

Scenarios with Composite Higgs Bosons

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Typical models with composite Higgs bosons are briefly reviewed. We also introduce the isospin symmetric Higgs model recently proposed in Ref. [1].

I. INTRODUCTION

Recently, the ATLAS and the CMS Collaborations at the Large Hadron Collider (LHC) discovered a new boson h in the mass range 125–126 GeV [2]. In addition, the Standard Model (SM) Higgs boson has been excluded at 95% C.L. in the mass range 110–149 GeV, except for the narrow region 122.8–127.8 GeV [3]. The mass range from 127 to 600 GeV was previously excluded [4]. It is also noticeable that the mass $m_h = 125$ –126 GeV perfectly agrees with the LEP precision measurements [5]. On the other hand, the contact interactions in the processes of $pp \rightarrow \text{jet}$ and $pp \rightarrow \ell^+ \ell^-$ are severely constrained, i.e., the compositeness scale Λ should be larger than, say, 10 TeV [6]. Against this situation, is there still a room for some strong dynamics responsible for the electroweak symmetry breaking (EWSB)?

We give an overview of typical models with composite Higgs bosons. It might give some hint for the origin of the EWSB. We will also introduce the isospin symmetric Higgs model, which is recently proposed in Ref. [1], as an example of the dynamical EWSB scenario.

II. DYNAMICAL EWSB

The earliest idea of the dynamical EWSB is Technicolor (TC) [7]: The chiral condensate of (techni-) fermions is dynamically generated by the technicolor gauge interaction and it breaks the electroweak gauge symmetry, as in low-energy QCD. The would-be Nambu-Goldstone (NG) bosons are eaten by the weak gauge bosons. Then W and Z acquire their masses proportional to the technipion decay constant (~ 100 GeV), which is analogous to the pion decay constant $f_\pi \simeq 93$ MeV in QCD. In order to produce the masses of the SM fermions, the extended technicolor (ETC) has been proposed [8, 9]. Although it was beautiful, this old-fashioned TC has been already excluded by several reasons [10, 11]. For example, the constraint of the S -parameter [12] rules out this QCD-like TC with many weak doublets of the technifermions [13].

A modern version of TC is the walking TC where the gauge coupling of the TC gauge group runs very slowly, or “walks” [10, 11]. The walking TC resolves the difficulties of the old-fashioned TC. The estimate of the S -parameter expected from QCD is not applicable to walking TC. Even in walking TC, however, it is difficult to generate the observed mass of the top quark from the ETC interactions without producing unacceptably large isospin breaking. Also, the walking TC usually predicts a heavy composite Higgs boson. Noticing that the S -parameter constraint requires a heavy technirho bound state ρ_T , it is quite nontrivial to get a light composite Higgs, $m_h \sim 100$ GeV, and simultaneously to obtain the heavy ρ_T , say, $M_{\rho_T} \gtrsim \text{few TeV}$.

To generate the mass of the top quark, the topcolor dynamics is useful [11]. In the topcolor scenario, we assume that the new topcolor interaction strongly couples to the third generation of quarks and then the top quark condensate mainly yields the top quark mass. In the simplest four dimensional model that the top condensate is responsible both for the EWSB and m_t , and that there appears only one (composite) Higgs doublet, too large top quark mass is predicted, however. In a model with extra dimensions, this difficulty is relaxed [14]. Another approach to avoid too large top mass is to assume that the top quark condensate is responsible only for m_t and the EWSB takes place by some other mechanism. In topcolor assisted technicolor (TC2), the TC interaction causes the EWSB [15]. Because the chiral symmetry is extended in TC2, there appears the extra NG bosons, so-called top-pions. The masses of the top-pions are generally light and thus they are severely constrained. In a model in Ref. [16], we employed a subcritical dynamics (although nearcritical, i.e., strong) for the topcolor interaction, so that the mass of the scalar bound state of the top and the anti-top quarks is naturally heavy. This mechanism is used in the isospin symmetric (IS) Higgs model recently proposed in Ref. [1].

We introduce the IS Higgs model in the next section.

III. IS HIGGS MODEL AND ITS PREDICTIONS

The ATLAS and CMS experiments did not only announced the mass of the new discovered boson h , but they also reported the nature of h : While the decay channels of $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$ are fairly consistent with the SM, the diphoton branching ratio $\text{Br}(h \rightarrow \gamma\gamma)$ is about 1.6 times larger than the SM value [2]. In the latest results, the ATLAS collaboration confirmed the similar enhancement in the diphoton channel [17]. On the other hand, the CMS group changed their previous results of the signal strength from $\sigma/\sigma_{\text{SM}} = 1.6 \pm 0.4$ to $\sigma/\sigma_{\text{SM}} = 0.78_{-0.26}^{+0.28}$ for the mass-fit-MVA analysis and $\sigma/\sigma_{\text{SM}} = 1.11_{-0.31}^{+0.32}$ for the cut-based analysis [3]. The situation thus becomes unclear at present. In any case, the deviation from the SM in the diphoton channel, if established, would be an indication of a new physics beyond the SM.

Let us introduce the IS Higgs boson model.

The main characteristics of the IS Higgs boson model are as follows [1, 16]: a) It is assumed that the dynamics primarily responsible for the EWSB leads to the mass spectrum of quarks with no (or weak) isospin violation. *Moreover, it is assumed that the values of these masses are of the order of the observed masses of the down-type quarks.* b) The second (central) assumption is introducing the horizontal interactions for the quarks in the three families. As a first step, a *subcritical* (although nearcritical, i.e., strong) diagonal horizontal interactions for the top quark is utilized which lead to the observed ratio $\frac{m_t}{m_b} \simeq 41.5$ [13]. The second step is introducing *equal* strength horizontal flavor-changing-neutral (FCN) interactions between the t and c quarks and the b and s ones. As was shown in Ref. [16], these interactions naturally provide the observed ratio $m_c/m_s \simeq 13.4$ in the second family [13]. As to the mild isospin violation in the first family, it was studied together with the effects of the family mixing, reflected in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [16].

In this scenario, the main source of the isospin violation is only the strong top quark interactions. However, because these interactions are subcritical, the top quark plays a minor role in EWSB. This distinguishes the IS Higgs scenario from the top quark condensate model [11].

One of the signatures of this scenario is the appearance of a composite top-Higgs boson h_t composed of the quarks and antiquarks of the third family [16]. Note that unlike TC2 [15], this class of models utilizes subcritical dynamics for the top quark, so that the top-Higgs h_t is heavy in general. Here we also emphasize that while the top-Higgs boson h_t has a large top-Yukawa coupling, the IS Higgs boson h does not, $y_t \simeq y_b \sim 10^{-2}$. On the other hand, the hWW^* and hZZ^* coupling constants are close to those in the SM. Also, the mixing between h and much heavier h_t should be small.

We now describe the decay processes of the IS Higgs h .

It is well known that the W -loop contribution to $H \rightarrow \gamma\gamma$ is dominant in the SM, while the top-loop effect is destructive against the W -loop. In the IS Higgs model, however, the Yukawa coupling between the top and the IS Higgs h is as small as the bottom Yukawa coupling, so that the top-loop contribution is strongly suppressed. The partial decay width of $h \rightarrow \gamma\gamma$ is thus enhanced without changing essentially $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$. A rough estimate taking the isospin symmetric top and bottom Yukawa couplings $y_t \simeq y_b \approx 10^{-2}$ is as follows:

$$\frac{\Gamma^{\text{IS}}(h \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(H \rightarrow \gamma\gamma)} \simeq 1.56, \quad \frac{\Gamma^{\text{IS}}(h \rightarrow WW^*)}{\Gamma^{\text{SM}}(H \rightarrow WW^*)} = \frac{\Gamma^{\text{IS}}(h \rightarrow ZZ^*)}{\Gamma^{\text{SM}}(H \rightarrow ZZ^*)} = \left(\frac{v_h}{v}\right)^2 \simeq 0.96. \quad (1)$$

Here using the Pagels-Stokar formula [18], we estimated the vacuum expectation value (VEV) of the top-Higgs h_t as $v_t = 50$ GeV, and the VEV v_h of the IS Higgs h is given by the relation $v^2 = v_h^2 + v_t^2$ with $v = 246$ GeV. Note that the values of the ratios in Eq. (1) are not very sensitive to the value of v_t , e.g., for $v_t = 40$ – 100 GeV, the suppression factor in the pair decay modes to WW^* and ZZ^* is 0.97–0.84 and the VEV v_h of the IS Higgs h is given by the relation $v^2 = v_h^2 + v_t^2$ with $v = 246$ GeV. Note that the values of the ratios in Eq. (1) are not very sensitive to the value of v_t , e.g., for $v_t = 40$ – 100 GeV, the suppression factor in the pair decay modes to WW^* and ZZ^* is 0.97–0.84 and the enhancement factor in the diphoton channel is 1.58–1.37. For the decay mode of $h \rightarrow Z\gamma$, this model yields

$$\frac{\Gamma^{\text{IS}}(h \rightarrow Z\gamma)}{\Gamma^{\text{SM}}(H \rightarrow Z\gamma)} \simeq 1.07. \quad (2)$$

The values in Eq. (1) agree well with the data in the ATLAS and CMS experiments. However, obviously, the main production mechanism of the Higgs boson, the gluon fusion process $gg \rightarrow h$, is now in trouble. The presence of new chargeless colored particles, which considered by several authors [19] can help to resolve this problem. We pursue this possibility in the next section.

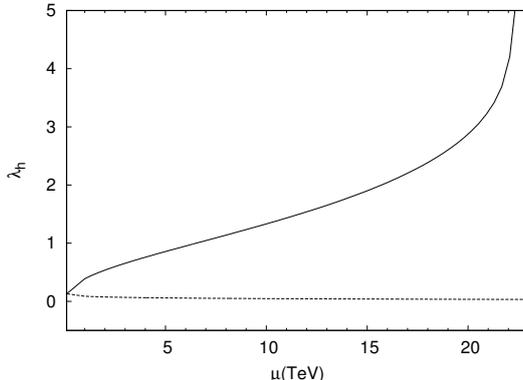


FIG. 1: The running behavior of the IS Higgs quartic coupling λ_h . The solid and dashed lines correspond to λ_h and the SM Higgs quartic coupling, respectively. We fixed the IS Higgs mass $m_h = \sqrt{2\lambda_h}v_h = 125$ GeV and took $\lambda_{hS} = 1.8$ and $\lambda_S = 1.5$. Unlike the SM, the IS Higgs quartic coupling grows up due to a large Higgs-portal coupling λ_{hS} and a small top-Yukawa coupling y_t .

IV. BENCHMARK MODEL WITH COLORED SCALAR

As a benchmark model, we may introduce a real scalar field S in the adjoint representation of the color $SU(3)_c$:

$$\mathcal{L} \supset \mathcal{L}_S = \frac{1}{2}(D_\mu S)^2 - \frac{1}{2}m_{0,S}^2 S^2 - \frac{\lambda_S}{4}S^4 - \frac{\lambda_{hS}}{2}S^2\Phi_h^\dagger\Phi_h, \quad (3)$$

where Φ_h represents the IS Higgs doublet. The effective Lagrangian \mathcal{L} also contains the IS Higgs quartic couplings λ_h , $\mathcal{L} \supset -\lambda_h|\Phi_h|^4$. The IS Higgs mass is $m_h = \sqrt{2\lambda_h}v_h$, and we will take it to be equal to 125 GeV. The mass-squared term for the scalar S is $M_S^2 = m_{0,S}^2 + \frac{\lambda_{hS}}{2}v_h^2$, and should be positive in order to avoid the color symmetry breaking. Typically, $M_S \sim 200$ GeV.

Taking into account the S contribution to $gg \rightarrow h$, we find appropriate values of the Higgs-portal coupling,

$$\lambda_{hS} \simeq 2.5\text{-}2.7 \times \frac{M_S^2}{vv_h}. \quad (4)$$

As a typical value, we may take $\lambda_{hS} = 1.8$ for $M_S = 200$ GeV and $v_t = 50$ GeV.

A comment concerning the IS Higgs quartic coupling λ_h is in order. In the SM, the Higgs mass 125 GeV suggests that the theory is perturbative up to an extremely high energy scale [20]. On the contrary, in the present model, when we take a large Higgs-portal coupling λ_{hS} that reproduces $gg \rightarrow h$ correctly, the quartic coupling λ_h will grow because the β -function for λ_h contains the λ_{hS}^2 term. Also, there is no large negative contribution to the β -function for λ_h from the top-Yukawa coupling $y_t \sim 10^{-2}$.

One can demonstrate such a behavior more explicitly by using the renormalization group equations. In Fig. 1, the running of the coupling λ_h is shown. Taking a large Higgs-portal coupling $\lambda_{hS} = 1.8$ and the S^4 -coupling $\lambda_S = 1.5$, it turns out that the coupling λ_h rapidly grows. The blowup scale strongly depends on the initial values of λ_{hS} and λ_S . A detailed analysis will be performed elsewhere.

Last but not least, we would like to mention that other realizations of the enhancement of the h production are also possible.

V. CONCLUSION

We gave the overview of the typical scenarios with the dynamical EWSB and also introduced the IS Higgs boson model.

In particular, the IS Higgs model can explain the enhanced Higgs diphoton decay rate observed at the LHC, and also makes several predictions. The most important of them is that the value of the top-Yukawa coupling $h\text{-}t\text{-}\bar{t}$ should be close to the bottom-Yukawa one. Another prediction relates to the decay mode $h \rightarrow Z\gamma$, which

is enhanced only slightly, $\Gamma^{\text{IS}}(h \rightarrow Z\gamma) = 1.07 \times \Gamma^{\text{SM}}(H \rightarrow Z\gamma)$, unlike $h \rightarrow \gamma\gamma$. Last but not least, the LHC might potentially discover the top-Higgs resonance h_t , if lucky. For details, see Ref. [1].

I would like to emphasize that the window of the composite Higgs models is still open. Stay tuned!

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