SLHAplus: a library for implementing extensions of the standard model

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Abstract

We provide a library to facilitate the implementation of new models in codes such as matrix element and event generators or codes for computing dark matter observables. The library contains a SLHA reader routine as well as diagonalisation routines. This library is available in CalcHEP and micrOMEGAs. The implementation of models based on this library is supported by LanHEP and FeynRules.

1 Introduction

In the very near future the LHC will have the opportunity to test the TeV scale relevant to address the outstanding issues in the standard model and its extensions: the symmetry breaking problem and the dark matter problem. Furthermore numerous astroparticle searches will help refine the dark matter properties. Confronting the various extensions of the standard model that have been proposed with observations at colliders and astroparticle searches will therefore provide powerful tests of the new physics model. Sophisticated tools have been developed to compute the predictions for observables such as particle spectra, decay rates or cross sections that are relevant at colliders (for a repository of available tools see [1]) while other tools explore the implications of new physics models for dark matter observables [2, 3, 4, 5, 6]. The interpretation of a new signature might require extending those tools to adapt them to work with different models.

Tools such as LanHEP [7], FeynRules [8] and SARAH [9] have been developed to facilitate the implementation of new models in generic matrix element and event generators such as Madgraph [10], CompHEP [11, 12], CalcHEP [13], FeynArts/FormCalc [14, 15], Whizard [16] and Sherpa [17]. They require mainly the implementation of a new Lagrangian and provide the model file adapted to the chosen generator. While these tools are very powerful they often leave some tedious and repetitive tasks for the user. Here we provide a library that contains some routines to facilitate the implementation of new models. The library first contains a routine for reading a SUSY Les Houches Accord (SLHA) file [18, 19]. An SLHA file is a standardized file format specifying input and output parameters that was developed in the framework of supersymmetry to facilitate the passing of information between codes as varied as spectrum calculators, matrix element generators and event generators. We have generalised the procedure to take into account an arbitrary number of blocks so that the reader can be used in generic models.

¹Another SLHA reader library that can be used with the MSSM and its extensions is available at [20].
including non supersymmetric ones. The library also contains routines to diagonalise real
and complex mass matrices with either unitary or bi-unitary transformations. Finally
it contains some routines for evaluating the running strong coupling constant as well as
running quark masses and effective quark masses. This library was designed and used in
CalcHEP [13], micrOMEGAs [3], LanHEP [7] and FeynRules [8] but can be incorporated in
other tools as well.

In this paper we describe the set of functions used for the SLHA reader (section 2),
the QNUMBERS reader (section 4), matrix diagonalisation (section 4), QCD functions
(section 5) and their Fortran counterparts (section 6). In section 7 we describe how
to compile and link this code. Section 8 comments on special features of this package
in LanHEP and CalcHEP. Section 9 comments on the use of this library when using
FeynRules with CalcHEP. Finally, in section 10 we conclude. We also include an appendix
with an example of using this package with LanHEP and CalcHEP for the MSSM.

2 SLHA reader

The SUSY Les Houches Accord [18, 19] specifies a unique set of conventions for the
MSSM and its extensions (NMSSM, CPVMSSM) together with generic file structures for
specification of input parameters, supersymmetric particle masses and couplings as well
as decay tables. This allows, for example, for dedicated external programs to perform
an accurate calculation of the particle spectrum. The results for particle masses, mixing
angles and other model parameters are then written in a file using a standard format that
can be used by other codes [21, 22, 23, 24, 25, 26]. A similar file format can also be
used for other extensions of the MSSM or for non-supersymmetric models. The routine
we describe here allows for reading of files in the SLHA format.

In general a SLHA file contains several pieces of information which are called blocks. A
block is characterized by its name and if relevant by an energy scale. Each block contains
the values of several physical parameters characterized by a key. The key consists of a
sequence of integer numbers. For example for masses the key is the PDG code [27], for
mixing matrices the rows and columns of the matrix and for decays the PDG codes of the
mother and daughter particles:

```
BLOCK MASS  # Mass spectrum
# PDG Code  mass  particle
 25  1.15137179E+02  # lightest neutral scalar
 37  1.48428409E+03  # charged Higgs
```

```
BLOCK NMIX  # Neutralino Mixing Matrix
 1 1  9.98499129E-01  # Zn11
 1 2 -1.54392008E-02  # Zn12
```

```
BLOCK Au Q= 4.42653237E+02  # The trilinear couplings
 1 1 -8.22783075E+02  # A_u(Q) DRbar
 2 2 -8.22783075E+02  # A_c(Q) DRbar
```

```
DECAY 36 2.10E-06  # Lightest pseudoscalar
 9.54085917E-03 2 21 21  # BR(A_1 -> gluon gluon)
 2.12111874E-04 2 -13 -13  # BR(A_1 -> muon muon)
```
The functions described below allow to read the information contained in this file, including the blocks that contain the model parameters, the masses and other physical parameters as well as other information such as particle decay widths.

- **slhaRead(filename, mode)**
  reads all or part of the data from the file `filename`. `mode` is an integer which determines which part of the data should be read from the file, `mode = 1*m1 + 2*m2 + 4*m4 + 8*m8 + 16*m16`

  - `m1 = 0/1` - overwrites all/keeps old data
  - `m2 = 0/1` - ignore errors in input file/stop in case of error
  - `m4 = 0/1` - read DECAY/do not read DECAY
  - `m8 = 0/1` - read BLOCK/do not read BLOCK
  - `m16 = 0/1` - read QNUMBERS/do not read QNUMBERS

  For example `mode=20` (m4=1,m16=1) is an instruction to overwrite all previous data and read only the information stored in the BLOCK sections of `filename`. In the same manner `mode=25=1+8+16` is an instruction to add information from DECAY to the data obtained previously.

  The function `slhaRead` returns the values:

  - 0 - successful reading
  - -1 - can not open file
  - -2 - invalid data as indicated by SPINFO
  - -3 - no data
  - n>0 - wrong file format at line n

- **slhaValExists(BlockName, keyLength, key1, key2,...)**
  checks the existence of specific data in a given block. `BlockName` can be substituted with any case spelling. The `keyLength` parameter defines the length of the key set `{key1,key2,...}`. For example `slhaValExists("Nmix",2,1,2)` will return 1 if the neutralino mass mixing element $Z_{n12}$ is given in the file and 0 otherwise.

- **slhaVal(BlockName,Q, keyLength, key1, key2,...)**
  is the main routine which allows to extract the numerical values of parameters. `BlockName` and `keyLength` are defined above. The parameter `Q` defines the scale dependence. This parameter is relevant only for the blocks that contain scale dependent parameters, it will be ignored for other blocks, for example those that give the particle pole masses. In general a SLHA file can contain several blocks with the same name but different scales (the scale is specified after the name of the block). `slhaVal` uses the following algorithm to read the scale dependent parameters. If `Q` is less(greater) than all the scales used in the different blocks for a given parameter `slhaVal` returns the value corresponding to the minimum(maximum) scale contained in the file. Otherwise `slhaVal` reads the values corresponding to the two scales $Q_1$ and $Q_2$ just below and above $Q$ and performs a linear interpolation in $\log(Q)$ to evaluate the returned values.
• **slhaWarnings(FD)**
  writes into the file FD the warnings or error message stored in the SPINFO block and returns the number of warnings. If FD=NULL the warnings are not written in a file.
• **slhaWrite(Filename)**
  writes down the information stored by readSLHA into the file. This function can be used for testing purposes.
• **slhaDecayExists(pNum)**
  checks whether information about the decay of particle pNum exists in the SLHA file. pNum is the particle PDG code. This function returns the number of decay channels listed. In particular zero means that the SLHA file contains information only about the total width, not on branching ratios while -1 means that even the total width is not given.
• **slhaWidth(pNum)**
  returns the value of the particle width.
• **slhaBranch(pNum,N, nCh)**
  returns the branching ratio of particle pNum into the N-th decay channel. Here 0<N<=slhaDecayExists(pNum). The array nCh is an output which specifies the PDG numbers of the decay products, the list is terminated by zero.

The functions slhaValExists, slhaVal, slhaDecayExists, slhaWidth can be used directly in CalcHEP model files. For example, the mass of the lightest neutralino can be specified in the CalcHEP file `func1.mdl` as

```
MNE1 | slhaVal("MASS",QSUSY,1,1000022)
```

Some applications might need the full list of SLHA blocks and DECAY items obtained with slhaRead. The following functions serve this purpose
• **allBlocks(K,L, blockName, &keyLength, keyArray, &val)**
• **allDecays(K,L, &pdg, &decayLength,&decayArray,&width,&branching)**
  where K specifies the block or decay to be read in numerical order. A K of 1 specifies that the first block (or decay) should be read, a K of 2 specifies that the second should be read, and so on. L specifies which record inside the block (or decay) should be read, again in numerical order. These functions return 1 as long as the requested information exists and return 0 otherwise. For the blocks, the name of the block is stored in the string blockName, the number of keys is recorded in keyLength, the array of keys is stored in keyArray and val contains the value. For decays, pdg stores the pdg of the particle, decayLength specifies the number of outgoing particles, decayArray the array of outgoing particles, and width and branching the total width and branching for each channel.

## 2.1 Writing an input SLHA file

This package contains three routines which allow to write an SLHA input file and launch a spectrum calculator.
• **openAppend(fileName)**
  deletes the input file fileName if it exists and creates a new empty file with the same name. The string fileName is stored in memory for subsequent usage with the function aPrintF.

2 FILE* type in C and channel number in Fortran
• **aPrintF(format,...)** opens the file `fileName` and writes at the end of the file the input parameters needed in the SLHA format or in any other format understood by the spectrum calculator. The arguments of `aPrintF` are similar to the arguments of the standard `printf` function.

• **System(format,...)** generates a shell command using `format` and subsequent arguments. This command is then launched by the standard `system` C-function.

For example, to write directly the SLHA model file needed by SuSpect [21] to compute the spectrum in a CMSSM(SUGRA) model, one needs to specify the standard model input parameters (\(m_b(m_b), m_t(pole)\)) as well as the SUSY input parameters \(m_0, m_{1/2}, \tan \beta, \text{sign}(\mu), A_0\). For this one must add the following sequence in the CalcHEP `func1.mdl` model file.

```plaintext
open |openAppend("suspect2_lha.in")
input1|aPrintF("Block MODSEL # Select model
 1 1 # SUGRA\n")
input2|aPrintF("Block SMINPUTS
 5 %E#mb(mb)\n 6 %E#mt(pole)\n",MbMb,Mtp)
input3|aPrintF("BLOCK MINPAR
 1 %E #m0\n 2 %E #m1/2\n",Mzero,Mhalf)
input4|aPrintF("3 %E #tb\n 4 %E #sign(mu)\n 5 %E #A0\n",tb,sgn,A0)
sys |System("%s/suspect2.exe",path())
rd |slhaRead("suspect2_lha.out",0)
```

In this example `path()` specifies the path to the directory where the SuSpect executable is located.

### 3 SLHAplus for parton shower generators.

Information about parton level events can be transferred to parton shower generators via a file written in the XML format [41]. In a generic extension of the Standard Model, the parton shower generator also needs information about the quantum numbers of new particles, their masses, widths and decay modes. In Ref. [42] it was proposed to include the corresponding SLHA Block and Decay items in the header section of the XML event file, using the subtags `<slha>` and </slha> to delimit the beginning and the end of the corresponding subsection of the header. A new SLHA block, `QNUMBERS`, was designed to provide information about the quantum numbers of new particles. For example a new neutral scalar particle called `balleron` could be defined as

```plaintext
BLOCK QNUMBERS 7654321 # balleron
  1 0 # 3 times electric charge
  2 1 # number of spin states (2S+1)
  3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
  4 0 # Particle/Antiparticle distinction (0=own anti)
```

Strictly speaking the block `QNUMBERS` does not fit the definition of a standard SLHA block as used in this paper. We treat it as an exceptional block. This block can be read by the `slhaRead` routine but for this special routines are required, which we now describe.

• **findQnumbers(PDG,&eQ3,&spinDim,&cDim,&neutral)**

gives the quantum numbers `eQ3,spinDim,cDim,neutral` for the particle specified by its PDG code (see the example of the `QNUMBERS` block given above). `findQnumbers` returns
1 if the file contains the quantum numbers for a given PDG particle, -1 if instead the information about the antiparticle is contained in the file, and 0 if the file contains no data on this (anti)particle.

A parton shower generator may also need the complete list of new particles. For this, one can use

- \texttt{allQnumbers(K,&PDG,&eQ3,&spinDim,&cDim,&neutral)}

where K specifies the QNUMBERS block to be read in order. If \( K = 1 \), the first QNUMBERS block is read, if \( K = 2 \), then the second and so on. As long as K is less than the number of blocks, the function returns 1, otherwise the function returns zero. Note that here the PDG code is a return parameter.

One cannot use \texttt{slhaRead} to extract SLHA information from an XML event file since the event information is written in a different format. For this reason we include another file reader which works with an already open file until the tag signalling the end of the SLHA section in the event file (\(<\text{slha}>\)) is reached

- \texttt{slhaReadStream(FD,mode,"\<\text{slha}>")}

FD is a file descriptor, and mode is an integer that determines which data has to be read from the file, it has the same meaning as in \texttt{slhaRead}. This function returns the same value as \texttt{slhaRead}.

4 Matrix diagonalisation

In a new model one often has to diagonalise mass matrices. These squared matrices can be real or complex and their properties depend on whether one deals with fermionic or bosonic fields. In a Lagrangian, mass terms for \( d \) real boson fields \( \Phi = (\phi_1, \phi_2 ... \phi_d) \) are written as

\[
\frac{1}{2} \Phi^T M_{rs} \Phi
\]

where \( M_{rs} \) is a real symmetric matrix. To get the physical fields which are mass eigenstates of the Hamiltonian one has to perform an orthogonal rotation

\[
\Phi_{phys} = V \Phi
\]

such that

\[
V^T M_{rs} V = M_{diag}
\]

where the diagonal mass matrix has elements

\[
(M_{diag})_{\alpha\beta} = m_\alpha \delta_{\alpha\beta}
\]

(Here \( m_\alpha \) stands for a mass squared.) For complex boson fields the mass matrix is hermitian and the mass term reads

\[
\Phi^\dagger M_h \Phi
\]

In this case the physical fields are obtained by an unitary rotation \( V \) such that

\[
V^\dagger M_h V = M_{diag}
\]

For spinor fields, and in particular for Dirac fermions, the mass term has the generic form

\[
\bar{\Psi}^R M_c \Psi^L + h.c
\]
where $\Psi^L$ and $\Psi^R$ are the left and right components of the Dirac spinors and $M_c$ is a complex matrix. The left and right components of Dirac fields can be rotated independently since the kinetic terms in the Lagrangian are split between the left and right parts.

$$\Psi_{\text{phys}}^L = V\Psi^L \quad \Psi_{\text{phys}}^R = U\Psi^R$$

Diagonalisation requires two unitary matrices $U$ and $V$,

$$U^\dagger M_c V = M_{\text{diag}}$$

(4)

In the special case where the mass matrix is real, for example for the chargino sector of the MSSM, the $U$ and $V$ matrices are orthogonal and the diagonalisation condition reads

$$U^T M_r V = M_{\text{diag}}$$

(5)

Finally in the case of Majorana fermions, the mass matrix is complex and symmetric, $M_{cs}$. Because Majorana fermions are real we have the constraint $U = V^*$ therefore only one unitary matrix is necessary to perform the diagonalisation,

$$V^T M_{cs} V = M_{\text{diag}}.$$  

(6)

4.1 Jacobi algorithm and matrix diagonalisation.

The Jacobi diagonalisation procedure consists in a sequence of rotations in 2-dimensional planes each rotation eliminating one off-diagonal element. The convergence of the Jacobi method can be simply understood. It relies on the fact that the sum of the squared elements of a matrix remains the same after multiplication by an orthogonal/unitary matrix. Each rotation which eliminates one off-diagonal element while leaving the others unchanged will therefore decrease the sum of the square of all off-diagonal elements. The Jacobi method is not the most efficient one for matrices of high dimensions. However in particle physics the dimension of field multiplets is usually not large and the time needed for matrix diagonalisations is negligible as compared to the time needed for calculation of matrix elements and Monte Carlo phase space integration.

In our library we have included routines that can perform the diagonalisation of the matrices in Eqs. 1, 3, 4, 5, they are respectively

- rJacobi(d, Mrs, Mdiag, Vo)
- cJacobiH(d, Mh, Mdiag, Vu)
- cJacobiA(d, Mc, Mdiag, UU, Vu)
- rJacobiA(d, Mr, Mdiag, Uo, Vo)
- cJacobiS(d, Mcs, Mdiag, Vu)

Here $d$ is the matrix dimension, the second argument is the initial mass matrix. The functions return $M_{\text{diag}}$ the array of eigenvalues obtained after the diagonalisation and $V$ and $U$ are the rotation matrices. The indices $u, o$ are used to distinguish unitary and orthogonal matrices. All matrices are expressed via one-dimensional arrays. The conversion is done with the formula

$$A_{ij} \rightarrow A[i \cdot d + j] \quad \text{where} \quad 0 \leq i, j < d$$

(7)

For the symmetric or hermitian mass matrices $(M_{rs}, M_{cs}, M_h)$ only half the off-diagonal elements are independent and need to be specified, the conversion to one-dimensional
arrays uses the formula

\[ A_{ij} \rightarrow A[i(d - (i + 1)/2) + j] \quad \text{where} \quad 0 \leq i \leq j < d \]  

(8)

The \( M_h, M_{cs}, M_c, V_u, U_u \) matrices have complex elements. Complex numbers in our package are characterized by the standard C99 type \texttt{double complex}. The Jacobi functions return zero after a successful diagonalisation and 1 otherwise. The eigenvalues are sorted in increasing order of their absolute value. For \( \text{Eq. 4} \), there is an ambiguity in the phase of the eigenvalues. We assume that all eigenvalues are real and positive.

Our code is based on the \texttt{jacobi} routine provided in [28]. For another realisation of diagonalisation routines for high energy physics see for instance [33].

4.2 SLHAplus format for diagonalisation routines.

Some packages for matrix element calculation do not allow the use of arrays. Only simple expressions are allowed. We therefore write the diagonalisation routines presented above in a format readable by MC calculators.

To use the same routine for a matrix of arbitrary size, we use a C language option that allows to write routines with an arbitrary number of argument. Any diagonalisation routine returns a number which specifies an identifier (ID number) for the rotation and mass matrices obtained in the diagonalisation process.

- \texttt{initDiagonal()} should be called once before the other diagonalisation routines described below. \texttt{initDiagonal()} assigns a zero value to the internal counter of eigenvalues and rotation matrices and returns zero.
- \texttt{rDiagonal(d,M11,M12,..M1d,M22,M23,...Mdd)}
- \texttt{cDiagonalH(d,M11,M12,..M1d,M22,M23,...Mdd)}
- \texttt{cDiagonalS(d,M11,M12,..M1d,M22,M23,...Mdd)}

diagonalise symmetric(Eq. 1), hermitian (Eq. 3) and complex symmetric(Eq. 6) matrices of dimension \( d \) respectively. The \( d(d + 1)/2 \) matrix elements, \( M_{ij} (i \leq j) \), are given as arguments. The functions return an integer number \( id \) which serves as an identifier for the eigenvalues vector and rotation matrices.
- \texttt{cDiagonalA(d,M11,M12,..M1d,M21,M22,...Mdd)}
- \texttt{rDiagonalA(d,M11,M12,..M1d,M21,M22,...Mdd)}

diagonalise complex (Eq. 4) and real (Eq. 5) non-Hermitian matrices. Here all \( d^2 \) matrix elements are given as arguments.

For these five different routines the eigenvalues can be obtained by the same function

- \texttt{MassArray(id, i)} where \( id \) is the identifier associated with the diagonalisation procedure corresponding to any of the [cr]\texttt{Diagonal[HAS]} routines. The index \( i \) starts with 1. The elements of the rotation matrices are obtained using the functions

- \texttt{MixMatrix(id,i,j)} - for orthogonal matrices
- \texttt{MixMatrixU(id,i,j)} - for the U orthogonal matrix in Eq. 5
- \texttt{cMixMatrix(id,i,j)} - for unitary matrices
- \texttt{cMixMatrixU(id,i,j)} - for the U hermitian matrix in Eq. 4
4.3 Errors
The global variable FError signals fatal problems that occur in the execution of slhaRead, slhaVal, slhaWrite, slhaBranch, System as well as [c]Diagonal [HAS] and [c]MixMatrix [U]. When FError=1, numerical calculations in CalcHEP will be interrupted automatically.

5 QCD functions
Here we describe some QCD functions which can be useful for implementing a new model.

- **initQCD(alsMZ,McMc,MbMb,Mtp)**
  This function initializes the parameters needed for the functions listed below. It has to be called before any of these functions. The input parameters are the QCD coupling at the Z scale, \( \alpha_s(M_Z) \), and the running quark masses, \( m_c(m_c), m_b(m_b) \) and \( m_t(pole) \).

- **alphaQCD(Q)**
  calculates the running \( \alpha_s \) at the scale \( Q \) in the \( \overline{MS} \) scheme. The calculation is done using the NNLO formula in [29]. Thresholds for b-quark and t-quark are included in \( n_f \) at the scales \( m_b(m_b) \) and \( m_t(m_t) \) respectively.

- **MtRun(Q), MbRun(Q), McRun(Q)**
  calculates top, bottom and charm quarks running masses evaluated at NNLO [30].

- **MtEff(Q), MbEff(Q), McEff(Q)**,
  calculates effective top, bottom and charm quark masses using [31]
  \[
  M_{eff}^2(Q) = M(Q)^2 \left[ 1 + 5.67a + (35.94 - 1.36n_f)a^2 \\
  + (164.14 - n_f(25.77 - 0.259n_f))a^3 \right]
  \]
  where \( a = \alpha_s(Q)/\pi \), \( M(Q) \) and \( \alpha_s(Q) \) are the running quark masses and strong coupling in the \( \overline{MS} \)-scheme. These effective masses at the scale \( Q = M_h \) give the Yukawa couplings that reproduce the QCD corrections to the partial decay width of the Higgs.

6 Features of the C, C++ and Fortran versions
All routines of the SLHAplus library can be used either in C, C++ or Fortran. In general the C, C++ and Fortran routines have the same names except for the functions with a varying number of arguments which are not supported in Fortran. Furthermore C++ cannot handled such functions if a parameter is a complex number.

For each function with a varying number of parameters we include in our package a set of functions with a fixed number of parameters. The parameter which specifies the number of arguments is removed from the list of arguments and is instead attached to the function name. For example the generic function slhaVal(BlockName, Q, keyLength,...) has to be replaced by

\[
\text{slhaVal0(Blockname,Q)} \\
\text{.....} \\
\text{slhaVal3(Blockname,Q,key1,key2,key3)}
\]
For slhaVal and slhaValExists the digit attached to the name specifies the keyLength and can be 0, 1, 2 or 3. For the functions Diagonal this number specifies the dimension of the matrices. For the function aPrintf(format,...) the digit attached describes the number of arguments following the parameter format. In this case all these arguments have to be of real type.

The function System is replaced by two functions System1(format) and System2(format,txt) with text parameters. The second function can be used to provide the destination of the executable.

Another difference between C, C++ and Fortran concerns error messages. The variable FError gets a non-zero value in case of a fatal error. In C or C++ FError is a global variable while in Fortran it is included as

\[
\text{integer FError}
\]

\[
\text{COMMON/FError/Ferror}
\]

The file SLHAplus.h contains the function prototypes for C routines. It has to be included in C and C++ routines which use SLHAplus. The file SLHAplus.fh includes a Fortran description of the types of Fortran functions and COMMON/FError/ declaration. It has to be included in each Fortran routines.

7 Compilation and testing

The command make generates the static library file libSLHAplus.a which contains all the functions of the package.

The subdirectory test contains three test programs each available as C, C++ or Fortran codes.

- tJacobi.[c/cpp/F]
tests all Jacobi functions included in the package. Used in a cycle it fills the corresponding matrices by random numbers, diagonalises them, prints eigenvalues, restores the non-diagonal matrix and calculates the difference between the original \( (M) \) and restored \( (M') \) matrices, \( \Delta = \sqrt{\sum_{i,j} (M_{ij} - M'_{ij})^2} \). A typical difference \( \Delta \approx 10^{-15} \) means that the precision in the diagonalisation reaches the precision of the computer. The dimension of the matrix and the number of steps in the cycle can be changed via a redefinition of the parameters DIM and nTest which are defined at the top of the file.

- tChDiag.[c/cpp/F]
tests the diagonalisation functions rDiagonal[A] of Section 4.2. Here the matrix dimension is 2. This is for a quick test that the elements of the original matrix have been passed correctly.

- tSlha.[c/cpp/F]
is an independent program for testing the SLHA reader. The program reads the files spectr.sila and decay.sila and writes on screen the information stored in the files.

To compile a test program use the command

\[
\text{make main=<name of source code>}
\]
The name of the executable corresponds to the name of the source file.

\[\text{3In Fortran they have to be of REAL*8 type.}\]
8 Special features of LanHEP and CalcHEP

Here we describe some special features relevant for the implementation of a new model in LanHEP and CalcHEP.

8.1 Particle widths

The particle widths do not generally need to be defined as input parameters, indeed the widths depend on the fundamental parameters of the model and therefore can be computed automatically by CalcHEP using the relevant Feynman diagrams. In order to inform CalcHEP that a particle width has to be computed before the calculation of a scattering process, the width of the particle must be preceded by an exclamation mark in the particle table. This can be done in LanHEP by adding the auto record after the width declaration. For instance,

```
scalar h/h: (' Higgs 1', pdg 25, mass Mh, width wh=auto).
```

will generate the following line in the `prtcls1.mdl` model file.

| Full Name  | P | aP | number | spin2 | mass | width | color |
|------------|---|----|--------|-------|------|-------|-------|
| Higgs 1    | h | h  | 25     | 0     | Mh   | !wh   | 1     |

If an SLHA file contains information about particle widths, then the widths can also be defined using the function `slhaWidth(PDGcode)`.

8.2 Matrix diagonalisation routines

As an example we give here the LanHEP code for describing the neutralino matrix in the MSSM, the mass eigenvalues and the elements of the mixing matrices.

```
parameter NeDiag= rDiagonal(4, MG1, zero, -MZ*SW*cb, MZ*SW*sb, MG2, MZ*CW*cb, -MZ*CW*sb, zero, -mu, zero).
_i=1-4 in parameter MNE_i=MassArray(NeDiag, _i).
_i=1-4, _j=1-4 in parameter Zn_i_j=MixMatrix(NeDiag, _i, _j).
```

The elements of the mass matrix can either be written explicitly by the user or extracted from LanHEP. Indeed LanHEP contains a facility to examine the mass sector of the Lagrangian. When the CheckMasses statement is used, LanHEP creates the file named `masses.chk`. This file contains information about mass terms which are not given in the output files specifying only the Feynman rules. In particular this can be useful for fields that are rotated by orthogonal matrices that diagonalise mass terms, LanHEP can recognize the mixing matrix if the elements of this matrix were used in an OrthMatrix statement. LanHEP restores and prints the original mass matrix before the fields rotation. For example, in the case of the neutralino this output reads:

```
Looking for the mixing matrix...
It is recognized that these fields are rotated by matrix:
```
The mass matrix before introducing this rotation:

\[ M_{11} = (+1 \times MG1) \]
\[ M_{12} = 0 \]
\[ M_{13} = (-1/CW \times MW \times SW \times cb) \]
\[ M_{14} = (+1/CW \times MW \times SW \times sb) \]
\[ M_{22} = (+1 \times MG2) \]
\[ M_{23} = (+1 \times MW \times cb) \]
\[ M_{24} = (-1 \times MW \times sb) \]
\[ M_{33} = 0 \]
\[ M_{34} = (-1 \times mu) \]
\[ M_{44} = 0 \]

This information can be copied and pasted as argument of the `rDiagonal` function.

### 8.3 External function prototyping and linking

In general one has to provide information about the types of parameters and returned values of external functions to C/Fortran compilers. As well LanHEP needs these prototypes for numerical processing. The functions included in the SLHAplus library are known to LanHEP, CalcHEP and micrOMEGAs, therefore there is no need to specify the prototypes. The SLHAplus library is included into these packages and linked automatically. If one wants to use other external functions to calculate couplings or masses the following rules have to be used.

In CalcHEP the `extlibN.mdl` model file (\( N \) is an integer which specifies the model) can include prototypes of C-routines used in the model. Function declaration has to start on a new line, the first word has to be `extern` and declaration should be terminated on the same line with a semicolon. For all other details we follow the C-syntax. Prototypes for functions which return values of type `double` and have all arguments of the same type can be omitted. Other records in the `extlibN.mdl` files are treated as definition of external libraries that are provided to the linker. micrOMEGAs ignores CalcHEP linker instructions and assumes that all external functions are stored in the file `lib/aLib.a`.

The current version of LanHEP allows only functions which return `double` and have all arguments of the same type. Such functions have to be declared in LanHEP by instructions such as `external_func(name, N, lib)` whose arguments describe the function name, the number of arguments and the name of the shared library which contains this function. In general, the library will be linked when processing LanHEP for numerical checks. The `lib` parameter can be omitted. In this case only symbolic LanHEP processing will be valid.

\[ ^4 \text{Note that LanHEP does not generate the extlib file and that CalcHEP generates automatically an empty file.} \]
There are some specific features for writing an external function \( s \) in LanHEP. First, to pass a string parameter one has to use the `str` function. For example to read the SLHA value for one element of the neutralino mixing matrix at the scale \( \text{QSUSY} \)

\[
Z_{n12} = \text{slhaVal}(\text{str}(\text{NMIX}), \text{QSUSY}, 2, 1, 2).
\]

Functions with zero number of parameters should appear in LanHEP source files without brackets, for example

```latex
\text{external_func(initDiagonal,0).}
\text{parameter zero=initDiagonal.}
```

### 8.4 Complex numbers in CalcHEP

Despite the fact that CalcHEP cannot work directly with complex parameters, following the procedure described above it is possible to declare functions with complex parameters and/or a complex return value. Complex parameters have to be constructed by writing explicitly the real and imaginary parts using the parameter \( I \) where \( I^2 = -1 \). Complex return values can be transformed to real values using the C99 functions `creal` and `cimag`. Prototypes of these functions are automatically declared in CalcHEP. This way the complex rotation matrices mentioned in section 4.2 can be implemented in CalcHEP.

### 9 FeynRules Support

Support for the SLHA parameter reading routines of this library has been included in the FeynRules (FR)CalcHEP (CH) output interface which will be released later this year. Since FR has been described in \[8, 35\], we will just describe the support for the SLHA parameter files. The author of a FR model file does not need to do anything different to use this functionality. It is all handled automatically by the FR CH interface. There is a new option for the FR CH interface `LHASupport`. For example, the user could issue the command:

```latex
\text{WriteCHOutput[L,LHASupport -> True]}
```

in their FR session, where \( L \) is the Lagrangian. If this option is set to True, the FR-CH interface will write the CH model files which use the functions of the SLHAplus library. In addition, a SLHA parameter file is written to the model directory called `varsN.lha` where \( N \) is the model number. To use this model, the user can import this model into CH just as with any other CH model. Since the name of the SLHA parameter file is called explicitly in the model files, if the user changes the name of the SLHA file, the user will need to make the corresponding change to the model files. In particular, in the file `funcN.mdl`, the line containing `readSLHA` must be changed to contain the correct filename. This SLHA parameter file will then need to be copied to the results directory of a CH numerical session.

The SLHA parameter file that FeynRules creates does not have any scales specified for the blocks. For this reason, the CH model files that FR writes call the SLHA reader routines with a default scale of 0 (for example, `slhaVal("SMINPUTS",0,1,1) in the FeynRules Standard Model implementation). Since the default parameter file does not specify any scales, this is ignored. However, if a SLHA parameter file from another source was
used instead that had blocks with more than 1 scale specified, the model files would need to be modified as appropriate.

The matrix diagonalization and QCD routines in SLHaplus are not supported in FR at this time.

10 Conclusion

The library SLHaplus provides a set of functions to facilitate the implementation of new models in codes for computing physical observables. It was developed primarily to be used in LanHEP, CalcHEP and micrOMEGAs although the routines are general enough to be used with other codes. In the library we also provide the LanHEP source code for two different implementation of the MSSM, these can serve as a basis for the implementation of extensions of the minimal supersymmetric model. The library is available at wwwlapp.in2p3.fr/lapth/micromegas/slhaplus.

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Appendices

A The MSSM model files in LanHEP

As an example of an application of the routines of the SLHaplus library, we present the LanHEP code to generate the MSSM model files in the format of CalcHEP and micrOMEGAs. The Lagrangian of the MSSM is described in [36] and some technical details for the implementation into LanHEP are explained in Ref. [37, 38]. In this example we describe an MSSM model which takes into account higher order corrections in the Higgs sector as described below. However we do not include other higher-order corrections such as the SUSY-QCD corrections to the $Hb\bar{b}$ vertices [32] or corrections to stop/sbottom interactions. Finally we assume massless fermions for the first two generations. Therefore the model generated cannot be used for the calculation of the dark matter direct detection rates in micrOMEGAs which needs non-zero light quark masses. Note that when using the SLHA interface with a spectrum calculator that includes radiative corrections to masses and mixings in all sectors of the model, some gauge invariance problems could remain.

A.1 LanHEP source files

The LanHEP sources for the MSSM are provided in the sub-directory MSSM. The source files have an extension .src and contain...
• var.src - definition of the independent parameters;
• prtcls.src - list of particles of the model;
• Let.src - Substitutions to express field multiplets in terms of physical particles;
• W.src - superpotential: F-terms and Yukawa interactions;
• DD.src - scalar supersymmetric potential, D-terms;
• softsbt.src - soft SUSY breaking terms;
• fgauge.src - Gauge fixing terms and Faddeev-Popov ghost for the gauge group SU(3) × SU(2) × U(1);
• ggi.src - self-interaction of gauge multiplets;
• gmi.src - Interactions of the gauge and matter multiplets;
• higgs4.src - effective potential for the Higgs sector;
• func.src - external functions for implementaton of high order corrections, SLHA interface as well as computation of mass eigenvalues when the tree-level option is chosen.
• startup.src - main file including the instructions to read all other source files.

To compile the model, launch

lhep startup.src -evl 2

The source files generate three different versions of the MSSM at the electroweak symmetry breaking scale. The default setting

keys SLHA=On

in startup.src compiles the model files in the format needed for an SLHA interface while the setting keys SLHA=Off will generate the tree level model that requires the matrix diagonalisation routines for calculating the spectrum. The

keys LambdaTH=On/Off.

defines the setting for the computation of the Higgs potential described below.

The running of quark masses is included by defining effective masses for quarks as described in section 5. These masses depend on an external parameter $Q$ which specifies the QCD scale relevant for the process under consideration.

Note that to include the SLHA model files created in this example into CalcHEP it is necessary to include the suspect2.exe file in the CalcHEP working directory.

A.2 The Higgs sector

In the MSSM the Higgs sector receives large loop corrections. In order to have a realistic tree level model, in particular to have a light Higgs mass heavier than the experimental limit, it is necessary to include some higher order corrections to the Higgs sector. To do this in a gauge invariant manner, we introduce an effective Lagrangian with five independent parameters, $\lambda_1$ to $\lambda_5$. We provide three different methods to include loop corrections in the Higgs sector. In the first, the analytical formulae for the one-loop QCD and SUSY-QCD corrections to the effective Lagrangian are included in the model.

---

5The most general Lagrangian needs 7 parameters but $\lambda_6$ and $\lambda_7$ are in general small and can be neglected.
file. The masses of the Higgs particles are then computed from the effective Lagrangian, for this one chooses the settings \texttt{SLHA=Off}. The last two options, which correspond to the setting \texttt{SLHA=On}, are available when the higher order corrections to the Higgs masses and mixing angle are computed by an external program. In the second method, the parameters of the effective Lagrangian are reconstructed from the physical masses, $m_{h}, m_{H}, m_{H^{+}}$ and the Higgs mixing angle that are provided through the SLHA interface \cite{[40]}. Here we follow the procedure described in \cite{[33]}. As there are only four independent physical parameters, the analytical formulae for the corrections to $\lambda_1$ are used even in this case, the coefficients $\lambda_2...\lambda_5$ are then extracted from the physical parameters. For this option one chooses the setting \texttt{LambdaTH=Off}. This implementation guarantees that the higher order corrections to the Higgs sector are taken into account in a gauge invariant way \cite{[33]}. Finally a third possibility consists in substituting analytical formulas for the Higgs couplings \cite{[39]} instead of solving equations to extract them from the masses. In this case one must set \texttt{LambdaTH=On}. Since the spectrum calculators include in general additional higher-order corrections in the computation of the Higgs masses, the masses obtained with the first option differ from the last two, similarly the Higgs potentials can be slightly different in the last two cases.

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SLHAplus: a library for implementing extensions of the standard model

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Abstract

We provide a library to facilitate the implementation of new models in codes such as matrix element and event generators or codes for computing dark matter observables. The library contains a SLHA reader routine as well as diagonalisation routines. This library is available in CalcHEP and micrOMEGAs. The implementation of models based on this library is supported by LanHEP and FeynRules.

1 Introduction

In the very near future the LHC will have the opportunity to test the TeV scale relevant to address the outstanding issues in the standard model and its extensions: the symmetry breaking problem and the dark matter problem. Furthermore numerous astroparticle searches will help refine the dark matter properties. Confronting the various extensions of the standard model that have been proposed with observations at colliders and astroparticle searches will therefore provide powerful tests of the new physics model. Sophisticated tools have been developed to compute the predictions for observables such as particle spectra, decay rates or cross sections that are relevant at colliders (for a repository of available tools see [1]) while other tools explore the implications of new physics models for dark matter observables [2, 3, 4, 5, 6]. The interpretation of a new signature might require extending those tools to adapt them to work with different models.

Tools such as LanHEP [7], FeynRules [8] and SARAH [9] have been developed to facilitate the implementation of new models in generic matrix element and event generators such as Madgraph [10], CompHEP [11, 12], CalcHEP [13], FeynArts/FormCalc [14, 15], Whizard [16] and Sherpa [17]. They require mainly the implementation of a new Lagrangian and provide the model file adapted to the chosen generator. While these tools are very powerful they often leave some tedious and repetitive tasks for the user. Here we provide a library that contains some routines to facilitate the implementation of new models. The library first contains a routine for reading a SUSY Les Houches Accord (SLHA) file [18, 19]. An SLHA file is a standardized file format specifying input and output parameters that was developed in the framework of supersymmetry to facilitate the passing of information between codes as varied as spectrum calculators, matrix element generators and event generators. [1] We have generalised the procedure to take into account an arbitrary number of blocks so that the reader can be used in generic models.

1Another SLHA reader library that can be used with the MSSM and its extensions is available at [20].
including non supersymmetric ones. The library also contains routines to diagonalise real
and complex mass matrices with either unitary or bi-unitary transformations. Finally
it contains some routines for evaluating the running strong coupling constant as well as
running quark masses and effective quark masses. This library was designed and used in
CalcHEP [13], micrOMEGAs [3], LanHEP [7] and FeynRules [8] but can be incorporated in
other tools as well.

In this paper we describe the set of functions used for the SLHA reader (section 2),
the QNUMBERS reader (section 4), matrix diagonalisation (section 4), QCD functions
(section 5) and their Fortran counterparts (section 6). In section 7 we describe how
to compile and link this code. Section 8 comments on special features of this package
in LanHEP and CalcHEP. Section 9 comments on the use of this library when using
FeynRules with CalcHEP. Finally, in section 10 we conclude. We also include an appendix
with an example of using this package with LanHEP and CalcHEP for the MSSM.

2 SLHA reader

The SUSY Les Houches Accord [18, 19] specifies a unique set of conventions for the
MSSM and its extensions (NMSSM, CPV-MSSM) together with generic file structures for
specification of input parameters, supersymmetric particle masses and couplings as well
as decay tables. This allows, for example, for dedicated external programs to perform
an accurate calculation of the particle spectrum. The results for particle masses, mixing
angles and other model parameters are then written in a file using a standard format that
can be used by other codes 21, 22, 23, 24, 25, 26. A similar file format can also be
used for other extensions of the MSSM or for non-supersymmetric models. The routine
we describe here allows for reading of files in the SLHA format.

In general a SLHA file contains several pieces of information which are called blocks. A
block is characterized by its name and if relevant by an energy scale. Each block contains
the values of several physical parameters characterized by a key. The key consists of a
sequence of integer numbers. For example for masses the key is the PDG code [27], for
mixing matrices the rows and columns of the matrix and for decays the PDG codes of
the mother and daughter particles:

| BLOCK | MASS # Mass spectrum |
|-------|-----------------------|
| # PDG Code | mass | particle |
| 25 | 1.15137179E+02 | lightest neutral scalar |
| 37 | 1.48428409E+03 | charged Higgs |

| BLOCK | NMIX # Neutralino Mixing Matrix |
|-------|--------------------------------|
| 1 1 | 9.98499129E-01 | Zn11 |
| 1 2 | -1.54392008E-02 | Zn12 |

| BLOCK | Au Q= 4.42653237E+02 # The trilinear couplings |
|-------|-----------------------------------------------|
| 1 1 | -8.22783075E+02 | A_u(Q) DRbar |
| 2 2 | -8.22783075E+02 | A_c(Q) DRbar |

| DECAY | 36 2.10E-06 # Lightest pseudoscalar |
|-------|----------------------------------|
| 9.54085917E-03 | 2 | 21 | 21 | BR(A_1 -> gluon gluon) |

\[2\] The PDG code must be less than 10 digits
2.12111874E-04  2  13  -13  # BR(A_1 -> muon muon)
5.88191379E-02  2  15  -15  # BR(A_1 -> tau tau)
6.97107293E-04  2  3   3    # BR(A_1 -> s sbar)
1.62828588E-03  2  4   -4  # BR(A_1 -> c cbar)
9.29088642E-01  2  5   -5  # BR(A_1 -> b bbar)

Strictly speaking the SLHA [18] does not specify the structure of blocks. However in order to write an universal SLHA reader one has to restrict the structure of blocks. We impose the additional requirements that the number that describe a physical quantity is the last number for each block record and that there is only one such number for each record. We also require that all textual information is included as a comment. All examples of SLHA blocks described in [18, 19] satisfy these conditions. Note however that for decays the SLHA does not follow the normal BLOCK structure, for each record the branching ratio is given as the first number. SLHAplus can read correctly the format of the block DECAY as displayed in the example above.

Finally we have implemented in the SLHA reader the possibility to work with complex numbers. Complex numbers have to be written in a Fortran-like format, with a comma separating the real and imaginary parts and placing the components into brackets. (real, imaginary).

The functions described below allow to read the information contained in this file, including the blocks that contain the model parameters, the masses and other physical parameters as well as other information such as particle decay widths.

* slhaRead(filename, mode)
  reads all or part of the data from the file filename. mode is an integer which determines which part of the data should be read from the file, mode= 1*m1+2*m2+4*m4+8*m8+16*m16 where

  m1 = 0/1  -  overwrites all/keeps old data
  m2 = 0/1  -  ignore errors in input file/ stop in case of error
  m4 = 0/1  -  read DECAY /do not read DECAY
  m8 = 0/1  -  read BLOCK/do not read BLOCK
  m16 = 0/1 -  read QNUMBERS/do not read QNUMBERS

  For example mode=20 (m4=1, m16=1) is an instruction to overwrite all previous data and read only the information stored in the BLOCK sections of filename. In the same manner mode=25=1+8+16 is an instruction to add information from DECAY to the data obtained previously.

  The function slhaRead returns the values:

  0  -  successful reading
-1  -  can not open file
-2  -  invalid data as indicated by SPINFO
-3  -  no data
  n>0 - wrong file format at line n

* slhaValExists(BlockName, keyLength, key1, key2,...)
  checks the existence of specific data in a given block. BlockName can be substituted

---

3We thank Peter Skands for pointing that out to us.
with any case spelling. The keyLength parameter defines the length of the key set \{key1, key2, \ldots \}. For example `slhaValExists("Nmix",2,1,2)` will return 1 if the neutralino mass mixing element Z12 is given in the file and 0 otherwise.

- **cslhaVal(BlockName, Q, keyLength, key1, key2, \ldots \ldots \ldots)** is the main routine which allows to extract the numerical values of parameters. BlockName and keyLength are defined above. The parameter Q defines the scale dependence. This parameter is relevant only for the blocks that contain scale dependent parameters, it will be ignored for other blocks, for example those that give the particle pole masses. In general a SLHA file can contain several blocks with the same name but different scales (the scale is specified after the name of the block). `slhaVal` uses the following algorithm to read the scale dependent parameters. If Q is less(greater) than all the scales used in the different blocks for a given parameter `slhaVal` returns the value corresponding to the minimum(maximum) scale contained in the file. Otherwise `slhaVal` reads the values corresponding to the two scales $Q_1$ and $Q_2$ just below and above Q and performs a linear interpolation in $\log(Q)$ to evaluate the returned values. `cslhaVal` returns complex number. If the data file contains real number then imaginary part of return value is zero.

- **`slhaVal(BlockName, Q, keyLength, key1, key2, \ldots \ldots \ldots)`**

  This function is defined as `creal(cslhaVal(...))`. It can be used instead of `cslhaVal` for all models with only real parameters.

- **`slhaWarnings(FD)`**

  writes into the file FD the warnings or error message stored in the SPINFO block and returns the number of warnings. If FD=NULL the warnings are not written in a file.

- **`slhaWrite(Filename)`**

  writes down the information stored by `readSLHA` into the file. This function can be used for testing purposes.

- **`slhaDecayExists(pNum)`**

  checks whether information about the decay of particle pNum exists in the SLHA file. pNum is the particle PDG code. This function returns the number of decay channels listed. In particular zero means that the SLHA file contains information only about the total width, not on branching ratios while -1 means that even the total width is not given.

- **`slhaWidth(pNum)`**

  returns the value of the particle width.

- **`slhaBranch(pNum, N, nCh)`**

  returns the branching ratio of particle pNum into the N-th decay channel. Here $0 < N = slhaDecayExists(pNum)$. The array nCh is an output which specifies the PDG numbers of the decay products, the list is terminated by zero.

  The functions `slhaValExists`, `slhaVal`, `slhaDecayExists`, `slhaWidth` can be used directly in CalcHEP model files. For example, the mass of the lightest neutralino can be specified in the CalcHEP file `func1.mdl` as

  \[
  MNE1 \mid \text{slhaVal("MASS",QSUSY,1,1000022)}
  \]

  Some applications might need the full list of SLHA blocks and DECAY items obtained with `slhaRead`. The following functions serve this purpose

  - **allBlocks(K,L, blockName, &keyLength, keyArray, &val)**
  - **allDecays(K,L, &pdg, &decayLength,&decayArray,&width,&branching)**

  \footnote{FILE* type in C and channel number in Fortran}
where \( K \) specifies the block or decay to be read in numerical order. A \( K \) of 1 specifies that the first block (or decay) should be read, a \( K \) of 2 specifies that the second should be read, and so on. \( L \) specifies which record inside the block (or decay) should be read, again in numerical order. These functions return 1 as long as the requested information exists and return 0 otherwise. For the blocks, the name of the block is stored in the string blockName, the number of keys is recorded in keyLength, the array of keys is stored in keyArray and val contains the value. For decays, pdg stores the pdg of the particle, decayLength specifies the number of outgoing particles, decayArray the array of outgoing particles, and width and branching the total width and branching for each channel. If \( L = 0 \), the function allBlocks fills only the parameters blockName and val. In this case val corresponds to the scale at which the data in the block are specified. When \( L = 0 \), allDecays only fills the pdg and width parameters.

In general, SLHA files also contain textual comments. After a call of allBlocks or allDecays this information is stored in the global variable slhaComment. In the Fortran version, this variable is contained in COMMON/SLHACOMMENT/. In particular, for \( L = 0 \) allBlocks/allDecays will return the general comment from the file, while if \( L > 0 \), these functions will return the comment for the \( L^{th} \) record.

2.1 Writing an input SLHA file

This package contains three routines which allow to write an SLHA input file and launch a spectrum calculator.

- **openAppend(fileName)** deletes the input file fileName if it exists and creates a new empty file with the same name. The string fileName is stored in memory for subsequent usage with the function aPrintf.
- **aPrintf(format,...)** opens the file fileName and writes at the end of the file the input parameters needed in the SLHA format or in any other format understood by the spectrum calculator. The arguments of aPrintf are similar to the arguments of the standard printf function.
- **System(format,...)** generates a shell command using format and subsequent arguments. This command is then launched by the standard system C-function.

For example, to write directly the SLHA model file needed by SuSpect [21] to compute the spectrum in a CMSSM(SUGRA) model, one needs to specify the standard model input parameters \( (m_b, m_t(pole)) \) as well as the SUSY input parameters \( m_0, m_{1/2}, \tan \beta, \text{sign}(\mu), A_0 \). For this one must add the following sequence in the CalcHEP func1.mdl model file.

```plaintext
open |openAppend("suspect2_lha.in")
input1|aPrintf("Block MODSEL # Select model
 1 1 # SUGRA
")
input2|aPrintf("Block SMINPUTS
 5 %E#mb(mb)
 6 %E#mt(pole)",MbMb,Mtp)
input3|aPrintf("BLOCK MINPAR
 1 %E #m0
 2 %E #m1/2
",Mzero,Mhalf)
input4|aPrintf("3 %E #tb
 4 %E #sign(mu)
 5 %E #A0
",tb,sgn,A0)
sys |System("%s/suspect2.exe",path())
rd |slhaRead("suspect2_lha.out",0)
```

In this example path() specifies the path to the directory where the SuSpect executable is located.
3 SLHAplus for parton shower generators.

Information about parton level events can be transferred to parton shower generators via a file written in the XML format [41]. In a generic extension of the Standard Model, the parton shower generator also needs information about the quantum numbers of new particles, their masses, widths and decay modes. In Ref. [42] it was proposed to include the corresponding SLHA Block and Decay items in the header section of the XML event file, using the subtags <slha> and </slha> to delimit the beginning and the end of the corresponding subsection of the header. A new SLHA block, QNUMBERS, was designed to provide information about the quantum numbers of new particles. For example a new neutral scalar particle called balleron could be defined as

```
BLOCK QNUMBERS 7654321 # balleron
  1 0 # 3 times electric charge
  2 1 # number of spin states (2S+1)
  3 1 # colour rep (1: singlet, 3: triplet, 8: octet)
  4 0 # Particle/Antiparticle distinction (0=own anti)
```

Strictly speaking the block QNUMBERS does not fit the definition of a standard SLHA block as used in this paper. We treat it as an exceptional block. This block can be read by the slhaRead routine but for this special routines are required, which we now describe.

- findQnumbers(PDG,&eQ3,&spinDim,&cDim,&anti)
gives the quantum numbers eQ3,spinDim,cDim,anti for the particle specified by its PDG code (see the example of the QNUMBERS block given above). findQnumbers returns 1 if the file contains the quantum numbers for a given PDG particle, -1 if instead the information about the antiparticle is contained in the file, and 0 if the file contains no data on this (anti)particle.

A parton shower generator may also need the complete list of new particles. For this, one can use

- allQnumbers(K,&PDG,&eQ3,&spinDim,&cDim,&anti)
where K specifies the QNUMBERS block to be read in order. If K = 1, the first QNUMBERS block is read, if K = 2, then the second and so on. As long as K is less than the number of blocks, the function returns 1, otherwise the function returns zero. Note that here the PDG code is a return parameter. If in the SLHA file the QNUMBER block contains a comment, it is stored in the global variable slhaComment.

One can not use slhaRead to extract SLHA information from an XML event file since the event information is written in a different format. For this reason we include another file reader which works with an already open file until the tag signalling the end of the SLHA section in the event file (</slha>) is reached

- slhaReadStream(FD,mode,"</slha>")
FD is a file descriptor, and mode is an integer that determines which data has to be read from the file, it has the same meaning as in slhaRead. This function returns the same value as slhaRead.
4 Matrix diagonalisation

In a new model one often has to diagonalise mass matrices. These squared matrices can be real or complex and their properties depend on whether one deals with fermionic or bosonic fields. In a Lagrangian, mass terms for \( d \) real boson fields \( \Phi = (\phi_1, \phi_2, \ldots, \phi_d) \) are written as

\[
\frac{1}{2} \Phi^T M_{rs} \Phi
\]

where \( M_{rs} \) is a real symmetric matrix. To get the physical fields which are mass eigenstates of the Hamiltonian one has to perform an orthogonal rotation

\[
\Phi_{\text{phys}} = V \Phi
\]

such that

\[
V M_{rs} V^T = M_{\text{diag}}
\]  

where the diagonal mass matrix has elements

\[
(M_{\text{diag}})_{\alpha \beta} = m_\alpha \delta_{\alpha \beta}
\]  

(Here \( m_\alpha \) stands for a mass squared.) For complex boson fields the mass matrix is hermitian and the mass term reads

\[
\Phi^\dagger M_h \Phi
\]

In this case the physical fields are obtained by an unitary rotation \( V \) such that

\[
V M_h V^\dagger = M_{\text{diag}}
\]

For spinor fields, and in particular for Dirac fermions, the mass term has the generic form

\[
\bar{\Psi}^R M_c \Psi^L + \text{h.c}
\]

where \( \Psi^L \) and \( \Psi^R \) are the left and right components of the Dirac spinors and \( M_c \) is a complex matrix. The left and right components of Dirac fields can be rotated independently since the kinetic terms in the Lagrangian are split between the left and right parts.

\[
\Psi_{\text{phys}}^L = V \psi^L \quad \Psi_{\text{phys}}^R = U \psi^R
\]

Diagonalisation requires two unitary matrices \( U \) and \( V \),

\[
U M_c V^\dagger = M_{\text{diag}}
\]

In the special case where the mass matrix is real, for example for the chargino sector of the MSSM, the \( U \) and \( V \) matrices are orthogonal and the diagonalisation condition reads

\[
U M_r V^T = M_{\text{diag}}
\]

Finally in the case of Majorana fermions, the mass matrix is complex and symmetric, \( M_{cs} \). Because Majorana fermions are real we have the constraint \( U = V^* \) therefore only one unitary matrix is necessary to perform the diagonalisation,

\[
V^* M_{cs} V^\dagger = M_{\text{diag}}.
\]
4.1 Jacobi algorithm and matrix diagonalisation.

The Jacobi diagonalisation procedure consists in a sequence of rotations in 2-dimensional planes each rotation eliminating one off-diagonal element. The convergence of the Jacobi method can be simply understood. It relies on the fact that the sum of the squared elements of a matrix remains the same after multiplication by an orthogonal/unitary matrix. Each rotation which eliminates one off-diagonal element while leaving the others unchanged will therefore decrease the sum of the square of all off-diagonal elements. The Jacobi method is not the most efficient one for matrices of high dimensions. However in particle physics the dimension of field multiplets is usually not large and the time needed for matrix diagonalisations is negligible as compared to the time needed for calculation of matrix elements and Monte Carlo phase space integration.

In our library we have included routines that can perform the diagonalisation of the matrices in Eqs. [13][14][15][16] they are respectively

- \( rJacobi(d,Mrs,Mdiag,Vo) \)
- \( cJacobiH(d,Mh,Mdiag,Vu) \)
- \( cJacobiA(d,Mc,Mdiag,Uu,Vu) \)
- \( rJacobiA(d,Mr,Mdiag,Uo,Vo) \)
- \( cJacobiS(d,Mcs,Mdiag,Vu) \)

Here \( d \) is the matrix dimension, the second argument is the initial mass matrix. The functions return \( Mdiag \) the array of eigenvalues obtained after the diagonalisation and \( V \) and \( U \) are the rotation matrices. The indices \( u, o \) are used to distinguish unitary and orthogonal matrices. All matrices are expressed via one-dimensional arrays. The conversion is done with the formula

\[
A_{ij} \rightarrow A[i \cdot d + j] \quad \text{where} \quad 0 \leq i, j < d
\]  

(7)

For the symmetric or hermitian mass matrices \((M_{rs}, M_{cs}, M_h)\) only half the off-diagonal elements are independent and need to be specified, the conversion to one-dimensional arrays uses the formula

\[
A_{ij} \rightarrow A[i(d - (i + 1)/2) + j] \quad \text{where} \quad 0 \leq i \leq j < d
\]  

(8)

The \( M_h, M_{cs}, M_c, V_u, U_u \) matrices have complex elements. Complex numbers in our package are characterized by the standard C99 type `double complex`. The Jacobi functions return zero after a successful diagonalisation and 1 otherwise. The eigenvalues are sorted in increasing order of their absolute value. For, there is an ambiguity in the phase of the eigenvalues. We assume that all eigenvalues are real and positive.

Our code is based on the `jacobi` routine provided in [28]. For another realisation of diagonalisation routines for high energy physics see for instance [34].

4.2 SLHAplus format for diagonalisation routines.

Some packages for matrix element calculation do not allow the use of arrays. Only simple expressions are allowed. We therefore write the diagonalisation routines presented above in a format readable by MC calculators.

To use the same routine for a matrix of arbitrary size, we use a C language option that allows to write routines with an arbitrary number of argument. Any diagonalisation
routine returns a number which specifies an identifier (ID number) for the rotation and mass matrices obtained in the diagonalisation process.

- **initDiagonal()**

should be called once before the other diagonalisation routines described below. **initDiagonal()** assigns a zero value to the internal counter of eigenvalues and rotation matrices and returns zero.

- **rDiagonal(d,M11,M12,..M1d,M22,M23,...Mdd)**
- **cDiagonalH(d,M11,M12,..M1d,M22,M23,...Mdd)**
- **cDiagonalS(d,M11,M12,..M1d,M22,M23,...Mdd)**

diagonalise symmetric (Eq. 1), hermitian (Eq. 3) and complex symmetric (Eq. 6) matrices of dimension \(d\) respectively. The \(d(d + 1)/2\) matrix elements, \(M_{ij} (i \leq j)\), are given as arguments. The functions return an integer number \(id\) which serves as an identifier for the eigenvalues vector and rotation matrices.

- **cDiagonalA(d,M11,M12,..M1d,M21,M22,...Mdd)**
- **rDiagonalA(d,M11,M12,..M1d,M21,M22,...Mdd)**

diagonalise complex (Eq. 4) and real (Eq. 5) non-Hermitian matrices. Here all \(d^2\) matrix elements are given as arguments.

For these five different routines the eigenvalues can be obtained by the same function

- **MassArray(id, i)** where \(id\) is the identifier associated with the diagonalisation procedure corresponding to any of the [cr]Diagonal [HAS] routines. The index \(i\) starts with 1. The elements of the rotation matrices are obtained using the functions

- **MixMatrix(id,i,j)** - for orthogonal matrices
- **MixMatrixU(id,i,j)** - for the \(U\) orthogonal matrix in Eq. 5
- **cMixMatrix(id,i,j)** - for unitary matrices
- **cMixMatrixU(id,i,j)** - for the \(U\) hermitian matrix in Eq. 4

### 4.3 Errors

The global variable **FError** signals fatal problems that occur in the execution of **slhaRead**, **slhaVal**, **slhaWrite**, **slhaBranch**, **System** as well as [cr]Diagonal [HAS] and [c]MixMatrix[U]. When **FError=1**, numerical calculations in **CalcHEP** will be interrupted automatically.

### 5 QCD functions

Here we describe some QCD functions which can be useful for implementing a new model.

- **initQCD(alfsMZ,McMc,MbMb,Mtp)**

This function initializes the parameters needed for the functions listed below. It has to be called before any of these functions. The input parameters are the QCD coupling at the Z scale, \(\alpha_s(M_Z)\), and the running quark masses, \(m_c(m_c)\), \(m_b(m_b)\) and \(m_t(pole)\).

- **alphaQCD(Q)**

calculates the running \(\alpha_s\) at the scale \(Q\) in the \(\overline{MS}\) scheme. The calculation is done using the NNLO formula in [29]. Thresholds for b-quark and t-quark are included in \(n_f\) at the scales \(m_b(m_b)\) and \(m_t(m_t)\) respectively.

- **MtRun(Q)**, **MbRun(Q)**, **McRun(Q)**

calculates top, bottom and charm quarks running masses evaluated at NNLO [30].
• $M_{\text{Eff}}(Q)$, $M_{\text{bEff}}(Q)$, $M_{\text{cEff}}(Q)$, calculates effective top, bottom and charm quark masses using \[31\]

$$
M_{\text{eff}}^2(Q) = M(Q)^2 \left[ 1 + 5.67a + (35.94 - 1.36n_f)a^2 + (164.14 - n_f(25.77 - 0.259n_f))a^3 \right]
$$

(9)

where $a = \alpha_s(Q)/\pi$, $M(Q)$ and $\alpha_s(Q)$ are the running quark masses and strong coupling in the $\overline{\text{MS}}$-scheme. These effective masses at the scale $Q = M_h$ give the Yukawa couplings that reproduce the QCD corrections to the partial decay width of the Higgs.

6 Features of the C, C++ and Fortran versions

All routines of the SLHaplus library can be used either in C, C++ or Fortran. In general the C,C++ and Fortran routines have the same names except for the functions with a varying number of arguments which are not supported in Fortran. Furthermore C++ cannot handled such functions if a parameter is a complex number.

For each function with a varying number of parameters we include in our package a set of functions with a fixed number of parameters. The parameter which specifies the number of arguments is removed from the list of arguments and is instead attached to the function name. For example the generic function $\text{slhaVal(BlockName, Q, keyLength,...)}$ has to be replaced by

$$
\text{slhaVal0(Blockname,Q)}
$$

......

$$
\text{slhaVal3(Blockname,Q,key1,key2,key3)}
$$

For $\text{slhaVal}$ and $\text{slhaValExists}$ the digit attached to the name specifies the keyLength and can be 0, 1, 2 or 3. For the functions $\text{[cr]Diagonal[ASH]}$ this number specifies the dimension of the matrices. For the function $\text{aPrintf(format,...)}$ the digit attached describes the number of arguments following the parameter format. In this case all these arguments have to be of real type.

The function $\text{System}$ is replaced by two functions $\text{System1(format)}$ and $\text{System2(format,txt)}$ with text parameters. The second function can be used to provide the destination of the executable.

Another difference between C,C++ and Fortran concerns error messages. The variable $\text{FError}$ gets a non-zero value in case of a fatal error. In C or C++ $\text{FError}$ is a global variable while in Fortran it is included as

```
integer \text{FError}
\text{COMMON/FError/Ferror}
```

The file SLHaplus.h contains the function prototypes for C routines. It has to be included in C and C++ routines which use SLHaplus. The file SLHaplus.fh includes a Fortran description of the types of Fortran functions and $\text{COMMON/FError/}$ declaration. It has to be included in each Fortran routines.

5In Fortran they have to be of REAL*8 type.
7 Compilation and testing

The command `make` generates the static library file `libSLHAplus.a` which contains all the functions of the package.

The subdirectory `test` contains three test programs each available as C, C++ or Fortran codes.

- `tJacobi.[c/cpp/F]` tests all Jacobi functions included in the package. Used in a cycle it fills the corresponding matrices by random numbers, diagonalises them, prints eigenvalues, restores the non-diagonal matrix and calculates the difference between the original ($M$) and restored ($M'$) matrices, $\Delta = \sqrt{\sum_{i,j} \left( M_{ij} - M'_{ij} \right)^2}$. A typical difference $\Delta \approx 10^{-15}$ means that the precision in the diagonalisation reaches the precision of the computer. The dimension of the matrix and the number of steps in the cycle can be changed via a redefinition of the parameters `DIM` and `nTest` which are defined at the top of the file.

- `tChDiag.[c/cpp/F]` tests the diagonalisation functions `rDiagonal[A]` of Section 4.2. Here the matrix dimension is 2. This is for a quick test that the elements of the original matrix have been passed correctly.

- `tSlha.[c/cpp/F]` is an independent program for testing the SLHA reader. The program reads the files `spectr.slha` and `decay.slha` and writes on screen the information stored in the files.

To compile a test program use the command

```
make main=<name of source code>
```

The name of the executable corresponds to the name of the source file.

8 Special features of LanHEP and CalcHEP

Here we describe some special features relevant for the implementation of a new model in LanHEP and CalcHEP.

8.1 Particle widths

The particle widths do not generally need to be defined as input parameters, indeed the widths depend on the fundamental parameters of the model and therefore can be computed automatically by CalcHEP using the relevant Feynman diagrams. In order to inform CalcHEP that a particle width has to be computed before the calculation of a scattering process, the width of the particle must be preceded by an exclamation mark in the particle table. This can be done in LanHEP by adding the `auto` record after the width declaration. For instance,

```
scalar h/h: (' Higgs 1',pdg 25,mass Mh,width wh=auto).
```

will generate the following line in the `prtcls1.mdl` model file.

```
Full Name | P | aP| number |spin2|mass|width|color|
Higgs 1   |h |h |25  |0     |Mh |!!wh |1    |
```

If an SLHA file contains information about particle widths, then the widths can also be defined using the function `slhaWidth(PDGcode)`.
8.2 Matrix diagonalisation routines

As an example we give here the LanHEP code for describing the neutralino matrix in the MSSM, the mass eigenvalues and the elements of the mixing matrices.

\[
\text{parameter } \text{NeDiag} = \text{rDiagonal}(4, \text{MG1}, \text{zero}, -\text{MZ}\text{*SW}\text{*cb}, \text{MZ}\text{*SW}\text{*sb}, \\
\text{MG2, MZ}\text{*CW}\text{*cb}, -\text{MZ}\text{*CW}\text{*sb, zero, -mu, zero}).
\]

\[
_i=1-4 \text{ in parameter } \text{MNE}_i=\text{MassArray} (\text{NeDiag, } _i).
\]

\[
_i=1-4, _j=1-4 \text{ in parameter } \text{Zn}_i_j=\text{MixMatrix} (\text{NeDiag, } _i, _j).
\]

The elements of the mass matrix can either be written explicitly by the user or extracted from LanHEP. Indeed LanHEP contains a facility to examine the mass sector of the Lagrangian. When the CheckMasses statement is used, LanHEP creates the file named masses.chk. This file contains information about mass terms which are not given in the output files specifying only the Feynman rules. In particular this can be useful for fields that are rotated by orthogonal matrices that diagonalise mass terms, LanHEP can recognize the mixing matrix if the elements of this matrix were used in an OrthMatrix statement. LanHEP restores and prints the original mass matrix before the fields rotation. For example, in the case of the neutralino this output reads:

Looking for the mixing matrix...

It is recognized that these fields are rotated by matrix:

\[
\begin{pmatrix}
\text{Zn11} & \text{Zn12} & \text{Zn13} & \text{Zn14} \\
\text{Zn21} & \text{Zn22} & \text{Zn23} & \text{Zn24} \\
\text{Zn31} & \text{Zn32} & \text{Zn33} & \text{Zn34} \\
\text{Zn41} & \text{Zn42} & \text{Zn43} & \text{Zn44}
\end{pmatrix}
\]

The mass matrix before introducing this rotation:

\[
\begin{align*}
\text{M11} &= (+1\text{*MG1}) \\
\text{M12} &= 0 \\
\text{M13} &= (-1/\text{CW}\text{*MW}\text{*SW}\text{*cb}) \\
\text{M14} &= (+1/\text{CW}\text{*MW}\text{*SW}\text{*sb}) \\
\text{M22} &= (+1\text{*MG2}) \\
\text{M23} &= (+1\text{*MW}\text{*cb}) \\
\text{M24} &= (-1\text{*MW}\text{*sb}) \\
\text{M33} &= 0 \\
\text{M34} &= (-1\text{*mu}) \\
\text{M44} &= 0
\end{align*}
\]

This information can be copied and pasted as argument of the rDiagonal function.
8.3 External function prototyping and linking

In general one has to provide information about the types of parameters and returned values of external functions to C/Fortran compilers. As well LanHEP needs these prototypes for numerical processing. The functions included in the SLHAplus library are known to LanHEP, CalcHEP and micrOMEGAs, therefore there is no need to specify the prototypes. The SLHAplus library is included into these packages and linked automatically. If one wants to use other external functions to calculate couplings or masses the following rules have to be used.

In CalcHEP the extlibN.mdl model file (\(N\) is an integer which specifies the model) can include prototypes of C-routines used in the model. Function declaration has to start on a new line, the first word has to be \texttt{extern} and declaration should be terminated on the same line with a semicolon. For all other details we follow the C-syntax. Prototypes for functions which return values of type \texttt{double} and have all arguments of type \texttt{double} can be omitted. Other records in the extlibN.mdl files are treated as definition of external libraries that are provided to the linker. micrOMEGAs ignores CalcHEP linker instructions and assumes that all external functions are stored in the file lib/aLib.a.

The current version of LanHEP allows only functions which return \texttt{double} and have all arguments of type \texttt{double}. Such functions have to be declared in LanHEP by instructions such as

\begin{verbatim}
external_func(name, N, lib)
\end{verbatim}

whose arguments describe the function name, the number of arguments and the name of the shared library which contains this function. In general, the library will be linked when processing LanHEP for numerical checks. The \texttt{lib} parameter can be omitted. In this case only symbolic LanHEP processing will be valid.

There are some specific features for writing an external functions in LanHEP. First, to pass a string parameter one has to use the \texttt{str} function. For example to read the SLHA value for one element of the neutralino mixing matrix at the scale QSUSY

\begin{verbatim}
Zn12 = slhaVal(str(NMIX),QSUSY,2,1,2).
\end{verbatim}

Functions with zero number of parameters should appear in LanHEP source files without brackets, for example

\begin{verbatim}
external_func(initDiagonal,0).
\end{verbatim}

8.4 Complex numbers in CalcHEP

Despite the fact that CalcHEP cannot work directly with complex parameters, following the procedure described above it is possible to declare functions with complex parameters and/or a complex return value. Complex parameters have to be constructed by writing explicitly the real and imaginary parts using the parameter \(I\) where \(I^2 = -1\). Complex return values can be transformed to real values using the C99 functions \texttt{creal} and \texttt{cimag}. Prototypes of these functions are automatically declared in CalcHEP. This way the complex rotation matrices mentioned in section 4.2 can be implemented in CalcHEP.

6Note that LanHEP does not generate the extlib file and that CalcHEP generates automatically an empty file.
9  FeynRules Support

Support for the SLHA parameter reading routines of this library has been included in the FeynRules (FR)CalcHEP (CH) output interface which will be released later this year. Since FR has been described in [3, 35], we will just describe the support for the SLHA parameter files. The author of a FR model file does not need to do anything different to use this functionality. It is all handled automatically by the FR CH interface. There is a new option for the FR CH interface LHASupport. For example, the user could issue the command:

\[
\text{WriteCHOutput}[L, \text{LHASupport} \rightarrow \text{True}] \]

in their FR session, where \(L\) is the Lagrangian. If this option is set to True, the FR-CH interface will write the CH model files which use the functions of the SLHAplus library. In addition, a SLHA parameter file is written to the model directory called “varsN.lha” where \(N\) is the model number. To use this model, the user can import this model into CH just as with any other CH model. Since the name of the SLHA parameter file is called explicitly in the model files, if the user changes the name of the SLHA file, the user will need to make the corresponding change to the model files. In particular, in the file funcN.mdl, the line containing \textit{readSLHA} must be changed to contain the correct filename. This SLHA parameter file will then need to be copied to the results directory of a CH numerical session.

The SLHA parameter file that FeynRules creates does not have any scales specified for the blocks. For this reason, the CH model files that FR writes call the SLHA reader routines with a default scale of 0 (for example, \textit{slhaVal(“SMINPUTS”,0,1,1)} in the FeynRules Standard Model implementation). Since the default parameter file does not specify any scales, this is ignored. However, if a SLHA parameter file from another source was used instead that had blocks with more than 1 scale specified, the model files would need to be modified as appropriate.

The matrix diagonalization and QCD routines in \textbf{SLHAplus} are not supported in FR at this time.

10  Conclusion

The library \textbf{SLHAplus} provides a set of functions to facilitate the implementation of new models in codes for computing physical observables. It was developed primarily to be used in \textit{LanHEP}, \textit{CalcHEP} and \textit{micrOMEGAs} although the routines are general enough to be used with other codes. In the library we also provide the \textit{LanHEP} source code for two different implementation of the MSSM, these can serve as a basis for the implementation of extensions of the minimal supersymmetric model. The library is available at \texttt{lappweb.in2p3.fr/lapth/micromegas/slhaplus}.

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Appendices

A The MSSM model files in LanHEP

As an example of an application of the routines of the SLHAplus library, we present the LanHEP code to generate the MSSM model files in the format of CalcHEP and micrOMEGAs. The Lagrangian of the MSSM is described in [36] and some technical details for the implementation into LanHEP are explained in Ref. [37, 38]. In this example we describe an MSSM model which takes into account higher order corrections in the Higgs sector as described below. However we do not include other higher-order corrections such as the SUSY-QCD corrections to the $Hg\bar{b}$ vertices [32] or corrections to stop/sbottom interactions. Finally we assume massless fermions for the first two generations. Therefore the model generated cannot be used for the calculation of the dark matter direct detection rates in micrOMEGAs which needs non-zero light quark masses. Note that when using the SLHA interface with a spectrum calculator that includes radiative corrections to masses and mixings in all sectors of the model, some gauge invariance problems could remain.

A.1 LanHEP source files

The LanHEP sources for the MSSM are provided in the sub-directory MSSM. The source files have an extension .src and contain

- var.src - definition of the independent parameters;
- prtcls.src - list of particles of the model;
- Let.src - Substitutions to express field multiplets in terms of physical particles;
- W.src - superpotential: F-terms and Yukawa interactions;
- DD.src - scalar supersymmetric potential, D-terms;
- softsbts.src - soft SUSY breaking terms;
- fgauge.src - Gauge fixing terms and Faddeev-Popov ghost for the gauge group $SU(3) \times SU(2) \times U(1)$;
- ggi.src - self-interaction of gauge multiplets;
- gmi.src - Interactions of the gauge and matter multiplets;
- higgs4.src - effective potential for the Higgs sector;
- func.src - external functions for implementatge of high order corrections, SLHA interface as well as computation of mass eigenvalues when the tree-level option is chosen.
- startup.src - main file including the instructions to read all other source files.

To compile the model, launch

```
lhep startup.src -evl 2
```

The source files generate three different versions of the MSSM at the electroweak symmetry breaking scale. The default setting
keys SLHA=On

in startup.src compiles the model files in the format needed for an SLHA interface while
the setting keys SLHA=Off will generate the tree level model that requires the matrix
diagonalisation routines for calculating the spectrum. The

keys LambdaTH=On/Off.

defines the setting for the computation of the Higgs potential described below.

The running of quark masses is included by defining effective masses for quarks as
described in section 5. These masses depend on an external parameter $Q$ which specifies
the QCD scale relevant for the process under consideration.

Note that to include the SLHA model files created in this example into CalcHEP it is
necessary to include the suspect2.exe file in the CalcHEP working directory.

A.2 The Higgs sector

In the MSSM the Higgs sector receives large loop corrections. In order to have a realistic
tree level model, in particular to have a light Higgs mass heavier than the experimental
limit, it is necessary to include some higher order corrections to the Higgs sector. To
do this in a gauge invariant manner, we introduce an effective Lagrangian with five in-
dependent parameters, $\lambda_1$ to $\lambda_5$.\footnote{The most general Lagrangian needs 7 parameters but $\lambda_6$ and $\lambda_7$ are in general small and can be
neglected.} We provide three different methods to include loop
corrections in the Higgs sector. In the first, the analytical formulae for the one-loop QCD
and SUSY-QCD corrections to the effective Lagrangian \cite{39} are included in the model
file. The masses of the Higgs particles are then computed from the effective Lagrangian,
for this one chooses the settings SLHA=Off. The last two options, which correspond to the
setting SLHA=On, are available when the higher order corrections to the Higgs masses and
mixing angle are computed by an external program. In the second method, the parameters
of the effective Lagrangian are reconstructed from the physical masses, $m_h, m_H, m_{H^+}$,
and the Higgs mixing angle that are provided through the SLHA interface \cite{40}. Here
we follow the procedure described in \cite{33}. As there are only four independent physical
parameters, the analytical formulae for the corrections to $\lambda_1$ are used even in this case, the
coefficients $\lambda_2...\lambda_5$ are then extracted from the physical parameters. For this option one
chooses the setting LambdaTH=Off. This implementation guarantees that the higher order
corrections to the Higgs sector are taken into account in a gauge invariant way \cite{33}. Finally
a third possibility consists in substituting analytical formulas for the Higgs couplings \cite{39}
instead of solving equations to extract them from the masses. In this case one must set
LambdaTH=On. Since the spectrum calculators include in general additional higher-order
corrections in the computation of the Higgs masses, the masses obtained with the first
option differ from the last two, similarly the Higgs potentials can be slightly different in
the last two cases.
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