Can WIMP Dark Matter Overcome the Nightmare Scenario?

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Even if new physics beyond the standard model indeed exists, the energy scale of new physics might be beyond the reach at the Large Hadron Collider (LHC), and the LHC could find only the Higgs boson but nothing else. This is the so-called ''nightmare scenario.'' On the other hand, the existence of the dark matter has been established from various observations. One of the promising candidates for thermal relic dark matter is a stable and electric charge-neutral weakly interacting massive particle (WIMP) with mass below the TeV scale. In the nightmare scenario, we introduce a WIMP dark matter singlet under the standard model gauge group, which only couples to the Higgs doublet at the lowest order, and investigate the possibility that such WIMP dark matter can be a clue to overcome the nightmare scenario via various phenomenological tests such as the dark matter relic abundance, the direct detection experiments for the dark matter particle, and the production of the dark matter particle at the LHC.

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I. INTRODUCTION

In spite of the tremendous success of the standard model (SM) of particle physics, it is widely believed that new physics beyond the SM should appear at a certain high energy scale. The main theoretical insight on this belief is based on the hierarchy problem in the SM. In other words, the electroweak scale is unstable against quantum corrections and is, in turn, quite sensitive to the ultraviolet energy scale, which is naturally taken to be the scale of new physic beyond the SM. Therefore, in order for the SM to be naturally realized as a low energy effective theory, the scale of new physics should not be far beyond the TeV scale and the most likely at the TeV scale.

After the recent success of the first collision of protons at the Large Hadron Collider (LHC) with the center of energy 7 TeV, the LHC is now taking data to explore particle physics at the TeV scale. The discovery of new physics at the TeV scale as well as the Higgs boson which is the last particle in the SM to be directly observed is the most important mission of the LHC. New physics beyond the SM, once discovered, will trigger a revolution in particle physics.

However, it is generally possible that even if new physics beyond the SM indeed exists, the energy scale of new physics might be beyond the LHC reach and that the LHC could find only the Higgs boson but nothing else. This is the so-called ''nightmare scenario''. The electroweak precision measurements at the LEP may support this scenario. The LEP experiment has established excellent agreements of the SM with results and has provided very severe constraints on new physics dynamics. We consider some of nonrenormalizable operators invariant under the SM gauge group as effective operators obtained by integrating out some new physics effects, where the scale of new physics is characterized by a cutoff scale of the operators. It has been shown [1] that the lower bound on the cutoff scale given by the results of the LEP experiment is close to 10 TeV rather than 1 TeV. This fact is the so-called ''LEP paradox.'' If such higher dimensional operators are from tree level effects of new physics, the scale of new physics lies around 10 TeV, beyond the reach of the LHC. As the scale of new physics becomes higher, the naturalness of the SM gets violated. However, for the 10 TeV scale, the fine-tuning required to realize the correct electroweak scale is not so significant but about a few percent level [2]. Such little hierarchy may be realized in nature.

On the other hand, recent various cosmological observa tions, in particular, the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [3], have established the ΛCDM cosmological model with a great accuracy. The relic abundance of the cold dark matter at 2σ level is measured as

$$\Omega_{\rm CDM} h^2 = 0.1131 \pm 0.0034. \tag{1}$$

To clarify the nature of the dark matter is still a prime open problem in particle physics and cosmology. Since the SM has no suitable candidate for the cold dark matter, the observation of the dark matter indicate new physics beyond the SM. Many candidates for dark matter have been proposed in various new physics models.

Among several possibilities, the weakly interacting massive particle (WIMP) is one of the most promising candidates for dark matter and in this case, the dark matter in the present Universe is the thermal relic and its relic abundance is insensitive to the history of the early Universe before the freeze-out time of the dark matter particle, such as the mechanism of reheating after inflation etc. This scenario allows us to evaluate the dark matter relic density

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by solving the Boltzmann equation, and we arrive at a very interesting conclusion: in order to obtain the right relic abundance, the WIMP dark matter mass lies below the TeV. Therefore, even if the nightmare scenario is realized, it is plausible that the mass scale of the WIMP dark matter is accessible to the LHC.[1]

In this paper, we extend the SM by introducing the WIMP dark matter in the context of the nightmare scenario, and investigate a possibility that the WIMP dark matter can overcome the nightmare scenario through various phenomenology such as the dark matter relic abundance, the direct detection experiments for the dark matter particle, and LHC physics. Among many possibilities, we consider the "worst case" that the WIMP dark matter is singlet under the SM gauge group, otherwise the WIMP dark matter can be easily observed through its coupling with the weak gauge boson. In this setup, the WIMP dark matter communicates with the SM particles through its coupling with the Higgs boson, so that the Higgs boson plays a crucial role in phenomenology of dark matter.

The paper is organized as follows: In the next section, we introduce the WIMP dark matter which is singlet under the SM gauge group. We consider three different cases for the dark matter particle; a scalar, fermion and vector dark matter, respectively. In Sec. III, we investigate cosmological aspects of the WIMP dark matter and identify a parameter region which is consistent with the WMAP observation and the direct detection measurements for the WIMP dark matter. The collider signal of the dark matter particle is explored in Sec. IV. The dark matter particles are produced at the LHC associated with the Higgs boson production. The last section is devoted to summary and discussions.

II. THE MODEL

Since all new particles except a WIMP dark matter are supposed to be at the scale of 10 TeV in the nightmare scenario, the effective Lagrangian at the scale of 1 TeV involves only a field of the WIMP dark matter and those of the SM particles. We consider the worst case of the WIMP dark matter, namely, the dark matter is assumed to be singlet under gauge symmetries of the SM. Otherwise, the WIMP dark matter accompanies a charged partner with mass at the scale less than 1 TeV. In a future collider such as the International Linear Collider and the Compact Linear Collider, the charged partner can be produced through photon and Z-boson exchange processes. If the mass difference between the WIMP dark matter and its charged partner is large enough, the charged partner would be easily detected, and such a scenario is not nightmare (see, however, [4]). We postulate the global Z_2 symmetry (parity) in order to guarantee the stability of the dark matter, where the WIMP dark matter has odd charge while particles in the SM have even one. We consider three cases for the spin of the dark matter; the scalar dark matter ϕ, the fermion dark matter χ, and the vector dark matter V_μ. In all cases, the dark matter is assumed to be an identical particle for simplicity, so that these are described by real Klein-Gordon, Majorana, and real Proca fields, respectively.

The Lagrangian which is invariant under the symmetries of the SM is written as

$$\mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial\phi)^2 - \frac{M_S^2}{2}\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{d_S}{4!}\phi^4, \quad (2)$$

$$\mathcal{L}_F = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - M_F)\chi - \frac{c_F}{2\Lambda}|H|^2\bar{\chi}\chi - \frac{d_F}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}, \quad (3)$$

$$\mathcal{L}_V = \mathcal{L}_{\rm SM} - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{M_V^2}{2}V_\mu V^\mu + \frac{c_V}{2}|H|^2 V_\mu V^\mu - \frac{d_V}{4!}(V_\mu V^\mu)^2, \quad (4)$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $B_{\mu\nu}$ is the field strength tensor of the hypercharge gauge boson, and $\mathcal{L}_{\rm SM}$ is the Lagrangian of the SM with H being the Higgs boson. The last terms in the right-hand side (RHS) in Eqs. (2) and (4) proportional to coefficients d_S and d_V represent self-interactions of the WIMP dark matter, which are not relevant for the following discussion. On the other hand, the last term in RHS in Eq. (3) proportional to the coefficient d_F is the interaction between WIMP dark matter and the hypercharge gauge boson, however this term is most likely obtained by 1-loop diagrams of new physics dynamics at the scale of 10 TeV, since the dark matter particle carries no hypercharge. The term therefore can be ignored in comparison with the term proportional to c_F which can be obtained by tree-level diagrams. As can be seen in the Lagrangian, the WIMP dark matter in our scenario interacts with particles in the SM only through the Higgs boson. Such a scenario is sometimes called the "*Higgs portal*" scenario.

After the electroweak symmetry breaking, masses of the dark matters are given by

$$m_S^2 = M_S^2 + c_S v^2/2, \quad (5)$$

$$m_F = M_F + c_F v^2/(2\Lambda), \quad (6)$$

$$m_V^2 = M_V^2 + c_V v^2/2, \quad (7)$$

where the vacuum expectation value of the Higgs field is set to be $\langle H\rangle = (0, v)^T/\sqrt{2}$ with v being $v \simeq 246$ GeV.

[1] In this paper, we consider the nightmare scenario with a WIMP dark matter. If this is not a case and the dark matter particle is a particle such as the axion, it would be very difficult to access the dark matter in terms of direct detection experiments and LHC signals. This scenario would be a more adequately named "nightmare scenario.

Although the model parameter $M_{\rm DM}$ (DM $= S$, F, and V) may be related to the parameter $c_{\rm DM}$ and may depend on details of new physics at the scale of 10 TeV, we treat $m_{\rm DM}$ and $c_{\rm DM}$ as free parameters in the following discussion. There are some examples of new physics models with dark matter, which realize the Higgs portal scenario at low energies. The scenario with the scalar Higgs portal dark matter appears in models discussed in Refs. [5–7]. R parity invariant supersymmetric standard models with the bino-like lightest super particle can correspond to the fermion Higgs portal dark matter scenario [8] when the other super-partners are heavy enough. The vector dark matter can be realized in such as the littlest Higgs model with T parity if the breaking scale is very high [9].

III. COSMOLOGICAL ASPECTS

We first consider cosmological aspects of the scenario with paying particular attention to the WMAP experiment [3], and direct detection measurements for the dark matter particle by using the data from CDMS-II [10] and the first data from the XENON100 [11] experiment. We also discuss whether the signal of the WIMP dark matter is observed or not in near future at XMASS [12] and SuperCDMS [13] and XENON100 [14] experiments.

A. Relic abundance of dark matter

The WIMP dark matter in our scenario annihilates into particles in the SM only through the exchange of the Higgs boson. Processes of the annihilation are shown in Fig. 1, where h is the physical mode of H, $W(Z)$ is the charged (neutral) weak gauge boson, and f represents quarks and leptons in the SM.

The relic abundance of the WIMP dark matter, which is nothing but the averaged mass density of the dark matter in the present universe, is obtained by integrating out the following Boltzmann equation [15]:

$$\frac{dY}{dx} = -\frac{m_{\rm DM}}{x^2}\sqrt{\frac{\pi}{45 g_*^{1/2} G_N}}\left(g_{*s} + \frac{m_{\rm DM}}{3x}\frac{dg_{*s}}{dT}\right)\langle\sigma v\rangle \times \left[Y^2 - \left\{\frac{45x^2 g_{\rm DM}}{4\pi^4 g_{*s}}K_2(x)\right\}^2\right], \tag{8}$$

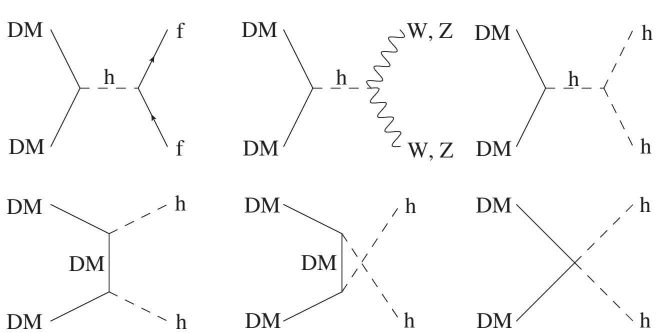

FIG. 1. Feynman diagrams for dark matter annihilation.

where $x \equiv m_{\rm DM}/T$ and $Y \equiv n/s$ with m, T, n, and s being the mass of the dark matter, the temperature of the universe, the number density of the dark matter, and the entropy density of the universe, respectively. The gravitational constant is denoted by $G_N = 6.7 \times 10^{-39}$ GeV^{-2}. The massless degree of freedom in the energy (entropy) density of the universe is given by $g_*(g_{*s})$, while $g_{\rm DM}$ is the spin degree of freedom of the dark matter. The function $K_2(x)$ is the second modified Bessel function, and $\langle\sigma v\rangle$ is the thermal average of the total annihilation cross section (times relative velocity) of the dark matter. With the asymptotic value of the yield $Y(\infty)$, the cosmological parameter of the dark matter density $\Omega_{\rm DM}h^2$ is written

$$\Omega_{\rm DM}h^2 = \frac{m_{\rm DM}s_0 Y(\infty)}{\rho_c/h^2}, \tag{9}$$

where $s_0 = 2890$ cm^{-3} is the entropy density of the present Universe, while $\rho_c/h^2 = 1.05 \times 10^{-5}$ GeV cm^{-3} is the critical density.

We have numerically integrated out the Boltzmann Eq. (8) including the effect of temperature-dependent $g_*(T)$ and $g_{*S}(T)$ to obtain the relic abundance accurately. The result is shown in Fig. 2 as magenta regions, where the regions are consistent with the WMAP experiment at 2σ level in $(m_{\rm DM}, c_{\rm DM})$ plain. In upper three figures, the Higgs mass is fixed to be $m_h = 120$ GeV, while $m_h = 150$ GeV in lower ones. It can be seen that the coupling constant $c_{\rm DM}$ should not be so small in order to satisfy the con straint from the WMAP experiment except the region $m_{\rm DM} \simeq m_h/2$ where the resonant annihilation due to the s-channel Higgs boson is efficient.

B. Direct detection of dark matter

After integrating the Higgs boson out, Eqs. (2)–(4) lead to effective interactions of the WIMP dark matter with gluon and light quarks such as

$$\mathcal{L}_S^{(\rm eff)} = \frac{c_S}{2m_h^2}\phi^2\left(\sum_q m_q\bar{q}q - \frac{\alpha_s}{4\pi}G_{\mu\nu}G^{\mu\nu}\right), \tag{10}$$

$$\mathcal{L}_F^{(\rm eff)} = \frac{c_F}{2\Lambda m_h^2}\bar{\chi}\chi\left(\sum_q m_q\bar{q}q - \frac{\alpha_s}{4\pi}G_{\mu\nu}G^{\mu\nu}\right), \tag{11}$$

$$\mathcal{L}_V^{(\rm eff)} = -\frac{c_V}{2m_h^2}V_\mu V^\mu\left(\sum_q m_q\bar{q}q - \frac{\alpha_s}{4\pi}G_{\mu\nu}G^{\mu\nu}\right), \tag{12}$$

where q represents light quarks (u, d, and s quarks) with m_q being their current masses. Strong coupling constant is denoted by α_s and the field strength tensor of the gluon field is given by $G_{\mu\nu}$. Using these interactions, the scattering cross section between dark matter and nucleon for the momentum transfer being small enough is calculated as

$$\sigma_S(\phi N \to \phi N) = \frac{c_S^2}{4m_h^4}\frac{m_N^2}{\pi(m_S + m_N)^2}f_N^2, \tag{13}$$

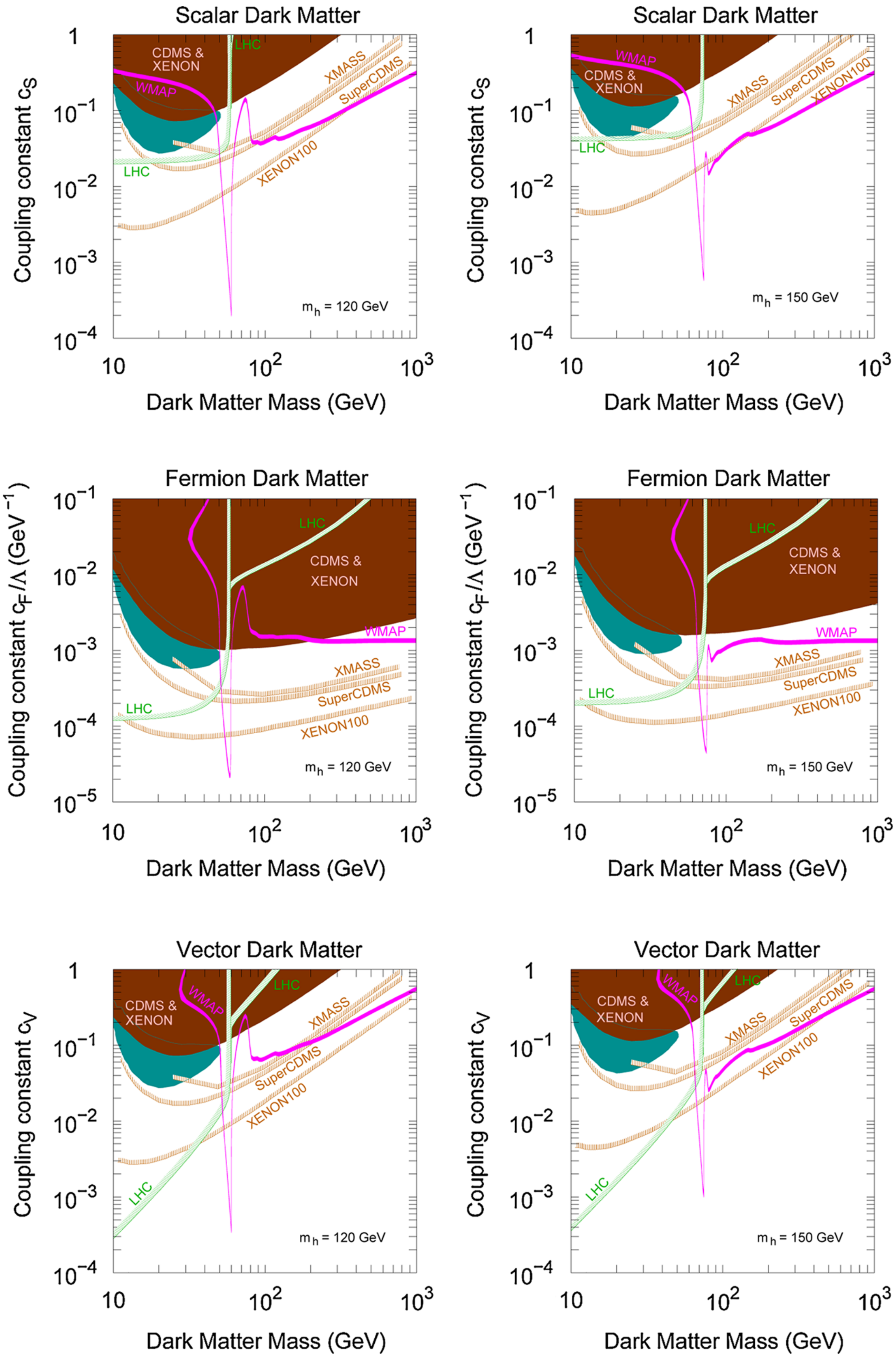

FIG. 2 (color online). Constraints on the nightmare scenario from WMAP, Xenon100 first data, and CDMS-II experiments. Higgs mass is fixed to be 120 GeV in left three figures, while 150 GeV in right three figures. Expected sensitivities to detect the signal of the dark matter at XMASS, SuperCDMS, Xenon100, and LHC experiments are also shown in these figures. See the text for the detail of the region painted by dark cyan (light gray).

$$\sigma_F(\chi N \to \chi N) = \frac{c_F^2}{4\Lambda^2 m_h^4}\frac{4m_N^2 m_F^2}{\pi(m_F + m_N)^2} f_N^2, \qquad (14)$$

$$\sigma_V(VN \to VN) = \frac{c_V^2}{4m_h^4}\frac{m_N^2}{\pi(m_V + m_N)^2} f_N^2, \qquad (15)$$

where N represents a nucleon (proton or neutron) with the mass of the nucleon $m_N \simeq 1$ GeV. The parameter f_N depends on hadronic matrix elements,

$$\begin{aligned} f_N &= \sum_q m_q \langle N|\bar{q}q|N\rangle - \frac{\alpha_s}{4\pi}\langle N|G_{\mu\nu}G^{\mu\nu}|N\rangle \\ &= \sum_q m_N f_{Tq} + \frac{2}{9} m_N f_{TG}. \end{aligned} \qquad (16)$$

The value of f_{Tq} has recently been evaluated accurately by the lattice QCD simulation using the overlap fermion formulation. The result of the simulation has shown that $f_{Tu} + f_{Tu} \simeq 0.056$ and $|f_{Ts}| \leq 0.08$[2] [16]. On the other hand, the parameter f_{TG} is obtained by f_{Tq} trough the trace anomaly, $1 = f_{Tu} + f_{Td} + f_{Ts} + f_{TG}$ [17].

The result from CDMS-II and the new data from the XENON 100 experiment give the most severe constraint on the scattering cross section between dark matter particle and nucleon. The result of the constraint is shown in Fig. 2, where the regions in brown are excluded by the experiments at 90% confidence level. It can be seen that most of the parameter space for a light dark matter particle has already been ruled out. In Fig. 2, we also depict experimental sensitivities to detect the signal of the dark matter in near future experiments, XMASS, SuperCDMS, and Xenon100. The sensitivities are shown as light brown lines, where the signal can be discovered in the regions above these lines at 90% confidence level. Most of the parameter region will be covered by the future direct detection experiments. Note that the WIMP dark matter in the nightmare scenario predicts a large scattering rate in the region $m_h \lesssim 80$ GeV. It is interesting to show a region corresponding to "positive signal" of dark matter particle reported by the CDMS-II experiment very recently [10], which is depicted in dark cyan and this closed region only appears at 1σ confidence level [18]. The parameter region consistent with the WMAP results has some overlap with the signal region. When a lighter Higgs boson mass is taken, the two regions better overlap.

IV. SIGNALS AT THE LHC

Finally, we investigate the signal of the WIMP dark matter at the LHC experiment [19]. The main purpose here is to clarify the parameter region where the signal can be detected. We first consider the case in which the mass of the dark matter is less than a half of the Higgs boson mass. In this case, the dark matter particles can be produced through the decay of the Higgs boson. Then, we consider the other case where the mass of the dark matter particle is heavier than a half of the Higgs boson mass.

A. The case $m_{\rm DM} < m_h/2$

In this case, the coupling of the dark matter particle with the Higgs boson can cause a significant change in the branching ratio of the Higgs boson while the production process of the Higgs boson at the LHC remains the same. The partial decay width of the Higgs boson into dark matter particles is given by

$$\Gamma_S = \frac{c_S^2 v^2}{32\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}, \qquad (17)$$

$$\Gamma_F = \frac{c_F^2 v^2 m_h}{16\pi\Lambda^2}\left(1 - \frac{4m_F^2}{m_h^2}\right)^{3/2}, \qquad (18)$$

$$\Gamma_V = \frac{c_V^2 v^2 m_h^3}{128\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)\sqrt{1 - \frac{4m_V^2}{m_h^2}}. \qquad (19)$$

When the mass of the Higgs boson is not heavy ($m_h \lesssim 150$ GeV), its partial decay width into quarks and leptons is suppressed due to small Yukawa couplings. As a result, the branching ratio into dark matter particles can be almost 100% unless the interaction between the dark matter and the Higgs boson is too weak. In this case, most of the Higgs boson produced at the LHC decay invisibly.

There are several studies on the invisible decay of the Higgs boson at the LHC. The most significant process for investigating such a Higgs boson is found to be its production through weak gauge boson fusions. For this process, the forward and backward jets with a large pseudorapidity gap show the missing transverse energy corresponding to the production of the invisibly decaying Higgs boson. According to the analysis in Ref. [20], the 30 fb^{-1} data can allow us to identify the production of the invisibly decaying Higgs boson at the 95% confidence level when its invisible branching ratio is larger than 0.250 for $m_h = 120$ GeV and 0.238 for $m_h = 150$ GeV. In this analysis [20], both statistical and systematical errors are included. We interplet the results in Ref. [20] into the parameter space of $m_{\rm DM}$ and $C_{\rm DM}$. For parameters in the left of the plot in Fig. 2 the production of the invisibly decaying Higgs boson can be identified at the 95% confidence level. Most of parameter regions with $m_{\rm DM} \leq m_h/2$ can be covered by investigating the signal of the invisible decay at the LHC. It is also interesting to notice that the signal of the WIMP dark matter can be obtained in both direct detection measurement and LHC experiment, which arrow us to perform a nontrivial check for the scenario.

[2] For conservative analysis, we use $f_{Ts} = 0$ in our numerical calculations.

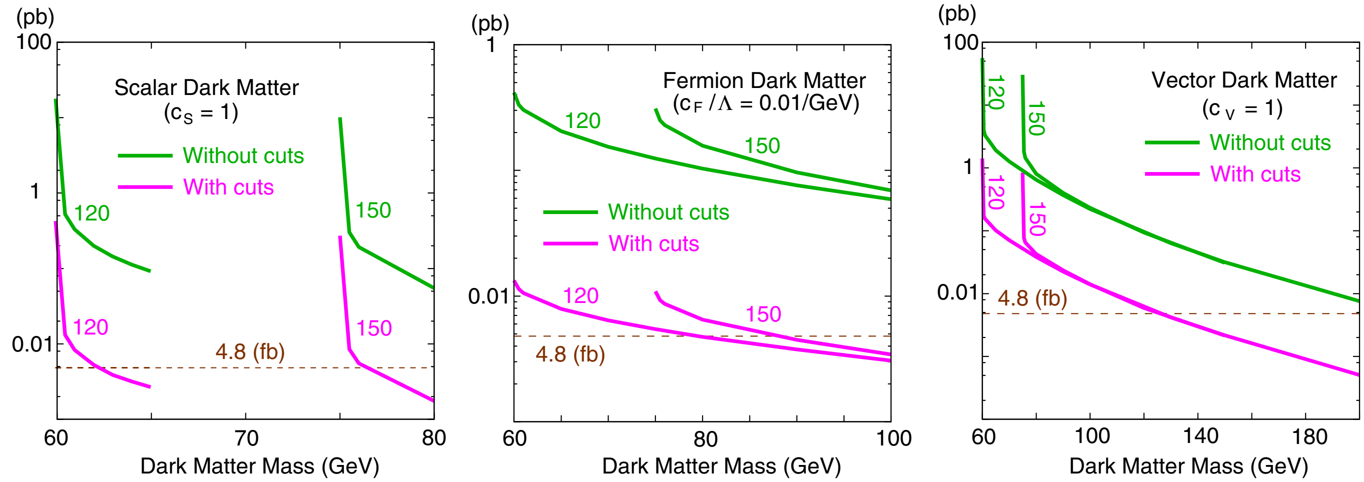

FIG. 3 (color online). Cross section of the dark matter signal at the LHC with and without kinematical cuts in Eq. (20). The parameter m_h and $c_{\rm DM}$ are fixed as shown in these figures.

B. The case $m_{\rm DM} \geq m_h/2$

In this case, the WIMP dark matter cannot be produced from the decay of the Higgs boson. We consider, however, the process of weak gauge boson fusions again. With V and h^* being a weak gauge boson and virtual Higgs boson, the signal is from the process $qq \to qqVV \to qqh^* \to qq$DMDM, which is characterized by two energetic quark jets with large missing energy and a large pseudorapidity gap between them.

There are several backgrounds against the signal. One is the production of a weak boson associated with two jets thorough QCD or electroweak interaction, which mimics the signal when the weak boson decays into neutrino. Another background is from the production of three jets thorough QCD interaction, which mimics the signal when one of the jets is missed to detect. Following the Ref. [21], we apply kinematical cuts for two tagging jets in order to reduce these backgrounds,

$$\begin{aligned} &p_T^j > 40\ \text{GeV}, \qquad \not{p}_T > 100\ \text{GeV}, \\ &|\eta_j| < 5.0, \qquad |\eta_{j_1} - \eta_{j_2}| > 4.4, \qquad \eta_{j_1} \cdot \eta_{j_2} < 0, \\ &M_{j_1 j_2} > 1200\ \text{GeV}, \qquad \phi_{j_1 j_2} < 1, \end{aligned} \tag{20}$$

where p_T^j, $\not{p}_T$, and η_j are the transverse momentum of j, the missing energy, and the pseudorapidity of j, respectively. The invariant mass of the two jets is denoted by M_{jj}, while ϕ_{jj} is the azimuthal angle between two jets. We also impose a veto of central jet activities with $p_T > 20$ GeV in the same manner of this reference. From the analysis of these backgrounds, it turns out that, at the LHC with the energy of $\sqrt{s} = 14$ TeV and the integrated luminosity of 100 fb^{-1}, the signal will be detected at 95% confidence level when its cross section exceeds 4.8 fb after applying these kinematical cuts.

Cross sections of the signal before and after applying the kinematical cuts are depicted in Fig. 3 as a function of the dark matter mass with m_h being fixed to be 120 and 150 GeV. We also fix the coupling constant between dark matter and Higgs boson as shown in these figures. It turns out that the cross section after applying the kinematical cuts exceeds 4.8 fb if the mass of the dark matter particle is small enough. With this analysis, we have estimated the experimental sensitivity to detect the signal at the LHC. The result is shown in Fig. 2 as green lines for $m_{\rm DM} \geq m_h/2$, where with an integrated luminosity of 100 fb^{-1} the signal at 95% confidence level can be observed in the regions above these lines. The sensitivity does not reach the region consistent with the WMAP observation, but it is close for fermion and vector dark matters with $m_h = 120$ GeV. When we use more sophisticated analysis or accumulate more data, the signal may be detectable.

V. SUMMARY AND DISCUSSIONS

The physics operation of the LHC has begun and exploration of particle physics at the TeV scale will continue over next decades. Discovery of not only the Higgs boson but also new physics beyond the SM is highly expected for the LHC experiment. However, the little hierarchy might exist in nature and if this is the case, new physics scale can be around 10 TeV, so that the LHC could find only the SM-like Higgs boson but nothing else. This is the nightmare scenario.

On the other hand, cosmological observations strongly suggest the necessity of extension of the SM so as to incorporate the dark matter particle. According to the WIMP dark matter hypothesis, the mass scale of the dark matter particle lies below the TeV, hence, within the reach of the LHC.

We have investigated the possibility that the WIMP dark matter can be a clue to overcome the nightmare scenario. As the worst case scenario, we have considered the WIMP dark matter singlet under the SM gauge symmetry, which communicates with the SM particles only through the Higgs boson. Analyzing the relic density of the dark matter particle and its elastic scattering cross section with nucleon, we have identified the parameter region which is consistent with the WMAP observation and the current direct detection measurements of the dark matter particle. The direct detection measurements provide severe constraints on the parameter space and in near future almost of all parameter region can be explored except a region with a dark matter mass close to a half of Higgs boson mass.

We have also considered the dark matter signal at the LHC. The dark matter particle can be produced at the LHC only through its interaction with the Higgs boson. If the Higgs boson is light, $m_h \lesssim 150$ GeV, and the dark matter particle is also light, $m_{\rm DM} < m_h/2$, the Higgs boson decays into a pair of dark matter particles with a large branching ratio. Such an invisibly decaying Higgs boson can be explored at the LHC by the Higgs boson production process through the weak gauge boson fusions. When the invisible branching ratio is sizable, $B(h \to {\rm DMDM}) \gtrsim 0.25$, the signal of invisibly decaying Higgs boson can be observed. Interestingly, corresponding parameter region is also covered by the future experiments for the direct detection measurements of dark matter particle. In the case of $m_{\rm DM} \geq m_h/2$, we have also analyzed the dark matter particle production mediated by the virtual Higgs boson in the weak boson fusion channel. Although the detection of the dark matter particle production turns out to be challenging in our present analysis, more sophisticated analysis may enhance the ratio of the signal to background.

Even if the nightmare scenario is realized in nature, the WIMP dark matter may exist and communicate with the SM particles only through the Higgs boson. Therefore, the existence of new physics may be revealed associated with the discovery of the Higgs boson. Finding the Higgs boson but nothing else would be more of a portal to new findings, the WIMP dark matter, rather than nightmare.

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