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 $\sigma$?

Could the observed “Higgs” be a composite techniscalar?

$\Lambda =$ scale of strong EWSB

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

$$+ \frac{\Lambda^2}{16\pi^2} g^2 W^2 + \frac{\Lambda}{4\pi} g^2 \sigma W^2 + \cdots$$

(NDA)

$m_{W,Z} \Rightarrow \Lambda \sim 4\pi v \sim 3$ TeV  \hspace{1cm} (\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?

\[ m_\sigma \ll \Lambda \Rightarrow \text{unexplained suppression} \sim \frac{m_h^2}{\Lambda^2} \sim 0.1\% \]

"tuning"

σ^3 coupling is relevant ⇒ must be suppressed to avoid unitarity violation down to \( m_h \)

cubic suppression \( \sim \frac{m_h}{\Lambda} \sim 4\% \) additional tuning

\[ g_{\sigmaVV} \sim g_{hVV}^{(SM)} \quad \text{...but } \sim 100\% \text{ corrections expected} \]

\[ \frac{\Delta g_{hVV}}{g_{hVV}^{(SM)}} \sim 10^{-1} \Rightarrow 10\% \text{ tuning} \]

\[ \frac{\Delta g_{hff}}{g_{hff}^{(SM)}} \sim 2 \times 10^{-1} \Rightarrow 20\% \text{ tuning} \]
“Higgs” as $\sigma$?

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 $\varphi(x) \mapsto \lambda \varphi(\lambda x)$  \hspace{1cm} \lambda = \text{scale parameter}

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

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

$\varphi$ couples to mass like a standard model Higgs.
“Higgs” as Dilaton?

Two problems:

• “tuning”

• Requires special structure of UV theory
Dilaton Tuning?

\[ V_{\text{eff}} = \frac{\kappa}{4!} \phi^4 \]

Allowed by nonlinearly realized conformal symmetry
⇒ expect \( \kappa \sim (4\pi)^2 \)

\[ \phi = f + \phi' \quad \Rightarrow \quad \mathcal{L}_{\text{int}} = \frac{m_W^2}{f} \phi' W^2 + \cdots \]

Need \( f = \nu \) to 10% to explain \( g_{\phiVV} \approx g_{hVV}^{(\text{SM})} \)

⇒ tuning \( \sim \frac{\text{allowed range of } \kappa}{\text{expected value}} \sim 0.5\% \)

Does not explain \( g_{\phi gg} \approx g_{hgg}^{(\text{SM})}, g_{\phi \gamma \gamma} \approx g_{h\gamma \gamma}^{(\text{SM})} \)
UV Theory for Dilaton?

*Spontaneous* breaking of conformal invariance requires special structure.

Conformal symmetry *explicitly* broken by running at $\Lambda$ 
\[ \Rightarrow \text{no light dilaton expected.} \]

Need approximate conformal symmetry at $\Lambda$ 
\[ \Rightarrow \text{break conformal symmetry with } \Delta \simeq 4 \text{ operator.} \]
Natural Dilaton

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

\[ \Delta \mathcal{L}_{UV} = \lambda \mathcal{O}, \quad \Delta \mathcal{O} = 4 - \epsilon \]

\[ V_{\text{eff}} = \frac{\kappa(\lambda(\phi))}{4!} \phi^4 \quad \kappa \text{ depends on } \lambda \]

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

\[ \Rightarrow \langle \kappa \rangle = O(\epsilon) \]

\[ \epsilon \sim 10^{-3} \Rightarrow \langle \phi \rangle \sim \nu \]

\[ \text{tuning?} \]

Still need \( \sim 10\% \) tuning to get \( g_{\phiVV} \approx g_{hVV}^{(\text{SM})} \)

...and \( g_{\phi gg} \approx g_{hgg}^{(\text{SM})}, g_{\phi \gamma \gamma} \approx g_{h\gamma \gamma}^{(\text{SM})} \).
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 $\lambda$
  $\Rightarrow$ modifications of UV action are not irrelevant!
PNGB Higgs

Strong sector has global symmetry $G$ spontaneously broken to $H$

$\Rightarrow$ NGBs $\in G/H$ \hspace{1cm} 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 $\sim \frac{\nu^2}{f^2}$ (or "little Higgs" structure)

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

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

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

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

...or top partners with mass below $\Lambda$. 
Top Partners

Top + top partners fill out $G$ multiplet
⇒ reduces $G$ breaking in top + top partner loops.

$$\Delta m_{H}^{2} \sim \frac{N_{c}y_{t}^{2}}{16\pi^{2}}m_{T}^{2} \quad \Rightarrow m_{T} \lesssim 1 \text{ TeV}$$

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 \( \Rightarrow [\Psi] > \frac{3}{2} \)

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

\( \Rightarrow \) 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 $4 \times 4 + 6 \times 5$
Barnard, Gherghetta, Ray [arXiv:1311.6562]

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