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Full Text

Preamble

Dark Matter in the Singlet Extension of MSSM: Explanation of PAMELA and Implication on Higgs Phenomenology

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Abstract

As discussed recently by Hooper and Tait, the singlino-like dark matter in the Minimal Supersymmetric Standard Model (MSSM) extended by a singlet Higgs superfield can provide a perfect explanation for both the relic density and the PAMELA result through Sommerfeld-enhanced annihilation into singlet Higgs bosons (a or h followed by h → aa) with a being light enough to decay dominantly to muons or electrons. In this work we analyze the parameter space required by such a dark matter explanation and also consider the constraints from LEP experiments.

We find that although the light singlet Higgs bosons have small mixings with the Higgs doublets in the allowed parameter space, their couplings with the SM-like Higgs boson hSM (the lightest doublet-dominant Higgs boson) can be enhanced by the soft parameter A and, in order to meet the stringent LEP constraints, hSM tends to decay into the singlet Higgs pairs aa or hh instead of $b\bar{b}$. Consequently, the hSM produced at the LHC will give a multi-muon signal, hSM $\rightarrow$ 4 or hSM $\rightarrow$ 8 .

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INTRODUCTION

The PAMELA experiment has observed an excess of cosmic ray positrons in the energy range 10–100 GeV [1], which is difficult to explain by conventional cosmic ray sources [2]. While mundane explanations such as pulsars [3] and the acceleration of positron secondaries in cosmic ray acceleration regions [4] may exist, the dark matter interpretation [5, 6] is especially interesting since it may be related to new physics to be probed at the LHC. However, explaining the PAMELA excess through dark matter annihilations presents several challenges.

First, the dark matter must annihilate dominantly into leptons since PAMELA has observed no excess of antiprotons [1] (though as pointed out in [7], this statement may not be so robust due to significant astrophysical uncertainties associated with their propagation). Second, the explanation of the PAMELA excess requires an annihilation rate that is too large to account for the relic abundance if the dark matter is produced thermally in the early universe. To address these difficulties, a new theory of dark matter was proposed in [6]. In this theory, the Sommerfeld effect from a new force in the dark sector can greatly enhance the annihilation rate when the dark matter velocity is much smaller than the velocity at freeze-out in the early universe, and the dark matter annihilates into light particles that are kinematically allowed to decay to muons or electrons.

This elegant idea is difficult to realize in the popular Minimal Supersymmetric Standard Model (MSSM) because there is no new force in the neutralino dark matter sector to induce Sommerfeld enhancement, and neutralino dark matter annihilates largely to final states consisting of heavy quarks or gauge and/or Higgs bosons [8, 9]. However, as discussed in [10], in the extension of the MSSM by introducing a singlet Higgs superfield, the idea of [6] can be realized through singlino-like neutralino dark matter (hereafter the singlino-like neutralino is simply called singlino): (i) The singlino dark matter annihilates to pairs of light singlet Higgs bosons and the relic density can be naturally obtained from the interaction between singlino and singlet Higgs bosons; (ii) The singlet Higgs bosons, not related to electroweak symmetry breaking, can be light enough to be kinematically allowed to decay dominantly into muons or electrons through tiny mixings with the Higgs doublets; (iii) The Sommerfeld enhancement needed to explain the PAMELA result can be induced by the light singlet Higgs boson (h).

Such a dark matter explanation requires that the singlet Higgs field has very small mixing with the Higgs doublets, which might suggest that the singlino dark matter could remain hidden and irrelevant to LHC experiments. However, we note that the singlet extension of the MSSM has a quite large parameter space, and thus the coupling of the light singlet Higgs (h, a) with the doublet Higgs (the lightest one is called hSM) may be enhanced by other parameters. For example, through the soft term A S^3 (where S is the singlet Higgs field) with a large A , a pair of singlet Higgs bosons may couple sizably to a doublet Higgs boson even though the mixing between singlet and doublet Higgs fields is small. Therefore, this model may allow for exotic Higgs phenomenology at the LHC.

In this work we study the parameter space allowed by the explanation of the PAMELA result plus relic density via Sommerfeld enhancement and also consider constraints from LEP experiments. We find that although the light singlet Higgs bosons have small mixings with the Higgs doublets, their couplings with the SM-like Higgs boson (hSM) can be enhanced by the soft parameter A , and in order to meet the stringent LEP constraints, hSM tends to decay into the singlet Higgs pairs aa or hh instead of $b\bar{b}$. This implies that the hSM produced at the LHC will give a multi-muon signal, hSM $\rightarrow$ 4 or hSM $\rightarrow$ 8 .

This work is organized as follows. In Sec. II we discuss the Higgs and neutralino sectors in the singlet extension of the MSSM. In Sec. III we scan the parameter space allowed by the dark matter explanation and LEP experiments, and discuss the implications for Higgs phenomenology. Finally, a summary is given in Sec. IV.

II. HIGGS AND NEUTRALINOS IN SINGLET EXTENSION OF MSSM

The Higgs superpotential in the general singlet extension of the MSSM is given by [10]

$$W = \mu H_u H_d + \lambda S H_u H_d + \eta S + \frac{1}{3}\kappa S^3$$

where S is the singlet Higgs superfield while H_u and H_d are the doublet Higgs superfields.

The Higgs scalar potential consists of the D-term, the F-term, and the soft SUSY-breaking term. Since S is a singlet, the D-term is the same as in the MSSM. The F-term from the superpotential is given by

$$V_F = |\mu + \lambda S|^2(|H_u|^2 + |H_d|^2) + |\eta + \mu_s S + \lambda H_u H_d + \kappa S^2|^2$$

The soft SUSY-breaking terms are given by

$$V_{\rm soft} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + (B\mu H_u H_d + C\eta S + \lambda A_\lambda H_u H_d S + B_s\mu_s S^2 + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.})$$

So the Higgs potential reads

$$V = V_D + V_F + V_{\rm soft}$$

where $g^2 = (g_1^2 + g_2^2)/2$ with g_1 and g_2 being respectively the coupling constants of U(1) and SU(2) in the SM.

After the Higgs fields develop VEVs h_u, h_d, and s, i.e.,

$$H_u^0 = h_u + H_{uR} + iH_{uI}, \quad H_d^0 = h_d + H_{dR} + iH_{dI}, \quad S = s + S_R + iS_I$$

we obtain a 3×3 mass matrix for CP-even Higgs bosons, a 3×3 mass matrix for CP-odd Higgs bosons, and a 2×2 mass matrix for charged Higgs bosons:

(1) The CP-even Higgs mass matrix in the basis (H_{uR}, H_{dR}, S_R) is given by

$$\mathcal{M}_{h,11} = g^2 h_u^2 + \cot\beta[\lambda s(A_\lambda + \kappa s + \mu_s) + B\mu],$$

$$\mathcal{M}_{h,22} = g^2 h_d^2 + \tan\beta[\lambda s(A_\lambda + \kappa s + \mu_s) + B\mu],$$

$$\mathcal{M}_{h,33} = \lambda(A_\lambda + \mu_s)\frac{h_u^2 + h_d^2}{s} + \kappa s(A_\kappa + 4\kappa s + 3\mu_s),$$

$$\mathcal{M}_{h,12} = (2\lambda^2 - g^2)h_u h_d - \lambda s(A_\lambda + \kappa s + \mu_s) - \lambda h_d(A_\lambda + 2\kappa s + \mu_s),$$

$$\mathcal{M}_{h,13} = 2\lambda(\mu + \lambda s)h_u - \lambda h_d(A_\lambda + 2\kappa s + \mu_s),$$

$$\mathcal{M}_{h,23} = 2\lambda(\mu + \lambda s)h_d - \lambda h_u(A_\lambda + 2\kappa s + \mu_s),$$

where $\tan\beta = h_u/h_d$. This mass matrix can be diagonalized by a rotation with an orthogonal matrix U. The mass eigenstates are ordered as $m_{h_1} < m_{h_2} < m_{h_3}$.

In the MSSM limit ($\lambda, \eta, \mu_s, \kappa \to 0$ and $h_3 \to S_R$) the elements of the first 2×2 sub-matrix of U are related to the MSSM angle α as

$$U_{11} = \cos\alpha, \quad U_{21} = \sin\alpha, \quad U_{12} = -\sin\alpha, \quad U_{22} = \cos\alpha.$$

(2) The CP-odd Higgs mass matrix in the basis (H_{uI}, H_{dI}, S_I) is given by

$$\mathcal{M}_{a,11} = \cot\beta[\lambda s(A_\lambda + \kappa s + \mu_s) + B\mu],$$

$$\mathcal{M}_{a,22} = \tan\beta[\lambda s(A_\lambda + \kappa s + \mu_s) + B\mu],$$

$$\mathcal{M}_{a,33} = 4\lambda\kappa h_u h_d + \lambda(A_\lambda + \mu_s)\frac{h_u^2 + h_d^2}{s} + \kappa s(3A_\kappa + \mu_s) - 2B_s\mu_s,$$

$$\mathcal{M}_{a,12} = \lambda s(A_\lambda + \kappa s + \mu_s) + B\mu,$$

$$\mathcal{M}_{a,13} = \lambda h_d(A_\lambda - 2\kappa s - \mu_s),$$

$$\mathcal{M}_{a,23} = \lambda h_u(A_\lambda - 2\kappa s - \mu_s).$$

The diagonalization of this mass matrix can be performed in two steps. The first step is to rotate into a basis $(\tilde{A}, \tilde{G}, S_I)$ with $\tilde{G}$ being a massless Goldstone mode:

$$\begin{pmatrix} \tilde{G} \\ \tilde{A} \\ S_I \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta\&0 \\ -\sin\beta & \cos\beta\&0 \\ 0\&0 & 1 \end{pmatrix} \begin{pmatrix} H_{uI} \\ H_{dI} \\ S_I \end{pmatrix}$$

Dropping the Goldstone mode, the remaining 2×2 mass matrix in the basis $(\tilde{A}, S_I)$ is given by

$$\mathcal{M}'_{a,11} = (\tan\beta + \cot\beta)[\lambda s(A_\lambda + \kappa s + \mu_s) + B\mu],$$

$$\mathcal{M}'_{a,22} = 4\lambda\kappa h_u h_d + \lambda(A_\lambda + \mu_s)\frac{h_u^2 + h_d^2}{s} + \kappa s(3A_\kappa + \mu_s) - 2B_s\mu_s,$$

$$\mathcal{M}'_{a,12} = \lambda(h_u^2 + h_d^2)\frac{A_\lambda - 2\kappa s - \mu_s}{s}.$$

It can be diagonalized by an orthogonal 2×2 matrix P' and the physical CP-odd states a_i are given by (ordered as $m_{a_1} < m_{a_2}$)

$$a_1 = P'_{11}\tilde{A} + P'_{12}S_I = P'_{11}(\cos\beta H_{uI} + \sin\beta H_{dI}) + P'_{12}S_I,$$

$$a_2 = P'_{21}\tilde{A} + P'_{22}S_I = P'_{21}(\cos\beta H_{uI} + \sin\beta H_{dI}) + P'_{22}S_I.$$

(3) The charged Higgs mass matrix in the basis (H_u^+, H_d^{-*}) is given by

$$\mathcal{M}_c = \lambda s(A_\lambda + \kappa s + \mu_s) + B\mu + h_u h_d \left(\frac{g_2^2}{2} - \lambda^2\right) \begin{pmatrix} \cot\beta\&1 & \\ 1 & \tan\beta \end{pmatrix}$$

which gives one eigenstate $H^\pm$ of mass $m_{H^\pm}$ and one massless Goldstone mode $G^\pm$:

$$H_u^\pm = \cos\beta H^\pm - \sin\beta G^\pm, \quad H_d^\pm = \sin\beta H^\pm + \cos\beta G^\pm.$$

The neutralino mass matrix can be read from the Lagrangian

$$\mathcal{L} \supset M_1\lambda_1\lambda_1 + M_2\lambda_2\lambda_2 + \lambda(s)\psi_u^0\psi_d^0 + \lambda_1(h_u\psi_u^0 - h_d\psi_d^0) + \lambda_2(h_u\psi_u^0 + h_d\psi_d^0) + \frac{1}{2}(\mu + \lambda s)\psi_u^0\psi_d^0 + \frac{1}{2}(\kappa s + \mu_s)\psi_s\psi_s + \text{h.c.}$$

where λ_1 is the U(1)_Y gaugino and λ_2 is the neutral SU(2) gaugino. In the basis $\psi^0 = (\psi_d, \psi_u, \psi_s)$ we obtain

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1\&0 & -\frac{g_1 h_d}{\sqrt{2}} & \\ 0\&M_2 & \frac{g_2 h_u}{\sqrt{2}} & \\ -\frac{g_1 h_d}{\sqrt{2}} & \frac{g_2 h_u}{\sqrt{2}} & 0 \end{pmatrix} + \begin{pmatrix} 0 & -(\mu + \lambda s) & \lambda h_u \\ -(\mu + \lambda s) & 0 & \lambda h_d \\ \lambda h_u & \lambda h_d \& 2\kappa s + \mu_s & \end{pmatrix}$$

Diagonalizing this mass matrix, one obtains 5 mass eigenstates (ordered in mass) $\tilde{\chi}_i^0 = N_{ij}\psi_j^0$.

III. EXPLANATION OF PAMELA AND IMPLICATION ON HIGGS DECAYS

In our study the lightest CP-odd neutral Higgs boson a_1 is singlet-dominant, while for the CP-even neutral Higgs bosons the lightest one h_1 is singlet-dominant and the next-to-lightest h_2 is doublet-dominant. We use the notation:

$$h \equiv h_1, \quad h_{SM} \equiv h_2, \quad a \equiv a_1.$$

As discussed in [10], when the lightest neutralino $\tilde{\chi}_1^0$ in Eq.(31) is singlino-dominant, it can be a perfect candidate for dark matter. As shown in Fig.1, such singlino dark matter annihilates to a pair of light singlet Higgs bosons followed by the decay $h \to aa$ (h has very small mixing with the Higgs doublets and thus has very small couplings to fermions). In order to decay dominantly into muons, a must be light enough. Further, in order to induce the Sommerfeld enhancement, h must also be light enough. From the superpotential term $\kappa\hat{S}^3$ we know that the couplings $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $a\tilde{\chi}_1^0\tilde{\chi}_1^0$ are proportional to κ. To obtain the relic density of dark matter, κ should be $\mathcal{O}(1)$.

[Figure 1: see original paper]

FIG. 1: Feynman diagrams for singlino dark matter annihilation where Sommerfeld enhancement is induced by exchanging h.

Since h, a must be singlet-dominant and $\tilde{\chi}_1^0$ must be singlino-dominant, this implies small mixing between singlet and doublet Higgs fields. From the superpotential in Eq.(1) we see that this means the mixing parameter λ must be small enough. On the other hand, the smallness of λ is also required by the lightness of h_1 and a_1 whose masses are approximately given by

$$m_h^2 \approx \kappa s(4\kappa s + 3\mu_s + A_\kappa) - \frac{\kappa^2 s^4}{h_u^2 + h_d^2},$$

$$m_a^2 \approx \kappa s(3A_\kappa + \mu_s) - \frac{\kappa^2 s^4}{h_u^2 + h_d^2} + 2B_s\mu_s - \frac{3\kappa^2 s^4}{h_u^2 + h_d^2}.$$

In the following we scan over the parameter space. We modify the package NMSSMTools [11] and use it in our calculations. As discussed above, λ must be small enough in order to get a singlino-dominant $\tilde{\chi}_1^0$ and singlet-dominant h, a (we checked from our scan that λ must be smaller than 0.01 in order to get $m_a < 0.5$ GeV and $m_h < 20$ GeV). So in our following scan we fix $\lambda = 10^{-4}$. Further, κ is taken as 0.5, and for the squark sector the soft masses and the trilinear terms are fixed as 500 GeV. Other parameters vary in the ranges:

$$-500 \text{ GeV} < C, \mu, \mu_s, B, A_\lambda, M_1, M_2 < 500 \text{ GeV},$$

$$-(500 \text{ GeV})^2 < \eta < (500 \text{ GeV})^2, \quad s < 500 \text{ GeV}, \quad 2 < \tan\beta < 40.$$

In order to get small $\mathcal{M}_{h,33}$ and $\mathcal{M}_{a,22}$, the third terms in Eqs.(33,34), which are not suppressed by a small λ, must also be small. Therefore, in our scan we require parameters A_κ and B_s to be in the ranges:

$$\kappa s(4\kappa s + 3\mu_s + A_\kappa) \in 20 \text{ GeV} \pm (3 \text{ GeV})^2,$$

$$\kappa s(3A_\kappa + \mu_s) + 2B_s\mu_s \in \kappa s^2 \pm (3 \text{ GeV})^2.$$

In addition, we consider the following constraints: (i) Constraints from LEP experiments, including the LEP1 bound on invisible Z decay and LEP2 direct searches for Higgs bosons; (ii) $m_{a_1} < 0.5$ GeV; (iii) The singlino-like $\tilde{\chi}_1^0$ must give the dark matter relic density $\Omega_{\tilde{\chi}_1^0} h^2$ in the range 0.01–0.2, which can be calculated from the approximate formula [10]

$$\Omega_{\tilde{\chi}_1^0} h^2 \approx 0.1 \times \left(\frac{\kappa}{0.5}\right)^2 \left(\frac{200 \text{ GeV}}{M_{\tilde{\chi}_1^0}}\right)^2 .$$

To calculate the Sommerfeld enhancement we follow [6] to numerically solve the Schrödinger equation with the boundary condition $\chi(r \to \infty) = \sin(kr + \delta)$:

$$\frac{1}{M}\frac{d^2\chi}{dr^2} + V(r)\chi = k^2\chi,$$

where M and k are respectively the mass and momentum of the dark matter particle. $V(r)$ is the Yukawa potential induced by exchanging h and is given by

$$V(r) = \alpha \frac{e^{-m_h r}}{r}, \quad \alpha = \frac{\kappa^2}{4\pi}.$$

The Sommerfeld enhancement is then given by

$$S = \frac{1}{k}\left|\frac{d\chi}{dr}(0)\right|^2 .$$

The survived points are displayed in different planes in Figs.2–6. We see from Fig.2 that for $\lambda = 10^{-4}$ in the range $2m_\mu < m_a < 2m_\pi$, a decays dominantly into muons. From Fig.3 it is clear that h can be as light as a few GeV, which is light enough to induce the necessary Sommerfeld enhancement as shown in Fig.4. In the calculation of the Sommerfeld enhancement, we assumed the dark matter moves with a velocity of 150 km/s.

The fit to the PAMELA result has been given in [10]. As shown in Table I of [10], for the parameter space in Figs.2–4 with $2m_\mu < m_a < 2m_\pi$ and m_h as light as a few GeV (so the Sommerfeld enhancement factor is large enough), the PAMELA positron excess can be naturally explained.

In Fig.5 we show the branching ratios of h_{SM} decays. We see that in the allowed parameter space h_{SM} tends to decay into aa or hh instead of $b\bar{b}$. This can be understood as follows. The MSSM parameter space is stringently constrained by LEP experiments if h_{SM} is relatively light and decays dominantly to $b\bar{b}$, and to escape such stringent constraints h_{SM} tends to have exotic decays into aa or hh. As a result, the allowed parameter space tends to favor a large A_κ, as shown in Fig.6, which greatly enhances the couplings $h_{SM}aa$ and $h_{SM}hh$ through the soft term $\kappa A_\kappa S^3$ although S has a small mixing with the doublet Higgs bosons.

Such an enhancement can be easily seen. Take the coupling $h_{SM}hh$ as an example. The soft term $\kappa A_\kappa S^3$ gives a term $\kappa A_\kappa S_R^3$ which then gives the interaction $\kappa A_\kappa U_{13}^2 U_{23} h_{SM} hh$ because $S_R = U_{13}h_1 + U_{23}h_2 + U_{33}h_3$ with $h_1 \equiv h$ and

$h_2 \equiv h_{SM}$ (see Eqs.12 and 32). Although the mixing $U_{13}^2 U_{23}$ is small for a small λ, a large A_κ can enhance the coupling $h_{SM}hh$.

The SM-like Higgs boson h_{SM} will be intensively searched at the LHC and its dominant decay mode in the MSSM is $b\bar{b}$. In the singlet extension of the MSSM, its dominant decay mode may be changed to aa or hh, as shown in our results above. Such new decay modes will give a multi-muon signal for h_{SM} at the LHC, i.e., $h_{SM} \to 4\mu$ or $h_{SM} \to 8\mu$. Thus the phenomenology of h_{SM} will be quite different from the MSSM predictions.

Finally, we make some remarks regarding our results: (1) The recent D0 search for $h \to 4\mu$ or $2\mu 2\tau$ channels obtained null results, which constrained the parameter space for the CP-odd Higgs a in the mass range of 3.6–9.5 GeV [12]. However, these results do not constrain the parameter space considered in our analysis because we examine a much lighter CP-odd Higgs a with mass below 0.5 GeV. Also, as pointed out in [10], such a light a is allowed by $\Upsilon(3s) \to \gamma a \to \gamma\mu^+\mu^-$ [13] and $\Upsilon(3s) \to \pi^+\mu^+\mu^-$ [14] because in our scenario a is overwhelmingly singlet-dominated. (2) In the allowed parameter space displayed in our results, the mass of the SM-like Higgs boson h_{SM} is rather below its theoretical upper bound (about 135 GeV in the MSSM). The reason is that, in order to push up its mass, loop effects from heavy stops are needed (note that in the singlet extension the tree-level upper bound can be enhanced by a term proportional to λ, which is very small in our scenario). In our calculations the soft mass parameters in the squark sector are fixed to be 500 GeV and hence the stops are not heavy enough to push the mass of h_{SM} up to 135 GeV. Of course, we can choose heavy stops to push up the mass of h_{SM}, in which case the allowed parameter space displayed in our results (with a relatively light h_{SM} decaying dominantly into aa or hh) can still survive. (3) For specific singlet extensions like the nMSSM and NMSSM [15], the simultaneous explanation of PAMELA and relic density through Sommerfeld enhancement is not possible. The reason is that the parameter space of such models is stringently constrained by various experiments and dark matter relic density requirements [16], and as a result the neutralino dark matter may explain either the relic density or PAMELA, but cannot explain both via Sommerfeld enhancement [17]. For example, in the nMSSM various experimental constraints and dark matter relic density requirements confine the neutralino dark matter particle to a narrow mass range [16], which is too light to explain PAMELA.

IV. SUMMARY

The singlino-like dark matter in the MSSM extended by a singlet Higgs superfield can provide a perfect explanation for both the relic density and the PAMELA result through Sommerfeld-enhanced annihilation into singlet Higgs bosons (a or h followed by $h \to aa$) with a being light enough to decay dominantly to muons. In this work we analyzed the parameter space allowed by such a dark matter explanation and also considered constraints from LEP experiments. We found that although the light singlet Higgs bosons have small mixings with the Higgs doublets in the allowed parameter space, their couplings with the SM-like Higgs boson h_{SM} can be enhanced by the soft parameter A_κ, and in order to meet the stringent LEP constraints, h_{SM} tends to decay into the singlet Higgs pairs aa or hh instead of $b\bar{b}$, which will give a multi-muon signal for h_{SM} produced at the LHC: $h_{SM} \to 4\mu$ or $h_{SM} \to 8\mu$.

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