PM–02–39
CERN TH/2002–325
November 2002

SuSpect: a Fortran Code for the Supersymmetric and Higgs Particle Spectrum in the MSSM*

Abdelhak DJOUADI[1,2], Jean–Loïc KNEUR[1] and Gilbert MOULTAKA[1]

[1] *Laboratoire de Physique Mathématique et Théorique, UMR5825–CNRS, Université de Montpellier II, F–34095 Montpellier Cedex 5, France.*

[2] *Theory Division, CERN, CH–1211 Genève 23, Switzerland.*

Abstract

We present the Fortran code SuSpect version 2.1, which calculates the Supersymmetric and Higgs particle spectrum in the Minimal Supersymmetric Standard Model (MSSM). The calculation can be performed in constrained models with universal boundary conditions at high scales such as the gravity (mSUGRA), anomaly (AMSB) or gauge (GMSB) mediated breaking models, but also in the non–universal MSSM case with R–parity and CP conservation. Care has been taken to treat important features such as the renormalization group evolution of parameters between low and high energy scales, the consistent implementation of radiative electroweak symmetry breaking and the calculation of the physical masses of the Higgs bosons and supersymmetric particles taking into account the dominant radiative corrections. Some checks of important theoretical and experimental features, such as the absence of non desired minima, large fine-tuning in the electroweak symmetry breaking condition, as well as agreement with precision measurements can be performed. The program is user friendly, simple to use, self–contained and can easily be linked with other codes; it is rather fast and flexible, thus allowing scans of the parameter space with several possible options and choices for model assumptions and approximations.

*The program with all relevant information can be downloaded from the web at the http site: `www.lpm.univ-montp2.fr:6714/~kneur/Suspect` or obtained by sending an E–mail to one of the authors, `djouadi@lpm.univ-montp2.fr`, `kneur@lpm.univ-montp2.fr`, `moultaka@lpm.univ-montp2.fr`.

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1. Introduction

Supersymmetric theories (SUSY) [1], which provide an elegant way to stabilize the large hierarchy between the Grand Unification (GUT) and the electroweak scales and to cancel the quadratic divergences of the radiative corrections to the Higgs boson masses, are by far the most studied extensions of the Standard Model (SM). The most economical low–energy SUSY extension of the SM, the Minimal Supersymmetric Standard Model (MSSM), which allows for a consistent unification of the SM gauge couplings and provides a natural solution of the Dark Matter problem, has been widely investigated; for reviews see Refs. [2-5]. As a corollary, the search for Supersymmetric particles and for the extended Higgs spectrum has become the main goal of present and future high–energy colliders [6].

It is well–known that in the unconstrained MSSM, it is a rather tedious task to deal with the basic parameters of the Lagrangian and to derive in an exhaustive manner their relationship with the physical parameters, i.e. the particle masses and couplings. This is mainly due to the fact that in the MSSM, despite of the minimal gauge group, minimal particle content, minimal couplings imposed by R–parity conservation and the minimal set of soft SUSY-breaking parameters, there are more than hundred new parameters [7]. Even if one constrains the model to have a viable phenomenology [we will call later such a model the phenomenological MSSM], assuming for instance no intergenerational mixing to avoid flavor changing neutral currents, no new source of CP violation, universality of first and second generation sfermions to cope with constraints from kaon physics, etc.., there are still more than 20 free parameters left. This large number of input enters in the evaluation of the masses of $\mathcal{O}(30)$ SUSY particles and Higgs bosons as well as their complicated couplings, which involve several non–trivial aspects, such as the mixing between different states, the Majorana nature of some particles, etc. The situation becomes particularly difficult if one aims at rather precise calculations and hence, attempts to include some refinements such as higher order corrections, which for the calculation of a single parameter need the knowledge of a large part of, if not the whole, spectrum.

Thus, the large number of free parameters in the unconstrained or even phenomenological MSSM, makes a detailed phenomenological analysis of the spectra and the comparison with the outcome or expectation from experiment, a daunting task, if possible at all. Fortunately, there are well motivated theoretical models where the soft SUSY–breaking parameters obey a number of universal boundary conditions at the high (GUT) scale, leading to only a handful set of basic parameters. This is the case for instance of the minimal Supergravity model (mSUGRA) [8], where it is assumed that SUSY–breaking occurs in a hidden sector which communicates with the visible sector only through "flavor–blind" gravitational interactions. This leads to the simpler situation where the entire spectrum of superparticles and Higgs bosons is determined by the values of only five free parameters and makes comprehensive scans of the parameter space and detailed studies of the spectrum feasible.

However, there are also similarly constrained and highly predictive alternative SUSY–breaking models in the literature, such as anomaly mediated [9, 10] or gauge mediated [11, 12] SUSY–breaking models for instance, which should be investigated as well. We then have to trade a complicated situation where we have one model with many input parameters, with a not less complicated situation where we have many models with a small number of basic parameters. In addition, in these unified models, the low–energy parameters are derived from the high–energy (GUT and/or possibly some intermediate scales) input parameters through Renormalization Group Equations (RGE) and they should also necessarily involve radiative electroweak symmetry breaking (EWSB), which sets additional constraints on the model. The implementation of the RG evolution and the EWSB mechanism poses numerous non–trivial technical problems if they have to be done in an accurate way, i.e. including higher order effects. This complication has to be added to the one from the calculation of the particle masses and couplings with radiative corrections (RC) which is still present.

Therefore, to deal with the supersymmetric spectrum in all possible cases, one needs very sophisticated programs to encode all the information and, eventually, to pass it to other programs or Monte Carlo generators to simulate the physical properties of the new particles, decay branching ratios, production cross sections at various colliders, etc... These programs should have a high degree of flexibility in the choice of the model and/or the input parameters and an adequate level of approximation at different stages, for instance in the incorporation of the RGEs, the handling of the EWSB and the inclusion of radiative corrections to (super)particle masses, which in many cases can be very important. They should also be reliable, quite fast to allow for rapid comprehensive scans of the parameter space and simple enough to be linked with other programs. There are several public codes, in particular `ISASUGRA` [13], `SOFTSUSY` [14] and `SPHENO` [15], as well as a number of private codes, which deal with this problem. In this paper we present our program `SuSpect`.

`SuSpect`, in the version 2.1 that we present here, is a FORTRAN code which calculates the supersymmetric and Higgs particle spectrum in the constrained and unconstrained MSSMs. The acronym is an abbreviation of SUsy SPECTrum and a preliminary version of the program is available since some time and has been described in Ref. [16]. At the present stage, it deals with the "phenomenological MSSM" with 22 free parameters defined either at a low or high energy scale, with the possibility of RG evolution to arbitrary scales, and the most studied constrained models, namely mSUGRA, AMSB and GMSB. Many "intermediate" models [e.g. constrained models but without unification of gaugino or scalar masses, etc..] are also easily handled. The program includes the three major ingredients which should be incorporated in any algorithm for the constrained MSSMs: i) renormalization group evolution of parameters between the low energy scale [M_Z and/or the electroweak symmetry breaking scale] and the high–energy scale [17–19]; *ii*) consistent implementation of radiative electroweak symmetry breaking [loop corrections to the effective potential are included using the tadpole method] [20–23]; *iii*) calculation of the physical (pole) masses of the superparticles and Higgs bosons, including all relevant features such as the mixing between various states [diagonalization of mass matrices] and the radiative corrections when important [24–31].

The code contains two source files: the main subroutine `suspect2.f` and a separate calling routine file `suspect2_call.f`, plus one input file, `suspect2.in`. Any choice and option is driven either from the input file [which is sufficient and convenient when dealing with a few model points] or from the `suspect2_call.f` file, which also provides examples of call for different model choices with all the necessary features [this option is useful to interface with other routines or to perform scans of the parameter space]. The program has several flags which allow to select the model to be studied and its input parameters, the level of accuracy of the algorithm [e.g. the iterations for the RGEs and the convergence of the EWSB], the level of approximation in the calculation of the various (s)particle masses [e.g. inclusion or not of RC]. Besides the fact that it is flexible, the code is self–contained [the default version includes all routines needed for the calculation], rather fast [thus allowing large scans of the parameter space] and can be easily linked to other routines or Monte–Carlo generators [e.g. to calculate branching ratios, cross sections, relic densities]. All results, including comments when useful and some theoretical and experimental constraints, are found in the output file `suspect2.out` which is created at any run of the program. It is hoped that the code may be readily usable even without much prior knowledge on the MSSM.

This "users' manual" for the program, is organized as follows. In section 2, we briefly discuss the main ingredients of the unconstrained and phenomenological MSSMs as well as the constrained models mSUGRA, AMSB and GMSB, to set the notations and conventions used in the program. In section 3, we summarize the procedure for the calculation of the (s)particle spectrum: the soft SUSY–breaking terms [including the treatment of the input, the RG evolution and the implementation of EWSB], the physical particle masses [summarizing our conventions for the sfermion, gaugino and Higgs sectors] as well as the theoretical [CCB, UFB, fine-tuning] and experimental [electroweak precision measurements, the muon $g-2$, $b \to s\gamma$] constraints that we impose on the spectra, and give an example on how it can be used for scans. In section 4, we summarize the basic practical facts about the program and discuss the content of the input and output files with all possible choices. In section 5, we make a brief comparison with other similar existing codes, discuss the interface with other programs, the maintenance on the web and some future improvements. In section 6, we list the main changes from the previous versions of the code. A conclusion will be given in section 7. In Appendix A, we list some of the analytical formulae used in the program and in Appendix B, the various subroutines and functions used in the program are explicited.

2. The constrained and unconstrained MSSMs

In this section, we will summarize the basic assumptions which define the MSSM and the various constraints which can be imposed on it. This will also set the notations and conventions used in the program. We will mainly focus on the unconstrained MSSM, what we will call the phenomenological MSSM with 22 free parameters, and constrained models such as the minimal Supergravity (mSUGRA), anomaly mediated (AMSB) and gauge mediated (GMSB) supersymmetry breaking models.

2.1 The unconstrained MSSM

The unconstrained MSSM is defined usually by the following four basic assumptions [32, 8]:

(a) Minimal gauge group: the MSSM is based on the group $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$, i.e. the SM symmetry. SUSY implies then that the spin–1 gauge bosons and their spin–1/2 partners, the gauginos [bino $\tilde{B}$, winos $\tilde{W}_{1-3}$ and gluinos $\tilde{G}_{1-8}$], are in vector supermultiplets.

(b) Minimal particle content: there are only three generations of spin–1/2 quarks and leptons [no right–handed neutrino] as in the SM. The left– and right–handed chiral fields belong to chiral superfields together with their spin–0 SUSY partners, the squarks and sleptons: $\hat{Q}, \hat{u}_R, \hat{d}_R, \hat{L}, \hat{l}_R$. In addition, two chiral superfields $\hat{H}_d$, $\hat{H}_u$ with respective hypercharges -1 and $+1$ for the cancellation of chiral anomalies, are needed. Their scalar components, H_d and H_u, give separately masses to the isospin $+1/2$ and $-1/2$ fermions and lead to five Higgs particles: two CP–even h, H bosons, a pseudoscalar A boson and two charged $H^\pm$ bosons. Their spin–1/2 superpartners, the higgsinos, will mix with the winos and the bino, to give the "ino" mass eigenstates: the two charginos $\chi^\pm_{1,2}$ and the four neutralinos $\chi^0_{1,2,3,4}$.

(c) Minimal Yukawa interactions and R–parity conservation: to enforce lepton and baryon number conservation, a discrete and multiplicative symmetry called R–parity is imposed. It is defined by $R_p = (-1)^{2s+3B+L}$, where L and B are the lepton and baryon numbers and s is the spin quantum number. The R–parity quantum numbers are then $R_p = +1$ for the ordinary particles [fermions, gauge and Higgs bosons], and $R_p = -1$ for their supersymmetric partners. In practice, the conservation of R–parity has important consequences: the SUSY particles are always produced in pairs, in their decay products there is always an odd number of SUSY particles, and the lightest SUSY particle (LSP) is absolutely stable.

The three conditions listed above are sufficient to completely determine a globally supersymmetric Lagrangian. The kinetic part of the Lagrangian is obtained by generalizing the notion of covariant derivative to the SUSY case. The most general superpotential, compatible with gauge invariance, renormalizability and R–parity conservation is written as:

$$W = \sum_{i,j=gen} -Y^u_{ij}\, \hat{u}_{Ri} \hat{H}_u.\hat{Q}_j + Y^d_{ij}\, \hat{d}_{Ri} \hat{H}_d.\hat{Q}_j + Y^l_{ij}\, \hat{l}_{Ri} \hat{H}_u.\hat{L}_j + \mu \hat{H}_u.\hat{H}_d \tag{1}$$

The product between $\mathrm{SU(2)_L}$ doublets reads $H.Q \equiv \epsilon_{ab} H^a Q^b$ where a, b are $\mathrm{SU(2)_L}$ indices and $\epsilon_{12} = 1 = -\epsilon_{21}$, and $Y_{ij}^{u,d,l}$ denote the Yukawa couplings among generations. The first three terms in the previous expression are nothing else but a superspace generalization of the Yukawa interaction in the SM, while the last term is a globally supersymmetric Higgs mass term. The supersymmetric part of the tree–level potential $V_{\rm tree}$ is the sum of the so–called F– and D–terms [33], where the F–terms come from the superpotential through derivatives with respect to all scalar fields ϕ_a, $V_F = \sum_a |W^a|^2$ with $W^a = \partial W / \partial \phi_a$, and the D–terms corresponding to the $\mathrm{U(1)_Y}$, $\mathrm{SU(2)_L}$, and $\mathrm{SU(3)_C}$ gauge symmetries are given by $V_D = \frac{1}{2} \sum_{i=1}^3 (\sum_a g_i \phi_a^* T^i \phi_a)^2$ with T^i and g_i being the generators and the coupling constants of the corresponding gauge groups.

(d) Minimal set of soft SUSY–breaking terms: to break Supersymmetry, while preventing the reappearance of the quadratic divergences [soft breaking], one adds to the supersymmetric Lagrangian a set of terms which explicitly but softly break SUSY [8]:

- Mass terms for the gluinos, winos and binos:

$$-\mathcal{L}_{\rm gaugino} = \frac{1}{2} \left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a \ + \ \text{h.c.} \right] \tag{2}$$

- Mass terms for the scalar fermions:

$$-\mathcal{L}_{\rm sfermions} = \sum_{i=gen} m^2_{\tilde{Q}i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L}i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u}i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{l}i} |\tilde{l}_{R_i}|^2 \tag{3}$$

- Mass and bilinear terms for the Higgs bosons:

$$-\mathcal{L}_{\rm Higgs} = m^2_{H_u} H_u^\dagger H_u + m^2_{H_d} H_d^\dagger H_d + B\mu (H_u.H_d + \text{h.c.}) \tag{4}$$

- Trilinear couplings between sfermions and Higgs bosons

$$-\mathcal{L}_{\rm tril.} = \sum_{i,j=gen} \left[A^u_{ij} Y^u_{ij} \tilde{u}_{R_i} H_u.\tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}_{R_i} H_d.\tilde{Q}_j + A^l_{ij} Y^l_{ij} \tilde{l}_{R_i} H_u.\tilde{L}_j \ + \ \text{h.c.} \right] \tag{5}$$

The soft SUSY–breaking scalar potential is the sum of the three last terms:

$$V_{\rm soft} = -\mathcal{L}_{\rm sfermions} - \mathcal{L}_{\rm Higgs} - \mathcal{L}_{\rm tril.} \tag{6}$$

Up to now, no constraint is applied to this Lagrangian, although for generic values of the parameters, it might lead to severe phenomenological problems, such as flavor changing neutral currents [FCNC] and unacceptable amount of additional CP–violation [34] color and charge breaking minima [35] an incorrect value of the Z boson mass, etc... The MSSM defined by the four hypotheses (a)–(d) above, will be called the unconstrained MSSM.

2.2 The "phenomenological" MSSM

In the unconstrained MSSM, and in the general case where one allows for intergenerational mixing and complex phases, the soft SUSY breaking terms will introduce a huge number (105) of unknown parameters, in addition to the 19 parameters of the SM [7]. This large number of free parameters makes any phenomenological analysis in the general MSSM very complicated as mentioned previously. In addition, many "generic" sets of these parameters are excluded by the severe phenomenological constraints discussed above. A phenomenologically viable MSSM can be defined by making the following three assumptions: (*i*) All the soft SUSY–breaking parameters are real and therefore there is no new source of CP–violation generated, in addition to the one from the CKM matrix. (*ii*) The matrices for the sfermion masses and for the trilinear couplings are all diagonal, implying the absence of FCNCs at the tree–level. (*iii*) First and second sfermion generation universality at low energy to cope with the severe constraints from K^0–$\bar{K}^0$ mixing, etc [this is also motivated by the fact that one can neglect for simplicity all the masses of the first and second generation fermions which are small enough to have any effect on the running of the SUSY–breaking parameters].

Making these three assumptions will lead to 22 input parameters only:

$\tan\beta$: the ratio of the vevs of the two–Higgs doublet fields.
$m^2_{H_u}, m^2_{H_d}$: the Higgs mass parameters squared.
M_1, M_2, M_3: the bino, wino and gluino mass parameters.
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: the first/second generation sfermion mass parameters.
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: the third generation sfermion mass parameters.
A_u, A_d, A_e: the first/second generation trilinear couplings.
A_t, A_b, A_τ: the third generation trilinear couplings.

Two remarks can be made at this stage:

(*i*) The Higgs–higgsino (supersymmetric) mass parameter $|\mu|$ (up to a sign) and the soft SUSY–breaking bilinear Higgs term B are determined, given the above parameters, through the electroweak symmetry breaking conditions as will be discussed later. Alternatively, one can trade the values of $m^2_{H_u}$ and $m^2_{H_d}$ with the "more physical" pseudoscalar Higgs boson mass M_A and parameter μ [such an alternative choice is explicitly possible in `SuSpect` by appropriate setting of the input parameters; see section 4].

(*ii*) Since the trilinear sfermion couplings will be always multiplied by the fermion masses, they are important only in the case of the third generation. However, there are a few (low scale) situations, such as the muon $(g-2)$ and the neutralino–nucleon scattering for direct Dark Matter searches, where they will play a role. We therefore add them as input.

Such a model, with this relatively moderate number of parameters [especially that, in general, only a small subset appears when one looks at a given sector of the model] has much more predictability and is much easier to investigate phenomenologically, compared to the unconstrained MSSM. We will refer to this 22 free input parameters model as the "phenomenological" MSSM or pMSSM [4].

2.3 The mSUGRA model

Almost all problems of the general or unconstrained MSSM are solved at once if the soft SUSY–breaking parameters obey a set of universal boundary conditions at the GUT scale. If one takes these parameters to be real, this solves all potential problems with CP violation as well. The underlying assumption is that SUSY–breaking occurs in a hidden sector which communicates with the visible sector only through gravitational–strength interactions, as specified by Supergravity. Universal soft breaking terms then emerge if these Supergravity interactions are "flavor–blind" [like ordinary gravitational interactions]. This is assumed to be the case in the constrained MSSM or minimal Supergravity (mSUGRA) model [8].

Besides the unification of the gauge coupling constants $g_{1,2,3}$ of the U(1), SU(2) and SU(3) groups, which is verified given the experimental results from LEP1 [36] and which can be viewed as fixing the Grand Unification scale $M_{\rm GUT} \sim 2 \cdot 10^{16}$ GeV [37], the unification conditions in mSUGRA, are as follows:

– Unification of the gaugino [bino, wino and gluino] masses:

$$M_1(M_{\rm GUT}) = M_2(M_{\rm GUT}) = M_3(M_{\rm GUT}) \equiv m_{1/2} \tag{7}$$

– Universal scalar [i.e. sfermion and Higgs boson] masses [i is the generation index]:

$$\begin{aligned} M_{\tilde{Q}_i}(M_{\rm GUT}) &= M_{\tilde{u}_{Ri}}(M_{\rm GUT}) = M_{\tilde{d}_{Ri}}(M_{\rm GUT}) = M_{\tilde{L}_i}(M_{\rm GUT}) = M_{\tilde{l}_{Ri}}(M_{\rm GUT}) \\ &= M_{H_u}(M_{\rm GUT}) = M_{H_d}(M_{\rm GUT}) \equiv m_0 \end{aligned} \tag{8}$$

– Universal trilinear couplings:

$$A^u_{ij}(M_{\rm GUT}) = A^d_{ij}(M_{\rm GUT}) = A^l_{ij}(M_{\rm GUT}) \equiv A_0\, \delta_{ij} \tag{9}$$

Besides the three parameters $m_{1/2}, m_0$ and A_0, the supersymmetric sector is described at the GUT scale by the bilinear coupling B and the supersymmetric Higgs(ino) mass parameter μ. However, one has to require that EWSB takes place at some low energy scale. This results in two necessary minimization conditions of the two–Higgs doublet scalar potential which, at the tree–level, has the form [to have a more precise description, one–loop corrections to the scalar potential have to be included, as will be discussed later]:

$$\begin{aligned} V_{\rm Higgs} &= \overline{m}_1^2 H_d^\dagger H_d + \overline{m}_2^2 H_u^\dagger H_u + \overline{m}_3^2 (H_u \cdot H_d + {\rm h.c.}) \\ &+ \frac{g_1^2 + g_2^2}{8} (H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{g_2^2}{2} (H_d^\dagger H_u)(H_u^\dagger H_d), \end{aligned} \tag{10}$$

where we have used the usual short–hand notation: $\overline{m}_1^2 = m_{H_d}^2 + \mu^2, \overline{m}_2^2 = m_{H_u}^2 + \mu^2$, $\overline{m}_3^2 = B\mu$ and the SU(2) invariant product of the two doublets $\phi_1 \cdot \phi_2 = \phi_1^1 \phi_2^2 - \phi_1^2 \phi_2^1$. The two minimization equations $\partial V_{\rm Higgs}/\partial H_d^0 = \partial V_{\rm Higgs}/\partial H_u^0 = 0$ can be solved for μ^2 and $B\mu$:

$$
\begin{aligned}
\mu^2 &= \frac{1}{2}\Big[\tan 2\beta (m_{H_u}^2 \tan\beta - m_{H_d}^2 \cot\beta) - M_Z^2 \Big] \\
B\mu &= \frac{1}{2} \sin 2\beta \Big[m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 \Big]
\end{aligned}
\quad (11)
$$

Here, $M_Z^2 = (g_1^2 + g_2^2) \cdot (v_u^2 + v_d^2)/4$ and $\tan\beta = v_u/v_d$ is defined in terms of the vacuum expectation values of the two neutral Higgs fields. Consistent EWSB is only possible if eq. (11) gives a positive value of μ^2. The sign of μ is not determined. Therefore, in this model, one is left with only four continuous free parameters, and an unknown sign[1]:

$$
\tan\beta \ , \ m_{1/2} \ , \ m_0 \ , \ A_0 \ , \ \ {\rm sign}(\mu). \quad (12)
$$

All the soft SUSY breaking parameters at the weak scale are then obtained through Renormalization Group Equations.

2.4 The AMSB model

In mSUGRA, Supersymmetry is broken in a hidden sector and the breaking is transmitted to the visible sector by gravitational interactions. In Anomaly Mediated Supersymmetry Breaking models, the SUSY–breaking occurs also in a hidden sector, but it is transmitted to the visible sector by the super–Weyl anomaly [9]. The gaugino, scalar masses and trilinear couplings are then simply related to the scale dependence of the gauge and matter kinetic functions. This leads to soft SUSY–breaking scalar masses for the first two generation sfermions that are almost diagonal [when the small Yukawa couplings are neglected] which solves the SUSY flavor problem which affects mSUGRA for instance.

In terms of the gravitino mass $m_{3/2}$ [which is much larger than the gaugino and squark masses, a cosmologically appealing feature], the β functions for the gauge and Yukawa couplings g_a and Y_i, and the anomalous dimensions γ_i of the chiral superfields, the soft SUSY breaking terms are given by:

$$
M_a = \frac{\beta_{g_a}}{g_a} m_{3/2} \ , \ A_i = \frac{\beta_{Y_i}}{Y_i} m_{3/2}
$$

[1]Note that the number of parameters can be further reduced by introducing an additional constraint which is based on the assumption that the b and τ Yukawa couplings unify at the GUT scale, as predicted in minimal SU(5). This restricts $\tan\beta$ to two narrow ranges around $\tan\beta \sim 1.5$ and $\sim m_t/m_b$ [38]. The low $\tan\beta$ solution is ruled out since it leads to a too light an h boson, in conflict with searches at LEP2 [39]. However, Yukawa unification is not particularly natural in the context of Superstring theories, and minimal SU(5) predictions are known to fail badly for the lighter generations. We therefore treat all three third generation Yukawa couplings as independent parameters.

$$m_i^2 = -\frac{1}{4}\left(\Sigma_a \frac{\partial \gamma_i}{\partial g_a}\beta_{g_a} + \Sigma_k \frac{\partial \gamma_i}{\partial Y_k}\beta_{Y_k}\right) m_{3/2}^2 \tag{13}$$

These equations are RG invariant and thus valid at any scale and make the model highly predictive. The additional parameters, μ^2 and B are obtained as usual by requiring the correct breaking of the electroweak symmetry. One then has, in principle, only three input parameters $m_{3/2}, \tan\beta$ and sign(μ). However, this rather simple picture is spoiled by the fact that the anomaly mediated contribution to the slepton scalar masses squared is negative and the sleptons are in general tachyonic. This problem can be cured by adding a positive non–anomaly mediated contribution to the soft masses. The simplest phenomenological way of parameterizing the non–anomaly contribution is to add a common mass parameter m_0 at the GUT scale, which would be then an additional input parameter to all the (squared) scalar masses. However in the general case, the non–anomaly mediated contribution might be different for different scalar masses and depend on the specific model which has been chosen. One should then write a general non–anomalous contribution at the GUT scale for each scalar mass squared:

$$m_{\tilde{S}_i}^2 = c_{S_i} m_0^2 - \frac{1}{4}\left(\Sigma_a \frac{\partial \gamma_i}{\partial g_a}\beta_{g_a} + \Sigma_k \frac{\partial \gamma_i}{\partial Y_k}\beta_{Y_k}\right) m_{3/2}^2 + \text{D terms.} \tag{14}$$

where the coefficients c_{S_i} depend on the considered model.

A few examples of models with different non–anomalous contributions are:

– The minimal anomaly mediated supersymmetry breaking model with a universal m_0 [40]:

$$c_Q = c_{u_R} = c_{d_R} = c_L = c_{e_R} = c_{H_u} = c_{H_d} = 1 \tag{15}$$

– The gaugino assisted AMSB model where one assumes that gauge and gaugino fields reside in the bulk of an extra dimension [41]:

$$c_Q = 21/10, c_{u_R} = 8/5, c_{d_R} = 7/5, c_L = 9/10, c_e = 3/5, c_{H_u} = 9/10 = c_{H_d} \tag{16}$$

– Models where an extra U(1) factor is added; a particular scenario is interesting phenomenologically since it leads to a light top squark [42]:

$$c_Q = 3, c_{u_R} = c_{d_R} = -1, c_L = c_e = 1, c_{H_u} = c_{H_d} = -2 \tag{17}$$

A simple way to account for all the different models is to add to the three continuous and one discrete original basic parameters, the set of coefficients c_{S_i} as input to specify, and therefore one would have the set of input parameters:

$$m_0 \ , \ m_{3/2} \ , \ \tan\beta \ , \ \text{sign}(\mu) \text{ and } c_{S_i} \tag{18}$$

This is the approach that we will follow in the program.

2.5 The GMSB model

In Gauge Mediated Supersymmetry Breaking models, SUSY–breaking is transmitted to the MSSM fields via the SM gauge interactions. In the original scenario [43], the model consists of three distinct sectors: a secluded sector where SUSY is broken, a "messenger" sector containing a singlet field and messenger fields with $\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$ quantum numbers, and a sector containing the fields of the MSSM. Another possibility, the so–called "direct gauge mediation" [44] has only two sectors: one which is responsible for the SUSY breaking and contains the messenger fields, and another sector consisting of the MSSM fields. In both cases, the soft SUSY–breaking masses for the gauginos and squared masses for the sfermions arise, respectively, from one–loop and two–loop diagrams involving the exchange of the messenger fields, while the trilinear Higgs–sfermion–sfermion couplings can be taken to be negligibly small at the messenger scale since they are [and not their square as for the sfermion masses] generated by two–loop gauge interactions. This allows an automatic and natural suppression of FCNC and CP–violation; for a review see, Ref. [11].

In the GMSB models that we will consider, the source of SUSY breaking is parameterized by an $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge–singlet chiral superfield $\hat{S}$ whose scalar and auxiliary components acquire vacuum expectation values denoted by S and F_S, respectively. We assume $n_{\hat{q}}$ pairs of $\hat{q}, \hat{\bar{q}}$ quark–like [resp. $n_{\hat{l}}$ pairs of $\hat{l}, \hat{\bar{l}}$ lepton–like] messenger superfields transforming as $(3, 1, -\frac{1}{3}), (\bar{3}, 1, \frac{1}{3})$ [resp. $(1, 2, \frac{1}{2}), (1, 2, -\frac{1}{2})$] under $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ and coupled to $\hat{S}$ through a superpotential of the form $\lambda \hat{S}\hat{q}\hat{\bar{q}} + \lambda \hat{S}\hat{l}\hat{\bar{l}}$. Soft SUSY–breaking parameters are then generated at the messenger scale $M_{\rm mes} = \lambda S$,

$$
\begin{aligned}
M_G(M_{\rm mes}) &= \frac{\alpha_G(M_{\rm mes})}{4\pi} \Lambda\, g\left(\frac{\Lambda}{M_{\rm mes}}\right) \sum_m N_R^G(m) &\quad (19)\\
m_s^2(M_{\rm mes}) &= 2\Lambda^2 f\left(\frac{\Lambda}{M_{\rm mes}}\right) \sum_{m,G} \left[\frac{\alpha_G(M_{\rm mes})}{4\pi}\right]^2 N_R^G(m) C_R^G(s) &\quad (20)\\
A_f(M_{\rm mes}) &\simeq 0 &\quad (21)
\end{aligned}
$$

where $\Lambda = F_S/S$, $G = \mathrm{U(1), SU(2), SU(3)}$, m labels the messengers and s runs over the Higgs doublets as well as the left–handed doublets and right–handed singlets of squarks and sleptons. The one– and two loop functions g and f are given by [$\mathrm{Li_2}$ is the Spence function]:

$$
\begin{aligned}
g(x) &= \frac{1}{x^2}[(1+x)\log(1+x) + (1-x)\log(1-x)] \\
f(x) &= \frac{1+x}{x^2}\left[\log(1+x) - 2\mathrm{Li}_2\left(\frac{x}{1+x}\right) + \frac{1}{2}\mathrm{Li}_2\left(\frac{2x}{1+x}\right)\right] + (x \leftrightarrow -x) &\quad (22)
\end{aligned}
$$

Defining the Dynkin index N_R^G by

$$
\mathrm{Tr}\,(T_R^a T_R^b) = \frac{N_R^G}{2}\delta^{ab} \quad (23)
$$

for non–abelian groups, and $N^{U(1)_Y} = (6/5)Y^2$ where $Y \equiv Q_{\rm EM} - T_3$, one has (see eq.(19))

$$\begin{aligned}
\sum_m N_R^{U(1)_Y}(m) &= \frac{1}{5}(2n_{\hat{q}} + 3n_{\hat{l}}) \\
\sum_m N_R^{SU(2)_L}(m) &= n_{\hat{l}} \\
\sum_m N_R^{SU(3)_c}(m) &= n_{\hat{q}}
\end{aligned} \tag{24}$$

With the Casimir invariant $C^G_{\mathbf{N}}$ given by

$$\Sigma_a T^a_{\mathbf{N}} T^a_{\mathbf{N}} = C^{SU(N)}_{\mathbf{N}} \mathbf{1} = \frac{N^2-1}{2N}\mathbf{1} \tag{25}$$

for the $\mathbf{N}$ of $SU(N)$, and $C^{U(1)_Y} = (3/5)Y^2$, one finds for

$$\mathcal{NC}(s) \equiv \sum_{m,G} \left[\frac{\alpha_G(M_{\rm mes})}{4\pi}\right]^2 N_R^G(m) C_R^G(s)$$

(see eq.(20)) the following values:

$$\begin{aligned}
\mathcal{NC}(\tilde{Q}) &= \frac{1}{16\pi^2}\left[(\frac{n_{\hat{l}}}{100} + \frac{n_{\hat{q}}}{150})\alpha_1^2 + \frac{3n_{\hat{l}}}{4}\alpha_2^2 + \frac{4n_{\hat{q}}}{3}\alpha_3^2\right] \\
\mathcal{NC}(\tilde{U}) &= \frac{1}{16\pi^2}\left[(\frac{4n_{\hat{l}}}{25} + \frac{8n_{\hat{q}}}{75})\alpha_1^2 + \frac{4n_{\hat{q}}}{3}\alpha_3^2\right] \\
\mathcal{NC}(\tilde{D}) &= \frac{1}{16\pi^2}\left[(\frac{n_{\hat{l}}}{25} + \frac{2n_{\hat{q}}}{75})\alpha_1^2 + \frac{4n_{\hat{q}}}{3}\alpha_3^2\right] \\
\mathcal{NC}(\tilde{L}) &= \frac{1}{16\pi^2}\left[(\frac{9n_{\hat{l}}}{100} + \frac{3n_{\hat{q}}}{50})\alpha_1^2 + \frac{3n_{\hat{l}}}{4}\alpha_2^2\right] \\
\mathcal{NC}(\tilde{E}) &= \frac{1}{16\pi^2}\left[(\frac{9n_{\hat{l}}}{25} + \frac{6n_{\hat{q}}}{25})\alpha_1^2\right] \\
\mathcal{NC}(\tilde{H}_u) &= \mathcal{NC}(\tilde{H}_d) = \mathcal{NC}(\tilde{L})
\end{aligned} \tag{26}$$

The freedom in choosing independently the number of $n_{\hat{q}}$ and $n_{\hat{l}}$ messengers allows to study various model configurations: for instance when the messengers are assumed to form complete representations of some grand unification group (e.g. $\mathbf{5} + \bar{\mathbf{5}}$ of SU(5)) where $n_{\hat{q}} = n_{\hat{l}}$, or when they transform under larger unification group factors with some extra discrete symmetries where typically $n_{\hat{q}} \neq n_{\hat{l}}$ [45]. [When $n_{\hat{q}} = n_{\hat{l}} = 1$ one retrieves the minimal model [43]. In this case the gaugino masses have the same *relative* values as if they were unified at $M_{\rm GUT}$ despite the fact the boundary conditions are set at $M_{\rm mes}$ and that scalar masses are flavor independent. Furthermore when $\Lambda/M_{\rm mes} \ll 1$, one has $f(x) \simeq g(x) \simeq 1$.] In addition, some constraints are in general needed in order to have a viable spectrum, for instance: $\Lambda/M_{\rm mes} < 1$ to avoid negative mass squared for bosonic members of the messenger scale and $\Lambda/M_{\rm mes} \lesssim 0.9$ to avoid too much fine–tuning in EWSB. Note also that $n_{\hat{q}} > n_{\hat{l}}$ improves the fine–tuning issue [46].

Once the boundary conditions are set at $M_{\rm mes}$, the low energy parameters are obtained via the usual RGEs and the proper breaking of the EW symmetry is required.

Therefore, in the GMSB model that we are considering, there are six input parameters

$$\tan\beta \ , \ {\rm sign}(\mu) \ , \ M_{\rm mes} \ , \ \Lambda \ , \ n_{\hat{q}} \ , \ n_{\hat{l}} \tag{27}$$

In addition, one has to include as input the mass of the gravitino $\tilde{G}$ which, in this case is the lightest SUSY particle. This mass, $m_{\tilde{G}} = F/(\sqrt{3}M_P)$ with M_P the reduced Planck mass, will depend on an additional free parameter F which parameterizes the scale of the full SUSY breaking and whose typical size is of $\mathcal{O}(F_S)$ in direct mediation and much larger in secluded mediation. The choice of this parameter, which plays a role only for the lifetime of the next–to–lightest SUSY particle, is left to the user.

2.6 Non–universal models

mSUGRA, AMSB and GMSB are well defined models of which the possible phenomenological consequences and experimental signatures have been widely studied in the literature. However, none of these models should be considered as THE definite model, in the absence of a truly fundamental description of SUSY–breaking, and some of the basic assumptions inherent to these scenarii might turn out not to be correct. For instance some of the universality conditions postulated in the mSUGRA scenario are naturally violated in some cases [47–50] as will be discussed below.

To be on the safe side from the experimental point of view, it is therefore wiser to allow for a departure from these models, and to study the phenomenological implications of relaxing some defining assumptions. However, it is often desirable to limit the number of extra free parameters, in order to retain a reasonable amount of predictability when attempting detailed investigations of possible signals of SUSY. Therefore, it is more interesting to relax only one [or a few] assumption at a time and study the phenomenological implications. Of course, since there are many possible directions, this would lead to several intermediate MSSMs between these constrained models and the phenomenological MSSM with 22 free parameters discussed in section 2.2.

Taking the most studied model mSUGRA as the reference model, examples of such non universal scenarii are for instance:

i) non unification of the soft SUSY–breaking gaugino mass terms:

$$M_1(M_U) \neq M_2(M_U) \neq M_3(M_U) \tag{28}$$

This occurs for instance in Superstring motivated models in which the SUSY breaking is moduli dominated such as in the O–I and O–II models [47], or in extra dimensional SUSY–GUT models in which the additional dimensions lead to the breaking of the large gauge symmetry and/or to Supersymmetry, or SUSY models where the breaking occurs through a non SU(5) singlet F term; see Ref. [48] for phenomenology oriented discussions.

ii) mSUGRA with non–unification of the two first and third generation scalar masses [i.e. with different scalar mass terms m_0 at the high scale or with a common mass which becomes different at the low–energy scale]:

$$m_{0\tilde{Q}} = m_{0\tilde{L}} \cdots \neq m_{0\tilde{q}} = m_{0\tilde{l}} \cdots \tag{29}$$

This occurs in models where the soft SUSY–breaking scalar masses at the GUT scale are influenced by the fermion Yukawa couplings. This is the case for the so–called inverted mass hierarchy models [49] where the scalar mass terms of the first two generations can be very heavy $\mathcal{O}$(10 TeV), while those of the third generation sfermions and the Higgs bosons are rather light, solving thus the SUSY flavor and CP problems, which are related to the first two generations, while still satisfying naturalness constraints.

iii) mSUGRA-like models, but with non–unification of the sfermion and Higgs boson scalar masses, e.g.:

$$m_{\tilde{Q}} = m_{\tilde{e}_R} = m_{\tilde{u}_R} \neq m_{\tilde{d}_R} = m_{\tilde{L}} \neq M_{H_u} = M_{H_d} \tag{30}$$

This occurs for instance in SO(10) models with universal boundary conditions but with extra D–term contributions to the scalar masses associated to the reduction in rank when SO(10) breaks to the SM group [50]. In practice, it amounts to disconnect the Higgs sector from the sfermionic sector and introduces two additional input parameters: the pseudoscalar Higgs boson mass M_A and the higgsino mass parameter μ [which have a more direct "physical" interpretation than the scalar mass terms M_{H_u}, M_{H_d}]. This allows to perform more general phenomenological or experimental analyzes; c.f. some LEP and LHC Higgs analyzes [51] or some recent Dark Matter studies [52].

iv) Partially unified models where one relaxes one or a few parameters to fit some collider zoo event or to analyze a phenomenological situation which introduces new features. This is the case, for instance, for the light top squark scenario which can be set by hand to discuss some theoretical [such as baryogenesis in the MSSM [53] for instance] or phenomenological [such as new decay or production modes of top squarks [54] for instance] situations.

An easy and practical way to implement these various non–unified or partially unified scenarii, is to allow for the possibility of choosing all the soft SUSY–breaking parameters listed above for the phenomenological MSSM of section 2.2 [the 22 parameters except for $\tan\beta$] at the high–energy or GUT scale, with the boundary conditions set by hand and chosen at will. One can even chose the scale at which the boundary conditions are set to account for intermediate scales. If this scale is the electroweak symmetry breaking scale, then we have simply the MSSM with the soft SUSY–breaking parameters defined at the low energy scale, i.e. the phenomenological MSSM. All these options are provided by our code.

3. The Particle Spectrum Calculation with Suspect

In this section, we discuss our procedure for calculating the SUSY and Higgs particle spectrum. We will take as example the sophisticated cases of the constrained MSSMs with universal boundary conditions at the high scale, mSUGRA AMSB and GMSB, where all ingredients included in the `SuSpect` algorithm are present: RGEs, radiative EWSB and calculation of the physical particle masses. We will first describe the general algorithm, then discuss the calculation of the soft SUSY–breaking terms, the determination of the particle masses, the various theoretical and phenomenological tests that we impose on the model parameters and show an example of how the parameter space can be scanned.

3.1 General algorithm

As mentioned previously, there are three main steps for the calculation of the supersymmetric particle spectrum in constrained MSSMs, in addition to the choice of the input parameters and the check of the particle spectrum:

i) Renormalization group evolution of parameters back and forth between the low energy scales, such as M_Z and the electroweak symmetry breaking scale, and the high–energy scale, such as the GUT scale or the messenger scale in GMSB models [17–19]. This is the case for the SM gauge and Yukawa couplings and for the soft SUSY–breaking terms (scalar and gaugino masses, bilinear and trilinear couplings and $\tan\beta$) and μ. This procedure has to be iterated in order to include SUSY threshold effects or radiative corrections due to Higgs and SUSY particles. In the first step, these thresholds are only guessed since the spectrum has not been calculated yet, and the radiative corrections are not implemented.

ii) The implementation of radiative electroweak symmetry breaking [20–23] and the calculation of B and $|\mu|$ from the one–loop effective scalar potential. Here, we use the tadpole method to include the loop corrections [21]. The procedure has to be iterated until a convergent value for these two parameters is obtained. In the first step, the values of μ^2 and the electroweak symmetry breaking scale are guessed, and one of course uses the tree–level potential since no sparticle or Higgs mass has been calculated yet.

iii) Calculation of the pole masses of the Higgs bosons and the SUSY particles, including the mixing between the current states and the radiative corrections when they are important [24–31]. In this context, we will follow the paper of Pierce, Bagger, Matchev and Zhang [24], to which we will refer as PBMZ. Iterations, which are made to coincide with those necessary for the RGEs, are also needed to obtain a sufficient accuracy.

The general algorithm is depicted in Figure 1, and we will discuss the various steps in some detail in the following subsections and in Appendix A.

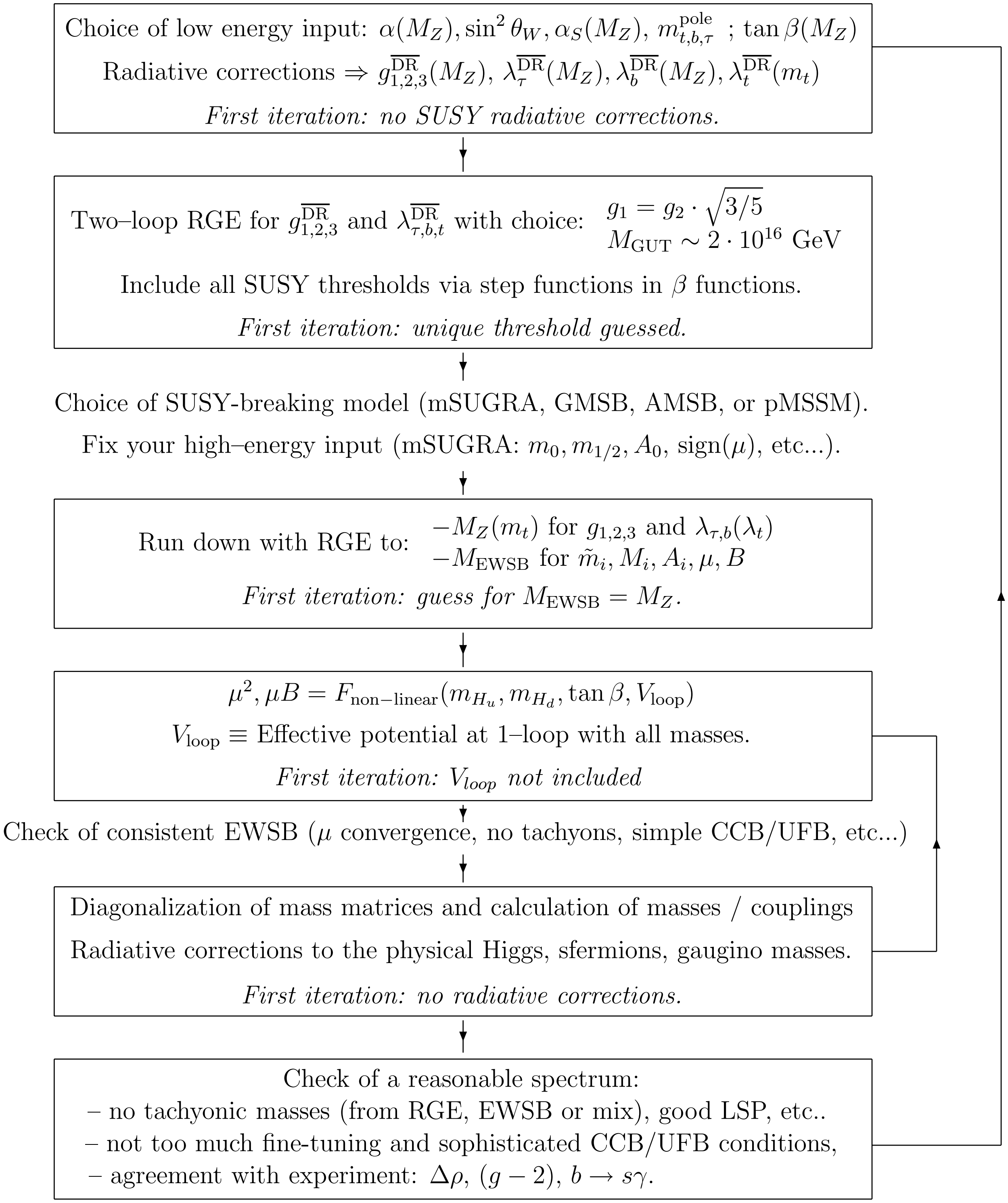

Figure 1: Iterative algorithm for the calculation of the SUSY particle spectrum in `SuSpect` *from the choice of input (first step) to the check of the spectrum (last step). The steps are detailed in the various subsections. The EWSB iteration [calculationally fast] on μ is performed until $|\mu_i - \mu_{i-1}| \leq \epsilon|\mu_i|$ (with $\epsilon \sim 10^{-3}$) while the RG/RC "long" iteration [calculationally longer] needs to be performed 3 to 4 times to reach sufficient stability/accuracy.*

3.2 Calculation of the soft SUSY–breaking terms

For the calculation of the soft SUSY–breaking terms in constrained models with boundary conditions at the unification scale, we proceed as follows:

3.2.1 Choice and treatment of the SM input

We first chose the low–energy input values of the SM parameters. The gauge couplings constants are given in the $\overline{\rm MS}$ scheme at the scale M_Z [$\bar{s}_W^2 = 1 - \bar{c}_W^2 \equiv \sin^2\theta_W|^{\overline{\rm MS}}$]:

$$g_1^2 = \frac{4\pi\alpha_{\rm em}^{\overline{\rm MS}}(M_Z)}{\bar{c}_W^2} \ , \ g_2^2 = \frac{4\pi\alpha_{\rm em}^{\overline{\rm MS}}(M_Z)}{\bar{s}_W^2} \ , \ g_3^2 = 4\pi\alpha_s^{\overline{\rm MS}}(M_Z) \tag{31}$$

Their values have been obtained from precision measurements at LEP and Tevatron [36]:

$$\alpha_{\rm em}^{\overline{\rm MS}}(M_Z) = 1/127.938 \ , \ \alpha_s^{\overline{\rm MS}}(M_Z) = 0.1192 \ , \ \bar{s}_W^2 = 0.23117 \tag{32}$$

The pole masses of the heavy SM fermions are chosen as [36]:

$$M_t = 174.3 \text{ GeV} \quad , \quad M_b = 4.87 \text{ GeV} \quad , \quad M_\tau = 1.778 \text{ GeV} \tag{33}$$

[while the Z boson mass is fixed to $M_Z = 91.187$ GeV, the W boson mass is not a free parameter and is obtained from the relation $M_W = M_Z\bar{c}_W$]. Note, however, that for maximum flexibility, all those SM input default values in eqs. (32,33) can be changed at will in the input file, see section 4 for details.

Next, the $\overline{\rm DR}$–scheme values of the gauge and Yukawa couplings at the scale M_Z (M_t for the top quark) are extracted from these input [19]. The latter are defined by [note that the SM vacuum expectation value at the scale M_Z is $v \simeq 174.1$ GeV]:

$$\lambda_t(M_t) = \frac{\overline{m}_t(M_t)}{v\sin\beta} \ , \ \lambda_b(M_Z) = \frac{\overline{m}_b(M_Z)}{v\cos\beta} \ , \ \lambda_\tau(M_Z) = \frac{\overline{m}_\tau(M_Z)}{v\cos\beta} \ . \tag{34}$$

For the bottom and top quark pole masses [55], one obtains the running $\overline{\rm DR}$ masses using the two loop relations. The relation between the pole masses (M_Q) and the running $\overline{\rm MS}$ masses ($\overline{m}_Q$) at the scale of the pole mass are given by [56]

$$\overline{m}_Q(M_Q) = M_Q\Big[1 + \frac{4}{3}\frac{\alpha_s(M_Q)}{\pi} + K_Q\left(\frac{\alpha_s(M_Q)}{\pi}\right)^2\Big]^{-1} \tag{35}$$

with the numerical values of the NNLO coefficients reading $K_t \simeq 10.9$ and $K_b \simeq 12.4$. The evolution from m_b upward to a renormalization scale μ close to M_Z is given by [57]

$$\overline{m}_b\,(\mu) \ = \ \overline{m}_b\,(M_b)\,\frac{c\,[\alpha_s\,(\mu)/\pi]}{c\,[\alpha_s\,(M_b)/\pi]} \text{ with } c(x) = \left(\frac{23}{6}\,x\right)^{\frac{12}{23}} \ [1 + 1.175x + 1.501\,x^2] \tag{36}$$

One then determines the $\overline{\rm DR}$ masses at the scale M_Z for the b–quark and M_t for the top quark [58]. For the b–quark we use:

$$m_b(M_Z)^{\overline{\rm DR}} \;=\; m_b(M_Z)^{\overline{\rm MS}}\left[1-\frac{\alpha_s}{3\pi}-\frac{35\alpha_s^2}{72\pi^2}+\frac{3g_2^2}{128\pi^2}+\frac{13g_1^2}{1152\pi^2}\right] \tag{37}$$

while for the top quark, we include only QCD corrections:

$$m_t(M_t)^{\overline{\rm DR}} \;=\; m_t(M_t)^{\overline{\rm MS}}\left[1-\frac{\alpha_s}{3\pi}-0.975\alpha_s^2\right] \tag{38}$$

Once the Supersymmetric particle spectrum has been obtained [see below], we include all the important SUSY radiative corrections to the gauge and Yukawa couplings. In the case of the gauge couplings, only the large logarithmic corrections are implemented by including the multiple SUSY particle (and top quark) thresholds [via step functions] in the β functions [59]. In the case of the Yukawa couplings, we include all relevant SUSY corrections to the third generation fermion masses. For the bottom quark (τ lepton) mass, we include the SUSY–QCD and stop–chargino (sneutrino–chargino) one–loop corrections at zero–momentum transfer [60] which, according to PBMZ, is an extremely good approximation. These corrections to the b and τ masses are enhanced by terms $\propto \mu\tan\beta$ and can be rather large. We therefore re–sum these corrections in the case of the b–quark [61]:

$$m_b(Q)^{\overline{\rm DR}}_{\rm SUSY} = \bar{m}_b(Q)^{\overline{\rm DR}}_{\rm SM}(1+\Delta^{\rm SUSY}m_b/m_b) \to \bar{m}_b(Q)^{\overline{\rm DR}}_{\rm SM}/(1-\Delta^{\rm SUSY}m_b/m_b) \tag{39}$$

For the top quarks, the inclusion of only the leading corrections at zero momentum transfer is not an accurate approximation, and we include the full one–loop SUSY–QCD [i.e stop and gluino loops] and electroweak [i.e. with gauge, Higgs boson and chargino/neutralino exchange] corrections *à la* PBMZ [24]. More details are given in Appendix A.

3.2.2 Renormalization Group Evolution

All gauge and (third generation) Yukawa couplings are then evolved up to the GUT scale using the two–loop RGEs [18, 19]. In the initial step, no SUSY particle threshold is taken into account (since no particle spectrum has been yet determined). The GUT scale, $M_{\rm GUT} \simeq 2\cdot 10^{16}$ GeV can be either fixed by hand or, by appropriate user's choice in the input file, calculated consistently to be the scale at which the electroweak gauge coupling constants [with the adequate normalization] unify, $g_1 = g_2 \cdot \sqrt{3/5}$. In contrast, we do not enforce exact $g_2 = g_3$ unification at the GUT scale and assume that the small discrepancy, of at most a few percent, is accounted for by unknown GUT–scale threshold corrections [59].

One can then chose the parameter $\tan\beta$, given at the scale M_Z, the sign of the μ parameter and, depending on the chosen model, the high energy and the low energy input. For instance, one can set the high–energy scale $E_{\rm High}$, which in mSUGRA or AMSB can be either forced to be $M_{\rm GUT}$ [the scale at which g_1 and g_2 unify] or chosen at will [any particular intermediate scale between M_Z and $M_{\rm GUT}$ can be allowed in general and in the case of the GMSB model this scale corresponds to the messenger scale $M_{\rm mes}$]. Similarly the low energy scale $E_{\rm Low}$, where the RGEs start or end may be chosen [which is in general taken to be M_Z or the EWSB scale to be discussed later]. The additional input in the various models are:

- mSUGRA: the universal trilinear coupling A_0, the common scalar mass m_0 and the common gaugino mass $m_{1/2}$, all defined at the scale $M_{\rm GUT}$.
- AMSB: the common scalar mass m_0, the gravitino mass $m_{3/2}$ and the set of coefficients c_{S_i} for the non–anomalous contributions, to be as general as possible.
- GMSB: the scale Λ, the messenger scale $M_{\rm mes}$ which corresponds to $E_{\rm High}$, as well as the numbers of messengers n_q and n_l.
- pMSSM with boundary conditions: the various soft SUSY–breaking parameters listed in section 2.2 [21 parameters in total, in addition to $\tan\beta$] defined at the scale $E_{\rm High}$. These input can also be chosen at will at the low–energy scale $E_{\rm Low}$ which is also provided as input. In this case, one simply has to set the appropriate input choice [see section 4 for more details] and the RGE part will be switched off. Note also that here, a very convenient option is provided which allows to trade the input parameters $M_{H_u}^2$ and $M_{H_d}^2$ with the more "physical" parameters M_A and μ [again in such a way that EWSB is consistently realized, with a warning flag whenever it is not the case].

Given these boundary conditions, all the soft SUSY breaking parameters and couplings are evolved down to the weak scale, using one–loop RGEs for the scalar masses and trilinear couplings and two–loop RGEs for the gaugino masses[2]; see Appendix A. Our default choice for the EWSB scale is the geometric mean of the two top squark masses,

$$M_{\rm EWSB} = (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2} \tag{40}$$

which minimizes the scale dependence of the one–loop effective potential [22] discussed below [before the stop masses are calculated, we use the geometric mean of the soft SUSY–breaking stop masses instead as a first guess]. Note, however, that other arbitrary values of the EWSB scale can be chosen easily by an appropriate input setting; see input file in section 4. Since $\tan\beta$ is defined at M_Z, the vevs have to be evolved down from $M_{\rm EWSB}$ to M_Z.

Once the SUSY spectrum is calculated [as will be discussed later], the heavy (s)particles are taken to contribute to the RGEs of the gauge coupling constants at scales larger than their mass, i.e. multiple thresholds are included in the running of the couplings via step functions. The one–loop soft scalar masses and trilinear couplings and the two–loop SUSY breaking gaugino masses are then frozen at the scale $M_{\rm EWSB}$.

[2] The full two–loop RGEs in the MSSM have been recently derived [62]. However, their impact for the soft SUSY–breaking scalar masses and trilinear couplings should be rather modest. We nevertheless plan to include them in a future upgrade of the code.

3.2.3 Electroweak Symmetry Breaking

At some stage, we require that the electroweak symmetry is broken radiatively and use eq. (11) to determine the parameters $\mu^2(M_{\rm EWSB})$ and $B(M_{\rm EWSB})$. It is well known that the one–loop radiative corrections to the Higgs potential play a major role in determining the values of these two parameters, which at tree level are given in terms of the soft SUSY–breaking masses of the two Higgs doublet fields. We treat these corrections using the tadpole method. This means that we can still use eq. (11) to determine $\mu^2(M_{\rm EWSB})$, one simply has to add one–loop tadpole corrections [21, 24]

$$m_{H_u}^2 \to m_{H_u}^2 - t_u/d_u \text{ and } m_{H_d}^2 \to m_{H_d}^2 - t_d/v_d \tag{41}$$

We include the dominant third generation fermion/sfermion loops, as well as sub–dominant contributions from sfermions of the first two generations, gauge bosons, the MSSM Higgs bosons, charginos and neutralinos[3], with the running parameters evaluated at $M_{\rm EWSB}$. The analytical expressions of the tadpoles are given in Appendix A for completeness.

As far as the determination of μ^2 and $B\mu$ is concerned, this is equivalent to computing the full one–loop effective potential at scale $M_{\rm EWSB}$. Since $|\mu|$ and B affect the masses of some (s)particles appearing in these corrections, this gives a non-linear equation for $|\mu|$ (see Fig. 1), which is solved by a standard iteration algorithm until stability is reached and a consistent value of μ is obtained. From a practical point of view this requires only three or four iterations for an accuracy of $\mathcal{O}(10^{-4})$, if one starts from the values of $|\mu|$ and B as determined from minimization of the RG–improved tree–level potential at scale $M_{\rm EWSB}$ and the procedure is extremely fast in CPU as compared to the (iterated) RGE calculation.

At this stage, `SuSpect` includes a check on whether the complete scalar potential has charge and/or color breaking (CCB) minima which can be lower than the electroweak minimum, or whether the tree-level scalar potential is unbounded from below (UFB). In the present version of the code, we consider only the following simple (tree–level) criteria [35]

$$\text{CCB1}: \quad A_f^2 < 3\,(m_{\tilde f_L}^2 + m_{\tilde f_R}^2 + \mu^2 + m_{H_u}^2). \tag{42}$$

$$\text{UFB1}: \quad m_{H_u}^2 + m_{H_d}^2 \geq 2|B\mu| \;\; \text{at scale } Q^2 > M_{\rm EWSB}^2 \tag{43}$$

where f denotes any of the three fermion generations. Eq. (42) ensures that there is no deep CCB breaking minimum [due to very small Yukawa couplings] in some D–flat directions. One can either take this as a consistency necessary constraint on the MSSM parameters, or disregard it appealing to the fact that such minima are usually well separated from the electroweak minimum so that the latter can be reasonably stable at cosmological scales[4].

[3]The contributions of the charginos and neutralinos can be rather sizable and are very important to minimize the scale dependence of the one–loop effective potential [23].

[4]But one would still lack for a compelling reason why the EW minimum is chosen in the first place!

For the third generation and in particular in the top sector, the CCB minimum is not much deeper than the electroweak minimum, since y_t is not very small, and not much separated from it. In this case one should apply eq. (42) with some caution since tunneling effects can be important. On the other hand the "boundedness-from-below" condition of eq. (43) is actually an indication of possible dangerous non physical minima which could form when radiative corrections are included. At any rate, since both eqs. (42) and (43) are merely tree–level conditions, they should be checked at the highest energy scale. Note that in the present version of the code, the calculation is still performed, even if these conditions are not fulfilled, but a warning flag is given [see the output file content in section 4 for more details]. An upcoming version of `SuSpect` will have more sophisticated treatments, taking into account loop corrections [63] as well as the geometric configurations of the true minima [64, 65] as will be discussed later.

Finally, we reject of course all points in the parameter space which lead to tachyonic pseudo–scalar Higgs boson or sfermion masses:

$$\text{No Tachyon :} \qquad M_A^2 > 0 \;\;,\;\; m_{\tilde{f}}^2 > 0. \tag{44}$$

Again the occurrence of such problems in the spectrum is signaled in `SuSpect` by appropriate flags as will be discussed in section 4. The electroweak symmetry breaking mechanism is assumed to be consistent when all these conditions are satisfied.

3.3 Calculation of the physical particle masses

Once all the soft SUSY–breaking terms are obtained and eventually EWSB is radiatively realized [as should be the case in unified models] one can then calculate all the physical particle masses. The whole procedure (namely, RGE + EWSB + spectrum calculation) is iterated at least twice until stability is reached (see the overall algorithm in Fig 1), in order to take into account: (*i*) realistic (multi–scale) particle thresholds in the RG evolution of the dimensionless couplings via step functions in the β functions for each particle threshold and (*ii*) radiative corrections to SUSY particle masses, using the expressions given in Ref. [24], where the renormalization scale is set to $M_{\rm EWSB}$.

Our conventions for the mass matrices in the gaugino, sfermion and Higgs sectors will be specified below. We basically follow the conventions of PBMZ with some important exceptions: (*i*) The μ parameter is defined with the opposite sign (see below). (*ii*) The vevs are different by a factor $\sqrt{2}$ and in our case $v = 174.1$ GeV. (*iii*) The sfermion masses are defined such that $\tilde{f}_1$ and $\tilde{f}_2$ are, respectively, the lightest and the heaviest one. (*iv*) The matrices diagonalizing the chargino and neutralino mass matrices are taken to be real.

For the calculation of the physical masses and the implementation of the radiative corrections, the various sectors of the MSSM are then treated as follows [with some details on the notation and conventions we use; more details, in particular on the radiative corrections, will be given in the Appendix]:

3.3.1. The sfermion sector

In the third generation sfermion sector $[\tilde{t}, \tilde{b}, \tilde{\tau}]$, mixing between "left" and "right" current eigenstates is included [66]. The radiatively corrected running fermion masses [essentially the Yukawa coupling times vevs] at scale $M_{\rm EWSB}$ are employed in the sfermion mass matrices [this is important at large $\tan\beta$, where these corrections can be quite sizable]. As mentioned above, contrary to PBMZ, the masses are defined such that $m_{\tilde{f}_1}$ and $m_{\tilde{f}_2}$ correspond to the mass of respectively, the lightest and the heaviest sfermion, and therefore, care should be made in interpreting the sfermion mixing angle $\theta_{\tilde{f}}$ as compared to PBMZ. [Note that a protection which prevents negative mass squared for third generation sfermions in the presence of too large mixing is provided.] The sfermion mass matrices and the physical masses and mixing angles are given by:

$$M_{\tilde{f}}^2 \ = \ \left[\begin{array}{cc} m_{\tilde{f}_L}^2 + (I_f^3 - e_f s_W^2) M_Z^2 \cos 2\beta + m_f^2 & m_f (A_f - \mu r_f) \\ m_f (A_f - \mu r_f) & m_{\tilde{f}_R}^2 - e_f s_W^2 M_Z^2 \cos 2\beta + m_f^2 \end{array} \right] \tag{45}$$

where $m_{\tilde{f}_{L,R}}, A_f, \mu$ and m_f are respectively, the $\overline{\rm DR}$ soft SUSY scalar masses, trilinear couplings, higgsino mass parameter and running fermion masses at the scale $M_{\rm EWSB}$ and $r_b = r_\tau = 1/r_t = \tan\beta$. These matrices are diagonalized by orthogonal matrices; the mixing angles θ_f and the squark eigenstate masses are given by

$$\sin 2\theta_f = \frac{2 m_f (A_f - \mu r_f)}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \quad , \quad \cos 2\theta_f = \frac{m_{\tilde{f}_L}^2 - m_{\tilde{f}_R}^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2}$$

$$m_{\tilde{f}_{1,2}}^2 = m_f^2 + \frac{1}{2} \left[m_{\tilde{f}_L}^2 + m_{\tilde{f}_R}^2 \mp \sqrt{(m_{\tilde{f}_L}^2 - m_{\tilde{f}_R}^2)^2 + 4 m_f^2 (A_f - \mu r_f)^2} \right] \tag{46}$$

The radiative corrections to the sfermion masses are included according to Ref. [24], i.e. only the QCD corrections for the superpartners of light quarks [including the bottom squark] plus the leading electroweak corrections to the two top squarks; the small electroweak radiative corrections to the slepton masses [which according to PBMZ are at the level of one percent] have been neglected in the present version.

3.3.2 The gaugino sector

The 2×2 chargino and 4×4 neutralino mass matrices depend on the $\overline{\rm DR}$ parameters M_1, M_2, μ at the scale $M_{\rm EWSB}$ and on $\tan\beta$. The chargino mass matrix given by:

$$\mathcal{M}_C = \left[\begin{array}{cc} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{array} \right] \tag{47}$$

is diagonalized by two real matrices U and V. The chargino masses are obtained analytically, with the convention that χ_1^+ is the lightest state [see Appendix A].

The neutralino mass matrix, in the $(-i\tilde{B}, -i\tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0)$ basis, has the form

$$\mathcal{M}_N = \left[\begin{array}{cccc} M_1 & 0 & -M_Z s_W \cos\beta & M_Z s_W \sin\beta \\ 0 & M_2 & M_Z c_W \cos\beta & -M_Z c_W \sin\beta \\ -M_Z s_W \cos\beta & M_Z c_W \cos\beta & 0 & -\mu \\ M_Z s_W \sin\beta & -M_Z c_W \sin\beta & -\mu & 0 \end{array} \right] \quad (48)$$

It is diagonalized using analytical formulae [67] by a single matrix Z which is chosen to be real, leading to the fact that some (in general one) of the neutralino eigenvalues is negative [see Appendix A]. The physical masses are then the absolute values of these eigenvalues with some reordering such that the neutralinos $\chi^0_{1,2,3,4}$ are heavier with increasing subscript and χ_1^0 is the lightest neutralino.

For the gluino, the running $\overline{\rm DR}$ mass $m_{\tilde{g}}$ at scale $M_{\rm EWSB}$ is identified with $M_3(M^2_{\rm EWSB})$

$$m_{\tilde{g}}^{\rm tree} = M_3(M^2_{\rm EWSB}) \quad (49)$$

The full one–loop QCD radiative corrections to the gluino mass are incorporated [19], while in the charginos/neutralinos case the radiative corrections to the masses are simply included in the gaugino and higgsino limits, which is a very good approximation [24]. These radiative corrections are explicitly given in Appendix A.

3.3.3. The Higgs sector

The running $\overline{\rm DR}$ mass of the pseudoscalar Higgs boson at the scale $M_{\rm EWSB}$, $\bar{M}_A$, is obtained from the soft SUSY–breaking Higgs mass terms frozen at $M_{\rm EWSB}$ and including the full one–loop tadpole corrections [24]

$$\bar{M}_A^2(M_{\rm EWSB}) \;=\; \frac{1}{\cos 2\beta}\left(m^2_{H_d} - \frac{t_d}{v_d} - m^2_{H_u} + \frac{t_u}{v_u} \right) - \bar{M}_Z^2 + \sin^2\beta \frac{t_d}{v_d} + \cos^2\beta \, \frac{t_u}{v_u} \quad (50)$$

This mass, together with the Z boson mass $\bar{M}_Z$ at scale $M_{\rm EWSB}$ are then used as input in the CP–even Higgs boson 2×2 mass matrix $\mathcal{M}_S$. Including the dominant contributions of the self–energies of the unrotated CP–even neutral Higgs fields H_u^0 and H_d^0 (as well as the tadpole contributions), this matrix reads at a given scale q^2

$$\mathcal{M}^S(q^2) = \left[\begin{array}{cc} \bar{M}_Z^2 \cos\beta^2 + \bar{M}_A^2 \sin^2\beta - s_{11}(q^2) & -\frac{1}{2}(\bar{M}_Z^2 + \bar{M}_A^2)\sin 2\beta - s_{12}(q^2) \\ -\frac{1}{2}(\bar{M}_Z^2 + \bar{M}_A^2)\sin 2\beta - s_{12}(q^2) & \bar{M}_Z^2 \sin^2\beta + \bar{M}_A^2 \cos^2\beta - s_{22}(q^2) \end{array} \right] \quad (51)$$

One obtains the running CP–even Higgs boson masses in terms of the matrix elements $\mathcal{M}^S_{ij}$

$$\bar{M}^2_{h,H} = \frac{1}{2}\left[\mathcal{M}^S_{11} + \mathcal{M}^S_{22} \mp \sqrt{(\mathcal{M}^S_{11} - \mathcal{M}^S_{22})^2 + 4(\mathcal{M}^S_{12})^2} \right] \quad (52)$$

The mixing angle α which diagonalizes the matrix $\mathcal{M}^S$ and rotates the fields H_u^0, H_d^0 into the physical CP–even Higgs boson fields h, H

$$\left(\begin{array}{c} H \\ h \end{array} \right) = \left(\begin{array}{cc} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{array} \right) \left(\begin{array}{c} H_d^0 \\ H_u^0 \end{array} \right) \tag{53}$$

is given by

$$\sin 2\alpha = \frac{2\mathcal{M}_{12}^S}{\bar{M}_H^2 - \bar{M}_h^2} \ \ , \ \cos 2\alpha = \frac{\mathcal{M}_{11}^S - \mathcal{M}_{22}^S}{\bar{M}_H^2 - \bar{M}_h^2} \quad \left(-\frac{\pi}{2} < \alpha < \frac{\pi}{2} \right) \tag{54}$$

The running charged Higgs boson mass at the EWSB scale is given by

$$\bar{M}_{H^\pm}^2 \ \ = \ \ \bar{M}_A^2 + \bar{M}_W^2 - \sin^2\beta \, \frac{t_d}{v_d} - \cos^2\beta \, \frac{t_u}{v_u} \tag{55}$$

The pole masses of all the Higgs bosons are then obtained by including the self–energy corrections evaluated at the masses of the Higgs bosons themselves.

In the evaluation of the radiative corrections in the MSSM Higgs sector which are known to be very important [26], we have made several options available:

(i) Approximate one–loop and two–loop contributions to the self–energies (and tadpole) corrections s_{ij} in the mass matrix $\mathcal{M}^S$. These expressions, given in Ref. [31], provide an excellent approximation (at the percent level) for the masses of the CP–even Higgs bosons and the angle α for a wide range of input parameters. This approximation (see the Appendix) is sufficient for most practical purposes and since it makes the program running faster, it is set as the default choice. A full one loop calculation of these corrections, supplemented by the two–loop QCD and Yukawa corrections at zero–momentum transfer [27] is under implementation and will appear soon.

(ii) For a very accurate determination of the Higgs masses and couplings, we have implemented the radiative corrections in the MSSM Higgs sector *à la* `HDECAY` [68] i.e.
vspace*-2mm the program is interfaced with the three most commonly used routines[5]:

– The routine `subhpolem` of Carena, Quiros and Wagner [28] which calculates the two–loop QCD corrected Higgs masses in the effective potential approach [with the update including the contributions of the gluinos which can be important].

– The routine `HMSUSY` of Haber, Hempfling and Hoang [29] which approximates the one and two–loop corrections again in the effective potential approach.

– The routine `FeynHiggsFast` of Heinemeyer, Hollik and Weiglein [30, 31] which calculates the one–loop and two–loop QCD corrections in the Feynman diagrammatic approach. It is supplemented with the routine of Brignole, Degrassi, Slavich and Zwirner for the contributions of the $\mathcal{O}(\alpha_t^4)$ corrections [27].

[5]We thank Michael Spira for saving us a lot of time, in performing these interfaces.

3.4 Theoretical and Experimental Constraints on the spectra[6]

Once the SUSY and Higgs spectrum is calculated one can check that some theoretical and experimental requirements are fulfilled. Examples of theory requirements are for instance, the absence of charge and color breaking (CCB) minima and that the potential is not unbounded from below (UFB), the absence of too much fine–tuning (FT) in the determination of the masses of the Z boson from EWSB as well as in the determination of the top quark mass. For experimental requirements on the spectrum, one can demand for instance that it does not lead to large radiative corrections to the precisely measured electroweak parameters or too large values for the anomalous magnetic moment of the muon and the branching ratio of the radiative decay of the b–quark. The program `SuSpect` will provide such tests.

3.4.1 CCB and UFB

As explained previously, in `Suspect`, the EWSB conditions are consistently implemented by iteration on the parameters μ and B and the occurrence of a local minimum is checked numerically. In the same time one needs to check for the non existence of deep CCB minima or UFB directions. Avoiding such cases may put strong constraints on the model and we mentioned in section 3.2.3 that we have already implemented two simple CCB and UFB conditions [35] and the program gives a warning when they are not satisfied.

In a near future, we will address the question of CCB minima and UFB directions in the most complete possible way, given the present state of the art. Three complementary features should be considered in relation to the CCB minima: (*i*) the directions in the space of scalar fields along which such minima can develop (*ii*) whether they are lower than the EWSB minimum (*iii*) whether the EWSB (then false) vacuum can still be sufficiently stable. In Ref. [63] a systematic study of point (*i*) has been carried out considering subspaces involving the fields $H_u, \tilde{Q}_u, \tilde{u}_R$ (H_d and possibly $\tilde{L}$). However, the identified D–flat directions contain the true minima only in the case of universal scalar soft masses at the low energy relevant scales, otherwise they constitute only *sufficient* conditions for the occurrence of CCB minima. While such directions provide very good approximations for the first two generations, special attention should be paid to the third generation sector, as was stressed in [64]. This is relevant in particular to codes like `SuSpect` where various SUSY model assumptions can be considered, including non–universality. Furthermore, the check of point (*ii*) as done in [63] involves a numerical scan over field values. Actually there are cases where field-independent conditions can be obtained even in the case of 5-field directions $H_u, \tilde{Q}, \tilde{u}_R, H_d, \tilde{L}$, leading to faster algorithms; see [64] and unpublished study. We will thus optimize in `SuSpect` the various available complementary approaches. Point (*iii*) has also its importance as it

[6]The implementation of some of the points discussed in this subsection is still subject to cross checks. These features will be included in a next release of the program but we nevertheless discuss them here.

can increase the phenomenologically allowed regions of the MSSM parameter space. Some simple criteria will be encoded, following for instance Ref. [65]. Finally, the UFB directions as identified in [63], in particular UFB-3, lead to very strong constraints. Nonetheless, there is still room for some improvements by optimizing the criterion of "deepest direction", leading in some cases to even stronger constraints which will be also implemented in `SuSpect`.

3.4.2 Fine–Tuning

One of the main motivations for low energy SUSY is that it solves technically the hierarchy and naturalness problems. However, since the Z boson mass is determined by the soft SUSY–breaking masses $M^2_{H_u}, M^2_{H_u}$ and the parameter μ^2, as can be seen from eq. (11), naturalness requires that there are no large cancellations when these parameters are expressed in terms of the fundamental parameters of the model [for instance $m_0, m_{1/2}, \mu, B$ in mSUGRA], otherwise fine tuning is re–introduced [18, 69, 70]. A similar problem occurs in the case of the top quark mass, since it is related to the top Yukawa coupling and $\tan\beta$. Various criteria for quantifying the degree of fine tuning in the determination of M_Z and m_t have been proposed and some subjectivity is involved in the statement of how much fine tuning can be allowed. Therefore, in our case, we will simply evaluate the sensitivity coefficients for M^2_Z and m_t with respect to a given parameter a [70]

$$\delta M^2_Z/M^2_Z = C(M^2_Z, a)\, \delta a/a \quad , \quad \delta m_t/m_t = C(m_t, a)\, \delta a/a \tag{56}$$

and leave to the user the decision of whether the amount of fine–tuning [large values of the C coefficients] is bearable or not. We will evaluate only the fine–tuning with respect to variations of the parameters μ^2 and $B\mu$, for which the coefficients take the simple form:

$$\begin{aligned}
\text{FT1MZ} \quad &: \quad C(M^2_Z, \mu^2) = \frac{2\mu^2}{M^2_Z}\left[1 + t_\beta \frac{4\tan^2\beta(\bar{m}^2_1 - \bar{m}^2_2)}{(\bar{m}^2_1 - \bar{m}^2_2)t_\beta - M^2_Z}\right] \\
\text{FT1MZ} \quad &: \quad C(M^2_Z, B\mu) = 4t_\beta\, \tan^2\beta\, \frac{\bar{m}^2_1 - \bar{m}^2_2}{M^2_Z(\tan^2\beta - 1)^2} \\
\text{FT1MT} \quad &: \quad C(m_t, \mu^2) = \frac{1}{2}C(M^2_Z, \mu^2) + \frac{2\mu^2}{\bar{m}^2_1 + \bar{m}^2_2}\frac{1}{\tan^2\beta - 1} \\
\text{FT1MT} \quad &: \quad C(m_t, B\mu) = \frac{1}{2}C(M^2_Z, B\mu) + \frac{1}{1 - \tan^2\beta}
\end{aligned} \tag{57}$$

with $t_\beta = (\tan^2\beta + 1)/(\tan^2\beta - 1)$. Further fine-tuning tests can be made, in particular with respect to the t, b Yukawa couplings and are planned to be included in future versions.

3.4.3 Electroweak precision measurements

Loops involving Higgs and SUSY particles can contribute to electroweak observables which have been precisely measured at LEP, SLC and the Tevatron. In particular, the radiative corrections to the self–energies of the W and Z bosons, Π_{WW} and Π_{ZZ}, might be sizable if there is a large mass splitting between some particles belonging to the same SU(2) doublet; this can generate a contribution which grows as the mass squared of the heaviest particle. The dominant contributions to the electroweak observables, in particular the W boson mass and the effective mixing angle s_W^2, enter via a deviation from unity of the ρ parameter [71], which measures the relative strength of the neutral to charged current processes at zero momentum transfer, i.e. the breaking of the global custodial SU(2) symmetry:

$$\rho = (1-\Delta\rho)^{-1} \ ; \ \Delta\rho = \Pi_{ZZ}(0)/M_Z^2 - \Pi_{WW}(0)/M_W^2 \tag{58}$$

Most of the MSSM contributions to the ρ parameter are small, $\Delta\rho \lesssim 10^{-4}$ [72]. In the case of the Higgs bosons, the contributions are logarithmic, $\sim \alpha \mathrm{Log}(M_h/M_Z)$, and are similar to those of the SM Higgs boson [and identical in the decoupling limit]. The chargino and neutralino contributions are small because the only terms in the mass matrices which could break the custodial SU(2) symmetry are proportional to M_W. Since in general, first/second generation sfermions are almost degenerate in mass, they also give very small contributions to $\Delta\rho$. Therefore, only the third generation sfermion sector can generate sizable corrections to the ρ parameter, because left–right mixing and [in case of the stop] the SUSY contribution $\propto m_f^2$ leads to a potentially large splitting between the sfermion masses.

We have thus calculated $\Delta\rho$ in the MSSM, taking into account only the contributions of the third generation sfermions. We include full mixing and in the case of the stop/sbottom doublet, also the two–loop QCD corrections due to gluon exchange and the correction due to gluino exchange in the heavy gluino limit, which can increase the contribution by 30% or so [73]. One can then require the SUSY contribution not to exceed two standard deviations from the SM expectation [74]: $\Delta\rho(\mathrm{SUSY}) \lesssim 2 \cdot 10^{-3}$.

3.4.4 The muon (g-2)

The muon $(g-2)$ anomalous magnetic moment has been very precisely measured to be [75]:

$$(g_\mu - 2) \equiv a_\mu^{\mathrm{exp}} = (11\,659\,202 \pm 8)\,10^{-10}, \tag{59}$$

The value predicted in the SM, including the QED, QCD and electroweak corrections is: $a_\mu^{\mathrm{SM}} = 11\,659\,169\ (11)\,10^{-10}$ [76] where the errors are mainly originating from the hadronic uncertainties. The measured value and the SM prediction are consistent at the 3σ level. Therefore, this sets strong constraints on the additional contribution from SUSY particles.

The contribution of SUSY particles to $(g_\mu - 2)$ [77, 78] is mainly due to neutralino–smuon and chargino–sneutrino loops [if no flavor violation is present as is the case here]. In many models (such as mSUGRA), the contribution of chargino–sneutrino loops usually dominates.

If the SUSY particles are relatively heavy, the contribution of $\chi_i^\pm$–$\tilde{\nu}$ loops can be approximated by [$\tilde{m}$ is the mass of the heaviest particle per GeV]: $|\Delta a_\mu^{\tilde{\chi}^\pm \tilde{\nu}}| \sim 10^{-5} \times (\tan\beta/\tilde{m}^2)$, to be compared with the contribution of χ_i^0–$\tilde{\mu}$ loops, $|\Delta a_\mu^{\tilde{\chi}^0 \tilde{\mu}}| \sim 10^{-6} \times (\tan\beta/\tilde{m}^2)$, which is an order of magnitude smaller. These contributions are large for large values of $\tan\beta$ and small values of the scalar and gaugino masses and their sign is equal to the sign of μ.

We have included a routine which calculates the full one–loop contributions of chargino–sneutrino and neutralino–smuon loops in the MSSM, using the analytical expressions given in Ref. [78]. In this case, the full mixing in the smuon sector is of course included [this is the only place where the A_μ parameter plays a role in the code]. The sum of the chargino and neutralino contributions should lie in the 3σ range allowed by the experimental measurement.

3.4.5 The radiative decay $b \to s\gamma$

Another observable where SUSY particle contributions might be large is the radiative flavor changing decay $b \to s\gamma$ [79, 80]. In the SM this decay is mediated by loops containing charge 2/3 quarks and W–bosons but in SUSY theories, additional contributions come from loops involving charginos and stops, or top quarks and charged Higgs bosons [contributions from loops involving gluinos or neutralinos are very small [79] in the models considered here]. Since SM and SUSY contributions appear at the same order of perturbation theory, the measurement of the inclusive $B \to X_s\gamma$ decay branching ratio [36]

$$\mathrm{BR}(b \to s\gamma) = (3.37 \ \pm 0.37 \ \pm 0.34 \ \pm 0.24^{+0.35}_{-0.16} \ \pm 0.38) \cdot 10^{-4} \tag{60}$$

[where the first three errors are due respectively to statistics, systematics, and model dependence, while the fourth error is due to the extrapolation from the data to the full range of possible photon energies and the fifth error is an estimate of the theory uncertainty] is a very powerful tool for constraining the SUSY parameter space.

Recently, the authors of Ref. [80, 81] have calculated the next–to–leading order QCD corrections to the decay rate in the MSSM and provided a Fortran code which gives the most up–to–date determination of $\mathrm{BR}(b \to s\gamma)$ where all known perturbative and non–perturbative effects are implemented, including all the possibly large contributions which can occur at NLO, such as terms $\propto \tan\beta$ and/or terms containing logarithms of M_{EWSB}/M_W. We have interfaced this routine with our code[7] and plan to make this interface available in a next version of `SuSpect`. Besides the fermion and gauge boson masses and the gauge couplings that we have as input, we will use the values of the other SM input parameters required for the calculation of the rate given in Ref. [82], except for the cut–off on the photon energy, $E_\gamma > (1-\delta)m_b/2$ in the bremsstrahlung process $b \to s\gamma g$, which we fix to $\delta = 0.9$ as in Ref. [81].

[7]We thank Paolo Gambino for providing us with his code and for his help in interfacing it with ours.

3.5 Scanning the parameter space

Using the theoretical and experimental constraints discussed previously, one can perform a full scan of the MSSM parameter space with `SuSpect`This can be done straightforwardly upon simply adding appropriate FORTRAN (do) loops on the input parameter space within the main `SuSpect` calling routine `suspect2_call.f` that we will describe later. In the following, we give for illustration an example of such a scan taken from an update of the analysis of the mSUGRA model performed in Ref. [83].

For the values $\tan\beta = 40$, $A_0 = 0$ and with a positive μ parameter, we vary the scalar mass parameter m_0 from 10 to 2500 GeV with a grid of 10 GeV and the gaugino mass parameter $m_{1/2}$ from 5 to 1250 GeV with a grid of 5 GeV. This makes 62.500 points to scan in the $(m_{1/2}, m_0)$ plane, which takes a few hours on a 1 GHz PC as discussed later. We impose the following constraints, in addition to the ones which are signaled by default in `SuSpect` (such as proper EWSB, no CCB and UFB, non–tachyonic particles, etc..):

– The experimental bounds from negative searches of charginos, sleptons and third generation squarks at LEP2 and squarks and gluinos at the Tevatron [36]: $m_{\chi_1^+} \geq 104$ GeV, $m_{\tilde{f}} \geq 100$ GeV with $\tilde{f} = \tilde{t}_1, \tilde{b}_1, \tilde{l}^{\pm}, \tilde{\nu}$ and $m_{\tilde{g}} \geq 300$ GeV, $m_{\tilde{q}_{1,2}} \geq 260$ GeV with $\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$. We also require that the LSP is the lightest neutralino χ_1^0.

– The Higgs mass constraints [39]: i.e. the 95% CL lower bound on the mass of a SM–like Higgs from LEP2 searches, $M_{H^0} \geq 114$ GeV [in the MSSM, this bound is valid in the decoupling regime where the pseudoscalar A boson is very heavy] and for small values of M_A, the combined exclusion limit of $M_h \sim M_A \geq 92$ GeV [in the intermediate region an interpolation has to be made]. We will also display the region where a SM–like Higgs boson with a mass $M_{H^0} = 115.5 \pm 1.5$ GeV, as suggested by the 2σ excess at LEP2, is possible.

– Constraints from electroweak precision observables: the dominant contributions to the deviation from unity of the ρ parameter are due to the third generation $(\tilde{t}, \tilde{b})$ and $(\tilde{\tau}, \tilde{\nu})$ weak iso–doublets, and one has to require that these contributions stay below the acceptable [2σ deviations from the measurement] level of $\Delta\rho(\tilde{f}) \leq 2.2 \cdot 10^{-3}$ [74].

– The $b \to s\gamma$ decay branching ratio: where SUSY particle contributions might be rather large as discussed in subsection 3.4.5. Using the routine `bsg.f` which gives the most up–to–date determination in the MSSM of the $b \to s\gamma$ decay rate including NLO QCD corrections [81], we allow the full SM+SUSY value of the branching ratio to vary in the 2σ range: $2.0 \times 10^{-4} \leq \mathrm{BR}(b \to s\gamma) \leq 5.0 \times 10^{-4}$.

– The contribution to the muon $g-2$: where the new measurement of the Brookhaven experiment differs from the predicted SM average value by 3σ or 1.5σ if one takes into account data from τ decay [76]. We interpret the discrepancy as being a SUSY contribution from chargino–sneutrino and neutralino–smuon loops.

The effects of all these constraints on the $(m_{1/2}, m_0)$ parameter space are shown in Fig. 2. The most stringent theoretical constraint is the requirement of proper electroweak symmetry breaking. In the small green area, the pseudoscalar Higgs boson mass takes tachyonic values. The region with tachyonic sfermion masses is indicated in dark blue. In the yellow area the iteration to determine $|\mu|$ does not converge to a value $\mu^2 > 0$. The latter constraint plays an important role and excludes, depending on the value of $\tan\beta$ [and/or $m_t, m_b, M_{\rm EWSB}$ as discussed in [83] for instance], many scenarii with $m_0 \gg m_{1/2}$. The requirement that the LSP is indeed the lightest neutralino rules out the region (in light blue) of small values of m_0 where the less massive $\tilde{\tau}_1$ slepton is lighter than $\tilde{\chi}_1^0$.

Turning to the experimental constraints on SUSY particle masses, the requirement that the lightest charginos are heavier than ~ 104 GeV (brown area) extends the region of no EWSB while the requirement of heavy enough sleptons, $m_{\tilde{l}} \gtrsim 100$ GeV (dark area), slightly extends the region where sfermions are tachyonic. For small values of m_0 the right–handed side of the boundary does not depend on m_0; in this region, $\tilde{\chi}_1^\pm$ is wino–like and its mass is approximately given by $m_{\tilde{\chi}_1^\pm} \sim M_2 \sim 0.8 m_{1/2}$. For larger values of m_0, one enters the "focus point" [84] region where $\tilde{\chi}_1^\pm$ is a mixture of higgsino and gaugino states; for even larger values of m_0, μ becomes smaller and the chargino is higgsino–like with $m_{\tilde{\chi}_1^\pm} \sim |\mu|$, until one reaches the "no EWSB" region where no consistent value of μ is obtained. Note that for the values of $\tan\beta$ and A_0 used here, there are no points, not already ruled out by the constraints on EWSB and the SUSY particle mass bounds, which are excluded by the $\Delta\rho$ constraint, since the splitting between the top squarks remains moderate. The CCB constraint, which is somewhat related, is also not effective in this case, because $A_t(M_{\rm EWSB})$ remains moderate compared to the masses of the stop eigenstates in this mSUGRA scenario.

The lightest Higgs boson mass constraint $M_h > 114$ GeV (in the light red area of the top–right figure) is only effective if $m_0 \lesssim 1$ TeV and $m_{1/2} \lesssim 300$ GeV since we are in a large $\tan\beta$ scenario where M_h can easily be sufficiently large. The "evidence" of a SM–like Higgs boson with a mass between 114 and 117 GeV (darker red area) covers a much larger parameter space. The constraint from the measurement of the $b \to s\gamma$ branching ratio excludes only a small additional part of the parameter space (green area) with low m_0 and $m_{1/2}$ values (medium green area) leading to light charginos and top squarks [the constraint would have been stronger for $\mu < 0$]. The contribution of SUSY particles to the $(g-2)_\mu$ (blue area) accounting for the deviation from the central experimental value extends from values $m_0 \lesssim 0.8$ TeV for small $m_{1/2}$ to the boundary where the neutralino $\tilde{\chi}_1^0$ is not the LSP for large values, $m_{1/2} \sim 0.5$ TeV, except in a little corner for values $m_{1/2} \sim m_0$ of a few hundred GeV, where the SUSY contribution exceeds the 3σ upper bound. In this area, charginos and smuons have relatively small masses and can give too large a contribution to $(g_\mu - 2)$.

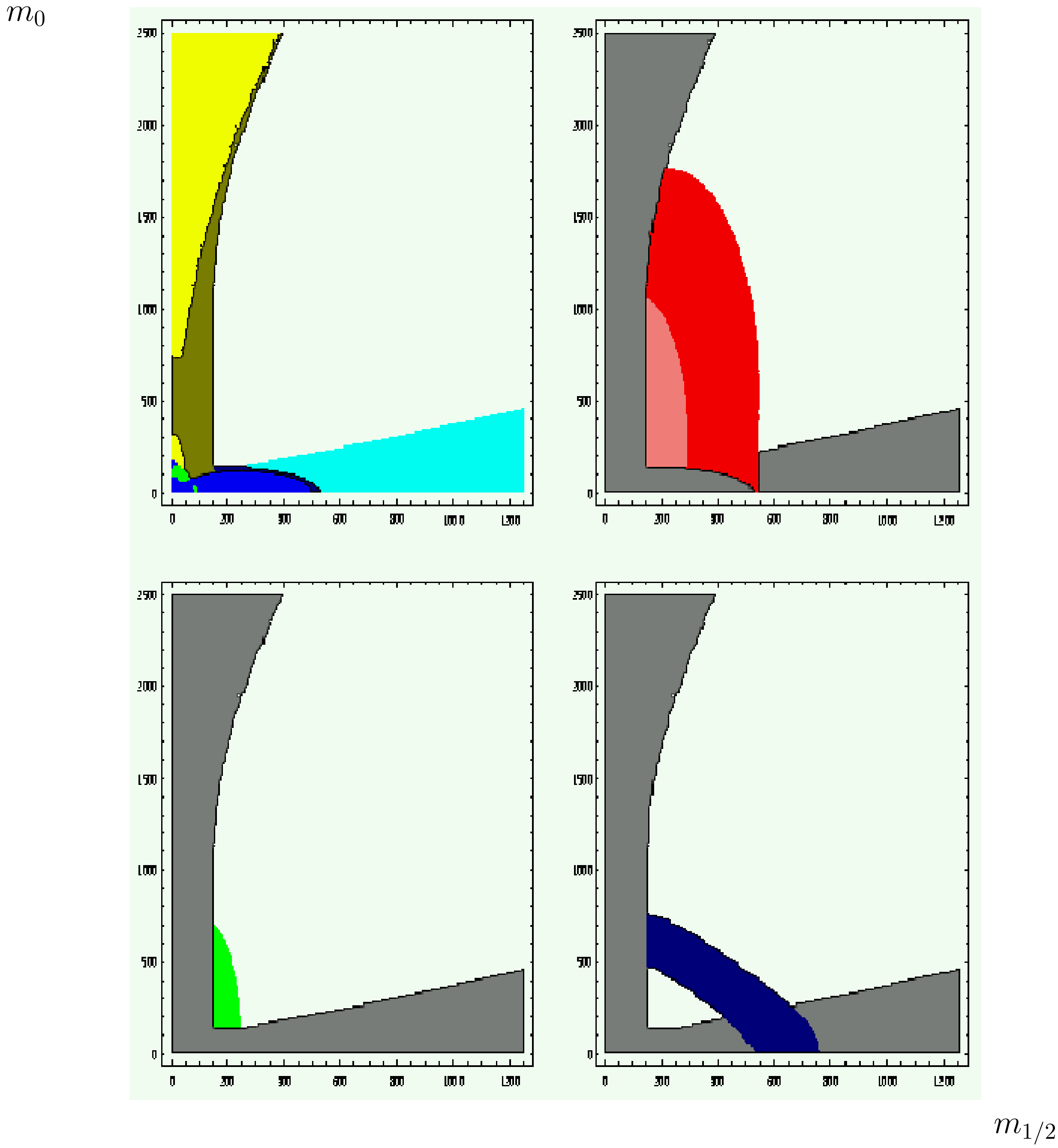

Figure 2: Constraints on the $(m_{1/2}, m_0)$ mSUGRA plane for $\tan\beta = 40, A_0 = 0, \mathrm{sign}(\mu) > 0$. Top–Left: individual constraints from non–convergent μ (yellow region), tachyonic M_A (green), tachyonic sfermions (blue), light sfermions (dark), light charginos (brown), χ_1^0 non–LSP (light blue). Top–Right: constraint on the Higgs boson mass (light red) and the LEP2 evidence for a 115.5 GeV Higgs (red). Bottom–Left: constraint from BR$(b \to s\gamma)$ (green) and Bottom–Right: the SUSY contribution to the $(g-2)_\mu$ (blue). The gray areas are those already excluded by the contraints of the top–left figure.

4. Running SuSpect

4.1 Basic facts about SuSpect

The program `Suspect` is composed of several files and routines:

i) The input file `suspect2.in`: here one can select the model to be investigated, the accuracy of the algorithm, the input data (SM fermion masses and gauge couplings). Some reasonable default values are set in the example of input file which is discussed in the next subsection. One would then simply select the SUSY model (pMSSM, mSUGRA, GMSB and AMSB), choose the corresponding input parameters and possibly make a few choices concerning the physical calculation (such as enforcing or not unification of the gauge couplings, changing the scale at which EWSB occurs, including or not radiative corrections to the masses and choosing the routine calculating the Higgs boson masses).

ii) The program `suspect2_call.f`: this is an example of a routine which calls the main subroutine `suspect2.f`. This program is necessary to run `SuSpect` since it defines the primary algorithm control input parameters needed by the latter. In particular, there is a parameter (`INPUT`) which allows to bypass the reading of the input file `suspect2.in`, in which case all the parameters and choices are to be defined by the user in this calling routine. This is particularly useful for interfacing `SuSpect` with other routines and/or for scans of the parameter space. A file example is discussed in Appendix B where details can be found.

iii) The main routine `suspect2.f`: here all the calculation of the spectrum is performed, once the input is supplied by `suspect2.in` or `suspect2_call.f`. This routine is self–contained, except for the determination of the Higgs boson masses, where it needs to call the three routines discussed in subsection 3.3.3 that we also supplied: `subh_hdec.f`, `feynhiggs.f` and `hmsusy.f`. [Note that `suspect2.f` has its own approximate calculation of the Higgs masses, but these three routines will be anyway needed for the compilation].

iv) An output file `suspect.out`: this file is in principle generated by default [it can be switched off by an appropriate value of the control parameter `INPUT` in `suspect2_call.f`] at each run of the program and gives the results for the output soft SUSY–breaking parameters [when they are calculated] and the masses and mixing angles of the Higgs and SUSY particles. Some warnings and comments are also given when the obtained spectrum is problematic. Examples of output files are given in subsection 4.3.

The routine `suspect2.f` consists of about 6.000 lines of code and takes about 200 Ko of memory, while the input and the calling routines have only a few hundred lines (most of them being comments). However, the accompanying routines for the calculation of the Higgs masses are somewhat longer; in particular, the routine `FeynHiggsFast` has more than 16.000 lines of code. As mentioned previously, these routines are provided separately. The complete executable code takes about 1.7 Mo space.

The FORTRAN files have to be compiled altogether and, running for instance on a PC using GNU FORTRAN, the compilation and link commands are:

```
g77 -c -finit-local-zero suspect2_call.f suspect2.f hmsusy.f subh_hdec.f feynhiggs.f
g77 -o suspect suspect2_call.o suspect2.o hmsusy.o subh_hdec.o feynhiggs.o
suspect
```

[The compilation option `-finit-local-zero` is mandatory due to the usual non-initialization by default with GNU FORTRAN; no other compilation option is in principle needed]. The running time for a typical model point, for instance the mSUGRA point discussed below, is about 0.5 seconds on a PC with a 1 GHz processor.

In the next sections, we will exhibit the input and output files taking a few examples in the various models that we consider [this allows to compare with spectra given by other routines]. For illustration, we will use the benchmark points from the Snowmass Points and Slopes [85] for the followings models [for the first point, we will calculate the SUSY–breaking parameters at the EWSB scale and then inject them as if we were in the pMSSM]:

$$\begin{aligned}
\text{pMSSM (SPS6)} &: \; 2m_0 = \frac{M_1}{1.6} = M_2 = M_3 = 300 \text{ GeV} \;,\; A_0 = 0 \;,\; \tan\beta = 30 \;,\; \mu > 0 \\
\text{mSUGRA (SPS1b)} &: \; m_0 = 200 \text{ GeV} \;,\; m_{1/2} = 400 \text{ GeV} \;,\; A_0 = 0 \;,\; \tan\beta = 30 \;,\; \mu > 0 \\
\text{GMSB (SPS8)} &: \; \Lambda = 100 \text{ TeV} \;, M_{\rm mes} = 200 \text{ TeV} \;,\; n_l = n_q = 1 \;,\; \tan\beta = 15 \;,\; \mu > 0 \\
\text{AMSB (SPS9)} &: \; m_0 = 450 \text{ GeV} \;,\; m_{3/2} = 60 \text{ TeV} \;,\; \tan\beta = 10 \;,\; \mu > 0 \;,\; c_i = 1
\end{aligned}$$

The input and output files are self–explanatory and will not be commented further, in particular since some details will be given in Appendix B. Furthermore, for convenience, we will exhibit the warning/error message part of the output file which normally appears at each `SuSpect` run only once, at the end of the first point, since "everything is fine" for all the chosen input here [i.e. there is no problem with the spectrum].

4.2 The input file

```
                              SUSPECT2.1 INPUT FILE
                              ---------------------
* Initialize various options (choice of models, algorithm  control etc..)
ICHOICE(1): Choice of the model to be considered:
            Arbitrary soft-terms at low scale (no RGE): 0
            Arbitrary soft-terms at high scale (RGE)  : 1
            mSUGRA (cMSSM)                            : 10
            GMSB   (cMSSM)                            : 11
            AMSB   (cMSSM)                            : 12
          10
```

```
ICHOICE(2): All the RGEs are at 1-loop order          : 11
            2-loop RGEs for gauge+Yukawas+gauginos    : 21
          21

ICHOICE(3): GUT scale imposed (HIGH to be given below): 0
            GUT (at g_1=g_2) scale derived from input : 1
          0

ICHOICE(4): RGE sufficiently accurate and fast        : 1
            RGE very accurate but rather slow         : 2
          1

ICHOICE(5): No radiative EWSB imposed (only in pMSSM) : 0
            Consistent EWSB (automatic in cMSSMs)     : 1
          1

ICHOICE(6): M_A, MU as input     (only in pMSSM)      : 0
            M_Hu, M_Hd as input  (only in pMSSM)      : 1
          1

ICHOICE(7): SUSY radiative corrections to the (s)particles masses:
            No R.C. (! except for Higgs masses)       : 0
            R.C also in mb,mt,mtau + Yukawa couplings : 1
            R.C. to squark/gaugino masses in addition : 2
          2

ICHOICE(8): Default EWSB scale=(mt_L*mt_R)^(1/2)      : 1
            Arbitrary EWSB scale (to be given below)  : 0
          1

ICHOICE(9): Nb of (long: RGE + full spectrum) iterations: >= 3
          3

ICHOICE(10): Routine for the calculation of the Higgs boson masses:
             SUSPECT calculation (gen. sufficient)    : 0
             SUBH_HDEC (Carena et al.) from HDECAY     : 1
```

```
            HMSUSY (Haber et al.) routine            : 2
            FEYNHIGGSFAST1.2.2 (Heinemeyer et al.)   : 3
         0

* Initialize "SM" parameters (default values here):
1/alpha(MZ),   s^2_W(MZ),   alpha_S(MZ),  M_t(pole), M_b(pole),   M_tau
127.938        0.23117       0.1192        174.3      4.9         1.7771

* RGE scales(GeV): HIGH (=GUT scale if imposed), Low RGE ends; EWSB scale:
1.9d16         91.19                  175.

* mSUGRA model input parameters:
*  m_0        m_1/2        A_0    tan(beta)   sign(mu)
  200.        400.         0.     30.          1.

* GMSB model input parameters:
* MGM_mes     MGM_susy   tan(beta)   sign(mu) Nl_mes    Nq_mes
  200.d3      100.d3     15.         1.       1         1

* AMSB model input parameters:
* M_3/2    m_0     tan(beta)   sign(MU)  cQ  cuR  cdR  cL  ceR cHu cHd
  60.d3    450.    10          1.        1.  1.   1.   1.  1.  1.  1.

* Non-universal MSSM input (irrelevant if constrained MSSM chosen):
M_Hu^2    M_Hd^2  (V_Higgs mass terms)   tan(beta)  sign(mu)
-0.15d6   0.62d5                          10.        1.
M_1       M_2      M_3                              (gaugino mass terms)
200.      230.     700.
M_tauL    M_tauR   M_QL    M_tR    M_bR (3rd gen. L and R mass terms)
260.      235.     600.    515.    630.
M_eL      M_eR     M_qu    M_uR    M_dR (1/2 gen. L and R mass terms)
260.      240.     660.    640.    630.
A_tau     A_t      A_b     A_e     A_u    A_d   (trilinear couplings)
-200.    -570.     -850.  -220.   -930.   -910.

M_A   MU   if input instead of M_Hu, M_Hd (not in constrained MSSM):
470.  386.
```

4.3 The output files

4.3.1 The output in the pMSSM case

```
             SUSPECT2.1 OUTPUT: pMSSM CASE
No RGEs: only spectrum calculation at the low energy scale
             -----------------------------
Input values:
-------------
  M_top      M_bot      M_tau      1/alpha    sw**2(M_Z)   alpha_S
  174.3      4.900      1.777      127.94     0.2312       0.1192

Input non-universal soft terms at M_EWSB
----------------------------------------
  mu         M_A        tan(beta)  sign(mu)
  386.0      469.2      10.00      1.000
  M_1        M_2        M_3
  200.0      230.0      700.0
  m_eR       m_eL       m_dR       m_uR       m_qL
  240.0      260.0      630.0      640.0      660.0
  m_tauR     m_tauL     m_bR       m_tR       m_QL
  235.0      260.0      630.0      515.0      600.0
  Atau       Abottom    Atop       Al         Ad         Au
 -200.0     -850.0     -570.0     -220.0     -910.0     -930.0

Mass matrices and mixing angles:
--------------------------------
  tan(beta)  alpha_(h,H)
  10.00    -0.1077
  thet_tau   thet_b     thet_t
  1.142     0.3227      1.059
  Z(i,j)
  0.9308     -0.2599      0.2232     -0.1271
  0.3292      0.9013     -0.2371      0.1517
  0.4761E-01 -0.8145E-01 -0.6978     -0.7100
  0.1512     -0.3368     -0.6380      0.6758
  U(i,j)                  V(i,j)
 -0.9084      0.4181     -0.9639      0.2661
  0.4181      0.9084      0.2661      0.9639
```

```
Final Higgs and SUSY particle masses:
-------------------------------------
  h          A          H          H+
  111.1      469.2      469.5      475.8

  chi+_1     chi+_2     chi0_1     chi0_2     chi0_3     chi0_4
  218.1      410.0      190.9      221.1     -388.8      411.3

  gluino
  746.1

  stop_1     stop_2     sup_1      sup_2
  523.9      666.8      668.5      687.0

  sbot_1     sbot_2     sdown_1    sdown_2
  629.4      663.5      660.1      691.6

  stau_1     stau_2     snutau     selec_1    selec_2    snuelec
  231.9      270.4      252.0      243.9      264.2      252.0

Warning/Error Flags: errmess(1)-(10):
-------------------------------------
   0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
---------------------------------
errmess(i)= 0: Everything is fine.
errmess(1)=-1: tachyon 3rd gen. sfermion from RGE
errmess(2)=-1: tachyon 1,2 gen. sfermion from RGE
errmess(3)=-1: tachyon A    (maybe temporary: see final mass)
errmess(4)=-1: tachyon 3rd gen. sfermion from mixing
errmess(5)=-1: mu(M_GUT) guess inconsistent
errmess(6)=-1: non-convergent mu from EWSB
errmess(7)=-1: EWSB maybe inconsistent        (!but RG-improved only check)
errmess(8)=-1: V_Higgs maybe UFB or CCB       (!but RG-improved only check)
errmess(9)=-1: Higgs boson masses are NaN
errmess(10)=-1: RGE problems (non-pert and/or Landau poles)
```

4.3.2 The output in the mSUGRA case

```
             SUSPECT2.1 OUTPUT: MSUGRA CASE
             ------------------------------


Input values:
-------------
  m_0         m_1/2       A_0         tan(beta)  sign(mu)
  200.0       400.0       0.000       30.00      1.000

  M_top       M_bot       M_tau       1/alpha    sw**2(M_Z)   alpha_S
  174.3       4.900       1.777       127.94     0.2312       0.1192

  M_GUT       M_EWSB      E_LOW        (input or ouput scales)
 0.1900E+17  716.9       91.19

Fermion masses and gauge couplings: HIGH/EWSB
---------------------------------------------
  M_top       M_bot       M_tau      g1**2      g2**2      g3**2
  72.01       1.053       1.473      0.5129     0.5132     0.5008
  155.1       2.681       1.856      0.2130     0.4255      1.521

mu parameter and soft terms at M_EWSB:
--------------------------------------
  mu          B           M^2_Hu       M^2_Hd
  493.0       20.99     -0.2416E+06    7432.

  M_1         M_2         M_3
  166.0       309.7       913.4

  m_tauR      m_tauL      m_bR        m_tR       m_QL
  221.7       327.5       781.9       669.6      769.8

  m_eR        m_eL        m_dR        m_uR       m_qL
  251.3       338.1       823.4       828.0      862.8

  Atau        Abottom     Atop        Al         Ad          Au
 -182.5      -989.0      -724.8      -195.6     -1117.      -965.2
```

```
Mass matrices and mixing angles:
--------------------------------
  tan(beta)  alpha_(h,H)
  29.98    -0.3468E-01

  thet_tau   thet_b     thet_t
  1.190     0.6847      1.126

  Z(i,j)
  0.9936     -0.2089E-01  0.1041     -0.3742E-01
  0.5208E-01  0.9541     -0.2485      0.1588
  0.4536E-01 -0.6705E-01 -0.7009     -0.7086
  0.8893E-01 -0.2911     -0.6604      0.6865

  U(i,j)                 V(i,j)
 -0.9349      0.3550     -0.9739      0.2271
  0.3550      0.9349      0.2271      0.9739

Final Higgs and SUSY particle masses:
-------------------------------------
  h          A          H          H+
  113.8      556.0      557.1      562.5

  chi+_1     chi+_2     chi0_1     chi0_2     chi0_3     chi0_4
  304.8      514.1      162.6      305.0     -497.6      513.4

  gluino
  969.0

  stop_1     stop_2     sup_1      sup_2
  682.9      825.3      856.9      890.3

  sbot_1     sbot_2     sdown_1    sdown_2
  781.8      832.5      853.5      894.0

  stau_1     stau_2     snutau     selec_1    selec_2    snuelec
  200.1      347.2      321.1      255.1      341.4      331.9
```

4.3.3 The output in the GMSB case

```
             SUSPECT2.1 OUTPUT: GMSB CASE
             ----------------------------


Input values:
-------------
  M_mess     M_susy     nl         nq         tan(beta)  sign(mu)
 0.2000E+06 0.1000E+06   1           1        15.00      1.000

  M_top      M_bot      M_tau      1/alpha    sw**2(M_Z)   alpha_S
  174.3      4.900      1.777      127.94     0.2312       0.1192

  M_GUT      M_EWSB     E_LOW       (input or ouput scales)
 0.1900E+17  1020.      91.19

Fermion masses and gauge couplings: HIGH/EWSB
---------------------------------------------
  M_top      M_bot      M_tau     g1**2      g2**2      g3**2
  71.27      1.035      1.391     0.5137     0.5127     0.4999
  155.2      2.727      1.811     0.2130     0.4256      1.522

mu parameter and soft terms at M_EWSB:
--------------------------------------
  mu         B          M^2_Hu       M^2_Hd
  411.1      49.51    -0.1531E+06   0.1088E+06

  M_1        M_2        M_3
  144.7      272.2      756.3

  m_tauR     m_tauL     m_bR       m_tR       m_QL
  170.1      354.3      1057.      975.5      1070.

  m_eR       m_eL       m_dR       m_uR       m_qL
  172.4      354.9      1062.      1067.      1115.

  Atau       Abottom    Atop       Al         Ad         Au
 -26.83     -271.4     -245.7     -26.89     -278.1     -263.1
```

```
Mass matrices and mixing angles:
--------------------------------
  tan(beta)  alpha_(h,H)
  15.00    -0.7095E-01

  thet_tau   thet_b     thet_t
  1.458      1.177      1.481

  Z(i,j)
  0.9895     -0.3415E-01  0.1306     -0.5230E-01
  0.8335E-01  0.9252     -0.3060      0.2084
  0.5211E-01 -0.7595E-01 -0.6987     -0.7095
  0.1063     -0.3703     -0.6334      0.6712

  U(i,j)                 V(i,j)
 -0.8972      0.4416     -0.9535      0.3013
  0.4416      0.8972      0.3013      0.9535

Final Higgs and SUSY particle masses:
-------------------------------------
  h          A          H          H+
  112.9      553.6      554.0      559.1

  chi+_1     chi+_2     chi0_1     chi0_2     chi0_3     chi0_4
  262.4      436.4      140.0      262.8     -413.8      436.3

  gluino
  909.5

  stop_1     stop_2     sup_1      sup_2
  1023.      1110.      1098.      1144.

  sbot_1     sbot_2     sdown_1    sdown_2
  1086.      1106.      1094.      1147.

  stau_1     stau_2     snutau     selec_1    selec_2    snuelec
  172.2      359.1      348.5      177.9      358.0      349.0
```

4.3.4 The output in the AMSB case

```
             SUSPECT2.1 OUTPUT: AMSB CASE
             ----------------------------


Input values:
-------------
  M_3/2      m_0        tan(beta)  sign(mu)
 0.6000E+05  450.0      10.00      1.000
  cQ      cuR     cdR     cL      ceR     cHu     cHd
  1.00    1.00    1.00    1.00    1.00    1.00    1.00
  M_top      M_bot      M_tau      1/alpha    sw**2(M_Z)   alpha_S
  174.3      4.900      1.777      127.94     0.2312       0.1192
  M_GUT      M_EWSB     E_LOW       (input or ouput scales)
 0.1900E+17  967.6      91.19

Fermion masses and gauge couplings: HIGH/EWSB
---------------------------------------------
  M_top      M_bot      M_tau     g1**2      g2**2      g3**2
  73.76      1.026      1.390     0.5111     0.5123     0.4960
  156.6      2.639      1.793     0.2132     0.4255      1.512

mu parameter and soft terms at M_EWSB:
--------------------------------------
  mu         B          M^2_Hu       M^2_Hd
  998.9      109.7    -0.9798E+06   0.1009E+06

  M_1        M_2        M_3
  554.1      167.9     -1272.

  m_tauR     m_tauL     m_bR       m_tR       m_QL
  322.4      399.2      1200.      865.0      1123.

  m_eR       m_eL       m_dR       m_uR       m_qL
  336.2      404.8      1216.      1221.      1285.

  Atau       Abottom    Atop       Al         Ad         Au
  601.3      2502.      1090.      620.2      2905.      2239.
```

```
Mass matrices and mixing angles:
--------------------------------
  tan(beta)  alpha_(h,H)
  9.977    -0.1021

  thet_tau   thet_b     thet_t
  1.302     0.9955E-01  1.789

  Z(i,j)
  0.3616E-02 -0.9963      0.8322E-01 -0.2248E-01
  0.9971      0.9836E-02  0.6388E-01 -0.3902E-01
  0.1791E-01 -0.4288E-01 -0.7052     -0.7075
  0.7326E-01 -0.7423E-01 -0.7012      0.7053

  U(i,j)                  V(i,j)
 -0.9931      0.1171     -0.9995      0.3170E-01
  0.1171      0.9931      0.3170E-01  0.9995

Final Higgs and SUSY particle masses:
-------------------------------------
  h          A          H          H+
  113.3      1048.      1049.      1054.

  chi+_1     chi+_2     chi0_1     chi0_2     chi0_3     chi0_4
  174.9      1008.      174.9      544.8     -1004.      1009.

  gluino
  1193.

  stop_1     stop_2     sup_1      sup_2
  907.5      1164.      1255.      1317.

  sbot_1     sbot_2     sdown_1    sdown_2
  1162.      1237.      1252.      1319.

  stau_1     stau_2     snutau     selec_1    selec_2    snuelec
  318.4      407.5      394.0      339.0      407.5      399.7
```

5. Calculations with SuSpect

5.1 Comparison with other codes

Our results for some representative points of the MSSM parameter space have been carefully cross–checked against other existing codes. Most of the earlier comparisons have been performed in the context of mSUGRA type models. We obtain in general a very good agreement, at the percent level, with the program `SOFTSUSY1.4` [14] and with the code `SPHENO1.0` [15] which will appear publicly very soon[8]. We also find rather good agreement, in general at the few percent level, for the SUSY particle masses computed by the program `ISASUGRA` [13] version 7.58, once we chose the same configuration [soft SUSY breaking masses frozen at M_Z, some radiative corrections to sparticle masses are not included, etc..]; a better agreement is found with the more recent 7.63 version. A detailed comparison of a previous version of `SuSpect` (version 2.005) with these programs has been given in Ref. [86]. Even in the delicate cases of large $\tan\beta$ value [where the b–quark Yukawa coupling, which needs a special treatment and the inclusion of important radiative corrections, is strong] and large m_0 values [the "focus point" region where EWSB is rather problematic to achieve], the discrepancies between `SuSpect` and the program `SOFTSUSY` for instance, are rather moderate.

In the case of the AMSB and GMSB models, no very detailed comparisons have been made. We have simply compared our output values for the two SPS points discussed previously for the minimal versions of these models, with those obtained with `ISASUGRA` and we find a rather good agreement, in general at the level of a few percent. [Note that in the numbers given in Ref. [87], the difference can go up to 10% in some cases; however, we have slightly different values for the input parameters $m_t, \alpha_s, \sin^2\theta_W$, etc..].

The most sophisticated parameter to obtain in this context is the lightest Higgs boson mass, since it incorporates all possible ingredients: the RGE's for the evaluation of M_{H_u} and M_{H_d}, the effective potential and the EWSB for the determination of M_A and the tadpoles, the radiative corrections to the Higgs sector which involve also the two–loop corrections, etc. The value that we obtain[9] for M_h is for instance slightly different than the one from `ISASUGRA` [even if we switch off the $\mathcal{O}(\lambda_t^2)$ corrections which are not implemented there] and this is presumably due to the more sophisticated treatment of the Higgs potential made by the routines to which `SuSpect` is linked. We note however, that there are already differences for M_h obtained with the three routines used by `SuSpect` as well as for the approximation which is incorporated, a reflection of the different degree of accuracy of these routines.

[8] We thank Ben Allanach, Sabine Kraml and Werner Porod for their gracious help in performing these detailed comparisons of the programs

[9] Note that the comparison with the program `SuSpect` made in Ref. [86] was with an earlier version which had only a very approximate determination of the Higgs boson masses. The new version, since it is linked to several Higgs routines, gives a much better determination of these parameters.

5.2 Interface with other programs

In the way it is written, `SuSpect` can be easily interfaced with other programs or Monte–Carlo event generators[10]. In fact, private versions exist which are already interfaced with some programs, and we give a short list of them:

- `micrOMEGAs` [88]: for the automatic (analytical and then numerical) calculation of the cosmological relic density of the lightest neutralinos, including all possible annihilation and co–annihilation channels[11].
- `DARKSUSY` [89]: also for the calculation of the relic density of the lightest neutralinos and their direct and indirect detection rates [the program has its own calculation of the SUSY spectrum, but it is rather approximate][12] .
- `HDECAY` [68]: for the calculation of the decay branching ratios and total decay widths of the SM and MSSM Higgs bosons [in fact some routines, in particular those for the QCD running and for the interface with the routines calculating the Higgs boson masses, are borrowed from there].
- `SDECAY` [92]: for the calculation of the decay widths and branching ratios of SUSY particles including higher order [three–body decays for gauginos and stops, four–body decays for the lightest stop and QCD corrections to the two–body decays of squarks and gluinos], which will appear soon.
- `SUSYGEN` [93]: a Monte–Carlo event generator for Higgs and SUSY particle production in the MSSM [mainly in e^+e^- collisions but some processes in ep and pp collisions are implemented]. The program is also interfaced with `HDECAY`.

As discussed already, we have also interfaced `SuSpect` with the FORTRAN code `bsf.f` which calculate the branching ratio of the radiative decay $b \to s\gamma$ at next-to-leading order [81] as well as with the codes calculating the radiative corrections to the Higgs boson masses [which is in fact part of the interface with `HDECAY`]. An interface with two of the major Monte–Carlo event generators[13] `PYTHIA` [94] and `HERWIG` [95] is in progress.

Most of the interfaces with these programs are still under checks and will hopefully be made available in a next release of the program.

[10]To make this interfacing easier, we have provided a set of obvious commons for the input and output parameters needed or calculated by `SuSpect` and named all commons, subroutines and functions used with a prefix `SU_`, not to be in conflict with those used by other programs.

[11]Note that we have also interfaced the program with a private code written by Manuel Drees calculating the cosmological relic density of the lightest neutralinos for the complete analysis of the mSUGRA parameter space performed in Ref. [83] and summarized in Section 3.5.

[12]Note that a private `Suspect/DARKSUSY` interface has been already used for prediction studies of indirect LSP detection [90, 91]

[13]We thank by anticipation, Stefano Moretti, Peter Richardson and Peter Skands for their help and collaboration in implementing the interfaces with these event generators.

5.3 Future upgrades

The program is under rapid development and we plan to make several upgrades in a near future. A brief list of points which will be implemented in the next releases [maybe not all in the next one] of the program includes [some of these points have been discussed previously, but we list them also here for completeness]:

1) Implementation of the theoretical and experimental constraints: the first improvement which is under checks and which will be done rather quickly, as was discussed in section 3.4, will be to include all the routines to constrain the SUSY spectrum in the MSSM which are almost already available: the implementation of the more sophisticated CCB and UFB conditions, the calculation of the fine–tuning criteria parameters for the EWSB mechanism and the experimental constraints from $\Delta\rho$, the muon $(g-2)$ and the radiative $b \to s\gamma$ decay.

2) More refined calculations including higher–orders: we plan to improve the determination of the SUSY parameters and particle masses by including several important higher order corrections: the two–loop SUSY–QCD corrections to the top and bottom quark masses [96], the full one loop corrections to the Higgs boson masses *à la* PBMZ [24], additional radiative corrections to some SUSY particle masses such as the full one–loop corrections to the chargino and neutralinos which are available and leading electroweak corrections to squarks and sleptons [25] and possibly, the full two loop RGEs for the soft SUSY–breaking parameters as calculated recently [62].

3) The interface with other routines: our first goal would be to make the interface fully operative with the programs `HDECAY` and `SDECAY` for Higgs and SUSY particle decay widths and branching ratios. One would then, with the three programs [which have many common features already], have a very complete description of the properties of the new particles in the MSSM, except from the production part which is in general the *chasse gardée* of the Monte–Carlo event generators. For the later aspect or purpose, an interface of this new version of `SuSpect` with `PYTHIA` and `HERWIG` as well as with `SUSYGEN`, will be provided quite soon as mentioned previously. The interface with the routines for Dark Matter calculations such as `MICROMEGAS` and `DARKSUSY` will also be made publicly available.

4) Include additional theoretical models: the most important upgrade that we plan for a not too far future is to discuss additional theoretically interesting models. Examples of models that we have on our agenda are:

- The (M+1)SSM with an additional Higgs singlet field. The RGEs and the EWSB mechanisms have been discussed in detail by one of the authors in Ref. [97] and can be implemented easily in the program. Additional work will be needed to discuss the extended superparticle and Higgs spectrum [one would have one additional neutralino and one Higgs boson compared to the MSSM], in particular if radiative corrections are to be taken into account [98]

– Some other theoretically discussed models, such as superstring-inspired models, can be dealt with by the present version of the program, using the pMSSM machinery with the RGE option. However, some extensions will need more input to be specified: this is the case with SO(10) models with right–handed sneutrinos [in which some additional contributions to the D–terms of the scalar masses have to be implemented] [99] or the O–I and O–II string models [47]. This will be done in the future.

– Models with R–parity violation [100]. The RGE's for the SM Yukawa couplings and all the MSSM R–parity violating Yukawa couplings in these models [with a discussion of the quasi fixed point properties] have been studied in detail by one of us in Ref. [101]. The implementation of this analysis in `SuSpect` should not be problematic but some additional work will be needed to fully cover the subject.

– Models with CP–violation. In principle, this will alter substantially only the part where the superparticle and Higgs particle spectrum is calculated. For the case of the chargino, neutralino and sfermion sectors, this is already available. Only in the Higgs sector the calculation will need extra work [102], since one has to implement the radiative corrections which are important in this context.

5) Include additional tools: finally, there are some tools in the context of the MSSM discussed here, which can have some theoretical and experimental interest, that are already more or less available as separate codes and can be interfaced with `SuSpect`:

– `INVERTER`: this is a routine whose purpose is to determine the inverted spectrum relationship [i.e. recovering the Lagrangian parameter values directly from physical masses and/or couplings]. The algorithm in its present form essentially deals with the non–trivial inversion in the gaugino parameter sector, where the input can be either two charginos and one neutralino, or two neutralinos and one chargino physical masses. The output are the Lagrangian parameters, μ, M_1, M_2. This has been done following the approach of Ref. [103] and will be generalized to the case of the sfermion and the Higgs sector [the inclusion of radiative corrections might be problematic here].

– `RG EXACT`: this is a routine which implements an exact RG evolution solver limited to one–loop approximation following the approach of Ref. [104] to which we refer for a detailed discussion of the procedure. We simply mention here, that these exact solutions of the relevant SUSY RGEs which have been derived for arbitrary values of $\tan\beta$, should not only be useful to improve the general RG evolution algorithm, but more importantly, should provide a better control on some non–trivial issues of the evolution, such as the occurrence of Landau poles in the Yukawa couplings typically.

As stated previously, this rather ambitious program will take some time to be fully achieved, but we will definitely try to have everything available before the starting of the LHC (and certainly before the advent of VLHC and CLIC)!

5.4 Web information and maintenance

A web page devoted to the `SuSpect` program can be found at the http address:

`http://www.lpm.univ-montp2.fr:6714/~ kneur/Suspect`

It contains all the information that one needs on the program:

– Short explanations of the code and how to run it.

– The complete "users manual" can be obtained in post-script or PDF form.

– A regularly updated list of important changes/corrected bugs in the code.

– A mailing list to which one can subscribe to be automatically advised about future `SuSpect` updates or eventual corrections.

One can also download directly the various files of the program:

– `suspect2.in`: the input file of the program.

– `suspect2_call.f`: the calling program sample.

– `suspect2.f`: the main routine of the program.

– `subh_hdec.f, hmsusy.f, feynhiggs.f`: the three Higgs routines.

– `SuSpect2_New.uu`: all needed routines in uu compressed format for the latest version.

– `SuSpect2_Old.uu`: the routines for the previous versions of the program.

A new feature is that we have provided a way to use directly the program interactively on the web[14]. For the present time, this is only possible in the constrained models: mSUGRA, GMSB and AMSB, which need only a small set of input parameters. The Standard Model input parameters [fermion masses and gauge couplings], the algorithmic choices for various accuracy of the program [accuracy and iterations on the RGEs], choice of scales [GUT and EWSB scales] as well as the choices for the radiative corrections for the sparticles and Higgs bosons, have been set to default values which are those displayed in the input file displayed in section 4.2. On then has simply to select the model to be considered, i.e. either mSUGRA, GMSB or AMSB, type in the corresponding input parameters in the required fields and click on a field to submit the run of the code. The output will be the usual `SuSpect` output. Besides $\tan\beta$ and the sign of the μ parameter, these input are [see Fig. 3]:

— mSUGRA: the scalar m_0 and gaugino $m_{1/2}$ masses and the trilinear coupling A_0,

– GMSB: the scale Λ, the messenger scale $M_{\rm mes}$ and messenger numbers n_q and n_l,

– AMSB: the common scalar and gravitino masses m_0 and $m_{3/2}$ and the coefficients c_{S_i}.

This very easy and friendly way of running `SuSpect` should be very useful for those who need to know the spectrum only for a few cMSSM points and do not want to download and run the program themselves.

[14]We thank our system–manager in Montpellier, Dominique Caron, for setting-up this possibility.

http://www.lpm.univ-montp2.fr:7082/~kneur/Suspect/susweb.html

An interactive tour of SUSY: SuSpect_Web

An easy and possibly amusing (depending on the output...) of using SuSpect.
Please first make your model choice, fill the required fields and then submit!
A few simple rules to follow:

- Do not fill the fields of a model that you did not choose.
- Do not put space or a character not recognized by Fortran.
- Be reasonable with the inputs (tan(beta)=100 won't work..).

Enjoy yourself!

Model Choice : [mSUGRA]

mSUGRA		GMSB		AMSB	
m_0:	?	M_mes :	0	M_3/2:	0
m_1/2 :	?	M_susy :	0	m_0 :	0
A_0 :	?	tan(beta) :	0	tan(beta) :	0
tan(beta) :	?	sign(mu) :	1	sign(mu):	1
sign(mu):	1	Nl_mes:	0	c_Q:	0
		Nq_mes:	0	c_uR:	0
				c_dR:	0
				c_L:	0
				c_eR:	0
				c_Hu:	0
				c_Hd:	0

[Submit SuSpect] [Clear fields] [View input file]

This page has been set-up by Dominique Caron: one of the greatest (and less modest) system managers in the world. Merci Domi! And in case you want to offer him a glass of wine (some Bordeaux would be welcome) or simply thank him (please do not overdo it...) for the "fabulous results" that you have obtained, let him know! .

Back to the SuSpect Home Page.

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Figure 3: Web page of interactive SuSpect running where one can rapidly evaluate some point in the parameter space of the mSUGRA, AMSB and GMSB constrained models.

6. List of changes compared to previous versions

This section, anticipating the next upgrades of the program, will be devoted to the summary of all the important changes made after each new release. For the present time, we will briefly summarize the history of the program and list the major changes compared to the earlier versions `SuSpect`1.0 and `SuSpect`2.0 which were available only on our web page.

6.1 The version `SuSpect1.0`

This was the first version of the program and was released in 1998. It was available on the web, but was not intended for a large public and was mainly used in the framework of the French "GDR–Supersymétrie" for the experimentalists and the theorists of the working groups to have a common tool for SUSY[15]. The code was at a rather preliminary stage [a patchwork of several bits of codes written by the authors for various purposes], was largely open to discussions and suggestions and its main purpose, as mentioned earlier, was to propose some conventions, definitions and possible flexibility choices in the framework of the GDR. The program was not very well documented until a short explanation was given in the mid–term report of the MSSM working group of the GDR in December 1998 [4].

At that time, the program had only two extremes models implemented: mSUGRA and the pMSSM but with the possibility of RG evolution, and the calculation of the spectrum was made using several rough approximations. For instance, simple threshold effects with a single SUSY scale were included in the running of the SM gauge and Yukawa couplings but the important radiative corrections to the fermion and SUSY particles masses were not implemented. In addition, the effective scalar potential for EWSB and the radiative corrections in the Higgs sector had only the leading contributions from the third generation (s)fermion sector. Several "algorithmic" choices [like the choice of the GUT or EWSB scales and the ones for the accuracy of the RGEs] were not present.

6.2 The version `SuSpect2.0`

An important upgrade was made in the version `SuSpect`2.0 released in 2001, which still did not have a detailed users manual and was only available on the web page [where we started to display some useful information, like the list of changes, a users E–mail list, etc ...]. For instance, we have included all dominant radiative corrections to the third generation fermion masses and Yukawa couplings as well as to the SUSY particle masses. The effective potential

[15] In fact, the first version of the program was called `MSSMSpect` but some members of the GDR complained about the name which seemed to be difficult to pronounce by some of our (presumably not Arabic nor Slavic) colleagues, probably due to a local cluster of consonants. We then proposed a change of name to `SUSYSPECT` and then, to make short, to `SuSpect` (since every code, a priori, is).

included also the full one-loop contributions from the SUSY particles. Some refinements and more possibilities were made available for the various model and approximation choices. A few bugs and inconsistencies had been fixed. But still, the model choices were limited and the Higgs sector was treated only approximately.

6.3 The version `SuSpect2.1`

A major upgrade has been performed, leading to the version that we are presenting here. The changes compared to the latest version, `SuSpect`2.005, displayed on the web page, can be summarized as follows:

i) An upgrade concerning the supersymmetry-breaking models has been performed by providing the possibility of calculating the MSSM particle spectrum in the AMSB and GMSB models. Some flexibility in the choice of the input parameters [in particular the choice of the messenger fields in the GMSB scenario and of the non–anomalous contribution to the scalar fields in the AMSB model] has been made available and should allow the possibility to analyze a large number of the theoretical scenarii discussed in the literature.

ii) A major upgrade was made in the calculation of the Higgs boson masses. Following the program `HDECAY`, we have provided an interface with all the available public routines which evaluate the radiative corrections in the MSSM Higgs sector, namely the latest versions of `subhpolem`, `FeynHiggsFast` and `HMSUSY`. We have also provided a simple routine [included in the program] which gives a rather good approximation of these corrections.

iii) Some important refinements in the calculation of the radiative corrections to the fermion and SUSY particle masses have been made. For instance, we have included the two–loop QCD corrections to the heavy t, b quark masses, the chargino–neutralino loop corrections in the determination of the running top quark mass and Yukawa coupling and the effective scalar potential, etc..

iv) The program has been completely reorganized and some parts rewritten to make it easier to read [for instance, many comments on the purpose of the subroutines and explanations of the input/output files or commons have been included and the routines were reorganized according to their actual purpose] and to interface with other programs [for instance, we renamed all subroutines, functions and commons to start with the prefix `SU_` to minimize the possible conflicts with names used by other routines and provided a full list of input/output commons which should be sufficient for interfacing with any other code].

v) Finally, we have provided an interactive way of using the program on the web, which we hope will be useful for those who would like to quickly and easily obtain the Supersymmetric spectrum in the constrained models mSUGRA, GMSB and AMSB, without downloading all the files and running the program themselves.

7. Conclusion

We have presented the version 2.1 of the FORTRAN code `SuSpect` which calculates the Supersymmetric and Higgs particle spectrum in the MSSM. The calculation can be performed in constrained models with universal boundary conditions at high scales such as the gravity (mSUGRA), anomaly (AMSB) or gauge (GMSB) mediated breaking models, but also in the non–universal or unconstrained MSSM case, with up to 22 free input parameters which can be set either at the electroweak symmetry breaking scale or obtained from boundary conditions on some common parameter at a high–energy scale.

A particular care has been taken to treat all the mandatory features which are needed to describe accurately these various scenarii: the renormalization group evolution of parameters between low and high energy scales, the consistent implementation of radiative electroweak symmetry breaking and the calculation of the physical masses of the Higgs bosons and supersymmetric particles taking into account all dominant radiative corrections. The program provides several options [for accuracy, scale choice, etc...] to deal with these aspects.

The program can check the fulfillment of theoretical constraints, such as the absence of tachyonic particles and improper lightest SUSY particle, the absence of non desired charge and color breaking as well as unbounded from below minima and a large fine–tuning in the electroweak symmetry breaking conditions. A verification that the obtained spectrum is in agreement with high precision measurements such as the ρ parameter, the muon $g-2$ and the radiative $b \to s\gamma$ decay, can also be performed.

The program has a high degree of flexibility in the choice of the model and/or the input parameters and an adequate level of approximation at different stages. It is rather precise and quite reliable [since it has been compared with several other similar existing codes], relatively fast to allow for rapid comprehensive scans of the parameter space and simple enough to be linked with other programs dealing with MSSM particle properties or with Monte–Carlo event generators. We have also provided a very simple way to run the code interactively on the web in the constrained models.

The program is also self–contained since it includes all needed routines, except for the Higgs sector where we have provided links to most of the publicly available routines which calculate the radiative corrections [although it can also make an approximate calculation of these corrections; a more accurate routine is under way]. Several upgrades, which include the possibility to analyze additional theoretical models and to make the interface with programs for (s)particle decay branching ratios and Dark Matter calculations and with some Monte–Carlo event generators to simulate the production properties, are planned and will be made available soon.

Acknowledgments:

The program SuSpect has been developed in the framework of the *Groupe de Recherche sur la Supersymétrie* (GDR–SUSY), organized by the French *Centre National de la Recherche Scientifique* (CNRS), and has been checked and "debugged" during the last few years with the help of several members of the "MSSM" and "Tools" working groups of the GDR to whom we are indebted. We thank in particular, Genevieve Bélanger, Pierre Binetruy, Fawzi Boudjema, Marie-Bernadette Causse, Jean-Baptiste de Vivie, Laurent Duflot, Nabil Ghodbane, Jean-Francois Grivaz, Cyril Hugonie, Stavros Katsanevas, Vincent Lafage, Imad Laktineh, Christophe Le Mouël, Yann Mambrini, Steve Muanza, Margarete Mühlleitner, Emmanuel Nezri, Jean Orloff, Emmanuelle Perez, Sylvie Rosier–Lees, Roberto Ruiz de Austri, Aurore Savoy–Navarro and Charling Tao. We have as well similarly benefited from the more recent working group "SUSY Dark Matter" of the GDR *Phénomènes Cosmiques de Hautes Energies*. We thank all members of this group, in particular Julien Guy, Agnieszka Jacholkowska, Julien Lavalle, Eric Nuss and Mariusz Sapinski for various cross-checks. We have also benefited from several discussions, comments and help from: Ben Allanach, Andreas Birkedal, Francesca Borzumati, Aseshkrishna Datta, Manuel Drees, Paolo Gambino, Naveen Gaur, Sven Heinemeyer, Jan Kalinowski, Yeong Gyun Kim, Sabine Kraml, Filip Moortgat, Stefano Moretti, Takeshi Nihei, Werner Porod, Peter Richardson, Leszek Roszkowski, Pietro Slavich, Peter Skands, Michael Spira. We thank them all. Finally, un grand merci to our system–manager in Montpellier, Dominique Caron, for setting–up the page where one can run SuSpect on the web.

Appendix A: Some analytic expressions used in SuSpect

In this Appendix, we present for completeness analytical formulae used in `SuSpect` for the RG evolution of all parameters, the determination of the one-loop effective potential for the EWSB mechanism and the radiative corrections to the sparticle and Higgs boson masses.

A.1: Renormalization Group Evolution

The RG evolution of the SM and MSSM parameters from the high to low energy scales [and in the case of SM parameters, also in the reverse direction] is one of the main ingredients of the `SuSpect` program [and in fact, this is the feature which takes most of the CPU running time]. In the following, we list the complete set of the RGE β functions used in the program. For many purposes, using the one–loop β functions is a very good approximation and is appropriate, since in particular, it makes the program run much faster. However, the there is an option, `ichoice(2)=21`, which forces the program to use the two–loop RGEs for the gauge and the Yukawa couplings as well as for the soft SUSY–breaking gaugino mass parameters. This allows for a more accurate RGE evolution at the expense of rendering the program slower. We will therefore also display the two–loop β functions for the couplings. The list of β functions given below is ordered as in the program `SuSpect`[and more precisely, as in in the subroutines `SU_DERIV1` and `SU_DERIV2`, for the one and two–loop β functions, respectively], i.e. it gives the vector `y(n)` with `n=1-31` [see Appendix B for details on the routines and their purposes].

• Gauge couplings squared [`y(1)-(y3)`] with n_g the generation number, related to the flavor number by $n_f = 2n_g$; the full SUSY coefficients b_i (i.e. after the inclusion of the SUSY threshold effects) are $b_1 = 3/5 + 2n_g, b_2 = -5 + 2n_g$ and $b_3 = -9 + 2n_g$:

$$\frac{dg_1^2}{dt} = -\frac{g_1^4}{16\pi^2}b_1 - \frac{g_1^4}{(16\pi^2)^2}\Big[\Big(\frac{19}{15}n_f + \frac{9}{25}\Big)g_1^2 + \Big(\frac{3}{5}n_f + \frac{9}{5}\Big)g_2^2 + \frac{44}{15}n_f\, g_3^2 - \frac{26}{5}Y_t^2 - \frac{14}{5}Y_b^2 - \frac{18}{5}Y_\tau^2\Big] \tag{A.1}$$

$$\frac{dg_2^2}{dt} = -\frac{g_2^4}{16\pi^2}b_2 - \frac{g_2^4}{(16\pi^2)^2}\Big[\Big(\frac{1}{5}n_f + \frac{3}{5}\Big)g_1^2 + (7n_f - 17)g_2^2 + 4n_f\, g_3^2 - 6Y_t^2 - 6Y_b^2 - 2Y_\tau^2\Big] \tag{A.2}$$

$$\frac{dg_3^2}{dt} = -\frac{g_3^4}{16\pi^2}b_3 - \frac{g_3^4}{(16\pi^2)^2}\Big[\frac{11}{3}n_f g_1^2 + \frac{3}{2}n_f\, g_2^2 + \Big(\frac{34}{4}n_f - 54\Big)g_3^2 - 4Y_t^2 - 2Y_b^2\Big] \tag{A.3}$$

- Third generation Yukawa couplings [y(4)-y(6)]

$$
\begin{aligned}
\frac{dY_\tau}{dt} &= -\frac{Y_\tau}{32\pi^2}\Big[4Y_\tau^2+3Y_d^2-3(g_1^2+g_2^2)\Big] \\
&\quad -\frac{Y_\tau}{2(16\pi^2)^2}\Big[-10Y_\tau^4-9Y_b^4-9Y_b^2Y_\tau^2-3Y_b^2Y_t^2 \\
&\qquad +\Big(6g_2^2+\frac{6}{5}g_1^2\Big)Y_\tau^2+\Big(-\frac{2}{5}g_1^2+16g_3^2\Big)Y_b^2 \\
&\qquad +\Big(\frac{9}{5}n_f+\frac{27}{10}\Big)g_1^4+\Big(3n_f-\frac{21}{2}\Big)g_2^4+\frac{9}{5}g_1^2g_2^2\Big] \qquad \text{(A.4)} \\
\frac{dY_b}{dt} &= -\frac{Y_b}{32\pi^2}\Big[6Y_b^2+Y_\tau^2+Y_t^2-\Big(\frac{7}{9}g_1^2+3g_2^2+\frac{16}{3}g_3^2\Big)\Big] \\
&\quad -\frac{Y_b}{2(16\pi^2)^2}\Big[-22Y_b^4-5Y_t^4-5Y_b^2Y_t^2-3Y_b^2Y_\tau^2-3Y_\tau^2 \\
&\qquad +\frac{4}{5}g_1^2Y_t^2+\Big(\frac{2}{5}g_1^2+6g_2^2+16g_3^2\Big)Y_b^2+\frac{6}{5}g_1^2Y_\tau^2 \\
&\qquad +\Big(\frac{7}{15}n_f+\frac{7}{18}\Big)g_1^4+\Big(3n_f-\frac{21}{2}\Big)g_2^4+\Big(\frac{16}{3}n_f-\frac{304}{9}\Big)g_3^4 \\
&\qquad +g_1^2g_2^2+\frac{8}{9}g_1^2g_3^2+8g_2^2g_3^2\Big] \qquad \text{(A.5)} \\
\frac{dY_t}{dt} &= -\frac{Y_t}{32\pi^2}\Big[6Y_t^2+Y_b^2-\Big(\frac{13}{9}g_1^2+3g_2^2+\frac{16}{3}g_3^2\Big)\Big] \\
&\quad -\frac{Y_t}{2(16\pi^2)^2}\Big[-22Y_t^4-5Y_b^4-5Y_b^2Y_t^2-Y_b^2Y_\tau^2 \\
&\qquad +\frac{2}{5}g_1^2Y_b^2+\Big(\frac{6}{5}g_1^2+6g_2^2+16g_3^2\Big)Y_t^2\frac{6}{5}g_1^2Y_\tau^2 \\
&\qquad +\Big(\frac{13}{15}n_f+\frac{403}{450}\Big)g_1^4+\Big(3n_f-\frac{21}{2}\Big)g_2^4+\Big(\frac{16}{3}n_f-\frac{304}{9}\Big)g_3^4 \\
&\qquad +g_1^2g_2^2+\frac{136}{45}g_1^2g_3^2+8g_2^2g_3^2\Big] \qquad \text{(A.6)}
\end{aligned}
$$

- The vacuum expectation values v_u and v_d [y(7)-y(8)]

$$
\begin{aligned}
\frac{dv_u}{dt} &= \frac{v_u}{32\pi^2}\Big[3Y_t^2-\frac{3}{4}\Big(\frac{1}{3}g_1^2+g_2^2\Big)\Big] \qquad \text{(A.7)} \\
\frac{dv_d}{dt} &= \frac{v_d}{32\pi^2}\Big[3Y_d^2+Y_\tau^2-\frac{3}{4}\Big(\frac{1}{3}g_1^2+g_2^2\Big)\Big] \qquad \text{(A.8)}
\end{aligned}
$$

- The third generation trilinear A couplings [y(9)-y(11)]:

$$
\begin{aligned}
\frac{dA_t}{dt} &= -\frac{1}{32\pi^2}\Big[12A_tY_t^2+2A_bY_b^2+\Big(\frac{26}{9}g_1^2M_1+6g_2^2M_2+\frac{32}{3}g_3^2M_3\Big)\Big] \qquad \text{(A.9)} \\
\frac{dA_b}{dt} &= -\frac{1}{32\pi^2}\Big[12A_bY_b^2+2A_tY_t^2+2A_\tau Y_\tau^2+\Big(\frac{14}{9}g_1^2M_1+6g_2^2M_2+\frac{32}{3}g_3^2M_3\Big)\Big] \qquad \text{(A.10)} \\
\frac{dA_\tau}{dt} &= -\frac{1}{32\pi^2}\Big[8A_\tau Y_\tau^2+6A_dY_d^2+6(g_1^2M_1+g_2^2M_2)\Big] \qquad \text{(A.11)}
\end{aligned}
$$

• The scalar Higgs masses [`y(12)-y(13)`]: here and for the scalar fermion masses, factors $P_{\tilde{f}}$ appear and are defined as $P_{\tilde{t},\tilde{b},\tilde{\tau}} \equiv m^2_{H_u,H_d,H_d} + m^2_{\tilde{Q},\tilde{Q},\tilde{L}} + m^2_{\tilde{t}_R,\tilde{b}_R,\tilde{\tau}_R} + A^2_{t,b,\tau}$; a term $\mathrm{Tr}(Ym^2)$ also appears and is the isospin pondered sum of the squared soft masses of the scalar fermions, $\mathrm{Tr}(Ym^2) = \sum_{i=1}^{n_g}(m^2_{\tilde{Q}^i} - m^2_{\tilde{u}^i_R} + m^2_{\tilde{d}^i_R} - m^2_{\tilde{L}+i} + m^2_{\tilde{e}^i_R}) + m^2_{H_u} - m^2_{H_d}$ [in the case of universal soft masses, the trace vanishes at any scale, reflecting the anomaly cancellation]:

$$\frac{dm^2_{H_d}}{dt} = -\frac{1}{16\pi^2}\Big[3Y_b^2 P_{\tilde{b}} + Y_\tau^2 P_{\tilde{\tau}} - \frac{1}{2}g_1^2\mathrm{Tr}(Ym^2) - (g_1^2M_1^2 + 3g_2^2M_2^2)\Big] \quad \text{(A.12)}$$

$$\frac{dm^2_{H_u}}{dt} = -\frac{1}{16\pi^2}\Big[3Y_t^2 P_{\tilde{t}} + \frac{1}{2}g_1^2\mathrm{Tr}(Ym^2) - (g_1^2M_1^2 + 3g_2^2M_2^2)\Big] \quad \text{(A.13)}$$

• The third generation scalar fermion masses [`y(14)-(y18)`]

$$\frac{dm^2_{\tilde{\tau}_R}}{dt} = -\frac{1}{16\pi^2}\Big[2Y_\tau^2 P_{\tilde{\tau}} + g_1^2\mathrm{Tr}(Ym^2) - 4g_1^2M_1^2\Big] \quad \text{(A.14)}$$

$$\frac{dm^2_{\tilde{L}}}{dt} = -\frac{1}{16\pi^2}\Big[Y_\tau^2 P_{\tilde{\tau}} - \frac{1}{2}g_1^2\mathrm{Tr}(Ym^2) - (g_1^2M_1^2 + 3g_2^2M_2^2)\Big] \quad \text{(A.15)}$$

$$\frac{dm^2_{\tilde{b}_R}}{dt} = -\frac{1}{16\pi^2}\Big[2Y_b^2 P_{\tilde{b}} + \frac{1}{3}g_1^2\mathrm{Tr}(Ym^2) - \Big(\frac{4}{9}g_1^2M_1^2 + \frac{16}{3}g_3^2M_3^2\Big)\Big] \quad \text{(A.16)}$$

$$\frac{dm^2_{\tilde{t}_R}}{dt} = -\frac{1}{16\pi^2}\Big[2Y_t^2 P_{\tilde{t}} - \frac{2}{3}g_1^2\mathrm{Tr}(Ym^2) - \Big(\frac{16}{9}g_1^2M_1^2 + \frac{16}{3}g_3^2M_3^2\Big)\Big] \quad \text{(A.17)}$$

$$\frac{dm^2_{\tilde{Q}}}{dt} = \frac{-1}{16\pi^2}\Big[Y_t^2 P_{\tilde{t}} + Y_b^2 P_{\tilde{b}} + \frac{1}{6}g_1^2\mathrm{Tr}(Ym^2) - \Big(\frac{1}{9}g_1^2M_1^2 + 3g_2^2M_2^2 + \frac{16}{3}g_3^2M_3^2\Big)\Big] \quad \text{(A.18)}$$

• The bilinear soft SUSY–breaking parameter B [`y(19)`]

$$\frac{dB}{dt} = -\frac{1}{16\pi^2}\Big[3A_tY_t^2 + 3A_bY_b^2 + A_\tau Y_\tau^2 + (g_1^2M_1 + 3g_2^2M_2)\Big] \quad \text{(A.19)}$$

• The gaugino mass parameters [`y(20)-(y22)`]: their RGE's are related to those of the gauge couplings [from the corresponding equations at one–loop order, one can see that $d/dt(M_i/g_i^2) = 0$]; here we will not write the two–loop contributions for simplicity.

$$\frac{dM_1}{dt} = \frac{1}{16\pi^2}\Big(-1 - \frac{10}{3}n_g\Big)M_1g_1^2 \quad \text{(A.20)}$$

$$\frac{dM_2}{dt} = \frac{1}{16\pi^2}(5 - 2n_g)M_2g_2^2 \quad \text{(A.21)}$$

$$\frac{dM_3}{dt} = \frac{1}{16\pi^2}(9 - 2n_g)M_3g_3^2 \quad \text{(A.22)}$$

• The parameter μ [`y(23)`]:

$$\frac{d\mu}{dt} = -\frac{\mu}{32\pi^2}\Big[3Y_t^2 + 3Y_b^2 + Y_\tau^2 - (g_1^2 + 3g_2^2)\Big] \quad \text{(A.23)}$$

• The first and second generation scalar fermion masses [y(24)-(y28)]

$$\begin{aligned}
\frac{dm^2_{\tilde{e}_R}}{dt} &= -\frac{1}{16\pi^2}\Big[g_1^2 \mathrm{Tr}(Ym^2) - 4g_1^2 M_1^2\Big] &\text{(A.24)}\\
\frac{dm^2_{\tilde{l}}}{dt} &= -\frac{1}{16\pi^2}\Big[-\frac{1}{2}g_1^2 \mathrm{Tr}(Ym^2) - (g_1^2 M_1^2 + 3g_2^2 M_2^2)\Big] &\text{(A.25)}\\
\frac{dm^2_{\tilde{d}_R}}{dt} &= -\frac{1}{16\pi^2}\Big[\frac{1}{3}g_1^2 \mathrm{Tr}(Ym^2) - \Big(\frac{4}{9}g_1^2 M_1^2 + \frac{16}{3}g_3^2 M_3^2\Big)\Big] &\text{(A.26)}\\
\frac{dm^2_{\tilde{u}_R}}{dt} &= -\frac{1}{16\pi^2}\Big[-\frac{2}{3}g_1^2 \mathrm{Tr}(Ym^2) - \Big(\frac{16}{9}g_1^2 M_1^2 + \frac{16}{3}g_3^2 M_3^2\Big)\Big] &\text{(A.27)}\\
\frac{dm^2_{\tilde{q}}}{dt} &= \frac{-1}{16\pi^2}\Big[\frac{1}{6}g_1^2 \mathrm{Tr}(Ym^2) - \Big(\frac{1}{9}g_1^2 M_1^2 + 3g_2^2 M_2^2 + \frac{16}{3}g_3^2 M_3^2\Big)\Big] &\text{(A.28)}
\end{aligned}$$

• The first and second generation trilinear A couplings [y(29)-y(31)]:

$$\begin{aligned}
\frac{dA_u}{dt} &= -\frac{1}{32\pi^2}\Big[6A_t Y_t^2 + \frac{26}{9}g_1^2 M_1 + 6g_2^2 M_2 + \frac{32}{3}g_3^2 M_3\Big] &\text{(A.29)}\\
\frac{dA_d}{dt} &= -\frac{1}{32\pi^2}\Big[6A_b Y_b^2 + 2A_\tau Y_\tau^2 + \frac{14}{9}g_1^2 M_1 + 6g_2^2 M_2 + \frac{32}{3}g_3^2 M_3\Big] &\text{(A.30)}\\
\frac{dA_e}{dt} &= -\frac{1}{32\pi^2}\Big[6A_b Y_b^2 + 2A_\tau Y_\tau^2 + 6g_1^2 M_1 + 6g_2^2 M_2\Big] &\text{(A.31)}
\end{aligned}$$

The evolution parameter t is defined here as $t = \mathrm{Log}(M_U^2/Q^2)$; this is different from the one used in the RGE's of the program where $t = (1/2)\mathrm{Log}(Q^2/M_U^2)$.

Finally, to include the threshold effects in the gauge couplings, one needs to change the coefficients b_i of the one–loop β functions to include step functions $s_p = \theta(Q^2 - m_p^2)$ for each new particle p with mass m_p crossing the threshold Q [the top quark and the supersymmetric and Higgs particles; the thresholds for the other SM particles have been already included in the constant terms]:

$$\begin{aligned}
b_1 &= \frac{103}{30} + \frac{17}{30}s_t + \Sigma_i\Big(\frac{s_{\tilde{Q}^i}}{30} + \frac{4s_{\tilde{u}^i_R}}{15} + \frac{s_{\tilde{d}^i_R}}{15} + \frac{s_{\tilde{l}^i}}{10} + \frac{s_{\tilde{e}^i_R}}{5}\Big) + \frac{1}{10}(s_{H_u} + s_{H_d}) + \frac{1}{5}(s_\mu + s_Z)\\
b_2 &= -\frac{23}{6} + \frac{1}{2}s_t + \Sigma_i\Big(\frac{1}{2}s_{\tilde{Q}^i} + \frac{1}{6}s_{\tilde{l}^i}\Big) + +\frac{1}{6}(s_{H_u} + s_{H_d}) + \frac{1}{3}(s_\mu + s_Z) + \frac{4}{3}s_{\tilde{W}}\\
b_3 &= -\frac{23}{3} + \frac{2}{3}s_t + \Sigma_i\Big(\frac{1}{3}s_{\tilde{Q}^i} + \frac{1}{6}s_{\tilde{u}^i_R} + \frac{1}{6}s_{\tilde{d}^i_R}\Big) + 2s_{\tilde{g}} \qquad \text{(A.32)}
\end{aligned}$$

For simplicity, we have sometimes identified the SUSY particle masses with their corresponding soft SUSY–breaking parameters, i.e. we neglected the mixing between the current eigenstates (and the D–terms in the case of the sfermions). In the case of the charginos and neutralinos for instance, the steps are for the higgsino states with masses μ and M_Z and the bino $\tilde{B}$ and wino $\tilde{W}$ states with masses M_1 and M_2. This provides a good approximation.

A.2: The one-loop scalar potential and EWSB

To the MSSM tree–level scalar potential $V_{\rm Higgs}$ given by:

$$
\begin{aligned}
V_{\rm Higgs} &= (m_{H_d}^2+\mu^2)H_d^\dagger H_d + (m_{H_u}^2+\mu^2)H_u^\dagger H_u + B\mu(H_u\cdot H_d + {\rm h.c.}) \\
&+ \frac{g_1^2+g_2^2}{8}(H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{g_2^2}{2}(H_d^\dagger H_u)(H_u^\dagger H_d) \qquad \text{(A.33)}
\end{aligned}
$$

we have added the full one–loop corrections, including the contributions of third generation fermions, all sfermions, Higgs bosons and gauge bosons as well as the contributions of chargino and neutralino states. We have used the tadpole method and implemented *à la* PBMZ the following corrections:

$$
\begin{aligned}
16\pi^2\,\frac{t_d}{v_d} &= -6\lambda_b^2 A_0(m_b) - 2\lambda_\tau^2 A_0(m_\tau) + \sum_{\tilde f_i} N_c^{\tilde f}\frac{g_2}{2M_W\cos\beta}\lambda_{H_d\tilde f_i\tilde f_i}A_0(m_{\tilde f_i}) \qquad \text{(A.34)} \\
&+\frac{g_2^2}{8c_W^2}\Big[2(\cos2\beta+6c_W^2)A_0(M_W)+(\cos2\beta+6)A_0(M_Z) \\
&+4(c_W^2-\cos2\beta)A_0(M_{H^\pm})-\cos2\beta A_0(M_A) \\
&+(4\sin^2\alpha-1+\sin2\alpha\tan\beta)A_0(M_h)+(4\cos^2\alpha-1-2\sin2\alpha\tan\beta)A_0(M_H)\Big] \\
&-\frac{g_2^2}{M_W\cos\beta}\Big[\sum_i^4 m_{\chi_i^0}Z_{i3}\Big(Z_{i2}-\frac{s_W}{c_W}Z_{i1}\Big)A_0(m_{\chi_i^0})+\sqrt{2}\sum_{i=1}^2 m_{\chi_i^+}V_{i1}U_{i2}A_0(m_{\chi_i^+})\Big] \\
16\pi^2\,\frac{t_u}{v_u} &= -6\lambda_t^2 A_0(m_t) + \sum_{\tilde f_i} N_c^{\tilde f}\frac{g_2}{2M_W\sin\beta}\lambda_{H_u\tilde f_i\tilde f_i}A_0(m_{\tilde f_i}) \qquad \text{(A.35)} \\
&+\frac{g_2^2}{8c_W^2}\Big[-2(\cos2\beta-6c_W^2)A_0(M_W)-(\cos2\beta-6)A_0(M_Z) \\
&+4(c_W^2+\cos2\beta)A_0(M_{H^\pm})+\cos2\beta A_0(M_A) \\
&+(4\cos^2\alpha-1+\sin2\alpha\cot\beta)A_0(M_h)+(4\sin^2\alpha-1-2\sin2\alpha\cot\beta)A_0(M_H)\Big] \\
&+\frac{g_2^2}{M_W\sin\beta}\Big[\sum_i^4 m_{\chi_i^0}Z_{i4}\Big(Z_{i2}-\frac{s_W}{c_W}Z_{i1}\Big)A_0(m_{\chi_i^0})-\sqrt{2}\sum_{i=1}^2 m_{\chi_i^+}V_{i2}U_{i1}A_0(m_{\chi_i^+})\Big]
\end{aligned}
$$

with the Passarino–Veltman one–point function defined as usual by:

$$
A_0(m) = m^2\Big[1-{\rm Log}\frac{m^2}{Q^2}\Big] \qquad \text{(A.36)}
$$

where we have subtracted the pole in $1/\epsilon$ and where Q stands for the renormalization scale that we take to be the EWSB scale. The internal loop masses appearing in the previous expressions should be pole masses while the couplings should be $\overline{\rm DR}$ running couplings at the EWSB scale. All these couplings have been defined previously, except for the H_u, H_d couplings to up– and down–type sfermions which, in the current field basis, are given by:

$$
\begin{aligned}
\lambda_{H_u\tilde{f}_L\tilde{f}_L} &= -\frac{g_2}{c_W}M_Z(I^{3L}_{\tilde{f}} - e_{\tilde{f}}s_W^2)\sin\beta + \delta_{\tilde{f}_L\tilde{u}_L}\sqrt{2}\lambda_u m_u \\
\lambda_{H_u\tilde{f}_R\tilde{f}_R} &= -\frac{g_2}{c_W}M_Z(I^{3R}_{\tilde{f}} - e_{\tilde{f}}s_W^2)\sin\beta + \delta_{\tilde{f}_R\tilde{u}_R}\sqrt{2}\lambda_u m_u \\
\lambda_{H_u\tilde{f}_L\tilde{f}_R} &= \delta_{\tilde{f}_L\tilde{d}_R}\frac{1}{\sqrt{2}}\lambda_d\mu + \delta_{\tilde{f}_L\tilde{u}_R}\frac{1}{\sqrt{2}}\lambda_u A_u \qquad \text{(A.37)} \\
\lambda_{H_d\tilde{f}_L\tilde{f}_L} &= \frac{g_2}{c_W}M_Z(I^{3L}_{\tilde{f}} - e_{\tilde{f}}s_W^2)\cos\beta + \delta_{\tilde{f}_L\tilde{d}_L}\sqrt{2}\lambda_d m_d \\
\lambda_{H_d\tilde{f}_R\tilde{f}_R} &= \frac{g_2}{c_W}M_Z(I^{3R}_{\tilde{f}} - e_{\tilde{f}}s_W^2)\cos\beta + \delta_{\tilde{f}_R\tilde{d}_R}\sqrt{2}\lambda_d m_d \\
\lambda_{H_d\tilde{f}_L\tilde{f}_R} &= -\delta_{\tilde{f}_L\tilde{u}_R}\frac{1}{\sqrt{2}}\lambda_u\mu + \delta_{\tilde{f}_L\tilde{d}_R}\frac{1}{\sqrt{2}}\lambda_d A_d \qquad \text{(A.38)}
\end{aligned}
$$

One has then to make rotations to obtain the couplings in the mass eigenvalue basis

$$
\begin{pmatrix} \lambda_{H_i\tilde{f}_1\tilde{f}_1} & \lambda_{H_i\tilde{f}_1\tilde{f}_2} \\ \lambda_{H_i\tilde{f}_2\tilde{f}_1} & \lambda_{H_i\tilde{f}_2\tilde{f}_2} \end{pmatrix} = \begin{pmatrix} c_{\tilde{f}} & s_{\tilde{f}} \\ -s_{\tilde{f}} & c_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \lambda_{H_i\tilde{f}_L\tilde{f}_L} & \lambda_{H_i\tilde{f}_L\tilde{f}_R} \\ \lambda_{H_i\tilde{f}_R\tilde{f}_L} & \lambda_{H_i\tilde{f}_R\tilde{f}_R} \end{pmatrix} \begin{pmatrix} c_{\tilde{f}} & -s_{\tilde{f}} \\ s_{\tilde{f}} & c_{\tilde{f}} \end{pmatrix} \qquad \text{(A.39)}
$$

We then apply the minimization conditions on the full one-loop potential

$$
\frac{\partial V^{1-\text{loop}}_{\text{Higgs}}}{\partial H_d^0} = \frac{\partial V^{1-\text{loop}}_{\text{Higgs}}}{\partial H_u^0} = 0 \qquad \text{(A.40)}
$$

which are equivalent to the requirement that the tree–level plus one–loop tadpoles vanish, and obtain the loop corrected values of μ^2 and $B\mu$:

$$
\begin{aligned}
\mu^2 &= \frac{1}{2}\left\{ \tan 2\beta\left[\left(m^2_{H_u} - \frac{t_u}{v_u}\right)\tan\beta - \left(m^2_{H_d} - \frac{t_d}{v_d}\right)\cot\beta\right] - \overline{M}^2_Z\right\} \\
B\mu &= \frac{1}{2}\sin 2\beta\left[\left(m^2_{H_u} + \frac{t_u}{v_u}\right) + \left(m^2_{H_d} - \frac{t_u}{v_u}\right) + 2\mu^2\right] \qquad \text{(A.41)}
\end{aligned}
$$

as well as the running pseudo–scalar Higgs boson mass at the EWSB scale:

$$
\begin{aligned}
\overline{M}^2_A(M_{EWSB}) &= \frac{1}{\cos 2\beta}\left[\left(m^2_{H_d} - \frac{t_d}{v_d}\right) - \left(m^2_{H_u} - \frac{t_u}{v_u}\right)\right] - \overline{M}^2_Z \\
&\quad + \sin^2\beta\,\frac{t_d}{v_d} + \cos^2\beta\,\frac{t_u}{v_u} \qquad \text{(A.42)}
\end{aligned}
$$

[The Z boson mass appearing in the above expressions should be the running mass at the EWSB scale; however, the difference between this and the pole mass value is rather small and we have neglected it in the program].

Once the running pseudoscalar Higgs bosons mass is obtained, it will serve as input to the calculation of the other Higgs boson masses as discussed in section 3.3 and also later in this Appendix. One also has to derive the pole M_A value by including the one–loop (and potentially two–loop) contributions. This part of the calculation is in principle performed by the Higgs routines.

A.3: The particle spectrum

A.3.1 Diagonalization of the mass matrices

In section 3.3, we have discussed how to obtain the tree–level Higgs boson and SUSY particle mass spectrum from the soft SUSY–breaking parameters. While this discussion was more or less complete for the sfermion and Higgs boson sectors, some details will be given here in the case of chargino and neutralino sectors.

The general 2×2 chargino mass matrix $\mathcal{M}_C$ given in eq. (47) is diagonalized by two real matrices U and V,

$$U^* \mathcal{M}_C V^{-1} \quad \rightarrow \quad U = \mathcal{O}_- \text{ and } V = \begin{cases} \mathcal{O}_+ & \text{if } \det\mathcal{M}_C > 0 \\ \sigma_3 \mathcal{O}_+ & \text{if } \det\mathcal{M}_C < 0 \end{cases} \tag{A.43}$$

where σ_3 is the Pauli matrix and the rotations matrices are given by:

$$\mathcal{O}_\pm = \begin{bmatrix} \cos\theta_\pm & \sin\theta_\pm \\ -\sin\theta_\pm & \cos\theta_\pm \end{bmatrix} \tag{A.44}$$

with the mixing angles defined by:

$$\begin{aligned} \tan 2\theta_- &= \frac{2\sqrt{2} M_W (M_2 \cos\beta + \mu \sin\beta)}{M_2^2 - \mu^2 - 2M_W^2 \cos\beta} \\ \tan 2\theta_+ &= \frac{2\sqrt{2} M_W (M_2 \sin\beta + \mu \cos\beta)}{M_2^2 - \mu^2 + 2M_W^2 \cos\beta} \end{aligned} \tag{A.45}$$

This leads to the two chargino $\chi^+_{1,2}$ masses

$$\begin{aligned} m_{\chi^+_{1,2}} = & \frac{1}{\sqrt{2}} \Big[M_2^2 + \mu^2 + 2M_W^2 \\ & \mp \left\{ (M_2^2 - \mu^2)^2 + 4M_W^4 \cos^2 2\beta + 4M_W^2 (M_2^2 + \mu^2 + 2M_2 \mu \sin 2\beta) \right\}^{\frac{1}{2}} \Big]^{\frac{1}{2}} \end{aligned} \tag{A.46}$$

In the case of the neutralinos, the four-dimensional mass matrix eq. (48) has be diagonalized analytically by a single real matrix Z; the [positive] masses of the neutralino states $m_{\chi^0_i}$ are given by:

$$\begin{aligned} \epsilon_1 m_{\chi^0_1} &= C_1 - \left(\frac{1}{2}a - \frac{1}{6}C_2\right)^{1/2} + \left[-\frac{1}{2}a - \frac{1}{3}C_2 + \frac{C_3}{(8a - 8C_2/3)^{1/2}}\right]^{1/2} \\ \epsilon_2 m_{\chi^0_2} &= C_1 + \left(\frac{1}{2}a - \frac{1}{6}C_2\right)^{1/2} - \left[-\frac{1}{2}a - \frac{1}{3}C_2 - \frac{C_3}{(8a - 8C_2/3)^{1/2}}\right]^{1/2} \\ \epsilon_3 m_{\chi^0_3} &= C_1 - \left(\frac{1}{2}a - \frac{1}{6}C_2\right)^{1/2} - \left[-\frac{1}{2}a - \frac{1}{3}C_2 + \frac{C_3}{(8a - 8C_2/3)^{1/2}}\right]^{1/2} \\ \epsilon_4 m_{\chi^0_4} &= C_1 + \left(\frac{1}{2}a - \frac{1}{6}C_2\right)^{1/2} + \left[-\frac{1}{2}a - \frac{1}{3}C_2 - \frac{C_3}{(8a - 8C_2/3)^{1/2}}\right]^{1/2} \end{aligned} \tag{A.47}$$

where $\epsilon_i = \pm 1$; the coefficients C_i and a are given by

$$\begin{aligned}
C_1 &= (M_1 + M_2)/4 \\
C_2 &= M_1 M_2 - M_Z^2 - \mu^2 - 6C_1^2 \\
C_3 &= 2C_1 \left[C_2 + 2C_1^2 + 2\mu^2 \right] + M_Z^2 (M_1 c_W^2 + M_2 s_W^2) - \mu M_Z^2 \sin 2\beta \\
C_4 &= C_1 C_3 - C_1^2 C_2 - C_1^4 - M_1 M_2 \mu^2 + (M_1 c_W^2 + M_2 s_W^2) M_Z^2 \mu \sin 2\beta
\end{aligned} \tag{A.48}$$

and

$$a = \frac{1}{2^{1/3}} \mathrm{Re} \left[S + i \left(\frac{D}{27} \right)^{1/2} \right]^{1/3} \tag{A.49}$$

with

$$\begin{aligned}
S &= C_3^2 + \frac{2}{27} C_2^3 - \frac{8}{3} C_2 C_4 \\
D &= \frac{4}{27} (C_2^2 + 12 C_4)^3 - 27 S^2
\end{aligned} \tag{A.50}$$

A.3.2 Radiative corrections to the fermion masses

Since the fermion masses provide one of the main input, it is important to include the leading radiative corrections to these parameters, in particular those due to strong interactions and Yukawa couplings. The fermion masses which have to be used in the mass matrices eq. (45) are the masses $\hat{m}_f(Q^2)$, evaluated in the $\overline{\mathrm{DR}}$ scheme at the scale $Q = M_{\mathrm{EWSB}}$ and which, in terms of the pole masses m_f, are given by:

$$m_f = \hat{m}_f(Q^2) \left(1 + \frac{\Delta m_f}{m_f} \right) \tag{A.51}$$

In the case of top quarks, it is in general sufficient to include the one–loop QCD corrections originating from standard gluon exchange (first term of the expression below) and gluino–stop exchange (second term):

$$\begin{aligned}
\frac{\Delta m_t}{m_t} &= \frac{\alpha_s}{3\pi} \left[3 \log \left(\frac{Q^2}{m_t^2} \right) + 5 \right] \\
&- \frac{\alpha_s}{3\pi} \left[B_1(m_{\tilde{g}}, m_{\tilde{t}_1}) + B_1(m_{\tilde{g}}, m_{\tilde{t}_2}) - \sin 2\theta_t \frac{m_{\tilde{g}}}{m_t} \Big(B_0(m_{\tilde{g}}, m_{\tilde{t}_1}) - B_0(m_{\tilde{g}}, m_{\tilde{t}_2}) \Big) \right]
\end{aligned} \tag{A.52}$$

where in terms of $M = \max(m_1, m_2)$, $m = \min(m_1, m_2)$ and $x = m_2^2/m_1^2$, the two Passarino–Veltman functions $B_{0,1}(m_1, m_2) \equiv B_{0,1}(0, m_1^2, m_2^2)$ simply read in this limit

$$\begin{aligned}
B_0(m_1, m_2) &= -\log \left(\frac{M^2}{Q^2} \right) + 1 + \frac{m^2}{m^2 - M^2} \log \left(\frac{M^2}{m^2} \right) \\
B_1(m_1, m_2) &= \frac{1}{2} \left[-\log \left(\frac{M^2}{Q^2} \right) + \frac{1}{2} + \frac{1}{1-x} + \frac{\log x}{(1-x)^2} - \theta(1-x) \log x \right]
\end{aligned} \tag{A.53}$$

[one has also to include the two–loop $\mathcal{O}(\alpha_s^2)$ standard QCD terms as discussed in Section 3.2]. However, this approximation fails in some cases and we have incorporated the full one–loop corrections at finite momentum transfer and including the contributions of all SUSY particles [the only approximation was to neglect the mixing between gauginos and Higgsinos].

In the case of bottom quarks, the first important correction which has to be included is the one due to standard QCD corrections and the running from the scale m_b to the high scale Q, as was discussed in Section 3.2. Once this is done, one has to include the sbottom–gluino and the stop–chargino corrections which are the most important ones, in particular for large $\tan\beta$ and μ values:

$$\begin{aligned}
\frac{\Delta m_b}{m_b} &= -\frac{\alpha_s}{3\pi}\left[B_1(m_{\tilde{g}},m_{\tilde{b}_1})+B_1(m_{\tilde{g}},m_{\tilde{b}_2})-\sin 2\theta_b \frac{m_{\tilde{g}}}{m_b}\Big(B_0(m_{\tilde{g}},m_{\tilde{b}_1})-B_0(m_{\tilde{g}},m_{\tilde{b}_2})\Big)\right] \\
&- \frac{\alpha}{8\pi s_W^2}\frac{m_t\mu}{M_W^2\sin 2\beta}\sin 2\theta_t\left[B_0(\mu,m_{\tilde{t}_1})-B_0(\mu,m_{\tilde{t}_2})\right] \qquad \text{(A.54)} \\
&- \frac{\alpha}{4\pi s_W^2}\left[\frac{M_2\mu\tan\beta}{\mu^2-M_2^2}\Big(\cos^2\theta_t B_0(M_2,m_{\tilde{t}_1})+\sin^2\theta_t B_0(M_2,m_{\tilde{t}_2})\Big)+(\mu\leftrightarrow M_2)\right]
\end{aligned}$$

For the τ lepton mass, the only relevant corrections to be included are those stemming from chargino–sneutrino loops, and which simply read

$$\frac{\Delta m_\tau}{m_\tau} = -\frac{\alpha}{4\pi s_W^2}\frac{M_2\mu\tan\beta}{\mu^2-M_2^2}\left[B_0(M_2,m_{\tilde{\nu}_\tau})-B_0(\mu,m_{\tilde{\nu}_\tau})\right] \qquad \text{(A.55)}$$

A.3.3 Radiative corrections to the sparticle masses

The gluino mass is given at the tree–level by $m_{\tilde{g}}=M_3(M_{\rm EWSB})$. To obtain the pole gluino mass, one has to include the standard and SUSY QCD corrections, $m_{\tilde{g}}=M_3+\Delta M_3/M_3$. These corrections are given by [assuming a universal squark mass for simplicity]:

$$\frac{\Delta M_3}{M_3} = \frac{3\alpha_s}{2\pi}\left\{2B_0(M_3^2,M_3,0)-B_1(M_3^2,M_3,0)-2B_1(M_3^2,0,m_{\tilde{q}})\right\} \qquad \text{(A.56)}$$

with the finite parts of the Passarino–Veltman two–point functions B_0 and B_1 given by:

$$\begin{aligned}
B_0(q^2,m_1,m_2) &= -{\rm Log}\left(\frac{q^2}{Q^2}\right)-2 \\
&\quad -{\rm Log}(1-x_+)-x_+{\rm Log}(1-x_+^{-1})-{\rm Log}(1-x_-)-x_-{\rm Log}(1-x_-^{-1}) \\
B_1(q^2,m_1,m_2) &= \frac{1}{2q^2}\left[m_2^2\left(1-\log\frac{m_2^2}{Q^2}\right)-m_1^2\left(1-{\rm Log}\frac{m_1^2}{Q^2}\right)\right. \\
&\quad \left.+(q^2-m_2^2+m_1^2)B_0(q^2,m_1,m_2)\right] \qquad \text{(A.57)}
\end{aligned}$$

with Q^2 denoting the renormalization scale which we take to be the EWSB scale, and the variables $x_\pm$ are given by:

$$x_\pm = \frac{1}{2q^2}\left(q^2-m_2^2+m_1^2\pm\sqrt{(q^2-m_2^2+m_1^2)^2-4q^2(m_1^2-i\epsilon)}\right) \qquad \text{(A.58)}$$

In the case of the charginos and neutralinos, we work in an approximation where one corrects only the gaugino and higgsino entries in the mass matrices and not the states themselves. This gives, according to PBMZ, a very good approximation of the complete result. Using the Passarino–Veltman two–point functions above, the dominant one–loop corrections to the electroweak gaugino masses M_1, M_2 are[24]:

$$
\begin{aligned}
\frac{\Delta M_1}{M_1} &= -\frac{\alpha}{4\pi c_W^2}\Big\{11B_1(M_1^2,0,m_{\tilde q}) + 9B_1(M_1^2,0,m_{\tilde l}) - \frac{\mu}{M_1}\sin 2\beta \\
&\quad \times\Big[B_0(M_1^2,\mu,M_A) - B_0(M_1^2,\mu,M_Z)\Big] + B_1(M_1^2,\mu,M_A) + B_1(M_1^2,\mu,M_Z)\Big\}
\end{aligned} \tag{A.59}
$$

$$
\begin{aligned}
\frac{\Delta M_2}{M_2} &= -\frac{\alpha}{4\pi s_W^2}\Big\{9B_1(M_2^2,0,m_{\tilde q}) + 3B_1(M_1^2,0,m_{\tilde l}) - \frac{\mu}{M_2}\sin 2\beta \\
&\quad \times\Big[B_0(M_2^2,\mu,M_A) - B_0(M_2^2,\mu,M_Z)\Big] + B_1(M_2^2,\mu,M_A) + B_1(M_2^2,\mu,M_Z) \\
&\quad -8B_0(M_2^2,M_2,M_W) + 4B_1(M_2^2,M_2,M_W)\Big\}
\end{aligned} \tag{A.60}
$$

while the corrections to the higgsino mass parameter are given by:

$$
\begin{aligned}
\frac{\delta\mu}{\mu} &= \frac{-3}{32\pi^2}\Big[\lambda_t^2\left(B_1(\mu^2,m_t,m_{\tilde t_1}) + B_1(\mu^2,m_t,m_{\tilde t_2})\right) \\
&\quad +\lambda_b^2\left(B_1(\mu^2,m_b,m_{\tilde b_1}) + B_1(\mu^2,m_b,m_{\tilde b_2})\right)\Big] \\
&\quad \frac{-3\alpha}{16\pi}\Big[B_1(\mu^2,M_2,M_A) + B_1(\mu^2,M_2,M_Z) + 2B_1(\mu^2,\mu,M_Z) - 4B_0(\mu^2,\mu,M_Z)\Big]
\end{aligned} \tag{A.61}
$$

For the masses of the squarks, except for the stops which need a special treatment, one needs to include only the QCD corrections neglecting the masses of the partner quarks. This leads to a simple expression for the pole squark masses squared,

$$
m_{\tilde q}^2 = \hat m_{\tilde q}^2(Q^2)\left(1 + \frac{\Delta m_{\tilde q}^2}{m_{\tilde q}^2}\right) \tag{A.62}
$$

with

$$
\frac{\Delta m_{\tilde q}^2}{m_{\tilde q}^2} = \frac{2\alpha_s}{3\pi}\Big[2B_1(m_{\tilde q}^2,m_{\tilde q},0) + \frac{A(m_{\tilde g})}{m_{\tilde q}^2} - \left(1 - \frac{m_{\tilde g}^2}{m_{\tilde q}^2}\right)B_0(m_{\tilde q}^2,m_{\tilde g},0)\Big] \tag{A.63}
$$

For the two top squarks, simply including the QCD corrections as above is not an enough good approximation and one has to incorporate also the electroweak corrections which can be important, in particular those involving the possibly large Yukawa couplings. We have incorporated the full set of electroweak corrections a la PBMZ.

Finally, in the case of the sleptons, the radiative corrections are very small, less than one percent according to PBMZ, and we have neglected them in the program.

A.3.4 Radiative corrections to the Higgs boson masses

We have interfaced `SuSpect` with several routines calculating the Higgs bosons masses in the MSSM. These routines, that we provide with the main program, use different methods and approximations but include the most important contributions. One is therefore in principle guaranteed to have the most accurate and up–to date value for these Higgs sector parameters. However, in some cases an accuracy of a few percent in the determinations of these masses is sufficient. To have a complete and self-contained program, we have therefore provided a default choice where one uses simple expressions for these radiative corrections to the Higgs masses, which provide a rather good approximation [a complete one–loop and leading two–loop routine is in preparation].

For the CP–even Higgs bosons masses, we use the procedure described in Section 3.3.3, with the following values for the corrections s_{ij}. Defining first, to simplify the expressions, the reduced variables:

$$x_t = \left(\frac{A_t - \mu\cot\beta}{M_S}\right)^2 \ , \quad y_t = \frac{\bar{m}_t^2}{M_S^2} \ , \quad z_t = \frac{M_Z^2}{\bar{m}_t^2} \tag{A.64}$$

with $\bar{m}_t$ being the $\overline{\rm MS}$ top quark mass corrected at one-loop only with pure QCD corrections

$$\bar{m}_t = m_t(1+4\alpha_s/3\pi)^{-1} \tag{A.65}$$

and M_S an average SUSY scale taken to be in terms of the soft stop masses

$$M_S = [\, m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2 + \bar{m}_t^2(m_{\tilde{Q}}^2 + m_{\tilde{t}_R}^2) + \bar{m}_t^4 \,]^{1/4} \tag{A.66}$$

one obtains for the various s_{ij} corrections at zero–momentum transfer [31]:

$$s_{11} = \frac{\sqrt{2}G_F}{\pi^2} M_Z^4 \left(\frac{1}{8} - \frac{1}{3}s_W^2 + \frac{4}{9}s_W^4\right) \cos^2\beta {\rm Log}(y_t) \tag{A.67}$$

$$s_{12} = \frac{\sqrt{2}G_F}{\pi^2} M_Z^2 \cot\beta \Big[\frac{3}{8}\bar{m}_t^2 - \left(\frac{1}{8} - \frac{1}{3}s_W^2 + \frac{4}{9}s_W^4\right)\sin^2\beta M_Z^2\Big] {\rm Log}(y_t) \tag{A.68}$$

$$\begin{aligned} s_{22} = & \frac{\sqrt{2}G_F}{\pi^2}\frac{\bar{m}_t^4}{8\sin^2\beta}\Big[\Big(12 - 6z_t\sin^2\beta + z_t^2\left(\frac{1}{8} - \frac{1}{3}s_W^2 + \frac{4}{9}s_W^4\right)\sin^4\beta\Big){\rm Log}(y_t) \\ & -2z_t + \frac{11}{10}z_t^2 + x_t(-12+4z_t+6y_t) + x_t^2(1-4y_t+3y_t^2) \\ & + x_t^3\left(\frac{3}{5}y_t - \frac{12}{5}y_t^2 + 2y_t^3\right) + x_t^4\left(\frac{3}{7}y_t^2 - \frac{12}{7}y_t^3 + \frac{3}{2}y_t^4\right)\ \Big] \\ + & \frac{\sqrt{2}G_F}{\pi^2}\frac{\alpha_s}{\pi}\frac{\bar{m}_t^4}{\sin^2\beta}\Big[4 + 3{\rm Log}^2(y_t) + 2{\rm Log}(y_t) - 6\sqrt{x_t} - x_t(3{\rm Log}(y_t)+8) + \frac{17}{12}x_t^2\Big] \\ - & \frac{9G_F^2}{16\pi^4}\frac{\bar{m}_t^6}{\sin^2\beta}\Big[{\rm Log}^2(y_t) - 2x_t{\rm Log}(y_t) + \frac{1}{6}x_t^2{\rm Log}(y_t)\Big] \end{aligned} \tag{A.69}$$

The radiative corrections to the pseudoscalar and charged Higgs boson masses, which are in principle generally rather tiny, have not been included in this approximation.

Appendix B: Contents of the Fortran Code

B.1: The subroutines and their main purpose

We list below all the subroutines and functions contained in the program `SuSpect` and shortly describe their main purpose and content.

B.1.1 The main routine

```
SUBROUTINE SUSPECT2(iknowl,input,ichoice,errmess)
```

This is the main routine of the program, to be be used as it is or to be called by any other routine (such as `suspect2_call.f`, as will be discussed below). It has the following four basic input control parameters:

`IKNOWL`: which sets the degree of control on the various parts of the algorithm. It has three possible values at present:

– `IKNOWL=0`: totally blind use of the program, i.e. no control on any "algorithmic" parameter, no warning and other messages. Reasonable default values are set for the control parameters and the program gives just the results from the physical input.

– `IKNOWL=1`: in which there is no control on any algorithmic feature but some warning/error messages are collected in the `suspect.out` file (this is the recommended choice in general).

– `IKNOWL=2`: is for a more "educated" use. One can control some algorithmic parameters and gets all warning/error messages (with many printed on the screen). One has to set personally by hand the appropriate values of some other parameters control. This option is therefore not recommended unless for debugging.

`INPUT`: is for the physical input setting and works in three modes:

– `INPUT=0`: the model and option parameters `ichoice(1)-(10)` as well as the values of the physical input parameters are read off from the file `suspect2.in`.

– `INPUT=1`: when you want to define yourself all the relevant input choices and parameters within your calling program. The required list of parameters to be defined (with consistent names etc), can be found in the commons given below, and their meaning is also explained in the `suspect2.in` file.

– `INPUT=11`: same as `INPUT=1`, but with no output file `suspect.out` generated (this option is convenient e.g. for scans of the MSSM parameter space).

`ICHOICE`: initializes the various options for the models to be considered, the degree of accuracy to be required, the features to be included, etc. There are 10 possible choices at present and the options are described in detail in the input file:

– ICHOICE(1): Choice of the model to be considered.
– ICHOICE(2): For the perturbative order (1 or 2 loop) of the RGEs.
– ICHOICE(3): To impose or not the GUT scale.
– ICHOICE(4): For the accuracy of the RGEs.
– ICHOICE(5): To impose or not the radiative EWSB.
– ICHOICE(6): To chose different input in general MSSM.
– ICHOICE(7): For the radiative corrections to the (s)particles masses.
– ICHOICE(8): To set the value of the EWSB scale.
– ICHOICE(9): For the number of (RGE + full spectrum) iterations.
– ICHOICE(10): For the routine calculating the Higgs boson masses.

ERRMESS: which provides a useful set of warning/error message flags, that are automatically written in the output file suspect.out:

– ERRMESS(i)= 0: Everything is fine,
– ERRMESS(1)=-1: tachyon 3rd gen. sfermion from RGE,
– ERRMESS(2)=-1: tachyon 1,2 gen. sfermion from RGE,
– ERRMESS(3)=-1: tachyon A boson (maybe temporary: see final mass),
– ERRMESS(4)=-1: tachyon 3rd gen. sfermion from mixing,
– ERRMESS(5)=-1: $\mu(M_{\rm GUT})$ guess inconsistent,
– ERRMESS(6)=-1: non–convergent μ from EWSB,
– ERRMESS(7)=-1: EWSB maybe inconsistent (! but RG-improved only check),
– ERRMESS(8)=-1: $V_{\rm Higgs}$ maybe UFB or CCB (! but RG-improved only check),
– ERRMESS(9)=-1: Higgs boson masses are NaN,
– ERRMESS(10)=-1: RGE problems (non-pert and/or Landau poles).

B.1.2 Routines for the models

There are two main routines for the model boundary conditions, one for the AMSB and one for the GMSB models [because of historical reasons, the calculation in the mSUGRA model is performed directly in the main routine suspect2.f].

```
      SUBROUTINE SU_AMSBSUB(m0,m32,cq,cu,cd,cl,ce,chu,chd,g12,g22,g32,
     . ytau,yb,yt,al,ad,au,mhu2,mhd2,mtaur2,msl2,mbr2,mtr2,msq2,mer2,mel2,
     . mdr2,mur2,muq2,m1,m2,m3)
```

Calculates the initial conditions at initial scale where the RGE starts in the general AMSB model [i.e. including a soft SUSY–breaking scalar mass m_0 with a different weight c_i for every Higgs and sfermion scalar mass].

The input parameters at the initial scale are:
m32: the gravitino mass,
m0 : the soft-SUSY breaking scalar mass term,
cq,cu,cd,cl,ce,chu,chd: weights of m0 for the different soft terms,
(for the original AMSB model: $c_i = 0$ and usual minimal AMSB model: $c_i = 1$),
g12,g22,g23: gauge couplings squared,
ytau,yb,yt : third generation Yukawa gauge couplings squared.

The ouputs at the initial scale are:
m1,m2,m3: gaugino mass terms,
au,ad,al,au1,ad1,l1: 3d and 1st/2d generation trilinear couplings,
au,ad,al,au1,ad1,l1: 3d and 1st/2d generation trilinear couplings,
mhu2,mhd2,mtaur2,msl2,mbr2,mtr2,msq2,mer2,mel2,mdr2,mur2,muq2: Higgs and sfermion soft mass terms squared.

```
      SUBROUTINE SU_GMSBSUB(mgmmess,mgmsusy,nl,nq, g12,g22,g32,
     . al,ad,au,mhu2,mhd2,mtaur2,msl2,mbr2,mtr2,msq2,mer2,mel2,
     . mdr2,mur2,muq2,m1,m2,m3)
```

Calculates the GMSB model initial conditions at the messenger scale $M_{\rm Mes}$ where the RGE start in this case.

The input at the messenger scale are:
mgmmess,mgmsusy: messenger and SUSY-breaking scales,
nl, nq number of lepton/ quark messengers (in minimal GMSB, $n_l = n_q = 1$),
g12,g22,g23: gauge couplings squared.

The output parameters at the messenger scale are:
m1,m2,m3: gaugino masses,
au,ad,al,au1,ad1,al1: trilinear sfermion couplings,
mhu2,mhd2,mtaur2,msl2,mbr2,mtr2,msq2,mer2,mel2,mdr2,mur2,muq2: Higgs and sfermion soft mass terms squared.

The routine needs to evaluate a Spence function which is supplied:

```
      REAL*8 FUNCTION SU_PLI2(x)
```

B.1.3. Routines for the fermion masses and α_s

The following three routines are for the evaluation of the (SUSY) radiative corrections to the generation fermion masses. They will need to evaluate the one–loop real (A) and two-loop complex (B_0 and B_1) Passarino–Veltman functions which are supplied:

```
REAL*8 FUNCTION SU_A(m)
COMPLEX*16 FUNCTION SU_B0(qsq,m1,m2)
COMPLEX*16 FUNCTION SU_B1(s,mi,mj)
```

The arguments are the internal pole masses and the momentum transfer squared.

```
  SUBROUTINE SU_TOPMSCR(alpha_s,mt,mb,rmt,rmb,yt,yb,tbeta,
.            mql,mur,mdr,at,ab,mu, delmtop)
```

Calculates the radiative corrections to the top quark mass including the standard and SUSY QCD corrections (the standard corrections are also calculable with RUNM) and the electroweak corrections including the contributions of gauge bosons, Higgs bosons, charginos and neutralinos. The input are respectively: the strong coupling constant, the pole masses, running masses and Yukawa couplings of the top and bottom quarks, $\tan\beta$, the 3d generation squark mass terms and trilinear couplings and μ. The output `delmtop` is the radiative correction to the top quark mass.

```
   SUBROUTINE SU_BMSUSYCR(alphas,mb,rmt,rmb,yt,tbeta,m2,mgluino,
.             mql,mur,mdr,at,ab,mu, delmb)
```

Calculates the SUSY radiative corrections to the bottom mass including the SUSY QCD corrections (the standard ones are calculated with RUNM) and the dominant electroweak corrections due to the Yukawa couplings. The input are respectively: the strong coupling constant, pole b mass, the running top and bottom masses, the top Yukawa coupling, $\tan\beta$, the SU(2) gaugino mass, the gluino mass, the 3d generation squark mass terms, the 3d generation trilinear couplings and the parameter μ. The output `delmb` is the SUSY radiative correction to the bottom mass. These corrections are then re-summed in the main routine.

```
   SUBROUTINE SU_TAUMSCR(tgbeta,mu,m2,mnstau, delmtau)
```

Calculates the dominant SUSY radiative corrections to the τ lepton mass with the contribution of charginos/stau-sneutrinos without re–summation. The input are respectively: $\tan\beta$, the higgsino mass parameter μ, the SU(2) gaugino mass parameter and the 3d generation sneutrino mass. The output `delmtau` is the radiative correction to the tau lepton mass.

There are also routines for the QCD running of the quark masses and for the evaluation of the strong coupling constant α_s at various scales. They are given in the following.

```
SUBROUTINE ALSINI(ACC)
```

Subroutine for initialization in the evaluation of the strong coupling constant α_s. It needs the two iteration functions to determine the improved values of QCD scale $\Lambda_{\rm QCD}$ for a given number of quark flavor and masses, loop order, etc..:

```
DOUBLE PRECISION FUNCTION XITER(Q,XLB1,NF1,XLB,NF2,ACC)
DOUBLE PRECISION FUNCTION XITLA(NO,ALP,ACC)
```

There are also two important functions for the calculation of the running of the QCD coupling at scale Q and perturbative order N:

```
DOUBLE PRECISION FUNCTION ALPHAS(Q,N)
```

and the running of the quark masses at scale Q and with NF quark flavors:

```
DOUBLE PRECISION FUNCTION RUNM(Q,NF)
```

These routines are borrowed from the program HDECAY version 2.2

B.1.4 Routines for the SUSY and Higgs particle masses

The following routines are for the evaluation of the chargino/neutralino, sfermion and Higgs boson masses including the radiative corrections *à la PBMZ*. For these radiative corrections, they also need the one– and two–loop Passarino–Veltman functions discussed above.

```
SUBROUTINE SU_GAUGINO(mu,m1,m2,m3,b,a,mc,mn,xmn)
```

Calculates the chargino and neutralino masses and mixing angles (with analytical expressions) including radiative corrections in the higgsino and gaugino limits.

The input parameters at EWSB scale are:
mu,m1.m2,m3: Higgs mass parameter and gaugino mass parameters,
b,a: the angle β and the mixing angle α in the Higgs sector.

The output parameters are:

mc: the two chargino masses,
mn: the four neutralino masses (absolute values),
mx: the four neutralino masses (including signs).

The masses are ordered with increasing value. The diagonalizing (ordered) mass matrices U,V for charginos and Z for neutralinos are given in the common block SU_MATINO/u,v,z.

```
 SUBROUTINE SU_CINORC(ml1,mq1,mq3,mu3,md3,ma,yt,yb,m1,m2,mu,tb,
.           rcm1,rcm2,rcmu)
```

Calculates the radiative corrections to the gaugino and higgsino mass parameters *à la PBMZ*.

The input parameters at EWSB scale are:
ml1,mq1,mq3,mu3,md3: sfermion mass parameters of 1st and 3d generations
ma,tb: pseudoscalar Higgs boson mass and tan(beta),
yt,yb: top and bottom Yukawa couplings,
m1,m2,mu: bare gaugino and Higgs mass parameters.

The outputs are the radiative corrections `rcm1, rcm2, rcmu` to M_1, M_2, μ.

```
      SUBROUTINE SU_GINOCR(alphas,m3, mb,mt, delgino)
```

Calculates the radiative correction to the gluino mass, `delgino` (output).

The input parameters at EWSB scale are:
alphas,m3: the strong coupling constant and the SU(3) gaugino mass,
mb, mt: the bottom and top pole masses;
msu1,msu2,msd1,msd2,msb1,msb2,mst1,mst2: the squark masses (input via the common/SU_bpew/.. calculated by the subroutine SU_SFERMION).

```
      SUBROUTINE SU_SFERMION(mql,mur,mdr,mel,mer,mql1,mur1,mdr1,mel1,mer1,
     .            al,at,ab,mu, mst,msb,msl,msu,msd,mse,msn)
```

Calculates the sfermion masses including radiative corrections *à la PBMZ* and the mixing angles for the third generation sfermions.

The input parameters at EWSB scale are:
mql,mur,mdr,mel,mer,mql1,mur1,mdr1,mel1,mer1: sfermion mass terms,
al,at,ab,mu: 3d generation trilinear couplings and the parameter μ.

The outputs are the sfermions masses: mst,msb,msl,msu,msd,mse,msn.

The masses msf=msf(1) and msf(2) are ordered such that the lightest is 1 and the heaviest is 2. The mixing angles of third generation sfermions are in the common block `COMMON/SU_MIXANG/thet,theb,thel` which is to be treated with care because of the ordering of the sfermion masses, when compared to other calculations.

```
      SUBROUTINE SU_SQCR(alphas,mgluino,msquark,dmsquark)
```

Calculates the QCD (standard+SUSY) correction to squark (except stop) masses. The input are: the strong coupling constant α_s, the gluino and tree-level squark masses and the output is the correction to the squark mass dmsquark. Squark mixing and Yukawa's are neglected.

```
       SUBROUTINE SU_STOPCR(alphas,mgluino,mu,ma,thet,bet,mst1,mst2,msb,
     .             yt,yb,at,ab, crll,crlr,crrr)
```

Calculates radiative corrections to the two stop masses, including standard and SUSY-QCD corrections and the Yukawa corrections *à la PBMZ*. The input at the EWSB scale are, respectively: the strong coupling constant, the gluino mass, mu parameter, pseudoscalar Higgs boson mass, stop mixing angle, the angle beta, the two stop masses, the right sbottom mass parameter, the top and bottom Yukawa couplings and trilinear couplings. The outputs are the radiative corrections to the LL, LR, RR entries of the stop squark mass matrix.

```
SUBROUTINE SU_SUSYCP(TGBET)
```

Calculates the MSSM Higgs bosons masses and the angle α including radiative corrections for a given input value of the parameter $\tan\beta$. The other input parameters (soft SUSY–breaking parameters, sparticle masses and mixing angles, SM parameters), are called via common blocks. This routine is adapted from the one in the program HDECAY version 3.0. It returns the masses of the pole masses of the CP-odd (ama), lighter CP–even (aml), heavier CP–even (amh), charged Higgs boson (amch) as well as the running CP–odd (amar) Higgs masses, which are given in the block:

```
COMMON/SU_HMASS/ama,aml,amh,amch,amar
```

It gives also the couplings of the angle beta at the EWSB scale, the mixing α and the Higgs boson couplings to standard particles in:

```
COMMON/SU_HCOUP/b,a,gat,gab,glt,glb,ght,ghb,ghvv,glvv
```

It returns also the couplings of the Higgs bosons to sfermions

```
COMMON/SU_CPLHSF/gcen,gctb,glee,gltt,glbb,ghee,ghtt,ghbb
.                    gatt,gabb,gaee
```

and the Higgs couplings to charginos and neutralinos:

```
COMMON/SU_CPLHINO/ac1,ac2,ac3,an1,an2,an3,acnl,acnr
```

For the radiative correction in the Higgs sector, there is the default option where the calculation is made in an approximation based on the of work Heinemeyer, Hollik and Weiglein and which is in general sufficient, or uses the `HDECAY` procedure which depending on the flag `IMODEL=ichoice(10)`, calls the following routines:

```
1:  SUBH_HDEC from Carena, Quiros and Wagner adapted by HDECAY
2:  HMSUSY from Haber, Hempfling and Hoang
3:  FEYNHIGGSFAST1.2.2 from Heinemeyer, Hollik and Weiglein
```

as follows:

```
      CALL SUBH_HDEC(ama,tgbet,amsq,amur,amdr,amt,au,ad,amu,amchi,
     .           amlr,amhr,amch,sa,ca,tanba,amglu)

      CALL HMSUSY0(tgbet,sa,ca)

      CALL FEYNHIGGS(ama,tgbet,amt,xmst1,xmst2,stt,xmsb1,
     .               xmsb2,stb,amu,amglu,am2,amlr,amhr,sa,ca)
```

B.1.5 The routine for the EWSB

The following routine is for the one–loop effective scalar potential

```
      SUBROUTINE SU_VLOOP2(q2,MU,AT,AB,AL,  dVdvd2,dVdvu2)
```

which is the main and in fact only subroutine for the EWSB and calculates the tadpole corrections to the Higgs mass terms squared.

The input at the EWSB scale are:
q2: the scale at which EWSB is supposed to happen,
MU: the higgsino parameter mu at EWSB scale,
AT,AB,AL: the third generation trilinear couplings at EWSB scale,
Ytau, Yt, Yb: the Yukawa couplings (at EWSB scale), input via the common/SU_yukaewsb/..,
msta1,msta2,msb1,msb2,mst1,mst2,..,thet,theb,thel: masses and mixing of tau,b,top,.. etc sfermions at EWSB scale (input via common/su_bpew/.., calculated by the subroutine SU_SFERMION).

Other important input parameters, such as the Higgs, chargino, neutralino masses and couplings as well as SM parameters are called via commons.

The output, `dVdvd2` and `dVdvu2`, are (up to some appropriate overall constants) the derivatives of the full one–loop scalar potential including the contributions of all SM and SUSY particles a la PBMZ. The consistency of the EWSB mechanism is performed by the main program.

B.1.6 Routines for the RGE

The following routines are for the numerical RGE evolution of the parameters

```
            SUBROUTINE SU_ODEINT(y,n,x1,x2,eps,h1,hmin,nok,nbad,
     .                           SU_DERIVS,SU_RKQC)
```

This is the routine for the RGE evolution of parameter between low and high energy scales, borrowed from Numerical Recipes. It returns a set of n mass and coupling parameters "y" at a specified scale $exp(x2)$ when given at an initial scale exp(x2). It uses the two routines:

```
SUBROUTINE SU_RKQC(y,dydx,n,x,htry,eps,yscal,hdid,hnext,SU_DERIVS)
SUBROUTINE SU_RK4(y,dydx,n,x,h,yout,SU_DERIVS)
```

which are the fourth order Runge–Kutta numerical algorithms solving differential equations by Numerical Recipes[105].

The four routines:

```
SUBROUTINE SU_DERIV1(x,y,dydx)
SUBROUTINE SU_DERIV2(x,y,dydx)
SUBROUTINE SU_DERIV1T(x,y,dydx)
SUBROUTINE SU_DERIV2T(x,y,dydx)
```

are the derivatives of the RG running parameters $y(xN)$, i.e the beta functions $\beta(y) = d(y)/dln(Q)$. The analytic expressions of the functions are taken from (up to some sign conventions which have been changed) from Castano, Ramond and Piard and from Barger, Berger and Ohmann. Thus y(n) is a vector containing all the n RG evolving parameters at various possible scales depending on evolution stages. The parameters are

```
y(1) = g_1^2   U(1) gauge coupling squared
y(2) = g_2^2   SU(2)_L gauge coupling squared
y(3) = g_3^2   SU(3) gauge coupling squared
y(4) = Y_\tau  tau lepton Yukawa coupling
y(5) = Y_b     bottom  quark Yukawa coupling
y(6) = Y_t     top quark Yukawa coupling
y(7) = Ln(v_u) logarithm of the vev vu
y(8) = Ln(v_d) logarithm of the vev vd
y(9) = A_\tau  trilinear coupling for stau
y(10)= A_b     trilinear coupling for sbottom
y(11)= A_t     trilinear coupling for stop
y(12)=(m_Hu)^2 scalar phi_u mass term squared
y(13)=(m_Hd)^2 scalar phi_d mass term squared
y(14)=m_\taur^2 right-handed stau mass term squared
y(15)= msl^2   left-handed stau mass term squared
y(16)= mbr^2   right-handed sbottom mass term squared
y(17)= mtr^2   right-handed stop mass term squared
y(18)= msq^2   left-handed stop mass term squared
y(19)= B       the (dimensionful) bilinear parameter B
y(20)= Ln|M_1| logarithm of the bino mass term
y(21)= Ln|M_2| logarithm of the wino mass term
```

```
y(22)= Ln|M_3| logarithm of the gluino mass term
y(23)= Ln|\mu| logarithm of the mu parameter
y(24)= mer^2   right-handed selectron (smuon) mass term squared
y(25)= mel^2   left-handed selectron (smuon) mass term squared
y(26)= mdr^2   right-handed sdown (sstrange) mass term squared
y(27)= mur^2   right-handed sup (scharm) mass term squared
y(28)= muq^2   left-handed sup (scharm) mass term squared
y(29)= A_l     trilinear coupling for selectron (smuon)
y(30)= A_d     trilinear coupling for sdown (sstrange)
y(31)= A_u     trilinear coupling for sup (scharm).
```

Note that the number of running parameters does not coincide with the 22 parameters of the phenomenological MSSM since one has to add the gauge and the Yukawa couplings, as well as those which are linearly dependent.

Note that:

`DERIV1` : includes only 1-loop RGE with simple (unique scale) threshold.
`DERIV2` : includes 2-loop RGE for gauge, Yukawa couplings and gaugino masses.
`DERIV1T`: includes 1-loop RGE with realistic multi scale threshold.
`DERIV2T`: includes 2-loop RGEs and multi-scale thresholds.

B.1.7 Routines for the checks of the spectrum

There are already three routines which allow to check the particle spectrum which are already implemented in `SuSpect` but which are not called [and no output is given yet]:

```
SUBROUTINE SU_GMINUS2(mel,mer,Amu,mu,tb,u,v,z,mn,mc1,mc2,gmuon)
```

Calculates the leading chargino and neutralino loop SUSY contributions c to the muon anomalous magnetic moment. The inputs are:

mel,mer,Amu: relevant soft terms for the 2d generation smuon sector,
mu, tb: μ and $\tan\beta$,
U,V,Z, mn, mc1,mc2: chargino and neutralino mixing matrices and masses.

The output `gmuon` is $a_\mu = g_\mu - 2$ in standard units.

```
SUBROUTINE SU_DELRHO(mt,gmst,gmsb,gmstau,msn,thetat,thetab,thel,drho)
```

Calculates the leading one–loop SUSY contributions of third generation sfermions (plus leading two–loop QCD contributions in the case of squarks) to the ρ parameter. The inputs are:

mt, gmst(2), gmsb(2), gmstau(2), msn: top and 3d generation sfermion masses.

thetat,thetab,thel: stop, sbottom, stau mixing angles.

The output `drho` is the SUSY contribution to $\rho - 1$.

```
SUBROUTINE SU_FINETUNE(mu,tb,mhd2,mhu2,czmu,czbmu,ctmu,ctbmu)
```

Calculates the degree of fine–tuning in a given model (at the moment with respect to M_Z and m_t only). The inputs are:

mu,tbeta, mHd2, mHu2: $\mu, \tan\beta, M^2_{H_u}, M^2_{H_d}$ at the EWSB scale.

The output `czmu, czbmu, ctmu, ctbmu` are the (dimensionless) measures of the degree of fine–tuning on M_Z and m_t with respect to μ and $B\mu$, respectively. The larger those numbers ($\gg 1$), the more the model is "fine–tuned".

Two additional routines will be included very soon (some checks are being performed presently): one for the evaluation of the $b \to s\gamma$ branching ratio and one for the test of the CCB and UFB minima.

B.2: List of the various COMMONs

We list below the various `COMMON`s used in the program with some short explanations. The `COMMON`s for the input and output parameters are important since they are possibly called by `suspect_call.f` and are needed for interfacing with other codes.

B.2.1 COMMONs for input parameters

Standard Model input parameters (couplings and fermion masses):

```
COMMON/SU_SMPAR/dalfinv,dsw2,dalphas,dmt,dmb,dmtau
```

RG evolution scale parameters (EWSB scale, high and low RGE ends):

```
COMMON/SU_RGSCAL/dqewsb,dehigh,delow
```

Soft SUSY–breaking MSSM parameters of the scalar potential:

```
COMMON/SU_MSSMHPAR/dmhu2,dmhd2,dMA,dMU
```

The U(1), SU(2), SU(3) SUSY–breaking gaugino masses:

```
COMMON/SU_MSSMGPAR/dm1,dm2,dm3
```

The soft-SUSY breaking slepton mass terms (3d and then 1/2 generations):

```
COMMON/SU_MSSMSLEP/dmsl,dmtaur,dmel,dmer
```

The soft-SUSY breaking squark mass terms (3d and then 1/2 generations):

```
COMMON/SU_MSSMSQUA/dmsq,dmtr,dmbr,dmuq,dmur,dmdr
```

The soft-SUSY breaking trilinear couplings (3d and then 1/2 generations):

```
COMMON/SU_ATRI3/dal,dau,dad
COMMON/SU_ATRI12/dal1,dau1,dad1
```

The sign of μ and the input $\tan\beta$ value:

```
COMMON/SU_RADEWSB/sgnmu0,tgbeta
```

mSUGRA case input parameters:

```
COMMON/SU_MSUGRA/m0,mhalf,a0
```

GMSB case input parameters:

```
COMMON/SU_GMSB/mgmmess,mgmsusy,nl,nq
```

AMSB case input parameters:

```
COMMON/SU_AMSB/m32,am0,cq,cu,cd,cl,ce,chu,chd
```

B.2.2 COMMONs for output masses and mixing angles

Light h, heavy H, charged Higgs H^+ Higgs masses and mixing angle α:

```
COMMON/SU_OUTHIGGS/dml,dmh,dmch,alfa
```

Charginos $\chi^{\pm}_{1,2}$ masses, neutralinos $\chi^0_{1..4}$ masses, gluino $\tilde{g}$ mass:

```
COMMON/SU_OUTGINOS/dmc1,dmc2,dmn1,dmn2,dmn3,dmn4,mgluino
```

Stop $\tilde{t}_{1,2}$ masses and Sup $\tilde{u}_{1,2}$, Scharm $\tilde{c}_{1,2}$ masses:

```
COMMON/SU_OUTSQU/dmst1,dmst2,dmsu1,dmsu2
```

Sbottom $\tilde{b}_{1,2}$ masses and Sdown $\tilde{d}_{1,2}$, Sstrange $\tilde{s}_{1,2}$ masses:

```
COMMON/SU_OUTSQD/dmsb1,dmsb2,dmsd1,dmsd2
```

Stau $\tilde{\tau}_{1,2}$ masses and Selectron $\tilde{e}_{1,2}$, Smuon $\tilde{s}_{1,2}$ and Sneutrino masses:

```
COMMON/SU_OUTSLEP/dmsl1,dmsl2,dmse1,dmse2,dmsn1,dmsntau
```

The soft-SUSY breaking trilinear couplings (3d and then 1/2 generations):

```
COMMON/SU_ATRI3/dal,dau,dad
COMMON/SU_ATRI12/dal1,dau1,dad1
```

Stop, sbottom, stau mixing angles:

```
COMMON/SU_MIX/thet,theb,thel
```

The values of $\tan\beta$ and the angle α at the EWSB scale:

```
COMMON/SU_HMIX/beta,adum
```

U, V chargino and Z neutralino diagonalyzing matrices:

```
COMMON/SU_MATINO/U,VV,Z
```

Final bottom, top tau masses and gauge couplings at EWSB scale:

```
COMMON/SU_YUKAEWSB/ytauewsb,ybewsb,ytewsb,alsewsb,g2ewsb,g1ewsb
```

B.2.3 Internal COMMONs

These commons are internal to the SuSpect routine and the user should not need to care about any of them in principle, except in case of debugging. We list them without any detailed comment, in case they are needed:

```
COMMON/SU_strc/irge,isfrc,inorc
COMMON/SU_stepwi/wistep,h1,kpole
COMMON/SU_stegut/ifirst,jfirst,ygut
COMMON/SU_errsf/sterr,sberr,stauerr,stnuerr
COMMON/SU_qcdflag/nnlo,idrflag
COMMON/SU_hflag/ihflag
COMMON/SU_tachyrc/tachsqrc
COMMON/SU_good/iflop
COMMON/SU_sthresh/rmtop,susym,egut
```

```
      COMMON/SU_gunif/kunif
      COMMON/SU_param/gf,alpha,mz,mw
      COMMON/SU_cte/nf,cpi,zm,wm,tbeta
      COMMON/SU_als/xlambda,mc0,mb0,mt0,n0
      COMMON/SU_fmasses/mtau,mbpole,mtpole
      COMMON/SU_runmasses/mtaurun,mbrun,mtrun
      COMMON/SU_yuka/ytau,yb,ytop
      COMMON/SU_treesfer/msbtr1,msbtr2,msttr1,msttr2
      COMMON/SU_hmass/ma,ml,mh,mch,marun
      COMMON/SU_break/msl,mtaur,msq,mtr,mbr,al,au,ad,
     .                mu,m1,m2,m3
      COMMON/SU_break2/mel,mer,muq,mur,mdr
      COMMON/SU_smass/gmn,xmn,gmc,gmst,msb,gmsl,gmsu,gmsd,gmse,gmsn
      COMMON/SU_hcoup/bcoup,a,gat,gab,glt,glb,ght,ghb,ghvv,glvv
      COMMON/SU_cplhsf/gcen,gctb,glee,gltt,glbb,ghee,ghtt,ghbb,
     .                 gatt,gabb,gaee
      COMMON/SU_cplhino/ac1,ac2,ac3,an1,an2,an3,acnl,acnr
      COMMON/SU_cteloop/vu,vd,atop,ab,atau,rmllt,rmllb,rmlltau,
     .                 rmrrt,rmrrb,rmrrtau
      COMMON/SU_soft/rmtaur,rml,rmbr,rmtr,rmq
      COMMON/SU_cpl/g22,sw2
      COMMON/SU_sgnm123/sgnm1,sgnm2,sgnm3
      COMMON/SU_renscale/scale
```

B.3: Example of a calling routine

Here is an example of a program calling the main routine `suspect2.f` and that one can use to inteface with other programs or to make scans of the parameter space. The file is provided with the program and is called `suspect2_call.f`

```
c  +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c                     The calling program suspect_call.f
c  +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c  VERSION 2.1
c  Last changes : November 20, 2002
c  +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c  This program is the example routine calling the main program SuSpect2.f.
c  It has to be compiled together with suspect2.f in all cases, but it is
c  particularly useful when performing e.g. a scan of the parameter space
c  (and not only to obtain the spectrum for one point as can be done in the
c  SuSpect2.f routine by setting the control parameter INPUT to the value 1)
c  and/or to interface SuSpect with another program. In this routine you have
c  to set the four control parameters which are the inputs arguments of the
c  main program:

c         SUBROUTINE SuSpect2(iknowl,input,ichoice,errmess)
c  The input are (see details in the comments of begining of SuSpect2.f):
c  IKNOWL which sets the degree of control on various parts of the algorithm:
c  =0: blind use of the program, no control on parameters and no warning.
c  =1: no control on the algorithm but warning/error messages in output file.
c  =2: control some algorithmic parameters and all warning/error messages.
c  INPUT is for the physical input setting and works in three modes:
c  =0: model and option parameters and physical input read in SuSpect.in
c  =1: define yourself IN THIS FILE the relevant input choices and parameters.
c  =11: same as input=1, but with no output file SuSpect.out generated
c       (more convenient e.g. for scan over the model parameter space).
c  ICHOICE intialises the various model/accuracy options to be considred:
c  - ICHOICE(1): Choice of the model to be considered.
c  - ICHOICE(2): For the perturbative order (1 or 2 loop) of the RGEs.
c  - ICHOICE(3): To impose or not the GUT scale.
c  - ICHOICE(4): For the accuracy of the RGEs.
c  - ICHOICE(5): To impose or not the radiative EWSB.
c  - ICHOICE(6): To chose different (scalar sector) input in general MSSM.
```

```
c  - ICHOICE(7): For the radiative corrections to the (s)particles masses.
c  - ICHOICE(8): To set the value of the EWSB scale.
c  - ICHOICE(9): For the number of (long: RGE + full spectrum) iterations:
c  - ICHOICE(10): For the routine calculating the Higgs boson masses.
c  ERRMESS provides a useful set of warning/error message flags in output file.
c  - ERRMESS(i)= 0: Everything is fine.
c  - ERRMESS(1)=-1: tachyon 3rd gen. sfermion from RGE
c  - ERRMESS(2)=-1: tachyon 1,2 gen. sfermion from RGE
c  - ERRMESS(3)=-1: tachyon A    (maybe temporary: see final mass)
c  - ERRMESS(4)=-1: tachyon 3rd gen. sfermion from mixing
c  - ERRMESS(5)=-1: mu(M_GUT) guess inconsistent
c  - ERRMESS(6)=-1: non-convergent mu from EWSB
c  - ERRMESS(7)=-1: EWSB maybe inconsistent  (!but RG-improved only check)
c  - ERRMESS(8)=-1: V_Higgs maybe UFB or CCB (!but RG-improved only check)
c  - ERRMESS(9)=-1: Higgs boson masses are NaN
c  - ERRMESS(10)=-1: RGE problems (non-pert and/or Landau poles)
c  +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c                      The program starts here
c  +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      PROGRAM main
c
      implicit real*8(a-h,m,o-z)
      dimension ichoice(10),errmess(10)
      dimension u(2,2),vv(2,2),z(4,4)
c
c
c=======================  COMMONs for input ===========================
c   These are the commons for the parameters that can be read in the file
c   suspect2.in (together with the various ichoices).
c   !Important note: to interface your program with SuSpect2.f, these
c    commons (plus the output ones below) are the only ones needed.
c
c   "Standard model" INPUT parameters (couplings and fermion masses):
       COMMON/SU_SMPAR/alfinv,sw2,alphas,mt,mb,mc,mtau
c   RG evolution scale parameters (EWSB scale, high and low RGE ends):
       COMMON/SU_RGSCAL/qewsb,ehigh,elow
c   (Soft-SUSY breaking) MSSM parameters of the scalar potential:
```

```
      COMMON/SU_MSSMHPAR/mhu2,mhd2,ma,mu
c   The U(1), SU(2), SU(3) SUSY-breaking gaugino masses
      COMMON/SU_MSSMGPAR/m1,m2,m3
c   The soft-SUSY breaking slepton mass terms (3d and then 1/2 gen.):
      COMMON/SU_MSSMSLEP/msl,mtaur,mel,mer
c   The soft-SUSY breaking squark mass terms (3d and then 1/2 gen.):
      COMMON/SU_MSSMSQUA/msq,mtr,mbr,muq,mur,mdr
c   The soft-SUSY breaking trilinear couplings (3d and then 1/2 gen.):
      COMMON/SU_ATRI3/atau,at,ab
      COMMON/SU_ATRI12/al,au,ad
c   mSUGRA case input parameters:
      COMMON/SU_MSUGRA/m0,mhalf,a0
      COMMON/SU_RADEWSB/sgnmu0,tgbeta
c   GMSB case input parameters:
      COMMON/SU_GMSB/mgmmess,mgmsusy,nl,nq
c   AMSB case input parameters:
      COMMON/SU_AMSB/m32,am0,cq,cu,cd,cl,ce,chu,chd
c
c========================  COMMONs for output =============================
c
c     COMMON/SU_OUTHIGGS/ml,mh,mch,alfa
c   light, heavy, charged Higgs masses, Higgs mix angle alpha
      COMMON/SU_OUTGINOS/mc1,mc2,mn1,mn2,mn3,mn4,gluino
c   charginos 1,2 masses, neutralinos 1-4 masses, gluino mass
      COMMON/SU_OUTSQU/mst1,mst2,msu1,msu2
c   stop 1,2 and sup 1,2 = scharm 1,2 masses
      COMMON/SU_OUTSQD/msb1,msb2,msd1,msd2
c   sbottom 1,2 and sdown 1,2 = sstrange 1,2 masses
      COMMON/SU_OUTSLEP/msl1,msl2,mse1,mse2,msn1,msntau
c   stau 1,2 ; selectron (=smuon) 1,2; sneut_e,mu, sneut_tau masses
      COMMON/SU_OUTMIX/thet,theb,thel
c   stop, sbottom, stau mixing angles
      COMMON/SU_MATINO/u,vv,z
c   U,V chargino and Z neutralino diagonalizing matrices
     COMMON/SU_YUKAEWSB/ytauewsb,ybewsb,ytewsb,alsewsb,g2ewsb,g1ewsb
c   (final) bottom, top tau masses and gauge couplings at EWSB scale
c Note for soft terms: OUTPUT values are contained in the same commons as
```

```
c for their input values: MSSMhpar, MSSMgpar, MSSMslep,
c                          MSSMsqua, MSSMAtri
c
c (NB if meaning ambiguous, see detailed parameter definitions and
c  conventions in suspect2.f file)
c
c========================  Setting the running input ======================
c   Here you set your command for reading the input SuSpect2.in and/or writing
c   (see functions in the comments above) in the output file SuSpect.out
       IKNOWL = 1
       INPUT  = 0
c  other possible choice: INPUT = 11:
c Same as INPUT = 1 , but NO OUTPUT File (suspect2.out) generated
c (convenient e.g. for scan on MSSM/mSUGRA parameters)
c  In case your INPUT choice is 1 or 11, the following lines will be read
c  (so that you have to set yourself ICHOICE(1)-(10) and the physical input
c   parameters, see details in the input file suspec2.in or in the comments of
c   the main suspect2.f file).
c=======  Example of choice for the model/accuracy, etc, parameters
      if(input.eq.0) goto 99
c control parameters input:
      ichoice(1) = 10
c (minimal SUGRA case)
c
      ichoice(2) = 21
c (2-loop RGE for gauge, yukawas, gauginos)
      ichoice(3) = 0
c (ichoice(3)= 0: GUT scale imposed (then EHIGH = input!);
c            = 1: gauge unif scale calculated from gauge cpls. input
c
      ichoice(4) = 1
c  (RG accuracy: 1: moderately accurate and fast (generally sufficient)
c                2: very accurate but rather slow!
      ichoice(5) = 1
c (consistent EWSB)
      ichoice(6) = 1
c (M_Hu, M_Hd (= m_0 in mSUGRA) input)
```

```
      ichoice(7) = 2
c ICHOICE(7):  SUSY radiative corrections to the (s)particles masses:
c                      No Radiative corrections     : 0
c                      only in mb,mt,mtau +Yukawas : 1
c                      all squarks + gaugino R.C. in addition: 2
      ichoice(8) = 1
c (ichoice(8) = 1 for default EWSB scale=(m_t_L*m_t_R)^(1/2), =0 if not)
c then IF ichoice(8)=0 EWSB scale is set by user from input file/calling
c routine by the value of Qewsb
      ichoice(9) = 3
c ichoice(9) >= 3: Nb of (long: RGE + Full spectrum) iterations
      ichoice(10) = 1
c ICHOICE(10): Higgs mass options:
c             SUSPECT approximate m_h calculation      : 0
c             SUBH_HDEC (Carena et al.) from HDECAY    : 1
c             HMSUSY (Haber et al.) routine            : 2
c             FEYNHIGGSFAST1.2.2 (Heinemeyer et al.)   : 3
c
c======= Then define the needed SM and SUSY input parameters (example below)
c        (these are the parameters contained in the commons for input above):
c  "SM-like" input:
      alfinv= 127.938d0
      sw2 = .23117d0
      alphas =.1192d0
      mt =175.d0
      mb = 4.9d0
      mtau =1.7771d0
c
c RG evolution parameters:
      ehigh = 1.9d16
      elow =91.19d0
      qewsb = 200.d0
c (!! qewsb value only relevant if ichoice(8) = 0, see above)
c
c  minimal SUGRA case input sample (SNOWMASS point 1):
c
      m0 = 400.d0
```

```
      mhalf =400.d0
      A0 = 0.d0
      sgnmu0 = 1.d0
      tgbeta = 40.d0
c
c
c  Gauge Mediated Supersymmetry Breaking (GMSB) input sample:
c
CC       mgmmess = 50.d3
CC       mgmsusy = 5.d3
CC       nl = 1
CC       nq = 1
CC       tgbeta = 30.d0
CC       sgnmu0 = 1.d0
c
c
c  Anomaly Mediated Supersymmetry Breaking (AMSB) input sample:
c
CC       m32 = 40.d3
CC       am0  = 100.d0
CC       tgbeta = 30.d0
CC       sgnmu0 = 1.d0
CC       cq  =1.d0
CC       cu = 1.d0
CC       cd = 1.d0
CC       cl = 1.d0
CC       ce = 1.d0
c
c   non-universal case input sample:
c
CC         MHU2     = .5d4
CC         MHD2     = 5.d5
CC         M1       = 50.D0
CC         M2       = 200.D0
CC         M3       = 350.D0
CC         MSL      = 4.7D2
CC         MTAUR    = 4.7D2
```

```
CC        MSQ      = 367.5d0
CC        MTR      = 123.5d0
CC        MBR      = 4.7D2
CC        MEL      = 4.7D2
CC        MER      = 4.7D2
CC        MUQ      = 4.7D2
CC        MUR      = 4.7D2
CC        MDR      = 4.7D2
CC        Atau     = 1.5D3
CC        At       = -300.d0
CC        Ab       = 1.5D3
CC        AL       = 1.5D3
CC        AU       = -300.d0
CC        AD       = 1.5D3
c  special case of MA, MU input (instead of MHU2, MHD2)
CC        MA       = 1000.d0
CC        MU       = 100.d0
c
  99  continue
c    At this stage you can call the main subroutine suspect:
c%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
c
       CALL suspect2(IKNOWL, INPUT, ICHOICE,ERRMESS)
c
c  (ALL relevant OUTPUT will be written in suspect.out file;
c   except if INPUT=11 chosen, and you may continue with output
c   values within this program)
c
c   ......sequel of your own program continues e.g. here
c   ....  Bonne route!
c
      end
c  ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

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