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Partially composite two-Higgs doublet model

DONG-WON JUNG
School of Physics, KIAS Seoul 130-722, Korea
E-mail: dwjung@kias.re.kr

Abstract. In the extra dimensional scenarios with gauge fields in the bulk, the Kaluza–Klein (KK) gauge bosons can induce Nambu–Jona–Lasinio (NJL) type attractive four-fermion interactions, which can break electroweak symmetry dynamically with accompanying composite Higgs fields. We consider a possibility that electroweak symmetry breaking (EWSB) is triggered by both a fundamental Higgs and a composite Higgs arising in a dynamical symmetry breaking mechanism induced by a new strong dynamics. The resulting Higgs sector is a partially composite two-Higgs doublet model with specific boundary conditions on the coupling and mass parameters originating at a compositeness scale Λ. The phenomenology of this model is discussed including the collider phenomenology at LHC and ILC.

Keywords. Dynamical electroweak symmetry breaking; technicolor and composite models; Higgs physics.

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1. Introduction

Although the standard model (SM) has been successful to describe the physics up to $E \sim 200$ GeV, the origin of the electroweak symmetry breaking (EWSB) still remains a mystery. Among the various models for the EWSB, the extra dimensional scenarios have many interesting characteristics. Under this extra dimensional setup, the EWSB can occur in various ways. It can be accomplished by fundamental Higgs bosons, and/or some dynamical way by bulk QCD, and/or nontrivial boundary conditions, etc. It is an interesting observation that in the extra dimensional scenarios the EWSB can be achieved by both fundamental Higgs boson and dynamical fermion condensates. With this philosophy in mind, we study an extension of Bardeen–Hill–Lindner (BHL) scenario [1]. The BHL scenario is particularly interesting since the heavy top mass is intimately related with a new strong dynamics that condenses the $t\bar{t}$ bilinear, and breaks the EW symmetry. The original version of BHL scenario predicts that the top mass should be larger than ~200 GeV, which is no longer viable. The extension of BHL with two composite Higgs doublets has a similar shortcoming [2]. In our model [3], a fundamental scalar particle is introduced in addition to the $t\bar{t}$ condensate, and we successfully fit the top and bottom quark masses simultaneously. Our model predicts $\tan\beta$ between 0.45 and 1. In addition, our model can be tested in the future collider experiments.

2. Model description

We introduce a strong dynamics to the standard model at some high scale Λ, which is effectively described by the NJL-type four-fermion interaction term.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + G(\bar{\psi}_{\rm L} t_{\rm R})(\bar{t}_{\rm R}\psi_{\rm L}), \tag{1}$$

where

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_f + \mathcal{L}_\phi + (y_{t0}\ \bar{\psi}_{\rm L} t_{\rm R}\tilde{\phi} + {\rm H.c.}) + (y_{b0}\ \bar{\psi}_{\rm L} b_{\rm R}\phi + {\rm H.c.}) \tag{2}$$

and $\tilde{\phi} \equiv i\sigma_y \phi^*$. Introducing an auxiliary scalar doublet field $\Phi(x)$, we can rewrite the NJL term in eq. (1) as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + g_{t0}(\bar{\psi}_{\rm L} t_{\rm R}\tilde{\Phi} + {\rm H.c.}) - M^2\Phi^\dagger\Phi, \tag{3}$$

where $G = g_{t0}^2/M^2$ and g_{t0} is a newly defined Yukawa coupling. The mass scale M will be generally of order Λ. The new scalar field Φ describes the composite scalar bosons that appear when the $\langle \bar{t}t\rangle$ develops nonvanishing VEV and breaks the electroweak symmetry. Then we have one fundamental scalar field ϕ and one composite scalar field Φ, although Φ is not a dynamical field at the scale Λ. Far below the scale Λ, the Φ field will develop the kinetic term due to quantum corrections and become dynamical. The resulting low energy effective field theory will be two-Higgs doublet model. The large FCNC problem can be avoided by assigning a Z_2 discrete symmetry [4]

$$(\Phi,\ \psi_{\rm L},\ U_{\rm R}) \to +(\Phi,\ \psi_{\rm L},\ U_{\rm R}),\ (\phi, D_{\rm R}) \to -(\phi, D_{\rm R}).$$

Then the Yukawa term $(y_{t0}\bar{\psi}_{\rm L} t_{\rm R}\phi + {\rm H.c.})$ is forbidden and only the y_{b0} coupling term remains. From now on, we will rename y_{b0} as g_{b0}. As a consequence, our model becomes the Type-II two-Higgs doublet model. We write the effective Lagrangian far below Λ as

$$\begin{aligned}\mathcal{L} = {} & \mathcal{L}_{\rm gauge} + \mathcal{L}_f + (D_\mu\phi)^\dagger(D^\mu\phi) + (D_\mu\Phi)^\dagger(D^\mu\Phi) \\ & + (g_b\bar{\psi}_{\rm L} b_{\rm R}\phi + {\rm H.c.}) + (g_t\bar{\psi}_{\rm L} t_{\rm R}\tilde{\Phi} + {\rm H.c.}) - V(\phi,\Phi),\end{aligned} \tag{4}$$

where the most general Higgs potential is given by

$$\begin{aligned}V(\phi,\Phi) = {} & \mu_1^2\phi^\dagger\phi + \mu_2^2\Phi^\dagger\Phi + (\mu_{12}^2\phi^\dagger\Phi + {\rm H.c.}) + \frac{1}{2}\lambda_1(\phi^\dagger\phi)^2 \\ & + \frac{1}{2}\lambda_2(\Phi^\dagger\Phi)^2 + \lambda_3(\phi^\dagger\phi)(\Phi^\dagger\Phi) + \lambda_4|\phi^\dagger\Phi|^2 \\ & + \frac{1}{2}[\lambda_5(\phi^\dagger\Phi)^2 + {\rm H.c.}].\end{aligned} \tag{5}$$

In the scalar potential, we have introduced a dimension-two μ_{12}^2 term that breaks the Z_2 discrete symmetry softly in order to generate the nonzero mass for the CP-odd Higgs boson. This μ_{12}^2 parameter will be traded with m_A^2. The renormalized at low energy is given by

$$\mathcal{L}_{\rm ren} = Z_\phi (D_\mu\phi)^\dagger(D^\mu\phi) + Z_\Phi(D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\sqrt{Z_\phi}\phi, \sqrt{Z_\Phi}\Phi) + \sqrt{Z_\Phi} g_t(\bar\psi_{\rm L} t_{\rm R}\tilde\Phi + {\rm H.c.}) + \sqrt{Z_\phi} g_b(\bar\psi_{\rm L} b_{\rm R}\phi + {\rm H.c.}), \quad (6)$$

and matching the Lagrangian with eq. (3) at the compositeness scale Λ, we obtain the matching condition

$$\sqrt{Z_\phi} \to 1, \quad \sqrt{Z_\Phi} \to 0, \quad Z_\phi\mu_1^2 \to m_0^2, \quad Z_\Phi\mu_2^2 \to M^2, \quad Z_\phi\lambda_1 \to \lambda_{10}, \quad Z_\Phi^2\lambda_2 \to 0, \quad Z_\phi Z_\Phi \lambda_{i=3,4,5} \to 0, \quad (7)$$

as the scale $\mu \to \Lambda$. Note that our model has nonvanishing $\sqrt{Z_\phi}$ and $Z_\phi\lambda_1$ unlike the Luty's model, and we can fit both the bottom and top quark masses.

3. Particle spectrum

Our model is defined in terms of three parameters: Higgs self-coupling λ_{10}, the compositeness scale Λ (where λ_{10} and the NJL interaction are specified), and the CP-odd Higgs boson mass m_A. Using the field redefinition

$$\phi \to Z_\phi^{-1/2}\phi, \quad \Phi \to Z_\Phi^{-1/2}\Phi, \quad (8)$$

we rewrite the matching condition given in eq. (2.7) as

$$g_b \to g_{b0}, \quad g_t \to \infty, \quad \lambda_1/g_b^4 \to \lambda_{10}/g_{b0}^4, \quad \lambda_{2,3,4,5} \to 0, \quad (9)$$

for the rescaled couplings. These conditions are the boundary conditions for the RG equations. We will use the one-loop RG equations given in ref. [5]. After numerical analysis, we find that the allowed parameter space is rather restricted as Λ increases. Since m_A is a free parameter in our model, other Higgs boson masses can be calculated in various parameter regions. Again, we can get rather narrow band for the Higgs masses as a function of m_A. For $\Lambda \sim 10^{15}$ GeV, m_h larger than 250 GeV is predicted. Also the charged Higgs can be lighter than h, and could be the first signal of our model at future colliders. Generally charged Higgs boson is lighter than the CP-odd Higgs.

4. Higgs production at LHC and ILC

The ratio of self-couplings to the SM values $\lambda_{hhh}/\lambda_{hhh}^{\rm SM}$, $\lambda_{hhhh}/\lambda_{hhhh}^{\rm SM}$ are enhanced for the small mass of the light Higgs boson h. In most parameter region, our triple gauge coupling is negative and it can lead to many interesting phenomenology [3].

The cross-sections predicted in our model are modified from those in the SM by factors [6],

$$\sigma(pp \to gg \to h^0) = \left(\frac{\cos\alpha}{\sin\beta}\right)^2 \sigma_{\rm SM}(pp \to gg \to h^0),$$
$$\sigma(e^+e^- \to Z + h^0/H^0) = \sin^2/\cos^2(\beta-\alpha)\sigma_{\rm SM}(e^+e^- \to Z + h^0/H^0),$$
$$\sigma(e^-e^+ \to \bar\nu_e\nu_e + h^0/H^0) = \sin^2/\cos^2(\beta-\alpha)\sigma_{\rm SM}(e^-e^+ \to \bar\nu_e\nu_e + h^0/H^0). \quad (10)$$

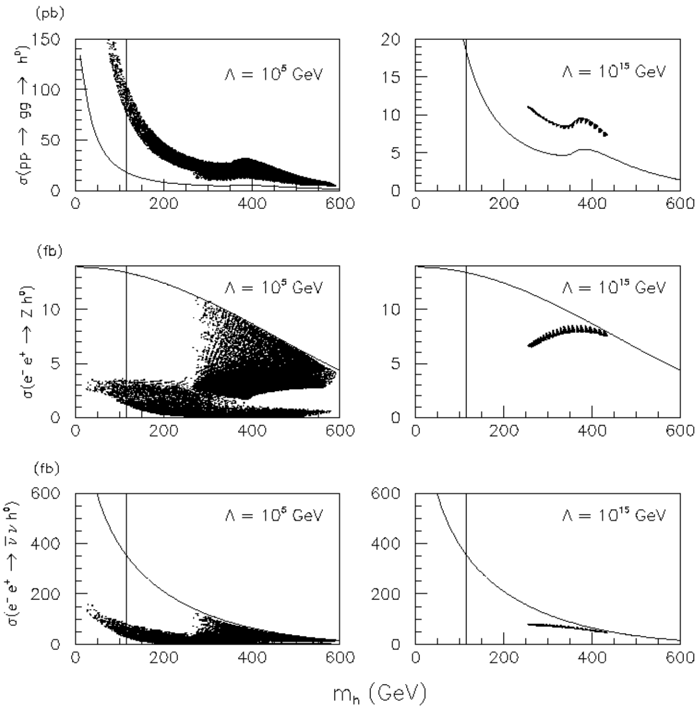

Figure 1. Production cross-section of the neutral Higgs boson at the LHC and ILC. $\sqrt{s} = 14$ TeV for the LHC and $\sqrt{s} = 1$ TeV for the ILC are assumed. The solid curves denote the SM predictions.

In figure 1, we show the single Higgs boson production cross-sections at the LHC and the ILC for different Λ and m_h, etc. For higher Λ, the allowed m_h has a narrow region. Therefore, the cross-sections are almost definitely determined for large Λ, and they will be a strong signature of our model.

5. Summary

We considered an interesting possibility that the Higgs boson produced at the future colliders is neither a fundamental scalar nor a composite scalar, but a mixed state of them. This scenario could be easily realized, if we embed the SM in a higher dimension with bulk gauge interactions. We have constructed the simplest model with the NJL-type four-fermion interaction of top quarks as the strong dynamics inspired by the BHL and study the phenomenology of the two-Higgs doublets model with the compositeness condition as the low energy effective theory. The resulting theory can accommodate the observed top mass, and give specific predictions for neutral and charged Higgs masses at a given value of Λ. The charged Higgs boson is always lighter than the CP-odd Higgs neutral boson, although the mass difference is very small. For $\Lambda \sim 10^{15}$ GeV, the allowed parameter region is rather restricted, and we predict $m_h > 250$ GeV. The cross-sections for the Higgs boson production are modified in our model, and it will be observed in the future colliders, i.e., LHC and ILC.

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