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Direct detection of singlet dark matter in classically scale-invariant standard model

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ABSTRACT

Classical scale invariance is one of the possible solutions to explain the origin of the electroweak scale. The simplest extension is the classically scale-invariant standard model augmented by a multiplet of gauge singlet real scalar. In the previous study it was shown that the properties of the Higgs potential deviate substantially, which can be observed in the International Linear Collider. On the other hand, since the multiplet does not acquire vacuum expectation value, the singlet components are stable and can be dark matter. In this letter we study the detectability of the real singlet scalar bosons in the experiment of the direct detection of dark matter. It is shown that a part of this model has already been excluded and the rest of the parameter space is within the reach of the future experiment.

1. Introduction

Higgs boson was discovered in 2012 at the CERN Large Hadron Collider [1,2]. Since then, its properties, such as spin, parity and couplings to the standard model fermions and gauge bosons, have been measured and it turned out that they are consistent with the standard model prediction. In spite of the success of the standard model up to now, however, it is commonly believed that the standard model is not the ultimate theory of particle physics. In fact there are lots of unsolved problems in the field of particle physics as well as cosmology.

One of them is the origin of the spontaneous symmetry breakdown of the electroweak gauge group. In the standard model, the electroweak symmetry is broken by Higgs field that has an ad hoc tachyonic mass term. One explanation for the tachyonic mass is supersymmetry. In supersymmetric extension of the standard model, the negative mass term is induced radiatively. On the other hand, radiative symmetry breaking is possible in non-supersymmetric theory, which is known as Coleman–Weinberg (CW) mechanism [3]. In the CW mechanism spontaneous symmetry breaking is induced at quantum level from classically scale-invariant scalar potential. Although it turned out that the CW mechanism with a Higgs does not work for the electroweak symmetry breaking, simple extensions of the Higgs sector are known to be phenomenologically viable (see, e.g., [4–29]).

Recently Higgs properties were studied in a classically scale-invariant standard model augmented by an electroweak singlet scalars that form a multiplet of global $O(N)$ symmetry [30]. It was shown that the Higgs self-couplings deviate significantly from the standard model prediction. Such feature can be observed as a prominent signal of this model at the next-generation lepton collider experiment, such as the International Linear Collider (ILC) [31–33]. On the other hand, it was also shown that the singlet field does not get a Vacuum Expectation Value (VEV). Then, other Higgs properties are unaffected since there is no mixing between the singlet and Higgs. Another important consequence is the stability of the singlet field due to unbroken $O(N)$ symmetry. If the reheating temperature of the universe is higher than the mass of the singlet, the singlet field is thermalized. Then non-vanishing thermal relic of the singlet remains, which can play a role of dark matter.

In this letter we study direct detection of the real singlet dark matter with $O(N)$ symmetry. It was pointed out in a similar framework where the thermal relic abundance of the singlet dark matter is too small to explain the present energy density of dark matter by taking into account the 125 GeV Higgs [7,10,12]. This is due to an enhanced annihilation cross section caused by a large singlet-Higgs coupling. On the contrary, however, the large singlet-Higgs coupling may result in a large scattering cross section of the singlet with nucleon. According to the study of Ref. [30], the couplings of the singlet with the standard model particles are fixed for the successful electroweak symmetry breaking via the CW mechanism, which makes it possible to determine the relic abundance and the scattering cross section of the singlet with nucleon at a

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high precision. The scattering cross section of singlet scalar dark matter is also discussed in several literature mentioned above. We revise the calculation of the spin-independent cross section of singlet scalar particle by adopting the formalism given in Ref. [34] where next-to-leading order QCD effect is properly taken into account. It will be shown that part of the model has already been excluded by recent LUX result [35] and the future experiments will be able to probe almost the entire parameter space of the model.

Here is the organization of this letter. In Section 2 we briefly explain the model, including the prescription how to determine model parameters. Then the thermal relic and the scattering cross section of the singlet are calculated, and the detection of the singlet scalar is discussed in Section 3. Section 4 is dedicated to conclusion.

2. The model

In the framework with classical scale invariance it is known that the standard model without the Higgs mass term has already been excluded. In order to construct phenomenologically viable model, therefore, it is necessary to extend the model, e.g., by adding a new particle to the model. The simplest extension is to introduce a gauge singlet real scalar field. Such a singlet scalar can couple to the Higgs in general, then the singlet contributes to the CW potential. The effect strongly depends on the degree of freedom of the singlet field. To see the impact we introduce a fundamental representation of a global $O(N)$ symmetry, $S = (S_1, \cdots, S_N)^T$. Consequently, the tree-level scalar potential which is allowed under the symmetry is

$$V = \lambda_H (H^\dagger H)^2 + \lambda_{HS} H^\dagger H\, S_i S_i + \frac{\lambda_S}{4}(S_i S_i)^2 , \tag{2.1}$$

where H is the Higgs doublet field $H = (H^+, H^0)^T$, and summed over $i = 1, \cdots, N$ for $N \geq 2$. Z_2 symmetry is assumed for $N = 1$ case, whereas it is also a subgroup of $O(N)$ symmetry and always survives in the scale-invariant tree-level potential for $N \geq 2$.

The electroweak symmetry breaking is induced via the CW mechanism. To see this, the scalar fields can be taken without loss of generality as $H = (1/\sqrt{2})\,(0, \phi)^T$ and $S = (\varphi, 0, \cdots, 0)^T$ where ϕ and φ are classical fields of the real scalars. Then the effective potential at one-loop level is given by

$$V_{\rm eff}(\phi, \varphi) = V_{\rm tree}(\phi, \varphi) + V_{\text{1-loop}}(\phi, \varphi) , \tag{2.2}$$

with

$$V_{\rm tree}(\phi, \varphi) = \frac{\lambda_H}{4}\phi^4 + \frac{\lambda_{HS}}{2}\phi^2\varphi^2 + \frac{\lambda_S}{4}\varphi^4 , \tag{2.3}$$

$$V_{\text{1-loop}}(\phi, \varphi) = \frac{1}{4(4\pi)^2}\sum_i n_i M_i^4(\phi, \varphi)\left[\ln\frac{M_i^2(\phi, \varphi)}{\mu^2} - c_i\right] , \tag{2.4}$$

in $\overline{\rm MS}$-scheme with renormalization scale μ. Index i denotes the fields which run in the loop diagrams. (n_i, M_i^2 and c_i are given in Appendix A.) The electroweak symmetry is spontaneously broken if $\partial V_{\rm eff}/\partial\phi|_{\phi=\langle\phi\rangle} = 0$ with $\langle\phi\rangle \neq 0$, which implies $\lambda_H \sim \frac{N\lambda_{HS}^2}{16\pi^2} - \frac{3y_t^4}{16\pi^2}$ as a necessary condition. Then λ_H should be regarded as the next-to-leading order in terms of the order counting of the dimensionless couplings. Consequently we rewrite the effective potential as

$$V_{\rm eff} = V_{\rm LO} + V_{\rm NLO} , \tag{2.5}$$

with $V_{\rm LO}$ and $V_{\rm NLO}$ being regarded as Leading Order (LO) and Next-to-Leading Order (NLO) of the scalar potential;

$$V_{\rm LO} = \frac{\lambda_{HS}}{2}\phi^2\varphi^2 + \frac{\lambda_S}{4}\varphi^4 , \tag{2.6}$$

$$\begin{aligned} V_{\rm NLO} = {} & \frac{\lambda_H}{4}\phi^4 + \frac{F_{+\rm app}{}^2(\phi,\varphi)}{64\pi^2}\left[\ln\left(\frac{F_{+\rm app}(\phi,\varphi)}{\mu^2}\right) - \frac{3}{2}\right] \\ & + \frac{3}{64\pi^2}\left(\lambda_{HS}\varphi^2\right)^2\left[\ln\left(\frac{\lambda_{HS}\varphi^2}{\mu^2}\right) - \frac{3}{2}\right] \\ & + \frac{N-1}{64\pi^2}\left(\lambda_{HS}\phi^2 + \lambda_S\varphi^2\right)^2\left[\ln\left(\frac{\lambda_{HS}\phi^2 + \lambda_S\varphi^2}{\mu^2}\right) - \frac{3}{2}\right] \\ & - \frac{12}{64\pi^2}M_t{}^4(\phi)\left[\ln\left(\frac{M_t{}^2(\phi)}{\mu^2}\right) - \frac{3}{2}\right] \\ & + \frac{6}{64\pi^2}M_W{}^4(\phi)\left[\ln\left(\frac{M_W{}^2(\phi)}{\mu^2}\right) - \frac{5}{6}\right] \\ & + \frac{3}{64\pi^2}M_Z{}^4(\phi)\left[\ln\left(\frac{M_Z{}^2(\phi)}{\mu^2}\right) - \frac{5}{6}\right] , \end{aligned} \tag{2.7}$$

where $F_{+\rm app}$ is given in Appendix A. In Ref. [30] it is shown that the successful electroweak symmetry breaking with the Higgs mass $m_h \simeq 125$ GeV can be realized in a given number of N. Table 1 shows the results.[1] Roughly speaking, the Higgs mass is expected to be $m_h \sim (\sqrt{N}\lambda_{HS}/4\pi)v_H$ with $v_H = 246$ GeV, which is consistent with the numerical results in Table 1. With the proper order counting, the effective potential around the VEV is obtained by replacing the scalar fields as $\phi \to v_H + h$, $\varphi^2 \to s_i s_i$ and expanding by powers of h and $s_i s_i$;

$$\begin{aligned} V_{\rm eff} = {} & {\rm const} + \frac{1}{2}m_h{}^2 h^2 + \frac{1}{2}m_s{}^2 s_i s_i + \frac{\lambda_{hhh}}{3!}\, v_H h^3 + \frac{\lambda_{hhhh}}{4!}h^4 \\ & + \frac{\lambda_{hss}}{2}\, v_H\, h\, s_i s_i + \frac{\lambda_{hhss}}{4}h^2 s_i s_i + \frac{\lambda_{ssss}}{4!}\,(s_i s_i)^2 + \cdots , \end{aligned} \tag{2.8}$$

where m_s is the mass of singlet. We have taken $\mu = v_H$ and omitted irrelevant terms in our later discussion. The results for λ_{hhhh}, λ_{hhh}, λ_{hhss}, λ_{hss}, λ_{ssss} and m_s are summarized in Table 2 [30].[2] Basically λ_H and λ_{HS} are chosen to give rise to $v_H = 246$ GeV and $m_h = 125$ GeV, which determine the couplings (except for the singlet self-coupling) and the singlet mass. λ_S, on the other hand, has little impact on these results. Since the Higgs self-couplings λ_{hhhh} and λ_{hhh} significantly deviate from the SM prediction, the precise measurement of the Higgs self-couplings is a viable way to test this model.

Another important fact shown in Ref. [30] is that the singlet does not get VEV.[3] Without a VEV of the singlet, Higgs properties, such as Higgs production or decay rates, are unaffected. On the other hand, unbroken $O(N)$ symmetry forbids s_i to decay. Such stable particles can change the thermal history of the universe. If the reheating temperature in the early universe is higher than the singlet mass, the singlet particles are thermalized and their number densities freeze out eventually. Then the thermal relics can be components of dark matter. In this model the parameters which determine the interaction of s_i with the standard model particles (the Higgs field in our case) are completely fixed as discussed

[1] This is the results derived from the potential referred as (I) in Ref. [30].

[2] The couplings are obtained from the parameters shown in Table 1 which corresponds to case (I) in Ref. [30]. Since the couplings change by a few % in cases (II) or (III), we will use the couplings from case (I) in our later calculation.

[3] This fact is guaranteed to all orders in perturbative expansion. Strictly speaking, non-perturbative effect might break $O(N)$, which could allow non-zero VEV for the singlet. Possible (or known) non-perturbative effect is anomaly. In our model, however, $O(N)$ multiplet is scalar, thus it is anomaly free. Though one may concern another unknown non-perturbative effect, the situation is the same for the standard model, i.e. unbroken $U(1)_{\rm em}$ symmetry.