SuSeFLAV: program for supersymmetric mass spectra with seesaw mechanism and rare lepton flavor violating decays

Debtosh Chowdhury, Raghuveer Garani and Sudhir K. Vempati

Centre for High Energy Physics,
Indian Institute of Science,
Bangalore 560 012, India
E-mail: debtosh@cts.iisc.ernet.in, rgarani@cts.iisc.ernet.in,
vempati@cts.iisc.ernet.in

ABSTRACT: Accurate supersymmetric spectra are required to confront data from direct and indirect searches of supersymmetry. SuSeFLAV\(^1\) is a numerical tool which is capable of computing supersymmetric spectra accurately for various supersymmetric breaking scenarios applicable even in the presence of flavor violation. The program solves MSSM RGEs with complete 3 × 3 flavor mixing at 2-loop level and one loop finite threshold corrections to all MSSM parameters by incorporating radiative electroweak symmetry breaking conditions. The program also incorporates the Type-I seesaw mechanism with three massive right handed neutrinos at user defined mass scales and mixing. It also computes branching ratios of flavor violating processes such as \(l_j \rightarrow l_i \gamma\), \(l_j \rightarrow 3 l_i\), \(b \rightarrow s \gamma\) and supersymmetric contributions to flavor conserving quantities such as \((g_\mu - 2)\). A large choice of executables suitable for various operations of the program are provided.

KEYWORDS: MSSM, Right Handed Neutrinos, Lepton Flavor Violation

\(^1\)http://cts.iisc.ernet.in/Suseflav/main.html
1 Introduction

Low energy supersymmetry [1] is currently being probed by the Large Hadron Collider (LHC) at CERN and the Tevatron collider at the Fermilab. On the other hand, there is already a huge amount of information which has been collected and is being collected which gives information on low energy supersymmetric lagrangian indirectly. For example, the flavor experiments in the hadronic and the leptonic sectors place strong constraints on the flavor off-diagonal entries in the lagrangian. Similarly, the astrophysical data on dark
matter which has been improved with the latest WMAP 7-year results [2] also strongly restricts the parameter space where the mass and the couplings of the lightest supersymmetric particle (LSP) correspond to the observed relic density. While experimental evidence for supersymmetry is definitely far more superior compared to the indirect detection of supersymmetry, the power of indirect experimental data to constrain the parameter space cannot be underestimated. Furthermore, as it is well known even if there is a positive experimental signal at the LHC, it would be very hard to reconstruct the supersymmetric breaking lagrangian unambiguously due to the large number of degeneracies present in the parameter space which can give similar signals at the colliders [3]. It has also been noted that flavor violating observables and dark matter could help to break these degeneracies [4].

Obviously, the flavor observables depend on the supersymmetric model in which they are calculated. Unfortunately, most of the present supersymmetric mass spectrum calculators do not take in to consideration the effect of flavor violation in the running of soft mass parameters either in the hadronic sector or the leptonic sector. In hadronic sector, typically the CKM is considered to be the only source of flavor violation, while this works very well, as long as one restricts to the scheme of Minimal Flavor Violation (MFV), in a more general scheme of supersymmetric models, such an assumption cannot be supported. Recently ‘observed’ deviations from the Standard Model CKM paradigm [5, 6] might find explanations in terms of a supersymmetric standard model with some amount of flavor violation [7]. To study the associated phenomenology of such kinds of models either for dark matter relic density, collider searches or other theoretical aspects such as threshold corrections to fermion masses, gauge coupling unification etc., would require precise computation of the mass spectrum in these models.

In the leptonic sector, the case for flavor violation is even more stronger. Firstly, neutrinos have non-zero masses and secondly their flavor mixing is large as has been observed in the neutrino oscillation experiments. Most of mechanisms of generating neutrino masses and mixing inevitably lead to large flavor violation in supersymmetric theories. One of the simplest ways to generate neutrino masses is the so called ‘seesaw mechanism’. In the present work, we have restricted ourselves to Type-I seesaw mechanism, though the program can be generalized to incorporate other seesaw mechanisms with significant modifications. The Type-I seesaw mechanism has three singlet right handed neutrinos added to the Standard Model which leads to two additional terms, the Dirac mass term combining the left and right neutrino fields and the lepton number violating Majorana mass term for the right handed singlet fields. The interplay between these two terms leads to small Majorana masses to the left handed neutrinos in the limit of heavy Majorana masses for the right neutrinos. The supersymmetric version of the seesaw mechanism was proposed long ago [9] and some of its consequences for leptonic flavor violations have immediately been noticed. Over the years, other theoretical/phenomenological consequences of having right handed neutrinos has been observed. In the following we list some of them.

1 The recent version of SPheno [34] is an exception.
2 For a summary of the seesaw mechanisms, please see [8].
\textbf{\textit{Y}}_{\tau} − \textbf{Y}_{\tau} \textbf{Unification:} The presence of right handed neutrinos could significantly modify regions where $\tau − b$ Yukawa couplings unify at the GUT scale in unified theories like SO(10) or SU(5) \cite{10–13}. This is due to the fact that the neutrino Dirac Yukawa couplings enter the renormalisation group equations (RGE) of the $Y_b$ and $Y_\tau$ at 2-loop level and $Y_t$ at the 1-loop. This is enough to change the $Y_b/Y_\tau$ ratio at the weak scale, if the neutrino Yukawa couplings are large.

\textbf{\textit{Lepton Flavor Violation:}} As mentioned previously, one of the main consequences of the seesaw mechanism in supersymmetric theories is the violation of lepton numbers leading to rare flavor violating decays\cite{9}. This flavor violation will be generated through the RGE even if the supersymmetry breaking mechanism at the high scale conserves flavor as in mSUGRA. In particular GUT models, the generated flavor violations could be large enough to strongly constrain observability of supersymmetry at the LHC \cite{14, 16–18}. On going experiments like MEG and future experiments like PRISM/PRIME and Super-B factories have enhanced sensitivity to large amounts of parameter space even with small mixing and small $\tan \beta$ \cite{16, 18}.

\textbf{\textit{Dark Matter:}} One of the most surprising phenomenological aspects of seesaw mechanism and SUSY-GUT models has been the impact on Dark matter phenomenology. The presence of a single right handed neutrino with a large Yukawa coupling could significantly enhance the efficiency of the electroweak symmetry breaking and thus making the focus point region unviable within mSUGRA like models \cite{19, 20}. Similarly, GUT effects can significantly effect the stau co-annihilation region \cite{19}. The co-annihilation region and the focus point regions seem to be most vulnerable to these effects in other GUT models and mSUGRA incorporating Type II or Type III seesaw mechanisms \cite{21}. It has been recently realized that even flavor effects could play a role in the relic density calculations in the early universe \cite{22}.

\textbf{\textit{Hadronic flavor violation:}} Incorporating Type I seesaw mechanism in Grand Unified Theories (GUT) also has effects on the hadronic sector. For example, CP violation in the neutrino sector could be transmitted to the quark sector in SU(5) or SO(10) theories \cite{23, 24}. The large phases of the neutrino mass matrix can be transmitted to the hadronic sector with effects in $K$ and $B$ physics phenomenology. More generally in GUT theories, hadronic and leptonic flavor violations are related to each other by the underlying GUT symmetry\cite{25}.

\textbf{\textit{Collider Signals:}} Lepton flavor violation which might be inevitable due to the presence of a seesaw mechanism, can lead to flavor violation in the sleptonic sector as we have mentioned above. Such flavor violation can be studied at the colliders by measuring the mass differences between the sleptons by observing such as sleptonic oscillations etc. \cite{26–29}.

\textbf{\textit{Gauge Coupling Unification:}} Finally, let us note that it has been pointed that the presence of massive right handed neutrinos with large Yukawa couplings in the MSSM lagrangian improves the accurate unification of the gauge couplings because
The above points provide enough justification to determine the supersymmetric mass spectrum in seesaw models at a high precision level including the effects due to flavor violation. Unfortunately, while there exist very good spectrum calculators for supersymmetric theories like ISASUSY [31], SUSPECT [32] and SOFTSUSY [33], they do not consider full flavor violating structure in the computation of the soft spectrum either in their RGE’s or their mass matrices. For these reasons, present versions of these programs might not be suitable for attacking problems listed above unless one significantly modifies them. Our program was written to address this deficiency in publicly available codes. We, however point out that the recent version [34] of SPheno [35] is very similar to the program we are presenting here. It has full flavor structure for the soft masses as well as Yukawas at the 2-loop level and considers the full $6 \times 6$ mass matrices for the sparticles. The preliminary version of our program was first presented at [36]. The present version is an expanded and more structured version of the same. This paper explains the code in detail. We attempted to link the physics discussion with the file structure of the code wherever possible such that the user can modify the code with minimal efforts.

SuSeFLAV is a program written in Fortran 95 in a fixed length format. The recommended compiler for this program is gfortran available in various distributions of Linux. The program can be made executable using other Fortran compilers too, such as ifort and g77, by modifying the Makefile in the main directory. In addition to studying the spectrum of supersymmetric particles the code also computes leptonic flavor violating decays and some hadronic decays. We have implemented the SLHA 2.2 [37] format for dealing with the input parameters and output data. This way, the output of the code can be fed in to other publicly available programs either for computing Dark Matter relic density or for calculating supersymmetric particle decays and production cross-sections at LHC etc. While the main set of RGE’s are written for Type I seesaw mechanism, extending the program for other seesaw mechanisms or even other models would require coding the RGE’s from respective models. However, other parts of the code, like mass spectrum, one-loop corrections etc., which are given in separate files in the source directory can be used to suit the user’s needs.

The rest of the paper is organized as follows. In section 2 we describe the MSSM Lagrangian with Type I Seesaw mechanism. In section 3, we discuss the various supersymmetry breaking scenarios considered in SuSeFLAV. In section 4 we describe the calculation of the low energy supersymmetric spectrum implemented in the program. In section 6 we discuss about the various low energy observables computed in the program. We close with a small set of instructions on how to install and execute SuSeFLAV.

2 Minimal Supersymmetric Seesaw Model

Since 1998, ever increasing data from neutrino sector has firmly established that neutrinos have non-zero masses and that their flavors mix with at least two of their angles being close
to maximal [38]. One of the elegant mechanisms to generate non-zero neutrino masses is through the seesaw mechanism [39], where right handed singlet fields are added to the Standard Model particle spectrum. These singlet neutrinos break lepton number typically at a scale much larger than the standard model scale through their Majorana masses.

Supersymmetric version of the seesaw mechanism is straightforward extension of the Minimal Supersymmetric Standard Model [1] by adding right handed neutrino superfields. The field content of the MSSMRN (MSSM + Right Handed Neutrinos) and their transformation properties under the gauge group $G_{SM} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is given as

$$
L : \left( 1, 2, -\frac{1}{2} \right); \quad e^c : (1, 1, +1); \quad \nu^c : (1, 1, 0);
$$

$$
Q : \left( 3, 2, +\frac{1}{6} \right); \quad u^c : \left( 3, 1, -\frac{2}{3} \right); \quad d^c : \left( 3, 1, \frac{1}{3} \right);
$$

$$
H_u : \left( 1, 2, +\frac{1}{2} \right); \quad H_d : \left( 1, 2, -\frac{1}{2} \right)
$$

where $Q$ and $L$ stand for the $SU(2)_L$ doublet quarks and leptons, $u^c$, $d^c$, $e^c$ and $\nu^c$ stand for the $SU(2)_L$ singlet quarks and leptons, and the two Higgs doublet chiral superfields are denoted by $H_u$ and $H_d$. At the seesaw scale and above, $q^2 \gtrsim M^2_R$, the superpotential takes the form:

$$
W = Y^d_{ij} d^c_i Q_j H_d + Y^u_{ij} u^c_i Q_j H_u + Y^e_{ij} e^c_i L_j H_d
+ Y^{\nu c}_{ij} \nu^c_i L_j H_u + \mu H_u H_d - \frac{1}{2} M_R \nu^c_i \nu^c_i.
$$

where $i, j = \{1, 2, 3\}$ are generation indices. Note that the right handed neutrino Majorana mass matrix is diagonal. The $SU(2)$ and $SU(3)$ contractions are suppressed in the above Lagrangian. In the program, the seesaw scale is taken to be $q^2 = M^2_R$. At this scale, the right handed neutrino mass matrix can be diagonalized by a rotation of the right handed neutrino fields. The Dirac Yukawa matrix $Y^{\nu}$ is defined at this scale in the basis where the right handed neutrino mass matrix is diagonal. SuSeFLAV considers the inputs at the scale $M_{R_3}$ where right handed neutrino masses as well as the neutrino Dirac Yukawa coupling matrix. Finally it should be noted that in the present version of SuSeFLAV, the ordering of the right handed neutrino mass eigenvalues is taken as $M_{R_1} \lesssim M_{R_2} \lesssim M_{R_3}$. We have not included the option of inverted hierarchy for the right handed neutrinos in the present version. The program will abort if such a choice is made.

Below the seesaw scale, once the right handed neutrinos are integrated out, we are left with the five dimensional operator defining the the light neutrino mass matrix as

$$
W = Y^d_{ij} d^c_i Q_j H_d + Y^u_{ij} u^c_i Q_j H_u + Y^e_{ij} e^c_i L_j H_d
+ \mu H_u H_d + \frac{\kappa_{ij}}{\Lambda} L_i H_u L_j H_u
$$

The light neutrino mass matrix is given at the weak scale after the $SU(2)_L \times U(1)_Y$ breaking as

$$
M_\nu = \frac{\kappa_{ij}}{\Lambda} (H_u^0)^2
$$

\[ \text{(2.4)} \]
where $\Lambda$ represents the right handed neutrino mass scale or the seesaw scale and $\langle H^0_u \rangle$ is the vev of the $H_u$ superfield. The five dimensional operator is renormalized from the seesaw scale to the electroweak scale. These corrections can be significant for inverse hierarchal and degenerate spectrum for neutrino masses [40]. The present version of the program does not contain the renormalisation for the light neutrinos, we refer users to use the existing programs like REAP [40]. The main reason for not including the RG effects for light neutrinos has been the famous ambiguity in relating the light neutrino masses to the neutrino Yukawa couplings [41]. Furthermore, we are more interested in the effects of seesaw mechanism on the soft supersymmetric masses and couplings. However, we do provide the option for the users to define the Yukawa matrices in terms of the Casas-Ibarra $R$-parameterization [41]. In this parametrization the neutrino Yukawa matrix $Y^\nu$ is defined in terms of light neutrino masses as well as the right handed neutrino masses. In $R$-parametrization, $Y^\nu$ at the seesaw scale defined as

$$Y^\nu = \frac{1}{\langle H^0_u \rangle^2} D_{\sqrt{M_R}} R D_{\sqrt{M_\nu}} U_{PMNS}^\dagger$$  \hspace{1cm} (2.5)$$

where $U_{PMNS}$ is the Pontecorvo-Maki-Nakagawa-Sakata matrix [42] and $R$ is any $3 \times 3$ orthogonal matrix. The $D_{\sqrt{M_R}}$ and $D_{\sqrt{M_\nu}}$ are defined as

$$D_{\sqrt{M_R}} = \text{diagonal}(\sqrt{M_{R_1}}, \sqrt{M_{R_2}}, \sqrt{M_{R_3}})$$  \hspace{1cm} (2.6)$$

$$D_{\sqrt{M_\nu}} = \text{diagonal}(\sqrt{\kappa_1}, \sqrt{\kappa_2}, \sqrt{\kappa_3})$$  \hspace{1cm} (2.7)$$

where $\kappa_1$, $\kappa_2$ and $\kappa_3$ are light neutrino mass eigenvalues. It is important to note that $R$ can be complex in nature also, but in the present version of SuSeFLAV we take $R$ to be real orthogonal matrix. One can parametrize the $R$ matrix in terms of 3 angles but in SuSeFLAV we have not parametrized the $R$ matrix and left all the 9 elements of $R$ as user defined input. Various other parametrization of the $Y^\nu$ matrix have also been carried out in [43].

In addition to the user defined $Y^\nu$ at the seesaw scale, we also provide two other choices for $Y^\nu$ and $M_R$ based on Grand Unified Models like SO(10). Both these cases consider hierarchal masses for the light neutrinos ($M_\nu$). These are

1. **CKM Case:**

   In this case the $Y^\nu$ and $M_R$ are given as

   $$Y^\nu = \begin{pmatrix} h_u & 0 & 0 \\ 0 & h_c & 0 \\ 0 & 0 & h_t \end{pmatrix} V_{CKM}$$  \hspace{1cm} (2.8)$$

   Diagonal[M_R] = \{M_{R_3}, M_{R_2}, M_{R_1}\} = \{10^{14}, 10^9, 10^6\} \text{ GeV}$$

   where $h_u, h_c, h_t$ are the Yukawa couplings of the up, charm and the top quarks and $V_{CKM}$ is the quark sector mixing matrix.

2. **PMNS Case:**

   - 6 -
In this case the $Y^\nu$ and $M_R$ are given as

$$Y^\nu = \begin{pmatrix} h_u & 0 & 0 \\ 0 & h_c & 0 \\ 0 & 0 & h_t \end{pmatrix} \text{U}_{PMNS} \quad (2.9)$$

Diagonal$[M_R] = \{M_{R_3}, M_{R_2}, M_{R_1}\} = \{10^{14}, 10^9, 10^6\}$ GeV

where $\text{U}_{PMNS}$ is the leptonic mixing matrix. Both $V_{CKM}$ and $\text{U}_{PMNS}$ are defined in the `stdinputs.h` file in the `src/` directory. Below the seesaw scale, $q^2 \lesssim M_{R_3}^2$, the right handed neutrinos (and sneutrinos) decouple from the theory, and the model is defined by MSSM.

The soft supersymmetric breaking terms in the seesaw enhanced MSSM are same as in the MSSM together with the additional terms involving the right handed sneutrinos. These include the mass terms for the gauginos, mass squared terms for all the scalar particles and also the bilinear terms and trilinear terms:

$$- \mathcal{L}_{\text{soft}} = \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right) + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_{\widetilde{L}_i}^2 \widetilde{L}_i \widetilde{L}_j + m_{\widetilde{e}_i}^2 \widetilde{e}_i \widetilde{e}_j + m_{\nu_i}^2 \nu_i \nu_j + \ldots$$

$$+ B_{\mu} H_u H_d + B_{M_{ij}} \nu_i \nu_j + \text{h.c.}$$

$$+ A_{U_{ij}} \sqrt{3} \widetilde{Q}_i \nu_j H_u + A_{D_{ij}} \widetilde{d}_i \widetilde{d}_j H_d + A_{E_{ij}} \widetilde{e}_i \nu_j H_d + A_{\nu_{ij}} \widetilde{L}_i \nu_j H_u \quad (2.10)$$

We use the factorization $\widetilde{A}^u \equiv A^u Y^u$, for all the trilinear couplings at the weak scale $^3$. As noted before, at the energies $q^2 \lesssim M_{R_3}^2$, the right handed sneutrinos also decouple from the theory, along with the right handed neutrinos. In the program, we decouple the right handed neutrinos sequentially at different scales: the heaviest right handed neutrino at $M_{R_3}$ and the second heaviest one at $M_{R_2}$ and the lightest one at $M_{R_1}$.

The right handed neutrinos can be easily removed from the model to recover MSSM without right handed neutrinos, by choosing $Y^\nu = 0$. This automatically decouples the right handed neutrinos in the theory. An explicit option is also provided in the input files, where by turning on/off the parameter `rhn`, one can either include/remove right handed neutrinos in the theory. Finally, let us note that quantum effects above the scale of seesaw $q^2 \gg M_{R_3}^2$ will make the mass matrix $M_R$ non-diagonal. The running of the Majorana mass matrix can also effect the $B_M$ term in the soft potential, described below, at the 1-loop level. The $B_M$ can have implications for flavor physics and EDMs, if it is large through finite terms. These effects [44] are not computed in SuSeFLAV.

The complete set of 2-loop RGE for a general superpotential and MSSM are presented in [45]. For the supersymmetric seesaw model, we use the RGE’s from Ref. [46].

### 3 SUSY Breaking Mechanisms

Supersymmetry is broken spontaneously in a hidden sector and is then communicated to the MSSM sector through the ‘messenger sector’. The messengers could be gauge interactions

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$^3$The RGEs are however, defined in terms of $\tilde{A}^f$, which sets the format for inputs at the high scale. In mSUGRA, we have $\tilde{A}^f = A_0 I$
or gravitational interactions. The result of this communication leads to soft supersymmetry breaking terms in the MSSM. While the form of the soft Lagrangian eq.(2.10) is itself not dependent on the mediation mechanism, the physical quantities i.e., the masses, the couplings etc., are determined in terms of few ‘fundamental’ parameters depending on the mediation mechanism. Popular among such supersymmetry breaking schemes are (i) minimal Supergravity (mSUGRA) (ii) Gauge Mediated Supersymmetry Breaking (GMSB) (iii) Anomaly Mediated Supersymmetry Breaking (AMSB) (iv) Gaugino mediation (v) Moduli mediation etc. among a host of other possibilities [47]. In addition there could be variations within each of the above schemes. In the SuSeFLAV, we have in-built (i) mSUGRA and some of its variations: (a) Non-Universal Higgs Models (NUHM), (b) Non-Universal Gaugino Models (NUGM) and (c) Complete Non-Universal Model (CNUM) and (ii) Gauge Mediated Supersymmetry Breaking (GMSB) models. The corresponding input files are given in the examples/ directory. An input file with completely non-universal soft parameters is also presented for supergravity mediation, where the users can define the boundary conditions of their choice. For other supersymmetric breaking models, the users can modify appropriately the slha.in file and run the program accordingly. In the section below we describe the two supersymmetric breaking scenarios considered in SuSeFLAV.

3.1 mSUGRA and its variations

Supersymmetry is broken spontaneously in a hidden sector and the communicated to the visible sector through the gravitational interactions. If the supergravity Kähler metric is canonical in matter fields, the soft terms resultant after integrating out the supergravity multiplet (while keeping the gravitino mass fixed), are universal in nature [48]. The property universal refers to the flavor space i.e. all the soft terms take the same value irrespective of the flavor at the mediation scale. In SuSeFLAV we have considered the mediation scale to be $M_{GUT}$. At this scale, all the soft terms are determined by four parameters and the sign of a parameter.

1. At $M_{GUT}$ the gaugino masses are universal to a value $M_{1/2}$, i.e.

$$M_1(M_{GUT}) = M_2(M_{GUT}) = M_3(M_{GUT}) \equiv M_{1/2} \quad (3.1)$$

2. The scalar and the Higgs masses are given by the parameter $m_0^2$ at $M_{GUT}$.

$$m_{Q_i}^2(M_{GUT}) = m_{u_{R_i}}^2(M_{GUT}) = m_{d_{R_i}}^2(M_{GUT}) = m_{l_i}^2(M_{GUT}) = m_{l_i}^2(M_{GUT}) \equiv m_0^2 1$$

$$m_{H_u}^2(M_{GUT}) = m_{H_d}^2(M_{GUT}) \equiv m_0^2 \quad (3.2)$$

3. The trilinear couplings are given by the parameter $A_0$ at $M_{GUT}$

$$A_{ij}^u(M_{GUT}) = A_{ij}^d(M_{GUT}) = A_{ij}^l(M_{GUT}) \equiv A_0 1_{ij} \quad (3.3)$$

To specify the spectrum at the weak scale, two more parameters need to be fixed. First is the ratio of the vacuum expectation values (vevs) of the two Higgs fields, $\tan \beta = v_u/v_d$. Second is a discrete parameter, the sign of $\mu$ or the Higgsino mass parameter. The magnitude of $\mu$ is fixed by the radiative electroweak symmetry breaking mechanism which has been incorporated in the program.
3.1.1 Non-Universal Models

In models based on Grand Unified theories, it has been proposed that the strictly universal feature of the soft masses might not be valid and in fact some amount of non-universalities can enter in a model-dependent fashion. For example, in models where the hidden sector gauge kinetic function is no longer singlet under the GUT group, gaugino masses would become non-universal at the high scale. However the non-universalities enter in a predictive fashion when a particular gauge group is chosen, as the ratios of the gaugino masses are now fixed by the Clebsch-Gordan coefficients of respective decomposition. These ratios are well known for the GUT models based on various gauge groups, e.g., SU(5) [49–52], SO(10) [53–55]. Without resorting to any particular model, we have incorporated non-universal gaugino mass scenario in SuSeFLAV, by considering

$$M_1(M_{\text{GUT}}) \neq M_2(M_{\text{GUT}}) \neq M_3(M_{\text{GUT}}).$$

(3.4)

The user has the freedom of choosing any ratios among these three parameters at GUT scale. The corresponding input file is /sinputs-nugm.in. A second class of non-universality which has been incorporated in SuSeFLAV is for the Higgs [56]. It has been argued that since in Grand Unified theories (GUTs) like SO(10), all the matter sits in a single representation while the Higgs sits in separate representation, the universality of the soft masses need not include Higgs, especially when supersymmetry breaking mediation happens close to the GUT scale. It has also been realized that introducing such non-universality makes the $\mu$ parameter free and thus leading to completely different phenomenology at the weak scale especially for dark matter. Thus the boundary conditions at the high scale in our notation are given by

$$m_{\tilde{Q}_i}(M_{\text{GUT}}) = m_{\tilde{u}_R}(M_{\text{GUT}}) = m_{\tilde{d}_R}(M_{\text{GUT}}) = m_{\tilde{L}_i}(M_{\text{GUT}}) = m_{\tilde{L}_i}(M_{\text{GUT}}) \equiv m_0^2 1$$

$$m_{\tilde{H}_u}(M_{\text{GUT}}) \equiv m_{10}^2 \quad ; \quad m_{\tilde{H}_d}(M_{\text{GUT}}) \equiv m_{20}^2$$

(3.5)

Note that we intermittently use the notation $m_{10}$ and $m_{20}$ for the Higgs mass parameters as defined above in the non-universal Higgs mass model. The input file for this case /sinputs-nuhm.in.

3.2 GMSB

The second class of supersymmetric breaking models incorporated in SuSeFLAV is Gauge Mediated Supersymmetric Breaking (GMSB). As before, supersymmetry is broken spontaneously in the hidden sector, but now communicated to the MSSM sector through gauge interactions. The minimal set of models under this category goes under the name, Minimal Messenger Model (MMM) [57]. In this model, a set of messenger superfields transforming as complete representations of SU(5) (⊃ $G_{\text{SM}}$) gauge group and couple directly to a singlet field which parametrized the supersymmetry breaking in the hidden sector. Supersymmetry breaking is then transmitted to the MSSM through SM gauge interactions. The following superpotential represents the messenger sector coupling to the hidden sector

$$\mathcal{W} = \lambda X \Phi_i \bar{\Phi}_i$$

(3.6)
where $\Phi$ and $\bar{\Phi}$ are messenger sector superfields transforming as 5 and $\bar{5}$ of SU(5) and $i$ runs for the number of messenger sector superfields, typically $i = [1, 5]$. The $X$ superfield representing the hidden sector is parameterized by the vacuum expectation values for both its scalar component $\langle X \rangle$ as well as its auxiliary component $\langle F_X \rangle$. Gauge interactions with the messenger fields lead to gauginos attaining masses at 1-loop which at the Messenger scale are given by

$$M_a (M_{mess}) = \frac{\alpha_a (M_{mess})}{4\pi} \Lambda g \left( \frac{\Lambda}{M_{mess}} \right) \sum_i n_a (i);$$

(3.7)

where the Messenger scale $M_{mess} = \lambda (X)$ and $\Lambda = \langle F_X \rangle / \langle X \rangle$. Here $n_a (i)$ is the Dynkin index for the messenger pair $\Phi, \bar{\Phi}$ and the sum runs over all the messengers in each group.

The scalars attain their masses from the 2-loop diagrams. These are given as

$$m_a^2 (M_{mess}) = 2 \alpha^2 f \left( \frac{\Lambda}{M_{mess}} \right) \sum_{a,i} n_a (i) C_a \left( \frac{\alpha_a (M_{mess})}{4\pi} \right)^2$$

(3.8)

Where $C_a$ is the quadratic Casimir invariant of the MSSM fields and the function $g(x)$ and $f(x)$ are defined in [58] and [59] respectively. The leading order contribution to the tri-linear couplings comes from the 2-loop diagrams but they are suppressed by an extra $\alpha/4\pi$ factor compared to the gauging masses. Thus to an very good approximation we can take

$$\tilde{A}_{ij} (M_{Mess}) \simeq 0$$

(3.9)

Thus in minimal GMSB model considered in SuSeFLAV we have the following 5 parameters as inputs

$$\tan \beta, \text{sign}(\mu), M_{mess}, \Lambda \text{ and } n.$$  

(3.10)

The input file `sinput-gmsb.in` and `slha-gmsb.in` are built-in files to specify the inputs of the GMSB model in the `examples/` directory of SuSeFLAV.

4 Calculation of Supersymmetric Spectrum

Once the user chooses the particular model of supersymmetry breaking by typing in the various parameters in the relevant input file, the program computes the spectrum at the weak scale, checks for the various direct and indirect search limits and computes the various observables including the flavor violating ones like $\mu \rightarrow e + \gamma$. The computation of the spectrum involves several complicated intermediate steps which has been already explained in detail by various existing programs [60, 61]. In SuSeFLAV we follow a similar approach in computing the spectrum, however including flavor mixing as well as couplings with right handed neutrinos. In Fig. (1), we have shown the flowchart of the computation of the spectrum and the observables in the program. We can summarize the computation in terms of three steps which however, are not independent of each other as the procedure involves significant number of iterations.
• **RGE evolution:** Using the MSSM RGE for the Yukawa and gauge couplings, run all the known SM parameters like gauge couplings, Yukawa couplings up to the scale of supersymmetry breaking. In the case of mSUGRA, run to the scale where the gauge couplings corresponding to SU(2) \(_L\) \((g_2)\) and U(1) \(_Y\) \((g_1 \equiv \sqrt{\frac{1}{3}} g_Y)\) meet, this determines the GUT scale \((M_{\text{GUT}})\). At the SUSY breaking scale \((M_{\text{GUT}}\) in case of mSUGRA and \(M_{\text{mess}}\) in case of GMSB), with the user defined input parameters and using the GUT scale SM parameters as the boundary conditions, run all the MSSM RGEs including those for the soft terms all the way down to \(M_{\text{SUSY}}\). For the initial run \(M_{\text{SUSY}}\) is defined to be 1 TeV. If seesaw mechanism is switched on, the program takes in to consideration the running of user defined neutrino Yukawa couplings between the seesaw scale and the supersymmetric breaking scale in both directions.

• **Radiative Electroweak symmetry breaking:** The resultant soft parameters at the \(M_{\text{SUSY}}\) are used to check if they satisfy the tree level electroweak symmetry breaking conditions and compute the \(\mu\) parameter. The full one loop effective potential corrections are then computed using the ‘tree level’ \(\mu\) parameter, which is then used to derive the 1-loop corrections to the \(\mu\) parameter. This is repeated iteratively until the \(\mu\) parameter converges.

• **Convergence of the Spectrum:** In the final step, we run all the soft terms to the scale \(M_Z\) where corrections to the SM parameters are added. We compute the supersymmetric corrections to the SM gauge couplings and the third generation fermion masses (top, bottom and tau). The resultant masses are fed in to the RGE routine.
as shown in Fig.(1) and the soft spectrum is evaluated and run to MZ scale. This full iteration is continued until the SM third generation fermion masses converges to user defined precision (usually $O(10^{-3} - 10^{-4})$). Once this masses get converged we calculate various low energy observables (e.g. $\text{BR} (\mu \rightarrow e \gamma)$, $\text{BR} (b \rightarrow s \gamma)$ etc.). In section 6 we have discussed the low energy observables $\text{SuSeFLAV}$ calculates.

In the following we describe each of these steps in more detail.

**4.1 RGE Evolution**

The standard model fermion masses and gauge couplings are the inputs to the program at the weak scale, taken to be equal to the Z-boson mass $M_Z$ in the program. The parameters are divided into two subsets depending on whether radiative corrections are added or not. The parameters, masses of the first two generations quarks and leptons and CKM matrix, for which we do not add radiative corrections are put in the file `src/stdinputs.h`. Other parameters contained in the same file are the leptonic mixing matrix, $U_{\text{PMNS}}$, the $\overline{\text{MS}}$ values of Z-boson mass, $M_Z$, W-boson mass, $M_W$. The pole masses of the top quark $m_t^{\text{pole}}(m_t)$ and tau lepton, $m_\tau^{\text{pole}}(m_\tau)$ and the $\overline{\text{MS}}$ mass of the bottom quark mass, $M_b^{\overline{\text{MS}}}(m_b)$, whose default values are taken to be those from PDG of 2010 [62] are defined in the file `src/SuSemain.f`. The $\overline{\text{MS}}$ gauge couplings, electromagnetic, $\alpha_{\text{em}}(M_Z)$ and the strong coupling, $\alpha_s(\overline{\text{MS}}(M_Z))$ are also considered as inputs and are contained in the file `src/SuSemain.f`. The $\overline{\text{MS}}$ inputs are converted to $\overline{\text{DR}}$ as the RGEs are written in the $\overline{\text{DR}}$ scheme. The conversion for the gauge couplings is given by

$$\alpha_{\text{em}}^{\overline{\text{DR}}}(M_Z) = \left( \frac{1}{\alpha_{\text{em}}^{\overline{\text{MS}}}(M_Z)} - \frac{1}{6\pi} \right)^{-1}, \quad \alpha_s^{\overline{\text{DR}}}(M_Z) = \left( \frac{1}{\alpha_s^{\overline{\text{MS}}}(M_Z)} - \frac{1}{4\pi} \right)^{-1} \quad (4.1)$$

The so defined $\alpha_{\text{em}}^{\overline{\text{DR}}}$ is in turn used to define the $\overline{\text{DR}}$ values of the $\alpha_{1,2}$.

$$\alpha_1(M_Z) \equiv \frac{g_2^2}{4\pi} = \frac{5\alpha_{\text{em}}^{\overline{\text{DR}}}(M_Z)}{3\cos^2 \theta_W}, \quad \alpha_2(M_Z) \equiv \frac{g_1^2}{4\pi} = \frac{\alpha_{\text{em}}^{\overline{\text{DR}}}(M_Z)}{\sin^2 \theta_W} \quad (4.2)$$

In a similar fashion, the bottom mass is converted from the $\overline{\text{MS}}$ to $\overline{\text{DR}}$ using [63]

$$m_b^{\overline{\text{DR}}}(M_Z) = m_b^{\overline{\text{MS}}}(m_b) \cdot \left[ 1 - \frac{\alpha_s(M_Z)}{3\pi} - \frac{23\alpha_2^2(M_Z)}{72\pi^2} + \frac{3\alpha_2(M_Z)}{32\pi} + \frac{13\alpha_1(M_Z)}{288\pi} \right], \quad (4.3)$$

where the coupling constants appearing in the parenthesis are their $\overline{\text{DR}}$ values. The masses of the tau lepton and top quark are converted from their pole masses using the following relations:

$$m_\tau^{\overline{\text{DR}}}(M_Z) = m_\tau^{\text{pole}} \cdot \left[ 1 - \frac{3}{8} \left( \alpha_1(M_Z) - \frac{\alpha_2(M_Z)}{4} \right) \right]$$

$$m_t^{\overline{\text{DR}}}(M_Z) = m_t^{\text{pole}} \cdot \Delta_{m_t}^{QCD} \quad (4.4)$$

where $\Delta_{m_t}^{QCD}$ is given by [64]

$$\Delta_{m_t}^{QCD} = 1 - \frac{\alpha_s(m_t)}{3\pi} \left( 5 - 3\Delta_{t\tau} \right) - \frac{\alpha_s^2(m_t)}{3\pi} \left( 0.538 - \frac{43\Delta_{t\tau}}{24\pi} + \frac{3\Delta_{t\tau}^2}{8\pi^2} \right), \quad (4.5)$$
with \( \Delta_{t_z} = 2 \ln \left( \frac{m_t^{\text{pole}}/M_Z}{M_t} \right) \) and

\[
\alpha_s(m_t) = \frac{\alpha_s^{\overline{\text{DR}}}(M_Z)}{1 + \frac{3}{4\pi} \alpha_s^{\overline{\text{DR}}}(M_Z) \Delta_{t_z}}
\]  

(4.6)

The \( \overline{\text{DR}} \) corrected masses are used to define the \( 3 \times 3 \) Yukawa matrices at the \( M_Z \) scale which form the inputs to the RGE.

\[
Y^u = \frac{\sqrt{2}}{v \sin \beta} \text{Diag}[m_u, m_c, m_t] \cdot V_{\text{CKM}}; \quad Y^d = \frac{\sqrt{2}}{v \cos \beta} \text{Diag}[m_d, m_s, m_b];
\]

\[
Y^e = \frac{\sqrt{2}}{v \cos \beta} \text{Diag}[m_e, m_\mu, m_\tau]
\]

(4.7)

We use the above defined Yukawas to run the full 2-loop RGEs from the weak scale (\( M_Z \)) up to the scale at which the two gauge couplings (\( g_1 \) and \( g_2 \)) unify with an accuracy of 1%. For GMSB scenario this scale is set by the user as messenger scale or \( M_{\text{mess}} \). In the case of right handed neutrinos three intermediate scales get introduced in the theory. As mentioned in the section 2, we consider the seesaw scale to be the mass of the heaviest right handed neutrino, \( M_{R_3} \). At this scale we set the neutrino Yukawa (\( Y^\nu \)) and run the RGEs with this Yukawa up to the high scale. At the high scale, depending on the model, we set the SUSY breaking boundary conditions and then run the RGEs down to the heaviest right handed neutrino mass scale i.e., \( M_{R_3} \). Below this mass scale we decouple the heaviest right handed neutrino by setting its couplings in the neutrino Yukawa matrix to zero. From \( M_{R_3} \) we run down the RGEs to the next heaviest right handed neutrinos i.e., \( M_{R_2} \) and then form \( M_{R_2} \) to \( M_{R_1} \). Below each of these scale, i.e., \( M_{R_2} \) and \( M_{R_1} \), we decouple the corresponding right handed neutrino by setting their couplings to zero. From \( M_{R_1} \) we run the RGEs down to the scale \( M_{\text{SUSY}} \). For the first iteration we take a guess value for \( M_{\text{SUSY}} \) which is 1 TeV. From the second iteration onwards the Electro-Weak Symmetry Breaking (EWSB) scale is set to the geometric mean of the two stop masses or \( \sqrt{m_{\tilde{t}_1} \cdot m_{\tilde{t}_2}} \).

At this scale we check for the EWSB condition and then we calculate the supersymmetric spectrum. A schematic picture of the integration of the RGE’s in mSUGRA with seesaw mechanism is summarized in Figure(2). In GMSB models, the high scale is the messenger scale, \( M_{\text{mess}} \) instead of \( M_{\text{GUT}} \) and the procedure of the integration is very similar. The seesaw mechanism can be incorporated in this class of models as long as heaviest right handed neutrino is lighter than the messenger scale (\( M_{R_3} < M_{\text{mess}} \)).

4.2 Radiative Electroweak Symmetry Breaking

The tree level EWSB conditions at the \( M_{\text{SUSY}} \) scale are defined as below

\[
|\mu|^2 = \frac{1}{2} \left[ \tan^2 \beta (m_{H_u}^2 \tan \beta - m_{H_d}^2 \cot \beta) - M_Z^2 \right]
\]

\[
B_\mu = \frac{\sin 2\beta}{2} \left[ m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 \right]
\]

(4.8)

where \( m_{H_u}^2 \) and \( m_{H_d}^2 \) are the RGE output at \( M_{\text{SUSY}} \). For consistent electroweak symmetry breaking we require \(|\mu|^2 > 0^4\). The tree level \(|\mu|^2\) and RGE output of the other SUSY soft

\(^4\)Further, there should not be any tachyons in the physical Higgs spectrum.
masses is used to calculate the tree level spectrum as described in appendix A. Radiative corrections can however significantly modify the tree level value of $\mu$. Using tree level sparticle spectrum, we calculate the radiative corrections to the higgs potential up to one-loop order as given by BPMZ [65]. The tadpoles modify the $m^2_{H_u}$ and $m^2_{H_d}$ as

$$m^2_{H_u} \to m^2_{H_u} - \frac{t_1}{v_1}; \quad m^2_{H_d} \to m^2_{H_d} - \frac{t_2}{v_2}.$$  \hspace{1cm} (4.9)

With these radiatively corrected higgs, using eq.(4.8), we calculate the radiatively corrected $|\mu|^2$. This is repeated iteratively until the convergence of $|\mu|^2$ reaches the desired accuracy (default value is $O(10^{-4})$). This accuracy level can be changed by changing the parameter tol in file src/ewsbiterate.f. There could be regions where the $\mu$ parameter does not converge within a small number of iterations. In such regions, the program considers the parameter point as $|\mu|$-non convergent. Once $|\mu|$ has converged we calculate $B_\mu$ as

$$B_\mu = \frac{\sin 2\beta}{2} \left[ m^2_{H_u} + m^2_{H_d} + 2|\mu|^2 \right].$$  \hspace{1cm} (4.10)

It is important to note here that at $M_{\text{SUSY}}$, SuSeFLAV checks for D-flat directions in the potential as well as whether the potential is unbounded from below. It also checks for charge and color breaking minima. More details about these checks are discussed in the next section. Even if these conditions are not satisfied the program still proceeds to compute the spectrum however, a flag is raised and written in the output file.
Once $\mu$ is converged, the program uses it to compute complete one loop corrections to the sparticle spectrum. We follow the work of BPMZ \cite{65} in computing these corrections\(^5\). Corrections to sfermions, neutralinos and charginos are evaluated at external momenta equal to $M_{\text{SUSY}}$ as prescribed by BPMZ. In appendix B we have discussed more about these threshold corrections to the sparticles. As mentioned before all the parameters of the code are considered real, including the diagonalising matrices. In determining the neutral higgs masses the user has a choice to employ approximations for two loop which are mostly top-stop enhanced \cite{66} or full one loop tadpole corrections as described in BPMZ or full one loop together with leading order two loop corrections.

### 4.3 Convergence of the Spectrum

In final step, the program evaluates the full one loop flavor conserving supersymmetric threshold corrections to SM parameters. The parameters which are corrected are $m_t$, $m_b$, $m_\tau$, $\alpha_s$, $\alpha_{em}$ and $\sin^2\theta_W$. One loop corrected running masses are given by the following,

\[
\Delta m_t(M_Z) = \Sigma_{t}^{BPMZ} + \Delta QCD, \quad m_t(M_Z) = m_{t}^{\text{pole}}[1 + \Delta m_t(M_Z)]
\]

\[
m_b(M_Z)_{\overline{\text{DR}}}^{\overline{\text{SM}}} = m_b(M_Z)_{\overline{\text{DR}}}^{\overline{\text{SM}}} \frac{1 + \Delta m_t^{BPMZ}}{1 + \Delta m_b^{BPMZ}}
\]

\[
m_\tau(M_Z) = m_\tau^{\text{pole}}[1 + \Sigma_{\tau}^{BPMZ}]
\]

The quantity $\Sigma_{t}^{BPMZ}$ one loop correction to the top quark mass is evaluated at external momenta equal to $m_t^{\overline{\text{DR}}}(M_Z)$. Whereas, $\Delta m_b^{BPMZ}$ and $\Sigma_{\tau}^{BPMZ}$ are evaluated in the limit of external momenta tending to zero. The expressions of these parameters are described in the appendix B. The three gauge couplings get corrected as below

\[
\alpha_1(M_Z) = \frac{5\alpha_{em}^{\overline{\text{DR}}}(M_Z)}{3(1 - \Delta_{\alpha_{em}}) \cos^2 \theta_W}
\]

\[
\alpha_2(M_Z) = \frac{\alpha_{em}^{\overline{\text{DR}}}(M_Z)}{(1 - \Delta_{\alpha_{em}}) \sin^2 \theta_W}
\]

\[
\alpha_3(M_Z) = \frac{\alpha_s(M_Z)}{(1 - \Delta_{\alpha_s})}
\]

where $\Delta_{\alpha_{em}}$ and $\Delta_{\alpha_s}$ are one loop corrections to the electromagnetic and strong coupling described in the appendix B. Note that $\sin^2 \theta_W$ used in the above expressions is also radiatively corrected. Iterative method is implemented to correctly evaluate SUSY contributions to $\sin^2 \theta_W$. The above corrected $\alpha_1(M_Z)$, $\alpha_2(M_Z)$ and $\alpha_3(M_Z)$ and also the third generation SM fermions ($m_t$, $m_b$, $m_\tau$) masses are used as the input for the next long iteration.

\(^5\)Current version of the program does not include flavor violating contributions from sleptons to all the 1-loop corrections. The slepton contributions are neglected in this version in the presence of flavor violation.
The iteration continues until the SM third generation fermions, namely top, bottom and tau mass are converged to user defined precision (usually $\mathcal{O}(10^{-3})$). This precision can be changed by the parameter named spectrum tolerance defined in the input files. Once the SM fermion masses get converged the program proceeds to calculate the various low energy observables. Finally, lets note that if both $LL$ and $RR$ type leptonic flavor violation is present, it could lead to corrections to lepton self energies\cite{67}, which are not included in the present version of the code.

5 Theoretical and Phenomenological Constraints

The requirement of consistent evaluation of supersymmetric spectrum involves a check for theoretical constraints such as charge and color breaking minima (CCB), scalar potential unbounded from below (UFB) and efficient electroweak symmetry breaking at EWSB scale.

With every iterative step of the program SuSeFLAV checks for CCB and UFB conditions at the tree level \cite{68}. These conditions are governed by equations 5.1, 5.2 and are simultaneously implemented while computing the tree level $\mu$ parameter (checking for efficient EWSB, see section 4.2 for the complete description).

\begin{align*}
\text{CCB} : & \quad 3 \left( m_{Q_u}^2 + m_f^2 + |\mu|^2 + m_{H_f}^2 \right) \geq |A_f|^2 \\
\text{UFB} : & \quad m_{H_u}^2 + m_{H_d}^2 + 2 |\mu|^2 \geq 2 |B_\mu|^2 \text{ at } Q > M_{EWSB}
\end{align*}

(5.1)

(5.2)

It is important to note that the complete MSSM spectrum is still calculated even if CCB and UFB conditions are not satisfied. However, if the supersymmetric scalar potential has a charge and color breaking minima which is lower than electroweak minimum a warning flag \text{CCB} is generated. Similarly, if the complete supersymmetric scalar is unbounded from below a warning flag \text{UFB} is generated.

Apart from the above described theoretical constraints the program also imposes additional phenomenological constraints on the obtained spectrum. From the direct non-observation of charged dark matter in the Universe we require $m_{\tilde{\tau}} > m_{\chi^0}$ or LSP being neutral. Regions for which this condition is not true is excluded as $\tilde{\tau}$ LSP regions. Consequently the flag is marked as \text{Stau LSP}. Also, we require the the spectrum to be non-tachyonic. If tachyonic spectrum is encountered it is flagged as \text{tachyon}. The program also indicates the sector where the tachyon occurs, for example: a tachyon in slepton sector is marked as \text{tachyon: slepton sector}. Some lower bounds on various sparticle masses that result from direct searches at colliders, e.g., the lightest Higgs mass $m_h > 114.1$ GeV, and the Chargino mass $m_{\chi^\pm} > 103.5$ GeV \cite{69} are also incorporated in the program. Points failing to satisfy these bounds are flagged as \text{Higgs LEP Limit} and \text{Chargino LEP Limit} respectively. The present version does not include recent direct search limits from LHC \cite{70}.
6 Low Energy Observables

Once the complete supersymmetric spectrum is obtained we compute the following low energy observables in SuSeFLAV.

- **Fine Tuning:** In MSSM the standard model masses and gauge couplings, e.g. $M_Z$, $m_t$, $m_b$ etc. are function of the input parameters of the model, i.e., for mSUGRA $m_0$, $M_{1/2}$, $A_0$, $\tan \beta$ and sign($\mu$). Now, we can recast the EWSB eq.(4.8) as below:

$$M_Z^2 = -2|\mu|^2 + \tan 2\beta \left(m_{H_u}^2 \tan \beta - m_{H_d}^2 \cot \beta\right), \quad (6.1)$$

where, all the parameters on the right side of Eq.(6.1) are at the weak scale. Given that $M_Z$ is know at a few percent level, it can be seen that some amount of ‘tuning’ between the parameters in the right side is needed. Various measures [71–74] have been proposed to quantify the ‘tuning’ needed in some input parameter. In SuSeFLAV, we have followed Barbieri and Giudice [71, 74], in evaluating the fine tuning for a given parameter $\lambda_i$ of the model as

$$\frac{\delta M_Z^2}{M_Z^2} = f(M_Z^2, \lambda_i) \frac{\delta \lambda_i}{\lambda_i} \quad (6.2)$$

Where Barbieri-Giudice function or $f(M_Z^2, \lambda_i)$ is defined as

$$f(M_Z^2, \lambda_i) = \lambda_i \frac{\partial M_Z^2}{\partial \lambda_i} \quad (6.3)$$

We derive the fine tuning in $M_Z^2$ with respect to $\mu^2$ for which $f(M_Z^2, \mu^2)$ takes the following form

$$f(M_Z^2, \mu^2) = \frac{2|\mu|^2}{M_Z^2} \left[1 + \frac{(\tan^2 \beta + 1)}{(\tan^2 \beta - 1)^3} \frac{4 \tan^2 \beta \left(m_{H_d}^2 - m_{H_u}^2\right)}{m_{H_d}^2 + m_{H_u}^2}\right]. \quad (6.4)$$

The fine tuning in $m_t$ with respect to $\mu^2$ or $f(M_Z^2, m_t)$ is expressed as follows

$$f(m_t, \mu^2) = \frac{1}{2} f(M_Z^2, \mu^2) + \frac{1}{\tan^2 \beta - 1} \frac{2|\mu|^2}{m_{H_u}^2 + m_{H_d}^2} \quad (6.5)$$

- **Electro-Weak Precision Measurement:** The electroweak observables $\rho$ parameter and $\sin^2 \theta_W$ are defined in 6.6 and 6.7.

$$\rho = \frac{M_W}{M_Z \cos \theta_W} \quad (6.6)$$
$$\sin^2 \theta_W = 1 - \frac{M_Z^2}{M_W^2} \quad (6.7)$$

At the tree level $\rho$ parameter is unity and $\sin^2 \theta_W = 0.2286$. A deviation from these values are observed at one-loop level stemming from SM and supersymmetric
corrections to $W$ and $Z$ boson masses. A measure of this deviation to $\rho$ parameter is given below

$$\Delta \rho = \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2}$$

(6.8)

and

$$\rho = \frac{1}{(1 - \Delta \rho)}$$

(6.9)

The correction to $\sin^2 \theta_W$ is described in appendix B. A precise measurement of these parameters by LEP, SLC and Tevatron imposes stringent constraints on $\Delta \rho$, requiring $\Delta \rho \leq 2 \times 10^{-3}$ for a physically viable spectrum.

- **BR($b \to s\gamma$) Constraint:** Another sector where the effect of SUSY particles can be seen is the radiative flavor changing decay of bottom quark, $b \to s\gamma$ [75]. In the Standard model, this decay is mediated by loops containing charge $\frac{2}{3}$ quarks and $W$ bosons but in SUSY theories, additional contributions come from loops involving charginos ($\tilde{\chi}^\pm$) and stop ($\tilde{t}$) squarks and charged Higgs bosons ($H^\pm$). Since SM and SUSY contributions appear at the same order of perturbation theory, the measurement of BR($b \to s\gamma$) is a very powerful tool for constraining the SUSY parameter space. In SuSeFLAV we have followed Bartl et al. [76], which includes Standard model NLO as well as MSSM LO contributions. Like the other observables, this branching ratio is calculated for all the valid points and written in the SLHA file. More precise evaluations of this process are available publicly in the [34, 77].

- **Anomalous Magnetic Moment of Muon ($g_\mu - 2$):** The muon anomalous magnetic moment ($g_\mu - 2$) has been precisely measured by Muon ($g - 2$) collaboration [78, 79]. Due to supersymmetric particles in the loop, ($g_\mu - 2$) gets non-negligible correction apart from the SM contribution. The experimentally measured value of anomalous magnetic moment of muon is:

$$a^{exp}_\mu = \frac{(g_\mu - 2)}{2} = (11659208 \pm 6) \times 10^{-10}$$

(6.10)

Whereas, the difference in theoretical prediction by SM and experimental value, i.e $a^{exp}_\mu - a^{SM}_\mu = (28.7 \pm 8.0) \times 10^{-10}$ [81]. Here the difference arises because of the fact of different estimates of hadronic vacuum polarization contribution. The contribution from the supersymmetric particles to ($g_\mu - 2$) is through ($\tilde{\chi}^0 - \tilde{\mu}/\tilde{\tau}/\tilde{e}$) loop or through ($\tilde{\chi}^\pm - \tilde{\nu}$) loop. Supersymmetric parameter space can be severely constrained [80]. Moreover, both these contributions are $\tan \beta$ enhanced, so large values of $\tan \beta (\gtrsim 30)$ are more severely constrained. We have taken the expression for one-loop contribution, due to supersymmetric particles, to the ($g_\mu - 2$) from Hisano et al. [14]. For a given set of input parameter SuSeFLAV calculates the ($g_\mu - 2$) and writes it into the SLHA file. Two loop contributions are not added in the present version which could be important in the very large $\tan \beta$ regime[82].

- **Lepton Flavor Violating Decays:** Subject to satisfying phenomenological constraints at $M_{\text{SUSY}}$, we evaluate decay rates of rare lepton flavor violating processes.
The decay rates and branching ratios for the following processes are computed \( \mu \to e\gamma \), \( \tau \to e\gamma \), \( \tau \to \mu\gamma \), \( \mu \to e^+e^-e^- \), \( \tau^- \to \mu^+\mu^- \), \( \tau^- \to e^+e^-e^- \) and \( \mu - e \) conversion rate in the nuclei. The search for charged lepton flavor violating decays can play a pivotal role in studying and discovering new physics beyond the standard model at TeV scale and above. In calculating the amplitudes we closely follow the notations and expressions provided in [14, 15]. The contribution to \( \mu - e \) conversion rate in the nuclei is through penguin diagram where \( \gamma, Z \) is exchanged and through box diagrams containing \( \chi^0 - \tilde{l}_i - q_{u,d} \) loops or \( \chi^- - \tilde{\nu}_i - q_{u,d} \) loops. The current experimental upper bound on various LFV processes is tabulated in Table 1.

In the current version of SuSeFLAV we use the tree level masses and full \( 6 \times 6 \) slepton mixing matrix to calculate LFV observables. The output is written in the BLOCK Low Energy in SLHA format.

7 Executing SuSeFLAV

Instruction to compile and install the package is provided in README file. Note that LAPACK [87] library is a prerequisite to the package. SuSeFLAV package produces three executables when compiled, namely suseflav, suseflavslha and suseflavscan. To compute the spectrum for a single point the usage of executables suseflav and suseflavslha is recommended. The user must modify the corresponding input files sinputs.in and slha.in where all the input parameters are specified. To scan the parameter space the usage of the executable suseflavscan is recommended. The corresponding input parameters are in the input file sinputs.scan.in.

7.1 Sample Input/Output

In this section we provide examples of input files which can be used to run the program. SuSeFLAV has two input/output modes. This can be broadly classified into SLHA I/O interface and non-SLHA or traditional SuSeFLAV I/O interface. The directory examples/ contains a variety of input files with which the user can run different models.
7.1.1 SLHA Interface

The main source file is runslha.f. To use the SLHA interface the user should execute suseflavslha by modifying the corresponding input file slha.in. Note that the user must rename the required slha file as slha.in to use that particular file as input. To run the program type the following command at the terminal

```bash
./suseflavslha
```

This sample input/output corresponds to SPS2 [88] or ‘focus point’ with Type I see-saw mechanism with maximal mixing in mSUGRA/CMSSM scenario.

```
Block MODSEL # Select model
  1 0 # sugra
Block SMINPUTS # Standard Model inputs
  1 1.27908953E+02 # alpha_em^(-1)(MZ) SM MSbar
  2 1.16637000E-05 # G_Fermi
  3 1.17200000E-01 # alpha_s(MZ) SM MSbar
  5 4.23000000E+00 # mb(mb) SM MSbar
  6 1.73100000E+02 # mtop(pole)
  7 1.77700000E+00 # Mtau
Block MINPAR # Input parameters
  1 1.45000000E+03 # m0
  2 3.00000000E+02 # m1/2
  3 10.00000000E+00 # tanb
  4 1.00 # sign(mu)
  5 0.00000000E+00 # A0
Block EXTPAR
Block SUSEFLAV # Algorithm specific inputs
  1 1.000000000e-03 # spectrum tolerance
  2 1.000000000E+00 # Right handed neutrino (1 = yes; 0 = no)
  3 1.000000000E+00 # print Control (0 = do not print output; 1 = print output)
  4 2.000000000E+00 # RHN mixing : 1 = ckm; 2 =PMNS; 3 = user defined
  5 2.000000000E+00 # 2-loop running (1 = 1loop; 2 = 2loop)
  6 1.680000000E-01 # Ue3, if mixing is pmns
  7 1.000000000E+06 # MR1, Lightest rhn decoupling scale
  8 1.000000000E+09 # MR2, second lightest rhn decoupling scale
  9 1.000000000E+12 # MR3, Heaviest rhn decoupling scale
 10 0.000000000E+00 # Dirac neutrino mixing matrix 1,1
 11 0.000000000E+00 # Dirac neutrino mixing matrix 1,2
 12 0.000000000E+00 # Dirac neutrino mixing matrix 1,3
 13 0.000000000E+00 # Dirac neutrino mixing matrix 2,1
 14 0.000000000E+00 # Dirac neutrino mixing matrix 2,2
 15 0.000000000E+00 # Dirac neutrino mixing matrix 2,3
 16 0.000000000E+00 # Dirac neutrino mixing matrix 3,1
 17 0.000000000E+00 # Dirac neutrino mixing matrix 3,2
```
The corresponding SLHA output is generated in slha.out

# BLOCK SPINFO # Program information
1 SuSeFLAV # Spectrum calculator
2 1.0 # version number
#
# BLOCK MODSEL # MODEL NAME
1 0 mSUG+RHN
#
# BLOCK MINPAR # Input parameters
1 1.45000000E+03 # m0
2 3.00000000E+02 # m_1/2
3 1.00000000E+01 # tanbeta
4 1.00000000E+00 # sign(mu)
5 0.00000000E+00 # A0
#
# BLOCK SMINPUTS # Standard Model inputs
1 1.27908953E+02 # alpha_em (M_Z)^MSbar
2 1.16637000E-05 # G_F [GeV^-2]
3 1.17200000E-01 # alpha_S(M_Z)^MSbar
4 9.11876000E+01 # M_Z pole mass
5 4.23000000E+00 # mb(mb)_MSbar
6 1.73100000E+02 # mt pole mass
7 1.77700000E+00 # mtau pole mass
#
# BLOCK EXTPAR # Input parameters
0 1.11007905E+03 # EWSB scale
#
# BLOCK MASS # Mass Spectrum
# PDG code mass particle
24 8.03980000E+01 # W+
25 1.14627152E+02 # h
35 1.57979980E+03 # H
36 1.57158145E+03 # A
37 1.58436060E+03 # H+
5 4.23000000E+00 # b pole mass calculated from mb(mb)_MSbar
1000001 1.54662250E+03 # ~d_L
2000001 1.54348048E+03 # ~d_R
1000002 1.54438338E+03 # ~u_L
2000002 1.54234459E+03 # ~u_R
1000003 1.54616904E+03 # s_L
2000003 1.54344296E+03 # s_R
1000004 1.54386767E+03 # c_L
2000004 1.54216100E+03 # c_R
1000005 1.28027654E+03 # b_1
2000005 1.53642807E+03 # b_2
1000006 9.57438477E+02 # t_1
2000006 1.30949732E+03 # t_2
1000011 1.45536277E+03 # e_L
2000011 1.45237611E+03 # e_R
1000012 1.45621835E+03 # nu_eL
1000013 1.45515677E+03 # mu_L
2000013 1.45238122E+03 # mu_R
1000014 1.45743959E+03 # nu_muL
1000015 1.37985560E+03 # tau_1
2000015 1.43974260E+03 # tau_2
1000016 1.38315587E+03 # nu_tauL
1000021 8.00501135E+02 # g
1000022 1.22111121E+02 # chi_10
1000023 2.35849664E+02 # chi_20
1000025 6.46536229E+02 # chi_30
1000035 -6.47047202E+02 # chi_40
1000024 2.29600397E+02 # chi_1+
1000037 6.41409970E+02 # chi_2+

# BLOCK LOW ENERGY # PARAMETERS
1 4.57703348E-03 # Delta rho parameter
2 1.63880224E-11 # g_mu -2
3 3.93481028E-04 # Br(b -> s gamma)
4 7.88849738E-15 # Br(tau -> mu gamma)
5 2.04763719E-21 # Br(tau -> e gamma)
6 7.68247896E-09 # Br(mu -> e gamma)
7 4.09278568E-17 # Br(tau -> mu mu mu)
8 2.69634537E-23 # Br(tau -> e e e)
9 5.55320321E-11 # Br(mu -> e e e)

# BLOCK FINETUNE # fine-tuned if >>1
1 4.84909023E+01 # delta mZ^2/mZ^2 (mu^2)
2 9.69700899E+01 # delta mt/mt (mu^2)

# BLOCK NMIX # Neutralino Mixing Matrix
1 1 -9.99984262E-01 # N_11
1 2 -2.75706387E-04 # N_12

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# BLOCK STOPMIX  # Stop Mixing Matrix
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# BLOCK SBTMIX  # Sbottom Mixing Matrix
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<td>-3.02513960E-02</td>
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# BLOCK STAUMIX  # Stau Mixing Matrix
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<td># cos(theta_tau)</td>
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<td>7.01503955E-02</td>
<td># sin(theta_tau)</td>
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<td>-7.01503955E-02</td>
<td># -sin(theta_tau)</td>
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2 2 9.97524681E-01 # cos(\theta_{\tau})

# BLOCK ALPHA # Higgs mixing
-1.04280371E-01 # Mixing angle in the neutral Higgs boson ser

# BLOCK HMIX Q= 1.11007905E+03 # DRbar Higgs Parameters
  1 6.42293220E+02 # mu(Q)
  2 9.61690427E+00 # tanbeta(Q)
  3 2.44078407E+02 # vev(Q)
  4 2.49535067E+06 # M_A^2(Q)

# BLOCK GAUGE Q= 1.11007905E+03 # The gauge couplings
  1 3.61224938E-01 # gprime(Q) DRbar
  2 6.47307359E-01 # g(Q) DRbar
  3 1.07204094E+00 # g_3(Q) DRbar

# BLOCK Au Q= 1.11007905E+03 # The trilinear couplings
  1 1 -7.04371021E+02 # A_u(Q) DRbar
  2 2 -7.04359518E+02 # A_c(Q) DRbar
  3 3 -5.33637535E+02 # A_t(Q) DRbar

# BLOCK Ad Q= 1.11007905E+03 # The trilinear couplings
  1 1 -8.74412923E+02 # A_d(Q) DRbar
  2 2 -8.89277117E+02 # A_s(Q) DRbar
  3 3 -9.03971853E+02 # A_b(Q) DRbar

# BLOCK Ae Q= 1.11007905E+03 # The trilinear couplings
  1 1 -1.77265415E+02 # A_e(Q) DRbar
  2 2 -1.77262031E+02 # A_mu(Q) DRbar
  3 3 -1.75316021E+02 # A_tau(Q) DRbar

# BLOCK Yu Q= 1.11007905E+03 # The Yukawa couplings
  3 3 8.81895531E-01 # y_top(Q) DRbar

# BLOCK Yd Q= 1.11007905E+03 # The Yukawa couplings
  3 3 1.36059968E-01 # y_b(Q) DRbar

# BLOCK Ye Q= 1.11007905E+03 # The Yukawa couplings
  3 3 1.02288419E-01 # y_tau(Q) DRbar

# BLOCK MSOFT Q= 1.11007905E+03 # soft SUSY breaking masses at thscale Q
  1 1.22720963E+02 # M_1
  2 2.30547137E+02 # M_2
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<td>22</td>
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<td># M^2_Hu</td>
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<td>34</td>
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<td>35</td>
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<td># M_bR</td>
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# BLOCK SLEPMIX  # Slepton Mixing Matrix

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The program prints BLOCK SLEPMIX in the SLHA output, which contains the elements of the tree level 6×6 slepton mixing matrix. The notation and the method of diagonalization is explained in more detail in the appendix.

7.1.2 Non-SLHA Interface

The main source file for non-SLHA input is runonce.f. To use the traditional SuSeFLAV interface the user should execute suseflav by modifying the corresponding input file. This executable takes the following input files, sinputs.in for mSUGRA/CMSSM models, sinputs-gmsb.in for GMSB models, sinputs-nuhm.in for non-universal higgs model (NUHM2) models and sinputs-cnum.in for complete non-universal models. For example, to run the program with complete non-universal boundary conditions type the following command in the terminal

```
./suseflav <sinputs-cnum.in
```

The sample input/output below corresponds to the SPS1a [88] with Type I see-saw mechanism with minimal mixing in the context of mSUGRA/CMSSM scenario. To execute the program for the sample point type the following command in the terminal

```
./suseflav <sinputs.in
```
# 1= rhn on; 0 = rhn off
CKM  # case: CKM/MNS/USD
0.10000  # ue3 : relevant if case is MNS
1.0000E-03  # spectrum tolerance
1.7270E+02  # Mtpole
4.23000  # Mbpole
1.77000  # Mtaupole
1.0000E+06  # MR1
1.0000E+09  # MR2
1.0000E+14  # MR3
0.0000E+00  # Ynu(1,1)
0.0000E+00  # Ynu(1,2)
0.0000E+00  # Ynu(1,3)
0.0000E+00  # Ynu(2,1)
0.0000E+00  # Ynu(2,2)
0.0000E+00  # Ynu(2,3)
0.0000E+00  # Ynu(3,1)
0.0000E+00  # Ynu(3,2)
0.0000E+00  # Ynu(3,3)

The Output in SuSeFLAV format is contained in the file suseflav.out.

******* begin program SuSeFLAV ************
loop 2
tanbeta = 10.00000000000000
m0 = 100.00000000000000
a0 = -100.00000000000000
M12 = 250.00000000000000
m10 = 100.00000000000000
m20 = 100.00000000000000
sign mu = 1.00000000000000
rhn = 1
Ue3 = 0.000000000000000E+00

case = CKM
top pole mass = 172.70000000000000
MR1 1000000.00000000
MR2 1000000000.00000
MR3 100000000000000.

********************************************
100.00000000000000 250.00000000000000 -100.00000000000000

LEP excluded – higgs
up-type yukawa at high energy:

<table>
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<tr>
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lepton-type yukawa at high energy:

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neutrino yukawa at high energy:

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lepton-type yukawa at msusy:

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alpha_1 = 1.7238E-02

alpha_2 = 3.3412E-02

alpha_3 = 9.7424E-02

Spectrum at ms, 4.7514E+02

vev1 = 2.4534E+01
vev2 = 2.3888E+02
newtbeta = 9.7365E+00
\mu = 3.6888E+02
\tilde{\text{gluino}} = 6.1674E+02
\tilde{\text{stop}}_1 = 4.1019E+02
\tilde{\text{stop}}_2 = 5.8576E+02
\tilde{\text{scharm}}_R = 5.4765E+02
\tilde{\text{scharm}}_L = 5.6403E+02
\tilde{\text{sup}}_R = 5.4767E+02
\tilde{\text{sup}}_L = 5.6406E+02
\tilde{\text{sbottom}}_1 = 5.1580E+02
\tilde{\text{sbottom}}_2 = 5.4902E+02
\tilde{\text{sstrange}}_R = 5.4749E+02
\tilde{\text{sstrange}}_L = 5.6975E+02
\tilde{\text{sdown}}_R = 5.4752E+02
\tilde{\text{sdown}}_L = 5.6999E+02
\tilde{\text{stau}}_1 = 1.3540E+02
\tilde{\text{stau}}_2 = 2.0577E+02
\tilde{\text{smu}}_R = 1.4105E+02
\tilde{\text{smu}}_L = 1.0233E+02
\tilde{\text{sel}}_R = 1.4588E+02
\tilde{\text{sel}}_L = 1.0290E+02
\tilde{\tau}_{\text{usnu}} = 1.9448E+02
\tilde{\mu}_{\text{usnu}} = 1.9719E+02
\tilde{\text{elsnu}} = 1.9718E+02

Higgs Spectrum
mA0 = 4.0400E+02
mh_{\text{charged}} = 4.2047E+02
mh0 = 1.1148E+02
mH = 4.1036E+02

Neutralino spectrum
N1 = -372.350950946618
N2 = 100.207525184981
N3 = 370.720867716668
N4 = 193.762699042750

Chargino spectrum
C1 = -1.9073E+02
C2 = 3.6830E+02

Low Energy Observables
### 8 Outlook

The MEG experiment has recently reported the latest limits on the rare leptonic decay $\mu \to e + \gamma$ [83]. Simultaneously, there are results from LHC as well as direct detection dark matter experiments. *SuSeFLAV* is designed to compute supersymmetric spectrum with full flavor violation and further to compute most of the leptonic flavor violating observables. The program can be coupled to Dark Matter routines such as *micrOMEGAs*, *DarkSUSY* and *SuperIso* to compute the relic density and direct detection rates. The program is free under the GNU Public License and can be downloaded from the following websites:

- [http://cts.iisc.ernet.in/SuSeflav/main.html](http://cts.iisc.ernet.in/SuSeflav/main.html)
- [http://projects.hepforge.org/suseflav/](http://projects.hepforge.org/suseflav/)

In the present version of the program only Type I seesaw mechanism is implemented. Future versions will include other seesaw mechanisms as well as other improvements like inclusion new flavor violating decays rates in the quark sector.

### Acknowledgments

We appreciate discussions with and acknowledge suggestions and inputs from L. Calibbi, S. Kraml, W. Porod and O. Vives. We thank U. Chattopadhyaya, Aseeshkrishna Dutta, D. Grellscheid and M. Guchait for encouragement. SKV thanks M. Ciuchini, A. Faccia, A. Masiero, P. Paradisi and L. Silvestrini for collaborations during which parts of this program were written. SKV acknowledges support from DST project “Complementarity between direct and indirect searches for Supersymmetry” and also support from DST Ramanujan Fellowship SR/S2/RJN-25/2008. RG acknowledges support from SR/S2/RJN-25/2008. DC acknowledges partial support from SR/S2/RJN-25/2008.

<table>
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<tr>
<td>$\text{Fine tuning, } C_{m\mu}^2 = 1.6601 \times 10^1$</td>
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<tr>
<td>$\text{Br}(\mu \to e,\gamma) = 5.1611 \times 10^{-11}$</td>
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<td>$\text{Br}(\tau \to \mu,\gamma) = 3.7558 \times 10^{-3}$</td>
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<tr>
<td>$\text{Br}(\tau \to e,\gamma) = 1.6131 \times 10^{-7}$</td>
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<tr>
<td>$\text{Br}(\tau \to e,e,e) = 4.5897 \times 10^{-12}$</td>
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<tr>
<td>$\text{Br}(\mu \to e,e,e) = 3.8643 \times 10^{-12}$</td>
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<td>$\frac{(g-2)}{2} = 1.8184 \times 10^{-10}$</td>
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<table>
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A Tree-Level Masses

Here we suppress any gauge indices and follow the notation of BPMZ\textsuperscript{6} [65] closely. The Lagrangian contains the neutralino mass matrix as

\[ -\frac{1}{2} \tilde{\psi}^0 \mathcal{M}_{\tilde{\psi}^0} \tilde{\psi}^0 + h.c., \] (A.1)

where \( \tilde{\psi}^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u)^T \) and

\[
\mathcal{M}_{\tilde{\psi}^0} = \begin{pmatrix}
M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\
0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\
-M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\
M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0
\end{pmatrix}. \] (A.2)

We use the letter \( s \) and \( c \) for sine and cosine, so that \( s_\beta = \sin \beta \), \( c_\beta = \cos \beta \) and \( s_W(c_W) \) is the sine (cosine) of the weak mixing angle. The 4 \( \times \) 4 neutralino mixing matrix is an orthogonal matrix \( O \) with real entries, such that \( O^T \mathcal{M}_{\tilde{\psi}^0} O \) is diagonal. The neutralinos \( \chi_0^i \) are defined such that their absolute masses increase with increasing \( i \). Some of their mass values can be negative.

We make the identification \( \tilde{W}^\pm = (\tilde{W}^1 \mp i\tilde{W}^2)/\sqrt{2} \) for the charged winos and \( \tilde{H}_u^+, \tilde{H}_d^- \) for the charged higgsinos. The Lagrangian contains the chargino mass matrix as

\[ -\frac{1}{2} \tilde{\psi}^- \mathcal{M}_{\tilde{\psi}^-} \tilde{\psi}^- + h.c., \] (A.3)

where \( \tilde{\psi}^+ = (\tilde{W}^+, \tilde{H}_u^+)^T \), \( \tilde{\psi}^- = (\tilde{W}^-, \tilde{H}_d^-)^T \) and

\[
\mathcal{M}_{\tilde{\psi}^\pm} = \begin{pmatrix}
M_2 & \sqrt{2} M_W s_\beta \\
\sqrt{2} M_W c_\beta & \mu
\end{pmatrix}. \] (A.4)

The chargino masses are found by acting on the matrix \( \mathcal{M}_{\tilde{\psi}^\pm} \) with a bi-unitary transformation, so that \( U^T \mathcal{M}_{\tilde{\psi}^\pm} V \) is a diagonal matrix containing the two chargino mass eigenvalues, \( m_{\tilde{\chi}^\pm_i} \). The matrices \( U \) and \( V \) are easily found, as they diagonalize, respectively, the matrices \( \mathcal{M}_{\tilde{\psi}^+} \mathcal{M}_{\tilde{\psi}^+}^T \) and \( \mathcal{M}_{\tilde{\psi}^-} \mathcal{M}_{\tilde{\psi}^-}^T \). And we have taken the \( U \) and \( V \) matrices to be real.

At tree level the gluino mass, \( m_3 \), is given by \( M_3 \).

The tree-level squark and slepton mass squared values for the family \( i \) are found by diagonalising the following mass matrices \( \mathcal{M}^2_{ij} \) defined in the \((\tilde{f}_L, \tilde{f}_R)^T\) basis:

\[
\begin{pmatrix}
(m_Q^2)_{ii} + m_{u_i}^2 + \left( \frac{1}{2} - \frac{3}{2} s_W^2 \right) M_Z^2 c_2 \beta \\
m_{u_i} \left( A_{\tilde{d}} \right)_{ii} - \mu c_\beta \\
m_{u_i} \left( A_{\tilde{d}} \right)_{ii} + \mu \cot \beta
\end{pmatrix}, \] (A.5)

\[
\begin{pmatrix}
(m_Q^2)_{ii} + m_d^2 - \left( \frac{1}{2} - \frac{3}{2} s_W^2 \right) M_Z^2 c_2 \beta \\
m_d \left( A_{\tilde{d}} \right)_{ii} - \mu \tan \beta \\
m_d \left( A_{\tilde{d}} \right)_{ii} + \mu \beta
\end{pmatrix}. \] (A.6)

\textsuperscript{6}Except in our case the sign of \( \mu \) parameter is opposite of BPMZ.
\[
\begin{bmatrix}
(m^2_f)_{ii} + m^2_{\tilde{e}_i} - \left(\frac{1}{2} - s_W^2\right) M^2_Z c_{2\beta} & m_{e_i} \left(\tilde{A}_e\right)_{ii} - \mu \tan \beta \\
m_{e_i} \left(\tilde{A}_e\right)_{ii} - \mu \tan \beta & (m^2_{\tilde{e}_i})_{ii} + m^2_{\tilde{e}_i} - s_W^2 M^2_Z c_{2\beta}
\end{bmatrix},
\tag{A.7}
\]

where, \(m_f, e_f\) are the mass and electric charge of fermion \(f\) respectively. The mixing of the first two families is suppressed by a small fermion mass, which we approximate to zero. The sfermion mass eigenstates are given by

\[
\begin{pmatrix}
(m^2_{\tilde{f}_1}) & 0 \\
0 & (m^2_{\tilde{f}_2})
\end{pmatrix} = \begin{pmatrix} c_f & s_f \\ -s_f & c_f \end{pmatrix} \begin{pmatrix} c_f - s_f \\ s_f \end{pmatrix},
\tag{A.8}
\]

where \(c_f\) is the cosine of the sfermion mixing angle, \(\cos \theta_f\), and \(s_f\) is \(\sin \theta_f\). These angles are given by

\[
\tan(2\theta_u) = \frac{2 m_u \left(\tilde{A}_u - \mu \cot \beta\right)}{m^2_Q - m^2_u + \left(\frac{1}{2} - 2 e_u s^2_W\right) M^2_Z c_{2\beta}},
\tag{A.9}
\]

\[
\tan(2\theta_d) = \frac{2 m_d \left(\tilde{A}_d - \mu \tan \beta\right)}{m^2_Q - m^2_d + \left(-\frac{1}{2} - 2 e_d s^2_W\right) M^2_Z c_{2\beta}}.
\tag{A.10}
\]

To calculate the lepton flavor violating decays, we diagonalize the full \(6 \times 6\) sleptonic mass matrix \((M^2_\tilde{l})\) by \(U^T M^2_\tilde{l} U\), where \(U\) is the sleptonic mixing matrix with real entries. In the gauge basis of \(\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\}^T\) the sleptonic mass matrix is defined as

\[
M^2_\tilde{l} = \begin{bmatrix}
m^2_{\tilde{e}_L} + [m^2_{\tilde{e}_i} - \left(\frac{1}{2} - s_W^2\right) M^2_Z c_{2\beta}] & 1 \\
m_{e_i} \left(\tilde{A}_e\right)_{ii} - \mu \tan \beta & m^2_{\tilde{e}_e} + [m^2_{\tilde{e}_i} - s_W^2 M^2_Z c_{2\beta}] & 1
\end{bmatrix},
\tag{A.11}
\]

where \(m^2_{\tilde{e}_L}, m^2_{\tilde{e}_e}\) and \(\tilde{A}_e\) are the scalar mass matrices and tri-linear coupling matrix respectively. Using the full \(6 \times 6\) sleptonic mixing matrix we define the lepton flavor violating couplings following Hisano et al. \[14\]. With these couplings we calculate the rare lepton flavor violating decays as described in section 6.

Given values for \(\tan \beta\) one can write the CP-odd Higgs-boson mass, \(m_A\), and the other Higgs masses at tree level by

\[
m^2_A = \frac{2 B_\mu}{\sin 2\beta} = 2 |\mu|^2 + m^2_{H_u} + m^2_{H_d},
\tag{A.12}
\]

\[
m^2_{H_{\pm}} = \frac{1}{2} \left(m^2_A + M^2_Z \pm \sqrt{(m^2_A + M^2_Z)^2 - 4 m^2_A M^2_Z c^2_{2\beta}}\right),
\tag{A.13}
\]

and

\[
m^2_{H^{\pm}} = m^2_A + M^2_W.
\tag{A.14}
\]

The CP-even gauge eigenstates \((H^0_d, H^0_u)\) are rotated by the angle \(\alpha\) into the mass eigenstates \((H, h)\) as follows,

\[
\frac{1}{\sqrt{2}} \begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \Re H^0_d \\ \Re H^0_u \end{pmatrix}.
\tag{A.15}
\]
At tree level, the angle $\alpha$ is given by

$$\tan 2\alpha = \frac{m^2_A + M^2_Z}{m^2_A - M^2_Z} \tan 2\beta .$$  \hfill (A.16)

## B One Loop Threshold Corrections

We compute flavor conserving complete one-loop corrections to masses and couplings in MSSM following BPMZ [65]. In this appendix we present the summary of one-loop corrections implemented in SuSeFLAV.

- **Quarks and Leptons**

  The corrections to fermions are evaluated at the weak scale. The running masses $m_f$ are related to the corresponding DR masses by the expression

  $$m_f = m_f \pm \Sigma_f^{BPMZ}(m_f^2)$$ \hfill (B.1)

  Where, $\Sigma_f^{BPMZ}(m_f^2)$ is the one loop self-energy of the fermion $f$. We follow equation D.18 of BPMZ [65]. At the present version of SuSeFLAV we add the correction only to the third generation fermions.

- **W and Z Bosons**

  Corrections to W and Z bosons are evaluated at the weak scale as well as EWSB scale. The DR running W and Z boson mass squared at the scale $Q$ ($\hat{M}_Z^2(Q)$ and $\hat{M}_W^2(Q)$) are related to the physical pole mass of gauge bosons as follows

  $$M^2_Z = \hat{M}_Z^2(Q) - \Pi^{ZZ}_{\hat{f}}(M^2_Z)$$  \hfill (B.2)

  $$M^2_W = \hat{M}_W^2(Q) - \Pi^{WW}_{\hat{f}}(M^2_W)$$  \hfill (B.3)

  Where, $\Pi^{ZZ}_{\hat{f}}(M^2_Z)$ and $\Pi^{WW}_{\hat{f}}(M^2_W)$ are the transverse part of self energy terms. Consult appendix D of BPMZ [65] for detailed discussion and the complete expression of the self energy terms.

- **sQuarks and sLeptons**

  Flavor conserving one-loop masses and mixings for squarks and sleptons are evaluated by diagonalizing $M_f^2(p^2)$ for eigenvalues at the EWSB scale.

  $$M_f^2(p^2) = \begin{pmatrix}
  M^2_{\hat{f}_L\hat{f}_L} - \Pi_{\hat{f}_L\hat{f}_L}(p^2) & M^2_{\hat{f}_L\hat{f}_R} - \Pi_{\hat{f}_L\hat{f}_R}(p^2) \\
  M^2_{\hat{f}_R\hat{f}_L} - \Pi_{\hat{f}_R\hat{f}_L}(p^2) & M^2_{\hat{f}_R\hat{f}_R} - \Pi_{\hat{f}_R\hat{f}_R}(p^2)
  \end{pmatrix}$$ \hfill (B.4)

  $M^2_{\hat{f}\hat{f}}$ is the $2 \times 2$ tree level mass matrix defined in equations A.5, A.6 and A.7. The self-energy terms of the above matrix ($\Pi_{\hat{f}_L\hat{f}_L}$, $\Pi_{\hat{f}_L\hat{f}_R}$, $\Pi_{\hat{f}_R\hat{f}_L}$, $\Pi_{\hat{f}_R\hat{f}_R}$) are defined in appendix D of BPMZ [65].
• Higgs Bosons

The mass of the two loop CP-even higgs are obtained by diagonalizing \( \mathcal{M}_s^2(p^2) \) at the EWSB scale. Where the matrix \( \mathcal{M}_s^2(p^2) \) is given by,

\[
\mathcal{M}_s^2(p^2) = \begin{pmatrix}
\hat{M}_Z^2 c_\beta^2 + \hat{m}_A^2 s_\beta^2 - \Pi_{s1s1}(p^2) + t_1/v_1 & -(\hat{M}_Z^2 + \hat{m}_A^2)s_\beta c_\beta - \Pi_{s1s2}(p^2) \\
-(\hat{M}_Z^2 + \hat{m}_A^2)s_\beta c_\beta - \Pi_{s2s1}(p^2) & \hat{M}_Z^2 s_\beta^2 + \hat{m}_A^2 c_\beta^2 - \Pi_{s2s2}(p^2) + t_2/v_2
\end{pmatrix}
\]

(B.5)

The self energy terms \( \Pi_{s1s1}, \Pi_{s1s2}, \Pi_{s2s1} \) and \( \Pi_{s2s2} \) are presented in appendix D of BPMZ [65]. Whereas, one loop tadpole contributions \( t_1/v_1 \) and \( t_2/v_2 \) are presented in appendix E of BPMZ [65]. Besides the complete one loop correction to \( m_h \) and \( m_H \), we evaluate the top mass enhanced dominant two loop corrections provided in [66].

The tree level mass of CP-odd higgs boson, \( m_A \) and charged higgs boson \( m_{H^\pm} \) is given by equations A.12 and A.14 respectively. The one loop correction to masses is evaluated at EWSB scale and given by

\[
\hat{m}_A^2 = m_A^2 + \Pi_{AA}(m_A^2) - b_A \quad \text{(B.6)}
\]

\[
\hat{m}_{H^\pm} = m_{H^\pm}^2 + M_W^2 + \Pi_{AA}(m_A^2) + \Pi_{WW}(M_W^2) - \Pi_{H^+H^-}(m_{H^\pm}^2) \quad \text{(B.7)}
\]

Where, \( b_A = s_\beta^2 t_1/v_1 + c_\beta^2 t_2/v_2 \).

• Neutralino and Chargino

The one loop corrected neutralino mass matrix has the following form,

\[
\mathcal{M}_{\tilde{\psi}0} + \frac{1}{2} \left( \delta \mathcal{M}_{\tilde{\psi}0}(p^2) + \delta \mathcal{M}_{\tilde{\psi}0}^T(p^2) \right)
\]

(B.8)

where

\[
\delta \mathcal{M}_{\tilde{\psi}0}(p^2) = -\Sigma^0_R(p^2) \mathcal{M}_{\tilde{\psi}0} - \mathcal{M}_{\tilde{\psi}0} \Sigma^0_L(p^2) - \Sigma^0_S(p^2)
\]

(B.9)

Where, \( \mathcal{M}_{\tilde{\psi}0} \) is the tree level neutralino mass matrix defined in A.2. And the matrix \( \delta \mathcal{M}_{\tilde{\psi}0}(p^2) \) is the one loop correction to the neutralino mass matrix.

The one-loop chargino mass matrix is as follows,

\[
\mathcal{M}_{\tilde{\psi}^+} - \Sigma^+_R(p^2) \mathcal{M}_{\tilde{\psi}^+} - \mathcal{M}_{\tilde{\psi}^+} \Sigma^+_L(p^2) - \Sigma^+_S(p^2)
\]

(B.10)

Where, \( \mathcal{M}_{\tilde{\psi}^+} \) is the tree level chargino mass matrix defined in A.4. We evaluate the self energies \( \Sigma^+_L,R,S \) with \( p^2 = Q(\text{EWSB scale}) \). See appendix D of BPMZ for the complete expressions of these self-energies. One loop neutralino and chargino mass matrices are then diagonalized to obtain the eigenvalues and eigenvectors at EWSB scale.

• Gauge Couplings and \( \sin^2 \theta_W \)

The correction to \( \frac{\alpha_{em}}{1 - \Delta \alpha} \) electromagnetic coupling at the weak scale is given by,

\[
\hat{\alpha} = \frac{\alpha_{em}}{1 - \Delta \alpha} \quad \text{and} \quad \alpha_{em} = \frac{1}{127.934}
\]

(B.11)
Where $\Delta \hat{\alpha}$ contains contribution from SM particles as well as SUSY particles. Similarly, the correction to strong coupling $\alpha_s$ at the weak scale is given by,

$$\hat{\alpha}_s = \frac{\alpha_s}{1 - \Delta \alpha_s} \quad (B.12)$$

$\Delta \alpha_s$ receives contribution from top quark, gluino and squarks. The exact expression given by equation 3 of BPMZ [65]. The correction to $\hat{\alpha}_s$ weak mixing angle is given by,

$$\sin^2 2\hat{\theta}_W = \frac{4\pi \hat{\alpha}}{\sqrt{2}M_Z^2 G_\mu (1 - \Delta \hat{r})} \quad (B.13)$$

The exact expression of $\Delta \hat{\alpha}$ and $\Delta \hat{r}$ is presented in the appendix C of BPMZ [65].

- **Gluino**

One loop corrected gluino mass $m_{\tilde{g}}$ at scale $Q$ is given by,

$$m_{\tilde{g}} = M_3(Q) - \Sigma_{\tilde{g}}(m_{\tilde{g}}) \quad (B.14)$$

Where $M_3(Q)$ is the tree level gluino mass generated by the RGEs and $\Sigma_{\tilde{g}}(m_{\tilde{g}})$ is the one loop self-energy contribution to the gluino mass. See equation D.44 of BPMZ [65] for the complete expression.

### C Program File Structure

![Figure 3. File structure and program flow](image)

In this appendix we briefly list the subroutines of interest in the program and its purpose (for more details see the technical manual provided with the program). Figure [3] depicts the program structure and the flow of variables in the program. The subroutine
name is printed in bold and the respective file which contains the subroutine is indented in brackets.

The program begins by reading inputs from the main program contained in the files ‘runonce.f’, ‘runslha.f’ (for slha input format), ‘scanning.f’. The convention followed in the program is such that all the input parameters which do not receive one-loop susy threshold correction such as the masses of the first two generation of quarks and leptons are contained in the file ‘stdinputs.h’. Whereas, parameters such as $\sin^2 \theta_W$, gauge couplings and the third generation quark and lepton masses which receive one-loop susy threshold correction are contained in the file ‘SuSemain.f’. Moreover, the complete $3 \times 3$ structure of the yukawas and soft terms are defined in ‘SuSemain.f’.

- **rgeiterate.f**: The heart of the program. The iterative algorithm is contained here.
- **softspectrum.f**: Given the RGE output at low scale, this routine computes the complete tree level susy spectrum by diagonalizing the mass matrices using lapack routines.
- **slha.f**: Contains the ingredients for SLHA input/output interface.
- **mueconvernew.f**: Contains routines which calculate the decay rates and branching fractions of rare lepton flavor violating decays.
- **mssmrge.f**: The complete MSSM two loop RGEs are contained in this file.
- **one loop particle.f**: A set of several files which contain the one loop corrections to the corresponding particle, which could be gauge, neutralino, charging, sfermion etc.
- **oneloopPV.f**: The analytical form of all scalar one loop Passarino-Veltman functions are contained in this file.
- **math.f**: Routines for matrix manipulations, integration routine for ordinary differential equations using Runge-Kutta with adaptive step size and other general purpose functions such as random number generator.

References


[69] R. Barate et al. [ LEP Working Group for Higgs boson searches and ALEPH and DELPHI...

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