DIRECT DETECTION OF NEUTRALINO DARK MATTER IN THE NMSSM

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We address the direct detection of neutralino dark matter in the framework of the Next-to-Minimal Supersymmetric Standard Model. We conduct a detailed analysis of the parameter space, taking into account all the available constraints from LEP II, and compute the neutralino-nucleon cross section. We find that sizable values for the detection cross section, within the reach of dark matter detectors, are attainable in this framework, and are associated with the exchange of very light Higgses, \( m_h \gtrsim 70 \) GeV, the latter exhibiting a significant singlet composition.

1. Introduction
Supersymmetric (SUSY) theories offer some excellent candidates for dark matter. In particular, the lightest neutralino, \( \tilde{\chi}_1^0 \), is the leading one within the class of Weakly Interacting Massive Particles (WIMPs). WIMPs can 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\(^1\).

We have studied the theoretical predictions for the direct detection of neutralino dark matter in the framework of the Next-to-Minimal Supersymmetric Standard Model (NMSSM)\(^2\). Via the introduction of a singlet superfield \( S \), the NMSSM offers an elegant solution to the \( \mu \) problem of the Minimal Supersymmetric Standard Model (MSSM), while at the same time it also renders the Higgs “little fine tuning problem” of the MSSM less severe. The new fields in the model mix with the corresponding MSSM ones, giving rise to a richer and more complex phenomenology. In particular, a very light neutralino may be present and a very light Higgs boson is not experimentally excluded\(^3\). The latter aspects, among other features, may modify the results concerning the neutralino-nucleon cross section with respect to those of the MSSM.
2. Neutralino-nucleon cross section in the NMSSM

The NMSSM is defined by the following superpotential

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

(1)

with \( S \) a singlet under the Standard Model (SM) gauge group. After spontaneous electroweak symmetry breaking, the neutral Higgs scalars develop vacuum expectation values, \( \langle H_1^0 \rangle = v_1, \langle H_2^0 \rangle = v_2, \langle S \rangle = s \), and an effective \( \mu \) term is thus generated, \( \mu \equiv \lambda s \).

In the absence of CP violation in the Higgs sector, the CP-even and CP-odd states do not mix. In the NMSSM, we find three scalar and two pseudoscalar Higgs states. Of particular relevance to our analysis is the lightest scalar, \( h_1^0 \), which can be written in terms of the original fields as

\[ h_1^0 = S_{11} H_1^0 + S_{12} H_2^0 + S_{13} S, \]  

(2)

where \( S_{ab} \) diagonalises the \( 3 \times 3 \) scalar Higgs mass matrix\(^2\). In the neutralino sector, the singlino (\( \tilde{S} \)) mixes with the Bino, Wino and Higgsinos, and in this model, the lightest neutralino can be expressed as the combination

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

(3)

with \( N \) the matrix that diagonalises the \( 5 \times 5 \) neutralino mass matrix\(^2\).

The leading contributions to the neutralino-nucleon cross section \( (\sigma \tilde{\chi}^0_1 - p) \) are associated with the scalar, spin- and velocity-independent term \( \alpha_3 \tilde{\chi}^0_1 \tilde{\chi}^0_1 \tilde{q} \tilde{q} \) in the effective Lagrangian\(^1\), which receives contributions from squark and Higgs exchange diagrams\(^2,4\). The term \( \alpha_3 \tilde{\chi}^0_1 \tilde{\chi}^0_1 \tilde{q} \tilde{q} \) is formally identical to the MSSM case, differing only in the new neutralino mixings stemming from the presence of a fifth component, and plays a sub-leading role in our analysis. Regarding the Higgs mediated interaction term \( (\alpha_3 \tilde{\chi}^0_1) \), the situation is slightly more involved since both vertices and the exchanged Higgs scalar significantly reflect the new features of the NMSSM\(^2\). It should be emphasised that the exchange of light Higgs scalars in the \( t \)-channel might provide a considerable enhancement to the neutralino-nucleon cross section.

3. Results and discussion

In our study\(^2\), we were particularly interested in the various NMSSM scenarios which might potentially lead to values of \( \sigma \tilde{\chi}^0_1 - p \) in the sensitivity range of detectors which are currently running or in preparation. The analysis of the NMSSM parameter space (minimization of the potential, computation of spectrum and compatibility with LEP experimental constraints) was done using the program NMHD\(^5\).
Figure 1. On the left, ($\lambda, \kappa$) parameter space with the corresponding constraints for the case $A_\lambda = 200$ GeV, $A_\kappa = -200$ GeV, $\mu = 110$ GeV and $\tan \beta = 3$. Shaded areas are excluded, while dotted lines in the accepted region represent contours of $\sigma_{\tilde{\chi}^0_1 p}$. From top to bottom, solid lines indicate different values of lightest scalar Higgs mass, $m_{h_0^1} = 114, 75, 25$ GeV, dashed lines separate the regions where the lightest scalar Higgs has a singlet composition given by $S_{213} = 0, 0.9$ and a dot-dashed line reflects the singlino composition of the lightest neutralino (below/above $N_{215}^0 = 0.1$). On the right, and for the same choice of input parameters, scatter plot of $\sigma_{\tilde{\chi}^0_1 p}$ as a function of the neutralino mass, with the sensitivities of present and projected experiments. Black dots fulfil all constraints, while in grey are those experimentally excluded.

At the electroweak scale, we have the following set of free, independent parameters: $\lambda, \kappa, \mu (= \lambda s), \tan \beta$, the soft trilinear terms for the Higgs scalars, $A_\lambda, A_\kappa$, the soft gaugino masses $M_i$, and a common SUSY scale for the remaining squark masses and trilinear couplings, $M_{SUSY}$.

Not only the cross section itself, but also the allowed regions of the low-energy NMSSM parameter space are strongly sensitive to variations of the input parameters. It proved very illustrative to analyse the relevant features of the model in the plane generated by the Higgs couplings in the superpotential, $\lambda$ and $\kappa$.

As an example, we plot in Fig.1 the ($\lambda, \kappa$) parameter space and the cross section versus the lightest neutralino mass for $\tan \beta = 3$, $A_\lambda = 200$ GeV, $A_\kappa = -200$ GeV and $\mu = 110$ GeV (taking $M_2 = 2M_1 = M_{SUSY} = 1$ TeV). Significant regions of the parameter space are excluded due to theoretical and experimental constraints. The first class comprises the presence of tachyonic CP-even Higgs scalars (gridded area) and the occurrence of false minima and Landau poles (vertically and horizontally ruled regions, respectively). The grey area is associated to points that do not satisfy...
the LEP constraints. As can be clearly seen from both plots, very large values of \( \sigma_{\tilde{\chi}_1^0-p} \) (in fact, even points already excluded by direct searches) can be obtained. From the inspection of the \((\lambda, \kappa)\) plane, it is clear that such large values are associated with very light Higgs states (as light as 20 GeV), which are experimentally viable due to their important singlet character (0.9 \( \lesssim \) \( S_{1\lambda}^2 \) \( \lesssim \) 0.95). In this case, the NMSSM nature is clearly patent in the compositions of the lightest neutralino (a mixed singlino-Higgsino state) and of \( h_1^0 \) (light, and mostly singlet-like).

Another example, but for a distinct region in the NMSSM parameter space, is depicted in Fig. 2, for \( A_\lambda = 300 \) GeV, \( \mu = 110 \) GeV, \( A_\kappa = 50 \) GeV, and \( \tan \beta = 3 \). In this case, tachyons arise in both CP-even and CP-odd sectors, and close to these areas the experimental constraints from the Higgs sector are more severe. Nevertheless, regions with very light Higgses and \( \tilde{\chi}_1^0 \) are experimentally viable. In particular, neutralinos with an important singlino composition, \( N_{21}^2 \lesssim 0.45 \), can be obtained with \( m_{\tilde{\chi}_1^0} \gtrsim 45 \) GeV. Moreover, the lightest Higgses (\( m_{h_1^0} \approx 65 - 90 \) GeV) are all singlet-like, and this favours large values of the cross section (\( \sigma_{\tilde{\chi}_1^0-p} \lesssim 2 \times 10^{-7} \) pb).

Until here we have only addressed cases where \( \tilde{\chi}_1^0 \) is essentially a singlino-Higgsino mixture, and this stems from the chosen hierarchy, \( \mu < M_1 < M_2 \). By relaxing the latter, more general compositions for the neutralino can be found. Let us go back to the example already analysed in Fig. 1, but now taking two different values for \( \mu, \mu = 200, 500 \) GeV. Re-

![Figure 2](image-url)
Figure 3. Scatter plot of the scalar neutralino-nucleon cross section as a function of $m_{\tilde{\chi}_0^1}$ for $A_\lambda = 200$ GeV, $A_\kappa = -200$ GeV, $\tan \beta = 3$, $\mu = 200, 500$ GeV. The gaugino masses satisfy the GUT relation, with $M_1$ in the range $50$ GeV $\leq M_1 \leq 500$ GeV.

garding the gaugino masses, we allow variations in the Bino mass as 50 GeV $\leq M_1 \leq 500$ GeV, with the GUT relation $M_1 = \frac{1}{2} M_2$. As the value of $\mu$ increases, so does the gaugino composition of $\tilde{\chi}_1^0$. Simultaneously, the lightest Higgs becomes heavier and more doublet-like. For $\mu = 500$ GeV, neutralinos lighter than $m_{\tilde{\chi}_1^0} \lesssim 375$ GeV are all Bino-like. The Higgs mediated interaction is now negligible and detection only takes place through the squark mediated interaction. In contrast to the previous examples, Bino-like neutralinos would have $\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-9}$ pb, and thus would be beyond the sensitivities of even the largest projected dark matter detectors.

Finally, it is important to conduct a more general survey of the NMSSM parameter space in order to obtain a global view on the theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$, and their compatibility with present and projected detectors. We focus on the case $\mu = 110$ GeV, with heavy gaugino masses, $M_1 = \frac{1}{2} M_2 = 500$ GeV, since this choice leads to larger predictions for $\sigma_{\tilde{\chi}_1^0-p}$. The rest of the input parameters are allowed to vary in the ranges $-600$ GeV $\leq A_\lambda \leq 600$ GeV, $-400$ GeV $\leq A_\kappa \leq 400$ GeV, and we take $\tan \beta = 2, 3, 4, 5, 10$, with $\lambda, \kappa \in [0.01, 0.8]$. The results of this scan are shown in Fig.4. Points with large predictions for $\sigma_{\tilde{\chi}_1^0-p}$ are found, and correspond to very light singlet-like Higgses, even with $m_{h_1^\pm} \gtrsim 15$ GeV, which are more easily obtained for low values of $\tan \beta$ ($\tan \beta \lesssim 5$), and typically originate from regions where $\mu A_\lambda > 0$. 
Figure 4. Scalar neutralino-nucleon cross section as a function of the lightest neutralino mass (left) and of the lightest Higgs mass (right). The input parameters are $\mu = 110$ GeV, $-600 \text{ GeV} \leq A_\lambda \leq 600 \text{ GeV}$, $-400 \text{ GeV} \leq A_\kappa \leq 400 \text{ GeV}$, and $\tan \beta = 2, 3, 4, 5, 10$.

4. Conclusions

We have performed a systematic analysis of the low-energy parameter space of the Next-to-Minimal Supersymmetric Standard Model (NMSSM), studying the implications for the direct detection of neutralino dark matter\(^2\). In the computation of $\sigma_{\tilde{\chi}^0_1-p}$ we have taken into account the relevant constraints on the parameter space from accelerator data. We have found that large values of $\sigma_{\tilde{\chi}^0_1-p}$, even within the reach of present dark matter detectors (see e.g. Fig.4), can be obtained, and this is essentially due to the exchange of very light Higgses, $m_{h^0_1} \lesssim 70$ 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.

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References