Direct detection of neutralino dark matter in the NMSSM.

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Abstract. The direct detection of neutralino dark matter is analysed in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). Sizable values for the neutralino detection cross section, within the reach of dark matter detectors, are attainable, due to the exchange of very light Higgses, which have a significant singlet composition. The lightest neutralino exhibits a large singlino-Higgsino composition, and a mass in the range $50 \lesssim m_{\tilde{\chi}^0_1} \lesssim 100$ GeV.

We have studied the theoretical predictions for the direct detection of neutralino dark matter in the NMSSM [1]. More specifically, we have analysed the parameter space, taking into account the most recent experimental constraints, computed the neutralino-nucleon cross section, $\sigma_{\tilde{\chi}^0_1-p}$, and compared it with the sensitivities of present and projected dark matter experiments.

The NMSSM is a very well motivated extension of the MSSM. It provides an elegant solution to the $\mu$ problem through the introduction of a new chiral superfield, $S$, which is a singlet under the SM gauge group. Its superpotential contains two additional terms involving the Higgs doublet superfields, $H_1, H_2$, and the singlet $S$,

$$
W = Y_u H_2 Q u + Y_d H_1 Q d + Y_e H_1 L e - \lambda S H_1 H_2 + \frac{1}{3} \kappa S^3.
$$

(1)

Associated trilinear soft supersymmetry-breaking terms, $A_\lambda$ and $A_\kappa$, are also present in the Lagrangian. After spontaneous electroweak symmetry breaking, the neutral Higgs scalars develop vacuum expectation values, $\langle H^0_1 \rangle = v_1$, $\langle H^0_2 \rangle = v_2$, $\langle S \rangle = s$, and an effective $\mu$ term is generated, $\mu \equiv \lambda s$, which is naturally of the order of the electroweak scale.

In terms of component fields, the NMSSM contains an extra CP-odd and CP-even neutral Higgs, as well as a new neutralino, which mix with the MSSM fields, leading to a richer phenomenology. The lightest CP-even Higgs is a thus linear combination of the MSSM Higgs states and the new singlet field,

$$
h^0_1 = S_{11} H^0_1 + S_{12} H^0_2 + S_{13} S.
$$

(2)

In the neutralino sector the fermionic component of $S$, the singlino, $\tilde{S}$, mixes with the neutral Higgsinos and gives rise to a fifth state. Neutralinos are now described by a $5 \times 5$ mass matrix and the lightest neutralino can therefore be written as

$$
\tilde{\chi}^0_1 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}^0_3 + N_{13} \tilde{H}^0_1 + N_{14} \tilde{H}^0_2 + N_{15} \tilde{S}.
$$

(3)
The singlino composition of $\tilde{\chi}_1^0$ is then determined by $N_{15}^2$. This, together with the changes in the Higgs sector, has important implications on the direct detection properties of neutralinos.

The spin-independent part of the neutralino-nucleon cross section receives contributions from squark and neutral Higgs exchanging diagrams [2, 3, 1]. The squark exchanging amplitude is formally identical to that of the MSSM and is typically sub-leading. On the other hand, the Higgs mediated interaction is deeply modified, since both vertices as well as the exchanged scalar Higgses reflect the new features of the NMSSM. More specifically, CP-even neutral Higgses mediate the neutralino-quark scattering through a $t$-channel. Consequently, the smaller the Higgs masses are, the larger the amplitude for this process becomes. In the NMSSM very light Higgses can be phenomenologically viable provided their singlet component is sizable [4]. Should this occur, and if these states are not pure singlets (in which case the Higgs-quark-quark coupling is substantially reduced) this amplitude can be considerably enhanced. This can induce an overall increase in $\sigma^{SI}_{\tilde{\chi}_1^0-np}$ of several orders of magnitude.

We consider [1] the following set of independent parameters: $\lambda, \kappa, \mu (= \lambda s), \tan \beta$, the soft trilinear terms for the Higgs scalars, $A_\lambda, A_\kappa$, and the soft gaugino masses $M_i$. A common SUSY scale for the remaining squark masses and trilinear couplings, $M_{SUSY} = 1$ TeV, is taken. We assume the GUT relation for the gaugino masses and use $M_1 = 500$ GeV (departures from this case can be found in [1]). We scanned over the parameter space using the code NHMDECAY [5], which minimises the potential, evaluates the supersymmetric spectrum and checks compatibility with all LEP experimental constraints. For each point in the parameter space one also requires the absence of Landau singularities and verifies that the physical minimum is a true one.

The $(\lambda, \kappa)$ parameter space is represented in Fig.1, together with the corresponding predictions for $\sigma^{SI}_{\tilde{\chi}_1^0-np}$ as a function of the neutralino mass for an example with the rest of the parameters fixed. The effect of the different constraints is shown explicitly. Extensive areas are disallowed due to the presence of Landau poles (ruled area) or the appearance of tachyons in
the Higgs sector (gridded area). Also, experimental constraints on the Higgses and neutralino are responsible for the exclusion of the gray regions.

Notice that the singlino composition of the Higgs increases and its mass decreases towards the region with large $\lambda$ and small $\kappa$. Remarkably, very light Higgses are allowed in that area due to their significant singlet character ($0.9 \lesssim S_{13}^2 \lesssim 0.95$). As a consequence, sizable values for $\sigma_{\tilde{\chi}_1^0-p}$ appear (some of which even enter the area excluded by present direct searches). The lightest neutralino is in these cases a mixed singlino-Higgsino state, with $N_{215}^2 \lesssim 0.3$ and $N_{213}^2 + N_{14}^2 \gtrsim 0.7$.

Similar results can be obtained for different choices of the input parameters. Although most of the observables are very sensitive to variations of these, and despite the fact that the absence of tachyons and Landau poles always poses stringent constraints on the parameter space, it is often possible to find regions with light singlet-like Higgses towards the areas with large $\lambda$ and small $|\kappa|$. Consequently, the occurrence of large $\sigma_{\tilde{\chi}_1^0-p}$ is not uncommon.

In order to obtain a global view of the theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$, it is useful to carry out a general survey of the parameter space. Since we are interested in regions predicting large $\sigma_{\tilde{\chi}_1^0-p}$, we take $\mu = 110$ GeV, with $M_1 = \frac{1}{2} M_2 = 500$ GeV. The resulting $\sigma_{\tilde{\chi}_1^0-p}$ is represented in Fig. 2 as a function of the neutralino mass and the lightest Higgs mass. The scan reveals again how large values for $\sigma_{\tilde{\chi}_1^0-p}$ are attainable, even within the reach of present detectors. The correlation of large $\sigma_{\tilde{\chi}_1^0-p}$ with small values of $m_{h_1^0}$ is also manifest. Detection cross sections above the present experimental sensitivity correspond to very light Higgses, 15 GeV $\lesssim m_{h_1^0} \lesssim 70$ GeV. The NMSSM nature is evidenced in this result, since such Higgses have a significant singlet composition, thus escaping detection and being in agreement with accelerator data.

References

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