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Higgs as a Top-Mode Pseudo*

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In this talk, in the spirit of the top quark condensation, we introduce a model which has a naturally light composite Higgs boson, “tHiggs", to be identified with the 126 GeV Higgs discovered at the LHC. The tHiggs emerges as a pseudo Nambu-Goldstone boson (NGB), “Top-Mode Pseudo", together with the exact NGBs (eaten by the W and Z bosons) as well as another Top-Mode Pseudo (CP-odd composite scalar). Those five NGBs are dynamically produced simultaneously by a four-fermion dynamics.

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1. Introduction

A key clue to access a dynamical origin of the 126 GeV Higgs boson at the LHC [2, 3] would be deduced from an observed coincidence among masses of top quark, Higgs boson and electroweak gauge bosons. This coincidence may imply that the top quark plays a crucial role for both the generation of the electroweak symmetry breaking (EWSB) scale and the generation of the mass of the Higgs boson. Top quark condensation [4, 5, 6] naturally provides such a close relation between those mass scales. However, the original top quark condensate model is somewhat far from a realistic situation, e.g. a Higgs boson predicted as a $t\bar{t}$ bound state has the mass in a range of $m_t < m_H < 2m_t$, which cannot be identified with the 126 GeV Higgs boson at the LHC.

Based on [1] [1], we introduce a new class of the top quark condensate model, where a composite Higgs boson emerges as a pseudo Nambu–Goldstone boson (PNGB) associated with the spontaneous breaking of a global symmetry, which can be as light as the 126 GeV Higgs boson at the LHC.

2. Model

Let us consider a Nambu–Jona-Lasinio (NJL)-like model constructed from the third generation quarks in the SM, $q = (t, b)$, and an $SU(2)_L$ singlet quark (χ). The left-handed quarks q_L and χ_L form a triplet $\psi_L^i \equiv (t_L, b_L, \chi_L)^{T\,i}, (i = 1, 2, 3)$ under the flavor $U(3)_{\psi_L}$ group, while the right-handed top and bottom quarks $q_R^i \equiv (t_R, b_R)^i, (i = 1, 2)$ and χ_R are a doublet and singlet under the $U(2)_{q_R}$ group, respectively. The electroweak gauge symmetry is embedded as a subgroup of the global symmetry. We thus write the global $U(3)_{\psi_L} \times U(2)_{q_R} \times U(1)_{\chi_R}$-invariant Lagrangian: $\mathscr{L}_{\text{kin.}} + \mathscr{L}^{4f}$ where

$$\mathscr{L}^{4f} = G(\bar{\psi}_L^i \chi_R)(\bar{\chi}_R \psi_L^i)\,, \tag{2.1}$$

and G denotes the four-fermion coupling strength. We can derive the gap equations for fermion dynamical masses $m_{t\chi}$ and $m_{\chi\chi}$ through the mean field relations $m_{t\chi} = -G\langle \bar{\chi}_R t_L \rangle$ and $m_{\chi\chi} = -G\langle \bar{\chi}_R \chi_L \rangle$ in the large N_c limit: $m_{t\chi,\chi\chi} = m_{t\chi,\chi\chi}[N_c G/(8\pi^2)][\Lambda^2 - (m_{t\chi}^2 + m_{\chi\chi}^2)\ln\Lambda^2/(m_{t\chi}^2 + m_{\chi\chi}^2)]$ where Λ stands for the cutoff of the model. There exist nontrivial solutions $m_{t\chi} \neq 0$ and $m_{\chi\chi} \neq 0$ when the criticality condition is satisfied: $G > G_{\text{crit}} = 8\pi^2/(N_c\Lambda^2)$ under which we have the nonzero dynamical masses as well as the nonzero condensates, $\langle \bar{\chi}_R q_L \rangle \neq 0$ and $\langle \bar{\chi}_R \chi_L \rangle \neq 0$.

In order to make the structure of the symmetry breaking clearer, we may change the flavor basis of fermions $\psi_L \to \tilde{\psi}_L$ by an orthogonal rotation. The above gap equations are then reduced to a single gap equation, $1 = [N_c G/(8\pi^2)]\left[\Lambda^2 - m_{\tilde{\chi}\chi}^2 \ln\Lambda^2/m_{\tilde{\chi}\chi}^2\right]$ with $m_{\tilde{\chi}\chi}^2 \equiv m_{t\chi}^2 + m_{\chi\chi}^2 \neq 0$. Accordingly, the associated two condensates are reduced to a single nonzero condensate on the basis of $\tilde{\psi}_L$: $\langle \bar{\chi}_R \tilde{\chi}_L \rangle \neq 0$. We thus see that, with the criticality condition satisfied, the four-fermion dynamics triggers the global symmetry breaking pattern $U(3)_{\tilde{\psi}_L} \times U(1)_{\chi_R} \to U(2)_{\tilde{q}_L} \times U(1)_{V=\tilde{\chi}_L+\chi_R}$. The broken currents associated with this symmetry breaking are found to be $J_{3L}^{a,\mu} = \bar{\tilde{\psi}}_L \gamma^\mu \lambda^a \tilde{\psi}_L$ and $J_A^{a,\mu} \equiv (1/4)(\chi_R \gamma^\mu \chi_R - \bar{\tilde{\psi}}_L \lambda^A \tilde{\psi}_L)$ where $\lambda^a (a = 4, 5, 6, 7, A)$ are the Gell-Mann matrices normalized as $\text{tr}[\lambda^a \lambda^b] = 2\delta^{ab}$ and $\lambda^A = \text{diag}(0, 0, \sqrt{2})$. The associated five NGBs emerge with the

[1] At almost the same time as [1] a similar model was proposed in a slightly different context [7].

decay constant f as $\langle 0 | J_\mu^a(x) | \pi_t^b(p)\rangle = -if\delta^{ab}p_\mu e^{-ip\cdot x}$ where the decay constant f is calculated through the Pagels-Stokar formula [8]: $f^2 = (N_c/8\pi^2)m_{\tilde{\chi}\chi}^2 \ln(\Lambda^2/m_{\tilde{\chi}\chi}^2)$. The five NGBs (π_t^a) can be expressed as composite fields (interpolating fields) made of the fermion bilinears on the basis of $(\tilde{\psi}_L,\ \chi_R)$. Besides these composite NGBs, there exists a composite scalar (H_t^0) corresponding to the σ mode in the usual NJL model, $H_t^0 \sim \bar{\chi}_R\tilde{\chi}_L + \bar{\tilde{\chi}}_L\chi_R$ with the mass $m_{H_t^0}^2 = 4m_{\tilde{\chi}\chi}^2$. The H_t^0 will be regarded as a heavy Higgs boson with the mass of $\mathscr{O}(1)$ TeV, not the light Higgs boson at around 126 GeV.

We incorporate explicit breaking terms into the Lagrangian to give masses to some NGBs: $\mathscr{L}_{\text{kin.}} + \mathscr{L}^{4f} + \mathscr{L}^h$ where $(\Delta_{\chi\chi}, G' > 0)$

$$\mathscr{L}^h = -\left[\Delta_{\chi\chi}\bar{\chi}_R\chi_L + \text{h.c.}\right] - G'\left(\bar{\chi}_L\chi_R\right)\left(\bar{\chi}_R\chi_L\right). \tag{2.2}$$

The gap equations for fermion dynamical masses $m_{t\chi,\chi\chi}$ are given by $m_{t\chi} = m_{t\chi}[N_cG/(8\pi^2)][\Lambda^2 - m_{\tilde{\chi}\chi}^2 \ln\Lambda^2/m_{\tilde{\chi}\chi}^2]\,, m_{\chi\chi} = \Delta_{\chi\chi} + m_{\chi\chi}[N_c(G-G')/(8\pi^2)][\Lambda^2 - m_{\tilde{\chi}\chi}^2 \ln\Lambda^2/m_{\tilde{\chi}\chi}^2]$ where $m_{\tilde{\chi}\chi}^2 = m_{t\chi}^2 + m_{\chi\chi}^2$. In this case, the nonzero $\Delta_{\chi\chi}$ and G' allow to determine the ratio of two dynamical masses $m_{t\chi}$ and $m_{\chi\chi}$, i.e. $\tan\theta = m_{t\chi}/m_{\chi\chi}$, in contrast to the previous gap equations which only determine the squared-sum of two, $m_{t\chi}^2 + m_{\chi\chi}^2$. It turns out that Eq.(2.2) does not affect the criticality of the four-fermion dynamics at all. Eq.(2.2) forces the vacuum to choose a specific direction, $\langle\bar{\chi}_R\tilde{\chi}_L\rangle \neq 0$, and give masses to some of the NGBs. In fact, Eq.(2.2) is invariant under the chiral transformation associated with the broken currents $(J_{3L}^{6,\mu} \pm iJ_{3L}^{7,\mu})$ and $(J_{3L}^{4,\mu}\cos\theta + J_{3L}^{A,\mu}\sin\theta)$, but not for $J_{\mu 3L}^5$ and $(-J_{3L}^{4,\mu}\sin\theta + J_{3L}^{A,\mu}\cos\theta)$. Hence Eq.(2.2) gives masses only to the NGBs associate with latter two:

$$m_{z_t^0}^2 = m_{w_t^\pm}^2 = 0 \quad , \quad m_{A_t^0}^2 = \frac{2\langle\bar{\chi}_R\tilde{\chi}_L\rangle\langle\bar{\chi}_R\chi_L\rangle}{f^2\cos\theta} \quad , \quad m_{h_t^0}^2 = m_{A_t^0}^2\sin^2\theta\,. \tag{2.3}$$

The would-be NGBs $(z_t^0, w_t^\pm)$ eaten by the Z and W bosons are found to be $z_t^0 \equiv \pi_t^4\cos\theta + \pi_t^A\sin\theta\,, w_t^\pm \equiv (1/\sqrt{2})(\pi_t^6 \mp i\pi_t^7)$. Other NGBs remain as physical states: $h_t^0 \equiv \pi_t^5\,, A_t^0 \equiv -\pi_t^4\sin\theta + \pi_t^A\cos\theta$ and these NGBs become pseudo NGBs, called "Top-Mode Pseudos", obtaining their masses once explicit breaking effects are introduced as Eq.(2.2).

We identify the CP-even Top-Mode Pseudo, h_t^0, as the 126 GeV Higgs, called tHiggs. The mass of h_t^0 is proportional to $m_{t\chi}$ associated with the EWSB scale v_{EW} as $\sin\theta = m_{t\chi}/m_{\tilde{\chi}\chi} = v_{\text{EW}}/f$, just like the case of the SM Higgs boson, while the mass of A_t^0 is not. We thus set the mass of h_t^0 to $\simeq 126$ GeV: $m_{h_t^0} = m_{A_t^0}\sin\theta \simeq 126\,\text{GeV}$.

3. Phenomenological constraints on Top-Mode Pseudos

After adding four-fermion interactions to give the SM fermion masses, we find the tHiggs h_t^0 couplings to the SM particles in the present model are described by (see [1, 10] for details)

$$g_{hVV}\frac{v_{\text{EW}}}{2}\left(g^2 h_t^0 W_\mu^+ W^{-\mu} + \frac{g^2+g'^2}{2}h_t^0 Z_\mu Z^\mu\right) - \sum_{f=t,b\tau} g_{hff}\frac{m_f}{v_{\text{EW}}}h_t^0\bar{f}f\,, \tag{3.1}$$

where $g_{hVV} = g_{hbb} = g_{h\tau\tau} = \cos\theta$ and $g_{htt} = \sqrt{(1+\cos^2\theta)/2}$. We see that the h_t^0 couplings to the W and Z bosons and to the SM fermions become the same as the SM Higgs ones when we take the limit $\cos\theta \to 1$, i.e., $g_{hVV} = g_{hbb} = g_{h\tau\tau} = g_{htt} = g^{\text{SM}}(=1)$ when $\sin\theta = v_{\text{EW}}/f \to 0$ by $f \to \infty$ with

$v_{\rm EW} = 246\,{\rm GeV}$ fixed. Examining Eq.(3.1), we see that the couplings of h_t^0 to the W and Z bosons deviate from the SM Higgs ones by $\kappa_V \equiv g_{hVV}/g_{hVV}^{\rm SM} = \cos\theta$ where $V = W$ and Z. The current LHC data give the constraint on κ_V to be $\kappa_V > 0.94$ at 95% C.L. for the 126 GeV Higgs boson [9]. Therefore, we obtain the following constraint on the angle θ: $\sin\theta < 0.34$. This bound combined with the mass relation in Eq.(2.3) constrains the A_t^0 mass to be $m_{A_t^0} \gtrsim 370\,{\rm GeV}$. The A_t^0 does not couple to the W and Z bosons due to the CP-symmetry and couplings to other SM particles are generically suppressed by $\sin\theta (< 0.34)$. Hence the A_t^0 is distinguishable from that of the SM-like Higgs boson in the high-mass SM Higgs boson search at the LHC. More detailed LHC study is discussed in [10].

4. Summary

We introduced a model which has a naturally light composite Higgs boson, tHiggs, to be identified with the 126 GeV Higgs in the spirit of the top quark condensation based on [1]. The tHiggs, a bound state of the top quark and its flavor (vector-like) partner, emerges as a pseudo NGB. The coupling properties of the tHiggs are shown to be consistent with the currently available data reported from the LHC.

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