

micrOMEGAs 2.0: a program to calculate the relic density of dark matter in a generic model .

G. Bélanger¹, F. Boudjema¹, A. Pukhov², A. Semenov³

1) *Laboratoire de Physique Theorique LAPTH, F-74941 Annecy-le-Vieux, France*

2) *Skobeltsyn Inst. of Nuclear Physics, Moscow State Univ., Moscow 119992, Russia*

3) *Joint Institute for Nuclear Research (JINR), 141980, Dubna, Russia*

February 2, 2008

Abstract

`micrOMEGAs 2.0` is a code which calculates the relic density of a stable massive particle in an arbitrary model. The underlying assumption is that there is a conservation law like R-parity in supersymmetry which guarantees the stability of the lightest odd particle. The new physics model must be incorporated in the notation of CalcHEP, a package for the automatic generation of squared matrix elements. Once this is done, all annihilation and coannihilation channels are included automatically in any model. Cross-sections at $v = 0$, relevant for indirect detection of dark matter, are also computed automatically. The package includes three sample models: the minimal supersymmetric standard model (MSSM), the MSSM with complex phases and the NMSSM. Extension to other models, including non supersymmetric models, is described.

1 Introduction

Precision cosmological measurements have recently provided strong evidence that the universe is dominated by dark energy and also contains a large dark matter component [1, 2, 3]. Furthermore, the amount of dark matter today, the relic density, has been measured with good precision by WMAP, $0.094 < \Omega h^2 < 0.128$ [1, 2]. While one can show, based on general arguments [4], that a reasonable value for the relic density of cold dark matter, can be obtained in any model with a stable particle that is weakly interacting, the precision reached allows to actually test in details the implication of the new physics models that propose a dark matter candidate, thus putting strong constraints on new models. It is particularly interesting that models for new physics whose prime goal is to solve the hierarchy problem, for example supersymmetry, can in many cases also provide a viable candidate for dark matter. In the minimal supersymmetric standard model (MSSM) one introduces a discrete symmetry, called R-parity, to prevent too fast proton decay. This symmetry also ensures consistency with electroweak precision measurements. This discrete symmetry then guarantees the stability of the lightest R-parity odd particle, in this case the lightest supersymmetric particle (LSP). Within this context a number of studies have examined the impact of the precise measurement of the relic density and shown that it puts strong constraints on supersymmetric models, either the MSSM [5, 6, 7] or high scale models such as minimal supergravity (mSUGRA) [8, 9, 10, 11, 12, 13, 14], non-universal SUGRA [15, 16, 17, 18, 19], or string inspired models [20]. Furthermore, studies of relic density of dark matter in some generalizations of the MSSM such as the

MSSM with CP violation [21, 22, 23, 24], the NMSSM which contains an extra singlet [25, 26] or even the MSSM with an extended gauge structure such as an extra $U(1)$ [27] or the left-right symmetric model [28], all emphasize the presence of new channels that can lead to a reasonable value of the relic density of dark matter where it was not possible within the MSSM. However candidates for dark matter go far beyond the much studied neutralino LSP in the MSSM. Besides the extensions of the MSSM mentioned above, explicit examples include a model with universal extra dimensions [29, 30] where the cold dark matter (CDM) candidate is the partner of the hypercharge gauge boson, a model with warped extra dimensions [31] where the CDM is the Kaluza-Klein excitation of a right-handed neutrino and little Higgs models where in some cases the partner of the hypercharge gauge boson is the CDM candidate [32, 33] while in other cases the CDM is a heavy neutrino [34]. One can even have a scalar CDM candidate, for example in theory space models [32]. In all these models that propose alternate solutions to the hierarchy problem, a discrete symmetry like R-parity conservation is either present by construction or needs to be introduced for the viability of the model. The main problems that this discrete symmetry alleviates are rapid proton decay, as in warped extra dimensions, or consistency with electroweak precision measurements as in universal extra dimensions or the littlest Higgs model. These discrete symmetries then naturally ensure the stability of the lightest odd particle (LOP) ¹.

Sophisticated tools have been developed to perform a precise computation of the relic density within R-parity conserving supersymmetric models, three are publicly available: `micrOMEGAs 1.3` [35, 36], `DarkSUSY` [37] and `IsaTOOLS` [38]. In view of the diversity of the new physics models and of the CDM candidates, there is a clear need for complete and precise codes to calculate the relic density of dark matter in different models, to the level of what has been achieved in the MSSM. Here we propose an extension of `micrOMEGAs 1.3` that serves this purpose.

One of the difficulty of the computation of the relic density is that a large number of channels can contribute to the (co-)annihilation cross-section of dark matter. For example in the general MSSM, close to 3000 processes can contribute, in particular a large number of processes are relevant when the spectrum is such that many particles are not much heavier than the dark matter candidate. Therefore a certain level of automation is desirable. The structure of `micrOMEGAs` which is based on `CalcHEP` [39] a program that automatically calculates cross-sections in a given model, makes it in principle straightforward to make a complete code for the relic density calculation in a new model. Once the new model is implemented into `CalcHEP` and Feynman rules defined, all annihilation and coannihilation channels are calculated automatically. The standard `micrOMEGAs` routines can then be used to compute the relic density. To automatize as much as possible the procedure for implementing a new model, it is possible to use a program like `LanHEP` [40], which starts from a Lagrangian in a human readable format and derives all the necessary Feynman rules. Note that a similar approach has been adopted by the authors of `DM++` [41]. Using `CalcHEP` [39] for the automatic generation of matrix elements, they have computed the relic density of dark matter in a little Higgs model.

The approach that we propose here is very general and, as long as one sticks to tree-level masses and cross-sections, necessitates minimal work from the user beyond the definition of the model file. However it has been demonstrated that for an accurate

¹In the following we will use R-parity to designate generically the discrete symmetry that guarantees the stability of the LOP.

relic density calculation is necessary in many cases to take into account higher-order corrections. In particular corrections to the mass of either the LOP or of any particle that can appear in s-channel are important. In the MSSM or in the NMSSM such corrections to Higgs masses are known to be very important. The large QCD corrections to the Higgs width must also be taken into account when annihilation occurs near a Higgs resonance. In general one expects that these loop corrections can be implemented via an effective Lagrangian. In practice then it might be necessary for the user to implement additional routines or interface other programs to take these effects into account.

Another advantage of our approach based on a generic program like `CalcHEP` is that one can compute in addition any cross-section or decay width in the new model considered. In particular, tree-level cross-sections for $2 \rightarrow 2$ processes and 2-body decay widths of particles are available. Furthermore the cross-sections times relative velocity, σv , for neutralino annihilation at $v \rightarrow 0$ and the yields for the continuum $\gamma, e^+, \bar{p}, \nu$ spectra, relevant for indirect detection of neutralinos, are also automatically computed. The procedure that derives the $\gamma, e^+, \bar{p}, \nu$ spectrum from the different channels for two-body annihilation of the dark matter particles was developed for the MSSM [42] and can be applied to a generic model.

As compared to an earlier version of `micrOMEGAs 1.3` that was developed specifically for the MSSM, `micrOMEGAs 2.0` gives the possibility to compute the relic density in a generic model. Furthermore, improvements have been made within the MSSM and its extensions. Note however that the relic density calculation itself has not been modified for the MSSM in this new version. Specifically, the new features of `micrOMEGAs 2.0` are:

- Possibility to include in the package any particle physics model with a discrete symmetry that guarantees the stability of the cold dark matter candidate (LOP) and to compute the relic density of CDM.
- Compute automatically the cross-sections for annihilation of the LOP at small velocities into SM final states and provide the energy spectra for $\gamma, e^+, \bar{p}, \nu$ final states.
- For the MSSM with input parameters defined at the GUT scale, the interface with any of the spectrum calculator codes reads an input file in the *SUSY Les Houches Accord format* (SLHA) [43].
- Implementation of the MSSM with complex parameters (CPV-MSSM) with an interface to CPsuperH to calculate the spectrum.
- Routine to calculate the electric dipole moment of the electron in the CPV-MSSM
- In the NMSSM, new interface compatible with NMHDECAY2.1.

Generically `micrOMEGAs 2.0` was developed under the assumption that the model contains a symmetry like R-parity and that particles are either odd or even under this parity. In the case of a model with a Z_3 -parity, one can effectively use the classification of odd and even particles and the model can be incorporated in `micrOMEGAs` as for the simple R-parity model. The extension to more complicated symmetry groups, especially when they lead to two stable particles, is not straightforward. Such models cannot be implemented through an automatic procedure as described here. We further assume, as is the case in the MSSM, that odd particles which contribute to coannihilation processes are

in relative thermal equilibrium in the early universe and that for even particles produced in annihilation of the LOP, there are no significant branching ratios into odd particles.

In this manual, we first briefly review the relic density calculation. In section 3 we then present the various features of `micrOMEGAs 2.0` and the routines available for handling parameters, computing the relic density, all cross-sections and decay widths as well as the annihilation cross-sections at small velocities. A description of specific routines developed for the MSSM, for the CPV-MSSM and for the NMSSM follows in section 4. We then describe the implementation of new models in `micrOMEGAs 2.0` in Section 5. Finally we explain the installation procedure. Examples of a `micrOMEGAs 2.0` session and possible problems in compilation can be found in the appendices.

2 Relic density of dark matter

A relic density calculation entails solving the evolution equation for the abundance of the dark matter, $Y(T)$, defined as the number density divided by the entropy density, (here we follow closely the approach in [44, 45])

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2) \quad (1)$$

where g_* is an effective number of degree of freedom [44], M_p is the Planck mass and $Y_{eq}(T)$ the thermal equilibrium abundance. $< \sigma v >$ is the relativistic thermally averaged annihilation cross-section. The dependence on the specific model for particle physics enters only in this cross-section which includes all annihilation and coannihilation channels,

$$< \sigma v > = \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sum_{k,l} \sigma_{ij;kl}(s)}{2T \left(\sum_i g_i m_i^2 K_2(m_i/T) \right)^2}, \quad (2)$$

where g_i is the number of degree of freedom, $\sigma_{ij;kl}$ the total cross-section for annihilation of a pair of supersymmetric particles with masses m_i, m_j into some Standard Model particles (k, l) , and $p_{ij}(\sqrt{s})$ is the momentum (total energy) of the incoming particles in their center-of-mass frame.

Integrating Eq. 1 from $T = \infty$ to $T = T_0$ leads to the present day abundance $Y(T_0)$ needed in the estimation of the relic density,

$$\Omega_{LOP} h^2 = \frac{8\pi}{3} \frac{s(T_0)}{M_p^2 (100(\text{km/s/Mpc}))^2} M_{LOP} Y(T_0) = 2.742 \times 10^8 \frac{M_{LOP}}{\text{GeV}} Y(T_0) \quad (3)$$

where $s(T_0)$ is the entropy density at present time and h the normalized Hubble constant.

To compute the relic density, `micrOMEGAs` solves the equation for the abundance Eq. 1, numerically without any approximation. In addition, `micrOMEGAs` also estimates the relative contribution of each individual annihilation or coannihilation channel to the relic density. For this specific purpose only, we use the freeze-out approximation (for more details, see [24]).

As in previous versions, we include in the thermally averaged cross-section, Eq. 2, only the processes involving the LOP as well as those particles for which the Boltzmann suppression factor, B , is above some value B_e

$$B = \frac{K_1((m_i + m_j)/T)}{K_1(2m_{LOP}/T)} \approx e^{-X \frac{(m_i + m_j - 2M_{LOP})}{M_{LOP}}} > B_\epsilon \quad (4)$$

where m_i, m_j are the masses of the incoming particles, $X = M_{LOP}/T$. The value recommended is $B_\epsilon = 10^{-6}$ [35] and corresponds roughly to $m_{\chi_i} < 1.5M_{LOP}$. As in previous versions of **micrOMEGAs**, new processes are compiled and added only when necessary, in run-time.

In the framework of the MSSM, as realized in **micrOMEGAs 1.3**, the computation of all annihilation and coannihilation cross-sections are done exactly at tree-level. For this we rely on **CalcHEP** [39], a generic program which once given a model file containing the list of particles, their masses and the associated Feynman rules describing their interactions, computes any cross-section in the model. To generalize this program to other particle physics models one only needs to replace the calculation of the thermally averaged annihilation cross-section for the stable particle that plays the role of dark matter. This can be done easily after specifying the new model file into **CalcHEP**. Then to solve numerically the evolution equation (Eq. 1) and calculate Ωh^2 one uses the standard **micrOMEGAs** routines. Full details on this can be found in Ref. [36]

In order that the program finds the list of processes that need to be computed for the effective annihilation cross-section, one needs to specify the analogous of R-parity and assign a parity odd or even to every particle in the model. The standard model particles and other particles such as Higgses have an even parity. The lightest odd particle will then be identified to the dark matter candidate.

After specification of the R-parity odd particles, **micrOMEGAs** automatically generate all processes of the type

$$\sim \chi_i \sim \chi_j \rightarrow X, Y$$

where $\sim \chi_i$ designates all R-parity odd particle and X,Y all R-parity even particles, for example standard model particles and Higgses. **micrOMEGAs** then looks for s-channel poles as well as for thresholds to adapt the integration routines for higher accuracies in these specific regions, and performs the relic density calculation. Note that there is no automatic procedure to check that the LOP is colorless and neutral, the relic density calculation can be performed even for such candidates².

3 Structure and general routines

The **micromegas_2.0** package contains the following files and directories:

- the directory **CalcHEP_src** with **CalcHEP** source files;
- the directory **sources** which contains general routines for relic density calculation;
- the directory **MSSM** with the MSSM model files and auxiliary routines necessary for the model implementation as well as constraints on the model;
- the **Makefile** used for package installation.
- the **newProject** command file for implementation of new models.
- the **cgwRun** command file to run the program under Cygwin.

²This can be used for example to calculate the density of the charged NLSP from which one can extract the relic density of CDM in models where the gravitino is the LSP [46].

One can also include additional packages developed for specific models. These packages contain a directory with the name of the model, e.g. NMSSM or CPV-MSSM, and they should be installed separately in the main `micromegas_2.0` directory.

The directory for each model, including the new model that can be defined by the user, all have the same structure, they contain three directories

`calchep/` `work/` `lib/`

as well as a `Makefile`, that compiles the code, and some sample main programs for the calculation of Ωh^2 . In general, `work` is intended for model implementation and `CalcHEP` sessions needed for the generation of matrix elements `lib` - for all special functions necessary for the model and `calchep` - for interactive `CalcHEP` sessions only.

The `work/` directory contains several files and directories, in particular the `models/` subdirectory where the model is defined in `CalcHEP` notation. The contents of this subdirectory will be detailed in Section 5, at this point we only need to mention that two files `vars1.mdl` and `func1.mdl` contain the independent parameters and functions of the model. The `work/so_generated` subdirectory is used to store shared libraries of matrix elements generated by `CalcHEP`. When one `micrOMEGAs` routine needs a matrix element it looks for the corresponding dynamic library in the `so_generated/` directory. If this library exists it is linked, if not, `micrOMEGAs` launches a `CalcHEP` session in `work/calchep` and generates the requested library. Note however that the specific contents of the library are not checked, when modifying a model it is necessary to remove all files in `so_generated/`.

In this section we review the general routines of `micrOMEGAs 2.0` that can be used in any model. These routines are located in the `sources` directory and compiled in `sources/micromegas.a`. Most of these routines were described in more details in Ref. [36] in the context of the MSSM. We include them here for the sake of completeness. First note that we provide two sets of programs and routines to allow the user to work either with *C* or *Fortran*. Most of the *C* and *Fortran* commands have the same format. We list first the *C* commands and when necessary the analogous *Fortran* call in squared brackets. We do not write explicitly the Fortran call when it is identical to the C call³. Note that in C, the variable `file` is of `FILE*` type, whereas in Fortran it is an integer which specifies the input/output channel number. In both cases the `fname` variable which specifies the file is used for a text type variable. All information about the variable types can be found in the files `sources/micromegas.h` (C version) and `sources/micromegas_f.h` (Fortran version). Finally, many of the functions described in this section are used in the sample *main* routines provided with the package and described in Section 4.1. It could be instructive for the user to study the examples included with the MSSM and/or the NMSSM.

3.1 Model parameters

The parameters needed for the computation of cross-sections in a given model are specified within `micrOMEGAs 2.0` in the notation of `CalcHEP`. These include both the independent parameters of the model, hereafter also called variables, as well as all internal functions, the so-called constraints of the models. All model files can be found in the `work/models` subdirectory of each model. The variables are defined in the `vars1.mdl` model file while the constraints are derived from the independent parameters and are

³The `&` symbol is used in C to designate the address of the corresponding parameter, it is not needed in Fortran.

calculated by `CalcHEP` as specified in the `func1.mdl` model file. Both these files contain some comments to explain the meaning of parameters. Example of constraints are the vertex functions written in terms of independent parameters of the model. In some models, masses are constraints whereas in the MSSM, masses are independent variables. The variables used in the MSSM in fact include all masses and mixing matrices, a partial list can be found in Ref. [36], Table 2. Note that what we call here independent parameters from the point of view of computing matrix elements are not necessarily free parameters of the model. For example in the MSSM, the independent parameters can be derived from a much reduced set of input parameters, the 5 input parameters of the SUGRA model or the soft SUSY breaking parameters of the MSSM. Within `micrOMEGAs` there is no check of the self-consistency of the model, we assume that constraints are imposed by other functions. Therefore one has to be careful when changing by hand some of the variables of the model. For example, the neutralino mass matrix depends at tree-level on only four parameters, so changing the value of the mass of only one neutralino without appropriate modifications to other masses and to the mixing matrix to ensure a self-consistent system could lead to wrong results.

3.2 Setting of parameters.

In the following we describe the few routines that allow to set or read the value of any independent parameters listed in the `vars1.mdl` file.

- `assignVal(name, val)` and `assignValW(name, val)` assigns value *val* to variable *name*.
- `findVal(name, &val)` finds the value of variable *name* and assigns it to parameter *val*.
- `findValW(name)` just returns the value of variable *name*.

If *name* does not correspond to any variable of the model, both `assignVal` and `findVal` return a non-zero error code whereas `assignValW` and `findValW` write a warning on the screen.

- `readVar(file)` reads variables from the *file*. This file should contain two columns, the first one specifying the names of variables, and the second one the corresponding numerical values. `readVar` returns zero when the file has been read successfully, a negative value when the file can not be opened for reading and a positive value to signal a wrong file record at the line corresponding to the value of the error code.

- `printVar(file)` prints the numerical values of all variables into *file*. Of course, this file should have been opened previously.

- `findParam(name, &err)` returns the value of the parameters *name* defined in `models/func1.mdl`.

Not all parameters are accessible automatically by this command, for details see Section 5. A non-zero error code means that a parameter was not found.

3.3 Calculation of Relic density.

The first step before performing a relic density calculation is to find among all the R-parity odd particles, the lightest stable one. Once this is done, the generic `micrOMEGAs` routine for calculating the relic density can be called. The routines that find the LOP, give information about particle masses and calculate the relic density are described below.

- `sortOddParticles(message)` sorts the odd particles with increasing masses. *message* contains the name of the LOP. This routine returns a non zero error code when a wrong set of parameters is used, for example one for which some constraints cannot be calculated, the corresponding constraint is listed in *message*. This routine has to be called before any other routine described in this section.
- `lopmass_()` [`lopmass()`] gives the mass of the lightest odd particle.
- `printMasses(file,sort)` prints all masses of odd particles into the file *file*. If *sort* \neq 0 the masses are sorted so the mass of the LOP is given first.
- `darkOmega(&Xf,fast,Beps)` is the main routine to calculate Ωh^2 . $X_f = M_{LOP}/T_f$ characterizes the freeze-out temperature. This routine does not use the freeze-out approximation. 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 Ωh^2 , see `printChannels` below. The *fast* = 1 flag forces the fast calculation (for more details see Ref. [36]). This is the recommended option and gives an accuracy around 1%. The parameter *Beps* defines the criteria for including a given channel in the computation of the thermally averaged cross-section, Eq. 4. The recommended value is $Beps = 10^{-4} - 10^{-6}$, on the other hand if *Beps* = 1 only annihilation of the lightest odd particle is computed.
- `printChannels(Xf,cut,Beps,prcnt,file)` writes into the file *file* the contributions of different channels to $(\Omega h^2)^{-1}$. The *cut* parameter specifies the lowest value to be printed. If *prcnt* \neq 0 the contributions are given in percent. Note that it is only for this specific purpose that we use the freeze-out approximation.

3.4 Calculation of cross-sections and widths.

For a relic density calculation one needs to compute the cross-sections for annihilations of any pairs of R-parity odd particles. In `micrOMEGAS` the codes for the generation of the corresponding matrix elements are generated using `CalcHEP`. In fact any $2 \rightarrow 2$ cross-section or two-body decay width within a given model is also available in `CalcHEP`, for example cross-sections for production of pairs of SUSY particles in e^+e^- collisions. Cross-sections involving 3 or more particles in the final state can also be computed by `CalcHEP` but since special care is required for the phase space integration, for example in case of resonances, they are not provided automatically. To obtain a given cross-section or decay width, the first step consists in generating the corresponding matrix element with `CalcHEP`. Then one can check the contents of the new libraries and finally perform the numerical calculation of cross-sections or decay widths.

- `newProcess(procName, libName)` [`newProcess(procName, libName, address)`] compiles the codes for any $2 \rightarrow 2$ or $1 \rightarrow 2$ reaction. The result of the compilation is stored in the library

`work/so-generated/libName.so.`

If the library *libName* already exists, it is not recompiled and the correspondence between the contents of the library and the *procName* parameter is not checked. *libName* is also inserted into the names of routines in the *libName.so* library. Thus *libName* can not contain symbols that cannot be used in identifiers, for example the symbols +, -, *, /, . The name of a given process, *procName*, has to be specified in `CalcHEP` notation, for example in the MSSM

`"e,E->~1+,~1-"`

stands for the lightest chargino pair production in e^+e^- collisions. Note that *procName* should not contain any blank space. Multi-process generation is also possible by using the symbol $2*x$. For example, " $e,E \rightarrow 2*x$ " designates all possible two particle final states for an e^+e^- collision. Note that all library names starting with `omg` or `2width_` are reserved for internal calls of the `darkOmega` routines and cannot be used for new libraries. Although such libraries cannot be created by the user, the ones already compiled in `micrOMEGAs` can be loaded and used to calculate the corresponding matrix elements. In this case the *procName* argument can be left blank. These internal `micrOMEGAs` libraries are named `omg<particle>_<particle>.so` and `2width_<particle>.so`. Here `<particle>` is the particle name where "+", "-", "~" are replaced respectively by "_P", "_M", "_t". 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 returned⁴.

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

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

provides information about the total number of subprocesses (*ntot*) stored in the library specified by *address* as well as the number of incoming (*nin*) and outgoing (*nout*) particles for these subprocesses. Typically, for collisions (decays), $nin = 2(1)$ and $nout = 2$.

- `procInfo2(address, nsub, N, M)`

fills for subprocess *nsub* ($1 \leq nsub \leq ntot$) an array of particle names *N* and an array of particle masses *M*. These arrays have size $nin + nout$ and the elements are numbered in the usual CalcHEP notation starting with the initial state.

Once the source code for the relevant matrix elements have been generated, two different procedures for the numerical calculation of cross-sections or decay widths are available.

- `cs22(address, nsub, P, c1, c2, &err)`

calculates the cross-section for a given $2 \rightarrow 2$ process, *nsub*, with center of mass momentum *P*(GeV). The differential cross-section is integrated from $c1 < \cos \theta < c2$ and θ 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 *nsub* exceeds the maximum value for the number of subprocesses (given by the argument *ntot* in the routine `procInfo1`).

- `pWidth2(address, nsub)`

returns the partial decay width (in GeV) for subprocess number *nsub* > 0 . If the parameter *Q* which specifies the QCD scale is involved in the width calculation, its value is automatically set to the mass of the incoming particle. For example *Q* allows to account for running Yukawa coupling in $h_i \bar{q}q$ vertices.

- `decay2Info(Particle, file)`

returns the total width for the particle specified by its name in CalcHEP notation and writes all partial widths in *file*. If *file* = *NULL* (or *file.eq.0* in Fortran) only the total width is given as output. This procedure uses the routine `pWidth2` described above. Note that all the widths of *odd* particles are independent parameters in the model, see Section 5.3. So, for reactions where such widths can play a role they should first be calculated by `decay2Info`. The numerical value can be assigned to the appropriate variable via the

⁴In Fortran, instead of *address* we use a two element `INTEGER` array, this length is sufficient to store a computer address.

`assignVal` command.

Examples on how to use the routines described in this section can be found in the sample main programs `MSSM/cs_br.c/F`.

3.5 Calculation of annihilation spectra.

The indirect detection rate of dark matter in the galactic halo through their decay products in photons, positrons or antiprotons depend on the annihilation cross-section of dark matter at small relative velocity. The cross-sections for the different 2-body annihilation channel of the LOP are calculated automatically in any model. We then provide the continuum spectrum for γ , e^+ , \bar{p} , ν production. Here we describe the general procedure used to calculate the spectrum and the different routines available. Note however that an improved and more complete version of the indirect detection module, including integration over various dark matter profiles and propagation of positrons and antiprotons will be presented in a separate publication [42, 47].

The procedure we follow is similar to the one implemented in **DarkSUSY** [37]. For the basic channels, $q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^- , ZZ , we provide tables for γ , e^+ , \bar{p} , ν production as obtained by PYTHIA⁵. For channels containing two different particles, AB , we obtain the final spectrum by taking half the sum of the $A\bar{A}$ and $B\bar{B}$ spectra. For channels with Higgses, or other particles whose mass are a priori unknown, we recursively calculate all $1 \rightarrow 2$ decay channels until we obtain particles in the basic channels. If during these decays we get a pair of particles AB where A is one of the basic channel, we suppose that half of the spectrum is obtained from $A\bar{A}$ and continue to decay B .

The gamma ray flux can be evaluated as

$$\Phi_\gamma = \frac{\sigma v}{M_{LOP}^2} N_{tot} H \left(\frac{photons}{cm^2 sec sr} \right) \quad (5)$$

where N_{tot} is the number of particles with energy $E > E_{min}$. The factor H includes the integral of the squared of the dark matter density over the line of sight,

$$H = \frac{1}{8\pi} \int_0^\infty dr \bar{\rho}_Q^2 \left(\sqrt{r^2 + r_0^2 - 2rr_0 \cos(\phi)} \right) \quad (6)$$

where ϕ is the angle in the direction of observation, in radians, $\bar{\rho}_Q^2(r)$ is the averaged squared dark matter density in GeV/cm^3 , r is the distance from the Galactic center in kpc and $r_0 = 8.5\text{kpc}$ is the distance of the Sun to the center of the galaxy. In the present version, we have implemented only the modified isothermal distribution,

$$\bar{\rho}_Q^2(r) = \left(\frac{0.3\text{GeV}}{cm^3} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2} \right)^2 \quad (7)$$

where $a_0 = 3.5\text{kpc}$ is the length scale.

The main routines to calculate the γ , e^+ , \bar{p} , ν spectrum are

- `calcSpectrum(v,outP,tab,&err)`

calculates σv in cm^3/sec and writes the spectrum of one collision in the array *tab*. This array has to contain 250 elements of type *double*. The input parameters are the relative velocity v in natural units,⁶ and the type of the outgoing particle, *outP*. We use

⁵For this version, we use the **DarkSUSY** tables. Improved and more versatile tables will be presented in [42].

⁶Note that for neutralino collisions in the galactic halo v should be about 0.001.

$outP = 0, 1, 2$ for $-\gamma, e^+, \bar{p}$ and $3, 4, 5$ for ν_e, ν_μ, ν_τ . A non-zero error code indicates that one of the particle appearing in the decay products does not have 2-body decay modes.

• **zInterp(x, tab)**

interpolates the table **tab** obtained by **calcSpectrum**. Here $x = \log(E/M)$, where E is the energy of the outgoing particle and M the LOP mass. This returns the value dN/dx , where N is the number of particles.

• **spectrInfo(Xmin, tab, &Ntot, &Etot)**

calculates some statistical information about the spectra stored in table **tab**. $Xmin = E_{min}/M_{LOP}$ defines the minimal energy considered. The routine calculates $Ntot$ - the number of particles with energy $E > E_{min}$; $Etot$ - the total energy (divided by M_{LOP}) of the particles produced. When working in C, NULL can be substituted as an argument for any unnecessary output parameters.

• **spectrTable(tab, fname, mess, Xmin, N)** writes in file *fname* the spectrum stored in the *tab* array. *mess* contains some text that describes the plot. $Xmin$ is the minimal energy, $N < 300$ is the number of points. This file can be read by the **CalcHEP** program **tab_view** (see example in **spectrum.c** file) or by other graphics program.

• **rhoQisothermal(r)** is the averaged squared dark matter density with the modified isothermal distribution, Eq. 7, r is the distance from the galactic center in kpc.

• **HaloFactor(fi, rhoQ)** performs the integration of the squared dark matter density over the line of sight, Eq. 6. The function **rhoQ** can be either the default function **rhoQisothermal** or another function provided by the user.

3.6 QCD routines.

Many auxiliary routines were developed within the context of a specific model and will be detailed in the next section. However a few functions are available for all models, for example the functions that compute the running standard parameters: QCD coupling and heavy quark masses.

• **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 α_s at the scale Q in the \overline{MS} scheme. The calculation is done using the NNLO formula in [48]. Thresholds for b-quark and t-quark are included in n_f at the scales $m_b(m_b)$ and $m_t(m_t)$ respectively.

• **MtRun(Q), MbRun(Q), McRun(Q)**

calculates top, bottom and charm quarks running masses evaluated at NNLO.

• **MtEff(Q), MbEff(Q), McEff(Q),**

calculates effective top, bottom and charm quark masses using [48]

$$M_{eff}^2(Q) = M(Q)^2 [1 + 5.67a + (35.94 - 1.36n_f)a^2 + (164.14 - n_f(25.77 - 0.259n_f))a^3] \quad (8)$$

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 $Q = 2M_{LOP}$.

4 Sample models : specific routines

4.1 MSSM

In the case of the MSSM, special routines were developed both for specifying the independent parameters as well as for including higher order corrections. These have already been described in [36], for completeness we summarize the main points here and we point out the modifications implemented. In the MSSM, we use loop corrected superparticle masses and mixing matrices. These masses and mixing matrices are then used to compute exactly at tree-level all annihilation/coannihilation cross-sections. Higher order corrections to the Higgs masses are also calculated by one of the spectrum calculators. QCD corrections to Higgs partial widths are included as well as the important SUSY corrections, the Δm_b correction, that are relevant at large $\tan\beta$. These higher-order corrections also affect directly the Higgs- $q\bar{q}$ vertices and are taken into account in all the relevant annihilation cross-sections. These routines were described in [36] and have not been changed. A description of parameters can be found in the `MSSM/lib/pmodel.h` file.

The independent parameters of the model include all masses and mixing matrices as specified in the SLHA [43]. We have chosen this enlarged set of parameters rather than the MSSM soft SUSY breaking parameters used in the original version of `micrOMEGAs` for the greater flexibility it provides in modifying parameters and in incorporating models. In this approach once the MSSM has been implemented within `CalcHEP`, the same model file can be used for either `mSUGRA`, `AMSB` or the general MSSM. The only difference will be in the definition of the input parameters and the use of different routines to determine the independent parameters.

To define the spectrum one can either read the independent parameters defined in the *SLHA* format [43] from an input file, calculate the set of independent parameters starting from the GUT scale input parameters and using one of the spectrum calculator, or calculate the set of independent parameters from the weak scale MSSM parameters. For input parameters specified at the GUT scale, for example in the context of `SUGRA` models, loop corrections are obtained from one of the public codes which calculate the supersymmetric spectrum using renormalization group equations (RGE), `SUSPECT 2.3`[49], `SOFTSUSY 1.9`[50], `SPHENO 2.2.2`[51] or `ISAJET 7.69`[52].

The routines that define the spectrum are

- `specSUGRA` defines the independent parameters of the MSSM starting from a set of input parameters in the `SUGRA` model. Here `spec` stands for one of the spectrum calculators `suspect`, `isajet`, `spheno`, or `softSusy`.
- `specAMSB` does the same as above within the `AMSB` model.
- `specEwsbMSSM` calculates the masses of Higgs and supersymmetric particles in the MSSM including one-loop corrections starting from weak scale input parameters. Here `spec` stands for one of the spectrum calculators `suspect`, `isajet`, `spheno`, or `softSusy`.
- `assignValW("dMb", deltaMb())` needs to be called in order to include the threshold correction to the $Hb\bar{b}$ vertex. This call must be done only after the spectrum has been calculated using one of the commands above.

Some facilities to read or write directly SLHA files are also available

- `readLesH(f)` reads the SLHA input file *f*.
- `writeLesH(f)` saves into the file *f* the SLHA MSSM parameters.

The default spectrum calculator package is **SUSPECT 2.3**. To work with another package one has to specify the appropriate path in **MSSM/lib/Makefile**. For this the environment variables **ISAJET**, **SPHENO** or **SOFTSUSY** must be redefined accordingly. Note that we also provide a special interface for **ISAJET** to read a SLHA file. This means that the user must upgrade his original **ISAJET** libraries to include this interface. Specific instructions are provided in the **README** file.

There are two spectrum information commands which in **micrOMEGAs 1.3** were included in **printMasses**,

- **HiggsMasses(file)** prints into **file** the masses and widths of Higgs particles.
- **olContents(file)** prints into **file** the neutralino LSP components in terms of *bin*_o, *win*_o, *higgsino1*, and *higgsino2* fractions.

The MSSM package also includes routines that calculate other constraints such as $\delta\rho$ (**deltarho_**), $(g-2)_\mu$ (**gmuon_**), collider limits (**masslimits_**), $Br(b \rightarrow s\gamma)$ (**bsgnlo_**), and $Br(B_s \rightarrow \mu^+\mu^-)$ (**bsmumu_**), see Ref. [36].

4.1.1 Sample main programs

The directory **MSSM** contains several examples of *main* programs written in C (or Fortran), these include programs to calculate Ωh^2 with either SUGRA or MSSM models as well as programs to calculate cross-sections and branching ratios or spectrum of outgoing particle for dark matter annihilation. In general when these sample programs are launched without arguments, the arguments needed are explained on the screen.

- **sugomg.c/F** calculates the spectrum of Higgs and SUSY particles as well as the relic density Ωh^2 and other constraints.
- **s_cycle.c** calculates the relic density of Ωh^2 in a cycle. For the set of mSUGRA parameters used in this example, the output should correspond to the file **data/s_cycle.res**.
- **omg.c/F** calculate Ωh^2 for a set of MSSM input parameters to be read from a file. The name of this file is given as an argument of the executable **omg**. The appropriate format is given in the sample files provided in the directory **data**. It is possible to execute the program with several files (arguments) in one call. The results corresponding to the sample input data files **omg data/data*** can be found in the **data/omg.res** file.
- **cs_br.c/F** give some examples for the calculation of partial widths and cross-sections.
- **spectrum.c/F** give examples of calculation of neutralino annihilation spectrum. The output is a graphical plot which is displayed on the screen.

4.2 CPV-MSSM

In the MSSM model described above all parameters are assumed to be real, generically though the parameters of the MSSM can be complex (CPV-MSSM). Furthermore, it is possible that electroweak baryogenesis could work in MSSM scenarios with complex phases. A new CPV-MSSM model file with complex parameters was rebuilt in the **CalcHEP** notation [39] using **LanHEP** [40], thus specifying all relevant Feynman rules. For the Higgs sector, an effective potential was written in order to include in a consistent manner higher-order effects [53]. Although this model is only a simple extension

of the MSSM, the implementation within `micrOMEGAs` is done differently. The independent parameters of the model include in addition to some standard model parameters only the weak scale MSSM input parameters. The constrained parameters, in particular the masses, are evaluated through auxiliary functions. Masses, mixing matrices and parameters of the effective potential are read directly from CPsuperH [53], together with masses and mixing matrices of neutralinos, charginos and third generation sfermions. On the other hand, masses of the first two generations of sfermions are evaluated (at tree-level) within `micrOMEGAs` in terms of independent parameters of the model. This means that in this model it is not possible to get the value of the mass of the SUSY particles, say the lightest neutralino, using the `findVal("MNE1")` command, rather one has to call `findParam("MNE1",err)`. The code for CPsuperH is included in our package.

Among the special routines that were described for the MSSM in the previous section, only the ones that give information about the spectrum can also be used in this model, `HiggsMasses(file)` and `o1Contents(file)`. The latter gives the real and imaginary part of the $\text{bino}/\text{wino}/\text{Higgsino}_1/\text{Higgsino}_2$ components of the LSP. Since the phases in the CPV-MSSM are strongly constrained by measurements of electric dipole moments, it is important to take into account. We have developed a special routine for this purpose

- `edm_(&de,&dTI)` returns the value of the electric dipole moment of the electron, d_e in units of ecm as well as the dipole moment of Thallium, d_{TI} . One-loop neutralino/chargino contributions as well as two-loop squark, quark and chargino contributions are included [24, 54, 55, 56] as well as the four-fermion operator for d_{TI} . The latter two contributions can dominate, especially for large values of $\tan\beta$. The upper limit from the measurement of the electric dipole moment of the electron is actually $d_e < 2.2 \times 10^{-27} ecm$ [57].

4.3 NMSSM

The NMSSM is the simplest extension of the MSSM with one extra singlet, as a result the model contains one additional neutralino as well as additional scalars. A new model file was implemented into `CalcHEP` and as in the MSSM, an improved effective potential for the Higgs sector was defined. More details on the model can be found in Ref. [25].

The independent parameters of the model include, in addition to some standard model parameters, the weak scale NMSSM input parameters as defined in the SLHA2 [58]. The constrained parameters, in particular the masses, are evaluated through auxiliary functions. For this we call NMHDECAY [59] specifying an input file in the SLHA2 format (`slhainp.dat`). The masses, mixing matrices are then read directly from the output file of NMHDECAY [60] written in the SLHA2 format (`spectr.dat`). These two SLHA files are available in the main NMSSM directory. The parameters of the Higgs potential are derived from the physical masses and mixing matrices of the charged and neutral Higgses as described in [25]. Note however that in NMHDECAY, the masses are computed using the \overline{DR} values of the independent parameters of the Higgs sector, $\lambda, \kappa, \tan\beta, \mu, A_\lambda, A_\kappa$ and include additional loop corrections. Some of these parameters, in particular μ, A_λ, A_κ receive large corrections. To take these corrections into account we have modified the procedure to extract the parameters of the Higgs potential that used previously the input value at weak scale. We have a good agreement with NMHDECAY for the partial widths of heavy Higgses into lighter Higgs particles.

The `HiggsMasses(file)` and `o1Contents(file)` routines described in the MSSM can also be used in this model. The latter gives the $\text{bino}/\text{wino}/\text{Higgsino}_1/\text{Higgsino}_2/\text{singlino}$

components of the LSP. As in the MSSM the function `bsgnlo_()` returns the value of $Br(b \rightarrow s\gamma)$. This value is calculated within NMHDECAY [60, 59]⁷. Note that in this model it is not possible to get the value of the mass of the SUSY particles using the `findVal` command, since these are constrained parameters. Rather one has to call `findParam`.

Theoretical and experimental constraints on the model are checked thoroughly within NMHDECAY, a function has been written specifically for the NMSSM :

- `NMHwarn(file)` returns the number of constraints that are not satisfied as provided by NMHDECAY. Information about these constraints is stored in `file`. The description of different experimental (e.g. LEP limits on Higgs masses) and theoretical constraints on the model can be found in Ref. [60].

5 New models.

In general, to implement a new model the user only needs to write the model in the CalcHEP format. The directory for the new model can be created by the

```
newProject <NewModel>
```

command. The new directory `<NewModel>` will contain in particular, a directory `work` for the description of the model and a directory `lib` implementation of external functions. It also contains a directory `calchep` as well as examples of *main* programs for the calculation of Ωh^2 , `omg.c` and `omg.F`, and finally a `Makefile` that compiles the code. Note that this `Makefile` is created automatically and does not need to be modified by the user.

We have tried to minimize the amount of user “intervention”. In general the user has only to include the CalcHEP model files in `work/models`, put the external codes that calculate external functions of the model as well as auxiliary routines in the directory `lib`, write the corresponding `lib/Makefile` for their compilation. All other files and subdirectories are generated automatically and do not need to be modified by the user.

5.1 The directory work

To implement a new model, the first step consists in writing the new CalcHEP model files in the sub directory `work/models`. This model has to be the first in the list, thus the files must have names `*1.mdl`. More precisely the model must include five files that specify the list of particles (`prtcls1.mdl`), the independent variables (`vars1.mdl`), the Lagrangian with all vertices (`lgrng1.mdl`), all internal functions (`func1.mdl`) and external libraries required for the model (`extlib1.mdl`). Note that to automatize as much as possible the procedure for creating a new model, it is possible to use a program like LanHEP[40], which starts from the Lagrangian and derives all the necessary Feynman rules⁸. Alternatively the user can write by hand the model files of the new model. Slight modifications to the standard CalcHEP model files are necessary, specific requirements are given below in Section 5.3.

The directory `work/so_generated` contains the libraries of matrix elements generated automatically by CalcHEP . As mentioned earlier, since the contents of libraries in

⁷Note that for the moment, NMHDECAY computes only the one-loop contribution to $Br(b \rightarrow s\gamma)$.

⁸LanHEP was developed for CompHEP [61] but there exists a simple tool to make a conversion to the CalcHEP notation.

`so_generated/` are not checked, this directory should be cleaned every time a model is modified. It will be then regenerated automatically.

5.2 The directory lib

Additional external functions may also be required to have a complete model, these should be included in the directory `lib`. The functions required by `func1.mdl` have to be incorporated as a shared library `lib/mLib.so`⁹. Other auxiliary routines not needed for the model should be included in `lib/aLib.a`.

As explained in Section 4.1, it is sometimes more convenient to choose an enlarged set of independent parameters for a given model even though physically these parameters are not truly independent. Clearly, constraints on these parameters have to be imposed before the calculation of matrix elements. Such is the case in the MSSM implementation described here where all masses and mixings are chosen as independent parameters. As usual, independent parameters have to be listed in `vars1.mdl` and should not be defined in `func1.mdl`. Also the relevant functions should be compiled in `lib/aLib.a` rather than in `lib/mLib.so`. It is not compulsory to implement one or even both of these libraries. The presence of these libraries are always checked by `micrOMEGAs` commands before passing them to the linker. The execution of the `Makefile` in `<NewModel>` launches the `lib/Makefile` in order to update the user's libraries.

5.3 Specific requirements for the implementation of a new model.

The general format to be used for model files is described in [39]. Here we explain only specific points needed for `micrOMEGAs`.

Names of odd particles. The name of odd particles must start with `~`. With this convention, automatic identification of the R-parity odd particles is done by `micrOMEGAs`. For the purpose of optimizing the code, it is recommended that the first odd particle in the `models/prtcls1.mdl` list be a potential LOP candidate.

Masses of odd particles. A `*` symbol should be added before the masses of R-parity odd particles that are not independent parameters of the model, that is the ones that are found in the `models/func1.mdl` file. This is to force the inclusion of the corresponding parameter in any generated code.

Widths of odd particles. The widths of odd particles should be independent parameters of the model. All odd particles, including the LOP, must have a width in order to avoid divergences in cross-sections. For example, in coannihilation processes with exchange of the LOP in t-channel, one can meet a pole if the width of the LOP is zero. The width of the LOP is set within `micrOMEGAs` to $M_{LOP}/100$, see explanations in [36].

Automatic calculation of widths. In previous `CalcHEP` versions the widths of particles were treated as independent parameters. Starting from `CalcHEP_2.4` there is an option to calculate widths automatically. To switch on the mechanism of automatic

⁹In the case of Cygwin the shared libraries have the extension `.dll`

width calculation one must add the '!' symbol in front of the width in the particle list (`models/prtcls1.mdl`). If necessary, the corresponding parameter should be removed from the list of independent parameters (`models/vars1.mdl`) and/or from the list of constrained parameters (`models/func1.mdl`). For the relic density calculation, this trick is used for widths of Higgs particles which occur as s-channel resonances.

5.4 Compilation of libraries.

Specific requirements for writing the `lib/Makefile` are detailed in this section. The `mLib.so` library is used for external names resolution in the generation of *shared* libraries of matrix elements. Such name resolution is a strict requirement of *Darwin* and *Cygwin* platforms. We recommend the use of the compiler flags stored in the `CalcHEP/FlagsForMake` file, in particular the option `SHARED` needed to generate a *shared library* instead of an executable code.

Whenever operating with shared libraries there is a general a problem in finding the location of the library in run-time. Normally, each shared library has a record which specifies its location, while linking this information is passed to the *main* program. Usually in order to write this record correctly one has to specify the full path of the library after the `-o` instruction. On some other platforms, for instance *OSF1*, one needs an additionnal linker flag. In `flagsForMake`, this flag is named `SONAME` and it should be followed by the full name of the library. The `MSSM/lib/Makefile` gives an example on how to use the `SHARED` and `SONAME` flags. All these options do not work with the *Cygwin* version of UNIX. In this particular case only the shared libraries whose paths are included in the `PATH` environment variable can be linked in run-time. For this reason, in the case of *Cygwin*, `micrOMEGAs` executables have to be launched via the command

```
./cgwRun <exec> <param>
```

which corrects the `PATH` environment parameters before starting the `micrOMEGAs` executable. Here `exec` stands for the name of the executable and `param` for the input parameters.

We assume that `mLib.so` does not contain calls to functions described in Section 3 or calls to external functions not needed for matrix element generation. On the other hand, there are no such restrictions for `aLib.a`. It can call any function in `sources/micromegas.a`, for example the `assignValW` function to set the value of independent parameters of the model. `aLib.a` can also use any function implemented in `mLib.so`, in particular functions used in `models/func1.mdl`. Thus the user can access the value of constrained parameters. For example, in the NMSSM, `nMass(1000022)` will give the value of the mass of the lightest neutralino. Here the PDG [48] code is used for particle names. Alternatively, we provide a more convenient function that serves the same purpose. The function

```
findParam(name,&err)
```

will return the value of the parameters `name` defined in `models/func1.mdl`. A non-zero error code `err` signals failure to find the needed parameter. The parameters that are accessible automatically by this command are, for technical reasons, the ones that enter the calculation of the matrix element for pair annihilation of the first odd particle listed in `prtcls1.mdl`. It is possible to access all other parameters in `models/func1.mdl`. For this, the user must insert a `*` in front of the corresponding parameter in `func1.mdl` and recompile the model ¹⁰.

¹⁰For this, the generated shared libraries for matrix elements should first be cleaned. It is only when

Use of external programs. When one function implemented in the CalcHEP model makes use of some large external program, we recommend to use a `system` function call to launch the corresponding external program separately. Communication with this external program can proceed via files. There is no need to rewrite external functions as shared libraries. For example we have adopted this procedure in the MSSM to call spectrum calculators, the SLHA files provide a format for reading the input/output files of these external programs. A similar procedure is used for calls to NMHDECAY or CPSuperH in the NMSSM or the CPV-MSSM.

Code optimization. The evaluation of some external functions or constraints implemented in the model can be time consuming. Sometimes `micrOMEGAs` recalculates all constraints several times with slightly different parameters. We recommend that the user inserts, in the time consuming functions, some checks of input parameters and uses the previous result if the arguments were not changed.

5.5 Check of the new model

We strongly recommend, before the first launch of `micrOMEGAs 2.0` with a new model, to check the model in an interactive `CalcHEP` session. For this purpose first launch `./calchep` in the `work` directory, find the `Edit model` menu and make some modification without really changing the model, say add and remove one symbol. When you will leave the `Edit model` menu, after you have confirmed your corrections, `CalcHEP` will start to check the model. You should remove all bugs detected before starting your `micrOMEGAs` session. The completeness of the `mLib.so` library for the model can also be checked. For this one must first add to `work/models/extlib1.mld` one record,

```
../../lib/mLib.so
```

Then, within an interactive `CalcHEP` session, the check will be performed at the compilation of a new process, for example some decay width. An error message will signal a problem in the `mLib.so` library.

6 Installation

The package can be obtained from the web page wwwlapp.in2p3.fr/micromegas. Unpacking the file `micromegas_2.0.tgz` will create the directory `micromegas_2.0` described in previous sections. This file contains the full implementation of the MSSM model. The NMSSM and the CPV-MSSM model files and auxiliary routines for implementation of the model are obtained independently from `NMSSM.tgz` and `CPVMSSM.tgz`. They have to be downloaded, unpacked, and copied in the `micromegas_2.0` directory.

The installation consists of two steps, the general installation of `micromegas_2.0` and the installation of special models. The general installation is realized by the command

```
gmake11
```

This command identifies the Unix platform, compiles the `CalcHEP` executable `CalcHEP_src/bin/s_calchep` as well as the general function library `sources/micromegas.a`.

To install a new model one must use the command

`micrOMEGAs` recompiles the libraries that the parameter will be accessible via `findParam`.

¹¹If `gmake` is not available, for example with Darwin, one should use `make` instead

```
./newProject <Name>
```

which creates a new sub-directory `<Name>` containing all files and sub-directories needed for a new model. This directory has the same structure as the `MSSM` directory but does not contain special MSSM routines and model files. How this directory should be updated to implement completely a new model, was explained in Section 5.

At last, in order to compile an executable file for the calculation of relic density in the framework of a model one has to move to the corresponding directory, say `MSSM`, and call

```
gmake main=<filename>
```

where `<filename>` designates the name of C or Fortran *main* routines. This `<filename>` should have the corresponding `.c` or `.F` extension. The executable generated will have the same name without an extension. To launch the executable with `Cygwin` one must instead use the command

```
./cgwRun <name of exec> <param>
```

This commands improves the `PATH` environment parameters so that the shared libraries are readable.

Acknowledgements

This work was supported in part by GDRI-ACPP of CNRS. The work of A. Semenov was also supported by grants from the Russian Federal Agency for Science, NS-8122.2006.2 and RFBR-04-02-17448. The authors thank A. Belyaev and U. Ellwanger for fruitful discussions, S. Kraml for her contributions in the implementation of the CPV-MSSM and C. Balazs for the first implementation of `micrOMEGAs 2.0` for models with universal extra dimensions. We also thank C. Hugonie for discussions on NMHDECAY, for his contribution in the implementation of the NMSSM and for his help in making a version compatible with Darwin.

A Problems in compilation.

The code was tested on several UNIX platforms with standard configuration, OSF1, SunOS, Darwin, Cygwin. In general it should work without special tuning. Some common problems and their solution are listed below.

At first `gmake` launches the `getFlags` routines in the `CalcHEP_src` subdirectory. This `getFlags` checks the UNIX platform and writes the `FlagsForSh` file which contains compiler flags and special linker options accordingly. After that `getFlags` checks compiles and writes an error message, if some option are not available. If `FlagsForSh` already exists, then `getFlags` only checks compilers. This way, compiler options can be improved by users.

B Example of micrOMEGAs session.

Here we present a sample output of the particle spectrum and relic density calculation in the case of the `mSUGRA` model. First the user has to compile general routines with `./gmake` launched in the directory `micromegas_2.0`, then the C version of `sugomg` main program should be compiled in the `MSSM` directory with

```
gmake main=sugomg.c
```

This generates the executable `sugomg`. This executable needs at least 4 parameters, additional parameters are set to their default value if not provided. The meaning of the input parameters are written on the screen when launching the programs without input parameters. Out test run, which uses by default `SUSPECT 2.3` for the spectrum calculation, should give the following output:

```
./sugomg 100 100 0 10
```

Higgs masses and widths

```
Mh      = 100.67 (wh      =2.5E-02)
MHH     = 173.71 (wHh     =8.5E-01)
MH3     = 172.58 (wH3     =1.2E+00)
MHc     = 190.85
```

Masses of Odd particles:

```
~o1 : MNE1 = 28.6 || ~1+ : MC1 = 50.0 || ~o2 : MNE2 = 55.8
~n1 : MSn1 = 101.9 || ~ne : MSne = 102.4 || ~nm : MSnm = 102.4
~l1 : MSl1 = 107.9 || ~eR : MSeR = 115.1 || ~mR : MSmR = 115.1
~eL : MSeL = 129.6 || ~mL : MSmL = 129.6 || ~l2 : MSl2 = 134.3
~o3 : MNE3 = 158.0 || ~o4 : MNE4 = 188.2 || ~2+ : MC2 = 190.6
~t1 : MSt1 = 192.5 || ~b1 : MSb1 = 240.6 || ~uR : MSuR = 254.4
~cR : MScR = 254.4 || ~uL : MSuL = 257.4 || ~cL : MScL = 257.4
~dR : MSdR = 257.5 || ~sR : MSsR = 257.5 || ~b2 : MSb2 = 261.0
~dL : MSdL = 269.4 || ~sL : MSsL = 269.4 || ~g : MSG = 270.1
~t2 : MSt2 = 332.9 ||
```

```
~o1 = 0.828*bino -0.302*wino +0.453*higgsino1 -0.135*higgsino2
Omega= 7.01E-02
```

Channels which contribute to $1/(\text{omega})$ more than 1%.

Relative contributions in % are displayed

```
44% ~o1 ~o1 -> b B
7% ~o1 ~o1 -> d D
4% ~o1 ~o1 -> u U
4% ~o1 ~o1 -> c C
7% ~o1 ~o1 -> s S
17% ~o1 ~o1 -> l L
8% ~o1 ~o1 -> m M
8% ~o1 ~o1 -> e E
```

```
deltarho= 5.64E-04
```

```
gmuon= 1.22E-08
```

```
bsgnlo= 1.63E-04
```

```
bsmumu= 3.74E-09
```

WARNING: Chargino below LEP limit

References

- [1] C. L. Bennett *et. al.*, *Astrophys. J. Suppl.* **148** (2003) 1, [[astro-ph/0302207](#)].
- [2] D. N. Spergel *et. al.*, **WMAP** Collaboration *Astrophys. J. Suppl.* **148** (2003) 175, [[astro-ph/0302209](#)].
- [3] M. Tegmark *et. al.*, **SDSS** Collaboration *Phys. Rev.* **D69** (2004) 103501, [[astro-ph/0310723](#)].
- [4] G. Jungman, M. Kamionkowski, and K. Griest, *Phys. Rept.* **267** (1996) 195–373, [[hep-ph/9506380](#)].
- [5] S. Profumo and C. E. Yaguna, *Phys. Rev.* **D70** (2004) 095004, [[hep-ph/0407036](#)].
- [6] B. C. Allanach, G. Belanger, F. Boudjema, and A. Pukhov, *JHEP* **12** (2004) 020, [[hep-ph/0410091](#)].
- [7] N. Arkani-Hamed, A. Delgado, and G. F. Giudice, *Nucl. Phys.* **B741** (2006) 108–130, [[hep-ph/0601041](#)].
- [8] J. R. Ellis, K. A. Olive, Y. Santoso, and V. C. Spanos, *Phys. Rev.* **D69** (2004) 095004, [[hep-ph/0310356](#)].
- [9] H. Baer and C. Balazs, *JCAP* **0305** (2003) 006, [[hep-ph/0303114](#)].
- [10] C. Pallis and M. E. Gomez, [hep-ph/0303098](#).
- [11] U. Chattopadhyay, A. Corsetti, and P. Nath, *Phys. Rev.* **D68** (2003) 035005, [[hep-ph/0303201](#)].
- [12] E. A. Baltz and P. Gondolo, *JHEP* **10** (2004) 052, [[hep-ph/0407039](#)].
- [13] G. Belanger, S. Kraml, and A. Pukhov, *Phys. Rev.* **D72** (2005) 015003, [[hep-ph/0502079](#)].
- [14] A. Djouadi, M. Drees, and J.-L. Kneur, *JHEP* **03** (2006) 033, [[hep-ph/0602001](#)].
- [15] J. R. Ellis, T. Falk, K. A. Olive, and Y. Santoso, *Nucl. Phys.* **B652** (2003) 259–347, [[hep-ph/0210205](#)].
- [16] V. Bertin, E. Nezri, and J. Orloff, *JHEP* **02** (2003) 046, [[hep-ph/0210034](#)].
- [17] A. Birkedal-Hansen and B. D. Nelson, *Phys. Rev.* **D67** (2003) 095006, [[hep-ph/0211071](#)].
- [18] H. Baer, A. Mustafayev, S. Profumo, A. Belyaev, and X. Tata, *JHEP* **07** (2005) 065, [[hep-ph/0504001](#)].
- [19] G. Belanger, F. Boudjema, A. Cottrant, A. Pukhov, and A. Semenov, *Czech. J. Phys.* **55** (2005) B205–B212, [[hep-ph/0412309](#)].
- [20] P. Binetruy, Y. Mambrini, and E. Nezri, *Astropart. Phys.* **22** (2004) 1–18, [[hep-ph/0312155](#)].

- [21] C. Balazs, M. Carena, A. Menon, D. E. Morrissey, and C. E. M. Wagner, *Phys. Rev.* **D71** (2005) 075002, [[hep-ph/0412264](#)].
- [22] T. Nihei and M. Sasagawa, *Phys. Rev.* **D70** (2004) 055011, [[hep-ph/0404100](#)].
- [23] S. Y. Choi and Y. G. Kim, *Phys. Lett.* **B637** (2006) 27–31, [[hep-ph/0602109](#)].
- [24] G. Belanger, F. Boudjema, S. Kraml, A. Pukhov, and A. Semenov, [hep-ph/0604150](#).
- [25] G. Belanger, F. Boudjema, C. Hugonie, A. Pukhov, and A. Semenov, *JCAP* **0509** (2005) 001, [[hep-ph/0505142](#)].
- [26] J. F. Gunion, D. Hooper, and B. McElrath, [hep-ph/0509024](#).
- [27] V. Barger, C. Kao, P. Langacker, and H.-S. Lee, *Phys. Lett.* **B600** (2004) 104–115, [[hep-ph/0408120](#)].
- [28] D. A. Demir, M. Frank, and I. Turan, [hep-ph/0604168](#).
- [29] K. Kong and K. T. Matchev, [hep-ph/0509119](#).
- [30] G. Servant and T. M. P. Tait, *Nucl. Phys.* **B650** (2003) 391–419, [[hep-ph/0206071](#)].
- [31] K. Agashe and G. Servant, *JCAP* **0502** (2005) 002, [[hep-ph/0411254](#)].
- [32] A. Birkedal-Hansen and J. G. Wacker, *Phys. Rev.* **D69** (2004) 065022, [[hep-ph/0306161](#)].
- [33] J. Hubisz and P. Meade, *Phys. Rev.* **D71** (2005) 035016, [[hep-ph/0411264](#)].
- [34] A. Martin, [hep-ph/0602206](#).
- [35] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *Comput. Phys. Commun.* **149** (2002) 103–120, [[hep-ph/0112278](#)].
- [36] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *Comput. Phys. Commun.* **174** (2006) 577–604, [[hep-ph/0405253](#)].
- [37] P. Gondolo *et. al.*, *JCAP* **0407** (2004) 008, [[astro-ph/0406204](#)].
- [38] H. Baer, C. Balazs, and A. Belyaev, *JHEP* **03** (2002) 042, [[hep-ph/0202076](#)].
- [39] A. Pukhov, [hep-ph/0412191](#).
- [40] A. V. Semenov, [hep-ph/0208011](#).
- [41] A. Birkedal, A. Noble, M. Perelstein, and A. Spray, [hep-ph/0603077](#).
- [42] P. Brun, [astro-ph/0603387](#).
- [43] P. Skands *et. al.*, *JHEP* **07** (2004) 036, [[hep-ph/0311123](#)].
- [44] G. B. Gelmini, P. Gondolo, and E. Roulet, *Nucl. Phys.* **B351** (1991) 623–644.

- [45] J. Edsjo and P. Gondolo, *Phys. Rev.* **D56** (1997) 1879–1894, [[hep-ph/9704361](#)].
- [46] J. L. Feng, A. Rajaraman, and F. Takayama, *Phys. Rev.* **D68** (2003) 063504, [[hep-ph/0306024](#)].
- [47] G. Belanger, F. Boudjema, P. Brun, A. Pukhov, S. Rosier-Lees, P. Salati, and A. Semenov, in **preparation**.
- [48] S. Eidelman *et. al.*, **Particle Data Group** Collaboration *Phys. Lett.* **B592** (2004) 1.
- [49] A. Djouadi, J.-L. Kneur, and G. Moultaka, [hep-ph/0211331](#).
- [50] B. C. Allanach, *Comput. Phys. Commun.* **143** (2002) 305–331, [[hep-ph/0104145](#)].
- [51] W. Porod, *Comput. Phys. Commun.* **153** (2003) 275–315, [[hep-ph/0301101](#)].
- [52] F. E. Paige, S. D. Protopescu, H. Baer, and X. Tata, [hep-ph/0312045](#).
- [53] J. S. Lee *et. al.*, *Comput. Phys. Commun.* **156** (2004) 283–317, [[hep-ph/0307377](#)].
- [54] S. Y. Choi, M. Drees, and B. Gaissmaier, *Phys. Rev.* **D70** (2004) 014010, [[hep-ph/0403054](#)].
- [55] D. Chang, W.-Y. Keung, and A. Pilaftsis, *Phys. Rev. Lett.* **82** (1999) 900–903, [[hep-ph/9811202](#)].
- [56] A. Pilaftsis, *Nucl. Phys.* **B644** (2002) 263–289, [[hep-ph/0207277](#)].
- [57] K. Hagiwara *et. al.*, **Particle Data Group** Collaboration *Phys. Rev.* **D66** (2002) 010001.
- [58] B. C. Allanach *et. al.*, Presented at Les Houches Workshop on Physics at TeV Colliders, Les Houches, France, 2-20 May 2005.
- [59] U. Ellwanger and C. Hugonie, [hep-ph/0508022](#).
- [60] U. Ellwanger, J. F. Gunion, and C. Hugonie, *JHEP* **02** (2005) 066, [[hep-ph/0406215](#)].
- [61] A. Pukhov *et. al.*, [hep-ph/9908288](#).