The question of the nature of the dark matter in the Universe remains one of the most outstanding unsolved problems in basic science. One of the best motivated particle physics candidates is the lightest supersymmetric particle, assumed to be the lightest neutralino. We here describe DarkSUSY, an advanced numerical FORTRAN package for supersymmetric dark matter calculations which we release for public use. With the help of this package, the masses and compositions of various supersymmetric particles can be computed, for given input parameters of the minimal supersymmetric extension of the Standard Model (MSSM). For the lightest neutralino, the relic density is computed, using accurate methods which include the effects of resonances, pair production thresholds and coannihilations. Accelerator bounds are checked to identify viable dark matter candidates. Finally, detection rates are computed for a variety of detection methods, such as direct detection and indirect detection through antiprotons, gamma-rays and positrons from the Galactic halo or neutrinos from the center of the Earth or the Sun.

1 Introduction

One of the favourite candidates for the dark matter is a Weakly Interacting Massive Particle, a WIMP. In supersymmetric extensions of the standard model, the neutralino emerges as a natural WIMP candidate for the dark
matter of the universe. There is, however, not a unique way of extending the standard model with supersymmetry, but it is a general practice to use the simplest possible model, the minimal supersymmetric enlargement of the standard model (the MSSM), usually with some additional simplifying assumptions.

Over several years, we have developed analytical and numerical FORTRAN tools for dealing with the sometimes quite complex calculations necessary to go from given input parameters in the MSSM to actual quantitative predictions of relic density in the universe of the neutralinos, and the direct and indirect detection rates. The program package, which we have named DarkSUSY, has now reached such a level of sophistication and maturity that we find the time appropriate for its public release. In the following sections, we briefly describe the different components of DarkSUSY, and refer the reader to our upcoming paper \(^1\) for more details.

For download of the latest version of DarkSUSY please visit the official DarkSUSY website, \http://www.physto.se/~edsjo/darksusy/\. The version of DarkSUSY described here is 3.14.01-beta.

2 Definition of the Supersymmetric model

We work in the framework of the minimal supersymmetric extension of the standard model defined by, besides the particle content and gauge couplings required by supersymmetry, the superpotential and the soft supersymmetry-breaking potential. See \(^1,2\) for details.

It is obvious that the parameter space of the most general MSSM is huge, being specified by 124 a priori free parameters \(^3\). In DarkSUSY we reduce this set by assuming that the off-diagonal elements of the trilinear matrices \(A\) and the scalar mass matrices \(M\) are zero, and imposing CP conservation (except in the CKM matrix).

We then calculate all masses and most of the vertices entering the Feynman rules, which are all available to the user. We include several options for the loop corrections to the Higgs masses.\(^4,5,6,7\) We also include loop corrections to the neutralino and chargino masses.\(^8,9\)

3 Accelerator bounds

Accelerator bounds can be checked by a call to a subroutine. By modifying an option, the user can impose bounds as of different moments in time. The default option in version 3.14.01-beta adopts the 2000 limits by the Particle Data Group \(^10\) modified slightly for the Higgs masses. The user is also free
to use his own routine to check for experimental bounds, in which case he or she would only need to provide an interface to DarkSUSY.

4 Calculation of the relic density

In DarkSUSY, we calculate the relic density by using the full cross section, including all resonances and thresholds and solve the Boltzmann equation numerically with the method given in 11,12.

When other supersymmetric particles are close in mass to the lightest neutralino they will also be present at the time of freeze-out in the early Universe. When this happens so called coannihilations can take place between all these supersymmetric particles. We include the coannihilation processes between all charginos and neutralinos lighter than $f_{\text{co}} m_{\chi}$. The mass fraction parameter $f_{\text{co}}$ is by default set to 2.1 or 1.4 depending on how the relic density routines are called (high accuracy or fast calculation), but can be set to anything by the user. We have not included coannihilations with squarks and staus which occurs more accidentally than the in many cases unavoidable mass degeneracy between the lightest neutralinos and the lightest chargino.

We have included all two-body final states that occur at tree level, both for neutralino-neutralino, neutralino-chargino and chargino-chargino annihilations. Annihilation to $gg$, $\gamma\gamma$ and $Z\gamma$ that occur at the 1-loop level are also included.

5 Detection rates

The different detection rates for neutralino dark matter have been calculated by many authors in the past. We will here only give a brief review about what is included in DarkSUSY, and which calculations they are based on. For a more extensive list of references, we refer to 1.

5.1 Halo models

Currently implemented in DarkSUSY is the spherical family of halo profiles $\rho(r) \propto 1/\left[\left(\frac{r}{a}\right)^{\gamma} + \left(\frac{r}{a}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}$ where e.g. the Navarro, Frenk and White profile 13 is given by $(\alpha, \beta, \gamma) = (1, 3, 1)$ and the isothermal sphere is given by $(\alpha, \beta, \gamma) = (2, 2, 0)$. The velocity distribution is assumed to be a standard isotropic gaussian distribution.
5.2 Direct detection

These routines calculate the spin-dependent and spin-independent scattering cross sections on protons and neutrons assuming the quark contributions to the nucleon spin from \(^{14}\). The older set of data from \(^{15}\) is also available as an option, but the user can set their own values if they wish.

5.3 Monte Carlo simulations

In several of the indirect detection processes below we need to evaluate the yield of different particles per neutralino annihilation. The hadronization and/or decay of the annihilation products are simulated with PYTHIA \(^{16}\) and the results are tabulated. These tables are then used by DarkSUSY.

5.4 Neutrinos from the Sun and Earth

Neutralinos can accumulate in the Earth and the Sun where they can annihilate pair-wise producing high energy muon neutrinos. The branching ratios for different annihilation channels are calculated and the PYTHIA simulations are used to evaluate the yield of neutrinos. Neutrino interactions in the Sun as well as the charged current neutrino-nucleon interaction near the detector are also simulated with PYTHIA.

There are routines to calculate a) the neutrino flux, b) the neutrino-to-muon conversion rate and c) the neutrino-induced muon flux either differential in energy and angle or integrated within an angular cone and above a given threshold. The new population of neutralinos in the solar system (arising from neutralinos that have scattered in the outskirts of the Sun) as described in \(^{17,18,19}\) can optionally be included as well.

5.5 Antiprotons from halo annihilations

Neutralinos can also annihilate in the Milky Way halo producing e.g. antiprotons. These propagate in the galaxy before reaching us. We have implemented the propagation method described in \(^{20}\). Optionally, the antiproton fluxes can also be solar modulated with the spherically symmetric model of \(^{21}\). There are also other propagation models\(^{22}\) available as options. The antiproton fluxes are given differential in energy.

5.6 Positrons from halo annihilations

In neutralino annihilations in the halo we can also produce positrons. The flux of positrons is calculated with the propagation model in \(^{23}\) (with two
choices of the energy dependence of the diffusion constant). The model in \(^{24}\) can also be used as an option. The positron fluxes are given differential in energy.

5.7 Gamma rays from halo annihilations

We can also produce gamma rays from the halo annihilations. These are either monochromatic, produced from 1-loop annihilation \(^{25}\) into \(\gamma\gamma\) and \(^{26}\) \(Z\gamma\), or with a continuous energy spectrum, produced from \(\pi^0\) decays in quark jets\(^{27}\).

The flux of gamma rays can be obtained in any given direction on the sky for the user’s choice of \((\alpha, \beta, \gamma)\) in the halo profile. There are also routines to average the flux over a chosen angular resolution. The continuous gamma rays use PYTHIA simulations to calculate the gamma ray flux (differential in energy, or integrated above an energy threshold).

5.8 Neutrinos from halo annihilations

We can also produce neutrinos from neutralino annihilations in the halo. Although the fluxes are small, there are routines to calculate a) the neutrino flux, b) the neutrino-to-muon conversion rate and c) the neutrino-induced muon flux either differential in energy and angle or integrated within an angular cone and above a given energy threshold.

6 Conclusions

Over the years we have developed this numerical package, DarkSUSY, for neutralino dark matter calculations in the Minimal Supersymmetric Standard Model, MSSM. The package is now publically released and available for download from http://www.physto.se/~edsjo/darksusy. We have here presented an overview of what the program can do, and refer the reader to the upcoming paper \(^{1}\), where the details will be given. A test program, provided with the distribution, shows in more detail how DarkSUSY is used.

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