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Vector WIMP miracle

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ABSTRACT

Weakly interacting massive particle (WIMP) is well known to be a good candidate for dark matter, and it is also predicted by many new physics models beyond the standard model at the TeV scale. We found that, if the WIMP is a vector particle (spin-one particle) which is associated with some gauge symmetry broken at the TeV scale, the Higgs mass is often predicted to be 120–125 GeV, which is very consistent with the result of Higgs searches recently reported by ATLAS and CMS Collaborations at the Large Hadron Collider experiment. In this Letter, we consider the vector WIMP using a non-linear sigma model in order to confirm this result as general as possible in a bottom-up approach. Near-future prospects to detect the vector WIMP at both direct and indirect detection experiments of dark matter are also discussed.

1. Introduction

There are many compelling evidences for the existence of dark matter in our universe, and many experimental efforts are presently devoted to detect the dark matter directly and indirectly [1]. On the other hand, because the detailed nature of the dark matter is not revealed yet, many dark matter candidates have been proposed so far from the viewpoint of new physics beyond the standard model (SM) at the TeV scale. Among those, the weakly interacting massive particle (WIMP), whose mass is postulated to be 10–1000 GeV, is known to be a good candidate for dark matter, because it can easily satisfy all constraints imposed by cosmological and astrophysical dark matter experiments and naturally explain the dark matter abundance observed today [2]. In this Letter, we especially focus on the vector (spin-one) WIMP which is associated with some gauge symmetry broken at the TeV scale. Since the vector particle acquires its mass from the symmetry breaking, the mass is predicted to be 100–1000 GeV, which is very consistent with the WIMP hypothesis.

The simplest model of the vector WIMP dark matter is described based on $\mathrm{SU}(2)_L \times \mathrm{U}(1)_1 \times \mathrm{U}(1)_2$ gauge symmetry. In order to guarantee the stability of the dark matter, the Z_2 symmetry is also imposed by postulating that the Lagrangian of the model is invariant under the exchange of $\mathrm{U}(1)_1$ and $\mathrm{U}(1)_2$ gauge interactions. The $\mathrm{U}(1)_1 \times \mathrm{U}(1)_2$ symmetry is assumed to be broken at the TeV scale into the diagonal U(1), which is identified with the SM gauge interaction of $\mathrm{U}(1)_Y$. This fact means that the dark matter particle is provided as the partner of the hyper-charge gauge boson. As will be discussed in Section 2, the strength of the coupling between two Higgs bosons and two dark matter particles is definitely given by $(g')^2/4$ with g' being the $\mathrm{U}(1)_Y$ gauge coupling.[1] This simplest model is embedded in several realistic models for the new physics predicting the vector WIMP such as universal extra-dimension models [3] and little Higgs models with T-parity [4].

When no other new particles, which could be predicted in the new physics at the TeV scale, are degenerated in mass to the vector WIMP dark matter, the annihilation of the dark matter is governed by the process into $W(Z)$ boson pair through the s-channel exchange of the Higgs boson. Its annihilation cross section and, as a result, the thermal relic abundance of the dark matter therefore depend only on the masses of dark matter and Higgs boson. The abundance turns out to be consistent with the WMAP observation when the Higgs mass is within the range of 120–125 GeV as will be shown in Section 3, which is very attractive from the viewpoint of the result of Higgs searches recently reported by ATLAS and CMS Collaborations at the Large Hadron Collider (LHC) experiment [6]. Interestingly, this result is insensitive to the dark matter mass (m_{DM}) as long as $m_{\mathrm{DM}} \sim 100$ GeV. According to this result, we also discuss future prospects to discover the vector WIMP in direct and indirect detection experiments of dark matter in this

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[1] Opposite directions that reconcile the WMAP region with the LHC excess by adjusting the interactions between the Higgs boson and vector dark matter have been discussed in Higgs-portal dark matter models [5].

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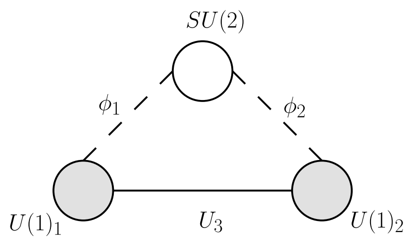

Fig. 1. The structure of the $SU(2)_L \times U(1)_1 \times U(1)_2$ model for the vector WIMP dark matter expressed by using the moose notation. See the text for more details.

section. We found that the signal of the dark matter can be discovered at both experiments in the near future.

2. Simplest model for the vector WIMP

We consider the simplest model for the vector WIMP dark matter in this section, which is described based on the $SU(2)_L \times U(1)_1 \times U(1)_2$ gauge theory in its electroweak sector. The structure of the gauge-Higgs sector in this model involving symmetries and their breaking patterns is schematically expressed by using the 'moose' notation [7] as shown in Fig 1, where the white circle stands for the SM $SU(2)_L$ gauge symmetry, while black ones are U(1) gauge symmetries ($U(1)_1$ and $U(1)_2$). On the other hand, the solid line represents the non-linear sigma field, $U_3 \equiv \exp(i\pi_3/v_3)$, and broken lines are linear sigma fields, namely, Higgs fields denoted by ϕ_1 and ϕ_2. All of non-linear sigma and Higgs fields spontaneously break the symmetries connected to them into their diagonal ones. In order to guarantee the stability of the vector WIMP, the Z_2 symmetry is imposed by postulating that the model is invariant under the exchange of $U(1)_1$ and $U(1)_2$ gauge interactions, which can be expressed by the symmetry under the left–right reflection of the diagram in Fig 1: $\phi_1 \to \phi_2$, $\phi_2 \to \phi_1$, and $U_3 \to U_3^*$. Both gauge couplings of $U(1)_1$ and $U(1)_2$ interactions as well as vacuum expectation values (VEVs) of two Higgs fields ϕ_1 and ϕ_2 are therefore taking the same value.

With the use of the diagram shown in Fig 1, the Lagrangian (kinetic terms) of non-linear sigma and Higgs fields (U_3, ϕ_1, and ϕ_2) are given as follows:

$$\mathcal{L}_{\text{higgs}} = \left(D_\mu \phi_1^\dagger D^\mu \phi_1\right) + \left(D_\mu \phi_2^\dagger D^\mu \phi_2\right) + \frac{v_3^2}{2}\left(D_\mu U_3^\dagger D^\mu U_3\right) - V(\phi_1, \phi_2, U_3), \tag{1}$$

where the Higgs field ϕ_i ($i = 1, 2$) is decomposed to be $\phi_i = (v_i + h_i + i\tau^a\pi_i^a) \cdot (0, 1)^T/\sqrt{2}$ with τ^a and v_i being the Pauli matrix and the VEV of the Higgs field, respectively. The Higgs potential is simply denoted by $V(\phi_1, \phi_2, U_3)$. The covariant derivatives of the non-linear sigma field and Higgs fields are defined by following equations:

$$D_\mu \phi_i = \partial_\mu \phi_i + ig\left(\tau^a/2\right)W_\mu^a \phi_i + i\left(g_i'/2\right)B_\mu^{(i)}\phi_i, \tag{2}$$

$$D_\mu U_3 = \partial_\mu U_3 + i(Y_3/4)g_1' B_\mu^{(1)} U_3 - i(Y_3/4)g_2' B_\mu^{(2)} U_3, \tag{3}$$

where W_μ^a and $B_\mu^{(i)}$ are $SU(2)_L$ and $U(1)_i$ gauge fields, respectively. Because of the Z_2 symmetry, we take $g_1' = g_2'$ as well as $v_1 = v_2$ later, where the gauge coupling $g_1' = g_2'$ relates to that of the SM $U(1)_Y$. The $U(1)_1$ and $U(1)_2$ charges of the non-linear sigma field U_3 are set to be $Y_3/4$ and $-Y_3/4$, respectively, in order to have the Z_2 symmetry, which makes π_3 an Z_2 odd particle (would-be NG boson).

As can be seen from the Lagrangian, the model has five gauge bosons and seven NG bosons. Four NG bosons are eaten and the gauge bosons except photon become massive. The rest of three NG bosons become pseudo-NG bosons, because we can write down gauge-invariant mass terms such as $(\phi_1^\dagger\phi_2)(U_3)^{2/Y_3}$ which is naturally involved in the Higgs potential $V(\phi_1, \phi_2, U_3)$. There are five particles which are odd under the Z_2 parity; a linear combinations of the U(1) gauge fields $(B^{(1)} - B^{(2)})/\sqrt{2}$ which is nothing but the vector WIMP, a linear combination of the Higgs fields $(h_1 - h_2)/\sqrt{2}$, and three linear combinations of the pseudo-NG bosons. The later four scalars acquire their masses through the Higgs potential, so that they can be heavy enough compared to the vector WIMP. We therefore concentrate on the vector WIMP and other particles which are even under the Z_2 symmetry in following discussions. Mass matrices of the gauge bosons are eventually summarized as follows:

$$\frac{g^2v^2}{4}W_\mu^+W^{-\mu} + \frac{v^2}{8}\begin{pmatrix} W_\mu^3 & B_\mu \end{pmatrix}\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} + \frac{g'^2}{8}\left(v^2 + Y_3^2 v_3^2\right)V_\mu V^\mu, \tag{4}$$

where $v \equiv \sqrt{2}v_1 = \sqrt{2}v_2$ and $g' \equiv g_1'/\sqrt{2} = g_2'/\sqrt{2}$, while $W_\mu^\pm = (W_\mu^1 \mp iW_\mu^2)/\sqrt{2}$, $B_\mu \equiv (B_\mu^{(1)} + B_\mu^{(2)})/\sqrt{2}$, and $V_\mu \equiv (B_\mu^{(1)} - B_\mu^{(2)})/\sqrt{2}$. With the use of the Weinberg angle defined by $\sin\theta_W \equiv s_W^2 = g'^2/(g^2 + g'^2)$ ($\cos\theta_W = c_W^2 = 1 - s_W^2$) and the Z boson mass m_Z, the mass of the vector WIMP dark matter is expressed by

$$m_{\text{DM}} \equiv m_Z s_W \sqrt{1 + Y_3^2 v_3^2/v^2} \simeq 178\ \text{GeV}(Y_2 v_3/1\ \text{TeV}). \tag{5}$$

It can be seen that the mass of the vector WIMP dark matter is O(100) GeV when the breaking scale associated with $U(1)_1 \times U(1)_2 \to U(1)_Y$ is the TeV scale.

We consider interactions between Higgs boson and vector WIMP dark matter, which are the most important interactions to discuss phenomenology of the dark matter, as will be seen in the next section. Kinetic terms of the Higgs bosons ϕ_1 and ϕ_2 involve following gauge interactions:

$$\left[\frac{1}{2}(v_1 + h_1)^2 + \frac{1}{2}(v_1 + h_2)^2\right]\frac{g'^2}{4}V_\mu V^\mu = \frac{g'^2}{8}V_\mu V^\mu h^2 + \frac{g'^2 v}{4}V_\mu V^\mu h + \cdots, \tag{6}$$

where $h \equiv (h_1 + h_2)/\sqrt{2}$. This scalar particle is identified with the SM-like Higgs boson, because it is the only Z_2-even scalar which remains as a physical state. It is very important to notice that the interactions between Higgs boson and vector WIMP are governed by the gauge coupling of the SM $U(1)_Y$ interaction.

Before closing this section, we mention the fermion sector for the sake of completeness although the structure of fermions does not affect the properties of the vector WIMP dark matter, which are discussed in the subsequent sections. The assignment of the $SU(2)_L \times U(1)_1 \times U(1)_2$ quantum numbers for the left-handed quark q_L, right-handed up-type quark u_R and right-handed down-type quark d_R is given in Table 1. It is clear from this expression that the quark fields are Z_2-invariant. The SM quark mass terms stem from the following Z_2-invariant Yukawa interactions:

Table 1
Quantum numbers for the quark sector.

	$SU(2)_L$	$U(1)_1$	$U(1)_2$
q_L	**2**	1/12	1/12
u_R	**1**	1/3	1/3
d_R	**1**	−1/6	−1/6