Extended composite Higgs models

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Work in collaboration with G. Durieux, C. Grojean, L. Lima,
and O. Matsedonskyi. Based on 1703.10624 and 1705.03013
Composite Higgs models
(very good candidates for new physics)

- No hierarchy problem because the Higgs is a bound state,
- This is lighter than the new physics scale (presumably slightly above the TeV) because it is a Goldstone of $G/H$,
- Fermion masses are induced by non-hierarchical couplings in the UV,

(almost) a high-energy copy of QCD
The composite Higgs paradigm
(a high-energy copy of QCD)

$L \sim \lambda [\Lambda_{UV}] \overline{q}_i O^d_{F} + \text{new global } \mathcal{G}$

parton condensate

$L \sim \lambda [\text{TeV}] \overline{q}_i Q^i$

$q \quad h \quad y_q \sim \left(\frac{\lambda}{m_Q}\right)^2 \quad \mathcal{H} \supset \mathcal{G}_{SM}$
Non-minimal composite Higgs models
(even better candidates for new physics)

- No hierarchy problem because the Higgs is a bound state,
- This is lighter than the new physics scale (presumably slightly above the TeV) because it is a Goldstone of $\mathcal{G}/\mathcal{H}$,
- Fermion masses are induced by non-hierarchical couplings in the UV,

provide dark matter candidates, explanation for baryon anti-baryon asymmetry, feasible UV completions...
Non-minimal composite Higgs models
(table taken from Bellazzini et al, 1401.2457)

<table>
<thead>
<tr>
<th>G</th>
<th>H</th>
<th>C</th>
<th>N_G</th>
<th>r_H = r_{SU(2) \times SU(2)}(r_{SU(2) \times U(1)})</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(5)</td>
<td>SO(4)</td>
<td>✓</td>
<td>4</td>
<td>4 = (2, 2)</td>
<td>11</td>
</tr>
<tr>
<td>SU(3) × U(1)</td>
<td>SU(2) × U(1)</td>
<td>✓</td>
<td>5</td>
<td>2_{\pm 1/2} + 1_0</td>
<td>10, 35</td>
</tr>
<tr>
<td>SU(4)</td>
<td>Sp(4)</td>
<td>✓</td>
<td>5</td>
<td>5 = (1, 1) + (2, 2)</td>
<td>29, 47, 64</td>
</tr>
<tr>
<td>SU(4)</td>
<td>[SU(2)]² × U(1)</td>
<td>✓*</td>
<td>8</td>
<td>(2, 2)_{\pm 2} = 2 \cdot (2, 2)</td>
<td>65</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(6)</td>
<td>✓</td>
<td>6</td>
<td>6 = 2 \cdot (1, 1) + (2, 2)</td>
<td>-</td>
</tr>
<tr>
<td>SO(7)</td>
<td>G₂</td>
<td>✓*</td>
<td>7</td>
<td>7 = (1, 3) + (2, 2)</td>
<td>66</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(5) × U(1)</td>
<td>✓*</td>
<td>10</td>
<td>10_0 = (3, 1) + (1, 3) + (2, 2)</td>
<td>-</td>
</tr>
<tr>
<td>SO(7)</td>
<td>[SU(2)]³</td>
<td>✓*</td>
<td>12</td>
<td>(2, 2, 3) = 3 \cdot (2, 2)</td>
<td>-</td>
</tr>
<tr>
<td>Sp(6)</td>
<td>Sp(4) × SU(2)</td>
<td>✓</td>
<td>8</td>
<td>(4, 2) = 2 \cdot (2, 2)</td>
<td>65</td>
</tr>
<tr>
<td>SU(5)</td>
<td>SU(4) × U(1)</td>
<td>✓*</td>
<td>8</td>
<td>4_{-5} + 4_{+5} = 2 \cdot (2, 2)</td>
<td>67</td>
</tr>
<tr>
<td>SU(5)</td>
<td>SO(5)</td>
<td>✓*</td>
<td>14</td>
<td>14 = (3, 3) + (2, 2) + (1, 1)</td>
<td>9, 47, 49</td>
</tr>
<tr>
<td>SO(8)</td>
<td>SO(7)</td>
<td>✓</td>
<td>7</td>
<td>7 = 3 \cdot (1, 1) + (2, 2)</td>
<td>-</td>
</tr>
<tr>
<td>SO(9)</td>
<td>SO(8)</td>
<td>✓</td>
<td>8</td>
<td>8 = 2 \cdot (2, 2)</td>
<td>67</td>
</tr>
<tr>
<td>SO(9)</td>
<td>SO(5) × SO(4)</td>
<td>✓*</td>
<td>20</td>
<td>(5, 4) = (2, 2) + (1 + 3, 1 + 3)</td>
<td>34</td>
</tr>
<tr>
<td>[SU(3)]²</td>
<td>SU(3)</td>
<td>✓</td>
<td>8</td>
<td>8 = 1_0 + 2_{\pm 1/2} + 3_0</td>
<td>8</td>
</tr>
<tr>
<td>[SO(5)]²</td>
<td>SO(5)</td>
<td>✓*</td>
<td>10</td>
<td>10 = (1, 3) + (3, 1) + (2, 2)</td>
<td>32</td>
</tr>
<tr>
<td>SU(4) × U(1)</td>
<td>SU(3) × U(1)</td>
<td>✓*</td>
<td>7</td>
<td>3_{-1/3} + 3_{+1/3} + 1_0 = 3 \cdot 1_0 + 2_{\pm 1/2}</td>
<td>35, 41</td>
</tr>
<tr>
<td>SU(6)</td>
<td>Sp(6)</td>
<td>✓*</td>
<td>14</td>
<td>14 = 2 \cdot (2, 2) + (1, 3) + 3 \cdot (1, 1)</td>
<td>30, 47</td>
</tr>
<tr>
<td>[SO(6)]²</td>
<td>SO(6)</td>
<td>✓*</td>
<td>15</td>
<td>15 = (1, 1) + 2 \cdot (2, 2) + (3, 1) + (1, 3)</td>
<td>36</td>
</tr>
</tbody>
</table>
Source of breaking: \[ L \sim \lambda [\text{TeV}] \bar{q}_i Q^i \]
(driven mainly by the top mixing)

Coefficients estimated via SILH formalism \[\text{[Giudice, Grojean, Pomarol, Rattazzi, hep-ph/0703164]}\]

\[
L \sim \frac{c_1}{f^2} \left[ \partial_\mu (H^\dagger H) \right]^2 + \frac{c_2}{f^2} |H|^2 |D_\mu H|^2 \\
- \frac{c_3}{f^2} (H^\dagger H)^3 + \frac{c_4^{ij}}{f^2} (H^\dagger H \bar{\psi}_L^i L H \psi_R^j) + \cdots
\]
Source of breaking: $L \sim \lambda [\text{TeV}] q_i Q_i$

(driven mainly by the top mixing)


$$L \sim \frac{c_1}{f^2} \left[ \partial_\mu (H^\dagger H) \right]^2 + \frac{c_2}{f^2} |H|^2 |D_\mu H|^2$$

$$-\frac{c_3}{f^2} (H^\dagger H)^3 + \frac{c_{ij}^5}{f} (\overline{S \psi_L^i H \psi_R^j}) + \cdots$$
The EFT of next-to-minimal CHMs

(the scalar sector consists of $H+S$)

- $1S1C\left(f, g_\rho; m_\rho = g_\rho f\right) +$ dimensional analysis determines the scaling of the effective operators, [Panico, Wulzer 1506.01961]

- Operator coefficients of order one, up to selection rules

- It captures the features of many non-minimal CHMs

\[
m_\rho f^2 \left[ \frac{N_c y_t^2}{(4\pi)^2} \right] \#^L \left[ \frac{N_f g_\rho^2}{(4\pi)^2} \right] \#^L \left[ \frac{y_q \bar{q} q}{m_\rho f} \right] \#^q q \left[ \frac{g_A A}{m_\rho} \right] \#^A \left[ \frac{S}{f} \right] \#^S \left[ \frac{H}{f} \right] \#^H \left[ \frac{\partial_\mu}{m_\rho} \right] \#^\partial
\]
There is \textit{a priori} no reason for the mass of S to be tuned. It is then expected that

\[ m_S^2 \sim m_\rho^2 \frac{N_c y_t^2}{(4\pi)^2} \sim \frac{f^2}{v^2} m_h^2 \sim (500 \text{ GeV})^2 \ll m_\rho^2 \]
The coset $SO(6)/SO(5)$

(Gripaios, Pomarol, Riva, Serra 0902.1483)

\[
V \sim f^2 \left[ c_1 - \frac{7}{4} c_2 \right] h^2 + (c_2 - c_1) h^4
\]

\[-c_2 f^2 S^2 + (c_2 - c_1) h^2 S^2 \]
The coset $SO(6)/SO(5)$

(Gripaios, Pomarol, Riva, Serra 0902.1483)

$$V \sim \frac{1}{2} \mu^2 h^2 + \frac{1}{4} \lambda_h h^4$$

$$+ \frac{1}{3} \lambda_h f^2 (1 - 2\epsilon) S^2 + \frac{1}{4} \lambda_h h^2 S^2$$
The coset \( SO(7)/G_2 \)

(MC 1210.6208; Ballesteros, MC, Carmona 1704.07388)

\[
V \sim \frac{1}{2} \mu^2 h^2 + \frac{1}{4} \lambda_h h^4 \\
+ \frac{1}{3} \lambda_h f^2 (1 - 2\epsilon) S^2 + \frac{1}{4} \lambda_h h^2 S^2
\]
The EFT of next-to-minimal CHMs
(the scalar sector consists of H+S)

\[ \rho \sim \text{few TeV} \]

Strong sector

Integrating out S,

\[ S|H|^2, S\bar{q}Hq \]

\[ (a + b)|H|^2\bar{q}Hq \]

EW scale

Higgs Hunting 2017, July 25th 2017
A basis for the EFT of $H+S$
(regarding $S$, we focus on dimension 5)

Caveat: eliminating operator redundancies can break the power counting estimates:

$$\frac{1}{f} |D_\mu H|^2 S \rightarrow \frac{1}{2f} |H|^2 \Box S$$

$$- \frac{1}{2f} (H^\dagger \Box H S + \text{h.c})$$
A basis for the EFT of $H+S$
(regarding $S$, we focus on dimension 5)

- Caveat: eliminating operator redundancies can break the power counting estimates.
- We end up with the minimal set of operators

$$
\begin{array}{c|c}
SX^2, S^{2,4} & SD_\mu H^2, S^{3,5} \\
S\bar{q}Hq, S^2|H|^2 & S|H|^2, S|H|^4, S^3|H|^2 \\
\end{array}
$$
Estimated size of the dimension-5 operators
(cases beyond the PNGB one are also present)

<table>
<thead>
<tr>
<th></th>
<th>scalar</th>
<th></th>
<th>pseudo-scalar</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>generic</td>
<td>PNGB</td>
<td>generic</td>
<td>PNGB (PC)</td>
<td>PNGB (anom.)</td>
</tr>
<tr>
<td>$k_X S X^2$</td>
<td>$\frac{g_X^2}{g^2} \frac{1}{f}$</td>
<td>$\frac{3y^2}{(4\pi)^2} \frac{g_X^2}{g^2} \frac{1}{f}$</td>
<td>$\frac{g_X^2}{g^2} \frac{1}{f}$</td>
<td>$\frac{3y^2}{(4\pi)^2} \frac{g_X^2}{g^2} \frac{1}{f}$</td>
<td>$\frac{N_f^{(X)}}{(4\pi)^2} \frac{g_X^2}{g^2} \frac{1}{f}$</td>
</tr>
<tr>
<td>$k_q S \bar{q} H q$</td>
<td>$y_q \frac{1}{f}$</td>
<td>$y_q \frac{1}{f}$</td>
<td>$i y_q \frac{1}{f}$</td>
<td>$i y_q \frac{1}{f}$</td>
<td>—</td>
</tr>
<tr>
<td>$k_H S</td>
<td>D_\mu H</td>
<td>^2$</td>
<td>$\frac{1}{f}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$k_{H1} S</td>
<td>H</td>
<td>^2$, $k_{H2} S</td>
<td>H</td>
<td>^4/f^2$, $k_{H3} S^3</td>
<td>H</td>
</tr>
<tr>
<td>$k_{H4} S^2</td>
<td>H</td>
<td>^2$</td>
<td>—</td>
<td>$\frac{3y_t^2}{(4\pi)^2} \frac{m_\rho^2}{f^2}$</td>
<td>$\frac{3y_t^2}{(4\pi)^2} \frac{m_\rho^2}{f^2}$</td>
</tr>
<tr>
<td>$k_M S^2$, $k_A S^4/f^2$</td>
<td>$m_\rho^2$</td>
<td>$\frac{3y_t^2}{(4\pi)^2} m_\rho^2$</td>
<td>$m_\rho^2$</td>
<td>$\frac{3y_t^2}{(4\pi)^2} m_\rho^2$</td>
<td>$\frac{\tilde{N}<em>f g</em>\rho^2}{(4\pi)^2} m_\rho^2$</td>
</tr>
<tr>
<td>$k_3 S^3$, $k_5 S^5/f^2$</td>
<td>$\frac{m_\rho^2}{f}$</td>
<td>$\frac{3y_t^2}{(4\pi)^2} m_\rho^2$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Impact on Higgs physics
(cases beyond the PNGB one are also present)
Limits on new vector-like quarks

(MC 1705.03013; see also Serra 1506.05110)

Bounds considering all branching ratios (also elusive decays) in light of 1505.04306, ATLAS-2016-102, ATLAS-2016-104, ATLAS-2017-015, CMS-SUS-16-029
Limits on new vector-like quarks

(MC 1705.03013; see also Serra 1506.05110)

Bounds can be automatically obtained using VLQ-limits, available at http://github.com/mikaelchala/vlqlimits
Conclusions
• Non-minimal composite Higgs models are very good candidates for new physics

• Power counting estimates suggest that extra scalar singlets $S$ are heavier than the Higgs boson

• We have worked out a basis of dimension-5 operators for $S$. Some redundant operators must be kept in order not to break the power counting

• The effects of $S$ on Higgs physics can be larger than those coming from the strong sector

• VLQs are very different from what current analyses are searching for
Thank you very much for your attention!
Backup