Neutralino dark matter in the NMSSM: phenomenological viability

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We study the viability of the lightest neutralino as a dark matter candidate in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). In our analysis we take into account accelerator constraints as well as bounds on low-energy observables (muon anomalous magnetic moment, rare K and B meson decays). We further impose consistency with present bounds on the neutralino relic density. We also address the prospects for the direct detection of neutralino dark matter in the allowed regions of the parameter space, comparing the results with the sensitivities of present and projected dark matter experiments. We find regions of the NMSSM parameter space where the neutralino has the correct relic abundance and its detection cross section is within the reach of dark matter detectors, essentially owing to the presence of very light singlet-like Higgses, and either singlino dominated or very light neutralinos.

1 Introduction

Supersymmetric (SUSY) models with R-parity conservation offer excellent candidates for dark matter. In particular, the lightest neutralino ($\tilde{\chi}_1^0$) is one of the most interesting within the class of Weakly Interactive Massive Particles (WIMPs). WIMPs can in principle be directly detected via elastic scattering on target nuclei, and there are currently a large number of experiments devoted to the direct detection of WIMP dark matter [1].

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is an extension of the Minimal Supersymmetric Standard Model (MSSM) by a singlet superfield $\hat{S}$. The NMSSM provides an elegant solution to the so-called μ problem of the MSSM, while at the same time rendering the Higgs "little fine tuning problem" of the MSSM less severe. The presence of additional fields, namely an extra CP-even and CP-odd neutral Higgs bosons, as well as a fifth neutralino, leads to a richer and more complex phenomenology. This also translates into the possibility of dark matter scenarios that can be very different from those encountered in the MSSM, both regarding the relic density and the prospects for direct detection. In particular, the exchange of very light Higgses can lead to large direct detection cross sections, within the reach of the present generation of dark matter detectors [2]. A systematic analysis of the low-energy NMSSM parameter space has recently been conducted [3], including the constraints from LEPII and Tevatron as well as those from the SUSY contribution to the muon anomalous magnetic moment, and bounds from K- and B-meson decays. By further including the constraints on the neutralino relic density, we evaluate the prospects for the neutralino detection cross section on the allowed regions of the parameter space, comparing the results with the sensitivity of dark matter detectors.

2 Constraints on the NMSSM low-energy parameter space

The addition of a gauge singlet superfield $\hat{S}$ modifies the MSSM superpotential as follows:

$$W_{\mathrm{NMSSM}} = \epsilon_{ij} \left(Y_u \, \hat{H}_2^j \, \hat{Q}^i \, \hat{u} + Y_d \, \hat{H}_1^i \, \hat{Q}^j \, \hat{d} + Y_e \, \hat{H}_1^i \, \hat{L}^j \, \hat{e} \right) - \epsilon_{ij} \lambda \, \hat{S} \, \hat{H}_1^i \hat{H}_2^j + \frac{1}{3} \kappa \hat{S}^3 \,. \tag{1}$$

After the spontaneous breaking of electroweak (EW) symmetry, the neutral Higgs scalars develop vacuum expectation values (VEVs), $\langle H_1^0 \rangle = v_1$, $\langle H_2^0 \rangle = v_2$ and $\langle S \rangle = s$. This leads to the dynamical generation of an effective interaction $\mu \hat{H}_1 \hat{H}_2$, with $\mu \equiv \lambda s$.

In the NMSSM spectrum, we now have three CP-even and two CP-odd Higgs states. In particular, the lightest Higgs scalar can be written as $h_1^0 = S_{11} H_1^0 + S_{12} H_2^0 + S_{13} S$, where S is the unitary matrix that diagonalises the 3×3 scalar Higgs mass matrix. In the neutralino sector, the singlino mixes with the bino, wino and Higgsinos. The lightest state can be now expressed as $\tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0 + N_{15} \tilde{S}$, where N diagonalises the 5×5 neutralino mass matrix.

The low-energy NMSSM parameter space can be described in terms of the λ, κ, $\tan\beta$, μ, A_λ, A_κ degrees of freedom, as well as the soft SUSY-breaking terms, namely gaugino masses, $M_{1,2,3}$ [a], scalar masses, $m_{Q,L,U,D,E}$, and trilinear parameters, $A_{Q,L,U,D,E}$. A thorough analysis of the low-energy NMSSM phenomenology (minimisation of the potential, computation of spectrum and compatibility with LEP/Tevatron bounds) can be obtained using the NMHDECAY 2.0 code [4]. Additionally, we have also included in our analysis [3] a more precise computation of the $b \to s\gamma$ decay in the NMSSM [5], taking into account next-to-leading order contributions, and imposing consistency at the 2σ level with the experimental central value [6],

$$\mathrm{BR}^{\mathrm{exp}}(b \to s\gamma) = (3.55 \pm 0.27) \times 10^{-4} \,. \tag{2}$$

Likewise, we have also incorporated the constraints coming from the contribution of a light pseudoscalar a^0 in the NMSSM to the rare B- and K-meson decays [5]. Finally, in our analysis we have also included the constraints coming from the SUSY contributions to the muon anomalous magnetic moment, $a_\mu = (g_\mu - 2)$. At present, the observed excess in a_μ^{exp} [7] constrains a possible SUSY contribution to be [8] $a_\mu^{\mathrm{SUSY}} = (27.6 \pm 8) \times 10^{-10}$. Concerning the evaluation of the SUSY contributions to a_μ, the only change with respect to the MSSM is due to the fifth neutralino state and the corresponding modified neutralino-lepton-slepton coupling. For the regions of the parameter space exhibiting good prospects regarding the direct detection of dark matter [2], the SUSY contributions are in general quite small. A sufficiently large a_μ^{SUSY} can nevertheless be obtained when slepton (and gaugino) masses are decreased, in association with large values of the slepton trilinear couplings [b].

Regarding the bounds arising from K- and B-meson physics, the most important role is played by the $b \to s\,\gamma$ decay, which can in principle exclude important regions of the parameter

[a] We impose at low energies a relation for M_i that mimics a hypothetical GUT unification, $M_3 = 2M_2 = 6M_1$.

[b] For example, assuming $m_{E,L} = 150$ GeV and $A_E = -2500$ GeV, and setting bino mass to $M_1 = 160$ GeV, leads to a sufficiently large a_μ^{SUSY} ($\mathcal{O}(10^{-9})$).

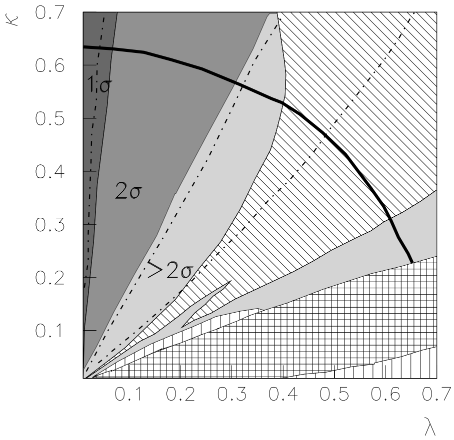

Figure 1: Effects of the experimental constraints on the (λ, κ) plane for an example with $\tan\beta = 3$, $A_\lambda = 200$ GeV, $A_\kappa = -200$ GeV and $\mu = 130$ GeV. The gridded area is excluded due to the appearance of tachyons, while the vertically ruled area corresponds to the occurrence of unphysical minima. The oblique ruled area is associated with points that do not satisfy the LEP and/or Tevatron constraints. The region above the thick black line is disfavoured due to the occurrence of a Landau pole below the GUT scale. Grey areas represent the theoretical predictions for BR$(b \to s\,\gamma)$. From left to right, 1σ (dark), 2σ (medium) and excluded (light) regions are shown. Dot-dashed lines stand for the different values of the charged Higgs mass, $m_{H^\pm} = 1000$, 500, 450 GeV (from left to right).

space. Under our assumptions [c], the most important contributions to BR$(b \to s\,\gamma)$ arise in general from charged Higgs diagrams [3]. In the NMSSM, the charged Higgs masses are given by

$$m^2_{H^\pm} \;=\; \frac{2\,\mu^2}{\sin(2\beta)}\,\frac{\kappa}{\lambda} \;-\; v^2\,\lambda^2 \;+\; \frac{2\,\mu\,A_\lambda}{\sin(2\beta)} \;+\; M^2_W\,, \tag{3}$$

leading to the conclusion that larger values of $m^2_{H^\pm}$, and thus smaller BR$(b \to s\,\gamma)$, should be obtained when κ/λ is sizable (for positive values of κ) or for small κ/λ (if $\kappa < 0$). In general, smaller values of the BR$(b \to s\,\gamma)$ will be also associated to larger values of the product $\mu\,A_\lambda$ and to larger values of $\tan\beta$.

As an example [d], we represent on Fig. 1 the (λ, κ) parameter space for $\tan\beta = 3$, $A_\lambda = 200$ GeV, $A_\kappa = -200$ GeV and $\mu = 130$ GeV. Exclusion areas due to the violation of theoretical (Landau poles, false minima, tachyons) and/or experimental constraints (in this case due to conflict with LEP/Tevatron data) are depicted. The isosurfaces for BR$(b \to s\,\gamma)$ on the (λ, κ) plane are also displayed. The resulting branching ratio is typically large, especially in regions with small κ/λ, where the charged Higgs mass is smaller. In this example, only a small triangular region with $\lambda \lesssim 0.05$, for $\kappa < 0.7$, is within a 1σ deviation from the experimental bound of Eq. (2) and $\lambda \lesssim 0.35$ is needed in order to be within 2σ of that result. In the plot we also indicate with dot-dashed lines the different values of the charged Higgs mass, thus illustrating the correlation between its decrease and the increase in BR$(b \to s\,\gamma)$.

In order to be a good dark matter candidate, the lightest NMSSM neutralino must also comply with the increasingly stringent bounds on its relic density. Astrophysical constraints [1] suggest the following range for the WIMP relic abundance

$$0.1 \lesssim \Omega h^2 \lesssim 0.3\,, \tag{4}$$

which can be further reduced to

$$0.095 \lesssim \Omega h^2 \lesssim 0.112\,, \tag{5}$$

[c] We do not take into account any source of flavour violation other than the Cabibbo-Kobayashi-Maskawa matrix. We will also be systematically considering large values for the squark and gluino masses (above 1 TeV).

[d] For a comprehensive study of the parameter space see [3].

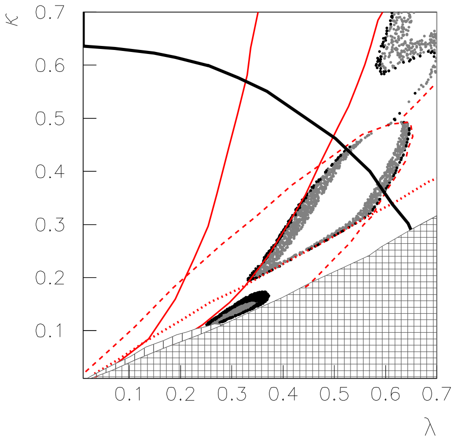

Figure 2: (λ, κ) parameter space with information about the neutralino relic density. On the left, an example with $M_1 = 160$ GeV, $\tan\beta = 5$, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, and $\mu = 130$ GeV. The gridded (vertically rules) area is excluded due to the appearance of tachyons (false minima), while the region above the thick black line is associated with the occurrence of a Landau pole below the GUT scale. The dark shaded area corresponds to points which are experimentally viable, and whose relic density complies with the astrophysical bound of Eq. (4). Points in black are those in agreement with experimental constraints and WMAP bounds (c.f. Eq. (5)). The dashed red lines indicate the resonances of the lightest neutralino annihilation channels through the second lightest CP-even Higgs, $2\, m_{\tilde{\chi}_1^0} = m_{h_2^0}$. In the region below the red dotted line the lightest neutralino mass is larger than the mass of the lightest Higgs. Along the red solid lines the neutralino mass is equal to the Z and W mass (from left to right, respectively).

taking into account the recent three years data from the WMAP satellite [9]. Compared to what occurs in the MSSM, one would expect several alterations regarding the dominant processes that lead to $\Omega_{\tilde{\chi}_1^0} h^2$: first, and given the presence of a fifth neutralino (singlino), the composition of the annihilating WIMPs can be significantly different. The possibility of a singlino-like lightest supersymmetric particle (LSP), associated with new couplings in the interaction Lagrangian, may favour the coupling of WIMPs to a singlet-like Higgs, whose mass can be substantially lighter than in the MSSM, given the more relaxed experimental constraints. Secondly, in the NMSSM we have new open channels for neutralino annihilation. For instance, the presence of additional Higgs states may favour annihilation via s-channel resonances. On the other hand, light h_1^0 and a_1^0 states, that are experimentally viable, suggest that new channels with annihilation into $Z\, h_1^0$, $h_1^0\, h_1^0$, $h_1^0\, a_1^0$ and $a_1^0\, a_1^0$ (either via s-channel Z, h_i^0, a_i^0 exchange or t-channel neutralino exchange) can provide important contributions to the annihilation and co-annihilation cross-sections [10].

Since the goal of our work was to discuss the potential of NMSSM-like scenarios regarding the theoretical predictions for $\sigma_{\tilde{\chi}_1^0 - p}$, we focus on the regions of the parameter space likely to have large neutralino detection cross sections [2]. As an example, let us take $M_1 = 160$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, and $\mu = 130$ GeV, with $\tan\beta = 5$, which is consistent with bounds on $a_\mu^{\rm SUSY}$ and BR$(b \to s\,\gamma)$. The results for the neutralino relic density, obtained from an NMHDECAY link to MicrOMEGAS [10], are depicted in the (λ, κ) plane on Fig. 2.

For large values of κ and small λ, the lightest neutralino is relatively heavy and has a mixed bino-Higgsino composition. Due to its important Higgsino component, the relic density is too small to account for $\Omega_{\tilde{\chi}_1^0} h^2$. Moving towards smaller values of κ and larger values of λ, the neutralino becomes lighter and has a larger singlino component, thus leading to an increase in $\Omega_{\tilde{\chi}_1^0} h^2$. As the neutralino mass decreases, some annihilation channels become kinematically forbidden, such as annihilation into a pair of Z or W bosons when $m_{\tilde{\chi}_1^0} < M_Z$ or $m_{\tilde{\chi}_1^0} < M_W$, respectively. Below these, the resulting relic density can be large enough to fulfil the WMAP constraint. Notice that the mass and composition of the lightest Higgs can also play a key role, given that when the Higgs is sufficiently light new annihilation channels are available for the neutralino, thus decreasing its relic density.

As we can see, in the present example the correct relic density is only obtained when either the singlino composition of the neutralino is large enough or when the annihilation channels into Z, W, or h_1^0 are kinematically forbidden. Interestingly, some allowed areas are very close to the tachyonic border, which as we will verify, can give rise to very large direct detection cross sections.

3 Prospects for NMSSM direct dark matter detection

As pointed out in [2], the existence of a fifth neutralino state, together with the presence of new terms in the Higgs-neutralino-neutralino interaction (which are proportional to λ and κ), trigger new contributions to the spin-independent part of the neutralino-nucleon cross section, $\sigma_{\tilde{\chi}_1^0-p}$. On the one hand, although the term associated with the s-channel squark exchange is formally identical to the MSSM case, it can be significantly reduced if the lightest neutralino has a major singlino composition. On the other hand, and more importantly, the dominant contribution to $\sigma_{\tilde{\chi}_1^0-p}$, associated to the exchange of CP-even Higgs bosons on the t-channel, can be largely enhanced when these are very light. Consequently, large detection cross sections can be obtained, even within the reach of the present generation of dark matter detectors. Let us begin by revisiting the same example as in Fig. 2, displayed on the left-hand side of Fig. 3.

Regions of the parameter space where the neutralino fulfils all experimental constraints and has the correct relic density can be found [3]. The latter are characterised by neutralinos with a significant singlino fraction and/or a small mass. In this case, one of the allowed regions is close to the tachyonic area and exhibits very light singlet-like Higgses, potentially leading to large detection cross sections. This is indeed the case, as evidenced on the left-hand side of Fig. 3, where the theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$ are plotted versus the lightest neutralino mass. The resulting $\sigma_{\tilde{\chi}_1^0-p}$ spans several orders of magnitude, but, remarkably, areas with $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-7}$ pb are found. These correspond to the above mentioned regions of the parameter space with very light singlet-like Higgses (25 GeV $\lesssim m_{h_1^0} \lesssim$ 50 GeV with $S_{13}^2 \gtrsim 0.99$). The neutralino is a mixed singlino-Higgsino state ($N_{15}^2 \approx 0.35$) with mass around 75 GeV. The sensitivities of present and projected dark matter experiments are also depicted for comparison.

On the right-hand side of Fig. 3 we show the resulting $\sigma_{\tilde{\chi}_1^0-p}$ when the neutralino composition is changed, namely when the Higgsino component is enhanced. Such neutralinos annihilate more efficiently, thus leading to a reduced $\Omega_{\tilde{\chi}_1^0} h^2$, so that the astrophysical constraint becomes more stringent. On the right-hand side of Fig. 3, the various resonances appear as funnels in the predicted $\sigma_{\tilde{\chi}_1^0-p}$ for the regions with the correct $\Omega_{\tilde{\chi}_1^0} h^2$ at the corresponding values of the neutralino mass ($m_{\tilde{\chi}_1^0} \approx M_Z/2$ and $m_{\tilde{\chi}_1^0} \approx m_{h_1^0}/2$). Below the resonance with the Z boson, light neutralinos are obtained $m_{\tilde{\chi}_1^0} \lesssim M_Z/2$ with a large singlino composition which have the correct relic abundance. The lightest Higgs is also singlet-like and very light, leading to a very large detection cross section, $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}$ pb.

4 Conclusions

We have carried a systematic analysis of the low-energy parameter space of the Next-to-Minimal Supersymmetric Standard Model (NMSSM), addressing the implications of experimental and astrophysical constraints on the direct detection of neutralino dark matter. We have found very stringent constraints on the parameter space coming from low-energy observables, especially a_μ^{SUSY} and $b \to s\gamma$. Compatibility with the neutralino relic density leads us to regions of the parameter space where either the neutralino mass is small enough for some annihilation channels to be kinematically forbidden or when the singlino component of the lightest neutralino is large enough to suppress neutralino annihilation. Some of the regions fulfilling all the experimental

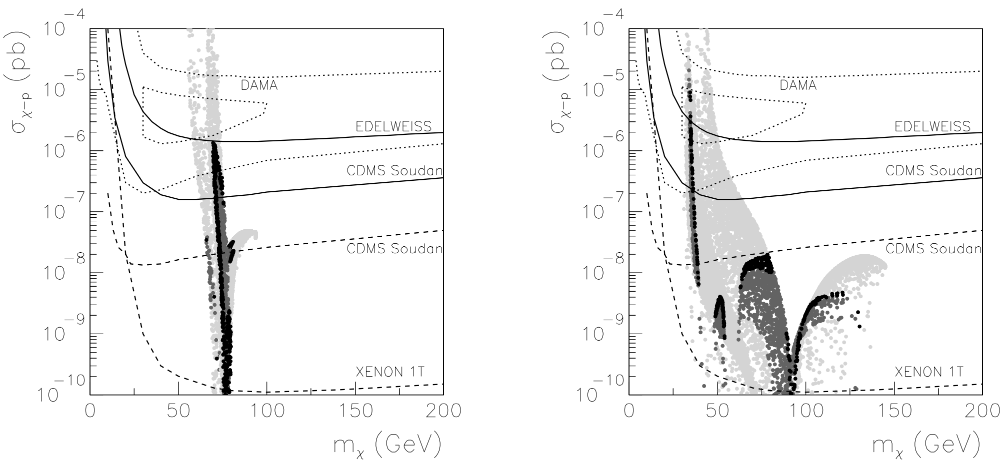

Figure 3: Scatter plot of the scalar neutralino-nucleon cross section as a function of the lightest neutralino mass. On the left, an example with $M_1 = 160$ GeV, $\tan\beta = 5$, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, and $\mu = 130$ GeV. All the points represented are in agreement with LEP/Tevatron, $a_\mu^{\rm SUSY}$, and BR($b \to s\,\gamma$) bounds. Dark gray dots represent points which, in addition, fulfil $0.1 \leq \Omega_{\tilde{\chi}_1^0}\, h^2 \leq 0.3$, whereas black dots are those in agreement with the WMAP constraint. The sensitivities of present and projected experiments are also depicted, with solid and dashed lines, respectively. On the right we show a different example with $M_1 = 330$ GeV, $\tan\beta = 5$, $A_\lambda = 570$ GeV, $A_\kappa = -60$ GeV, with $\mu = 160$ GeV, a case where the resulting $a_\mu^{\rm SUSY}$ is outside the experimental 2σ region.

and astrophysical constraints display very light, singlet-like Higgses, and are associated with very large values of $\sigma_{\tilde{\chi}_1^0-p}$, even within the reach of dark matter experiments. In addition, the presence of singlino-Higgsino-like neutralinos is also representative of the NMSSM.

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