Physics Letters B 752 (2016) 217–220

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Discriminative phenomenological features of scale invariant models for electroweak symmetry breaking

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ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 14 November 2015
Accepted 15 November 2015
Available online 29 November 2015
Editor: J. Hisano

ABSTRACT

Classical scale invariance (CSI) may be one of the solutions for the hierarchy problem. Realistic models for electroweak symmetry breaking based on CSI require extended scalar sectors without mass terms, and the electroweak symmetry is broken dynamically at the quantum level by the Coleman–Weinberg mechanism. We discuss discriminative features of these models. First, using the experimental value of the mass of the discovered Higgs boson $h(125)$, we obtain an upper bound on the mass of the lightest additional scalar boson ($\simeq 543$ GeV), which does not depend on its isospin and hypercharge. Second, a discriminative prediction on the Higgs-photon–photon coupling is given as a function of the number of charged scalar bosons, by which we can narrow down possible models using current and future data for the di-photon decay of $h(125)$. Finally, for the triple Higgs boson coupling a large deviation ($\sim +70\%$) from the SM prediction is universally predicted, which is independent of masses, quantum numbers and even the number of additional scalars. These models based on CSI can be well tested at LHC Run II and at future lepton colliders.

By the discovery of the Higgs boson at LHC, the idea of spontaneous breaking of the electroweak (EW) symmetry was confirmed by its correctness [1]. Detailed measurements of the property of the discovered Higgs particle $h(125)$ with the mass 125 GeV showed that the standard model (SM) with the one Higgs doublet field is a good description of the physics around the scale of 100 GeV within the uncertainty of the data [2]. Nevertheless, the essence of the Higgs boson and the structure of the Higgs sector remain unknown. The discovery of $h(125)$ provided us a step to explore the physics behind the EW symmetry breaking (EWSB). New physics beyond the SM is also required to explain phenomena such as dark matter, neutrino oscillation, baryon asymmetry of the universe and cosmic inflation. Physics of the Higgs sector is an important window to approach these problems.

In the SM, it is known that quadratic ultraviolet divergences appear in radiative corrections to the Higgs boson mass, which cause the hierarchy problem [3]. In order to solve the problem, several new physics paradigms have been proposed such as supersymmetry and scenarios of dynamical symmetry breaking. These paradigms have been thoroughly tested by experiments. Simple models of dynamical symmetry breaking like Technicolor models have been strongly constrained by EW precision data at LEP/SLC experiments [2]. Supersymmetric extensions of the SM are also now being in trouble due to the non-observation of supersymmetric partner particles at LHC, although there is still hope that they can be discovered at the LHC Run II experiment.

There is another idea that would avoid the hierarchy problem, which is based on the notion of classical scale invariance (CSI), originally proposed by Bardeen [4]. In a class of models based on CSI, parameters with mass dimensions are not introduced to the Lagrangian. EWSB can dynamically occur via the mechanism by Coleman and Weinberg (CW) [5], and masses of particles are generated by the dimensional transmutation. After the discovery of $h(125)$, models along this line have become popular as a possible alternative paradigm. The minimal scale-invariant model with one Higgs doublet has already been excluded by the data, so that extended scalar sectors have to be considered as realistic models [6–14]. In Refs. [7,11], strongly first order EW phase transition was studied in extended Higgs models with CSI for a successful scenario of EW baryogenesis. An additional scalar field in models with CSI could be a dark matter if it is stable [12,13]. In Ref. [15],

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http://dx.doi.org/10.1016/j.physletb.2015.11.044

in the CSI model with N-singlet fields under the $O(N)$ symmetry, the upper bound on N was obtained from the direct search results of dark matter. In Refs. [16,17], dark matter and inflation were investigated in models with CSI. Scale invariant models for neutrino masses were discussed in Ref. [18].

In this Letter, we discuss discriminative phenomenological features of models for EWSB based on CSI. We study a full set of the models with additional scalar fields to $h(125)$, which can contain arbitrary number of isospin singlet fields, additional doublets or higher representation fields with arbitrary hypercharges. An unbroken symmetry may be added so that additional scalars do not have vacuum expectation values (VEVs). Otherwise, additional doublets or higher multiplets can share the VEV v ($\simeq 246$ GeV) of EWSB with the SM-like Higgs field. However, we here do not discuss the case where singlets have VEVs which are irrelevant to the Fermi constant G_F ($\simeq 1/\sqrt{2}v^2$) [19,12,16].

First of all, a general upper bound C on the mass $m_1^{\rm CSI}$ of the lightest scalar boson other than $h(125)$ is obtained in all models of this category,

$$m_1^{\rm CSI} \leq C \simeq 543 \text{ GeV}. \tag{1}$$

If we specify the structure of the model, a stronger upper bound is obtained. Second, a discriminative prediction on the di-photon coupling of $h(125)$ is obtained. In terms of the scaling factor $\kappa_\gamma^{\rm CSI}$ of the $h\gamma\gamma$ coupling, it is approximately given by

$$\kappa_\gamma^{\rm CSI} \simeq 1 - \frac{n}{16} - \frac{m}{4}, \tag{2}$$

where n and m are the numbers of singly- and doubly-charged scalar bosons, respectively. Finally, the triple Higgs boson coupling $\Gamma_{hhh}^{\rm CSI}$ is universally predicted at the leading order as

$$\Gamma_{hhh}^{\rm CSI} = \frac{5m_h^2}{v} = \frac{5}{3} \times \Gamma_{hhh}^{\rm SM\ tree}, \tag{3}$$

where $\Gamma_{hhh}^{\rm SM}$ is defined by $\mathcal{L}_{\rm SM} = \cdots + (1/3!)\Gamma_{hhh}^{\rm SM} h^3 + \cdots$. Although these results have partially been obtained in some specific models of CSI [9–11,14], we would like to emphasize that they are common in all models for EWSB based on CSI. In the following, we discuss these results in more detail.

The vacuum in these models is analyzed using the well-known method by Gildener and Weinberg [6]. The vacuum is surveyed along the flat direction, and the minimum of the effective potential can be found at the one-loop level by the CW mechanism [5]. In terms of the order parameter φ along the flat direction, we can in general write the effective potential as [6]

$$V_{\rm eff}(\varphi) = A\varphi^4 + B\varphi^4 \ln \frac{\varphi^2}{Q^2}, \tag{4}$$

where Q is the scale of renormalization, and

$$A = \frac{1}{64\pi^2 v^4}\left[3\,{\rm Tr}\left(M_V^4 \ln \frac{M_V^2}{v^2}\right) - 4\,{\rm Tr}\left(M_f^4 \ln \frac{M_f^2}{v^2}\right) + {\rm Tr}\left(M_S^4 \ln \frac{M_S^2}{v^2}\right)\right], \tag{5}$$

$$B = \frac{1}{64\pi^2 v^4}\left[3\,{\rm Tr}\left(M_V^4\right) - 4\,{\rm Tr}\left(M_f^4\right) + {\rm Tr}\left(M_S^4\right)\right], \tag{6}$$

where the first, the second and the third terms in the right hand side of Eqs. (5) and (6) are respectively loop effects of the vector bosons, those of fermions, and those of extra scalar bosons [6]. Loop effects of $h(125)$ are not included, as they are of higher order contributions. Notice that we can approximately identify the SM-like Higgs boson $h(125)$ as the "scalon" [6]. From the stationary condition,

$$\left.\frac{\partial V_{\rm eff}}{\partial \varphi}\right|_{\varphi=v} = 0, \tag{7}$$

we obtain

$$\ln \frac{v^2}{Q^2} = -\frac{1}{2} - \frac{A}{B}, \tag{8}$$

by using which, the mass of $h(125)$ is obtained as

$$m_h^2 \equiv \left.\frac{\partial^2 V_{\rm eff}}{\partial \varphi^2}\right|_{\varphi=v} = 8Bv^2 \simeq (125 \text{ GeV})^2. \tag{9}$$

In the case where we only extend the scalar sector and do not extend the vector boson sector nor the fermion sector, Eq. (9) can be rewritten as[1]

$${\rm Tr}\, M_S^4 = 8\pi^2 v^2 m_h^2 - 3m_Z^4 - 6m_W^4 + 12m_t^4 \ (\equiv C^4). \tag{10}$$

Because all quantities in the right hand side are known from the current data [2], this equation gives the constraint on the scalar sector. When the scalar sector contains N scalar bosons in addition to $h(125)$, masses of these extra bosons can be written as $m_1 \leq m_2 \leq \cdots \leq m_N$, where m_i is the mass of the i-th scalar boson. We then obtain an upper bound on the mass $m_1^{\rm CSI}$ of the lightest scalar boson other than $h(125)$ as

$$m_1^{\rm CSI} \leq \frac{C}{\sqrt[4]{N_{0,0} + 2N_{0,1} + 4N_{\frac{1}{2},\frac{1}{2}} + 3N_{1,0} + 6N_{1,1} + \cdots}}, \tag{11}$$

where $N_{I,Y}$ is the number of additional scalar fields with isospin I and hypercharge Y. Since $N_{0,0} + 2N_{0,1} + 4N_{\frac{1}{2},\frac{1}{2}} + 3N_{1,0} + 6N_{1,1} + \cdots \geq 1$, we obtain the general upper bound $C (\simeq 543$ GeV) as given in Eq. (1). This bound is given for all models for EWSB based on CSI with extended scalar bosons.

If we specify models, for example, to those with only doublets, we obtain the stronger bound as

$$m_1^{\rm CSI} \leq \frac{C}{\sqrt[4]{4N_{\frac{1}{2},\frac{1}{2}}}} \sim \frac{1}{\sqrt[4]{N_{\frac{1}{2},\frac{1}{2}}}} \times 383 \text{ GeV}. \tag{12}$$

In Ref. [9], the similar bound has been discussed for the case of $N_{\frac{1}{2},\frac{1}{2}} = 1$ in addition to the unitarity bound. Each specified model in general can receive constraint from experimental data, strongly depending on parameters of the model. For $N_{\frac{1}{2},\frac{1}{2}} = 1$, namely, for the scale invariant two Higgs doublet model, constraint from the electroweak precision data has been studied in Refs. [8,9]. Notice that our bound $m_1^{\rm CSI} < 383$ GeV is independent of the parameters of the model, which has not yet been excluded by the experimental data.

Next, the decoupling theorem [22] states that quantum effects of heavy particles on low-energy observables decouple in the large mass limit. However, this is not the case for the models for EWSB based on CSI, where all massive particles obtain their masses from v, the VEV of EWSB. In such a case, significant non-decoupling effects can cause large deviations in low energy observables from their SM predictions.

As an example, let us discuss the one-loop induced coupling $h\gamma\gamma$ in models with n singly-charged scalar bosons and m doubly-charged ones. The ratio of the decay rate $\Gamma_{h\to\gamma\gamma}^{(n,m)}$ to the SM value

[1] Existence of chiral fourth generation fermions has already been excluded by experiments [20,21]. Hence, we do not consider additional fermions.