We consider a possibility that electroweak symmetry breaking (EWSB) is triggered by 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 $\Lambda$. The phenomenology of this model is discussed including the collider phenomenology at LHC and ILC.

Keywords: dynamical electroweak symmetry breaking, composite higgs, two-higgs doublet

1. Introduction

EWSB is the origin of the masses of chiral fermions and electroweak gauge bosons as well as CP violation in the quark sector within the standard model (SM). It is most important in particle physics to understand the origin of EWSB, and LHC will serve for this purpose. There have been many attempts to construct interesting models for EWSB beyond the SM.\(^1\)

Dynamical symmetry breaking à la Miransky, Tanabashi, Yamawaki (MTY)\(^2\) and Bardeen, Hill, Lindner (BHL)\(^3\) is a particularly interesting scenario, 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 down to $U(1)_{EM}$. Both heavy top mass and Higgs mass are generated dynamically, in analogy with superconductivity of Bardeen-Cooper-Schrieffer (BCS).

However, there are basically two drawbacks in this model. First, the origin of the new strong interactions that triggers EWSB is not clear. The attractive 4-fermion interaction is simply put in by hand within the BHL model. Also, the original version of BHL with 3 families or its extension with two Higgs doublets\(^4\) predict that the top mass should be significantly heavier than the experimental observation: $m_t = 170.9 \pm 1.1(\text{stat}) \pm 1.5(\text{sys})$
However, these two drawbacks could be evaded within extra dimensional scenarios, without ruining its niceties. If QCD is a bulk theory, then it is possible that the KK gluon exchange can induce attractive Nambu-Jona-Lasinio (NJL) type four-fermion interaction in the low energy regime, and dynamical symmetry breaking can occur in a natural way. It should be emphasized that this is completely different from another popular way of symmetry breaking in extra dimension, namely symmetry breaking by boundary conditions. Therefore, in extra dimensional scenarios, electroweak symmetry can be broken by fundamental Higgs, by boundary condition or by some dynamical mechanism. Generically all three possibilities could be present altogether. In most recent studies, the gauge symmetries were broken by the nontrivial boundary conditions with or without fundamental Higgs. In this talk, I discuss another possibility, where electroweak symmetry is broken by fundamental Higgs VEV’s, as well as dynamically by $t\bar{t}$ condensate. This way we will find that we can avoid both drawbacks of BHL model.

2. A Model of Dynamical EWSB with a Fundamental Scalar

Our model is a simple extension of the SM. We assume there is a new strong dynamics at some high energy scale $\Lambda$, which is effectively described by the NJL type four-fermion interaction term:

$$ L = L_{SM} + G(\bar{\psi}_L t_R ) (\bar{t} R \psi_L), $$

where the SM Higgs doublet $\phi$ is included from the beginnnig, unlike the BHL model. The explicit forms of the SM lagrangians can be found in Ref. The Yukawa couplings for the 1st and the 2nd generations do not play any roles in our analysis, and will be ignored in the following. We don’t specify the origin of this NJL type interaction, but the KK gauge boson exchange in extra dimension scenarios could be one possible origin of this new strong interaction. As a minimal extension of the SM, we assume that this new strong dynamics acts only (or dominantly) on top quark.

We can rewrite the NJL term in Eq.(2.1) in terms of an auxiliary scalar field $\Phi$:

$$ L = L_{SM} + g_{t0}(\bar{\psi}_L t_R \Phi + H.c.) - M^2 \Phi^\dagger \Phi, $$

where $G = g_{t0}^2 / M^2$ with $M \sim \Lambda$. $g_{t0}$ is a newly defined Yukawa coupling between the top quark and the auxiliary scalar field $\Phi$. $\Phi$ describes the composite scalar bosons that appear when the $\langle t\bar{t} \rangle$ develops nonvanishing...
VEV and breaks the electroweak symmetry. 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, one being a fundamental Higgs \( \phi \) and the other being a composite Higgs \( \Phi \). Thus it can be called a partially composite two-Higgs doublet (PC2HD) model.

In order to avoid too large FCNC mediated by neutral Higgs bosons, we assign a \( Z_2 \) discrete symmetry under which the lagrangian is invariant:

\[
(\Phi, \psi_L, U_R) \rightarrow + (\Phi, \psi_L, U_R), \quad (\phi, D_R) \rightarrow - (\phi, D_R).
\]

(3)

With this \( Z_2 \) discrete symmetry, \( t \) and \( b \) couple to \( \Phi \) and the SM Higgs, respectively. In consequence, our model becomes the Type-II two-Higgs doublet model as the minimal supersymmetric standard model (MSSM).

The renormalized lagrangian for the scalar fields at low energy is given by

\[
\mathcal{L}_\text{ren} = Z_\phi (D_\mu \phi)\dagger (D^\mu \phi) + Z_\Phi (D_\mu \Phi)\dagger (D^\mu \Phi) - V(\sqrt{Z_\phi} \phi, \sqrt{Z_\Phi} \Phi) \\
+ \sqrt{Z_\phi} g_t (\psi_L t_R \tilde{\Phi} + \text{h.c.}) + \sqrt{Z_\Phi} g_b (\psi_L b_R \phi + \text{h.c.}),
\]

(4)

with

\[
V(\phi, \Phi) = \mu_1^2 \phi^\dagger \phi + \frac{\mu_2^2}{2} \Phi^\dagger \Phi + (\mu_{12} \phi^\dagger \Phi + \text{H.c.}) + \frac{1}{2} \lambda_1 (\phi^\dagger \phi)^2 + \frac{1}{2} \lambda_2 (\Phi^\dagger \Phi)^2 \\
+ \lambda_3 (\phi^\dagger \phi)(\Phi^\dagger \Phi) + \lambda_4 |\phi^\dagger \Phi|^2 + \frac{1}{2} [\lambda_5 (\phi^\dagger \Phi)^2 + \text{H.c.}],
\]

(5)

In the scalar potential, we have introduced a dimension-two \( \mu_{12}^2 \) term that breaks the discrete symmetry softly in order to generate the nonzero mass for the CP-odd Higgs boson. Otherwise the CP-odd Higgs boson \( A \) would be an unwanted axion related with spontaneously broken global \( U(1) \) Peccei-Quinn symmetry, which would be a phenomenological disaster. This \( \mu_{12}^2 \) parameter will be traded with the \( m_A^2 \), the (mass)\(^2 \) parameter of the CP-odd Higgs boson, which is another free parameter of our model.

Matching the lagrangian with Eq. (2.5) at the compositeness scale \( \Lambda \), we obtain the following matching conditions as \( \mu \rightarrow \Lambda \):

\[
\sqrt{Z_\phi} \rightarrow 1, \quad \sqrt{Z_\Phi} \rightarrow 0, \quad Z_\phi \mu_1^2 \rightarrow n_0^2, \quad Z_\Phi \mu_2^2 \rightarrow M^2, \\
Z_\phi \lambda_1 \rightarrow \lambda_{10}, \quad Z_\Phi \lambda_2 \rightarrow 0, \quad Z_\phi Z_\Phi \lambda_{i=3,4,5} \rightarrow 0.
\]

(6)

These conditions are the boundary conditions for the RG equations.

Before proceeding, we would like to compare our model with Luty’s model.\(^4\) In Luty’s model, both Higgs doublets are composite, and thus the
matching conditions for $Z_{\phi}$ and $\lambda_1$ become

$$\sqrt{Z_{\phi}} \rightarrow 0, \quad Z_{\phi} \lambda_1 \rightarrow 0,$$

which are different from those in our model. These different matching conditions lead to very different predictions for the scalar boson spectra compared to the Luty’s model. Also we have additional Yukawa coupling $g_b$ so that we can fit both the bottom and the top quark masses without difficulty unlike the models by BHL or Luty.

3. Particle Spectra and predictions

Our model is defined in terms of three parameters: Higgs self coupling $\lambda_{10}$, the compositeness scale $\Lambda$ where $\lambda_{10}$ and the NJL interaction are specified, and the CP-odd Higgs boson mass $m_A$. Since $\lambda_{10}$ is also present in the SM, our model has two more parameters compared with the SM. It is straightforward to analyze the conditions for the correct EWSB and the particle spectra. The details can be found in the original paper.\(^7\) In the following, I highlight the main results of our model:

- We can fit both the top and the bottom masses without difficulty in our model, unlike the BHL model or the Luty model, since the bottom quark get massive due to the fundamental Higgs. The allowed region of $\tan \beta$ is rather narrow: $0.45 \lesssim \tan \beta \lesssim 1$. Therefore the $W$ and the $Z$ boson get their masses almost equally from the fundamental Higgs and the $t \bar{t}$ condensation in our model.
- Since $\tan \beta \lesssim 1$, there is a strong constraint from $B \rightarrow X_s \gamma$, which implies that the charged Higgs boson should be heavier than $\sim 400$ GeV.
- There is no CP violating mixing in the neutral Higgs boson sector, since $\lambda_5$ remains zero at all scale within our model.
- $m_{H^\pm} \lesssim m_A$ in our model, and the charged Higgs can be even lighter than the lightest neutral Higgs boson, when the composite scale $\Lambda$ is high. See Fig. 1.
- Triple and quartic self couplings of Higgs bosons can deviate from the SM values by significant amounts.
- Higgs coupling to the top quark is enhanced in our model so that the Higgs production rate at LHC is larger than the SM values. On the other hand, the Higgs productions at the ILC through Higgs–strahlung and the $WW$ fusion are suppressed compared to the SM values. See Fig. 2.
4. Conclusions

In this talk, I considered a 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. It could be a generic feature, if there exists a strong dynamics at a high scale which give rise to the dynamical electroweak symmetry breaking, in addition to the usual Higgs mechanism due to the nonvanishing VEV of a fundamental Higgs. It is interesting that this scenario could be easily realized, if we embed the SM lagrangian in a higher dimension with bulk gauge interactions. 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. Whether such scenario is realized or not in nature could be studied at LHC and ILC.

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Fig. 1. Masses of neutral Higgs bosons $h$ (inside the solid lines), $H$ (inside the dashed lines) and the charged Higgs boson $H^\pm$ (dashed-dotted line) with respect to $m_A$. 
Fig. 2. 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.