Search for light pNGB with taus:
The promising mass window of 15 to 65 GeV

Hugo Serôdio

based on:
A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, HS, A. Parolini [PRD 94 (2016) no 1, 015004]
G. Cacciapaglia, G. Ferretti, T. Flacke, HS, [arXiv: 1710.11142]

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
June 18, 2018
Outline

Composite Higgs and Underlying Dynamics

Timid composite pseudo-scalar (TCP)

Search for light pseudo-scalar with taus

Conclusions/Outlook
Composite Higgs and Underlying Dynamics
General Picture

- gauge HC group

Global symmetry

Condensation

\[ \langle \bar{\psi} \psi \rangle \neq 0 \]

How to build such models?

New fermionic content

Yukawa

Gauge

SM
General Picture

gauge HC group

New fermionic content

Condensation

$\langle \bar{\psi} \psi \rangle \neq 0$

How to build such models?
Fermion masses

**The bilinear approach.**
(as in Technicolor)
[Dimopoulos, Susskind], [Eichten, Lane]

$$\lambda t \frac{q_L O t_R}{\Lambda_{d-1}^{d/2}} + \text{h.c.}$$

\(O\) carries Higgs quantum numbers.
**Alert:** dangerous 4-fermion operators
[Dimopoulos, Ellis]

**The linear approach**
(Partial Compositeness)
[Kaplan]

$$\frac{\lambda_{qL}}{\Lambda_{dL-5/2}^{d/2}} O^R q_L + \frac{\lambda_{tR}}{\Lambda_{dL-5/2}^{d/2}} O^L t_R + \text{h.c.}$$

\(O_{L,R}\) fermionic operators carrying quarks quantum numbers.

$$|\text{SM}\rangle = \cos\varphi |\text{elem}\rangle + \sin\varphi |\text{comp}\rangle$$

**Better:** 4-fermion operators

GIM-like:

$$\langle \bar{q}q \rangle^2 \frac{\sin^4 \varphi}{M^2_*}$$
Building an underlying theory that contains both a composite Higgs and composite top partners is not an easy task, as many conditions need to be satisfied: [Ferretti, Karateev]

- Simple hypercolor group \( G_{HC} \)
- Asymptotically free theories
- Absence of gauge anomalies and Witten’s global anomalies
- Symmetry breaking pattern: \( G_F \rightarrow H_F \supset C_{cus} \supset G_{SM} \)
- The most attractive channel (MAC) should not break neither \( G_{HC} \) nor \( G_{cus} \)
- \( G/H \ni (1, 2, 2)_0 \) of \( G_{cus} \). (the Higgs boson)
- Fermionic hypercolor singlets \( \in (3, 2)_{1/6} \) and \( (3, 1)_{2/3} \) of \( G_{SM} \) (at least 3\(^{rd}\) family) (Top-partners)
- \( B \) and \( L \) symmetry
We shall consider models with two chiral fermion species, each with \( n_i \) flavours:

Global symmetry: \( U(n_{\psi}) \times U(n_{\chi}) \)

- Colourless \( \psi \), which produce the Higgs as a pNGB, after condensation occurs;
- Colourfull \( \chi \), since we want to obtain the top partners.

**EW coset**

- Complex: \( \frac{SU(4) \times SU(4)'}{SU(4)_D} \)
- Pseudoreal: \( \frac{SU(4)}{Sp(4)} \)
- Real: \( \frac{SU(5)}{SO(5)} \)

**Colour coset**

- Complex: \( \frac{SU(3) \times SU(3)'}{SU(3)_D} \)
- Pseudoreal: \( \frac{SU(6)}{Sp(6)} \)
- Real: \( \frac{SU(6)}{SO(6)} \)
<table>
<thead>
<tr>
<th>Coset</th>
<th>HC</th>
<th>$\psi$</th>
<th>$\chi$</th>
<th>$-q_\chi/q_\psi$</th>
<th>$Y_\chi$</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(5)/SO(5) \times SU(6)/SO(6)$</td>
<td>$SO(7)$</td>
<td>$5 \times F$</td>
<td>$6 \times \text{Spin}$</td>
<td>$5/6$</td>
<td>$5/12$</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>$SO(9)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M2</td>
</tr>
<tr>
<td></td>
<td>$SO(7)$</td>
<td></td>
<td>$5 \times \text{Spin}$</td>
<td>$6 \times F$</td>
<td>$5/6$</td>
<td>$2/3$</td>
</tr>
<tr>
<td></td>
<td>$SO(9)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M4</td>
</tr>
<tr>
<td>$SU(5)/SO(5) \times SU(6)/Sp(6)$</td>
<td>$Sp(4)$</td>
<td>$5 \times A_2$</td>
<td>$6 \times F$</td>
<td>$5/3$</td>
<td>$1/3$</td>
<td>M5</td>
</tr>
<tr>
<td>$SU(5)/Sp(4) \times SU(6)/SO(6)$</td>
<td>$Sp(4)$</td>
<td>$4 \times F$</td>
<td>$6 \times A_2$</td>
<td>$1/3$</td>
<td>$2/3$</td>
<td>M8</td>
</tr>
<tr>
<td></td>
<td>$SO(11)$</td>
<td>$4 \times \text{Spin}$</td>
<td>$6 \times F$</td>
<td>$8/3$</td>
<td></td>
<td>M9</td>
</tr>
<tr>
<td>$SU(4)/Sp(4) \times SU(6)/SO(6)$</td>
<td>$SO(10)$</td>
<td>$4 \times (\text{Spin, Spin})$</td>
<td>$6 \times F$</td>
<td>$8/3$</td>
<td>$2/3$</td>
<td>M10</td>
</tr>
<tr>
<td></td>
<td>$SU(4)$</td>
<td>$4 \times (F, \overline{F})$</td>
<td>$6 \times A_2$</td>
<td>$2/3$</td>
<td></td>
<td>M11</td>
</tr>
<tr>
<td>$SU(4)/SU(4) \times SU(6)/SO(6)$</td>
<td>$SU(5)$</td>
<td>$4 \times (F, \overline{F})$</td>
<td>$3 \times (A_2, \overline{A}_2)$</td>
<td>$4/9$</td>
<td>$2/3$</td>
<td>M12</td>
</tr>
</tbody>
</table>

Always 2 $U(1)$s that are spontaneously broken: $U(1)_\psi, U(1)_\chi$.
One combination of the two has an anomaly with the $G_{HC}$:

$$U(1)_{\psi, \chi}G_{HC}^2 \neq 0 \Rightarrow [U(1)_\psi + U(1)_\chi]G_{HC}^2 \neq 0$$

For the anomaly free light pNGB, we have $q_\psi N_\psi T(\psi) + q_\chi N_\chi T(\chi) = 0$
Timid composite pseudo-scalar
A timid composite pseudo-scalar (TCP)

The pNGBs $\phi = \{a, \eta'\}$ can be both described by the effective Lagrangian.

$$\mathcal{L} = \frac{1}{2} \left( \partial_\mu \phi \partial^\mu \phi - M_\phi^2 \phi^2 \right) - \sum_i C_f \frac{m_f}{f_\phi} \phi \overline{\Psi}_f \gamma_5 \Psi_f$$

$$+ \frac{\phi}{f_\phi} \left( \frac{g_s^2 K_g}{16\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2} W^i_{\mu\nu} \tilde{W}^{i\mu\nu} + \frac{g''^2 K_B}{16\pi^2} B_{\mu\nu} B^{\mu\nu} \right)$$

- spurion mass term
  $$-m_t(h) e^{i C_t a / f_a} \overline{\Psi}_{tL} \Psi_{tR}$$
- WZW coefficients $K_i$ are fully determined by $\psi, \chi$ quant. num.;
- $C_f$ is also fixed for each individual model;
- $K_{g}^{\text{eff}} \simeq K_g - C_t / 2$ (top loop)

### Decoupling limit: $m_{\eta'} \gg m_a$

<table>
<thead>
<tr>
<th></th>
<th>$K_g$</th>
<th>$K_W$</th>
<th>$K_B$</th>
<th>$C_f$</th>
<th>$f_a / f_\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>-7.2</td>
<td>7.6</td>
<td>2.8</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>M2</td>
<td>-8.7</td>
<td>12.</td>
<td>5.9</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>M3</td>
<td>-6.3</td>
<td>8.7</td>
<td>-8.2</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td>M4</td>
<td>-11.</td>
<td>12.</td>
<td>-17.</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>M5</td>
<td>-4.9</td>
<td>3.6</td>
<td>0.40</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>M6</td>
<td>-4.9</td>
<td>4.4</td>
<td>1.1</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>M7</td>
<td>-8.7</td>
<td>13.</td>
<td>7.3</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>M8</td>
<td>-1.6</td>
<td>1.9</td>
<td>-2.3</td>
<td>1.9</td>
<td>2.8</td>
</tr>
<tr>
<td>M9</td>
<td>-10.</td>
<td>5.6</td>
<td>-22.</td>
<td>0.70</td>
<td>1.2</td>
</tr>
<tr>
<td>M10</td>
<td>-9.4</td>
<td>5.6</td>
<td>-19.</td>
<td>0.70</td>
<td>1.5</td>
</tr>
<tr>
<td>M11</td>
<td>-3.3</td>
<td>3.3</td>
<td>-5.5</td>
<td>1.7</td>
<td>3.1</td>
</tr>
<tr>
<td>M12</td>
<td>-4.1</td>
<td>4.6</td>
<td>-6.3</td>
<td>1.8</td>
<td>2.6</td>
</tr>
</tbody>
</table>

- Free parameters: $M_a, M_{\eta'}$ and $f$;
- Note: in general we have 4 independent scales $f_{a\psi}, f_{a\chi}, f_{a\psi}, f_{a\chi}$.

Under reasonable assumptions we can reduce it to a single scale $f (\equiv f_\psi)$. $m_w = (g/2)f \sin \theta$ ($\theta \rightarrow \pi/2$ Technicolor limit)
TCP Phenomenology: M6 and M8

We shall pick 2 models:

**M6**

\[ SU(4)_{HC} : \left\{ \begin{array}{l} \psi \sim 5 \times A_2 \\ \chi \sim 3 \times (F, \overline{F}) \end{array} \right. \]

\[ \frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)} \]

[Ferretti JHEP1406,142]

**M8**

\[ Sp(4)_{HC} : \left\{ \begin{array}{l} \psi \sim 4 \times F \\ \chi \sim 6 \times A_2 \end{array} \right. \]

\[ \frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)} \]

[Barnard, et al. JHEP1402,002]
Lattice: [Bennett, et al. JHEP1803,185]
TCP Phenomenology

- $\phi$ is produced in gluon fusion;
- Small couplings to $W$ and $Z$; Assec. production with a $Z$ is tiny; No bounds from LEP;
- Weak indirect bounds from $h \rightarrow aa$ (BSM).
TCP Phenomenology: M6 and M8

- M8 weakly constrained;
- Decoupling limit and light $a$: needs exploration;

Large production XS for low masses (gluon fusion)
Search for light pseudo-scalar with taus
How to explore the mass gap 15 to 65 GeV?

- $h \rightarrow aa$ (BSM) will not dramatically increase $f_a \sim BR(h \rightarrow aa)^{1/4}$
- Extending $\mu\mu$ resonance searches to higher mass?
- Extending $\gamma\gamma$ resonance searches to even lower mass?
- ... or looking for other decay channels: $\tau\tau$!

- Soft $\tau_{lep}$ of $\tau_{had}$ can not be used to trigger. But ISR can boost $gg \rightarrow a \rightarrow \tau\tau$ system;
- Prod. XS for $a$ gets reduced. Not a big problem.
How to explore the mass gap 15 to 65 GeV?

- **Proof of principle analysis:** \( j\tau_\mu \tau_e \)

- **Cuts:** \( p_{T\mu} > 52 \text{ GeV}; \ p_{T\mu} > 10 \text{ GeV}; \ p_{T\mu} > 10 \text{ GeV}; \ p_{Tj} > 150 \text{ GeV}; \ m_{\mu e} < 100 \text{ GeV}; \ \Delta R_{\mu j} > 0.5; \ \Delta R_{ej} > 0.5; \ \Delta R_{\mu e} < 1; \)

\[
\begin{align*}
\text{BG Z/\gamma^*}&\rightarrow\tau\tau \\
\text{BG t\bar{t}} & \\
\text{BG W^+ W^-} & \\
\text{SG m_a=20 GeV} & \\
\text{SG m_a=80 GeV} & 
\end{align*}
\]

Crucial discriminating variable:
- \( \Delta R_{\mu e} > 0 \) or \( \Delta R_{\mu e} > 0.2 \)

- **Generate signal sample**
  \( pp \rightarrow a \rightarrow \tau^+ \tau^- \).

- **Projected reach** after an integrated Luminosity of 300 fb\(^{-1}\) and 3000 fb\(^{-1}\) @13TeV
How to explore the mass gap 15 to 65 GeV?

- **Low-mass $\gamma\gamma$ resonances** projections in red; [Mariotti, et al. 1710.01743]
- In some cases can be competitive with boosted $\tau\tau$. 

▶ 10^4
▶ 10^3

$M_a$ [GeV]

$\Delta \gamma > 0$

$\Delta \gamma > .2$

$@14$ TeV [arXiv:1710.1743]
Conclusions/Outlook
Conclusions/Outlook

- CHM provide a viable solution to the hierarchy problem with still many challenges and room for exploration;
- EFT descriptions of CHM are only a part of the story. UV embeddings need to be studied in detail, and they will lead to novel BSM signatures;
- UV descriptions generally contain a SM singlet pNGB which couples to the SM gauge bosons through the WZW term; Fully determined by the quantum numbers of the underlying fermions;
- In a mass range of 15 - 65 GeV, to our knowledge, none of the existing LEP, Tevatron, and LHC searches are sensitive to this pseudo-scalar. (timid composite pseudo-scalar (TCP))
- Searching for the TCP in the di-tau channel with ISR against which the di-tau system recoils looks promising. Initial study shows very good sensitivity in this mass window.
- Room for improvement in the analysis:
  - No use any τ ID or triggers.
  - More careful background analysis.
  - Systematic uncertainties.