1 - m_{H_2}^2 H_i^{2*} H_i^2 - (m_L^2)^{IJ} L_i^{I*} L_i^J - (m_E^2)^{IJ} E^{I*} E^J \\ & - (K m_Q^2 K^\dagger)^{IJ} Q_1^{I*} Q_1^J - (m_Q^2)^{IJ} Q_2^{I*} Q_2^J - (m_D^2)^{IJ} D^{I*} D^J - (m_U^2)^{IJ} U^{I*} U^J \end{aligned} . \quad (6)$$

5. Trilinear scalar couplings corresponding to superpotential Yukawa terms.

$$m_{12}^2 \epsilon_{ij} H_i^1 H_j^2 + \epsilon_{ij} A_l^{IJ} H_i^1 L_j^I E^J + \epsilon_{ij} A_d^{IJ} H_i^1 Q_j^I D^J + \epsilon_{ij} A_u^{IJ} H_i^2 Q_j^I U^J + \text{h.c.} \quad (7)$$

6. Non-standard trilinear scalar couplings involving complex conjugated Higgs fields (sometimes called “non-analytic terms”).

$$A_l'^{IJ} H_i^{2*} L_i^I E^J + A_d'^{IJ} H_i^{2*} Q_i^I D^J + A_u'^{IJ} H_i^{1*} Q_i^I U^J + \text{h.c.} \quad (8)$$

²The modifications to the phenomenology of the MSSM from the presence of a heavy right neutrino supermultiplet are discussed in [43]. Some numerical codes concerning the problem can be obtained from its authors.

Usually these couplings are not considered as they are not generated in standard SUSY breaking models. However, for completeness they are included in `SUSY_FLAVOR` and by default initialized to zero. Users of `SUSY_FLAVOR` may decide to set them to some non-vanishing values in order to check their impact on rare decay phenomenology.

In general, the mass parameters μ , m_{12}^2 , m_Q^2 , $M_{1,2,3}$, and the trilinear soft couplings may be complex. Global rephasing of all fermion fields of the theory and of one of the Higgs multiplets can render two of these parameters real [4]. We choose them to be the gluino mass M_3 and the soft Higgs mixing term m_{12}^2 . The latter choice keeps the Higgs vacuum expectation values (VEV) and, therefore, the parameter $\tan\beta$ real at tree level.

2.2 Physical tree level masses and mixing angles

Mass matrices of the MSSM particles can be written in terms of the parameters of Section 2.1. In `SUSY_FLAVOR`, following [14], we consistently use matrix notation for all fields, including neutral and charged Higgs bosons. Such a notation simplifies the expressions for loop calculations. In this Section we explicitly write down all mass matrices to fix our sign conventions relative to other choices in the literature.

1. Higgs sector. We denote the CP-even and CP-odd neutral scalars as H_i^0 and A_i^0 , respectively, with $i = 1, 2$. In terms of more common notation, $(H_1^0, H_2^0) \equiv (H^0, h^0)$ and $(A_1^0, A_2^0) \equiv (A^0, G^0)$. These are related to the initial Higgs doublets by (no sum over i):

$$\begin{aligned}\Re e H_i^i &= \frac{1}{\sqrt{2}}(Z_R^{ij}H_j^0 + v_i) , \\ \Im m H_i^i &= \frac{1}{\sqrt{2}}Z_H^{ij}A_j^0 .\end{aligned}\quad (9)$$

In these formulae v_1, v_2 are the VEVs of the two neutral components of the Higgs doublets and Z_R, Z_H are the mixing matrices in the CP-even and CP-odd Higgs sectors, respectively.

The mixing matrix Z_R and the masses of H_i^0 can be obtained by diagonalizing the CP-even Higgs mass² matrix:

$$Z_R^T \begin{pmatrix} -m_{12}^2 \frac{v_2}{v_1} + \frac{e^2 v_1^2}{4s_W^2 c_W^2} & m_{12}^2 - \frac{e^2 v_1 v_2}{4s_W^2 c_W^2} \\ m_{12}^2 - \frac{e^2 v_1 v_2}{4s_W^2 c_W^2} & -m_{12}^2 \frac{v_1}{v_2} + \frac{e^2 v_2^2}{4s_W^2 c_W^2} \end{pmatrix} Z_R = \begin{pmatrix} M_{H_1^0}^2 & 0 \\ 0 & M_{H_2^0}^2 \end{pmatrix} \equiv \begin{pmatrix} M_H^2 & 0 \\ 0 & M_h^2 \end{pmatrix} . \quad (10)$$

$A_1^0 (\equiv A^0)$ has mass $M_A^2 = M_{H_1}^2 + M_{H_2}^2 + 2|\mu|^2$. `SUSY_FLAVOR` assumes R_ξ gauge with $\xi = 1$, so the neutral Goldstone boson $A_2^0 (\equiv G^0)$ has the mass $M_{G^0} = M_Z$.

The mixing matrices Z_H, Z_R are parametrized as follows:

$$Z_H = \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} , \quad Z_R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} , \quad (11)$$

with the angles α and β determined by

$$\begin{aligned} \tan \beta &= \frac{v_2}{v_1}, & 0 \leq \beta \leq \frac{\pi}{2}, \\ \tan 2\alpha &= \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}, & -\frac{\pi}{2} \leq \alpha \leq 0. \end{aligned} \quad (12)$$

Charged Higgs scalars are denoted by $H_i^\pm \equiv H^\pm, G^\pm$ and are related to the initial Higgs doublet again by the matrix Z_H :

$$\begin{pmatrix} H_2^{1*} \\ H_1^2 \end{pmatrix} = Z_H \begin{pmatrix} H_1^+ \\ H_2^+ \end{pmatrix}. \quad (13)$$

The physical charged Higgs boson has mass

$$M_{H_1^\pm}^2 = M_W^2 + m_{H_1}^2 + m_{H_2}^2 + 2|\mu|^2, \quad (14)$$

while the charged Goldstone bosons G^\pm have masses $M_{G^\pm} = M_W$.

2. Gaugino sector. The chargino masses and mixing matrices Z_+ and Z_- are defined by the relation

$$(Z_-)^T \begin{pmatrix} M_2 & \frac{ev_2}{\sqrt{2}s_W} \\ \frac{ev_1}{\sqrt{2}s_W} & \mu \end{pmatrix} Z_+ = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix}. \quad (15)$$

In SUSY_FLAVOR we choose Z_-, Z_+ such that both masses M_{χ_i} are real positive and $M_{\chi_2} > M_{\chi_1}$.

The neutralino tree level masses are given by

$$Z_N^T \begin{pmatrix} M_1 & 0 & \frac{-ev_1}{2c_W} & \frac{ev_2}{2c_W} \\ 0 & M_2 & \frac{ev_1}{2s_W} & \frac{-ev_2}{2s_W} \\ \frac{-ev_1}{2c_W} & \frac{ev_1}{2s_W} & 0 & -\mu \\ \frac{ev_2}{2c_W} & \frac{-ev_2}{2s_W} & -\mu & 0 \end{pmatrix} Z_N = \begin{pmatrix} M_{\chi_1^0} & & 0 & \\ & \ddots & & \\ 0 & & & M_{\chi_4^0} \end{pmatrix}, \quad (16)$$

where again we use the ambiguity in the definition of the Z_N matrix to choose to make all $M_{\chi_i^0}$ real positive and increasingly ordered.

3. Slepton sector. The three complex sneutrino fields have tree level masses and the mixing matrix $Z_{\tilde{\nu}}$ defined by:

$$Z_{\tilde{\nu}}^\dagger \left(\frac{e^2(v_1^2 - v_2^2)}{8s_W^2 c_W^2} \hat{1} + m_L^2 \right) Z_{\tilde{\nu}} = \begin{pmatrix} M_{\tilde{\nu}_1}^2 & & 0 \\ & \ddots & \\ 0 & & M_{\tilde{\nu}_3}^2 \end{pmatrix}. \quad (17)$$

The mass matrix for the six charged sleptons

$$\mathcal{M}_L^2 = \begin{pmatrix} \frac{e^2(v_1^2 - v_2^2)(1 - 2c_W^2)}{8s_W^2 c_W^2} + \frac{v_1^2 Y_l^2}{2} + (m_L^2)^T & \frac{v_2}{\sqrt{2}}(Y_l \mu^* - A'_l) + \frac{v_1}{\sqrt{2}}A_l \\ \frac{v_2}{\sqrt{2}}(Y_l \mu - A'^\dagger_l) + \frac{v_1}{\sqrt{2}}A_l^\dagger & -\frac{e^2(v_1^2 - v_2^2)}{4c_W^2} + \frac{v_1^2 Y_l^2}{2} + m_E^2 \end{pmatrix} \quad (18)$$

is diagonalized by the unitary matrix Z_L ,

$$Z_L^\dagger \mathcal{M}_L^2 Z_L = \begin{pmatrix} M_{L_1}^2 & & 0 \\ & \ddots & \\ 0 & & M_{L_6}^2 \end{pmatrix}. \quad (19)$$

4. Squark sector. Analogously, for the up and down squarks one has:

$$\mathcal{M}_U^2 = \begin{pmatrix} \frac{e^2(v_1^2-v_2^2)(4c_W^2-1)}{24s_W^2c_W^2} + \frac{v_2^2Y_u^2}{2} + (Km_Q^2K^\dagger)^T & -\frac{v_1}{\sqrt{2}}(Y_u\mu^* + A'_u) - \frac{v_2}{\sqrt{2}}A_u \\ -\frac{v_1}{\sqrt{2}}(Y_u\mu + A_u'^\dagger) - \frac{v_2}{\sqrt{2}}A_u^\dagger & \frac{e^2(v_1^2-v_2^2)}{6c_W^2} + \frac{v_2^2Y_u^2}{2} + m_U^2 \end{pmatrix}, \quad (20)$$

$$Z_U^T \mathcal{M}_U^2 Z_U^* = \begin{pmatrix} M_{U_1}^2 & & 0 \\ & \ddots & \\ 0 & & M_{U_6}^2 \end{pmatrix}. \quad (21)$$

$$\mathcal{M}_D^2 = \begin{pmatrix} -\frac{e^2(v_1^2-v_2^2)(1+2c_W^2)}{24s_W^2c_W^2} + \frac{v_2^2Y_d^2}{2} + (m_Q^2)^T & \frac{v_2}{\sqrt{2}}(Y_d\mu^* - A'_d) + \frac{v_1}{\sqrt{2}}A_d \\ \frac{v_2}{\sqrt{2}}(Y_d\mu - A_d'^\dagger) + \frac{v_1}{\sqrt{2}}A_d^\dagger & -\frac{e^2(v_1^2-v_2^2)}{12c_W^2} + \frac{v_1^2Y_d^2}{2} + m_D^2 \end{pmatrix}, \quad (22)$$

$$Z_D^\dagger \mathcal{M}_D^2 Z_D = \begin{pmatrix} M_{D_1}^2 & & 0 \\ & \ddots & \\ 0 & & M_{D_6}^2 \end{pmatrix}. \quad (23)$$

Note that Z_U is defined with a complex conjugate compared to the definitions of Z_L and Z_D . Thus all positively charged sfermion mass eigenstates are multiplied by Z_X^{ij} , while negatively charged eigenstates are multiplied by Z_X^{ij*} .

2.3 Interfacing with the Les Houches Accord

SUSY_FLAVOR has been in development since 1996, long before the Les Houches Accord [44] (SLHA) for common MSSM Lagrangian conventions was agreed. Because of that, it was not feasible to change the internal **SUSY_FLAVOR** structure as it would require careful checking and rewriting of thousands of lines of a complicated code. Therefore we have decided to keep the conventions of [14] for the internal calculations in **SUSY_FLAVOR**. In Table 2 we summarize the differences of our conventions and those of the latest extended SLHA 2 [42]. These differences are quite minor and translation can be done by changing few signs and/or transposing matrices in the soft SUSY breaking sector. Thus, for the input parameters of **SUSY_FLAVOR** we leave the choice of convention as a user-defined option.

SLHA 2 [42]	Ref. [14]
$\hat{T}_U, \hat{T}_D, \hat{T}_E$	$-A_u^T, +A_d^T, +A_l^T$
\hat{m}_Q^2, \hat{m}_L^2	m_Q^2, m_L^2
$\hat{m}_{\tilde{u}}^2, \hat{m}_{\tilde{d}}^2, \hat{m}_{\tilde{l}}^2$	$(m_U^2)^T, (m_D^2)^T, (m_E^2)^T$
$\mathcal{M}_{\tilde{u}}^2, \mathcal{M}_{\tilde{d}}^2$	$(\mathcal{M}_U^2)^T, (\mathcal{M}_D^2)^T$

Table 2: Comparison of SLHA [42] and Ref. [14] conventions.

Currently `SUSY_FLAVOR` does not use the super-PMNS basis for the lepton and slepton sector; only the charged lepton Yukawa matrix (and not the neutrino mass matrix) is diagonalized. The super-PMNS basis can become helpful once new experiments are able to identify the flavor of the neutrinos produced in rare decays, but at present this is not experimentally feasible.

3 Structure of the code

Calculations in `SUSY_FLAVOR` take the following steps:

- 1. Parameter initialization.** This is the most important step for `SUSY_FLAVOR` users and is described in detail Section 4. Users can adjust the basic Standard Model parameters according to latest experimental data and initialize all (or the chosen subset of) supersymmetric soft masses and couplings and Higgs sector parameters listed in Section 2.1.
- 2. Calculation of the physical masses and the mixing angles.** After setting the input parameters, `SUSY_FLAVOR` calculates the eigenvalues of the mass matrices of all MSSM particles and their mixing matrices at the tree level. Diagonalization is done numerically without any approximations.
- 3. Calculation of Wilson coefficients at the SUSY scale.** Physical tree-level masses and mixing matrices are used to evaluate exact one-loop Wilson coefficients of the effective operators required for a given process. Again, the formulae used in the code are exact, i.e. do not rely on any approximations, such as the MIA expansion. In the current version, `SUSY_FLAVOR` calculates Wilson coefficients generated by the diagrams listed in Table 3. All Wilson coefficients are calculated at the high energy scale, assumed to be the average mass of SUSY particles contributing to a given process or the top quark scale.

It is important to stress that `SUSY_FLAVOR` accepts fermion generation indices and Higgs boson indices as input parameters. Thus in Table 3 d and u, l and ν denote quarks or leptons of *any* generation and, similarly, H_i^0 and A_i^0 denote *any* type of the neutral Higgs bosons. Hence, the actual number of amplitudes which can be calculated using combinations of these form factors is much larger than needed for the rare decay rates currently implemented fully in `SUSY_FLAVOR`. We plan to add new processes in future releases of our library.

Box	Penguin	Self energy
$dddd$	$Z\bar{d}d, \gamma\bar{d}d, g\bar{d}d$	d -quark
$uuuu$	$H_i^0\bar{d}d, A_i^0\bar{d}d$	u -quark
$dlll$	$H_i^0\bar{u}u, A_i^0\bar{u}u$	
$dd\nu\nu$		

Table 3: One loop parton level diagrams implemented in **SUSY_FLAVOR**.

4. Strong corrections. In its final step **SUSY_FLAVOR** performs (when necessary) the QCD evolution of Wilson coefficients from the high energy (SUSY or top quark mass) scale to the low energy scale appropriate for a given rare decay, calculates the relevant hadronic matrix elements, and outputs predictions for physical quantities. The formulae for QCD and hadronic corrections are primarily based on calculations performed in the SM and supplemented, when necessary, with contributions from non-standard operators which usually are neglected in the SM, because they are suppressed by powers of the light quark Yukawa couplings. This part of **SUSY_FLAVOR** is based on analyses published by other authors, whereas points 1-3 are implemented using our own calculations. The accuracy of strong corrections differ from process to process, from negligible or small (leptonic EDM, “gold-plated” decay modes $K \rightarrow \pi\bar{\nu}\nu$ [45]) to order of magnitude uncertainties (unknown long distance contributions to Δm_K or Δm_D). Even in the case of large QCD uncertainties, the result of the calculation performed by **SUSY_FLAVOR** can be of some use. Flavor violation in the sfermion sector can lead to huge modifications of many observables, sometimes by several orders of magnitude, so that comparison with experimental data can help to constrain the soft flavor-violating terms even if strong corrections are not very well known.

Below we list the files included in the **SUSY_FLAVOR** library with a brief description of their content and purpose.

eisch1.f: auxiliary numerical routine - hermitian matrix diagonalization

vegas.f: auxiliary numerical routine - Vegas Monte Carlo integration

rombint.f: auxiliary numerical routine - Romberg numerical integration

sflav_io.f: input routine for reading of the SLHA2 format; test output routines

b_fun.f: general 2-point loop functions

db_fun.f: derivatives of general 2-point loop functions

c_fun.f: general 3-point loop functions

cd_fun.f: 3-, 4- and some 5-point loop functions at vanishing external momenta

vh_def.f: definitions of Higgs boson tree-level vertices

vg_def.f: definitions of gauge boson tree-level vertices

vf_def.f: definitions of fermion tree-level vertices
mh_init.f: initialization of MSSM parameters
mh_diag.f: diagonalization of tree level mass matrices; outputs physical masses and mixing angles
qcd_fun.f: auxiliary QCD calculations - running α_s , running quark masses etc.
d_self0.f: d -quark self-energy
u_self0.f: u -quark self-energy
sff_fun0.f: form factors of the general scalar-fermion-fermion 1-loop triangle diagram
sdd_vert0.f: CP-even Higgs- d quark- d quark 1-loop triangle diagram
pdd_vert0.f: CP-odd Higgs- d quark- d quark 1-loop triangle diagram
suu_vert0.f: CP-even Higgs- u quark- u quark 1-loop triangle diagram
puu_vert0.f: CP-odd Higgs- u quark- u quark 1-loop triangle diagram
zdd_vert0.f: Z boson- d quark- d quark 1-loop triangle diagram
ddg_fun.f: form factors for the general gauge boson-fermion-fermion 1-loop triangle diagram
dd_gluon.f: d quark- d quark-gluon 1-loop triangle diagram
dd_gamma.f: d quark- d quark-photon 1-loop triangle diagram
bsg_nl.f: formulae for $\text{Br}(B \rightarrow X_s \gamma)$, including QCD corrections
dd_ll.f: d quark- d quark-lepton-lepton 1-loop box diagram
dd_vv.f: d quark- d quark-neutrino-neutrino 1-loop box diagram
phen_2q.f: formulae for $\text{Br}(K_L^0 \rightarrow \pi^0 \bar{\nu} \nu)$, $\text{Br}(K^+ \rightarrow \pi^+ \bar{\nu} \nu)$ and $\text{Br}(B_{s(d)} \rightarrow l^+ l^-)$ including QCD corrections and hadronic matrix elements
dd_mix.f: 4- d quark 1-loop box diagram
uu_mix.f: 4- u quark 1-loop box diagram
phen_4q.f: formulae for the meson mixing observables: Δm_K , ϵ_K , Δm_D , $\Delta m_{B_{d(s)}}$ including QCD corrections and hadronic matrix elements
edm_l.f: lepton electric dipole moment
cdm_d.f: d -quark chromoelectric dipole moment
cdm_u.f: u -quark chromoelectric dipole moment
cdm_g.f: gluon chromoelectric dipole moment
edm_d.f: d -quark electric dipole moment

`edm_u.f`: u -quark electric dipole moment

`edm_n.f`: u -quark electric dipole moment

All the 2-, 3- and 4-point Green functions are calculated for vanishing external momenta. As mentioned before, by “ u quark” and “ d quark” we mean all generations of quarks.

In addition to the files listed above, the library contains the master driver file `susy_flavor.f` which illustrates the proper initialization sequence for `SUSY_FLAVOR` parameters and produces a set of test results for the implemented observables.

4 Parameter initialization in `SUSY_FLAVOR`

We now list the input parameters used by `SUSY_FLAVOR`. These are not always directly the MSSM Lagrangian parameters given in Section 2.1 – for example, instead of using the μ parameter and the soft Higgs masses $m_{H_i}^2, m_{12}^2$, it is customary to use $\tan\beta$ and the CP-odd Higgs mass M_A to parametrize MSSM Higgs sector. In its first step, `SUSY_FLAVOR` restores the Lagrangian parameters of Section 2.1 for the given set of more human-friendly input parameters. Then, the remaining routines use the “raw” Lagrangian parameters—if necessary they can also be directly modified by (experienced!) users.

In the rest of this section we describe step-by-step the basic initialization routines used by `SUSY_FLAVOR`, their arguments and, when necessary, the FORTRAN common blocks storing the most important data (other common blocks serve for the internal purposes and usually do not need to be accessed by users).

By default, `SUSY_FLAVOR` uses the following implicit type declaration in all routines:

```
implicit double precision (a-h,o-z)
```

so that all variables in `SUSY_FLAVOR` with the names starting from `a` to `h` and from `o` to `z` are automatically defined as `double precision` and those with names starting from `i` to `n` are of `integer` type. In what follows we explicitly indicate variables that do not obey this rule. Such variables are always listed in explicit type statements inside the procedures. Complex parameters mentioned in this article are declared in `SUSY_FLAVOR` as `double complex` type. Mass parameters are always given in GeV.

`SUSY_FLAVOR` provides two ways of initializing input parameters. As the first option, they can be read from the file `susy_flavor.in`. The structure of this file follows the SLHA2 convention [42], with some extensions which we describe in Section 4.1. Initializing parameters in the input file is simple, it is done by a call to single subroutine `sflav_input` and does not require detailed knowledge of the program internal structure. This option is particularly convenient for testing a single parameter set but can be cumbersome for scans over the MSSM parameter space. Therefore, as a second option, `SUSY_FLAVOR` also provides a set of routines designed to initialize parameters defined in the program, which can easily be used

to prepare programs that scan over large parameter sets. As described in Section 4.2, these routines require more care in use, as they should be initialized in the proper order, i.e. the gauge sector first, then the fermion sector, Higgs sector, and SUSY sectors at the end (the initialization sequences for the gaugino, slepton and squark sectors are independent).

An example of a full initialization sequence for `SUSY_FLAVOR`, illustrating both options mentioned above, is presented Appendix B. The sample input file `susy_flavor.in` is given in Appendix C. Test output generated for parameters used in Appendices B and C is enclosed in Appendix D.

4.1 Parameter initialization from the input file

Input parameters for `SUSY_FLAVOR` can be set by editing appropriate entries of the file `susy_flavor.in` and subsequently calling the subroutine `sflav_input`, which reads the input file, stores the the MSSM Lagrangian parameters in FORTRAN common blocks and calculates tree-level physical masses and mixing matrices. After calling `sflav_input`, all physical observable described in Section 5 can be calculated.

The input file `susy_flavor.in` is written in the SLHA2 format, with some extensions which we list below (for an example of a complete input file see Appendix C).

1. We define a non-standard **Block SOFTIMP**. Currently it contains two control variables, `iconv` and `input_type`. These serve to choose input conventions in the sfermion sector (in other sectors SLHA2 and Ref. [14] agree).

Variable value	Sfermion sector parametrization
<code>iconv = 1</code>	MSSM parameters defined in SLHA 2 conventions.
<code>iconv = 2</code>	MSSM parameters defined in conventions of Ref. [14].
<code>input_type = 1</code>	sfermion diagonal trilinear mixing terms given as dimensionless parameters; all off-diagonal soft terms are given as dimensionless mass insertions—see comments below on the data blocks defining the sfermion soft terms.
<code>input_type = 2</code>	sfermion soft terms given as absolute values of dimension mass ² .

2. `SUSY_FLAVOR` uses the W boson mass as a basic parameter rather than Fermi constant G_F . Therefore, in `susy_flavor.in` we use entry 30 of **Block SMINPUTS** (not used in the standard SLHA2) to define M_W .
3. We allow complex values for μ and two of the gaugino masses—chosen to be the $U(1)$ and $SU(2)$ mass terms M_1 and M_2 . Their real and imaginary parts are defined in blocks **EXTPAR** and **IMEXTPAR**. We use $\tan\beta$ and the CP-odd Higgs mass M_A as the input parameters for the Higgs sector.
4. Following the SLHA2 convention, we only define the upper triangle of each of the hermitian sfermion soft mass matrices in the `MSL2IN`, `MSE2IN`, `MSQ2IN`, `MSD2IN`, `MSU2IN`

and `IMMSL2IN`, `IMMSE2IN`, `IMMSQ2IN`, `IMMSD2IN`, `IMMSU2IN` blocks. It is obligatory to define all entries, both diagonal and upper off-diagonal, since `SUSY_FLAVOR` does not read diagonal sfermion masses from the `EXTPAR` block. The `iconv` parameter defined in the `SOFTINP` block determines if sfermion parameters are given in SLHA2 or Ref. [14] conventions (see Table 2). Finally, the `input_type` parameter in the `SOFTINP` block defines the format of the off-diagonal mass terms. If `input_type` = 1, the off-diagonal entries given in `susy_flavor.in` are assumed to be dimensionless mass insertions and the flavor violating sfermion mass terms are calculated as

$$(m_X^2)_{IJ} = (m_X^2)_{JI}^* = \delta_X^{IJ} \sqrt{(m_X^2)_{II}(m_X^2)_{JJ}}, \quad (24)$$

where $X = L, E, Q, U, D$ and I, J enumerate superpartners of the mass-eigenstate quarks.

5. The blocks `TEIN`, `TDIN`, `TUIN` and `IMTEIN`, `IMTDIN`, `IMTUIN` define the trilinear sfermion mixing matrices which are generally non-hermitian. One is required to define all entries. As for the soft mass terms, the `iconv` parameter chooses the input convention, SLHA2 or Ref. [14]. For the trilinear mixing, the parameter `input_type` defines the format and dimension of both the diagonal and off-diagonal terms. If `input_type` = 1, then all relevant `susy_flavor.in` entries are treated as dimensionless numbers and expanded to full trilinear mixing matrices using eqs. (25,26). For the diagonal LR terms, `SUSY_FLAVOR` uses the formulae

$$\begin{aligned} A_l^{II} &= Y_l^I \left((m_L^2)_{II}(m_E^2)_{II} \right)^{1/4} a_l^I, \\ A_d^{II} &= Y_d^I \left((m_Q^2)_{II}(m_D^2)_{II} \right)^{1/4} a_d^I, \\ A_u^{II} &= Y_u^I \left((m_Q^2)_{II}(m_U^2)_{II} \right)^{1/4} a_u^I, \end{aligned} \quad (25)$$

where a_l^I, a_d^I, a_u^I are the diagonal trilinear mixing terms read from the input file.

For the off-diagonal LR terms, `SUSY_FLAVOR` uses

$$\begin{aligned} A_l^{IJ} &= \delta_{LLR}^{IJ} \sqrt{2}/v_1 \sqrt{(m_L^2)_{II}(m_E^2)_{JJ}}, \\ A_d^{IJ} &= \delta_{DLR}^{IJ} \sqrt{2}/v_1 \sqrt{(m_Q^2)_{II}(m_D^2)_{JJ}}, \\ A_u^{IJ} &= \delta_{ULR}^{IJ} \sqrt{2}/v_2 \sqrt{(m_Q^2)_{II}(m_U^2)_{JJ}}. \end{aligned} \quad (26)$$

Note that in eqs. (25,26) for simplicity we use $(m_Q^2)_{II}$ as the diagonal mass scale for both up and down left squark fields (in general related by the CKM rotation, see eqs. (20,22)).

4.2 Parameter initialization inside the program

`SUSY_FLAVOR` input parameters can also be initialized directly inside the driver program using the set of routines described below. Before the proper initialization sequence, the user can set the `iconv` variable value to choose the input convention:

<code>common/sf_cont/eps, indx(3,3), iconv</code>	
<code>iconv=1</code>	SLHA2 [42] input conventions
<code>iconv=2</code>	[14] input conventions

After choosing the input conventions, one should subsequently initialize the gauge, matter fermion, Higgs, SUSY fermion and sfermion sectors, using the procedures described in detail in the following sections.

4.2.1 Gauge sector

As input, `SUSY_FLAVOR` takes the gauge boson masses (M_W, M_Z) and the gauge coupling constants (electromagnetic and strong) at the M_Z scale. They are initialized by:

Routine and arguments	Purpose and MSSM parameters
<code>vpar_update(zm,wm,alpha_em)</code>	Sets electromagnetic sector parameters
<code>zm</code>	M_Z , Z boson mass
<code>wm</code>	M_W , W boson mass
<code>alpha_em</code>	$\alpha_{em}(M_Z)$, QED coupling at M_Z scale
<code>lam_fit(alpha_s)</code>	Sets $\alpha_s(M_Z)$ and Λ_{QCD} for 4-6 flavors at the NNLO level
<code>lam_fit_nlo(alpha_s)</code>	Sets $\alpha_s(M_Z)$ and Λ_{QCD} for 4-6 flavors at the NLO level
<code>alpha_s</code>	$\alpha_s(M_Z)$, strong coupling at M_Z scale

4.2.2 Matter fermion sector

`SUSY_FLAVOR` assumes that neutrinos are massless. Pole masses of the charged leptons are initialized in the file `mh_init.f` in block data `init_phys`. They are stored in the `em` array in `common/fmass/em(3), um(3), dm(3)` and can be directly modified there. Their default values are:

Lepton mass	Value
m_e	<code>em(1) = 0.000511</code>
m_μ	<code>em(2) = 0.105659</code>
m_τ	<code>em(3) = 1.777</code>

In the quark sector the most important input parameters are the running top and bottom masses at a given renormalization scale and the CKM matrix angles and phase. They can be set by:

Routine and arguments	Purpose and MSSM parameters
<code>init_fermion_sector(tm,tscale,bm,bscale)</code>	Sets running top and bottom quark mass $m_t(\mu_t)$, running $\overline{\text{MS}}$ top quark mass $m_b(\mu_b)$, running $\overline{\text{MS}}$ bottom quark mass
<code>tm,tscale</code>	
<code>bm,bscale</code>	
<code>ckm_init(s12,s23,s13,delta)</code>	Initialization of the CKM matrix $\sin \theta_{12}, \sin \theta_{23}, \sin \theta_{13}$, sines of the CKM angles
<code>s12,s23,s13</code>	
<code>delta</code>	δ , the CKM phase in radians

The light quark masses are also initialized in the `block data init_phys` of the file `mh_init.f` and stored in `common/fmass_high/umu(3),uml(3),amu(3),dmu(3),dml(3),amud(3)`. The arrays `uml(dml)` contain up(down) quark masses at the scale `amu(amu)`, respectively. Their default values are:

Running quark mass	Mass value	Mass scale
$m_d(\mu_d)$	<code>dml(1) = 0.007</code>	<code>amud(1) = 2</code>
$m_s(\mu_s)$	<code>dml(2) = 0.11</code>	<code>amud(2) = 2</code>
$m_b(\mu_b)$	<code>dml(3) = 4.17</code>	<code>amud(3) = 4.17</code>
$m_u(\mu_u)$	<code>uml(1) = 0.004</code>	<code>amu(1) = 2</code>
$m_c(\mu_c)$	<code>uml(2) = 1.279</code>	<code>amu(2) = 1.279</code>
$m_t(\mu_t)$	<code>uml(3) = 163.5</code>	<code>amu(3) = 163.5</code>

The variables of the arrays `uml`, `amu`, `dml`, `amud` can be directly accessed and modified if necessary. However, for consistency, after such modifications the user should call the routine `init_run_qmass` which calculates running quark masses at the high m_t scale (stored in `common/fmass_high/` in the arrays `umu,dmu` and in `common/fmass/` in the arrays `um, dm`) for later use in the running Yukawa couplings and in SUSY loop calculations.

4.2.3 Higgs sector

Following the common convention, we take the Higgs mixing parameter μ , the CP-odd Higgs boson mass M_A , and the ratio of vacuum expectation values $\tan \beta = v_2/v_1$ as the input parameters. Other Higgs sector parameters listed in Section 2.1 can be expressed as:

$$\begin{aligned} m_{H_1}^2 &= \frac{1}{2}(M_A^2 - 2|\mu|^2 - (M_A^2 + M_Z^2) \cos 2\beta) , \\ m_{H_2}^2 &= \frac{1}{2}(M_A^2 - 2|\mu|^2 + (M_A^2 + M_Z^2) \cos 2\beta) , \\ m_{12}^2 &= -\frac{M_A^2}{2 \sin 2\beta} . \end{aligned} \quad (27)$$

The MSSM Higgs sector at the tree level can be effectively parametrized in terms of just M_A and $\tan \beta$, but the μ parameter is necessary for the chargino and neutralino sectors. Here it

is used to calculate the original Higgs soft mass parameters $m_{H_1}^2$ and $m_{H_2}^2$ for completeness and future applications; they currently have no further use.

Routine and arguments	Purpose and MSSM parameters
<code>init_higgs_sector(pm,tb,amu,ierr)</code>	Higgs sector initialization
<code>pm</code>	CP-odd Higgs mass M_A
<code>tb</code>	Ratio of Higgs VEVs, $\tan \beta = \frac{v_2}{v_1}$
<code>amu</code>	Higgs mixing parameter μ (complex)
<code>ierr</code>	output error code: $ierr \neq 0$ if Higgs sector initialization failed
<code>init_yukawa</code>	Initialization of the running Yukawa couplings Y_l, Y_u, Y_d for all generations (at the same scale as the running quark masses)

4.2.4 Supersymmetric fermion sector

Initialization is done by the routine:

Routine and arguments	Purpose and MSSM parameters
<code>init_ino_sector(gm1, gm2, gm3, amu, tb, ierr)</code>	gaugino sector initialization
<code>gm1, gm2</code>	$U(1), SU(2)$ gaugino masses (complex)
<code>gm3</code>	$SU(3)$ gaugino mass
<code>tb</code>	$\tan \beta = \frac{v_2}{v_1}$, the ratio of Higgs VEVs
<code>amu</code>	the Higgs mixing parameter μ (complex)
<code>ierr</code>	output warning code: $ierr \neq 0$ if a chargino or a neutralino is lighter than $M_Z/2$

If one sets $M_1 = 0$ in the call to `init_ino_sector` then the GUT-derived relation $M_1 = \frac{5}{3} \tan^2 \theta_W M_2$ is used in the gaugino mass calculations.

4.2.5 Sfermion sector

This is the most complicated MSSM sector; it contains a large number of free parameters. `SUSY_FLAVOR` supplies two subroutines for the sfermion parameters initialization, `init_slepton_sector` and `init_squark_sector`. They accept as input only dimensionless mass insertions and dimensionless diagonal trilinear soft mixing terms, expanded in `SUSY_FLAVOR` to entries of the soft mass matrices as defined by eqs. (24,25,26) (this is only a particular choice of parametrization and does not lead to any loss of generality). The sfermion initialization routines have the following arguments:

```

subroutine init_slepton_sector(sll,slr,asl,ierr,slmi_l,slmi_r)

Argument      MSSM parameters

sll           Array of the diagonal left slepton masses  $(m_L^2)_{II} = \text{sll}(I)^2$ ,  $I = 1 \dots 3$ 
slr           Array of the diagonal right slepton masses  $(m_E^2)_{II} = \text{slr}(I)^2$ ,  $I = 1 \dots 3$ 
asl           Array of the dimensionless diagonal slepton trilinear mixing terms  $a_l^I = \text{asl}(I)$ ,  $I = 1 \dots 3$  (complex parameters).
ierr          output error code:  $ierr \neq 0$  if slepton sector initialization failed
slmi_l        Array of the off-diagonal left slepton mass insertions  $\delta_L^{12} = \text{slmi\_l}(1)$ ,  $\delta_L^{23} = \text{slmi\_l}(2)$ ,  $\delta_L^{13} = \text{slmi\_l}(3)$  (complex parameters); remaining LL mass insertions are initialized via hermitian conjugation
slmi_r        Array of the off-diagonal right slepton mass insertions  $\delta_E^{12} = \text{slmi\_r}(1)$ ,  $\delta_E^{23} = \text{slmi\_r}(2)$ ,  $\delta_E^{13} = \text{slmi\_r}(3)$  (complex parameters); remaining RR mass insertions are initialized via hermitian conjugation
slmi_lr       Matrix with off-diagonal slepton trilinear LR mass insertions  $\delta_{LLR}^{IJ} = \text{slmi\_lr}(I, J)$ ,  $I, J = 1 \dots 3$  (complex parameters)

subroutine init_squark_sector(sql,squ,sqd,asu,asd,ierr,
                             sqmi_l,sumi_r,sdmi_r,sumi_lr, sdmi_lr)

Argument      MSSM parameters

sql            Array of the diagonal left squark masses  $(m_Q^2)_{II} = \text{sql}(I)^2$ ,  $I = 1 \dots 3$ 
squ            Array of the diagonal right up-squark masses  $(m_U^2)_{II} = \text{squ}(I)^2$ ,  $I = 1 \dots 3$ 
sqd            Array of the diagonal right down-squark masses  $(m_D^2)_{II} = \text{sqd}(I)^2$ ,  $I = 1 \dots 3$ 
asu            Array of the dimensionless diagonal soft LR up-squark mixing terms  $a_u^I = \text{asu}(I)$ ,  $I = 1 \dots 3$  (complex parameters)
asd            Array of the dimensionless diagonal soft LR down-squark mixing terms  $a_d^I = \text{asd}(I)$ ,  $I = 1 \dots 3$  (complex parameters)
ierr          output error code:  $ierr \neq 0$  if squark sector initialization failed
sqmi_l        Array of the off-diagonal left squark mass insertions  $\delta_Q^{12} = \text{sqmi\_l}(1)$ ,  $\delta_Q^{23} = \text{sqmi\_l}(2)$ ,  $\delta_Q^{13} = \text{sqmi\_l}(3)$  (complex parameters); remaining QLL mass insertions are initialized via hermitian conjugation
sumi_r        Array of the off-diagonal right up-squark mass insertions  $\delta_U^{12} = \text{sumi\_r}(1)$ ,  $\delta_U^{23} = \text{sumi\_r}(2)$ ,  $\delta_U^{13} = \text{sumi\_r}(3)$  (complex parameters); remaining URR mass insertions are initialized via hermitian conjugation
sdmi_r        Array of the off-diagonal right down-squark mass insertions  $\delta_D^{12} = \text{sdmi\_r}(1)$ ,  $\delta_D^{23} = \text{sdmi\_r}(2)$ ,  $\delta_D^{13} = \text{sdmi\_r}(3)$  (complex parameters); remaining DRR mass insertions are initialized via hermitian conjugation
sumi_lr       Matrix with off-diagonal up-squark trilinear LR mass insertions  $\delta_{ULR}^{IJ} = \text{sumi\_lr}(I, J)$ ,  $I, J = 1 \dots 3$  (complex parameters)
sdmi_lr       Matrix with off-diagonal down-squark trilinear LR mass insertions  $\delta_{DLR}^{IJ} = \text{sdmi\_lr}(I, J)$ ,  $I, J = 1 \dots 3$  (complex parameters)

```

If necessary, experienced **SUSY_FLAVOR** users can directly modify the soft breaking sfermion parameters stored in common blocks `/msoft/` and `/soft/` (see Table 4 in Section 4.3). One must subsequently call the routines `sldiag`, `sqdiag` (see file `mh_diag.f`) to recalculate the tree-level sfermion masses and mixing matrices. This may, however, require a deeper understanding of the **SUSY_FLAVOR** initialization sequence and its data structure.

4.3 Tree-level physical masses and mixing angles

After performing the full initialization sequence in **SUSY_FLAVOR**, all the MSSM Lagrangian parameters listed in Section 2.1, physical tree-level particle masses (with the exception of the running quark masses), and mixing matrices are calculated and stored in common blocks. If necessary, they can be directly accessed and modified. Note, however, that after any modifications of the Lagrangian parameters, relevant procedures calculating physical masses and mixing angles have to be called again. In Table 4 we list the important blocks storing MSSM parameters. Common blocks containing masses and mixing angles are listed in Table 5.

All parameters, tree-level masses, and mixing angles can be printed for test purposes, e.g. by calling the subroutines `print_MSSM_par` and `print_MSSM_masses`.

5 List of processes

In this section we list the set observables whose computation is fully implemented in **SUSY_FLAVOR** v1.0. For all of them, **SUSY_FLAVOR** takes into account one-loop supersymmetric contributions. QCD corrections and hadronic matrix elements are extracted from the papers of various authors, mostly from analyses done in the Standard Model. They are assumed to work reasonably well also in the MSSM since supersymmetric strong corrections from gluino and squarks are suppressed by large masses of these particles.

In most cases, QCD and hadronic corrections are known at the level of few to tens %, while variations of supersymmetric flavor and CP violating parameters can change observables by orders-of-magnitude. Thus, as long as the MSSM parameters are not measured very precisely, the current implementation of strong corrections is sufficient for analyses performed in the framework of the general MSSM.

Calculations of the hadronic matrix elements are particularly difficult as they have to be performed, at least partially, in the regime of strongly coupled QCD. Results of such calculations can differ significantly depending on the methods used and thus carry significant theoretical uncertainties. Therefore, in **SUSY_FLAVOR**, quantities which require hadronic

Common block and variables	Lagrangian parameters
common/vpar/st,ct,st2,ct2,sct,sct2,e,e2,alpha,wm,wm2,zm,zm2,pi,sq2 st,ct,st2,ct2,sct,sct2 e,e2,alpha wm,wm2,zm,zm2 pi,sq2	Weinberg angle functions, respectively $s_W, c_W, s_W^2, c_W^2, s_W c_W, s_W^2 c_W^2$ electric charge powers at M_Z scale: e, e^2, α_{em} gauge boson masses: M_W, M_W^2, M_Z, M_Z^2 numerical constants, π and $\sqrt{2}$
common/hpar/hm1,hm2,hm12,hmu hm1,hm2 hm12 hmu	soft Higgs masses $m_{H_1}^2, m_{H_2}^2$ soft Higgs mixing parameter m_{12}^2 Higgs mixing parameter μ (complex)
common/vev/v1,v2 v1,v2	Higgs vacuum expectation values v_1, v_2
common/yukawa/y1(3),yu(3),yd(3) y1(3) yu(3) yd(3)	charged lepton Yukawa couplings Y_e, Y_μ, Y_τ Running $\overline{\text{MS}}$ up-quark Yukawa couplings at m_t scale: Y_u, Y_c, Y_t Running $\overline{\text{MS}}$ down-quark Yukawa couplings at m_t scale: Y_u, Y_c, Y_t
common/gmass/gm3,gm2,gm1 gm1,gm2 gm3	$U(1), SU(2)$ gaugino masses M_1, M_2 (complex) $SU(3)$ gaugino mass M_3
common/msoft/lms(3,3),rms(3,3),ums(3,3),dms(3,3),qms(3,3) lms(3,3),rms(3,3) ums(3,3),dms(3,3),qms(3,3)	hermitian slepton soft mass matrices m_L^2, m_E^2 (complex) hermitian squark soft mass matrices m_U^2, m_D^2, m_Q^2 (complex)
common/soft/ls(3,3),ks(3,3),ds(3,3),es(3,3),us(3,3),ws(3,3) ls(3,3),ds(3,3),us(3,3) ks(3,3),es(3,3),ws(3,3)	trilinear soft LR mixing matrices A_l, A_d, A_u (complex) trilinear “non-holomorphic” soft mixing matrices A'_l, A'_d, A'_u (complex)

Table 4: Common blocks storing the MSSM Lagrangian parameters. We omit flavor indices in the fermion and sfermion sectors.

Common block and variables	Masses and mixing matrices
<code>common/fmass/</code> <code>em(3)</code> , <code>um(3)</code> , <code>dm(3)</code>	
<code>em(3)</code>	Charged lepton pole masses m_e, m_μ, m_τ
<code>um(3)</code>	Running $\overline{\text{MS}}$ up-quark masses at the m_t scale: m_u, m_c, m_t
<code>dm(3)</code>	Running $\overline{\text{MS}}$ down-quark masses at the m_t scale: m_u, m_c, m_t
<code>common/hmass/cm(2)</code> , <code>rm(2)</code> , <code>pm(2)</code> , <code>zr(2,2)</code> , <code>zh(2,2)</code>	
<code>rm(2)</code>	neutral CP-even Higgs masses $\text{rm}(1) = M_H,$ $\text{rm}(2) = M_h$
<code>pm(2)</code>	neutral CP-odd Higgs mass <code>pm(1)</code> and Goldstone mass <code>pm(2)</code>
<code>cm(2)</code>	charged Higgs mass <code>cm(1)</code> and charged Goldstone mass <code>cm(2)</code>
<code>zr(2,2)</code>	CP-even Higgs mixing matrix Z_R
<code>zh(2,2)</code>	CP-odd and charged Higgs mixing matrix Z_H
<code>common/charg/fcm(2)</code> , <code>zpos(2,2)</code> , <code>zneg(2,2)</code>	
<code>fcm(2)</code>	chargino masses $M_{\chi_i^+}, i = 1, 2$
<code>zpos(2,2)</code> , <code>zneg(2,2)</code>	chargino mixing matrices Z_+, Z_- (complex)
<code>common/neut/fnm(4)</code> , <code>zn(4,4)</code>	
<code>fnm(4)</code>	neutralino masses $M_{\chi_i^0}, i = 1 \dots 4$
<code>zn(4,4)</code>	neutralino mixing matrix Z_N (complex)
<code>common/slmass/vm(3)</code> , <code>slm(6)</code> , <code>zv(3,3)</code> , <code>zl(6,6)</code>	
<code>vm(3)</code>	sneutrino masses $M_{\tilde{\nu}_I}, I = 1 \dots 3$
<code>slm(6)</code>	charged slepton masses $M_{L_i}, i = 1 \dots 6$
<code>zv(3,3)</code>	sneutrino mixing matrix $Z_{\tilde{\nu}}$ (complex)
<code>zl(6,6)</code>	charged slepton mixing matrix Z_L (complex)
<code>common/sqmass/sum(6)</code> , <code>sdm(6)</code> , <code>zu(6,6)</code> , <code>zd(6,6)</code>	
<code>sum(6)</code>	up-squark masses $M_{U_i}, i = 1 \dots 6$
<code>sdm(6)</code>	down-squark masses $M_{D_i}, i = 1 \dots 6$
<code>zu(6,6)</code>	up-squark mixing matrix Z_U (complex)
<code>zd(6,6)</code>	down-squark mixing matrix Z_D (complex)

Table 5: Common blocks storing physical particle masses and mixing matrices.

matrix element estimates and other QCD related quantities are treated as external parameters. They are initialized to the default values listed below for each observable and can be directly modified by users by changing the relevant variables in the common blocks where they are stored. Currently most of the hadronic (and related) input parameters used in **SUSY_FLAVOR** are taken from the Table 3 of Ref. [46].

5.1 Electric Dipole Moments of charged leptons

Lepton EDMs are defined as the coefficient d_{l^I} in the effective Hamiltonian for the flavor-diagonal lepton-lepton-photon interaction:

$$\mathcal{H}_e = \frac{id_{l^I}}{2} \bar{l}^I \sigma_{\mu\nu} \gamma_5 l^I F^{\mu\nu}, \quad (28)$$

where $I = 1, 2, 3$ is the generation index of the lepton as usual. In **SUSY_FLAVOR** lepton EDM is calculated by:

Routine:	double precision function <code>edm_1(I)</code>
Input:	$I = 1, 2, 3$ for e, μ, τ respectively
Output:	EDM for the charged lepton specified by I
QCD related factors:	none, QCD corrections are small and not included
Details of calculations:	Ref. [4]

5.2 Neutron Electric Dipole Moment

The neutron EDM can be approximated by the sum of the electric dipole moments of the constituent d and u quarks plus contributions of the chromoelectric dipole moments (CDM) of quarks and gluons. The EDMs of the individual quarks are defined analogously to eq. (28). The CDM c_q of quark q is defined as:

$$\mathcal{H}_c = -\frac{ic_q}{2} \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{\mu\nu a}. \quad (29)$$

The gluonic dipole moment c_g is defined as:

$$\mathcal{H}_g = -\frac{c_g}{6} f_{abc} G_{\mu\rho}^a G_{\nu}^{b\rho} G_{\lambda\sigma}^c \epsilon^{\mu\nu\lambda\sigma}. \quad (30)$$

The exact calculation of the neutron EDM requires knowledge of its hadronic wave function. **SUSY_FLAVOR** uses the “naïve” chiral quark model approximation [47]:

$$E_n = \frac{\eta_e}{3} (4d_d - d_u) + \frac{e\eta_c}{4\pi} (4c_d - c_u) + \frac{e\eta_g \Lambda_X}{4\pi} c_g \quad (31)$$

where η_i and Λ_X are the QCD correction factors [48] and the chiral symmetry breaking scale [47], respectively. Various models give significantly different η_i factors. As a result, even the sign of the neutron EDM is not certain. Thus the **SUSY_FLAVOR** result should be

treated as an order of magnitude estimate only. The calculations are performed by calling

Routine	double precision function <code>edm_n()</code>
Input	none
Output	neutron EDM
QCD related factors:	
common/edm_qcd/eta_e,eta_c,eta_g,alamx	
η_e	<code>eta_e</code> = 1.53
η_g	<code>eta_c</code> = 3.4
η_g	<code>eta_g</code> = 3.4
Λ_X	<code>alamx</code> = 1.18
Details of calculations:	Ref. [4]

5.3 $K_L^0 \rightarrow \pi^0 \bar{\nu} \nu$ and $K^+ \rightarrow \pi^+ \bar{\nu} \nu$ decay rates

The relevant part of the effective Hamiltonian generated by the top quark and SUSY particle exchanges can be written as

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_w} \sum_{l=e,\mu,\tau} [X_L(\bar{s}d)_{V-A}(\bar{\nu}_l \nu_l)_{V-A} + X_R(\bar{s}d)_{V+A}(\bar{\nu}_l \nu_l)_{V-A}]. \quad (32)$$

The branching ratios for the $K \rightarrow \pi \nu \bar{\nu}$ decays are then given by

$$Br(K^+ \rightarrow \pi^+ \bar{\nu} \nu) = \kappa_+ \left[\left(\frac{\Im(X_L + X_R)}{\lambda^5} \right)^2 + \left(\frac{\Re(K_{cs}^* K_{cd})}{\lambda} P_c + \frac{\Re(X_L + X_R)}{\lambda^5} \right)^2 \right] \quad (33)$$

$$Br(K_L^0 \rightarrow \pi^0 \bar{\nu} \nu) = \kappa_L \left(\frac{\Im(X_L + X_R)}{\lambda^5} \right)^2 \quad (34)$$

where κ [49], λ (one of the Wolfenstein parameters [50]), and the NLO charm quark contribution P_c [45, 51, 52] can be modified by `SUSY_FLAVOR` users (note that κ and P_c depend on V_{us} , m_c and α_s) Branching ratio calculations are performed by calling

Routine	subroutine <code>k_pivv(br_k0,br_kp)</code>
Input	none
Output	<code>br_k0</code> = $Br(K_L^0 \rightarrow \pi^0 \bar{\nu} \nu)$ <code>br_kp</code> = $Br(K^+ \rightarrow \pi^+ \bar{\nu} \nu)$
QCD related factors	
common/kpivv/ak0,del_ak0,akp,del_akp,pc,del_pc,alam	
$\kappa_L \pm \Delta \kappa_L$	<code>ak0</code> = $2.231 \cdot 10^{-10}$, <code>del_ak0</code> = $0.013 \cdot 10^{-10}$
$\kappa_+ \pm \Delta \kappa_+$	<code>akp</code> = $5.173 \cdot 10^{-11}$, <code>del_akp</code> = $0.025 \cdot 10^{-11}$
$P_c \pm \Delta P_c$	<code>pc</code> = 0.41, <code>del_pc</code> = 0.03
λ	<code>alam</code> = 0.225
Details of calculations:	Ref. [11]

5.4 $B_d^0 \rightarrow l^{I+}l^{J-}$ and $B_s^0 \rightarrow l^{I+}l^{J-}$ decay rates

The general expression for these branching ratios are rather complicated and can be found in [12]. For most users it is sufficient to know that, in addition to the MSSM parameters, the dilepton B decays depend on the B meson masses and the hadronic matrix elements of the down quark vector and scalar currents:

$$\langle 0 | \bar{b} \gamma_\mu P_{L(R)} s | B_{s(d)}(p) \rangle = -(+) \frac{i}{2} p_\mu f_{B_{s(d)}} , \quad (35)$$

$$\langle 0 | \bar{b} P_{L(R)} s | B_{s(d)}(p) \rangle = +(-) \frac{i}{2} \frac{M_{B_{s(d)}}^2 f_{B_s}}{m_b + m_{s(d)}} , \quad (36)$$

where p_μ is the momentum of the decaying $B_{s(d)}$ -meson of mass $M_{B_{s(d)}}$. The $B_d^0 \rightarrow l^{I+}l^{J-}$ and $B_s^0 \rightarrow l^{I+}l^{J-}$ decay branching ratios are calculated by:

Routine	double precision function b_11(K,L,I,J)
Input	$I, J = 1, 2, 3$ - outgoing leptons generation indices K, L - generation indices of the valence quarks of the B^0 meson: setting $(K, L) = (3, 1), (1, 3), (3, 2)$ and $(2, 3)$ chooses respectively $B_d^0, \bar{B}_d^0, B_s^0$ and \bar{B}_s^0 decay
Output	Branching ratios of the decay defined by K, L, I, J
QCD related factors	common/meson_data/dmk, amk, epsk, fk, dmd, amd, fd, amb(2), dmb(2), gam_b(2), fb(2)
M_{B_d}	amb(1) = 5.2794
M_{B_s}	amb(2) = 5.368
f_{B_d}	fb(1) = 0.2
f_{B_s}	fb(2) = 0.245
Details of calculations:	Ref. [12]

5.5 $\bar{K}^0 K^0$ meson mixing parameters

SUSY_FLAVOR calculates two parameters measuring the amount of CP-violation in neutral K meson oscillations: ε_K and the $\bar{K}^0 - K^0$ mass difference ΔM_K .

$$\Delta M_K = 2\Re e \langle \bar{K}^0 | H_{\text{eff}}^{\Delta S=2} | K^0 \rangle , \quad (37)$$

$$\varepsilon_K = \frac{\exp(i\pi/4)}{\sqrt{2}\Delta M_K} \Im m \langle \bar{K}^0 | H_{\text{eff}}^{\Delta S=2} | K^0 \rangle . \quad (38)$$

QCD dependent corrections are known with reasonable accuracy for the ε_K parameter. The long distance contributions to ΔM_K are large and difficult to control. Thus the result given by SUSY_FLAVOR for ΔM_K should be treated as an order of magnitude estimate only.

Apart from the MSSM parameters, the calculation of the $\bar{K}^0 K^0$ meson mixing requires knowledge of the meson masses and of the hadronic matrix elements of the following set of four-quark operators:

$$\begin{aligned}
Q_1^{\text{VLL}} &= (\bar{q}_\alpha^I \gamma_\mu P_L q_\alpha^J)(\bar{q}_\beta^I \gamma^\mu P_L q_\beta^J), \\
Q_1^{\text{LR}} &= (\bar{q}_\alpha^I \gamma_\mu P_L q_\alpha^J)(\bar{q}_\beta^I \gamma^\mu P_R q_\beta^J), \\
Q_2^{\text{LR}} &= (\bar{q}_\alpha^I P_L q_\alpha^J)(\bar{q}_\beta^I P_R q_\beta^J), \\
Q_1^{\text{SLL}} &= (\bar{q}_\alpha^I P_L q_\alpha^J)(\bar{q}_\beta^I P_L q_\beta^J), \\
Q_2^{\text{SLL}} &= (\bar{q}_\alpha^I \sigma_{\mu\nu} P_L q_\alpha^J)(\bar{q}_\beta^I \sigma^{\mu\nu} P_L q_\beta^J)
\end{aligned} \tag{39}$$

where α, β are color indices, for the $\bar{K}^0 K^0$ mixing one should choose flavor indices $I = 2$ and $J = 1$. The matrix elements can be written as:

$$\begin{aligned}
\langle \bar{K}^0 | Q_1^{\text{VLL}}(\mu) | K^0 \rangle &= \frac{1}{3} M_K F_K^2 B_1^{\text{VLL}}(\mu), \\
\langle \bar{K}^0 | Q_1^{\text{LR}}(\mu) | K^0 \rangle &= -\frac{1}{6} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K F_K^2 B_1^{\text{LR}}(\mu), \\
\langle \bar{K}^0 | Q_2^{\text{LR}}(\mu) | K^0 \rangle &= \frac{1}{4} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K F_K^2 B_2^{\text{LR}}(\mu), \\
\langle \bar{K}^0 | Q_1^{\text{SLL}}(\mu) | K^0 \rangle &= -\frac{5}{24} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K F_K^2 B_1^{\text{SLL}}(\mu), \\
\langle \bar{K}^0 | Q_2^{\text{SLL}}(\mu) | K^0 \rangle &= -\frac{1}{2} \left(\frac{M_K}{m_s(\mu) + m_d(\mu)} \right)^2 M_K F_K^2 B_2^{\text{SLL}}(\mu),
\end{aligned} \tag{40}$$

where F_K is the K -meson decay constant. By default, **SUSY_FLAVOR** uses the B_i^X values at the scale $\mu = 2$ GeV given in [53] using the NDR renormalization scheme (quark masses at the scale 2 GeV are stored in `common/fmass_high/`, see Section 4.2.2).

In addition to the hadronic matrix elements, QCD corrections depend also on the “ η ” factors describing the evolution of the relevant Wilson coefficients from the high to low energy scale. These factors are automatically calculated at NLO by **SUSY_FLAVOR**. For the SM contribution to the Wilson coefficient of the Q^{VLL} operator a separate careful calculation of the evolution factors has been performed [54, 55]. Therefore **SUSY_FLAVOR** treats this contribution separately, setting B_{SM}^{VLL} and the η_{SM} factor to default values given in [56] (see [53] for a very detailed discussion of the structure of the QCD corrections in $\bar{B}^0 B^0$ and $\bar{K}^0 K^0$ systems, including their renormalization scheme dependence and calculations of the evolution factors “ η ” implemented in **SUSY_FLAVOR**).

The kaon mass difference ΔM_K and the ε_K parameter measuring the amount of CP violation in $\bar{K}^0 K^0$ mixing are calculated by

Routine	subroutine dd_kaon(eps_k,delta_mk)
Input	none
Output	$\text{eps_k} = \varepsilon_K$ parameter $\text{delta_mk} = \Delta M_K$ mass difference
QCD related factors:	
common/meson_data/dmk, amk, epsk, fk, dmd, amd, fd, amb(2), dmb(2), gam_b(2), fb(2)	
M_K	$\text{amk} = 0.497672$
Measured ΔM_K^{exp}	$\text{dmk} = 3.49 \cdot 10^{-15}$
Measured ε_K^{exp}	$\text{epsk} = 2.26 \cdot 10^{-3}$
f_K	$\text{fk} = 0.1598$
common/bx_4q/bk(5), bd(5), bb(2,5), amu_k, amu_d, amu_b	
$B_1^{\text{VLL}}(\mu_K)$	$\text{bk}(1) = 0.61$
$B_1^{\text{SLL}}(\mu_K)$	$\text{bk}(2) = 0.76$
$B_2^{\text{SLL}}(\mu_K)$	$\text{bk}(3) = 0.51$
$B_1^{\text{LR}}(\mu_K)$	$\text{bk}(4) = 0.96$
$B_2^{\text{LR}}(\mu_K)$	$\text{bk}(5) = 1.30$
Renormalization scale μ_K	$\text{amu_k} = 2$
common/sm_4q/eta_cc, eta_ct, eta_tt, eta_b, bk_sm, bd_sm, bb_sm(2)	
B_{SM}^{VLL}	$\text{bk_sm} = 0.724$
η_{cc}	$\text{eta_cc} = 1.44$
η_{ct}	$\text{eta_ct} = 0.47$
η_{tt}	$\text{eta_tt} = 0.57$
Details of calculations:	Ref. [10, 53]

5.6 $\bar{D}^0 D^0$ meson mass difference

Calculations of the mass difference Δm_D of the neutral D mesons have large theoretical uncertainties due to unknown long-distance strong corrections. Thus, as in the case of Δm_K , the **SUSY_FLAVOR** result for Δm_D should be treated as an order of magnitude estimate only.

The structure of strong corrections is analogous to those in the K meson system. However, in this case hadronic matrix elements and QCD evolution calculations available in the literature are much less refined. **SUSY_FLAVOR** uses the NLO evolution for the “ η ” factors and sets, by default, all the relevant hadronic matrix elements $B_i = 1$, i.e. it uses the “vacuum saturation” approximation (this can be changed easily when new results become available).

Routine	<code>subroutine uu_bmeson(delta_md)</code>
Input	<code>none</code>
Output	<code>delta_md = ΔM_D</code> mass difference
QCD related factors:	
<code>common/meson_data/dmk, amk, epsk, fk, dmd, amd, fd, amb(2), dmb(2), gam_b(2), fb(2)</code>	
M_D	<code>amd = 1.8645</code>
Measured ΔM_D^{exp}	<code>dmd = $4.61 \cdot 10^{-14}$</code>
f_D	<code>fd = 0.165</code>
<code>common/bx_4q/bk(5), bd(5), bb(2,5), amu_k, amu_d, amu_b</code>	
$B_1^{VLL}(\mu_D)$	<code>bd(1) = 1</code>
$B_1^{SLL}(\mu_D)$	<code>bd(2) = 1</code>
$B_2^{SLL}(\mu_D)$	<code>bd(3) = 1</code>
$B_1^{LR}(\mu_D)$	<code>bd(4) = 1</code>
$B_2^{LR}(\mu_D)$	<code>bd(5) = 1</code>
Renormalization scale μ_D	<code>amu_d = 2</code>
<code>common/sm_4q/eta_cc, eta_ct, eta_tt, eta_b, bk_sm, bd_sm, bb_sm(2)</code>	
B_{SM}^{VLL}	<code>bd_sm = 1</code>
Details of calculations:	Performed by authors, unpublished

5.7 $\bar{B}_d^0 B_d^0$ and $\bar{B}_s^0 B_s^0$ mass differences

Mixing and CP violation phenomena are also observed in the neutral B meson systems. In particular, the mass differences in the $\bar{B}_d^0 B_d^0$ and $\bar{B}_s^0 B_s^0$ oscillations have been measured,

$$\Delta M_{B_{d(s)}} = 2|\langle \bar{B}_{d(s)}^0 | H_{\text{eff}}^{\Delta B=2} | B_{d(s)}^0 \rangle| . \quad (41)$$

In addition to the MSSM parameters, theoretical calculations of Δm_{B_d} and Δm_{B_s} depend, as for K and D oscillations, on the relevant hadronic matrix elements and QCD evolution factors. The formulae for $\bar{B}^0 B^0$ mixing can be obtained by making the obvious replacements in the formulae presented in Section 5.5. Currently **SUSY_FLAVOR** uses the same set of B_i factors for both the B_d and B_s sectors, but it leaves the possibility to distinguish between them in future, if necessary. For this one needs to independently initialize the arrays `bb(1,i)` (B_d meson hadronic matrix elements) and `bb(2,i)` (B_s meson hadronic matrix elements) stored in `common/bx_4q/`.

The values of the B meson masses and coupling constants are the same as those listed in Section 5.4. **SUSY_FLAVOR** calculates the mass differences $\Delta M_{B_{d(s)}}$ as defined by eq. (41):

Routine	<code>subroutine dd_bmeson(i,delta_mb)</code>
Input	$i = 1, 2$ - generation index of the lighter valence quark in the B^0 meson, i.e. $i = 2$ chooses B_s^0 and $i = 1$ chooses B_d^0 .
Output	$\text{delta_mb} = \Delta m_{B_d}$ for $i = 1$ $\text{delta_mb} = \Delta m_{B_s}$ for $i = 2$
QCD related factors:	
<code>common/meson_data/dmk,amk,epsk,fk,dmd,amd,fd,amb(2),dmb(2),gam_b(2),fb(2)</code>	
Measured $\Delta M_{B_d}^{exp}$	$\text{dmb}(1) = 3.01 \cdot 10^{-13}$
Measured $\Delta M_{B_s}^{exp}$	$\text{dmb}(2) = 1.2 \cdot 10^{-11}$
Measured width $\Gamma_{B_d}^{exp}$	$\text{gam}_b(1) = 1.53 \cdot 10^{-12}$
Measured width $\Gamma_{B_s}^{exp}$	$\text{gam}_b(1) = 1.466 \cdot 10^{-12}$
<code>common/bx_4q/bk(5),bd(5),bb(2,5),amu_k,amu_d,amu_b</code>	
$B_1^{VLL}(\mu_B)$	$\text{bb}(1,1) = \text{bb}(2,1) = 0.87$
$B_1^{SLL}(\mu_B)$	$\text{bb}(1,2) = \text{bb}(2,2) = 0.8$
$B_2^{SLL}(\mu_B)$	$\text{bb}(1,3) = \text{bb}(2,3) = 0.71$
$B_1^{LR}(\mu_B)$	$\text{bb}(1,4) = \text{bb}(2,4) = 1.71$
$B_2^{LR}(\mu_B)$	$\text{bb}(1,5) = \text{bb}(2,5) = 1.16$
Renormalization scale μ_B	$\text{amu}_b = 4.6$
<code>common/sm_4q/eta_cc,eta_ct,eta_tt,eta_b,bk_sm,bd_sm,bb_sm(2)</code>	
$B_{SM B_d}^{VLL}$	$\text{bb_sm}(1) = 1.22$
$B_{SM B_s}^{VLL}$	$\text{bb_sm}(2) = 1.22$
η_b	$\text{eta}_b = 0.55$
Details of calculations:	Ref. [10]

5.8 $B^0 \rightarrow X_s \gamma$ decay rate

Both the SUSY contributions and the QCD corrections to the calculation of the $B^0 \rightarrow X_s \gamma$ decay rate are quite complex. Their implementation in **SUSY_FLAVOR** is based on the SUSY loop calculations performed by the authors (not published in a general form) and on the QCD evolution published in [57]. There are no user-accessible QCD factors apart from the arguments of the **bxg_nl** routine.

Routine	<code>double precision function bxg_nl(del,amiu_b)</code>
Input	<code>del</code> - relative photon energy infrared cutoff scale, $E_\gamma \geq (1 - \text{del})E_\gamma^{max}$, $0 < \text{del} < 1$
Output	amiu_b - renormalization scale $\text{Br}(B \rightarrow X_s \gamma)$.
Details of calculations:	General SUSY diagrams unpublished, QCD corrections based on [57]

6 Summary and Outlook

We have presented **SUSY_FLAVOR**, a tool for calculating the set of important FCNC and CPV observables in the general R -parity conserving MSSM. All implemented physical quantities (listed in Table 1) can be calculated simultaneously for a given set of MSSM parameters. The calculations of the SUSY particle spectrum and flavor mixing matrices are performed exactly, so the code can be used for a completely general pattern of soft SUSY flavor violating terms and complex phases, without restrictions on the size of sfermion mass insertions.

Besides complete routines for calculating the physical observables, **SUSY_FLAVOR** also provides an extensive library of parton-level Green's functions and Wilson coefficients of many effective quark and lepton operators (see Table 3). This set actually contains many more functions than are necessary to compute the quantities listed in Table 1. These intermediate building blocks can be used by **SUSY_FLAVOR** users to construct amplitudes for processes beyond those already fully implemented by dressing appropriate combinations of available form factors in QCD corrections and hadronic matrix elements, without repeating tedious one-loop SUSY calculations from scratch. For instance, the form factors implemented in **SUSY_FLAVOR** for the analysis of $B \rightarrow X_s\gamma$ and $B_{d(s)} \rightarrow l^+l^-$ decays [3, 12] are sufficient to also calculate the $B \rightarrow Kl^+l^-$ decay rate.

SUSY_FLAVOR internally uses the conventions of Ref. [14], however in order to facilitate comparison with other programs that analyze various sectors of MSSM, we have implemented an option to input parameters in the SLHA2 format [42].

SUSY_FLAVOR has been written in FORTRAN 77 and runs fairly quickly; it is capable of producing a reasonably wide-range scan over the MSSM parameters within hours or days on a typical personal computer.

The **SUSY_FLAVOR** library is an open project. We want to gradually add more features in its future versions. In particular, we plan to:

- add more observables in the B -meson system, like the CP asymmetries in $\bar{B}B$ meson mixing and in $B \rightarrow X_s\gamma$ decay, as well as observables associated with $B \rightarrow Kl^+l^-$ decay.
- add observables for lepton flavor-violating processes like $\ell^J \rightarrow \ell^I\gamma$, $\ell^J \rightarrow \ell^K\ell^L\ell^M$, and for the lepton anomalous magnetic moments, $(g-2)_l$
- include quantities related to FCNCs in the top sector, like $t \rightarrow cX$ with $X = \gamma, Z, g, H$, in order to probe the flavor violation in up-squark mass matrices that are (almost) unconstrained to this moment.
- implement full resummation of leading large $\tan\beta$ effects beyond the MFV scenario.

With the increasing accuracy of experimental data on flavor and CP violation in rare

processes, it may eventually become possible to not only constrain the MSSM parameters, but also, if significant deviations from the SM predictions are found, to recover their actual values. For that multi-process analysis, such as the one performed by **SUSY_FLAVOR**, will be necessary. Therefore, we hope that **SUSY_FLAVOR** becomes an important tool that is useful not only to theorists working on MSSM but also to experimentalists fitting the MSSM onto forthcoming data from the Tevatron, LHC, and B -factories.

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A Installation of the program

The installation and execution of **SUSY_FLAVOR** is very simple. On Unix or Linux systems, just follow these steps :

1. Download the code from http://www.fuw.edu.pl/susy_flavor and unpack it.
2. Change directory into **susy_flavor**.
3. Edit **Makefile** and change `F77 = gfortran` and `FOPT = -O -fno-automatic -Wall` into your compiler name and options, respectively.
4. Exit **Makefile** and type `make` (or `gmake`).
5. If everything go through the code will ask you whether to read the input file **susy_flavor.in** or to use the parameters defined inside the driver file.
6. To run the code from now on just type `./sflav`.

The authors tested **SUSY_FLAVOR** on Linux machines. With few straightforward modifications the procedure describe above can be adapted to install program on other systems.

The output of the program is displayed on the screen. In addition a file named `mssm_data.txt` is created. It contains information about the MSSM Lagrangian parameters and the tree-level mass spectrum corresponding to the input parameter set. A sample set of input parameters and corresponding `SUSY_FLAVOR` output are listed in the following appendices.

B Example of the SUSY_FLAVOR initialization sequence

Below we present the contents of `susy_flavor.f`, the master driver file for the `SUSY_FLAVOR` library. The driver program illustrates the correct initialization sequence for all relevant MSSM parameters (see Section 4) and shows how to perform calls to the routines calculating physical observables (Section 5).

The driver file asks if the input parameters should be given directly inside the program or read from the default input file named `susy_flavor.in` (in this case skipping the values given in the program). Defining the input parameters in the separate file is probably more straightforward, but the ability to initialize parameters from within the program could be more useful for performing multi-dimensional scans over the MSSM parameter space.

```

program susy_flavor
implicit double precision (a-h,o-z)
dimension sll(3),slr(3),sql(3),squ(3),sqd(3)
double complex asl(3),asu(3),asd(3)
double complex slmi_l(3),slmi_r(3),slmi_lr(3,3)
double complex sqmi_l(3),sdmi_r(3),sumi_r(3)
double complex sdmi_lr(3,3),sumi_lr(3,3)
double complex amg,amgg,amue
common/sf_cont/eps,indx(3,3),iconv

c      decide if input parameters are read from file susy_flavor.in or defined inside the program
write(*,'(a,$)')'Read input from file susy_flavor.in (no=1,yes=2)? '
read(*,*) input_type
if (input_type.eq.2) then
    call sflav_input           ! Parameters read from file susy_flavor.in
    goto 100
end if

c      Parameters defined inside the code. Start from input convention choice
c      iconv = 1                  ! SLHA2 input conventions
c      iconv = 2                  ! hep-ph/9511250 input conventions

c      SM basic input initialization
zm0 = 91.1876d0                 ! M_Z
wm0 = 80.398d0                  ! M_W

```

```

alpha_z = 1/127.934d0           ! alpha_em(M_Z)
call vpar_update(zm0,wm0,alpha_z)

c   QCD parameters
alpha_s = 0.1172d0             ! alpha_s(M_Z)
call lam_fit(alpha_s)          ! fits Lambda_QCD at 3 loop level
call lam_fit_nlo(alpha_s)      ! fits Lambda_QCD at NLO level

c   CKM matrix initialization
alam = 0.2258d0                ! lambda
apar = 0.808d0                 ! A
rhobar = 0.177d0                ! rho bar
etabar = 0.360d0                ! eta bar
call ckm_wolf(alam,apar,rhobar,etabar)

c   Fermion mass initialization, input: MSbar running quark masses
top_scale = 163.2d0
top = 163.2d0                  ! m_t(top_scale)
bot_scale = 4.17d0
bot = 4.17d0                   ! m_b(bot_scale)
call init_fermion_sector(top,top_scale,bot,bot_scale)

c   Higgs sector parameters
pm = 200                         ! M_A
tanbe = 10                        ! tan(beta)
amue = (200.d0,100.d0)            ! mu parameter
call init_higgs_sector(pm,tanbe,amue,ierr)
if (ierr.ne.0) stop 'negative tree level Higgs mass^2?',

c   Gaugino sector parameters: if M1=0 set here then program uses  $M1 = 5s_W^2/3c_W^2 M_Z$ 
amgg = (0.d0,0.d0)                ! M1 (bino mass, complex)
amg = (200.d0,0.d0)               ! M2 (wino mass, complex)
amglu = 3*abs(amg)                ! M3 (gluino mass)
call init_ino_sector(amgg,amg,amglu,amue,tanbe,ierr)
if (ierr.ne.0) write(*,*) '-ino mass below M_Z/2?'

c   Slepton diagonal soft breaking parameters
sll(1) = 300.d0                  ! left selectron mass scale
sll(2) = 300.d0                  ! left smuon mass scale
sll(3) = 300.d0                  ! left stau mass scale
slr(1) = 300.d0                  ! right selectron mass scale
slr(2) = 300.d0                  ! right smuon mass scale
slr(3) = 300.d0                  ! right stau mass scale
c   Dimensionless (normalized to masses) slepton diagonal LR mixing

```

```

      asl(1) = (1.d0,0.d0)          ! 1st generation
      asl(2) = (1.d0,0.d0)          ! 2nd generation
      asl(3) = (1.d0,0.d0)          ! 3rd generation
c   Slepton LL and RR mass insertions (hermitian matrices, only upper part given)
c   slmi_x(1),slmi_x(2), slmi_x(3) are 12,23,31 entry, respectively
      do i=1,3
        slmi_l(i) = (0.d0,0.d0)    ! slepton LL mass insertion
        slmi_r(i) = (0.d0,0.d0)    ! slepton RR mass insertion
      end do
      slmi_l(2) = (2.d-2,1.d-2)    ! example, non-vanishing LL 23 entry
c   Slepton LR mass insertions, non-hermitian in general
      do i=1,3
        do j=1,3
          slmi_lr(i,j) = (0.d0,0.d0) ! slepton LR ij mass insertion
        end do
      end do
c   Calculate slepton physical masses and mixing angles
      call init_slepton_sector(sll,slr,asl,ierr,slmi_l,slmi_r,slmi_lr)
      if (ierr.ne.0) stop 'negative tree level slepton mass^2?'
c   Squark diagonal soft breaking parameters
      sql(1) = 500.d0              ! left squark mass, 1st generation
      sql(2) = 500.d0              ! left squark mass, 2nd generation
      sql(3) = 400.d0              ! left squark mass, 3rd generation
      sqd(1) = 550.d0              ! right down squark mass
      sqd(2) = 550.d0              ! right strange squark mass
      sqd(3) = 300.d0              ! right sbottom mass
      squ(1) = 450.d0              ! right up squark mass
      squ(2) = 450.d0              ! right charm squark mass
      squ(3) = 200.d0              ! right stop mass
c   Dimensionless (normalized to masses) squark diagonal LR mixing
      asd(1) = (1.d0,0.d0)         ! down squark LR mixing, 1st generation
      asd(2) = (1.d0,0.d0)         ! down squark LR mixing, 2nd generation
      asd(3) = (1.d0,0.d0)         ! down squark LR mixing, 3rd generation
     asu(1) = (1.d0,0.d0)         ! up squark LR mixing, 1st generation
     asu(2) = (1.d0,0.d0)         ! up squark LR mixing, 2nd generation
     asu(3) = (1.d0,0.d0)         ! up squark LR mixing, 3rd generation
c   Squark LL and RR mass insertions (hermitian matrices, only upper part given)
c   sqmi_l(1),sqmi_l(2), sqmi_l(3) are 12,23,31 entry, etc.
      do i=1,3
        sqmi_l(i) = (0.d0,0.d0)    ! squark LL mass insertion
        sumi_r(i) = (0.d0,0.d0)    ! up-squark RR mass insertion
        sdmi_r(i) = (0.d0,0.d0)    ! down-squark RR mass insertion
      end do

```

```

sqmi_ll(2) = (2.d-2,-1.d-2)      ! example, non-vanishing LL 23 entry
c
      Squark LR mass insertions, non-hermitian in general
      do i=1,3
          do j=1,3
              sumi_lr(i,j) = (0.d0,0.d0) ! up-squark LR ij mass insertion
              sdmi_lr(i,j) = (0.d0,0.d0) ! down-squark LR ij mass insertion
          end do
      end do
c
      Calculate squark physical masses and mixing angles
      call init_squark_sector(sql,squ,sqd,asu,asd,ierr,sqmi_ll,sumi_r,
      $      sdmi_r,sumi_lr,sdmi_lr)
      if (ierr.ne.0) stop 'negative tree level squark mass^2?'
c
      reset status of physical Higgs mass after parameter changes
      call reset_phys_data
c
      Neutral CP-even Higgs masses in the 1-loop Effective Potential Approximation.
c
      Only real mu, A_t, A_b allowed - replace x→abs(x)
      call fcorr_EPA(tanbe,pm,top,abs(amue),sql(3),sqd(3),squ(3),
      $      abs(asd(3)),abs(asu(3)),ierr)
      if (ierr.ne.0) stop 'negative 1-loop EPA CP-even Higgs mass^2?'
c
100    continue                      !!! End of input section !!!
c
      Control output: Lagrangian parameters and tree level masses written on file mssm_data.txt
      ifl = 1                           ! output file number
      open(ifl,file='mssm_data.txt',status='unknown')
      call print_MSSM_par(ifl)          ! Lagrangian parameters
      call print_MSSM_masses(ifl)       ! tree level physical masses
      close(ifl)
c
      Results for implemented rare decays:
      write(*,99)'Electric dipole moments:'
      write(*,99)'Electron EDM = ',edm_l(1)
      write(*,99)'Muon EDM = ',edm_l(2)
      write(*,99)'Tau EDM = ',edm_l(3)
      write(*,99)'Neutron EDM = ',edm_n()

      write(*,99)'Neutrino K decays:'
      call k_pivv(br_k0,br_kp)
      write(*,99)'BR( $K_L^0 \rightarrow \pi^0 vv$ ) = ',br_k0
      write(*,99)'BR( $K^+ \rightarrow \pi^+ vv$ ) = ',br_kp

      write(*,99)'Leptonic B decays:'
      write(*,99)'BR( $B_d \rightarrow \mu^+ \mu^-$ ) = ',b_ll(3,1,2,2)
      write(*,99)'BR( $B_s \rightarrow \mu^+ \mu^-$ ) = ',b_ll(3,2,2,2)

```

```

      write(*,99)'B→ X_s photon decay:'
c      Physical quantities for BR(B→X_s g) calculation
      delb = 0.99d0                      ! Photon energy infrared cutoff
      amiu_b= 4.8d0                       ! Renormalization scale miu_b
      write(*,99)'BR(B → X_S gamma) = ',bxg_nl(delb,amiu_b)

      write(*,99)'KK mixing:'
      call dd_kaon(eps_k,delta_mk)
      write(*,99)'eps_K = ',eps_k
      write(*,99)'Delta m_K = ',delta_mk

      write(*,99)'DD mixing:'
      call uu_dmeson(delta_md)
      write(*,99)'Delta m_D = ',delta_md

      write(*,99)'BB mixing:'
      call dd_bmeson(1,delta_mbd)
      write(*,99)'Delta m_B_d = ',delta_mbd
      call dd_bmeson(2,delta_mbs)
      write(*,99)'Delta m_B_s = ',delta_mbs

      99 format(a,1pe11.4)
      end

```

C Example of SUSY_FLAVOR input file

By default, the driver file `susy_flavor.f` reads input parameters from the file `susy_flavor.in`. Below we provide an example input file defining a set of parameters equivalent to those in the driver file presented in Appendix B.

```

# Example input of SUSY_FLAVOR in Les Houches Accord-like format
#
# CAUTION: users can modify numerical data in this file but they
# should not remove existing data lines within blocks SMINPUTS,
# VCKMIN, EXTPAR, MSL2IN, MSE2IN, MSQ2IN, MSU2IN, MSD2IN, TEIN, TUIN,
# TDIN, IMMSL2IN, IMMSE2IN, IMMSQ2IN, IMMSU2IN, IMMSD2IN, IMTEIN,
# IMTUIN, IMTDIN. New data lines in each block can be added but only
# after the already defined ones. Also, comment-only lines starting
# from # as a first character can be added only just after or before
# Block XXX statements, i.e. not between data lines. Otherwise
# SUSY_FLAVOR input routine sflav_input will denounce input file as

```

```

# corrupted or read incorrect values.
#
# Full new data blocks can be added, sflav_input will ignore them.
#
Block MODSEL
    1 0                                # Select model
    3 0                                # General MSSM
    4 0                                # MSSM particle content
    5 2                                # R-parity conserving MSSM
    6 3                                # CP violated
    7 0                                # Lepton and quark flavor violated
Block SOFTINP
# convention = 1:
#   sfermion input parameters in SLHA2 conventions
# convention = 2:
#   sfermion input parameters in conventions of hep-ph/9511250
# input_type = 1:
#   sfermion off-diagonal terms given as dimensionless mass insertions
#   LR diagonal terms given as dimensionless parameters
# input_type = 2:
#   sfermion soft terms given as absolute values
# See comment in Blocks MSXIN2, TXIN below
    1 2                                # sfermion convention, SLHA2 or hep-ph/9511250
    2 1                                # input_type (dimension of soft mass entries)
Block SMINPUTS
    1 1.279340000e+02                 # Standard Model inputs
    3 1.172000000e-01                 # alpha-1 SM MSbar(MZ)
    4 9.118760000e+01                 # alpha_s(MZ) SM MSbar
    5 4.170000000e+00                 # MZ(pole)
    6 1.632000000e+02                 # mb(mb) SM MSbar
    7 1.777000000e+00                 # mtop(mt) SM MSbar
    11 5.110000000e-04                # mtau(pole)
    13 1.056590000e-01                # me(pole)
    21 7.000000000e-03                # mmu(pole)
    22 4.000000000e-03                # md(2 GeV) MSbar
    23 1.100000000e-01                # mu(2 GeV) MSbar
    24 1.279000000e+00                # ms(2 GeV) MSbar
    30 8.039800000e+01                # mc(mc) MSbar
                                         # MW (pole), not standard SLHA2 entry!!!
Block VCKMIN
    1 2.258000000e-01                # CKM matrix
    2 8.080000000e-01                # lambda
    3 1.770000000e-01                # A
    4 3.600000000e-01                # rho bar
                                         # eta bar
Block EXTPAR
    1 0.000000000e+02                # non-minimal input parameters, real part
                                         # Re(m1), U(1) gaugino mass

```

```

2 2.000000000e+02          # Re(m2), SU(2) gaugino mass
3 6.000000000e+02          # m3, SU(3) gaugino mass
23 2.000000000e+02         # Re(mu)
25 1.000000000e+01         # tan(beta)
26 2.000000000e+02         # MA
Block IMEXTPAR               # non-minimal input parameters, imaginary part
1 0.000000000e+00          # Im(m1), U(1) gaugino mass
2 0.000000000e+00          # Im(m2), SU(2) gaugino mass
23 1.000000000e+02         # Im(mu)

# if abs(m1) = 0 SUSY_FLAVOR uses m1=5/3 s_W^2/c_W^2 m2
#
# Soft sfermion mass matrices
#
# Off-diagonal entries may be given as absolute entries or as
# dimensionless mass insertions - then real off-diagonal entries of
# SLHA2 blocks are calculated by SUSY_FLAVOUR as
# M^2(I,J) = (mass insertion)(I,J) sqrt(M^2(I,I) M^2(J,J))
# (see comments at the top of subroutine sflav_input)
#
# Below we give an example of dimensionless off-diagonal entries
#
Block MSL2IN                  # left soft slepton mass matrix, real part
1 1 9.000000000e+04          # Left slepton diagonal mass2, 1st generation
2 2 9.000000000e+04          # Left slepton diagonal mass2, 2nd generation
3 3 9.000000000e+04          # Left slepton diagonal mass2, 3rd generation
1 2 0.000000000e+00          # Dimensionless left slepton mass insertion 12
2 3 2.000000000e-02          # Dimensionless left slepton mass insertion 23
1 3 0.000000000e+00          # Dimensionless left slepton mass insertion 13
Block IMMSL2IN                 # left soft slepton mass matrix, imaginary part
1 2 0.000000000e+00          # Dimensionless left slepton mass insertion 12
2 3 1.000000000e-02          # Dimensionless left slepton mass insertion 23
1 3 0.000000000e+00          # Dimensionless left slepton mass insertion 13
Block MSE2IN                   # right soft slepton mass matrix, real part
1 1 9.000000000e+04          # Right selectron diagonal mass2
2 2 9.000000000e+04          # Right smuon diagonal mass2
3 3 9.000000000e+04          # Right stau diagonal mass2
1 2 0.000000000e+00          # Dimensionless right slepton mass insertion 12
2 3 0.000000000e+00          # Dimensionless right slepton mass insertion 23
1 3 0.000000000e+00          # Dimensionless right slepton mass insertion 13
Block IMMSE2IN                 # right soft slepton mass matrix, imaginary part
1 2 0.000000000e+00          # Dimensionless right slepton mass insertion 12
2 3 0.000000000e+00          # Dimensionless right slepton mass insertion 23
1 3 0.000000000e+00          # Dimensionless right slepton mass insertion 13
Block MSQ2IN                   # left soft squark mass matrix, real part

```

```

1 1 2.500000000e+05          # Left squark diagonal mass2, 1st generation
2 2 2.500000000e+05          # Left squark diagonal mass2, 2nd generation
3 3 1.600000000e+05          # Left squark diagonal mass2, 3rd generation
1 2 0.000000000e+00          # Dimensionless left squark mass insertion 12
2 3 2.000000000e-02          # Dimensionless left squark mass insertion 23
1 3 0.000000000e+00          # Dimensionless left squark mass insertion 13
Block IMMSQ2IN
1 2 0.000000000e+00          # left soft squark mass matrix, imaginary part
2 3 -1.000000000e-02          # Dimensionless left squark mass insertion 12
1 3 0.000000000e+00          # Dimensionless left squark mass insertion 23
# Dimensionless left squark mass insertion 13
Block MSU2IN
1 1 2.025000000e+05          # right soft up-squark mass matrix, real part
2 2 2.025000000e+05          # Right u-squark diagonal mass2
3 3 4.000000000e+04          # Right c-squark diagonal mass2
1 2 0.000000000e+00          # Right stop diagonal mass2
2 3 0.000000000e+00          # Dimensionless right up-squark mass insertion 12
1 3 0.000000000e+00          # Dimensionless right up-squark mass insertion 23
# Dimensionless right up-squark mass insertion 13
Block IMMSU2IN
1 2 0.000000000e+00          # right soft up-squark mass matrix, imaginary part
2 3 0.000000000e+00          # Dimensionless right up-squark mass insertion 12
1 3 0.000000000e+00          # Dimensionless right up-squark mass insertion 23
# Dimensionless right up-squark mass insertion 13
Block MSD2IN # right soft down-squark mass matrix, real part
1 1 3.025000000e+05          # Right d-squark diagonal mass2
2 2 3.025000000e+05          # Right s-squark diagonal mass2
3 3 9.000000000e+04          # Right sbottom diagonal mass2
1 2 0.000000000e+00          # Dimensionless right down-squark mass insertion 12
2 3 0.000000000e+00          # Dimensionless right down-squark mass insertion 23
1 3 0.000000000e+00          # Dimensionless right down-squark mass insertion 13
Block IMMSD2IN
1 2 0.000000000e+00          # right soft down-squark mass matrix, imaginary part
2 3 0.000000000e+00          # Dimensionless right down-squark mass insertion 12
1 3 0.000000000e+00          # Dimensionless right down-squark mass insertion 23
# Dimensionless right down-squark mass insertion 13
#
# Soft sfermion trilinear mixing matrices
#
# LR mixing parameters can be given as absolute entries or as
# dimensionless diagonal A-terms and dimensionless ff-diagonal mass
# insertions - see comments at the top of subroutine sflav_input
#
# Below we give an example of dimensionless A terms.
#
# Diagonal entries below are dimensionless "A parameters"
# Diagonal entries of SLHA2 LR blocks are calculated by SUSY_FLAVOUR as
# TL(I,I) = AL(I,I) Yukawa_L(I) sqrt(ML2(I,I)*ME2(I,I))

```

```

# TU(I,I) = AU(I,I) Yukawa_U(I) sqrt(MQ2(I,I)*MU2(I,I))
# TD(I,I) = AD(I,I) Yukawa_D(I) sqrt(MQ2(I,I)*MD2(I,I))
#
# Off-diagonal entries are dimensionless "mass insertions"
# Off-diagonal entries of SLHA2 LR blocks are calculated by SUSY_FLAVOUR as
#
# TL(I,J) = AL(I,J) sqrt(2 ML2(I,I)*ME2(J,J))/v1
# TU(I,J) = AU(I,J) sqrt(2 MQ2(I,I)*MU2(J,J))/v2
# TD(I,J) = AD(I,J) sqrt(2 MQ2(I,I)*MD2(J,J))/v1
#
Block TEIN
  1 1 1.000000000e+00          # slepton trilinear mixing, dimensionless, real part
  2 2 1.000000000e+00          # Diagonal AL term, 1st generation
  3 3 1.000000000e+00          # Diagonal AL term, 2nd generation
  1 2 0.000000000e+00          # Diagonal AL term, 3rd generation
  2 1 0.000000000e+00          # Slepton LR mass insertion 12
  2 3 0.000000000e+00          # Slepton LR mass insertion 21
  3 2 0.000000000e+00          # Slepton LR mass insertion 23
  1 3 0.000000000e+00          # Slepton LR mass insertion 32
  3 1 0.000000000e+00          # Slepton LR mass insertion 13
Block IMTEIN
  1 1 0.000000000e+00          # Slepton LR mass insertion 31
  2 2 0.000000000e+00          # slepton trilinear mixing, dimensionless, imag. part
  3 3 0.000000000e+00          # Diagonal AL term, 1st generation
  1 2 0.000000000e+00          # Diagonal AL term, 2nd generation
  2 1 0.000000000e+00          # Diagonal AL term, 3rd generation
  2 3 0.000000000e+00          # Slepton LR mass insertion 12
  3 2 0.000000000e+00          # Slepton LR mass insertion 21
  1 3 0.000000000e+00          # Slepton LR mass insertion 23
  3 1 0.000000000e+00          # Slepton LR mass insertion 32
Block TUIN
  1 1 1.000000000e+00          # Slepton LR mass insertion 13
  2 2 1.000000000e+00          # Up-squark trilinear mixing, dimensionless, real part
  3 3 1.000000000e+00          # Up-squark trilinear mixing, dimensionless, imag. part
  1 2 0.000000000e+00          # Diagonal AU term, 1st generation
  2 1 0.000000000e+00          # Diagonal AU term, 2nd generation
  3 2 0.000000000e+00          # Diagonal AU term, 3rd generation
  1 3 0.000000000e+00          # Up-squark LR mass insertion 12
  3 1 0.000000000e+00          # Up-squark LR mass insertion 21
Block IMTUIN
  1 1 0.000000000e+00          # Up-squark LR mass insertion 23
  2 2 0.000000000e+00          # Up-squark LR mass insertion 32
  3 3 0.000000000e+00          # Up-squark LR mass insertion 13
  1 2 0.000000000e+00          # Up-squark LR mass insertion 31
  2 1 0.000000000e+00          # up-squark trilinear mixing, dimensionless, real part
  3 2 0.000000000e+00          # up-squark trilinear mixing, dimensionless, imag. part
  1 3 0.000000000e+00          # Diagonal AU term, 1st generation
  3 1 0.000000000e+00          # Diagonal AU term, 2nd generation
  2 3 0.000000000e+00          # Diagonal AU term, 3rd generation

```

```

1 2 0.000000000e+00          # Up-squark LR mass insertion 12
2 1 0.000000000e+00          # Up-squark LR mass insertion 21
2 3 0.000000000e+00          # Up-squark LR mass insertion 23
3 2 0.000000000e+00          # Up-squark LR mass insertion 32
1 3 0.000000000e+00          # Up-squark LR mass insertion 13
3 1 0.000000000e+00          # Up-squark LR mass insertion 31
Block TDIN
1 1 1.000000000e+00          # down-squark trilinear mixing, dimensionless, real part
2 2 1.000000000e+00          # Diagonal AD term, 1st generation
3 3 1.000000000e+00          # Diagonal AD term, 2nd generation
# Diagonal AD term, 3rd generation
1 2 0.000000000e+00          # Down-squark LR mass insertion 12
2 1 0.000000000e+00          # Down-squark LR mass insertion 21
2 3 0.000000000e+00          # Down-squark LR mass insertion 23
3 2 0.000000000e+00          # Down-squark LR mass insertion 32
1 3 0.000000000e+00          # Down-squark LR mass insertion 13
3 1 0.000000000e+00          # Down-squark LR mass insertion 31
Block IMTDIN
1 1 0.000000000e+00          # down-squark trilinear mixing, dimensionless, imag. part
2 2 0.000000000e+00          # Diagonal AD term, 1st generation
3 3 0.000000000e+00          # Diagonal AD term, 2nd generation
# Diagonal AD term, 3rd generation
1 2 0.000000000e+00          # Down-squark LR mass insertion 12
2 1 0.000000000e+00          # Down-squark LR mass insertion 21
2 3 0.000000000e+00          # Down-squark LR mass insertion 23
3 2 0.000000000e+00          # Down-squark LR mass insertion 32
1 3 0.000000000e+00          # Down-squark LR mass insertion 13
3 1 0.000000000e+00          # Down-squark LR mass insertion 31

```

D Example of SUSY_FLAVOR output

The parameters defined inside the driver program in Appendix B and in the input file listed in Appendix C should produce identical output. We enclose it here so that SUSY_FLAVOR users can check that the program gives the same result on their own computers and FORTRAN compilers.

The driver file `susy_flavor.f` writes the MSSM Lagrangian parameters and tree-level particle masses to the file `mssm_data.txt`. For the parameters defined in Appendices B and C one has:

```

***** MSSM Lagrangian parameters *****
QED coupling 1/alpha_em(M_Z)      = 1.2793E+02
Weinberg angle s_W^2              = 2.2265E-01
Z boson mass                      = 9.1188E+01

```

W boson mass	= 8.0398E+01	
QCD coupling alpha_s(M_Z)	= 1.1720E-01	
Higgs mixing parameter mu (complex)	= 2.0000E+02	1.0000E+02
Higgs soft mixing parameter m_{12}^2	= -3.9604E+03	
Higgs soft masses $m_{H_1}^2, m_{H_2}^2$	= -6.3208E+03	-5.3679E+04
U(1) gaugino mass (complex)	= 9.5472E+01	0.0000E+00
SU(2) gaugino mass (complex)	= 2.0000E+02	0.0000E+00
SU(3) gaugino mass (real)	= 6.0000E+02	
Left slepton mass matrix, real part:		
9.00009E+04	0.00000E+00	0.00000E+00
0.00000E+00	9.00018E+04	1.80004E+03
0.00000E+00	1.80004E+03	9.00027E+04
Left slepton mass matrix, imaginary part:		
0.00000E+00	0.00000E+00	0.00000E+00
-0.00000E+00	0.00000E+00	9.00022E+02
-0.00000E+00	-9.00022E+02	0.00000E+00
Right slepton mass matrix, real part:		
8.99991E+04	0.00000E+00	0.00000E+00
0.00000E+00	8.99982E+04	0.00000E+00
0.00000E+00	0.00000E+00	8.99973E+04
Right slepton mass matrix, imaginary part:		
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
Slepton LR mixing matrix, real part:		
-9.00010E-03	0.00000E+00	0.00000E+00
0.00000E+00	-1.86094E+00	0.00000E+00
0.00000E+00	0.00000E+00	-3.12978E+01
Slepton LR mixing matrix, imaginary part:		
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
Left squark mass matrix, real part:		
2.50003E+05	0.00000E+00	0.00000E+00
0.00000E+00	2.50005E+05	4.00010E+03
0.00000E+00	4.00010E+03	1.60005E+05
Left squark mass matrix, imaginary part:		
0.00000E+00	0.00000E+00	0.00000E+00

0.00000E+00	0.00000E+00	-2.00005E+03
0.00000E+00	2.00005E+03	0.00000E+00

Right up-squark mass matrix, real part:

2.02498E+05	0.00000E+00	0.00000E+00
0.00000E+00	2.02496E+05	0.00000E+00
0.00000E+00	0.00000E+00	3.99988E+04

Right up-squark mass matrix, imaginary part:

0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00

Right down-squark mass matrix, real part:

3.02497E+05	0.00000E+00	0.00000E+00
0.00000E+00	3.02494E+05	0.00000E+00
0.00000E+00	0.00000E+00	8.99973E+04

Right down-squark mass matrix, imaginary part:

0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00

Up-squark LR mixing matrix, real part:

6.18168E-03	0.00000E+00	0.00000E+00
0.00000E+00	1.79332E+00	0.00000E+00
0.00000E+00	0.00000E+00	2.71002E+02

Up-squark LR mixing matrix, imaginary part:

0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00

Down-squark LR mixing matrix, real part:

-1.19597E-01	0.00000E+00	0.00000E+00
0.00000E+00	-1.87938E+00	0.00000E+00
0.00000E+00	0.00000E+00	-5.56628E+01

Down-squark LR mixing matrix, imaginary part:

0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00
0.00000E+00	0.00000E+00	0.00000E+00

***** Particle masses in GeV: *****

* Fermion masses **

Charged lepton masses	5.110E-04	1.057E-01	1.777E+00
-----------------------	-----------	-----------	-----------

Running u quark masses at m_t scale	2.220E-03	6.440E-01	1.632E+02
---------------------------------------	-----------	-----------	-----------

Running d quark masses at m_t scale	3.885E-03	6.104E-02	2.737E+00
---------------------------------------	-----------	-----------	-----------

```

* Higgs masses **
Tree level (H,h,A,H+):           2.010E+02 8.893E+01 2.000E+02 2.156E+02
1-loop, EPA approximation (H,h): 2.005E+02 1.137E+02

* Tree level SUSY masses **

Sneutrino masses      2.897E+02 2.931E+02 2.965E+02
Slepton masses        2.953E+02 3.028E+02 3.030E+02 3.037E+02 3.038E+02 3.114E+02
U squark masses       2.178E+02 4.486E+02 4.487E+02 4.489E+02 4.971E+02 4.974E+02
D squark masses       2.999E+02 4.049E+02 5.035E+02 5.037E+02 5.505E+02 5.505E+02
Chargino masses       1.552E+02 2.808E+02
Neutralino masses     8.865E+01 1.584E+02 2.322E+02 2.808E+02
Gluino mass          6.000E+02

```

The output for the physical observables is printed on the standard output, usually the computer screen of the console. It should look like:

Electric dipole moments:

Electron EDM	= 4.7256E-25
Muon EDM	= 9.7726E-23
Tau EDM	= 1.6425E-21
Neutron EDM	= 5.9331E-24

Neutrino K decays:

BR($K_L^0 \rightarrow \pi^0 vv$)	= 2.8555E-11
BR($K^+ \rightarrow \pi^+ vv$)	= 7.3932E-11

Leptonic B decays:

BR($B_d \rightarrow \mu^+ \mu^-$)	= 1.2012E-10
BR($B_s \rightarrow \mu^+ \mu^-$)	= 4.7395E-09

$B \rightarrow X_s$ photon decay:

BR($B \rightarrow X_s \gamma$)	= 2.5756E-04
----------------------------------	--------------

KK mixing:

ϵ_K	= 2.3366E-03
Δm_K	= 2.4362E-15

DD mixing:

Δm_D	= 1.6656E-17
--------------	--------------

BB mixing:

Δm_{B_d}	= 3.6999E-13
Δm_{B_s}	= 1.3242E-11

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PROGRAM SUMMARY

Manuscript Title: SUSY_FLAVOR: a computational tool for FCNC and CP-violating processes in the MSSM

Authors: J. Rosiek, P. H. Chankowski, A. Dedes, S. Jäger, P. Tanedo

Program Title: SUSY_FLAVOR

Journal Reference:

Catalogue identifier:

Licensing provisions: None

Programming language: Fortran 77

Operating system: Any, tested on Linux

Keywords: Supersymmetry, K physics, B physics, rare decays, CP-violation

PACS: 12.60.Jv, 13.20.He

Classification: 11.6 Phenomenological and Empirical Models and Theories

Nature of problem:

Predicting CP-violating observables, meson mixing parameters and branching ratios for set of rare processes in the general R-parity conserving MSSM.

Solution method:

We use standard quantum theoretical methods to calculate Wilson coefficients in MSSM and at one loop including QCD corrections at higher orders when this is necessary and possible. The input parameters can be read from an external file in SLHA format.

Restrictions:

The results apply only to the case of MSSM with R-parity conservation.

Unusual features:

Running time:

For single parameter set approximately 1s in double precision on a PowerBook Mac G4

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