micrOMEGAs: A program for calculating the relic density in the MSSM

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Abstract

We present a code that calculates the relic density of the lightest supersymmetric particle (LSP) in the minimal supersymmetric standard model. All tree-level processes for the annihilation of the LSP are included as well as all possible coannihilation processes with neutralinos, charginos, sleptons, squarks and gluinos. In all we have included over 2800 processes not counting charged conjugate states. The cross-sections extracted from `CompHEP` are calculated exactly. Relativistic formulae for the thermal average are used and care is taken to handle poles and thresholds by adopting specific integration routines. The input parameters can be either the soft SUSY parameters in a general MSSM or the five parameters of a SUGRA model. A link with `ISASUGRA/ISAJET` allows to calculate the parameters of the MSSM at the weak scale for an input at the GUT scale. The Higgs masses are calculated with `FeynHiggsFast`. Routines calculating $(g-2)_\mu$ and $b \rightarrow s\gamma$ are also included.

PROGRAM SUMMARY

Title of program: micrOMEGAs

Program obtainable from: http://wwwlapp.in2p3.fr/lapth/micromegas

Computers for which the program is designed and others on which it has been tested: PC, Alpha, Silicon graphics, Sun

Opaerating systems under which the program has been tested : Linux, OSF1, IRIX64, SunOS

Programming language used: C

Memory required to execute with typical data: 17MB depending on the number of processes required.

No. of processors used: 1

Has the code been vectorized or parallelized: no

No. of bytes in distributed program, including test data: 3102kB

Nature of physical problem: Calculation of the relic density of the lightest supersymmetric particle in the MSSM.

Method of solution: In solving the Boltzmann equation, relativistic formulae for the thermal average are used. All tree-level processes for annihilation and coannihilation of SUSY particles are included. The cross-sections for all processes are calculated exactly with CompHEP. Two-loop corrections to the Higgs masses are calculated with FeynHiggsFast. QCD corrections to the Higgs width are extracted from HDECAY. A link to ISASUGRA is provided as an option to calculate the parameters of the MSSM at the weak scale.

Typical running time: 0.2 sec.

Unusual features of the program: Depending on the parameters of the model, the program generates additional new code, compiles it and loads it dynamically.

1   Introduction

One of the very attractive arguments in favour of supersymmetry(SUSY) is that it provides a natural solution to the dark matter problem. In R-parity conserving supersymmetric models there exists a neutral stable particle, the lightest supersymmetric particle(LSP), which could constitute the cold dark matter in the universe. As there are strong constraints on stable charged particles, only if the LSP is a neutralino or a sneutrino could SUSY provide a suitable dark matter candidate. Cosmological constraints however as

well as direct searches disfavour the sneutrino [1] leaving the neutralino as the preferred candidate for dark matter.

The contribution of neutralinos to the relic density is however very model dependent and varies by several orders of magnitude over the whole allowed parameter space of the MSSM. The relic density then imposes stringent constraints on the parameters of the MSSM often favouring solutions with light supersymmetric particles. In this context the inclusion of the relic density constraints, by giving a handle on the supersymmetric particle spectrum, has important consequences both for studies of SUSY at colliders and in astroparticle experiments.

It has been known for some time that coannihilation processes where the LSP interacts with slightly heavier sparticles can significantly reduce the estimate of the relic density, leading to acceptable values even with a rather heavy sparticle spectrum. In principle these coannihilations can occur with any supersymmetric particle [2]. The importance of the coannihilation channels were emphasized before both for gauginos [3, 4], sleptons [5, 6] or stops [7, 8]. Here, *ALL* channels will be included. In some regions of the parameter space the neutralinos annihilate so fast that they cannot constitute the only source of dark matter. This happens for example when the masses are such that the neutralinos can annihilate through a s-channel Higgs resonance [9, 10] or a s-channel Z resonance [11]. When solving the Boltzmann equation, one needs to evaluate the thermally averaged cross-section for annihilation of neutralinos (and when necesssary coannihilation of SUSY particles). One approximation is to expand the cross-section as a power series in the velocity of the neutralino. While this approximation works well in many cases, it was shown to be inappropriate in regions near poles [2]. The method described in [18] for the relativistic treatment of the thermally averaged annihilation cross-section, with its generalization to the case of coannihilations [4], allows to evaluate with high accuracy the relic density even in regions near poles and thresholds. This is the method we will follow here.

There exist many calculations of the relic density in supersymmetry, using various approximations both in the evaluation of cross-sections and in solving the density equation [9],[12],[13],[14], [15],[16]. Among these, only `Neutdriver`[12] and `DarkSusy`[13] are publicly available. Our purpose is to provide a tool that is both fast, flexible and upgradable and that goes beyond `DarkSusy` as far as the calculation of the relic density is concerned. Although we use basically the method proposed by one of the authors of `DarkSusy` for calculating the relic density [18], we differ from that code in that we still rely on approximations for the solution of the relic density equations and the determination of the freeze-out temperature. This allows to significantly increase the speed of the program and proves to be very useful when scanning over a large parameter space. The main

characteristics of this program, called `micrOMEGAs`, are

- Complete tree-level matrix elements for all subprocesses

- Includes all coannihilation channels with neutralinos, charginos, sleptons, squarks and gluinos.

- Loop-corrected Higgs masses and widths

- Speed of calculation

`micrOMEGAs` is the first program to include all possible coannihilation channels and to calculate exactly the cross-sections for all these processes. All calculations of cross-sections are based on `CompHEP`[17], an automatic program for the evaluation of tree-level Feynman diagrams. The fact that we include the sfermion coannihilation channels as well as one-loop corrections to the Higgs width and that we use an approximate solution for the solution of the relic density equation constitute the main differences with `DarkSusy`. Although we will generally assume that the neutralino is the LSP, `micrOMEGAs` can be used to compute the relic density with any supersymmetric particle as the LSP, in particular the sneutrino. This is because all (co-)annihilation of any pairs of supersymmetric particles into any pairs of standard model or Higgs particles are included.

The program for the relic density calculation described here is contained in a package that lets the user choose between weak scale parameters or parameters of SUGRA models as input parameters. The latter is achieved through a link with `ISASUGRA/Isajet`[19]. In `micrOMEGAs`, the calculation of the Higgs masses are done with `FeynHiggsFast`[20] and QCD corrections to the Higgs partial widths into fermions are extracted from `HDECAY`[21]. In addition we provide subroutines that calculate various constraints on the MSSM parameters: direct limits from colliders, $\Delta\rho$, $b \to s\gamma$ and $(g-2)_\mu$. All these constraints can be updated or replaced easily.

The total number of processes which can contribute to the relic density exceeds 2800. However, due to a strong Boltzmann suppression factor, only processes with SUSY particles close in mass to the LSP are relevant for the calculation. Therefore in most cases only a small fraction of the available processes are needed. In principle, compilation of the full set of subprocesses is possible, but such a program would be huge and could not be distributed easily. To avoid this problem, we include in our package the program `CompHEP`[17] which generates, while running, the subprocesses needed for a given set of MSSM parameters. The generated code is linked during the run to the main program and executed. The corresponding "shared" library is stored on the user disk space and is acessible for all subsequent calls, thus each process is generated and compiled only once. Such approach can be realized only on Unix platforms which support dynamic linking.

The paper is organized as follows. After we summarize the important equations for the calculation of the relic density, we give a short description of the parameters of the supersymmetric model. A description of the package follows. Finally we present some results and comparisons with another program in the public domain, `DarkSusy`.

2   Calculation of the relic density

The relic density at present in units of the critical density, $\rho_{\text{crit}} = 3H^2/8\pi G$, can be expressed as

$$\Omega_{\tilde{\chi}_1^0} = \frac{m_{\tilde{\chi}_1^0} n_{\tilde{\chi}_1^0}}{\rho_{\text{crit}}} = \frac{m_{\tilde{\chi}_1^0} s_0 Y_0}{\rho_{\text{crit}}} \tag{2.1}$$

where $m_{\tilde{\chi}_1^0}$ is the mass of the lightest neutralino, $H = 100h \text{ km} s^{-1} Mpc^{-1}$ is the Hubble constant and G Newton constant. The entropy conservation assumption makes it easier to work with the abundance Y rather than the number density, $n_{\tilde{\chi}_1^0}$. $s_0 = s(T_0)$ defines today's entropy to be evaluated at $T_0 = 2.726K$, the temperature of the microwave background, with

$$s(T) = h_{\text{eff}}(T)\frac{2\pi^2}{45}T^3 \tag{2.2}$$

where h_{eff} is a function that depends slowly on the temperature T [22]. The code in fact returns the relic density

$$\Omega_{\tilde{\chi}_1^0}h^2 = 2.755 \times 10^8 \frac{m_{\tilde{\chi}_1^0}}{GeV}Y_0 \tag{2.3}$$

One thus needs to find $Y_0 = Y(T = T_0)$. The most complete formulae for the calculation of $Y(T)$ were presented in [18, 4] and we will follow their approach rather closely.

The evolution equation of Y is

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45G}} < \sigma v > (Y^2 - Y_{eq}^2) \tag{2.4}$$

$g_*(T)$ is a degrees of freedom parameter derived from the thermodynamics describing the state of the universe [22, 23] and $Y_{eq} = Y_{eq}(T)$ represents the thermal equilibrium abundance

$$Y_{eq}(T) = \frac{45}{4\pi^4 h_{eff}(T)} \sum_i g_i \frac{m_i^2}{T^2} K_2(\frac{m_i}{T}) \tag{2.5}$$

where we sum over all supersymmetric particles i with mass m_i and g_i degrees of freedom. K_n is the modified Bessel function of the second kind of order n [24]. Note that Y_{eq} falls

rather rapidly as the temperature decreases. $< \sigma v >$ is the relativistic thermally averaged annihilation cross-section

$$< \sigma v >= \frac{\sum\limits_{i,j} g_i g_j \int\limits_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T \left(\sum\limits_{i} g_i m_i^2 K_2(m_i/T) \right)^2} \ , \qquad (2.6)$$

where σ_{ij} is the total cross section for annihilation of a pair of supersymmetric particles into some Standard Model particles, and p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

$$p_{ij} = \frac{1}{2} \left[\frac{(s - (m_i + m_j)^2)(s - (m_i - m_j)^2)}{s} \right]^{\frac{1}{2}} \qquad (2.7)$$

The summation is over all supersymmetric particles. Integrating Eq. 2.4 from $T = \infty$ to $T = T_0$ would lead Y_0.

2.1   Freeze-out and approximate solution

Although one can solve for Y numerically, the procedure is extremely time consuming especially when scanning over a large parameter space and when we include a great number of processes. It is therefore important to seek as good an approximation as possible to speed up the code. We will follow the usual procedure of defining a freeze-out temperature T_f[18]. At high T, the LSP are very close to equilibrium and thus $Y \simeq Y_{eq}$. This will hold until freeze-out, where Y will be almost constant whereas Y_{eq} will decrease significantly. At high T, one can make the approximation that $d(Y - Y_{eq})/dT$ is negligible. The freeze-out temperature T_f can be defined from $Y_f = Y(T_f) = (1 + \delta) Y_{eq}(T_f)$ with δ some (small) constant number, T_f can then be extracted by solving

$$\frac{d ln(Y_{eq})}{dT} = \sqrt{\frac{\pi g_*(T)}{45G}} < \sigma v > Y_{eq} \delta(\delta + 2) \qquad (2.8)$$

In the second regime, where $Y \gg Y_{eq}$, one can neglect Y_{eq}^2 completely. One finds[18]

$$\frac{1}{Y(0)} = \frac{1}{Y_f} + \sqrt{\frac{\pi}{45G}} \int_{T_0}^{T_f} g_*^{1/2}(T) < \sigma v > dT \ , \qquad (2.9)$$

In our code, we in fact integrate from $T = 0$ rather than $T = T_0$. This above approach to finding an approximation was used in numerous papers [25, 6]. However one usually omits the $1/Y_f$ term but choose $\delta = .5$. The authors of ref.[18] state that Y_0 as given in (2.9) with $\delta = 1.5$ agrees better with the precise numerical solution. We checked this statement for a wide set of MSSM parameters and reached the same conclusion. The approximation agrees with the exact result of a full numerical solution within 2% [2].

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[2]The widely used approximation without the $1/Y_f$ term in Eq. 2.9 and $\delta = 0.5$ sometimes gives an error of about 10%.

Furthermore we find that the solution (2.9) does not depend significantly on δ, varying δ in the range $1 < \delta < 2$ only affects the result by at most 1%.

It is convenient to express the freeze-out temperature T_f in term of

$$X_f = \frac{m_{\chi_1^0}}{T_f} \tag{2.10}$$

Typically $X_f \approx 25$, this provides a good initial value for the iterative solution of Eq. 2.8. Only a few iterations are necessary to find a solution that satisfies Eq. 2.8 with $\delta = 1.5 \pm .2$.

Typical freeze-out temperatures vary between 1GeV and 10GeV, in this temperature range, the h_{eff} and g_* functions can vary by about 20% [18]. Thus, if one needs an accuracy better than 10%, one cannot use a constant value for these functions as it is done in some papers [6]. In our program we use the numerical tables of the `DarkSUSY` package [13] for a precise evaluation of h_{eff} and g_*.

2.2 Numerical integration and summation

In order to find T_f by solving Eq. 2.8, we have to evaluate several integrals and perform a summation over different annihilation channels. In the evaluation of the thermally averaged cross-section we have included all two-body subprocesses involving two LSP's, the LSP and a co-annihilating SUSY particle (all the particles of the MSSM) as well as all subprocesses involving two coannihilating SUSY particles. The final states include all possible standard model and Higgs particles that contribute to a given process at tree-level. The total number of processes exceeds 2800 not including charged conjugate processes. In practice processes involving the heavier SUSY particles contribute only when there is a near mass degeneracy with the LSP since there is a strong Boltzmann suppression factor B_f in Eq. 2.6.

$$B_f = \frac{K_1((m_i + m_j)/T_f)}{K_1(2m_{\tilde{\chi}_1^0}/T_f)} \approx e^{-X_f \frac{(m_i + m_j - 2m_{\tilde{\chi}_1^0})}{m_{\tilde{\chi}_1^0}}} \tag{2.11}$$

where m_i, m_j are the masses of the incoming particles. To speed up the program a given subprocess is removed from the sum (2.6) if the total mass of the incoming particles is such that B_f is below some limit, B_ϵ defined by the user. In most cases the cross-section for a subprocess with coannihilation is of the same order as the one for the main subprocess with only the LSP, $\sigma_{coan} \approx \sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^0}$. To give a precision of 1% it would be sufficient to use $B_\epsilon = 10^{-2}$. However, in our calculation we use a more restrictive value, $B_\epsilon = 10^{-6}$, to be safe and to allow for cases where $\sigma_{coan} \gg \sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^0}$. This can occur for example for coannihilation processes with squarks which depend on α_s, for processes with poles or

in some regions of parameter space where $\sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^0}$ is suppressed. This criteria, in the case $X_f = 25$, corresponds to a restriction on the masses of the incoming particles

$$m_i + m_j < 2.55 \, m_{\tilde{\chi}_1^0} \tag{2.12}$$

In our program we provide two options to do the integrations, the *fast* one and the *accurate* one. The *fast* mode already gives a precision of about 1% which is good enough for all practical purposes. The *accurate* mode should be used only for some checks. In the *accurate* mode the program evaluates all integrals by means of an adaptative Simpson program. It automatically detects all singularities of the integrands and checks the precision. In the case of the *fast* mode the accuracy is not checked. We integrate the squared matrix elements over $\cos\theta$, the scattering angle, by means of a 5 point Gauss formula. For integration over s, Eq. 2.6 we use a restricted set of points which depends whether we are in the vicinity of a s-channel Higgs(Z,W or t-quark) resonance or not. We increase the number of poins if the Boltzmann factor corresponding to m_{pole} is larger than $0.01 \cdot B_\epsilon$.

2.3 Higgs width

When the LSP is near a Higgs resonance, they annihilate very efficiently. The value of the neutralino annihilation cross-section depends on the total width which can be very large at Higgs masses of 1TeV or so. This is particularly so at large $\tan\beta$ due to the enhancement in the $b\bar{b}$ channel. However the width of $h(H, A) \to b\bar{b}$ receives important QCD corrections. Typically for the heavy Higgses(> 1TeV) the partial width into $q\bar{q}$ can vary easily by a factor of 2 from the tree-level prediction, due mostly to the running of the quark mass at high scale. To take these corrections into account we have redefined the vertices $hq\bar{q}$, $Hq\bar{q}$ and $Aq\bar{q}$ using an effective mass that reproduces the radiatively corrected width. We used HDECAY[21] to produce a table of mass-dependent QCD-corrected Higgs partial widths.[3] From this, the effective quark masses $m_b(m_H)$ are extracted and simple interpolation can reproduce the one-loop corrected width for any value of m_H. In the region of physical interest, the precision on the width is at the per-mil level safe for the neutral Higgses partial widths near the $t\bar{t}$ threshold. However, this region does not contribute significantly to the neutralino cross-section. For the charged Higgs, one can extract from HDECAY both an effective m_t as well as an effective m_b using high and low $tan\beta$ values. This way we could reproduce at better than 1% level the partial width $H^+ \to t\bar{b}$. The effective quark mass $m_b(Q)$ evaluated at $Q = m_1 + m_2$, the sum of the

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[3]We have neglected the SUSY decay modes of the Higgses. These are small in the cases where the contribution of the Higgs channel to the relic density is very important, that is when $m_H \approx 2m_{LSP}$.

initial masses, is used by default in the $(h, H, A) - b\bar{b}$ vertices. This will lead to the correct result when the contribution of the Higgs resonance is very important $(M_H \approx 2m_{\tilde{\chi}_1^0})$.

2.4 Convention for MSSM parameters

The input parameters are the ones of the soft SUSY Lagrangian defined at the weak scale, using the same notation as in `CompHEP/SUSY` models[26]. In the model used, the masses of fermions of the first generation are set to zero. The masses of the quarks of the second generation are also set to zero, so that there is no mixing of the squarks of the first two generations. However we have kept the mass for the muon as well as the trilinear coupling A_μ as this is relevant for the calculation of the muon anomalous magnetic moment. Although first generation sleptons are pure left/right states, they are properly ordered according to their masses so that the correct coannihilating particle corresponding to the lightest slepton is taken into account. In order to avoid unnecessary confusion in the sign convention for the parameters μ and A, we give explicitly the mass matrices for SUSY particles.

The physical masses for charginos and neutralinos are obtained after diagonalizing the mass matrices, for charginos:

$$\mathcal{M}_\mathcal{C} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix} \tag{2.13}$$

and for neutralinos

$$\mathcal{M}_\mathcal{N} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta s_W & M_Z \sin\beta s_W \\ 0 & M_2 & M_Z \cos\beta c_W & -M_Z \sin\beta c_W \\ -M_Z \cos\beta s_W & M_Z \cos\beta c_W & 0 & -\mu \\ M_Z \sin\beta s_W & -M_Z \sin\beta c_W & -\mu & 0 \end{pmatrix} \tag{2.14}$$

For sfermions, the mixing becomes significant only for the third generation, for t-squark, the mass matrix reads

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{Q}3L}^2 + m_t^2 + M_Z^2 \cos 2\beta(\frac{1}{2} - \frac{2}{3}s_W^2) & m_t(A_t - \mu \cot\beta) \\ m_t(A_t - \mu \cot\beta) & m_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3}M_Z^2 \cos 2\beta s_W^2 \end{pmatrix} \tag{2.15}$$

while for b-squarks

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} m_{\tilde{Q}3L}^2 + m_b^2 + M_Z^2 \cos 2\beta(-\frac{1}{2} + \frac{1}{3}s_W^2) & m_b(A_b - \mu \tan\beta) \\ m_b(A_b - \mu \tan\beta) & m_{\tilde{b}_R}^2 + m_b^2 - \frac{1}{3}M_Z^2 \cos 2\beta s_W^2 \end{pmatrix} \tag{2.16}$$

and staus,

$$\mathcal{M}_{\tilde{\tau}}^2 = \begin{pmatrix} m_{\tilde{L}3L}^2 + m_\tau^2 + M_Z^2 \cos 2\beta(-\frac{1}{2} + s_W^2) & m_\tau(A_\tau - \mu \tan\beta) \\ m_\tau(A_\tau - \mu \tan\beta) & m_{\tilde{\tau}_R}^2 + m_\tau^2 - M_Z^2 \cos 2\beta s_W^2 \end{pmatrix} \tag{2.17}$$

3 Contents of the `microOMEGAs` Package

`microOMEGAs` is a C program that also calls some external FORTRAN functions. `microOMEGAs` relies on `CompHEP`[17] for the definition of the parameters and the evaluation of all cross-sections. In the package three sample main programs are provided. The first uses an input file to read the weak scale soft SUSY parameters, the last two give the user the option of working in the context of a SUGRA-type model. In the latter case, a sample file containing a call to `ISASUGRA`[4] to run the renormalization group equations from the GUT scale to the weak scale is provided. This assumes that the user has already installed `ISASUGRA` independently [19]. The user has the choice to substitute his/her own favourite RGE code. `microOMEGAs` is a self-contained program with all subroutines included safe for the `ISASUGRA` routines. The package includes routines for the input of the MSSM/SUGRA parameters, calls to `CompHEP` to calculate physical parameters, calculation of Ωh^2 as well as calls to other subroutines that check for other constraints on the model such as $b \to s\gamma, (g-2)_\mu$ as well as direct limits on the masses of the sparticles.

Some test input files with the MSSM weak scale parameters are stored in the `data/` and `datap/` directories together with the reference output file for comparison purposes.

3.1 Input parameters

Weak scale parameters

When running `microOMEGAs`, the input file must specify the set of weak scale SUSY parameters as in Table 1. The sfermion masses correspond to the soft masses without the D-term. The convention for the third generation of sfermions is specified explicitly in Eq. 2.15. As in the `CompHEP/SUSY` model[26], only the mass matrices for the third generation will then be diagonalized to obtain the physical masses.

In addition to these parameters one can choose to redefine parameters, such as the standard model parameters (Table 2), that are fixed by default [5]. One can also redefine SUSY parameters that do not appear in Table 1, such as the widths of Higgses or SUSY particles. For example, in processes with t-channel poles it is sometimes necessary to specify a width for some particles such as gauginos. By default these widths have been set to 1GeV. Even though the LSP is assumed to be stable, to avoid any spurious pole it is necessary to introduce also a small width. Numerically, the results do not depend on

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[4]The link to Isajet is done here for Version 7.58.

[5]The value of the strong coupling constant cannot be changed directly. This can only be done by adjusting the free parameter Λ_5 from which the value of the coupling $\alpha_s(Q, \Lambda_5, 5)$ is calculated in the range $m_b < Q < m_t$[27]. In this range, a good approximation is $\alpha_s(M_Z, \Lambda_5, 5) = 0.1173 + 0.09 * (\Lambda_5 - .2) - 0.2 * (\Lambda_5 - .2)^2$.

Table 1: Weak scale input parameters in the notation of `CompHEP`

mu	μ Higgs mass parameter
MG1	M_1 Gaugino mass
MG2	M_2 Gaugino mass
MG3	M_3 Gaugino mass
Ml1	Left-handed slepton mass, 1st generation, $m_{\tilde{L}_{1L}}$
Ml2	Left-handed slepton mass, 2nd generation, $m_{\tilde{L}_{2L}}$
Ml3	Left-handed slepton mass, 3rd generation, $m_{\tilde{L}_{3L}}$
Mr1	Right-handed selectron mass, $m_{\tilde{e}_R}$
Mr2	Right-handed smuon mass, $m_{\tilde{\mu}_R}$
Mr3	Right-handed stau mass, $m_{\tilde{\tau}_R}$
Mq1	Left-handed squark mass, 1st generation, $m_{\tilde{Q}_{1L}}$
Mq2	Left-handed squark mass, 1st generation, $m_{\tilde{Q}_{2L}}$
Mq3	Left-handed squark mass, 1st generation, $m_{\tilde{Q}_{3L}}$
Mu1	Right-handed u-squark mass, $m_{\tilde{u}_R}$
Mu2	Right-handed c-squark mass, $m_{\tilde{c}_R}$
Mu3	Right-handed t-squark mass, $m_{\tilde{t}_R}$
Md1	Right-handed d-squark mass, 1st generation$m_{\tilde{d}_R}$
Md2	Right-handed s-squark mass, $m_{\tilde{s}_R}$
Md3	Right-handed b-squark mass, $m_{\tilde{b}_R}$
Atop	Trilinear coupling for top quark, A_t
Ab	Trilinear coupling for b-quark, A_b
Atau	Trilinear coupling for τ-lepton, A_τ
Am	Trilinear coupling for μ, A_μ
MH3	Mass of Pseudoscalar Higgs (M_A)
tb	Ratio of the vacuum expectation values of the scalar doublets

the exact value chosen for these widths. A complete list of widths for all supersymmetric particles can be found in Table 3.

SUGRA GUT-scale Parameters

The value of the weak scale soft supersymmetric Lagrangian can be extracted from `ISASUGRA`. To use this option it is necessary to specify the path for the `Isajet` libraries. The only difference between this option and the weak scale parameters we have just mentionned is that the `readInitFile` has been replaced and an additional call to the `sugraVar` function is done (see the description of these functions in Section 3.2).

The set of input parameters for the SUGRA model are the usual

```
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) or the  ratio of vacuum expectation values

sgn     +/-1,  sign of Higgsino mass term
```

Table 2: Standard Model Parameters

EE	0.31223	Electromagnetic coupling constant
lambd5	0.2	QCD Λ_5
SW	0.473	sin of the Weinberg angle, $\sin\theta_W$
s12	0.221	sin of Cabibbo angle
MZ	91.1884	Z mass
Mm	0.1057	mass of muon
Mtau	1.777	mass of tau-lepton
Mc	1.42	c-quark mass
Mtop	175	top quark mass
Mb	4.62	b-quark mass
wtop	1.7524	width of top quark
wZ	2.4944	Z-boson width
wW	2.08895	W-boson width

```
mtop     pole mass of the top quark

model    = 1  SUGRA model

         = 2  SUGRA with true gauge coupling unification at the GUT scale
```

3.2   Functions of `micrOMEGAs`

All functions provided with the package are briefly described below. The user can find examples of how to call these routines in the `omg.c` or `sugomg.c` file located in the root directory. The types of functions called are specified in Table 5.

- `darkOmega(Xf,fast,Beps)`

This is the basic function of the package which returns the relic density Ωh^2 (Eq. 2.3). `Xf` is the initial value of the X_f parameter needed for solving iteratively the freeze-out temperature, Eq. (2.8). We recommend to use `Xf`= 25 for the first call, this is the value set by default in the sample main file. The value of `Xf` returned by `darkOmega` corresponds to the solution of the freeze-out equation (2.8). If the user calls `darkOmega` in a scan where the model parameters are modified slowly, we recommend to use the preceding `Xf` value as input for the next iteration. Otherwise, it is better to assign to `Xf` some fixed value before each call. The parameter `Beps` defines the criteria for including a given channel in the sum for the calculation of the thermally averaged cross-section, Eq. (2.11), 10^{-6} is the recommended value.

If `fast` $\neq$ `0`, the program uses the *fast* mode, otherwise the *accurate* mode is used, see Section 2.2. If some problem is encountered, `darkOmega` returns -1.

- `readInitFile(filename)`

Table 3: Names, masses and widths of supersymmetric particles in `CompHEP/SUSY` notation

Name	symbol	mass	width	Name	symbol	mass	width
chargino 1	˜1+	MC1	wC1	mu-sneutrino	˜nm	MSnmu	wSnmu
chargino 2	˜2+	MC2	wC2	tau-sneutrino	˜nl	MSntau	wSntau
neutralino 1	˜o1	MNE1	wNE1	u-squark L	˜uL	MSuL	wSu1
neutralino 2	˜o2	MNE2	wNE2	u-squark R	˜uR	MSuR	wSu2
neutralino 3	˜o3	MNE3	wNE3	c-squark 1	˜c1	MSc1	wSc1
neutralino 4	˜o4	MNE4	wNE4	c-squark 2	˜c2	MSc2	wSc2
gluino	˜g	MSG	wSG	t-squark 1	˜t1	MStop1	wStop1
selectron 1	˜e1	MSe1	wSe1	t-squark 2	˜t2	MStop2	wStop2
selectron 2	˜e2	MSe2	wSe2	d-squark L	˜dR	MSdL	wSd1
smuon 1	˜m1	MSmu1	wSmu1	d-squark R	˜dL	MSdR	wSd2
smuon 2	˜m2	MSmu2	wSmu2	s-squark L	˜sL	MSsL	wSs1
stau 1	˜l1	MStau1	wStau1	s-squark R	˜sR	MSsR	wSs2
stau 2	˜l2	MStau2	wStau2	b-squark 1	˜b1	MSbot1	wSbot1
e-sneutrino	˜ne	MSne	wSne	b-squark 2	˜b2	MSbot2	wSbot2

Table 4: Parameters for Higgs particles in `CompHEP/SUSY` notation

Name	symbol	mass	width	Name	symbol	mass	width
Light Higgs	h	Mh	wh	CP-odd Higgs	H3	MH3	wH3
Heavy higgs	H	MHH	wHh	Charged Higgs	H+	MHc	wHc

Reads the input file, `filename`. The input parameters of the MSSM that need to be specified are given in Table 1. The function returns:

    `0` - then the input has been read correctly;

    `-1` - if the file does not exist or can not be opened for reading;

    `n` - when the line number `n` has been written in the wrong format.

The correct format of a line is

        `<name of variable><space><numerical value>`

for example

        `MG3 1500.`

This function writes a WARNING if one of the variables of Table 1 is not defined in `filename`

●`assignVal(name,val)`

Changes the value of one of the standard model or MSSM parameters. `name` is either one of the parameter names given in Tables 1,2 or a width of a particle whose name is specified in Tables 3,4. `val` is the new value. The function returns 0 when it successfully recognizes the parameter name and 1 otherwise. The only reason for an error is a wrong parameter name.

●`calcDep(LC,Widths)`

Table 5: Main functions called

`double darkOmega(double *Xf,int fast, double Beps)`
`int readInitFile(char * filename)`
`int assignVal(char * name, double val)`
`int sugraVar(float m0,float mhf,float a0,float tb,float sgn, float mtop,`
`int model)`
`int calcDep(int LC, int Widths)`
`int findVal(char * name, double * val)`
`void printMasses(FILE * f, int sort)`
`char * lsp(void)`
`void printMainChannels(FILE *f, double cut)`
`void printMSSMvar(FILE *f)`
`double delrho(void)`
`double gmuon(void)`
`int MassLimits(void)`
`double bsganew(void)`

Calculates all parameters of the MSSM model including physical masses and mixings as well as couplings. The calculation of the Higgs masses is based on `FeynHiggsfast`[20].

`calcDep` returns a non zero error code when it is unable to calculate some physical parameter. For example, this can occur when the input parameters are such that one ends up with a negative squared mass for a sfermion. The input parameters of `calcDep` should be set to `LC=1` and `Width=1`. We provide this option only to give the possibility to make comparisons with other programs. `LC=0` switches off the QCD loop correction for the Higgs bosons decays to `b`,`c`,and `t` quarks. `Width=0` switches off the automatic calculation of widths of Higgs bosons. If `Width=0` the user has to define the Higgs width values by means of either `readInitFile` or `assignVal`. The names of the corresponding variables are listed in Table 4. Note that the choice for the `Width` parameter affects only the Higgs width in the propagator. The value of the Hqq vertex is calculated independently either at the tree-level(LC=0) or one-loop level(LC=1) and could be different from the one that reproduces the Higgs total width.

We have to emphasize that the user must call `calcDep` after having defined the free MSSM parameters and before the calculation of the relic density. Otherwise the calculated relic density is not valid.

●`findVal(name,&val)`

Outputs the value of a parameter of the MSSM, either one of the input parameters or one of the derived parameters. `name` should be the name of a variable (free or constrained one). `findVal` returns zero if the name indeed corresponds to some variable and `1` otherwise.

For a name that has been correctly specified, `findVal` assigns to `val` the numerical value of the parameter. This function is particularly useful if one wants to impose constraints on the masses of the superparticles. The names of the masses of superparticles and Higgses together with the names of sparticles in `CompHEP` notation can be found in Tables 3,4 [6].

●`printMasses(filename, sort)`

This routine prints the masses of the supersymmetric particles mentionned in Table 3 as well as all Higgs masses and widths into the specified file `filename`. To see the masses on the screen replace `filename` by `stdout`. If sort$\neq 0$ the masses are sorted in order of increasing mass.

●`printMSSMvar(filename)`

Prints the MSSM parameters presented in the Table 1. To see the parameters on the screen replace `filename` by `stdout`.

●`printMainChannels(filename,cut)`

Allows the user to see which channels dominate in the calculation of Ωh^2. This function writes into the file `filename`, the channels whose relative contribution to $1/\Omega h^2$ exceeds the value chosen for `cut`. The value of the contribution in percent is also written. If `cut=0`, all channels will be displayed.

●`sugraVar(m0,mhf,a0,tb,sgn,mtop,model)`

This function solves the renormalization group equations and assigns a value to all the MSSM weak scale parameters in Table 1, except for the trilinear coupling for the muon, `Am` (A_μ). We have used the approximation, $A_\mu = A_0 - .7 * M_{1/2}$ to define this parameter. This function calls the `Isajet` package, which must be installed by the user. `sugraVar` returns zero for a succesful assignment of weak scale parameters or the `Isajet` error code for a wrong set of parameters. The error code corresponds to the NOGOOD parameter of COMMON /SUGPAS/, (see the `Isajet` manual[19]). To substitute another RGE code, the user must modify the files sources/sugrac.c.

●`lsp()`

This function returns the name of the LSP. The relic density can be calculated with any particle being the LSP. If the user wants to impose a specific LSP, the nature of the LSP must be checked after calling `calcDep`. In the sample `omg.c` file that is provided in the package, this is done for the conventional choice of a neutralino LSP.

●`bsganew()`

---

[6]Note that some of the mass parameters can be negative, the masses of particles are automatically redefined such that they correspond to the absolute values for these parameters.

Returns the value of the branching ratio for $b \to s\gamma$. For $b \to s\gamma$ we have improved on the results of [28] by including some very recent new contributions beyond the leading order that are especially important for high $\tan\beta$. We include these terms by following [29]. This function should be called after all parameters of the MSSM have been defined in `calcDep`.

● `gmuon()`

Returns the value of the supersymmetric contribution to the anomalous magnetic moment of the muon[30, 11]. The result depends only on the parameters of the gaugino mass matrices as well as on the smuon parameters, in particular A_μ the trilinear coupling. This parameter has been added in the function `sugraVar` described above as this is not calculated by `ISASUGRA/Isajet`.

● `delrho()`

Computes the stop/sbottom contribution to the $\Delta\rho$ parameter, including the two-loop gluon exchange and pure scalar diagrams[31]. Returns the value for $\Delta\rho$ and a WARNING if the value exceeds the limit $\Delta\rho > 1.3 \times 10^{-3}$. This routine is included in `FeynHiggsFast`[20].

● `MassLimits()`

This function returns a value greater than 1 and prints a WARNING when the choice of parameters conflicts with a direct accelerator limits on sparticle masses. Only the direct limits from LEP in the general MSSM are implemented. In constrained models more severe limits can be set, this should be added by the user. The constraint on the light Higgs mass is not implemented and must be added by the user.

4   Compilation and installation instructions.

The package can be obtained at
`http://wwwlapp.in2p3.fr/lapth/micromegas`

After unpacking the files, the root directory of the package,

```
 micromegas_1.1
```

will be created. This directory contains a makefile, three sample main programs `omg.c`, `sugomg.c` and `scycle.c` and two directories for data files. The compiler options and the location of the `Isajet` libraries, when needed, should be defined in the makefile. The compiler options for Linux, Alpha and Silicon Graphics workstations are defined automatically. At the moment the package cannot be compiled on HP Workstations.

To compile, type

```
make
```

This creates the `omg` executable file for the omg.c main program which does not require the `Isajet` library. If `omg` is launched without an argument it calculates the relic density for the default parameters which corresponds to the datap/dataA file MSSM. The output is presented in Section 5.

If `omg` is launched with some arguments, it treats all of them as names of input files and calculates the relic densities for each of them. Say,

```
omg datap/*
```

produces the results presented in the Table 6.

As the compilation of the code for more than 2800 processes would take a long time while in most cases only a small fraction of processes are needed, we have generated the processes and linked them dynamically only when they are needed. The first time new processes need to be linked compilation can take up to a few minutes, the actual computation time remains insignificant.

The `sugomg.c` code contains an example of application of the `sugraVar` routine. It can be compiled by

```
make main=sugomg
```

The corresponding executable file is `sugomg`. It is necessary to first install the `Isajet` package. The environment variable SUGRA is used to define the path to the `isajet.a` library. This variable should be defined properly by modifying the `makefile`.

A sample file `scycle.c` for making a scan over two parameters $(m_0, m_{1/2})$ in the SUGRA model is also provided. The range of values for $m_0, m_{1/2}$ need to be specified, the remaining parameters have to be given as inputs. It can be compiled by

```
make main=scycle
```

The corresponding executable file is `scycle`.

To install the package one needs initially about 10MB of disk space. As the program generates libraries for annihilation processes only at the time they are required, the total disk space necessary can increase significantly after running the program for different models. These libraries are stored in the `sources/2-2/` subdirectory and can be removed by the user. However, this is done at the expense of slowing down the compilation whenever the program will need again these libraries.

5 Sample Output

Running `micrOMEGAs` with the default value of the standard parameters and with the input file datap/dataA, which contains the parameters of the MSSM as specified in Table 6 model A, will produce the following output:

```
Initial file  "datap/dataA"


Higgs masses and widths
h   : Mh    =  125.1 (wh    =3.2E-03)
H   : MHH   = 1000.8 (wHh   =2.3E+00)
H3  : MH3   = 1000.0 (wH3   =2.4E+00)
H+  : MHc   = 1003.1 (wHc   =2.3E+00)


Masses of SuperParticles:
~o1 : MNE1  =    22.4 || ~ne : MSne  =    80.0 || ~nm : MSnmu =    80.0
~l1 : MStau1=    92.7 || ~nl : MSntau=    93.1 || ~m1 : MSmu1 =   108.0
~e1 : MSe1  =   108.2 || ~e2 : MSe2  =   111.2 || ~m2 : MSmu2 =   111.3
~l2 : MStau2=   124.7 || ~1+ : MC1   =   198.6 || ~o2 : MNE2  =   200.1
~o3 : MNE3  =   270.3 || ~g  : MSG   =   300.0 || ~2+ : MC2   =   332.4
~o4 : MNE4  =   332.6 || ~t1 : MStop1=   813.0 || ~b1 : MSbot1=   998.4
~c1 : MSc1  =   998.7 || ~uL : MSuL  =   998.7 || ~uR : MSuR  =   999.4
~c2 : MSc2  =   999.4 || ~dR : MSdR  =  1000.3 || ~sR : MSsR  =  1000.3
~dL : MSdL  =  1001.6 || ~sL : MSsL  =  1001.6 || ~b2 : MSbot2=  1003.5
~t2 : MStop2=  1175.8 ||


Channels which contribute more than 1 %.
 25% ~o1 ~o1 -> e E
 25% ~o1 ~o1 -> m M
 39% ~o1 ~o1 -> l L
  4% ~o1 ~o1 -> ne Ne
  4% ~o1 ~o1 -> nm Nm
  2% ~o1 ~o1 -> nl Nl
Omega=2.48E-01
g2=2.55E-09
bsgamma=4.4E-04
```

Running `micrOMEGAs` in the SUGRA case, with `ISASUGRA` version 7.58 and the input parameters

```
sugomg 100 400 0 10 +1 175 1
```

will write the values of the input parameters, the value of the weak scale parameters
as calculated by `ISASUGRA`, the corresponding list of weak scale parameters in `CompHEP`
notation followed by the usual output of `microMEGAs` as described above:

```
 MSSM parameters:
mu       513.940063
MG1      162.922958
MG2      311.489258
MG3      914.497253
Ml1      286.277618
Ml2      286.277618
Ml3      285.412537
Mr1      178.365540
Mr2      178.365540
Mr3      175.411743
Atau     -244.407349
Am       -280.000000
Mq1      819.445862
Mq2      819.445862
Mq3      760.147278
Mu1      793.780884
Mu2      793.780884
Mu3      659.573975
Md1      790.153137
Md2      790.153137
Md3      785.846619
Atop     -723.817383
Ab       -1038.150269
MH3      576.585266


Higgs masses and widths
h   : Mh    =  115.2 (wh    =3.2E-03)
H   : MHH   =  576.9 (wHh   =1.2E+00)
H3  : MH3   =  576.6 (wH3   =1.3E+00)
H+  : MHc   =  582.2 (wHc   =1.3E+00)
```

```
Masses of SuperParticles:
~o1 : MNE1   =    160.8 || ~l1 : MStau1=    175.7 || ~m1 : MSmu1 =    183.4
~e1 : MSe1   =    183.4 || ~nl : MSntau=    278.2 || ~ne : MSne  =    279.1
~nm : MSnmu  =    279.1 || ~e2 : MSe2   =    290.2 || ~m2 : MSmu2 =    290.2
~l2 : MStau2=    292.3 || ~1+ : MC1    =    297.0 || ~o2 : MNE2  =    297.3
~o3 : MNE3   =    518.2 || ~o4 : MNE4   =    534.5 || ~2+ : MC2   =    534.6
~t1 : MStop1=    623.2 || ~b1 : MSbot1=    752.2 || ~dR : MSdR  =    790.5
~sR : MSsR   =    790.5 || ~uR : MSuR   =    793.0 || ~c1 : MSc1  =    793.0
~b2 : MSbot2=    796.1 || ~uL : MSuL   =    817.7 || ~c2 : MSc2  =    817.7
~t2 : MStop2=    818.3 || ~dL : MSdL   =    821.6 || ~sL : MSsL  =    821.6
~g  : MSG    =    914.5 ||

Channels which contribute more than 1 %.
  1% ~o1 ~o1 -> b B
 17% ~o1 ~o1 -> e E
 17% ~o1 ~o1 -> m M
 18% ~o1 ~o1 -> l L
  5% ~o1 ~l1 -> Z l
 20% ~o1 ~l1 -> A l
  1% ~o1 ~m1 -> Z m
  5% ~o1 ~m1 -> A m
  1% ~o1 ~e1 -> Z e
  4% ~o1 ~e1 -> A e
  3% ~l1 ~l1 -> l l
Omega=2.07E-01
g2=1.46E-09
bsgamma=3.48E-04
```

6   Results and Comparisons

The microOMEGAs code was extensively tested against another public package for calculating the relic density, DarkSUSY. As discussed previously, the two codes differ somewhat in the numerical method used for solving the density equations. microOMEGAs includes more subprocesses(e.g. all coannihilations with sfermions), loop-corrected Higgs widths, and complete tree-level matrix elements for all processes. DarkSUSY includes on the other hand some loop induced processes such as $\chi\chi \to gg, \gamma\gamma$ which are generally small. Whenever the coannihilation channels with sfermions and the Higgs pole are not important

Table 6: Sample results and comparison with `DarkSusy`

Model	A	B	C	D	E	F
tb	5.	10.	10.	10.	45.	50.
mu	264.5	400.	518.6	-1200.	500.	1800.
MG1	25.9	500.	166.1	300.	180.	850.
MG2	258.9	1000.	317.9	600.	350.	1600.
MG3	800.	3000.	931.8	1800.	1000.	4000.
Ml1	101.	1000.	289.0	1000.	500.	2000.
Ml3	112.	1000.	288.1	1000.	500.	2000.
Mr1	100.	1000.	177.0	1000.	300.	1600.
Mr3	88.	1000.	174.1	1000.	250.	1600.
Mq1	1000.	1000.	834.1	1000.	1000.	3500.
Mq3	1000.	1000.	773.9	1000.	1000.	3500.
Mu1	1000.	1000.	803.1	500.	1000.	3500.
Mu3	1000.	1000.	671.8	500.	1000.	3500.
Md1	1000.	1000.	799.3	500.	1000.	3500.
Md3	1000.	1000.	799.7	500.	1000.	3500.
Atop	2400.	0.	-738.1	-1800.	-1000.	-3000.
Ab	2400.	0.	-1058.	-1800.	-1000.	-3000.
Atau	0.	0.	-249.2	0.	-100.	-500.
Mh3	1000.	1000.	581.9	1000.	500.	1700.
$m_{\tilde{\chi}_1^0}$	22.4	384.3	164.	299.9	178.2	849.3
$m_{\tilde{\chi}_2^0}$	200.3	402.7	303.5	597.9	333.9	1585.4
$m_{\tilde{\chi}_1^+}$	198.6	395.5	303.3	597.9	333.8	1585.3
$m_{\tilde{e}_1}$	108.2	1000.9	182.1	1000.9	303.0	1600.6
$m_{\tilde{\tau}_1}$	92.7	997.5	174.4	990.3	236.9	1595.0
$m_{\tilde{t}_1}$	813.0	1007.7	635.6	326.8	930.7	3439.9
m_h	125.1	111.2	115.3	118.4	118.1	121.7
$g-2(\times 10^{-10})$	25.5	1.88	13.9	-1.66	30.4	2.07
$b \to s\gamma(\times 10^{-4})$	4.4	3.8	3.5	4.9	2.8	3.5
`micrOMEGAs`	.25	.024	.14	.06	.22	.26
Ω_{tree}^{χ}	.25	.024	.32	.74	.13	.56
`DarkSusy`	.25	.018	.32	.74	.13	.55

we expect good agreement with `DarkSUSY`. We have first compared `micrOMEGAs` with a version of `DarkSUSY` where we have replaced the matrix elements by `CompHEP` matrix elements. As expected, we found excellent numerical agreement between the two programs (at the 2% level) for all points tested. We have then made comparisons with the original version of `DarkSUSY`. The results of these comparisons are displayed for a few test points in Table 6. We found in general good agreement between the two codes. However we have observed some discrepancies that could reach up to (30%) in particular in the process $\chi_1^0 \chi_1^+ \rightarrow t\bar{b}$(model B in Table 6) [7]. As displayed in the line Ω_{tree}^χ, when removing non-gaugino coannihilation channels and reverting to the tree-level treatment of the Higgs width we recover results similar to `DarkSUSY`. The impact of these extra channels, model C for sleptons and model D for squarks can be as large as an order of magnitude and depends critically on the mass difference with the lightest neutralino.

The effect of the Higgs width is particularly important at large $\tan \beta$ with the enhanced contribution of the b-quark. However the one-loop correction amounts to a reduced effective b-quark mass and a much smaller width especially at large values of m_H. If it was not for the strong Boltzmann suppression factor singling out the contribution at $\sqrt{s} \approx 2m_\chi$ there will be little difference after integrating over the peak for the one-loop or tree-level result. However the effect observed can be as much as a factor 2. For $m_\chi \approx M_A/2$ the narrower resonance suffers less from the Boltzmann reduction factor leading to $< \sigma^{1-loop} > / < \sigma_{tree} >> 1$ and $\Omega_{1-loop} < \Omega_{tree}$ (model F). Further away from the pole however one catches the contribution from the wider resonance without excessive damping from the Boltzmann factor, as expected $\Omega_{1-loop} > \Omega_{tree}$ (model E).

Our numerical results were also compared with Ref. [33]. Qualitative agreement is found in the case of SUGRA model although we use a different RGE code. Precise comparisons necessitates a careful tuning of parameters to make sure we have the same parameters at the weak scale. A random scan over $m_0 - m_{1/2}$ for $\mu > 0$ shows the typical shape of the allowed region ($.1 < \Omega h^2 < .3$) in SUGRA model for moderate values of $\tan \beta$.

7   Conclusion

The package `micrOMEGAs` allows to calculate the relic density of the LSP in the most general MSSM with R_P conservation. The package is self-contained safe for the `ISASUGRA` package that is required when using the SUGRA option. All possible channels for coannihilations are included and all matrix elements are calculated exactly at tree level with the help of `CompHEP`. Loop corrections for the masses of Higgs particles (two-loop) and

---

[7]The `CompHEP` result for this matrix element agrees with the result of `GraceSUSY`[32].

Figure 1: Ωh^2 in the $m_0 - m_{1/2}$ plane in a SUGRA model with $\tan\beta = 10$, $\mu > 0$ and $m_{top} = 175$GeV. The dark (blue) region corresponds to $.1 < \Omega h^2 < .3$ and the light (pink) region to $\Omega h^2 < .1$. In the white region at large $m_0 - m_{1/2}$, the relic density is above the present limit $\Omega > .3$ and in the region at small m_0, the $\tilde{\tau}$ is the LSP. The yellow (light grey) region correspond to the region excluded by $b \to s\gamma$. The LEP limit on $m_h = 113$GeV is also displayed.
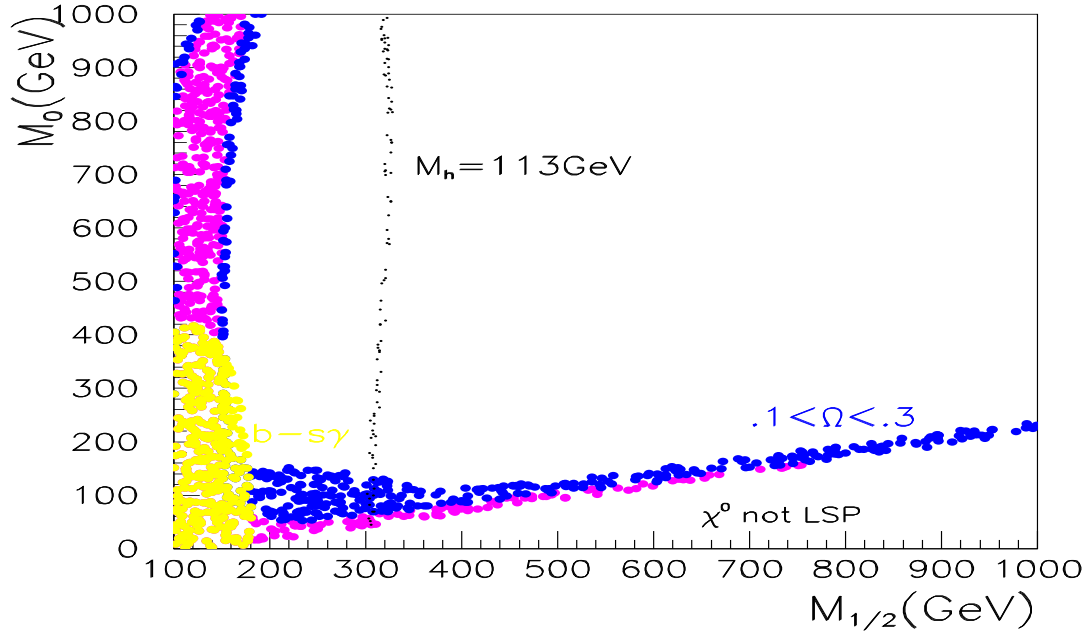
the width of the Higgs (QCD one-loop) are implemented. Good agreement with existing calculations is found when identical set of channels are included. Future versions will include loop corrections to neutralino masses. Even though these corrections are only a few GeV's they can alter significantly the calculation of the relic density when there is a near mass degeneracy with the next to lightest supersymmetric particle that contributes to a coannihilation channel [33]. Although the loop processes are in general small, we will include $\chi\chi \to \gamma\gamma, \gamma Z, gg$ in an update of `micrOMEGAs`.

8 Acknowledgements

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