**SPheno**, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at $e^+e^-$ colliders

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April 17, 2003

**Abstract**

SPheno is a program that accurately calculates the supersymmetric particle spectrum within a high scale theory, such as minimal supergravity, gauge mediated supersymmetry breaking, anomaly mediated supersymmetry breaking, or string effective field theories. An interface exists for an easy implementation of other models. The program solves the renormalization group equations numerically to two-loop order with user-specified boundary conditions. The complete one-loop formulas for the masses are used which are supplemented by two-loop contributions in case of the neutral Higgs bosons and the $\mu$ parameter. The obtained masses and mixing matrices are used to calculate decay widths and branching ratios of supersymmetric particles as well as of Higgs bosons, $b \rightarrow s\gamma$, $\Delta \rho$ and $(g - 2)_\mu$. Moreover, the production cross sections of all supersymmetric particle as well as Higgs bosons at $e^+e^-$ colliders can be calculated including initial state radiation and longitudinal polarization of the incoming electrons/positrons. The program is structured such that it can easily be extend to include non-minimal models and/or complex parameters.

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1 Introduction

Supersymmetry (SUSY) [1, 2, 3] provides an attractive extension of the Standard Model (SM). It provides a qualitative understanding of various phenomena in particle physics: It stabilizes the gap between the Grand Unification scale / Planck scale and the electroweak scale [4]. It allows the unification of the three gauge couplings at a scale $M_U \simeq 2 \cdot 10^{16}$ GeV in a straight forward way [5]. The large top mass generates radiative electroweak symmetry breaking [6]. In addition it provides the lightest supersymmetric particle as a cold dark matter candidate [7]. Therefore, the search for supersymmetric particles is one of the main topics in the experimental program of present and future high energy colliders [8, 9, 10, 11].
The Minimal Supersymmetric Standard Model (MSSM) consists of taking the Standard Model and adding the corresponding supersymmetric partners [3]. In addition a second Higgs doublet is needed to obtain an anomaly-free theory. The second Higgs doublet is also needed to give mass to u-type quarks and down-type quarks at the same time. The MSSM in its most general form contains more than 100 unknown parameters [12] which are clearly too many for an exhaustive study. This number drastically reduces if one embeds the MSSM in a high scale theory, such as minimal supergravity theories [13], gauge mediated supersymmetry breaking [14], or anomaly mediated supersymmetry breaking [15]. There is not yet a theoretical preferred scheme for supersymmetry breaking. For this reason it is important to know whether the precision of on-going and future experiments is sufficient: (i) To distinguish between the various schemes. (ii) To which extent it is possible to reconstruct the underlying theory. It has been demonstrated that the expected experimental accuracies at future $e^+e^-$ colliders complemented with data from the LHC allow for a successful reconstruction of such an underlying supersymmetric high scale theory [16]. Connected with these questions is the question if the theoretical accuracy matches the experimental one. The present version of the program SPheno\(^1\) is thought as a further step in getting accurate theoretical results to match finally the experimental precision.

In the view of ongoing and future experiments it is highly desirable to have various and independent tools at hand performing the calculation of the supersymmetric spectrum, of decay widths, of branching ratios and of production cross sections. This allows for a cross check of the tools and by comparing the implemented methods and approximations one can also get a rough understanding of the theoretical error. SPheno is a program performing an accurate calculation of the supersymmetric spectrum, of the branching ratios of supersymmetric particles and the Higgs bosons and of the production cross sections of supersymmetric particles and the Higgs bosons in $e^+e^-$ annihilation including longitudinal beam polarization. Moreover, the spectrum is used to calculate the branching of the rare decay $b \rightarrow s\gamma$, the supersymmetric contributions to the anomalous magnetic of the muon $a_\mu$ as well as supersymmetric contributions to the $\rho$ parameter.

For the calculation of the spectrum the programs ISASUSY [17], SOFTSUSY [18] and SUSPECT [19] are widely used. A comparison of the results among these programs and with SPheno is given in [20]. The calculation of the branching ratios of supersymmetric particles as well as the production cross sections in $e^+e^-$ annihilation can be done with SPheno, ISASUSY [17], SPYTHIA [21] and SUSYGEN [22]. A comparison of the results of these programs will be given in a future paper.

SPheno has been written in Fortran90. The main focus has been on accuracy and on stable numerical results and less on speed. However, on a modern PC a typical running time is in the order of one second. The calculation is done using two-loop renormalization group equations (RGEs) [23], complete one-loop correction to all SUSY and Higgs masses [24] supplemented by the 2-loop corrections to the neutral Higgs bosons [25, 26] and to the $\mu$ parameter [26]. The present version of SPheno does all calculations for real parameters neglecting the flavour structure in the fermion as well as in the sfermion sector. Decay widths and cross sections are calculated using tree-level formulas. However, the couplings involved are running couplings and thus important numerical effects of higher order corrections are already taken into account. The program has been structured in such a way that the future inclusion of complex phases and mixing between the generations has already been considered.

\(^1\)SPheno stands for Supersymmetric Phenomenology
in the design of the interfaces as well as in the definition of the various variables. Moreover, extensions of the MSSM, e.g. models with broken R-parity, can be implemented easily.

The aim of this paper is to provide a manual of the program, version 2.0, to describe the approximations used and to display the results of a run. In Sect. 2 we will summarize the MSSM parameters and we give the tree-level formulas for the supersymmetric particles. Moreover, a short summary of the implemented high scale models is given. In Sect. 3 we list the implemented decay modes of supersymmetric particles and the Higgs bosons. We also discuss shortly the approximations used. In Sect. 4 we present the implemented cross sections in $e^+e^-$ annihilation. In Sect. 5 we discuss give details on the implemented low energy constraints. In Sect. 6 we discuss the implemented algorithm in some detail. In Sect. 7 the main program is presented in detail providing the necessary information so that this program can be easily adapted to the user’s requirement. In the appendices we discuss the possible switches for influencing the program as well as a detailed discussion of possible input files. Moreover, we list the output of the program for a typical example. The source code as well as precompiled versions of the program can be obtained from the author via email: porod@physik.unizh.ch; or it can be downloaded from http://www-theorie.physik.unizh.ch/~porod/SPheno.html.

2 MSSM parameters, particle spectrum, and High Scale Models

In this section we fix our notation concerning the parameters and present the tree-level formulas for the masses as well as the mixing matrices. In the following we assume that the physical masses are ordered: $m_i \leq m_j$ if $i < j$ except for the sfermions as explained below. We also give a short overview over various high scale models which are implemented in the program.

2.1 Ingredients for the Lagrangian

The pure supersymmetric Lagrangian is specified by the Kähler potential giving the gauge interactions and by the Superpotential $W$ giving the Yukawa interactions:

$$W = \epsilon_{ab} \left( Y^L_{ij} \hat{L}^a_i \hat{H}_i^b \hat{E}^c_j + Y^D_{ij} \hat{Q}^a_i \hat{H}_i^b \hat{D}^c_j + Y^U_{ij} \hat{Q}^b_i \hat{H}_a^1 \hat{U}^c_j - \mu \hat{H}_1^a \hat{H}_2^b \right)$$

where $\hat{L}$, $\hat{E}$, $\hat{Q}$, $\hat{D}$, and $\hat{U}$ denote the matter superfields. The $SU(2)_L$ representation indices are denoted by $a, b = 1, 2$ and the generation indices by $i, j = 1, 2, 3$; $\epsilon_{ab}$ is the totally antisymmetric tensor with $\epsilon_{12} = 1$. Note that the sign of $\mu$ is identical to the one in ISASUSY [17] and SOFTSUSY [18] but opposite to the convention in [24]. Presently, real Yukawas $Y^L$, $Y^D$, $Y^U$ only are included. They and the gauge couplings $g_i$ are $\bar{D}R$ quantities. $g_1$ is defined in the Grand Unification normalization $g_1 = \sqrt{5/3} g'$ where $g'$ is the Standard Model hypercharge gauge coupling.

The next ingredient is the soft SUSY breaking Lagrangian, which is given by mass terms for the gauginos

$$L_{\text{soft,1}} = \frac{1}{2} \left( M_1 \hat{B} \hat{B} + M_2 \hat{W}_a \hat{W}^a + M_3 \hat{g}_a \hat{g}^a \right) + h.c.$$
mass terms for scalar matter fields and Higgs fields

\begin{align}
L_{\text{soft,2}} &= -M_{H_1}^2 H_1^* H_1^* - M_{H_2}^2 H_2^* H_2^* - M_{\tilde{E}_i}^2 \tilde{E}_i \tilde{E}_i - M_{\tilde{E}_j}^2 \tilde{E}_j \tilde{E}_j \\
&- M_{\tilde{Q}_{ij}}^2 \tilde{Q}_{ij} \tilde{Q}_{ij} - M_{\tilde{U}_{ij}}^2 \tilde{U}_{ij} \tilde{U}_{ij} - M_{\tilde{D}_{ij}}^2 \tilde{D}_{ij} \tilde{D}_{ij}
\end{align}

(3)

and trilinear couplings of scalar matter fields and Higgs fields

\begin{align}
L_{\text{soft,3}} &= -\epsilon_{ab} \left( A_{ij}^T \tilde{L}_i \tilde{H}_1^T \tilde{E}_j^* + A_{ij}^D \tilde{Q}_i \tilde{H}_1^T \tilde{D}_j + A_{ij}^U \tilde{Q}_i \tilde{H}_2^T \tilde{U}_j - B \mu \tilde{H}_1^T \tilde{H}_2 \right) + \text{h.c.}
\end{align}

(4)

### 2.2 Masses and Mixing Matrices

The masses of the various particles are induced by the soft SUSY breaking parameters and the vacuum expectation values \( v_i \) of the neutral Higgs fields \( v_i = < H_0^i > \). The ratio of the vacuum expectation values is denoted by \( \tan \beta = v_2/v_1 \). The sum of the vacuum expectation values (vevs) squared is fixed by the gauge boson masses:

\begin{align}
m_W^2 &= \frac{1}{4} g^2 (v_1^2 + v_2^2), \\
m_Z^2 &= \frac{1}{4} (g^2 + g'^2)(v_1^2 + v_2^2)
\end{align}

(5)

Neglecting the mixing between different generations, the Standard Model fermion masses are given by:

\begin{align}
m_u &= \frac{1}{\sqrt{2}} Y_u^U v_2, \\
m_d &= \frac{1}{\sqrt{2}} Y_d^D v_1, \\
m_l &= \frac{1}{\sqrt{2}} Y_l^L v_1
\end{align}

(6)

for u-quarks, d-quarks and leptons, respectively.

The gluino mass is given by \( m_{\tilde{g}} = |M_3| \). The charginos are combination of the charged winos \( \tilde{w}^\pm = (\tilde{w}^1 \mp i \tilde{w}^2)/\sqrt{2} \) and the charged higgsinos \( \tilde{h}_1^\pm, \tilde{h}_2^\pm \). The Lagrangian contains the chargino mass term \(- (\tilde{\psi}^-)^T X \tilde{\psi}^+ \) where \( \psi^- = (- i \tilde{w}^- , \tilde{h}_1^-)^T \), \( \psi^+ = (- i \tilde{w}^+ , \tilde{h}_2^+)^T \) and

\begin{align}
X &= \begin{pmatrix} M & \frac{\sqrt{2} v_2}{v_1} \\ \frac{\sqrt{2} v_2}{v_1} & \mu \end{pmatrix}
\end{align}

(7)

The matrix is diagonalized by two unitary matrices \( U \) and \( V \):

\begin{align}
M_{D,\chi^\pm} &= U^T X V^{-1}.
\end{align}

(8)

The neutral gauginos \( \tilde{b}, \tilde{w}^3 \) as well as the neutral higgsinos \( \tilde{h}_1^0, \tilde{h}_2^0 \) form the neutralinos. In the basis \( \tilde{\psi}^0 = (\tilde{b}, \tilde{w}^3, \tilde{h}_1^0, \tilde{h}_2^0)^T \) one finds the mass term \(- (\tilde{\psi}^0)^T Y \tilde{\psi}^0 \) with

\begin{align}
Y &= \begin{pmatrix} M_1 & 0 & -\frac{\sqrt{2}}{2} v_1 & \frac{\sqrt{2}}{2} v_2 \\ 0 & M_2 & \frac{\sqrt{2}}{2} v_1 & -\frac{\sqrt{2}}{2} v_2 \\ -\frac{\sqrt{2}}{2} v_1 & \frac{\sqrt{2}}{2} v_1 & 0 & -\mu \\ \frac{\sqrt{2}}{2} v_2 & -\frac{\sqrt{2}}{2} v_2 & -\mu & 0 \end{pmatrix}
\end{align}

(9)

This matrix is diagonalized by an unitary matrix \( N \):

\begin{align}
M_{D,\chi^0} &= N^T Y N^\dagger.
\end{align}

(10)
The CP-even electroweak eigenstates \((H_1^0, H_2^0)\) are rotated by the angle \(\alpha\) into the Higgs mass eigenstates \((h^0, H^0)\) as follows:

\[
\begin{pmatrix}
  h^0 \\
  H^0
\end{pmatrix} = \begin{pmatrix}
  -\sin \alpha & \cos \alpha \\
  \cos \alpha & \sin \alpha
\end{pmatrix} \begin{pmatrix}
  H_1^0 \\
  H_2^0
\end{pmatrix}
\]

(11)

with \(m_{h^0} < m_{H^0}\). The CP-odd and the charged Higgs masses are given by

\[m_{A_0}^2 = B \mu (\tan \beta + \cot \beta), \quad m_{H^+}^2 = m_{A_0}^2 + m_W^2\]

(12)
at tree level.

Neglecting generation mixing, the sneutrino masses are given by:

\[M_{\tilde{\nu}_i}^2 = M_{L,ii}^2 + \frac{1}{2} m_Z^2 \cos 2\beta\]

(13)
The other sfermion mass matrices are 2 \times 2 matrices:

\[
M_{\tilde{f},ii}^2 = \begin{pmatrix}
M_{L,ii}^2 - \left(\frac{1}{2} - s_W^2\right) c_{2\beta} m_{Z}^2 + m_{i,i}^2 & \frac{1}{\sqrt{2}} \left(v_1 (A_{L,ii})^* - \mu Y_{L}^i v_2\right) \\
\frac{1}{\sqrt{2}} \left(v_1 A_{L,ii}^* - (\mu Y_{L}^i)^* v_2\right) & M_{E,ii}^2 - s_W^2 c_{2\beta} m_{Z}^2 + m_{i,i}^2
\end{pmatrix}
\]

(14)

\[
M_{\tilde{u},ii}^2 = \begin{pmatrix}
M_{Q,ii}^2 + \left(\frac{1}{2} - \frac{2}{3} s_W^2\right) c_{2\beta} m_{Z}^2 + m_{u,i}^2 & \frac{1}{\sqrt{2}} \left(v_2 (A_{L,ii})^* - (\mu Y_{L}^i)^* v_1\right) \\
\frac{1}{\sqrt{2}} \left(v_2 A_{L,ii}^* - (\mu Y_{L}^i)^* v_1\right) & M_{U,ii}^2 + \frac{2}{3} s_W^2 c_{2\beta} m_{Z}^2 + m_{u,i}^2
\end{pmatrix}
\]

(15)

\[
M_{\tilde{d},ii}^2 = \begin{pmatrix}
M_{Q,ii}^2 - \left(\frac{1}{2} - \frac{2}{3} s_W^2\right) c_{2\beta} m_{Z}^2 + m_{d,i}^2 & \frac{1}{\sqrt{2}} \left(v_1 (A_{L,ii})^* - (\mu Y_{L}^i)^* v_2\right) \\
\frac{1}{\sqrt{2}} \left(v_1 A_{L,ii}^* - (\mu Y_{L}^i)^* v_2\right) & M_{D,ii}^2 - \frac{2}{3} s_W^2 c_{2\beta} m_{Z}^2 + m_{d,i}^2
\end{pmatrix}
\]

(16)

where \(c_{2\beta} = \cos 2\beta\) and \(s_W^2 = \sin^2 \theta_W\). These matrices are diagonalized by 2 \times 2 matrices \(R_{f,i}\) with

\[m_{f}^2 = R_{f,i}^* M_{f}^2 R_{f,j}\]

(17)

Sfermions are first ordered according to the generation and inside a generation according to their masses. For example, in the slepton sector the ordering is \(\tilde{e}_1, \tilde{e}_2, \tilde{\mu}_1, \tilde{\mu}_2, \tilde{\tau}_1, \tilde{\tau}_2\) and similarly for squarks.

### 2.3 High scale models

In this section we summarize the key ingredients of the high scale models implemented in SPheno. We also present the formulas for the boundary conditions in the various models. In all cases the modulus \(|\mu|\) is determined by requiring correct radiative symmetry breaking. At tree level the corresponding formula reads as:

\[|\mu|^2 = \frac{1}{2} \left[ \tan 2\beta \left( M_{H_2}^2 \tan \beta - M_{H_1}^2 \cot \beta \right) - m_Z^2 \right].\]

(18)

Moreover, in all cases the high scale parameters are supplemented by the sign of \(\mu\) and \(\tan \beta\).
2.3.1 Minimal Supergravity

The minimal supergravity (mSUGRA) scenario is characterized by a set of universal parameters \([13, 2]\) at the GUT scale \(M_{\text{GUT}}\): the gaugino mass parameter \(M_1/2\), the scalar mass parameter \(M_0\), and the trilinear coupling \(A_0\):

\[
\begin{align*}
M_i(M_{\text{GUT}}) &= M_i/2 \\
M_2^j(M_{\text{GUT}}) &= M_0^j \\
A_i(M_{\text{GUT}}) &= A_0 Y_i(M_{\text{GUT}})
\end{align*}
\]

2.3.2 Minimal Supergravity including right handed neutrinos

In addition to the parameters of the mSUGRA model above the following parameters appear in this case: \(m_{\nu_R}\), a common mass for all right handed neutrinos, and \(m_{\nu_i}\) \((i = 1, 2, 3)\), the light neutrino masses. In this case the MSSM RGEs are run up to the scale \(m_{\nu_R}\) where the neutrino Yukawa couplings are calculated using the formula \(Y_{\nu,i} = \sqrt{m_{\nu_R} m_{\nu_i}}/v_2\). In the range between \(m_{\nu_R}\) and \(M_{\text{GUT}}\) the effect of neutrino Yukawa couplings is included in the RGEs of gauge and Yukawa couplings. At the GUT-scale the right sneutrino mass parameters as well as the trilinear coupling \(A_{\nu,i}\) are given by:

\[
\begin{align*}
M_2^R(M_{\text{GUT}}) &= M_0^R \\
A_{\nu,i}(M_{\text{GUT}}) &= A_0 Y_{\nu,i}(M_{\text{GUT}})
\end{align*}
\]

The corresponding RGEs are used in the running from \(M_{\text{GUT}}\) to \(m_{\nu_R}\). At the scale \(m_{\nu_R}\) the neutrino Yukawa couplings \(Y_{\nu,i}\), the trilinear couplings \(A_{\nu,i}\) and the soft masses \(M_{2,j}^R\) for the right sneutrinos are taken out of the RGEs and below the \(m_{\nu_R}\) the usual set of MSSM RGEs are used.

2.3.3 Gauge Mediated Supersymmetry Breaking

Gauge mediated supersymmetry breaking \([14, 27]\) (GMSB) is characterized by the mass \(M_M \sim \langle S \rangle\) of the messenger fields and the mass scale \(\Lambda = \langle F_S \rangle/\langle S \rangle\) setting the size of the gaugino and scalar masses. The gaugino masses

\[
M_i(M_M) = (N_5 + 3N_{10})g(\Lambda/M_M)\alpha_i(M_M)\Lambda
\]

are generated by loops of scalar and fermionic messenger component fields; \(N_i\) is the multiplicity of messengers in the \(5 + \bar{5}\) and \(10 + \bar{10}\) vector-like multiplets, and

\[
g(x) = \frac{1 + x}{x^2} \log(1 + x) + (x \to -x)
\]

is the messenger–scale threshold function \([28]\) which approaches unity for \(\Lambda \ll M_M\). Masses of the scalar fields in the visible sector are generated by 2-loop effects of gauge/gaugino and messenger fields:

\[
M_j^2(M_M) = 2(N_5 + 3N_{10})f(\Lambda/M_M)\sum_{i=1}^{3} k_i C_i^j \alpha_i^2(M_M)\Lambda^2
\]

with \(k_i = 1, 1, 3/5\) for \(SU(3), SU(2)\), and \(U(1)\), respectively; the coefficients \(C_i^j\) are the quadratic Casimir invariants, being \(4/3, 3/4,\) and \(Y^2/4\) for the fundamental representations \(j\)
in the groups $i = SU(3), SU(2)$ and $U(1)$, with $Y = 2(Q - I_3)$ denoting the usual hypercharge; also the threshold function [28]

$$f(x) = \frac{1+x}{x^2} \left[ \log(1+x) - 2 \text{Li}_2 \left( \frac{x}{1+x} \right) + \frac{1}{2} \text{Li}_2 \left( \frac{2x}{1+x} \right) \right]$$


(27)

approaches unity for $\Lambda \ll M_M$. As evident from Eq. (26) scalar particles with identical Standard–Model charges squared have equal masses at the messenger scale $M_M$. In the minimal version of GMSB, the $A$ parameters are generated at 3-loop level and they are practically zero at $M_M$. However, the program permits to set a value for $A_0$ different from zero but universal for all sfermions.

### 2.3.4 Anomaly Mediated Supersymmetry Breaking

In anomaly mediated supersymmetry breaking (AMSB) the SUSY breaking is transmitted from the hidden sector to the visible sector via the super–Weyl anomaly [15]. The soft SUSY breaking parameters are given by:

$$M_a = \frac{1}{g_a} \beta_a m_{3/2}$$

$$A_i = \beta_Y i m_{3/2}$$

$$M_j^2 = \frac{1}{2} \gamma_j m_{3/2}^2$$

(28)

(29)

(30)

where $\beta_a$ and $\beta_Y$ are the beta functions of gauge and Yukawa couplings, respectively. The $\gamma_j$ are the anomalous dimensions of the corresponding matter superfield and $m_{3/2}$ is the gravitino mass. Equation (30) leads to negative mass squared for the sleptons which is phenomenologically not acceptable. There are several possibilities to solve this problem [29] and the simplest one is to add a common scalar mass $M_0$ so that eq. (30) reads as

$$M_j^2 = M_0^2 + \frac{1}{2} \gamma_j m_{3/2}^2$$

(31)

This extension has been implemented in the program.

### 2.3.5 String Effective Field Theories

Four–dimensional strings naturally give rise to a minimal set of fields for inducing supersymmetry breaking; they play the rôles of the fields in the hidden sectors: the dilaton $S$ and the moduli $T_m$ chiral superfields which are generically present in large classes of 4–dimensional heterotic string theories. The vacuum expectation values of $S$ and $T_m$, generated by genuinely non–perturbative effects, determine the soft supersymmetry breaking parameters [30, 31].

In the following we assume that all moduli fields get the same vacuum expectation values and that they couple in the same way to matter fields. Therefore, we omit the index $m$ and take only one moduli field $T$. The properties of the supersymmetric theories are quite different for dilaton and moduli dominated scenarios as discussed in [30, 31]. The mass scale of the supersymmetry parameters is set by the gravitino mass $m_{3/2}$.

In the program we implemented the complete 1-loop formulas given in [31]. Three classes of models are implemented in the program: two versions of OII compactification defined by
the sets A and B of boundary conditions in [31] as well as an OI compactification scheme. For the implementation of the OI compactification scheme we have used formulas Eqs. (3.21) - (3.23) of [31]:

\[
M_i = -g_i^2 m_{3/2} \left\{ \sqrt{3} \sin \theta + \left[ b_i + s \sqrt{3} \sin \theta g_s^2 \left( C_i - \sum_j C_i^j \right) \right. \right.
\]
\[
+ 2 t \cos \theta G_2(t) \left( \delta_{GS} + b_i - 2 \sum_j C_i^j (1 + n_j) \right) /16 \pi^2 \right\} \tag{32}
\]
\[
M_j^2 = m_{3/2}^2 \left\{ (1 + n_j \cos^2 \theta) + 2 \sqrt{3}s \sin \theta \left[ \sum \gamma_j^i g_i^2 - \frac{1}{2s} \sum_{km} \gamma_j^{km} \right] \right.
\]
\[
+ \gamma_j + 2 t \cos \theta G_2(t) \sum_{km} \gamma_j^{km} (n_j + n_k + n_m + 3) \right\} \tag{33}
\]
\[
A_{jkm} = m_{3/2} \left[ -\sqrt{3} \sin \theta - 2 t \cos \theta (n_j + n_k + n_m + 3) G_2(t) + \gamma_j + \gamma_k + \gamma_m \right] \tag{34}
\]

\[s = \langle S \rangle\] is the vacuum expectation values of the dilaton field. \[t = \langle T \rangle/m_{3/2}\] is the vacuum expectation value of the moduli field(s), and \[G_2(t) = 2 \zeta(t) + 1/2 t\] is the non-holomorphic Eisenstein function with \(\zeta\) denoting the Riemann zeta function. \(\delta_{GS}\) is the parameter of the Green-Schwarz counterterm. \(\gamma_j\) are the anomalous dimensions of the matter fields, the \(\gamma_j^i\) and \(\gamma_j^{km}\) are their gauge and Yukawa parts, respectively. \(C_i, C_i^j\) are the quadratic Casimir operators for the gauge group \(G_i\), respectively, in the adjoint representation and in the matter representation. The indices \(i, j, k\) denote \(H_1, H_2, E, L, D, U\) and \(\tilde{Q}\). The \(A\)-parameters are finally given by:

\[A_{e,n}(GUT) = Y_{e,n}(GUT) A_{\tilde{E}_n \tilde{L}_n H_1} \tag{35}\]
\[A_{d,n}(GUT) = Y_{d,n}(GUT) A_{\tilde{D}_n \tilde{Q}_n H_1} \tag{36}\]
\[A_{u,n}(GUT) = Y_{u,n}(GUT) A_{\tilde{U}_n \tilde{Q}_n H_2} \tag{37}\]

where \(n\) denotes the generation.

In case of the OII compactification scheme the gaugino masses are given by Eqs. (3.11) of [31]:

\[M_i = -g_i^2 m_{3/2} \left\{ \sqrt{3} \sin \theta / 2k_s^{1/2} + \frac{1}{16 \pi^2} \left[ 2 t \cos \theta G_2(\delta_{GS} + b_i) + b_i \right. \right. \right.
\]
\[
+ \frac{\sqrt{3} g_s^2 \sin \theta}{2k_s^{1/2}} (C_i - \sum_j C_i^j) \right\}. \tag{38}\]

For the sfermion parameters we have implemented two sets of boundary conditions: set (A) is specified by formulas Eqs. (3.15) and (3.19) of [31]:

\[M_i^2 = m_{3/2}^2 \left\{ \sin^2 \theta + \gamma_i + \frac{\sqrt{3} \sin \theta}{k_s^{1/2}} \left[ \sum_a \gamma_i^a g_a^2 + \frac{1}{2} \sum_{jk} \gamma_i^{jk} (k_s + k_s^j) \right] \right\}, \tag{39}\]
\[A_{ijk} = m_{3/2} \left\{ \gamma_i + \gamma_j + \gamma_k - \frac{\sqrt{3} k_s \sin \theta}{k_s^{1/2}} \right\}. \tag{40}\]
Set \((B)\) is specified by formulas Eqs. (3.16) and (3.20) of [31]:

\[
M_i^2 = m_3^2/2 \left[ \frac{\sqrt{3} \sin \theta}{k_s^{1/2}} \left[ 1 + 2 t \cos \theta G_2 \right] \left[ \sum_a g_a \gamma_i^a + \frac{1}{2} \sum_{jk} \gamma_i^{jk} (k_s + k_\sigma) \right] + \sin^2 \theta \left[ 1 + \gamma_i + \ln |2 t| \eta(t)|^4 \right] \left( \sum_a \gamma_i^a + 2 \sum_{jk} \gamma_i^{jk} \right) - \sum_a \gamma_i^a \ln(g_a^2) \right] \right. \\
\left. - \frac{9 \sin^2 \theta}{k_s \sigma} \left[ \sum_a \gamma_i^a \left( \frac{g_a^4}{4} \right) \left( \ln(g_a^2) + \frac{5}{3} \right) \right. \\
\left. + \ln \left[ (t + \bar{t}) \eta(t) \right] \left( \sum_a g_a^2 \left( \gamma_i^a + \gamma_j^a + \gamma_k^a \right) \right) \right] \right) \right) \\
\left( \gamma_i + \gamma_j + \gamma_k \right) \left[ 1 + 2 t \cos \theta G_2 \right]
\]

\[
A_{ijk} = m_3/2 \left\{ \left( \gamma_i + \gamma_j + \gamma_k \right) \left[ 1 + 2 t \cos \theta G_2 \right] \\
+ \left( \frac{\sqrt{3} \sin \theta}{k_s^{1/2}} \right) \left[ k_s + \sum_a \frac{g_a^2}{2} (\gamma_i^a + \gamma_j^a + \gamma_k^a) \left( 1 - \ln(g_a^2) \right) \left[ (t + \bar{t}) \eta(t) \right] \left( \sum_a g_a^2 (\gamma_i^a + \gamma_j^a + \gamma_k^a) \right) \\
- \sum_{lm} k_s (\gamma_i^{lm} + \gamma_j^{lm} + \gamma_k^{lm}) \right) \right\}.
\]

In all three cases we have assumed that terms proportional to the \(\log(\mu_i)\) can be neglected (\(\mu_i\) denote the Pauli Villar masses).

### 2.3.6 General High Scale Model

It is clear from the examples above that up to now there is no unique mechanism for supersymmetry breaking. Therefore, we have implemented the possibility to specify rather freely a high scale model. This model is specified by: a set of three in principal non–universal gaugino mass parameters \(M_{1/2}[U(1)], M_{1/2}[SU(2)], M_{1/2}[SU(3)]\); a scalar mass for each type of sfermion, resulting in fifteen parameters: \(M_{0,E,ii}, M_{0,L,ii}, M_{0,D,ii}, M_{0,U,ii}, M_{0,Q,ii}\); two Higgs mass parameters \(M_{H1}^0, M_{H2}^0\); nine different \(A\) parameters \(A_{0,E,ii}, A_{0,D,ii}\) and \(A_{0,u,ii}\). Here \(ii\) denotes that only the diagonal entries can be set, because in the current version the effects of generation mixing is not taken into account. A model of this kind has been used in [32] for the study of low energy observables and the supersymmetric spectrum. It also can be used, for example, to set the boundary conditions for the gaugino mediated supersymmetry breaking [33]. This general model will be denoted by SUGRA.

### 3 Decays of supersymmetric particles and Higgs bosons

The programs calculates the most important two- and three-body decays of supersymmetric particles at tree level. In case of three-body decays the formulas are implemented such, that the effects of decay widths in the propagators are taken into account [34]. Therefore, it is possible to perform the calculation even in case that some of the intermediate particles are on-shell. This is useful in the case that the two–body decays have small phase space, because then the calculation of the three-body decays gives a more accurate result, e.g. \(\Gamma(\tilde{\chi}_1^+ \rightarrow \cdots)\).
\( \tilde{\chi}_1^0 W^+ \times \text{BR}(W^+ \rightarrow \nu l^+) \) can be quite different from \( \Gamma(\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \nu l^+) \) if the decay \( \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^+ \) has only small phase space.

The following sfermion decays are calculated:

\[
\begin{align*}
\tilde{f}_i & \rightarrow f \tilde{\chi}_k^0, \ f' \tilde{\chi}_k^\pm \\
\tilde{f}_i & \rightarrow \tilde{f}_j Z^0, \ \tilde{f}_j^\prime W^\pm \\
\tilde{f}_i & \rightarrow \tilde{f}_j (h^0, H^0, A^0), \ \tilde{f}_j^\prime W^\pm
\end{align*}
\]  

(43)  
(44)  
(45)

In case of the lighter stop, it is possible that all two-body decays modes are kinematically forbidden at tree-level. In this case the following decay modes are important [35, 36, 37]:

\[
\begin{align*}
\tilde{t}_1 & \rightarrow c \tilde{\chi}_{1,2}^0 \\
\tilde{t}_1 & \rightarrow W^+ b \tilde{\chi}_1^0, \ H^+ b \tilde{\chi}_1^0 \\
\tilde{t}_1 & \rightarrow b \nu \tilde{t}_i^+, \ b t^+ \tilde{\nu}
\end{align*}
\]  

(46)  
(47)  
(48)

where \( l = e, \mu, \tau \). The corresponding widths are calculated within SPheno using the formulas given in [36]. In case of GMSB models scenarios exist where the charged sleptons are next to lightest supersymmetric particles (NLSP) and the gravitino \( \tilde{G} \) is the LSP. In this case the sleptons decay according to:

\[
\tilde{l}_i \rightarrow l \tilde{G}
\]  

(49)

Here we use the formulas given in [27].

It is well known that the partial widths of sfermions can receive considerable radiative corrections [38]. However, the branching ratios are not that strongly affected [39]. Therefore, for the moment being tree-level formulas are implemented. Some important numerical effects of higher order corrections are nevertheless implemented by using 1-loop corrected masses and running couplings in the formulas. The complete implementation of higher-order corrections is left for future versions of the program.

In case of charginos and neutralinos the following decay modes are calculated:

\[
\begin{align*}
\tilde{\chi}_i^0 & \rightarrow Z^0 \tilde{\chi}_j^0, \ W^\pm \tilde{\chi}_k^\mp \\
\tilde{\chi}_i^0 & \rightarrow (h^0, H^0, A^0) \tilde{\chi}_j^0, \ H^\pm \tilde{\chi}_k^\mp \\
\tilde{\chi}_i^0 & \rightarrow f \tilde{f}_j, \ \tilde{f} \tilde{f}_j \\
\tilde{\chi}_k^+ & \rightarrow Z^0 \tilde{\chi}_s^+, \ W^+ \tilde{\chi}_j^0 \\
\tilde{\chi}_k^+ & \rightarrow (h^0, H^0, A^0) \tilde{\chi}_s^+, \ H^+ \tilde{\chi}_j^0 \\
\tilde{\chi}_k^+ & \rightarrow f \tilde{f}_i
\end{align*}
\]  

(50)  
(51)  
(52)  
(53)  
(54)  
(55)

In case that all two body decay modes are kinematically forbidden the following three–body decays are calculated:

\[
\begin{align*}
\tilde{\chi}_i^0 & \rightarrow f \tilde{f} \tilde{\chi}_j^0, \ f f' \tilde{\chi}_k^\mp \\
\tilde{\chi}_i^0 & \rightarrow q \tilde{q} \tilde{g} \\
\tilde{\chi}_k^+ & \rightarrow f \tilde{f} \tilde{\chi}_s^+, \ f f' \tilde{\chi}_j^0 \\
\tilde{\chi}_k^- & \rightarrow q q' \tilde{g}
\end{align*}
\]  

(56)  
(57)  
(58)  
(59)
In the calculation we have included all contributions from gauge bosons, sfermions and Higgs bosons [34, 40]. The Higgs contributions can be important in certain regions of parameter space [41]. Similarly to case of the sleptons there exist parameter regions in GMSB models where the lightest neutralino is the NLSP and it decays according to
\[
\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \tag{60}
\]
\[
\tilde{\chi}_1^0 \rightarrow Z^0 \tilde{G} \tag{61}
\]
\[
\tilde{\chi}_1^0 \rightarrow h^0 \tilde{G} \tag{62}
\]
Here we use the formulas given in [27].

In case of gluinos the following two–body decays are calculated:
\[
\tilde{g} \rightarrow q \tilde{q}_i \tag{63}
\]
with \(q = u, d, c, s, t, b\). Again, in case that these decays are kinematically suppressed, the three-body decay modes are calculated:
\[
\tilde{g} \rightarrow \tilde{\chi}_i^0 q \tilde{q} \tag{64}
\]
\[
\tilde{g} \rightarrow \tilde{\chi}_j^+ q' \tilde{q} \tag{65}
\]
\[
\tilde{g} \rightarrow \tilde{b}_W^- \tilde{t}_1, b W^+ \tilde{t}_1^* \tag{66}
\]
Here we have implemented the formulas given in [42].

In case of Higgs bosons the following decays are calculated:
\[
\phi \rightarrow f \bar{f} \tag{67}
\]
\[
\phi \rightarrow \tilde{f}_i \tilde{f}_j \tag{68}
\]
\[
\phi \rightarrow \tilde{\chi}_k^0 \tilde{\chi}_l^0 \tag{69}
\]
\[
\phi \rightarrow \tilde{\chi}_r^+ \tilde{\chi}_s^- \tag{70}
\]
\[
H^0 \rightarrow Z^0 Z^0, W^+ W^- \tag{71}
\]
\[
H^0 \rightarrow h^0 h^0 \tag{72}
\]
\[
A^0 \rightarrow h^0 Z^0 \tag{73}
\]
\[
H^+ \rightarrow f \bar{f} \tag{74}
\]
\[
H^+ \rightarrow \tilde{f}_i \tilde{f}_j \tag{75}
\]
\[
H^+ \rightarrow \tilde{\chi}_k^0 \tilde{\chi}_s^- \tag{76}
\]
\[
H^+ \rightarrow h^0 W^+ \tag{77}
\]
with \(\phi = h^0, H^0, A^0\) and \(f = \nu_t, e, \mu, \tau, u, d, c, s, t, b\). It is well known, that the widths as well as the branching ratios of the Higgs bosons can receive large one–loop corrections [43, 44, 45]. In the present version only the gluonic QCD corrections for the decays into quarks [43] have been implemented. Therefore, the numbers provided by SPheno have to be taken with care and for refined analysis other programs, such as HDECAY [46] should be used.

4 Production of supersymmetric particles and Higgs bosons

The program calculates the following cross sections:
\[
e^+ e^- \rightarrow \tilde{f}_i \tilde{f}_j \quad (f = l, \nu, q) \tag{78}
\]
We have taken the formulas of [47] for sfermion production, [48, 34] for production of charginos and neutralinos and [45] for Higgs boson production. Initial state radiation has been included using the formula given in [49]. In case of squarks in addition QCD corrections due to gluon exchange are included [49, 50]. Care has to be taken in case one calculates the cross sections near threshold because then higher order corrections are important to get reliable results [51] and, thus, the numbers obtained in the program have to be taken with care near the threshold. All cross sections are implemented such, that one can specify the degree of longitudinal polarization $P_{e^-}$ of the incoming electron beam as well as the degree of longitudinal polarization $P_{e^+}$ of the incoming positron beam. Here $P_{e^-}$ is within the range $[-1, 1]$, where $\{-1, 0, 1\}$ denote 100% left-handed electrons, completely unpolarized electrons and 100% right-handed electrons, respectively. The same notation is used in case of positrons. For example, $P_{e^-} = -0.8$ ($P_{e^+} = -0.8$) means that 80% of the electrons (positrons) are left-polarized whereas the remaining 20% are unpolarized.

5 Low Energy Constraints

The supersymmetric parameters are constrained by direct searches at colliders and by loop-effects which supersymmetric particles induce observables of low energy experiments. Provided one neglects mixing between different sfermion generations the following quantities constrain several parameters of the MSSM: the rare decay $b \to s \gamma$, the anomalous magnetic moment of the muon $a_\mu$ and the supersymmetric contributions to the $\rho$ parameter. These constraints are implemented in the program using the formulas given in [52, 53] for $b \to s \gamma$ supplemented by the QCD corrections as given in [54], [55] for $a_\mu$ and [56] for the sfermion contributions to the $\rho$ parameter. In all cases we use the running couplings at $m_Z$ for the calculation of the observables. The use of running couplings together with the correct implementation of supersymmetric threshold corrections for the couplings results in taking into account the most important higher order corrections as has been pointed out e.g. in [57, 58] for the case of $b \to s \gamma$. The implementation of the supersymmetric threshold corrections to the couplings will be discussed in the next section.

6 Details of the Calculation

In this section we describe the algorithm used. It is schematically displayed in Fig. 1. The following standard model parameters are used as input: fermion and gauge boson pole masses, the fine structure constant $\alpha$, the Fermi constant $G_F$ and the strong coupling constant $\alpha_s(m_Z)$. It is assumed that $\alpha(m_Z)$ and $\alpha_s(m_Z)$ are given in the $\overline{MS}$ scheme.
Calculate $g_i(M_Z), h_{t,b,\tau}(M_Z)$ at tree level.

Run to $M_X$ at 1-loop. Apply soft SUSY breaking boundary condition

Run to $M_{EW_{SB}}$. Calculate $|\mu|$ and sparticle pole masses at tree level

SM and SUSY radiative corrections to $g_i(M_Z), h_{t,b,\tau}(M_Z)$

Run to $M_X$. Apply soft SUSY breaking boundary condition

Run to $M_{EW_{SB}}$. Calculate $|\mu|$ and sparticle pole masses at loop level

Check if required precision is achieved

Calculate decay widths and branching ratios

Calculate cross sections

Calculate low energy observables

Figure 1: Algorithm used to calculate the SUSY spectrum, decay widths, production cross sections and low energy observables. Each step (represented by a box) is explained in the text. The initial step is the uppermost one. $M_{EW_{SB}}$ is the scale at which the EWSB conditions are imposed, and $M_X$ is the scale at which the high energy SUSY breaking boundary conditions are imposed.
6.1 First rough calculation of SUSY and Higgs boson masses

In a first step, we calculate gauge and Yukawa couplings at \(m_Z\) scale using tree-level formulas. These are used as input for the one-loop RGEs to get the gauge and Yukawa couplings at the high scale where also the boundary conditions for the high scale model under study are imposed. Afterwards one-loop RGEs are used to get a first set of parameters at the electroweak scale. These parameters are used to get a first set of supersymmetric particle masses and Higgs masses using tree-level formulas except for the neutral CP-even Higgs bosons where one-loop effects due to (s)quarks of the third generation are taken into account. These masses are the starting point for the iterative loop which calculates the spectrum within the required precision as described below.

6.2 Main loop for the calculation of SUSY and Higgs boson masses

In the next step the gauge couplings and \(\sin^2 \theta_W\) are calculated at \(m_Z^2\) in the \(\overline{\text{DR}}\) scheme using the formulas given Appendix C of [24]. For the calculation of the Yukawa couplings we use the complete formulas for the fermion masses and the vacuum expectation values given in Appendix D of [24]. In case of third generation Yukawa couplings we use the following improvements. In case of the bottom quark we use 3-loop relationship between the pole mass and the \(\overline{\text{MS}}\) mass \(m_{b,\overline{\text{MS}}}(m_b)\) as given in [59]. The three–loop RGEs [60] are solved numerically to obtain \(m_{b,\overline{\text{MS}}}(m_Z)\). Afterwards the shift from the \(\overline{\text{MS}}\) scheme to the \(\overline{\text{DR}}\) scheme arising from massless gauge bosons is calculated using the formula [61, 62]:

\[
m_{b,\overline{\text{DR}}}(m_Z) = m_{b,\overline{\text{MS}}}(m_Z) \left(1 - \frac{\alpha_s}{3\pi} - \frac{35\alpha_s^2}{72\pi^2}\right)
\]

where \(\alpha_s\) is given in the \(\overline{\text{DR}}\) scheme which is the reason for the different factor in front of \(\alpha_s^2\) compared to [62]. We use the complete formulas given in Appendix D of [24] to calculate the SUSY contribution denoted by \(\Delta m_{b,SUSY}(m_Z)\). For the calculation we use running gauge and Yukawa couplings at \(m_Z\). The SUSY contributions \(\Delta m_{b,SUSY}(m_Z)\) are then resummed using [63]

\[
m_{b,\overline{\text{DR}}}(m_Z) = \frac{m_{b,\overline{\text{DR}}}(m_Z)}{1 - \frac{\Delta m_{b,SUSY}(m_Z)}{m_{b,\overline{\text{DR}}}(m_Z)}}
\]

The analogue resumation is done in case of the tau Yukawa coupling. In case of the top quark we take the complete formulas given in Appendix D of [24]. We also add the 2-loop contribution due to gluons in the \(\overline{\text{DR}}\) scheme [61] which reads as:

\[
\Delta m_t^{2\text{-loop}}(Q) = -m_t\alpha_s^2 \left(0.538 - \frac{43}{24\pi^2}L + \frac{3}{8\pi^2}L^2\right)
\]

where \(m_t\) is the on–shell top mass and \(L = \ln(m_t^2/Q^2)\). The obtained gauge and Yukawa couplings are evolved to the high scale using two–loop RGEs [23]. The high scale can either be fixed or can be calculated from the requirement \(g_1 = g_2\) at the high scale. The various cases are discussed in Sect. 7 and Appendix A. At the high scale the boundary conditions for the soft SUSY breaking parameters are set. The implemented models are summarized in Sect. 2.3; see also Appendix B.3. The complete set of two–loop RGEs [23] is used to
evolve the parameters down to the electroweak scale $M_{EW}=\sqrt{m_{t_1}m_{t_2}}$ (there exists also the possibility to set $M_{EW}$ by hand as explained in Appendix A).

The parameters are used as input to calculate the sparticle pole masses at one–loop order and in case of the neutral Higgs at two–loop order. Here we use the complete formulae given in the appendices of [24] for the one–loop contributions and for the 2-loop corrections $O(\alpha_s\alpha_t + \alpha_t^2 + \alpha_s\alpha_b)$ for the neutral Higgs boson the formulas given in [25, 26]. For the $O(\alpha_s\alpha_t)$ contributions we use the complete expressions which can be obtained from the $O(\alpha_s\alpha_t)$ contributions by appropriate replacements. In case of sfermions we have included in all cases left–right mixing. All gauge and Yukawa couplings are understood as $\overline{\text{DR}}$ quantities at $M_{EW}$. Also tan $\beta$ and the vacuum expectation values are evaluated at $M_{EW}$ to get a consistent set of input parameters. Note, that we express in all couplings the fermion masses and gauge boson masses by their corresponding expressions due to gauge couplings, Yukawa couplings and vacuum expectations values in the formulas of [24]. In all cases running masses are used as input for the loop integrals. In addition we have implemented the $O(\alpha_s\alpha_t + \alpha_t^2 + \alpha_s\alpha_b)$ corrections for the calculation of $|\mu|$ [26]. The numerical evolution of the one–loop integrals is based on the FF package [64] and the LoopTools package [65].

The masses obtained are used as input for the next iteration which starts again by calculating the SUSY contributions to gauge and Yukawa couplings at $m_Z$. In the case that during this iterative process an unphysical situation occurs, e.g. a pole mass squared being negative, the program terminates and it provides information on the exact reason for termination. The iteration is continued until all relative differences between the sparticle masses are smaller then the user imposed quantity $\delta$:

$$\delta > \frac{|m_i - m_{i-1}|}{m_i} \quad (87)$$

for all sparticle masses; $i$ denotes the $i$-th iteration. In most cases this achieved after three to four iterations. In the case that more than the maximal allowed number of iterations (user specified) are necessary, the program leaves the iteration giving a warning message.

### 6.3 Calculation of the other observables

The masses and mixing angles are then used to calculate the branching ratios and decay widths. Here two- and three body decays of supersymmetric particles are calculate. Note that we use the couplings as input which are renormalized at the scale $M_{EW}$. The user has the possibility to force the program to calculate three body decays even if one or more of the intermediate particles are on-shell. This possibility is useful in the case where the 2-body decay has only small phase because then the calculation of the three body decay width(s) give a more reliable result.

Afterwards the production cross sections at an $e^+e^-$ collider of all supersymmetric particles as well as all Higgs bosons are calculated. Here the user has the possibility to specify the centre of mass energy as well as the degree of longitudinal polarization of the incoming beams. Moreover, the user can specify if initial state radiation shall be included in the calculation or not.

Finally, the low–energy constraints described in Section 5 are calculated: $BR(b \rightarrow s\gamma)$, SUSY contributions to $a_\mu$ and the sfermion contributions to $\Delta \rho$. For the the calculation of these quantities we evolve the gauge and Yukawa couplings from the scale $M_{EW}$ down to $m_Z$. The couplings at $m_Z$ are then used as input for the calculation of the low energy
observables. For example in calculation of \( BR(b \to s \gamma) \) the most important contributions to the \( C_7 \) coefficients are implemented as

\[
C_7(W^+) = \frac{K_{ts} K_{tb} x_{tW}}{4 m_W^2} \left( \frac{2}{3} F_1(x_{tW}) + F_2(x_{tW}) \right) \\
(88)
\]

\[
C_7(H^+) = -\frac{K_{ts} K_{tb}}{4 m_{H^+}^2} \left[ \frac{Y_i^2 \cos^2 \beta}{4} \left( \frac{2}{3} F_1(x_{tH^+}) + F_2(x_{tH^+}) \right) \right. \\
- \left. \frac{Y_b Y_t \cos \beta \sin \beta m_t}{m_b} \left( \frac{2}{3} F_3(x_{tH^+}) + F_4(x_{tH^+}) \right) \right] \\
(89)
\]

\[
C_7(\tilde{\chi}^+) = \sum_{i,j=1}^2 \frac{K_{ts} K_{tb}}{4 m_{\tilde{t}_i}^2} \left[ C_{R,ij}^2 \left( \frac{2}{3} F_2(x_{\tilde{\chi}^+_j \tilde{t}_i}) + F_1(x_{\tilde{\chi}^+_j \tilde{t}_i}) \right) \right. \\
- \left. \left. C_{L,ij} C_{R,ij} \left( \frac{2}{3} F_4(x_{\tilde{\chi}^+_j \tilde{t}_i}) + F_3(x_{\tilde{\chi}^+_j \tilde{t}_i}) \right) \right] \\
(90)
\]

\[
C_{L,ij} = Y_b R_{i1} U_{j2} \\
(91)
\]

\[
C_{R,ij} = -g R_{i1} V_{j1} + Y_t R_{i2} V_{j2} \\
(92)
\]

Here \( Y_i \) are the Yukawa couplings, \( U \) and \( V \) are the chargino matrices, \( K \) is the CKM matrix, \( R_i \) is the stop mixing matrix and \( x_{ab} = m_a^2/m_b^2 \). The loop functions \( F_i \) are given in [52]. A similar replacement is done in the contributions to the \( C_8 \) coefficient. Moreover, in the program also the contributions from the first two generation of (s)fermions to \( C_7,8 \) are included for completeness. We then use [54] to obtain

\[
BR(b \to s \gamma) = 1.258 + 0.382 r_7^2 + 0.015 r_8^2 + 1.395 r_7 + 0.161 r_8 + 0.083 r_7 r_8 \\
(93)
\]

where \( r_7 = C_7/C_7(W^+) \) and \( r_8 = C_8/C_8(W^+) \). In this way important higher order corrections are taken into account, in particular the large \( \tan \beta \) effects in case of \( b \to s \gamma \) [58].

### 7 A sample example

In this section we discuss the executable statements of the main program given in the file `SPheno.f90`. In the first statements the required modules are loaded and the various variables are defined. Afterwards a series of initialization routines are called:

Call InitializeControl(11,"SPheno.out","SPheno")
Call InitializeLoopFunctions
Call InitializeStandardModel

The routine InitializeControl opens the file `Messages.out` at channel 10 where all warnings and/or debugging informations are stored. In addition it reads the file `Control.in` if present. For the description of `Control.in` see Appendix B.1. Moreover, it opens the output file `SPheno.out` at channel 11. The last entry "SPheno" is the name of the calling program and is used for the initialization of the debugging system. The routine InitializeLoopFunctions initializes the routines for the calculation of the loop functions which are needed to calculated the loop corrected masses. The routine InitializeStandardModel reads data from the file `StandardModel.in`. In case that this file is not present, default values are used as described in Appendix B.4.

Afterwards the routine HighScaleInput is called:
Table 1: Variables for parameters and couplings. The parameters are explained in Section 2. dp means double precision.

<table>
<thead>
<tr>
<th>parameter/coupling</th>
<th>type &amp; Fortran name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{i\phi}$</td>
<td>complex(dp) :: phase_mu</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>real(dp) :: tanb</td>
</tr>
<tr>
<td>$M_1, M_2, M_3$</td>
<td>complex(dp) :: Mi(3)</td>
</tr>
<tr>
<td>$M_L^2, M_L^2$</td>
<td>complex(dp), dimension(3,3) :: M2_E, M2_L</td>
</tr>
<tr>
<td>$M_D^2, M_Q^2, M_U^2$</td>
<td>complex(dp), dimension(3,3) :: M2_D, M2_Q, M2_U</td>
</tr>
<tr>
<td>$A_l, A_d, A_u$</td>
<td>complex(dp) :: A_l, A_d, A_u</td>
</tr>
<tr>
<td>$\mu$</td>
<td>complex(dp) :: mu</td>
</tr>
<tr>
<td>$B\mu$</td>
<td>complex(dp) :: B</td>
</tr>
<tr>
<td>$M_D^2$</td>
<td>real(dp) :: M2_H(2)</td>
</tr>
<tr>
<td>$g', g$</td>
<td>real(dp) :: gp, g</td>
</tr>
<tr>
<td>$Y_l, Y_d, Y_u$</td>
<td>complex(dp), dimension(3,3) :: Y_l, Y_d, Y_u</td>
</tr>
<tr>
<td>$v_1, v_2$</td>
<td>real(dp) :: vevSM(2)</td>
</tr>
<tr>
<td>$g', g, g_s$</td>
<td>real(dp) :: gauge(3)</td>
</tr>
</tbody>
</table>

Call HighScaleInput

The source code for this routine is given in the file SPheno.f90. This routine reads in the data from the file HighScale.in which specifies the model used as well as the high scale boundary conditions. A short description of the implemented models is given in Sect. 2.3 and details of the file HighScale.in are given in Appendix B.3. Afterwards a first rough estimate of the parameters and couplings is given by calling the routine FirstGuess:

```
Call FirstGuess(phase_mu, tanb, Mi, M2_E, M2_L, A_l, M2_D &
    & , M2_Q, M2_U, A_d, A_u, mu, B, M2_H, gp, g, Y_l &
    & , Y_d, Y_u, vevSM, mP02, mP0)
```

The meaning of the various variables and their type is given in Table 1 except for mP02, mP0 which are given in Table 2. The parameters obtained are used to get the initial values for the spectrum at tree-level:

```
Call TreeMasses(gp, g, vevSM, Mi(1), Mi(2), Mi(3), mu, B &
    & , tanb, M2_E, M2_L, A_l, Y_l, M2_D, M2_U, M2_Q, A_d &
    & , A_u, Y_d, Y_u, mGlu, PhaseGlu, mC, mC2, U, V, mN &
    & , mN2, N, mSneut, mSneut2, Raneut, mSlepton, mSlepton2 &
    & , RSlepton, mSdown, mSdown2, RSdown, mSup, mSup2, RSup &
    & , mP0, mP02, RP0, mS0, mS02, RS0, mSp, mSp2, RSp, kont)
```

The variables for the masses and mixing matrices are given in Table 2. Variable names ending with “2” indicate masses squared. The variables for the mixing matrices are already structured for a latter extension to include the effects of generation mixing and/or complex phases: the sfermion mixing matrices are $6 \times 6$ (except for sneutrions which is a $3 \times 3$ matrix). In the present release most of the entries are zero except for the diagonal $2 \times 2$ blocks which contain the left–right mixing for every species of sfermions. For example, the 11, 12, 21 and 22 entries in Rslepton specify the left–right mixing of selectrons, and similarly the 33, 34,
Table 2: Variables for masses and mixing matrices as given by the routine Sugra. Their connection to the parameters at tree–level is explained in Section 2. dp means double precision.

<table>
<thead>
<tr>
<th>masses / mixing matrix</th>
<th>type &amp; Fortran name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{g}}$</td>
<td>real(dp) :: mglu</td>
</tr>
<tr>
<td>$e^{i\varphi}$</td>
<td>complex(dp) :: PhaseGlu</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}^+}$</td>
<td>real(dp) :: mC(2)</td>
</tr>
<tr>
<td>$U, V$</td>
<td>complex(dp) :: U(2,2), V(2,2)</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}^0}$</td>
<td>real(dp) :: N(4)</td>
</tr>
<tr>
<td>$N$</td>
<td>complex(dp) :: N(4,4)</td>
</tr>
<tr>
<td>$m_{h^0}, m_{H^0}$</td>
<td>real(dp) :: mS0(2)</td>
</tr>
<tr>
<td>$R_{\alpha}$</td>
<td>real(dp) :: RS0(2,2)</td>
</tr>
<tr>
<td>$m_{G^0}, m_{A^0}$</td>
<td>real(dp) :: mP0(2)</td>
</tr>
<tr>
<td>$R_{\beta}$</td>
<td>real(dp) :: RP0(2,2)</td>
</tr>
<tr>
<td>$m_{G^+}, m_{H^+}$</td>
<td>real(dp) :: mSp(2)</td>
</tr>
<tr>
<td>$R'_{\beta}$</td>
<td>complex(dp) :: RSp(2,2)</td>
</tr>
<tr>
<td>$m_{\tilde{\nu}}$</td>
<td>real(dp) :: mSneut(3)</td>
</tr>
<tr>
<td>$R_{\tilde{\nu}}$</td>
<td>complex(dp) :: Rsneut(3,3)</td>
</tr>
<tr>
<td>$m_{\tilde{l}}$</td>
<td>real(dp) :: mSlep(6)</td>
</tr>
<tr>
<td>$R_{\tilde{l}}$</td>
<td>complex(dp) :: Rslep(6,6)</td>
</tr>
<tr>
<td>$m_{\tilde{u}}$</td>
<td>real(dp) :: mSup(6)</td>
</tr>
<tr>
<td>$R_{\tilde{u}}$</td>
<td>complex(dp) :: Rsup(6,6)</td>
</tr>
<tr>
<td>$m_{\tilde{d}}$</td>
<td>real(dp) :: mSdown(6)</td>
</tr>
<tr>
<td>$R_{\tilde{d}}$</td>
<td>complex(dp) :: Rsdown(6,6)</td>
</tr>
<tr>
<td>$U_{u_1}, U_{u_2}$</td>
<td>complex(dp) :: uU_L(3,3), uU_L(3,3)</td>
</tr>
<tr>
<td>$U_{d_1}, U_{d_2}$</td>
<td>complex(dp) :: uD_L(3,3), uD_L(3,3)</td>
</tr>
<tr>
<td>$U_{l_1}, U_{l_2}$</td>
<td>complex(dp) :: uL_L(3,3), uL_L(3,3)</td>
</tr>
</tbody>
</table>
43 and 44 (55, 56, 65 and 66) entries specify the left–right mixing of smuons (staus). The squark mixing matrices have the same generation structure.

These initial values serve as input for the more accurate calculation of the parameters including higher order corrections. Before calling the subroutine Sugra, which performs these calculations, the user has the possibility to fix the high scale and/or the scale where the parameters and the loop corrected masses are calculated. For this purpose one or both of the following lines must be uncommented in the program:

```fortran
! Call SetGUTScale(2.e16_dp) ! please put the GUT scale
! Call SetRGEScale(1.e3_dp**2) ! please put the scale M_EWSB squared
```

The default is that these scales are calculated by the program. The high scale is computed from the requirement $g_1 = g_2$ (except in GMSB where the high scale is an input). The scale $M_{EWSB}$ is given by $M_{EWSB} = \sqrt{m_{\tilde{t}1}m_{\tilde{t}2}}$.

The accurate calculation of the SUSY parameters and the spectrum is done by the following call:

```fortran
delta = 1.e-3_dp
WriteOut = .False.
n_run = 20
Call Sugra(delta, vevSM, mC, U, V, mN, N, mS0, mS02, RS0 &
          & mP0, mP02, RP0, mSpm, mSpm2, RSpm, mSdown, mSdown2 &
          & mSdown, mSup, mSup2, RSup, mSlepton, mSlepton2 &
          & RSup, mSlepton2, mSneut, mSneut2, RSpme, PhaseGlu &
          & gauge, uL_L, uL_R, uD_L, uD_R, uU_L, uU_R, Y_1 L &
          & Y_d, Y_u, Mi, A_1, A_d, A_u, M2_E, M2_L, M2_D &
          & M2_Q, M2_U, M2_H, mu, B, m_GUT, kont, WriteOut, n_run)
```

The meaning of the various variables and their type is given in Tables 1 and 2. Note that the quantities $uL_L$, $uL_R$, $uD_L$, $uD_R$, $uU_L$, $uU_R$ are $3 \times 3$ unit matrices in the present implementation. Also all SUSY parameters, Yukawa couplings and the sfermion masses are flavour diagonal. However, we have constructed the interface already in such a way that an extension to include mixing effects between the generations is facilitated. Compared to the previous calls of routines the following new variable appear:

- **delta**: specifies the required relative precision on the masses. If the maximal relative differences between the physical masses obtained between two runs is smaller than delta, the routine Sugra leaves the iteration loop.

- **m_GUT**: the value of the scale where the high energy boundary conditions are imposed.

- **kont**: A variable which is 0 provided everything is o.k. Otherwise either a numerical problem has occurred and/or the parameters belong to an unphysical region, e.g. a minimum of the potential where charge and/or colour breaking minima occur. In such a case the information is written to the file Messages.out.

- **WriteOut**: If it is set True. then intermediate debugging information is written to the screen and the file Messages.out.
n_run specifies the maximal number of iterations of the main loop. A warning will be given in the case that the required precision delta has not been reached within n_run iterations.

Note that the parameters are running parameters at the scale $M_{EWSB}$. The complete spectrum is calculated at 1–loop level using the formulas given in [24]. The exceptions are the masses of the neutral Higgs bosons (scalar and pseudo-scalar), where in addition the 2–loop corrections $O(\alpha_s \alpha_t + \alpha_s ^2 + \alpha_s \alpha_b)$ are included [25, 26], and the $\mu$ parameter where also the $O(\alpha_s \alpha_t + \alpha_s ^2 + \alpha_s \alpha_b)$ corrections [26] are included.

In the next part the branching ratios, the partial decay widths and the total decay widths are calculated provided that L_BR=.TRUE. and kont.eq.0:

If ((L_BR).and.(kont.eq.0)) then
  
  epsI = 1.e-5_dp
  deltaM = 1.e-3_dp
  CalcTBD = .False.
  ratioWoM = 1.e-4_dp
  
  If (HighScaleModel.Eq."GMSB") Is_GMSB = .True.
  Call CalculateBR(gauge, mGlu, PhaseGlu, mC, U, V, mN, N &
  & , mSneut, RSneut, mSlepton, RSlepton, mSup, RSup &
  & , mSdown, RSdown, uL_L, uL_R, uD_L, uD_R, uU_L, uU_R &
  & , mS0, RSO, mP0, RPO, mSp, RSpm, epsI, deltaM &
  & , CalcTBD, kont, ratioWoM, Y_d, A_d, Y_l, A_l, Y_u &
  & , A_u, mu, vevSM, Fgmsb, m32 &
  & , gP_S1, gT_S1, BR_S1, gP_Sn, gT_Sn, BR_Sn, gP_Sd &
  & , gT_Sd, BR_Sd, gP_Su, gT_Su, BR_Su, gP_C2, gT_C &
  & , BR_C2, gP_C3, BR_C3, gP_N2, gT_N, BR_N2, gP_N3 &
  & , BR_N3, gP_G2, gT_G, BR_G2, gP_G3, BR_G3, gP_P0 &
  & , gT_P0, BR_P0, gP_S0, gT_S0, BR_S0, gP_Spm, gT_Spm &
  & , BR_Spm)
end if

Variables starting with gP_-, gT_ and BR_ indicate partial widths, total widths and branching ratios, respectively; they are Real(dp) vectors. The first index is the index of the decaying particle whereas the second one gives the mode. The correspondence between the second index and the modes is summarized for sfermions (variables ending Sl, Sn, Sd and Su for sleptons, sneutrino, d-squarks and u-squarks, respectively) in Table 3, for charginos in Table 4, for neutralinos in Table 5, for gluinos in Table 6 and for the Higgs bosons in Tables 7 and 8.

Here the following variables are new:

- **epsI**: gives the accuracy to which the phase space integrals in three body decays are calculated.

- **deltaM**: this variable affects the calculation of the phase space integrals in three body decays. In case that $m_i/(m - \sum_i m_i) < \text{deltaM}$ than $m_i$ is set to zero in the calculation of the phase space integrals. $m$ denotes here mass of the decaying particle and $m_i$ (i=1,2,3) are the masses of the decay products.

- **CalcTBD**: if this variable is set .TRUE. then in all chargino-, neutralino- and gluino decays the three body modes will be calculated. This option has to be taken with care, because it can slow down the program considerably.
Table 3: Correspondence between the indices for sfermion partial widths (branching ratios) and the modes.

<table>
<thead>
<tr>
<th>mode</th>
<th>( i )</th>
<th>( \tilde{\nu} )</th>
<th>( \tilde{d} )</th>
<th>( \tilde{u} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{f}_1 \to f \tilde{x}_k^0 )</td>
<td>1-4</td>
<td>1-4</td>
<td>1-4</td>
<td>1-4</td>
</tr>
<tr>
<td>( \tilde{f}_i \to f' \tilde{x}_j^\pm )</td>
<td>5-6</td>
<td>5-6</td>
<td>5-6</td>
<td>5-6</td>
</tr>
<tr>
<td>( \tilde{f}_i \to f \tilde{g} )</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>( \tilde{f}_i \to W^\pm \tilde{f}_j^0 )</td>
<td>7</td>
<td>7-8</td>
<td>8-9</td>
<td>8-9</td>
</tr>
<tr>
<td>( \tilde{f}_i \to H^\pm \tilde{f}_j^0 )</td>
<td>8</td>
<td>9-10</td>
<td>10-11</td>
<td>10-11</td>
</tr>
<tr>
<td>( \tilde{f}_2 \to Z^0 \tilde{f}_1 )</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>( \tilde{f}_2 \to A^0 \tilde{f}_1 )</td>
<td>10</td>
<td>12</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>( \tilde{f}_2 \to h^0 \tilde{f}_1 )</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>( \tilde{f}_2 \to H^0 \tilde{f}_1 )</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>( \tilde{l}_1 \to l \tilde{G} )</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4: Correspondence between the second indices for chargino partial widths (branching ratios) and the decay modes. In case of two body decays the variables are \( g_{P,C2} (BR_{C2}) \) and in case of three body decays \( g_{P,C3} (BR_{C3}) \).

<table>
<thead>
<tr>
<th>mode</th>
<th>index of ( g_{P,C2} (BR_{C2}) )</th>
<th>index of ( g_{P,C3} (BR_{C3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\chi}<em>i^+ \to \tilde{l}</em>{m,k}^+ \nu_m )</td>
<td>1-6</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_i^+ \to \tilde{\nu}_m^+ l_m^+ )</td>
<td>7-9</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}<em>i^+ \to \tilde{d}</em>{m,k} u_m )</td>
<td>10-15</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}<em>i^+ \to \tilde{u}</em>{m,k} d_m )</td>
<td>16-21</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_i^+ \to \tilde{\chi}_j^0 W^+ )</td>
<td>22-25</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_i^+ \to \tilde{\chi}_j^0 H^+ )</td>
<td>26-29</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ Z^0 )</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ A^0 )</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ h^0 )</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ H^0 )</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_j^0 u_m \tilde{d}_m )</td>
<td>1-12</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_j^0 l_m^+ \nu_m )</td>
<td>13-24</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{g} u_m \tilde{d}_m )</td>
<td>25-27</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ u_m \tilde{u}_m )</td>
<td>28-30</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ d_m \tilde{d}_m )</td>
<td>31-33</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ l_m \tilde{l}_m^+ )</td>
<td>34-36</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \to \tilde{\chi}_1^+ \sum \nu_m \tilde{\nu}_m )</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>
Table 5: Correspondence between the second indices for neutralino partial widths (branching ratios) and the decay modes. In case of two body decays the variables are $g_{P_{C2}}$ ($BR_{C2}$) and in case of three body decays $g_{P_{C3}}$ ($BR_{C3}$).

<table>
<thead>
<tr>
<th>mode</th>
<th>index of $g_{P_{C2}}$ ($BR_{C2}$)</th>
<th>index of $g_{P_{C3}}$ ($BR_{C3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\nu}_{m,k} \tilde{l}_m$</td>
<td>1-6</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\nu}_m \tilde{l}^+_m$</td>
<td>7-9</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{u}_{m,k} \tilde{u}_m$</td>
<td>10-15</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{d}_{m,k} \tilde{d}_m$</td>
<td>16-21</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^- j \tilde{W}^+$</td>
<td>22-23</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^- j \tilde{H}^+$</td>
<td>24-25</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0 j \tilde{Z}^0$</td>
<td>26-(24+i)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0 j \tilde{A}^0$</td>
<td>25+i)-(23+2 i)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0 j \tilde{H}^0$</td>
<td>27+i)-(21+4 i)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \to \gamma \tilde{G}$</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \to Z^0 \tilde{G}$</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \to h^0 \tilde{G}$</td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mode</th>
<th>index of $g_{P_{C2}}$ ($BR_{C2}$)</th>
<th>index of $g_{P_{C3}}$ ($BR_{C3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0_j \tilde{u}_m \tilde{d}_m$</td>
<td>1-(3*i-3)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0_j \tilde{d}_m \tilde{d}_m$</td>
<td>(3<em>i-2)-(6</em>i-6)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0_j \tilde{l}_m \tilde{e}_m$</td>
<td>(6<em>i-5)-(9</em>i-9)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{\chi}^0_j \sum \nu_m \bar{\nu}_m$</td>
<td>(9<em>i-8)-(10</em>i-9)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{G} \tilde{u}_m \tilde{u}_m$</td>
<td>(10<em>i-8) - (10</em>i-6)</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^0_i \to \tilde{G} \tilde{d}_m \tilde{d}_m$</td>
<td>(10<em>i-5) - (10</em>i-3)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Correspondence between the indices for gluino partial widths (branching ratios) and the decay modes. In case of two body decays the variables are $g_{P_{G2}}$ ($BR_{G2}$) and in case of three body decays $g_{P_{G3}}$ ($BR_{G3}$).

<table>
<thead>
<tr>
<th>mode</th>
<th>index of $g_{P_{C2}}$ ($BR_{C2}$)</th>
<th>index of $g_{P_{C3}}$ ($BR_{C3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \to \tilde{\chi}^0_{m,k} \tilde{d}_m$</td>
<td>1-6</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\chi}^0_{m,k} \tilde{u}_m$</td>
<td>7-12</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\chi}^0_{m,k} \tilde{u}_m$</td>
<td>1-12</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\chi}^0_{m,k} \tilde{d}_m$</td>
<td>13-24</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\chi}^0_{m,k} \tilde{d}_m$</td>
<td>25-30</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\ell}_i \tilde{W}^- \tilde{b}$</td>
<td>31-32</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \to \tilde{\ell}_i \tilde{c}$</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>
Table 7: Correspondence between the indices for the partial widths (branching ratios) of the neutral Higgs bosons and the decay modes. The variables are $g_{P\, S0}$ ($BR_{S0}$) and $g_{P\, S0}$ ($BR_{S0}$) for the partial decay widths (branching ratios) of the CP-even Higgs bosons ($h^0$, $H^0$) and CP-odd Higgs boson ($A^0$). In case of $g_{P\, S0}$ ($BR_{S0}$) the first (second) index denotes decay modes of $h^0$ ($H^0$). Here $\phi$ stands for $h^0$, $H^0$ and $A^0$. The index runs from 1 to 3.

<table>
<thead>
<tr>
<th>mode</th>
<th>$h^0$</th>
<th>$H^0$</th>
<th>$A^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \rightarrow l_m^+ l_m^-$</td>
<td>1-3</td>
<td>1-3</td>
<td>1-3</td>
</tr>
<tr>
<td>$\phi \rightarrow d_m d_m$</td>
<td>4-6</td>
<td>4-6</td>
<td>4-6</td>
</tr>
<tr>
<td>$\phi \rightarrow u_m \bar{u}_m$</td>
<td>7-9</td>
<td>7-9</td>
<td>7-9</td>
</tr>
<tr>
<td>$H^0 \rightarrow l_{m,1}^+ l_{m,1}^-$</td>
<td>$- 10 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow \tilde{e}_m^+ \tilde{\nu}_e$</td>
<td>$- 11 + 3^*(m-1)$</td>
<td>$11 + 3^*(m-1)$</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow l_{m,2}^+ l_{m,2}^-$</td>
<td>$- 12 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow \tilde{\nu}_m \nu_m$</td>
<td>$- 19 + m$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow \bar{d}<em>{m,1} d</em>{m,1}$</td>
<td>$- 22 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow d_{m,1} d_{m,2}$</td>
<td>$- 23 + 3^*(m-1)$</td>
<td>$20 + 3^*(m-1)$</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow \bar{d}<em>{m,2} d</em>{m,2}$</td>
<td>$- 24 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow \bar{u}<em>{m,1} u</em>{m,1}$</td>
<td>$- 31 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow \bar{u}<em>{m,1} u</em>{m,2}$</td>
<td>$- 32 + 3^*(m-1)$</td>
<td>$29 + 3^*(m-1)$</td>
<td></td>
</tr>
<tr>
<td>$H^0 \rightarrow \bar{u}<em>{m,2} u</em>{m,2}$</td>
<td>$- 33 + 3^*(m-1)$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow \tilde{\chi}_r^0 \tilde{\chi}_s^0$ ($r \leq s$)</td>
<td>40-49</td>
<td>40-49</td>
<td>37-46</td>
</tr>
<tr>
<td>$\phi \rightarrow \tilde{\chi}_k^+ \tilde{\chi}_n^-$ ($k \leq n$)</td>
<td>50-52</td>
<td>50-52</td>
<td>47-49</td>
</tr>
<tr>
<td>$H^0 \rightarrow Z^0 Z^0$</td>
<td>-</td>
<td>53</td>
<td>-</td>
</tr>
<tr>
<td>$H^0 \rightarrow W^+ W^-$</td>
<td>-</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>$H^0 \rightarrow h^0 h^0$</td>
<td>-</td>
<td>59</td>
<td>-</td>
</tr>
<tr>
<td>$A^0 \rightarrow h^0 Z^0$</td>
<td>-</td>
<td>-</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 8: Correspondence between the indices for the partial widths (branching ratios) of the charged Higgs and the decay modes. The variables are $g_{P\, Spm}$ ($BR_{Spn}$) and in case of partial decay widths (branching ratios).

<table>
<thead>
<tr>
<th>mode</th>
<th>index</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^+ \rightarrow l_m^- \nu_m$</td>
<td>1-3</td>
</tr>
<tr>
<td>$H^+ \rightarrow u_m \bar{d}_m$</td>
<td>4-6</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{e}_i^+ \tilde{\nu}_e$</td>
<td>7-8</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{\mu}<em>i^+ \tilde{\nu}</em>\mu$</td>
<td>9-10</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{\tau}<em>i^+ \tilde{\nu}</em>\tau$</td>
<td>11-12</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{u}_i d_j$</td>
<td>$12 + 2^*(i-1) + j$</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{c}_i \tilde{s}_j$</td>
<td>$16 + 2^*(i-1) + j$</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{t}_i \tilde{b}_j$</td>
<td>$20 + 2^*(i-1) + j$</td>
</tr>
<tr>
<td>$H^+ \rightarrow \tilde{\chi}_r^+ \tilde{\chi}_s^0$</td>
<td>$24 + 4^*(r-1) + s$</td>
</tr>
<tr>
<td>$H^+ \rightarrow h^0 W^+$</td>
<td>34</td>
</tr>
</tbody>
</table>
- **ratioWoM**: this variable is used to decide whether two body decays or three body decay modes are calculated in case of charginos, neutralino and gluino. The program tries first two-body decay modes. In the case that the ratio of the width $\Gamma$ over the mass $m$ of the decaying particle is small: $\Gamma/m < \text{ratioWoM}$, then three body decay modes are calculated.

- **Fgmsb** and m32 : the $F$ parameter and the gravitino mass in the GMSB model. These parameters are calculated from the input and are set to huge numbers in all other models. They are needed for the calculation of the decay width(s) of the NLSP into a gravitino.

The next statements call the routine for the calculation of the cross sections provided $L_{\text{CS}} = .\text{TRUE.}$ and $\text{kont} = 0$:

```
If ((L_CS).and.(kont.eq.0)) then
  Call InitializeCrossSections(Ecms, Pm, Pp, ISR)
  Call CalculateCrossSections(Ecms, Pm, Pp, ISR & & SigSup, SigSdown, mf_u, mglu & & SigSlepton, SigSlepton & & mSneut, RSneut, SigSle, SigSn, mC, U, V, mN, N & & SigC, SigChi0, mS0, RS0, vevSM, mPO, RPO, mSpm & & RSpm, SigS0, SigSP, SigHp )
End If
```

Here the following additional input is needed:

- **Ecms**: the centre of mass energy of the collider
- **Pm, Pp**: degree of polarization of the incoming electron and positron, respectively
- **ISR**: logical variable, if .TRUE. then initial state radiation is taken into account using the formulas given in [49]

These variables can be set in the file CrossSections.in. The cross sections are stored in the variables starting with Sig which are summarized in Table 9. Please note, that in case of sfermions the structure of the variables is already put such that the case of generation mixing can easily be implemented. In the non–mixing case the cross sections are stored in the $2 \times 2$ diagonal blocks and they are sorted according to the generations as in the case of the sfermion mixing matrices.

Finally the low energy constraints $b \rightarrow s\gamma$, $a_\mu$ and $\Delta \rho$ are calculated provided that calculation of the spectrum had been performed successfully ($\text{kont}. eq.0$):

```
If (kont.eq.0) then
  Call CalculateLowEnergyConstraints(gauge, Y_l, Y_d, Y_u & & mSp2, RSpm, mC, U, V, mN, N , mSup2, RSup, mSdown2 & & RSdown, mSlepton2, RSlepton, mSneut2, RSneut & & BRbtosgamma, a_mu, Delta_Rho)
Else
  BRbtosgamma = 0._dp
  a_mu = 0._dp
  Delta_Rho = 0._dp
End If
```
Table 9: Correspondence between the production cross sections and the variables used in the program.

<table>
<thead>
<tr>
<th>process</th>
<th>Fortran name and type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \tilde{u}_i \tilde{u}_j$</td>
<td>real(dp) :: SigSup(6,6)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{d}_i \tilde{d}_j$</td>
<td>real(dp) :: SigSdown(6,6)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{l}_i \tilde{l}_j$</td>
<td>real(dp) :: SigSle(6,6)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{\nu}_i \tilde{\nu}_j$</td>
<td>real(dp) :: SigSn(6,6)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{\chi}^0_k \tilde{\chi}^0_n$</td>
<td>real(dp) :: SigChi0(4,4)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{\chi}^+_i \tilde{\chi}^-_j$</td>
<td>real(dp) :: SigN(4,4)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow h^0, Z, H^0 H^0$</td>
<td>real(dp) :: SigS0(2)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow h^0 A^0, H^0 A^0$</td>
<td>real(dp) :: SigSP(2)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow H^+ H^-$</td>
<td>real(dp) :: SigHp</td>
</tr>
</tbody>
</table>

Here $BR_{btosgamma}$, $a_\mu$, and $\Delta Rho$ denote $10^4 \times BR(b \rightarrow s\gamma)$, the SUSY contributions to $a_\mu$ and the sfermion contributions to $\Delta \rho$, respectively.

Afterwards the statement

```
Call WriteOutPut0(11, 1.e-6_dp, 1.e-3_dp)
```

is used to write all information to the file connected with unit 11 (first entry). The second entry puts a lower bound on the branching ratios to be written. In the case above, branching ratios smaller than $10^{-6}$ will not be given. The third entry gives the minimum value for the cross section in $fb$ which will be written to the output file. In the example given above cross sections smaller than $10^{-3}$ will not be written to the output file.

The last statement closes all open files.

```
call closing() ! closes the files
```

8 Conclusions

We have described SPheno, a program calculating the spectrum, branching ratios and cross sections of supersymmetric particle in $e^+e^-$ annihilation within the MSSM. The user can choose between the following high scale models: minimal supergravity, minimal supergravity including right handed neutrinos, gauge mediated supersymmetry breaking, anomaly mediated supersymmetry breaking, and string effective field theories based on OI and OII compactification. The calculation of the spectrum are done using two-loop renormalization group equations and the complete one-loop formulas for the SUSY masses. In case of the neutral Higgs bosons and the $\mu$ parameter leading two-loop effects are included. The masses and mixing angles are used to calculate the most important two body and three body decay modes. They are also used for the calculation of the SUSY production cross sections in $e^+e^-$ annihilation. Here the effects of initial state radiation and longitudinal beam polarization is included. Finally the following low energy quantities are calculated: $BR(b \rightarrow s\gamma)$, the supersymmetric contributions to the anomalous magnetic moment of the muon $a_\mu$ and the sfermion contributions to the $\rho$ parameter.

The program is set up in such a way that extensions can easily be included. The plans for upcoming versions are to include complex phases for the supersymmetric parameters, to include generation mixing, to include QCD and Yukawa corrections for various processes
such as Sfermion and Higgs production and decays. In addition beam strahlung for various
collider designs will be implemented.

**Acknowledgements**

I would like to thank B. Allanach, A. Djouadi and S. Kraml for discussions on higher order
corrections to the Yukawa couplings. Special thanks go to P. Slavich for discussions on 2-loop
corrections of the Higgs boson masses and for providing a Fortran code performing the 2-loop
corrections to the neutral Higgs boson masses and the $\mu$ parameter. I would like to thank
G. Blair and P. Zerwas for an enjoyable and fruitful collaboration from which the work on
this program originated. This work is supported by the Erwin Schrödinger fellowship No.
J2095 of the ‘Fonds zur Förderung der wissenschaftlichen Forschung’ of Austria and partly
by the Swiss ‘Nationalfonds’.

**A Switches**

In this appendix we describe the switches for influencing the behaviour of the program. Inside
the main program one can set two scales:

1. The electroweak scale $M_{\text{EW}}$, which is the scale where the loop contributions to the
masses and mixing matrices are calculated. The default is to calculate this scale from

\[ M_{\text{EW}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}. \]

By calling

```
Call SetRGEScale(1.e3_dp**2)
```

$M_{\text{EW}}$ will be set to the fixed value of $10^3$ GeV in this example. Note that the input
is the scale squared. In the case one uses a zero or a negative number as input for
\texttt{SetRGEScale} then the scale will be calculated from the stop masses.

2. The high energy scale, where the boundary conditions of the model under study are
set. Except for GMSB, where the scale is fixed by default, the high scale is calculated
from the requirement $g_1 = g_2$. By calling

```
Call SetGUTScale(2.e16_dp)
```

$M_{\text{GUT}}$ will be set to $2 \cdot 10^{16}$ GeV in this example. In the case one uses a zero or a
negative number as input for \texttt{SetGUTScale} then the scale will be calculated from the
requirement $g_1 = g_2$ except for GMSB.

In general the strong coupling $g_s$ will be different from $g_1$ and $g_2$ in GUT theories if one works
at the two loop level [66]. In case someone wants to enforce strict universality at the high
scale, this can be done by using the following statement:

```
test = SetStrictUnification(.TRUE.)
```

where \texttt{test} is a logical variable to which the old value of \texttt{SetStrictUnification} is assigned.
The same functions can also be used to set this option \texttt{.FALSE.}.
B Input files

In this section the input files are described. Among these files only the file HighScale.in has to be provided by the user. The other files Control.in, CrossSections.in and StandardModel.in can be used to change the default values which are given below in Appendices B.1, B.2 and B.4.

B.1 Control.in

This file contains three entries as shown below:

0 ! ErrorLevel
.True. ! Calculation of branching ratios
.True. ! Calculation of cross sections

The values given above are the default values inside the program and are used if the file Control.in is not present. Here ErrorLevel is an integer in the range [-2,2] where the numbers correspond to the following behaviour of the program:

-2 do not print severe warnings
-1 do not print warnings
0 print every warning
1 abort in case of a severe warning
2 abort even in case of a warning

A warning is called severe if either a result is unphysical or if a numerical procedure gives an unreliable result.

B.2 CrossSections.in

This file contains four entries as shown below:

500. ! c.m.s. energy in GeV
0. ! degree of longitudinal polarization of electrons
0. ! degree of longitudinal polarization of positrons
.True. ! calculation of initial state radiation if .TRUE.

The values given above are the default values inside the program and are used if the file CrossSections.in is not present.

B.3 HighScale.in

In this section we describe the input file for the high scale boundary conditions. The package contains several files starting with Highscale.in and ending in the models described below. One has to rename the model file to the name Highscale.in to use it as input for SPheno. Note that in all examples below the value of $A_0$ given below will be multiplied by the Yukawas coupling at the high scale and that this product enters the RGEs. For most of the examples below we have used the so-called SPS points defined in [67]. In Appendix C we display the output for the point SPS1a.
B.3.1 mSUGRA

The minimal SUGRA version is defined by four parameters and the sign of the $\mu$ parameter. The parameters are the gaugino mass parameter $M_{1/2}$, the scalar mass parameter $M_0$, the trilinear parameter $A_0$ as well as $\tan \beta$. The file reads for example

```
mSugra
250. ! M_1/2
100. ! M_0
-100. ! A_0
10. ! tan(beta)
1. ! sign of mu
.TRUE. ! if 2-loop RGEs should be used
```

B.3.2 mSUGRA including right handed neutrinos

In this case one needs four more input values compared to the case of mSUGRA described above: a common right handed neutrino mass $m_{\nu_R}$ and the light neutrino masses $m_{\nu_i}$ ($i = 1, 2, 3$). The file reads for example

```
mSugra
250. ! M_1/2
100. ! M_0
-100. ! A_0
10. ! tan(beta)
1. ! sign of mu
1.e14 ! m_nu_R
1.e-14 3.e-12 0.06e-9 ! m_nu_i
.TRUE. ! if 2-loop RGEs should be used
```

B.3.3 GMSB

The GMSB scenario is characterized by two mass parameters $M_M$ and $\Lambda$; the multiplicity $N_5$ and $N_{10}$ of messengers in the $5 + \overline{5}$ and $10 + \overline{10}$ vector-like multiplets, respectively; $\tan \beta$ and the sign of $\mu$ as described in Sect. 2.3.3. In addition one can set a common value for the $A$ parameters at the scale $M_M$. Note, however, that in the minimal model this value is practically zero. The file reads for example

```
GMSB
100000. ! Lambda
200000. ! M_M
1 ! N_5
0 ! N_10
0. ! A0
15. ! tan(beta)
1. ! sign of mu
.TRUE. ! if 2-loop RGEs should be used
```
B.3.4 AMSB

The implemented AMSB scenario is characterized by the gravitino mass $m_{3/2}$, a common scalar mass $M_0$, $\tan \beta$ and the sign of $\mu$. The file reads for example

```
AMSB       ! model
60000.     ! M_3/2
450.       ! M_0
10.        ! tan(beta)
1.         ! sign of mu
.TRUE.      ! if 2-loop RGEs should be used
```

B.3.5 String I

This scenario is characterized by the gravitino mass $m_{3/2}$, the common vev $<t>$ of the moduli fields, the string coupling squared $g_s^2$, the sine squared of the mixing angle between the dilaton fields and moduli fields $\sin^2 \theta$, the parameter $\delta_{GS}$ of the Green–Schwarz counter-term, the modular weights $n_i$ characterizing the couplings between moduli fields and matter fields, which are assumed to be generation independent in the current implementation. Moreover, one needs to specify $\tan \beta$ and the sign of $\mu$. The file reads for example as

```
String_OI
180.     ! M_3/2
14.0     ! <t>
0.5      ! g_s^2
0.9      ! sin^2(theta)
0.       ! delta_GS
-1 -3    ! n_E n_L
1 -2 0   ! n_D n_U n_Q
-1 -1    ! n_H1 n_H2
10.      ! tan(beta)
-1.      ! phase(mu)
.TRUE.    ! if 2-loop RGEs should be used
```

B.3.6 String II

This scenario is characterized by the gravitino mass $m_{3/2}$, the common vev of the moduli fields $<t>$, the string coupling squared $g_s^2$, the sine squared of the mixing angle between the dilaton fields and moduli fields $\sin^2 \theta$, the parameter of the Green–Schwarz counter-term $\delta_{GS}$. Moreover, one needs to specify $\tan \beta$ and the sign of $\mu$. There are two different scenarios implemented denoted as `String_OIIa` and `String_OIIb` corresponding to boundary conditions $(A)$ and $(B)$ of [31], respectively. The files read for example as

```
String_OIIa
300.     ! M_3/2
14.6     ! <t>
0.5      ! g_s^2
0.9      ! sin^2(theta)
0.       ! delta_GS
```
5. \! tan(\beta)
1. \! phase(\mu)
.TURE. \! if 2-loop RGEs should be used

and

\text{String}\_\text{OIIb}
300. \! M_{3/2}
14.6 \! <t>
0.5 \! g_s^2
0.9 \! \sin^2(\theta)
0. \! \delta_{\text{GS}}
5. \! tan(\beta)
1. \! phase(\mu)
.TURE. \! if 2-loop RGEs should be used

\subsection*{B.3.7 SUGRA}

This input file serves as an interface for more general models with gauge couplings unification. Here the user can specify non-universal gaugino masses at the high scale \(M_{1/2}[U(1)], M_{1/2}[SU(2)], M_{1/2}[SU(3)]\), 15 different values of the sfermion mass parameters for every type of sfermions: \(M_{E_{ii}}, M_{L_{ii}}, M_{D_{ii}}, M_{U_{ii}}, M_{Q_{ii}}, M_{H_1}, M_{H_2}\); two Higgs mass parameters \(M_{H_1}, M_{H_2}\); nine different \(A\) parameters \(A_{0,e,ii}, A_{0,d,ii}\) and \(A_{0,u,ii}\). Here \(ii\) denotes that only the diagonal entries can be set.

\text{Sugra}
480. 300. 300. \! M_{1/2}_{ii}
150. 150. 150. \! M_{0,E_{ii}}
150. 150. 150. \! M_{0,L_{ii}}
150. 150. 150. \! M_{0,D_{ii}}
150. 150. 150. \! M_{0,Q_{ii}}
150. 150. 150. \! M_{0,U_{ii}}
150. 150. \! M_{0,H_{ii}}
0. 0. 0. \! A_{0,u_{ii}}
0. 0. 0. \! A_{0,d_{ii}}
0. 0. 0. \! A_{0,e_{ii}}
10. \! tan(\beta)
1. \! phase(\mu)
.TURE. \! if 2-loop RGEs should be used

\subsection*{B.4 StandardModel.in}

This file contains the values of the Standard Model parameters and must include all lines given below. Otherwise the default values given in the listing below are used:

91.187 \! Z boson mass
2.490 \! width of Z-boson
0.14 0.14 0.14 0.14 \! Br(Z \to q q) q=u,d,c,s,b
0.035 0.035 0.03 \! Br(Z \to l l) l=e, mu, tau
0.2 ! Br(Z -> invisible)
80.41 ! W boson mass
2.06 ! width of W-boson
0.35 0.35 ! Br(W -> q q)
0.1 0.1 0.1 ! Br(W -> l nu)
0.51099906e-3 ! electron mass
0.105658 ! muon mass
1.7771 ! tau mass
0.004 ! u-quark mass
1.4 ! c-quark mass
174.3 ! t-quark mass
0.01 ! d-quark mass
0.15 ! s-quark mass
4.62 ! b-quark mass
0.2315 ! sin(theta_W) squared
137.0359895 ! 1 / Alpha
127.9 ! 1 / Alpha at m_Z
0.119 ! Alpha_s at m_Z
1.16639e-5 ! G_F, Fermi constant
0.220 ! s12 of CKM, parametrized as particle data book
0.039 ! s23 of CKM
0.0031 ! s13 of CKM
0. ! phase of CKM
2.19709e-6 ! life time of muon
3.4e-13 ! life time of tau

All masses are given in GeV and Br denotes “branching ratio” in the list above.

C Sample output

Here we give the content of the file SPheno.out provided one uses the content of HighScale.in for the mSUGRA scenario described in Appendix B.3.1 and the default values of the files Control.in, CrossSections.in and StandardModel.in.

mSugra input at the GUT scale 1.8193751412503776E+16
M_1/2 : 2.5000000000000000E+02
M_0 : 1.0000000000000000E+02
A_0 : -1.0000000000000000E+02
tan(beta) : 10.0000000000000000
phase(mu) : 1.0000000000000000

Parameters at the scale 4.8387163690920886E+02

Gaugino mass parameters
  1.0256160300628754E+02  1.9230453743751079E+02  8.695416971423458E+02

    tan(beta), mu, B
Slepton mass parameters
A_L
-7.2960260902552873E-03 -1.5085451901504909 -25.2233192083639537
M2_E
1.8409373246520361E+04 1.8407069022083171E+04 1.7758366624396785E+04
M2_L
3.7890957725749206E+04 3.7889823466403272E+04 3.7570561651708413E+04

Squark mass parameters
A_d
-0.2294422308452373 -3.441636998921720 -1.070594718316641E+02
A_u
-7.4845500397144014E-03 -2.6195690984405484 -4.4984080721097047E+02
M2_D
2.7694850270662527E+05 2.7694564371571731E+05 2.7392874700277165E+05
M2_U
2.7918011844082910E+05 2.7917785219910560E+05 1.7963017265859758E+05
M2_Q
2.989053958833648E+05 2.9890250621627242E+05 2.4881821604275642E+05

Higgs mass parameters
3.2728705451079368E+04 -1.2647888724841128E+05

Masses and mixing matrices
Gluino : 5.9431308258414890E+02 1.0000000000000000

Charginos
1.8128399897496990E+02 3.7972508491362004E+02
U
-0.915146173 0.403122168
  0.403122168 0.915146173
V
-0.969411416 0.245441450
  0.245441450 0.969411416

Neutralinos
97.630137960382843 1.8286658240938323E+02 3.616932535757582E+02
3.795651786694593E+02
N
1 1 ( -0.985173736, 0.000000000)
1 2 ( 0.055759050, 0.000000000)
1 3 ( -0.152169890, 0.000000000)
1 4 ( 0.056284663, 0.000000000)
2 1 ( -0.105870636, 0.000000000)
2 2 ( -0.93999692, 0.000000000)
e-sneutrino mass : $1.9045601012611243E+02$
mu-sneutrino mass : $1.9045285310250864E+02$
tau-sneutrino mass : $1.8956097209694545E+02$

selectron masses
  $1.4386950800164570E+02$ $2.0663378686036157E+02$
\[ R_e \]

\[ \begin{array}{c}
  0.000088274 & 0.999999996 \\
-0.999999996 & 0.000088274
\end{array} \]

smuon masses
  $1.4383537094841918E+02$ $2.0664861475069350E+02$
\[ R_{\mu} \]

\[ \begin{array}{c}
  0.018241899 & 0.999833603 \\
-0.999833603 & 0.018241899
\end{array} \]

stau masses
  $1.345799501666027E+02$ $2.1033431394260100E+02$
\[ R_{\tau} \]

\[ \begin{array}{c}
  0.268468657 & 0.963288420 \\
-0.963288420 & 0.268468657
\end{array} \]

u-squark masses
  $5.4780614315239006E+02$ $5.6490633570208024E+02$
\[ R_u \]

\[ \begin{array}{c}
  0.000077527 & 0.999999997 \\
-0.999999997 & 0.000077527
\end{array} \]

c-squark masses
  $5.4779164376198435E+02$ $5.6491659043591176E+02$
\[ R_c \]

\[ \begin{array}{c}
  0.027104541 & 0.999632604 \\
-0.999632604 & 0.027104541
\end{array} \]

t-squark masses
  $3.9757274604952244E+02$ $5.8855899352335769E+02$
\[ R_t \]
\[
\begin{array}{cc}
0.554536381 & 0.832159481 \\
-0.832159481 & 0.554536381 \\
\end{array}
\]

**d-squark masses**
\[ 5.4761741237742456 \times 10^2 \quad 5.6953755385412876 \times 10^2 \]

\[ R_d \]
\[
\begin{array}{cc}
0.000836413 & 0.999999650 \\
-0.999999650 & 0.000836413 \\
\end{array}
\]

**s-squark masses**
\[ 5.4761111206790952 \times 10^2 \quad 5.6953840728628120 \times 10^2 \]

\[ R_s \]
\[
\begin{array}{cc}
0.012543035 & 0.999921333 \\
-0.999921333 & 0.012543035 \\
\end{array}
\]

**b-squark masses**
\[ 5.1664747823588539 \times 10^2 \quad 5.4745980835840328 \times 10^2 \]

\[ R_b \]
\[
\begin{array}{cc}
0.951026325 & 0.309109898 \\
-0.309109898 & 0.951026325 \\
\end{array}
\]

**m_A0, m_H+**
\[ 3.9716087632673568 \times 10^2 \quad 4.0654002309066368 \times 10^2 \]

**m_h0, m_H0**
\[ 1.1166181009637616 \times 10^2 \quad 3.9789685848133115 \times 10^2 \]

\[ R_S0 \]
\[
\begin{array}{cc}
0.113896390 & 0.993492633 \\
-0.993492633 & 0.113896390 \\
\end{array}
\]

**Low energy constraints**
\[ 10^{-4} \text{ Br}(b \rightarrow s \gamma) : 0.3838177 \times 10^1 \]
\[ \Delta(a_{\mu}) : 0.5447498 \times 10^{-8} \]
\[ \Delta(\rho) : 0.1829291 \times 10^{-3} \]

**Decay widths (GeV) and branching ratios**

Selectron_1
Neutralino_1 e 0.21131224 100.00000000
Total width : 0.21131224

Selectron_2
Neutralino_1 e 0.12712238 52.26317145
| Neutralino_2 e     | 0.04013733 | 16.5045248   |
| Chargino_1 neutrino | 0.07597540 | 31.2357607   |
| **Total width**    | **0.24323511** |          |

| Smuon_1            |
|-------------------|-------------|-------------|
| Neutralino_1 mu   | 0.21104744  | 100.0000000 |
| **Total width**    | **0.21104744** |          |

| Smuon_2            |
|-------------------|-------------|-------------|
| Neutralino_1 mu   | 0.12728238  | 52.28029028 |
| Neutralino_2 mu   | 0.04016202  | 16.49625242 |
| Chargino_1 neutrino| 0.07601710  | 31.22345730 |
| **Total width**    | **0.24346150** |          |

| Stau_1             |
|--------------------|-------------|-------------|
| Neutralino_1 tau   | 0.14597684  | 100.0000000 |
| **Total width**     | **0.14597684** |          |

| Stau_2             |
|--------------------|-------------|-------------|
| Neutralino_1 tau   | 0.16310412  | 55.22030445 |
| Neutralino_2 tau   | 0.04619971  | 15.64130946 |
| Chargino_1 neutrino| 0.08606600  | 29.13838609 |
| **Total width**     | **0.29536983** |          |

| e-Sneutrino        |
|--------------------|-------------|-------------|
| Neutralino_1 neutrino | 0.15829938  | 90.39621196 |
| Neutralino_2 neutrino | 0.00372885  | 2.12934196  |
| Chargino_1 e       | 0.01308905  | 7.4744608   |
| **Total width**     | **0.17511727** |          |

| mu-Sneutrino       |
|--------------------|-------------|-------------|
| Neutralino_1 neutrino | 0.15829302  | 90.40278693 |
| Neutralino_2 neutrino | 0.00372587  | 2.12788095  |
| Chargino_1 mu      | 0.01307861  | 7.4693212   |
| **Total width**     | **0.17509749** |          |

<p>| tau-Sneutrino      |
|--------------------|-------------|-------------|
| Neutralino_1 neutrino | 0.15649412  | 92.23051574 |
| Neutralino_2 neutrino | 0.00292840  | 1.72586668  |
| Chargino_1 tau     | 0.01025464  | 6.04361757  |</p>
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**Sbottom_2**

| Neutralino_1 b-quark | 0.24397318 | 33.44230042 |
| Neutralino_2 b-quark | 0.08601743 | 11.79072502 |
| Neutralino_3 b-quark | 0.03700740 | 5.07274017 |
| Neutralino_4 b-quark | 0.05304386 | 7.27091758 |
| Chargino_1 t-quark | 0.11582889 | 15.87709181 |
| **Stop_1 W-** | 0.19366391 | 26.54622500 |
| **Total width:** | 0.72953467 | |

**Sup_1**

| Neutralino_1 u-quark | 1.15181264 | 98.48926332 |
| Neutralino_2 u-quark | 0.01120273 | 0.95792374 |
| Neutralino_3 u-quark | 0.00152307 | 0.13023466 |
| Neutralino_4 u-quark | 0.00494195 | 0.42257635 |
| Chargino_1 d-quark | 0.00000002 | 0.00000193 |
| **Total width:** | 1.16948041 | |

**Sup_2**

| Neutralino_1 u-quark | 0.03620866 | 0.66423008 |
| Neutralino_2 u-quark | 1.72553982 | 31.65418423 |
| Neutralino_3 u-quark | 0.00517093 | 0.09485826 |
| Neutralino_4 u-quark | 0.06407609 | 1.17544453 |
| Chargino_1 d-quark | 3.53559056 | 64.85867992 |
| Chargino_2 d-quark | 0.08463583 | 1.55260297 |
| **Total width:** | 5.45122190 | |

**S-charm_1**

| Neutralino_1 c-quark | 1.15098392 | 98.14036844 |
| Neutralino_2 c-quark | 0.01253940 | 1.06919075 |
| Neutralino_3 c-quark | 0.00158298 | 0.13497525 |
| Neutralino_4 c-quark | 0.00492241 | 0.41971639 |
| Chargino_1 s-quark | 0.00276378 | 0.23565786 |
| Chargino_2 s-quark | 0.00000107 | 0.00009130 |
| **Total width:** | 1.17279356 | |

**S-charm_2**

<p>| Neutralino_1 c-quark | 0.03701501 | 0.67941726 |
| Neutralino_2 c-quark | 1.72415946 | 31.64725980 |</p>
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**Stop_1**
- Neutralino_1 t-quark  | 0.39250239 | 19.40691906  |
- Neutralino_2 t-quark  | 0.22674584 | 11.21123908  |
- Chargino_1 b-quark     | 1.38120247 | 68.29228464  |
- Chargino_2 b-quark     | 0.02203615 | 1.08955722   |
| **Total width**        | **2.02248685** |            |

**Stop_2**
- Neutralino_1 t-quark  | 0.22161960 | 2.91852834   |
- Neutralino_2 t-quark  | 0.62619038 | 8.24635720   |
- Neutralino_3 t-quark  | 0.34624563 | 4.55973974   |
- Neutralino_4 t-quark  | 1.54482109 | 20.34388720  |
- Chargino_1 b-quark     | 1.54991244 | 20.41093566  |
- Chargino_2 b-quark     | 1.51409588 | 19.93926416  |
- Stop_1 Z               | 1.51313204 | 19.92657136  |
- Stop_1 h0              | 0.27752232 | 3.65471634   |
| **Total width**        | **7.59353939** |            |

**Chargino_1**
- neutralino_1 d u      | 0.00033235 | 1.99860842   |
- neutralino_1 s c       | 0.00033232 | 1.99844982   |
- neutralino_1 e nu      | 0.00058806 | 3.53637657   |
- neutralino_1 mu nu     | 0.00063093 | 3.79415091   |
- neutralino_1 tau nu    | 0.01474527 | 88.67241428  |
| **Total width**         | **0.01662893** |            |

**Chargino_2**
- Selectron_2 neutrino  | 0.12652636 | 5.19161956   |
- Smuon_1 neutrino      | 0.00000150 | 0.00006154   |
- Smuon_2 neutrino      | 0.12656625 | 5.19325658   |
- Stau_1 neutrino       | 0.00104893 | 0.04303979   |
- Stau_2 neutrino       | 0.13749520 | 5.64169248   |
- e-sneutrino e         | 0.05302870 | 2.17586926   |
- mu-sneutrino mu       | 0.05309068 | 2.17841255   |
- tau-sneutrino tau     | 0.07070699 | 2.90124380   |
- Neutralino_1 W        | 0.17302320 | 7.09947452   |
- Neutralino_2 W        | 0.67940247 | 27.87718885  |
- Chargino_1 Z          | 0.58927646 | 24.17914547  |
Chargino_1 \ h0 \quad 0.42696015 \quad 17.51899560

Total width : 2.43712690

Neutralino_1 : stable

Neutralino_2
Selectron_1 e \quad 0.00154723 \quad 7.10543425
Smuon_1 mu \quad 0.00160018 \quad 7.34859632
Stau_1 tau \quad 0.01862788 \quad 85.54596943

Total width : 0.02177529

Neutralino_3
Selectron_1 e \quad 0.00503923 \quad 0.26009421
Selectron_2 e \quad 0.00218588 \quad 0.11282149
Smuon_1 mu \quad 0.00508346 \quad 0.26237682
Smuon_2 mu \quad 0.00227146 \quad 0.11723867
Stau_1 tau \quad 0.02025229 \quad 1.04529883
Stau_2 tau \quad 0.02419151 \quad 1.24861727
e-sneutrino neutrino \quad 0.01234523 \quad 0.63718479
mu-sneutrino neutrino \quad 0.01234554 \quad 0.63720099
tau-sneutrino neutrino \quad 0.01243421 \quad 0.64177746
Chargino_1 W \quad 1.14827835 \quad 59.26707890
Neutralino_1 Z \quad 0.22657242 \quad 11.69427718
Neutralino_2 Z \quad 0.40462398 \quad 20.88420588
Neutralino_1 h0 \quad 0.04071375 \quad 2.10139378
Neutralino_2 h0 \quad 0.02112676 \quad 1.09043373

Total width : 1.93746405

Neutralino_4
Selectron_1 e \quad 0.02090064 \quad 0.79655160
Selectron_2 e \quad 0.05130301 \quad 1.95626710
Smuon_1 mu \quad 0.02086555 \quad 0.79521429
Smuon_2 mu \quad 0.05145801 \quad 1.96113393
Stau_1 tau \quad 0.01565228 \quad 0.59652937
Stau_2 tau \quad 0.08419943 \quad 3.20895348
e-sneutrino neutrino \quad 0.13486416 \quad 5.13985427
mu-sneutrino neutrino \quad 0.13486717 \quad 5.13996895
tau-sneutrino neutrino \quad 0.13571657 \quad 5.17234103
Chargino_1 W \quad 1.34016810 \quad 51.07560769
Neutralino_1 Z \quad 0.05567616 \quad 2.12189348
Neutralino_2 Z \quad 0.04779240 \quad 1.82143249
Neutralino_1 h0 \quad 0.17892991 \quad 6.81925922
Neutralino_2 h0 \quad 0.35146997 \quad 13.39499312

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| **h0**         |        |         |
| electrons      | 0.00000000 | 0.00000125 |
| muons          | 0.00000103 | 0.05351444 |
| taus           | 0.00029239 | 15.14367767 |
| d-quark        | 0.00000001 | 0.00031725 |
| s-quark        | 0.00000138 | 0.07138010 |
| b-quark        | 0.00152831 | 79.15466880 |
| u-quark        | 0.00000000 | 0.00045556 |
| c-quark        | 0.00010767 | 5.57639494 |
| Total width :  | 0.00193079 |         |

<p>| <strong>H0</strong>         |        |         |
| muons          | 0.00028014 | 0.04201232 |
| taus           | 0.07938694 | 11.90538074 |
| d-quark        | 0.00000168 | 0.00025219 |
| s-quark        | 0.00037836 | 0.05674169 |
| b-quark        | 0.07322960 | 53.34169360 |
| c-quark        | 0.00000511 | 0.00076636 |
| t-quark        | 0.03081125 | 4.62065503 |
| Selectron 1 1  | 0.00039974 | 0.05994791 |
| Smuon 1 1      | 0.00040732 | 0.06108426 |
| Smuon 1 2      | 0.00000334 | 0.00559954 |
| Stau 1 1       | 0.00433734 | 0.65045550 |
| Stau 1 2       | 0.00799437 | 1.19888731 |
| e-Sneutrino    | 0.00073208 | 0.10978775 |
| mu-Sneutrino   | 0.00073222 | 0.10980771 |
| tau-Sneutrino  | 0.00076881 | 0.11529554 |
| neutralino_1 neutralino_1 | 0.01687144 | 2.53015073 |
| neutralino_1 neutralino_2 | 0.04686601 | 7.02833048 |
| neutralino_2 neutralino_2 | 0.01058042 | 1.58670780 |
| chargino_1 chargino_1 | 0.03027976 | 4.54094909 |</p>
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Total cross sections in fb for:

E_{c_m s} : 500.0000000 GeV

Degree of polarization: P_{e-} = 0.000000 P_{e+} = 0.000000
Initial state radiation is included

u-squarks: kinematically not possible

c-squarks: kinematically not possible

t-squarks: kinematically not possible

d-squarks: kinematically not possible

s-squarks: not possible

b-squarks: not possible

selectrons

1 1 290.9786253 fb
1 2 81.1156881 fb
2 2 43.5380487 fb

smuons

1 1 57.2730680 fb
1 2 0.0058106 fb
2 2 18.4801616 fb

staus

1 1 62.1659720 fb
1 2 1.2151999 fb
2 2 15.5585302 fb

e-sneutrino

412.6967832 fb

mu-sneutrino

12.9553932 fb

tau-sneutrino

13.2367076 fb

neutralinos

1 1 284.9858436 fb
1 2 64.4974860 fb
1 3 8.0550495 fb
1 4 1.0888651 fb


References


[34] W. Porod, in preparation.


