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# Neutralino dark matter in the NMSSM

**Daniel E López-Fogliani**

Departamento de Física Teórica C-XI & Instituto de Física Teórica C-XVI, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain

E-mail: [lopezd@delta.ft.uam.es](mailto:lopezd@delta.ft.uam.es)

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## Abstract

We analyse the direct detection of neutralino dark matter in the framework of the next-to-minimal supersymmetric standard model. Taking into account all the available constraints from LEP II and Tevatron, including bounds from the muon anomalous magnetic moment and flavour constraint as  $b \rightarrow s\gamma$ , we compute the neutralino–nucleon cross section and compare the results with the sensitivity of dark matter detectors. We also study the relic abundance of neutralinos, comparing it with WMAP observations. We show that a light singlet-like Higgs can escape accelerator constraints allowing for scenarios with large cross sections and a very interesting phenomenology.

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## 1. Introduction

Weakly interacting massive particles (WIMPs) are excellent candidates for dark matter and can in principle be detected via elastic interaction with a nucleus. Actually, a large number of experiments are devoted to the direct detection of WIMPs. Collaborations such as DAMA/LIBRA, EDELWEISS, CDMS, XENON 1 Tonne of Ge/Xe, etc are running and/or in progress [1].

Supersymmetric (SUSY) theories with R-parity conservation offer an appealing candidate for dark matter: the neutralino as the lightest supersymmetric particle (LSP). The theoretical predictions for the direct detection of neutralino dark matter in the framework of the next-to-minimal supersymmetric standard model (NMSSM) have been analysed recently [2, 3], and we will use these analyses in what follows. Let us remark that the NMSSM provides a solution to the so-called  $\mu$ -problem and makes less severe the ‘Higgs-little fine tuning’ problem in the MSSM, via the introduction of a singlet field. Although the symmetries of the NMSSM may give rise to the possibility of a cosmological domain wall problem [4], this can be avoided by the introduction of suitable non-renormalizable operators [5]. On the other hand, the singlet field mixes with the MSSM Higgses, and the singlino field mixes with the

MSSM neutralinos, thus offering a richer phenomenology. In particular, it is possible to have very light neutralinos. In addition, it is also possible to have a very light Higgs which is experimentally viable for a sufficiently high singlet composition. The NMSSM superpotential is  $W = \epsilon_{ij}(Y_u H_2^j Q^i u + Y_d H_1^i Q^j d + Y_e H_1^i L^j e) - \epsilon_{ij} \lambda S H_1^i H_2^j + \frac{1}{3} \kappa S^3$  and, when the scalar component of  $S$  acquires a VEV, an effective interaction  $\mu H_1 H_2$  is generated, with  $\mu \equiv \lambda \langle S \rangle$ . We refer to [2] for a detailed analysis of the Higgs scalar potential and minimization conditions.

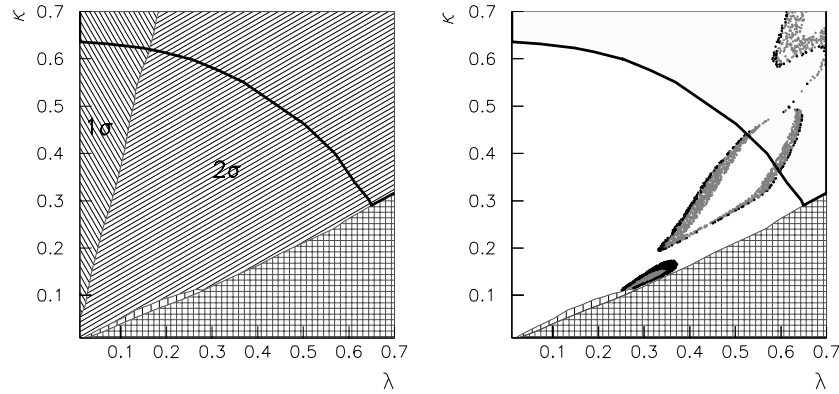
## 2. Constraints on the parameter space

In addition to ensuring the presence of a minimum of the potential, many other constraints, both theoretical and experimental, must be imposed on the parameter space of the NMSSM:  $\lambda, \kappa, \tan \beta, \mu$ , the trilinear soft parameters  $A_\lambda, A_\kappa, A_{U,D,E}$ , the gaugino masses  $M_{1,2,3}$ , and the scalar masses  $m_{Q,L,U,D,E}$ . Let us remark that in our computation all these parameters are specified at low scale. A comprehensive analysis of the low-energy NMSSM phenomenology can be obtained using the NMHDECAY 2.0 code [6]. We also impose flavour constraints, being the most relevant  $b \rightarrow s\gamma$ . The recent experimental World average for the branching ratio (BR) reported by the Heavy Flavour Averaging Group is [7]  $\text{BR}^{\text{exp}}(b \rightarrow s\gamma) = (3.55 \pm 0.27) \times 10^{-4}$ . We include in our code the calculation of the  $b \rightarrow s\gamma$  branching ratio at the NLO order, following the results of [8]. Finally, in our analysis we will also take into account the constraints coming from the SUSY contributions to the muon anomalous magnetic moment,  $a_\mu = (g_\mu - 2)$ . Note that the current average experimental value is  $a_\mu^{\text{exp}} = 11\,659\,208(6) \times 10^{-10}$  [9].

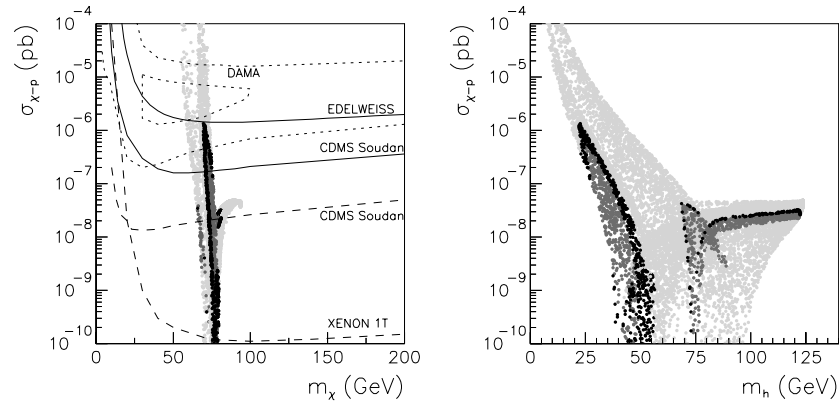
## 3. Results and discussion

The relevant parameters at low scale are  $\lambda, \kappa, \mu, \tan \beta, A_\lambda, A_\kappa$ , the soft gaugino masses  $M_1, M_2, M_3$ . In addition, we assume the relation  $M_1 = \frac{M_2}{2} = \frac{M_3}{6}$  that mimics the GUT unification. We are interested in the region of the parameter space that enables cross section in the sensitivity range of detectors. We further want to be within the  $2\sigma$  deviations of the central values of the anomalous magnetic moment of the muon. For this reason, we choose the relevant slepton parameters  $M_E = 150$  GeV,  $M_L = 150$  GeV and the trilinear  $A_E = -2500$  GeV. In the quark sector, we take  $M_{Q,D,U} = A_D = 1$  TeV,  $A_U = 2.4$  TeV. We consider that all flavour mixing comes from the CKM matrix. In this situation, the dominant channel for the  $b \rightarrow s\gamma$  is mediated by the charged Higgs. The  $\text{BR}(b \rightarrow s\gamma)$  closely follows the behaviour of the charged Higgs mass, which in the NMSSM is given at tree level<sup>1</sup> by  $m_{H^\pm}^2 = \frac{2\mu^2}{\sin(2\beta)} \frac{\kappa}{\lambda} - v^2 \lambda^2 + \frac{2\mu A_\lambda}{\sin(2\beta)} + M_W^2$ . From the above, we expect that smaller values of  $\text{BR}(b \rightarrow s\gamma)$  should be obtained for large  $\kappa/\lambda$  (for positive values of  $\kappa$ ) or small  $\kappa/\lambda$  (for  $\kappa < 0$ ). In general, smaller values of the  $\text{BR}(b \rightarrow s\gamma)$  will also be associated with larger values of the product  $\mu A_\lambda$ . On the other hand, we have also included in the computation the constraints on the relic abundance coming from the combination of the recent WMAP3 observations [10] with CMB, large-scale structure, and Hubble constant measurements,  $0.095 < \Omega h^2 < 0.112$ . With respect to the relic abundance, one of the regions where  $\Omega h^2$  is potentially within the WMAP range is roughly associated with the band where  $M_1 \approx \mu$  [11]. To fulfil the above constraints we also choose  $M_1 = 160$  GeV,  $A_\lambda = 400$  GeV,  $\mu = 130$  GeV,  $A_\kappa = -200$  GeV,  $\tan(\beta) = 5$ , as a first example. In figure 1, we present the  $\text{BR}(b \rightarrow s\gamma)$  (on the left) and the relic abundance (on the right), both in the  $(\lambda, \kappa)$  plane.

<sup>1</sup> We note that in our computation of the Higgs masses radiative corrections are taken into account [6].

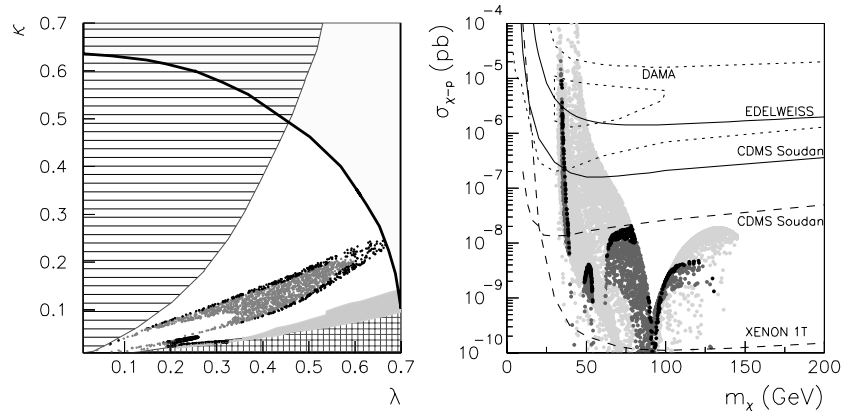


**Figure 1.**  $(\lambda, \kappa)$  parameter space for  $\tan \beta = 5$ ,  $A_\lambda = 400$  GeV,  $A_\kappa = -200$  GeV,  $\mu = 130$  GeV. In both cases the gridded area is excluded by tachyons and the region above the thick black line is excluded by the occurrence of a Landau Pole below the GUT scale (on the right this region appears in light grey). On the left we plot the  $1\sigma$  and  $2\sigma$  regions for the  $\text{BR}(b \rightarrow s\gamma)$ . On the right we plot the neutralino relic density where black points are in agreement with the recent observations mentioned in the text,  $0.095 < \Omega h^2 < 0.112$  [10]. For comparison points in agreement with old observations,  $0.1 \lesssim \Omega h^2 \lesssim 0.3$  [1], are shown in grey. The vertically ruled area corresponds to the occurrence of unphysical minima.



**Figure 2.** Scatter plot of the scalar neutralino–nucleon cross section,  $\sigma_{\chi_1^0-p}$ , as a function of the neutralino mass,  $m_{\chi_1^0}$  (on the left), and as a function of the lightest scalar Higgs mass,  $m_{h_1}$  (on the right). We take  $A_\lambda = 400$  GeV,  $\mu = 130$  GeV,  $A_\kappa = -200$  GeV and  $\tan \beta = 5$ . Black (grey) dots correspond to points fulfilling all the experimental constraints including the relic density in the range  $0.095 < \Omega h^2 < 0.112$  ( $0.1 \lesssim \Omega h^2 \lesssim 0.3$ ). Light grey dots represent those excluded. On the left the sensitivities of present and projected experiments are also depicted with solid and dashed lines, respectively. The large (small) area bounded by dotted lines is allowed by the DAMA experiment when astrophysical uncertainties are (are not) taken into account.

We find that for large values of  $\kappa$  with respect to  $\lambda$ , the LSP is a mixture of Bino and Higgsinos. This, together with a comparatively large mass, ensures an easy annihilation into gauge boson pairs, so that the relic density is negligible. For intermediate values of  $\kappa$ , we observe that both the LSP and the lightest Higgs become more singlino and singlet, respectively. In this example, the singlino composition of the neutralino is always less than 35%. As the neutralino mass decreases, some annihilation channels become kinematically



**Figure 3.** For  $M_1 = 330$  GeV,  $A_\lambda = 570$  GeV,  $\mu = 160$  GeV,  $A_\kappa = -60$  GeV and  $\tan\beta = 5$ . On the left the same conventions as on the right of figure 1. In addition, horizontal lines represent excluded points where the LSP is not the neutralino. On the right the same as on the left of figure 2.

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. In these cases,  $\Omega h^2$  can be large (above the WMAP3 range). Moreover, the spectrum is such that one can encounter  $m_{h_2^0} \approx 2m_{\tilde{\chi}_1^0}$  resonances. Finally, for the regions with very small values of  $\kappa$  the Higgs becomes lighter than the neutralino and new annihilation channels (the most important being  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h_1^0 h_1^0$  and  $Z h_1^0$ ) are available for the neutralino, thus decreasing its relic density. In figure 2, we plot on the left the neutralino–nucleon cross section as a function of the neutralino and on the right as a function of the lightest Higgs mass. Large cross section can be obtained for small Higgs masses  $m_{h^0} \approx 50$  GeV. In figure 3, we show another case in which it is possible to have a light neutralino with a large component of singlino. We display the results for the relic density and the cross section. In this case, all the  $(\lambda, \kappa)$  plane is within the  $2\sigma$  region of accuracy for  $\text{BR}(b \rightarrow s\gamma)$ . On the other hand,  $a_\mu$  is slightly beyond the  $2\sigma$  region. On the left-hand side of figure 3 we observed a region with horizontal lines corresponding to  $m_{\tilde{\chi}_1^0}$  where the neutralino is not the LSP.

#### 4. Conclusions

Working in the NMSSM, we have computed the theoretical predictions for the scalar neutralino–proton cross section  $\sigma_{\tilde{\chi}_1^0-p}$  and compared it with the sensitivities of present and projected dark matter experiments. In the computation we have taken into account all available experimental constraint from LEP and Tevatron on the parameter space, constraints coming from B and K physics and the muon anomalous magnetic moment. We have also checked the correspondence between the theoretical and observational values of the relic density. We have found that large values of  $\sigma_{\tilde{\chi}_1^0-p}$ , even within the reach of present dark matter detectors, can be obtained in regions of the parameter space. This is essentially due to the exchange of very light Higgses.

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