Fundamental Composite Higgs and Phase Structure

2020.02.20@KEK

Michio Hashimoto
(Musashi U)

Work in progress

I will talk

1. Composite Higgs and pNGB scenarios

2. Nature of composite Higgs

3. Fundamental composite Higgs and phase structure

4. 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 BEH 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).

$$h, \pi_W^{\pm}, \pi_Z$$

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

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

$$h, \eta, \pi_W^{\pm}, \pi_Z$$

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.

§.2 Nature of Composite Higgs

(1) Composite Higgs models are closely connected with exotica:

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

(2) In composite Higgs models, several couplings may deviate from the SM values:

hZZ/hWW, Yt, hhh, etc.

(3) In composite Higgs models, several off-shell production processes may also deviate from the SM values:

gg → h* → ZZ, qqbar → Z'* → Zh, gg → S* → hh, etc.

(4) Analysis of higher dim. operators is more general, but, only a few operators are analyzed.

Hint from VLQ models: Possibility of Enhanced Yt

(mixture of (1) and (2) in the previous slide)

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

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

Always suppressed!

Other Simple Cases

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:

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

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$q_L = (t,b)_L$	**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

$+5/3$

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

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

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

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

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

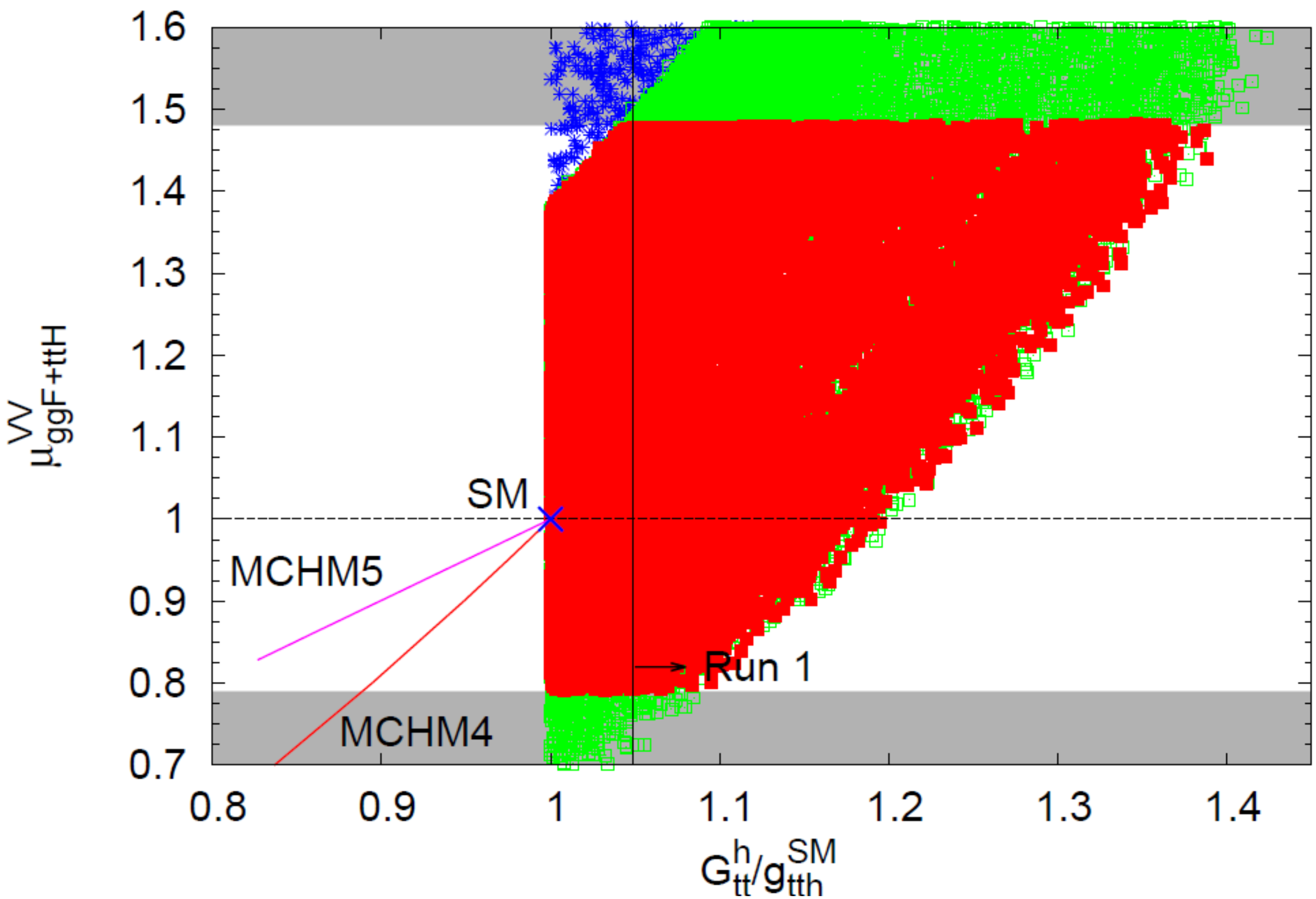
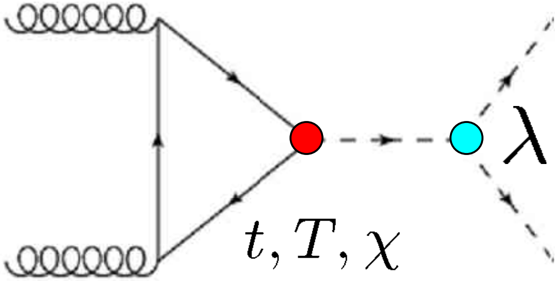
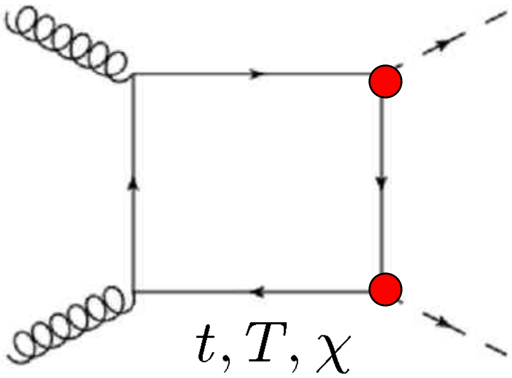


FIG. 1: $\mu^{VV}_{ggF+ttH}$ vs G^h_{tt}/g^{SM}_{tth}. We fixed $M_T = 1.2$ TeV and took the mass range, $1.5 \leq M_U \leq 3.5$ TeV. The upper and lower shaded regions are outside of the 2σ constraints (43). The red points are inside of the 2σ constraints of the LHC Run 1. The green points satisfy only 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,

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

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

In our case, we can show

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

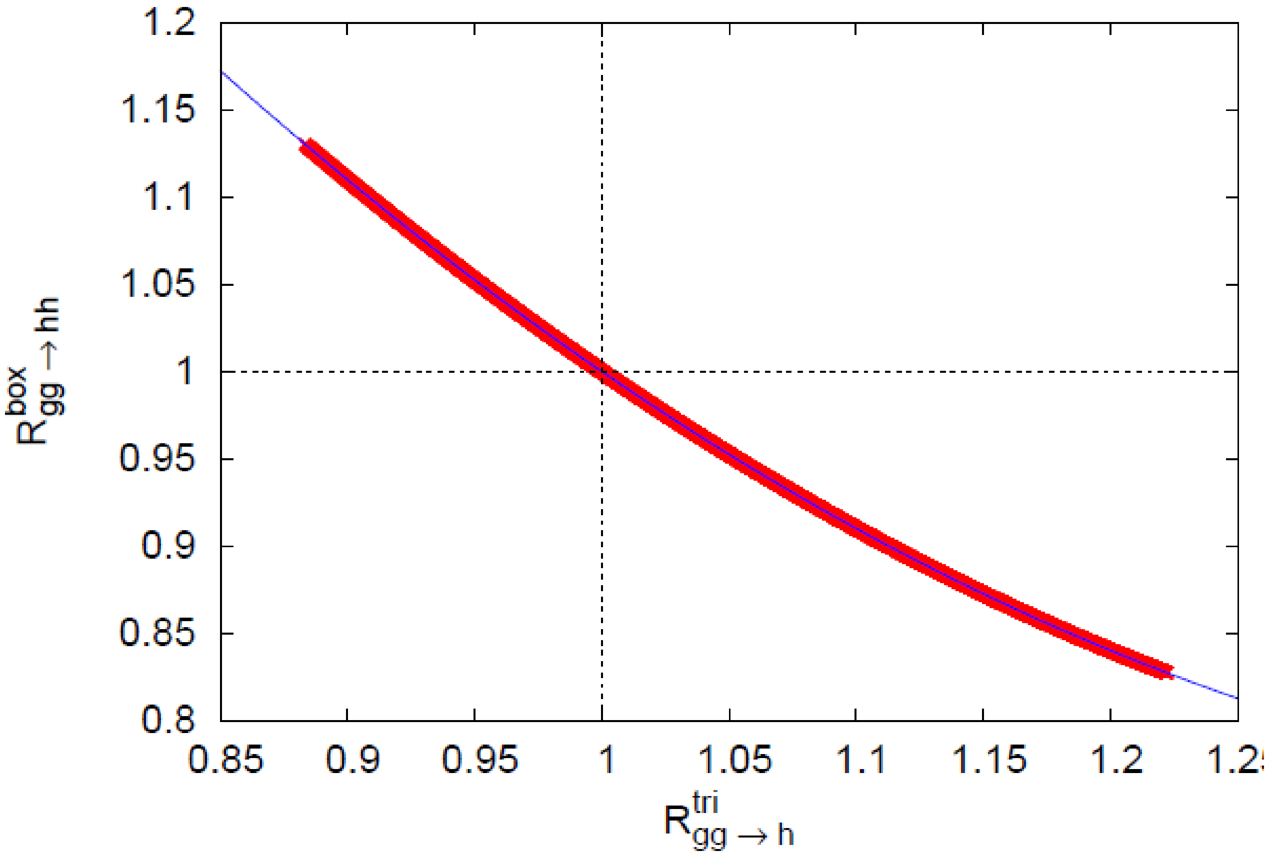
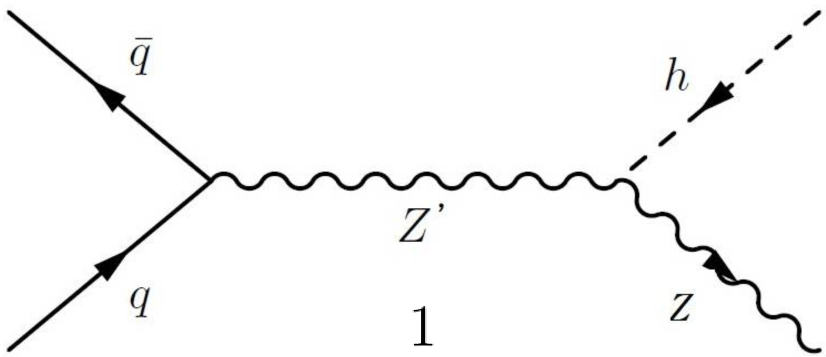


FIG. 5: $R^{\rm tri}_{gg\to h}$ vs $R^{\rm box}_{gg\to hh}$. The red points are inside of the 2σ constraints (43). The blue curve corresponds to the analytical relation, $R^{\rm box}_{gg\to hh} = \left(R^{\rm tri}_{gg\to h}\right)^2 - 3\left(R^{\rm tri}_{gg\to h} - 1\right)$, shown in Eq. (47).

(3) Off-shell production processes and Form Factor



$$\frac{1}{q^2 - M^2}$$

VMD like form factor:

$$\frac{q^2}{M^2}$$

Taylor expansion

If there exists an extra scalar S and it couples to h (125GeV) and top, we have a process,

gg → S* → hh

Similarly to the above process, we obtain the VMD like form factor below the mass scale of S.

If the 125 GeV Higgs boson has own size characterized by the underlying strong dynamics, there must appear a form factor F(q):

Schematically speaking,

point-like particle: $\delta(x) \rightarrow F(q) = 1$

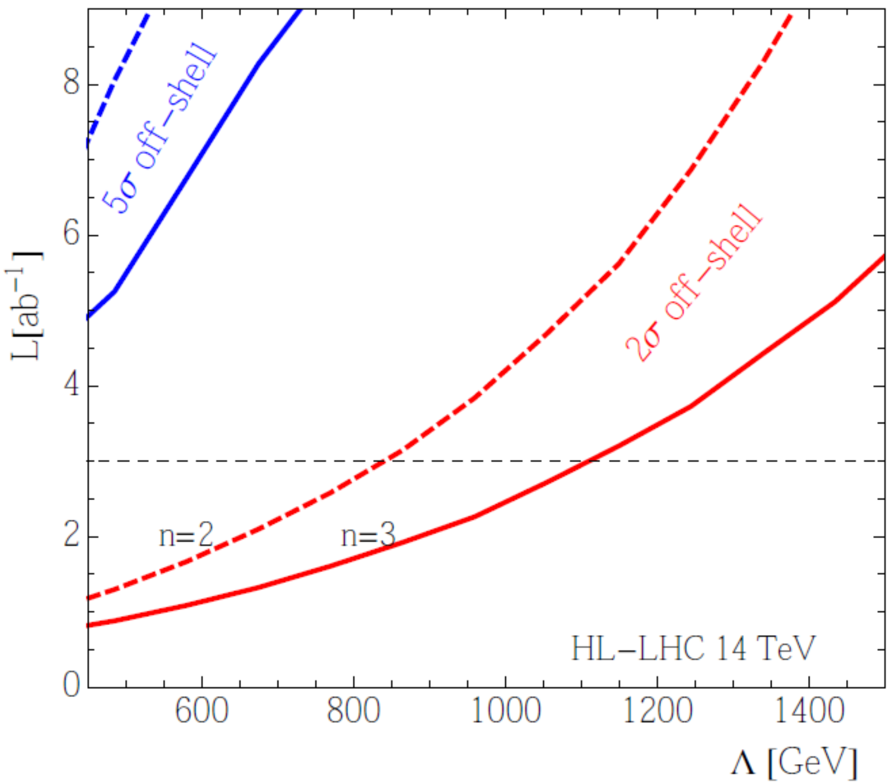
exponential-type: $e^{-r\Lambda}$

$$F(q) = \frac{1}{(1 + q^2/\Lambda^2)^2}$$

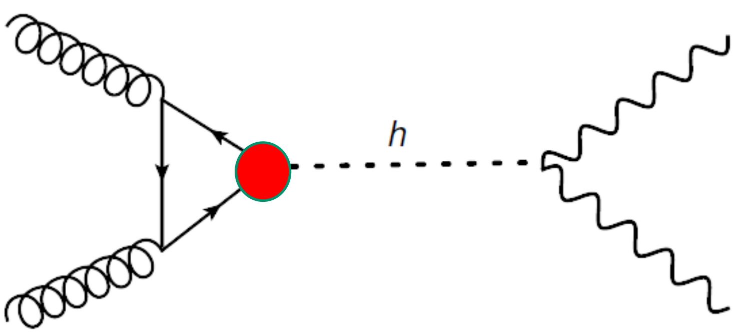
We may change the top-yukawa vertex by hand:

D.Goncalves, T.Han, S.Mukhopadhyay, PRD98(2018)015023.

$$Y_t(q^2) = g_{t\bar{t}h}^{\rm SM} \times \frac{1}{(1+q^2/\Lambda^2)^n}$$



$$gg \to ZZ \to 4\ell$$



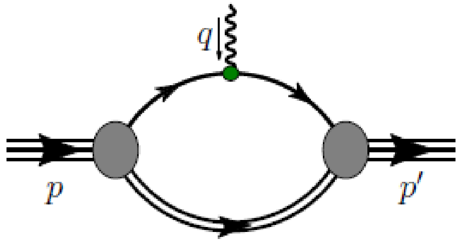
Note that

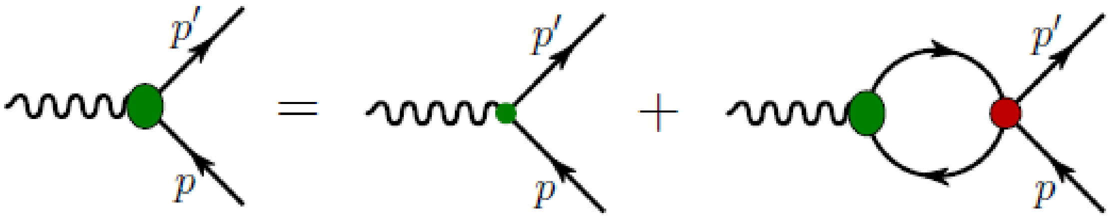
Nambu-Jona-Lasinio Model played an important role at the first step of SSB.

$$\mathscr{L}_{\mathrm{NJL}} = G[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\psi)^2]$$

The NJL model is still useful.

For example, we can calculate the nucleon form factor by using the Bethe-Salpeter eq.

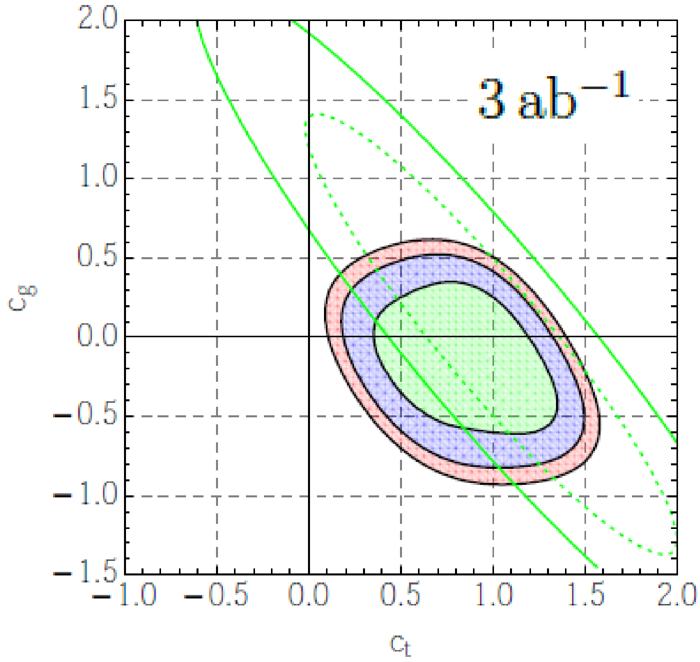




(4) Analysis via the higher dimensional operator

Azatov, Grojean, Paul, Salvioni, Zh.Eksp.Teor.Fiz.147(2015)410.

$$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} + \tilde{c}_g \frac{g_s^2}{32\pi^2 v^2} |H|^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$$



Prospect for HL-LHC

$$\begin{aligned}
N[250,400] &= 521 c_g c_t + 187.c_g^2 - 491.c_g + 381 c_t^2 - 687.c_t + 7044\,, \\
N[400,600] &= 394 c_g c_t + 143 c_g^2 - 229.c_g + 423 c_t^2 - 564 c_t + 1136\,, \\
N[600,800] &= 97 c_g c_t + 81 c_g^2 - 40 c_g + 139 c_t^2 - 210 c_t + 221\,, \\
N[800,1100] &= 23.c_g c_t + 65 c_g^2 + 3.6 c_g + 59 c_t^2 - 100 c_t + 80\,, \\
N[1100,1500] &= -2.4 c_g c_t + 40.c_g^2 + 11.3 c_g + 16.5 c_t^2 - 31 c_t + 22\,,
\end{aligned}$$

§.3 Fundamental composite Higgs and phase structure

Work in progress

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

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

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

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

Previously, I calculated an effective potential from a walking gauge theory: **MH, Phys.Rev. D83 (2011) 096003**

$$W[J] \equiv \frac{1}{i} \ln \int [d\psi d\bar{\psi}][\text{gauge}] e^{i \int d^4x (\mathcal{L} + J\bar{\psi}\psi)} \qquad \sigma(x) \equiv \bar{\psi}(x)\psi(x)$$

From $\frac{dV(\sigma)}{d\sigma} = J$ we find $V(\sigma) = \int d\sigma J$

In the broken phase, it is

$$V|_{B_0=m} = -\frac{N_{\mathrm{TC}} N_f}{4\pi^2} \frac{A^2}{16\lambda_*} m^4$$

m: dynamical mass

→ For many Higgs fields, it becomes complicated…

Probably, a NJL approach is useful for the first step.

NJL model = linear sigma model + compositeness condition

$$\mathscr{L}_{L\sigma} = \frac{1}{2}Z[(\partial\sigma)^2 + (\partial\pi)^2) - \underline{m^2(\sigma^2+\pi^2)} - \lambda(\sigma^2+\pi^2)^2$$

$$\underline{- y(\bar\psi\psi\sigma + \bar\psi i\gamma_5\psi\pi)}$$

Z=0, λ=0 at the compositeness scale → NJL model

$$\mathscr{L}_{\rm NJL} = G[(\bar\psi\psi)^2 + (\bar\psi i\gamma_5\psi)^2]$$

Non-linear realization = limit of $m_\sigma \to \infty$

global SU(4) fermion:

(left-handed notation)

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

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

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

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

After bosonization,

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

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

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

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

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.

For the top-Yukawa coupling, we itroduce the spurion fields:

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

with $Q_L \to g Q_L g^\dagger$ and $T_R \to g T_R g^\dagger$, and

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

The corresponding effective potential is

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

with $\quad m_t = \dfrac{y}{\sqrt{2}} h$

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

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

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

Assuming $m_1 \approx m_2$, we find

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

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.

§.4 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 composite Higgs. I'd like to emphasize in principle we can calculate the form factor of the composite Higgs via the Bethe-Salpeter equation. It will be performed in future.

Thank you!