SPheno 3.3.0: 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`.

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 BR($b \to s\gamma$), ΔM_{B_s}, rare lepton decays, such as 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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1. Introduction

In its orginal version `SPheno` had been designed to calculate the spectrum in the MSSM neglecting any effects due to generation mixing 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.

2. 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 6×6 mass matrices for squarks and charged leptons and the 1-loop corrected 3×3 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. For the 2-loop corrections to the Higgs-sector we use the formulas of ref. [7–11]. In the corresponding formulas generation mixing is neglected and, thus, they are implemented such that we take the third generation mass parameters in the super-CKM basis for the squarks and in the super-PMNS basis for the sleptons as input, where for the precise definition of the two bases we refer to ref. [2]. This approach gives reliable results provided in the mixing between 2nd and 3rd generation sfermions is small in the super-CKM basis. However, for a large mixing between these two generations, which is heavily restricted by B-physics data, see e.g. [12], this approach induce an additional theoretical uncertainty. Taking the same approach for the 1-loop calculation and multiplying the corresponding differences by α_s we get as a rough estimate an uncertainty of up to 1 GeV due to neglecting flavour mixing in the 2-loop calculation in case of a large mixing.

A comparison for the Higgs masses between the results of this code and the spectrum generators `SOFTSUSY` [13], `SuSpect` [14] and the program `FeynHiggs` [15] can be found in ref. [16], where also an estimate of the achieved accuracies for various scenarios can be found. In ref. [16] flavour mixing has not been considered. However, we have checked, that the results obtained in ref. [16] are qualitatively unchanged, when comparing `SPheno` with `FeynHiggs` 2.8.5 after turning on flavour mixing. Moreover, we added new output blocks which serve as input for the program `HiggsBounds` [17, 18] to calculate the constraints from experimental data related to the Higgs sector, see section 5.3.1.

Beside the calculation of the spectrum also the decay routines have been extended such that flavour effects in the two- and three body decays of supersymmetric particles and Higgs bosons are included. These decays are calculated using leading order formulas for the widths but using running gauge and Yukawa couplings evaluated at the scale corresponding to the masses of the decaying particle.

In the following we list the various implemented decays. The indices are understood to run of the following ranges: $i = 1, \ldots, 4$ for neutralinos, $i = 1, 2$ for charginos, $i = 1, 2, 3$ for SM-fermions and sneutrinos, $i = 1, \ldots, 6$ for sfermions except sneutrinos. The ordering is according to the masses: $i < j \Rightarrow m_i \leq m_j$. The following sfermion decays are calculated:

$$\tilde{f}_i \to f_j \, \tilde{\chi}_k^0, \; f'_j \, \tilde{\chi}_l^\pm \tag{1}$$

$$\tilde{f}_i \to \tilde{f}_j \, Z^0, \; \tilde{f}'_j \, W^\pm \tag{2}$$

$$\tilde{f}_i \to \tilde{f}_j \, (h^0, H^0, A^0), \; \tilde{f}'_j \, H^\pm \tag{3}$$

where $\tilde{f}_i$ denotes either a squark, a slepton or a sneutrino. Note, that in the latter case the decay into a Z-boson does not occur. In case of the lighter stop, it is possible that all two-body decays modes are

kinematically forbidden at tree–level. In this case the following decay modes are important [19–22]:

$$\begin{aligned}
\tilde{t}_1 &\to c\,\tilde{\chi}^0_{1,2} && (4)\\
\tilde{t}_1 &\to W^+\,b\,\tilde{\chi}^0_1,\ H^+\,b\,\tilde{\chi}^0_1 && (5)\\
\tilde{t}_1 &\to b\,\nu_i\,\tilde{l}^+_j,\ b\,l^+_i\,\tilde{\nu}_k\,. && (6)
\end{aligned}$$

In case of GMSB models scenarios exist where the charged sleptons are next to lightest supersymmetric particles (NLSP) and the gravitino $\tilde{G}$ is the LSP. In this case the sleptons decay according to:

$$\tilde{l}_i \to l_j\,\tilde{G} \qquad (7)$$

Here we use the formulas given in [23] which have been extended to include flavour effects [24]. Moreover, for sleptons and sneutrinos with masses close to the NLSP also three-body decays can be important [25, 26]

$$\begin{aligned}
\tilde{l}_i &\to l^+_j l^-_k\,\tilde{l}_n\,, \qquad (i=2,\ldots,6\,;\,n=1,\ldots,5\,;\,j,k=1,2,3) && (8)\\
\tilde{l}^-_i &\to l^-_j l^-_k\,\tilde{l}^+_n && (9)\\
\tilde{l}_i &\to \nu_j\bar{\nu}_k\,\tilde{l}_n && (10)\\
\tilde{l}_i &\to q\bar{q}\,\tilde{l}_n\,, \qquad (q=u,d,s,c,b) && (11)\\
\tilde{l}_i &\to \nu_j l_k\,\tilde{\nu}^*_m\,, \qquad (i=1,\ldots,6\,;\,m,j,k=1,2,3) && (12)\\
\tilde{l}_i &\to \bar{\nu}_j l_k\,\tilde{\nu}_m && (13)\\
\tilde{l}_i &\to q\bar{q}'\,\tilde{\nu}_m\,, \qquad (q=d,s,b\,,\,q'=u,c) && (14)
\end{aligned}$$

$$\begin{aligned}
\tilde{\nu}_i &\to l^-_j\,l^+_k\tilde{\nu}_m\,, \qquad (i=2,3\,;\,m=2,3\,;\,j,k=1,2,3) && (15)\\
\tilde{\nu}_i &\to \nu_j\bar{\nu}_k\,\tilde{\nu}_m && (16)\\
\tilde{\nu}_i &\to \nu_j\nu_k\,\tilde{\nu}^*_m && (17)\\
\tilde{\nu}_i &\to \nu_j l^\pm_k\,\tilde{l}^\mp_n\,, \qquad (i,j,k=1,2,3\,;\,n=1,\ldots,6) && (18)\\
\tilde{\nu}_i &\to \bar{q}q'\,\tilde{l}^-_n\,, \qquad (q=d,s,b\,,\,q'=u,c) && (19)
\end{aligned}$$

It is well known that the partial widths of sfermions can receive considerable radiative corrections [27–40]. However, the branching ratios are not that strongly affected [35, 41]. For flavour diagonal decays two programs are available to include higher corrections to sfermion decays: the QCD corrections have been included in`SDECAY` [42] and `SFOLD` [43] the complete QCD and electroweak corrections have been included.

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

$$\begin{aligned}
\tilde{\chi}^0_i &\to Z^0\,\tilde{\chi}^0_j,\ W^\pm\,\tilde{\chi}^\mp_k && (20)\\
\tilde{\chi}^0_i &\to (h^0,H^0,A^0)\,\tilde{\chi}^0_j,\ H^\pm\,\tilde{\chi}^\mp_k && (21)\\
\tilde{\chi}^0_i &\to f_k\tilde{f}^*_j,\ \bar{f}_k\tilde{f}_j && (22)\\
\tilde{\chi}^+_k &\to Z^0\,\tilde{\chi}^+_s,\ W^+\,\tilde{\chi}^0_j && (23)\\
\tilde{\chi}^+_k &\to (h^0,H^0,A^0)\,\tilde{\chi}^+_s,\ H^+\,\tilde{\chi}^0_j && (24)\\
\tilde{\chi}^+_k &\to f_i\tilde{f}'_j && (25)
\end{aligned}$$

Also for these decays it is well known, that radiative corrections are important [44–49]. QCD corrections are for flavour diagonal decays into squarks and quarks have been included in `SDECAY` [42] and the complete electroweak corrections for final states containing a $W^\pm$-boson can be calculated using the program `CNNDecays` [50].

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

$$\tilde{\chi}_i^0 \;\to\; f_j\,\bar{f}_k\,\tilde{\chi}_l^0,\; f_j\,f'_k\,\tilde{\chi}_m^{\mp} \tag{26}$$
$$\tilde{\chi}_i^0 \;\to\; q_i\,\bar{q}_j\,\tilde{g} \tag{27}$$
$$\tilde{\chi}_k^+ \;\to\; f_i\,\bar{f}_j\,\tilde{\chi}_s^+,\; f_i\,f'_j\,\tilde{\chi}_l^0 \tag{28}$$
$$\tilde{\chi}_k^+ \;\to\; q_i\,q'_j\,\tilde{g} \tag{29}$$

In the calculation we have included all contributions from gauge bosons, sfermions and Higgs bosons [51–53]. In addition the loop induced decays

$$\tilde{\chi}_i^0 \;\to\; \tilde{\chi}_j^0\,\gamma \tag{30}$$

are calculated [54] taking into account the flavour mixing of sfermions. Similarly to case of the sleptons there exist parameter regions in GMSB models where the lightest neutralino is the NLSP and it decays according to

$$\tilde{\chi}_1^0 \;\to\; \gamma\;\tilde{G}\;,\; Z^0\;\tilde{G}\;,\; h^0\;\tilde{G}\;. \tag{31}$$

Here we use the formulas given in [23].

In case of gluinos the following two–body decays are calculated:

$$\tilde{g} \to q_i\,\tilde{q}_j^*\,. \tag{32}$$

In case that these decays are kinematically suppressed, the three-body decay modes are calculated:

$$\tilde{g} \;\to\; \tilde{\chi}_i^0\,q_j\,\bar{q}_k \tag{33}$$
$$\tilde{g} \;\to\; \tilde{\chi}_j^{\pm}\,q'_j\,\bar{q}_k \tag{34}$$
$$\tilde{g} \;\to\; \bar{b}\,W^-\,\tilde{t}_1, b\,W^+\,\tilde{t}_1^* \tag{35}$$

where we have extended the formulas of [55] to include flavour mixing in the squark sector. In addition the decays

$$\tilde{g} \;\to\; \tilde{\chi}_i^0\,g \tag{36}$$

are calculated [54, 56] taking into account the flavour mixing of the squarks.

In case of Higgs bosons the following decays are calculated:

$$\phi \;\to\; f\,\bar{f} \tag{37}$$
$$\phi \;\to\; \tilde{f}_i\,\tilde{f}_j^* \tag{38}$$
$$\phi \;\to\; \tilde{\chi}_k^0\,\tilde{\chi}_l^0 \tag{39}$$
$$\phi \;\to\; \tilde{\chi}_r^+\,\tilde{\chi}_s^- \tag{40}$$
$$\phi \;\to\; g\,g\;,\;\gamma\,\gamma \tag{41}$$
$$h^0 \;\to\; Z^0\,Z^{0*},\; W^+\,W^{-*},\; W^{+*}\,W^- \tag{42}$$
$$H^0 \;\to\; Z^0\,Z^0\;,\; W^+\,W^-\;,\; h^0\,h^0 \tag{43}$$
$$A^0 \;\to\; h^0\,Z^0 \tag{44}$$
$$H^+ \;\to\; f\,\bar{f}' \tag{45}$$
$$H^+ \;\to\; \tilde{f}_i\,\tilde{f}_j'^* \tag{46}$$
$$H^+ \;\to\; \tilde{\chi}_k^0\,\tilde{\chi}_s^- \tag{47}$$
$$H^+ \;\to\; h^0\,W^+ \tag{48}$$

with $\phi = h^0, H^0, A^0$ and $f = \nu_i, e, \mu, \tau, u, d, c, s, t, b$. It is well known, that the widths as well as the branching ratios of the Higgs bosons can receive large one–loop corrections, see e.g. [57] and references

therein where also the formulas for the tree-level widths can be found. In the present version only the gluonic QCD corrections for the decays into quarks [58, 59] have been implemented. The decays into the $g\,g$ final state have been implemented using the lowest order formula as given in [60]. Therefore, the numbers provided by `SPheno` have to be taken with care and for refined analysis other programs, such as `HDECAY` [61], `FeynHiggs` [15, 62] of `HFOLD` [63] should be used.

We have checked that the results of the routines agree with the output of WHIZARD [64] using the toolbox package [65]. Moreover, several of the numerical results decays have been cross-checked by the authors of the program `SDECAY` [42, 66] as well as a cross-check of various results obtained in [67–69] have been performed. In addition the set of low energy observables has been extended as described in section 4.

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 $g_1(M_{\rm GUT}) = g_2(M_{\rm GUT})$. However, this scale can be set to a fixed value using entry 31 in block `SPhenoInput`, see section 5.2.6. In addition one specify freely the on-shell mass of the pseudoscalar and the superpotential parameter μ at the electroweak scale. Both possibilities allow for the implementation of non-universal Higgs mass parameters while keeping the sfermions universal as proposed and discussed e.g. in [70–74]
- 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 [2, 75].

In addition several classes of neutrino mass models have been included with additional states at high energy scales. For the data handling we extended the SLHA2 format which has now become part of a public proposal [76] and which are discussed in detail in sec. 5. The included models are

- 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 5.1.2. The parameters are set using the blocks `MNURNURIN` and `YNURLHUIN`, see sections 5.2.4 and 5.2.12, respectively. Using this the results of [77, 78] 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 [79] including the corrections presented in [80] and 2-loop RGEs for the gauge couplings and gaugino mass parameters as used in [81]. This variant is faster if one uses 2-loop RGEs but less accurate in particular for low seesaw scales [82].

  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 [83]. In both cases the blocks `M15IN` (`M15T15TBIN`), `YHD15THDIN`, `YHU15TBHUIN` and `Y15IN` (`YL15TLIN`) have to be used to transfer the data, see sections 5.2.1 (5.2.2), 5.2.9, 5.2.10 and 5.2.7 (5.2.11). The blocks in parenthis are to be used in case of $SU(2)$ triplets only.
- 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 [82]. The blocks `M24IN` and `Y24IN` can be used to set the parameters, see sections 5.2.3 and 5.2.8.
- A minimal $SU(5)$ model as described in [84]. The corresponding particle content can be chosen setting the entry 3 of the block `MODSEL` as described in section 5.1.2. The parameters are set using the blocks `MNURNURIN` and `YNURLHUIN`, see sections 5.2.4 and 5.2.12, respectively. The additional $SU(5)$ parameters can be set extending the block `MINPAR` as described in section 5.1.1.

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.

In case of seesaw type II and type III models additional charged particles are integrated out at the seesaw scale(s). This results in changes of the beta-coefficients for the gauge couplings and gaugino

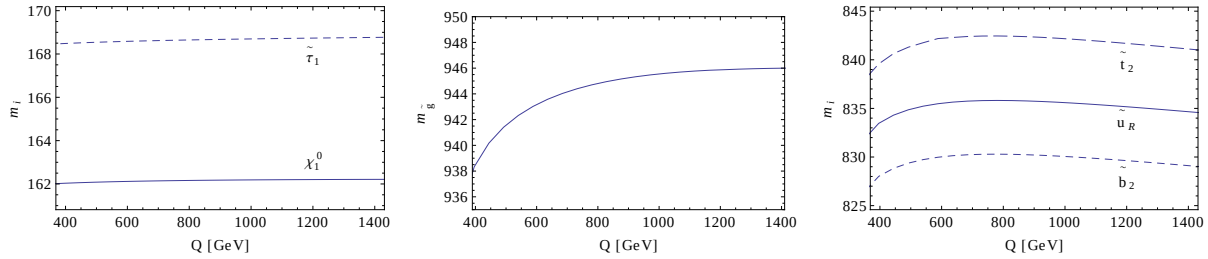

Figure 1: Residual scale dependence of various SUSY masses as a function of the renormalisation scale Q for $M_{1/2} =$ 400 GeV, $m_0 = 90$ GeV, A_0=0, $\tan\beta = 10$, $\mu > 0$. The lines correspond to the masses of $\tilde{\chi}_1^0$ (full line, left plot), $\tilde{\tau}_1$ (dashed line, left plot), $\tilde{g}$, (full line, middle plot), $\tilde{b}_2$ (dashed line, right plot), $\tilde{u}_R$ (full line, right plot) and $\tilde{t}_2$ (long dashed line, right plot).

mass parameters which we have included at the 2-loop level. Moreover, we have taken into account the corresponding threshold effects at 1-loop level for gauge couplings and gaugino mass parameters utilising the formulas given in [85, 86]. However, we have neglected the corresponding threshold corrections to the sfermion mass parameters which are proportional to the additional Yukawa couplings squared. These corrections are in general small as these couplings are small for seesaw scales below 10^{14} GeV. However, they might become important in case that there is a large mass splitting between fermions and scalars of the corresponding seesaw multiplet, see e.g. [87] where this has been investigated for the case of seesaw type I. Beside these uncertainties the remaining theoretical uncertainties are the same as in the usual MSSM scenarios without additional states below the GUT scale and they stem from neglecting higher order in both, the RGEs and the formulas for the mass calculation. As an estimate for the corresponding theoretical uncertainty induced one can study the residual dependence on the renormalisation scale where the SUSY spectrum is calculated. Per default the scale $Q_{EWSB} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ is used. Varying the scale between $Q_{EWSB}/2$ and $2Q_{EWSB}$ we find the masses of charginos, neutralinos and sleptons vary within a few per-mile where the variations of the strongly interacting particles are about a factor two larger than the ones with electroweak interactions only. The gluino shows the largest variation of up to 2 per-cent as can also be seen in figure 2 where we show the scale dependence of the masses of various particles taking SPS3 [88] as an example. These findings are independent of the seesaw scale models used, which is easy to understand, because one could consider a non-universal model at the GUT scale with just MSSM particle content below the GUT scale leading to the same masses as for the universal models with the additional seesaw particles. In ref. [89, 90] the 3-loop RGEs have been presented and in [91–93] the leading 2-loop corrections to masses of gluino, charginos and neutralinos are presented. By comparing the relative shifts given there with the scale dependence discussed above we find one sees that they are of the same order of magnitude. This indicates that studying the scale dependence gives indeed the correct measure of the theoretical uncertainty.

3. R-parity violation

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

$$W_{\not R} = \epsilon_i \widehat{L}_i \widehat{H}_u \tag{49}$$

and the corresponding soft SUSY breaking terms. The latter induce vacuum expectation values v_i for the sneutrinos. In this class of models neutrino physics can be explained due to the mixing of neutralinos with neutrinos and by loop contributions. The corresponding details can be found in [94, 95]. Moreover, R-parity violation leads to a mixing between SM-particles and SUSY particles: neutralinos mix with neutrinos, charginos with the charged leptons, sleptons with the charged Higgs, the real part of the sneutrinos with h^0 and H^0, and the imaginary part of the sneutrinos with A^0. The corresponding decays can be written in a compact form if one extends the neutralino index range to $i = 1, \ldots, 7$, the chargino index are $i = 1, \ldots, 5$ and the slepton index $i = 1, \ldots, 7$ and the corresponding states are denoted below by S_i^+. The neutral scalars S_i^0 and pseudoscalars P_j^0 have index ranges $i = 1, \ldots, 5$ and $j = 1, \ldots, 4$,

respectively. In all cases mass ordering is understood. For example, the two-body decays of the neutralinos read now

$$\tilde{\chi}_i^0 \rightarrow Z^0 \tilde{\chi}_j^0,\ W^{\pm} \tilde{\chi}_k^{\mp} \tag{50}$$
$$\tilde{\chi}_i^0 \rightarrow S_k^0 \tilde{\chi}_j^0\ ,\ P_k^0 \tilde{\chi}_j^0\ ,\ S_l^{\pm} \tilde{\chi}_k^{\mp} \tag{51}$$
$$\tilde{\chi}_i^0 \rightarrow q_k \tilde{q}_j^*,\ \bar{q}_k \tilde{q}_j \tag{52}$$
$$\tilde{\chi}_k^+ \rightarrow Z^0 \tilde{\chi}_s^+,\ W^+ \tilde{\chi}_j^0 \tag{53}$$
$$\tilde{\chi}_k^+ \rightarrow S_k^0 \tilde{\chi}_s^+,\ P_k^0 \tilde{\chi}_s^+,\ S_l^+ \tilde{\chi}_j^0 \tag{54}$$
$$\tilde{\chi}_k^+ \rightarrow q_i \tilde{q}_j' \tag{55}$$

In this way one can easily take over the decays listed in section 2 to the R-parity violating case. Detailed discussions of R-parity violating decays in the bilinear model including formulas for various couplings can be found in refs. [96–99]. 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 [96–98].

For the bilinear model 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 5.2.6 to calculate the ϵ_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 5.2.5.

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.

4. 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 in case of conserved R-parity.

4.1. B-physics observables

The following observables are calculated in `SPheno`: $BR(b \to s\gamma)$, $BR(b \to s\mu^+\mu^-)$, $BR(b \to s\sum_i \nu_i\nu_i)$, $BR(B_d^0 \to l^+l^-)$ and $BR(B_s^0 \to l^+l^-)$ $(l = e, \mu, \tau)$ $BR(B_u \to \tau^+\nu)$, $\Delta M_{B_s^0}$ 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. [100] 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

- $BR(b \to s\gamma)$ [100–102]; the value given is for $E_\gamma \geq 1.6$ GeV and $m_c/m_b = 0.23$.
- $BR(b \to s\mu^+\mu^-)$ [101–103]
- $BR(b \to s\sum_i \nu_i\nu_i)$ [101, 102]
- $BR(B_s^0 \to l^+l^-)$, $BR(B_d^0 \to l^+l^-)$ $(l = e, \mu tau)$ [101, 102, 104, 105]
- $BR(B_u \to \tau^+\nu)$ [106]

Table 1: Parameters used in the calculation of the B-physics observables. The masses and life times are taken from the PDG [108] whereas the decay constants and hadronic parameters are taken from ref. [109] including the update given in [110].

$\tau_{B^0} = 1.519$ ps	$\tau_{B_s^0} = 1.516$ ps	$\tau_{B_u^+} = 1.641$ ps	$\tau_{B_c^+} = 0.452$ ps
$f_B = 193$ MeV	$f_B\sqrt{B_{B_d}} = 216$ MeV	$f_{B_s} = 239$ MeV	$f_{B_s}\sqrt{B_{B_s}} = 275$ MeV
$M_{B^0} = 5.2796$ GeV	$M_{B_s^0} = 5.3667$ GeV	$\eta_B = 0.55$	

- $\Delta M_{B_s^0}$ and $\Delta M_{B_d^0}$ [102, 105]. For the hadronic parameters we follow [105]:

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

The remaining parameters used are given in table 1. The values of the decay constants can be changed by using the FLHA block `FCONST` [107], the B-meson masses by using the FLHA block `FMASS` [107] and life-times by using the FLHA block `FLIFE` [107]. We use the results of [111] for the calculation of the chirally enhanced couplings, e.g. the resummation of effects due to loop-induced aholomorphic couplings in case of large $\tan\beta$ and/or large trilinear couplings.

4.2. Kaon sector

In this sector we calculate ϵ_K, ΔM_K, BR($K^+ \to \pi^+\nu\nu$) and BR($K_L \to \pi^0\nu\nu$). We combine the formulas of refs. [112] and [105] to calculate ϵ_K and ΔM_K. Here we take the loop-corrections into account by using

$$\eta_{tt} = 0.5\ ,\ \eta_{ct} = 0.47\ ,\ \eta_{cc} = 1.44\ , \tag{56}$$

from ref. [113]. For the hadronic parameters we follow [112] and take

$$B_1^{VLL} = 0.61\ ,\ B_1^{SLL} = 0.76\ ,\ B_2^{SLL} = 0.51\ ,\ B_1^{LR} = 0.96\ ,\ B_2^{LR} = 1.2\ . \tag{57}$$

which are given at the scale $\mu = 2$ GeV. We set the decay constant f_K to 155.8 MeV. This can be changed by using the FLHA accord block `FCONST` [107] and the K-meson mass by using the FLHA block `FMASS` [107]. For completeness we note that ΔM_K suffers from significantly larger theoretical uncertainties than ϵ_K. For the branching ratios BR($K^+ \to \pi^+\nu\nu$) and BR($K_L \to \pi^0\nu\nu$) we use the formulas given [114] with $\kappa_L = 2.1310^{-11}$, $\kappa_+ = 5.1610^{-11}$ and $P_c = 0.39$.

4.3. 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 [115]
- electric dipole moments (EDMs) of the leptons [116, 117]
- two body decays $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ [117, 118]
- three body decays $\mu \to ee^+e^-$, $\tau \to ee^+e^-$ and $\tau \to \mu\mu^+\mu^-$ [119]
- Z decays, $Z \to e^\pm\mu^\mp$, $Z \to e^\pm\tau^\mp$ and $Z \to \mu^\pm\tau^\mp$, [120]

4.4. 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 [116] and we use the same hadronic parameters. Moreover, one can also calculate the SUSY contributions to the ρ-parameter as given in [121].

5. Extensions to SLHA

In this section we describe the SPheno specific extensions to the SUSY Les Houches Accord (SLHA) [2, 75]. 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].

5.1. Extensions of existing blocks

5.1.1. Block MINPAR

In case of extending the model by a minimal $SU(5)$ as used in [84] 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: λ-coupling of the Higgs 24-plet to the $\bar{5}_H$

10: λ'-coupling of the Higgs 24-plet to the 5_H

5.1.2. Block MODSEL

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.

Seven switches have been added to flag 3 (particle content), of which 111, 112, 113 and 114 correspond to the extensions proposed in [76]:

2: includes the particle content of a minimal $SU(5)$ model between $M_{\rm GUT}$ and a user chosen $SO(10)$ scale, where the SUSY boundary conditions are set. The details of this model are described in [84]. In this case the mass parameters of the right handed neutrinos are stored in the block MNURNURIN (section 5.2.4) and the corresponding neutrino Yukawa couplings can be stored in the block YNURLHUIN (section 5.2.12). 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 5.1.1

3: includes three right-handed (s)neutrinos with a common mass for all three neutrinos. The neutrino Yukawa couplings Y_ν can be specified at the GUT-scale, see section 5.2.12, and the mass of the right-neutrinos at their proper scale, see section 5.2.4.

5: includes one paor of 15-plet to realize the seesaw II where the formulas of [79] including the corrections presented in [80] and the 2-loop contributions to the RGEs of the gauge couplings and gaugino mass parameters have been implemented. This is an alternative to flag 112 neglecting the 2-loop running of the seesaw paramters between the triplet scale and the GUT-scale. This implies somewhat less accuracy compared to the complete case but is a good approximation, with relative differences below one per-cent, if the triplet-scale is above $5 \cdot 10^{13}$ GeV. The additional model data are specified in the blocks M15IN, YHD15THDIN, YHU15TBHUIN and Y15IN, see sections 5.2.1, 5.2.9, 5.2.10 and 5.2.7, respectively.

111: includes three right-handed (s)neutrinos which are included at their proper mass scale. The neutrino Yukawa couplings Y_ν can be specified at the GUT-scale, see section 5.2.12, and the masses of the right-neutrinos at their proper scale, see section 5.2.4.

112: includes one pair of Higgs 15-plet to realize the seesaw II where the complete 2-loop RGEs as given in [82] are used. The additional model data are specified in the blocks M15IN, YHD15THDIN, YHU15TBHUIN and Y15IN, see sections 5.2.1, 5.2.9, 5.2.10 and 5.2.7, respectively.

113: includes three Higgs 24-plets to realize the seesaw type III where the complete 2-loop RGEs as given in [82] are used. The additional model data are specified in the blocks M24IN and Y24IN, see sections 5.2.3 and 5.2.8, respectively.

114: includes one Higgs triplet to realize the seesaw II where the formulas of [79] including the corrections presented in [80] 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 `M15T15TBIN`, `YHD15THDIN`, `YHU15TBHUIN` and `YL15TLIN`, see sections 5.2.2, 5.2.9, 5.2.10 and 5.2.7, respectively.

5.2. New input blocks

Some of these blocks have become part of the proposal given in ref. [76]: `SEESAWGENERATIONS`. In the output the blocks will be given without the ending IN. It is understood that the input values are given at the GUT scale as a default.

5.2.1. Block `M15IN`

This gives the mass M_T of the 15-plet at the GUT scale. In addition the indices (1,1) have to be given to make the 1-generation case compatible with the case of several generations of 15-plets. The data are given in the format

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

At the scale M_T the 15-plet is split into three different represenations denoted by S, T, and Z [79] which have different masses due to RGE effects. The corresponding output blocks at this scale are `M15S15SB`, `M15T15TB` and `M15Z15ZB` and the same data format as for `M15IN` is used.

5.2.2. Block `M15T15TBIN`

This gives the mass M_T of the SU(2) triplet at the GUT scale. In addition the indices (1,1) have to be given to make the 1-generation case compatible with the case of several generations of triplets. The data are given in the format

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

5.2.3. Block `M24IN`

Here one can specify the mass matrix of the 24-plets M_{Wij} at $M_{\rm GUT}$ for the seesaw type III model using the formulas of [82], 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.

At the different scales corresponding to the mass parameters of the $SU(2)$ triplets the various mass matrices for the masses of the singlet, $SU(2)$-tripelt, the $SU(3)$-octet and the X-particles are given in the blocks `M24B24B`, `M24W24W`, `M24G24G` and `M24X24X`, respectively

5.2.4. Block `MNURNURIN`

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

Note, that the program assumes that the mass parameters are given in the basis where the mass matrix of the right handes neutrinos is diagonal.

5.2.5. Block `NeutrinoBoundsIn`

One can use `SPheno` to obtain R-parity violating parameters consistent with neutrino data. The corresponding default values are given in table 5.2.5. 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

Table 2: Default values for fitting R-parity violating parameters if the entries in block `NeutrinoBoundsIn` are not specified. The values are taken from [122] and correspond to the 1 σ 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	$\|U^2_{e3,min}\|^2$	0
$\tan^2\theta_{atm,max}$	1.3256	$\tan^2\theta_{sol,max}$	0.4970	$\|U_{e3,max}\|^2$	0.035
$\Delta m^2_{atm,min}$	$2.36 \cdot 10^{-21}$ GeV^2	$\Delta m^2_{sol,min}$	$7.46 \cdot 10^{-23}$ GeV^2		
$\Delta m^2_{atm,max}$	$2.54 \cdot 10^{-21}$ GeV^2	$\Delta m^2_{sol,max}$	$7.83 \cdot 10^{-23}$ GeV^2		

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

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

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 in GeV^2

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

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

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

5.2.6. 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 [123] 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.

6: if 1 then the neutrino Yukawa couplings will be set at the largest of the corresponding seesaw particle instead of at m_{GUT}. This applies for all three seesaw types.

9: Starting with version 3.3.0 the formulas of [111] are used to resum the chirally enhanced terms in the calculation of the Yukawa couplings of b-quark and τ lepton as this improves the numerical stability for large trilinear couplings. In case one wants to use the previous implemention for this resummation, one has to set this entry to 1.

10: Starting with version 3.3.3 the renormalistion scale M_{EWSB} is calculated using the tree-level values of the stop masses in contrast to previous versions where the loop-corrected masses had been used. In case one wants to use loop-corrected masses , one has to set this entry to 1.

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

13: if 0 then the branching ratios of the decays $h \to VV^*$ are folded with the branching ratios of the off-shell vector boson, otherwise these branching ratios are written as 2-body decays. 0 is the default.

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}

23: sets the electron polarisation P_m

24: sets the positron polarisation P_p

25: whether to use initial state radation 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 $M_{\rm GUT}$, otherwise $M_{\rm GUT}$ 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 Γ_Z, default is 2.49 GeV

42: sets the width of the W-boson Γ_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 5.2.5)

92: if 1 gives in case of R-parity violation only the 4×4 MSSM part of the neutrino/neutralino mixing matrix N and the correspondingly the 2×2 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` [124] or older versions of the program `Phythia` [125].

In case of the entries 22, 23 and 24 the program accepts up to 100 combinations of these quantities in a single run.

5.2.7. Block `Y15IN`

Here one can specify the neutrino Yukawa Y_{ij}^T coupling at $M_{\rm GUT}$ for the seesaw type II model with a complete 15-plet at the GUT scale [79, 80, 82], where the data is given in the `FORTRAN` format

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

where the first integers in this format corresponds to i, the second is always 1 as there is only 15-plet present and third one corresponds to j. The double precision number gives the corresponding entry of the Yukawa coupling.

At the scale M_T three different Yukawa couplings Y_S, Y_T and Y_Z are present [79] which are stored in the blocks `YD15SD`, `YL15TL` and `YD15ZL` using the format as for the input.

5.2.8. Block `Y24IN`

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 [82], 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.

5.2.9. Block `YHD15THDIN`

Here one can specify the Yukawa λ_1 coupling at $M_{\rm GUT}$ for the seesaw type II model where the data is given in the `FORTRAN` format

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

where the integers in this format are all 1 as in the implemented model only one H_d and pair of 15-plets (triplets) are present. The double precision number gives the Yukawa coupling.

5.2.10. Block `YHU15TBHUIN`

Here one can specify the Yukawa λ_2 coupling at $M_{\rm GUT}$ for the seesaw type II model where the data is given in the `FORTRAN` format

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

where the integers in this format are all 1 as in the implemented model only one H_u and pair of 15-plets (triplets) are present. The double precision number gives the Yukawa coupling.

5.2.11. Block `YL15TLIN`

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 [79], where the data is given in the `FORTRAN` format

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

where the first integers in this format corresponds to i, the second is always 1 as there is only triplet present and third one corresponds to j. The double precision number gives the corresponding entry of the Yukawa coupling.

5.2.12. Block `YNURLHUIN`

This block specifies the neutrino Yukawa couplings Y_ν 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 `YNuRLHuIN` with the FORTRAN format

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

and the imaginary parts in the block `IMYNuRLHuIN` with the same FORTRAN input. The thrird integer is always 1 as only H_u is considered in the implemented model.

5.3. New output blocks

5.3.1. Blocks to transfer data to `HiggsBounds`

The program `HiggsBounds` [17, 18] can be used to calculate constraints from the Higgs sectors in a large class of models. For the data transfer the additional blocks `HiggsBoundsInputHiggsCouplingsBosons` and `HiggsBoundsInputHiggsCouplingsFermions` are required [126] where varios ratios of couplings are stored. In `HiggsBoundsInputHiggsCouplingsFermions` the ratios of couplings of h^0, H^0 and A^0 to third generation fermions are stored, whereas `HiggsBoundsInputHiggsCouplingsBosons` contains the ratios of couplings to gauge bosons. In the latter case we give all required trilinear couplings including the loop induced coupling to gluons where we have taken the formulas of ref. [60]. The required loop-induced quartic couplings of one Higgs boson to two gluons and one Z-boson is not calculated and, thus, set to zero.

5.3.2. Block `SEESAWGENERATIONS`

This gives the number of generations of heavy particles involved in the corresponding seesaw mechanism [76]. Here the first entry gives the field and the second the numbe of generations. For the first entry the following numbers are used:

1: right-handed neutrinos

15: 15-plets

24: 24-plets

The data is given in the `FORTRAN` format

```
(1x,i2,3x,i3,"# ",a)
```

5.3.3. 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 $BR(B_d^0 \to e^+e^-)$

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

6 $BR(B_d^0 \to \tau^+\tau^-)$

7 $BR(B_s^0 \to e^+e^-)$

8 $BR(B_s^0 \to \mu^+\mu^-)$

9 $BR(B_s^0 \to \tau^+\tau^-)$

10 $BR(B_u \to \tau^+\nu)$

11 $BR(B_u \to \tau^+\nu)/BR(B_u \to \tau^+\nu)_{SM}$

12 $\Delta(M_{B_s^0})$ [in ps^{-1}]

13 $\Delta(M_{B_d^0})$ [in ps^{-1}]

16 ϵ_K

17 $\Delta(M_K)$

18 $BR(K_L \to \pi^0\nu\nu)$

19 $BR(K^+ \to \pi^+\nu\nu)$

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_μ

25 electric dipole moment of the tau d_τ

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 ρ-parameter

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

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

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

Note, that for the calculation of all observables we include all phases and flavour mixing.

6. Installation and implementing new models

6.1. 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 quadruple 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 quadruple 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.

6.2. Implementing new models

New models can easily implemented using the `SARAH` package [127, 128]. 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`.

7. 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 5 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.

8. 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 case of low energy observables the so-called Flavour Les Houches Accord [107] has been developed to give detailed information e.g. the values of the Wilson coefficients. The corresponding standard for the output will be within the next iterations. Partial information for C_7, C_8, C_9, C_{10} and C_{11} is given starting with version 3.3.0.

In section 4 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 extending the above mentioned Flavour Les Houches Accord.

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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 [2, 75] which are not yet supported:

- 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 `RealEigenSystems`

-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: singular matrix in routine `InverseMatrix`

-26: inversion failed in routine `InvMat3`

-27: stepsize underflow in routine `bsstep`

-28: too much extrapolation in routine `pzextr`

-29: too much extrapolation in routine `rzextr`

-30: matrix contains `NaN` in routine `RealEigenSystems`

-31: matrix contains `NaN` in routine `ComplexEigenSystems`

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 $m_{l_DR}/m_l < 0.1$ or $m_{l_DR}/m_l > 10$

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

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

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

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

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

-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 $m^2_{h^0} < 0$ in routine `LoopMassesMSSM`

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

-525 negative mass squared in routine `Sigma_SM_chirally_enhanced`

Appendix C.7. Module TwoLoopHiggsMass

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

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

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

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

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

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

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

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

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

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

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

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

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

  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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