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Effective interaction of electroweak-interacting dark matter with Higgs boson and its phenomenology

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ABSTRACT

We study phenomenology of electroweak-interacting fermionic dark matter (DM) with a mass of $\mathcal{O}(100)$ GeV. Constructing the effective Lagrangian that describes the interactions between the Higgs boson and the $SU(2)_L$ isospin multiplet fermion, we evaluate the electric dipole moment (EDM) of electron, the signal strength of Higgs boson decay to two photons and the spin-independent elastic-scattering cross section with proton. As representative cases, we consider the $SU(2)_L$ triplet fermions with zero/nonzero hypercharges and $SU(2)_L$ doublet fermion. It is found that the electron EDM gives stringent constraints on those model parameter spaces. In the cases of the triplet fermion with zero hypercharge and the doublet fermion, the Higgs signal strength does not deviate from the standard model prediction by more than a few % once the current DM direct detection constraint is taken into account, even if the CP violation is suppressed. On the contrary, $\mathcal{O}(10\text{–}20)$% deviation may occur in the case of the triplet fermion with nonzero hypercharge. Our representative scenarios may be tested by the future experiments.

1. Introduction

Nature of the dark matter (DM) in the Universe is one of the longstanding problems in both particle physics and cosmology. The DM abundance observed today is [1]

$$\Omega_{\mathrm{CDM}} h^2 = 0.1198 \pm 0.0026, \tag{1}$$

where h denotes the reduced Hubble constant. Much attention has been paid to Weakly-Interacting Massive particles (WIMPs) as the candidates for the DM since it is the natural consequence of physics at the TeV scale where the next physics threshold is expected to show up based on the naturalness argument.

Among the various DM scenarios, one of the simplest ones is that the DM particles are coupled to the standard model (SM) particles only through $SU(2)_L \times U(1)_Y$ gauge interactions. (For earlier studies, see, *e.g.*, [2–4].) In those cases, it is known that the DM particle mass would be completely fixed if the thermal relic explains the DM abundance in Eq. (1). For example, the mass of a fermionic DM that belongs to the $SU(2)_L$ doublet (triplet) with hypercharge $Y = 0$ should be about 1 (3) TeV. Those dark matter particles are realized in the supersymmetric (SUSY) standard model as Higgsino (Wino). In the non-thermal relic scenarios, on the other hand, the DM relic abundance could be satisfied as a result of a non-thermal production of the DM from late decay of some heavy particles such as gravitinos in SUSY models. In such a case, the DM particles do not necessarily have the multi-TeV scale mass, and they could be as light as $\mathcal{O}(100)$ GeV. If so, in addition to the standard DM searches, we may find DM signals indirectly in the collider or low energy experiments, even if they are not directly found.

In this Letter, we study the electroweak-interacting fermionic DM particles with the mass of $\mathcal{O}(100)$ GeV, and discuss their phenomenological consequences in a bottom-up approach. The interactions between the $SU(2)_L$ isospin multiplets and the Higgs boson are described by dimension-five operators. Such effective interactions violate CP symmetry generically, and thus CP-violating observables such as the electric dipole moments (EDMs) of electron, neutron and atoms are predicted. In addition, the effective interactions induce the spin-independent (SI) DM-nucleon elastic-scattering cross section and the Higgs boson decay to diphoton. In this paper we evaluate the electron EDM, the SI DM-nucleon cross

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section and the Higgs signal strength for the Higgs boson decay to diphoton mode, and confront them with current experimental data. Future prospects are also discussed.

2. Models

In this section, we will describe the effective couplings of the fermionic DM particles with the Higgs boson. Now we assume that the DM particle χ_0 is a fermion with the $SU(2)_L \times U(1)_Y$ gauge charges. The effective Higgs couplings depend on whether χ_0 has the $U(1)_Y$ interaction.

First, let us consider the case that χ_0 does not have the $U(1)_Y$ interaction ($Y = 0$). In this case χ_0 is a neutral component of an isospin-n multiplet χ_i ($i = -n, -n+1, \ldots, +n$) with n integer. We assume for simplicity that χ_i are chiral fermions ($\chi_i = P_L \chi_i$). The gauge interactions and the gauge-invariant mass term are

$$\mathcal{L} = \bar{\chi} i\not{D} \chi - \frac{1}{2} M \left(\bar{\chi^c} \chi + \text{h.c.} \right), \tag{2}$$

where $D_\mu = \partial_\mu + ig/\sqrt{2}(T_+ W_\mu^\dagger + T_- W_\mu) + ig_Z(T_3 - Q s_W^2) Z_\mu + ieQA_\mu$ with $Q = T_3 + Y$. Here, $(T_\pm)_{jk} (\equiv T_1 \pm iT_2) = \sqrt{n(n+1) - k(k \pm 1)} \delta_{j,k\pm1}$, $(T_3)_{jk} = k\delta_{jk}$, and $\bar{\chi^c}\chi = -\sum_{i=-n}^{n} (-1)^{i-1} \chi_i C \chi_{-i}$. The DM particle χ_0 has the Majorana mass term while other particles with non-zero electric charges j ($\neq 0$) have Dirac ones. We take M real positive in the following.

The DM particle does not have renormalizable interactions with the $SU(2)_L$ doublet Higgs boson H, since it is assumed to be a fermion. Now we take the hypercharge for the Higgs boson 1/2. The interactions are given with higher-dimensional ones, which are induced though integration of heavy particles. The dimension-five operators are

$$\mathcal{L}_H = -\frac{1}{2\Lambda} |H|^2 \bar{\chi^c} (1 + i\gamma_5 f) \chi + \text{h.c.} \tag{3}$$

Here, only the isoscalar couplings appear at the dimension five. While bilinears of isospin-n multiplets include an $SU(2)_L$ adjoint representation, it is antisymmetric if n integer. Those effective interactions are induced, for example, by integration of $SU(2)_L$ $(n \pm 1/2)$-multiplet heavy fermions with hypercharge $Y = \pm 1/2$ at the tree level. In the Wino case, the effective interaction with Higgs boson is generated by integration of the Higgsinos. In this paper, we do not adopt such concrete UV models and we take a bottom-up approach as mentioned above.

The effective couplings with the Higgs boson contribute to the masses for χ_i after the Higgs field gets the vacuum expectation value ($H = (0, v)^T$) as

$$M_{\text{phys}}^2 = M_R^2 + M_I^2, \tag{4}$$

where

$$M_R = M + \frac{v^2}{\Lambda}, \qquad M_I = f \frac{v^2}{\Lambda}. \tag{5}$$

The masses for χ_i are degenerate at the tree level. However, it is known that the electroweak corrections make their masses different so that χ_0 is the lightest. The mass difference between χ_j and χ_{j-1}, $\Delta M_{j,j-1}$, is[1]

$$\Delta M_{j,j-1} = \frac{\alpha_2}{4\pi} (2j - 1) \left(f(x_W) - c_W^2 f(x_Z) - s_W^2 f(0) \right) M_{\text{phys}}, \tag{6}$$

where

$$f(z) = \int_0^1 dx (2x + 2) \log\left(x^2 + (1 - x)z\right). \tag{7}$$

Here, $x_W = m_W^2/M_{\text{phys}}^2$ and $x_Z = m_Z^2/M_{\text{phys}}^2$, and α_2 is for the $SU(2)_L$ gauge coupling constant, and s_W ($= \sin\theta_W$) and c_W ($= \cos\theta_W$) are for the Weinberg angle θ_W. When 200 GeV $\lesssim M_{\text{phys}} \lesssim$ 3000 GeV, $\Delta M_{j,j-1} \simeq (2j - 1) \times$ (167–174) MeV.

Next, we present the case χ_0 has the $U(1)_Y$ interaction. In this case, χ_0 comes from Dirac fermions of an isospin-n multiplet, ψ_i ($i = -n, -n+1, \ldots, +n$). The gauge interactions and the gauge-invariant mass term are

$$\mathcal{L} = \bar{\psi} i\not{D} \psi - M \bar{\psi} \psi, \tag{8}$$

and the effective interactions of ψ and the Higgs boson are given up to dimension five as

$$\mathcal{L}_H = -\frac{1}{\Lambda_1} |H|^2 \, \bar{\psi} (1 + i\gamma_5 f_1) \psi - \frac{1}{\Lambda_2} H^\dagger T_a H \bar{\psi} (1 + i\gamma_5 f_2) T_a \psi. \tag{9}$$

In this case, the isovector couplings are also allowed. The physical masses for ψ_i receive the corrections from the effective interaction after the electroweak symmetry breaking as

$$M_{\text{phys}}^{(i)2} = M_R^{(i)2} + M_I^{(i)2}, \tag{10}$$

where

$$M_R^{(i)} = M + \frac{v^2}{\Lambda_1} - \frac{1}{2} (T_3)_{ii} \frac{v^2}{\Lambda_2}, \tag{11}$$

$$M_I^{(i)} = f_1 \frac{v^2}{\Lambda_1} - \frac{1}{2} (T_3)_{ii} f_2 \frac{v^2}{\Lambda_2}. \tag{12}$$

When the first term in Eq. (9) gives common corrections to the masses, the second term induces mass splitting among the components of multiplet. We take Λ_2 real without loss of generality and assume it positive for simplicity. The components with larger T_3 are lighter if the CP-violating coupling constant f_2 is negligible. Thus, the lightest state is ψ_n, and we have to take $Y = -n$ so that the lightest state is neutral. On the other hand, if the second term in Eq. (9) is negligible, the masses are degenerate up to the radiative corrections. In the case, the mass difference between particles with electric charges Q and $Q - 1$, $\Delta M_{Q,Q-1}$, is given as

$$\begin{aligned} \Delta M_{Q,Q-1} = & \frac{\alpha_2}{4\pi} (2Q - 1) \left(f(x_W) - c_W^2 f(x_Z) - s_W^2 f(0) \right) M_{\text{phys}} \\ & + \frac{\alpha_2}{4\pi} 2Y \left(f(x_Z) - f(x_W) \right) M_{\text{phys}}, \end{aligned} \tag{13}$$

and then $\Delta M_{Q,Q-1} \simeq (2Q - 1) \times$ (167–174) MeV $+ \, Y \times$ (262–357) MeV for 200 GeV $\lesssim M_{\text{phys}} \lesssim$ 3000 GeV. Thus, the neutral fermion is the lightest only when $Y = \pm n$, unless the tree- and loop-level contributions to the mass of the neutral fermion cancel each others accidentally.

Null results of the DM direct detection give a stringent constraint on the vector coupling of the dark matter particles. Thus, the DM particle has to be a Majorana fermion in order to forbid the vector current interaction. Now let us consider the case of $Y = -n$. The neutral component ψ_n with $T_3 = n$ is decomposed into the Majorana fermions (χ_0 and χ_0') as

$$\psi_n = \chi_0 + i\chi_0', \tag{14}$$

and they should not be degenerate in mass, so that the DM direct detection is suppressed. Such mass splitting is generated by the following fermion-number violating interaction,

[1] The mass difference for $n = 1$ is derived in Ref. [5].