Composite Higgs: Myth and Reality

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Outline

Could the observed 125 GeV “Higgs” particle be a composite of strong dynamics?

Can this be studied on the lattice?

- “Higgs” as light composite scalar in technicolor
- “Higgs” as dilaton
- “Higgs” as pseudo Nambu-Goldstone boson
- ~~Partially composite Higgs~~

“Higgs” as σ?

Could the observed “Higgs” be a composite techni-scalar?

$\Lambda =$ scale of strong EWSB

$$\mathcal{L}_{\text{eff}} \sim (\partial\sigma)^2 + \Lambda^2\sigma^2 + 4\pi\Lambda\sigma^3 + \cdots$$

$$+ \frac{\Lambda^2}{16\pi^2} g^2 W^2 + \frac{\Lambda}{4\pi} g^2 \sigma W^2 + \cdots \qquad \text{(NDA)}$$

$$m_{W,Z} \;\Rightarrow\; \Lambda \sim 4\pi v \sim 3\ \text{TeV} \qquad (\sim m_{\rho_{\text{TC}}})$$

1980s: flavor problems

1990s: Precision electroweak marginal (S, T, $\ldots$)

2010s: “Higgs” discovery

Focus on tuning of Higgs parameters...

σ Tuning?

$$m_\sigma \ll \Lambda \;\Rightarrow\; \underbrace{\text{unexplained suppression}}_{\text{“tuning”}} \sim \frac{m_h^2}{\Lambda^2} \sim 0.1\%$$

σ^3 coupling is relevant $\Rightarrow$ must be suppressed to avoid unitarity violation down to m_h

$$\text{cubic suppression} \sim \frac{m_h}{\Lambda} \sim 4\% \text{ additional tuning}$$

$g_{\sigma VV} \sim g_{hVV}^{(\mathrm{SM})}$ ...but $\sim 100\%$ corrections expected

$$\frac{\Delta g_{hVV}}{g_{hVV}^{(\mathrm{SM})}} \sim 10^{-1} \qquad \Rightarrow 10\% \text{ tuning}$$

$$\frac{\Delta g_{hff}}{g_{hff}^{(\mathrm{SM})}} \sim 2 \times 10^{-1} \qquad \Rightarrow 20\% \text{ tuning}$$

“Higgs” as σ?

total tuning $\sim 10^{-6}$

“Higgs” as Dilaton?

Goldberger, Grinstein, Skiba (2007)

Assume conformal symmetry is spontaneously broken at scale $\Lambda \gg m_h$ by strong dynamics.

$\Rightarrow$ dilaton $\varphi(x) \mapsto \lambda\varphi(\lambda x)$ $\qquad$ $\lambda =$ scale parameter

Spontaneous scale breaking $\Rightarrow$ all scales $\propto \langle\phi\rangle$

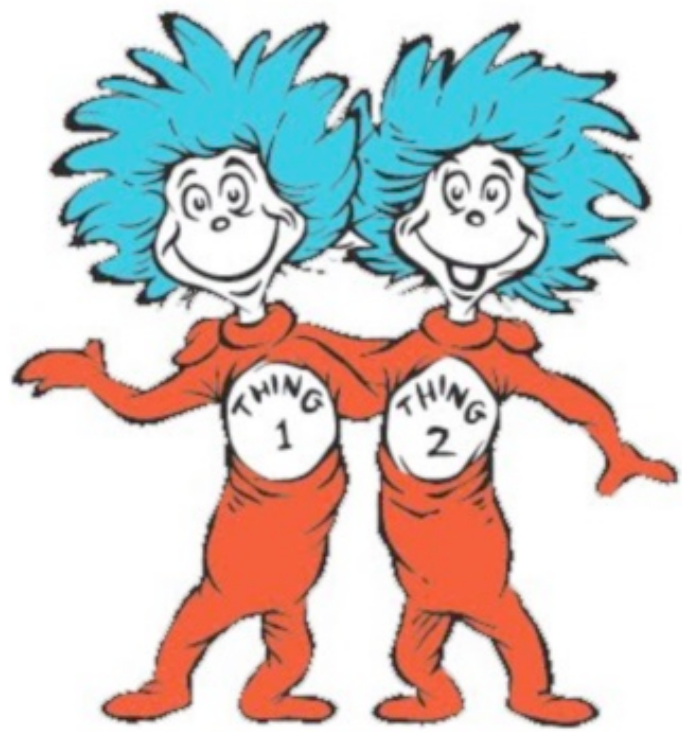
$$\Rightarrow \mathcal{L}_{\text{eff}} = \tfrac{1}{2}\frac{m_W^2}{f^2}\varphi^2 W^2 + \frac{m_t}{f}\varphi\bar{t}t + \cdots$$

φ couples to mass like a standard model Higgs.

“Higgs” as Dilaton?

Two problems:

- “tuning”
- Requires special structure of UV theory



Dilaton Tuning?

$$V_{\text{eff}} = \frac{\kappa}{4!}\varphi^4$$

Allowed by nonlinearly realized conformal symmetry

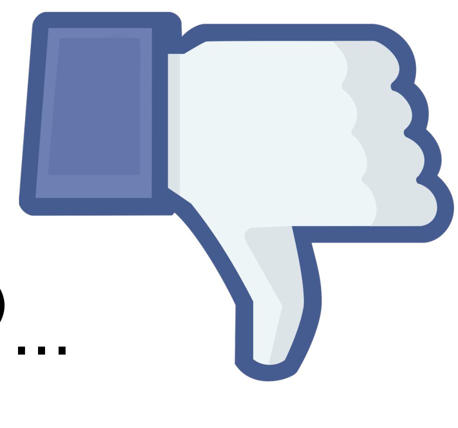
$\Rightarrow$ expect $\kappa \sim (4\pi)^2$

$$\varphi = f + \varphi' \qquad \Rightarrow \mathcal{L}_{\text{int}} = \frac{m_W^2}{f}\phi' W^2 + \cdots$$

Need $f = v$ to 10% to explain $g_{\varphi VV} \simeq g_{hVV}^{(\text{SM})}$

$$\Rightarrow \text{tuning} \sim \frac{\text{allowed range of } \kappa}{\text{expected value}} \sim 0.5\%$$

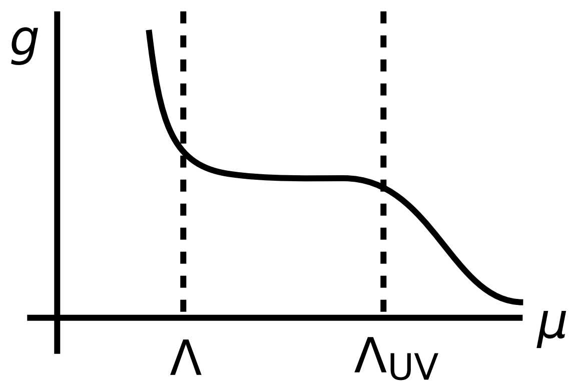
Does not explain $g_{\varphi gg} \simeq g_{hgg}^{(\text{SM})}$, $g_{\varphi\gamma\gamma} \simeq g_{h\gamma\gamma}^{(\text{SM})}$ ...



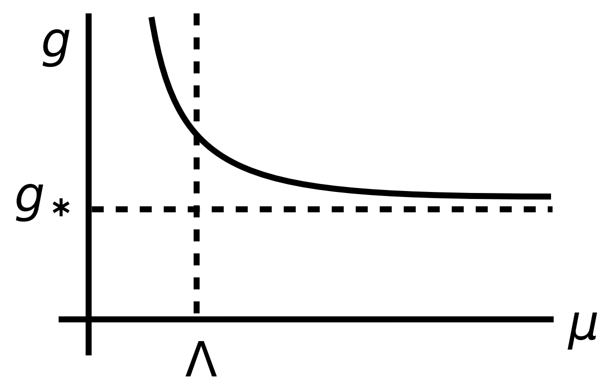
UV Theory for Dilaton?

Spontaneous breaking of conformal invariance requires special structure.

Walking technicolor



Conformal technicolor



$$\Delta\mathcal{L} = \Lambda^{4-\Delta}\mathcal{O}$$

$$\Delta < 4$$

Conformal symmetry *explicitly* broken by running at Λ

$\Rightarrow$ no light dilaton expected.

Need approximate conformal symmetry at Λ

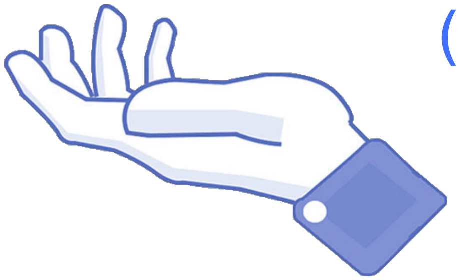
$\Rightarrow$ break conformal symmetry with $\Delta \simeq 4$ operator.

Natural Dilaton

Contino, Pomarol, Rattazzi (2010 [unpublished])
Chacko, Mishra (2012)
Coradeschi, Lodone, Pappadopulo, Rattazzi, Vitale (2013)
Bellazzini, Csaki, Hubisz, Serra, Terning (2013)

$\Delta\mathcal{L}_{\text{UV}} = \lambda\mathcal{O}, \qquad \Delta_{\mathcal{O}} = 4 - \epsilon$

$V_{\text{eff}} = \dfrac{\kappa(\lambda(\varphi))}{4!}\varphi^4 \qquad \kappa$ depends on λ



(Meh)

Assume $\kappa(\lambda) = 0$ at $\lambda = \lambda_* = \lambda(\phi_*)$

$\Rightarrow \langle\kappa\rangle = O(\epsilon)$

$\underbrace{\epsilon \sim 10^{-3}}_{\text{tuning?}} \quad \Rightarrow \quad \langle\phi\rangle \sim v$

Still need $\sim 10\%$ tuning to get $g_{\varphi VV} \simeq g_{hVV}^{(\text{SM})}$

...and $g_{\varphi gg} \simeq g_{hgg}^{(\text{SM})}$, $g_{\varphi\gamma\gamma} \simeq g_{h\gamma\gamma}^{(\text{SM})}$.

Dilaton on the Lattice?

Dilaton requires a theory with very special structure:

- Theory must have fixed point with nearly dimension-4 operator.

- Phase diagram depends on new marginal coupling λ
  $\Rightarrow$ modifications of UV action are not irrelevant!

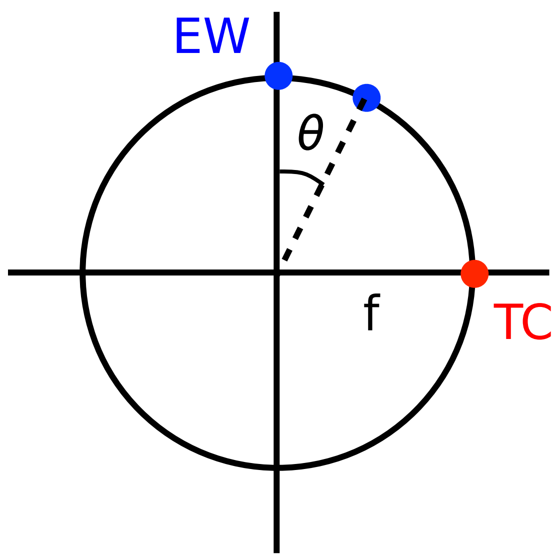
PNGB Higgs

Strong sector has global symmetry G spontaneously broken to H

$\Rightarrow$ NGBs $\in G/H$ *e.g.* $SO(5)/SO(4)$ or $SU(4)/Sp(4)$

G exact $\Rightarrow$ NGB's massless, derivatively coupled.

Theory has electroweak preserving vacuum:



Fluctuations about EW vacuum
$\Leftrightarrow$ Higgs

$v = f \sin\theta$

Recover standard model
for $v \ll f$

PNGB Higgs

Requires tuning $\sim \dfrac{v^2}{f^2}$ (or "little Higgs" structure)

$$g_{hVV} = g_{hVV}^{(\mathrm{SM})} \times \left[1 + O(v^2/f^2)\right]$$

$\Rightarrow$ tuning $\sim 10\%$

Top loops: $\Delta m_H^2 \sim \dfrac{N_c y_t^2}{16\pi^2}\Lambda^2 \sim 50 m_h^2$

$\Rightarrow$ additional $\sim 2\%$ tuning...

...or top partners with mass below Λ.

Top Partners

Top + top partners fill out G multiplet

$\Rightarrow$ reduces G breaking in top + top partner loops.

$$\Delta m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_T^2 \qquad \Rightarrow m_T \lesssim 1 \text{ TeV}$$

Current LHC bounds: $m_T \gtrsim$ 700–800 GeV

Flavor in composite Higgs?

Partial compositeness or Yukawa-type

Partial Compositeness

$$\Delta\mathcal{L}_{\text{flavor}} = z_{Q_L} Q_L \Psi_L^c + z_{t_R} t_R^c T_R^c + z_{b_R} b_R^c B_R^c$$

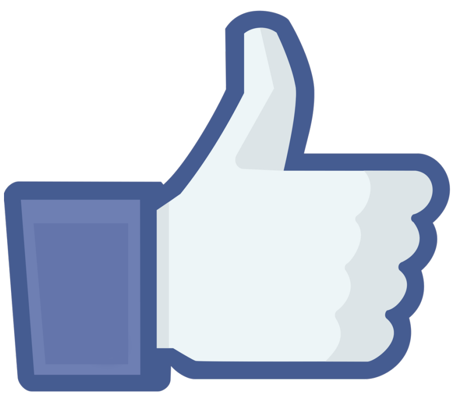
$\Psi_L, T_R, B_R =$ gauge-singlet fermion operators in strong sector (*e.g.* "baryon" operators)

$$m_t \propto z_{Q_L} z_{t_R}, \quad m_b \propto z_{Q_L} z_{b_R}$$

Unitarity $\Rightarrow [\Psi] > \frac{3}{2}$

$[z] = \frac{5}{2} - [\Psi] \Rightarrow z$'s may be nearly marginal or relevant

$\Rightarrow$ no ETC-like flavor problem.



On the Lattice?

Requirements for a successful model:

- Composite fermion operators with quantum numbers of Q_L, t_R, b_R.
- Dimension of fermion operators $\lesssim \frac{5}{2}$.
- Composite fermion states

Examples:

$Sp(4) \simeq SO(5)$ gauge theory with $4 \times \mathbf{4} + 6 \times \mathbf{5}$

Barnard, Gherghetta, Ray [arXiv:1311.6562]

$SU(4)$ gauge theory with $5 \times \mathbf{6} + 3 \times (\mathbf{4} \oplus \bar{\mathbf{4}})$

Ferretti, Karateev [arXiv:1312.5330]

Conclusions

Higgs compositeness requires some combination of

- dynamical accidents (tuning)
- special UV theories

This makes them hard to study on the lattice.

Most promising direction: PNGB Higgs models

- Composite fermion operators
- Top partners (baryons)
- Effective potential from top loops?