

# The micrOMEGAs user's manual, version 3.1

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## Abstract

We give an up-to-date description of micrOMEGAs functions. Only the routines which are available for the users are described. Examples on how to use these functions can be found in the sample main programs distributed with the code.

## 1 Introduction

**micrOMEGAs** is a code to calculate the properties of cold dark matter in a generic model of particle physics. First developed to compute the relic density of dark matter, the code also computes the rates for dark matter direct and indirect detection. It is assumed that a discrete symmetry like R-parity ensures the stability of the lightest odd particle (LOP). All annihilation and coannihilation channels are included in the computation of the relic density. This manual gives an up-to-date description of all **micrOMEGAs** functions. The method used to compute the dark matter properties are described in references [1, 2, 3, 4, 5, 6]. These references also contain a more complete description of the code. In the following the cold dark matter candidate also called LOP or weakly-interactive massive particle (WIMP) will be denoted by  $\chi$ .

**micrOMEGAs** contains both C and Fortran routines. Below we describe only the C-version of the routines, in general we use the same names and the same types of argument for both C and Fortran functions. We always use `double(real*8)` variables for float point numbers and `int(INTEGER)` for integers. In this manual we use *FD* for a file descriptor variables, the file descriptors are `FILE*` in C and `channel number` in Fortran. The symbol `&` before the names of variables in C-functions stands for the address of the variable. It is used for *output parameters*. In Fortran calls there is no need for `&` since all parameters are passed via addresses. In C programs one can substitute `NULL` for output parameters which the user chooses to ignore. In Fortran one can substitute `cNull`, `iNull`, `r8Null` for unneeded parameters of *character*, *integer* and *real\*8* type respectively.

A few C-functions use pointer variables that specify an *address* in the computer memory. Because pointers do not exist in Fortran one uses any other type of variable whose length is sufficient to store a computer address (4 or 8 bytes), for example an `INTEGER*4` array with length 2 or a `REAL*8` variable.

The complete format for all functions can be found in `sources/micromegas.h` (for C) or `sources/micromegas_f.h` (for Fortran). Examples on how to use these functions are provided in the `MSSM/main.c[F]` file.

**micrOMEGAs** assumes that all particles that are odd under the discrete symmetry have a name starting with '~', for example `~o1` for the lightest neutralino.

## 2 Downloading and compilation of micrOMEGAs.

To download micrOMEGAs, go to

<http://lapth.cnrs.fr/micromegas>

and unpack the file received, `micromegas_3.1.tgz`, with the command

```
tar -xvzf micromegas_3.1.tgz
```

This should create the directory `micromegas_3.1/` which occupies about 40 Mb of disk space. You will need more disk space after compilation of specific models and generation of matrix elements. In case of problems and questions

email: [micromegas@lapth.cnrs.fr](mailto:micromegas@lapth.cnrs.fr)

### 2.1 File structure of micrOMEGAs.

<code>Makefile</code>	to compile the kernel of the package
<code>CalcHEP_src/</code>	generator of matrix elements for micrOMEGAs
<code>Packages/</code>	external codes
<code>clean</code>	to remove compiled files
<code>man/</code>	— contains the manual: description of micrOMEGAs routines
<code>newProject</code>	to create a new model directory structure
<code>sources/</code>	micrOMEGAs code
<i>MSSM model directory</i>	
<code>MSSM/</code>	
<code>Makefile</code>	to compile the code and executable for this model
<code>main.c[pp]</code> <code>main.F</code>	files with sample <i>main</i> programs
<code>lib/</code>	directory for routines specific to this model
<code>Makefile</code>	to compile auxiliary code library <i>lib/aLib.a</i>
<code>*.c *.f</code>	source codes of auxiliary functions
<code>work/</code>	CalcHEP working directory for the generation of matrix elements
<code>Makefile</code>	to compile library <i>work/work_aux.a</i>
<code>models/</code>	directory for files which specifies the model
<code>vars1.mdl</code>	free variables
<code>func1.mdl</code>	constrained variables
<code>prtcls1.mdl</code>	particles
<code>lgrng1.mdl</code>	Feynman rules
<code>tmp/</code>	auxiliary directories for CalcHEP sessions
<code>results/</code>	
<code>so_generated/</code>	storage of matrix elements generated by CalcHEP
<code>calchep/</code>	directory for interactive CalcHEP sessions
<i>Directories of other models which have the same structure as MSSM/</i>	
<code>NMSSM/</code>	Next-to-Minimal SUSY Model[22, 16]
<code>CPVMSSM/</code>	MSSM with complex parameters[25, 15]
<code>IDM/</code>	Inert Doublet Model[8]
<code>LHM/</code>	Little Higgs Model[7]
<code>RHNM/</code>	Right-handed Neutrino Model[20]
<code>SM4/</code>	Toy model with a fourth generation of lepton and neutrino DM

## 2.2 Compilation of CalcHEP and micrOMEGAs routines.

CalcHEP and micrOMEGAs are compiled by *gmake*. Go to the micrOMEGAs directory and launch

```
gmake
```

If *gmake* is absent, then *make* should work like *gmake*. In principle micrOMEGAs defines automatically the names of *C* and *Fortran* compilers and the flags for compilation. If you meet a problem, open the file which contain the compiler specifications, CalcHEP\_src/FlagsForSh, improve it, and launch [g]make again. The file is written in *sh* script format and looks like

```
# C compiler
CC="gcc"
# Flags for C compiler
CFLAGS="-g -fsigned-char"
# Disposition of header files for X11
HX11=
# Disposition of lX11
LX11="-lX11"
# Fortran compiler
FC="gfortran"
FFLAGS="-fno-automatic"
.....
```

After a successful definition of compilers and their flags, micrOMEGAs rewrites the file *FlagsForSh* into *FlagsForMake* and substitutes its contents in all *Makefiles* of the package.

[g]make clean deletes all generated files, but asks permission to delete *FlagsForSh*.

[g]make flags only generates *FlagsForSh*. It allows to check and change flags before compilation of codes.

## 2.3 Module structure of main programs.

Each model included in micrOMEGAs is accompanied with sample files for C and Fortran programs which call micrOMEGAs routines, the *main.c*, *main.F* files. These files consist of several modules enclosed between the instructions

```
#ifdef XXXXX
.....
#endif
```

Each of these blocks contains some code for a specific problem

```
#define MASSES_INFO           //Displays information about mass spectrum
#define CONSTRAINTS           //Displays B->sgamma, Bs->mumu, etc
#define OMEGA                 //Calculates the relic density
```

```

#define INDIRECT_DETECTION //Signals of DM annihilation in galactic halo
#define LoopGAMMA //Gamma-Ray lines - available only in some models
#define RESET_FORMFACTORS //Redefinition of Form Factors and other
                        //parameters
#define CDM_NUCLEON //Calculates amplitudes and cross-sections
                        //for DM-nucleon collisions
#define CDM_NUCLEUS //Calculates number of events for 1kg*day
                        //and recoil energy distribution for various nuclei
#define NEUTRINO //Calculates flux of solar neutrinos and
                        //the corresponding muon flux
#define DECAYS //Calculate decay widths and branching ratios
#define CROSS_SECTIONS //Calculate cross sections
#define CLEAN // Removes intermediate files.
#define SHOWPLOTS //Display graphical plots on the screen

```

Other modules which require a link to external programs can also be defined, in this case the path to the required code must be specified, for example

```

#define HIGGSBOUNDS "../Packages/HiggsBounds-4.0.0"

```

All these modules are completely independent. The user can comment or uncomment any set of *define* instructions to suit his/her need.

## 2.4 Compilation of codes for specific models.

After compilation of micrOMEGAs one has to compile the executable to compute DM related observables in a specific model. To do this, go to the model directory, say MSSM, and launch

```
[g]make main=main.c
```

It should generate the executable `main`. In the same manner

```
gmake main=filename.ext
```

generates the executable `filename` based on the source file `filename.ext`. For *ext* we support 3 options: `'c'`, `'F'`, `'cpp'` which correspond to C, FORTRAN and C++ sources. `[g]make` called in the model directory automatically launches `[g]make` in subdirectories *lib* and *work* to compile

`lib/aLib.a` - library of auxiliary model functions, e.g. constraints,

`work/work_aux.a` - library of model particles, free and dependent parameters.

## 2.5 Command line parameters of main programs.

Default versions of *main.c/F* programs need some arguments which have to be specified in command lines. If launched without arguments *main* explains which parameter are needed. As a rule *main* needs the name of a file containing the numerical values of the free parameters of the file. The structure of a file record should be

```
Name      Value # comment ( optional)
```

For instance, an Inert Doublet model (IDM) input file contains

```

Mh      125    # mass of SM Higgs
MHC     200    # mass of charged Higgs ~H+
MH3     200    # mass of odd Higgs ~H3
MHX     63.2   # mass of ~X particle
la2     0.01   # \lambda_2 coupling
laL     0.01   # 0.5*(\lambda_3+\lambda_4+\lambda_5)

```

In other cases, different inputs can be required. For example, in the MSSM with input parameters defined at the GUT scale, the parameters have to be provide in a command line. Launching `./main` will return

```

This program needs 4 parameters:
m0      common scalar mass at GUT scale
mhf     common gaugino mass at GUT scale
a0      trilinear soft breaking parameter at GUT scale
tb      tan(beta)
Auxiliary parameters are:
sgn +/-1, sign of Higgsino mass term (default 1)
Mtp     top quark pole mass
MbMb    Mb(Mb) scale independent b-quark mass
alfSMZ  strong coupling at MZ
Example: ./main 120 500 -350 10 1 173.1

```

### 3 Global Parameters

The list of the global parameters and their default values are given in Tables 1, 2. The numerical value for any of these parameters can be simply reset anywhere in the code.

### 4 Setting of parameters, spectrum calculation, parameter display.

The independent parameters that characterize a given model are listed in the file `work/models/vars1.mdl`. Three functions can be used to set the value of these parameters:

- `assignVal(name,val)`
- `assignValW(name,val)`

assigns value *val* to parameter *name*. The function `assignVal` returns a non-zero value if it cannot recognize a parameter name while `assignValW` writes an error message.

- `readVar(fileName)`

reads parameters from a file. The file should contain two columns with the following format

```

name      value

```

`readVar` returns zero when the file has been read successfully, a negative value when the file cannot be opened for reading and a positive value corresponding to the line where a wrong file record was found.

Table 1: Global parameters of **micrOMEGAs**

Name	default value	units	comments
Mcdm		GeV	Mass of Dark Matter particle
deltaY	0		Difference of DM/anti-DM abundances
DMasymm	0		Asymmetry between relic density of DM- anti-DM
K_dif	0.0112	kpc <sup>2</sup> /Myr	The normalized diffusion coefficient
L_dif	4	kpc	Vertical size of Galaxy diffusive halo
Delta_dif	0.7		Slope of diffision coefficient
Tau_dif	10 <sup>16</sup>	s	Electron energy loss time
Vc_dif	0	km/s	Convective Galactic vind
Fermi_a	0.52	fm	nuclei surface thickness
Fermi_b	-0.6	fm	parameters to set the nuclei radius with
Fermi_c	1.23	fm	$R_A = cA^{1/3} + b$
Rsun	8.5	kpc	Distance from Sun to center of Galaxy
Rdisk	20	kpc	Radius of galactic diffusion disk
rhoDM	0.3	GeV/ $cm^3$	Dark Matter density at Rsun
Vearth	225.2	km/s	Galaxy velocity of Earth
Vrot	220	km/s	Galaxy rotation velocity at Rsun
Vesc	600	km/s	Escape velocity at Rsun

Table 2: Global parameters of **micrOMEGAs**: nucleon quark form factors

Proton		Neutron		comments
Name	value	Name	value	
ScalarFFPd	0.0191	ScalarFFNd	0.0273	Scalar form factor
ScalarFFPu	0.0153	ScalarFFNu	0.011	
ScalarFFPs	0.0447	ScalarFFNs	0.0447	
pVectorFFPd	-0.427	pVectorFFNd	0.842	Axial-vector form factor
pVectorFFPu	0.842	pVectorFFNu	-0.427	
pVectorFFPs	-0.085	pVectorFFNs	-0.085	
SigmaFFPd	-0.23	SigmaFFNd	0.84	Tensor form factor
SigmaFFPu	0.84	SigmaFFNu	-0.23	
SigmaFFPs	-0.046	SigmaFFNs	-0.046	

Note that in Fortran, numerical constants should be specified as Real\*8, for example

```
call assignValW('SW', 0.473D0)
```

A common mistake is to use Real\*4.

The constrained parameters of the model are stored in `work/models/func1.mdl`. Some of these parameters are treated as *public* parameters. The *public* parameters include by default all particle masses and all parameters whose calculation requires external functions (except simple mathematical functions like `sin`, `cos` .. ). The parameters listed above any *public* parameters in `work/models/func1.mdl` are also treated as *public*. It is possible to enlarge the list of *public* parameters. For this one has to add a special record in `work/models/func1.mdl`

```
%Local! |
```

Then all parameters listed above this record become *public*. See example in

```
MSSM/work/models/func1.mdl
```

The calculation of the particle spectrum and of all *public* model constraints is done with:

- `sortOddParticles(txt)`

which sorts the odd particles with increasing masses, writes the name of the lightest odd particle in `txt` and assigns the value of the mass of the lightest odd particle to the global parameter `Mcdm`. This routine returns a non zero error code for a wrong set of parameters, for example parameters for which some constraint cannot be calculated. The name of the corresponding constraint is written in `txt`. This routine has to be called after a reassignment of any input parameter.

- `qNumbers(pName, &spin2, &charge3, &cdim)`

returns the quantum numbers for the particle `pName`. Here `spin2` is twice the spin of the particle; `charge3` is three times the electric charge; `cdim` is the dimension of the representation of  $SU(3)_c$ , it can be 1, 3,  $-3$  or 8. The parameters `spin2`, `charge3`, `cdim` are variables of type `int` and `massPrt` should be `double*`. The value returned is the PDG code. If `pName` does not correspond to any particle of the model then `qNumbers` returns zero.

- `nextOdd(n, &pMass)`

returns the name and mass of the  $n^{th}$  odd particle assuming that particles are sorted according to increasing masses. For  $n = 0$  the output specifies the name and the mass of the CDM candidate. In the FORTRAN version this function is Subroutine `nextOdd(n, pName, pMass)`

- `pdg2name(nPDG)`

returns the name of the particle which PDG code is  $nPDG$ . If this particle does not exist in the model the return value is NULL. In the FORTRAN version this function is Subroutine `pdg2name(nPDG, pName)` and the character variable `pName` consists of white spaces if the particle does not exist in the model.

- `pMass(pName)`

returns numerical value of the particle mass.

- `findVal(name, &val)`

finds the value of variable `name` and assigns it to parameter `val`. It returns a non-zero value if it cannot recognize a parameter name.



- **findValW(name)** just returns the value of variable *name* and writes an error message if it cannot recognize a parameter name. The variables accessible by these commands are all free parameters and the constrained parameters of the model (in file `model/func1.mdl`) treated as *public*.

The following routines are used to display the value of independent and constrained *public* parameters:

- **printVar(FD)**  
prints the numerical values of all independent and *public* constrained parameters into FD
- **printMasses(FD, sort)**  
prints the masses of 'odd' particles (those whose names started with ~). If *sort*  $\neq 0$  the masses are sorted so the mass of the CDM is given first.
- **printHiggsMasses(FD, sort)**  
prints the masses and widths of 'even' scalars.

## 5 Relic density calculation.

- **vSigma(T,Beps,fast)**  
calculates the thermally averaged cross section for DM annihilation times velocity at a temperature  $T$  [GeV], see formula (2.6) in [1]. The value for  $\sigma v$  is expressed in [pb]. The parameter *Beps* defines the criteria for including coannihilation channels as for **darkOmega** described below. The *fast* = 1/0 option switches between the *fast/accurate* calculation. The global array **vSigmaTCh** contains the contribution of different channels to **vSigma**. **vSigmaTCh[i].weight** specifies the relative weight of the  $i^{th}$  channel  
**vSigmaTCh[i].prtcl[j]** ( $j=0, 4$ ) define particles names for the  $i^{th}$  channel.  
The last record in **vSigmaTCh** array has zero weight and NULL particle names. In the Fortran version, the function **vSigmaTCh(i,weight,pdg,process)** serves the same purpose. This function returns 0 if  $i$  exceeds the number of annihilation channels and 1 otherwise,  $i \geq 1$ . *real\*8 weight* gives the relative contribution of each annihilation channel. *real\*8 pdg(4)* contains codes of incoming and outgoing particles in the annihilation process. *character\*40 process* contains textual representation of annihilation process.
- **darkOmega(&Xf,fast,Beps)**  
calculates the dark matter relic density  $\Omega h^2$ . This routine solves the differential evolution equation using the Runge-Kutta method.  $X_f = M_{cdm}/T_f$  characterizes the freeze-out temperature. The value of  $X_f$  is given for information and is also used as an input for the routine that gives the relative contribution of each channel to  $\Omega h^2$ , see **printChannels** below. The *fast* = 1 flag forces the fast calculation (for more details see Ref. [2]). This is the recommended option and gives an accuracy around 1%. The parameter *Beps* defines the criteria for including a given coannihilation channel in the computation of the thermally averaged cross-section, [2]. The recommended value is  $Beps = 10^{-4} - 10^{-6}$ , on the other hand if  $Beps = 1$  only annihilation of the lightest odd particle is computed.
- **darkOmegaF0(&Xf, fast, Beps)**  
calculates the dark matter relic density  $\Omega h^2$  using the freeze-out approximation.
- **printChannels(Xf,cut,Beps,prcnt,FD)**  
writes into FD the contributions of different channels to  $(\Omega h^2)^{-1}$ . Here **Xf** is an input parameter which should be first evaluated in **darkOmega[F0]**. Only the channels whose



relative contribution is larger than `cut` will be displayed. `Beps` plays the same role as the `darkOmega[F0]` routine. If `prcnt`  $\neq 0$  the contributions are given in percent. Note that for this specific purpose we use the freeze-out approximation.

- `oneChannel(Xf,Beps,p1,p2,p3,p4)`

calculates the relative contribution of the channel  $p1, p2 \rightarrow p3, p4$  to  $(\Omega h^2)^{-1}$  where  $p1, \dots, p4$  are particle names. To make summation over several channels one can substitute "\*" instead of a particle name.

- `omegaCh` is an array that contains the relative contribution and particle names for each annihilation channel. In the Fortran version one uses instead the function `omegaCh(i,weight,pdg,process)`. These array and function are similar to `vSigmaTch` described above. The array `omegaCh` is filled after calling either `darkOmegaF0` or `printChannels`.

- `VWdecay, VZdecay`

Switches to turn on/off processes with off-shell gauge bosons in final states for DM annihilation and particle decays. If `VW/VZdecay=1`, the 3-body final states will be computed for annihilation processes only while if `VW/VZdecay=2` they will be included in coannihilation processes as well. By default the switches are set to `(VW/VZdecay=0)`.<sup>1</sup> Note that `micrOMEGAs` calculates the width of each particle only once. A second call to the function `pWidth` (whether an explicit call or within the computation of a cross section) will return the same result even if the user has changed the `VW/VZdecay` switch. To clean the decay table and re-activate the `VW/VZdecay` switches, one has to call

- `clearDecayTable()`

to force `micrOMEGAs` to recalculate particle widths according to the new value of `VW/VZdecay`. The `sortOddParticles` command which must be used to recompute the particle spectrum after changing the model parameters also cleans the decay table.

If particle widths were stored in the SLHA file downloaded by `micrOMEGAs`, then the SLHA value will be used by `micrOMEGAs`. To prevent downloading of decays one can download SLHA file using `slhaRead(fileName,mode=4)`, see description in Section 12.5.

Two new global parameters are available to set the DM asymmetry:

- `deltaY`

describes the difference between the DM and anti-DM abundances, see Ref. [6] .

- `DMasymm`

is the relic density asymmetry parameter in Eq. 9 in Ref. [6] and is evaluated by `micrOMEGAs` while calculating the relic density with an initial asymmetry `deltaY`. This parameter can also be reset after the relic density computation and will be taken into account for direct and indirect detection rates.

The temperature dependence of the effective number of degrees of freedom can be set with

- `loadHeffGeff(char*fname)`

allows to modify the temperature dependence of the effective number of degrees of freedom by loading the file `fname` which contains a table of  $h_{eff}(T), g_{eff}(T)$  . A positive return value corresponds to the number of lines in the table. A negative return value indicates the line which creates a problem (e.g. wrong format), the routine returns zero when the file `fname` cannot be opened. The default file is `std_thg.tab` and is downloaded automatically if `loadHeffGeff` is not called, five other files are provided in the sources/data directory from [10]. The user can substitute his/her own table as well, if so, the file must

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<sup>1</sup>Including the 3-body final states can significantly increase the execution time for the relic density.

contain three columns containing the numerical values for  $T$ ,  $h_{eff}$ ,  $g_{eff}$ , the data file can also contain comments on lines starting with #.

## 6 Direct detection.

### 6.1 Amplitudes for elastic scattering

- **nucleonAmplitudes(qBOX,pAsi,pAsd,nAsi,nAsd)**

calculates the amplitudes for WIMP-nucleon elastic scattering at zero momentum. **pAsi(nAsi)** are spin independent amplitudes for protons(neutrons) whereas **pAsd(nAsd)** are the corresponding spin dependent amplitudes. Each of these four parameters is an array of dimension 2. The zeroth (first) element of these arrays gives the  $\chi$ -nucleon amplitudes whereas the second element gives  $\bar{\chi}$ -nucleon amplitudes. Amplitudes are normalized such that the total cross section for either  $\chi$  or  $\bar{\chi}$  cross sections is<sup>2</sup>

$$\sigma_{tot} = \frac{4M_\chi^2 M_N^2}{\pi(M_\chi + M_N)^2} (|A^{SI}|^2 + 3|A^{SD}|^2) \quad (1)$$

If **qBOX=NULL** (**qBOX=NoLoop** in Fortran) tree level amplitudes are computed. In MSSM-type models with a spin 1/2 WIMP and scalar "squarks", **qBOX=FeScLoop** uses an improved tree-level calculation. **nucleonAmplitudes** returns a value different from zero only when there is an internal problem in calculation.

**nucleonAmplitudes** depends implicitly on form factors which describe the quark contents in the nucleon. These form factors are global parameters (see Table 1 for default values)

$$TypeFFPq \quad TypeFFNq$$

where *Type* is either "Scalar", "pVector", or "Sigma", FFP and FFN denote proton and neutron and *q* specifies the quark, *d*, *u* or *s*. Heavy quark coefficients are calculated automatically.

- **calcScalarQuarkFF( $m_u/m_d, m_s/m_d, \sigma_{\pi N}, \sigma_s$ )**

computes the scalar coefficients for the quark content in the nucleon from the quark mass ratios  $m_u/m_d, m_s/m_d$  as well as from  $\sigma_{\pi N}$  and  $\sigma_s$ . The default values given in Table 2 are obtained for  $\sigma_s = 42\text{MeV}$ ,  $\sigma_{\pi N} = 34\text{MeV}$ ,  $m_u/m_d = 0.56$ ,  $m_s/m_d = 20.2$  [11].

### 6.2 Scattering on nuclei

- **nucleusRecoil(f,A,Z,J,Sxx,qBOX,dNdE)**

This is the main routine of the direct detection module. The input parameters are:

- ◊ **f** - the DM velocity distribution normalized such that

$$\int_0^\infty v f(v) dv = 1$$

The units are  $km/s$  for *v* and  $s^2/km^2$  for *f(v)*.

- ◊ **A** - atomic number of nucleus;

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<sup>2</sup>All parameters in GeV.

- ◇ **Z** - number of protons in the nucleus, predefined values for a wide set of isotopes are called with  $Z_{\{Name\}}$ ;
- ◇ **J** - nucleus spin, predefined values for a wide set of isotopes are called with  $J_{\{Name\}}\{atomic\_number\}$ .
- ◇ **Sxx** - is a routine which calculates nucleus form factors for spin-dependent interactions (S00,S01,S11), it depends on the momentum transfer in  $fm^{-1}$ . The available form factors are

```

SxxF19   SxxNa23   SxxNa23A   SxxAl27   SxxSi29   SxxSi29A
SxxK39   SxxGe73   SxxGe73A   SxxNb92   SxxTe125   SxxTe125A
SxxI127   SxxI127A   SxxXe129   SxxXe129A
SxxXe131 SxxXe131A SxxXe131B

```

where  $xx$  is either 00, 11 or 01. The last character is used to distinguish different implementations of the form factor for the same isotope, see details in [4].

- ◇ **qBOX** - a parameter needed by **nucleonAmplitudes**, see the description above.

The form factors for the spin independent (SI) cross section are defined by a Fermi distribution and depend on the global parameters **Fermi\_a**, **Fermi\_b**, **Fermi\_c**.

The returned value gives the number of events per day and per kilogram of detector material. The result depends implicitly on the global parameter **rhoDM**, the density of DM near the Earth. The distribution over recoil energy is stored in the array  $dNdE$  which by default has  $Nstep = 200$  elements. The value in the  $i^{th}$  element corresponds to

$$dNdE[i] = \frac{dN}{dE} \Big|_{E=i*keV*step}$$

in units of (1/keV/kg/day). By default  $step$  is set to 1.

For a complex WIMP, **nucleusRecoil** averages over  $\chi$  and  $\bar{\chi}$ . For example for  $^{73}Ge$ , a call to this routine will be:

```
nucleusRecoil(Maxwell,73,Z_Ge,J_Ge73,S00Ge73,S01Ge73,S11Ge73,FeScLoop,dNdE);
```

- **setRecoilEnergyGrid(step,Nstep)**

changes the values of **step** and **Nstep** for the computation of **dNdE**.

- **Maxwell(v)**

returns

$$f(v) = \frac{c_{norm}}{v} \int_{|\vec{v}| < v_{max}} d^3\vec{v} \exp\left(-\frac{(\vec{v} - V_{Earth})^2}{\Delta v^2}\right) \delta(v - |\vec{v}|)$$

which corresponds to the isothermal model. Default values for the global parameters  $\Delta v = V_{rot}$ ,  $v_{max} = V_{esc}$ , **Vearth** are listed in Table 1.  $c_{norm}$  is the normalization factor. This function is an argument of the **nucleusRecoil** function described above.

- **nucleusRecoil0(f,A,Z,J,Sp,Sn,qBOX,dNdE)**

is similar to the function **nucleusRecoil** except that the spin dependent nuclei form factors are described by Gauss functions whose values at zero momentum transfer are

defined by the coefficients **Sp**, **Sn** [4]. Predefined values for the coefficients **Sp**, **Sn** are included for the nuclei listed in **nucleusrecoil** as well as  $^3\text{He}$ ,  $^{133}\text{Cs}$ . Their names are

$$\begin{aligned} &Sp_{\{Nucleus\ Name\}}\{Atomic\ Number\} \\ &Sn_{\{Nucleus\ Name\}}\{Atomic\ Number\} \end{aligned}$$

One can use this routine for nuclei whose form factors are not known.

### 6.3 Auxiliary routines

Two auxiliary routines are provided to work with the energy spectrum computed with **nucleusRecoil** and **nucleusRecoil0**.

- **cutRecoilResult(dNdE,E1,E2)**

calculates the number of events in an energy interval defined by the values **E1**, **E2** in keV.

- **displayRecoilPlot(dNdE,title,E1,E2)**

plots the generated energy distribution **dNdE**. Here **title** is a character string specifying the title of the plot and **E1**, **E2** are minimal and maximal values for the displayed energy in keV.

## 7 Indirect detection

### 7.1 Interpolation and display of spectra

Various spectra of particles relevant for indirect detection are stored in arrays with **NZ=250** elements. The  $i^{th}$  element of an array corresponds to  $dN/dz_i$  where  $z_i = \log(E_i/M_{\text{cdm}})$ . Here  $N$  stands for either a number of particles or a particle flux expressed in  $(\text{sec} \cdot \text{cm}^2\text{sr})^{-1}$ .<sup>3</sup>

Table interpolation can be done by two functions

- **zInterp(z,spectTab)**

or

- **SpectdNdE(E,spectTab)**

interpolates the tabulated spectra and returns the particle distribution  $dN/dE$  where **E** is the energy in GeV assuming that  $z = 0$  corresponds to **E=Mcdm**.

To display the spectra visualization one can use

- **displaySpectrum(Spectrum,message,Emin,Emax,Units)**

displays the resulting spectrum, **message** is a text string which gives a title to the plot. **Emin** and **Emax** define energy cuts. If **Units=0** the spectrum is written as a function of  $z = \log_{10}(E/M_{\text{cdm}})$  otherwise the spectrum is a function of the energy in GeV.

### 7.2 Annihilation spectra

- **calcSpectrum(key,Sg,Se,Sp,Sne,Snm,Snl,&err)**

calculates the spectra of DM annihilation at rest and returns  $\sigma v$  in  $\text{cm}^3/\text{s}$ . The calculated

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<sup>3</sup>The value of  $z_i$  can be obtained with the function  $Zi(i)$ . In the current version  $Zi(i) = \log\left((10^{-7})^{(i/NZ)^{1.5}}\right)$ . This function is in general not needed if one uses the functions described below.

spectra for  $\gamma$ ,  $e^+$ ,  $\bar{p}$ ,  $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$  are stored in arrays of dimension NZ as described above: **Sg**, **Se**, **Sp**, **Sg**, **Sne**, **Snm**, **Sn1**. To remove the calculation of a given spectra, substitute **NULL** for the corresponding argument. **key** is a switch to include polarisation of W,Z bosons (**key=1**) or photon radiation (**key=2**). Photon radiation is added to all subprocesses when computing the photon spectrum while only the 3-body process  $\chi\chi \rightarrow e^+e^-\gamma$  is included for the positron spectrum. When **key=4** the cross sections for each annihilation channel are written on the screen. More than one option can be switched on simultaneously by adding the corresponding values for **key**. For example both the W polarisation and photon radiation effects are included if **key=3**. A problem in the spectrum calculation will produce a non zero error code,  $err \neq 0$ . **calcSpectrum** interpolates and sums spectra obtained by Pythia. The spectra tables are provided only for  $M_{\text{cdm}} > 2\text{GeV}$ . The results for a dark matter mass below 2 GeV will therefore be wrong, for example an antiproton spectrum with kinetically forbidden energies will be produced. A warning is issued for  $M_{\text{cdm}} < 2\text{GeV}$ .

- **spectrInfo(Xmin,spectrTab,&Ntot,&Xtot)**

provides information on the spectra generated. Here **Xmin** defines the minimum cut for the energy fraction  $x=E/M_{\text{cdm}}$ , **Ntot** and **Xtot** are calculated parameters which give on average the total number and the energy fraction of the final particles produced per collision. Note that the upper limit is  $X_{\text{tot}}=2$ .

- **vSigmaCh** is an array that contains the relative contribution and particle names for each annihilation channel. In the Fortran version one uses instead the function **vSigmaCh(i,weight,pdg,process)**. These array and function are similar to **vSigmaTch** described above. The array **vSigmaCh** is filled by **calcSpectrum**.

### 7.3 Distribution of Dark Matter in Galaxy.

The indirect DM detection signals depend on the DM density in our Galaxy. The DM density is given as the product of the local density at the Sun with the halo profile function

$$\rho(r) = \rho_\odot F_{\text{halo}}(r) \quad (2)$$

In **micrOMEGAs**  $\rho_\odot$  is a global parameter **rhoDM** and the Zhao profile [12]

$$F_{\text{halo}}(r) = \left(\frac{R_\odot}{r}\right)^\gamma \left(\frac{r_c^\alpha + R_\odot^\alpha}{r_c^\alpha + r^\alpha}\right)^{\frac{\beta-\gamma}{\alpha}} \quad (3)$$

with  $\alpha = 1, \beta = 3, \gamma = 1, r_c = 20[\text{kpc}]$  is used by default.  $R_\odot$ , the distance from the Sun to the galactic center, is also a global parameter, **Rsun**. The parameters of the Zhao profile can be reset by

- **setProfileZhao( $\alpha, \beta, \gamma, r_c$ )**

The functions to set another density profile reads

- **setHaloProfile( $F_{\text{halo}}(r)$ )**

where  $F_{\text{halo}}(r)$  is any function from distance from Galactic center,  $r$  has to be defined in [kpc] units. For instance, **setHaloProfile(hProfileEinasto)** sets Einasto profile

$$F_{\text{halo}}(r) = \exp \left[ -\frac{2}{\alpha} \left( \left( \frac{r}{R_\odot} \right)^\alpha - 1 \right) \right]$$

where by default  $\alpha = 0.17$ , but can be changed by

- **setProfileEinasto( $\alpha$ )**

The command `setHaloProfile(hProfileZhao)` sets back Zhao profile. Note that both `setProfileZhao` and `setProfileEinasto` call `setHaloProfile` to install the corresponding profile.

Dark matter annihilation in the Galaxy depends on the average of the square of the DM density,  $\langle \rho^2 \rangle$ . This quantity can be significantly larger than  $\langle \rho \rangle^2$  when clumps of DM are present [?]. In `micrOMEGAS`, we use a simple model where  $f_{cl}$  is a constant that characterizes the fraction of the total density due to clumps and where all clumps occupy the same volume  $V_{cl}$  and have a constant density  $\rho_{cl}$ . Then assuming clumps do not overlap, we get

$$\langle \rho^2 \rangle = \rho^2 + f_{cl} \rho_{cl} \rho. \quad (4)$$

This simple description allows to demonstrate the main effect of clumps: far from the Galactic center the rate of DM annihilation falls as  $\rho(r)$  rather than as  $\rho(r)^2$ . The parameters  $\rho_{cl}$  and  $f_{cl}$  have zero default values. The routine to change these values is

- `setClumpConst( $f_{cl}, \rho_{cl}$ )`

To be more general, one could assume that  $\rho_{cl}$  and  $f_{cl}$  depend on the distance from galactic center. The effect of clumping is then described by the equation

$$\langle \rho^2 \rangle (r) = \rho(r)(\rho(r) + \rho_{clump}^{eff}(r)) \quad (5)$$

and the function

- `setRhoClumps( $\rho_{clump}^{eff}$ )`

allows to implement a more sophisticated clump structure.

## 7.4 Photon signal

The photon flux does not depend on the diffusion model parameters but on the angle  $\phi$  between the line of sight and the center of the galaxy as well as on the annihilation spectrum into photons

- `gammaFluxTab(fi, dfi, sigmav, Sg, Sobs)`

multiplies the annihilation photon spectrum with the integral over the line of sight and over the opening angle to give the photon flux. `fi` is the angle between the line of sight and the center of the galaxy, `dfi` is half the cone angle which characterizes the detector resolution (the solid angle is  $2\pi(1 - \cos(dfi))$ ), `sigmav` is the annihilation cross section, `Sg` is the DM annihilation spectra. `Sobs` is the spectra observed.

The function `gammaFluxTab` can be used for the neutrino spectra as well.

- `gammaFlux(fi, dfi, vcs)`

is the same function as `gammaFluxTab` above but corresponds to a discrete photon spectrum. `vcs` is the annihilation cross section, for instance in the  $\hat{M}SSM$  it is calculated with the `loopGamma` function. The function returns the number of photons per  $cm^2$  of detector surface per second. Note that for  $\chi\chi \rightarrow \gamma\gamma$  the result should be multiplied by a factor 2 as each annihilation leads to the production of two photons.

## 7.5 Propagation of charged particles.

The spectrum of charged particles observed strongly depends on their propagation in the Galactic Halo. The propagation depends on the global parameters

`K_dif`, `Delta_dif`, `L_dif`, `Rsun`, `Rdisk`



as well as

`Tau_dif (positrons), Vc_dif (antiprotons)`

- `posiFluxTab(Emin,sigmav, Se, Sobs)`

computes the positron flux at the Earth. Here `sigmav` and `Se` are values obtained by `calcSpectrum`. `Sobs` is the positron spectrum after propagation. `Emin` is the energy cut to be defined by the user. Note that a low value for `Emin` increases the computation time. The format is the same as for the initial spectrum. The function `SpectrdNdE(E,Sobs)` described above can also be used for interpolation, in this case the flux returned in  $(\text{GeV s cm}^2\text{sr})^{-1}$ .

- `pbarFlux(E,dSigmavdE)`

computes the antiproton flux for a given energy `E` and a differential cross section for antiproton production, `dSigmavdE`. For example, one can substitute

`dSigmavdE=σvSpectdNdE(E,SpP)`

where  $\sigma v$  and `SpP` are obtained by `calcSpectrum`. This function does not depend on the details of the particle physics model and allows to analyse the dependence on the parameters of the propagation model.

- `pbarFluxTab(Emin,sigmav, Sp, Sobs)`

computes the antiproton flux, this function works like `posiFluxTab`,

- `solarModulation(Phi, mass, stellarTab, earthTab)`

takes into account modification of the interstellar positron/antiproton flux caused by the electro-magnetic fields in the solar system. Here `Phi` is the effective Fisk potential in MeV, `mass` is the particle mass, `stellarTab` describes the interstellar flux, `earthTab` is the calculated particle flux in the Earth orbit.

Note that for `solarModulation` and for all `*FluxTab` routines one can use the same array for the spectrum before and after propagation.

## 8 Neutrino signal from Sun and Earth

After being captured, DM particles concentrate in the center of the Sun/Earth and then annihilate into Standard Model particles. These SM particles further decay producing neutrinos that can be observed at the Earth.

- `neutrinoFlux(f,forSun,nu, nu_bar)`

calculates muon neutrino/anti-neutrino fluxes near the surface of the Earth. Here `f` is the DM velocity distribution normalized such that  $\int_0^\infty v f(v) dv = 1$ . The units are  $km/s$  for `v` and  $s^2/km^2$  for `f(v)`. At first approximation, one can use the same `Maxwell` function introduced for direct detection.

If `forSun==0` then the flux of neutrinos from the Earth is calculated, otherwise this function computes the flux of neutrinos from the Sun. The calculated fluxes are stored in `nu` and `nu_bar` arrays of dimension `NZ=250`. The neutrino fluxes are expressed in  $[1/\text{Year}/km^2]$ . The function `SpectdNdE(E,nu)` returns the differential flux of neutrinos in  $[1/\text{Year}/km^2/\text{GeV}]$ , and

`displaySpectrum(nu,"nu from Sun  $[1/\text{Year}/km^2/\text{GeV}]$ ",Emin,Emax,1)`

allows to display the corresponding spectrum on the screen.

- `muonUpward(nu,Nu,rho, muon)`

calculates the muon flux which results from interactions of neutrinos with rocks below the



detector. Here `nu` and `Nu` are input arrays containing the neutrino/anti-neutrino fluxes calculated by `neutrinoFlux`. `rho` is the Earth density  $\approx 2.6 \text{ g/cm}^3$ . `muon` is an array which stores the resulting sum of  $\mu^+$ ,  $\mu^-$  fluxes. `SpectdNdE(E,muon)` gives the differential muon flux in  $[1/\text{Year}/\text{km}^2/\text{GeV}]$  units.

- `muonContained(nu,Nu,rho, muon)` calculates the flux of muons produced in a given detector volume. This function has the same parameters as `muonUpward` except that the outgoing array gives the differential muon flux resulting from neutrinos converted to muons in a  $\text{km}^3$  volume given in  $[1/\text{Year}/\text{km}^3/\text{GeV}]$  units. `rho` is the density of the detector in  $\text{g/cm}^3$ .

Two functions allow to estimate the background from atmospheric neutrinos creating muons after interaction with rocks below the detector or with water inside the detector.

- `ATMmuonUpward(cosFi,E)` calculates sum of muon and anti-muon fluxes appears in result of interaction of atmospheric neutrinos with rocks. Units are  $1/\text{Year}/\text{km}^2/\text{GeV}/\text{Sr}$ . `cosFi` is the energy between direction of observation and direction to the center of Earth. `E` - muon energy in  $\text{GeV}$ .

- `ATMmuonContained(cosFi, E, rho)` calculates flux of muon caused by atmospheric neutrinos which are produced in given ( detector) volume. Return value presented in units  $1/\text{Year}/\text{km}^3/\text{GeV}$ . `rho` is a density of detector in  $\text{g/cm}^3$  units. `cosFi` and `E` are the same as above.

## 9 Cross sections and decays.

The calculation of particle widths, decay channels and branching fractions can be done by the function

- `pWidth(particleName,&address)`

returns directly the particle width. If the  $1 \rightarrow 2$  decay channels are kinematically accessible then only these channels are included in the width. If not, `pWidth` compiles all open  $1 \rightarrow 3$  channels and use these for computing the width. An improved routine with a better matching between the  $1 \rightarrow 2$  and  $1 \rightarrow 3$  calculations is kept for the future. The returned parameter `address` gives an address where information about the decay channels is stored. In C, the address should be of type `txtList`.

- `printTxtList(address,FD)`

lists the decays and their branching fractions and writes them in a file. `address` is the address returned by `pWidth`.

- `findBr(address,pattern)`

finds the branching fraction for a specific decay channel specified in `pattern`, a string containing the particle names in the CalcHEP notation. The names are separated by commas or spaces and can be specified in any order.

- `slhaDecayPrint(pname,FD)`

Calculates the width and branching ratios of particle `pname` and writes down the result in SLHA format. The return value is the PDG particles code. In case of problem, for instance wrong particle names, this function returns zero. This function first tries to calculate  $1 \rightarrow 2$  decays. If such decays are kinematically forbidden then  $1 \rightarrow 3$  decay channels are computed. For models which read an SLHA parameter file, the values of the widths and branchings are taken from the SLHA file unless the user chooses not to read

this data, see (Section 12.5) for details.

- **newProcess(procName)**

compiles the codes for any  $2 \rightarrow 2$  or  $1 \rightarrow 2$  reaction. The result of the compilation is stored in the shared library disposed in `work/so-generated/` directory. The name of library is generated automatically corresponding to the process. If the library `libName` already exists, it is not recompiled.

The `newProcess` routine returns the *address* of the compiled code for further usage. If the process can not be compiled, then a NULL address is returned<sup>4</sup>. Note that it is also possible to compute processes with polarized massless beams, for example for a polarized electron beam use `e%` to designate the initial particle.

- **wimpAnnLib()**

is the name of the library for DM annihilation.

There are two routines which allow to check the library contents.

- **procInfo1(address,&ntot,&nin,&nout)**

provides information about the total number of subprocesses (`ntot`) stored in the library specified by `address` as well as the number of incoming (`nin`) and outgoing (`nout`) particles for these subprocesses. Typically, for collisions (decays),  $nin = 2(1)$  and  $nout = 2, 3$ . NULL can be substitute if this information is not needed.

- **procInfo2(address,nsup,N,M)**

fills for subprocess `nsup` ( $1 \leq nsup \leq ntot$ ) an array of particle names `N` and an array of particle masses `M`. These arrays have size  $nin + nout$  and the elements are listed in the same order as in CalcHEP starting with the initial state, see the example in `MSSM/main.c`.

- **cs22(address,nsup,P,c1,c2,&err)**

calculates the cross-section for a given  $2 \rightarrow 2$  process, `nsup`, with center of mass momentum  $P(\text{GeV})$ . The differential cross-section is integrated from  $c1 < \cos \theta < c2$  and  $\theta$  is the angle between  $\vec{p}_1$  and  $\vec{p}_3$  in the center-of-mass frame. Here  $\vec{p}_1$  ( $\vec{p}_3$ ) denote respectively the momentum of the first initial(final) particle. `err` contains a non zero error code if `nsup` exceeds the maximum value for the number of subprocesses (given by the argument `ntot` in the routine `procInfo1`). To set the polarization of the initial massless beam define `Helicity[i]` where  $i = 0, 1$  for the  $1^{th}$  and  $2^{nd}$  particles respectively. The helicity is defined as the projection of the particle spin on the direction of motion. It ranges from  $[-1, 1]$  for spin 1 particles and from  $[-0.5, 0.5]$  for spin  $1/2$  particles. By definition a left handed particle has a positive helicity.

- **hCollider(Pcm,pp,pName1,pName2)** calculates the cross section for particle production at hadron colliders. Here `Pcm` is the beam energy in the center-of-mass frame. `pp` is  $1(-1)$  for  $pp(p\bar{p})$  collisions. `pName1` and `pName2` are the names of outgoing particles. The value returned is the cross section in [pb]. The QCD scale is fixed to  $Q \approx M/3$ .

- **improveCrossSection( p1,p2,p3,p4, Pcm, &address)**

allows to substitute a new cross-section for a given process. Here `p1,p2` are the names of particles in the initial state and `p3,p4` those in the final state. `Pcm` is the center of mass momentum and `address ...` This function is useful if for example the user one wants to include his one-loop improved cross-section calculation in the relic density computation.

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<sup>4</sup>In Fortran the format is `call newProcess(procName, address)`

## 10 Tools for model independent analysis

A model independent calculation of the DM observables is also available. After specifying the DM mass, the cross sections for DM spin dependent and spin independent scattering on proton and neutron, the DM annihilation cross section times velocity at rest and the relative contribution of each annihilation channel to the total DM annihilation cross section, one can compute the direct detection rate on various nuclei, the fluxes for photons, neutrinos and antimatter resulting from DM annihilation in the galaxy and the neutrino/muonfluxes in neutrino telescopes.

- **nucleusRecoilAux(f,A,Z,J,S00,S01,S11,csIp,csIn,csDp,csDn,dNdE)**

This function is similar to **nucleusRecoil**. The additional input parameters include **csIp(csIn)** the SI cross sections for WIMP scattering on protons(neutrons) and **csDp(csDn)** the SD cross sections on protons(neutrons). A negative value for one of these cross sections is interpreted as a destructive interference between the proton and neutron amplitudes. Note that the rate of recoil depends implicitly on the WIMP mass, the global parameter **Mcdm**. The numerical value for the global parameter has to be set before calling this function.

- **nucleusRecoil0Aux(f,A,Z,J,Sp,Sn,csIp,csIn,csDp,csDn,dNdE)** is the corresponding modification of **nucleusRecoil0**.

For indirect detection, we also provide a tool for model independent studies

- **basicSpectra(pdgN, outN,Spectr)**

computes the spectra of outgoing particles and writes the result in an array of dimension 250, **Spectr**. **M** is the WIMP mass, **pdgN** is the PDG code of the particles produced in the annihilation of a pair of WIMPs. To get spectra generated by transverse and longitudinal W's substitute  $pdgN = 24 + 'T'$  and  $24 + 'L'$  correspondingly. In the same manner  $pdgN = 23 + 'T'$  and  $23 + 'L'$  provides spectra produced by a polarised Z boson. **outN** specifies the outgoing particle,

$$\text{outN} = \{0, 1, 2, 3, 4, 5\} \text{ for } \{\gamma, e^+, p^-, \nu_e, \nu_\mu, \nu_\tau\}$$

The output depends on **Mcdm**. Note that the propagation routines for  $e^+, p^-, \gamma$  can be used after this routine as usual. Note that the result of **basicSpectra** are not valid for  $Mcdm < 2\text{GeV}$  as explained in the description of **calcSpectrum**.

- **captureAux(f,forSun,csIp,csIn,csDp,csDn)**

calculates the number of DM particles captured per second assuming the cross sections for spin-independent and spin-dependent interactions with protons and neutrons **csIp, csIn, csDp, csDn** are given as input parameters (in [pb]). A negative value for one of the cross sections is interpreted as a destructive interference between the proton and neutron amplitudes. The first two parameters have the same meaning as in the **neutrinoFlux** routine Section 8. The result depends implicitly on the global parameters **rhoDM** and **Mcdm** in Table 1.

- **basicNuSpectra(forSun,pdgN, outN,nu)**

calculates the  $\nu_\mu$  and  $\bar{\nu}_\mu$  spectra corresponding to DM annihilating into particles specified by the PDG code **pdgN**. Effects of interaction with Sun/Earth medium as well as neutrino oscillation are taken into account [38]. **outN** should be chosen 1 for muon neutrino and -1 for anti-neutrino. The resulting spectrum is stored in the array **nu** with  $NZ=250$  elements which can be checked by the **SpectdNdE(E,nu)** function.

The files `main.c/F` in the directory `mdlIndep` contain an example of the calculation of the direct detection, indirect detection and neutrino telescope signals using the routines described in this section. The numerical input data in this sample file corresponds to 'MSSM/mssmh.dat'.

## 11 Additional routines for specific models

The models included in `micrOMEGAs` contain some specific routines which we describe here for the sake of completeness. The current distribution includes the following models: `MSSM`, `NMSSM`, `CPVMSSM`, `LHM`(little Higgs model) and `RHNM` (a Right-handed Neutrino model).

Each model contains a special routine for reading input parameters:

- `readVarMSSM`, `readVarNMSSM`, `readVarCPVMSSM`, `readVarlHiggs`, `readVarRHNM`.

These routines are similar to the general `readVar` routine described in Section 4 but they write a warning when a parameter is not found in the input file and display the default values for these parameters.

The supersymmetric models contain several additional routines to calculate the spectrum and compute various constraints on the parameter space of the models. Some functions are common to the `MSSM`, `NMSSM`, `CPVMSSM` models:

- `o1Contents(FD)`

prints the neutralino LSP components as the  $\tilde{B}, \tilde{W}, \tilde{h}_1, \tilde{h}_2$  fractions. For the `NMSSM` the fifth component is the singlino fraction  $\tilde{S}$ . The sum of the squares of the LSP components should add up to 1.

### 11.1 MSSM

The `MSSM` has a long list of low scale independent model parameters, those are specified in the SLHA [17, 13]. They are directly implemented as parameters of the model of particle interaction. The names of these parameters are presented in `MSSM/mssm[1/2].par` files. For **EWSB** scenario namely these parameters are treated as input. The user can assign new values to these parameters by means of `assignVal` procedure or `readVarMSSM` one.

- `spectEwsbMSSM()`

calculates the masses of Higgs and supersymmetric particles in the `MSSM` including one-loop corrections starting from weak scale input parameters.

In these functions *spect* stands for one of the spectrum calculators `suspect`, `isajet`, `spheno`, or `softSusy`. The default spectrum calculator package is `SuSpect`. To work with another package one has to specify the appropriate path in `MSSM/lib/Makefile`. For this the environment variables `ISAJET`, `SPHENO` or `SOFTSUSY` must be redefined accordingly. Note that we also provide a special interface for `ISAJET` to read a SLHA file. This means that the user must first compile the executable `isajet_slha` which sets up the SLHA interface in `ISAJET`. Specific instructions are provided in the `README` file.

For other `MSSM` scenarios parameters at EWSB scale are calculated using high scale input. The same packages `suspect`, `isajet`, `spheno`, or `softSusy` are used for this job. The corresponding routines are:

- `spectSUGRA(tb, MG1, MG2, MG3, A1, At, Ab, signMu, MHu, MHd, M11, M13, Mr1, Mr3, Mq1, Mq3,`

`Mu1,Mu3,Md1,Md3)`

treats all input parameters except `tb` and `signMu` as ones defined at GUT scale. In particular MSUGRA scenario can be realized by this manner.

- `spectSUGRAnuh(tb, MG1, MG2, MG3, A1, At, Ab, M11, M13, Mr1, Mr3, Mq1, Mq3, Mu1, Mu3, Md1, Md3, mu, MA)`

realizes SUGRA scenario with non universal Higgs parameters. Here instead `Mhu`, `MHd` parameters which defines Higgs potential at GUT scale we use the `mu` parameter defined at EWSB scale and pole mass of CP-even Higgs. The `signMu` parameter is omitted because `mu` is defined explicitly.

- `spectAMSB(am0, m32, tb, sng)`.

does the same as above within the `AMSB` model.

We have an option to directly read a SLHA input file, this uses the function

- `lesHinput(file_name)`

which returns non-zero number in case of problem.

The routines for computing constraints are (see details in [2]).

- `deltarho()`

calculates the  $\Delta\rho$  parameter which describes the MSSM corrections to electroweak observables. It contains stop/sbottom contributions, as well as the two-loop QCD corrections due to gluon exchange and the correction due to gluino exchange in the heavy gluino limit.

- `bsgnlo(&SMbsg)`

returns the value of the branching ratio for  $b \rightarrow s\gamma$ , see Appendix A. We have included some new contributions beyond the leading order that are especially important for high  $\tan\beta$ . `SMbsg` gives the SM contribution.

- `bsmumu()`

returns the value of the branching ratio  $B_s \rightarrow \mu^+\mu^-$  in the MSSM. It includes the loop contributions due to chargino, sneutrino, stop and Higgs exchange. The  $\Delta m_b$  effect relevant for high  $\tan\beta$  is taken into account.

- `btaunu()`

computes the ratio between the MSSM and SM branching fractions for  $\bar{B}^+ \rightarrow \tau^+\nu_\tau$ .

- `gmuon()`

returns the value of the supersymmetric contribution to the anomalous magnetic moment of the muon.

- `R123()`

computes the ratio of the MSSM to SM value for  $R_{123}$  in  $K^+ \rightarrow \mu\nu$  due to a charged higgs contribution, see Eq.70 in [6].

- `dtaunu(&dmmunu)`

computes the branching ratio for  $D_s^+ \rightarrow \tau^+\nu_\tau$ . `dmmunu` gives the branching ratio for  $D_s^+ \rightarrow \mu^+\nu_\mu$

- `masslimits()`

returns a positive value and prints a WARNING when the choice of parameters conflicts with a direct accelerator limits on sparticle masses from LEP. The constraint on the light Higgs mass from the LHC is included.

We have added a routine for an interface with `superIso` [31]. This code is not included in micrOMEGAs so one has first to define the global environment variable `superIso` to specify the path to the package.

- **callSuperIsoSLHA()**

launches superIso and downloads the SLHA file which contains the results. The return value is zero when the program was executed successfully. Results for specific observables can be obtained by the command **slhaValFormat** described in section (12.5). Both **superIso** and **callSuperIsoSLHA** use a file interface to exchange data. The **delFiles** flag specifies whether to save or delete the intermediate files.

- **loopGamma(&vcs\_gz,&vcs\_gg)**

calculates  $\sigma v$  for loop induced processes of neutralino annihilation into  $\gamma Z$  and into  $\gamma\gamma$ . The result is given in  $\frac{cm^3}{s}$ . In case of problem the function returns a non-zero value.

## 11.2 The NMSSM

As in the MSSM there are specific routines to compute the parameters of the model as specified in SLHA. The spectrum calculator is **NMSPEC** [22] in the **NMSSMTools\_4.0** package [28].

- **nmssmEWSB(void)**

calculates the masses of Higgs and supersymmetric particles in the NMSSM starting from weak scale input parameters which can be downloaded by the **readVarNMSSM** routine. [23]

- **nmssmSUGRA(m0,mhf,a0,tb,sgn,Lambda,aLambda,aKappa)**

calculates the parameters of the NMSSM starting from the input parameters of the **CNMSSM**.

The routines for computing constraints are taken from **NMSSMTools** (see details in [3]).

- **bsgnlo(&M,&P), bsmumu(&M,&P), btaunu(&M,&P), gmuon(&M,&P)**

are the same as in the MSSM case. Here the output parameters **M** and **P** give information on the lower/upper experimental limits [24]

- **deltaMd(),deltaMs()**

compute the supersymmetric contribution to the  $B_{d,s}^0 - \overline{B}_{d,s}^0$  mass differences,  $\Delta M_d$  and  $\Delta M_s$ .

- **NMHwarn(FD)**

is similar to **masslimits\_** except that it also checks the constraints on the Higgs masses, returns the number of warnings and writes down warnings in the file **FD**.

- **loopGamma(&vcs\_gz,&vcs\_gg)**

calculates  $\sigma v$  for loop induced processes of neutralino annihilation into  $\gamma Z$  and into  $\gamma\gamma$ . The result is given in  $\frac{cm^3}{s}$ . In case of problem the function returns a non-zero value.

## 11.3 The CPVMSSM

The independent parameters of the model include in addition to some standard model parameters only the weak scale soft SUSY parameters. The independent parameters are listed in **CPVMSSM/work/models/vars1.md1**. Masses, mixing matrices and parameters of the effective potential are read directly from **CPsuperH** [25, 26], together with masses and mixing matrices of neutralinos, charginos and third generation sfermions. On the other hand, masses of the first two generations of sfermions are evaluated (at tree-level) within **micrOMEGAs** in terms of the independent parameters of the model.

The routines for computing constraints are taken from **CPsuperH**, [27]



- `bsgnlo()`, `bsmumu()`, `btaunu()`, `gmuon()`

are the same as in the MSSM case.

- `deltaMd()`, `deltaMs()`

are the same as in the NMSSM case.

- `Bd11()`

computes the supersymmetric contribution to the branching fractions for  $B_d \rightarrow \tau^+ \tau^-$  in the CPVMSSM.

- `ABsg()`

computes the supersymmetric contribution to the asymmetry for  $B \rightarrow X_s \gamma$ .

- `EDMe1()`, `EDMmu()`, `EDMT1()`

return the value of the electric dipole moment of the electron,  $d_e$ , the muon,  $d_\mu$ , and of Thallium,  $d_{Tl}$  in units of  $ecm$ .

## 12 Tools for new model implementation.

It is possible to implement a new particle physics model in `micrOMEGAs`. For this the model must be specified in the CalcHEP format. `micrOMEGAs` then relies on CalcHEP to generate the libraries for all matrix elements entering DM calculations. Below we describe the main steps and tools for implementing a new model.

### 12.1 Main steps

- The command `./newProject MODEL` launched from the root `micrOMEGAs` directory creates the directory `MODEL`. This directory and the subdirectories contain all files needed to run `micrOMEGAs` with the exception of the new model files.
- The new model files in the CalcHEP format should then be included in the subdirectory `MODEL/work/models`. The files needed are `vars1.mdl`, `func1.mdl`, `prtcls1.mdl`, `lgrng1.mdl`, `extlib1.mdl`. For more details on the format and content of model files see [18].
- For odd particles and for the Higgs sector it is recommended to use automatic width calculation with CalcHEP/`micrOMEGAs`. For this one has to add the `'!`' symbol before the definition of the particle's width in the file `prtcls1.mdl`, for example

Full name	P	aP	PDG	2*spin	mass	width	color
Higgs 1	h1	h1	25	0	Mh1	!wh1	1

- Some models contain external functions, if this is the case they have to be compiled and stored in the `MODEL/lib/aLib.a` library. These functions should be written in C and both functions and their arguments have to be of type `double`. The library `aLib.a` can also contain some functions which are called directly from



the *main* program. The *MODEL/Makefile* automatically launches `make` in the `lib` directory and compiles the external functions provided the prototypes of these external functions are specified in *MODEL/lib/pmodel.h*. The user can of course rewrite his own `lib/Makefile` if needed be.

If the new `aLib.a` library needs some other libraries, their names should be added to the *SSS* variable defined in *MODEL/Makefile*.

The *MODEL* directory contains both C and FORTRAN samples of *main* routines. In these sample main programs it is assumed that input parameters are provided in a separate file. In this case the program can be launched with the command:

```
./main data1.par
```

Note that for the direct detection module all quarks must be massive. However the cross sections do not depend significantly on the exact numerical values for the masses of light quarks.

## 12.2 Automatic width calculation

Automatic width calculation can be implemented by inserting the `'!'` symbol before the name of the particle width in the CalcHEP particle table (file `prtcls1.mdl`). In this case the width parameter should not be defined as a free or constrained parameter. Actually the `pWidth` function described in section 9 is used for width calculation in this case. We recommend to use the automatic width calculation for all particles from the 'odd' sector and for Higgs particles. For models which use SLHA parameter transfer (Section 12.5), the automatic width option will use the widths contained in the SLHA file unless the user chooses the option to ignore this data in the SLHA file see section 12.5.

## 12.3 Using LanHEP for model file generation.

For complicated models such as the MSSM, it is more convenient to use an automatic tool to implement the model. LanHEP is a tool for Feynman rules generation. A few minor modifications to the default format of LanHEP have to be taken into account to get the model files into the `micrOMEGAS` format.

- The `lhcp` command has to be launched with the `-evl 2` flag

```
lhcp source_file -evl 2
```

Such a flag provides the correct level of optimization for the model's Feynman rules.

- The default format for the file `prtcls1.mdl` which specifies the particle content has to be modified to include a column containing the PDG code of particles. For this, first add the following command in the LanHEP source code, before specifying the particles

```
prtcf format fullname:
'Full Name ', name:' P ', aname:' aP', pdg:' number ',
spin2,mass,width, color, aux, texname: '> LaTeX(A) <',
atexname:'> LateX(A+) <' .
```

Then for each particle define the PDG code. For instance:

```
vector 'W+'/'W-': ('W boson', pdg 24, mass MW, width wW).
```

- LanHEP does not generate the file `extlib1.mdl`. `micrOMEGAs` works without this file but it is required for a `CalcHEP` interactive session. The role of this file is to provide the linker with the paths to all user's libraries needed at compilation. For example for the `lib/aLib.a` library define

```
$CALCHEP/./MODEL/lib/aLib.a
```

For examples see the `extlib1.mdl` files in the directory of the models provided.

## 12.4 QCD functions

Here we describe some QCD functions which can be useful for model construction.

- `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,  $\alpha_s(M_Z)$ , the 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 [21]. 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.

- `MtEff(Q)`, `MbEff(Q)`, `McEff(Q)`,

calculates effective top, bottom and charm quark masses using [21]

$$\begin{aligned} M_{eff}^2(Q) &= M(Q)^2 [1 + 5.67a + (35.94 - 1.36n_f)a^2 \\ &+ (164.14 - n_f(25.77 - 0.259n_f))a^3] \end{aligned} \quad (6)$$

where  $a = \alpha_s(Q)/\pi$ ,  $M(Q)$  and  $\alpha_s(Q)$  are the quark masses and running strong coupling in the  $\overline{MS}$ -scheme. In `micrOMEGAs`, we use the effective quark masses calculated at the scale  $Q = 2\text{Mcdm}$ . In some special cases one needs a precise treatment of the masses of light quarks. The function

- `MqRun(M2GeV, Q)`

returns the running quark mass defined at the scale 2 GeV. The corresponding effective mass needed for higgs decay width is presented by

- `Mqeff(M2GeV, Q)`

## 12.5 SLHA reader

Very often calculation of particle spectra for specific models is done by some external program which writes down the particle masses, mixing angles and other model parameters in a file with the so-called **SLHA** format [17, 13]. The `micrOMEGAs` package contains routines for reading files in the SLHA format. Such routines can be very useful for new model implementation.

In general a SLHA file contains several pieces of information which are called blocks. A block is characterized by its name and, sometimes, by its energy scale. Each block contains the values of several physical parameters characterized by a *key*. The key consists in a sequence of integer numbers. For example:

```
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
```

- `slhaRead(filename,mode)`

downloads 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` where

```
m1 = 0/1 -   overwrites all/keeps old data
m2 = 0/1 -   read DECAY /do not read   DECAY
m4 = 0/1 -   read BLOCK/do not read   BLOCK
```

For example `mode=2` (`m1=0,m2=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=3` is an instruction to add information from DECAY to the data obtained previously. `slhaRead` returns the values:

```
0 - successful reading
-1 - can not open file
-2 - error in spectrum calculator
-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 `Zn12` 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 with respect to  $\log(Q)$  to evaluate the returned values.

Recently it was proposed to use an extension of the SLHA interface to transfer Flavour Physics data [30]. Unfortunately the structure of the new blocks is such that they cannot be read with the `slhaVal` routine. We have added two new routines for reading such data

- `slhaValFormat(BlockName, Q, format)`

where the *format* string allows to specify data which one would like to extract from the given block `BlockName`. For instance, to get the  $b \rightarrow s\gamma$  branching ratio from the block

Block FOBS # Flavour observables

```
# ParentPDG type value      q   NDA ID1 ID2 ID3 ... comment
    5      1  2.95061156e-04  0    2   3  22      # BR(b->s gamma)
   521     4  8.35442304e-02  0    2 313  22      # Delta0(B->K* gamma)
   531     1  3.24270419e-09  0    2  13 -13      # BR(B_s->mu+ mu-)
...
```

one has to use the command `slhaValFormat("FOBS", 0., "5 1 %E 0 2 3 22")`. In this command the *format* string is specified in C-style. The same routine can be used to read HiggsBound SLHA output.

A block can also contain a textual information. For example, in HIGGSBOUNDS a block contains the following records,

Block HiggsBoundsResults

```
#CHANNELTYPE 1: channel with the highest statistical sensitivity
  1          1          328          # channel id number
  1          2           1          # HBresult
  1          3  0.72692779334500290  # obsratio
  1          4           1          # ncombined
  1          5 ||(p p)->h+..., h=1 where h is SM-like (CMS-PAS-HIG-12-008)|| # text description of channel
```

In particular, the last record contains the name of the channel which gives the strongest constraint on the Higgs. To extract the name of this channel one can use the new function

- `slhaSTRFormat("HiggsBoundsResults", "1 5 || %[~|]||", channel);`

which will write the channel name in text parameter *channel*.

- `slhaWarnings(fileName)`

writes into the file 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.

The SUSY Les Houches Accord also describes the format of the information given on particle decay widths. Even though `micrOMEGAs` also performs the width calculation, one might choose to read the information from the SLHA file.

- `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 particle width.

- `slhaBranch(pNum, N, nCh)`

returns the branching ratio of particle `pNum` into the `N`-th decay channel. Here  $0 < N \leq \text{slhaDecayExists}(pNum)$ . 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, see an example in `MSSM/calchep/models/func2.mdl`. Note that in this example the call to `slhaRead` is done within the function `suspectSUGRAc`.

### 12.5.1 Writing an SLHA input file

We have included in the `micrOMEGAS` package some routines which allow to write an SLHA input file and launch the spectrum generator via the CalcHEP *constraints* menu. This way a new model can be implemented without the use of external libraries. The routines are called from `func1.mdl`, see example below.

- `openAppend(fileName)`

deletes the input file `fileName` and stores its name. This file will then be filled 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(command, ...)` generates a command line which is launched by the standard `system` C-function. The parameter *command* works here like a format string and can contain `%s`, `%d` elements. These are replaced by the next parameters of the `System` call.

For example to write directly the SLHA model file needed by `SuSpect` to compute the spectrum in a CMSSM(SUGRA) model, one needs to add the following sequence in the `func1.mdl` model file.

```
open |openAppend("suspect2_lha.in")
input1|aPrintF("Block MODSEL # Select model\n 1 1 # SUGRA\n")
input2|aPrintF("Block SMINPUTS\n 5 %E#mb(mb)\n 6 %E#mt(pole)\n",MbMb,Mtp)
input3|aPrintF("BLOCK MINPAR\n 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("./suspect2.exe")
rd |slhaRead("suspect2_lha.out",0)
```

It is possible to cancel the execution of a program launched with `System` if it runs for too long. For this we have introduced two global parameters `sysTimeLim` and `sysTimeQuant`. `sysTimeLim` sets a time limit in milliseconds for `System` execution, if `sysTimeLim==0` (the default value) the execution time is not checked. The time interval between checks of the status of the program launched with `System` is specified by the parameter `sysTimeQuant`, the default value is set to 10. Note that it is preferable not too use too large a value for `sysTimeQuant` as it defines the lower time limit for a system call.

In Fortran use call `setSysTimeLim(sysTimeLim,sysTimeQuant)` to reset default time control parameters.

The function prototypes are available in  
`CalcHEP_src/c_source/SLHAplus/include/SLHAplus.h`

## 12.6 Routines for diagonalisation.

Very often in a new model one has to diagonalize mass matrices. Here we present some numerical routines for diagonalizing matrices. Our code is based on the `jacobi` routine provided in [29]. To use the same routine for a matrix of arbitrary size, we use a C option that allows to write routines with an arbitrary number of arguments.

- `initDiagonal()` should be called once before any other `rDiagonal(A)` routines described below. `initDiagonal()` assigns zero value to the internal counter of eigenvalues and rotation matrices. Returns zero.

- `rDiagonal(d,M11,M12,...M1d,M22,M23...Mdd)`

diagonalizes a symmetric matrix of dimension `d`. The  $d(d+1)/2$  matrix elements, `Mij` ( $i \leq j$ ), are given as arguments. The function returns an integer number `id` which serves as an identifier of eigenvalues vector and rotation matrix.

- `MassArray(id, i)`

returns the eigenvalues  $m_i$  ordered according to their absolute values.

- `MixMatrix(id,i,j)`

returns the rotation matrix  $R_{ij}$  where

$$M_{ij} = \sum_k R_{ki} m_k R_{kj}$$

A non-symmetric matrix, for example the chargino mass matrix in the MSSM, is diagonalized by two rotation matrices,

$$M_{ij} = \sum_k U_{ki} m_k V_{kj}.$$

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

diagonalizes a non-symmetric matrix, the  $d^2$  matrix elements, `Mij`, are given as arguments. The eigenvalues and the  $V$  rotation matrix are calculated as above with `MassArray` and `MixMatrix`.

- `MixMatrixU(id,i,j)`

returns the rotation matrix  $U_{ij}$ .

The function prototypes can be found in

`CalcHEP_src/c_source/SLHAplus/include/SLHAplus.h`

## 13 Mathematical tools.

Some mathematical tools used by `micrOMEGAs` are available only in C format. Prototypes of these functions can be found in

`sources/micromegas_aux.h`

- **simpson(F, x1, x2, eps)**

numerical integration of function  $F(x)$  in the interval  $[x1, x2]$  with relative precision  $eps$ . **simpson** uses an adaptive algorithm for integrand evaluation and increases the number of function calls in the regions where the integrand has peaks.

- **gauss(F, x1, x2, N)**

performs Gauss N-point integration for  $N < 8$ .

- **odeint(Y, Dim, x1, x2, eps, h1, deriv)**

solves a system of  $Dim$  differential equations in the interval  $[x1, x2]$ . The array  $Y$  contains starting variables at  $x1$  as an input and resulting values at  $x2$  as an output.  $eps$  determines the precision of the calculation and  $h1$  gives an estimation of step of calculation. The function  $deriv$  calculates  $Y'_i = dY_i/dx$  with the call  $deriv(x, Y, Y')$ . The Runge-Kutta method is used, see details in [29].

- **buildInterpolation(F, x1, x2, eps, &Dim, &X, &Y)**

constructs a cubic interpolation of the function  $F$  in the interval  $[x1, x2]$ .  $eps$  controls the precision of interpolation. If  $eps < 0$  the absolute precision is fixed, otherwise a relative precision is required. The function checks that after removing any grid point, the function at that point can be reproduced with a precision  $eps$  using only the other points. It means that the expected precision of interpolation is about  $eps/16$ .  $Dim$  gives the number of points in the constructed grid.  $X$  and  $Y$  are variables of the **double\*** type. The function allocates memory for  $Dim$  array for each of these parameters.  $X[i]$  contains the x-grid while  $Y[i] = F(X[i])$ .

- **polint4(x, Dim, X, Y)**

performs cubic interpolation for  $Dim$ -dimension arrays  $X, Y$ . A similar function, **polint3**, performs quadratic interpolation.

- **bessk0(x)**

The Bessel function of zero order of second kind.

- **displayFunc(F, x1, x2, title)**

displays a plot of function  $F(x)$  in the  $[x1, x2]$  interval. **title** is a text which appears as the title of the plot.

- **displayFunc10(F, x1, x2, title)**

displays  $F(10^x)$ .

## A An updated routine for $b \rightarrow s\gamma$ in the MSSM

The calculation of  $b \rightarrow s\gamma$  was described in micromegas1.3 [2]. The branching fraction reads

$$B(\bar{B} \rightarrow X_s \gamma) = B(\bar{B} \rightarrow X_c e \bar{\nu}) \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha_{em}}{\pi f(z_0)} K_{NLO}(\delta) \quad (7)$$

where  $\alpha_{em} = 1./137.036$ , the factor  $K_{NLO}$  involves the photon energy cut-off parameter  $\delta$  and  $f(z_0) = 0.542 - 2.23(\sqrt{z_0} - 0.29)$  depends on  $z_0 = (m_c/m_b)^2$  defined in terms of pole masses. In the code the standard model and Higgs contribution at NLO were included as well as the leading order SUSY contributions. However in the last few years the NNLO standard model contribution has been computed [32] and shown to lead to large corrections, shifting the standard model value by over 10%. It was also argued that the NNLO SM result could be reproduced from the NLO calculation by appropriately choosing the scale for the c-quark mass [33, 34].



$B(\bar{B} \rightarrow X_c e \bar{\nu})$	0.1064 [36]
$C_{sl}$	0.546 [34]
$ V_{ts}^* V_{tb}/V_{cb} ^2$	0.9613 [36]
$A$	0.808
$\lambda$	0.2253
$\bar{\rho}$	0.132
$\bar{\eta}$	0.341
$m_b/m_s$	50
$\lambda_2 \approx \frac{1}{4}(m_{B^*}^2 - m_B^2)$	0.12 GeV <sup>2</sup> [35]
$\alpha_s(M_Z)$	0.1189

Table 3: Default values in micrOMEGAs

In this improved version of the `bsgnlo` routine, we have changed the default value for the parameter  $z_1 = (m_c/m_b)^2$  where  $m_c$  is the  $\overline{MS}$  running charm mass  $m_c(m_b)$ . Taking  $z_1 = 0.29$  allows to reproduce the NNLO result. It is therefore no longer necessary to apply a shift to the micromegas output of  $b \rightarrow s\gamma$  to reproduce the SM value.

We have also updated the default values for the experimentally determined quantities in Eq. 7, see Table A, and we have replaced the factor  $f(z_0)$  by  $C_{sl}$  where

$$C_{sl} = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma(\bar{B} \rightarrow X_c e \bar{\nu})}{\Gamma(\bar{B} \rightarrow X_u e \bar{\nu})} \quad (8)$$

accounts for the  $m_c$  dependence in  $\bar{B} \rightarrow X_c e \bar{\nu}$ .

The CKM matrix elements in the Wolfenstein parametrisation given in Table A are used to compute the central value of  $ckmf$  with at order  $\lambda^4$ ,

$$ckmf = \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 = 1 + \lambda^2(2\bar{\rho} - 1) + \lambda^4(\bar{\rho}^2 + \bar{\eta}^2 - A^2) \quad (9)$$

With these default values the NLO- improved SM contribution is  $B(\bar{B} \rightarrow X_s \gamma)|_{\text{SM}} = 3.27 \times 10^{-4}$  which corresponds to the result of Gambino and Giordano [34] after correcting for the slightly different CKM parameter used ( $ckmf = 0.963$ ).

We have performed a comparison with superIso3.1 which includes the NNLO SM calculation for  $10^5$  randomly generated MSSM scenarios. The results are presented in Fig. A after applying a correction factor in superISO to account for the different value for the overall factor  $F = B(\bar{B} \rightarrow X_c e \bar{\nu}) \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 / C_{sl}$ . The ratio of  $F_{\text{micro}}/F_{\text{ISO}} = 0.942$ . The two codes agree within 5% most of the time.

## References

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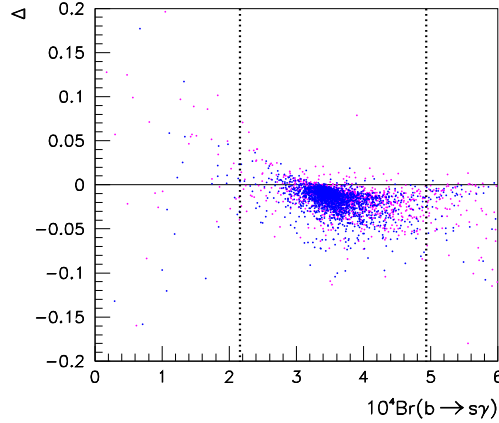


Figure 1: Relative difference for  $B(\bar{B} \rightarrow s\gamma)$  between micromegas2.4 and superIso3.1. the vertical lines show the  $3\sigma$  experimentally measured value.

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