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Scalar dark matter in leptophilic two-Higgs-doublet model

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ABSTRACT

Two-Higgs-Doublet Model of Type-X in the large $\tan\beta$ limit becomes leptophilic to allow a light pseudo-scalar A and thus provides an explanation of the muon $g-2$ anomaly. Introducing a singlet scalar dark matter S in this context, one finds that two important dark matter properties, nucleonic scattering and self-annihilation, are featured separately by individual couplings of dark matter to the two Higgs doublets. While one of the two couplings is strongly constrained by direct detection experiments, the other remains free to be adjusted for the relic density mainly through the process $SS \to AA$. This leads to the 4τ final states which can be probed by galactic gamma ray detections.

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1. Introduction

The existence of dark matter (DM) is supported by various astrophysical and cosmological observations in different gravitational length scales. The best candidate for dark matter is a stable neutral particle beyond the Standard Model (SM). The simplest working model is to extend the SM by adding a singlet scalar [1,2] and thus allowing its coupling to the SM Higgs doublet which determines the microscopic properties of the dark matter particle. This idea of Higgs portal has been very popular in recent years and studied extensively by many authors [3]. However, such a simplistic scenario is tightly constrained by the current direct detection experiments since a single Higgs portal coupling determines both the thermal relic density and the DM-nucleon scattering rate.

One is then tempted to study the scalar dark matter property in popular Two-Higgs-Doublet Models (2HDMs) [4]. Having more degrees of freedom, two independent Higgs portal couplings and extra Higgs bosons, one could find a large parameter space accommodating the current experimental limits and enriching phenomenological consequences [5].

The purpose of this work is to realize a scalar singlet DM through Higgs portal in the context of a specific 2HDM which can accommodate the observed deviation of the muon $g-2$. Among four types of Z_2-symmetric 2HDMs, the type-X model is found to be a unique option for the explanation of the muon $g-2$ anomaly [6] and the relevant parameter space has been explored more precisely [7–10]. Combined with the lepton universality conditions, one can find a large parameter space allowed at 2σ favoring $\tan\beta \gtrsim 30$ and $m_A \ll m_{H,H^\pm} \approx 200$–$400$ GeV [10]. The model can be tested at the LHC by searching for a light pseudo-scalar A through 4τ or $2\mu\,2\tau$ final states [11–13].

In the large $\tan\beta$ regime, the SM-like Higgs boson reside mostly on the Higgs doublet with a large VEV. Therefore its coupling to DM is severely constrained by the direct detection experiments. On the other hand, the other Higgs doublet with a small VEV contains mostly the extra Higgs bosons, the light pseudo-scalar A, heavy neutral and charged bosons H and $H^\pm$, and thus its coupling to DM controls the thermal relic density preferably through the annihilation channel $SS \to AA$.

In Sec. 2, we describe the basic structure of the model. In Sec. 3 and 4, we discuss the consequences of DM-nucleon scattering and DM annihilation which determines the relic density as well as the indirect detection, respectively. We conclude in Sec. 5.

2. L2HDM with a scalar singlet

Introducing two Higgs doublets $\Phi_{1,2}$ and one singlet scalar S stabilized by the symmetry $S \to -S$, one can write down the following gauge invariant scalar potential:

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_1\Phi_2^\dagger)$$

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$$+\frac{\lambda_1}{2}|\Phi_1|^4+\frac{\lambda_2}{2}|\Phi_2|^4+\lambda_3|\Phi_1|^2|\Phi_2|^2+\lambda_4|\Phi_1^\dagger\Phi_2|^2$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2+(\Phi_1\Phi_2^\dagger)^2\right]$$
$$+\frac{1}{2}m_0^2S^2+\frac{\lambda_S}{4}S^4+S^2\left[\kappa_1|\Phi_1|^2+\kappa_2|\Phi_2|^2\right], \quad (1)$$

where a softly-broken Z_2 symmetry is imposed in the 2HDM sector to forbid dangerous flavor violation. The model contains four more parameters compared to the usual 2HDMs: one mass parameter m_0 and three dimensionless parameters λ_S and $\kappa_{1,2}$ for the DM self-coupling and the DM-Higgs couplings, respectively. Extending the analysis in [4], one can find the following simple relations for the vacuum stability [14]:

$$\lambda_S>0,\quad \tilde\lambda_1>0,\quad \tilde\lambda_2>0,$$
$$\tilde\lambda_3>-\sqrt{\tilde\lambda_1\tilde\lambda_2}, \quad (2)$$
$$\tilde\lambda_3+\lambda_4-|\lambda_5|>-\sqrt{\tilde\lambda_1\tilde\lambda_2}$$

where $\tilde\lambda_1\equiv\lambda_1-\kappa_1^2/2\lambda_S$, $\tilde\lambda_2\equiv\lambda_2-\kappa_2^2/2\lambda_3$, and $\tilde\lambda_3\equiv\lambda_3-\kappa_1\kappa_2/2\lambda_S$. As we will see, the desired dark matter properties require $|\kappa_{1,2}|\ll 1$ and thus the vacuum stability condition can be easily satisfied in a large parameter space.

Minimization conditions determine the vacuum expectation values $\langle\Phi^0_{1,2}\rangle\equiv v_{1,2}/\sqrt{2}$ around which the Higgs doublets are expressed as

$$\Phi_{1,2}=\left[\eta^+_{1,2},\ \frac{1}{\sqrt{2}}\left(v_{1,2}+\rho_{1,2}+i\eta^0_{1,2}\right)\right]. \quad (3)$$

Removing the Goldstone modes, there appear five massive fields denoted by $H^\pm$, A, H and h. Assuming negligible CP violation, $H^\pm$ and A are given by

$$H^\pm, A=-s_\beta\,\eta_1^{\pm,0}+c_\beta\,\eta_2^{\pm,0}, \quad (4)$$

where the angle β is determined from $t_\beta\equiv\tan\beta=v_2/v_1$. The neutral CP-even Higgs bosons are diagonalized by the angle α:

$$h=-s_\alpha\rho_1+c_\alpha\rho_2,$$
$$H=+c_\alpha\rho_1+s_\alpha\rho_2, \quad (5)$$

where h denotes the lighter (125 GeV) state.

Normalizing the Yukawa couplings of the neutral bosons to a fermion f by m_f/v where $v=\sqrt{v_1^2+v_2^2}=246$ GeV, we have the following Yukawa couplings of the Higgs bosons:

$$-\mathcal{L}_Y=\sum_{f=u,d,\ell}\frac{m_f}{v}\left(y_f^h h\bar f f+y_f^H H\bar f f-iy_f^A A\bar f\gamma_5 f\right)$$
$$+\left[\sqrt{2}V_{ud}H^+\bar u\left(\frac{m_u}{v}y_u^A P_L+\frac{m_d}{v}y_d^A P_R\right)d\right.$$
$$\left.+\sqrt{2}\frac{m_l}{v}y_\ell^A H^+\bar\nu P_R\ell+\text{h.c.}\right]. \quad (6)$$

Recall that the type-X 2HDM assigns the Z_2 symmetry under which Φ_1 and right-handed leptons are odd; and the other particles are even, and thus Φ_2 couples to all the quarks and Φ_1 to leptons.

As a consequence, one has the normalized Yukawa couplings $y_f^{h,H,A}$ given by

$y^A_{u,d}$	y^A_ℓ	$y^H_{u,d}$	y^H_ℓ	$y^h_{u,d}$	y^h_ℓ
$\pm\frac{1}{t_\beta}$	t_β	$\frac{s_\alpha}{s_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$

(7)

As the 125 GeV Higgs (h) behaves like the SM Higgs boson, we can safely take the alignment limit of $\cos(\beta-\alpha)\approx 0$ and $|y_f^h|\approx 1$ and $y_{u,d}^{A,H}\propto 1/t_\beta$ and $y_l^{A,H}\propto t_\beta$. Notice that A and H couple dominantly to the tau in the large $\tan\beta$ limit.

The singlet and doublet scalar couplings are given by

$$V=\frac{1}{2}S^2\big[2v(\kappa_h h+\kappa_H H)+\kappa_{hh}h^2+2\kappa_{hH}hH$$
$$+\kappa_{HH}H^2+\kappa_{AA}(A^2+2H^+H^-)\big],$$

where $\kappa_h=-\kappa_1 s_\alpha c_\beta+\kappa_2 c_\alpha s_\beta\approx\kappa_1 c_\beta^2+\kappa_2 s_\beta^2$,

$$\kappa_H=+\kappa_1 c_\alpha c_\beta+\kappa_2 s_\alpha s_\beta\approx(\kappa_1-\kappa_2)c_\beta s_\beta.$$
$$\kappa_{hh}=\kappa_1 s_\alpha^2+\kappa_2 c_\alpha^2\approx\kappa_1 c_\beta^2+\kappa_2 s_\beta^2,$$
$$\kappa_{hH}=-(\kappa_1-\kappa_2)c_\alpha s_\alpha\approx(\kappa_1-\kappa_2)c_\beta s_\beta,$$
$$\kappa_{HH}=\kappa_1 c_\alpha^2+\kappa_2 s_\alpha^2\approx\kappa_1 s_\beta^2+\kappa_2 c_\beta^2,$$
$$\kappa_{AA}=\kappa_1 s_\beta^2+\kappa_2 c_\beta^2, \quad (8)$$

which shows interesting relations in the alignment limit: $\kappa_h\approx\kappa_{hh}$, $\kappa_H\approx\kappa_{hH}$, and $\kappa_{HH}\approx\kappa_{AA}$. Furthermore, one finds further simplification: $\kappa_{h,hh}\sim\kappa_2$, $\kappa_{H,hH}\sim 0$, and $\kappa_{AA,HH}\sim\kappa_1$ neglecting small contributions suppressed by $1/t_\beta$. This behavior determines the major characteristic of the model.

Before starting our main discussions, let us make a few comments on the LHC probe of the model. As shown in Eq. (7), the extra Higgs couplings to quarks are proportional to $1/t_\beta$ and thus their single production is suppressed by $1/t_\beta^2$ compared to the SM Higgs production. For this reason a light A (and H) is still allowed by the direct search of di-tau final state at ATLAS [15] in the large $\tan\beta$ limit, which also explains the muon $g-2$ anomaly. One can also look for usual electroweak productions of $pp\to HA, H^\pm A$, ending up with multi-tau signals [11], or the SM Higgs production and its exotic decay $h\to AA$ [13]. The $pp\to HA$ process is of particular interest in the model under consideration as it could lead to a promising signature of di-tau associated with large missing energy. Having $\kappa_H\propto 1/t_\beta$, however, the $H\to SS$ process (when allowed kinematically) is highly suppressed in the large $\tan\beta$ limit and thus hardly be probed at the LHC. The recent bounds on the multi-tau events searched by ATLAS in the case of the chargino/neutralino production [16] could be relevant for our model parameter space. Applying the same cuts, e.g., $\not{p}_T>150$ GeV and $p_T^{\tau_1,\tau_2}>50, 40$ GeV, to our processes, we find that no events survive for the final states searched in Ref. [16]. This is basically due to the following differences: (i) the $H^\pm A$ and HA production cross-sections are smaller than the chargino/neutralino production by almost one order of magnitude; (ii) our processes do not generate large missing energy, and τ's coming from a light A become too soft to pass the above hard cuts as indicated in Ref. [11]. We have also checked the recent bounds on $2\ell/3\ell+\not{p}_T$ final states with kinematic demands: $p_T^\ell\geq 20, 30$ GeV and $\not{p}_T\geq 130, 150$ GeV, etc. [17]. However, in the given parameter space we have the following branching fraction $\mathcal{B}(H\to AZ)\sim 68\%$, $\mathcal{B}(H\to\tau\tau)\sim 32\%$ and $\mathcal{B}(A\to\tau\tau)\sim 99\%$. The charged Higgs also dominantly decays to $AW^\pm$ ($\sim 70\%$), which makes all the dominant production modes, i.e. HA, $HH^\pm$ and $H^\pm A$, insensitive to the search of multi-lepton plus large missing energy final states. Thus the recent bounds on the multi-lepton plus missing energy events motivated to probe supersymmetric signals [17] can easily be evaded.

3. DM-nucleon scattering

The spin-independent (SI) nucleonic cross section of the DM is given by

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