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Light dark matter in the singlet-extended MSSM

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ABSTRACT

We discuss the possibility of light dark matter in a general singlet extension of the MSSM. Singlino LSPs with masses of a few GeV can explain the signals reported by the CRESST, CoGeNT and possibly also DAMA experiments. The interactions between singlinos and nuclei are mediated by a scalar whose properties coincide with those of the SM Higgs up to two crucial differences: the scalar has a mass of a few GeV and its interaction strengths are suppressed by a universal factor. We show that such a scalar can be consistent with current experimental constraints, and that annihilation of singlinos into such scalars in the early universe can naturally lead to a relic abundance consistent with the observed density of cold dark matter.

1. Introduction

Supersymmetry offers a very attractive solution to the dark matter puzzle since the lightest superpartner (LSP) is a quite compelling candidate for the observed cold dark matter (CDM). The LSP is usually assumed to be stable or, at least, long lived. Most studies on scenarios of supersymmetric dark matter focus on the LSPs with electroweak scale masses and cross sections, whose relic density can match the measured CDM density. However, recent results from the direct detection experiments CoGeNT [1] and CRESST [2] seem to hint at somewhat lighter dark matter particles with masses of a few GeV. This interpretation is also consistent with the DAMA signal [3,4]. Do we expect to have such particles in supersymmetric extensions of the standard model (SM)? Certainly, in the minimal supersymmetric SM (MSSM), such masses appear hardly justifiable for particles interacting strong enough to explain the above signals [5–7]. This is because, in the MSSM, such particles will typically contribute to the Z boson decay width. On the other hand, in singlet extensions of the MSSM this problem may be circumvented. While in the usual NMSSM it still appears difficult [8,9], but not impossible [10], to obtain particles with the desired properties, generalized singlet extensions of the MSSM [11] can indeed give rise to settings with light dark matter candidates whose interactions with nuclei are mediated by weakly coupled light scalars.

In this Letter we focus on a particularly simple scenario based on such a singlet extension of the MSSM in which the singlet sector is only weakly coupled to the MSSM. This will lead to a light Higgs-like scalar h_1 whose couplings to SM particles are determined by those of the SM Higgs boson with an overall suppression factor.[1] The scalar is accompanied by a singlino superpartner, which, as we shall see, has naturally the correct abundance to explain the observed CDM. Further, h_1 mediated scatterings of nuclei with the singlino can give rise to the signals reported by CRESST, CoGeNT and possibly also DAMA.

2. Light singlets in the S-MSSM

We consider the MSSM Higgs sector extended by a gauge singlet superfield S. The most general renormalizable superpotential reads [12][2]

$$\mathscr{W} = \mu H_u H_d + \lambda S H_u H_d + \frac{\mu_s}{2} S^2 + \frac{\kappa}{3} S^3. \tag{1}$$

In the so-called NMSSM the μ and μ_s terms are set to zero. On the other hand, it is well known that there are mechanisms that

[1] This is one of the aspects in which our analysis differs from those in [10,11] where scalars with enhanced couplings to down-type fermions are considered.

[2] A possible linear term in S can be absorbed into the quadratic and cubic terms [12].

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explain a suppressed μ term [13,14]; such mechanisms may also give rise to a μ_s parameter of the order of the electroweak scale. Recently the resulting scheme has been investigated in a different context and was dubbed 'S-MSSM' [15]; we will adopt this terminology. A simple setting where the smallness of μ and μ_s finds an explanation will be discussed elsewhere [16]. We include both dimensionful parameters in our analysis. In addition the scalar potential includes the following soft terms

$$V_{\text{soft}} = m_{h_u}^2|h_u|^2 + m_{h_d}^2|h_d|^2 + m_s^2|s|^2 + \left(B\mu h_u h_d + \lambda A_\lambda s h_u h_d + \frac{B\mu_s}{2}s^2 + \frac{\kappa}{3}A_\kappa s^3 + \text{h.c.}\right). \tag{2}$$

The singlet superfield S contains a complex scalar s and a Majorana fermion, the singlino $\tilde{s}$.

The important feature of the resulting model is that all interactions between the MSSM and the singlet sectors are controlled by a single parameter λ. As we shall see, in the region where λ is of the order $10^{-2\ldots3}$ and the singlet fields are light a simple explanation of the direct detection signals mentioned in the introduction emerges. To obtain light singlets we shall assume that all singlet mass terms are set by a scale $m_{\text{singlet}} \sim 10$ GeV. Relatively suppressed soft terms for the singlet can be motivated in settings in which the MSSM soft masses are dominated by the gaugino contribution in the renormalization group. In what follows, we start by discussing the limit $\lambda \to 0$, and then explore what happens if we switch on a finite but small λ.

2.1. Limit $\lambda \to 0$

All terms which mix the singlets with the MSSM contain the parameter λ, i.e. in the case $\lambda = 0$ both sectors are completely decoupled. The singlino mass is simply given by $m_{\tilde{s}} = \mu_s$, the complex scalar s receives additional mass contributions from the soft terms which also split its real and imaginary components. If we introduce the real scalar h_s and pseudoscalar a_s through the relation $s = (h_s + \mathrm{i}a_s)/\sqrt{2}$, we find $m_{h_s}^2 = m_s^2 + \mu_s^2 + B\mu_s$ and $m_{a_s}^2 = m_s^2 + \mu_s^2 - B\mu_s$. A light singlet sector can be obtained if we assume that all mass parameters $m_s^2, \mu_s^2, B\mu_s \sim m_{\text{singlet}}^2$ with $m_{\text{singlet}} \sim 10$ GeV. The following discussion is based on this assumption.

2.2. Small λ

Switching on a small λ leads to couplings to and mixings with the MSSM fields. Through the F- and soft terms of the MSSM Higgs fields there arises a linear term in s of the form $\lambda\mu_{\text{eff}}v_{\text{EW}}^2 s$, where we introduced $\mu_{\text{eff}} = \mu - v_1 v_2 A_\lambda/v_{\text{EW}}^2$. Here $v_1 = \langle h_d\rangle$, $v_2 = \langle h_u\rangle$ and $v_{\text{EW}}^2 = v_1^2 + v_2^2 \simeq (174\ \text{GeV})^2$. The linear term induces a vacuum expectation value $x = \langle s\rangle$ which can be estimated as

$$x \sim \lambda\frac{v_{\text{EW}}^2}{m_{\text{singlet}}^2}\mu_{\text{eff}}. \tag{3}$$

There are two competing effects, the smallness of λ and the m_{singlet}^2 in the denominator, such that x can be of the order of the electroweak scale. Note, however, that the impact of x on the SM Higgs masses is almost negligible. In the presence of the singlet VEV there will be new singlet mass terms such as $\kappa^2 s^2$ and $\kappa A_\kappa s$. Therefore, in order to keep the singlet sector light, we assume that the self-coupling κ is not too large, $\kappa \lesssim 0.1$, and that the trilinear coupling $A_\kappa \lesssim m_{\text{singlet}}$.

Let us look at the masses and mixings of the singlets. As λ is small we can treat MSSM and singlet sector separately and consider mixing as a perturbation. To simplify our analysis, we impose the decoupling limit on the MSSM Higgs fields. This allows us to ignore mixing of the singlets with the pseudoscalar and the heavy scalar MSSM Higgs.[3] We, however, keep track of the mixing between the light MSSM Higgs h and h_s. We further use the minimization conditions for the Higgs potential in order to eliminate the soft masses.

The mass of the singlet pseudoscalar is then given by

$$m_{a_s}^2 \simeq -2B\mu_s - x\kappa(3A_\kappa + \mu_s) - \lambda\frac{\mu_{\text{eff}}}{x}v_{\text{EW}}^2. \tag{4}$$

The scalar mass matrix in the basis (h, h_s) reads

$$M_H^2 = \begin{pmatrix} m_h^2 & m_{hh_s}^2 \\ m_{hh_s}^2 & m_{h_s}^2 \end{pmatrix} \tag{5}$$

with

$$m_{h_s}^2 \simeq \kappa x(A_\kappa + 4\kappa x + 3\mu_s) - \lambda\frac{\mu_{\text{eff}}}{x}v_{\text{EW}}^2, \tag{6}$$

$$m_{hh_s}^2 \simeq 2\lambda v_{\text{EW}}\mu_{\text{eff}}, \tag{7}$$

and m_h^2 as in the usual MSSM. Note that with the assumptions made all contribution to m_{a_s} and m_{h_s} are of the order m_{singlet} or smaller, i.e. we obtain $m_{a_s}, m_{h_s} \sim m_{\text{singlet}}$. Given our assumptions, $m_{hh_s} \sim m_{\text{singlet}}$.

As $m_h^2 \gg m_{hh_s}^2, m_{h_s}^2$ there is little mixing between h and h_s. The light physical mass eigenstate is mainly singlet with a small admixture from h,

$$h_1 \simeq \cos\theta h_s - \sin\theta h \tag{8}$$

with

$$\cos\theta \simeq 1, \tag{9}$$

$$\sin\theta \simeq \frac{m_{hh_s}^2}{m_h^2}. \tag{10}$$

The heavier state h_2 essentially coincides with the MSSM Higgs h. The mass of h_1 is given by

$$m_{h_1}^2 \simeq m_{h_s}^2 - \frac{m_{hh_s}^4}{m_h^2}. \tag{11}$$

In the fermion sector there is mixing between the singlino and the MSSM neutralinos. This mixing can maximally reach the size of $\sin\theta$ if the higgsinos are relatively light.[4] As such a small mixing in the fermion sector does not play a role in the following discussion, we ignore it and take the LSP to be a pure singlino with mass

$$m_{\tilde{s}} = \mu_s + 2\kappa x. \tag{12}$$

The couplings in the singlet sector are all controlled by κ. Most relevant for the following discussion are the trilinear interaction terms which comprise

$$\mathscr{L} \supset -\frac{1}{2}g_{h_1\tilde{s}\tilde{s}}h_1\bar{\tilde{s}}\tilde{s} - \frac{1}{2}g_{a_s\tilde{s}\tilde{s}}a_s\bar{\tilde{s}}\gamma_5\tilde{s} - \frac{1}{6}g_{h_1h_1h_1}h_1^3 - \frac{1}{2}g_{h_1a_sa_s}h_1a_s^2 \tag{13}$$

with

[3] Note that a very large A_λ could increase the mixing between singlet and heavy MSSM Higgs. In this regime we expect corrections to our analytic formulas.

[4] The possible exception of a bino with a mass close to $m_{\tilde{s}}$ is not considered here.

$$g_{h_1\tilde{s}\tilde{s}} \simeq \sqrt{2}\kappa, \tag{14a}$$

$$g_{a_s\tilde{s}\tilde{s}} \simeq -\mathrm{i}\sqrt{2}\kappa, \tag{14b}$$

$$g_{h_1h_1h_1} \simeq \sqrt{2}\kappa(3m_{\tilde{s}} + A_\kappa), \tag{14c}$$

$$g_{h_1a_sa_s} \simeq \sqrt{2}\kappa(m_{\tilde{s}} - A_\kappa). \tag{14d}$$

The coupling of h_1 to quarks and leptons is the SM Higgs coupling suppressed by a factor of $\sin\theta$.

In summary we have obtained a light scalar which shares the properties of the SM Higgs with two crucial differences: its mass can be in the GeV range and its couplings to SM matter are suppressed by a universal factor, essentially $\sin\theta$. The second feature is robust to the extent that the MSSM decoupling limit can be applied. As we shall see in Section 4.2, $\sin\theta$ can be so large that the interactions of the singlino with the light scalar h_1 lead to a coherent picture of singlino CDM in which the recent direct detection signals find an explanation. Before explaining these statements in detail, we will discuss in Section 3 that the required values of $\sin\theta$ can be consistent with experimental constraints.

3. Experimental constraints on light singlets

We start with a comment on the heavier scalar h_2: as mixing with the light singlets is suppressed, h_2 decays like the SM Higgs boson. Therefore the usual LEP limit $m_{h_2} > 114.4$ GeV applies.

Let us now study the light h_1. In experiments the light scalar behaves as a light SM Higgs with its coupling reduced by the mixing angle $\sin\theta$. Higgs searches by LEP – especially the data set from the L3 Collaboration [17] – set strong constraints on the cross section for $e^+e^- \to Z + h_1$ which can be translated directly in limits on $\sin\theta$.[5] Processes in which the resulting Z decays further into neutrinos are treated separately.

As we consider values of m_{h_1} in the GeV range we also have to consider the production and subsequent decay of h_1 in meson decays. The CLEO [18], and BaBar [19,20] Collaborations have measured the branching fractions of the radiative decays $\Upsilon \to \gamma + \ell^+\ell^-$ with $\ell = \tau, e$. Currently, the limits on $\sin\theta$ from Υ decay are rather weak (see e.g. [21]), but they may improve in the future.

Below the B meson threshold h_1 can further contribute to the inclusive and exclusive decay modes of B. Strong limits are set by the inclusive process $B \to h_1 + X_s$ followed by the decay $h_1 \to \mu^+\mu^-$. The branching ratio for this process can be taken from [22],

$$\mathrm{Br}(B \to h_1 + X_s) = 0.058\left(\frac{\sin\theta}{0.1}\right)^2\left(1 - \frac{m_{h_1}^2}{m_b^2}\right)^2, \tag{15}$$

the branching ratio for $\mathrm{Br}(h_1 \to \mu^+ + \mu^-)$ can be extracted from [21]. Measurements of the inclusive B decay by Belle [23] together with the calculation of the SM background [24,25] suggest that $\mathrm{Br}(B \to h_1 + X_s) \times \mathrm{Br}(h_1 \to \mu^+ + \mu^-) < 2.5 \times 10^{-6}$. This sets limits on $\sin\theta$ which we show together with the LEP constraints in Fig. 1.

4. Singlinos as dark matter

Let us now discuss whether the singlino discussed above is a viable dark matter candidate. We start by showing that the singlino has the right relic abundance to constitute the observed dark matter, continue by discussing how the interactions with the singlino may explain the current anomalies in direct detection experiments and finally present a benchmark scenario which is consistent with present data.

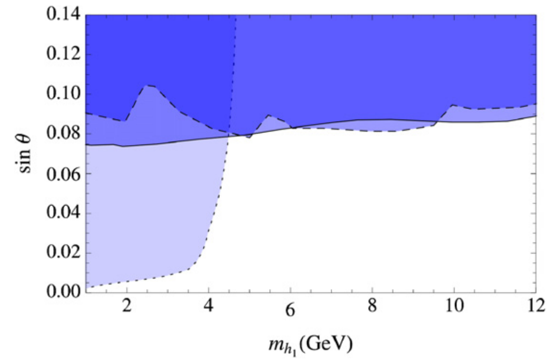

Fig. 1. Limit on $\sin\theta$ from LEP (solid line for neutrino channel, dashed line for all channels) and B decays (dotted line). The colored region is excluded. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

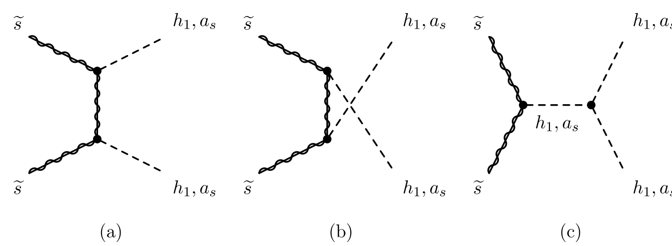

Fig. 2. Singlino annihilation into (pseudo)scalars.

4.1. Relic abundance

As singlinos are only very weakly coupled to the MSSM sector, annihilation into SM particles is suppressed. However, singlinos can efficiently annihilate into the light singlet (pseudo)scalars provided that $m_{\tilde{s}} > m_{h_1}, m_{a_s}$ (see Fig. 2). It is convenient to expand the cross section in powers of the relative singlino velocity $v_{\rm rel}$,

$$\sigma v_{\rm rel} = \sigma_0 + \sigma_1 v_{\rm rel}^2 + \mathcal{O}\left(v_{\rm rel}^4\right). \tag{16}$$

As an approximation we will only consider the leading contribution to $\sigma v_{\rm rel}$ which is the term σ_0 for a final state with one scalar and one pseudoscalar. If only final states with two scalars or two pseudoscalars are kinematically accessable σ_0 vanishes and the term σ_1 dominates. We distinguish the following three cases:

Case 1: $m_{h_1} + m_{a_s} > 2m_{\tilde{s}}$, but $m_{h_1} < m_{\tilde{s}}$. The dominant channel is $\tilde{s}\tilde{s} \to h_1h_1$ and

$$\sigma v_{\rm rel} \simeq \frac{17}{256\pi}\frac{\kappa^4}{m_{\tilde{s}}^2}\left(1 - \frac{22}{51}\frac{A_\kappa}{m_{\tilde{s}}} + \frac{1}{17}\frac{A_\kappa^2}{m_{\tilde{s}}^2}\right)v_{\rm rel}^2. \tag{17}$$

Case 2: $m_{h_1} + m_{a_s} > 2m_{\tilde{s}}$, but $m_{a_s} < m_{\tilde{s}}$. The dominant channel is $\tilde{s}\tilde{s} \to a_sa_s$ and

$$\sigma v_{\rm rel} \simeq \frac{9}{256\pi}\frac{\kappa^4}{m_{\tilde{s}}^2}\left(1 - \frac{14}{27}\frac{A_\kappa}{m_{\tilde{s}}} + \frac{1}{9}\frac{A_\kappa^2}{m_{\tilde{s}}^2}\right)v_{\rm rel}^2. \tag{18}$$

Case 3: $m_{h_1} + m_{a_s} < 2m_{\tilde{s}}$. The dominant channel is $\tilde{s}\tilde{s} \to h_1a_s$ and

$$\sigma v_{\rm rel} \simeq \frac{9}{64\pi}\frac{\kappa^4}{m_{\tilde{s}}^2}\left(1 + \frac{2}{3}\frac{A_\kappa}{m_{\tilde{s}}} + \frac{1}{9}\frac{A_\kappa^2}{m_{\tilde{s}}^2}\right). \tag{19}$$

In these formulas we have set masses of (pseudo)scalars to zero. For case 1 and case 2 this is a valid approximation as long as the

[5] Note that in the special case $2m_{a_s} < m_{h_1}$ the light Higgs can decay into pseudoscalars and the limits get weaker.

Table 1
Parameters of a phenomenologically viable benchmark point. We assume $m_h = 115$ GeV.

(a) Input parameters.

Quantity	Value
μ_{eff}	370 GeV
x	163 GeV
A_κ	−9 GeV
μ_s	−19 GeV
$B\mu_s$	0
λ	−0.003
κ	0.08

(b) Predictions.

Quantity	Value
m_{a_s}	28 GeV
$m_{\tilde{s}}$	7 GeV
m_{h_1}	4 GeV
$\sin\theta$	0.03
σ_n	$\sim 10^{-40}$ cm^2
Ωh^2	~ 0.1

final state particles are not degenerate in mass with the singlinos. In case 3 which is, however, not the main focus of this study, we expect significant corrections, e.g. if there is an s-channel resonance (i.e. $m_{h_1} \simeq 2m_{\tilde{s}}$).

The relic singlino density can be obtained from the annihilation cross section by numerically solving the corresponding Boltzmann equation. An analytic formula which reproduces our numerical results with good accuracy is [26]

$$\Omega_{\tilde{s}} h^2 = 8.5 \times 10^{-11}\ \text{GeV}^{-2} \frac{m_{\tilde{s}}}{\sqrt{g_*(T_F)} T_F (\sigma_0 + 3T_F \sigma_1/m_{\tilde{s}})}, \quad (20)$$

where g_* denotes the effective number of relativistic degrees of freedom and T_F the freeze-out temperature. For reasonable parameter choices we find $T_F \simeq m_{\tilde{s}}/20$. Note that in our setup the singlinos typically freeze out at a temperature close to the QCD phase transition temperature where the quantity g_* changes rapidly [27]. This induces an $\mathcal{O}(1)$ uncertainty in our estimate of the relic density.

Given that the singlet coupling is sizable ($\kappa = \mathcal{O}(0.1)$) and at least one of the discussed annihilation channels is available, it is possible to obtain a relic singlino density which matches the observed dark matter density. As we shall see, however, a sizable direct detection cross section for the singlino requires h_1 to be light. Specifically we find that mass patterns corresponding to case 1 are favored in explaining the signals seen at CoGeNT, CRESST and DAMA. A parameter choice of this type is presented in our benchmark scenario (Section 4.3).

Let us also mention that singlino annihilation could affect the galactic antiproton flux if σv_{rel} is not velocity suppressed and h_1, a_s decay dominantly into quarks. In this case there might already exist a slight tension with existing experimental data [28]. However, our benchmark scenario can evade such constraints due to velocity suppression. A detailed study of these issues will appear elsewhere.

4.2. Direct detection

At the same time, singlinos can explain the recently observed anomalies in direct dark matter detection experiments. The CoGeNT Collaboration has reported an excess of low energy scattering events in their germanium detector [1]. This signal is consistent with light weakly interacting massive particles (WIMPs) ($m \sim 5$–15 GeV) which exhibit a rather large cross section with nucleons, $\sigma_n \sim 10^{-40}$ cm^2. Preliminary data from the CRESST Collaboration seem to support this interpretation [2], although one should await precise information on their backgrounds. Particularly strong limits on light dark matter particles are set by the Xenon10/100 experiment [29,30]. At the moment, however, due to experimental uncertainties these cannot rule out WIMPs with mass $m \lesssim 10$ GeV as an explanation for CoGeNT and CRESST (see discussion in [31]). A recent analysis [32] suggests that WIMPs with $m \simeq 7$–8 GeV and $\sigma_n \simeq (1\text{–}3) \times 10^{-40}$ cm^2 could fit the signals seen at CoGeNT, CRESST and also DAMA simultaneously.

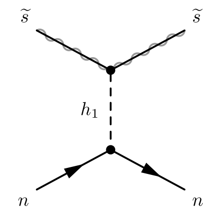

Fig. 3. Singlino nucleon elastic scattering.

We will show that the singlino discussed above may have a direct detection cross section in the range relevant for CoGeNT, CRESST and DAMA. Apart from its role in giving us the right singlino relic abundance, κ enters also the scattering cross section σ_n between singlino CDM and nucleons. This cross section is dominated by light Higgs exchange (see Fig. 3). The suppression of the h_1 quark coupling by $\sin\theta$ is compensated by the small m_{h_1} which enters the denominator of σ_n to the forth power. Exchange of heavier particles like Z or h_2 is relatively suppressed, exchange of a_s can be ignored as it is a spin-dependent interaction, and therefore does not experience the coherent enhancement of the h_1 mediated cross sections.

The cross section for h_1 exchange can be approximated by

$$\sigma_n \simeq \frac{4m_{\tilde{s}}^2 m_n^2}{\pi (m_{\tilde{s}} + m_n)^2} f_n^2 \simeq \frac{4m_n^2}{\pi} f_n^2. \quad (21)$$

Here m_n denotes the nucleon mass and f_n the effective singlino nucleon coupling which can be expressed as

$$f_n = m_n f_q \left(f_u^n + f_d^n + f_s^n + \frac{6}{27} f_G^n \right), \quad (22)$$

where f_q is the singlino quark coupling divided by the quark mass. In our model we have

$$f_q = g_{h_1 \tilde{s}\tilde{s}} \frac{\sin\theta}{\sqrt{2} v_{\text{EW}}} \frac{1}{m_{h_1}^2}. \quad (23)$$

Furthermore, f_u^n, f_d^n, f_s^n and f_G^n specify the up-, down-, strange-quark and gluon contribution to the nucleon mass which were determined in pion–nucleon scattering experiments. The cross section from [33] translates into $f_u^n \simeq 0.03$, $f_d^n \simeq 0.04$, $f_s^n \simeq 0.38$ and $f_G^n \simeq 0.55$. Note, however, that these quantities are subject to large uncertainties. Numerically we find

$$\sigma_n \sim 10^{-40}\ \text{cm}^2 \left(\frac{\kappa}{0.08}\right)^2 \left(\frac{\sin\theta}{0.03}\right)^2 \left(\frac{4\ \text{GeV}}{m_{h_1}}\right)^4. \quad (24)$$

4.3. A benchmark scenario

To illustrate our results, let us look at some benchmark values (Table 1). Due to the mass relation $m_{a_s} > m_{\tilde{s}} > m_{h_1}$ annihilation can only proceed into $h_1 h_1$ final states which was denoted by case 1 in Section 4.1. The cross section is determined by (17), from Eq. (20) it follows that the relic abundance of the singlino LSP has the appropriate value to match the observed CDM density. Eq. (24) shows that the singlino nucleon cross section is in a range where the CoGeNT, CRESST and DAMA signals can potentially be explained.

5. Conclusion

We have discussed a simple singlet extension of the MSSM in which the singlino LSP can constitute the observed cold dark matter of the universe. There is a scalar particle h_1 with mass in the few GeV region which behaves like the SM Higgs with universally reduced couplings. We have checked that the light h_1 is consistent with collider and flavor physics constraints. An important ingredient of our scenario is the h_1 singlino coupling κ, which is of the order 0.1. This facilitates efficient annihilation of singlinos into h_1 pairs, which decay further into quark and lepton pairs, such that the correct relic abundance can be obtained. The same coupling κ enters h_1 mediated interactions with nuclei, which can potentially explain the CoGeNT, CRESST and DAMA anomalies.

Our scenario will soon be tested in various experiments. Future direct detection experiments will confirm or rule out the dark matter interpretation of CoGeNT, CRESST and DAMA. Neutrino telescopes will soon reach the sensitivity where they can probe singlino annihilation in the sun, especially if a significant fraction of the annihilation products are taus. The hypothesis of a singlino LSP can be tested at the LHC. Promising signatures include the measurement of missing energy which is reduced against what one expects in the usual neutralino case. Further, the next-to-lightest superpartner may be charged, which can result in charged tracks and other interesting signatures. Finally, B factories offer the possibility to look for the light scalar h_1 in decays of Υ and B mesons.

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