Thermal right-handed sneutrino dark matter in the NMSSM

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Abstract. The right-handed sneutrino is a viable WIMP dark matter candidate within the context of the Next-to-MSSM. This is possible through the inclusion of a new singlet superfield with direct coupling to the singlet Higgs. I will review here the main details of this construction, together with the properties of the right-handed sneutrino, including its annihilation channels and direct detection prospects. Sneutrinos within a mass-range of 5-200 GeV can reproduce the correct dark matter relic abundance while not being excluded by current direct searches, and for natural values of the input parameters. Some interesting features regarding collider phenomenology are also pointed out.

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INTRODUCTION

A generic weakly interacting massive particle (WIMP) is one of the most attractive candidates for cold dark matter in our Universe, since it would be thermally produced in sufficient amount to account for the observed dark matter density today. Interestingly, WIMPs appear in many well motivated extensions of the standard model providing new physics at the TeV scale, such as supersymmetry (SUSY), in which the lightest supersymmetric particle (LSP) is stable if R-parity is assumed. The minimal supersymmetric extension of the standard model (MSSM) contains two possible candidates for WIMP dark matter, the neutralino [1] and the (left-handed) sneutrino [2]. The neutralino is a popular and widely studied candidate. On the contrary, the sneutrino in the MSSM was soon realised to be problematic. Being a left-handed field, it has a sizable coupling to the Z boson and either annihilates too rapidly (resulting in a very small relic abundance) or gives rise to a too large scattering cross-section off nuclei (being already excluded by direct searches of dark matter) [3].

Several attempts have been made to solve this conundrum through the reduction of the sneutrino coupling with the Z boson. This can be achieved by introducing a mixture of left- and right-handed sneutrino states [4, 5, 6], however a significant mixture is only possible if some particular supersymmetry breaking with a large trilinear term [4] is adopted. This is unnatural in the standard supergravity mediated supersymmetry breaking, where trilinear terms are proportional to the small neutrino Yukawa couplings. Another realization of large mixing consists in abandoning the canonical see-saw formula for neutrino masses [6] . Another possibility is to consider a pure right-handed sneutrino [7, 8, 9, 10]. These cannot be thermal relics, since their coupling to ordinary matter is extremely reduced by the neutrino Yukawa coupling [7, 8, 9], unless they are somehow

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coupled to the observable sector, for example via an extension of the gauge [10, 11] or Higgs [14, 15, 16, 17, 19] sectors. As a final possibility, non-LSP right-handed sneutrino dark matter was also proposed [18].

Extending the MSSM Higgs sector is particularly appealing in order to address the so-called "μ problem" [12]. The superpotential in the MSSM contains a bilinear term, $\mu H_1 H_2$, which has to be of order of the electroweak scale for successful radiative electroweak symmetry breaking (REWSB). Indeed, the next-to-minimal supersymmetric standard model (NMSSM) offers a simple solution by introducing a singlet superfield S and promoting the bilinear term to a trilinear coupling $\lambda S H_1 H_2$. After REWSB, S develops a vacuum expectation value (VEV) and provides an effective term, $\mu = \lambda \langle S \rangle$. The NMSSM has an attractive phenomenology, featuring light Higgses and interesting consequences for neutralino DM [13].

Motivated by the above arguments we study an extension of the MSSM where singlet scalar superfields are included. A singlet S in order to solve the μ problem as in the NMSSM and right-handed neutrinos N to obtain non-vanishing neutrino Majorana masses with a low scale see-saw mechanism. The presence of right-handed sneutrinos, $\tilde{N}$, with a weak scale mass provides a new DM candidate within the WIMP category. The model [16, 19] is specified by the following superpotential

$$\begin{aligned} W &= W_{\rm NMSSM} + \lambda_N S N N + y_N L \cdot H_2 N, \\ W_{\rm NMSSM} &= Y_u H_2 \cdot Q u + Y_d H_1 \cdot Q d + Y_e H_1 \cdot L e - \lambda S H_1 \cdot H_2 + \frac{1}{3} \kappa S^3, \end{aligned}$$

which is an extension of that of the NMSSM with a new trilinear coupling among the singlet superfields S and N and the corresponding Yukawa terms to provide neutrino masses. As in the NMSSM, a global Z_3 symmetry is imposed for each superfield, so that there are no supersymmetric mass terms in the superpotential. The terms NNN and SSN are gauge invariant but violate R-parity and thus are not included.

After REWSB takes place the Higgs fields take non-vanishing VEVs, $(v_{1,2}, v_s) = (\langle H_{1,2} \rangle, \langle S \rangle)$, and a Majorana mass term is generated, $M_N = 2\lambda_N v_s$. Light masses for left-handed neutrinos are then obtained via a see-saw mechanism, $m_{\nu_L} = y_N^2 v_2^2 / M_N$. Notice that this necessary implies small Yukawa couplings, $y_N \lesssim \mathscr{O}(10^{-6})$.

Our model contains three new inputs with respect to the NMSSM parameter space, namely the coupling λ_N, the associated soft trilinear term, A_{λ_N}, and the soft right-handed sneutrino mass, $m_{\tilde{N}}$. A crucial feature of this scenario is the existence of direct couplings of the right-handed sneutrino to Higgses and neutralinos. These emerge through the term $\lambda_N S N N$ in the superpotential, since the singlet and singlino components of S mix with the CP-even Higgs bosons and neutralinos, respectively. The strength of the interaction is therefore dependent on the value of λ_N and A_{λ_N}. The coupling between the lightest right-handed sneutrino, $\tilde{N}_1$ and a Higgs boson, H_i^0, determines most of the sneutrino phenomenological properties, and reads

$$C_{H_i^0 \tilde{N}_1 \tilde{N}_1} = \frac{2\lambda \lambda_N M_W}{\sqrt{2} g} \left(\sin\beta S^1_{H_i^0} + \cos\beta S^2_{H_i^0} \right) + \left[\left(4{\lambda_N}^2 + 2\kappa \lambda_N \right) v_s + \frac{\lambda_N A_{\lambda_N}}{\sqrt{2}} \right] S^3_{H_i^0} ,$$

where $S^j_{H_i^0}$ $(j = 1, 2, 3)$ are the elements of the Higgs diagonalisation matrix.

THERMAL PRODUCTION

The sneutrino coupling to the NMSSM Higgs sector provides tree-level interactions with ordinary matter. For adequate values of λ_N (and A_{λ_N}) these couplings would be of electroweak scale, thereby making the right-handed sneutrino a potential WIMP candidate. The possible annihilation products for right-handed sneutrinos are

(i) W^+W^-, ZZ, and $f\bar{f}$ via s-channel Higgs exchange;

(ii) $H_i^0 H_j^0$, via s-channel Higgs exchange, t- and u-channel sneutrino exchange, and a scalar quartic coupling;

(iii) $A_a^0 A_b^0$, and $H_i^+ H_j^-$, via s-channel Higgs exchange, and a scalar quartic coupling;

(iv) ZA_a^0 and $W^\pm H^\mp$ via s-channel Higgs exchange;

(v) A pair of right-handed neutrinos, NN, via s-channel Higgs exchange and via t- and u-channel neutralinos exchange.

The processes suppressed by the small neutrino Yukawa coupling (such as s-channel sneutrino annihilation mediated by the Z boson) are negligible.

The sneutrino relic abundance is calculated solving numerically the Boltzmann equations using the same procedure detailed in Ref. [20] for the case of the neutralino. The analysis of the low-energy NMSSM phenomenology has been performed with the `NMHDECAY` 2.0 code [21], based on which we have built a set of routines which numerically calculate the sneutrino spectrum and relic density. In our computation we do not include co-annihilation effects. The resulting relic density is compared with the recent measurement by the WMAP satellite, $0.1037 \leq \Omega h^2 \leq 0.1161$. [22].

As we explained above, the main feature of this construction is the direct coupling of the sneutrino to the Higgs fields. Hence, the sneutrino annihilation cross section is extremely sensitive to the structure of the Higgs sector. Although this introduces a strong dependence of our results on the NMSSM parameter space, there are some general features which are easy to identify and understand.

- The coupling λ_N determines the overall scale of the annihilation cross section. A larger λ_N implies more effective sneutrino annihilation, and in turn a smaller relic abundance, and viceversa. Regarding the supersymmetric spectrum, notice that λ_N only affects the right-handed neutrino and sneutrino masses and does not alter the rest of the NMSSM spectrum. Thus, having chosen a set of viable NMSSM input parameters, the value of λ_N (as well as $m_{\tilde{N}}$ and A_{λ_N}) can be freely varied in order to reproduce the correct sneutrino relic abundance.
- Annihilation into $H_i^0 H_j^0$ and $A_a^0 A_b^0$ are among the most effective channels. This is also the case in other models for thermal right-handed sneutrino [17]. However, in our case, the flexibility and interesting properties of the Higgs sector of the NMSSM make this possibility much more versatile. Whether these channels are kinematically allowed or not depends on the Higgs masses. Within the framework of the NMSSM, very light CP-even and CP-odd Higgses are possible (as long as they have a significant singlet component), making these channels available for a wide range of sneutrino masses, in particular, very light sneutrinos can thus reproduce the correct relic abundance (see, e.g., the right hand-side of Fig. 1).

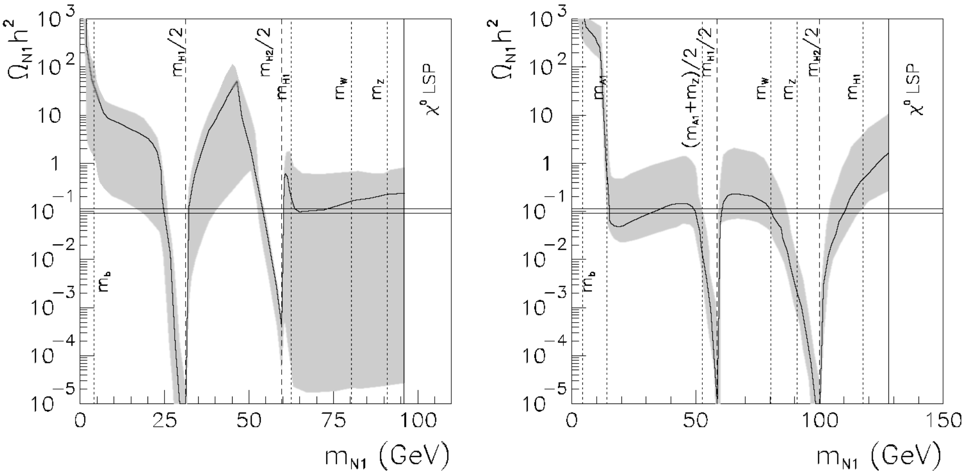

FIGURE 1. Theoretical predictions for the sneutrino relic density as a function of the sneutrino mass for a scan in the parameters corresponding, from left to right, to cases A) and B1) in Table 1 of Ref. [19]. Vertical dashed lines indicate the location of the resonances in the s-channels when $2m_{\tilde{N}_1} \approx m_{H_i^0}$, whereas vertical dotted lines indicate when the different annihilation channels become kinematically accessible. The vertical solid line indicates the point at which the neutralino becomes the LSP.

- Another relevant contribution to the total annihilation cross section is due to the annihilation into a pair of right-handed neutrinos.
- Finally, for all the possible annihilation products there is always a contribution coming from s-channel CP-even Higgs exchange. This implies that all of them are subject to a resonant effect when $2m_{\tilde{N}_1} \approx m_{H_i^0}$, for $i = 1,2,3$. Given the possibility of light scalar Higgses in the NMSSM, this resonant annihilation can be present even for light sneutrinos.

In order to illustrate these properties, Fig. 1 shows the sneutrino relic abundance as a function of the sneutrino mass for two representative examples in the NMSSM parameter space (corresponding, from left to right, to cases A) and B1) in Table 1 of Ref. [19]). We set $A_{\lambda_N} = 250$ GeV and vary λ_N and $m_{\tilde{N}}$ in the ranges $[0.05, 0.1]$ and $[0, 200]$ GeV, respectively, excluding points in which $\tilde{N}_1$ is not the LSP or is tachyonic. The large suppression on the Higgs resonances is clearly evidenced. The relic abundance increases as λ_N decreases due to the reduction in $C_{H_i^0 \tilde{N}_1 \tilde{N}_1}$. Remarkably, the correct relic density can be obtained with natural values of λ_N and without the need of resonant effects. For example, in case A) when annihilation into scalar Higgses is possible ($m_{\tilde{N}_1} > m_{H_1^0}$), one needs $\lambda_N \sim 0.06$. Notice also that in case B1), very light $\tilde{N}_1$ are viable when annihilation into light pseudoscalar Higgses is allowed. Other possibilities can be found in Ref. [19]), showing that the correct relic density can be obtained for sneutrinos within a mass range of 5-200 GeV. The right-handed sneutrino in this construction is therefore a WIMP.

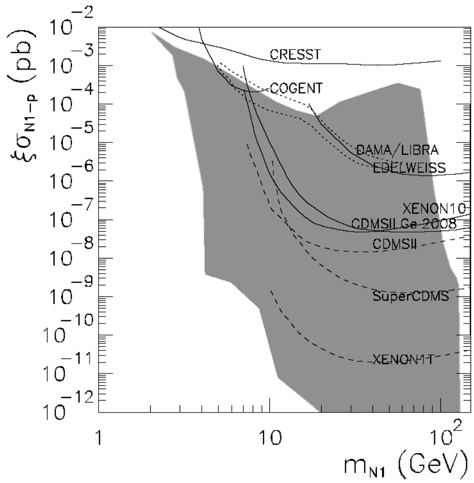

FIGURE 2. Theoretical predictions for the spin-independent component of the sneutrino-nucleon elastic scattering cross section as a function of the sneutrino mass for a scan in the NMSSM parameter space.

DIRECT DETECTION

The direct detection of sneutrinos could take place through their elastic scattering with nuclei inside a dark matter detector. In our case, there is only one diagram contributing (at tree level) to this process, namely, the t-channel exchange of neutral Higgses (the exchange of a Z boson is largely suppressed by the neutrino Yukawa squared). The effective Lagrangian describing the four-field interaction only contains a scalar coupling which reads

$$\mathscr{L}_{eff} \supset \sum_{j=1}^{3} \frac{C_{H_j^0 \tilde{N}_1 \tilde{N}_1} Y_{qi}}{m^2_{H_j^o}} \tilde{N}\tilde{N}\bar{q}_i q_i \equiv \alpha_{q_i} \tilde{N}\tilde{N}\bar{q}_i q_i \,,$$

where Y_{q_i} is the corresponding quark Yukawa coupling and i labels up-type quarks ($i = 1$) and down-type quarks ($i = 2$). Notice that the effective Lagrangian contains no axial-vector coupling since the sneutrino is a scalar field, therefore implying a vanishing contribution to the spin-dependent cross section. The total spin-independent sneutrino-proton scattering cross section yields

$$\sigma^{\rm SI}_{\tilde{N}_1-p} = \frac{1}{\pi} \frac{m_p^4}{(m_p + m_{\tilde{N}_1})^2} \left(\sum_{q_i=u,d,s} f^p_{Tq_i} \frac{\alpha_{q_i}}{m_{q_i}} + \frac{2}{27} f^p_{TG} \sum_{q_i=c,b,t} \frac{\alpha_{q_i}}{m_{q_i}} \right)^2 ,$$

The quantities $f^p_{Tq_i}$ and f^p_{TG} are the hadronic matrix elements which parametrize the quark content of the proton.

It is obvious from the previous formulae that the sneutrino detection cross section is extremely dependent on the features of the Higgs sector of the model. In particular,

$\sigma^{\rm SI}_{\tilde{N}_1-p}$ becomes larger when the sneutrino-sneutrino-Higgs coupling increases (which can be achieved by enhancing λ_N or with large values for $|A_{\lambda_N}|$). Moreover larger values of $\sigma^{\rm SI}_{\tilde{N}_1-p}$ can be obtained in those regions of the parameter space where the mass of the lightest Higgs becomes smaller.

The theoretical predictions for $\xi\sigma^{\rm SI}_{\tilde{N}_1-p}$ are represented as a function of the sneutrino mass in Fig. 2 for a wide scan in the NMSSM parameter space as described in Ref. [19]. The sneutrino fractional density ξ, is defined to be $\xi = \min[1, \Omega_{\tilde{N}_1}h^2/0.1037]$ in order to have a rescaling of the signal for subdominant DM in the halo [23]. As we can observe, the right-handed sneutrino in our model is not yet excluded by direct searches for dark matter. Interestingly, the predicted $\xi\sigma^{\rm SI}_{\tilde{N}_1-p}$ lies within the reach of projected DM experiments, for some regions in the parameter space. Of particular interest is the region with very light sneutrinos, for which the predictions differ from those obtained by neutralinos in the NMSSM [24].

COLLIDER PHENOMENOLOGY

As with other WIMP models, right-handed sneutrinos can be pair-produced in a collider and subsequently escape undetected, leaving events with missing transverse momentum. Thus, the relevant question is whether or not the identity of the missing particle (e.g., sneutrino or neutralino) can be determined. In this sense, the study of certain kinematic variables can give us crucial information about the mass and spin of the LSP [25].

Another attractive possibility is the production of right-handed neutrinos in the decay of either a Higgs boson or a neutralino (which can be the NLSP and decay into a sneutrino LSP and a right-handed neutrino). The right-handed neutrino would be long-lived and decay, through the tiny mixing with the left-handed component, into a W boson and a charged lepton, giving rise to a displaced vertex which could be observed.

As we have already stressed, sneutrino dark mater is very sensitive to the properties of the Higgs sector. A Higgs boson with significant singlet component can decay into a pair of LSP right-handed sneutrinos and a pair of right-handed neutrinos (missing momentums and long-lived particles). This is also a possible unique signal. There is a related consequence, namely the invisible decay of the Higgs boson, since the right-handed sneutrino interacts with the CP-even Higgs through the coupling $C_{H_i^0\tilde{N}_1\tilde{N}_1}$. This is a common feature of dark matter particles which predominantly annihilate through s-channel Higgs exchange and can be detected through t-channel Higgs exchange.

In addition, through collider studies, it is possible to discriminate our model from other models with thermal right-handed sneutrino dark matter. In particular, there exists a family of models in which thermal right-handed neutralino dark matter is viable thanks to the inclusion of a new gauge interaction through a $U(1)'$ [10] or $U(1)_{B-L}$ [11]. These scenarios present a Z' gauge boson which is not present in our construction. The detection or not of this Z' would discriminate among these models. Our model differs from other extensions of the Higgs sector [15, 17] in that the singlet Higgs in the latter models is quite heavy and the exchanging Higgses are MSSM-like. As a result, the correct relic abundance can only be realized with the help of the resonant annihilation. Hence, a strong correlation between the sneutrino mass and the Higgs mass is present.

CONCLUSIONS

The right-handed sneutrino is a viable thermal WIMP dark matter candidate in an extension of the NMSSM where a new superfield, N, is included to account for the smallness of neutrino masses. A direct coupling between N and the singlet Higgs provides a sufficiently large annihilation cross section sneutrino and a scattering cross-section off nuclei which is not excluded by current direct dark matter searches. Sneutrinos within a mass-range of 5-200 GeV can reproduce the correct dark matter relic abundance and the prospects for their direct detection can be within the range of future detectors.

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REFERENCES

1. H. Goldberg, Phys. Rev. Lett. **50** 1419 (1983); J. R. Ellis *et al.*, Phys. Lett. B **127** 233 (1983); Nucl. Phys. B **238** 453 (1984); L.M. Krauss, Nucl. Phys. B **227** 556 (1983).
2. L.E. Ibañez, Phys. Lett. B **137** 160 (1984); J.S. Hagelin, G.L. Kane and S. Raby, Nucl. Phys. B **241** 638 (1994).
3. T. Falk, K. A. Olive and M. Srednicki, Phys. Lett. B **339** 248 (1994).
4. N. Arkani-Hamed *et al.*, Phys. Rev. D **64** 115011 (2001); D. Hooper, J. March-Russell and S. M. West, Phys. Lett. B **605** 228 (2005).
5. C. Arina and N. Fornengo, JHEP **0711** (2007) 029.
6. C. Arina, *et al.*, Phys. Rev. Lett. **101** (2008) 161802.
7. T. Asaka, K. Ishiwata and T. Moroi, Phys. Rev. D **73** 051301 (2006); Phys. Rev. D **75** 065001 (2007).
8. S. Gopalakrishna, A. de Gouvea and W. Porod, JCAP **0605** (2006) 005.
9. J. McDonald, JCAP **0701** (2007) 001;
10. H. S. Lee, K. T. Matchev and S. Nasri, Phys. Rev. D **76** 041302 (2007).
11. R. Allahverdi, B. Dutta and A. Mazumdar, Phys. Rev. Lett. **99**, 261301 (2007).
12. J. E. Kim and H. P. Nilles, Phys. Lett. B **138** 150 (1984).
13. D. G. Cerdeño *et al.*, JHEP **0412** (2004) 048; JCAP **0706** (2007) 008.
14. R. Kitano and K. y. Oda, Phys. Rev. D **61** 113001 (2000).
15. B. Garbrecht *et al.*, JHEP **0612**, 038 (2006).
16. D. G. Cerdeño, C. Muñoz and O. Seto, Phys. Rev. D **79**, 023510 (2009).
17. F. Deppisch and A. Pilaftsis, JHEP **0810** (2008) 080.
18. D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D **79** (2009) 115016.
19. D. G. Cerdeño and O. Seto, arXiv:0903.4677 [hep-ph].
20. T. Nihei, L. Roszkowski and R. Ruiz de Austri, JHEP **0203** (2002) 031.
21. U. Ellwanger and C. Hugonie, Comput. Phys. Commun. **175**, 290 (2006); G. Belanger, F. Boudjema, C. Hugonie, A. Pukhov and A. Semenov, JCAP **0509**, 001 (2005).
22. J. Dunkley *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **180**, 306 (2009).
23. T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D **34**, 2206 (1986).
24. C. E. Aalseth *et al.*, Phys. Rev. Lett. **101** (2008) 251301 [Erratum-ibid. **102** (2009) 109903].
25. W. S. Cho, K. Choi, Y. G. Kim and C. B. Park, JHEP **0802** (2008) 035; Phys. Rev. D **79** (2009) 031701.