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# SDECAY — A FORTRAN CODE FOR THE CALCULATION OF SUPERSYMMETRIC PARTICLE DECAYS*

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The Fortran code SDECAY is presented which calculates the decay widths and branching ratios of all supersymmetric particles in the Minimal Supersymmetric Standard Model, including higher order effects. The program incorporates the usual two-body decays of sfermions and gauginos as well as the three-body decay modes of charginos, neutralinos and gluinos. The three-body stop and sbottom decays are implemented as well and even the four-body stop decays are calculated. Moreover, the important loop-induced decays, the QCD corrections to the two-body widths involving strongly interacting particles and the dominant electroweak effects to all processes are evaluated.

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## 1. Introduction

The search for supersymmetric (SUSY) particles is a major goal of present and future colliders. A lot of effort has been undertaken to determine the production mechanisms of these particles at future colliders, their decay modes and basic properties. Most of the studies have been done in the framework of the Minimal Supersymmetric Standard Model (MSSM) [1–3]. Although the MSSM is based on a minimal gauge structure, particle content and minimal interactions, it contains more than one hundred new parameters in the most general case. Even if the model is constrained to have a viable phenomenology there still remain over 20 free parameters. These enter in the evaluation of the masses of more than 30 supersymmetric particles and Higgs bosons and in their complicated couplings, so that it will be a very complicated task to pin down all the particle properties as well as to make detailed and complete phenomenological analyses and comparisons with the outcome from the experiments.

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Experimental studies have shown that the accuracy for the determination of the SUSY particle properties is expected to be of the order of a few per cent at the LHC [4] and at the per cent level and below at future $e^+e^-$ linear colliders [5]. In order to match this experimental accuracy the mass spectra, the various couplings, the production cross sections and the particle decays have to be calculated with rather high precision, which means that also higher order effects have to be included. The production cross sections which are dealt with by Monte Carlo event generators have in some cases been calculated at next-to-leading order (NLO) [6]. Concerning spectra and decays, the following requirements emerge:

— The physical (pole) masses of the SUSY and Higgs particles, the various couplings as well as the soft SUSY breaking parameters which enter these have to be calculated very accurately. They also have to take into account the masses of third-generation fermions, the mixing between the various states, and when important, the radiative corrections. In constrained MSSMs one has in addition to deal with the renormalization group evolution (RGE) of the parameters between the low-energy scale and the high-energy scale and the consistent implementation of radiative electroweak symmetry breaking (EWSB). Several RGE codes [7–10] have been developed which calculate the SUSY particle and Higgs boson masses and the soft SUSY breaking parameters in unconstrained and constrained MSSMs.

— All possible two-body tree level decays [11] have to be taken into account as well as the QCD corrections to the decays involving strongly interacting particles [12–14]. Since in some cases the electroweak radiative corrections can be as large as the QCD corrections they should also be taken into account. They are available at one-loop level only for some processes [15]. The bulk of these corrections might be accounted for, however, by taking the running parameters at the scale of the electroweak symmetry breaking in the gauge and third generation Yukawa couplings as well as for the soft SUSY breaking parameters and the third generation sfermion mixing angles entering in the various couplings.

— All higher order decays that can be important have to be included in the decay programs for SUSY particles as well. These are the three-body decays of the charginos, neutralinos and the gluino into other gauginos and a pair of fermions [16, 17] as well as the three-body stop and sbottom decays [18, 19]. Even the stop four-body decays [20] can possibly compete with the loop induced flavour changing neutral current (FCNC) decay of a stop into a charm quark and the lightest neutralino [21]. Further loop-induced decays that might play a role are the radiative decay of the next-to-lightest neutralino into the lightest neutralino and a photon [22, 23] and the decay of a gluino into a gluon and the LSP [24].

The Fortran code `SDECAY` [25] treats the SUSY particle decays in the framework of the MSSM. After the evaluation of the various couplings of the SUSY particles and Higgs bosons it calculates all tree-level two-body decays including the QCD corrections to the processes involving coloured particles. Furthermore, the loop-induced two-body modes have been implemented and the possibly important higher order decays, which are the three-body decays of the charginos, neutralinos, the gluino, the stops and sbottoms as well as the stop four-body decays. The program also calculates the top quark decays in the MSSM. The mass spectrum, the soft SUSY breaking parameters and all further Standard Model (SM) and SUSY parameters necessary for the evaluation of the couplings and the calculation of the SUSY particle decays are either taken from the linked RGE program `SuSpect` [8] or any input file following the so-called SUSY Les Houches Accord format [26]. The latter defines a general input/output file structure that has been developed to provide a universal interface between the various spectrum calculation programs, decay packages and high energy physics event generators.

In the following, the decay program `SDECAY` will be presented in detail. The implementation of the MSSM will be specified. All the decay modes that have been included will be discussed. The main features and the structure of the program will be summarized.

## 2. The MSSM implementation

The code `SDECAY` implements supersymmetry in its minimal version, *i.e.* in the framework of the MSSM which is based on the assumptions of a

— minimal gauge group, the Standard Model $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ one;

— minimal particle content, *i.e.* three generations of "chiral" sfermions $\tilde{f}^i_{\mathrm{L,R}}$ (no right-handed sneutrinos) and two Higgs field doublets, $H_1$ and $H_2$;

— minimal set of couplings imposed by $R$-parity conservation so that baryon and lepton number conservation is enforced in a simple way and which leads to a stable LSP;

— minimal set of soft SUSY breaking parameters: gaugino mass terms $M_i$, scalar mass terms $m_{H_i}$ and $m_{\tilde{f}_i}$, a bilinear term $B$ and trilinear sfermion couplings $A_i$.

In order to have a viable phenomenology and a reduced number of parameters, the following three assumptions have been made:

*(i)* All the soft SUSY breaking parameters are real so that no new source of CP-violation is generated in addition to the one from the CKM matrix.

*(ii)* In the matrices for the sfermion masses and for the trilinear couplings there is no intergenerational mixing, implying the absence of FCNCs at tree level.

*(iii)* The first and second sfermion generations are universal at low energy to cope with some severe experimental constraints. (For simplicity, also all the masses of the first- and second-generation fermions have been neglected since they are small enough not to have any significant effect.)

These three assumptions leave us with only 22 input parameters:
$\tan\beta$: the ratio of the vacuum expectation values (VEVs) of the two Higgs doublet fields;
$m^2_{H_1}, m^2_{H_2}$: the Higgs mass parameters squared;
$M_1, M_2, M_3$: the bino, wino and gluino mass parameters;
$m_{\tilde{q}}, m_{\tilde{u}_{\rm R}}, m_{\tilde{d}_{\rm R}}, m_{\tilde{l}}, m_{\tilde{e}_{\rm R}}$: the first/second-generation sfermion mass parameters;
$m_{\tilde{Q}}, m_{\tilde{t}_{\rm R}}, m_{\tilde{b}_{\rm R}}, m_{\tilde{\rm L}}, m_{\tilde{\tau}_{\rm R}}$: the third-generation sfermion mass parameters;
$A_u, A_d, A_e$: the first/second-generation trilinear couplings;
$A_t, A_b, A_\tau$: the third-generation trilinear couplings.

Requiring a proper electroweak symmetry breaking, the higgsino mass parameter $|\mu|$ (up to a sign) and the soft SUSY breaking bilinear Higgs term $B$ are determined, given the above parameters. In constrained models as for example minimal Supergravity (mSUGRA) [27], the gauge-mediated SUSY breaking (GMSB) [28] and anomaly-mediated SUSY breaking (AMSB) [29] models, most of the above 22 soft SUSY-breaking input parameters are derived from a set of universal boundary conditions at the high-energy scale. The low-energy soft SUSY-breaking parameters are then derived from the high-energy ones through RGEs. The pole masses of the Higgs bosons and all the supersymmetric particles can then be calculated, including the possible mixing between the current states and the radiative corrections [up to two loops in some cases] when they are important. This is done in the program `SuSpect` which is linked to `SDECAY`. For the calculation of the MSSM Higgs boson masses and the mixing angle $\alpha$ in the CP-even sector `SuSpect` uses the routine `twoloophiggs` [30] which has the same level of approximation [31] as the one used in `SuSpect`, since it includes the full one-loop radiative corrections and the dominant two-loop corrections at order $\alpha_s\lambda_f^2$ and $\lambda_f^4$, where $\lambda_f$ denotes the third-generation Yukawa couplings.

Of course, any other RGE program can easily be linked to `SDECAY`. A procedure that is not necessary if the RGE program provides the output for the mass spectrum and soft SUSY breaking parameters in the SUSY Les Houches Accord format that can be read in by `SDECAY`, so that the `SDECAY` user is flexible in the choice of where to take the input parameters from[1].

With these parameters `SDECAY` then calculates all the couplings of the SUSY particles and the MSSM Higgs bosons. The Feynman rules that are used in the code are those of Ref. [2], supplemented by the rules for Majorana fermions given in Ref. [32]. Using the input from `SuSpect` the couplings are thus defined in the $\overline{\mathrm{DR}}$ scheme and evaluated at the scale of EWSB. They, therefore, already include some radiative corrections, so that care has to be taken when they are used in one-loop corrected amplitudes in order to avoid double counting.

## 3. The supersymmetric particle decays

In the following the supersymmetric particle decays that have been included in `SDECAY` will be presented in detail, starting with

### *3.1. The tree-level two-body decays*

The main sfermion decay modes are the ones into their partner fermions and neutralinos and into their partner fermions and charginos, respectively,

$$\tilde{f}_i \to \tilde{\chi}_j f \,, \tag{1}$$

where $\tilde{\chi}_j$ collectively denotes the charginos and neutralinos and here and in the following no distinction between two isospin sfermion partners has been made. Squarks can also decay into gluino–quark final states

$$\tilde{q}_i \to \tilde{g} q \,. \tag{2}$$

Furthermore, the heavier sfermion can decay into a lighter one and a gauge boson or a Higgs boson, if the mass splitting between two sfermions of the same generation is large enough

$$\tilde{f}_i \to \tilde{f}_j V \,, \quad \text{with} \quad V = W^\pm, Z \,, \tag{3}$$

$$\tilde{f}_i \to \tilde{f}_j \Phi \,, \quad \text{with} \quad \Phi = h, H, A, H^\pm \,. \tag{4}$$

[1] Some care has to be taken, however, that there is still consistency between the linked program and `SDECAY`, especially when dealing with the QCD corrected decays, treated below.

The heavier neutralinos and charginos decay into the lighter ones and gauge or Higgs bosons as well as into sfermion–fermion pairs if there is enough phase space

$$\tilde{\chi}_i \rightarrow \tilde{\chi}_j V \,, \tag{5}$$

$$\tilde{\chi}_i \rightarrow \tilde{\chi}_j \Phi \,, \tag{6}$$

$$\tilde{\chi}_i \rightarrow \tilde{f}_j f \,. \tag{7}$$

Finally, for heavy enough gluinos the only relevant two-body decay is the one into a squark quark pair

$$\tilde{g} \rightarrow \tilde{q}_i q \,. \tag{8}$$

In case of a GMSB model, the lightest SUSY particle is the gravitino $\tilde{G}$, and the next-to-lightest (NLSP) SUSY state can be either the lightest neutralino or a sfermion, generally the $\tilde{\tau}_1$. For the respective NLSP, the possible decays into the gravitino final state have been included in `SDECAY`,

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma, \tilde{G}Z, \tilde{G}\phi \,, \qquad \text{with} \qquad \phi = h, H, A \,, \tag{9}$$

$$\tilde{\tau}_1 \rightarrow \tilde{G}\tau \,. \tag{10}$$

`SDECAY` calculates the partial widths and branching ratios for all these decays after checking if the respective decay is kinematically possible. It uses the pole masses in the phase space and the running $\overline{\mathrm{DR}}$ masses at the EWSB scale for the third-generation fermion Yukawa couplings. Likewise, the running $\overline{\mathrm{DR}}$ parameters at the EWSB scale are used for the soft SUSY breaking parameters and mixing angles which enter the couplings. For the QCD coupling constants and the third-generation Yukawa couplings, however, there is also the possibility to evaluate these couplings at any other user chosen scale, in which case only the QCD corrections are included in the running, though, [33].

### *3.2. The QCD corrected two-body decays*

For the two-body decays involving strongly interacting particles the one-loop QCD corrections [12–14] have the been incorporated in the program

$$\tilde{q}_i \rightarrow \tilde{g} q \qquad \text{and} \qquad \tilde{q}_i \rightarrow \tilde{\chi}_j q \,, \tag{11}$$

$$\tilde{q}_i \rightarrow \tilde{q}_j \Phi \qquad \text{and} \qquad \tilde{q}_i \rightarrow \tilde{q}_j V \,, \tag{12}$$

$$\tilde{g} \rightarrow \tilde{q}_j q \,, \tag{13}$$

$$\tilde{\chi}_i \rightarrow \tilde{q}_j q \,. \tag{14}$$

All the corrections are evaluated in the $\overline{\mathrm{DR}}$ scheme. Since some of the above references provide the results in the $\overline{\mathrm{MS}}$ scheme the formulae have been transformed to the $\overline{\mathrm{DR}}$ scheme beforehand. The results for the physical observables are of course the same in the two schemes up to the calculated order. In case the top and bottom quark masses and the stop and sbottom mixing angles (and thus the trilinear couplings $A_t$ and $A_b$) are obtained form `SuSpect`, they already include some one-loop contributions. Some care has, therefore, to be taken when dealing with the renormalization of these parameters and their one-loop counterterms in order to avoid double counting. In `SDECAY` the loop-corrected processes have been implemented in such a way that they are consistent with the parameters taken from `SuSpect`. This caveat, therefore, especially holds when the respective parameters are taken from any other RGE program.

The gauge and third-generation Yukawa couplings have been evaluated at the EWSB scale which is expected to account for the dominant electroweak radiative corrections. The remaining corrections (including photon emission in the initial and final state) which are of the order of the electromagnetic coupling constant are expected to lead to corrections at the few per cent level only and may, therefore, be neglected in this first approach.

### *3.3. Loop induced decays*

If the mass splitting between the next-to-lightest neutralino and the lightest neutralino is very small, the two-body neutralino decays are kinematically closed, and the virtuality of the exchanged particles in the allowed three-body decays is so large that loop-induced decays of at least $\tilde{\chi}_2^0$ into $\tilde{\chi}_1^0$ and a photon [22, 23]

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma\,, \tag{15}$$

might become important. This decay is mediated by triangle diagrams involving virtual charginos with $W$ and charged Higgs bosons and sfermion/fermion loops. The decay has been included in `SDECAY` as well as the gluino decay into a gluon and the lightest neutralino [24] which is induced by squark–quark loops

$$\tilde{g} \to g\tilde{\chi}_1^0\,. \tag{16}$$

In case the stop is too light to decay in a chargino/bottom or a neutralino/top pair, the only two-body decay channel that would be kinematically possible is the loop-induced and FCNC decay

$$\tilde{t}_i \to c\chi_1^0\,. \tag{17}$$

This decay is mediated by one-loop diagrams. Since a full calculation taking into account all loop diagrams is not yet available the decay has been implemented in the approximation used in [21] which takes into account the leading logarithmic contribution $\sim \log(\Lambda^2/M_W^2)$ where $\Lambda$ is an appropriate cut-off scale. In SDECAY it has been chosen equal to the Grand Unification (GUT) scale.

### *3.4. Multibody decays*

If the two-body decays are kinematically closed the multibody decays (as well as the loop-induced decays) become important and will be evaluated by SDECAY. It should be mentioned that there is a clear separation between the two-body and higher-order decays, *i.e.* the propagators of the exchanged virtual particles do not contain their total decay width so as to make a smooth transition between the two-body and multibody decays. There are issues of gauge invariance which have not been settled yet so that at the present stage of the program this way of dealing with the problem has been chosen.

As for the gaugino decays, the incorporated three-body decay channels are the ones into a lighter chargino/neutralino and a fermion pair

$$\tilde{\chi}_i \to \tilde{\chi}_j f\bar{f}\,. \tag{18}$$

Furthermore, the heavier charginos and neutralinos can also decay into a gluino and a quark pair, in particular in models with non-universal gaugino masses at high scale

$$\tilde{\chi}_i \to \tilde{g}q\bar{q}\,. \tag{19}$$

The gluino decays via the reverse process to (19) into a gaugino and a quark pair

$$\tilde{g} \to \tilde{\chi}_i q\bar{q}\,. \tag{20}$$

Further implemented higher-order gluino decays are

$$\tilde{g} \;\to\; \tilde{t}_1\bar{b}W^- \;+\; \text{c.c.}\,, \tag{21}$$
$$\tilde{g} \;\to\; \tilde{t}_1\bar{b}H^- \;+\; \text{c.c.}\,. \tag{22}$$

For stops there exists a variety of three-body decays. For $m_{\tilde{t}_1} > m_{W^\pm(H^\pm)} + m_{\tilde{\chi}_1^0}$ possible decay channels are

$$\tilde{t}_i \to bW^+\tilde{\chi}_1^0 \quad \text{and} \quad bH^+\tilde{\chi}_1^0\,. \tag{23}$$

If sleptons are lighter than squarks the modes

$$\tilde{t}_i \to bl^+\tilde{\nu}_l \quad \text{and} \quad b\tilde{l}^+\nu_l \tag{24}$$

become accessible. In addition, the stops can decay into the lightest sbottom and a fermion–antifermion pair

$$\tilde{t}_i \to \tilde{b}_1 f \bar{f} \,. \tag{25}$$

And for the heavier stop there is the possibility of decaying into the lighter stop and a fermion pair

$$\tilde{t}_2 \to \tilde{t}_1 f \bar{f} \,. \tag{26}$$

For the sbottom the three-body decays into a lighter stop and a fermion pair or into the lighter sbottom and a fermion pair in case of $\tilde{b}_2$ have been included

$$\tilde{b}_i \;\to\; \tilde{t}_j f \bar{f} \,, \tag{27}$$

$$\tilde{b}_2 \;\to\; \tilde{b}_1 f \bar{f} \,. \tag{28}$$

Furthermore, the decays into slepton, lepton and a top quark are evaluated

$$\tilde{b}_i \;\to\; t l^- \tilde{\nu}_l^* \,, \tag{29}$$

$$\tilde{b}_i \;\to\; t \tilde{l}^- \bar{\nu}_l \,. \tag{30}$$

In all these three-body decays the running $\overline{\mathrm{DR}}$ parameters at the EWSB scale have been taken in the couplings as for the two-body decays. The mixing in the third-generation sfermion sector has been taken into account. Furthermore, the masses of the fermion final states have been included, which will become important when the mass splitting between the decaying and the final state particles is small.

In case the three-body decays of the stops are kinematically not accessible, the four-body decays of the lightest stop into a $b$-quark, the LSP and two massless fermions may compete with the loop induced $\tilde{t}_1$ decay into a charm quark and lightest neutralino discussed above, which is of the same order of perturbation theory, *i.e.* $\mathcal{O}(\alpha^3)$. The decay [20]

$$\tilde{t}_1 \to b \tilde{\chi}_1^0 f \bar{f} \,, \tag{31}$$

has been, therefore, included in `SDECAY` as well.

### *3.5. Top quark decays*

The program also provides the decay widths and branching ratios for the top quark in the MSSM which are besides the standard decay

$$t \;\to\; b W^+ \tag{32}$$

the decays in a bottom quark and charged Higgs boson and a lighter stop and a neutralino

$$t \rightarrow bH^+ \,, \tag{33}$$
$$t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0 \,. \tag{34}$$

The one-loop SUSY–QCD radiative corrections are known [34] and are planned to be included in an updated version of the program.

## 4. The structure of SDECAY

Besides the necessary files for the parameter setting, *i.e.* either the `SuSpect` files or an input file in the SUSY Les Houches accord format, the program `SDECAY` consists of the following three files:

1. The input file `sdecay.in`: It allows the user to choose various options, such as whether or not to include the QCD corrections to the two-body decays, the multibody and/or loop-induced decays, the GMSB decays and/or the top decays. The scale for the running Yukawa and strong coupling constant can be changed. Furthermore, the choice where to take the spectrum from can be made, *i.e.* from `SuSpect` or an input in the SLHA format from any other RGE program.

2. The main routine `sdecay.f`: In this main body of the program the necessary couplings are evaluated and the decay branching ratios and total widths are calculated. The routine is self-contained and contains all the necessary files for the calculation. The results are then written out into `sdecay.out`.

3. The output file `sdecay.out`: This file contains the parameters that have been used for the calculation and all the calculated SUSY particle branching ratios and total widths. Up to the user's choice, this is done either in a simple transparent form or according to the rules of the SUSY Les Houches accord.

Thus the program `SDECAY` has the following structure:

— It reads in the input file containing all the necessary parameters (provided either by `SuSpect` or any other RGE program) and the input file `sdecay.in`;

— It calls the subroutine `SD_common_ini`[2] where all parameters necessary for the calculation of the couplings and decay widths are set;

[2] All functions and subroutines in the program carry the prefix `SD_` in order to avoid confusion when other programs are linked.

— It calls the subroutines for the calculation of the couplings necessary in the decay widths;

— It calls the subroutines for the two-body, the three-body and the loop decays as well as the stop four-body decays and the top decays in order to calculate the partial widths and finally the total widths and branching ratios. The routines call several help functions and subroutines for the loop decays and the QCD corrections and some matrix elements of the multibody decays;

— It writes in the output file `sdecay.out`.

The program is maintained regularly to include upgrades and newest theoretical developments in accordance with the present state of the art and the experimental needs.

A web page has been devoted to `SDECAY` which can be found at the address:

`http://people.web.psi.ch/muehlleitner/SDECAY/`

The user can download all the necessary files for the program from there. Short explanations of the code and how to run it are given. The complete user's manual can be found and a regularly updated list of important changes and corrected bugs in the code. Example output files are given as well which are too lengthy to be displayed here.

## 5. Summary

The Fortran code `SDECAY` has been presented which calculates not only the two-body widths and branching ratios of all SUSY particles in the framework of the MSSM but also the higher-order decays, such as loop-induced two-body decays of the lightest stop, the lightest neutralino and the gluino, as well as the three-body decays of the neutralinos, charginos, the gluino, the stops and sbottoms and even the four-body decays of the $\tilde{t}_1$. In addition, the QCD corrections to the decays involving strongly interacting particles as well as the electroweak corrections due to the running of the gauge and Yukawa couplings are incorporated. In the GMSB models, also the decays of the NLSP into a Gravitino can be calculated. The standard and SUSY decay modes of the top quark have been implemented, too.

The user can choose where to take the spectrum and all other SUSY and SM parameters necessary for the calculation of the couplings and decays from. There is the choice between the linked RGE code `SuSpect` or an input file in the SLHA accord provided by any other spectrum calculator which involves the same approximations for the radiative corrections. The program is user-friendly and flexible for the choice of options and approximations.

`SDECAY` is under continuous development and maintained regularly to be up-to-date with the theoretical developments and experimental needs.

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