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Perspectives of direct detection of supersymmetric dark matter in the NMSSM

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ABSTRACT

In the Next-to-Minimal-Supersymmetric-Standard-Model (NMSSM) the lightest supersymmetric particle (LSP) is a candidate for the dark matter (DM) in the universe. It is a mixture from the various gauginos and Higgsinos and can be bino-, Higgsino- or singlino-dominated. Singlino-dominated LSPs can have very low cross sections below the neutrino background from coherent neutrino scattering which is limiting the sensitivity of future direct DM search experiments. However, previous studies suggested that the combination of both, the spin-dependent (SD) and spin-independent (SI) searches are sensitive in complementary regions of parameter space, so considering both searches will allow to explore practically the whole parameter space of the NMSSM. In this letter, the different scenarios are investigated with a new scanning technique, which reveals that significant regions of the NMSSM parameter space cannot be explored, even if one considers both, SI and SD, searches.

1. Introduction

Experimental evidence shows that roughly 85% of the matter in the universe consists of dark matter (DM) [1], presumably made at least partially of Weakly Interacting Massive Particles (WIMPs). Supersymmetry (SUSY) [2–5] can provide a perfect WIMP candidate: the Lightest Supersymmetric Particle (LSP), in many models the lightest neutralino, has all the required WIMP properties: it is neutral, massive, stable and weakly interacting. The observed relic density is inversely proportional to the annihilation cross section [6] and indeed the LSP annihilation cross section can give the right amount of DM in the universe. This annihilation cross section is required to be some 10 orders of magnitude higher than the limits on the scattering cross section between WIMPs and nuclei, as found in the direct DM detection experiments, which try to detect WIMPs by measuring the recoil of a DM particle off a nucleus in deep underground experiments, see e.g. Refs. [7,8]. These many orders of magnitude between the scattering and annihilation cross section are easily explained in SUSY by a combination of the exchanged particle being a Higgs boson, which hardly couples to a nucleus because of the preponderance of light quarks inside a nucleus and the different kinematics from scattering and annihilation. The direct scattering can either be proportional to the spin (spin-dependent (SD)) or the scattering is coherent on the whole nucleus, in which case the cross section is enhanced by the square of the number of nuclei of the target material and independent of the spin (spin-independent (SI)).

In the Minimal-Supersymmetric-Standard-Model (MSSM) the LSP is a mixture of gauginos and Higgsinos, with the bino admixture typically being dominant. In this case the present limit of the SI cross section of $2 \cdot 10^{-10}$ pb from the LUX 2016 experiment starts to eliminate a significant fraction of the parameter space [9, 10]. Limits on the SD cross section are weaker and therefore neglected in the MSSM. With future expected sensitivity on the SI cross section of 10^{-13} pb [11] almost the whole parameter space will be accessible in the MSSM, so one would expect to either discover WIMP scattering or exclude the MSSM as the origin of DM.

However, in the Next-to-Minimal-Supersymmetric-Standard-Model (NMSSM) the situation is different, since the introduction of a Higgs singlet leads to an additional singlino. The Higgs singlet allows to avoid heavy stop masses and avoids the so-called μ-problem, see e.g. [12]. The LSP will mix with the singlino as well. So the LSP can become predominantly bino-, Higgsino- or

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singlino-like or be a mixture of them. The larger diversity of the LSP properties has led to many studies of direct DM detection in the NMSSM, see e.g. [13–29].

If the LSP is predominantly a singlino, it may hardly couple to any SM particle. In this case the non-observation of WIMP scattering may not exclude the NMSSM as the origin of DM, as was studied before in Ref. [22]. Here only the SI limits have been taken into account.

However, recently SD limits have become available [10,30], which have raised excitement, since they appeared to be complementary in that they exclude different regions of parameter space and it was suggested that in future the combination of SD and SI searches might be able to explore a large fraction of the NMSSM parameter space [24,25].

However, these papers relied on Markov Chain or random sampling of the NMSSM parameter space, in which case it is difficult to sample all regions of a multidimensional parameter space with highly correlated parameters [31,32]. The reason is simple: if 3 parameters are positively correlated, stepping through the parameter space with parameter 1 in one direction, one finds maximum likelihoods fastest, if the next steps of the other two parameters are in the same direction. In the constrained MSSM (NMSSM) the dimensionality of the parameter space is 5(9); in unconstrained models significantly larger. Without knowing the features of a likelihood function with its typical narrow features from correlated parameters, it is difficult to assure a complete sampling of the parameter space, as was demonstrated before for the 5-D parameter space of the MSSM [33–36] and the 10-D parameter space of the determination of the cosmological parameters of the CMB background [31,37,38].

We therefore use a new sampling technique assuring that no regions of parameter space will be missed in the sampling. The main idea is to project the highly correlated parameter space of the couplings onto a space spanned by uncorrelated Higgs masses, which is only 3-D, if one considers one Higgs boson mass fixed to the measured 125 GeV and the heavy Higgs masses to be degenerate. In this space the couplings are marginalized over by a fit. Hence, the Higgs parameter space is reduced from 7-D to 3-D with largely uncorrelated parameters, which allows for an efficient sampling. An alternative way of explaining the sampling technique is as follows: suppose the LHC would have discovered all 7 Higgs bosons of the NMSSM. Would we be able to determine all couplings in the Higgs sector? The answer is: there is not a unique solution, but there are two preferred regions in the parameter space, which we called Scenario I and Scenario II in Ref. [39]. By repeating the fit to determine the couplings for each combination of Higgs boson masses in a 3-D grid of Higgs masses one can delineate the parameter regions of Scenario I and Scenario II.

It is the purpose of this letter to check if there are regions in the NMSSM parameter space, which evade exploration by a combination of SD and SI searches. We find that there are indeed regions of parameter space, which have cross sections below the “neutrino floor”, both for the SD and SI searches. Below the “neutrino floor” direct detection will be difficult, because of the high background from the coherent scattering of neutrinos, which cannot be shielded in DM experiments. Only tails in the recoil spectrum, annual modulation or directional dependence of the events might allow to separate WIMP scattering from neutrino backgrounds given enough statistics, see Ref. [40] and references therein. Since in parameters regions near or below the neutrino floor the LSP is almost a pure singlino, these regions are not accessible at the LHC either.

After a short summary of the neutralino sector in the NMSSM and the elastic scattering processes, we discuss the fit strategy. We conclude by summarizing the impact of the DM constraints from future experiments on the NMSSM parameter space.

2. Semi-constrained NMSSM

Within the NMSSM the Higgs fields consist of the two Higgs doublets (H_u, H_d), which appear in the MSSM as well, but the NMSSM has an additional complex Higgs singlet S. The addition of a Higgs singlet yields more parameters in the Higgs sector to cope with the interactions between the singlet and the doublets and the singlet self interaction.

In the following we restrict the parameter space by assuming unification of couplings and masses at the GUT scale of about $2 \cdot 10^{16}$ GeV. Although this restricts the parameter space, it is a well motivated region of parameter space and it will be interesting to see if this region is within reach of the future experiments. In this case we have the GUT scale parameters of the Constrained-Minimal-Supersymmetric-Standard-Model (CMSSM): m_0 and $m_{1/2}$, where $m_0(m_{1/2})$ are the common mass scales at the GUT scale of the spin 0(1/2) SUSY particles, the trilinear coupling A_0 of the CMSSM Higgs sector and $\tan\beta$, the ratio of vacuum expectation values (vev) of the neutral components of the SU(2) Higgs doublets, i.e. $\tan\beta \equiv v_u/v_d$. For the NMSSM one has to add the coupling λ between the singlet and the doublets from the term $\lambda S H_u \cdot H_d$ and κ, the self-coupling of the singlet from the term $\kappa S^3/3$; A_λ and A_κ are the corresponding trilinear soft breaking terms; μ_{eff} represents an effective Higgs mixing parameter.

So in total the semi-constrained NMSSM has nine free parameters:

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu_{eff}. \tag{1}$$

The effective Higgs mixing parameter is related to the vev of the singlet s via the coupling λ, i.e. $\mu_{eff} \equiv \lambda s$. Being proportional to a vev, μ_{eff} is naturally of the order of the electroweak scale, thus avoiding the μ-problem [12]. The supersymmetric partner of the singlet leads to an additional Higgsino, thus extending the neutralino sector from 4 to 5 neutralinos. This leads to modifications of the SI and SD cross sections, which are discussed in the following subsections.

2.1. The NMSSM neutralino sector

Within the NMSSM the singlino, the superpartner of the Higgs singlet, mixes with the gauginos and Higgsinos, leading to an additional fifth neutralino. The resulting mixing matrix reads [12,41]:

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 & -\mu_{\rm eff} & -\lambda v_u \\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & -\mu_{\rm eff} & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix} \tag{2}$$

with the gaugino masses M_1, M_2, the gauge couplings g_1, g_2 and the Higgs mixing parameter μ_{eff} as parameters. Furthermore, the vacuum expectation values of the two Higgs doublets v_d, v_u, the singlet s and the Higgs couplings λ and κ enter the neutralino mass matrix.

The upper left 4×4 submatrix of the neutralino mixing matrix corresponds to the MSSM neutralino mass matrix, see e.g. Ref. [4].

The neutralino mass eigenstates are obtained from the diagonalization of $\mathcal{M}_0$ in Eq. (2) and are linear combinations of the gaugino and Higgsino states:

$$\tilde{\chi}_i^0 = \mathcal{N}(i,1)\left|\tilde{B}\right\rangle + \mathcal{N}(i,2)\left|\tilde{W}^0\right\rangle + \mathcal{N}(i,3)\left|\tilde{H}_u^0\right\rangle + \mathcal{N}(i,4)\left|\tilde{H}_d^0\right\rangle + \mathcal{N}(i,5)\left|\tilde{S}\right\rangle. \tag{3}$$