# SuSpect3: A C++ Code for the Supersymmetric and Higgs Particle Spectrum of the MSSM

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## Abstract

We present the program SuSpect3 that calculates the masses and couplings of the Higgs and supersymmetric particles predicted by the Minimal Supersymmetric Standard Model (MSSM). The model is implemented in both its non-constrained version, the MSSM, and its constrained versions, such as the minimal supergravity and the gauge or anomaly mediated supersymmetry breaking models, in which the soft supersymmetry–breaking parameters obey certain universal boundary conditions at the high energy scale. The low energy parameters are then obtained using renormalization group equations and electroweak symmetry breaking, and all the dominant radiative corrections have been consistently implemented. SuSpect3 is a major rewrite, in C++ object oriented programming, of the FORTRAN code SuSpect. It includes all the features of the earlier code in an improved and updated manner, and involves new options such as compressed SUSY scenarios, an MSSM-inflation model and the possibility of using the observed Higgs mass as an input. The main features and the use of the program are explained.

*Keywords:* Higgs; supersymmetry; sparticle; MSSM.

## PROGRAM SUMMARY

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Program Title: SuSpect3

Developer's repository link: http://suspect.in2p3.fr Licensing provisions(please choose one): GPLv3 Programming language: C++, compatible C++98, C++11, C++14, C++17 Compiler: gcc-4.8.5 and later (checked with gcc-8.1.0) Nature of problem:

Supersymmetric models such as the MSSM, mSUGRA, GMSB, AMSB and others have specific parameter sets and boundary conditions. SuSpect3 translates the parameter sets of the models into predictions of the Higgs and supersymmetric particles masses. The mixing matrices of the physical states as well as the mixing angles are calculated in addition to the scale dependent parameters. *Solution method:* 

The spectrum of the Higgs and supersymmetric particles depends on the model, its supersymmetric parameter set and the Standard Model parameters. The evolution of the parameters as function of the energy scale is calculated by solving numerically the Renormalization Group Equations. Model dependent boundary conditions are applied at the appropriate scale. Electroweak symmetry breaking is calculated iteratively at the electroweak scale. The application of radiative corrections translate the scale dependent particle masses into the physical pole masses. Additional comments including restrictions and unusual features:

The parameters and physical masses are defined to be real. Warnings are issued if intermediate results are unphysical.

## 1. Introduction

The discovery of a Standard-Model-like Higgs boson by the ATLAS and CMS experiments [1, 2] at the LHC with a mass of about 125 GeV [3, 4, 5] is compatible with TeV scale supersymmetric (SUSY) theories such as the minimal supersymmetric extension of the Standard Model (MSSM) (for reviews see e.g. [6, 7, 8, 9, 10, 11]). Indeed, in the MSSM the lightest Higgs boson h mass can receive large radiative corrections, as initially demonstrated in [12, 13, 14, 15, 16], (see e.g. [17, 18] for reviews and further references) and is predicted to be less than 130-140 GeV [19].

Further motivation to study SUSY models is driven by the capability of the MSSM to provide a particle candidate to explain [20, 21] the relic mass-energy density of cold dark matter [22]. Another motivation for supersymmetry is that it naturally stabilizes the large hierarchy between the Grand Unification scale ( $M_{GUT}$ ) and the electroweak scale ( $M_{EWSB}$ ): this reduces drastically the quadratic sensitivity of radiative corrections to the Higgs boson masses to high scales, as was first shown in [23, 24]. Furthermore, in TeV scale SUSY models, a consistent unification of the U(1)<sub>Y</sub>, SU(2)<sub>L</sub> and SU(3)<sub>c</sub> gauge couplings embedded in a larger symmetry group such as SU(5), is possible [25, 26, 27].

While the most general MSSM has more than 100 free parameters, more restrictive variants with only 31 real-valued parameters, 3 gaugino masses, 15 scalar fermion masses, 9 trilinear couplings in the scalar/Higgs sector, 2 masses in the Higgs sector,  $\tan \beta$  and the sign of  $\mu$ , have been defined. Incorporating phenomenologically motivated constraints was the motivation of the 'phenomenological MSSM' [11], which has only about 20 parameters. These parameters enter in the calculation of the SUSY particle and Higgs boson physical masses and their couplings as well as inducing mixing between different states.

The number of parameters can be reduced further in well motivated theoretical models where the soft supersymmetry–breaking (SSB) parameters obey certain universal boundary conditions at the  $M_{GUT}$ , at a high scale  $M_{High}$  below  $M_{GUT}$ , but above  $M_{EWSB}$ , or at an intermediate scale  $M_{MESS}$ . This is for instance the case of the minimal Supergravity model [28, 29, 30], or the gauge mediated [31, 32, 33] (see [34] for a review and further references), and anomaly mediated [35, 36] SUSY breaking models.

Evolving parameters between scales by solving the renormalization group equations (RGE) leads to an interdependence of the parameters at  $M_{EWSB}$ . Ensuring electroweak symmetry breaking (EWSB) at  $M_{EWSB}$  including radiative corrections further complicates the calculation. Precise calculations of the pole masses of the Higgs bosons and the SUSY particles involve loop contributions from most of the other (s)particles. Therefore, the complete mass spectrum has to be known. As the boundary conditions of the models are defined at at least two different scales, the two procedures, RGE evolution and EWSB, have to be repeated several times to converge to a stable result.

Sophisticated spectrum calculator programs have been developed to tackle these challenges, such as, non-exhaustively, SuSpect [37], SOFTSUSY [38], SPHENO [39, 40, 41], FeynHiggs [42, 43, 44, 45], and FlexibleSUSY [46]. SuSpect3, a major rewrite of SuSpect, will be presented in the following. A preliminary version has been presented at a Les Houches workshop [47] and used e.g. in [48].

Since its conception SuSpect2 has been updated and extended continuously leading to program that is at the same time robust and difficult to maintain. It is common, e.g., in long running experiments, to upgrade the software framework and tools to order "organically" grown code and make use of new features. C++ has several interesting features such as overloading of methods, encapsulation and inheritance which can make code maintenance and extension easier.

Spectrum calculators such as SuSpect3 tie together different fields of physics such as collider physics and cosmology in a concrete model by providing precise predictions for the particle properties. As the number of degrees of freedom to be explored in such a study is large, a robust and efficient algorithm is necessary. The implementation of a new electroweak symmetry breaking variant in SuSpect3 using as input parameter the measured Higgs boson mass is a step to reduce the number of parameters.

SuSpect3 provides a new model linking particle physics and cosmological inflation. The structure of SuSpect3 facilitates its implementation which necessitated the addition of the scale evolution of three additional parameters and the implementation of inflation specific boundary conditions.

The paper (and user's manual) is organized as follows. The underlying physics features are discussed in section 2. In section 3 the implementation of SuSpect3 is discussed. The main models implemented in SuSpect3 are outlined briefly in section 4. A short conclusion will be given in the last section. The appendix contains information on how to install and run the program as well as the full output of a calculation as example.

## 2. Physics

A basic description of the MSSM features and parameters is given in this section. For physics motivations and detailed descriptions, see the reviews of the MSSM and related models, e.g. [10] (and references therein).

In a SUSY theory the particle spectrum is extended with respect to the Standard Model (SM) by associating a fermionic degree of freedom to each bosonic degree of freedom and vice versa. Squarks  $\tilde{q}_L$  and  $\tilde{q}_R$  are scalar fields associated to the two chirality states of each quark q. In the leptonic sector, sleptons  $\tilde{\ell}_R$  and  $\tilde{\ell}_L$  are scalar fields associated to each charged lepton flavor  $\ell$ , whereas a sneutrino is associated to the left-chiral neutrino of the SM. The latter is assumed to be massless for simplicity.

In the MSSM, two chiral  $SU(2)_L$  doublet Higgs superfields of opposite hypercharge are needed to allow for supersymmetric and gauge invariant Yukawa couplings involving up and down right-handed quark chiral superfields, as well as for chiral anomaly cancellation. Their scalar components constitute the Higgs sector. The neutral components of the latter develop vacuum expectation values,  $v_u$  and  $v_d$ , that break electroweak symmetry and give masses to the up- and down-type fermions respectively. Physical states are two neutral CP–even Higgs bosons h and H, one neutral CP–odd Higgs boson A° and the charged Higgs bosons H<sup>±</sup>.

The fermionic partners of the neutral gauge and Higgs bosons mix to form the mass eigenstates, referred to as neutralinos,  $\tilde{\chi}_i^{\circ}$  with i = 1, ..., 4. Similarly the charged gauge and Higgs bosons are associated to the fermionic partners which mix to form the charginos,  $\tilde{\chi}_i^{\pm}$  with i = 1, 2.

#### 2.1. MSSM Parameters

The description of the MSSM content follows Refs. [11, 37, 49]. For convenience only the parameters are defined here; for further details and the definition of the mass matrices, mixing matrices and mixing angles see [37, 49].

The Higgs sector parameters are  $\tan \beta$ , the ratio of the vacuum expectation values  $v_u/v_d$ , the tree-level running mass of the pseudo scalar Higgs boson A° and the Higgs mass parameter  $\mu$ . SSB mass parameters are  $M_{H_u}^2$ and  $M_{H_d}^2$  for the up– and down–type Higgs fields.

In the squark sector a SSB mass parameter associated to an SU(2)<sub>L</sub> doublet is defined for each family:  $M_{\tilde{q}1_L}$ ,  $M_{\tilde{q}2_L}$  and  $M_{\tilde{q}3_L}$ . In addition each squark flavor has a SSB mass parameter for its SU(2)<sub>L</sub> singlet:  $M_{\tilde{u}_R}$ ,  $M_{\tilde{d}_R}$ ,  $M_{\tilde{c}_R}$ ,  $M_{\tilde{s}_R}$ ,  $M_{\tilde{t}_R}$ ,  $M_{\tilde{b}_R}$ . The off-diagonal entries in the squark mass matrices depend on the SSB trilinear couplings  $A_u$ ,  $A_d$ ,  $A_c$ ,  $A_s$ ,  $A_t$  and  $A_b$ . Flavor mixing due to SSB parameters, possible in the most general model [10], is assumed to be absent in the following.

The structure is similar in the slepton sector. The parameters  $M_{\tilde{\ell}1_L}$ ,  $M_{\tilde{\ell}2_L}$ and  $M_{\tilde{\ell}3_L}$  are the SSB mass parameters associated to the SU(2)<sub>L</sub> doublets. The SSB mass parameters associated to the SU(2)<sub>L</sub> singlets are  $M_{\tilde{e}_R}$ ,  $M_{\tilde{\mu}_R}$ and  $M_{\tilde{\tau}_R}$ . Three SSB trilinear couplings are defined,  $A_e$ ,  $A_\mu$  and  $A_\tau$ , one for each charged lepton flavor.

In the gaugino sector three SSB masses are defined,  $M_1$ ,  $M_2$  and  $M_3$ , associated respectively to the gauge groups  $U(1)_Y$ ,  $SU(2)_L$  and  $SU(3)_c$ . Without

loss of generality  $M_2$  and  $M_3$  are required to be positive, while  $M_1$  can be either positive or negative.

### 2.2. Models

The most general supersymmetric model implemented in SuSpect3 is the MSSM with its parameter set as defined above. Several variants of this model can be identified which differ only in the scale where most of the SUSY parameters are defined, either at  $M_{GUT}$ ,  $M_{High}$  or at  $M_{EWSB}$ . A new type of SUSY model, allowing for an inflationary scenario, generically referred to as *Inflation* in the following, has also been implemented. We provide hereafter in section 2.2.2 a short description of its main ingredients.

### 2.2.1. Constrained MSSM

The models for minimal Supergravity (mSUGRA), Gauge Mediated SUSY Breaking (GMSB) and Anomaly Mediated SUSY Breaking (AMSB) can be understood as subsets of the MSSM. In these models the boundary conditions reduce the number of free parameters either at  $M_{GUT}$  (mSUGRA, AMSB) or at an intermediate scale  $M_{MESS}$  between  $M_{GUT}$  and  $M_{EWSB}$  (GMSB)<sup>1</sup>. In these models  $M_{GUT}$  may be defined as the scale of gauge coupling unification and a separate scale  $M_{High}$  is used for the definition of the other scale–dependent parameters.

In addition to the general models GMSB and AMSB a minimal variant of these models is also provided, mGMSB and mAMSB. In these minimal models the number of free parameters is further reduced by additional assumptions.

## 2.2.2. Connecting the MSSM and Cosmological Inflation

In this model [50], the MSSM is extended by specific non-renormalizable superpotential terms lifting the so-called LLE or UDD MSSM flat directions [51] that can trigger an inflationary phase.<sup>2</sup> This involves two new a priori

<sup>&</sup>lt;sup>1</sup>See sections 4.2.1, 4.3 and 4.5 for details on the parameter definitions of minimal SUGRA, GMSB and AMSB models respectively.

<sup>&</sup>lt;sup>2</sup>LLE and UDD stand for the SU(3)<sub>c</sub> × SU(2)<sub>L</sub> × U(1)<sub>Y</sub> gauge invariant operators  $\epsilon_{\alpha\beta} L_i^{\alpha} L_j^{\beta} E_k$  and  $\epsilon_{abc} U_i^{a} D_j^{b} D_k^{c}$  in the superpotential, that parameterize the corresponding flat directions. *L* denotes SU(2)<sub>L</sub> doublets and *E*, *U*, *D*, SU(2)<sub>L</sub> singlets; *i*, *j*, *k* are generation indices, *a*, *b*, *c* color indices and  $\alpha, \beta$ , SU(2)<sub>L</sub> flavor indices. The relevant cases correspond to  $i \neq j$  for LLE and  $j \neq k$  for UDD.

free parameters: a supersymmetric coupling  $\lambda_6$  associated with a dimension-6 operator in the superpotential, and the corresponding SSB bi-trilinear coupling A<sub>6</sub>. A third important parameter is the inflaton mass  $m_{\phi}$ , which is however uniquely determined by the slepton/squark SSB masses when the inflaton rolls along the LLE/UDD directions.  $\lambda_6$  is presumably related to some unspecified UV completion of the MSSM. In contrast, the initial condition for A<sub>6</sub> can be in general linked to the other soft trilinear couplings of the MSSM at the SUSY-breaking scale, once a mediation scenario of this breaking is assumed. Following [52] we have implemented a simple relation between A<sub>6</sub> and A<sub>t</sub> obtained in the Polonyi model. However, any other relation can be easily implemented.

The RGE evolution of  $m_{\phi}$  is given by that of the SSB slepton/squark masses, already available in the code. Those of A<sub>6</sub> and  $\lambda_6$  can be extracted from the R-parity-violating MSSM (see e.g. [53]), including multiplicative factors for the non-renormalizable operators [54], and neglecting contributions suppressed by a heavy mass scale (usually taken as  $M_{planck}$ ) associated with these effective couplings. We have implemented the supplementary RGEs for all relevant LLE/UDD flavor directions including the complete gauge/gaugino Yukawa/trilinear-soft contributions. The  $\lambda_6$  parameter factorizes with respect to the other parameters and does not influence the MSSM spectrum calculation. Even so, we provide its RGE evolution alongside those of  $m_{\phi}$  and A<sub>6</sub> as the three parameters are instrumental for a precise determination of the effective potential of the inflaton at a given inflation scale. The latter is an important parameter that we implemented as an input. For a given set of MSSM parameters at the SUSY-breaking scale,  $A_6$  is calculated from  $A_t$ . The ensuing knowledge of  $A_6$  at the inflation scale, together with the (external) cosmology constraints (related to the determination of the Hubble flow parameters), fix uniquely  $m_{\phi}$  and  $\lambda_6$  at the inflation scale. This cosmologically consistent inflaton mass can be compared to the running  $m_{\phi}$  provided by SuSpect3 at the inflation scale allowing to check the consistency of the (input) squark/slepton soft masses with cosmological inflation. Incidentally,  $\lambda_6$  is run to all scales to enable the check of the perturbativity of this coupling.

## 2.3. EWSB

An attractive feature of the MSSM is the radiative electroweak symmetry breaking. Essentially, the parameter  $M_{H_u}^2$  evolved to the scale of  $M_{Z^\circ}$  becomes negative without leading to tachyonic particles. As the parameter is part of the Higgs potential, the champagne bottle bottom or Mexican hat form of the potential is radiatively generated instead of being enforced arbitrarily.

The minimization of the Higgs potential of the MSSM with respect to  $H_u$ and  $H_d$  leads to a pair of quadratic equations which relate the parameters of the Higgs sector. There are three distinct possibilities: Either the pair  $M_{H_u}^2$ ,  $M_{H_d}^2$  as well as the sign of  $\mu$ , the pair  $\mu$ ,  $m_{A^\circ}$  or the pair  $\mu$ ,  $m_{A^\circ}^2(Q)$  can be used to calculate the other parameters consistently.

Motivated by the precise measurement of the Higgs boson mass [3, 4] EWSB can also be calculated by using the mass of the lightest neutral Higgs boson  $m_{\rm h}$  as input. An algorithm has been recently developed in [55], based on diagrammatic fixed-order perturbative calculations up to two-loop precision where the trilinear coupling A<sub>t</sub> becomes an output parameter. This algorithm has been implemented in **SuSpect3**.

Requiring consistent EWSB necessitates multiple iterations to ensure that radiative corrections are calculated consistently.

## 2.4. Spectrum calculation

Determining the Higgs and sparticle pole masses consistently with the renormalization group evolution and the EWSB mechanism poses numerous non-trivial technical problems if to be done in an accurate way, i.e. including higher order radiative corrections. Indeed, the latter are known to be extremely important in particular in the Higgs sector. A calculation of the various couplings is also necessary and should be performed with the same accuracy. Note that one also has to consider radiative corrections to the Standard Model particle masses (those of the W, Z bosons, top, bottom quarks and tau lepton) and gauge and Yukawa couplings. In this context, SuSpect3, like former SuSpect, follows mainly Ref. [56], which provides most of the necessary radiative corrections at the one-loop level for the Higgs and sparticle masses, while the leading two-loop corrections to the masses of the (neutral) Higgs bosons [57, 58, 59, 60, 61] are implemented following Ref. [19].

#### 3. The program

In SuSpect3 the RGEs are solved to evolve parameters from one scale to another. Boundary conditions are defined at different scales either as input parameters or as constraints relating different parameters to each other as function of the chosen model. SuSpect3 ensures EWSB at  $M_{EWSB}$  for different choices of input. Finally, radiative corrections to the Higgs and sparticle masses are implemented to determine precisely the pole masses, as discussed in section 2.4.

The RGEs are implemented at one–loop and two–loop precision and evolve the parameters between up to five different energy scales. At  $M_{GUT}$ , determined from the approximate unification scale of the gauge couplings, or at  $M_{High}$  (an arbitrary user-defined high scale), a subset of the supersymmetry breaking parameters are also unified depending on the models, as specified below.

In mGMSB, GMSB and Inflation models an intermediate energy scale  $M_{MESS}$  is defined either to implement the boundary conditions on the SSB parameters, typically  $10^{10}$  GeV for mGMSB, GMSB, or to calculate the inflaton mass. At  $M_{EWSB}$  the minimization of the Higgs potential triggering EWSB is implemented. The radiative corrections on the SM parameters are calculated at  $M_{Z^{\circ}}$  and  $\tan \beta$  is defined at this scale. All RGEs and radiative corrections are calculated in the  $\overline{DR}$  renormalization scheme.

Due to the radiative corrections, relating RGE evolved parameters to pole masses, and the boundary conditions being defined at at least two scales, several iterations of the algorithm have to be performed. The algorithm consists of the RGE evolution between the highest scale of the model and  $M_{Z^{\circ}}$ , as well as enforcing EWSB iteratively at  $M_{EWSB}$ . After convergence, the physical pole masses are calculated.

#### 3.1. Technical Aspects

SuSpect3 is written in C++ in object oriented programming. The main program instantiates a suspect object. A method Run, implementing the initialization, execution and finalization of the object, must be called to obtain the spectrum. Initialize, Execute and Finalize are public methods which could also be called by the user. The C++ functionality of overloading methods is useful as the same method name can be used for different types of input. Run, for example, is overloaded three times, allowing to keep the same syntax whether the input is the filename, an SLHA4suspect object or a pointer to the SLHA4suspect object.

To cope with different types of input, e.g., from the standard SLHA format files [49] or via a C++ object, the Run and Initialize methods are overloaded. For input via an object, the object SLHA4suspect, which implements SLHAio blocks in memory, has to be created, and the parameter values in the input blocks initialized. The SLHA4suspect object given to suspect is copied internally. This has the advantage that SLHA4suspect has to be created only once for a scan of the parameter space, the parameter under study can be set to a new value without reinitializing all other parameters again. The results of the calculation are provided as terminal output, in a file or in memory as a SLHA4suspect object which can be retrieved from the suspect object.

Each of the models discussed in section 4 is implemented as an object. The model construction starts from a common base class which takes care of the basic configuration. The algorithmic flow is implemented in three generic objects, inheriting from the base class. These objects depend on the number of scales of the model: two scales with  $M_{EWSB}$  and  $M_{Z^{\circ}}$ , three scales with  $M_{GUT}$ ,  $M_{EWSB}$  and  $M_{Z^{\circ}}$ , four scales with  $M_{GUT}$ ,  $M_{MESS}$ ,  $M_{EWSB}$  and  $M_{Z^{\circ}}$  and five scales with  $M_{GUT}$ ,  $M_{High}$ ,  $M_{MESS}$ ,  $M_{EWSB}$  and  $M_{Z^{\circ}}$ . The explicit models inherit from the generic model objects. The use of inheritance has lead to a simplification of the code by removing duplicated code copied from one model to another. The implementation of a new model is easier.

The solution of the RGEs is coded and implemented as a separate object. The RGE evolution can be performed at one–loop or two–loop precision. This enables the use of the RGE evolution independent of the full model calculation.

Several iterations between the highest scale of the model and  $M_{Z^{\circ}}$  are necessary. In the calculation scalar SUSY mass parameters might become tachyonic at certain scales. SuSpect3 adds an error message to the block SPINFO in such a case. The tachyons can be a numerical artifact induced by the coupled RGEs through parameters, e.g., for EWSB, which have not converged yet or at the first iteration have not been defined yet. Therefore the errors are reset at each iteration at the highest scale applicable to the model.

The algorithmic flow of the determination of the EWSB output parameters is implemented in a base class. Each of the EWSB variants is implemented as a separate object, inheriting from the base class (EWSBHuHd, EWSBMAPoleMu, EWSBMA2TreeMu). In each object the derived parameters, e.g.,  $m_{A^{\circ}}^2(Q)$  and  $\mu$  in the case of EWSBHuHd, are calculated and the boundary conditions applied.

The determination of  $A_t$  from the lightest Higgs boson mass is implemented as separate object EWSBMh inheriting from the base class. Three objects EWSBHuHdMh, EWSBMAPoleMuMh, EWSBMA2TreeMuMh inherit from both the EWSBMh object and one of the objects EWSBHuHd, EWSBMAPoleMu, EWSB-MA2TreeMu. The diamond inheritance structure due to the common EWSBBase

class is treated by virtual inheritance. The inversion algorithm was developed initially only for EWSBHuHd. Inheritance made the extension of the other two variants simple. The implementation in SuSpect2 has not been successful.

The six variants of EWSB are complemented by a seventh variant. The non-application of EWSB consistency may also be imposed. In this mode the derived parameters are calculated, but no iteration is performed to ensure consistency.

The particles are defined as objects which can be configured to calculate the running masses (no extra radiative corrections), or the pole masses using the appropriate additional radiative corrections. While in SuSpect2 variables were used both for running and pole masses, data encapsulation allows for a clean separation and easier maintainability. By inheriting from a common base class an iteration over all objects is easy to implement for both variants.

After calculation of the spectrum, the absence of non-physical minima of the Higgs potential and the amount of fine-tuning in the EWSB conditions are checked. A limited set of the most common precision observables is calculated as well.

### 3.2. New Features and Repository

The updates of SuSpect3 with respect to SuSpect are:

- 1. The first and second generation supersymmetric scalar fermion parameters, previously identical, are fully independent.
- 2. The full one-loop radiative corrections in the chargino and neutralino sector are calculated on the chargino and neutralino pole masses instead of applying approximate effective corrections on the underlying parameters before mass diagonalization.
- 3. The range of models supported by SuSpect3 has been extended.
- 4. The option to use the tree-level running mass of the pseudoscalar A° as input for EWSB has been added.
- 5. The option of using the experimentally measured Higgs boson mass as input in EWSB to determine  $A_t$  has been added.
- 6. The input decoding has been made fully compatible with SLHA1 [49] with one additional block QEXTPAR taken from SLHA2 [62]. In particular the non-standard definition of the EWSB, i.e., setting the required EWSB in a separate input block, inherited from SuSpect has been removed.

- 7. The choice of EWSB is decoded from the defined input values instead of a required special variable.
- 8. The block QEXTPAR is decoded to determine the input scale for the  $\mu$  parameter.
- 9. The values of scale dependent parameters at scales other than those defined by the model is now available for all models and not only for the MSSM.

The code is available as a gzipped tar file on the suspect website (see Appendix A for further details). It is maintained in a gitlab repository provided by the computing center of the IN2P3. Continuous integration tests are implemented for all example input files provided to the user using a centos-7 image with the default gcc-g++ compiler. The absence of memory leaks was verified for all example files with valgrind.

SuSpect3 was developed with the gcc compiler version 4.8.5. The compilation and execution were checked explicitly with gcc-8.1.0 using -std=c++98, -std=c++11, -std=c++14 and -std=c++17.

### 4. Configuration of Models

As mentioned above, the input specifications for SuSpect3 follow closely the SLHA1 standard described in [49]. Additionally the block QEXTPAR of SLHA2) [62] is decoded to define the scale at which  $\mu$  is requested. No other parameters from this block are used. If  $m_{A^{\circ}}^{2}(Q)$  is requested, the scale for  $\mu$ is used for the parameter. The models available in SuSpect3 are discussed briefly in this section including the inheritance.

Common to all models are six input blocks: SUSPECT\_CONF, MODSEL, MINPAR, SMINPUTS, EXTPAR and QEXTPAR.

SUSPECT\_CONFIG defines the configuration of the calculation. The precision of the calculation for the RGEs as well as the number of loops used can be configured. The accuracy of the Higgs mass and the full spectrum can also be controlled by the user:

```
5
               2.0000000e+00
                                # choice for sparticles
# masses rad. corr. excluding Higgs):
# 2 ->all (recommended, default):
# 1->no R.C. in squarks & gauginos.
         7
               2.0000000e+00
                                # Final spectrum accuracy:
# 1 -> 1% acc.; 2 -> 0.01 % acc.(default)
               2.0000000e+00
         8
                                # Higgs boson masses
# rad. corr. calculation options:
# A simple approximation (advantage=fast)
                                           : 0
# Full one-loop calculation
                                            : 1
# One-loop+dominant DSVZ 2-loop (default)
                                           : 2
```

If the use of an externally provided RGE set is requested via entry 0, the object in src/RgeDataAndConditionsExternal.cxx is called. Three predefined methods have to be provided. In CalculateDerivative the implementation of the user defined RGEs is foreseen. Its inputs are a vector of the parameters in double precision and (optionally) a vector with boolean entries defining which parameters should be evolved to the new scale. The utility methods transferVector2SLHA and transferSLHA2Vector transfer the parameters to and from the SLHA blocks. The standard implementation is available in src/RgeDataAndConditionsInternal.cxx.

The accuracy of the solution of the RGE equations is controlled via entry 3. Moderate precision is a relative precision of  $1 \cdot 10^{-3}$ , accurate is defined as  $2 \cdot 10^{-5}$ . Specifying the expert input, the entry is used to specify the value of the relative precision in an allowed range from  $10^{-2}$  to  $10^{-6}$ .

In the block SMINPUTS the standard model parameters are defined for the input, the default values are:

1	127.934	<pre># alpha_em^(-1)(MZ) SM MSbar</pre>
2	1.16639E-5	# G_F
3	0.118	<pre># alpha_s(mZ) SM, MSbar</pre>
4	91.187	# mZ pole mass
5	4.18	# Mb(mb) SM MSbar
6	173.	# Mtop(pole)
7	1.777	# Mtau(pole)

For the scale of gauge coupling unification  $M_{GUT}$ , control is provided in the block MODSEL:

13 -1.00000000e+00 # Gauge coupling unification scale: # -1: calculated, value>0: value for scale fixed

The scale can either be calculated dynamically as part of the spectrum calculation (value -1) or forced to a specific input value. This functionality was previously part of the block SUSPECT\_CONFIG.

While in previous versions of SuSpect3 the values of the scale dependent parameters were provided at additional scales only for the basic MSSM, this functionality is now provided for all models via the block MODSEL:

11	10	#	MSSM	bottom-up	only:	number	of	points
12	1E16	#	MSSM	bottom-up:	high	scale		

A positive value for the number of points will trigger the RGE evolution from  $M_{Z^{\circ}}$  to the scale provided at index 12. The default for this scale is  $M_{EWSB}$ . The steps are equidistant in  $\log_{10}$ . This functionality is part of the Finalize method implemented in the base class of the models and therefore inherited by all models.

In addition to the gauge coupling unification scale, SuSpect provides furthermore control over  $M_{EWSB}$ , through index 14 of block MODSEL:

14 -1.0000000e+00 # EWSB scale: # -1 sqrt(stop1\*stop2), value>0: value for scale fixed

The default of -1 leads to the standard definition of  $M_{EWSB}$  as the geometric mean of the stop quark masses as specified by SLHA [49]. Specifying a positive value at this index overrides this choice and fixes  $M_{EWSB}$  to be the chosen value as suggested e.g. in [63].

After these common settings, the selection of the specific model via the MODSEL block will now be described. For some of the models, example input files are provided with the distribution in the subdirectory examples, see Appendix A for download and installation. In the following the relative pathname of the input file will be mentioned where available.

4.1. MSSM

The *MSSM* is configured in the MODSEL block as:

1 0 # MSSM:0, mSUGRA:1,....

The parameter  $\tan \beta$ , defined at  $M_{Z^{\circ}}$ , as well as the sign of  $\mu$  are configured in the block MINPAR:

2.0E+01 # tanbeta(MZ) 3 # sign(mu) 4 1.0

The other parameters are defined in the block  $\tt EXTPAR:$ 

BLOCK	EXTPAR		
	1	5.25225703e+02	# M_1
	2	9.54406026e+02	# M_2
	3	2.54213069e+03	# M_3
	11	-3.11637739e+03	# A_t
	12	-5.31256168e+03	# A_b
	13	-3.41866265e+03	# A_tau
	14	-4.60623573e+03	# A_u
	15	-5.91979687e+03	# A_d
	16	-3.53443255e+03	# A_e
	17	-4.60623573e+03	# A_c
	18	-5.91979687e+03	# A_s
	19	-3.53443255e+03	# A_mu
	21	4.86427234e+05	# M^2_Hd
	22	-4.01017724e+06	# M^2_Hu
#	23	2.01330021e+03	# mu(EWSB)
#	24	4.77432382e+06	<pre># m^2_A_run(EWSB)</pre>
#	26	2.14083063e+03	# mA
	31	1.18999153e+03	# M_eL
	32	1.18999153e+03	# M_muL
	33	1.12125121e+03	# M_tauL
	34	1.00009204e+03	# M_eR
	35	1.00009204e+03	# M_muR
	36	8.24069856e+02	# M_tauR
	41	2.44756888e+03	# M_q1L
	42	2.44756888e+03	# M_q2L
	43	2.02265804e+03	# M_q3L
	44	2.35965026e+03	# M_uR
	45	2.35965026e+03	# M_cR
	46	1.47723188e+03	# M_tR
	47	2.34881332e+03	# M_dR
	48	2.34881332e+03	# M_sR
	49	2.24171006e+03	# M_bR

Following the SLHA standard, as index 0 is not specified, the scale of the parameters is  $M_{EWSB}$ . To use a fixed user chosen  $M_{EWSB}$ , as discussed above, the parameter at index 14 in the MODSEL block has to be set to the chosen value.

The example shown here is for EWSB defined by  $M_{H_u}^2$ ,  $M_{H_d}^2$  and sign of  $\mu$ . For EWSB with  $\mu, m_{A^\circ}$  the indices 21 and 22 must be replaced by the indices 23 and 26. If EWSB with  $\mu, m_{A^\circ}^2(Q)$  is required, indices 23 and 24 must be provided. The sign of  $\mu$  specified in MINPAR is ignored in these two cases as  $\mu$  in EXTPAR is a signed parameter.

The detection of the EWSB option is done automatically: the default is defined as  $M_{H_u}^2, M_{H_d}^2$ , then EXTPAR is checked for the alternative inputs which override the default. No configuration variable has to be set in SUSPECT\_CONFIG for these three possibilities. SuSpect checks the consistency of the input, i.e., if the input is ambiguous, e.g., both the running and the pole mass of the A° are given, the execution is stopped and an error message is printed.

Using the Higgs boson mass as input parameter instead of  $A_t$  requires further specifications. In a large part of the supersymmetric parameter space the determination of  $A_t$  from the Higgs boson mass has a four-fold ambiguity. Each one of the solutions, ordered in  $A_t$  is requested via the block SUSPECT\_CONFIG:

4 1.01000000e+02 # 100-103: EWSB with Mh four solutions

This type of EWSB has been tested only for the benchmark point discussed in [55].

The request for this type of EWSB is triggered by adding  $m_{\rm h}$  in block SMINPUTS:

25 1.25012052e+02 # h

If the Higgs boson mass is specified in the input, the value of  $A_t$  in the EXTERNAL block is ignored.

In case partial unification of SSB parameters is requested, the corresponding unified parameter should be provided in MINPAR and the parameters removed from EXTPAR, e.g. sections 4.1.1, 4.1.2 and 4.2.1.

The mixing between the right– and left–handed sfermions due to the trilinear couplings of the first two generations is negligible due to the smallness of the corresponding SM fermion mass. The trilinear couplings are nevertheless part of the model specification since they have an impact on the RGE evolution of the parameters, especially between  $M_{GUT}$  and  $M_{EWSB}$ , thus modifying the predicted spectrum. The mixing matrix for the smuons is calculated for the prediction of the supersymmetric contributions to the anomalous magnetic moment of the muon.

Under the umbrella of the *MSSM* several distinct variants can be identified which are discussed in the following.

### 4.1.1. Low Scale MSSM

For the input configured, as discussed above, only two scales are relevant,  $M_{EWSB}$  and  $M_{Z^{\circ}}$ . The model, *Low Scale MSSM*, inherits in this case from the generic model with two scales. For SSB parameters not specified in EXTPAR the corresponding parameter in MINPAR will be used as defined in [49]. This enables the user to easily define partially unified models.

As EXTPAR(0) is not given, the scale  $M_{EWSB}$  is calculated as geometric mean of the stop pole masses. For convenience the scale is listed as output in block MODSEL:

15 1.72300647e+03 # OUTPUT ONLY: EWSB scale

An example input is provided in examples/LowScaleMSSM.in.

### 4.1.2. High Scale MSSM

Another variant of the MSSM is calculated if in the block EXTPAR the scale parameter is given:

## 0 1.34489071e+16 # scale for params in EXTPAR

If the value is -1, the model described in section 4.1.1 is calculated. If the scale is defined (> 0), the scale is interpreted as  $M_{High}$  from which the scale dependent parameters have to be evolved to  $M_{EWSB}$  before the calculation of the physical masses. As in section 4.1.1 partially unified models can be defined easily by specifying the corresponding MINPAR parameter and not specifying the EXTPAR parameters.

The model inherits from the generic model with four scales:  $M_{GUT}$  for gauge coupling unification,  $M_{High}$  which in this case is the SUSY-breaking scale,  $M_{EWSB}$  and  $M_{Z^{\circ}}$ .

An example input is provided in examples/HighScaleMSSM.in.

To ensure the equality of the gauge coupling unification scale  $M_{GUT}$  and the input scale for the supersymmetric parameters  $M_{High}$ , index 0 of EXTPAR and index 13 of MODSEL have to be set to the same value. In this case the GUT scale is imposed by the user. To obtain the equality of the two scales and calculate dynamically  $M_{GUT}$  the model configuration described in section 4.2.1 should be used.

The pMSSM [11] can be configured by specifying the same SSB model parameters for the first and second generation, but separate values for the quark and leptonic sectors. This cannot be done through the block MINPAR by omitting the parameters of one generation as only a single scalar SSB mass is defined.

4.2. Minimal Supergravity

The model minimal Supergravity is requested via MODSEL:

1 1 # MSSM:0, mSUGRA:1,....

For a review of minimal supergravity models see e.g. [10] and original references therein. A common parameter  $m_{\circ}$  is used for all scalar supersymmetry breaking parameters. The gaugino mass parameters are unified as  $m_{1/2}$ . A common trilinear parameter  $A_{\circ}$  initializes all individual trilinear parameters. The three parameters  $m_{\circ}$ ,  $m_{1/2}$  and  $A_{\circ}$ , defined at  $M_{GUT}$ , are input in the MINPAR block:

1	900.	#	mO
2	1200.	#	m1%2
5	-3000.	#	AO

in addition to the sign of  $\mu$  and  $\tan \beta$ . This model inherits from the generic three scales model as in this case  $M_{GUT}$  and  $M_{High}$  are identical.

An example input is provided in examples/mSUGRA.in.

#### 4.2.1. Supergravity inspired Models

A variant of mSUGRA is also implemented. If the EXTPAR parameters are given, the SSB parameters given in MINPAR are overwritten. This can be limited to a single parameter in EXTPAR. An example input is provided in examples/SUGRA.in.

The resulting model is identical to the model described in section 4.1.2 if  $M_{High}$  is specified at index 0 of EXTPAR. However if  $M_{High}$  is not specified, the scales  $M_{GUT}$  and  $M_{High}$  are identical and the gauge coupling unification, either dynamical (default) or user imposed through index 13 of MODSEL,

determines both scales. Having a dynamically calculated gauge unification scale exactly equal to the SUSY-breaking scale cannot be achieved with the standard SLHA MSSM input in contrast to this model.

## 4.3. Gauge Mediated SUSY Breaking

The Gauge Mediated SUSY-Breaking model, for a review see [34], is defined via MODSEL as:

1 102 # MSSM:0, mSUGRA:1,...

Its input parameters are defined in the block MINPAR:

1	100E3	# Lambda_susy		
2	200E3	# Lambda_mess		
52	1	# GMSB: N messenger SU2		
53	1	# GMSB: N messenger SU3		

in addition to the sign of  $\mu$  and  $\tan \beta$ . The number of U(1) messengers is calculated from the number of SU(2) and SU(3) messengers as defined in Eq. (24) of [37]. The boundary conditions are calculated and applied at M<sub>MESS</sub> (index 2).

The GMSB model inherits from the generic model with four scales. An example input is provided in examples/GMSB.in.

## 4.4. Minimal Gauge Mediated SUSY Breaking

The minimal Gauge Mediated SUSY-Breaking model is defined via MODSEL as:

1 2 # MSSM:0, mSUGRA:1,...

The input in block MINPAR is simplified with respect to GMSB in section 4.3 as the number of messengers SU(2) and SU(3) is fixed to unity.

mGMSB inherits from the GMSB model. An example input is provided in examples/mGMSB.in. 4.5. Anomaly Mediated SUSY Breaking

The Anomaly Mediated SUSY Breaking model [35, 36] is defined via MODSEL:

1 103 # MSSM:0, mSUGRA:1,...

Its input parameters are specified in MINPAR in addition to the sign of  $\mu$  and  $\tan\beta$  are:

1	450.	# mO
2	60E3	<pre># M_3%2 gravitino mass</pre>
5	3.	# c squarkLeft doublet
6	-1.	<pre># c up type squarkR singlet</pre>
7	-1.	<pre># c down type squarkR singlet</pre>
8	1.	<pre># c sleptonLeft doublet</pre>
9	1.	<pre># c sleptonRight singlet</pre>
10	-2.	# c Higgs u-type
11	-2.	# c Higgs d-type

The boundary conditions are calculated and applied at  $M_{GUT}$ . The input values with the indices 5 – 11 are model dependent factors which multiply the square of the common scalar mass parameter in the calculation of the boundary conditions at  $M_{GUT}$ .

AMSB inherits from the generic four scales model as the two scales  $M_{GUT}$  and  $M_{High}$  can be separated via MODSEL by requesting a fixed gauge coupling unification scale.

# 4.6. Minimal Anomaly Mediated SUSY Breaking

The minimal Anomaly Mediated SUSY-Breaking model is defined via MODSEL as:

1 3 # MSSM:0, mSUGRA:1,...

The input of MINPAR is simplified with respect to section 4.5 as the multiplicative factors for the scalar masses (indices 5 - 11) are set to unity.

The mAMSB model inherits from AMSB. An example input is provided in examples/mAMSB.in. 4.7. Compressed SuSy

The Compressed SUSY model [64] is requested in the MODSEL block as:

1 50 # MSSM:0, mSUGRA:1,

The gaugino mass parameters are calculated from a common parameter and three arbitrary coefficients  $C_i$  of the respective representations of the symmetric product of two adjoint representation of SU(5) (i.e. 24). For  $C_i \neq 0$ the gaugino mass degeneracy at GUT scale is lifted.

The input is defined in block MINPAR as:

1	100.	# mO
2	250.	# m1%2
5	-100.	# AO
3	1.0e+01	<pre># tanbeta(MZ)</pre>
4	1.0	# sign(mu)
6	0.22	#C24
7	0.00	#C75
8	0.00	#C200

The model inherits from the generic four scale model. An example input is provided in examples/CompressedSuSy.in

## 4.8. Inflation

The Inflation model is defined via MODSEL as:

1 200 # MSSM:0, mSUGRA:1,...

The inflation specific configuration is in the block SUSPECT\_CONFIG:

10	1.00000000e+00	#	Type of Inflation LLE=1, UDD=2
11	1.00000000e+00	#	index of L or U
12	2.00000000e+00	#	index of L or D
13	3.00000000e+00	#	index of E or D
14	1.0000000e-02	#	lambdaInflation(Inflation)

Either LLE or UDD can be chosen for the definition of the inflaton mass. The generational indices (values of indices 11-13 for i, j, k) can be chosen to specify a flat direction. The consistency of the choices noted in section 2.2.2 is checked. Inconsistent choices result in an error and stop of the calculation. The value of  $\lambda_6$  (index 14) at the inflation scale may also be specified as input. If the value is not specified, 1 is used as value.

The input parameters are specified in the block MINPAR, e.g.,

#### 2 8.5000000e+14 # INFLATION: Inflation scale

for the inflation scale in addition to  $\mu$  and tan  $\beta$ . In EXTPAR the parameters for the different variants of the MSSM described in section 4.1 are specified.

Compared to the MSSM the Inflation model has two additional parameters,  $A_6$  and  $\lambda_6$ . As boundary condition at the SUSY-breaking scale,  $A_6$  is calculated from  $A_t$ . The parameter  $\lambda_6$  has no influence on the calculation of the spectrum.

The two additional parameters as well as the inflaton mass are output in a scale dependent block INFLATION:

BLOCK INFLATION Q=8.5000000e+14

1	4.33371532e+04	# A6
2	1.14084300e+00	# lambda6
3	6.87081350e+03	# mPhi

where the inflaton mass is the square root of the mean of the soft breaking squared masses.

The model inherits from the generic five scale model:  $M_{GUT}$  for gauge coupling unification,  $M_{High}$  for the supersymmetry breaking parameters,  $M_{MESS}$  the inflation scale,  $M_{EWSB}$  and  $M_{Z^{\circ}}$ .

#### 4.9. External

An external model can be provided. Specifying MODSEL with

1 999 # MSSM:0, mSUGRA:1,...

calls this model. It can be provided by implementing the object ModelExternal inheriting from ModelBase and compile against the SuSpect3 library.

# 5. Calculation

As an example the calculation of a mSUGRA parameter set is performed for the parameters:

```
m_{\circ} = 900 \text{GeV}

m_{1/2} = 1200 \text{GeV}

A_{\circ} = -3000 \text{GeV}

\tan \beta = 20

\mu = +1
```

The full output is provided with the software distribution in the subdirectory **examples** in the file mSUGRA.out, only some of the blocks are listed here (and comments were edited):

```
BLOCK MODSEL
```

```
1.0000000e+00
                                # MSSM:0, mSUGRA:1, mGMSB=2,
         1
# mAMSB=3, (+100 for nonminimal GMSB, AMSB),
# Inflation: 200, External: 999
         3
               0.0000000e+00
                                # MSSM particle content:0,
# External: 99
        13
             -1.0000000e+00
                                # Gauge coupling unification
# scale: -1: calculated, value>0: value for scale fixed
        14
              -1.0000000e+00
                                # EWSB scale:
# -1: sqrt(stop1*stop2),
# value>0: value for scale fixed
BLOCK SUSPECT CONFIG
               2.1000000e+01
         0
                                # 21: 2-loop RGE (default),
# 11: 1-loop, 99: provided externally
               2.0000000e+00
                                # RGE accuracy: 1: moderate,
         3
# 2: accurate (default), 3: expert input via index 9
               2.0000000e+00
                                # choice for sparticles
         5
# masses rad. corr. excluding Higgs:
#
                2 ->all (recommended, default);
# 1->no R.C. in squarks & gauginos.
               2.0000000e+00
                                # Final spectrum accuracy:
         7
# 1 -> 1% acc.; 2 -> 0.01 % acc.(default)
         8
               2.0000000e+00
                                # Higgs boson masses
# rad. corr. calculation options:
# A simple (but very good) approximation (advantage=fast) : 0
```

```
# Full one-loop calculation
                                                            : 1
# One-loop + dominant DSVZ 2-loop (default,recommended)
                                                            : 2
BLOCK MINPAR
               9.0000000e+02
                                   MSUGRA: mO
         1
                                #
         2
               1.2000000e+03
                                #
                                   MSUGRA: m_1/2
         3
               2.0000000e+01
                                #
                                   tanbeta(mZ)
         4
               1.0000000e+00
                                #
                                   sign(mu)
                                   MSUGRA: AO
         5
              -3.0000000e+03
                                #
BLOCK SMINPUTS
         1
               1.27934000e+02
                                # alpha_em^-1(M_Z)^MSbar
         2
                                # G_F [GeV^-2]
               1.16639000e-05
         3
                                # alpha_S(M_Z)^MSbar
               1.1800000e-01
         4
               9.11870000e+01
                                # M_Z pole mass
         5
               4.1800000e+00
                                # mb(mb)^MSbar
         6
               1.7300000e+02
                                # mt pole mass
                                # mtau pole mass
         7
               1.77700000e+00
        13
               1.05658360e-01
                                # muon pole mass
        24
               1.4200000e+00
                                # charm pole mass
BLOCK HMIX Q=1.72400304e+03
         1
               2.01330599e+03
                                # mu(Q)
         2
                                # tanbeta(Q)
               1.92663632e+01
         3
                                # vev(Q)
               2.44003070e+02
         4
               4.77434506e+06
                                # MA^2(Q)
BLOCK GAUGE Q=1.34489088e+16
               5.44086472e-01
                                # gprime(Q) DRbar
         1
                                # g(Q) DRbar
         2
               7.02412615e-01
         3
               6.98524506e-01
                                # g_3(Q) DRbar
BLOCK MSOFT Q=1.72400304e+03
         1
               5.25225703e+02
                                # M_1
         2
                                # M_2
               9.54406026e+02
         3
               2.54213069e+03
                                # M_3
        21
               4.86427234e+05
                                # M^2_Hd
        22
              -4.01017724e+06
                                # M^2_Hu
        31
               1.18999153e+03
                                # M_eL
        32
               1.18999153e+03
                                # M_muL
        33
               1.12125121e+03
                                # M_tauL
        34
               1.00009204e+03
                                # M_eR
        35
               1.00009204e+03
                                # M_muR
```

	36	8.24069856	5e+02 #	# M_tauR
	41	2.44756888	3e+03 #	⊧ M_q1L
	42	2.44756888	3e+03 #	≠ M_q2L
	43	2.02265804	1e+03 #	ŧ M_q3L
	44	2.35965026	Se+03 #	≠ M_uR
	45	2.35965026	Se+03 #	≠ M_cR
	46	1.47723188	3e+03 #	≠ M_tR
	47	2.34881332	2e+03 #	≠ M_dR
	48	2.34881332	2e+03 #	t M_sR
	49	2.24171006	Se+03 #	≠ M_bR
BLO	CK MSOFT	Q=1.344890886	e+16	
	1	1.2000000	)e+03 #	* M_1
	2	1.2000000	)e+03 #	≠ M_2
	3	1.2000000	)e+03 #	ŧ M_3
	21	8.1000000	)e+05 #	≠ M^2_Hd
	22	8.1000000	)e+05 #	# M^2_Hu
	31	9.0000000	)e+02 #	ŧ M_eL
	32	9.0000000	)e+02 #	≠ M_muL
	33	9.0000000	)e+02 #	# M_tauL
	34	9.0000000	)e+02 #	# M_eR
	35	9.0000000	)e+02 #	≠ M_muR
	36	9.0000000	)e+02 #	# M_tauR
	41	9.0000000	)e+02 #	≠ M_q1L
	42	9.0000000	)e+02 #	≠ M_q2L
	43	9.0000000	)e+02 #	≠ M_q3L
	44	9.0000000	)e+02 #	# M_uR
	45	9.0000000	)e+02 #	≠ M_cR
	46	9.0000000	)e+02 #	≠ M_tR
	47	9.0000000	)e+02 #	≠ M_dR
	48	9.0000000	)e+02 #	t M_sR
	49	9.0000000	)e+02 #	≠ M_bR
BLO	CK AU Q=	1.72400304e+03	3	
1	1 -4	4.60623573e+03	3 <b>#</b> A_u	ı(Q) DRbar
2	2 -4	4.60623573e+03	3 # A_c	:(Q) DRbar
3	3 -:	3.11637739e+03	3 <b>#</b> A_t	;(Q) DRbar
BLO	CK ALPHA			
-	5.205082	37e-02 # Miz	king angl	e in the Higgs sector
BLO	CK MASS			

1	5.0000000e-03	# d quark mass
2	1.5000000e-02	# u quark mass
3	1.9000000e-01	# s quark mass
4	1.42000000e+00	# c pole mass
5	4.81354684e+00	<pre># b pole mass from mb(mb)_MSbar</pre>
6	1.73000000e+02	# t pole mass
11	5.11000000e-04	# electron mass
13	1.05658360e-01	# muon mass
15	1.77700000e+00	# tau mass
23	9.11870000e+01	# Z
24	8.04878483e+01	# W+
25	1.24911649e+02	# h
35	2.14067721e+03	# H
36	2.14080999e+03	# A
37	2.14258711e+03	# H+
1000001	2.51767568e+03	# ~d_L
1000002	2.51629841e+03	# ~u_L
1000003	2.51767568e+03	# ~s_L
1000004	2.51629841e+03	# ~c_L
1000005	2.06541208e+03	# ~b_1
1000006	1.49367951e+03	# ~t_1
1000011	1.20014656e+03	# ~e_L
1000012	1.19637831e+03	# ~nu_eL
1000013	1.20016602e+03	# ~mu_L
1000014	1.19637811e+03	# ~nu_muL
1000015	8.18162868e+02	# ~tau_1
1000016	1.12587444e+03	# ~nu_tauL
1000021	2.59653958e+03	# ~g
1000022	5.20861806e+02	# ~chi_10
1000023	9.85073613e+02	# ~chi_20
1000024	9.85246261e+02	# ~chi_1+
1000025	-2.00867791e+03	# ~chi_30
1000035	2.01085133e+03	# ~chi_40
1000037	2.01181065e+03	# ~chi_2+
2000001	2.41345033e+03	# ~d_R
2000002	2.42394519e+03	# ~u_R
2000003	2.41345033e+03	#~s_R
2000004	2.42394519e+03	# ~c_R

2000005	2.30563356e+03	# ~b_2
2000006	2.09869582e+03	# ~t_2
2000011	1.00344813e+03	# ~e_R
2000013	1.00342496e+03	# ~mu_R
2000015	1.13292099e+03	# ~tau_2

At  $M_{GUT}$  the gauge couplings are unified exactly for the couplings  $g_1$  and  $g_2$ when taking into account the factor  $\sqrt{\frac{3}{5}}$  from SU(5). They unify approximately with  $g_3$ .  $M_{EWSB}$  as geometric mean of the two stop masses is about 1.7 TeV. At  $M_{EWSB}$  tan  $\beta$  is slightly smaller than its input value which is defined at  $M_{Z^{\circ}}$ .

The supersymmetry soft breaking masses, unified at  $M_{GUT}$ , after RGE evolution lead to a non-unified spectrum. The benchmark point was chosen to lead to a mass of the lightest neutral Higgs boson of ~ 125GeV.

## 5.1. Comparisons

SuSpect2 has been compared extensively with other spectrum generators in the past, e.g. [65]. Furthermore a comparison with the spectrum calculator SoftSUSY was performed in [66] showing an excellent agreement within the theoretical uncertainties.

The implementation of the algorithms in SuSpect3 is similar, but not identical to the one in SuSpect2, therefore differences are expected, though these must be less than the theoretical uncertainties of the calculation. During the development of SuSpect3 extensive comparisons have been performed with SuSpect2 for each step of the calculation to ensure that each calculation, given the same input, results in identical results at machine level precision. For several specific parameter sets the comparisons were performed with extreme error settings, such as increasing the number of iterations in the calculation of the pole mass for the Higgs sector, leading to excellent agreement.

In the wino region the lightest neutralino and the lightest chargino are degenerate in their running masses at the EWSB scale. When calculating the radiative corrections in order to predict the pole masses, the mass of the chargino is shifted upward by  $\mathcal{O}(100)$  MeV. Such a parameter set is very sensitive to the details of the implementation of radiative corrections. Detailed comparisons between SuSpect3 and SuSpect2 showed an excellent agreement.



Figure 1: (Left) The supersymmetry breaking masses of the benchmark point section 5 at the EWSB scale are compared using SuSpect2 and SuSpect3. On the lower panel the normalized relative difference is shown. (Right) The pole masses are shown for SuSpect3 as function of the SuSpect2 calculation. On the lower panel the normalized relative mass difference.

In fig. 1 an illustration for the mSUGRA point defined and discussed in section 5 is shown for the default precision settings. On the left the RGE evolution is tested by comparing the running supersymmetry soft breaking masses at the EWSB scale between SuSpect3 and SuSpect2. In the Higgs sector the absolute value is displayed. The agreement is for most masses better than  $10^{-4}$ . The yukawa couplings on the bottom mass agree to the per mil level explaining the slightly worse agreement for  $M_{H_d}$ . On the right panel the pole masses are compared. The agreement is better than per mil for all masses and for most masses at the level of  $5 \cdot 10^{-5}$ .

The mSUGRA point has also been compared to the result of a SPHENO calculation. For this comparison the EWSB scale in SuSpect3 was set to 1 TeV as SPHENO was run with the SPA convention [63]. The value of  $\tan \beta(M_{Z^{\circ}})$ in SuSpect3 was adjusted so that  $\tan \beta(M_{EWSB}) = 20$  as output by SPHENO. The running mass of the block MSOFT and the pole masses of block MASS agree at the level of several  $10^{-3}$  for most of the masses.

### 6. Conclusion

The MSSM is an attractive extension of the Standard Model providing a light Higgs boson, gauge coupling unification and a candidate for dark matter. SuSpect3, written in C++, is a sophisticated tool translating input parameters into a particle spectrum of Higgs bosons and supersymmetric particles. The new structure of SuSpect3, a major rewrite of SuSpect, allows for an easier extension of the supported models. The RGE evolution of new parameters and the addition of new variants of EWSB is simplified. SuSpect3 provides a model for cosmological inflation as well as the RGE evolution of its parameters. The new variant of EWSB, where the measured Higgs boson mass is used as input instead of  $A_t$ , written initially for a single EWSB variant, is another example of the advantage of the new structure.

Superymmetry remains an attractive model to tie together different fields in a concrete model valid up to  $M_{GUT}$ . The exploration of multi dimensional parameter space depends on precise predictions and efficient algorithms. Future work will center on the improvement of the new EWSB variant to reduce the number of dimensions of these explorations.

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#### Appendix A. Installing SUSPECT3

The procedure to install SuSpect3 and run a mSUGRA calculation from an input file shipped with the package is:

```
wget http://suspect.in2p3.fr/tar/suspect3.tar.gz
mkdir myDir
mv suspect3.tar.gz myDir
cd myDir
tar xvfz suspect3.tar.gz
./configure
make
suspect3 -d examples/mSUGRA.in
```

In case wget is not available:

Open an internet browser enter the address: http://suspect.in2p3.fr download suspect3.tar.gz

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