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Light dark matter in the singlet-extended MSSM

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\textbf{A B S T R A C T}

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.

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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 \cite{1} and CRESST \cite{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 \cite{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 \cite{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 \cite{8, 9}, but not impossible \cite{10}, to obtain particles with the desired properties, generalized singlet extensions of the MSSM \cite{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.\footnote{This is one of the aspects in which our analysis differs from those in \cite{10, 11} where scalars with enhanced couplings to down-type fermions are considered.}

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 \cite{12}\footnote{A possible linear term in $S$ can be absorbed into the quadratic and cubic terms \cite{12}.}

$$\mathcal{W} = \mu H_u H_d + \lambda S H_u H_d + \frac{\mu_3}{2} S^2 + \frac{\kappa}{3} S^3.$$ (1)

In the so-called NMSSM the $\mu$ and $\mu_3$ terms are set to zero. On the other hand, it is well known that there are mechanisms that
explain a suppressed $\mu$ term [13,14]; such mechanisms may also
give rise to a $\mu_s$ 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 termi-
ology. A simple setting where the smallness of $\mu$ and $\mu_s$ finds
an explanation will be discussed elsewhere [16]. We include both
dimensionful parameters in our analysis. In addition the scalar po-
tential includes the following soft terms

$$V_{\text{soft}} = m_{h_u}^2 |h_u|^2 + m_{h_d}^2 |h_d|^2 + m_\nu^2 |\nu|^2$$

$$+ \left( B\mu_s h_d h_d + \lambda A_\nu s_h h_d 
+ \frac{B\mu_s}{2} s^2 + \frac{\kappa}{3} A_\kappa s^3 + \text{h.c.} \right).$$

(2)

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

The important feature of the resulting model is that all interac-
tions between the MSSM and the singlet sectors are controlled by
a single parameter $\lambda$. As we shall see, in the region where $\lambda$ is of
the order $10^{-2}$ and the singlet fields are light a simple explana-
tion 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 sup-
pressed soft terms for the singlet can be motivated in settings in
which the MSSM soft masses are dominated by the gaugino con-
tribution 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 $\lambda$.

2.1. Limit $\lambda \to 0$

All terms which mix the singlets with the MSSM contain the
parameter $\lambda$, i.e. in the case $\lambda = 0$ both sectors are completely
decoupled. The singlino mass is simply given by $m_3 = \mu_s s$, 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 $h_3$ and pseudoscalar $a_3$ through the
relation $\lambda = (h_3 + i a_3)/\sqrt{2}$, we find $m_{h_3}^2 = m_3^2 + \mu_s^2 + B\mu_s$ and
$m_{a_3}^2 = m_3^2 + \mu_s^2 - B\mu_s$. A light singlet sector can be obtained if
we assume that all mass parameters $m_{h_3}^2, m_{a_3}^2, B\mu_s \sim m^2_{\text{singlet}}$ with
$m_{\text{singlet}} \sim 10$ GeV. The following discussion is based on this
assumption.

2.2. Small $\lambda$

Switching on a small $\lambda$ 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 $\lambda \mu_{\text{eff}} v^2_{\text{EW}}/\sqrt{2}$, where
we introduced $\mu_{\text{eff}} = \mu - v_1 v_2 A_\lambda/v^2_{\text{EW}}$. Here $v_1 = (h_d), v_2 = (h_u)$
and $v^2_{\text{EW}} = v^2_1 + v^2_2 = (174$ GeV)$^2$. The linear term induces a vac-
uum expectation value $s = (s)$ which can be estimated as

$$\chi \sim \lambda \frac{v^2_{\text{EW}}}{m^2_{\text{singlet}}} \mu_{\text{eff}}.$$  

(3)

There are two competing effects, the smallness of $\lambda$ and the $m^2_{\text{singlet}}$
in the denominator, such that $\chi$ can be of the order of the elec-
troweeke scale. Note, however, that the impact of $\chi$ on the SM
Higgs masses is almost negligible. In the presence of the singlet
VEV there will be new singlet mass terms such as $\kappa s^2$ and $\kappa A_\kappa s$. There-
fore, in order to keep the singlet sector light, we assume that the
self-coupling $\kappa$ 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 $\lambda$ is
small we can treat MSSM and singlet sector separately and con-
sider 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 mix-
ing between the light MSSM Higgs $h$ and $h_1$. We further use the
minimization conditions for the Higgs potential in order to elimi-
nate the soft masses.

The mass of the singlet pseudoscalar is then given by

$$m_{a_3}^2 \simeq -2B\mu_s - \kappa x(3A_\kappa + \mu_s) - \lambda \frac{\mu_{\text{eff}}}{x} v^2_{\text{EW}}.$$  

(4)

The scalar mass matrix in the basis $(h, h_3)$ reads

$$M_H^2 = \begin{pmatrix} m_{h_3}^2 & m_{h_h}^2 \\ m_{h_h}^2 & m_{h_3}^2 \end{pmatrix}$$

with

$$m_{h_3}^2 \simeq \kappa x(A_\kappa + 4\kappa x + 3\mu_s) - \lambda \frac{\mu_{\text{eff}}}{x} v^2_{\text{EW}}.$$  

(5)

$$m_{h_h}^2 \simeq 2\lambda v^2_{\text{EW}} \mu_{\text{eff}}.$$  

(6)

and $m_{h_3}^2$ as in the usual MSSM. Note that with the assumptions
made all contribution to $m_{h_3}$ and $m_{h_3}$ are of the order of $m_{\text{singlet}}$ or
smaller, i.e. we obtain $m_{h_3}, m_{h_3} \sim m_{\text{singlet}}$. Given our assumptions,
$m_{h_3} \sim m_{\text{singlet}}$.

As $m_{h_3} \gg m_{h_h}, m_{h_3}^2$ there is little mixing between $h$ and $h_3$. The
light physical mass eigenstate is mainly singlet with a small ad-
mixture from $h_3$.

$$h_1 \simeq \cos \theta h_3 - \sin \theta h$$

(8)

with

$$\cos \theta \simeq 1,$$

$$\sin \theta \simeq \frac{m_{h_h}^2}{m_{h}^2}.$$  

(9)

(10)

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

$$m_{h_1}^2 \simeq m_{h}^2 - \frac{m_{h h}^2}{m_{h}^2}.$$  

(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

$$m_{3} = \mu_s + 2\kappa x.$$  

(12)

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

$$\mathcal{L} \supset \frac{1}{2} g_{h_1 h h_1} h_1 h_1^* - \frac{1}{2} g_{a_3 h_3 a_3} a_3 a_3^*$$

$$- \frac{1}{6} g_{h_1 h h_1} h_1^2 - \frac{1}{2} g_{a_3 a_3 h_1} a_3^2 a_3$$

(13)

\(^3\) Note that a very large $A_\lambda$ could increase the mixing between singlet and heavy
MSSM Higgs. In this regime we expect corrections to our analytic formula.

\(^4\) The possible exception of a higgsino with a mass close to $m_3$ is not considered here.
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 $e^+e^- \rightarrow Z + h_1$ which can be translated directly in limits on $\sin \theta$. 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 $\Upsilon \rightarrow \gamma + \ell^+\ell^-$ with $\ell = e, \mu$. Currently, the limits on $\sin \theta$ from $\Upsilon$ 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 $B \rightarrow h_1 + X_h$ followed by the decay $h_1 \rightarrow \mu^+\mu^-$. The branching ratio for this process can be taken from [22],

$$\text{Br}(B \rightarrow h_1 + X_h) = 0.058 \left( \frac{\sin \theta}{0.1} \right)^2 \left( 1 - \frac{m^2_{h_1}}{m^2_b} \right),$$

the branching ratio for $\text{Br}(h_1 \rightarrow \mu^+ + \mu^-)$ 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 $\text{Br}(B \rightarrow h_1 + X_h) \times \text{Br}(h_1 \rightarrow \mu^+ + \mu^-) < 2.5 \times 10^{-6}$. 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.

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 $m_{s} > m_{\tilde{s}}$, $m_{\tilde{a}}$ (see Fig. 2). It is convenient to expand the cross section in powers of the relative singlino velocity $v_{rel}$

$$\sigma v_{rel} = \sigma_0 + \sigma_1 v^2_{rel} + \mathcal{O}(v^4_{rel}).$$

As an approximation we will only consider the leading contribution to $\sigma v_{rel}$ which is the term $\sigma_0$ for a final state with one scalar and one pseudoscalar. If only final states with two scalars or two pseudoscalars are kinematically accessible $\sigma_0$ vanishes and the term $\sigma_1$ dominates. We distinguish the following three cases:

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

$$\sigma v_{rel} \approx \frac{17}{256\pi} \frac{k^4}{m^2_{\tilde{s}}} \left(1 - \frac{22}{51} \frac{A_x}{m^2_{\tilde{s}}} + \frac{1}{17} \frac{A^2_{\tilde{s}}}{m^4_{\tilde{s}}} \right) v^2_{rel}. \quad (17)$$

Case 2: $m_{h_1} + m_{\tilde{a}_i} > 2m_{\tilde{s}}$, but $m_{\tilde{a}_i} < m_{\tilde{s}}$. The dominant channel is $\tilde{s}\tilde{s} \rightarrow a_i a_i$ and

$$\sigma v_{rel} \approx \frac{9}{256\pi} \frac{k^4}{m^2_{\tilde{s}}} \left(1 - \frac{14}{27} \frac{A_x}{m^2_{\tilde{s}}} + \frac{1}{9} \frac{A^2_{\tilde{s}}}{m^4_{\tilde{s}}} \right) v^2_{rel}. \quad (18)$$

Case 3: $m_{h_1} + m_{\tilde{a}_i} < 2m_{\tilde{s}}$. The dominant channel is $\tilde{s}\tilde{s} \rightarrow h_1 a_i$ and

$$\sigma v_{rel} \approx \frac{9}{64\pi} \frac{k^4}{m^2_{\tilde{s}}} \left(1 + \frac{2}{3} \frac{A_x}{m^2_{\tilde{s}}} + \frac{1}{9} \frac{A^2_{\tilde{s}}}{m^4_{\tilde{s}}} \right) v^2_{rel}. \quad (19)$$

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

\[ g_{h_1 h_1} \approx \sqrt{2} \kappa, \]
\[ g_{h_1 h_1} \approx -i\sqrt{2} \kappa, \]
\[ g_{h_1 h_1} \approx \sqrt{2} (3m_\ell + A_x), \]
\[ g_{h_1 a_i a_i} \approx \sqrt{2} (m_\ell - A_x). \]
As GeNT Collaboration has reported an excess of low energy scat-
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. An important ingredient of our scenario is the $h_1$ singlino coupling $\kappa$, 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 $\kappa$ 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. 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 $\Upsilon$ and $B$ mesons.

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