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SOFTSUSY1.2: a program for calculating supersymmetric spectra

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Abstract: SOFTSUSY is a program which accurately calculates the spectrum of superparticles in the Minimal Supersymmetric Standard Model (MSSM). The program solves the renormalisation group equations with theoretical constraints on soft supersymmetry breaking terms provided by the user. Weak-scale gauge coupling and fermion mass data (including one-loop finite MSSM corrections) are used as a boundary condition, as well as successful radiative electroweak symmetry breaking. The program can also calculate a measure of fine-tuning. The program structure has been designed to easily generalise to extensions of the MSSM. This article serves as a self-contained guide to prospective users, and indicates the conventions and approximations used. Sample results are compared with similar calculations in the literature.

Keywords: Supersymmetric Standard Model, Beyond Standard Model.

Contents

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) provides an attractive weak-scale extension to the Standard Model. As well as solving the gauge hierarchy problem, it can be motivated by more fundamental models such as various string theories or supersymmetric grand unified theories. The MSSM provides a rich and complicated phenomenology. It predicts many states extra to the Standard Model (sparticles) and their indirect empirical effects and direct detection are vital for verification of the MSSM. Models that are more fundamental than the MSSM can provide stringent constraints upon the way supersymmetry (SUSY) is broken, with important implications for the spectrum which in turn affects the signatures available in experiments. It is therefore desirable to construct a calculational tool which may provide a spectrum and couplings of the MSSM sparticles so that studies of the capabilities of colliders, extraction of high scale parameters (if a signal is observed) and studies of constraints on the models are enabled. We present such a tool (`SOFTSUSY`) in this article.

1.1. The Nature of the Physical Problem

The determination of sparticle masses and couplings of SUSY particles in the R-parity conserving MSSM is the basic problem. Low energy data on Standard Model fermion masses, gauge couplings and electroweak boson masses are to be used as a constraint. SUSY radiative corrections from sparticle loops to these inputs depend upon the sparticle spectrum, and must be calculated. Theoretical constraints on the SUSY breaking parameters from a higher theory are often imposed at a high renormalisation scale, perhaps resulting from a supergravity or string theory. Often, the theoretical constraints drastically reduce the number of free parameters in the SUSY breaking sector (which numbers over 100 in the unconstrained case). These constraints then make phenomenological analysis tractable by reducing the dimensionality of parameter space sufficiently so that parameter scans over a significant volume of parameter space are possible. Finally, the MSSM parameters must also be consistent with a minimum in the Higgs potential which leads to the observed electroweak boson masses.

This problem has been addressed many times before in the literature (see for example [1, 2, 3, 5, 7]), with varying degrees of accuracy in each part of the calculation. It is our purpose here to provide a tool which will solve the problem with a high accuracy, including state-of-the-art corrections. Similar problems in the context of MSSM extensions[1] have also been studied. In anticipation of new forms of SUSY breaking constraints and new MSSM extensions, we designed the tool to be flexible and easily extended.

[1] By MSSM extension, we mean an extension applicable near the weak scale.

1.2. The Program

SOFTSUSY has been written in object-oriented C++, although there is a fortran interface currently available for universal SUGRA calculations. Accuracy and generalisability have taken priority over running speed in the design. For example, full three family mass and Yukawa matrices are employed, rather than the more usual dominant third family approximation, as used in the other publicly released code ISASUGRA, which comprises part of the ISAJET7.51 package [7]. This choice slows the renormalisation group evolution significantly, but will facilitate studies of sparticle or quark mixing. The running time is not foreseen as a bottleneck because it is a matter of a couple of seconds on a modern PC, and will certainly be negligible compared to any Monte-Carlo simulation of sparticle production and decay in colliders. It is possible for the user to specify their own high scale boundary conditions for the soft SUSY breaking parameters without having to change the SOFTSUSY code.

The code can be freely obtained from the SOFTSUSY web-page, which, at the time of writing, resides at URL

http://allanach.home.cern.ch/allanach/softsusy.html.

SOFTSUSY is a tool whose output could be used for Monte-Carlo studies of MSSM sparticle searches [8] such as HERWIG [9]. It may also be used for more theoretical studies such as gauge or Yukawa unification, as was the case[2] in refs. [10, 11], quasi-fixed points [12, 13], or new patterns of SUSY breaking [14].

1.3. Aims and Layout

The main aims of this article are to provide a manual for the use of SOFTSUSY, to describe the approximations employed and the notation used (to allow for user generalisation), to display some SOFTSUSY results and to provide a comparison with the results of ISASUGRA, which solves the same physical problem.

The rest of this paper proceeds as follows: the relevant MSSM parameters are presented in sec. 2. The approximations employed are noted in sec. 3, but brevity requires that they are not explicit. However, a reference is given so that the precise formulae utilised may be obtained in each case. The algorithm of the calculation is also outlined. In sec. 4, we present some sample results of computations. We quantitatively compare the results from SOFTSUSY in a universal minimal SUGRA point to those obtained from ISASUGRA [7] and SSARD [15]. A parameter scan over a hyper-surface of universal minimal SUGRA is displayed to demonstrate a fine-tuning calculation. Technical information related to running and extending the program is placed in appendices. The sample program is listed in appendix A together with a brief explanation of its use and input file. The output of the program is displayed in appendix B and the use of switches and constants is explained in appendix C. Finally, in appendix D, a description of the relevant objects and their relation to each other is presented.

[2]The version of SOFTSUSY used was more approximate than the current version.

2. MSSM Parameters

In this section, we introduce the MSSM parameters in the SOFTSUSY conventions. Translations to the actual variable names used in the source code are shown in appendix D.

2.1. Supersymmetric Parameters

The chiral superfields of the MSSM have the following $G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ quantum numbers

$$\begin{aligned} &L:\ (1,2,-\tfrac{1}{2}), \quad \bar{E}:\ (1,1,1), \qquad Q:\ (3,2,\frac{1}{6}), \quad \bar{U}:\ (3,1,\frac{2}{3}), \\ &\bar{D}:\ (3,1,-\tfrac{1}{3}), \quad H_1:\ (1,2,-\frac{1}{2}), \quad H_2:\ (1,2,\frac{1}{2}). \end{aligned} \tag{2.1}$$

Then, the superpotential is written as

$$W = \epsilon_{ab}\left[(Y_E)_{ij} L_i^a H_1^b \bar{E}_j + (Y_D)_{ij} Q_i^{ax} H_1^b \bar{D}_{jx} + (Y_U)_{ij} Q_i^{ax} H_2^b \bar{U}_{jx} + \mu H_2^a H_1^b\right] \tag{2.2}$$

Throughout this section, we denote an $SU(3)$ colour index of the fundamental representation by $x, y, z = 1, 2, 3$. The $SU(2)_L$ fundamental representation indices are denoted by $a, b, c = 1, 2$ and the generation indices by $i, j, k = 1, 2, 3$. ϵ_{ab} is the totally antisymmetric tensor, with $\epsilon_{12} = 1$. Note that the sign of μ is identical to the one in ISASUGRA [7], but is in the opposite convention to ref. [3]. Presently, real Yukawa couplings only are included. All MSSM running parameters are in the $\overline{DR}$ scheme. The Higgs vacuum expectation values (VEVs) are $\langle H_i^0 \rangle = v_i$ and $\tan\beta = v_2/v_1$. g_i are the MSSM $\overline{DR}$ gauge couplings and g_1 is defined in the Grand Unified normalisation $g_1 = \sqrt{5/3} g'$, where g' is the Standard Model hypercharge gauge coupling. Elements of fermion mass matrices are given by

$$(m_u)_{ij} = \frac{1}{\sqrt{2}}(Y_U)_{ij} v_2, \qquad (m_{d,e})_{ij} = \frac{1}{\sqrt{2}}(Y_{D,E})_{ij} v_1 \tag{2.3}$$

for the up quark, down quark and charged lepton matrices respectively.

2.2. SUSY Breaking Parameters

The soft SUSY breaking parameters are in the notation of Barger, Berger and Ohmann [2]. The trilinear scalar interaction potential is

$$V_3 = \epsilon_{ab}\left[\tilde{u}^*_{ix_R}(U_A)_{ij}\tilde{Q}^{xa}_{j_L} H_2^b + \tilde{d}^*_{ix_R}(D_A)_{ij}\tilde{Q}^{xa}_{j_L} H_2^b + \tilde{e}^*_{i_R}(E_A)_{ij}\tilde{L}^a_{j_L} H_2^b\right], \tag{2.4}$$

where fields with a tilde are the scalar components of the superfield with the identical capital letter. Note that

$$(A_{U,D,E})_{ij} = (U_A, D_A, E_A)_{ij}/(Y_{U,D,E})_{ij} \tag{2.5}$$

(no summation on i, j) are often referred to in the literature as soft A-parameters.

The scalar bilinear SUSY breaking terms are contained in the potential

$$V_2 = m_{H_1}^2 {H_{1a}}^* H_1^a + m_{H_2}^2 {H_{2a}}^* H_2^a + \tilde{Q}_{ixa}^* (m_{\tilde{Q}}^2)_{ij} \tilde{Q}_j^{xa} + \tilde{L}_{ia}^* (m_{\tilde{L}}^2)_{ij} \tilde{L}_j^a + \\ \tilde{u}_i^x (m_{\tilde{u}}^2)_{ij} \tilde{u}_{jx}^* + \tilde{d}_i^{xa} (m_{\tilde{d}}^2)_{ij} \tilde{d}_{jxa}^* + \tilde{e}_i^{xa} (m_{\tilde{e}}^2)_{ij} \tilde{e}_{jxa}^* . - \mu B \epsilon_{ab} H_1^a H_2^b . \tag{2.6}$$

Writing the bino as $\tilde{b}$, $\tilde{w}^{A=1,2,3}$ as the unbroken-SU(2)$_L$ gauginos and $\tilde{g}^{X=1...8}$ as the gluinos, the gaugino mass terms are contained in the Lagrangian

$$\mathcal{L}_G = \frac{1}{2} \left(M_1 \tilde{b}\tilde{b} + M_2 \tilde{w}^A \tilde{w}^A + M_3 \tilde{g}^X \tilde{g}^X \right) + h.c. \tag{2.7}$$

2.3. Tree-Level Masses

Here we suppress any gauge indices and follow the notation of ref. [3] closely. The Lagrangian contains the neutralino mass matrix as $-\tilde{\psi}^{0T} \mathcal{M}_{\tilde{\psi}^0} \tilde{\psi}^0$ + h.c., where $\tilde{\psi}^0 = (-i\tilde{b},\ -i\tilde{w}^3,\ \tilde{h}_1,\ \tilde{h}_2)^T$ and

$$\mathcal{M}_{\tilde{\psi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}. \tag{2.8}$$

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

We make the identification $\tilde{w}^\pm = (\tilde{w}^1 \mp i\tilde{w}^2)/\sqrt{2}$ for the charged winos and $\tilde{h}_1^-, \tilde{h}_2^+$ for the charged higgsinos. The Lagrangian contains the chargino mass matrix as $-\tilde{\psi}^{-T} \mathcal{M}_{\tilde{\psi}^+} \tilde{\psi}^+ + h.c.$, where $\tilde{\psi}^+ = (-i\tilde{w}^+,\ \tilde{h}_2^+)^T$, $\tilde{\psi}^- = (-i\tilde{w}^-,\ \tilde{h}_1^-)^T$ and

$$\mathcal{M}_{\tilde{\psi}^+} = \begin{pmatrix} M_2 & \sqrt{2}\, M_W s_\beta \\ \sqrt{2}\, M_W c_\beta & \mu \end{pmatrix}. \tag{2.9}$$

This matrix is then diagonalised by 2 dimensional rotations through angles θ_L, θ_R in the following manner:

$$\begin{pmatrix} c_{\theta_L} & s_{\theta_L} \\ -s_{\theta_L} & c_{\theta_L} \end{pmatrix} \mathcal{M}_{\tilde{\psi}^+} \begin{pmatrix} c_{\theta_R} & -s_{\theta_R} \\ s_{\theta_R} & c_{\theta_R} \end{pmatrix} = \begin{pmatrix} m_{\chi_1}^+ & 0 \\ 0 & m_{\chi_2}^+ \end{pmatrix} \tag{2.10}$$

where $m_{\chi_i}^+$ could be negative, with the mass parameter of the lightest chargino being in the top left hand corner.

At tree level the gluino mass, $m_{\tilde{g}}$, is given by M_3.

Strong upper bounds upon the intergenerational scalar mixing exist [16] and in the following we assume that such mixings are negligible. The tree-level squark and slepton masses for the family i are found by diagonalising the following mass matrices $\mathcal{M}_{\tilde{f}}$ defined in the $(\tilde{f}_{iL}, \tilde{f}_{iR})^T$ basis:

$$\begin{pmatrix} (m^2_{\tilde{Q}})_{ii} + m^2_{ui} + (\frac{1}{2} - \frac{2}{3}s^2_W)M^2_Z c_{2\beta} & m_{u_i}\left((A_U)_{ii} - \mu \cot\beta\right) \\ m_{u_i}\left((A_U)_{ii} - \mu\cot\beta\right) & (m^2_{\tilde{u}})_{ii} + m^2_{u_i} + \frac{2}{3}s^2_W M^2_Z c_{2\beta} \end{pmatrix} , \tag{2.11}$$

$$\begin{pmatrix} (m^2_{\tilde{Q}})_{ii} + m^2_{d_i} + (\frac{1}{2} - \frac{1}{3}s^2_W)M^2_Z c_{2\beta} & m_{d_i}\left((A_D)_{ii} - \mu \tan\beta\right) \\ m_{d_i}\left((A_D)_{ii} - \mu\tan\beta\right) & (m^2_{\tilde{d}})_{ii} + m^2_{d_i} - \frac{1}{3}s^2_W M^2_Z c_{2\beta} \end{pmatrix} , \tag{2.12}$$

$$\begin{pmatrix} (m^2_{\tilde{L}})_{ii} + m^2_{e_i} + (\frac{1}{2} - s^2_W)M^2_Z c_{2\beta} & m_{e_i}\left((A_E)_{ii} - \mu \tan\beta\right) \\ m_{e_i}\left((A_E)_{ii} - \mu\tan\beta\right) & (m^2_{\tilde{e}})_{ii} + m^2_{e_i} - s^2_W M^2_Z c_{2\beta} \end{pmatrix} , \tag{2.13}$$

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

$$\begin{pmatrix} m_{\tilde{f}_1} & 0 \\ 0 & m_{\tilde{f}_2} \end{pmatrix} = \begin{pmatrix} c_f & s_f \\ -s_f & c_f \end{pmatrix} \mathcal{M}_{\tilde{f}} \begin{pmatrix} c_f & -s_f \\ s_f & c_f \end{pmatrix} \tag{2.14}$$

where c_f is the cosine of the sfermion mixing angle, $\cos\theta_f$, and s_f the sine. θ_f are set in the convention that the two mass eigenstates are in no particular order and $\theta_f \in [-\pi/4, \pi/4]$. The sneutrinos of one family are not mixed and their masses are given by

$$m_{\tilde{\nu}_i} = (m^2_{\tilde{L}})_{ii} + \frac{1}{2}M^2_Z c_{2\beta}. \tag{2.15}$$

The CP-even gauge eigenstates (H^0_1, H^0_2) are rotated by the angle α into the mass eigenstates ($H^0\, h^0$) as follows,

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H^0_1 \\ H^0_2 \end{pmatrix} . \tag{2.16}$$

$m_{h^0} < m_{H^0}$ by definition, and $\alpha \in [-\pi/4, 3\pi/4]$. The CP-odd and charged Higgs masses are

$$m^2_{A^0} = B\mu(\tan\beta + \cot\beta), \qquad m^2_{H^\pm} = m^2_{A^0} + M^2_W \tag{2.17}$$

at tree level.

3. Calculation

We now show the algorithm used to perform the calculation. Standard Model parameters (fermion and gauge bosons masses, the fine structure constant α, the Fermi constant from muon decay G^μ_F and $\alpha_3(M_Z)$) are used as constraints. The soft SUSY breaking parameters and the superpotential parameter μ are then the free parameters. However, in what follows, $|\mu|$ is constrained by M_Z and $\tan\beta$ is traded for B as an input parameter. Therefore, the total list of unconstrained input parameters is: any fundamental soft SUSY breaking breaking parameters (except B), $\tan\beta$ and the sign of μ. First we describe the evolution of the low-energy Standard Model input parameters below M_Z, then detail the rest of the algorithm.

3.1. Below M_Z

$\alpha(M_Z)$, $\alpha_s(M_Z)$ are first evolved to 1 GeV using 3 loop QCD and 1 loop QED [17, 18, 19] with step-function decoupling of fermions at their running masses. We have checked that the contribution from 2-loop matching [20] is negligible; the 3-loop contribution effect is an order of magnitude larger. Then, the two gauge couplings and all Standard Model fermion masses except the top mass are run to M_Z. The β functions of fermion masses are taken to be zero at renormalisation scales below their running masses. The parameters at M_Z are used as the low energy boundary condition in the rest of the evolution.

3.2. Initial Estimate

The algorithm proceeds via the iterative method, and therefore an approximate initial guess of MSSM parameters is required. For this, the third family $\overline{DR}$ Yukawa couplings are approximated by

$$h_t(Q) = \frac{m_t(Q)\sqrt{2}}{v \sin\beta}, \qquad h_{b,\tau}(Q) = \frac{m_{b,\tau}(Q)\sqrt{2}}{v \cos\beta}, \tag{3.1}$$

where $v = 246.22$ GeV is the Standard Model Higgs VEV and $Q = m_t(m_t)$ is the renormalisation scale. The $\overline{MS}$ values of fermion masses are used for this initial estimate. The fermion masses and α_s at the top mass are obtained by evolving the previously obtained fermion masses and gauge couplings from M_Z to m_t (with the same accuracy). The electroweak gauge couplings are estimated by $\alpha_1(M_Z) = 5\alpha(M_Z)/(3c_W^2)$, $\alpha_2(M_Z) = \alpha(M_Z)/s_W^2$. Here, s_W is taken to be the on-shell value. These two gauge couplings are then evolved to m_t with 1-loop Standard Model β functions, including the effect of a light higgs (without decoupling it). In this initial guess, no SUSY threshold effects are calculated. The gauge and Yukawa couplings are then evolved to the unification scale M_X with the one-loop MSSM β functions, where the user-supplied boundary condition on the soft terms is applied. Also, $\mu(M_X) = \text{sgn}(\mu) \times 1$ GeV and $B(M_X) = 0$ are imposed. These initial values are irrelevant; they are overwritten on the next iteration by more realistic boundary conditions. $\mu(M_X)$ is set to be the correct sign because its sign does not change through renormalisation.

The whole system of MSSM soft parameters and SUSY couplings is then evolved to 1-loop order to M_Z. At M_Z, the tree-level electroweak symmetry breaking (EWSB) conditions are applied [8] to predict μ and B. The masses and mixings of MSSM superparticles are then calculated at tree-level order by using the SUSY parameters (and B) calculated at M_Z. The resulting set of MSSM parameters is then used as the initial guess for the iterative procedure described below.

3.3. Gauge and Yukawa Couplings

Figure 1 shows the iterative procedure, starting from the the top. The whole calculation is currently performed in the real full three family approximation, i.e. all Yukawa

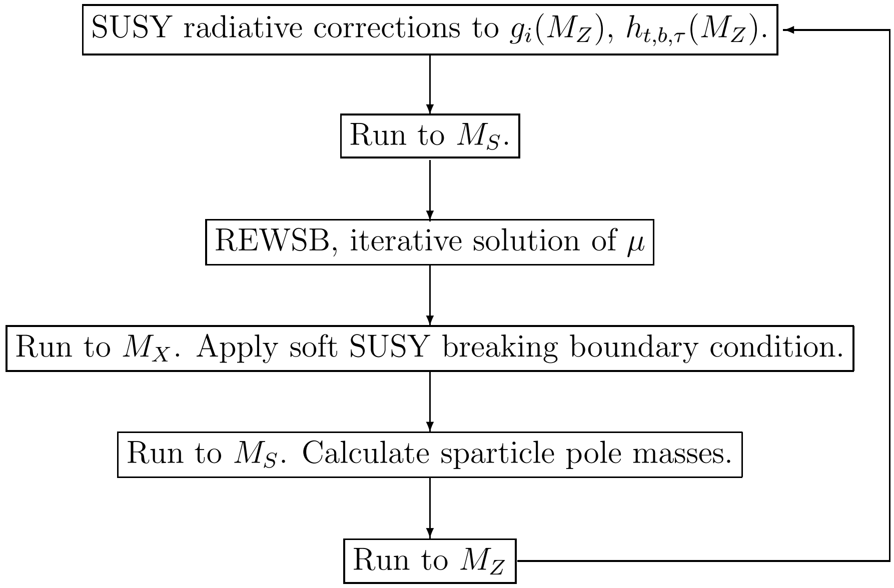

Figure 1: Iterative algorithm used to calculate the SUSY spectrum. Each step (represented by a box) is detailed in the text. The initial step is the uppermost one. M_S is the scale at which the EWSB conditions are imposed, as discussed in the text. M_X is the scale at which the high energy SUSY breaking boundary conditions are imposed.

couplings are set to be real, but quark mixing is incorporated. First of all, the one-loop radiative corrections are applied to the gauge and third-family Yukawa couplings. For these, we rely heavily on ref. [3] by Bagger, Matchev, Pierce and Zhang (BMPZ)[3]. The full one-loop supersymmetric contributions to $m_t(M_Z)$ including logarithmic and finite contributions (Eqs. (D.16)-(D.18) of BMPZ) are employed[4]. The full corrections are necessary because the region of valid EWSB is very sensitive to $m_t(m_t)$ [8]. The squark-gluino and squark-chargino contributions to $m_b(M_Z)$ that are enhanced by either μ or $\tan\beta$ are added using eqs. (13),(14),(15) of BMPZ. Chargino masses are set to M_2 and μ respectively in these corrections. Both finite and leading logarithmic corrections are included. The resulting chargino masses are valid to a few percent [3] and identical approximations are used to calculate $m_\tau(M_Z)$ (eq. (16) of BPMZ), which receives contributions from sneutrino-chargino loops. The one-loop $\overline{DR}$ values for $m_t(M_Z), m_b(M_Z), m_\tau(M_Z)$ are then substituted with the one-loop $\overline{DR}$ value of v into eq. (2.3) to calculate the third family $\overline{DR}$ Yukawa couplings at M_Z. The other diagonal elements of the Yukawa matrices are set by eq. (2.3) but with fermion masses replaced by the $\overline{MS}$ values. The Yukawa couplings are mixed using the central values

[3]Whenever a reference to an equation in BPMZ is made, it is understood that the sign of μ must be reversed.

[4]Following BMPZ, the two-loop $\overline{MS}$ QCD contribution $\Delta m_t/m_t = -1.11\alpha_s^2$ is added, assuming it to be close to the $\overline{DR}$ value.

of the CKM matrix [4]

$$V_{CKM} = \begin{pmatrix} 0.9752 & -0.2205 & -0.0031 \\ 0.2205 & 0.9745 & -0.0390 \\ 0.0085 & 0.0385 & -0.9993 \end{pmatrix}, \tag{3.2}$$

mixing the up (the default), or down Yukawa couplings at M_Z

$$(Y_U)' = V^T_{CKM}(Y^U)V_{CKM}, \qquad (Y_D)' = V_{CKM}(Y^D)V^T_{CKM} \tag{3.3}$$

where the primed Yukawa matrix is in the weak eigenbasis and the unprimed is in the mass eigenbasis. There are also options described in appendix C for performing the calculation in the unmixed, or dominant third-family approximation.

Full one-loop corrections to $g_i(M_Z)$ are included. The treatment of electroweak gauge couplings follows from appendix C of BMPZ, and includes: two-loop corrections from the top, electroweak boson and the lightest CP-even Higgs. $\alpha(M_Z)$ receives corrections from two-loop QED and QCD corrections. Because the EWSB constraints tend to depend sensitively upon $g_{1,2}(M_Z)$, accurate values for them are determined iteratively. An estimate of the $\overline{DR}$ value of s_W^2 is used to yield a better estimate until the required accuracy is reached (usually within 3 or 4 iterations). The QCD coupling is modified by gluino, squark and top loops as in eqs. (2),(3) of BMPZ.

3.4. MSSM Renormalisation

All soft breaking and SUSY parameters are then evolved to the scale

$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}, \tag{3.4}$$

where [21] the scale dependence of the electroweak breaking conditions is smallest. Throughout the iteration described here, the renormalisation group evolution (RGE) employs three family, 2-loop MSSM β functions for the supersymmetric parameters [2], except for $\tan\beta$, which is evolved to one-loop in the third family approximation [21]. The SUSY breaking parameters are evolved to one-loop order except for the gaugino masses, where two-loop corrections have been implemented. There is no step-function decoupling of sparticles: this is taken into account at leading logarithmic order in the radiative corrections previously calculated at M_Z and in the calculation of the physical sparticle spectrum at M_S, described below. All β functions are real and include 3 family (and mixing) contributions.

3.5. Electroweak Symmetry Breaking

The full one-loop EWSB conditions at this scale are then employed to calculate $B(M_S)$ and $\mu(M_S)$. $\mu(M_S)$ requires an iterative solution because the tadpoles depend upon the value of μ assumed. The symmetry breaking condition for μ can be phrased as [3]

$$\mu^2 = \frac{1}{2}\left(\tan 2\beta \left[m^2_{\bar{H}_2}\tan\beta - m^2_{\bar{H}_1}\cot\beta\right] - M^2_{\bar{Z}}\right), \tag{3.5}$$

where $m_{\bar{H}_i}^2 = m_{H_i}^2 - t_i/v_i$, $M_{\bar{Z}}^2 = M_Z^2 + \Re\Pi_{ZZ}^T(M_Z^2)$, t_i are the tadpole contributions, M_Z is the pole Z mass and Π_{ZZ}^T is the transverse Z self-energy. The value of μ coming from the tree-level EWSB condition (Eq. 3.5, with $\Re\Pi_{ZZ}^T = t_i = 0$) is utilised as an initial guess, then the one-loop contributions in the tadpoles and self-energy terms are added to provide a new value of $\mu(M_S)$. The tadpole corrections are then calculated using the new value of $\mu(M_S)$ and the procedure is repeated until it converges to a given accuracy. $B(M_S)$ is then determined by using the value of $\mu(M_S)$ in the EWSB

$$B = \frac{-s_{2\beta}}{2\mu}\left(m_{\bar{H}_1}^2 + m_{\bar{H}_2}^2 + 2\mu^2\right) \tag{3.6}$$

The ensemble of MSSM parameters are then evolved using the β functions detailed above to the user supplied scale M_X. The user-supplied boundary conditions are then imposed upon the soft terms before the model is evolved back down to M_S. The superparticle mass spectrum (except for the gluino mass) is determined at this scale. Because μ and B are more scale independent at M_S, the Higgs, neutralino and chargino masses also ought to be more scale independent by determining them at this scale.

3.6. SUSY Spectrum

In the following description of the approximations involved in the calculation of the superparticle spectrum, it is implicit that where M_Z or M_W appear in the tree-level mass matrices, their full one-loop $\overline{DR}$ values are employed as defined in BPMZ eqs. (D.2), (D.3). The running value of $s_W(\mu) = e(\mu)/g_2(\mu)$ is also employed. The neutralino and chargino masses are determined by an approximation to the full one-loop result. This consists of neglecting off-diagonal terms and setting their masses to $M_{1,2}$ or $|\mu|$ in the correction. All sparticle mixing is ignored in the correction term, g'/g is neglected, quark masses are set to zero, the squarks are approximated to be degenerate with mass squared $(m_{\tilde{Q}}^2)_{11}$ (the sleptons with mass squared $(m_{\tilde{L}}^2)_{11}$) and $m_{h^0} = M_Z$, $m_{H^0} = m_{H^+} = m_{A^0}$. h_τ is neglected. These approximations induce errors of order $(\alpha/4\pi)M_Z^2/\mu^2$ and $(\alpha/4\pi)M_Z^2/m_{A^0}^2$, which could be large if μ gets close to zero, as is often the case close to the boundary of correct EWSB. Eqs. (25),(27),(31) of BPMZ are used, and the resulting chargino and neutralino masses are accurate to better than 2% [3].

The physical gluino mass is calculated to full one-loop order as follows. The running parameters are evaluated at renormalisation scale $\mu = m_{\tilde{g}}$ and $p = M_3(\mu)$ in the following corrections:

$$\Delta_{\tilde{g}}(\mu) = \frac{g_3(\mu)^2}{16\pi^2}\left(15 + 9\ln\left(\frac{\mu^2}{p^2}\right) - \sum_q\sum_{i=1}^2 B_1(p, m_q, m_{\tilde{q}_i}, \mu) - \sum_{q=t,b}\frac{m_q}{M_3(\mu)} s_{2\theta_q}\left[B_0(p, m_q, m_{\tilde{q}1}, \mu) - B_0(p, m_q, m_{\tilde{q}2}, \mu)\right]\right). \tag{3.7}$$

The Passarino-Veltman functions $B_{0,1}$ are given in appendix B of BPMZ. The physical gluino mass is then given by

$$m_{\tilde{g}} = \frac{M_3(m_{\tilde{g}})}{1 - \Delta_{\tilde{g}}(m_{\tilde{g}})}, \tag{3.8}$$

corresponding to a re-summation of the one-loop corrections.

Quark masses are neglected in the one-loop corrections to the squark mass for the first two families and electroweak corrections are neglected for all squark masses, as in BPMZ eqs. (33),(34). For the third family of squarks, the complete one-loop corrections are used but neglecting loops with electroweak gauge bosons. BPMZ eq. (D.46) then gives the radiative corrections to the third family squark mass matrices.

The pseudo-scalar Higgs mass m_{A^0} is determined to full one-loop order as in eq. (E.6) of BMPZ in order to reduce its scale dependence, which can be large [22]. All one-loop corrections except the charged Higgs self-energy are included in the determination of the charged Higgs pole mass (eq. (E.7) of BMPZ). The two CP-even Higgs masses are determined as in ref. [23], including one and two-loop finite and logarithmic terms in the top/stop sector. Non top-stop corrections were included to one-loop order, but the only mixing terms included are those of the sbottoms [24]. For slepton pole masses, the tree-level result is used.

Finally, the running MSSM parameters are evolved back down to M_Z. The whole process is iterated as shown in figure 1, until the parameters $\mu(M_Z)$, $B(M_Z)$, $m^2_{H1}(M_Z)$, $m^2_{H_2}(M_Z)$ all converge to better than the desired accuracy.

3.7. Fine Tuning

We now detail the fine-tuning calculation. As lower bounds on superpartner masses are pushed up by colliders, m_{H_1} and m_{H_2} may be forced to be much larger than M_Z if they are related to the other superparticle masses, as is the case for example in the case of minimal supergravity. If we re-phrase eq. (3.5) as

$$M^2_{\bar{Z}} = -2\mu^2 + \tan 2\beta \left[m^2_{\bar{H}_2} \tan\beta - m^2_{\bar{H}_1} \cot\beta \right], \tag{3.9}$$

we see that the terms on the right-hand side must have some degree of cancellation in order to reproduce the observed value of M_Z. But μ has a different origin to the SUSY breaking parameters and the balancing appears unnatural. Various measures have been proposed in order to quantify the apparent cancellation, for example ref.s [25, 26]. The definition of naturalness c_a of a 'fundamental' parameter a employed here is [26]

$$c_a \equiv \left| \frac{\partial \ln M^2_Z}{\partial \ln a} \right|. \tag{3.10}$$

From a choice of a set of fundamental parameters defined at the scale M_X: $\{a_i\}$, the fine-tuning of a particular model is defined to be $c = \max(c_a)$. $\{a_i\}$ are any parameters in the user supplied boundary condition on the soft supersymmetry breaking parameters augmented by $h_t(M_X)$, $\mu(M_X)$ and $B(M_X)$. The derivatives in eq. (3.10) are calculated by numerically finding the derivative of $M_Z^{pole} = \hat{M}_Z + \Re\Pi_{ZZ}^T(M_Z^2)$ in eq. (3.5). The input parameters are changed slightly (one by one), then the MSSM parameter ensemble is run from M_X to M_S where the sparticle mass spectrum is determined along with the corresponding $\overline{MS}$ Higgs VEV parameter $v^2 \equiv v_1^2 + v_2^2$. First of all, $\tan\beta(M_S)$ is determined by inverting eq. (3.6) and the resulting value is utilised in a version of eq. (3.5) inverted to give M_Z^{pole} in terms of the other parameters. The resulting value of M_Z^{pole} is the prediction for the new changed input parameters, and its derivative is determined by examining its behaviour as the initial changes in input parameters tend to zero.

4. Results

We now compare the output of the code with that of ISASUGRA and ref. [15] to determine the level of agreement, then provide the spectra of a parameter scan.

4.1. Comparison with other codes

For the explicit comparison, we pick LHC universal (SUGRA) point II defined in the ATLAS TDR [27]:

$$m_0 = 400 \text{ GeV}, \ M_{1/2} = 400 \text{ GeV}, \ A_0 = 0, \ \tan\beta = 10, \ \mu > 0. \tag{4.1}$$

We also use $m_t^{pole} = 174.3$ GeV, $\alpha_s^{\overline{MS}}(M_Z) = 0.119$ and $M_X = 1.9 \times 10^{19}$ GeV as the unification scale. These input parameters are the ones provided in the sample program code detailed in appendix A. The SUSY spectrum was determined and is displayed in table 1 together with the percentage difference to the ISASUGRA result. As can be seen from table 1, the slepton masses agree to better than 1%. The largest

M_g	m_{u_L}	$m_{u_R^c}$	m_{d_L}	$m_{d_R^c}$	m_{b_1}	m_{b_2}	m_{t_1}	m_{t_2}	m_{ν_e}	m_{e_L}	$m_{e_R^c}$	m_{ν_τ}
963	950	922	953	918	856	911	669	891	475	482	431	474
2.5	**5.3**	**5.1**	**5.2**	**5.0**	**4.6**	**4.6**	**0.0**	**2.9**	**0.0**	**0.0**	**0.7**	**0.2**

m_{τ_1}	m_{τ_2}	$m_{\chi_1^0}$	$m_{\chi_2^0}$	$m_{\chi_3^0}$	$m_{\chi_4^0}$	$m_{\chi_1^+}$	$m_{\chi_2^+}$	m_{h^0}	m_{H^0}	m_{A^0}	$m_{H^\pm}$
425	482	155	308	498	517	308	517	118	692	676	684
0.9	**0.2**	**3.2**	**3.6**	**2.0**	**1.5**	**3.7**	**1.5**	**1.7**	**1.0**	**1.0**	**0.6**

Table 1: Comparison of SUSY spectra in ISASUGRA and SOFTSUSY at SUGRA point 2: $m_0 = M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$. We also use $m_t^{pole} = 174.3$ GeV, $\alpha_s^{\overline{MS}}(M_Z) = 0.119$ and $M_U = 1.9 \times 10^{19}$ GeV. The SOFTSUSY masses in GeV are shown in normal type-face, and the modulus of the percentage difference with the mass calculated by ISASUGRA is displayed in bold-face underneath.

discrepancy lies in the squark sector where the masses are typically 5% different to the

ISASUGRA value. We have checked that the other SUGRA points 1,3,4,5 provide similar levels of agreement. Note that the maximum fine-tuning parameter (often taken to be the overall definition of fine-tuning) for this point is $c_\mu = 121.2$.

At various stages of the calculation, there are accuracy choices which can produce differences in the calculation results. The number of loops used to perform the RGE is one obvious choice, but also there can be differences in input parameters, treatment of threshold effects (inclusion of finite terms or logarithmic re-summation), scale of imposition of EWSB etc. For example, if we neglect the one-loop corrections to the squarks in SOFTSUSY, their masses become in better agree with those of ISASUGRA(to better than 2.2% agreement for each squark). The finite part of these corrections is currently not included in ISASUGRA.

ISASUGRA is an independent calculation to SOFTSUSY and the level agreement between the two provides a verification of the validity of both programs. We also obtain rough ∼10% level agreement with the SUSPECT [5] program, but we neglect to perform a detailed comparison because a new more accurate release is forthcoming.

It might be argued that the LHC SUGRA points are quite innocuous points, that are easy to obtain agreement between different codes. For this reason, we now include a comparison of proposed post-LEP benchmark points [15]. This allows a comparison between SOFTSUSY and another SUSY spectrum code (SSARD). Some of these points are very close to the unacceptable electroweak symmetry breaking boundary or charged LSP boundary. These points are expected to provide larger differences between codes than the LHC SUGRA points.

Tables 2, 3 show the spectra for SOFTSUSY and SSARDrespectively. Note that while the unification scale M_X was a prediction from gauge unification in SSARD, SOFTSUSY set $M_X = 10^{19}$ GeV for all points. This should not provide any significant differences because parameters' dependence on $M_X = (1-3) \times 10^{19}$ GeV from gauge unification is logarithmic and therefore small. Table 2 also details the naturalness parameters with and without including the top-Yukawa coupling (c and c_{h_t}).

The most striking difference between the two tables was that SOFTSUSY found four of the points in mSUGRA space to not yield an acceptable solution. Points E and F did not yield an acceptable electroweak symmetry broken vacuum and points K, M also reached a Landau pole in the Yukawa couplings. Points E and F are close to the electroweak symmetry breaking boundary [15], which is notoriously sensitive to top mass, and other, threshold corrections [8].

The quoted values of $|\mu(M_Z)|$ all agree to better than 3%. h^0 is predicted to be systematically 2-3 GeV heavier in SOFTSUSY. H^0 typically has a difference of 0-3% except for point L(8%). A^0 has a difference of 3-5% except for high $\tan\beta$, where there are 15,11 and 67% discrepancies for points I,J,L respectively. Similarly, the charged Higgs mass also shows differences of 10,10 and 25% for I,J,L but 2-4% for the other points.

Charginos and neutralinos typically agree to 3% or better. However, at high $\tan\beta =$

35, there are discrepancies of 5-6% in $\chi^0_{3,4}, \chi^\pm_2$. Point M has even higher discrepancies of around 10% for these three masses. Right-handed sleptons typically agree to better than 1% between the two codes, whereas discrepancies between, 1-3% can be observed in the right-handed slepton sector, with the notable exception of ν_τ in point L, which shows a difference of 8%. The coloured sparticles are typically 4 to 6% lighter in SSARDthan in SOFTSUSY.

Unfortunately, there is no manual for SSARD, so it is hard to tell if the above discrepancies are due to different approximations in the codes. Removing the threshold corrections to the coloured sparticles improves the agreement between SOFTSUSYand SSARDby a factor of 2.

4.2. mSUGRA Parameter Scan

We now show a scan over part of universal mSUGRA parameter space using SOFTSUSY. Setting $\mu > 0$, $\tan\beta = 10$, we scan over a range $m_0 = 100 - 4000$ GeV and $M_{1/2} = 100 - 1000$ GeV. The constraints and fine-tuning are displayed in figure 2. The area marked 'REWSB' is incompatible with radiative EWSB and is roughly consistent with other recent calculations (see for example figure 1a of ref. [28]). The black region to the left of the REWSB region is excluded from the LEP2 limit [29] $m_{\chi_1^\pm} > 83$ GeV. The small black region to the top-left of the plot is excluded by the requirement that the LSP be neutral. The dashed line displays the LHC SUSY search reach, as calculated in ref. [8]. The fine-tuning in the background shows that the LHC can exclude fine-tunings up to 210 for $\mu > 0$ and $\tan\beta = 10$. c_{h_t} has not been included in this fine-tuning calculation. The white curves display contours of equal lightest Higgs mass and are labeled in GeV. Thus, if m_h^0 is below[5] 118 GeV, as suggested by the recent LEP2 signal [30, 31, 32], the LHC will discover SUSY particles (this analysis applies for $\tan\beta = 10$ and $\mu > 0$, but the result is more general [33]). However, $m_{h^0} < 118$ GeV also implies that the fine-tuning parameter is less than 95 for $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$.

A. Sample Program

We now present the sample program from which it is possible to run SOFTSUSY in a simple fashion. The most important features of the objects are described in appendix D. The sample program has the following form:

```
#include "iostream.h"
#include "complex.h"
#include "def.h"
#include "linalg.h"
#include "lowe.h"
```

[5]We allow for a ±3 GeV theoretical error in the determination of the MSSM Higgs mass

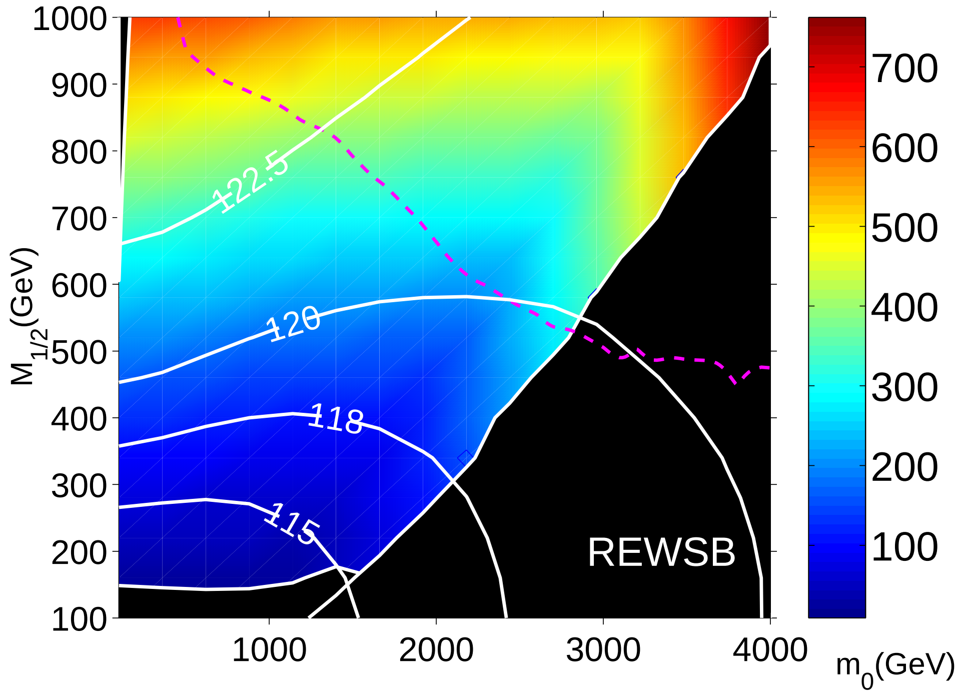

Figure 2: Fine-tuning and constraints on SUGRA parameter space for $\mu > 0$ and $\tan\beta = 10$. Blacked out regions are ruled out by lack of correct EWSB marked ('REWSB'), the LEP2 limit on the chargino mass (bottom left) and the requirement of a neutral lightest supersymmetric particle (top left). The background colour density records the fine-tuning parameter, as defined by the colour bar to the right. The white contours are of equal lightest Higgs mass, as labeled in GeV and the dotted line records the LHC search reach.

```
#include "rge.h"
#include "softsusy.h"
#include "softpars.h"
#include "susy.h"
#include "utils.h"
#include "numerics.h"
#include "rgeroutines.h"

// User supplied routine. Inputs m at the unification scale, and uses
// inputParameters vector to output m with high energy soft boundary
// conditions.
void sugraBcs(MssmSoftsusy & m, const DoubleVector & inputParameters)
{
  double m0 = inputParameters.display(1);
  double m12 = inputParameters.display(2);
  double a0 = inputParameters.display(3);

  // Sets scalar soft masses equal to m0, fermion ones to m12 and sets the
```

```
  // trilinear scalar coupling to be a0
  m.standardSugra(m0, m12, a0);

  return;
}

void userDefinedBcs(MssmSoftsusy & m, const DoubleVector & inputParameters) {
  m.methodBoundaryCondition(inputParameters);
  sugraBcs(m, inputParameters);
}

// outputs vector for use in above routine given SUGRA parameters
// m0,m12,a0
void translateSugra(DoubleVector & pars, double m0, double m12,
    double a0) {
  pars(1) = m0; pars(2) = m12; pars(3) = a0;
}

int main() {
 // Sets format of output: 2 decimal places
  outputCharacteristics(4);

  cout << "SOFTSUSY1.2 test program, Ben Allanach 2001\n";
  cout << "If you use SOFTSUSY, please refer to hep-ph/0104145\n\n";

  // Parameters used
  double m12 = 400., a0 = 0., mgut = 1.9e16, tanb = 10.0, m0 = 400.;
  int sgnMu = 1, accuracy = 3; // accuracy = 3 implies all loop/finite
                               // corrections will be used

  QedQcd oneset;
  readIn(oneset, "massIn");

  cout << "Low energy data:\n" << oneset;

  oneset.toMz();

  DoubleVector pars(3);

  // Return r as an MssmSoftsusy object consistent with unification
  // given by sugraBcs at mgut and the low energy data in oneset to
  // accuracy epsilon
  const double epsilon = EPS;
```

```
  MssmSoftsusy r;

  translateSugra(pars, m0, m12, a0);
  r.lowOrg(sugraBcs, mgut, pars, sgnMu, tanb, oneset, accuracy, epsilon);

  // Interfaces to Monte Carlo codes:
  //cout << "************** ISAWIG input **************\n";
  //r.isawigInterface751("softsusy.out", "softsusy.in");
  //cout << "\n\n************** ISAJET 7.51 par file input **************\n";
  //r.isajetInterface751();
  cout << "\n\n************** ISASUSY input **************\n";
  r.ssrunInterface751("softsusy.out");
  cout << endl << endl;

  cout << r << endl;

  cout << "******** Fine Tuning wrt (m0,m12,a0,mu,B,ht) **********" << endl;
  if (!r.displayProblem().test()) cout << r.fineTune(sugraBcs, pars, mgut);
}
```

The numbers supplied in this file are (respectively) $m_u(1\text{ GeV})$, $m_c(m_c)$, $m_t(m_t)$ (irrelevant here), the pole top mass m_t^{pole}, $m_d(1\text{ GeV})$, $m_s(1\text{ GeV})$, $m_b(m_b)$, $m_e(m_e)$, $m_\mu(m_\mu)$, $m_\tau(m_\tau)$ $\alpha(Q)$, $\alpha_s(Q)$, the renormalisation scale Q(GeV), the number of QCD loops utilised and finally the inclusion of step-function threshold effects in the QCD evolution (1), or not (0). The masses are given in units of GeV. The scale dependent quantities in this object are then evolved to M_Z by the method `toMz`, to provide the low-scale empirical boundary condition for the rest of the calculation.

The user must supply a void function that sets the supersymmetry breaking parameters from an input `DoubleVector`. In the sample code given above, this function is `sugraBcs` and is applied to the `MssmSoftsusy` object at the user-supplied scale `mgut`. It calls the `MssmSoftsusy` method `standardSugra(m0, m12, a0)`, which sets all scalar masses equal to `m0`, all gaugino masses to `m12` and all trilinear scalar couplings to `a0`, in the standard universal fashion. The method `lowOrg` calls the method that drives the calculation.

We have provided various interfaces to several other codes: `isawigInterface751`, `isajetInterface751` and `ssrunInterface751` which are described in appendix A.2. Finally, `fineTune` performs the fine-tuning calculation on the same SUGRA point.

The spectrum produced by the test program is summarised in table 1 and compared to the calculation of `ISASUGRA`. The actual output is displayed in appendix B.

A.1. Monte-Carlo Interfaces

The methods `MssmSoftsusy::isawigInterface751`, `MssmSoftsusy::isajetInterface751` and `MssmSoftsusy::ssrunInterface751` all provide output intended as input into `ISAWIG` [34], ISAJET7.51 parameter file [7] or SSRUN [7] respectively. HERWIG [9] or ISAJET could be used to simulate MSSM events based on the SOFTSUSY spectrum. SSRUN would calculate the branching ratios of the MSSM spectrum provided by SOFTSUSY.

At some stage, each of the three programs mentioned above use the ISAJET7.51 routine SSRUN. Because the input to SSRUN assumes certain tree-level relations between masses which are broken by the radiative corrections included in SOFTSUSY, the output of the SOFTSUSY interfaces is massaged in order to match the SOFTSUSY spectrum with the one that will be used in SSRUN. In most cases, this is done to better than 1 GeV for each mass. However, it was not possible to simultaneously fit the stop and input sbottom parameters. A choice was then made to fit the stop masses correctly, then some percent-level difference in the sbottom masses used by SSRUN is observed. Similarly, a decision to fit m_{A^0} was taken, resulting in differences in $m_{H^\pm}$ and m_{H^0} in SSRUN. These corrections can become significant at high $\tan\beta$, but should be percent level for $\tan\beta < 30$. For example, at LHC SUGRA point II, as detailed in table 1, the SSRUN values of $m_{\tilde{b}_{1,2}}$ are 1.0% different to the SOFTSUSY output, whereas $m_{H^\pm}$ is 0.3% different and m_{H^0} has a 2.2 % difference.

A.2. Fortran Interface

A fortran interface is provided, which can be called as

```
      call interfaceSugra(m0, m12, a0, mgut, tanb, signMu,
     c    runningParameters, physicalParameters, fineTuningMeasure)
```

Currently, only universal SUGRA boundary conditions are supported for inputs m0, m12, a0, mgut, tanb, signMu. The other parameters are outputs. runningParameters(110) contains all MssmSoftsusy running parameters, physicalParameters(54) contains the physical mass and mixing parameters and fineTuningMeasure(6) contains the fine tuning with respect to the input parameters. Release SOFTSUSY1.1 contains an example fortran main program that performs the calculation of the SUSY spectrum for LHC SUGRA point II. Within that program is information on the ordering of the output parameters.

B. Sample Output

```
SOFTSUSY1.2 test program, Ben Allanach 2001
If you use SOFTSUSY, please refer to hep-ph/0104145

Low energy data:
mU: 2.5000e-03  mC: 1.2500e+00  mt: 1.6661e+02  mt^pole: 1.7430e+02
mD: 6.0000e-03  mS: 1.2250e-01  mB: 4.2000e+00
mE: 5.1100e-04  mM: 1.0564e-01  mT: 1.7770e+00
aE: 7.8196e-03  aS: 1.1900e-01  scale: 9.1188e+01
```

```
loops: 3          thresh: 1


************** ISASUSY input **************
'softsusy.out'
1.7430e+02
9.6341e+02,4.9365e+02,6.7597e+02,9.6901e+00
9.5159e+02,9.1795e+02,9.2224e+02,4.7965e+02,4.2829e+02
8.4845e+02,9.0954e+02,7.2272e+02,4.7792e+02,4.2440e+02,
-7.1992e+02,-1.2432e+03,-2.3400e+02
9.5147e+02,9.1795e+02,9.2200e+02,4.7965e+02,4.2828e+02
1.5745e+02,3.2385e+02
/


----------------------------------------------------------
SUSY breaking MSSM parameters at Q=9.1188e+01
 UA(3,3):
-1.8251e-01 -7.9262e-01  6.2168e+00
-7.9261e-01 -3.5337e+00  2.8157e+01
 6.1982e+00  2.8073e+01 -7.2738e+02
 UD(3,3):
-1.3180e-01  6.0455e-05 -1.1403e-01
 2.9622e-06 -2.6907e+00 -5.1642e-01
-7.5429e-05 -7.0335e-03 -1.8307e+02
 UE(3,3):
-4.9007e-03  0.0000e+00  0.0000e+00
 0.0000e+00 -1.0131e+00  0.0000e+00
 0.0000e+00  0.0000e+00 -2.4260e+01
 mQLsq(3,3):
 1.0105e+06 -6.2770e+01  1.6105e+03
-6.2770e+01  1.0102e+06  7.2938e+03
 1.6105e+03  7.2938e+03  8.1593e+05
 mURsq(3,3):
 9.5317e+05 -1.2540e+02  3.2212e+03
-1.2540e+02  9.5263e+05  1.4588e+04
 3.2212e+03  1.4588e+04  5.7655e+05
 mDRsq(3,3):
 9.4527e+05  1.3573e-06 -2.5233e-03
 1.3573e-06  9.4527e+05 -2.3660e-01
-2.5233e-03 -2.3660e-01  9.3280e+05
 mLLsq(3,3):
 2.3315e+05  0.0000e+00  0.0000e+00
 0.0000e+00  2.3315e+05  0.0000e+00
```

```
 0.0000e+00  0.0000e+00  2.3131e+05
 mSEsq(3,3):
 1.8379e+05  0.0000e+00  0.0000e+00
 0.0000e+00  1.8378e+05  0.0000e+00
 0.0000e+00  0.0000e+00  1.8011e+05
B: 1.3909e+02 mH1sq: 2.1259e+05 mH2sq: -3.3272e+05
Gaugino masses(1,3):
 1.5428e+02  3.1085e+02  9.9391e+02
Gravitino mass M3/2: 0.0000e+00
---------------------------------------------------------------
Physical MSSM parameters
mh^0: 1.1835e+02 mA^0: 6.7597e+02 mH^0: 6.9210e+02 mH^+-: 6.8356e+02
alpha: -1.0775e-01
sneutrinos(1,3):
 4.7540e+02  4.7540e+02  4.7365e+02
mU~(2,3):
 9.5019e+02  9.5007e+02  8.9086e+02
 9.2151e+02  9.2127e+02  6.9985e+02
mD~(2,3):
 9.5333e+02  9.5321e+02  8.5634e+02
 9.1832e+02  9.1832e+02  9.1085e+02
mE~(2,3):
 4.8160e+02  4.8159e+02  4.8153e+02
 4.3061e+02  4.3060e+02  4.2488e+02
thetat: -4.3483e-01 thetab: 1.3555e-01 thetatau: -1.7704e-01
mGluino:  9.6341e+02
charginos(1,2):
 3.0746e+02  5.1688e+02
thetaL: -3.6929e-01 thetaR: -2.4925e-01
neutralinos(1,4):
 1.5498e+02  3.0767e+02 -4.9787e+02  5.1653e+02
neutralino mixing matrix (4,4):
 9.9287e-01  5.9077e-02 -4.3608e-02 -9.3871e-02
-2.5247e-02  9.5067e-01  6.0285e-02  3.0325e-01
 1.0799e-01 -2.5153e-01  7.0144e-01  6.5807e-01
-4.3635e-02  1.7169e-01  7.0884e-01 -6.8277e-01
Higgs VEV: 2.4953e+02
Data set:
mU: 1.0393e-03  mC: 6.0043e-01  mt: 1.6661e+02  mt^pole: 1.7430e+02
mD: 2.5080e-03  mS: 5.1205e-02  mB: 2.8070e+00
mE: 5.0266e-04  mM: 1.0391e-01  mT: 1.7519e+00
aE: 7.8196e-03  aS: 1.1900e-01  scale: 9.1188e+01
loops: 3         thresh: 1
lsp is neutralino of mass 1.5498e+02 GeV
```

```
----------------------------------------------------------------
Supersymmetric parameters at Q=9.1188e+01
 Y^U(3,3):
 1.8500e-04  8.0647e-04 -7.6418e-03
 8.0647e-04  3.6006e-03 -3.4611e-02
-7.6418e-03 -3.4611e-02  8.9600e-01
 Y^D(3,3):
 9.9864e-05  1.7791e-14 -3.3531e-11
 8.6650e-16  2.0389e-03 -1.5186e-10
-2.1526e-14 -2.0518e-12  1.4963e-01
 Y^E(3,3):
 2.0015e-05  0.0000e+00  0.0000e+00
 0.0000e+00  4.1377e-03  0.0000e+00
 0.0000e+00  0.0000e+00  9.9653e-02
tan beta: 1.0000e+01 smu: 4.8703e+02
g1: 4.6353e-01 g2: 6.1717e-01 g3: 1.1282e+00
thresholds: 3 #loops: 2
----------------------------------------------------------------
******** Fine Tuning wrt (m0,m12,a0,mu,B,ht) **********
(1,6):
 2.8945e+00  1.1446e+02  0.0000e+00  1.2116e+02  1.9625e+00
 1.0940e+02
```

After the output of the input `QedQcd` object and then the values it takes when evolved to M_Z, the result of the iteration algorithm in sec. 3 is output in the form of a `MssmSoftsusy` object. The soft SUSY breaking parameters were defined in sec. 2.2, and are listed in appendix D.6. First of all, the soft SUSY breaking parameters are displayed. In order, they are the up, down and charged lepton trilinear scalar matrices (in units of GeV). Next come the mass squared values of the left-handed squarks, right-handed up squarks, right-handed down squarks, left-handed sleptons, right-handed charged sleptons in GeV^2. B, $m_{H_1}^2$, $m_{H_2}^2$ and gaugino mass parameters follow. The parameter, $m_{3/2}$ (not used here) is the VEV of a compensator superfield in anomaly-mediation [14] and completes the SUSY breaking parameter list.

Physical MSSM parameters follow. The pole masses and mixing parameters are previously listed in sec. 2.3, and are detailed in appendix D.6. All masses are in units of GeV, and all mixing angles are given in radians. Respectively, there is: m_{h^0}, m_{A^0}, m_{H^0}, m_{H^0} and α. Scalar sparticle masses $m_{\tilde{\nu}}$, $m_{\tilde{u}}$, $m_{\tilde{d}}$, $m_{\tilde{e}}$ follow, as well as the mixing angles θ_t, θ_b, θ_τ. The gauginos are listed (in order): $m_{\tilde{g}}$, $m_{\chi^\pm}$, θ_L, θ_R, m_{χ^0} and O. The $\overline{DR}$ Higgs VEV $v(M_S)$ is then listed, followed by the $\overline{MS}$ low energy data used as a boundary condition at M_Z. Finally, the identity of the lightest supersymmetric particle is shown, together with its mass.

Supersymmetric parameters (see sections 2.1,D.5) are displayed next: Yukawa matrices Y^U, Y^D, Y^E, $\tan\beta$,g_i, the accuracy level of the calculation, bilinear superpotential

μ parameter, renormalisation scale and maximum number of loops used for RGE.

Any associated problems such as negative mass-squared scalars or inconsistent EWSB are flagged next. None of these are printed because the SUGRA II point displayed has none of these problems. Finally, as calculated in sec. 3.7, the fine-tuning parameters c_{m_0}, $c_{M_{1/2}}$, c_{A_0}, c_μ, c_B, c_{h_t} are shown.

C. Switches and Constants

The file `def.h` contains the switches and constants. If they are changed, the code must be recompiled in order to use the new values. Table 4 shows the most important parameters in `def.h`, detailing the default values that the constants have. All data on masses and couplings has been obtained using the latest particle data group numbers [4]. `def.h` also contains default values for un-initialised `QedQcd` objects, but we neglect these because they are not utilised here.

Setting `PRINTOUT` to a non-zero value gives additional information on each successive iteration. If `PRINTOUT>0`, a warning flag is produced when the overall iteration finishes. The predicted values of M_Z^{pole} and $\tan\beta(M_S)$ after iteration convergence are also output[6]. The level of convergence, $\mu(M_S)$, $B(M_S)$ and M_Z are output with each iteration, as well as a flag if the object becomes non-perturbative. `PRINTOUT>1` produces output on the fine-tuning calculation. The predicted values of M_Z^{pole} and $\tan\beta(M_S)$ are output with each variation in the initial inputs. A warning flag is produced when a negative-mass squared scalar is present. `PRINTOUT>2` prints output on the sub-iterations that determine $\mu(M_S)$ and $s_W(M_S)$.

`EPS` sets the accuracy of the whole calculation. The iteration of the MSSM EWSB parameters is required to converge to a fractional accuracy smaller than `EPS`. Sub-iterations are required to converge to a better accuracy than $10^{-2}\times$`EPS` for s_W and $10^{-4}\times$`EPS` for μ. The accuracy of the Runge-Kutta RGE changes from iteration to iteration but is proportional to the value of `EPS`.

`MIXING` determines what M_Z boundary condition will be used for the quark Yukawa matrix parameters. `MIXING=-1` sets all Yukawa couplings to zero at M_Z except for the third-family ones (dominant third-family approximation). `MIXING=0` sets the quark mixings to zero but includes the first two family's diagonal terms. `MIXING=1,2` sets all the mixing to be in the up-quark or down-quark sector respectively, at M_Z, as in eq. (3.3).

D. Object Structure

We now go on to sketch the objects and their relationship. This is necessary information for generalisation beyond the MSSM. Only methods and data which are deemed

[6]Note that the input value of $\tan\beta$ is the value at M_Z.

important for prospective users are mentioned here, but there are many others within the code itself.

D.1. Linear Algebra

The `SOFTSUSY` program comes with its own linear algebra classes: `Complex`, `DoubleVector`, `DoubleMatrix`, `ComplexVector`, `ComplexMatrix`. Constructors of the latter four objects involve the dimensions of the object, which start at 1. `Complex` objects are constructed with their real and imaginary parts respectively. For example, to define a vector $a_{i=1,2,3}$, a matrix $m_{i=1\ldots 3,j=1\ldots 4}$ of type `double` and a Complex number $b = 1 - i$:

```
DoubleVector a(3);
DoubleMatrix m(3, 4);
Complex      b(1.0, -1.0);
```

Obvious algebraic operators between these classes (such as multiplication, addition, subtraction) are defined with overloaded operators `*`, `+`, `-` respectively. Elements of the vector and matrix classes are referred to with brackets `()`. `DoubleVector` and `DoubleMatrix` classes are contained within each of the higher level objects that we now describe.

D.2. General Structure

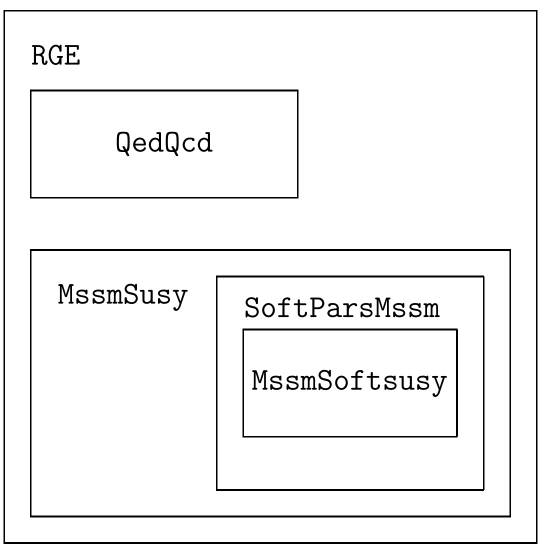

Figure 3: Heuristic high-level object structure of `SOFTSUSY`. Inheritance is displayed by enclosure.

From a RGE point of view, a particular quantum field theory model consists of a set of couplings and masses defined at some renormalisation scale μ. A set of β functions describes the evolution of the parameters and masses to a different scale μ'. This concept is embodied in an *abstract* `RGE` object, which contains the methods required to run objects of derived classes to different renormalisation scales. The other objects displayed in figure 3 are particular instances of `RGE`, and therefore inherit from it. `QedQcd` objects consist of data on the quark and lepton masses and gauge couplings. It contains the β functions for running in an effective QED$\otimes$QCD theory below m_t. An object of class `MssmSusy` contains the Yukawa couplings, and the three gauge couplings of the MSSM. It also contains the superpotential μ term (not to be confused with the renormalisation scale) and $\tan\beta$, the ratio of the two Higgs doublet VEVs. Its β functions are valid in the exact SUSY limit of the MSSM. The major part of the code resides within the `MssmSoftsusy` class. Objects of this type have all the functionality of `MssmSusy`, with soft SUSY breaking terms contained in the inherited class `SoftParsMssm`. It also contains an object of type `QedQcd` which contains weak scale empirical data. Code in the `MssmSoftsusy` class organises and performs the main part of the calculation.

D.3. `RGE` Class

The data and important methods in `RGE` are presented in table 5. Each of the higher level objects described in this appendix have explicitly named `display` and `set` methods that are used to access or change the data contained within each object. In table 5 (as in the following tables in this section), these accessing methods are listed on the same row as the relevant data variable.

The `RGE` method `runto(mup, eps)` will automatically run any derived object to the scale `mup` with a fractional accuracy of evolution `eps`. In order to define this evolution, any object that inherits from an `RGE` must contain three methods: `display`, `set`, `beta` shown in table 5. `DoubleVector display() const` must return a vector containing all masses and couplings of the object, in some arbitrary user-defined order. `void set(const DoubleVector & v)` must set these couplings given a `DoubleVector v` defined in the same order as the display function. `DoubleVector beta() const` must then return the β functions in a `DoubleVector` defined as

$$\beta_i = \frac{da_i}{d \ln \mu}, \tag{D.1}$$

where a_i denotes any mass or coupling of the model. The ordering of the a_i must be identical in each of the three methods.

D.4. `QedQcd` Class

The `QedQcd` class contains a `DoubleVector` of quark and lepton $\overline{MS}$ masses ($m_f = m_{u,d,e,c,s,\mu,t,b,\tau}(\mu)$), as shown in table 6. Its contents may be printed to standard output or read from standard input (with the same format in each case) by using the operators `<<` or `>>`, as can all the non-abstract objects mentioned in this section. The methods `toMz()`, `toMt()` act on an initial object defined with each fermion mass m_f defined at a scale

$$Q' = \max(1 \text{ GeV}, m_f(m_f)) \tag{D.2}$$

and gauge couplings at M_Z.

D.5. `MssmSusy` Class

The operators `<<`, `>>` have been overloaded to write or read a `MssmSusy` object to/from a file stream. Table 7 shows the data variables and important methods contained in the class. For the Yukawa and gauge couplings, methods exist to either set (or display) one element or a whole matrix or vector of them.

D.6. `MssmSoftsusy` Class

`MssmSoftSusy` objects contain a structure `sPhysical` encapsulating the physical information on the superparticles, as shown in table 9. Another structure within `MssmSoftsusy` of type `sProblem` flags various potential problems with the object, for example the lack of radiative EWSB or negative mass squared scalars (excluding the Higgs mass squared parameters). This structure is shown in table 10. In addition, the method `test` prints out if any of the possible data variables flagging problems are true. The `higgsUfb` flag is true if

$$m_{H_1}^2 + 2\mu^2 + m_{H_2}^2 - 2|\mu B| < 0 \tag{D.3}$$

is not satisfied, implying that the desired electroweak minimum is either a maximum or a saddle-point of the tree-level Higgs potential [2]. The contents of `sPhysical` and `sProblem` can be output with overloaded `<<` operators.

`MssmSoftsusy` data variables and accessors can be viewed in table 11 and the most important high-level methods are displayed in table 12. `addAmsb()` adds anomaly mediated supersymmetry breaking terms [35] to the model's soft parameters. Such terms are proportional to the VEV of a compensator superfield, so $m_{3/2}$ in table 11 must have been set before `addAmsb` is used.

The method `mpzCharginos` returns the 2 by 2 complex diagonalisation matrices U, V that result in positive chargino masses, as defined in ref. [3]. The method `mpzNeutralinos` is present in order to convert O to the complex matrix N defined in ref. [3] that would produce only positive neutralino masses. The operators `<<`, `>>` have been overloaded to write or read `MssmSoftusy` objects or `sPhysical` structures to/from a file stream.

The driver routine for the RGE evolution and unification calculation is

```
MssmSoftsusy MssmSoftsusy::lowOrg
(void (*boundaryCondition)(MssmSoftsusy &, const DoubleVector &),
 double mx, const DoubleVector & pars, int sgnMu,  double tanb,
 const QedQcd & oneset, int accuracy, double epsilon)
```

The user-supplied `boundaryCondition` function sets the soft parameters according to the elements of the supplied `DoubleVector` at `mx`, as discussed in appendix A. `pars` contains the actual `DoubleVector` of soft SUSY breaking parameters. `sgnMu` is the sign of the superpotential μ parameter, `tanb` is the value of $\tan\beta(M_Z)$ required and `oneset` contains the M_Z scale low energy data. `accuracy` gives the level of accuracy of the spectrum calculations (the recommended value is 3, which includes all available radiative corrections) and `epsilon` gives the fractional accuracy to which the EWSB parameters should converge (`1.0e-2` to `1.0e-6` works fine).

The fine tuning (as defined in sec. 3) can be calculated with the method

```
DoubleVector MssmSoftsusy::fineTune(void (*boundaryCondition)
        (MssmSoftsusy &, const DoubleVector &), const DoubleVector
 & bcPars, double mx) const
```

This function should only be applied to an `MssmSoftsusy` object which has been processed by `lowOrg`. `mx` is the unification scale and `boundaryCondition` is the function that sets the unification scale soft parameters, as discussed above. In derived objects, the virtual method `methodBoundaryCondition` may be used to set data additional to `MssmSoftsusy` from the `boundaryCondition` function. The method outputs the fine-tuning of a parameter $a_{i=1...n}$ in the `bcPars(n+3) DoubleVector`, with the $(n+1, n+2, n+3)^{th}$ element of `bcPars` being the fine-tuning with respect to the Higgs potential parameters (μ and B) and the top Yukawa coupling (h_t) respectively. `fineTune` is an optional feature.

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Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	$+$	$+$	$+$	$-$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$+$	$+$
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175
Masses													
$\|\mu(M_Z)\|$	734	321	492	629	-	-	460	1567	428	843	-	528	-
h^0	118	114	118	119	-	-	119	126	118	123	-	119	-
H^0	868	376	570	702	-	-	524	1852	457	880	-	455	-
A^0	854	363	553	714	-	-	492	1757	390	788	-	294	-
$H^\pm$	861	374	561	721	-	-	503	1769	408	809	-	335	-
χ_1^0	244	96	160	214	-	-	150	631	139	309	-	182	-
χ_2^0	472	179	305	418	-	-	286	1232	266	603	-	352	-
χ_3^0	734	327	495	634	-	-	463	1564	431	841	-	527	-
χ_4^0	751	351	514	642	-	-	481	1574	449	853	-	544	-
$\chi_1^\pm$	472	178	305	418	-	-	286	1233	266	603	-	352	-
$\chi_2^\pm$	751	351	514	642	-	-	482	1577	450	855	-	545	-
$\tilde{g}$	1372	617	945	1216	-	-	894	3194	841	1685	-	1063	-
e_L, μ_L	417	198	281	367	-	-	278	1045	296	572	-	459	-
e_R, μ_R	270	145	182	239	-	-	191	707	228	416	-	392	-
ν_e, ν_μ	410	183	270	359	-	-	267	1042	285	567	-	453	-
τ_1	417	202	283	368	-	-	285	1037	307	566	-	441	-
τ_2	269	137	175	234	-	-	166	671	160	337	-	241	-
ν_τ	410	183	270	359	-	-	267	1042	285	567	-	453	-
u_L, c_L	1249	569	862	1108	-	-	820	2894	782	1549	-	1018	-
u_R, c_R	1200	551	830	1066	-	-	791	2768	756	1488	-	985	-
d_L, d_L	1251	575	865	1111	-	-	824	2895	786	1551	-	1021	-
d_R, d_R	1193	550	827	1061	-	-	788	2749	753	1479	-	981	-
t_1	1176	585	836	1045	-	-	793	2632	745	1399	-	907	-
t_2	953	416	650	859	-	-	618	2268	584	1197	-	758	-
b_1	1145	522	790	1017	-	-	740	2630	672	1354	-	887	-
b_2	1190	548	823	1054	-	-	776	2693	723	1403	-	814	-
c_{h_t}	146	25	60	98	-	-	51	597	44	172	-	67	-
c	292	51	120	197	-	-	103	1195	88	344	-	134	-

Table 2: Post-LEP Benchmark points. Mass spectra in GeV for minimal SUGRA models calculated with program `SOFTSUSY1.2` and $M_X = 1.9 \times 10^{16}$ GeV, $A_0 = 0$. $\alpha_s(M_Z)$ is listed in units of 0.001. The naturalness parameter is listed, with and without including the top Yukawa coupling (c, c_{h_t}) respectively. Columns with dashes for spectra indicate points which did not break electroweak symmetry correctly.

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175
Masses													
$\lvert\mu(m_Z)\rvert$	739	332	501	633	239	522	468	1517	437	837	1185	537	1793
h^0	114	112	115	115	112	115	116	121	116	120	118	118	123
H^0	884	382	577	737	1509	3495	520	1794	449	876	1071	491	1732
A^0	883	381	576	736	1509	3495	520	1794	449	876	1071	491	1732
$H^\pm$	887	389	582	741	1511	3496	526	1796	457	880	1075	499	1734
χ^0_1	252	98	164	221	119	434	153	664	143	321	506	188	855
χ^0_2	482	182	310	425	199	546	291	1274	271	617	976	360	1648
χ^0_3	759	345	517	654	255	548	486	1585	462	890	1270	585	2032
χ^0_4	774	364	533	661	318	887	501	1595	476	900	1278	597	2036
$\chi^\pm_1$	482	181	310	425	194	537	291	1274	271	617	976	360	1648
$\chi^\pm_2$	774	365	533	663	318	888	502	1596	478	901	1279	598	2036
$\tilde{g}$	1299	582	893	1148	697	2108	843	3026	792	1593	2363	994	3768
e_L, μ_L	431	204	290	379	1514	3512	286	1077	302	587	1257	466	1949
e_R, μ_R	271	145	182	239	1505	3471	192	705	228	415	1091	392	1661
ν_e, ν_μ	424	188	279	371	1512	3511	275	1074	292	582	1255	459	1947
τ_1	269	137	175	233	1492	3443	166	664	159	334	951	242	1198
τ_2	431	208	292	380	1508	3498	292	1067	313	579	1206	447	1778
ν_τ	424	187	279	370	1506	3497	271	1062	280	561	1199	417	1772
u_L, c_L	1199	547	828	1061	1615	3906	787	2771	752	1486	2360	978	3703
u_R, c_R	1148	528	797	1019	1606	3864	757	2637	724	1422	2267	943	3544
d_L, s_L	1202	553	832	1064	1617	3906	791	2772	756	1488	2361	981	3704
d_R, s_R	1141	527	793	1014	1606	3858	754	2617	721	1413	2254	939	3521
t_1	893	392	612	804	1029	2574	582	2117	550	1122	1739	714	2742
t_2	1141	571	813	1010	1363	3326	771	2545	728	1363	2017	894	3196
b_1	1098	501	759	973	1354	3319	711	2522	656	1316	1960	821	3156
b_2	1141	528	792	1009	1594	3832	750	2580	708	1368	2026	887	3216

Table 3: Proposed CMSSM benchmark points and mass spectra (in GeV) from ref. [15], as calculated by `SSARD` and `FEYNHIGGS` [6]. $\alpha_s(m_Z)$ is shown in units of 0.001. It is also assumed that $A_0 = 0$.

variable	default	description
`PRINTOUT`	0	Level of output during iteration*
`EPS`	10^{-5}	Accuracy of calculation*
`MIXING`	1	What quark mixing to have*
`EPSTOL`	$10^{-14}\times$`EPS`	Underflow accuracy
`GMU`	1.16637 10^{-5}	G_μ, Fermi constant from muon decay
`MZ`	91.1882	Z pole mass M_Z
`MW`	80.419	W pole mass M_W
`ALPHAEMO`	1/137.036	fine structure constant α

Table 4: Switches and constants. Starred entries have more explanation in the text. All masses are in units of GeV and G_μ is in units of GeV^2.

data variable		methods
`double mu=` μ	renormalisation scale (GeV)	`setMu` `displayMu`
`int numpars`	number of scale dependent parameters	`setPars` `howMany`
`int loops`	accuracy of RGE	`setLoops` `displayLoops`
`int thresholds`	accuracy level of threshold computation	`setThresholds` `displayThresholds`

method	function
`DoubleVector display()`	displays all running parameters (*)
`void set(DoubleVector)`	sets all running parameters (*)
`DoubleVector beta`	displays beta functions of all running parameters (*)
`runto`	runs object to new value of `mu`

Table 5: Abstract `RGE` class. (*) indicates that derived objects *must* contain these methods (see text).

data variable		methods
`DoubleVector a` $\alpha(\mu), \alpha_s(\mu)$	$\overline{MS}$ gauge couplings	`setAlpha` `displayAlpha`
`DoubleVector m` $m_f(\mu)$	running fermion masses vector (1...9) (GeV)	`setMass` `displayMass`
`double mtpole` m_t^{pole}	pole top mass (GeV)	`setPoleMt` `displayPoleMt`

method	function
`runGauge`	runs gauge couplings *only*
`toMt, toMZ`	runs fermion masses and gauge couplings from Q' to m_t^{pole} or M_Z

Table 6: `QedQcd` class. Q' is defined in the text.

data variable		methods
`DoubleMatrix u, d, e` $(Y_U)_{ij}, (Y_D)_{ij}, (Y_E)_{ij}$	Yukawa couplings (3 by 3 matrix)	`setYukawaElement` `setYukawaMatrix` `displayYukawaElement` `displayYukawaMatrix`
`DoubleVector g` g_i	MSSM gauge couplings (1...3) vector	`setAllGauge` `setGaugeCoupling` `displayGauge` `displayGaugeCoupling`
`smu` μ	bilinear Higgs superpotential parameter	`setSusyMu` `displaySusyMu`
`tanb` $\tan\beta$	ratio of Higgs VEVs (at current renormalisation scale)	`setTanb` `displayTanb`

method	function
`setDiagYukawas`	calculates and sets all diagonal Yukawa couplings given fermion masses and a Higgs VEV
`getMasses`	calculates quark and lepton masses from Yukawa couplings
`getQuarkMixing`	mixes quark Yukawa couplings from mass to weak basis
`getQuarkMixedYukawas`	sets all entries of quark Yukawa couplings given fermion masses, Higgs VEV and CKM matrix

Table 7: `MssmSusy` class.

data		methods
`DoubleVector mGaugino` $M_{1,2,3}$	$(1\ldots3)$ vector of gaugino mass parameters	`setGauginoMass` `displayGaugino`

`DoubleMatrix ua,da,ea` U_A, D_A, E_A	(3 by 3) matrix of trilinear soft terms (GeV)	`setTrilinearElement`
		`displayTrilinearElement`
		`displaySoftA`

`DoubleMatrix mQLsq`
`mURsq,mDRsq,mLLsq`
`mSEsq`
$(m^2_{\tilde{Q}_L})$, $(m^2_{\tilde{u}_R})$, $(m^2_{\tilde{d}_R})$,
$(m^2_{\tilde{L}_L})$, $(m^2_{\tilde{e}_R})$
	(3 by 3) matrices of soft SUSY breaking masses (GeV^2)	`setSoftMassElement`
		`setSoftMassMatrix`
		`displaySoftMassSquared`

`double b,mH1sq,mH2sq`
B, $m^2_{H_1}$, $m^2_{H_2}$
	Bilinear Higgs parameters (GeV, GeV^2, GeV^2)	`setB`
		`setMh1Squared`
		`setMh2Squared`
		`displayB`
		`displayMh1Squared`
		`displayMh2Squared`

Table 8: `SoftParsMssm` class data and accessor methods.

data variable	description
`DoubleVector mhiggs`	$(1\ldots4)$ vector of $h^0, A^0, H^0, H^\pm$masses
`DoubleVector mnsu`	vector of $m_{\tilde{\nu}_{i=1\ldots3}}$ masses
`DoubleVector mch,mneut`	vectors of $m_{\chi^\pm{}_{i=1\ldots2}}$, $m_{\chi^0{}_{i=1\ldots4}}$ respectively
`double mGluino`	gluino mass $m_{\tilde{g}}$
`DoubleMatrix mixNeut`	4 by 4 orthoganol neutralino mixing matrix O
`double thetaL, thetaR`	$\theta_{L,R}$ chargino mixing angles
`double thetat, thetab`	$\theta_{t,b}$ sparticle mixing angles
`double thetatau, thetaH`	θ_τ, α sparticle and Higgs mixing angles
`DoubleMatrix mu, md, me`	(2 by 3) matrices of up squark, down squark and charged slepton masses
`double t1OV1Ms, t2OV2Ms`	tadpoles t_1/v_1 and t_2/v_2 evaluated at M_S

Table 9: `sPhysical` structure. Masses are pole masses, and stored in units of GeV. Mixing angles are in radian units.

data variable	flags
`noConvergence`	the main iteration routine doesn't converge
`noRhoConvergence`	the ρ iterative routine doesn't converge
`tachyon`	a non-Higgs scalar has negative mass squared
`muSqWrongSign`	μ^2 from eq. (3.5) has opposite sign to that specified
`b`	B from eq. (3.6) has incorrect sign
`higgsUfb`	eq. (D.3) is not satisfied
`nonperturbative`	a Landau pole was reached below the unification scale

Table 10: `sProblem` structure. All data variables are boolean values.

data		methods
`double m32` $m_{3/2}$	compensator VEV* (GeV)	`setM32`
`double HiggsVevMs` $v(M_S)$	Higgs VEV parameter (GeV)	`setHiggsVevMs` `displayHiggsVevMs`
`QedQcd dataset`	M_Z boundary condition on Standard Model couplings	`setData` `displayDataSet`

Table 11: `MssmSoftsusy` class data and accessor methods.

name	function
`lowOrg`	Driver routine for whole calculation*
`addAmsb`	Adds AMSB soft terms to current object*
`methodBoundaryCondition`	Boundary condition for derived objects*
`standardSugra`	Sets all universal soft terms
`universalScalars`	Sets universal scalar masses
`universalGauginos`	Sets universal gaugino masses
`universalTrilinears`	Sets universal soft breaking trilinear couplings
`itLowsoft`	Performs the iteration between M_Z and unification scale
`sparticleThresholdCorrections`	$\overline{DR}$ radiative corrections to Standard Model couplings at M_Z
`physical`	Calculates sparticle pole masses and mixings
`rewsb`	Sets μ, B from EWSB conditions
`mpzNeutralino`	Gives mixing matrices required to make neutralino masses positive*
`mpzChargino`	Gives mixing matrices required to make chargino masses positive*
`fineTune`	Calculates fine-tuning for soft parameters* and h_t
`getVev`	Calculates VEV $v^{\overline{DR}}$ at current scale
`calcSinthdrbar`	Calculates $s_W^{\overline{DR}}$ at current scale
`calcMs`	Calculates M_S
`printShort`	short list of important parameters printed out to standard output in columns
`printLong`	long list of important parameters printed out to standard output in columns

Table 12: `MssmSoftsusy` methods and related functions. Functions marked with an asterisk are mentioned in the text.