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DECAYS OF SUPERSYMMETRIC PARTICLES — THE PROGRAM SUSY-HIT*

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We present the program package `SUSY-HIT` SUspect-SdecaY-Hdecay-InTerface for the computation of supersymmetric particle decays within the framework of the Minimal Supersymmetric extension of the Standard Model. The code is based on two existing programs `HDECAY` and `SDECAY` for the calculation of the decay widths and branching ratios of, respectively, the MSSM Higgs bosons and the SUSY particles, and calls a program for the calculation of the SUSY particle spectrum such as `SuSpect`. Including all important higher order effects, the package allows the consistent calculation of the MSSM particle spectrum and decays with the presently highest level of precision.

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1. Introduction

Low energy Supersymmetry (SUSY) is considered as the prime candidate for physics beyond the Standard Model (SM) of the electroweak and strong interactions of elementary particles. It will be testable at the Large Hadron Collider (LHC) [1] and later on at the International Linear Collider (ILC) [2]. Once SUSY particles are discovered, their characteristics have to

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be determined with high accuracy to reconstruct the corresponding fundamental Lagrangian. This will be possible at the LHC at the few percent level, and a precision better than one percent will be achieved at the ILC. Therefore, theory should provide calculational tools which match the expected high precision of the experiments. The codes for the determination of the SUSY particle spectrum and their decays must take into account corrections at the highest possible level. And since beyond leading order the results depend on many ingredients such as the choice of the renormalization scheme and the definition of the input parameters, an inherently consistent package to cover the whole program of calculating the spectra and decays of the new particles at higher order is highly desired.

In this context, we have developed the Fortran code `SUSY-HIT` which includes the codes `HDECAY` [3] and `SDECAY` [4] that allow the calculation of decay widths of both SUSY particles and MSSM Higgs bosons, if the basic input parameters, the masses and the couplings of the particles are provided by a spectrum code[1]. For the latter purpose, we have by default used the program `SuSpect` [5], which can be replaced, however, by any spectrum calculator [6] using the SUSY Les Houches Accord (SLHA) format [7] in the output file which will be read in by `HDECAY` and `SDECAY`.

In the following, we will first present the three programs separately: `SuSpect`, the spectrum calculator which is linked by default, and the decay programs `HDECAY` and `SDECAY`, which constitute the heart of the package. We recall how the codes work and which level of accuracy they contain. The program package `SUSY-HIT` will be then briefly described.

2. The spectrum calculator: the example of `SuSpect`

Implementation of the MSSM: The Fortran code `SuSpect` calculates the supersymmetric and Higgs particle spectrum in the MSSM. It deals with the "phenomenological MSSM" with 22 free parameters defined either at a low or high energy scale, with the possibility of renormalization group evolution (RGE) to arbitrary scales, and with constrained models with universal boundary conditions at high scales. These are the minimal supergravity (mSUGRA), the anomaly mediated SUSY breaking (AMSB) and the gauge mediated SUSY breaking (GMSB) models. The basic assumptions of the most general possible MSSM scenario are (a) minimal gauge group, (b) minimal particle content, (c) minimal Yukawa interactions and R-parity conservation, (d) minimal set of soft SUSY breaking terms. Furthermore, *(i)* all soft SUSY breaking parameters are real (no CP-violation); *(ii)* the matrices for sfermion masses and trilinear couplings are diagonal; *(iii)* first

[1] The production of the SUSY and Higgs particles of the MSSM will be deferred to other programs and ultimately, will be dealt with by Monte Carlo generators.

and second sfermion generation universality is assumed. Here and in the following we refer the reader for more details to the user's manual [5].

The general algorithm: As for the calculation of the SUSY particle spectrum in constrained MSSMs, in addition to the choice of the input parameters, the general algorithm contains three main steps. These are *(i)* the RGE of parameters back and forth between the low energy scales, such as M_Z and the electroweak symmetry breaking (EWSB) scale, and the high-energy scale characteristic for the various models; *(ii)* the consistent implementation of (radiative) EWSB; *(iii)* the calculation of the pole masses of the Higgs bosons and the SUSY particles, including the mixing between the current eigenstates and the radiative corrections when they are important. The last step holds also in unconstrained models. Here the program mainly follows the content and notations of Ref. [8], and for the leading two-loop corrections to the Higgs boson masses the results given in Ref. [9] are used. The fulfilment of theoretical constraints as well as the agreement with high precision measurements can be also checked.

Necessary files and link to other programs: The necessary files for the use in `SUSY-HIT` are the input file `suspect2.in`, the main routine `suspect2.f`, the routine `twoloophiggs.f`, which calculates the Higgs masses, as well as `bsg.f` for the calculation of the $b \to s\gamma$ branching ratio; other precision observables such as $(g-2)_\mu, \Delta\rho$ are calculated directly in `suspect2.f`. Some of the files have been slightly modified for the use in the package (for details see below). In the input file one can select the model to be investigated, the accuracy of the algorithm and the input data (SM particle masses and gauge couplings). At each run `SuSpect` generates two output files: one easy to read, `suspect2.out`, and the other in the SLHA format which can be read in by `HDECAY` and `SDECAY`.

3. The Fortran code `HDECAY`

Implemented decays: The Fortran code `HDECAY` calculates the decay widths and branching ratios of the SM Higgs boson, and of the neutral and charged Higgs particles of the MSSM according to the current theoretical knowledge [10]. It includes all kinematically allowed decay channels with branching ratios larger than 10^{-4}; in addition to the 2-body decays, also the loop-mediated, important multi-body and, in the MSSM, the cascade and SUSY decay channels are incorporated. More specifically, it includes:

— All relevant higher-order QCD corrections to decays into quarks and to the quark loop mediated decays into gluons and photons [11].

— Double off-shell decays of the CP-even Higgs bosons into massive gauge bosons, subsequently decaying into four massless fermions [12].

— All important below-threshold or 3-body decays: with off-shell heavy top quarks; with one off-shell gauge boson as well as heavy neutral Higgs decays with one off-shell Higgs boson [13].

— In the MSSM the complete radiative corrections in the effective potential approach with full mixing in the stop and sbottom sectors; it uses the RG improved values of the Higgs masses and couplings with the relevant next-to-leading-order corrections implemented [14]. This will be needed to extract the Higgs self-couplings which the spectrum calculators do not provide by default.

— In the MSSM, all the decays into SUSY particles when they are kinematically allowed [15] and all SUSY particles are included in the loop mediated $\gamma\gamma$ and gg decay channels. In the gluonic and photonic decay modes the QCD corrections for quark [16] and squark loops [17] are implemented.

Updates: `HDECAY` has recently undergone a major upgrade. We have implemented the SLHA format[2], so that the program can now read in any input file in this format and also provide the output for the Higgs decay widths and branching ratios in this accord. So, the program can now be easily linked to any spectrum or decay calculator. Two remarks are in order:

(i) `HDECAY` calculates the higher order corrections to the Higgs boson decays in the $\overline{\rm MS}$ scheme whereas all scale dependent parameters read in from an SLHA input file provided by a spectrum calculator are given in the $\overline{\rm DR}$ scheme. Therefore, `HDECAY` translates the input parameters from the SLHA file into the $\overline{\rm MS}$ scheme where needed.

(*ii*) The SLHA parameter input file only includes the MSSM Higgs boson mass values, but not the Higgs self-interactions, which are needed in `HDECAY`. For the time being, `HDECAY` calculates the missing interactions internally within the effective potential approach. This is not completely consistent with the values for the Higgs masses, since the spectrum calculator does not necessarily do it with the same method and level of accuracy as `HDECAY`.

4. The Fortran code `SDECAY`

Implemented decays: The Fortran code `SDECAY`, which has implemented the MSSM in the same way as it is performed in `SuSpect`, calculates the decay widths and branching ratios of all SUSY particles in the MSSM, including the most important higher order effects. More specifically:

— In the default option, the usual 2-body decays for sfermions and gauginos are calculated at tree level. In GMSB models, the 2-body decays into the LSP gravitino have been implemented.

[2] M. Mühlleitner has been added to the list of `HDECAY` authors.

— It provides the unique possibility of calculating the SUSY-QCD corrections to the decays involving coloured particles [18], which are very important in some cases. The bulk of the electroweak corrections is accounted for by using running parameters where appropriate.

— If the 2-body decays are kinematically closed, multibody decays will be dominant and `SDECAY` calculates the 3-body decays of the gauginos, the gluino, the stops and sbottoms [19].

— Loop-induced decays of the lightest top squark [20], the next-to-lightest neutralino [21] and the gluino [22] are included.

— If the 3-body decays are kinematically forbidden, 4-body decays of the lightest stop [23] can compete with the loop-induced $\tilde{t}_1$ decay and have therefore been implemented.

— Finally, the top decays within the MSSM have been included.

Updates: `SDECAY` has been recently updated and we take here the opportunity to announce the major changes.
(*i*) For reasons of shortening the output file, only non-zero branching ratios are written out in the SLHA output file of the new version.
(*ii*) We have created common blocks for the branching ratios and total widths of the various SUSY particles.

5. The program package `SUSY-HIT`

The following files are needed to run the program `SUSY-HIT`:

Spectrum files: The spectrum can either be taken from any input file in the SLHA format or directly from `SuSpect`. In the first case, `SUSY-HIT` needs an SLHA input file which has to be named `slhaspectrum.in`. In the latter case, `SuSpect` provides this file and we need all the necessary `SuSpect` routines: `suspect2.in`, `suspect2.f`, `twoloophiggs.f` and `bsg.f`.

Decay files: For `HDECAY` we need the main file `hdecay.f` and for `SDECAY` the main program file `sdecay.f`.

Input file: The flags which can be set in the original programs `HDECAY` and `SDECAY` in their respective input file have been hard-coded for the use in `SUSY-HIT`. `SDECAY` will calculate by default the QCD corrections to the 2-body decays involving coloured particles, the multi-body and the loop-induced decays, the top decays and the next-to-lightest SUSY particle decays in GMSB models. The running strong coupling constant and quark masses are calculated in the $\overline{\rm DR}$ scheme at the EWSB scale. In `HDECAY`, higher order corrections and off-shell decays of all MSSM Higgs particles will be calculated, including the ones into SUSY particle final states. `SUSY-HIT` thus needs only one input file called `susyhit.in`. Here, the user can choose among two link options:

(*i*) The three programs SuSpect, HDECAY, SDECAY are linked and, hence, SuSpect provides the spectrum and SUSY breaking parameters at $M_{\rm SUSY}$.

(*ii*) Only HDECAY and SDECAY are linked, and the necessary inputs are taken from a file in the SLHA format provided by any spectrum calculator.

Furthermore, some parameters related to HDECAY can be set, like some quark masses, the W, Z total widths, some CKM matrix elements etc. All other necessary parameters are read in from slhaspectrum.in.

Changes and how the package works: SuSpect, HDECAY and SDECAY are linked via the SLHA format. Therefore, the name of the output file provided by SuSpect has to be the same as the SLHA input file read in by HDECAY and SDECAY. We called it slhaspectrum.in. This is the major change made in the programs with respect to their original version. The complete list of changes can be found on the web page given below, but we briefly comment on some of them in the following.

SDECAY: It is the main program and now reads in susyhit.in and calls HDECAY. It passes the necessary parameters from susyhit.in to HDECAY via a newly created common block called SUSYHITIN. As before, it calls SuSpect in case the spectrum is taken from there. The SLHA parameter and spectrum input file slhaspectrum.in is read in by both HDECAY and SDECAY. The output file created by SDECAY at each run is called susyhit_slha.out if it is in the SLHA format or simply susyhit.out if it is in an output format easy to read.

SuSpect: Some subroutines within the file twoloophiggs.f which are also used in hdecay.f have been renamed in order to avoid clashes.

HDECAY: It has become a subroutine which is called by SDECAY. In order to keep the package as small as possible, only one routine calculating the Higgs boson masses and Higgs self-couplings has been retained in HDECAY to extract the Higgs self-interaction strengths not provided by the spectrum calculators. A new common block SUSYHITIN has been created to take over necessary parameters from SDECAY. HDECAY does not create any output file within the package.

Remarks: The b-quark mass given in the SLHA input file is the running mass $m_b(m_b)^{\overline{\rm MS}}$ in the $\overline{\rm MS}$ scheme, which is the mass measured by the experiments. The three programs calculate internally the b-quark pole mass from this value. HDECAY and SuSpect do this differently. SDECAY takes the same value for the pole mass as provided by SuSpect. So slightly different b-quark pole masses will be used in the decay calculations. The difference in the pole mass is less than 3%. The user should furthermore keep in mind that the Higgs masses taken from the spectrum calculator and the Higgs

self-couplings which are used within HDECAY may be slightly inconsistent, since these masses and couplings are related, but not provided together by the SLHA input file.

Web page: We have created a web page at the following url address:
`http://lappweb.in2p3.fr/~muehlleitner/SUSY-HIT/`
There the user can download all files necessary for the program package as well as a `makefile` for compiling the programs. We use the newest versions of the various programs which will be updated regularly. Short instructions are given how to use the programs. A file with updates and changes is provided. Finally, some examples of output files are given.

6. Summary

We have briefly presented the program package SUSY-HIT for the calculation of the particle spectrum in the MSSM and the decay widths and branching ratios of the SUSY particles and the Higgs bosons. The core of the package are the already available decay codes SDECAY and HDECAY. They are linked by default to the MSSM spectrum calculator SuSpect which, however, can be replaced by any other spectrum code giving the output in the SLHA format. The program provides the decay widths and branching ratios of the SUSY particles and neutral/charged Higgs bosons of the MSSM, as well as the additional decays of the top quark, at the presently highest level of precision. Hence, except for the production processes which ultimately must be dealt with by Monte Carlo generators (the link with the latter can be easily made through the SLHA), the program SUSY-HIT provides all the necessary information needed for the search and the study of the new particles at high-energy colliders.

The package is self-contained, easy to use, flexible and rather fast. All files and further information can be found on the related homepage. SUSY-HIT will be upgraded regularly to keep up with the experimental needs and theoretical developments. Suggestions for improving and adapting the code from theorists and experimentalists are highly welcome.

We would like to thank the other authors of the original programs HDECAY, SDECAY and SuSpect, J. Kalinowski, J.-L. Kneur, Y. Mambrini and G. Moultaka for their support in the past.

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