Toward understanding the phase structure of the Fundamental Composite Higgs

Work in progress

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I will talk

1. Composite Higgs and pNGB scenarios

2. Fundamental composite Higgs and phase structure

3. Summary

§1 Composite Higgs and pNGB Scenarios

- A new boson was discovered in July, 2012 and it has been found that the nature is almost SM-like.

However, it is on-going problem whether or not the discovered scalar particle is really the SM higgs boson.

In particular, it is still big issue whether the Higgs boson is an elementary (point-like) particle or a composite object.

- Old fashioned Technicolor models had been severely constrained. A pseudo Nambu-Goldstone boson (pNGB) scenario is still viable.

S. Weinberg,PRD13,974(1976);PRD19,1277(1979); L. Susskind, PRD20,2619(1979).

Kaplan, Georgi, PLB136, 183 (1984); Kaplan, Georgi, Dimopoulos, PLB136, 187 (1984).

The minimal scenario of the pNGB Higgs is based on SO(5)/SO(4).

$$h, \pi^{\pm}_{W}, \pi_Z$$

Agashe, Contino, Pomarol, NPB719(2005)165.

A next to minimal scenario is based on SU(4)/Sp(4).

$$h, \eta, \pi^{\pm}_{W}, \pi_Z$$

Katz, Nelson, Walker, JHEP08(2005)074;
Evans, Galloway, Luty, Tacchi, JHEP10(2010)086;
Cacciapaglia, Sannino, JHEP04(2014)111.

Lattice simulation

Lewis, Pica, Sannino, PRD85(2012)014504;
Hietanen, Lewis, Pica, Sannino, JHEP12(2014)130.

Do the composite Higgs scenarios contradict experiments?

- Usually, the composite Higgs models predict several exotica:

Z’, W’, vector-like fermions Q, extra scalars S, etc.

↓

They might be heavy, or their detectability might be low…

- In the composite Higgs models, several couplings often deviate from the SM values:

hZZ/hWW, Yt, hhh, etc.

↓

Those effects might be hidden at present...

Hint from VLQ models: Possibility of Enhanced Yt

The top Yukawa coupling is still unclear and thus there is a room of BSM.
However, simple models cannot yield an enhanced top Yukawa coupling consistently with the experimental constraints.

The Simplest Vector-like Quark model

$$\text{Yt} = \cos^2\theta_L \, g_{\bar{t}th}^{\text{SM}}$$

Always suppressed!

Other Simple Cases

cf) 2HDM Yt= $\frac{m_t}{v}\frac{c_\alpha}{s_\beta}$

gg → h inevitably enhanced when Yt is bigger.

→ Big Yt requires more extra fields!

Previously, I studied the vector-like quark model with exotic hypercharge assuming one composite Higgs doublet:

MH, Phys.Rev. D96 (2017) no.3, 035020 .

$$\mathcal{L}_Y = -y_{11}\bar{q}_L\tilde{H}t_R - y_{13}\bar{q}_L\tilde{H}\chi_R - y_{21}\bar{Q}_L H t_R - y_{23}\bar{Q}_L H\chi_R - y_{32}\bar{\chi}_L H^\dagger Q_R,$$
$$\mathcal{L}_{\rm VM} = -m_{22}\bar{Q}_L Q_R - m_{33}\bar{\chi}_L\chi_R - m_{31}\bar{\chi}_L t_R,$$
$$\mathcal{L}_{\rm zero} = -0\bar{q}_L H Q_R$$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$q_L=(t,b)_L$	**3**	**2**	$\frac{1}{6}$
t_R	**3**	**1**	$\frac{2}{3}$
b_R	**3**	**1**	$-\frac{1}{3}$
$Q_{L,R}=(X,T)_{L,R}$	**3**	**2**	$\frac{7}{6}$
$\chi_{L,R}$	**3**	**1**	$\frac{2}{3}$

TABLE I: Charge assignment for the VLQ's

$+5/3$

$$\mathcal{L}_M = -(\bar{t}_L\ \bar{T}_L\ \bar{\chi}_L)\ \mathcal{M}\begin{pmatrix} t_R \\ T_R \\ \chi_R \end{pmatrix} - m_{22}\bar{X}_L X_R$$

$$\mathcal{M} \equiv \frac{v}{\sqrt{2}}\mathbf{Y} \oplus \mathbf{M} \oplus \mathbf{O}$$

$$= \frac{v}{\sqrt{2}}\begin{pmatrix} y_{11} & 0 & y_{12} \\ y_{21} & 0 & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_{22} & 0 \\ m_{31} & 0 & m_{33} \end{pmatrix}$$

$$\mathcal{M}_{12} \equiv 0,$$

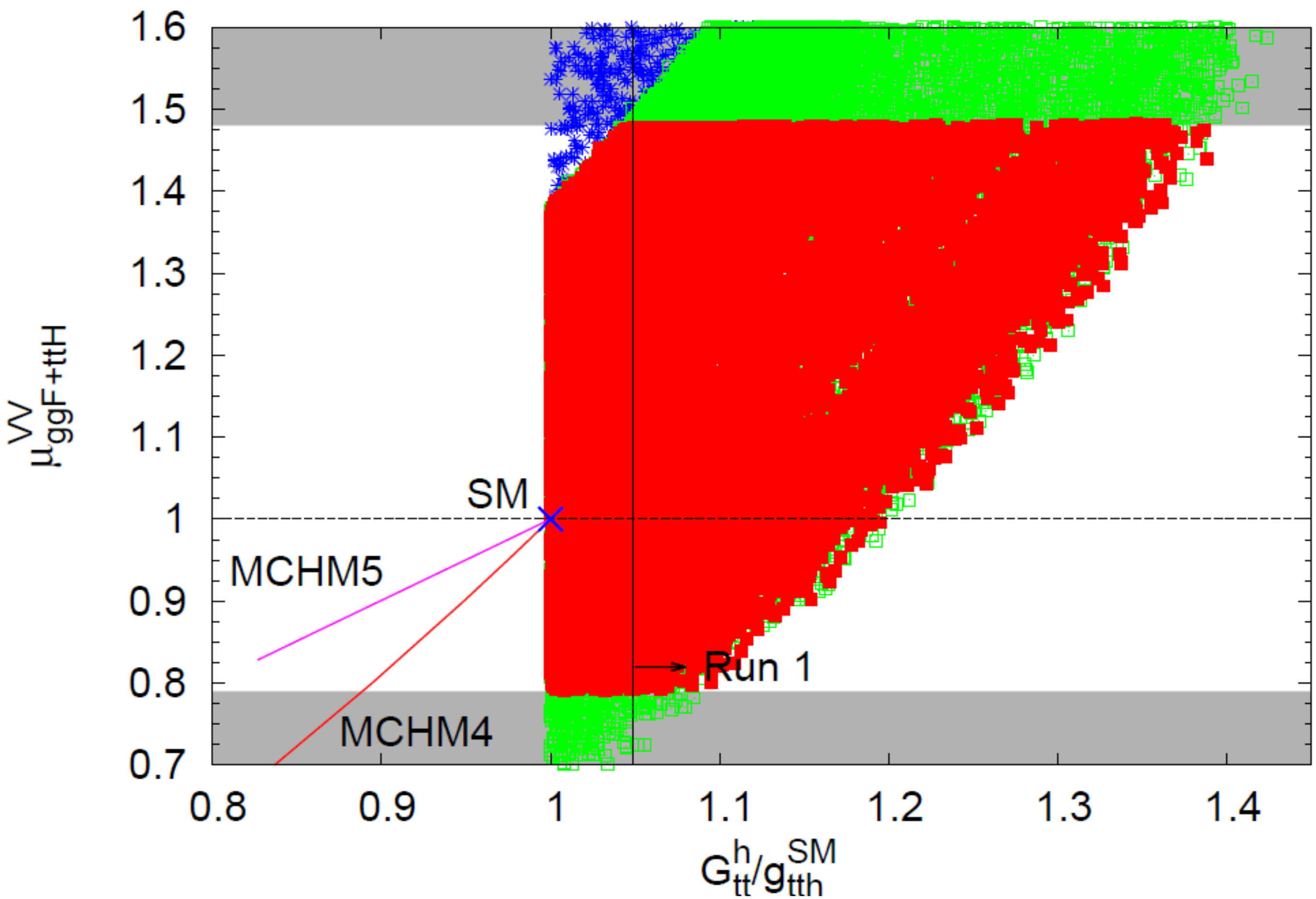
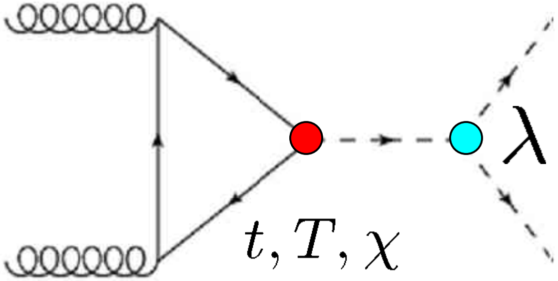
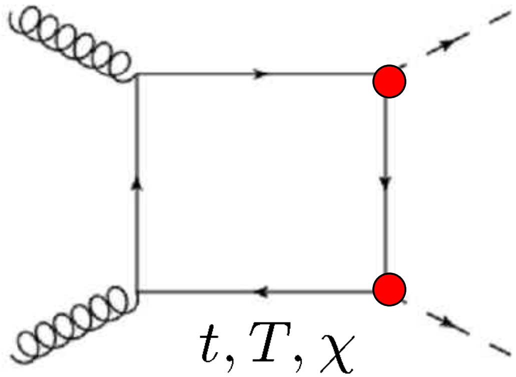


FIG. 1: $\mu^{VV}_{ggF+ttH}$ vs G^h_{tt}/g^{SM}_{tth}. We fixed $M_T = 1.2$ TeV and took the mass range, $1.5 \leq M_U \leq 3.5$ TeV. The upper and lower shaded regions are outside of the 2σ constraints (43). The red points are inside of the 2σ constraints of the LHC Run 1. The green points satisfy only the conditions of $G^h_{tt}/g^{SM}_{tth} > 1$ and $G^h_{TT} < 0$, and the S, T-constraints, while in the blue ones, $G^h_{tt}/g^{SM}_{tth} > 1$ and $G^h_{TT} > 0$. We do not show the results with $G^h_{tt}/g^{SM}_{tth} < 1$ in our model, although they exist. We also show the results for MCHM4 and MCHM5.

MH, Phys.Rev. D96 (2017) no.3, 035020 .

$gg \to hh$ process





In the lowest order of the 1/M expansion,

$$R^{\text{tri}}_{gg\to h} = \frac{\mathcal{A}_{gg\to h}}{\mathcal{A}^{\text{SM}}_{gg\to h}} = v\,\text{Tr}(\mathbf{G}^h \mathcal{M}^{-1}_{\text{diag}}),$$

$$R^{\text{box}}_{gg\to hh} = \frac{\mathcal{A}^{\text{box}}_{gg\to hh}}{\mathcal{A}^{\text{SM,box}}_{gg\to hh}} = v^2\,\text{Tr}(\mathbf{G}^h \mathcal{M}^{-1}_{\text{diag}} \mathbf{G}^h \mathcal{M}^{-1}_{\text{diag}}),$$

In our case, we can show

$$R^{\text{box}}_{gg\to hh} = \left(R^{\text{tri}}_{gg\to h}\right)^2 - 3\left(R^{\text{tri}}_{gg\to h} - 1\right)$$

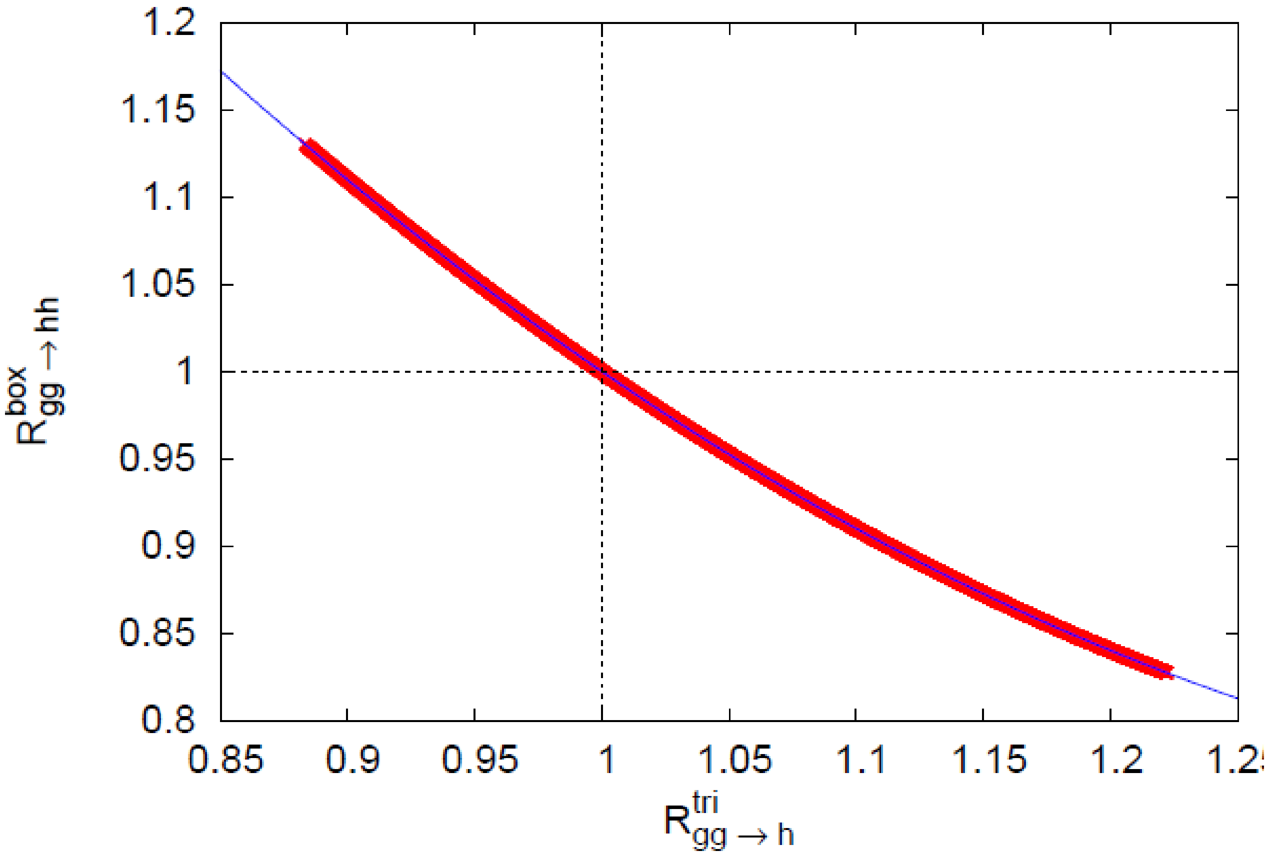


FIG. 5: $R^{\rm tri}_{gg\to h}$ vs $R^{\rm box}_{gg\to hh}$. The red points are inside of the 2σ constraints (43). The blue curve corresponds to the analytical relation, $R^{\rm box}_{gg\to hh} = \left(R^{\rm tri}_{gg\to h}\right)^2 - 3\left(R^{\rm tri}_{gg\to h} - 1\right)$, shown in Eq. (47).

§.2 Fundamental composite Higgs and phase structure

Work in progress

Composite Higgs based on $\mathrm{SU}(4)/\mathrm{Sp}(4)$

5 pNGBs = $\pi_{W^\pm}, \pi_z, h, \eta$

Cacciapaglia, Sannino, JHEP04(2014)111.

⇨ Let us study the effective potential and the phase structure based on a Nambu-Jona-Lasinio model.

global SU(4) fermion:

(left-handed notation)

$$\Psi \equiv \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix}$$

	$SU(2)_{\text{HC}}$	$SU(2)_W$	$U(1)_Y$
$\varphi = (\varphi_1, \varphi_2)^T$	$\square$	$\square$	0
χ_1	$\square$	$\mathbf{1}$	$-1/2$
χ_2	$\square$	$\mathbf{1}$	$+1/2$

$$\mathcal{L}_{\text{NJL}} = \frac{\kappa_1}{\Lambda^2}(\Psi^a i\sigma_2 \Psi^b)(\bar{\Psi}^a i\sigma_2 \bar{\Psi}^b) + \frac{\kappa_2}{4\Lambda^2}\left(\epsilon_{abcd}(\Psi^a i\sigma_2 \Psi^b)(\Psi^c i\sigma_2 \Psi^d) + (\text{h.c.})\right)$$

$i\sigma_2$ acts on SU(2) gauge int.

After bosonization,

$$\frac{1}{\Lambda^2}(\Psi^a i\sigma_2 \Psi^b) \sim \Phi^{ab} = \begin{pmatrix} (S + i\phi^5)\epsilon & i\phi^1\tau_1 + i\phi^2\tau_2 + i\phi^3\tau_3 + \phi^4\mathbf{1}_2 \\ -i\phi^1\tau_1 + i\phi^2\tau_2 - i\phi^3\tau_3 - \phi^4\mathbf{1}_2 & -(S - i\phi^5)\epsilon \end{pmatrix}$$

$$\mathcal{L}_{\text{int}} = -\frac{1}{\kappa_1 + \kappa_2}\left[(\kappa_1 \Phi^*_{ab} + \frac{1}{2}\kappa_2 \epsilon_{abcd}\Phi^{cd})(\Psi^a i\sigma_2 \Psi^b) + (\text{h.c.})\right] - \frac{\kappa_1 \Lambda^2}{(\kappa_1+\kappa_2)^2}\Phi^*_{ab}\Phi^{ab} - \frac{\kappa_2\Lambda^2}{4(\kappa_1+\kappa_2)^2}(\epsilon_{abcd}\Phi^{ab}\Phi^{cd} + (\text{h.c}))$$

Let us define $\langle S \rangle = s, \quad \langle \phi^4 \rangle = h, \quad \bar{m}^2 \equiv \frac{(\kappa_1 - \kappa_2)^2}{(\kappa_1 + \kappa_2)^2}(s^2 + h^2)$

ϕ^{1-5} is pNGBs

(S is NOT pNGB.)

The eff. pot. is

$$V_{\text{eff}} = \frac{\kappa_1 - \kappa_2}{(\kappa_1+\kappa_2)^2}\Lambda^2(s^2 + h^2) - \frac{\Lambda^4}{8\pi^2}\left[\log(1 + \bar{m}^2/\Lambda^2) - \frac{\bar{m}^4}{\Lambda^4}\log(1 + \Lambda^2/\bar{m}^2) + \bar{m}^2/\Lambda^2 - 1\right],$$

Λ is the momentum cutoff.

When $\frac{\kappa_1 - \kappa_2}{4\pi^2} > 1$ there appears a nontrivial solution.

To determine the VEVs of s and h, we need to incorporate the top loop effects and the explicit SU(4) breaking mass terms.

In fact, we can rotate away the VEV of h by using the SU(4) sym,

$$g = \begin{pmatrix} \cos\frac{\theta}{2}\mathbf{1}_2 & -\epsilon\sin\frac{\theta}{2} \\ \epsilon\sin\frac{\theta}{2} & \cos\frac{\theta}{2}\mathbf{1}_2 \end{pmatrix}, \quad \cos\theta \equiv \frac{s}{\sqrt{s^2+h^2}}, \qquad \sin\theta \equiv \frac{h}{\sqrt{s^2+h^2}}$$

$$\langle \Phi'^{\,ab} \rangle \equiv \langle g \Phi^{ab} g^T \rangle = \sqrt{s^2+h^2} \begin{pmatrix} \epsilon & 0 \\ 0 & -\epsilon \end{pmatrix}$$

In order to get the VEV of h, we introduce

$$\mathcal{L}_{\rm top} \sim \frac{Y}{\Lambda^2}(\bar{Q}^a_L T^b_R)(\Psi^a \varepsilon_{\rm HC} \Psi^b),$$

and after the bosonization, it gives the top yukawa int. like

$$\mathcal{L}_{\rm top} = y{\rm tr}\left[\,\bar{Q}_L \Phi T_R\,\right].$$

We introduced the spurion fields Q_L and T_R with

$$Q_L = \begin{pmatrix} 0 & 0 & t_L & 0 \\ 0 & 0 & b_L & 0 \\ -t_L & -b_L & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \qquad T_R = t_R \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

The corresponding effective potential is

$$V_t = -\frac{\Lambda^4}{8\pi^2}\Big[\log(1+m_t^2/\Lambda^2) - \frac{m_t^4}{\Lambda^4}\log(1+\Lambda^2/m_t^2) + m_t^2/\Lambda^2 - 1\Big],$$

with $$m_t = \frac{y}{\sqrt{2}}h$$

For the explicit breaking term of $SU(4)$, we may introduce another spurion field:

$$\mathcal{L}_M = -\Psi^T M \Psi + (\text{h.c}), \qquad M \to g^* M g^\dagger,$$

with

$$M = \begin{pmatrix} m_1\epsilon & 0 \\ 0 & m_2\epsilon \end{pmatrix}.$$

Assuming $m_1 \approx m_2$, we find $$V_M = -\frac{\Lambda^2 s}{4\pi^2}\Delta_M, \qquad \Delta_M \equiv m_1 - m_2.$$

Then, the total effective potential is

$$V_{\rm tot} = V(s^2 + h^2) + V_t(h^2) + V_M(s)$$

This strongly depends on the spurion fields…

Solving the gap equations, we find

$$s = \frac{\Delta_M}{y^2} \, .$$

We can also obtain the expression of the VEV h from the gap equation.

Outlook

★ We didn't include the weak gauge boson loop effects,
but, it is possible.

★ It is straightforward to calculate the mass terms for the Higgs and the extra scalars, and also the deviations from the SM couplings, for example, Yt, hWW/hZZ, etc.

★ Also, we can obtain the hhh coupling, the S-h-h interaction, etc.
(Note that the NGBs have only the derivative couplings, i.e., there is no hhh coupling without the explicit breaking terms.)

§.3 Summary

- There is a longstanding problem concerning with the origin of the Higgs field. The Higgs compositeness is still important issue.

- I discussed how to get the NJL model based on SU(4)/Sp(4). Such a NJL approach is useful at the first step to figure out the nature of the fundamental composite Higgs model.

Thank you!