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Perspectives of direct detection of supersymmetric dark matter in the MSSM and NMSSM

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Summary. — 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. These different scenarios are investigated in detail and compared with the sensitivity of future direct DM experiments, where we use an efficient sampling technique of the parameter space. We find that LSPs with a significant amount of Higgsino and bino admixture will have cross sections in reach of future direct DM experiments, so the background from coherent neutrino scattering is not yet limiting the sensitivity. Both the spin-dependent (SD) and spin-independent (SI) searches are important, depending on the dominant admixture. If the predicted relic density is too low, additional DM candidates are needed, in which case the LSP direct DM searches loose sensitivity of the reduced LSP density. This is taken into account for expected sensitivity. The singlino-like LSP has regions of parameter space with cross sections below the "neutrino floor". In this region the background from coherent neutrino scattering is expected to be too high, in which case the NMSSM DM will evade discovery via direct detection experiments.

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

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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.

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 spin-independent (SI) cross section of $2 \cdot 10^{-10}$ pb from the LUX 2016 experiment, a direct dark matter experiment which tries to detect WIMPs by measuring the recoil of a DM particle off a nucleus in deep underground experiments, see *e.g.* [6], starts to eliminate a significant fraction of the parameter space [7, 8]. The spin-dependent (SD) searches in contrast are not able to give further constraints, since the excluded parameter space from the SI searches contains the corresponding SD excluded region [9]. 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 [10] close to 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 LSP will become not only a mixture of the gauginos and $SU(2)$ Higgsinos, but will have a fraction of the partner of the singlet, the singlino, as well. So the LSP can become predominantly bino-, Higgsino- or 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.* [11-23]. If the LSP is bino-like one expects the future SI experiments to be sensitive enough to cover the whole parameter space, as in the MSSM. If the LSP is Higgsino-like one expects to cover the whole parameter space as well, since the LSP is likely to have a rather strong coupling to the exchanged Higgs boson, because of the mixing in the Higgs sector. However, 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. We use a efficient sampling technique of the NMSSM parameter space to determine the allowed cross section range for the SI and SD direct dark matter searches.

2. – The NMSSM neutralino sector

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 singlino, the superpartner of the Higgs singlet, mixes with the gauginos and Higgsinos, leading to an additional fifth neutralino.

The neutralino mass eigenstates are obtained from the diagonalization of the mixing matrix and are linear combinations of the gaugino and Higgsino states,

$$\tilde{\chi}_i^0 = \mathcal{N}(i,1)|\tilde{B}\rangle + \mathcal{N}(i,2)|\tilde{W}^0\rangle + \mathcal{N}(i,3)|\tilde{H}_1^0\rangle + \mathcal{N}(i,4)|\tilde{H}_2^0\rangle + \mathcal{N}(i,5)|\tilde{S}\rangle. \tag{1}$$

Typically, the diagonal elements of the mixing matrix dominate over the off-diagonal terms, so the neutralino masses are of the order of gaugino masses M_1, M_2, the Higgs mixing parameter μ_{eff} and in case of the NMSSM $2\kappa s = 2(\kappa/\lambda)\mu_{eff}$. λ results from the coupling 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 $\kappa S^3/3$.

The mass spectrum at the low mass SUSY scales is calculated from the GUT scale input parameters via the renormalization group equations (RGEs), which results in correlated masses including the large radiative corrections from the GUT scale to the electroweak scale. The gaugino masses at the electroweak scale are proportional to $m_{1/2}$ [2-4, 24], so $M_1 \approx 0.4 m_{1/2}$ and $M_2 \approx 0.8 m_{1/2}$.

In the CMSSM μ is typically much larger than $m_{1/2}$ to fulfill radiative electroweak symmetry breaking (EWSB) [2-4, 24], which leads to a bino-like lightest neutralino. In the NMSSM μ_{eff} is an input parameter, which is naturally of the order of the electroweak scale. In such natural NMSSM scenarios the lightest neutralino is singlino- or Higgsino-like and its mass can be degenerate with the second and third neutralino, all of which have a mass of the order of μ_{eff}. Bino-like neutralinos are also possible within the NMSSM but they require large values of $\mu_{\mathit{eff}} \gg M_1$. This is not excluded, but not expected in natural NMSSM models. However, if the LSP in the NMSSM is bino-like, the situation is similar to the MSSM, which has been studied in great detail previously [9]. So we will concentrate on LSPs being singlino- or Higgsino-like in the NMSSM.

The amount of the Higgsino and singlino content of the lightest neutralino depends on the ratio and the absolute value of κ and λ, as can be seen from the neutralino mixing matrix coefficient $\mathcal{M}_0(5,5) = 2\kappa s = 2(\kappa/\lambda)\mu_{\mathit{eff}}$. The Higgsino fraction, which determines the coupling to the Higgs, is crucial for the elastic scattering cross section, since this proceeds mainly via the exchange of a Higgs boson.

2˙1. *Elastic WIMP-nucleon scattering.* – A WIMP might be detected by measuring the recoil of a nucleus after an elastic scattering of a WIMP on a nucleus taking place. Since such collisions are non-relativistic, only two cases need to be considered [25]: the spin-spin interaction (SD), where the WIMP couples to the spin of the nucleus, and the scalar interaction (SI), where the WIMP couples to the mass of the nucleus.

The SI cross section is proportional to the Higgsino content of the lightest neutralino $\sigma_{SI} \propto N_{13}^2 + N_{14}^2$. The cross section is proportional to the mass of the nucleus squared, which leads to a substantial enhancement for heavy nuclei [26].

The experimental best limit on the SI WIMP nucleon cross section is given by the LUX experiment [27]. The SI cross section is inversely proportional to the Higgs mass squared, so the prediction of two light scalar Higgs bosons can enhance the SI cross section in the NMSSM. However, a negative interference between them suppresses the SI cross section if the two lightest Higgs bosons are close in mass. However, the SD cross section, which proceeds mainly by Z^0 exchange, does not suffer from such "blind" spots. Thus, the limits on the SD cross section can contribute to constrain the parameter space in the NMSSM in contrast to the CMSSM.

The dominant diagram for the SD scattering is the Z^0 boson exchange. The corresponding cross section includes the difference of the Higgsino components $\sigma_{SD} \propto |N_{13}^2 - N_{14}^2|$. If the admixture of the two Higgsino components are large but similar, the SD cross section can become small. But then the SI cross section ($\propto N_{13}^2 + N_{14}^2$) will be large, so they do not become small simultaneously. The current best limit on the SD cross section is given by LUX for the WIMP-neutron interaction [8]. We calculate all DM cross sections with micrOMEGAs 3.6.9.2 [28].

3. – Analysis

The additional particles and their interactions within the NMSSM lead to a large parameter space, even in the well-motivated subspace with unified masses and couplings at the GUT scale. We focus on the semi-constrained NMSSM and use the corresponding code NMSSMTools 4.6.0 [29] to calculate the SUSY mass spectrum from the NMSSM parameters. This program has an interface to micrOMEGAs [28], which was used to calculate the relic density and LSP scattering cross sections, as discussed before.

As discussed in the introduction, we use a systematic sampling technique by considering a space spanned by the masses as described in detail in ref. [30]. The determination of the free parameter set to obtain a certain Higgs mass combination is not unique. The SM Higgs boson in the NMSSM is fulfilled within two regions of the parameter space: either for large values of $\lambda - \kappa$ and small values of $\tan\beta$ which we call *Scenario I*. Another possibility, which we call *Scenario II*, are small values for $\lambda - \kappa$, which requires large values of $\tan\beta$ in order to reach a Higgs mass of 125 GeV. Within these two scenarios either the lightest or the second lightest Higgs can be the discovered 125 GeV Higgs boson. More details of the fit strategy can be taken from refs. [30, 31].

The specific scenarios have distinctly different features since the range of the couplings differ. However, the ratio of λ and κ, which determines the Higgsino-singlino mixture of the LSP, can be the same in both scenarios. The turning point for either a singlino or Higgsino-dominated LSP is around $2\kappa/\lambda = 1$ in both scenarios, which corresponds to the border where the neutralino mixing matrix element $\mathcal{M}_0(5,5)$ equals μ_{eff}.

Since the Higgsino content is crucial for the SD and SI cross section, we divide the two scenarios further into singlino- and Higgsino-dominated scenarios. This means that either the Higgsino elements $\sqrt{N_{13}^2 + N_{14}^2}$ or the singlino element $\sqrt{N_{15}^2}$ are above 0.8. All cases can be either fulfilled for the lightest or the second lightest Higgs boson being the SM Higgs boson, which gives in total 8 scenarios to be tested against the current SD and SI limits. Beside the direct DM detection the relic density Ωh^2 can be considered, either as a limit, if one assumes other particles contributing to the DM abundance in the universe as well, or one assumes that the LSPs saturate the relic density from the Planck data [32]. For the Higgsino-dominated LSPs the relic density is usually below the experimental value because of the large annihilation cross section into ZZ and W^+W^-. In contrast, the singlino-dominated LSP can cover a large range of relic densities, since many co-annihilation channels can contribute. Co-annihilation is important, because the lightest neutralinos all have similar masses of the order of μ_{eff}. If co-annihilation is not possible large relic densities are obtained, because the singlinos hardly couple to SM particles, leading to small annihilation cross sections. Such points over-close the universe and are rejected for further analyses. The correct relic density can also be fulfilled for resonant annihilation via Z^0 or H boson leading to narrow allowed regions around $m_{\tilde{\chi}_0^1} \approx 45$ and $m_{\tilde{\chi}_0^1} \approx 60$ GeV.

3·1. *Reach of direct DM searches.* – The sampled points from the parameter space spanned by the Higgs masses for Scenario I and II with the lowest χ^2 are assumed to be representative for the NMSSM, so these points are compared with the relic density and DM scattering cross section limits.

Many sampled points have an expected relic density Ω_{theo} below the observed relic density, which is allowed if the DM has additional contributions from other particles, like axions. In this case the sensitivity of direct DM experiments will be reduced by the factor $\zeta = \Omega_{theo}/\Omega_{obs}$ [22]. If $\Omega_{theo} > \Omega_{obs}$ the points are excluded, so ζ cannot be above 1. In order to calculate the reach of direct DM search experiments we multiply the expected cross section with $min(1, \zeta)$ to obtain, what we call the reduced cross section.

The sampled points can be projected into the WIMP mass-reduced cross section plane as shown in figs. 1, 2 for Scenario I, II and $m_{H_2} = 125$ GeV for the SI and SD cross sections separately, as indicated.

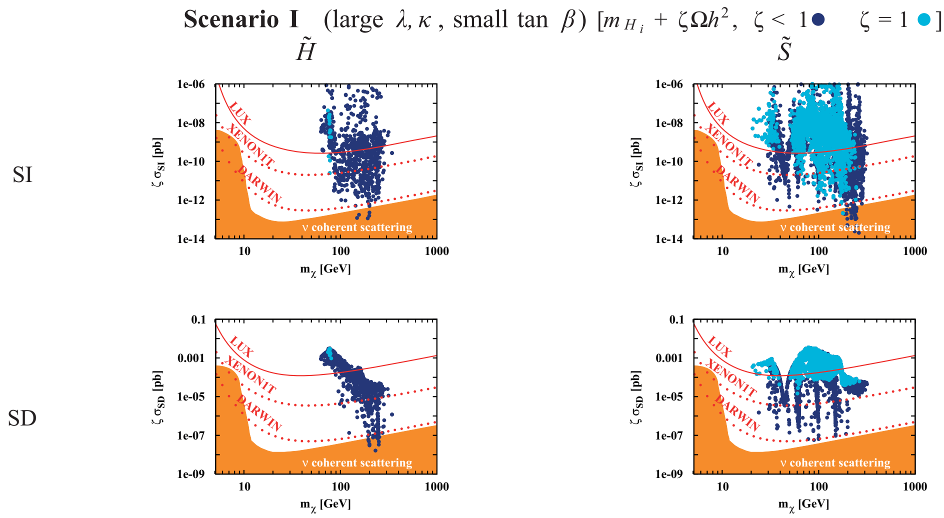

Fig. 1. – Plots of the reduced scattering cross sections (SI and SD, as indicated) *vs.* the WIMP mass for Scenario I and $m_{H_2} = 125\,\text{GeV}$. The plots for $m_{H_1} = 125\,\text{GeV}$ are similar. The left/right plots represent the Higgsino/singlino-dominated LSPs. The dark blue points fulfill the SM Higgs constraint while the light blue points also yield the correct relic density. The dark blue points have a cross section multiplied by the sensitivity factor $\zeta = \Omega_{theo}/\Omega_{obs}$. The red solid/dotted lines represent the current/future sensitivities for various experiments. The orange area below is the neutrino coherent scattering cross section from solar, atmospheric and diffuse supernova neutrinos on nuclei, which provides a high background for future searches. In this region discovery of WIMP scattering is practically excluded.

The left/right plots represent the Higgsino/singlino-dominated LSPs. The dark blue points fulfill the SM Higgs constraint, while the light blue points also yield the correct relic density, which is mostly possible for singlino-dominated LSPs. For the Higgsino-dominated LSPs the relic density is usually too low. The red solid lines represent the current limits on the SI and SD cross sections, while the red dotted lines are the expectations from the future direct DM experiments XENON1T [33] and DARWIN [10]. The orange area below is the coherent neutrino scattering cross section of solar, atmospheric and diffuse supernova neutrinos on nuclei, which limits the sensitivity of direct detection experiments [34]. Points within this area are expected to be not accessible in the future. We choose not to give the percentage of the excluded points, since this number varies strongly with the size of the initial parameter space.

The predicted neutralino mass ranges differ for the different scenarios. For the Higgsino-dominated LSP the mass range starts at around 100 GeV, since this is the lowest value of μ_{eff} which is the lowest possible mass for a Higgsino-dominated neutralino. For a singlino-dominated LSP the mass can be below μ_{eff}, since the mass is proportional to the ratio of κ and λ.

Most of the sampled points for the chosen scenarios will be within reach of the future direct DM searches. The comparison of the reduced cross section with the expected future sensitivity of DM experiments on the cross section, for which we take the proposed DARWIN experiment as an example, shows in figs. 1 and 2 that in parts both,

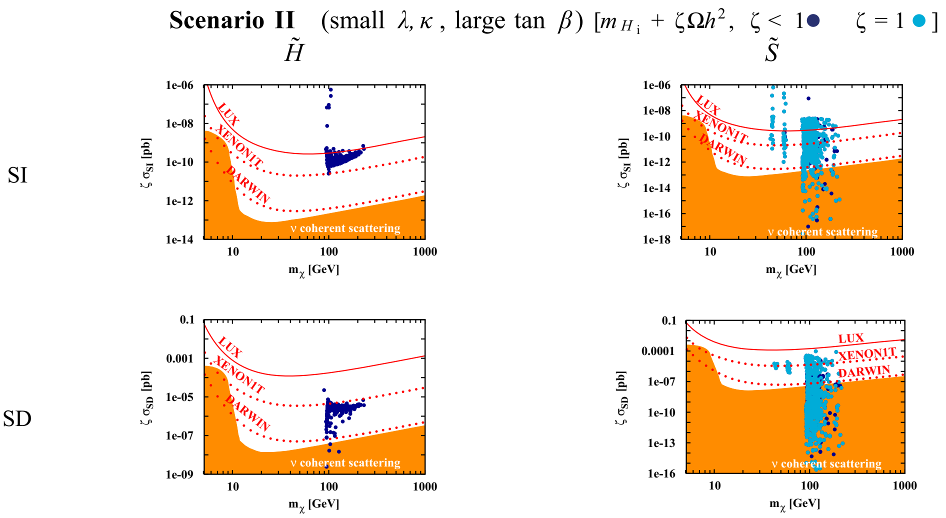

Fig. 2. – As in fig. 1 but for Scenario II. Note the different scales for the singlino cross section which have been adjusted to the lowest possible values for the corresponding cross sections. The points below the coherent neutrino background are outside the reach of the future experiments, because of a too high background.

singlino- and Higgsino-dominated LSPs can be out of reach of future experiments. The Higgsino-dominated LSPs can be out of reach mainly because of the high coupling to Higgs bosons, which reduces the relic density, thus leading to a small reduced scattering cross section by the small value of $\zeta \approx 10^{-4}$.

Singlino-dominated LSPs can be out of reach because of the small coupling to SM particles and thus small scattering cross section, which may be reduced even further by the factor ζ for relic density being below the observed relic density (dark blue points). Those points, which predict a low SI and SD cross section, require a large singlino component to be outside the reach of the future experiments, which is demonstrated in fig. 3. Here the singlino-dominated points for Scenario I/II (left/right) for either $m_{H_1} = 125\,\text{GeV}$ or $m_{H_2} = 125\,\text{GeV}$ are shown in the reduced SI-SD cross section plane. The color coding corresponds to the singlino content of the lightest neutralino. The vertical and horizontal dashed line show the lower limit on the SI and SD cross section from the future experiment DARWIN for a WIMP mass of about 100 GeV. The points in the lower left quadrant are below the "neutrino floor" and will escape future direct dark matter searches. Scenario I will be fully covered by future direct dark matter experiments, while for Scenario II many points will evade detection in the future. However, such points require a large singlino purity of about 99% which is only possible for small values of λ/κ below $\sim$0.03/0.01. In this case the lightest neutralino is decoupled and interacts weakly with SM particles, which is needed to get a small elastic scattering cross section. At the same time the annihilation cross section for the correct relic density is still fulfilled by the sum of many co-annihilation channels. Those points are often missed in Markov Chain sampling techniques. This is prevented in our analysis, since we first identify the relevant regions in the parameter space by defining Scenarios I and II leading to the correct Higgs mass but corresponding to different regions in the NMSSM parameter space.

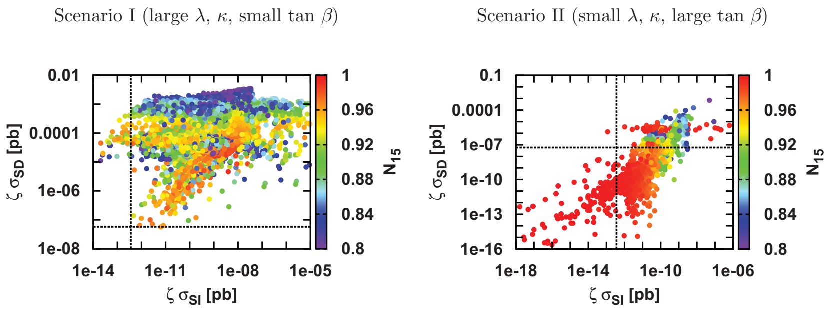

Fig. 3. – Sampled points for the singlino-dominated points for Scenario I/II (left/right) for either $m_{H_1} = 125\,\mathrm{GeV}$ or $m_{H_2} = 125\,\mathrm{GeV}$ in the reduced SI-SD cross section plane. The color coding corresponds to the singlino content of the lightest neutralino. The vertical and horizontal dashed line show the lower limit on the SI and SD cross section from the future experiment DARWIN for a averaged neutralino mass of about 100 GeV. Future limits will be able to constrain the singlino content of the lightest neutrino. Only points in the lower left quadrant are below the "neutrino floor" and will escape future direct dark matter searches. Such points are only possible within Scenario II (right-hand side), since they require a large singlino purity of above 99%. Such pure singlinos are only possible for values of λ/κ below $\sim$0.03/0.01.

4. – Conclusion

We surveyed the cross section for the SI and SD dark matter searches in the semi-constrained NMSSM. In order to limit the parameter space we restricted ourselves to the well-motivated common GUT scale masses for the SUSY partners. By projecting on the 3D space of the masses we were able to sample the parameter space in an efficient way and obtained the range of the neutralino masses and the corresponding SI and SD cross sections, as shown in figs. 1 and 2, for two different ranges of couplings.

In the NMSSM the LSP can be bino-, Higgsino- or singlino-dominated in contrast to the CMSSM, where the neutralino is mostly a bino. The bino-like case in the NMSSM has cross sections within reach of future SI searches, like in the CMSSM. The Higgsino-dominated WIMP usually leads to a too low relic densities because of the large coupling to Higgs bosons, which increases the annihilation cross section. A relic density below the observed value is allowed, if other particles, like axions, contribute to the relic density, but in that case the event yield in direct searches will be reduced by the sensitivity factor $\zeta = \Omega_{theo}/\Omega_{obs}$. The expected cross sections were multiplied by the sensitivity factor ζ, which reduces the cross section by four orders of magnitude in the Higgsino-dominated LSP case. Nevertheless, the majority of the allowed parameter space is still above the "neutrino floor", so although difficult, it is still accessible by future experiments. This is not true for pure singlino LSPs with a singlino content above 99%, so such regions of NMSSM parameter space will evade detection in future experiments.

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