Dynamical electroweak symmetry breaking and exotic scalars

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Why dynamical symmetry breaking?

What is the orgin of fermion masses?

We know most of the fermion masses and mixings
but do not understand their structure. For instance, why $m_t \gg m_f$?

The root of the problem could stem from the Yukawa couplings

- Contain many unphysical parameters
- Depend on the basis
- Depend on the renormalization scale

Linked to the Higgs mechanism which,

- Parametrizes with complete generality all we see
- It is renormalizable (no clue on new scales)

If the Higgs is not elementary:

- New scale
- No (fundamental) Yukawa couplings, and perhaps ...

The Bardeen-Hill-Lindner mechanism

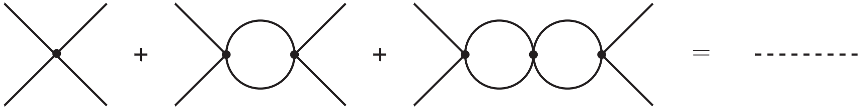
- SM with no Higgs
- With a new strong interaction between four top-quarks one can implement the Nambu-Jona-Lasinio (NJL) mechanism of SSB

$$\mathscr{L} = \mathscr{L}_{\not{H}\mathrm{SM}} + \mathscr{L}_{4\mathrm{f}}\,, \quad \mathscr{L}_{4\mathrm{f}} = G\left(\overline{Q_L} t_R\right)\left(\overline{t_R} Q_L\right)$$

The NJL approach:

The gap equation

The bubble sum

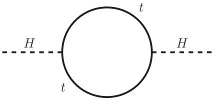


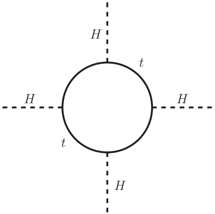
Bosonization approach

Four-fermion interaction equivalent to (just use the EM)

$$\mathscr{L}_{4\mathrm{f}} \to \mathscr{L}_{\mathrm{H}\Lambda} = -m_{0H}^2 |H|^2 + \left(g_{0t} \overline{Q_L} t_R H + \mathrm{h.c.} \right) , \qquad G = \frac{g_{0t}^2}{m_{0H}^2}$$

At $\mu = \Lambda$, H no kinetic term, no potential (apart from the mass term).
At $\mu < \Lambda$ top quark loops generate H kinetic terms and potential





$$\mathscr{L}_\mu = Z_H |\partial H|^2 - \tilde{m}_H^2 |H|^2 - \frac{1}{2} \tilde{\lambda}_H |H|^4 + \left(\tilde{g}_t \overline{Q}_L t_R H + \mathrm{h.c.} \right)$$

$$Z_H = g_{0t}^2 L \, , \, \tilde{\lambda}_H = 2 g_{0t}^4 L \, , \, \tilde{m}_H^2 = m_{0H}^2 - 2 g_{0t}^2 \frac{N_c}{16\pi^2} \left(\Lambda^2 - \mu^2 \right) \, , \, L \equiv \frac{N_c}{16\pi^2} \log \frac{\Lambda^2}{\mu^2}$$

Bosonization: the predictions for m_t and m_h

Now we rescale the field $H \to H/\sqrt{Z_H}$ and obtain the SM Lagrangian

$$\mathscr{L}_{\mu R} = |\partial H|^2 - m_H^2 |H|^2 - \frac{1}{2}\lambda_H |H|^4 + \left(g_t \overline{Q}_L t_R H + \text{h.c.} \right)$$

with

$$m_H^2 = \tilde{m}_H^2 / Z_H \,, g_t^2 = g_{0t}^2 / Z_H = \frac{1}{L} \,, \quad \lambda_H = \tilde{\lambda}_H / Z_H^2 = \frac{2}{L} = 2 g_t^2$$

g_t and λ_H diverge together when $\mu = \Lambda$ ($L = 0$). If $\langle H \rangle = v/\sqrt{2}$

$$m_t = g_t(m_t) \frac{v}{\sqrt{2}} \,, \quad m_h^2 \approx \lambda_H(m_t) v^2 = 2 g_t^2(m_t) v^2 = 4 m_t^2$$

Prediction for the top-quark mass once Λ is given

$$g_t^2(m_t) = \frac{1}{L} = \frac{16\pi^2}{N_c \log(\Lambda^2/m_t^2)} \quad \to \quad m_t^2 = \frac{8\pi^2 v^2}{N_c \log(\Lambda^2/m_t^2)}$$

$$m_t^2 = -\frac{8\pi^2 v^2}{N_c \Lambda^2 W_{-1}\left(-\frac{8\pi^2 v^2}{N_c \Lambda^2} \right)} \approx v^2 \frac{8\pi^2}{N_c} \frac{1}{\log\left(\frac{N_c \Lambda^2}{8\pi^2 v^2} \right)}$$

Connection with the RGE

From the equations above we can compute the fermion-loop RGE for g_t^2 and λ_H

$$\frac{dg_t^2}{dt} = 2N_c g_t^4 , \qquad \frac{d\lambda_H}{dt} = 4N_c g_t^4 , \quad t \equiv \frac{1}{16\pi^2} \log \frac{\mu}{m_z}$$

to be compared with the SM RGE
(for the moment we neglect gauge interactions)

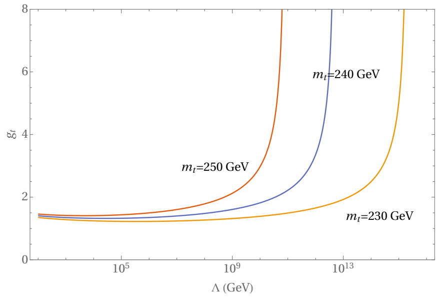
$$\frac{dg_t^2}{dt} = (3 + 2N_c) g_t^4 , \qquad \frac{d\lambda_H}{dt} = 12\lambda_H^2 + 4N_c \lambda_H g_t^2 - 4N_c g_t^4$$

agree if we take only fermion loops and use $\lambda_H = 2g_t^2$.
For $\mu < \Lambda$ Higgs and gauge interactions should be included

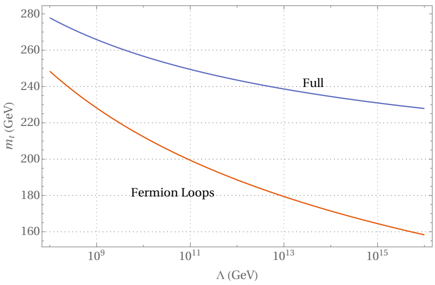
$$\frac{dg_t^2}{dt} = g_t^2 \left(9g_t^4 - 16g_3^2 - \frac{9}{2} g_2^2 - \frac{17}{6} g_1^2 \right)$$

The SM results: m_t

The IR fixed point



The predictions



- The IR fixed point gives robust predictions
- The predictions in the SM are too high:

$$m_t \approx 225\,\mathrm{GeV}\,, \quad \Lambda = 10^{16}\,\mathrm{GeV}$$

The Higgs boson mass

Only fermion loops give $\lambda_H = 2g_t^2$ but

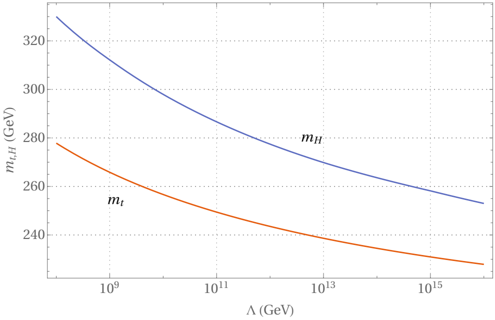
$$\frac{d\lambda_H}{dt} = 12\left(\lambda_H^2 + g_{2w}^4 + \lambda_H(g_t^2 - g_{1w}^2) - g_t^4\right)$$

$$g_{1w}^2 = \frac{1}{4}g'^2 + \frac{3}{4}g_2^2\,, \qquad g_{2w}^4 = \frac{1}{16}g'^4 + \frac{1}{8}g'^2 g_2^2 + \frac{3}{16}g_2^4$$

Neglecting EW interactions and taking $\lambda_H = cg_t^2$

$$m_h = m_t\sqrt{2c} = 1.3m_t$$

Including EW corrections



Why not additional interactions?

- Needed to explain lighter fermion masses
- Sometimes unavoidable

$$\left(\overline{Q_L}\gamma^\mu Q_L\right)\left(\overline{t_R}\gamma^\mu t_R\right) \to \left(\overline{Q_L}t_R\right)\left(\overline{t_R}Q_L\right)\,,\,\left(\overline{Q_L}\lambda^a t_R\right)\left(\overline{t_R}\lambda^a Q_L\right)$$

  Several attempts with four-fermion interactions leading to different low energy particle spectrum (for a review see Cvetic (1999),Hill & Simmons (2003)):
- 2HDM
- Supersymmetry
- Neutrino condensates
- General non-coloured bounstates
- New (boundstate) scalars introduced to give small radiative b, τ masses

In general difficult to obtain the right m_t and m_H

Bottom up approach

Which scalars can we couple to the top-quark?

$$\overline{Q_L} t_R \sim (1,2,1/2), (8,2,1/2)$$
$$\overline{Q_L} b_R \sim (1,2,-1/2), (8,2,-1/2)$$
$$\overline{Q_L} Q_L^c \sim (3_a, 1_a, -1/3), (3_a, 3_s, -1/3), (\bar{6}_s, 1_a, -1/3), (\bar{6}_s, 3_s, -1/3)$$
$$\overline{t_R} t_R^c \sim (\bar{6}_s, 1, -4/3)$$
$$\overline{t_R} b_R^c \sim (3_a, 1, -1/3), (\bar{6}_s, 1, -1/3)$$

For instance $(\overline{t_R} t_R^c)\left(\overline{t_R^c} t_R\right)$ obtained from color-sextet $g_\omega \overline{t_R} t_R^c \omega$

Additional (positive) contributions to the g_t running

$$\frac{dg_t^2}{dt} = g_t^2 \left(9 g_t^4 + 8 g_\omega^2 - 16 g_3^2 + \cdots\right)$$

Helps g_t to diverge faster!

Femion loop approximation with extra scalars

$$\mathscr{L}_\Lambda = -m_{0H}^2|H|^2 - m_{0\omega}^2|\omega|^2 + \left(g_{0t}\overline{Q}_L t_R H + g_{0\omega}\overline{t_R} t_R^c \omega + \text{h.c.}\right)$$

then

$$\mathscr{L}_\mu = Z_H|\partial H|^2 - \tilde{m}_H^2|H|^2 - \frac{1}{2}\tilde{\lambda}_H|H|^4 + \left(g_{0t}\overline{Q}_L t_R H + g_{0\omega}\overline{t_R} t_R^c \omega + \text{h.c.}\right) +$$

$$+Z_\omega|\partial\omega|^2 - \tilde{m}_\omega^2|\omega|^2 - \tilde{\lambda}_2|H|^2|\omega|^2 - \frac{1}{2}\tilde{\lambda}_\omega|\omega|^4$$

$$Z_H = g_{0t}^2 L, \quad \tilde{\lambda}_H = 2g_{0t}^4 L, \quad \tilde{m}_H^2 = m_{0H}^2 - 2g_{0t}^2\frac{N_c}{16\pi^2}\left(\Lambda^2 - \mu^2\right)$$

$$Z_\omega = g_{0\omega}^2\kappa_Z L, \quad \tilde{\lambda}_\omega = g_{0\omega}^4\kappa_\lambda L, \quad \tilde{\lambda}_2 = g_{0\omega}^2 g_{0t}^2\kappa_2 L$$

$$\tilde{m}_\omega^2 = m_{0\omega}^2 - 2g_{0\omega}^2\frac{\kappa_m}{16\pi^2}\left(\Lambda^2 - \mu^2\right)$$

Femion loop approximation predictions

Now after renormalization $H \to H/\sqrt{Z_H}$, $\omega \to \omega/\sqrt{Z_\omega}$

$$\mathscr{L}_\mu = |\partial H|^2 - m_H^2|H|^2 - \frac{1}{2}\lambda_H|H|^4 + \left(g_t \overline{Q}_L t_R H + g_\omega \overline{t_R} t_R^c \omega + \mathrm{h.c.}\right)$$
$$+|\partial\omega|^2 - m_\omega'^2|\omega|^2 - \lambda_2|H|^2|\omega|^2 - \frac{1}{2}\lambda_\omega|\omega|^4$$

with

$$m_H^2 = \tilde{m}_H^2/Z_H\,, g_t^2 = g_{0t}^2/Z_H = \frac{1}{L}\,, \quad \lambda_H = \tilde{\lambda}_H/Z_H^2 = \frac{2}{L} = 2g_t^2$$

$$m_\omega'^2 = \tilde{m}_\omega^2/Z_\omega\,, \qquad g_\omega^2 = g_{0\omega}^2/Z_\omega = \frac{1}{\kappa_Z L} = \frac{1}{\kappa_Z} g_t^2\,,$$

$$\lambda_\omega = \tilde{\lambda}_\omega/Z_\omega^2 = \frac{\kappa_\lambda}{\kappa_Z^2 L} = \frac{\kappa_\lambda}{\kappa_Z^2} g_t^2\,, \quad \lambda_2 = \tilde{\lambda}_2/(Z_H Z_\omega) = \frac{\kappa_2}{\kappa_Z L} = \frac{\kappa_2}{\kappa_Z} g_t^2$$

- Same prediction as the SM for the top quark mass
- Same prediction for the Higgs mass
- Rest of couplings predicted in terms of g_t

Complete Yukawas RGE's

Neglecting electroweak contributions

Sextet

$$\frac{dg_t^2}{dt} = g_t^2(9g_t^2 + 8g_\omega^2 - 16g_3^2)$$
$$\frac{dg_\omega^2}{dt} = g_\omega^2(4g_t^2 + 20g_\omega^2 - 16g_3^2)$$
$$\frac{dg_3^2}{dt} = -\frac{37}{3}g_3^4$$

General

$$\begin{aligned}\dot{x} &= x(a_{11}x + a_{12}y - c_1 z)\\ \dot{y} &= y(a_{21}x + a_{22}y - c_2 z)\\ \dot{z} &= -bz^2\end{aligned}$$

$$x = g_t^2\,, \quad y = g_\omega^2\,, \quad z = g_3^2$$

	a_{11}	a_{12}	a_{21}	a_{22}	c_1	c_2	b
SM	9	-	-	-	16	-	7
triplet	9	8	2	32	16	16	41/3
sextet	9	8	4	20	16	16	37/3
octet	9	8	3	10	16	16	10

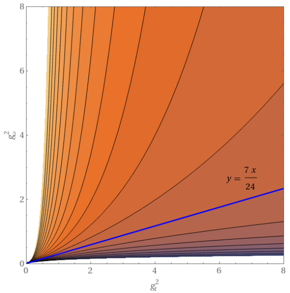
RGE solutions

If QCD neglected Lotka-Volterra type

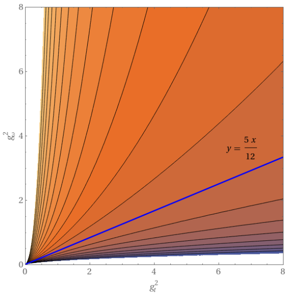
$$y - cx = Kx^{\alpha} y^{\beta}$$

$$c = \frac{a_{11} - a_{21}}{a_{22} - a_{12}}, \qquad \alpha = \frac{a_{22}(a_{11} - a_{21})}{a_{11}a_{22} - a_{12}a_{21}}, \qquad \beta = \frac{a_{11}(a_{22} - a_{12})}{a_{11}a_{22} - a_{12}a_{21}}$$

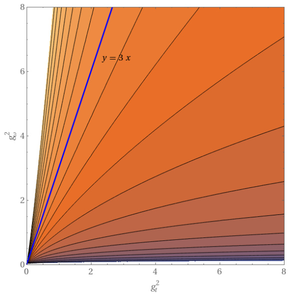
Triplet



Sextet



Octet



The IR fixed point

In presence of QCD, the beta functions can reach zero

- SM this happens for

$$g_t^2 = \frac{16}{9} g_3^2 \;\rightarrow \quad m_t \sim 280\,\mathrm{GeV}$$

- Extra scalars

$$a_{11} x + a_{12} y = c_1 z\,, \quad a_{21} x + a_{22} y = c_2 z$$
$$a_{21} x + a_{22} y = c_2 z$$

  - Triplet

$$g_t^2 = \frac{24}{17} g_3^2\,, \quad g_\omega^2 = \frac{7}{17} g_3^2 \rightarrow \quad m_t \sim 250\,\mathrm{GeV}$$

  - Sextet

$$g_t^2 = \frac{48}{37} g_3^2\,, \quad g_\omega^2 = \frac{20}{37} g_3^2 \rightarrow \quad m_t \sim 240\,\mathrm{GeV}$$

  - Octet

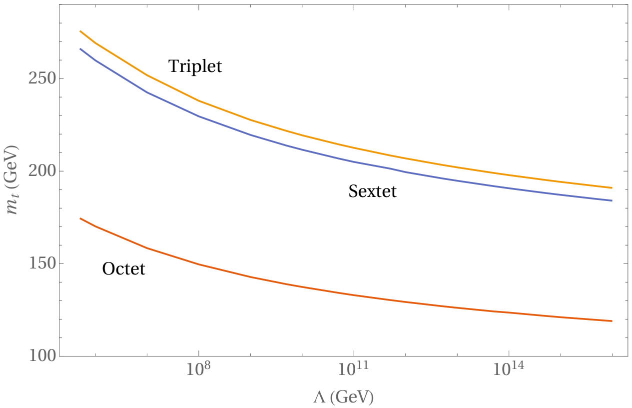
$$g_t^2 = \frac{16}{33} g_3^2\,, \quad g_\omega^2 = \frac{16}{11} g_3^2 \rightarrow \quad m_t \sim 150\,\mathrm{GeV}$$

Full result (Preliminary)

Including EW corrections

Stopping new scalar contributions at $m_\omega = 1\,\mathrm{TeV}$

m_t in composite coloured scalar extensions



The Higgs boson mass

$$\frac{d\lambda_H}{dt} = 12\left(\lambda_H^2 + g_{2w}^4 + \lambda_H(g_t^2 - g_{1w}^2) - g_t^4 + c_H\lambda_2^2\right)$$

$$c_H(\text{triplet}) = \frac{1}{8}, \quad c_H(\text{sextet}) = \frac{1}{4}, \quad c_H(\text{octet simplified}) = \frac{2}{3}$$

Strongly depends on the running of λ_2 which depends on all other couplings, for $\Lambda = 10^{16}\,\text{GeV}$

- Triplet: $m_H \gtrsim 210\,\text{GeV}$
- Sextet: $m_H \gtrsim 200\,\text{GeV}$
- Octet, tends to give a too light Higgs boson mass (for the correct top-quark mass) but the potential is very complicated

$$\begin{aligned} V \;=\; & \lambda\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_s^2\,\mathrm{Tr}S^{\dagger i}S_i + \lambda_1\,H^{\dagger i}H_i\,\mathrm{Tr}S^{\dagger j}S_j + \lambda_2\,H^{\dagger i}H_j\,\mathrm{Tr}S^{\dagger j}S_i \\ & + \left(\lambda_3\,H^{\dagger i}H^{\dagger j}\,\mathrm{Tr}S_iS_j + \lambda_4\,e^{i\phi_4}\,H^{\dagger i}\mathrm{Tr}S^{\dagger j}S_jS_i + \lambda_5\,e^{i\phi_5}\,H^{\dagger i}\mathrm{Tr}S^{\dagger j}S_iS_j + \text{H.c.}\right) \\ & + \lambda_6\,\mathrm{Tr}S^{\dagger i}S_iS^{\dagger j}S_j + \lambda_7\,\mathrm{Tr}S^{\dagger i}S_jS^{\dagger j}S_i + \lambda_8\,\mathrm{Tr}S^{\dagger i}S_i\,\mathrm{Tr}S^{\dagger j}S_j \\ & + \lambda_9\,\mathrm{Tr}S^{\dagger i}S_j\,\mathrm{Tr}S^{\dagger j}S_i + \lambda_{10}\,\mathrm{Tr}S_iS_j\,\mathrm{Tr}S^{\dagger i}S^{\dagger j} + \lambda_{11}\,\mathrm{Tr}S_iS_jS^{\dagger j}S^{\dagger i}. \end{aligned}$$

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The Bardeen-Hill-Lindner mechanism approach to compositness very predictive

- Predictivitiy not spoiled by including additional scalars
- Tried additional coloured scalars (one at once):
  Triplet, sextet and octet
- Triplet and sextet still give a too large m_t (and m_H) and require very large compositness scales
- Octet
  - Can explain m_t with relatively low compositness scales
  - Higgs mass prediction needs more work
    because very complicated potential
  - Naturally obtained form a vector interaction by Fierzing
  - Can implement Minimal Flavour Violation
  - Very interesting phenomenologically (see Victor Miralles talk)