# SPheno 3.1: extensions including flavour, CP-phases and models beyond the MSSM

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## Abstract

We describe recent extensions of the program `SPheno` including flavour aspects, CP-phases, R-parity violation and low energy observables. In case of flavour mixing all masses of supersymmetric particles are calculated including the complete flavour structure and all possible CP-phases at the 1-loop level. We give details on implemented seesaw models, low energy observables and the corresponding extension of the SUSY Les Houches Accord. Moreover, we comment on the possiblities to include MSSM extensions in `SPheno`.

## 1. Program Summary

**Program title**: SPheno
**Program Obtainable from**: `http://projects.hepforge.org/spheno/`
**Programming language**: F95
**Computers for which the program has been designed**: PC running under Linux, should run in every Unix environment
**Operating systems**: Linux, Unix
**Keywords**: Supersymmetry, renormalization group equations, mass spectra of supersymmetric models, Runge-Kutta, decays of supersymmetric particles, production
**Nature of problem**: The first issue is the determination of the masses and couplings of supersymmetric particles in various supersymmetric models the R-parity conserved MSSM with generation mixing and including CP-violating phases, various seesaw extensions of the MSSM and the MSSM with bilinear R-parity breaking. Low energy data on Standard Model fermion masses, gauge couplings and electroweak gauge boson masses serve as constraints. Radiative corrections from supersymmetric particles to these inputs must be calculated. Theoretical constraints on the soft SUSY breaking parameters from a high scale theory are imposed and the parameters at the electroweak scale are obtained from the high scale parameters by evaluating the corresponding renormalization group equations. These parameters must be consistent with the requirement of correct electroweak symmetry breaking. The second issue is to use the obtained masses and couplings for calculating decay widths and branching ratios of supersymmetric particles as well as the cross sections for theses particles in electron positron annihilation. The third issue is to calculate low energy constraints in the B-meson sector such as $\mathrm{BR}(b \to s\gamma)$, $\Delta M_{B_s}$, rare lepton decays, such as $\mathrm{BR}(\mu \to e\gamma)$, the SUSY contributions to anomalous magnetic moments and electric dipole moments of leptons, the SUSY contributions to the rho parameter as well as lepton flavour violating $Z$ decays.
**Solution method**: The renormalization connecting a high scale and the electroweak scale is calculated by the Runge-Kutta method. Iteration provides a solution consistent with with the multi-boundary conditions. In case of three-body decays and for the calculation of initial state radiation Gaussian quadrature is used for the numerical solution of the integrals.
**Restrictions:** In case of R-parity violation the cross sections are not calculated.
**Running time**: 0.2 second on a Intel(R) Core(TM)2 Duo CPU T9900 with 3.06GHz

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## 2. Introduction

In its orginal version `SPheno` had been designed to calculate the spectrum in the MSSM neglecting any effects due to generation mixing and/or CP violation [1]. Moreover, the two- and three-body decays of the SUSY particles as well as of the Higgs bosons can be calculated as well as the production rates of these particles in $e^+e^-$ annihilation. The code itself is written in `FORTRAN 95`.

The program has been extended to include flavour aspects, CP-violation and R-parity violation. Moreover, different variants of the seesaw mechanism have been implemented. In this paper we describe the corresponding changes and implementations. Details on the algorithms used can be found in the orginal manual [1]. Moreover, we give in the appendices the default values for various flags as well as the error coding.

## 3. Extensions with MSSM particle content at the electroweak scale and conserved R-parity

`SPheno` has been extended to include flavour and CP violating phases using the SLHA2 conventions [2] for the general MSSM. For this purpose the complete flavour structures including CP-phases have been implemented in the RGEs at the 2-loop level using the formulas given in [3]. We have extended the formulas of [4] for the 1-loop masses to account for the flavour structures, e.g. we calculate the 1-loop corrected $6 \times 6$ mass matrices for squarks and charged leptons and the 1-loop corrected $3 \times 3$ mass matrix for sneutrinos [5, 6]. Moreover, we take into account all possible phases in the calculation of all mass matrices at the 1-loop level but for one exception: we do not consider the loop induced mixing between the scalar and pseudoscalar Higgs bosons.

Beside the calculation of the spectrum also the decay routines have been extended to calculate all possible two- and three body decays of supersymmetric particles and Higgs bosons at leading order including flavour effects. In addition the set of low energy observables has been extended as described in section 5.

Within the MSSM several model classes are implemented

- High scale models like mSUGRA, GMSB, AMSB

- A SUGRA scenario where all soft SUSY breaking parameters are given freely at the GUT scale which is determined usually via the condition $g_1(M_{\mathrm{GUT}}) = g_2(M_{\mathrm{GUT}})$. However, this scale can be set to a fixed value using entry 31 in block `SPhenoInput`, see section 6.2.5.

- All MSSM parameters specified at the electroweak scale $Q_{EWSB}$ with a user specified value for $Q_{EWSB}$.

In all cases it is assumed that the required input is given via the SLHA convention [7, 2].

In addition several classes of neutrino mass models have been included with additional states at high energy scales:

- A seesaw I model with different masses for the right-handed neutrinos. The corresponding particle content can be chosen setting the entry 3 of the block `MODSEL` as described in section 6.1.2. The parameters are set using the blocks `MNURIN` and `YNUOIN`, see sections 6.2.2 and 6.2.7, respectively. Using this the results of [8, 9] have been obtained.

- Two variants of seesaw II model have been implemented. Here one can either choose a pair of $SU(2)$ triplets or a pair of $SU(5)$ 15-plets to generate neutrino masses. The first version uses the formulas [10] including the corrections presented in [11] and 2-loop RGEs for the gauge couplings and gaugino mass parameters as used in [12]. Here the blocks `Higgs3IN` and `YT0IN` have to be used to transfer the data, see sections 6.2.1 and 6.2.8. This variant is faster if one uses 2-loop RGEs but less accurate in particular for low seesaw scales [13].

  In case of a pair of $SU(5)$ 15-plets a second variant has been implemented using the complete 2-loop RGEs and corresponding threshold corrections at the seesaw scale as described in [14]. Here the blocks `Higgs3IN` and `YTIN` have to be used to transfer the data, see sections 6.2.1 and 6.2.9.

- A seesaw III model with three $SU(5)$ matter 24-plets using the complete 2-loop RGEs and corresponding threshold corrections at the seesaw scales as described in [13]. The blocks `MWMIN` and `YB3IN` can be used to set the parameters, see sections 6.2.3 and 6.2.6.

- A minimal $SU(5)$ model as described in [15]. The corresponding particle content can be chosen setting the entry 3 of the block `MODSEL` as described in section 6.1.2. The parameters are set using the blocks `MNURIN` and `YNUOIN`, see sections 6.2.2 and 6.2.7, respectively. The additional $SU(5)$ parameters can be set extending the block `MINPAR` as described in section 6.1.1.

Note, that in these models the particle content at the electroweak scale is the same as in the usual MSSM and that the differences are only due to the modified evaluation of the parameters.

## 4. R-parity violation

Currently the bilinear model is implemented, i.e. extending the superpotential by the terms

$$W_{\not R} = \epsilon_i \widehat{L}_i \widehat{H}_u \tag{1}$$

and the corresponding soft SUSY breaking terms. In this class of models neutrino physics can be explaining due to the mixing of neutralinos with neutrinos and by loop contributions. The corresponding details can be found in [16, 17]. The same parameters giving rise to neutrino masses also lead to the decay of the LSP and, thus, there are correlations between the LSP decay properties and neutrino physics [18, 19, 20, 21, 22, 23].

Here one has two options

- use within SLHA2 the blocks `EXTPAR`, `RVSNVEVIN` and `RVKAPPAIN` to specify the model parameters at the electroweak scale

- use one of the high scale models mSUGRA, GMSB or AMSB to calculate the R-parity conserving parameters at the electroweak scale. The R-parity parameters are then added at this scale using one of the two possiblities

  - add them using the blocks `RVSNVEVIN` and `RVKAPPAIN`
  - use the flag 91 of the block `SPhenoInput` as described in section 6.2.5 to calculate the $\epsilon_i$ and the sneutrino vacuum expectations values $v_i$ such, that neutrino physics is respected. The corresponding neutrino data can be specified in block `NeutrinoBoundsIn`, see section 6.2.4.

In this class of models the mass matrices are calculated at tree-level except for the neutrino/neutralino mass matrix which requires the inclusion of the full 1-loop contributions. Moreover, all possible R-parity violating decay modes are calculated.

## 5. Low energy observables

In this section we summarize the main references from which the formulas for the corresponding implementation have been taken. Moreover we give implementation specific details whenever necessary. For the moment the low energy observables are only calculated if there is an effective MSSM at the electroweak scale and conserved R-parity.

### 5.1. B-physics observables

The following observables are calculated in `SPheno`: $BR(b \to s\gamma)$, $BR(b \to s\mu^+\mu^-)$, $BR(b \to s\sum_i \nu_i\nu_i)$, $BR(B_d^0 \to \mu^+\mu^-)$, $BR(B_s^0 \to \mu^+\mu^-)$, $BR(B_u \to \tau^+\nu)$, $\Delta M_{B_s^0}$ and $\Delta M_{B_d^0}$. For the calculation of the Wilson coefficients we use running couplings and SUSY masses which are in general evolved at the scale $Q = m_Z$. The only exception is $BR(b \to s\gamma)$ as we use here the formula of ref. [24] where the corresponding coefficients have to be given at the scale $Q = 160$ GeV. For the calculation of the Wilson coefficients and the corresponding observables we have used

Table 1: Parameters used in the calculation of the $B$-physics observables.

| | | | |
|---|---|---|---|
| $\tau_{B^0} = 1.525$ ps | $\tau_{B^0_s} = 1.472$ ps | $\tau_{B^+_u} = 1.638$ ps | $\tau_{B^+_c} = 0.45$ ps |
| $f_B = 190$ MeV | $B_{B_d} = 1.22$ | $f_{B_s} = 230$ MeV | $B_{B_s} = 1.26$ |
| $M_{B^0} = 5.2795$ GeV | $M_{B^0_s} = 5.3663$ GeV | $\eta_B = 0.55$ | |

- $BR(b \to s\gamma)$ [25, 26, 24]; the value given is for $E_\gamma \geq 1.6$ GeV and $m_c/m_b = 0.23$.

- $BR(b \to s\mu^+\mu^-)$ [25, 26, 27]

- $BR(b \to s \sum_i \nu_i \nu_i)$ [26, 25]

- $BR(B^0_s \to \mu^+\mu^-)$, $BR(B^0_d \to \mu^+\mu^-)$ [28, 26, 29]

- $BR(B_u \to \tau^+\nu)$ [30]

- $\Delta M_{B^0_s}$ and $\Delta M_{B^0_d}$ [26, 29]. For the hadronic parameters we follow [29]:

$$\bar{P}_1^{LR} = -0.71 \ , \ \bar{P}_2^{LR} = -0.9 \ , \ \bar{P}_1^{SLL} = -0.37 \ , \ \bar{P}_1^{SLL} = -0.72 \ .$$

The remaining parameters used are given in table 1.

### 5.2. Lepton sector

In the leptonic sector a similar strategy is used: all parameters are evolved to $m_Z$ and then running masses and mixing matrices are used as input for the observables. The implemented formulas are based on

- SUSY contributions to the anomalous magnetic moment of the leptons [31]

- electric dipole moments (EDMs) of the leptons [32, 33]

- two body decays $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ [34, 33]

- three body decays $\mu \to ee^+e^-$, $\tau \to ee^+e^-$ and $\tau \to \mu\mu^+\mu^-$ [35]

- $Z$ decays, $Z \to e^\pm\mu^\mp$, $Z \to e^\pm\tau^\mp$ and $Z \to \mu^\pm\tau^\mp$, [36]

### 5.3. Other constraints

In addition the EDM of the neutron can be calculated using two different models for the neutron where the formulas are based on [32] and we use the same hadronic parameters. Moreover, one can also calculate the SUSY contributions to the $\rho$-parameter as given in [37].

## 6. Extensions to SLHA

In this section we describe the SPheno specific extensions to the SUSY Les Houches Accord (SLHA) [7, 2]. We start first with extensions to existing blocks and then discuss new blocks which either control the behaviour of SPheno or contain additional model parameters for MSSM extensions. Note, that all additional Yukawa couplings have been implemented in complex forms and the corresponding information can be passed by using the corresponding blocks starting with IM [2].

### 6.1. Extensions of existing blocks

#### 6.1.1. Block `MINPAR`

In the case that generation mixing is switched on, i.e. the entry 6 contains a non-zero value, then independent of this value flavour violation is switched on in the (s)lepton as well as in the (s)quark sector.

In case of extending the model by a minimal $SU(5)$ as used in [15] this block gets extended by the following entries

7: $SO(10)$ scale where the universal soft SUSY breaking parameters are defined.

8: extra $D$-terms due to the breaking of $SO(10)$ to $SU(5)$

9: $\lambda$-coupling of the Higgs 24-plet to the $\bar{5}_H$

10: $\lambda'$-coupling of the Higgs 24-plet to the $5_H$

#### 6.1.2. Block `MODSEL`

Four switches have been added to flag 3 (particle content)

2: includes the particle content of a minimal $SU(5)$ model between $M_{\mathrm{GUT}}$ and a user chosen $SO(10)$ scale, where the SUSY boundary conditions are set. The details of this model are described in [15]. In this case the mass parameters of the right handed neutrinos are stored in the block `MNURIN` (section 6.2.2) and the corresponding neutrino Yukawa couplings can be stored in the block `YNUOIN` (section 6.2.7). The data is understood to be defined at the GUT-scale. The additional $SU(5)$ parameters as well as the $SO(10)$ scale are specified as extensions of the block `MINPAR`, see section 6.1.1

3: includes three right-handed (s)neutrinos with a common mass for all three neutrinos. The neutrino Yukawa couplings $Y_\nu$ can be specified at the GUT-scale, see section 6.2.7, and the mass of the right-neutrinos at their proper scale, see section 6.2.2.

4: includes three right-handed (s)neutrinos which are included at their proper mass scale. The neutrino Yukawa couplings $Y_\nu$ can be specified at the GUT-scale, see section 6.2.7, and the masses of the right-neutrinos at their proper scale, see section 6.2.2.

5: includes a Higgs triplet (15-plet) to realize the seesaw II where the formulas of [10] including the corrections presented in [11] and the 2-loop contributions to the RGEs of the gauge couplings and gaugino mass parameters have been implemented. The additional model data are specified in the blocks `Higgs3IN` and `YT0`, see sections 6.2.1 and 6.2.8,respectively.

10: includes three Higgs 24-plets to realize the seesaw type III where the complete 2-loop RGEs as given in [13] are used. The additional model data are specified in the blocks `MWMIN` and `YB3IN`, see sections 6.2.3 and 6.2.6, respectively.

11: includes a Higgs 15-plet to realize the seesaw II where the complete 2-loop RGEs as given in [13] are used. The additional model data are specified in the blocks `Higgs3IN` and `YTIN`, see sections 6.2.1 and 6.2.9, respectively.

### 6.2. New input blocks

In the output the blocks will be given without the ending IN.

#### 6.2.1. Block `Higgs3IN`

Used to specifiy the model of the seesaw model type II. The data are given in the format

```
(2x,i3,2x,1p,e16.8,0p,2x,'# ',a)
```

and the entries correspond to

1: mass of the Higgs triplet (15-plet)

Table 2: Default values for fitting R-parity violating parameters if the entries in block `NeutrinoBoundsIn` are not specified. The values are taken from [38] and correspond to the 1 $\sigma$ range but for $|U_{e3,max}|^2$ which is 90% CL.

| $\tan^2 \theta_{atm,min}$ | 0.8182 | $\tan^2 \theta_{sol,min}$ | 0.4286 | $U^2_{e3,min}$ | 0 |
|---|---|---|---|---|---|
| $\tan^2 \theta_{atm,max}$ | 1.3256 | $\tan^2 \theta_{sol,max}$ | 0.4970 | $|U_{e3,max}|^2$ | 0.035 |
| $\Delta m^2_{atm,min}$ | $2.36 \cdot 10^{-3}$ eV$^2$ | $\Delta m^2_{sol,min}$ | $7.46 \cdot 10^{-5}$ eV$^2$ | | |
| $\Delta m^2_{atm,max}$ | $2.54 \cdot 10^{-3}$ eV$^2$ | $\Delta m^2_{sol,max}$ | $7.83 \cdot 10^{-5}$ eV$^2$ | | |

  2: real part of $\lambda_1$

  3 imaginary part of $\lambda_1$

  4: real part of $\lambda_2$

  5 imaginary part of $\lambda_2$

  6: if 0 (1) use RGEs for the triplet (15-plet) case

*6.2.2. Block* `MNURIN`

In this block one can specify the masses of the right-handed neutrinos within the seesaw I model. The masses $m_{Ri}$ are specified in the `FORTRAN` format

`(1x,i3,3x,1p,e16.8,3x,'#',a).`

*6.2.3. Block* `MWMIN`

Here one can specify the mass matrix of the 24-plets $M_{Wij}$ at $M_{\text{GUT}}$ for the seesaw type III model using the formulas of [13], where the data are given in the `FORTRAN` format

`(1x,2i3,3x,1p,e16.8,3x,'#',a)`

where the first two integers in the format correspond to $i$ and $j$ and the double precision number to the mass parameter.

*6.2.4. Block* `NeutrinoBoundsIn`

One can use `SPheno` to obtain R-parity violating parameters consistent with neutrino data. The corresponding default values are given in table 6.2.4. This block can be used to modify them. The `FORTRAN` format is

`(1x,i2,3x,1p,e16.8,0p,3x,#,1x,a)}`

and the entries correspond to

  1: $\Delta m^2_{atm,min}$ ... lower bound on the athmospheric mass difference

  2: $\Delta m^2_{atm,max}$ ... upper bound on the athmospheric mass difference

  3: $\tan^2 \theta_{atm,min}$ ... lower bound on the tan squared of the athmospheric mixing angle

  4: $\tan^2 \theta_{atm,max}$ ... upper bound on the tan squared of the athmospheric mixing angle

  5: $\Delta m^2_{sol,min}$ ... lower bound on the solar mass difference

  6: $\Delta m^2_{sol,max}$ ... upper bound on the solar mass difference

  7: $\tan^2 \theta_{sol,min}$ ... lower bound on the tan squared of the solar mixing angle

  8: $\tan^2 \theta_{sol,max}$ ... upper bound on the tan squared of the solar mixing angle

  9: $U^2_{e3,min}$ ... lower bound on the mixing element $U_{e3}$ squared (reactor angle)

  10: $U^2_{e3,max}$ ... upper bound on the mixing element $U_{e3}$ squared

*6.2.5. Block* `SPhenoInput`

This block sets the `SPheno` specific flags. The FORTRAN format is

    (1x,i2,3x,1p,e16.8,0p,3x,#,1x,a)}

and the entries correspond to

- 1: sets the error level

- 2: if 1 the the SPA conventions [39] are used

- 3: takes a spectrum which is given by an external program

- 4: introduces an extension of the SLHA output: in the case of flavour violation, flavour ordered states are used instead of mass ordered states.

- 11: if 1 then the branching ratios of the SUSY and Higgs particles are calculated, if 0 then this calculation is omitted.

- 12: sets minimum value for a branching ratios, so that it appears in the output

- 21: if 1 then the cross sections of SUSY and Higgs particles in $e^+e^-$ annihilation are calculated, if 0 then this calculation is omitted.

- 22: sets the center of mass energy $E_{cms}$, can be repeated up to 100 times

- 23: sets the electron polarisation $P_m$, can be repeated up to 100 times

- 24: sets the positron polarisation $P_p$, can be repeated up to 100 times

- 25: whether to use initial state radiation in the calculation of the cross sections

- 26: sets minimum value for a cross section, so that it appears in the output

- 31: sets the value of $M_{\mathrm{GUT}}$, otherwise $M_{\mathrm{GUT}}$ is determined by the condition $g_1 = g_2$

- 32: sets strict unification, i.e. $g_1 = g_2 = g_3$

- 34: sets the relative precision with which the masses are calculated, default is $10^{-6}$

- 35: sets the maximal number of iterations in the calculation of the masses, default is 40

- 36: whether to write out debug information for the loop calculations

- 38: this entry sets the loop order of the RGEs: either 1 or 2, default is 2, i.e. using 2-loop RGEs

- 41: sets the width of the Z-boson $\Gamma_Z$, default is 2.49 GeV

- 42: sets the width of the W-boson $\Gamma_W$, default is 2.06 GeV

- 80: if not set 0 the program exists with a non-zero value if a problem has occured

- 90: if 1 add R-parity to a high scale spectrum calculated either from mSUGRA, GMSB or AMSB boundary conditions

- 91: if 1 than bilinear parameters are calculated such that neutrino data are fitted in the experimenatal allowed range (the range can be changed using the Block `NeutrinoBoundsIn`, see section 6.2.4)

- 92: if 1 gives in case of R-parity violation only the $4 \times 4$ MSSM part of the neutrino/neutralino mixing matrix $N$ and the correspondingly the $2 \times 2$ parts of the charged lepton/chargino mixing matrices $U$ and $V$ as well as the block for the stau mixing. This is in particular useful in case one uses the program `Prospino` [40] or older versions of the program `Phythia` [41].

### 6.2.6. Block `YB3IN`

Here one can specify the neutrino Yukawa $Y_{ij}^{III}$ coupling at $M_{\rm GUT}$ for the seesaw type III model using the formulas of [13], where the data are given in the `FORTRAN` format

`(1x,2i3,3x,1p,e16.8,3x,'#',a)`

where the first two integers in the format correspond to $i$ and $j$ and the double precision number to Yukawa coupling.

### 6.2.7. Block `YNUOIN`

This block specifies the neutrino Yukawa couplings $Y_\nu$ at the GUT scale and the corresponding superpotential term is given by $W = Y_{\nu,ij}\hat{\nu}_i^C \hat{L}_j \hat{H}_u$. It is assumed that the right-handed neutrinos are in the mass eigenbasis. The real parts are specified in the block `YNUOIN` with the `FORTRAN` format

`(1x,i2,1x,i2,3x,1p,e16.8,0p,3x,'#',1x,a)`

and the imaginary parts in the block `IMYNUOIN` with the same `FORTRAN` input.

### 6.2.8. Block `YTOIN`

Here one can specify the neutrino Yukawa $Y_{ij}^T$ coupling at $M_{\rm GUT}$ for the seesaw type II model using the formulas of [10, 11]. The data is given in the `FORTRAN` format

`(1x,2i3,3x,1p,e16.8,3x,'#',a)`

where the first two integers in the format correspond to $i$ and $j$ and the double precision number to Yukawa coupling.

### 6.2.9. Block `YTIN`

Here one can specify the neutrino Yukawa $Y_{ij}^T$ coupling at $M_{\rm GUT}$ for the seesaw type II model using the formulas of [13], where the data is given in the `FORTRAN` format

`(1x,2i3,3x,1p,e16.8,3x,'#',a)`

where the first two integers in the format correspond to $i$ and $j$ and the double precision number to Yukawa coupling.

### 6.3. New output block

### 6.3.1. Block `SPhenoLowEnergy`

In this block the calculated values of the low energy observables are given:

1 $BR(b \to s\gamma)$

2 $BR(b \to s\mu^+\mu^-)$

3 $BR(b \to s \sum_i \nu_i \nu_i)$

4 $BR(B_d^0 \to \mu^+\mu^-)$

5 $BR(B_s^0 \to \mu^+\mu^-)$

6 $BR(B_u \to \tau^+\nu)$

7 $BR(B_u \to \tau^+\nu)/BR(B_u \to \tau^+\nu)_{SM}$

8 $\Delta(M_{B_s^0})$ [in ps$^{-1}$]

9 $\Delta(M_{B_d^0})$ [in ps$^{-1}$]

20 SUSY contribution to the anomalous magnetic moment of the electron $\Delta(\frac{g-2}{2})_e$

21 SUSY contribution to the anomalous magnetic moment of the muon $\Delta(\frac{g-2}{2})_\mu$

22 SUSY contribution to the anomalous magnetic moment of the tau $\Delta(\frac{g-2}{2})_\tau$

23 electric dipole moment of the electron $d_e$

24 electric dipole moment of the muon $d_\mu$

25 electric dipole moment of the tau $d_\tau$

26 $BR(\mu \to e\gamma)$

27 $BR(\tau \to e\gamma)$

28 $BR(\tau \to \mu\gamma)$

29 $BR(\mu^+ \to e^+e^+e^-)$

30 $BR(\tau^+ \to e^+e^+e^-)$

31 $BR(\tau^+ \to \mu^+\mu^+\mu^-)$

39 SUSY contribution to the $\rho$-parameter

40 $BR(Z^0 \to e^\pm\mu^\mp)$

41 $BR(Z^0 \to e^\pm\tau^\mp)$

42 $BR(Z^0 \to \mu^\pm\tau^\mp)$


## 7. Installation and implementing new models

### 7.1. Installation

SPheno can be downloaded from

http://projects.hepforge.org/spheno/

where the latest tar-ball SPheno3.x.y.tar.gz can found as well as older versions. Unpacking will create the directory SPheno3.x.y where x and y are integers corresponding to the sub-version. This directory will contain the following subdirectories:

- bin: here the executable SPheno will be stored

- doc: contains the SPheno documentations

- include: here all the mod-files are stored

- input: contains input example files

- lib: here the library libSPheno.a will be stored

- output: contains the output files corresponding to the examples stored in input

- src: contains the source code

The directory SPheno3.x.y contains a Makefile which can be used to compile SPheno. The default compiler is Intels ifort, but by typing make F90=compiler on the console one can use a different compiler where compiler has to replaced by the compiler's name. The following compilers have been added NAG nagfor, Lahey lf95 and g95.

It is well known that compilation of the module RGEs.F90 can be time consuming due to the length of the 2-loop RGEs for the seesaw models of type II and type III. For this reason they are not compiled by default. If the corresponding RGEs should be included then the line

```
PreDef = -DGENERATIONMIXING -DONLYDOUBLE
```

should be replaced by

```
                   PreDef = -DGENERATIONMIXING -DONLYDOUBLE -DSEESAWIII
```
i.e. add **-DSEESAWIII**.

In the case that one want to have quadrupole precision in various parts of the code instead of double precision, one has to take out the **-DONLYDOUBLE** in the line mentioned above. Note that this can substantially slow down SPheno. Moreover, not all parts are yet implemented with quadrupole precision. The main focus has been on the loop functions as well as on mixing between neutralinos and neutrinos in case of R-parity violation.

*7.2. Implementing new models*

New models can easily implemented using the `SARAH` package [42, 43]. For this purpose one has to put the code generated by `SARAH` in a new directory within the directory `SPheno3.x.y` and run the corresponding Makefile. An additional executable will be stored in the directory `bin`.

## 8. Input and output

Starting with version `SPheno` 3.1 there are two main differences with respect to the input and output

1. `SPheno` accepts only the SLHA input format as specified and all the output is given in this format. In section 6 we have described the extensions to control program specific features as well as model extensions. The orginal `SPheno` input using the files `HighScale.in`, `StandardModel.in` and `Control.in` as well as the output in the file `SPheno.out` have been disabled. Detailed error messages and warnings will also be written to the file `Messages.out`.

2. One can provide input name and output name as command line options where the first (second) name, if present, is interpreted as input (output) filename, e.g.

                   SPheno InName OutName

   takes `InName` for the file containing the input and will write the output to the file `OutName`. In case that the file `InName` is not found `SPheno` will look for a file called `LesHouches.in` as default. The default name for the output is `SPheno.spc`. The length of the names `InName` and `OutName` must not exceed 60 characters.

## 9. Conclusions and comments

`SPheno` is constantly developing, in particular in view of implementing additional models and low energy observables. In addition it is planed

- to implement the missing pieces of the SLHA conventions as listed in appendix Appendix B.

- mixing between $A_0$ and $H_0$ in case of CP phases

- low energy observables for the case of R-parity violation

In section 5 several hadronic parameters for the calculation of low energy observables are hard-coded in the program. It is planned to construct routines to allow user defined changes in the future.

## Acknowledgements

## Appendix A. Default SM values

The following default values will be used if not given in the file `LesHouches.in`.

- CKM-matrix, Wolfenstein parameters: $\lambda = 0.2265$, $A = 0.807$, $\rho = 0.141$, $\eta = 0.343$

- gauge sector: $1/\alpha_{em}(0) = 137.0359895$, $m_Z = 91.187$ GeV, $G_F = 1.16637 \cdot 10^{-5}\text{GeV}^{-2}$, $\alpha_s^{\overline{MS}}(m_Z) = 0.1184$

- lepton masses: $m_e = 510.99891$ keV, $m_\mu = 105.658$ MeV, $m_\tau = 1.7768$ GeV

- quark masses: $m_u(2\text{ GeV}) = 3$ MeV, $m_d(2\text{ GeV}) = 5$ MeV, $m_s(2\text{ GeV}) = 105$ MeV, $m_c(m_c) = 1.27$ GeV, $m_b(m_b) = 4.2$ GeV, $m_t = 171.3$ GeV; the top mass is interpreted as on-shell mass

## Appendix B. Unsupported SLHA features

Here we list the features of the SLHA conventions [7, 2] which are not yet supported:

- In `Block MODSEL` the following entries are currently ignored:

  11: the possiblity to give the parameters at $n$ equidistant values of $Q$ between $m_Z$ and $Q_{EWSB}$
  21: to give the mass parameters at the pole mass of each individual particle

- In `Block EXTPAR` the following entries are currently ignored:

  27: pole mass of the charged Higgs boson
  51: (GMSB only) $U(1)_Y$ messenger index
  52: (GMSB only) $SU(2)_L$ messenger index
  53: (GMSB only) $SU(3)_C$ messenger index

- the `Block QEXTPAR`

- the `Block RVLAMLLEIN`

- the `Block RVLAMLQDIN`

- the `Block RVLAMUDDIN`

- the `Block RVTLLEIN`

- the `Block RVTLQDIN`

- the `Block RVTUDDIN`

- the `Block RVDIN`

- the `Block RVM2LH1IN`

These features will be implemented within the next updates.

## Appendix C. Error messages and warnings, interpretation of the variable kont

Here we describe how to interpret the values of the variable `kont` which is used in the error system of `SPheno`. The corresponding warnings and error messages are also given in the file 'Messages.out' if the error level is set to the appropriate value.

*Appendix C.1. Module Mathematics*

-1: step size gets to small in routine `ODEint`

-2: maximal value $> 10^{36}$ `ODEint`

-3: too many steps are required in routine `ODEint`

-4: boundary conditions cannot fullfilled in routine `ODEintB`

-5: maximal value $> 10^{36}$ `ODEintB`

-6: step size gets too small in routine `ODEintB`

-7: too many steps are required in routine `ODEintB`

-8: boundary conditions cannot fullfilled in routine `ODEintC`

-9: maximal value $> 10^{36}$ `ODEintC`

-10: step size gets too small in routine `ODEintC`

-11: too many steps are required in routine `ODEintC`

-12: step size gets too small in routine `rkqs`

-13: the size of the arrays do not match in routine `ComplexEigenSystems`

-14: potential numerical problems in routine `ComplexEigenSystems`

-15: the size of the arrays do not match in routine `RealEigenSystemse`

-16: potential numerical problems in routine `RealEigenSystems`

-17: the size of the arrays do not match in routine `tqli`

-18: too many iterations in routine `tqli`

-19: too high accuracy required in routine `Dgauss`

-20: too high accuracy required in routine `DgaussInt`

-21: precision problem in routine `Kappa`

-22: step size gets too small in routine `IntRomb`

-23: too many steps are required in routine `IntRomb`

-24: singular matrix in routine `GaussJ`

-25: inversion failed in routine `InvMat3`

-26: singular matrix in routine `GaussJ`

*Appendix C.2. Module StandardModel*

-101: routine `CalculateRunningMasses`: $Q_{low} > m_b(m_b)$

-102: routine `CalculateRunningMasses`: $\mathrm{Max}(Q_{low}, m_b(m_b) > Q_{max})$

*Appendix  C.3.  Module SusyMasses*

-201: negative mass squared in routine `ChargedScalarMassEps1nt`

-202: negative mass squared in routine `ChargedScalarMassEps3nt`

-204: $|Y_\tau|^2 < 0$ in routine `CharginoMass3`

-205: $|Y_\tau|^2 < 0$ in routine `CharginoMass5`

-206: negative mass squared in routine `PseudoScalarMassEps1nt`

-207: negative mass squared in routine `PseudoScalarMassEps3nt`

-208: negative mass squared in routine `PseudoScalarMassMSSMnt`

-210: negative mass squared in routine `ScalarMassEps1nt`

-211: negative mass squared in routine `ScalarMassEps3nt`

-212: negative mass squared in routine `ScalarMassMSSMeff`

-213: negative mass squared in routine `ScalarMassMSSMnt`

-215: $m^2_{S^0_1} < 0$ in routine `ScalarMassMSSMeff`

-216: $m^2_{P^0_1} < 0$ in routine `ScalarMassMSSMeff`

-217: $m^2_{S^+} < 0$ in routine `ScalarMassMSSMeff`

-220: negative mass squared in routine `SfermionMass1Eps1`

-221: negative mass squared in routine `SfermionMass1Eps3`

-222: negative mass squared in routine `SfermionMass1MSSM`

-223: negative mass squared in routine `SfermionMass3MSSM`

-224: negative mass squared in routine `SquarkMass3Eps`

-225: $m^2_{\tilde\nu} < 0$ in routine `TreeMassesEps1`

-226: $m^2_{\tilde\nu} < 0$ in routine `TreeMassesMSSM`

-227: $m^2_{A^0} < 0$ in routine `TreeMassesMSSM`

-228: $m^2_{H^+} < 0$ in routine `TreeMassesMSSM`

-229: $m^2_{\tilde\nu} < 0$ in routine `TreeMassesMSSM2`

-230: $m^2_{A^0} < 0$ in routine `TreeMassesMSSM2`

-231: $m^2_{H^+} < 0$ in routine `TreeMassesMSSM2`

-232: $m^2_{\tilde\nu} < 0$ in routine `TreeMassesMSSM3`

*Appendix C.4. Module InputOutput*

-302: routine `LesHouches_Input`: unknown entry for Block MODSEL

-303: routine `LesHouches_Input`: model must be specified before parameters

-304: routine `LesHouches_Input`: unknown entry for Block MINPAR

-305: routine `LesHouches_Input`: model has not been specified completly

-306: routine `LesHouches_Input`: a serious error has been part of the input

-307: routine `LesHouches_Input`: Higgs sector has not been fully specified

-308: routine `ReadMatrixC`: indices exceed the given boundaries

-309: routine `ReadMatrixR`: indices exceed the given boundaries

-310: routine `ReadVectorC`: index exceeds the given boundaries

-311: routine `ReadVectorR`: index exceeds the given boundaries

-312: routine `ReadMatrixC`: indices exceed the given boundaries

*Appendix C.5. Module SugraRuns*

-401: routine `BoundaryEW`: negative scalar mass squared as input

-402: routine `BoundaryEW`: $m_Z^2(m_Z) < 0$

-403: routine `BoundaryEW`: $\sin^2 \theta_{\overline{DR}} < 0$

-404: routine `BoundaryEW`: $m_W^2 < 0$

-405: routine `BoundaryEW`: either $m_{l_D R}/m_l < 0.1$ or $m_{l_D R}/m_l > 10$

-406: routine `BoundaryEW`: either $m_{d_D R}/m_u < 0.1$ or $m_{d_D R}/m_d > 10$

-407: routine `BoundaryEW`: either $m_{u_D R}/m_d < 0.1$ or $m_{u_D R}/m_u > 10$

-408: routine `RunRGE`: entering non-perturbative regime

-409: routine `RunRGE`: nor $g_1 \neq g_2$ at $M_{\mathrm{GUT}}$ neither any other unification

-410: routine `RunRGE`: entering non-perturbative regime at $M_{\mathrm{GUT}}$

-411: routine `RunRGE`: entering non-perturbative regime at $M_{H_3}$

-412: routine `Sugra`: run did not converge

-413: routine `Calculate_Gi_Yi`: $m_Z^2(m_Z) < 0$

-414: routine `Calculate_Gi_Yi`: too many iterations to calculate $m_b(m_b)$ in the $\overline{MS}$ scheme

-415: routine `Sugra`: $|\mu|^2 < 0$ at $m_Z$

*Appendix C.6. Module LoopMasses*

-501 negative mass squared in routine `SleptonMass_1L`

-502 $p^2$ iteration did not converge in routine `SleptonMass_1L`

-503 negative mass squared in routine `SneutrinoMass_1L`

-504 $p^2$ iteration did not converge in routine `SneutrinoMass_1L`

-505 negative mass squared in routine `SquarkMass_1L`

-506 $p^2$ iteration did not converge in routine `SquarkMass_1L`

-507 $m_{h^0}^2 < 0$ in routine `LoopMassesMSSM`

-508 $m_{A^0}^2 < 0$ in routine `LoopMassesMSSM`

-509 $m_{H^+}^2 < 0$ in routine `LoopMassesMSSM`

-510 $|\mu|^2 > 10^{20}$ in routine `LoopMassesMSSM`

-511 $|\mu|^2 < 0$ in routine `LoopMassesMSSM`

-512 $m_Z^2(m_Z)^2 < 0$ in routine `LoopMassesMSSM`

-513 $m_{h^0}^2 < 0$ in routine `LoopMassesMSSM_2`

-514 $m_{A^0}^2 < 0$ in routine `LoopMassesMSSM_2`

-515 $m_{H^+}^2 < 0$ in routine `LoopMassesMSSM_2`

-516 $|\mu|^2 > 10^{20}$ in routine `LoopMassesMSSM_2`

-517 $|\mu|^2 < 0$ in routine `LoopMassesMSSM_2`

-518 $m_Z^2(m_Z)^2 < 0$ in routine `LoopMassesMSSM_2`

-519 $m_{h^0}^2 < 0$ in routine `LoopMassesMSSM_3`

-520 $m_{A^0}^2 < 0$ in routine `LoopMassesMSSM_3`

-521 $m_{H^+}^2 < 0$ in routine `LoopMassesMSSM_3`

-522 $|\mu|^2 > 10^{20}$ in routine `LoopMassesMSSM_3`

-523 $|\mu|^2 < 0$ in routine `LoopMassesMSSM_3`

-524 $m_Z^2(m_Z)^2 < 0$ in routine `LoopMassesMSSM_3`

*Appendix C.7. Module TwoLoopHiggsMass*

-601: routine `PiPseudoScalar2`: $m_{\tilde{t}}^2 < 0$

-602: routine `PiPseudoScalar2`: $m_{\tilde{b}}^2 < 0$

-603: routine `PiPseudoScalar2`: $m_{\tilde{\tau}}^2 < 0$

-604: routine `PiScalar2`: $m_{\tilde{t}}^2 < 0$

-605: routine `PiScalar2`: $m_{\tilde{b}}^2 < 0$

-606: routine `PiScalar2`: $m_{\tilde{\tau}}^2 < 0$

-607: routine `Two_Loop_Tadpoles`: $m_{\tilde{t}}^2 < 0$

-608: routine `Two_Loop_Tadpoles`: $m_{\tilde{b}}^2 < 0$

-609: routine `Two_Loop_Tadpoles`: $m_{\tilde{\tau}}^2 < 0$

*Appendix C.8. Module MathematicsQP*

-1001: the size of the arrays do not match in routine `ComplexEigenSystems_DP`

-1002: potential numerical problems in routine `ComplexEigenSystems_DP`

-1003: the size of the arrays do not match in routine `ComplexEigenSystems_QP`

-1004: potential numerical problems in routine `ComplexEigenSystems_QP`

-1005: the size of the arrays do not match in routine `RealEigenSystems_DP`

-1006: potential numerical problems in routine `RealEigenSystems_DP`

-1007: the size of the arrays do not match in routine `RealEigenSystems_QP`

-1008: the size of the arrays do not match in routine `Tqli_QP`

-1009: too many iterations in routine `Tqli_QP`

-1010: too many iterations in routine `Tql2_QP`

## Appendix D. Loop corrections

Here we list the improvements which have been implemented in `SPheno` with respect to ref. [4]:

- in the 1-loop corrections to the gluino mass we use for the gluon contribution

$$\Delta(\Sigma_{\tilde{g}}) = -\frac{3g_3^2}{8\pi^2} \left( B_1(p^2, m_{\tilde{g},T}^2, 0) - 2B_1(p^2, m_{\tilde{g},T}^2, 0) \right) \tag{D.1}$$

where $m_{\tilde{g},T}$ is the tree level gluino mass and which reduces for $p^2 = m_{\tilde{g},T}^2$ to the formula

$$\Delta(\Sigma_{\tilde{g}}) = -\frac{g_3^2}{16\pi^2} \left( 15 + 9\log\left( \frac{Q^2}{m_{\tilde{g},T}^2} \right) \right) \tag{D.2}$$

of ref. [4].

- In addition flavour violation has been taking into account and the corresponding formulas can be found in [5, 6].

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