

# The micrOMEGAs user's manual, version 5.3.34

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## Abstract

We give an up-to-date description of the **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.

## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>Discrete symmetry in micrOMEGAs</b>	<b>3</b>
<b>3</b>	<b>Downloading and compilation of micrOMEGAs</b>	<b>4</b>
3.1	File structure of <b>micrOMEGAs</b> . . . . .	4
3.2	Compilation of <b>CalcHEP</b> and <b>micrOMEGAs</b> routines . . . . .	5
3.3	External packages . . . . .	6
3.4	Module structure of main programs . . . . .	6
3.5	Compilation of codes for specific models . . . . .	7
3.6	Command line parameters of main programs . . . . .	8
<b>4</b>	<b>Global Parameters and constants</b>	<b>8</b>
<b>5</b>	<b>Setting of model parameters, spectrum calculation, parameter display</b>	<b>9</b>
<b>6</b>	<b>Relic density calculation</b>	<b>12</b>
6.1	Switches and auxilary routines . . . . .	12
6.2	Calculation of relic density for one-component Dark Matter models . . . . .	13
6.3	Calculation of relic density for two-component Dark Matter models . . . . .	16
6.4	Calculation of relic density for freeze-in . . . . .	17
6.5	Calculation of relic density for cospattering . . . . .	20

<b>7</b>	<b>Direct detection</b>	<b>22</b>
7.1	Amplitudes for elastic scattering . . . . .	22
7.2	Scattering on nuclei . . . . .	23
7.2.1	Nucleus form factors . . . . .	24
7.2.2	Velocity distribution . . . . .	25
7.3	Comparison with Direct Detection experiments . . . . .	27
7.3.1	Experimental data . . . . .	27
7.3.2	Recasting the experimental limits with micrOMEGAs . . . . .	27
7.3.3	Setting spin-dependent form factors . . . . .	28
<b>8</b>	<b>Indirect detection</b>	<b>29</b>
8.1	Interpolation and display of spectra . . . . .	29
8.2	Annihilation spectra . . . . .	29
8.3	Distribution of Dark Matter in Galaxy . . . . .	30
8.4	Photon signal . . . . .	31
8.5	Propagation of charged particles . . . . .	32
<b>9</b>	<b>Neutrino signal from the Sun and the Earth</b>	<b>33</b>
9.1	Comparison with IceCube results . . . . .	34
<b>10</b>	<b>Cross sections and decays</b>	<b>34</b>
<b>11</b>	<b>Tools for model independent analysis</b>	<b>37</b>
<b>12</b>	<b>Constraints from colliders</b>	<b>39</b>
12.1	The Higgs sector . . . . .	39
12.1.1	Lilith . . . . .	39
12.1.2	HiggsBounds and HiggsSignals . . . . .	40
12.1.3	Automatic generation of interface files . . . . .	41
12.2	Searches for New particles . . . . .	42
12.2.1	SModelS . . . . .	42
12.2.2	Other limits . . . . .	44
<b>13</b>	<b>Additional routines for specific models</b>	<b>45</b>
13.1	The MSSM . . . . .	45
13.2	The NMSSM . . . . .	47
13.3	The CPVMSSM . . . . .	48
13.4	The UMSSM . . . . .	48
<b>14</b>	<b>Tools for new model implementation</b>	<b>49</b>
14.1	Main steps . . . . .	49
14.2	Automatic width calculation . . . . .	50
14.3	Using LanHEP for model file generation . . . . .	50
14.4	QCD functions . . . . .	51
14.5	SLHA reader . . . . .	52
14.5.1	Writing an SLHA input file . . . . .	54
14.6	Routines for diagonalisation . . . . .	55

<b>15 Mathematical tools</b>	<b>56</b>
15.1 Integration . . . . .	56
15.2 Solution of differential equations. . . . .	57
15.3 Interpolation . . . . .	58
15.4 Functions with additional parameters . . . . .	58
15.5 Plots . . . . .	58
15.6 Bessel functions . . . . .	59
15.7 Statistics . . . . .	59
<b>A An updated routine for <math>b \rightarrow s\gamma</math> in the MSSM</b>	<b>59</b>

## 1 Introduction

`micrOMEGAs` is a code to calculate the properties of cold dark matter (CDM) 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. `micrOMEGAs` computes CDM properties in the framework of a model of particle interactions presented in `CalcHEP` format [1]. It is assumed that the model is invariant under a discrete symmetry like R-parity (even for all standard particles and odd for some new particles including the dark matter candidate) which ensures the stability of the lightest odd particle. Similarly in two-component dark matter models, a discrete symmetry that guarantees the stability of the lightest particle in each of the two dark matter sectors is assumed. The `CalcHEP` package is included in `micrOMEGAs` and used for matrix elements calculations. 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 methods used to compute the different dark matter properties are described in references [2–10]. These references also contain a more complete description of the code. In the following the cold dark matter candidate also called weakly-interactive massive particle (WIMP) will be denoted by  $\chi$ . Starting with version 5.0, `micrOMEGAs` also allows to compute the abundance of feebly interacting dark matter candidates (FIMP) through the freeze-in mechanism [10]

`micrOMEGAs` is written in C and uses some Fortran routines mostly in external packages. The complete format for all functions can be found in `include/.h` (for C). Examples on how to use these functions are provided in the `MSSM/main.c` file.

## 2 Discrete symmetry in `micrOMEGAs`

`micrOMEGAs` exploits the fact that models of dark matter exhibit a discrete symmetry and that the fields of the model transform as  $\phi \rightarrow e^{i2\pi X_\phi} \phi$  where the charge  $|X_\phi| < 1$ . The particles of the Standard Model are assumed to transform trivially under the discrete symmetry,  $X_\phi = 0$ . In the following all particles with charge  $X_\phi \neq 0$  will be called *odd* and the lightest odd particle will be stable. If neutral, it can be considered as a DM candidate. Typical examples of discrete symmetries used for constructing single DM models are  $Z_2$  and  $Z_3$ . Multi-component DM can arise in models with larger discrete groups. A simple example is a model with  $Z_2 \times Z'_2$  symmetry, the particles charged under  $Z_2(Z'_2)$  will belong to the first (second) dark sector. The lightest particle of each sector will be stable and

therefore a potential DM candidate. Another example is a model with a  $Z_4$  symmetry. The two dark sectors contain particles with  $X_\phi = \pm 1/4$  and  $X_\phi = 1/2$  respectively. The lightest particle with charge  $1/4$  is always stable while the lightest particle of charge  $1/2$  is stable only if its decay into two particles of charge  $1/4$  is kinematically forbidden. **micrOMEGAs** assumes that all odd particles have names starting with '~', for example, ~o1 for the lightest neutralino. In versions 4.X, to distinguish the particles with different transformation properties with respect to the discrete group, that is particles belonging to different 'dark' sectors, we use the convention that the names of particles in the second 'dark' sector starts with '~~'. Note that **micrOMEGAs** does not check the symmetry of the Lagrangian, it assumes that the name convention correctly identifies all particles with the same discrete symmetry quantum numbers. For models with FIMPs, new particles are considered to be in thermal equilibrium with the SM bath ( $\mathcal{B}$ ) unless explicitly defined as being feeble, ie belonging to  $\mathcal{F}$ . Both  $\mathcal{B}$  and  $\mathcal{F}$  can contain odd or even particles.

### 3 Downloading and compilation of micrOMEGAs

To download **micrOMEGAs**, go to

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

and unpack the file received, **micromegas\_5.3.34.tgz**, with the command

```
tar -xvzf micromegas_5.3.34.tgz
```

This should create the directory **micromegas\_5.3.34/** which occupies about 67Mb 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)

#### 3.1 File structure of micrOMEGAs

<b>calc</b>	calculator
<b>calchep.ini</b>	specify the fonts for graphics in CalcHEP
<b>Makefile</b>	to compile the kernel of the package
<b>README</b>	short description on how to run the code
<b>CalcHEP_src/</b>	generator of matrix elements for <b>micrOMEGAs</b>
<b>Packages/</b>	external codes
<b>clean</b>	to remove compiled files
<b>man/</b>	contains the manual: description of <b>micrOMEGAs</b> routines
<b>newProject</b>	to create a new model directory structure
<b>sources/</b>	<b>micrOMEGAs</b> code
<b>include/</b>	include files for <b>micrOMEGAs</b> routines or external codes
<b>lib/</b>	contains library <b>micromegas.a</b> when <b>micrOMEGAs</b> is compiled
<i>MSSM model directory</i>	
<b>MSSM/</b>	
<b>Makefile</b>	to compile the code and executable for this model
<b>main.c[pp]</b>	files with sample <i>main</i> programs
<b>lib/</b>	directory for routines specific to this model
<b>Makefile</b>	to compile the auxiliary code library <i>lib/aLib.a</i>

<code>*.c *.f *.h</code>	source codes of auxiliary functions
<code>work/</code>	CalcHEP working directory for the generation of matrix elements
<code>Makefile</code>	to compile the library <code>work/work_aux.a</code>
<code>calchep</code>	Executable for CalcHEP
<code>lanhep/</code>	directory containing lanhep source model files
<code>models/</code>	directory for files which specifies the model files <code>*1.mdl</code> are used in micrOMEGAs sessions. Other <code>*.mdl</code> files are intended for CalcHEP interactive sessions
<code>vars1.mdl</code>	free variables
<code>func1.mdl</code>	constrained variables
<code>prtcls1.mdl</code>	particles
<code>lgrng1.mdl</code>	Feynman rules
<code>results/</code>	
<code>so_generated/</code>	storage of matrix elements generated by CalcHEP
<i>Directories of other models which have the same structure as MSSM/</i>	
<code>NMSSM/</code>	Next-to-Minimal Supersymmetric Model [11, 12]
<code>CPVMSSM/</code>	MSSM with complex parameters [13, 14]
<code>IDM/</code>	Inert Doublet Model [15]
<code>LLL_scalar/</code>	Simplified model with singlet charged lepton and real scalar DM
<code>LHM/</code>	Little Higgs Model [16]
<code>RDM/</code>	Scalar Leptoquark and two singlet fermions [17]
<code>SingletDM/</code>	Singlet scalar DM model with $Z_2$ symmetry [18]
<code>STFM/</code>	Singlet-triplet fermionic model
<code>Z3IDM/</code>	Inert doublet model with $Z_3$ discrete symmetry [19, 20]
<code>Z4IDSM/</code>	Inert doublet and singlet model with $Z_4$ symmetry [19, 20]
<code>Z5M/</code>	Two scalar singlets model with $Z_5$ symmetry [21]
<code>ZpPortal/</code>	Simplified model with a $Z'$ portal and fermion DM
<code>mdlIndep/</code>	For model independent computation of DM signals

Other models can be downloaded on the web, <http://lapth.cnrs.fr/micromegas>, for example : `RHNM`, a right-handed Neutrino Model [22], `SM4`, a toy model with a 4th generation of leptons and neutrino DM, `UMSSM`, an  $U(1)$  extension of the MSSM [23, 24].

### 3.2 Compilation of CalcHEP and micrOMEGAs routines

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

```
gmake
```

If `gmake` is not available, 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 contains 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.

### 3.3 External packages

**micrOMEGAs** is interfaced with a number of external packages, some of which are directly included in the **micrOMEGAs** distributions and some which are downloaded automatically upon request. All these external codes are stored in the directory */Packages*.

The packages included in the **micrOMEGAs** distribution are the **Suspect2.41** [25], **NMSSMTools5.6.0** [26,27], and **CPsuperH2.3** [13,28] spectrum calculators for the MSSM, NMSSM, and CPVMSSM, respectively; **LoopTools** [29] for computing some loop-induced processes and **LanHEP** [30] for generating model files.

Automatically downloaded packages are : the SUSY spectrum generators **SOFT-SUSY** [31] and **SPheno** [32]; **superIso** [33] for flavor constraints; the codes **HiggsBounds** [34,35] and **HiggsSignals** [36,37] for checking Higgs-sector constraints; as well as **Lilith-2.1** [38–40] for checking Higgs signal strengths; and **SModels** [41–44] for simplified-model constraints from LHC searches.

The versions of the codes to be downloaded can be defined by the user via the parameter **VERSION** in the corresponding files:

```

include/SModels.inc,      include/hBandS.inc,      include/Lilith.inc,
sources/superIso.c,      MSSM/lib/spheno_call.c,  MSSM/lib/ssusy_call.c.

```

Note however, that care has to be taken that new versions are compatible with the existing interface structure.

We also point out that **Lilith** and **SModels** are python packages; for the latest versions of these codes, a python3 installation is required in addition to the compilers mentioned above.

### 3.4 Module structure of main programs

Each model included in **micrOMEGAs** is accompanied with sample files for C programs which call **micrOMEGAs** routines, the *main.c* 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 HIGGSBOUNDS           //Calls HiggsBounds to constrain the Higgs sector
#define HIGGSSIGNALS          //Calls HiggsSignal to constrain the Higgs boson
#define SUPERISO              //calls SuperISO to compute flavour observables
#define LILITH                //Calls LiLith to constrain the Higgs sector
#define SMODELS               //Calls SModelS to constrain the new physics sector
#define MONOJET               //Constrain the new physics sector using the monojet limit at LHC
#define OMEGA                 //Calculates the relic density
#define FREEZEIN              //Calculates the relic density in the freeze-in mechanism
#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,
                              //recoil energy distribution for various nuclei
                              //and compares with experimental data.
#define NEUTRINO              //Calculates flux of solar neutrinos and
                              //the corresponding muon flux
#define DECAYS                //Calculates decay widths and branching ratios
#define CROSS_SECTIONS        //Calculates cross sections
#define CLEAN                 //Removes intermediate files.

```

The flag

```

#define SHOWPLOTS             //switches on graphic facilities of micrOMEGAs.

```

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

### 3.5 Compilation of codes for specific models

After the 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
```

This should generate the executable `main` using the `main.c` source file. In general

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

generates the executable `filename` based on the source file `filename.ext`. For *ext* we support 2 options: `'c'`, `'cpp'` which correspond to C and C++ sources. `[g]make` called in the

model directory automatically launches `[g]make` in the subdirectories `lib` and `work` to compile

`lib/aLib.a` – the library of auxiliary model functions, and  
`work/work_aux.a` – the library of model particles, free and dependent parameters.

### 3.6 Command line parameters of main programs

The 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 model. 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 provided 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
```

## 4 Global Parameters and constants

The list of the global parameters and their default values are given in Tables 1 and 2. The numerical value for any of these parameters can be simply reset anywhere in the code. The numerical values of the scalar quark form factors can also be reset by the `calcScalarQuarkFF` routine presented below. Some physical values evaluated by `micrOMEGAs` also are presented as global variables, see Table 3.

All physical constants used in relic density calculations are defined in the file `include/micromegas_aux.h`, they are listed in Table 4.



Table 1: Global input parameters of **micrOMEGAs**

Name	default value	units	comments
deltaY	0		Difference between DM/anti-DM abundances
K_dif	0.0112	kpc <sup>2</sup> /Myr	The normalized diffusion coefficient
L_dif	4	kpc	Vertical size of the Galaxy diffusive halo
Delta_dif	0.7		Slope of the diffusion coefficient
Tau_dif	10 <sup>16</sup>	s	Electron energy loss time
Vc_dif	0	km/s	Convective Galactic wind
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 the Sun to the center of the Galaxy
Rdisk	20	kpc	Radius of the galactic diffusion disk
rhoDM	0.3	GeV/cm <sup>3</sup>	Dark Matter density at Rsun
vEarth	232	km/s	Galaxy velocity of the Earth
vRot	220	km/s	Galaxy rotation velocity at Rsun
vEsc	544	km/s	Escape velocity at Rsun
etaSHMpp	0.2		$\eta$ parameter of <b>SHM++</b>
betaSHMpp	0.9		$\beta$ parameter of <b>SHM++</b>

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	

## 5 Setting of model parameters, spectrum calculation, parameter display

The independent parameters of a given model are specified in `work/models/vars1.mdl`. Three functions can be used to set the values of these parameters:

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

assign 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.

Table 3: Evaluated global variables

Name	units	comments	Evaluated by
CDM1	<i>character</i>	name of first DM particle	sortOddParticles
CDM2	<i>character</i>	name of second DM particle	sortOddParticles
Mcdm1	GeV	Mass of the first Dark Matter particle	sortOddParticles
Mcdm2	GeV	Mass of the second DM particles	sortOddParticles
Mcdm	GeV	min(Mcdm1,Mcdm2) if both exist	sortOddParticles
dmAsymm		Asymmetry between relic density of $DM$ - $\overline{DM}$	darkOmega[FO]
fracCDM2		fraction of CDM2 in relic density.	darkOmega2
Tstart, Tend	GeV	Temperature interval for solving the differential equation	darkOmega[2]

Table 4: Some useful constants included in **micrOMEGAs**

Name	Value	Units	Description
<b>MPlanck</b>	$1.22091 \times 10^{19}$	GeV	Planck mass
<b>EntropyNow</b>	$2.8912 \times 10^9$	$\text{m}^{-3}$	Present day entropy, $s_0$
<b>RhoCrit100</b>	10.537	$\text{GeVm}^{-3}$	$\rho_c/h^2$ or $\rho$ for $H = 100\text{km/s/Mpc}$

- **readVar(fileName)**

reads parameters from a file. The file should contain two columns with the following format (see also Section 3.6)

```
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.

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 needed for the calculation of any *public* parameters in **work/models/func1.mdl** are also treated as *public*. It is possible to enlarge the list of *public* parameters. There are two ways to do this. One can type \* before a parameter name to make it *public* or one can add a special record in **work/models/func1.mdl**

```
%Local! |
```

Then all parameters listed above this record become *public*.

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

- **sortOddParticles(txt)**

For two DM models, this routine fills the text parameters **CDM1** and **CDM2** with the names of the lightest odd particle starting with one and two tildes respectively and assigns the value of the mass of the lightest odd particle in each sector to the global parameters **Mcdm1**

and `Mcdm2`. For models with only one DM candidate, `micrOMEGAs` will set `CDM2=NULL` and `Mcdm2=0`. 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. For  $N$  dark sectors, each containing particles in thermal equilibrium, this routine determines the number of sectors `Ncdm`, and fills the `Ncdm+1` dimensional array `McdmN` containing the minimal mass in each sector. `McdmN[0]=0` corresponds to the SM sector.

- `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,  $-3$ , 6,  $-6$  or 8. The parameters `spin2`, `charge3`, `cdim` are variables of type `int`. The value returned is the PDG code. If `pName` does not correspond to any particle of the model then `qNumbers` returns zero.

- `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`.

- `antiParticle(pName)`

returns the name of the anti-particle for the particle `pName`.

- `pMass(pName)`

returns the numerical value of the particle mass.

- `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.

- `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)`

returns the value of variable `name` and writes an error message if it cannot recognize a parameter name.

The variables accessible by these last two 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 the independent and the 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.

- `printHiggs(FD, sort)`

prints the masses and widths of 'even' colorless scalars.

## 6 Relic density calculation

### 6.1 Switches and auxiliary routines

- `VWdecay, VZdecay`

Switches to turn on/off processes with off-shell gauge bosons in the final state 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=1`).<sup>1</sup> Note that `micrOMEGAs` calculates the width of each particle only once and stores the result in *Decay Table*. 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. We recommend to call

- `cleanDecayTable()`

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

- `useSLHAwidth`

Switch to determine how the particle widths are computed. If `=1` the particle widths stored in a SLHA file (SUSY Les Houches Accord [45]) are downloaded by `micrOMEGAs`. These widths then do not depend on the `VW/VZdecay` switches. If `=0` `micrOMEGAs` will calculate the widths, it will also do so if the switch is set to 1 and the widths are not provided in the SLHA file. By default this switch is set to 0.

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 in the user's main program [46]. Five other files are provided in the sources/data directory: `HP_A_thg.tab`, `HP_B_thg.tab`, `HP_B2_thg.tab`, `HP_B3_thg.tab`, and `HP_C_thg.tab`. They correspond to sets A, B, B2, B3, C in [47]. The user can substitute his/her own table as well, if so, the file must contain three columns containing the numerical values for  $T, h_{eff}, g_{eff}$ , the data file can also contain comments for lines starting with `#`.

These functions are accessed via

- `gEff(T)`

---

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

returns the effective number of degrees of freedom for the energy density of radiation at a bath temperature  $T$ , only SM particles are included.

- **hEff(T)**

returns the effective number of degrees of freedom for the entropy density of radiation at a bath temperature  $T$ .

- **hEffLnDiff(T)**

returns the derivative of  $h_{eff}$  with respect to the bath temperature,  $\frac{d \log(h_{eff}(T))}{d \log(T)}$ .

- **Hubble(T)**

returns the Hubble expansion rate at a bath temperature  $T$ . This applies for the radiation-dominated era and is valid for  $T \gtrsim 100\text{eV}$ .

- **improveCrossSection( n1,n2,n3,n4, Pcm, &cs)**

allows to substitute a new cross-section for a given process instead of the one calculated by micrOMEGAs at tree level. Here **n1,n2** are PDG codes of particles in the initial state and **n3,n4** those in the final state. **Pcm** is the center of mass momentum and **cs** is the cross-section in  $[\text{GeV}^{-2}]$ . This function is useful if, for example, the user wants to include her/his one-loop improved cross-section calculation in the relic density computation. This function has to be written by the user. The corresponding code can be placed in the directory **MODEL/lib.micrOMEGAs** calls this routine substituting for the last parameter the address of memory where the calculated tree level cross section **cs** is stored, this way the default cross section can be replaced. **micrOMEGAs** contains a dummy version of this routine disposed in **sources/improveCS.c** which does not modify the default cross section. This file also contains some commented out example of the code for IDM model. The dummy version is used until the user adds his own code.

## 6.2 Calculation of relic density for one-component Dark Matter models

All routines to calculate the relic density in version 3 are available in further versions. For these routines, the difference between the two dark sectors is ignored. These routines are intended for models with either a  $Z_2$  or  $Z_3$  discrete symmetry.

- **vSigma(T,Beps,fast)**

calculates the thermally averaged cross section for DM annihilation times velocity at a temperature  $T$  [GeV],  $\sigma_v = \langle \sigma v \rangle$ ,

$$\sigma_v(T) = \frac{T}{8\pi^4 \bar{n}(T)^2} \int ds \sqrt{s} K_1 \left( \frac{\sqrt{s}}{T} \right) \sum_{\tilde{\alpha}, \tilde{\beta}} p_{\tilde{\alpha}\tilde{\beta}}^2(s) g_{\tilde{\alpha}} g_{\tilde{\beta}} \left( \sum_{x \geq y} \sigma_{\tilde{\alpha}\tilde{\beta} \rightarrow xy}(s) + \frac{1}{2} \sum_{x\tilde{\gamma}} \sigma_{\tilde{\alpha}\tilde{\beta} \rightarrow x\tilde{\gamma}}(s) \right) \quad (1)$$

$$\bar{n}(T) = \frac{T}{2\pi^2} \sum_{\tilde{\alpha}} g_{\tilde{\alpha}} m_{\tilde{\alpha}}^2 K_2 \left( \frac{m_{\tilde{\alpha}}}{T} \right), \quad (2)$$

Here  $\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}$  is used for **Odd** particles and  $x, y$  for **Even** particles.  $\sigma_{\tilde{\alpha}\tilde{\beta} \rightarrow x[\tilde{\gamma}/y]}$  is the cross section for the corresponding process averaged over the spins of incoming particles and summed over the spins of outgoing particles.  $\sigma_v$  should represent the rate of disappearance of **Odd** particles, therefore when a final state particle has a non-zero decay branching

ratio to odd particles, the annihilation cross section for this process is multiplied by the corresponding branching ratio of the decays into SM particles. For the same reason cross sections for semi - annihilation processes contribute to **vSigma** with a factor  $\frac{1}{2}$ .  $K_1, K_2$  are modified Bessel functions of the second kind, and  $m_{\tilde{\alpha}}$  and  $g_{\tilde{\alpha}}$  stand for the mass and the number of degrees of freedom of particle  $\tilde{\alpha}$ . Note, that if  $\tilde{\alpha} \neq \tilde{\beta}$  then each  $\sigma_{\tilde{\alpha}\tilde{\beta}}$  term will be presented twice. The value for  $\sigma_v$  is expressed in  $[pb \cdot c]$ . The parameter *Beps* defines the criteria for including coannihilation channels as for **darkOmega** described below. The *fast* = 1/0/ - 1 option switches between the *fast/accurate/very 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]** ( $j=0, 4$ ) defines the particles names for the  $i^{th}$  channel. The last record in **vSigmaTCh** array has zero weight and NULL particle names. *character\*40 process* contains a textual description of annihilation processes.

- **vSigmaCC(T,cc,mode)**

calculates the thermally averaged *cross section*  $\times$  *velocity* for  $2 \rightarrow 2$ ,  $2 \rightarrow 3$ , and  $2 \rightarrow 4$  processes. **T** is the temperature in [GeV], *cc* is the address of the code for each process. This address can be obtained by the function **newProcess** presented in Section 10. The returned value is given in  $[c \cdot pb]$ .

If *mode*  $\neq 0$ , **vSigmaCC** calculates the contribution of a given process to the total annihilation cross section, see Eq.1. The incoming particles should belong to the odd sector. For  $2 \rightarrow 2$  processes the result after summation over all subprocesses should be identical to the one obtained via **vSigma** above. For this mode, **vSigmaCC** includes combinatoric factors: 2 if  $\tilde{\alpha} \neq \tilde{\beta}$ , an additional factor 2 if the incoming state is not self-conjugated, and a factor  $\frac{1}{2}$  for semi-annihilation.

If *mode* = 0, **vSigmaCC** is defined by the integral

$$\langle v \sigma^{\tilde{\alpha}\tilde{\beta} \rightarrow X} \rangle_T = \frac{1}{2T m_{\tilde{\alpha}}^2 m_{\tilde{\beta}}^2 K_2(\frac{m_{\tilde{\alpha}}}{T}) K_2(\frac{m_{\tilde{\beta}}}{T})} \int ds \sqrt{s} K_1(\frac{\sqrt{s}}{T}) p_{cm}^2(s) \sigma^{\tilde{\alpha}\tilde{\beta} \rightarrow X}(p_{cm}(s))$$

where  $p_{cm}$  is the center of mass momentum of incoming particles. Note that

$$\lim_{T \rightarrow 0} \text{vSigmaCC}(T, cc, 0) = \lim_{p_{cm} \rightarrow 0} \sigma(p_{cm}) v_{rel}(p_{cm})$$

where  $v_{rel}(p_{cm})$  is the relative velocity of incoming particles. The result of **vSigmaCC** can be different from that of **vSigma** described above when there is an important contribution from NLSP's to the total number density of DM particles.

- **darkOmega(&Xf,fast,Beps,&err)**

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 which is defined by the condition  $Y(T_f) = 2.5 Y_{eq}(T_f)$ . For asymmetric DM this condition reads  $2\sqrt{Y^+(T_f)Y^-(T_f)} = 2.5 Y_{eq}(T_f)$ . 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. [3]). 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, [3]. The recommended value is  $Beps = 10^{-4} - 10^{-6}$  whereas if  $Beps = 1$  only annihilation of the lightest odd particle is computed. Non-zero error code means that the temperature where thermal equilibrium between the DM and SM sectors is too large  $M_{cdm}/T < 2$  or  $T > 10^5 \text{ GeV}$ .

**darkOmega** solves the differential equation for the abundance  $Y(T)$  in the temperature interval  $[T_{end}, T_{start}]$  defined by the conditions  $Y(T_{start}) \approx 1.1Y_{eq}(T_{start})$ ,  $Y(T_{end}) \approx 10Y_{eq}(T_{end})$ . For temperatures below **Tend**, the contribution for  $Y_{eq}$  is neglected and the differential equation is integrated explicitly. The solution in the interval  $[T_{end}, T_{start}]$  interval is tabulated and can be displayed via the function **YF(T)**. The equilibrium abundance can be accessed with the function **Yeq(T)**.

- **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 evaluated first in **darkOmega[F0]**. Only the channels whose relative contribution is larger than **cut** will be displayed. **Beps** plays the same role as in 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  $(\Omega h^2)^{-1}$ .  $p1, \dots, p4$  are particle names. To sum over several channels one can write "\*" instead of a particle name, e.g. "\*" in place of  $p1$ .

- **omegaCh** is an array that contains the relative contribution and particle names for each annihilation channel. These array and function are similar to **vSigmaTCh** described above. The array **omegaCh** is filled after calling either **darkOmegaF0** or **printChannels**.

- **darkOmegaTR(Tstart, Ystart, fast, Beps)**

This function is similar to **darkOmega** except that the initial temperature (**Tstart**) and abundance (**Ystart**) that are needed for solving the evolution equation have to be provided by the user as arguments to the function.

There is an option to calculate the relic density in models with  $DM-\overline{DM}$  asymmetry. In this case, we assume that the number difference of  $DM-\overline{DM}$  is conserved in all reactions. Thus a small difference in initial abundances can lead to a large DM asymmetry after freeze-out as is the case for the baryon asymmetry.

- **deltaY**

describes the difference between the DM and anti-DM abundances for the models where the number of DM particles minus the number of anti-DM is conserved in decays and collisions. In such models **deltaY** is a constant during the thermal evolution of the Universe, see Ref. [7].

- **dmAsymm**

is defined by the equation

$$\Omega_{\pm} = \Omega \frac{1 \pm \text{dmAsymm}}{2}$$

and evaluated by `micrOMEGAs` while calculating the relic density with an initial asymmetry `deltaY`, see [7]. This parameter can also be reset after the relic density computation and will then be taken into account for direct and indirect detection rates.

- `darkOmegaExt(&Xf, vs_a, vs_sa)`

calculates the dark matter relic density  $\Omega h^2$  for annihilation cross sections provided by external functions. Here `vs_a` is the annihilation cross section in [c-pb] as a function of the temperature in [GeV] units while `vs_sa` is the semi-annihilation cross section. `vs_a` is required for all models, while `vs_sa` is relevant only for models where semi-annihilation occurs. The user can substitute NULL for `vs_sa` when semi-annihilation is not possible.

`darkOmegaExt` can also be used if  $2 \rightarrow 2$  processes do not contribute to DM annihilation. In this case the appropriate annihilation or semi-annihilation cross sections can be calculated by `vSigmaCC` and the tabulated results stored in `vs_a` and `vs_sa`. Note that if the user substitute some function which is not in tabular form, `darkOmegaExt` can be slow as it has not been optimized.

`darkOmegaExt` solves the Runge-Kutta equation in the interval [Tstart, Tend] where Tstart is defined automatically while Tend has a fixed value  $10^{-3}$  GeV. `darkOmegaExt` is sensitive to effect of DM asymmetry.

### 6.3 Calculation of relic density for two-component Dark Matter models

- `darkOmega2(fast, Beps)`

Calculates  $\Omega h^2$  for either one- or two-components DM models. In the former case it should give the same result as `darkOmega`. The parameters `fast` and `Beps` have the same meaning as for the `darkOmega` routine. The returned value corresponds to the sum of the contribution of the two DM components to  $\Omega h^2$ . `darkOmega2` also calculates the global parameter `fracCDM2` which represents the mass fraction of CDM2 in the total relic density

$$\Omega = \Omega_1 + \Omega_2 \quad (3)$$

$$\text{fracCDM2} = \frac{\Omega_2}{\Omega} \quad (4)$$

This parameter is then used in routines which calculate the total signal from both DM candidates in direct and indirect detection experiments, `nucleusRecoil`, `calcSpectrum`, and `neutrinoFlux`. The user can change the global `fracCDM2` parameter before the calculation of these observables to take into account the fact that the value of the DM fraction in the Milky Way could be different than in the early Universe.

The routines that were described in section 6.2 are not available for two-component DM models. In particular the individual channel contribution to the relic density cannot be computed and DM asymmetry is ignored. After calling `darkOmega2` the user can check the cross sections for each class of reactions (but not for individual processes) which were tabulated during the calculation of the relic density. The functions

- `vsabcd F(T)`

computes the sum of the cross sections for each class of reactions ( $a, b, c, d = 0, 1, 2$ ) tabulated during the calculation of the relic density. Here T is the temperature in [GeV]



and the return value is  $v\sigma$  in [c·pb]. These functions are defined in the interval [Tstart, Tend] where Tstart is a global parameter defined by darkOmega2, Tend=10<sup>-3</sup>GeV. Specifically the functions available are

vs1100F	vs1110F	vs1120F	vs1112F	vs1122F	vs1210F	vs1211F
vs1220F	vs1222F	vs2200F	vs2210F	vs2220F	vs2211F	vs2221F

The temperature dependence of the abundances can also be called by the user, the functions are named Y1F(T) and Y2F(T) and are defined only in the interval  $T \in [Tend, Tstart]$ . The equilibrium abundances are accessible via the Yeq1(T), Yeq2(T) functions and the deviation from equilibrium by the functions dY1F(T)= Y1F(T)-Y1eq(T) and dY2F(T)=Y2F(T)-Y2eq(T).

- **darkOmega2TR(Tstart, Y1start, Y2start, fast, Beps)**

This function is similar to darkOmega2 described above, however the initial temperature (Tstart) and abundances (Y1start, Y2start) that are needed for solving the evolution equations should be passed by the user as arguments to the function.

## 6.4 Calculation of relic density for freeze-in

Several routines are provided in micrOMEGAs to compute the DM abundance in freeze-in scenarios. These can be found in the file sources/freezein.c. The first line of this file contains the statement

```
//#define NOSTATISTICS
```

This statement can be uncommented for micrOMEGAs to compute the relic density assuming a Maxwell-Boltzman distribution. This option is faster.

The auxiliary functions that are needed for the computation of the factors from statistical quantum mechanics are

- **Stat2(P/T, x<sub>Y</sub>, x<sub>1</sub>, x<sub>2</sub>, η<sub>1</sub>, η<sub>2</sub>),**

returns the  $S$  function defined in Eq. (5), that takes into account particle statistical distributions for the decay of a mediator  $Y \rightarrow a, b$  of fixed momentum  $P$ .

$$S(P/T, x_Y, x_a, x_b, \eta_a, \eta_b) = \frac{1}{2} \int_{-1}^1 d\cos\theta \frac{e^{E_Y/T}}{(e^{E_a(\cos\theta)/T} - \eta_a)(e^{E_b(\cos\theta)/T} - \eta_b)} . \quad (5)$$

where  $x_i \equiv m_i/T$ ,  $E_a, E_b$  are the energies of the outgoing particles and  $\eta_i \equiv \pm e^{\mu_i/T}$  and  $\mu_i$  is the chemical potential.

- **K1to2(x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>, η<sub>1</sub>, η<sub>2</sub>, η<sub>3</sub>),**

returns the  $\tilde{K}_1$  function defined in Eq. (6), that takes into account particle statistical distributions.

$$\tilde{K}_1(x_1, x_2, x_3, \eta_1, \eta_2, \eta_3) \equiv \frac{1}{(4\pi)^2 p_{\text{CM}} T} \int \prod_{i=1}^3 \left( \frac{d^3 p_i}{E_i} \frac{1}{e^{E_i/T} - \eta_i} \right) e^{E_1/T} \delta^4(P_1 - P_2 - P_3) \quad (6)$$

The code does *not* check whether or not a particle is in thermal equilibrium with the SM thermal bath and that it is the responsibility of the user to specify which particles belong

to the bath,  $\mathcal{B}$ , or are out of equilibrium,  $\mathcal{F}$ . This can be done through the function

- `toFeebleList(particle_name)`

which assigns the particle `particle_name` to the list of feebly interacting ones (*i.e.* those which belong to  $\mathcal{F}$ ). Feebly interacting particles can be odd or even. This function can be called several times to include more than one particle. All odd or even particles that are not in this list are assumed to be in thermal equilibrium with the SM and belong to  $\mathcal{B}$ . The treatment of the particles that belong to  $\mathcal{F}$  for the computation of  $\Omega h^2$  within the freeze-in routines is described below. Calling `toFeebleList(NULL)` will reassign all particles to  $\mathcal{B}$ .

The actual computation of the freeze-in DM abundance can be performed with the help of three functions:

- `darkOmegaFiDecay(TR, Name, KE, plot)`

calculates the DM abundance from the decay of the particle `Name` into all odd FP. Here we assume that all odd FP will decay into the lightest one which is the DM. `TR` is the reheating temperature and `KE` is a switch to specify whether the decaying particle is in kinetic equilibrium (`KE=1`) or not (`KE=0`) with the SM. The equations used for the three different cases are described in [10]. Numerically, the latter two methods give very similar results, however the function with `KE=1` is faster. The switch `plot=1` displays on the screen  $Y(T)$  for the decaying particle and  $dY/d\log(T)$  for DM.

- `darkOmegaFi22(TR, Process, vegas, plot, &err)`

calculates the DM abundance taking into account only DM production via the  $2 \rightarrow 2$  process defined by the parameter `Process`. For example `"b,B ->~x1,~x1"` for the production of DM (here  $\tilde{x}_1$ ) via  $b\bar{b}$  scattering. This routine allows the user to extract the contribution of individual processes. `TR` is the reheating temperature. When the switch `vegas=1`, the collision term is integrated directly as described in [10]. The execution time for this option is quite long, it is intended mostly for precision checks. The switch `plot=1` displays on the screen  $dY/d\log(T)$  for DM. `err` is the returned error code, it has the following meaning

- 1: the requested processes does not exist
- 2:  $2 \rightarrow 2$  process is expected
- 3: can not calculate local parameters // some constrain parameters can not be calculated.
- 4: the reheating temperature is too small, ( $T_R < 1keV$ )
- 5: one of the incoming particles belong to  $\mathcal{F}$ .
- 6: None of the outgoing particles are odd and feeble.
- 7: Lost of precision in temperature integrand
- 8: Pole in temperature integrand
- 9: NaN in temperature intergrand
- 10: Lost of precision in sqrt(s) integrand
- 11: Pole in sqrt(s) integrand
- 12: NaN in sqrt(s) intergrand
- 13: Lost of precision in angle integrand
- 14: Pole in angle integrand
- 15: NaN in angle intergrand
- 16: lost of precision caused by diagramm cancelation

When substituting NULL for the error code, the error message is displayed on the screen and in this case the message does not appear in the address of the variable used for passing the error code.

- **darkOmegaFi**(TR, &err)

calculates the DM abundance after summing over all  $2 \rightarrow 2$  processes involving particles in the bath  $\mathcal{B}$  in the initial state and at least one particle in  $\mathcal{F}$  in the final state. The routine checks the decay modes of all bath particles and if one of them has no decay modes into two other bath particles, the  $2 \rightarrow 2$  processes involving this particle are removed from the summation and instead the contribution to the DM abundance computed from the routine **darkOmegaFiDecay** is included in the sum. This is done to avoid appearance of poles in the corresponding  $2 \rightarrow 2$  cross-section. We recommend for such models to compute individual  $2 \rightarrow 2$  processes with **darkOmegaFi22** described above. As before, we assume that all odd FIMPs will decay into the lightest one which is the DM.  $T_R$  has the same meaning as above. **err** is the returned error code, **err=1** if feeble particles have not been defined.

- **printChannelsFi**(cut, prcnt, filename)

writes into the file **filename** the contribution of different channels to  $\Omega h^2$ . The **cut** parameter specifies the lowest relative contribution to be printed. If **prcnt**  $\neq 0$ , the contributions are given in percent. The routine **darkOmegaFi** fills the array **omegaFiCh** which contains the contribution of different channels ( $2 \rightarrow 2$  or  $1 \rightarrow 2$ ) to  $\Omega h^2$ . **omegaFiCh[i].weight** specifies the relative weight of the *i*th channel, **omegaFiCh[i].prtel[j]** (*j*=0, 4) defines the particles names for the *i*th channel. The last record in the array **omegaFiCh** has zero weight and NULL particle names.

Note that if no particle has been declared as being feebly interacting, the freeze-out routines **darkOmega**, **darkOmegaF0**, and **darkOmega2** [8] will work exactly like in previous versions of **micrOMEGAs**. A non-empty list of FIMPs, however, will affect these routines since **micrOMEGAs** will exclude all odd particles in this list from the computation of the relic density via freeze-out. For example, if the DM is a bath particle, excluding FPs can impact the freeze-out computation of  $\Omega h^2$  when they are nearly degenerate in mass with the DM, hence could potentially contribute to coannihilation processes. Note also that if, for example, the lightest odd particle (the DM) belongs to  $\mathcal{F}$  and the user computes the freeze-out abundance of the lightest odd bath particle, the resulting value of  $\Omega_{LBP} h^2$  will be automatically rescaled by a factor  $M_{LFP}/M_{LBP}$ , where  $M_{LBP}(M_{LFP})$  is the mass of the lightest odd particle in  $\mathcal{B}$  ( $\mathcal{F}$ ). Conversely, if the DM belongs to  $\mathcal{B}$  and the user computes the freeze-in abundance of the lightest feeble odd particle, the corresponding result for  $\Omega_{LFP} h^2$  will be rescaled by  $M_{LBP}/M_{LFP}$ . In other words, the answer obtained in both of these cases corresponds to the predicted density of the dark matter particles and not the heavier ones. Besides, **micrOMEGAs** does not check whether the decay rate of an odd particle to the feeble particles is much smaller than  $H(T_{FO})$  which would justify the fact that they should not be included in the freeze-out computation.

## 6.5 Calculation of relic density for cospattering

For the computation of cospattering, as in the case of  $N$ -component DM, the dark particles need to be divided into *sectors*, within each of which chemical equilibrium is observed. By default, this separation is defined by the number of  $\sim$  symbols in the beginning of the particle names. Thus,  $\sim x1$  and  $\sim\sim x2$  denote dark particles of two different sectors. Usually, the sector assignment corresponds to the charge of the discrete symmetry responsible for DM stability, cf. section 2. However, in the absence of chemical equilibrium, the splitting into sectors needs to be done differently. To this end, the function

- **defThermalSet( $n$ ,  $particles\_list$ )** moves all particles mentioned in *particles\_list* to sector  $n$ . All particles which were assigned to sector  $n$  before this command are returned to their default sectors specified by the number of  $\sim$  in the beginning of their names. Particles in the *particles\_list* have to be separated by commas, and particle and anti-particle automatically belong to the same sectors. By definition, sector 0 is the SM bath, while sector  $-1$  is used to define *feeble* particles which do not take part in freeze out, such particles will be ignored when solving for the relic density. Sectors  $n > 0$ , are used for all other cases.

**defThermalSet** returns an error code if *particles\_list* contains a particle name which is not defined in the model. In general, **defThermalSet** can define a set which includes particles with different charges of the discrete symmetry group (different number of  $\sim$  symbols) — in particular the set could include  $Z_2$  odd particles as well as SM particles. In this case the user must keep in mind that the abundance equations are solved for sectors  $n > 0$  only, such that a  $Z_2$  odd particle assigned to sector 0 will not be considered as potential DM candidate.

- **printThermalSets()** prints the contents of all particle sets specified by **defChEset** on the screen.

To verify whether chemical equilibrium is reached in one sector, one can use

- **checkTE( $n$ ,  $T$ ,  $mode$ ,  $Beps$ )** which checks the condition for chemical equilibrium in the  $n^{th}$  sector at temperature  $T$ . If  $mode=0$ , then both decay and co-scattering are taken into account. If  $mode=1$  (2), then only decay (co-scattering) processes are taken into account. **checkTE** returns the minimal value of  $\Gamma/H(T)$  obtained after testing all possible subsets of particles in sector  $n$ . The particle assignment corresponding to the minimal value of  $\Gamma/H(T)$  is printed on the screen. This value has to be  $\gg X_f$  to have chemical equilibrium, when this condition is satisfied the correction to the abundance calculated assuming chemical equilibrium is approximately  $\Delta Y/Y \approx X_f H/\Gamma$ .

- **YdmNEq( $T, \alpha$ )** calculates the thermal equilibrium abundance for particles of sector  $\alpha$ , where  $\alpha$  has to be presented by a text label. For instance, **YdmNEq( $T, "1"$ )**.

- **vSigmaN( $T$ ,  $channel$ )** calculates the thermally averaged cross section  $\langle v\sigma \rangle$  in [pb·c] units. Here *channel* is a text code specifying the reaction, e.g. **vSigmaN( $T, "1100"$ )** for  $1, 1 \leftrightarrow 0, 0$  processes.

To find the contribution of different processes to **vSigmaN**, one can call

- **vSigmaNCh( $T$ ,  $channel$ ,  $Beps$ ,  $\&vsPb$ )** which returns an array of annihilation processes together with their relative contributions to the total annihilation cross section. The cross section is given by the return parameter **vsPb** in [pb c] units. The elements of the array are sorted according to weights and the last element has weight=0. The structure of this array is identical to **vSigmaTCh** which was defined for one-DM models,

see 6.2. The input parameter `channel` is written in text format. The memory allocated by `outCh` can be cleaned after usage with the command `free(outCh)`. The following lines of code give an example on how to use this function

```
aChannel*outCh=vSigmaNCh(T, "1100", Beps, &vsPb);
for(int n=0;;n++)
{ if(outCh[n].weight==0) break;
  printf(" %.2E  %s %s -> %s %s\n", outCh[n].weight,
    outCh[n].prtc1[0], outCh[n].prtc1[1], outCh[n].prtc1[2], outCh[n].prtc1[3]);
}
free(outCh);
```

- `darkOmegaNTR(TR, Y, Beps, &err)` solves the equation of the thermal evolution of abundances starting from the initial temperature `TR`. The array `Y` has to contain the initial abundances at the temperature `TR`. After completion, `Y[k]` contains the abundances of sector  $k-1$  at the temperature `Tend` defined by the user<sup>2</sup>. The parameter `TR` is assigned to the global variable `Tstart`. The total resulting  $\Omega h^2$  is calculated as in [48] and corresponds to the value returned by `darkOmegaNTR`.

The error code `err` is a binary code which can signal several problems simultaneously. The codes 1, 2, 3, generated by the integration program `simpson`, mean

- 1 - NaN in integrand;
- 2 - too deep recursion;
- 3 - loss of precision;

In general, these codes can be treated as warnings, though it can be useful to check the calculation of integrals, which lead to problems, using e.g. the `gdb` debugging tools. See also the explanation of the `simpson` routine in section 14. The code 128 signals a problem in the solution of the differential equation, for example this problem can arise when `TR` is too large.

- `darkOmegaN(Y, Beps, &err)` finds the temperature where abundances are close to equilibrium values in each sector, the lowest temperature is assigned to `Tstart`, and calls `darkOmegaNTR`. If `Tstart` is not found, then the error code 64 is generated and `darkOmegaN` returns NaN.

- `YdmN(T,  $\alpha$ )` presents the evolution of abundances calculated by `darkOmegaN` or `darkOmegaNTR` for  $T \in [Tend, Tstart]$ .

For the above functions, `micrOMEGAs` provides the possibility to selectively exclude part of the terms in the evolution equation. This is realized via the string `ExcludedFor2DM`, which can be assigned specific keywords. The keyword `"DMdecay"` excludes decay processes which contribute to the DM evolution, while the keyword `"1100"` excludes  $1,1 \leftrightarrow 0,0$  processes. to exclude cospattering ( $2,0 \leftrightarrow 1,0$  or  $1,0 \leftrightarrow 2,0$ ) processes, set

```
ExcludedFor2DM="2010";
```

---

<sup>2</sup>Recall that by default `Tend`= $10^{-3}$ GeV, however when the decay contribution is important it is preferable to choose a smaller value such as `Tend`= $10^{-8}$ GeV which correspond to the temperature of the Universe today.

The behaviour is reset to default by `ExcludedFor2DM=NULL`; which means all channels are included.

Note that, for the computation of cospattering, the user defines which particles belong to sector 1 and sector 2. If a particle of dark sector 1 is wrongly assigned to dark sector 2, while it is in thermal equilibrium with sector 1, the two abundance equations will be solved and should give the same result as the single abundance equation, that is  $Y(\text{heavier particles}) = 0$  and  $Y(\text{lightest particle}) = Y$  of the single equation.

Finally, in the cospattering phase kinetic equilibrium may be lost; it is the responsibility of the user to verify that this is not the case for the parameters considered, so that the momentum-integrated Boltzmann equations remain a good approximation.

## 7 Direct detection

### 7.1 Amplitudes for elastic scattering

- `nucleonAmplitudes(CDM,pAsi,pAsd,nAsi,nAsd)`

calculates the amplitudes for CDM-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 (in  $\text{GeV}^{-2}$ ) are normalized such that the total cross section for either  $\chi$  or  $\bar{\chi}$  cross sections is

$$\sigma_{tot} = \frac{4M_\chi^2 M_N^2}{\pi(M_\chi + M_N)^2} (|A^{SI}|^2 + 3|A^{SD}|^2) \quad (7)$$

`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.

`micrOMEGAs` automatically takes into account loop contributions from box diagrams as calculated in [49] (DM spin 1/2 case) and [50] (DM spin 0 and 1 cases).

`nucleonAmplitudes` does not take into account an operator involving DM-DM-gluon-gluon interactions. It is by default assumed that such interactions are generated at one-loop from DM interactions with heavy colored particles and this loop-induced contribution of heavy coloured particles to DM-DM-gluon-gluon interactions<sup>3</sup> is taken into account automatically. Thus a direct contribution might lead to double counting. Note that to avoid double counting an Hgg vertex in the model file will also be ignored. To include the contribution of an additional operator that involves DM interactions with gluons, it is rather recommended to introduce a new auxiliary heavy color (dim=3) fermion in

---

<sup>3</sup>Heavy quarks include c,b,t quarks

the model file, the direct detection amplitude that results from the effective operator  $\alpha_s G_{\mu\nu} G^{\mu\nu} \bar{\chi}\chi$  can be represented by a term  $-12\pi M_F \bar{F} F \bar{\chi}\chi$ , where  $M_F$  is the fermion mass which should be chosen large enough to ensure that  $F$  does not contribute to other processes.

- `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  $\sigma_s = 42\text{MeV}, \sigma_{\pi N} = 34\text{MeV}, m_u/m_d = 0.56, m_s/m_d = 20.2$  [51]. The function `calcScalarQuarkFF(0.553, 18.9, 55., 243.5)` will reproduce the default values of the scalar quark form factors used in micrOMEGAs2.4 and earlier versions.

## 7.2 Scattering on nuclei

- `nucleusRecoil(f, A, Z, J, Sxx, dNdE)`

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

- ◇ `f` - the DM velocity distribution normalised such that

$$\int_0^\infty f(v) dv = 1 \quad (8)$$

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

- ◇ `A` - atomic number of nucleus;
- ◇ `Z` - number of protons in the nucleus;
- ◇ `J` - nucleus spin;
- ◇ `void Sxx(double p, double*S00, double*S01, double*S11)` - is a routine which calculates nucleus form factors for spin-dependent interactions (`S00, S01, S11`), it depends on the momentum transfer  $p$  in  $fm^{-1}$ . For nucleus with zero spin one has to substitute `NULL` for this parameter;
- ◇ The distribution over recoil energy is stored in the array `dNdE`

$$dNdE[n] = \frac{dN}{dE_n}$$

in units of  $(1/\text{keV}/\text{kg}/\text{day})$  where

```
En=RE_START*RE_STEP**n;    0<=n<RE_DIM
#define RE_DIM      150    // dimension of recoil energy array
#define RE_START    1.E-2  // energy [keV] corresponding to zero'th element
#define RE_STEP     1.08   // factor for recoil energy grid
                        // E_{n+1}=E_n*RE_STEP
```

The `include/micromegas.h` file contains predefined values for charges and spins of atomic nucleus. They are called with `Z_{Name}` and `J_{Name}{atomic_number}` where `Name` is the name of an atom. For example, for  $^{73}\text{Ge}$ , a call to this routine will be:



`nucleusRecoil(Maxwell,73,Z_Ge,J_Ge73,SxxGe73,dNdE);`

The returned value of the function `nucleusRecoil` 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. This routine is based on the spin-dependent and spin-independent cross sections, but also takes into account the modification of the recoil energy distribution caused by a light  $t$ -channel propagator. For a light mediator, the nucleus recoil energy distribution reads

$$\frac{dN_A}{dE} = \frac{M_{\text{med}}^4}{(M_{\text{med}}^2 + 2M_A E)^2} \frac{dN_A^{\text{std}}(M_{DM}, \sigma_0)}{dE} \quad (9)$$

where  $N_A^{\text{std}}$  is the standard expression for the number of recoil events for a point-like interaction with a DM- nucleon elastic scattering cross-section  $\sigma_0$ ,  $M_{\text{med}}$  is the mass of the  $t$ -channel mediator. The factor to correct the recoil energy distribution as in Eq.9 is introduced automatically in the code after an internal check for the existence of a light mediator. For a complex WIMP and if DM has only one component, `nucleusRecoil` averages over  $\chi$  and  $\bar{\chi}$  taking into account the asymmetry between  $\chi$  and  $\bar{\chi}$ . For models with 2 DM particles the result takes into account the relative contribution of each DM particle through the parameter `fracCDM2`.

- `dNdERecoil(E,dNdE)` interpolates the `dNdE` table.

### 7.2.1 Nucleus form factors

The form factors for the spin independent (SI) cross section are defined by the Fermi distribution

$$F_A(q) = \int e^{-qx} \rho_A(|x|) d^3x \quad (10)$$

$$\rho_A(r) = \frac{c_{\text{norm}}}{1 + \exp((r - R_A)/a)} \quad (11)$$

$$R_A = cA^{\frac{1}{3}} + b \quad (12)$$

where  $a, b, c$  are defined with the global parameters `Fermi_a`, `Fermi_b`, `Fermi_c`.

The spin dependent form factors collected in [52] are implemented in micrOMEGAs [5]:

SxxF19	SxxNa23	SxxNa23A	SxxAl27	SxxSi29	SxxSi29A
SxxK39	SxxGe73	SxxGe73A	SxxNb92	SxxTe125	SxxTe125A
SxxI127	SxxI127A	SxxXe129	SxxXe129A	SxxXe129M	
SxxXe131	SxxXe131A	SxxXe131B	SxxXe131Me		

Here the characters after the atomic number are used to distinguish different implementations of the form factor for the same isotope. Recently we have added some form factors used in XENON1T and PICO-60 experiments. See Table 5.

The minimal and maximal values for the SD form factors,  $S_{00}(q), S_{01}(q), S_{11}(q)$ , are computed in Ref. [54] within the shell model. The ID `SHELL` corresponds to the average

$$S_{ab} = (S_{ab}^{\text{min}} + S_{ab}^{\text{max}})/2 \quad (13)$$



Name	reference	ID
SxxF19EF SxxXe131EFT SxxXe129EFT	[53]	EFT
SxxF19SHELL SxxXe129SHELL SxxXe131SHELL	[54]	SHELL
SxxF19SHELLm SxxXe129SHELLm SxxXe131SHELLm	[54]	SHELLm

Table 5: Implemented form factors

which are obtained from the minimum and maximum fitted values in Table VI in [54].

The ID **SHELLm** corresponds to the form factors which lead to the most robust exclusion. Since  $S_{ab}^{min}$  often leads to a negative value for the subdominant component of the form factor, and this has no physical meaning, we use rather the minimum value of the proton-only,  $S_p^{min}$ , and neutron-only,  $S_n^{min}$ , form factors also given in [54]. These correspond to the minimal form factor for the case when only one type of interaction (with proton or neutron) is included. With this we construct the nucleus form factors

$$\begin{aligned}
S_{00} &= \frac{1}{4} \left( S_p^{min} + S_n^{min} \pm 2\sqrt{S_p^{min} S_n^{min}} \right) \\
S_{11} &= \frac{1}{4} \left( S_p^{min} + S_n^{min} \mp 2\sqrt{S_p^{min} S_n^{min}} \right) \\
S_{01} &= \frac{1}{2} (S_p^{min} - S_n^{min})
\end{aligned} \tag{14}$$

The sign in Eq. 14 is chosen to reproduce the ratio  $S_{00}(0)/S_{11}(0)$  for the central value of the form factors in Ref. [54].

For nuclei whose form factors are not known one can use the routine

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

which is similar to the function **nucleusRecoil** except that the spin dependent nuclei form factors are described by Gauss functions [5] whose values at zero momentum transfer are defined by the coefficients **Sp,Sn**. Predefined values for the coefficients **Sp,Sn** in the format

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

are presented in the file `include/micromegas.h`. For example,

```
#define Sn_He3      0.552
#define Sn_017      0.5
```

### 7.2.2 Velocity distribution

Ignoring the direction of motion of DM particles and the small effect of DM acceleration by the gravitational field of the Sun, the DM velocity distribution in the vicinity of the

direct detection experiment is given by

$$f(\mathbf{v}) = \int_{|\vec{v}| < \mathbf{vEsc}} d^3\vec{v} F_G(\vec{v} - \vec{v}_{Earth}) \delta(\mathbf{v} - |\vec{v}|) \quad (15)$$

where  $F_G$  is the DM velocity distribution in the frame of the galaxy,  $\vec{v}_{Earth}$  is the velocity of the Earth in the Galaxy and  $\mathbf{vEsc}$  is the maximal DM velocity in the Sun's orbit due to the finite gravitational potential of our Galaxy.  $\mathbf{vEsc}$  and  $\mathbf{vEarth} = |\vec{v}_{Earth}|$  are global parameters of micrOMEGAs.

The velocity distributions that are available in `micrOMEGAs` are the following

- `Maxwell(v)`

returns

$$F_G^M(\mathbf{v}) = c_{\text{norm}} \frac{1}{(2\pi \mathbf{vRot}^2)^{3/2}} \exp\left(-\frac{(\vec{v})^2}{\mathbf{vRot}^2}\right) \theta(\mathbf{vEsc} - |\vec{v}|) \quad (16)$$

which corresponds to the isothermal model. Here  $\mathbf{vRot}$  is the orbital velocity of stars in the Milky Way, it is also a global parameter of micrOMEGAs.  $c_{\text{norm}}$  is the normalization factor,

$$c_{\text{norm}}^{-1} = \text{erf}\left(\frac{\mathbf{vEsc}}{\mathbf{vRot}}\right) - \frac{2}{\sqrt{\pi}} \frac{\mathbf{vEsc}}{\mathbf{vRot}} \exp\left(-\frac{\mathbf{vEsc}^2}{\mathbf{vRot}^2}\right) \quad (17)$$

- `SHMpp(v)`

returns the velocity distribution `SHM++` proposed in [55].

$$F_G(\vec{v}) = (1 - \eta) F_G^M(\mathbf{v}) + \eta F_G^S(\mathbf{v}) \quad (18)$$

This distribution consists of two components. The first,  $F_G^M(\vec{v})$ , is the standard Maxwell velocity distribution described above. The second component is the velocity distribution from the *Gaia* sausage [56, 57], it is not spherically symmetric and is defined by the anisotropy parameter  $\beta$  with

$$F_G^S(\vec{v}) = \frac{c_{\text{norm}}}{(2\pi)^{3/2} \Delta v_r \Delta v_\theta \Delta v_\phi} \exp\left(-\left(\frac{v_r}{\Delta v_r}\right)^2 - \left(\frac{v_\theta}{\Delta v_\theta}\right)^2 - \left(\frac{v_\phi}{\Delta v_\phi}\right)^2\right) \theta(\mathbf{vEsc} - |\vec{v}|) \quad (19)$$

where

$$\Delta v_r = \frac{\mathbf{vRot}}{\sqrt{1 - \frac{2}{3}\beta}}, \quad \Delta v_\phi = \Delta v_\theta = \frac{\mathbf{vRot} \sqrt{1 - \beta}}{\sqrt{1 - \frac{2}{3}\beta}} \quad (20)$$

and

$$c_{\text{norm}}^{-1} = \text{erf}\left(\frac{\mathbf{vEsc}}{\mathbf{vRot}}\right) - \left(\frac{1 - \beta}{\beta}\right)^{1/2} \exp\left(-\frac{\mathbf{vEsc}^2}{\mathbf{vRot}^2}\right) \text{erfi}\left(\frac{\mathbf{vEsc}}{\mathbf{vRot}} \frac{\beta^{1/2}}{(1 - \beta)^{1/2}}\right) \quad (21)$$

where `erfi` is the imaginary error function.

The central values and uncertainties of the `SHM++` parameters are

$$\begin{aligned} \text{rhoDM} &= 0.55 \pm 0.17 \text{ GeV/cm}^3 \\ \mathbf{vRot} &= 233 \pm 3 \text{ km/s} \\ \mathbf{vEsc} &= 580 \pm 63 \text{ km/s} \\ \beta = \text{betaSHMpp} &= 0.9 \pm 0.05 \\ \eta = \text{etaSHMpp} &= 0.2 \pm 0.1 \end{aligned} \quad (22)$$

Note that these central values for the global parameters, `vRot`, `vEsc` and `rhoDM` are different from the ones in Table 1, thus the user has to change these parameters before using SHMpp.

### 7.3 Comparison with Direct Detection experiments

Examples on how to use the routines described below to impose constraints from direct detection experiments can be found in `mdlIndep/dd_exp.c` of micrOMEGAs.

#### 7.3.1 Experimental data

The SI 90% DD limits tabulated from the results presented by XENON1T [58], DarkSide-50 [59], PICO-60 [60] and CRESST-III [61] are accessible through the following functions

- `XENON1T_90(Mdm)` for  $6 < M_{DM} < 1000$  GeV, [58]
- `DS50_90(Mdm)` for  $0.7 < M_{DM} < 15$  GeV, [59]
- `PICO60_90(Mdm)` for  $3 < M_{DM} < 10000$  GeV, [60]
- `CRESST_III_90(Mdm)` for  $0.35 < M_{DM} < 12$  GeV. [61]

The corresponding SD 90% exclusion limits are contained in the functions

- `PICO60_SDp_90(Mdm)` for  $3 < M_{DM} < 10000$  GeV, [60]
- `XENON1T_SDp_90(Mdm)` for  $6 < M_{DM} < 1000$  GeV, [62]
- `XENON1T_SDn_90(Mdm)` for  $6 < M_{DM} < 1000$  GeV, [62]
- `CRESST_III_SDn_90(Mdm)` for  $0.35 < M_{DM} < 12$  GeV. [61]

These functions give the excluded cross sections in  $\text{cm}^2$ . For a DM mass outside the range specified the function returns NaN.

#### 7.3.2 Recasting the experimental limits with micrOMEGAs

- `DD_pvalCS(expCode, fv,  $\sigma_{SI_P}$ ,  $\sigma_{SI_N}$ ,  $\sigma_{SD_P}$ ,  $\sigma_{SD_N}$ , &expName)`  
calculates the value  $\alpha = 1 - C.L.$  for a model with DM-nucleon cross sections  $\sigma_{SI_P}$ ,  $\sigma_{SI_N}$ ,  $\sigma_{SD_P}$ ,  $\sigma_{SD_N}$ . Cross sections are specified in [pb] units. The return value 0.1 corresponds to a 90% exclusion. The `expCode` parameter can be any of the codes `XENON1T_2018`, `DarkSide_2018`, `CRESST_2019`, `PICO_2019` or their combination concatenated with the symbol `|`. There is also a predefined parameter that currently combines these experiments

`AllDDexp=XENON1T_2018|DarkSide_2018|PICO_2019|CRESST_2019;`

The parameter `char* expName` is used to indicate the experiment that provides the best exclusion among those specified in `expCode`. The function `DD_pvalCS` calculates the exclusion for each experiment independently, returns the smallest  $\alpha$ , and assigns the name of the corresponding experiment to `expName` if it is not NULL.

The  $f_v$  parameter specifies the DM velocity distribution in the detector frame. For example, one can use `Maxwell` or `SHMpp` which are included in micrOMEGAs, otherwise the user can define another distribution. The DM velocity distribution has to be normalized as in Eq.8. The units are  $\text{km/s}$  for  $v$  and  $\text{s/km}$  for  $f_v(v)$ . `DD_pvalCS` implicitly depends on

the global parameters `Mcdm` and `rhoDM` which specify the DM mass and DM local density respectively.

For Xenon1T one can chose between three recasting,  $p_{eff}^q$  with  $q = 0, 1, 2$ , see Ref. [63]. The flag `Xe1TnEvents=q` allows to choose the corresponding recasting, otherwise and by default the code uses  $p_{eff}^1$ . The three approaches agree within 5%. For PICO-60, the user can choose between the recasting based on Feldman-Cousins statistics, `PICO60Flag=0` which is the default value, or the one based on Neyman one side belt exclusion, `PICO60Flag=1`.

- `DD_factorCS(expCode,  $\alpha$ ,  $f_v$ ,  $\sigma_{SI_P}$ ,  $\sigma_{SI_N}$ ,  $\sigma_{SD_P}$ ,  $\sigma_{SD_N}$ , &expName)`

returns the overall factor which should be applied to the cross sections,  $\sigma_{SI_P}$ ,  $\sigma_{SI_N}$ ,  $\sigma_{SD_P}$ ,  $\sigma_{SD_N}$  to reach the exclusion level  $\alpha$ . All parameters are the same as in `DD_pvalCS` above.

- `*dNdEFact(Enr_kev, A)`

is the address of the function which modifies the nucleus recoil distribution for `DD_pvalCS` and `DD_factorCS` to take into account a t-channel propagator with small or zero mass. By default `dNdEfact=NULL` and this function does not contribute to the calculation of the direct detection cross sections. Otherwise it is taken as an additional factor in the nucleus recoil distribution, see Eq.9. The parameter `Enr_kev` is the recoil energy in [keV] units, `A` is the atomic number of the nucleus. This function should be defined by the user, an example is given in `mdlIndep/dd_exp.c`.

- `DD_pval(expCode,  $f_v$ , &expName)`
- `DD_factor(expCode,  $\alpha$ ,  $f_v$ , &expName)`

These functions are similar to `DD_pvalCS` and `DD_factorCS` described above but use the cross section calculated from the DM model under consideration in micrOMEGAs. The necessary corrections for a light mediator are implemented automatically, these functions do not use `dNdEFact`.

### 7.3.3 Setting spin-dependent form factors

The spin dependent form factors for XENON1T and PICO60 are defined via the parameters

`XENON1T_2018_sdXe129`      `XENON1T_2018_sdXe131`      `PICO_2019_sdF19`

The default values for these parameters correspond to the ones used by the experiments, namely

`SxxXe129SHELL`      `SxxXe131SHELL`      `SxxF19EFT`

They can be replaced by any form factor listed in Section 7.2.1 through direct assignment. Form factors can also be changed using the routine

- `setSpinDepFF(ExperimentID, setID)`

where the choice for `ExperimentID` is given in Section 7.3.2 and `setID` can be

`EFT` - corresponding to the form factors in [53]

`SHELL` - corresponding to the average form factors in [54], Eq. 13

`SHELLm` - corresponding to the minimal form factor of [54], Eq. 14. See section 7.2.1.

## 8 Indirect detection

### 8.1 Interpolation and display of spectra

Various spectra and fluxes of particles relevant for indirect detection are stored in arrays with **NZ=250** elements. To decode and interpolate the spectrum array one can use the following functions:

- **SpectdNdE(E,spectTab)**

interpolates the tabulated spectra and returns the particle distribution  $dN/dE$  where **E** is the energy in GeV. For a particle number distribution the returned value is given in  $\text{GeV}^{-1}$  while a particle flux is expressed in  $(\text{sec cm}^2 \text{ sr GeV})^{-1}$ .

To display the spectra as a function of energy one can use function **displayPlot**.

Even though the user does not need to know the structure of the spectrum array, we describe it below. The first (zeroth) element of the array contains the maximum energy  $E_{max}$ . As a rule  $E_{max}$  is the mass of the DM particle. The  $i^{th}$  element ( $1 \leq i < NZ - 1$ ) of the spectrum array contains the value of  $E_i \frac{dN}{dE_i}$  where  $E_i = E_{max} e^{Zi(i)}$ ,  $Zi(i) = -7 \ln 10 \left( \frac{i-1}{NZ} \right)^{1.5}$ . That is the array covers the energy interval  $E_{max} \geq E > 10^{-7} E_{max}$ .

- **addSpectrum(Spect,toAdd)**

sums the spectra **toAdd** and **Spect** and writes the result in **Spect**. For example, this routine can be useful for summing spectra with different maximal energy.

- **spectrMult(Spec, func)**

allows to multiply the spectrum **Spec** by any energy dependent function **func**

- **spectrInt(Emin,Emax,Spec)**

integrates a spectrum/flux, **Spec** from **Emin** to **Emax**.

- **spectrInfo(Emin,Spec,&Etot)**

provides information on the spectra. The returned value and **Etot** corresponds respectively to

$$N_{tot} = \int_{E_{min}}^{E_{max}} SpectdNdE(E, Spec) dE = spectrInt(E_{min}, E_{max}, Spec) \quad (23)$$

$$E_{tot} = \int_{E_{min}}^{E_{max}} E SpectdNdE(E, Spec) dE \quad (24)$$

where the first element of the table **Spec** contains the value of  $E_{max}$ .

### 8.2 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 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**, **Sne**, **Snm**, **Snl**. To remove the calculation of a given spectra, substitute **NULL** for the corresponding argument. **key** is a switch to include the polarisation

of the  $W, Z$  bosons (**key=1**) or photon radiation (**key=2**). Note that final state photon radiation (FSR) is always included. When **key=2** the 3-body process  $\chi\chi' \rightarrow XX + \gamma$  is computed for those subprocesses which either contain a light particle in the t-channel (of mass less than 1.2 Mcdm) or an outgoing  $W$  when  $\text{Mcdm} > 500\text{GeV}$ . The FSR is then subtracted to avoid double counting. Only the electron/positron spectrum is modified with this switch. When **key=4** the contributions for each channel to the total annihilation rate 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  $W$  polarization and photon radiation effects are included if **key=3**. A problem in the spectrum calculation will produce a non zero error code,  $\text{err} \neq 0$ . `calcSpectrum` interpolates and sums spectra obtained by Pythia. The spectra tables are provided only for  $\text{Mcdm} > 2\text{GeV}$ . The results for a dark matter mass below 2 GeV will therefore be wrong, for example an antiproton spectrum with kinematically forbidden energies will be produced. A warning is issued for  $\text{Mcdm} < 2\text{GeV}$ .

- **vSigmaCh**

is an array that contains the relative contribution and particle names for each annihilation channel. It is similar to `vSigmaTCh` described in Section 6.2. Note that the list of particles contains five elements to allow to include gamma radiation. For 2->2 processes `vSigmaCh[n].prctl[4]=NULL`. The array `vSigmaCh` is filled by `calcSpectrum`.

### 8.3 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

$$\rho(r) = \rho_{\odot} F_{\text{halo}}(r) \quad (25)$$

In `micrOMEGAs`  $\rho_{\odot}$  is a global parameter `rhoDM` and the Zhao profile [64]

$$F_{\text{halo}}(r) = \left(\frac{R_{\odot}}{r}\right)^{\gamma} \left(\frac{r_c^{\alpha} + R_{\odot}^{\alpha}}{r_c^{\alpha} + r^{\alpha}}\right)^{\frac{\beta-\gamma}{\alpha}} \quad (26)$$

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 function to set another density profile is

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

where  $F_{\text{halo}}(r)$  is any function which depends on the distance from the galactic center,  $r$ , defined in [kpc] units. For instance, `setHaloProfile(hProfileEinasto)` sets the Einasto profile

$$F_{\text{halo}}(r) = \exp\left[-\frac{2}{\alpha} \left(\left(\frac{r}{R_{\odot}}\right)^{\alpha} - 1\right)\right] \quad (27)$$

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

- `setProfileEinasto( $\alpha$ )`

The command `setHaloProfile(hProfileZhao)` sets back the Zhao profile. Note that

both `setProfileZhao` and `setProfileEinasto` call `setHaloProfile` to define 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 [65]. 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  $\rho_{cl}$ . Assuming clumps do not overlap, we get

$$\langle \rho^2 \rangle = \rho^2 + f_{cl} \rho_{cl} \rho. \quad (28)$$

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 the galactic center. The effect of clumping is then described by the equation

$$\langle \rho^2 \rangle(r) = \rho(r)(\rho(r) + \rho_{clump}^{eff}(r)), \quad (29)$$

and the function

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

allows to implement a more sophisticated clump structure. To return to the default treatment of clumps call `setRhoClumps(rhoClumpsConst)` or `setClumpConst`.

## 8.4 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 in  $1/(\text{GeV cm}^2 \text{ s})$  units.

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

- `gammaFluxTabGC( $l, b, dl, db, sigmav, Sg, Sobs$ )`

is similar to `gammaFluxTab` but uses standard galactic coordinates. Here  $l$  is the galactic longitude (measured along the galactic equator from the galactic center, and  $b$  is the latitude (the angle above the galactic plane). Both  $l$  and  $b$  are given in radians. The relation between the angle `fi` used above and the galactic coordinates is  $fi = \cos^{-1}(\cos(l) \cos(b))$ . `gammaFluxTabGC` integrates the flux over a rectangle  $[(l, b) - (l + dl, b + db)]$ .

- `loopGamma(&vcs_gz, &vcs_gg)`

calculates  $\sigma v$  for loop induced processes of DM pair annihilation into  $\gamma Z$  and into  $\gamma\gamma$ . The result is given in  $\frac{\text{cm}^3}{\text{s}}$ . The function returns a non-zero value to signal a problem. This function is available only for MSSM [66], NMSSM [67], CPVMSSM and IDM. Note that this function does not include non-perturbative effects that are in particular important when the mass of DM is much above the weak scale [68, 69].

- `gammaFlux(fi,dfi,dSigmavdE)`

computes the photon flux for a given energy  $E$  and a differential cross section for photon production, `dSigmavdE`. For example, one can substitute `dSigmavdE=sigma*SpecdNdE(E,SpA)` where  $\sigma$  and  $SpA$  are obtained by `calcSpectrum`. This function can also be used to compute the flux from a monochromatic gamma-ray line by substituting the cross section at fixed energy (in  $cm^3/s$ ) instead of `dSigmavdE`, for example the cross sections obtained with the `loopGamma` function in the MSSM, NMSSM, CPVMSSM models (`vcsAA` and `vcsAZ`). In this case the flux of photons can be calculated with `gammaFlux(fi,dfi,2*vcsAA+vcsAZ)`.

- `gammaFluxGC(l,b,dl,db,vcs)`

is the analog of `gammaFlux` when using standard galactic coordinates.

## 8.5 Propagation of charged particles

The observed spectrum of charged particles 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 the interpolation, in this case the flux is returned in  $(GeV\ s\ cm^2sr)^{-1}$ .

- `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=sigma*SpecdNdE(E,SpP)`

where  $\sigma$  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.



## 9 Neutrino signal from the Sun and the Earth

*This module does not work yet in case of 2DM*

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. The neutrino spectra originating from different annihilation channels into SM particles and taking into account oscillations and Sun medium effects were computed both in `WimpSim` [70] and in `PPPC4DM $\nu$`  [71]. We use the set of tables provided by these two groups as well as those from `DM $\nu$`  [72] which were included in previous versions of `micrOMEGAs`. The new global parameter `WIMPSIM` allows to choose the neutrino spectra. The default value `WIMPSIM=0`<sup>4</sup> corresponds to the `PPPC4DM $\nu$`  spectra while `WIMPSIM=1` corresponds to the `WimpSim` spectra and `WIMPSIM=-1` to the `DM $\nu$`  spectra.

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

calculates the 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)`. For example, one can use the same `Maxwell` function introduced for direct detection. This routine implicitly depends on the `WIMPSIM` switch.

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  $[1/Year/km^2]$ .

- `muonUpward(nu,Nu,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`. `muon` is an array which stores the resulting sum of  $\mu^+$ ,  $\mu^-$  fluxes. `SpectdNdE(E,muon)` gives the differential muon flux in  $[1/Year/km^2/GeV]$  units. The muon flux weakly depends on the propagation medium, e.g. rock or ice. The energy lost during propagation is described by the equation [73]

$$\frac{dE}{dx} = -(\alpha + \beta E)\rho \quad (30)$$

For propagation in ice (the switch `forRocks=0`), `micrOMEGAs` substitutes  $\rho = 1.0 g/cm^3$ ,  $\alpha = 0.00262 GeVcm^2/g$ ,  $\beta = 3.5 \times 10^{-6} cm^2/g$  [74], while for propagation in rocks,  $\rho = 2.6 g/cm^3$ ,  $\alpha = 0.002 GeVcm^2/g$ ,  $\beta = 3.0 \times 10^{-6} cm^2/g$  [73]. The result depends on the ratio  $\alpha/\beta$ .

- `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  $km^3$  volume given in  $[1/Year/km^3/GeV]$  units. `rho` is the density of the detector in  $g/cm^3$ .

- `atmNuFlux(nu,cs,E)`

returns the atmospheric muon neutrinos ( $nu > 0$ ) and anti-neutrinos spectrum ( $nu < 0$ )

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<sup>4</sup>Since `PPPC4DM $\nu$`  does not provide neutrino spectra produced at the center of the Earth, in this case and for `WIMPSIM=0` `micrOMEGAs` uses the `DM $\nu$`  spectra.

in  $[1/\text{Year}/\text{km}^2]$  units for a given cosine of the zenith angle, `cs`. This function is based on [75].

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 the sum of muon and anti-muon fluxes resulting from the interaction of atmospheric neutrinos with rocks in units of  $[1/\text{Year}/\text{km}^2/\text{GeV}/\text{Sr}]$ . `cosFi` is the energy between the direction of observation and the direction to the center of Earth. `E` is the muon energy in `GeV`. The result depends on the `forRock` switch.

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

## 9.1 Comparison with IceCube results

These functions are described in [76] and allow to compare the predictions for the neutrino flux from DM captured in the Sun with results of IceCube22.

- `IC22nuAr(E)`

effective area in  $[\text{km}^2]$  as a function of the neutrino energy,  $A_{\nu_\mu}(E)$

- `IC22nuBarAr(E)`

effective area in  $[\text{km}^2]$  as a function of the anti-neutrino energy,  $A_{\bar{\nu}_\mu}(E)$ .

- `IC22BGdCos(cs)`

angular distribution of the number of background events as a function of  $\cos \phi$ ,  $\frac{dN_{bg}}{d\cos \phi}$ .

- `IC22sigma(E)`

neutrino angular resolution in radians as a function of energy.

- `exLevIC22( nu_flux, nuB_flux,&B)`

calculates the exclusion confidence level for number of signal events generated by given  $\nu_\mu$  and  $\bar{\nu}_\mu$  fluxes, [76]. The fluxes are assumed to be in  $[\text{GeV km}^2 \text{ Year}]^{-1}$ . This function uses the `IC22BGdCos(cs)` and `IC22sigma(E)` angular distribution for background and signal as well as the event files distributed by IceCube22 with  $\phi < \phi_{cut} = 8^\circ$ . The returned parameter `B` is a Bayesian factor representing the ratio of likelihood functions for the model with given fluxes and the model with null signal. See details in [76].

- `fluxFactorIC22(exLev, nu,nuBar)`

For given neutrino, `nu`, and anti-neutrino fluxes, `nuBar`, this function returns the factor that should be applied to the fluxes (neutralino-proton cross sections) to obtain a given exclusion level `exLev` in `exLevIC22`. This is used to obtain limits on the SD cross section for a given annihilation channel.

## 10 Cross sections and decays

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

- `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 when `VWdecay,VZdecay= 0`. If not, `pWidth` compiles all open  $1 \rightarrow 3$  channels and use these for computing the width. If

all 1→3 channels are kinematically forbidden, `micrOMEGAs` compiles 1→4 channels. If `VWdecay(VZdecay) ≠ 0`, then `micrOMEGAs` also computes the processes with virtual  $W(Z)$  and adds these to the 1→2 decay channels. Note that 1→3 decay channels with a virtual  $W$  will be computed even if the mass of the decaying particle exceeds the threshold for 1→2 decays by several GeV's. This is done to ensure a proper matching of 1→2 and 1→3 processes. For particles other than gauge bosons, an improved routine with 3-body processes and a matching between the 1→2 and 1→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`. For models which read a SLHA parameter file, the values of the widths and branchings are taken from the SLHA file when `useSLHAwidth=1`.

- `printTxtList(address,FD)`

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

An option to calculate the width of any particle including the contribution from channels with different number of outgoing particles is defined

- `pWidthPref(particle_name, pref)` defines the switches for `pWidth` described above. By default `pWidth` checks the value of the `useSLHAwidth` flag, if `useSLHAwidth! = 0` and there are decay data in the loaded SLHA file, then `pWidth` returns the value stored in the file. Otherwise the widths are calculated at tree-level including only channels with the minimal number of outgoing particles. `pref` allows to override this prescription for a single particle. It can take the values

- 0 - widths are calculated using processes with minimal number of outgoing particles
- 1 – widths are calculated using processes with minimal and next to minimal number of outgoing particles excluding processes with s-channel resonances to avoid double counting.
- 2- widths are read from the SLHA file - if the SLHA file does not contain widths, they are calculated as in 0
- 3– widths are read from the SLHA file - if the SLHA file does not contain widths, they are calculated as in 1
- 4 – the default option of `pWidth` is used.

- `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. If the `pattern` contains `"*"`, then `findBr` sums all branching fractions which contain particles included in the `pattern`.

- `printPartialWidth(width,address,FD)`

prints the branching fractions and partial widths for each decay channel of a particle in the file `FD`. Here `width` and `address` are the result of the function `pWidth` described above.

- `slhaDecayPrint(pname,delVirt,FD)`

uses `pWidth` described above to calculate 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 computes  $1 \rightarrow 2$  decays. If such decays are kinematically forbidden then  $1 \rightarrow 3$  decay channels are computed. Decays via virtual W/Z bosons will be listed via their decay products when  $delVirt \neq 0$ .

- **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 in the directory **work/so-generated/**. The name of the library is generated automatically.

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.

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 electron.

- **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 an array of particle names **N** and an array of particle masses **M** for the subprocess **nsup** ( $1 \leq nsup \leq ntot$ ). 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  $P(\text{GeV})$ . All model parameters except the strong coupling **GG** can be specified with the functions **findVal[W]/assignVal[W]** described in Section 5. The strong coupling **GG** is defined via the scale parameter **GGscale**. The differential cross-section is integrated within the range  $c1 < \cos \theta < c2$ .  $\theta$  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<sup>st</sup> and 2<sup>nd</sup> 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,nf, Qren,Qfac, pName1,pName2,Tmin,wrt)** 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,  $nf \leq 5$  defines the number of quark flavors taken into account. The parameters **Qren** and **Qfac** define the renormalisation and factorization scales respectively. **pName1** and **pName2** are the names of outgoing particles. If  $T_{\min} \leq 0$  then **hCollider** calculates the total cross section for the 2-body final state process. Otherwise it calculates the cross section for

**proton, [a]proton -> pName1, pName2, jet**

where  $T_{\min} > 0$  defines the cut on the jet transverse momentum. The jet content is

defined by the parameter `nf`. If  $Q_{\text{fac}} \leq 0$ , then running  $\hat{s}$  is used for the factorization scale. If  $Q_{\text{ren}} \leq 0$ ,  $\hat{s}$  is used for the renormalization scale for a  $2 \rightarrow 2$  process and  $p_T$  of the jet is used for the renormalization scale for a process with a jet in the final state. The last argument in the `hCollider` routine allows to switch on/off (`wrt=1/0`) the printing of the contribution of individual channels to the total cross section. The value returned is the total cross section in [pb].

One of the arguments `pName1`, `pName2` can be NULL. Then the cross section for  $2 \rightarrow 1$  or  $2 \rightarrow 1 + \text{jet}$  process will be calculated.

By default `hCollider` uses the `NNPDF31_lo_as_0118` [77] structure function built-in the `micrOMEGAs` code. One can set any other parton distribution included in either `micrOMEGAs` or LHAPDF. The list of structure functions in `micrOMEGAs` can be obtained with the command

- `PDTList()`

and one of these can be activated by

- `setPDT(name)`

To work with other PDF's available in LHAPDF one should first define the environment variable `LHAPDFPATH` which specifies the path to the LHAPDF library. Then `micrOMEGAs` Makefile links it automatically. The list of available LHAPDF distributions can be obtained with the command

- `LHAPDFList`

and one of these can be activated by

- `setLHAPDF(nset,name)`

where `nset` specifies the subset number. Note, that if a wrong input is provided, `setLHAPDF` terminates the execution.

The parton densities are defined by the function

- `parton_distr(pdg,x,q)`

where `pdg` is the PDG code of a particle. Note that `parton_distr` defines the parton number density and contains a factor  $1/x$  with respect to the definition used in LHAPDF.

## 11 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/muon fluxes in neutrino telescopes. All the routines presented here depend implicitly on the global parameter `Mcdm` except for `basicSpectra` and `basicNuSpectra`. They also explicitly depend on spin-independent and spin-dependent cross sections of DM scattering on proton and neutron: `csIp`, `csIn`, `csDp`, `csDn`. These cross sections have to be specified in [pb]units. A negative value for one of these cross sections is interpreted as a destructive interference between the proton and neutron amplitudes.

These routines do not take into account the multi-component structure of DM and, in particular, possible differences between DM and anti-DM. For multi-component DM the user has to perform a summation over the different DM components.

The routines available include:

- `nucleusRecoilCS( $f_v, A, Z, J, S_{xx}, csIp, csIn, csDp, csDn, dNdE$ )`

is similar to `nucleusRecoil`, see Section 7.2.

- `nucleusRecoil0CS( $f_v, A, Z, J, Sp, Sn, csIp, csIn, csDp, csDn, dNdE$ )` is the corresponding modification of `nucleusRecoil0`.

- `DD_pvalCS(Exp, $f_v$, Sxx, csIp, csIn, csDp, csDn, \&expName)`

and

- `DD_factorCS(Exp, pval, $f_v$, Sxx, csIp, csIn, csDp, csDn, \&expName)`

are similar to `DD_pval`, `DD_factor` described in Section 7.3.

`DD_pvalCS`, `DD_factorCS` have an option to handle a low mass mediator which modifies the recoil energy distribution, see Eq.9.

- `(*dNdEfact)(Enr, MA)`

is the address of the function which modifies the nucleus recoil distribution to take into account a t-channel propagator with small or zero mass as described in Section 7.3.

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

- `basicSpectra(Mass, pdgN, outN, Spectr)`

computes the spectra of outgoing particles and writes the result in an array of dimension 250, `Spectr`, `pdgN` is the PDG code of the particles produced in the annihilation of a pair of WIMPs. To get the 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 the spectra produced by a polarized 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 `Mass` parameter defines the mass of the DM particle. 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` < 2GeV as explained in the description of `calcSpectrum`.

To get indirect detection signals one can substitute the obtained spectra in the `[photon/posi/pbar]FluxTab` routines. As long as one keeps the default setting `CDM1=CDM2=NULL` these routines will use the `Mcdm` parameter to calculate the number density of DM particles.

- `captureCS(f, forSun, Mass, 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 9. The result depends implicitly on the global parameters `rhoDM` and `Mcdm` in Table 1.

- `basicNuSpectra(forSun, Mass, pdg, pol, nu_tab, nuB_tab)`

calculates the  $\nu_\mu$  and  $\bar{\nu}_\mu$  spectra corresponding to the pair annihilation of DM in the center of the Sun/Earth into a particle-antiparticle pair with PDG code `pdg`. `Mass` is the DM mass. Note that this routine depends implicitly on the global parameter `WIMPSIM` (1,0,-1) which selects the neutrino spectra computed by `WimpSim` [70], `PPPC4DM $\nu$`  [71] and `DM $\nu$`  [72]. The parameter `pol` selects the spectra for polarized particles available in `PPPC4DM $\nu$` . `pol=-1(1)` corresponds to longitudinal (transverse) polarisation of vector bosons or to left-handed (right-handed) polarisation of fermions, `pol=0` is used for

unpolarized spectra. When polarized spectra are not available, the unpolarized ones are generated irrespective of the value of `pol`. The parameter `outN` is 1 for muon neutrino and -1 for anti-neutrino. The resulting spectrum is stored in the arrays `nu_tab` and `nuB_tab` with `NZ=250` elements.

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'.

## 12 Constraints from colliders

### 12.1 The Higgs sector

To obtain the limits on the Higgs sector for models with one or several Higgs bosons, the predictions for the signal strengths of the 125 GeV Higgs can be compared to the latest results of the LHC, for this an interface to the public code HiggsSignals [36] or Lilith [38–40] is provided. Moreover the exclusion limits obtained from Higgs searches in different channels at LEP, Tevatron and the LHC can be applied to other Higgses in the model using HiggsBounds [34].

#### 12.1.1 Lilith

Lilith [38–40] is a Python library that is used to construct a global likelihood function  $\mathcal{L}$  from the latest ATLAS and CMS results on the 125 GeV Higgs.<sup>5</sup> The Lilith inputs are the set of reduced couplings of the 125 GeV state, *i.e.*, couplings normalized by the SM ones, as well as the branching ratios of Higgs decays to invisible,  $\text{BR}_{\text{inv}}$ , or to undetected non-SM final states,  $\text{BR}_{\text{undetected}} = 1 - \text{BR}_{\text{inv}} - \sum \text{BR}(H \rightarrow \text{SM SM})$ . By default, the automatic generation of the input file assumes that only DM contributes to the invisible width. Note that the reduced couplings of the 125 GeV Higgs are defined for all the models provided with micrOMEGAs with the exception of the  $Z\gamma$  coupling. The latter is computed within Lilith assuming that only SM particles run in the loop. The file `include/Lilith.inc` (or `Lilith.inc_f`) contains the instructions to launch Lilith using a system call. The input file `Lilith_in.xml` for Lilith can be created by two commands

```
LilithMDL("Lilith_in.xml")
LilithMO("Lilith_in.xml")
```

both also return the number of neutral Higgs particles. `LilithMDL` requires that the reduced couplings be defined in `lib/lilith.c` of the model. These files are defined for all models provided with micrOMEGAs and should be written by the user for new models. On the other hand `LilithMO` generates automatically the input file required by Lilith. The functionality of `LilithMO` is described in Section 12.1.3. As input parameters, Lilith

---

<sup>5</sup>Lilith can test Higgs bosons with masses within the [123, 128] GeV interval, a warning will be issued if no such state can be found. In the case where two or more states have masses within this interval, their signal strengths will be summed incoherently and an effective Higgs state will be tested against the LHC measurements.



also requires the number of free parameters, `n_par`, and a reference likelihood point, `m2logL_reference`. Those are defined in the `main.c` file of each model and set to 0 by default.

The SLHA output file, `Lilith_out.slha`, consists of six entries which are respectively the log-likelihood evaluated at a parameter space point  $\mathcal{P}$ ,  $-2 \log \mathcal{L}(\mathcal{P})$ , the number of experimental degrees of freedom,  $n^{exp}$ , the reference likelihood point, the number of degrees of freedom,  $ndf$ , the p-value,  $p$  and the database version. For a detailed description of the various outputs and their interpretation see [38,39]. For example, one could flag or exclude points with too low p-value. In this context, a point with a p-value smaller than 0.3173, 0.0455, 0.0027 could be excluded at more than the  $1\sigma$ ,  $2\sigma$ ,  $3\sigma$  levels, respectively.

### 12.1.2 HiggsBounds and HiggsSignals

Constraints on the properties of the 125 GeV Higgs boson can also be obtained with `HiggsSignals`. Moreover exclusion limits provided by the experimental LHC and Tevatron collaborations on additional Higgs bosons are obtained through an interface to `HiggsBounds` [78]. These codes are no longer distributed with `micrOMEGAs` but are downloaded when required. The file `include/hBandS.inc` contains the instructions to call both `HiggsBounds` and `HiggsSignals`, in particular the options for running `HiggsSignals` are set in this file by fixing the `Dataset`, `Method` and `PDF` parameters. Moreover the interface uses the effective coupling option for specifying the input see [34] for more details. Two functions can be used to generate the input SLHA file, `HB.in`

```
hbBlocksMDL("HB.in",&NchHiggs)
hbBlocksM0("HB.in",&NchHiggs)
```

Both return the number of neutral Higgses and `NchHiggs` gives the number of charged Higgs particles. The function `hbBlocksMDL` is located in `lib/hbBlocks.c` for each MSSM-like model and contains the appropriate definition of the reduced couplings. The function `hbBlocksM0` generates automatically the required input file for any model and is thus very convenient to use for new models. The content of this function is described in Section 12.1.3. Note that the PDG numbers which will be considered by `HiggsBounds` for Higgs-like particles are only 25, 35, 36, 37, 45, and 46. Moreover `HiggsBounds` will check the contribution to the Higgs invisible width only for particles with PDG codes 1000022, 1000012, 1000014, 1000016, 1000017, 1000018 or 1000019. Also note that the theoretical uncertainty on the mass of the Higgs boson should be specified in the SLHA BLOCK `DMASS`, see the example given in `main.c/F` to set the uncertainty at 2 GeV.

The complete outputs of `HiggsBounds` and `HiggsSignals` are stored in the files `HB.out` and `HS.out` respectively and can be accessed and read by the user using the `slhaval` function [79]. The screen output of `micrOMEGAs` contains the following information

```
HiggsBounds(version number)
id   result  obsratio  channel
```

where three channels are listed, `result` = 0, 1, -1 denotes respectively whether a parameter point is excluded at 95% CL, not excluded, or invalid; `obsratio` gives the ratio of the theoretical expectation relative to the observed value for the channel specified in `channel`.



The first channel in this list is the one with the highest expected sensitivity and is the one that determines the overall exclusion, see [34], other channels are to be interpreted by the user.

The `HiggsSignals` output displayed on the screen is simply

```
HiggsSignals(version number)
Nobservables chi^2 pval
```

where `Nobservables` gives the number of observables used in the fit, `chi^2` the associated  $\chi^2$  and `pval` the p-value. The interpretation of these values is left to the user, see [36] for a detailed description.

### 12.1.3 Automatic generation of interface files

The functions `LiLithM0` and `hbBlocksM0` contain two routines that allow to extract the couplings contained in the model file, `lgrng1.mdl`. The first routine returns a description of a given vertex. The format used is

```
lVert* vv=getLagrVertex(name1,name2,name3,name4);
```

where `name1,...,name4` are the names of the particles included in the vertex; for vertices with three particles, `name4` should be replaced by `NULL`. The return parameter `vv` is the memory address of a structure which contains information about the vertex:

- `vv->GGpower` - power of strong coupling included in vertex
- `vv->nTerms` - number of different Lorentz structures in vertex
- `vv->SymbVert[i]` - text form of Lorentz structures  $i \in [0, nTerms]$

The second routine allows to obtain the numerical coefficients corresponding to each Lorentz structure. The command is

```
getNumCoeff(vv,coeff)
```

with `coeff[i]` the numerical coefficient for `SymbVert[i]`. Note that the strong coupling is factored out of the coefficients.

All the QCD-neutral scalars belonging to the even sector (not designated with  $\sim$ ) are considered as Higgs particles. For each of these, `micrOMEGAs` calculates the couplings to SM fermions and massive bosons and writes down into the interface file the ratio of these couplings to the corresponding SM Higgs coupling. Note that the couplings of the Higgs to SM fermions can significantly depend on the QCD scale; `micrOMEGAs` assumes that the quark masses entering the vertices are obtained at the same scale in both the SM and the new model, thus the scale dependence in the reduced couplings to fermions disappears. The loop-induced couplings of the Higgs to gluons and photons are calculated by the `LiLithM0/hbBlocksM0` routines whether or not the  $Hgg$  and  $H\gamma\gamma$  vertices are already implemented in the Lagrangian. This includes NLO-QCD corrections and is performed as described in [7, 80].

The various branching ratios and widths of the Higgs required by `HiggsBounds`, `HiggsSignals` or `LiLith` are also written automatically in the interface file. When these values are provided in an SLHA file, they will be used. Otherwise `LiLithMO/hbBlocksMO` check the existence of  $H \rightarrow gg$  and  $H \rightarrow \gamma\gamma$  in the table of decays generated from the model Lagrangian. If found, the branching ratios and total widths are written in the interface file without comparing with the internal calculations. If not found, then `LiLithMO/hbBlocksMO` add these channels and recompute the total widths and all branching ratios.

## 12.2 Searches for New particles

### 12.2.1 SModels

LHC limits on new (odd) particles can be obtained using `SModels` [41–44], a code which tests Beyond the Standard Model (BSM) predictions against Simplified Model Spectra (SMS) results from ATLAS and CMS searches for new physics. `SModels` decomposes any BSM model featuring a  $Z_2$ -like symmetry into its SMS components using a generic procedure where each SMS is defined by the vertex structure and the SM final state particles; BSM particles are described only by their masses, production cross sections and branching ratios. The underlying assumption is that differences in the event kinematics (e.g. from different production mechanisms or from the spin of the BSM particle) do not significantly affect the signal selection efficiencies. This provides a very fast way to cast BSM predictions for the LHC in a model independent framework, which can be directly confronted with the relevant experimental constraints; for the time being these are constraints from searches for R-parity conserving SUSY and, since version 1.2 [43, 81], also from certain searches for long-lived particles. `micrOMEGAs` is now interfaced to the recently released version 2.0 of `SModels` [44], which among other novelties features an improved treatment of lifetime-dependent constraints.

For running `SModels`, `micrOMEGAs` automatically generates

- an SLHA-type input file, containing the mass spectrum, decay tables<sup>6</sup> and production cross sections for the parameter point under investigation; moreover, this file contains QNUMBER blocks for the BSM particles as specification of the model.<sup>7</sup>

This input file, per default called `smodels.slha`, is located in the same directory as `main.c` and is written by `micrOMEGAs` by calling the function

```
smodels(Pcm, nf, csMinFb, fileName, version, wrt)
```

where `Pcm` is the proton beam energy in GeV and `nf` is the number of parton flavors used to compute the production cross sections of the odd-sector particles. (Note that  $u$ ,  $d$ ,  $\bar{u}$ ,  $\bar{d}$  and gluons are always included while  $s$ ,  $c$ , and  $b$  quarks are included for `nf` = 3, 4, 5 respectively.) By default `micrOMEGAs` uses the `NNPDF31_lo_as_0118` structure functions (set in the `hCollider()` function, see section 10). `csMinFb` defines the minimum production cross section in pb for odd particles; processes with lower cross sections are not added to the SLHA file passed to `SModels`, here denoted by `fileName`. Finally, `wrt`

<sup>6</sup>Note that all decay products in the decay table need to be on-shell.

<sup>7</sup>This is different from the interface to the `SModels`v1.x series, where two files were generated, an SLHA-type input file called `smodels.in` and a `particles.py` file defining the particle content of the model; see [9] for details.

is a steering flag for the screen output; if `wrt`  $\neq 0$  the computed cross sections will be also written on the screen.

The call of `smodels()` is by default done in the file `micromegas_5.2.X/include/SMODELS.inc`. For this functionality, the user first needs to specify which series of LHC results should be considered. This is done by setting in `main.c` the switch

`LHCrun = LHC8 and/or LHC13`

for Run 1 (8 TeV), Run 2 (13 TeV) or both. This determines whether 8 TeV or 13 TeV cross sections or both will be appended to the SLHA file, which in turn determines which simplified model results will be considered from the `SModelS` database.

The run parameters for `SModelS` can be set in the file

`micromegas_5.2.X/include/smodels_parameters.ini`.

This concerns for example the parameter `sigmacut`, which is the cutoff cross section for topologies to be considered in the decomposition. Another important option is the switch `combineSRs` (True/False), which turns the combination of signal regions on or off when a covariance matrix or full JSON likelihood is available, see [43, 82]. Also the database version to be used is set in this parameters file; the default is `path = official`, which means that the official database pickle file corresponding to the `SModelS` code version will be downloaded and used. An interesting alternative may be to set `path = latest`, in which case always the latest available database will be used. For detailed information on the different options and parameters available, see the [online SModelS manual](#).

The output is written in SLHA-type format to `smodels.slha.smodelsslha`, (or an alternative name selected by the user in `SMODELS.inc`). This output consists of the following blocks:

- `SModelS_Settings`, which lists the `SModelS` code and database versions as well as input parameters for the decomposition;
- `SModelS_Exclusion`, which contains as the first line the status information if a point is excluded (1), not excluded (0), or not tested (−1), the latter being reported when no matching SMS results are found; and
- `SModelS_Coverage`, which, if `testCoverage` is set to True (default) in the parameters file, lists the cross sections of missing topologies with prompt and/or displaced decays, and of topologies outside the grids of the experimental results

If a point is excluded (status 1), this is followed by a list of all results with  $r > 1$ , starting from the highest  $r$ -value. We remind the user that the `SModelS`  $r$ -values are defined as the ratio of the predicted theory cross section and the corresponding experimental upper limit at 95% confidence level. For each of these results, the SMS topology identifier as entry 0 (so-called Tx-name, see the [online SMS dictionary](#) for an explanation of the terminology), the  $r$ -value as entry 1, a measure of condition violation as entry 2, and the analysis identifier as entry 3 are listed. If the point is not excluded (status 0), the result with the highest  $r$ -value is given instead to show whether a point is close to the exclusion limit or not.

Last but not least, in order to exploit decay channels involving a SM-like Higgs for which the experimental collaborations assume SM branching ratios for the  $h$  with the

mass fixed to  $m_h = 125$  GeV, **micrOMEGAs** checks whether neutral scalar particles with a mass in the range 123–128 GeV have branching ratios to  $WW, ZZ, \tau\tau, b\bar{b}$  within 15% of those of a SM Higgs of the same mass. The corresponding particle will be identified as a SM Higgs by an entry of type

```
25 : "higgs",
-25 : "higgs"
```

in the **rEven** dictionary in the file **particles.py**. Note that the name **higgs** is reserved for a SM-like Higgs and should not be assigned generically. If no particle of that name is identified, then the corresponding SMS results requiring a Higgs in the final state are not used by **SModelS** to constrain the parameter point.

### 12.2.2 Other limits

Limits from searches for a new massive Abelian gauge boson at the LHC, from LEP on an invisible  $Z$  as well as limits on light neutralinos from LEP are provided through the functions:

- **Zinvisible()**

returns 1 and prints a WARNING if the invisible width of the  $Z$  boson of the Standard Model is larger than 0.5 MeV ([83]) and returns 0 if this constraint is fulfilled. This routine can be used in any model with one DM where the  $Z$  boson is uniquely defined by its PDG=23 and whether the neutral LSP is its own antiparticle or not.

- **Zprimelimits()**

returns 0 if the scenario considered is not excluded by  $Z'$  constraints, 1 if the point is excluded and 2 if both subroutines dealing with  $Z'$  constraints cannot test the given scenario. The routine can be used for any  $Z'$  uniquely defined by the PDG code 32. Currently two types of searches defined in different subroutines of **Zprimelimits()** are implemented. The 3.2/fb  $Z'$  search in the dilepton final state at  $\sqrt{s} = 13$  TeV from ATLAS [84] is considered in the first subroutine **Zprime\_dilepton**. If the scenario considered is allowed or not tested by **Zprime\_dilepton**, a second subroutine called **Zprime\_dijet** analyses the point using constraints from LHC dijet searches at  $\sqrt{s} = 8$  TeV [85–87] and at  $\sqrt{s} = 13$  TeV [88, 89]. This subroutine uses the recasting performed in [90] for a combination of ATLAS and CMS searches. **Zprimelimits()** returns 1 if  $M_{Z'} < 0.5$  TeV and 2 for points for which the narrow-width approximation is not valid, *i.e.*  $\Gamma/M_{Z'} > 0.3$ .

- **LspNlsp\_LEP()**

checks the compatibility with the upper limit [91] on the cross section for the production of neutralinos  $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_i^0)$ ,  $i \neq 1$ , when the heavier neutralino decays into quark pairs and the LSP,  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 q\bar{q}$ . The function returns  $\sigma \times BR = \sum_i \sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_i^0) \times BR(\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 q\bar{q})$  in pb as well as a flag greater than one if  $\sigma \times BR > 0.1(0.5)$  pb if  $m_{\text{NLSP}} > (<) 100$  GeV [91]. This function can also be applied for non-SUSY models which feature the same signature, in this case the function will compute the cross section for production of the LSP and any other neutral particle from the odd sector which can decay into the LSP and a  $Z$  boson.

- **monoJet(pName1, pName2)**

computes the cross section for  $p, p \rightarrow \text{pName1}, \text{pName2} + \text{jet}$  at  $\sqrt{s} = 8$  TeV where **pName1**, **pName2** are the names of neutral outgoing particles and *jet* includes light quarks (u,d,s)

and gluons. The function returns the resulting confidence level obtained with the CLs technique [92, 93] for each signal region of the 8 TeV CMS mono-jet analysis [94] and chooses the most constraining one.

## 13 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**, **IDM** (inert doublet model), **LHM** (little Higgs model), **Z3IDM** (Inert doublet model with  $Z_3$  symmetry), **Z4IDSM** (Inert doublet and singlet model with  $Z_4$  symmetry), **Z5M** (Two scalar singlets model with  $Z_4$  symmetry), **RDM** (scalar leptoquark and two singlet fermions), **STFM** (singlet-triplet fermionic model) as well as three models which serve as examples for freeze-in and for which there are currently no additional routines (**SingletDM**, **ZpPortal**, **LLL\_scalar**).

Some of these models contain a special routine for reading the input parameters:

- **readVarMSSM**, **readVarNMSSM**, **readVarCPVMSSM**, **readVarlHiggs**, **readVarRHM**.

These routines are similar to the general **readVar** routine described in Section 5 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**, **UMSSM** 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  $\tilde{S}$  and for the **UMSSM** the sixth component is the bino' fraction  $\tilde{B}'$ . The sum of the squares of the LSP components should add up to 1.

### 13.1 The MSSM

The **MSSM** has a long list of low scale independent model parameters, those are specified in the SLHA file [45, 95]. They are directly implemented as parameters of the model. **micrOMEGAs** can either read an SLHA file computed externally or generate this file in the framework of popular SUSY scenarios, these are specified by one of the instructions

```
#define SUGRA
#define SUGRANUH
#define AMSB
#define EWSB
```

If none of these instructions are given then **micrOMEGAs** reads the external SLHA file which should be passed as an argument when executing the *main* routine. To generate an SLHA file, **micrOMEGAs** uses either **SuSpect**, **SPHENO**, or **SoftSusy**. These codes, if need be, solve the RGE equations and calculate the masses of Higgs and SUSY particles including one-loop corrections. Note that **SuSpect** is included within the **micrOMEGAs** distribution while **SPHENO** or **SOFTSUSY** will be downloaded automatically when needed (see section 3.4). To specify the spectrum calculator the user has to define the parameter RGE in *main.c/main.cpp*. For instance

`#define RGE suspect`

Other possibilities for **RGE** are **softSusy**, **spheno** and **tree**. The option **tree** will generate the needed SLHA file for the spectrum using EWSB input parameters and tree-level formulas. One-loop corrections to the Higgs masses and to the effective Higgs potential are based on [96]. In this case, the realization of the MSSM is completely gauge invariant. This option can be useful to check the effect of loop corrections.

For **EWSB** scenarios the input parameters are the soft parameters, the names of these parameters are given in the `MSSM/mssm[1/2].par` files. The user can assign new values to these parameters by means of `assignVal` or `readVarMSSM`.

- `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` is defined by **RGE**.

For other MSSM scenarios, the parameters at the electroweak symmetry breaking scale are derived from an input at high scale. The same codes **suspect**, **spheno**, or **softSusy** are used for this. 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)`

assumes that all input parameters except `tb` and `signMu` are defined at the GUT scale. The SUGRA/CMSSM scenario is a special case of this general routine.

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

realizes a SUGRA scenario with non universal Higgs parameters. Here the `Mhu`, `Mhd` parameters in the Higgs potential are replaced with the `mu` parameter defined at the EWSB scale and `MA`, the pole mass of the CP-odd 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 a non-zero number in case of problem.

The routines for computing constraints are (see details in [3]).

- `deltarho()`

calculates the  $\Delta\rho$  parameter in the MSSM. It contains for example the 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. Code is based on [97].



- **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  $R_{l23}$  in  $K^+ \rightarrow \mu \nu$  due to a charged higgs contribution, see Eq.70 in [7].

- **dtaunu(&dmunu)**

computes the branching ratio for  $D_s^+ \rightarrow \tau^+ \nu_\tau$ . **dmunu** 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.

- **treeMSSM()**

This function transforms a loop improved model defined in an SLHA file into a tree level one. The masses and mixing angles are stored in the file **tree.slha**. This option can be useful to check the effect of loop induced masses and mixings. This option guarantees gauge invariance for all processes.

## 13.2 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** [11] in the **NMSSMTools\_5.0.1** package [26].

- **nmssmEWSB()**

calculates the masses of Higgs and supersymmetric particles in the NMSSM starting from the weak scale input parameters [27]. These can be downloaded by the **readVarNMSSM** routine.

- **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 [4]).

- **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 [98]

- **deltaMd(&M,&P), deltaMs(&M,&P)**

compute the supersymmetric contribution to the  $B_{d,s}^0 - \bar{B}_{d,s}^0$  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**.

### 13.3 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.mdl`. Masses, mixing matrices and parameters of the effective Higgs potential are read directly from CPsuperH [13, 99], together with the masses and the mixing matrices of the neutralinos, charginos and third generation sfermions. 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, [28]

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

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()`, `EDMTl()`

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  $ecm$ .

### 13.4 The UMSSM

The independent parameters of the UMSSM are the standard model parameters and weak scale soft SUSY parameters listed in `UMSSM/work/models/vars1.mdl`. All masses, mixing matrices and parameters of the different sectors of the model are computed by micrOMEGAs [23, 24].

Some routines for computing constraints were taken from the MSSM and were adapted to the UMSSM. For example

- `masslimits()` which is essentially the same as in the MSSM except that the constraint on the light Higgs mass from the LHC was removed as other routines in the UMSSM include this constrain, or

- `deltarho()`

calculates the  $\Delta\rho$  parameter in the UMSSM where in addition to MSSM contributions a pure UMSSM tree-level contribution from the extended Abelian gauge boson sector is included. Two other routines in C are included, `Zinvisible()` and `Zprimelimits()` that were defined above.

The remaining routines for computing  $B$ -physics,  $K$ -physics and Higgs observables as well as the anomalous magnetic moment of the muon were taken from `NMSSMTools_5.0.1` and adapted to the UMSSM [23, 100]. To call these routines use `umssmtools(PDG_LSP)` where `PDG_LSP` is the PDG code of the LSP. The result is contained in four files (`UMSSM_inp.dat`,



UMSSM\_spectr.dat, UMSSM\_decay.dat and SM\_decay.dat) and the WARNING messages from these routines can be displayed with `slhaWarnings(stdout)`.

As in the NMSSM the following routines are available :

- `bsg(&M,&P)`, `bsmumu(&M,&P)`, `btaunu(&M,&P)`, `gmuon(&M,&P)`, `deltamd(&M,&P)`, `deltams(&M,&P)`.

as well as the routines

- `bdg(&M,&P)`, `bdmumu(&M,&P)`, `bxislllow(&M,&P)`, `bxisllhigh(&M,&P)`, `bxisnunu(&M,&P)`, `bpkpnunu(&M,&P)`, `bksnunu(&M,&P)`, `rdtaul(&M,&P)`, `rdstaul(&M,&P)`

to compute respectively  $b \rightarrow d\gamma$ ,  $B_d \rightarrow \mu^+\mu^-$ , the  $b \rightarrow sl^+l^-$  transition in the low ( $[1, 6] \text{ GeV}^2$ ) and high ( $\geq 14.4 \text{ GeV}^2$ )  $m_{l+l}^2$  ranges,  $B \rightarrow X_s \nu \bar{\nu}$ ,  $B^+ \rightarrow K^+ \nu \bar{\nu}$ ,  $B \rightarrow K^* \nu \bar{\nu}$ ,  $R_D \equiv \frac{\text{BR}(B^+ \rightarrow D \tau^+ \nu_\tau)}{\text{BR}(B^+ \rightarrow D l^+ \nu_l)}$  and  $R_{D^*} \equiv \frac{\text{BR}(B^+ \rightarrow D^* \tau^+ \nu_\tau)}{\text{BR}(B^+ \rightarrow D^* l^+ \nu_l)}$ .

The  $K$ -physics observables  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ,  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ ,  $\Delta M_K$  and  $\epsilon_K$  can be computed respectively with

- `kppipnunu(&M,&P)`, `klpi0nunu(&M,&P)`, `deltamk(&M,&P)`, `epsk(&M,&P)`.

See the README of the UMSSM for further details.

## 14 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.

### 14.1 Main steps

- The command `./newProject MODEL` `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 [1].
- For odd particles and for the Higgs sector it is recommended to use the widths that are (automatically) calculated internally by `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 need 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 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.

## 14.2 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 10 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 14.5), the automatic width option will use the widths computed internally unless the user chooses to use those contained in the SLHA file by setting `useSLHAWidth=1`.

## 14.3 Using LanHEP for model file generation

For models with a large number of parameters and various types of fields/particles 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 `lhhep` command has to be launched with the `-ca` flag

```
lhhep -ca source_file
```

- 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

```
prtcformat 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.

## 14.4 QCD functions

Here we describe some QCD functions which can be useful for the implementation of 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,  $\alpha_s(M_Z)$ , 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 [101]. Thresholds for the 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 [101]

$$M_{eff}^2(Q) = M(Q)^2 [1 + 5.67a + (35.94 - 1.36n_f)a^2 + (164.14 - n_f(25.77 - 0.259n_f))a^3] \quad (31)$$

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  $Q = 2M_{cdm}$ . In some special cases one needs a precise treatment of the light quarks masses. The function

- `MqRun(M2GeV, Q)`

returns the running quark mass defined at a scale of 2 GeV. The corresponding effective mass needed for the Higgs decay width is given by

- `Mqeff(M2GeV, Q)`

## 14.5 SLHA reader

Very often the calculation of the 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 [45, 95]. The **micrOMEGAs** program contains routines for reading files in the SLHA format. Such routines can be very useful for the implementation of new models.

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 - reads DECAY /does not read DECAY
m4 = 0/1 - reads BLOCK/does 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 the 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 [102]. 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 || %[^\n]||",channel);`

which will write the channel name in the 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.

SLHA also describes the format of the information about 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. 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  $0 < N \leq \text{slhaDecayExists}(\text{pNum})$ . 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/work/models/func3.mdl`. Note that in this example the call to `slhaRead` is done within the function `suspectSUGRAc`.

### 14.5.1 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.

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

## 14.6 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 [103]. 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)** routine 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, **M<sub>ij</sub>** ( $i \leq j$ ), 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, **M<sub>ij</sub>**, 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/SLHApplus/include/SLHApplus.h`

## 15 Mathematical tools

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

```
include/micromegas_aux.h
```

### 15.1 Integration

• `simpson(F, x1, x2, eps,&err)`

performs numerical integration of the function  $F(x)$  in the interval  $[x1, x2]$ . `simpson` tries to reach relative precision `eps` or absolute precision  $\frac{eps}{10} \int_{x1}^{x2} |F(x)| dx$ . For one interval `simpson` compares the results of 3, 5 and 9 points formulas. If they do not agree within the required precision, `simpson` splits the interval in two and applies the same procedure recursively. The smallest interval is  $|x_2 - x_1|/2^{15-\log(eps)}$ .

A non-zero error code `err` means

- 1: NaN in integrand: `simpson` replaces NaN by zero and continues integration
- 2: Too deep recursion: one needs the smallest minimal interval to reach the required precision. For instance, these two error codes will show up in the integration of  $\int dx/\sqrt{|x|}$  with a precision  $eps = 10^{-3}$ .
- 4: Lost of precision: If in a small interval  $\approx |x1 - x2|/2^8$  the derivative of the function changes sign more than twice, it is treated as a lost of precision in the integrand and `simpson` decreases precision to `eps=0.01` and treats uncertainties of each interval as a random numbers.

In case of several error messages, `err` contains their sum. If the last argument of `simpson` is `NULL`, the error messages are displayed on the screen. If the integrand has a discontinuity or a pole, the requirement of reaching a fixed relative precision can not be satisfied. Thus we also stop the recursion if the integration uncertainty on the interval is small as compared to the current estimation of  $\frac{eps}{10} \int_{x1}^{x2} |F(x)| dx$ . Since the current estimation of this integral can be significantly smaller than the final one, we keep the sum of errors obtained at the end of the recursion chains and compare it with the final estimation of the total integral. If the sum of errors is small, then the error 2 is not generated.

We have implemented a debugging tool for the `simpson` code based on `gdb`. To initiate it the user has to launch the `./main` code under `gdb` and set a breakpoint

```
gdb ./main
break verifySimpson
r inputParameters           // to launch code
```

The execution of the program will stop when `simpson` generates an error code. With the `bt` command one can see the sequence of calls leading to the problematic call of `simpson`. After

```
n           // next
```

command one reaches the cycle which is executed until the variable `show`  $\neq$  0. The user should see on the screen

```
293 while(show) {drawP(f, par, x1, x2,ans,nErr);
```



By default `show=0` and the cycle is not executed, but it can be changed by the `set` command

```
set show=1
n
```

and the user will see a plot of the function  $F(x)$  on the screen. When the user closes the window with the plot, he/she will reach the next line of code

```
294      continue; }
```

Here the user can leave the cycle using the commands

```
set show=0
c          // continue
```

or verify a narrower range of the function  $F(x)$  by redefining the variables `x1` and `x2`.

The file `mdlIndep/simpson.c` contains several examples which allow to test how this routine works.

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

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

- `peterson21(F, x1, x2,&aErr)`

performs numerical integration of the function  $F(x)$  in the interval  $[x1, x2]$  using Gauss-Kronrod-Peterson formula with 21 points. `aErr` is a parameter which returns the accuracy of the calculation using 10 points subset.

## 15.2 Solution of differential equations.

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

solves a system of `Dim` differential equations in the interval  $[x1, x2]$ . The `Dim` component array `Y` contains the starting variables at `x1` as an input and is replaced by the resulting values at `x2` as an output. `eps` determines the precision of the calculation and `h1` gives an estimation of step of integration. 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 [103].

- `stiff ( first, x1, x2, Dim, Y, Yscal, eps, &htry,derivs)`

- `stifbs( first, x1, x2, Dim, Y, Yscal, eps, &htry,derivs)`

these two functions solve stiff differential equations. Both routines are slightly adapted codes from [103]. Here the parameters `x1`, `x2`, `Dim`, `Y` have the same meaning as in the routine `odeint` above. The parameter `first` should be set to one for the first call to the routines with a given number of equations `Dim` and to zero for subsequent calls. The flag `first` is used for memory allocation. If `Yscal=NULL` the parameter `eps` defines the absolute precision of calculation ( $\delta Y_i < eps$ ). Otherwise, the precision is defined by the condition  $\delta Y_i < epsYscale_i$ . The parameter `htry` defines the initial step of integration and contains the last step of integration used during calculations. The function `derivs` evaluates the differential equation  $F = dY/dx$  and its partial derivatives:

$$\text{derivs}(x, Y, F, h, dFdx, dFdY) \text{ where } dFdY[i*Dim+j] = \frac{dF_i}{dY_j}$$

This routine can be called with parameters `dFdx=NULL` and `dFdY=NULL`. The parameter `h` presents current step of integration and can be used for numerical evaluation of `dFdx`.

### 15.3 Interpolation

- `polint3(x,Dim,X,Y)`

performs cubic interpolation for *Dim*-dimension arrays X,Y. Similar functions, `polint1` performs linear interpolations.

- `spline(x, y, dim, y2)`
- `splint(x, y, y2, dim, double x0, &y0)`

`spline` constructs cubic spline and `splint` calculates spline interpolation `y0` for a given point `x0`. Here `x` and `y` are a grid of function arguments and function values  $y_i = Y(x_i)$ . The function `spline` fills an array of second derivatives `y2` which is used by `splint`.

- `buildInterpolation(F,x1,x2,eps,delt, &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 *delt* parameter limits the distance between interpolation points:  $|x_i - x_{i+1}| < delt|x2 - x1|$ . 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 the *Dim* array for each of these parameters. *X*[*i*] contains the x-grid while  $Y[i] = F(X[i])$ .

### 15.4 Functions with additional parameters

We use routines that work with functions of type `double F(double x,void*arg)`, where the structure of `arg` is open, here `arg` presents the memory address where these parameters are stored. This is useful for example for integrating a function  $f(x,y)$  over *x*, *y* is then passed as 'arg'. The functions available are `simpson_arg`, `peterson21_arg`, `buildInterpolation_arg`. The additional argument is the address `arg` which is specified just after the function name.

### 15.5 Plots

- `displayPlot(title,xName,xMin,xMax,lScale, N, ...)`

displays several curves/histograms on one plot. Here `title` contains some text, `xName` is the name of a variable, `xMin`, `xMax` are the lower and upper limits. If `lScale`  $\neq 0$ , a logarithmic scale is used for the *x* axis.

*N* is the number of curves/histograms to display. After the parameter *N*, `displayPlot` expects  $N \times 4$  parameters, where each tetrad can contain

text label	dimension of array	array of data	array of error
text label	dimension of array	array of data	NULL
text label	0	double *f(double x)	NULL
text label	0	double *f(double x, void *arg)	arg

where the first line is used for an histogram with error bars, the second line for a tabulated function, the third for a function  $f(x)$  and the fourth for a function  $f(x,arg)$  which also depends on some arguments contained in the structure `arg`. For a linear scale `lScale=0`,

the arrays of data and errors should correspond to a grid

$$x_i = \text{xMin} + (i + 0.5)(\text{xMax} - \text{xMin})/\text{Dim} ,$$

where  $i = 0, \dots, \text{Dim} - 1$ . For logarithmic scale

$$x_i = \text{xMin} \cdot \left( \frac{\text{xMax}}{\text{xMin}} \right)^{\frac{i+0.5}{\text{Dim}}}$$

## 15.6 Bessel functions

- `bessI0(x)`, `bessI1(x)`, `bessK0(x)`, `bessK1(x)`, `bessK2(x)`

Bessel functions  $I_0$ ,  $I_1$ ,  $K_1$ ,  $K_2$ .

- $\text{K1pol}(x) = K_1\left(\frac{1}{x}\right) e^{\frac{1}{x}} \sqrt{\frac{2}{\pi x}}$

- $\text{K2pol}(x) = K_2\left(\frac{1}{x}\right) e^{\frac{1}{x}} \sqrt{\frac{2}{\pi x}}$

`micrOMEGAs` uses these functions for calculating the relic density. For small values of  $x = T/M_{cdm}$ , where these functions can be presented as polynomials in  $x$ .  $\text{K1pol}(0) = \text{K2pol}(0) = 1$ .

## 15.7 Statistics

- `FeldmanCousins(n0, b, cl)`

is the Feldman-Cousins [104] function for a Poisson distribution. Here `n0` is the observed number of events, `b` - the expected background, `cl` < 1 - the requested confidence level. This function sets the upper limit on the number of signal events compatible with `n0` and `cl`.

- `ch2pval(ndf, chi2)`

returns the `p-value` assuming a  $\chi^2$  distribution with `ndf` degrees of freedom ( expected  $\chi^2$ ) and `chi2` is the observed  $\chi^2$ .

$$\text{ch2pval}(k, q) = \int_q^\infty \frac{1}{2^k \Gamma(\frac{k}{2})} Q^{\frac{k}{2}-1} e^{-\frac{Q}{2}} dQ$$

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

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

$$B(\bar{B} \rightarrow X_s \gamma) = B(\bar{B} \rightarrow X_c e \bar{\nu}) \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha_{em}}{\pi f(z_0)} K_{NLO}(\delta) \quad (32)$$

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 [105] 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 [106, 107].

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. 32, see Table 6, and we have replaced the factor  $f(z_0)$  by  $C_{sl}$  where

$$C_{sl} = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma(\bar{B} \rightarrow X_c e \bar{\nu})}{\Gamma(\bar{B} \rightarrow X_u e \bar{\nu})} \quad (33)$$

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

$B(\bar{B} \rightarrow X_c e \bar{\nu})$	0.1064 [108]
$C_{sl}$	0.546 [107]
$ V_{ts}^* V_{tb}/V_{cb} ^2$	0.9613 [108]
$A$	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> [109]
$\alpha_s(M_Z)$	0.1189

Table 6: Default values in `micrOMEGAs`

The CKM matrix elements in the Wolfenstein parametrisation given in Table 6 are used to compute the central value of  $ckmf$  at order  $\lambda^4$ ,

$$ckmf = \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 = 1 + \lambda^2(2\bar{\rho} - 1) + \lambda^4(\bar{\rho}^2 + \bar{\eta}^2 - A^2) \quad (34)$$

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 [107] after correcting for the slightly different CKM parameter used ( $ckmf = 0.963$ ).

We have performed a comparison with superIso which includes the NNLO SM calculation for  $10^5$  randomly generated MSSM scenarios. The results are presented in Fig. 1 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.

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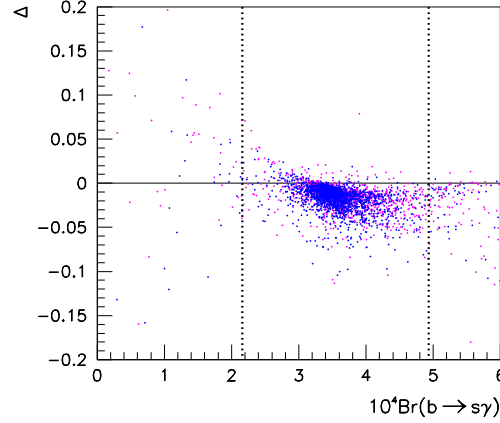


Figure 1: Relative difference for  $B(\bar{B} \rightarrow s\gamma)$  between micromegas2.4 and superIso3.1. the vertical lines show the  $3\sigma$  experimentally measured value.

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