Light scalars in composite Higgs models

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G. Cacciapaglia, G. Ferretti, T. Flacke, H. Serodio [EPJC 78 (2018) no.9, 724]
N. Bizot, G. Cacciapaglia, T. Flacke [JHEP 1806, 065]
G. Cacciapaglia, A Deandrea, T. Flacke, A. Iyer [CDFI; in preparation]

HPNP2019, Osaka, Feb 22nd, 2019
Outline

• Motivation for a composite Higgs
• Towards UV embeddings: Models
• Phenomenology of light BSM scalars
• Phenomenology of top partners
• Conclusions
Motivation for a composite Higgs

An alternative solution to the hierarchy problem:

• Generate a scale $\Lambda_{HC} \ll M_{pl}$ through a new confining gauge group.

• Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.

[Georgi, Kaplan (1984)]

The price to pay:

• additional resonances around $\Lambda_{HC}$ (vectors, vector-like fermions, scalars),

• additional light pNGBs / an extended sector (?) .

• deviations of the Higgs couplings from their SM values of $O(v/f)$. 

Running of the new strong coupling

$\Lambda_{HC} = g^* f \sim$ few TV

$f > 800$ GeV

“Higgs” $125$ GeV

$O(\text{few TeV})$
Composite Higgs Models: Towards underlying models

A wish list to construct and classify candidate models:
Underlying models of a composite Higgs should

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group,
- have a Higgs candidate amongst the pNGBs of the bound states,
- have a top-partner amongst its bound states (for top mass via partial compositeness),
- satisfy further “standard” consistency conditions (asymptotic freedom, no gauge anomalies).

The resulting models have several common features:
- All models contain several top partner multiplets.
- All models predict pNGBs beyond the Higgs multiplet.

*Gherghetta et al. (2014), Ferretti et al. (2014), PRD 94 (2016) no 1, 015004, JHEP 1701, 094*
Example: SU(4)/Sp(4) coset based on GHC = Sp(2Nc)

<table>
<thead>
<tr>
<th>Sp(2Nc)</th>
<th>SU(3)_c</th>
<th>SU(2)_L</th>
<th>U(1)_Y</th>
<th>SU(4)</th>
<th>SU(6)</th>
<th>U(1)</th>
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<tbody>
<tr>
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<td>□</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>1</td>
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<tr>
<td>ψ₂</td>
<td>□</td>
<td>1</td>
<td>1</td>
<td>1/2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>ψ₄</td>
<td>□</td>
<td>1</td>
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<td>1/2</td>
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<tr>
<td>χ₁</td>
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<td>1</td>
<td>2/3</td>
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<tr>
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<td>-2/3</td>
<td>1</td>
<td>6</td>
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Motivation

Phenomenology of quark partners

Towards a CH UV embedding and its phenomenology

Conclusions and Outlook

One example: SU(4)/Sp(4) coset based on GHC = Sp(2Nc)

Field content of the microscopic fundamental theory and property transformation under the gauged symmetry group

\[ \text{Sp}(2Nc) \times \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{SU}(4) \times \text{SU}(6) \times \text{U}(1) \]

Bound states of the model:

spin \[ \begin{pmatrix} \psi \psi \ 0 \ (6,1) \ \ (1,1) \ (5,1) \ 
\chi \chi \ 0 \ \ (1,21) \ \ (1,1) \ (1,20) 
\end{pmatrix} \]

contains \( SU(2)_L \times SU(2)_R \) bidoublet “H”

form a and \( \eta’ \); SM singlets

20 colored pNGB:
\( (8,1,1)_{0} \oplus (6,1,1)_{4/3} \oplus (\bar{5},1,1)_{-4/3} \)

contain \((3,2,2)_{2/3}\) fermions: \( t_L \)-partners

contain \((3,1,X)_{2/3}\) fermions: \( t_R \)-partners

Underlying field content

This is the BSM + Higgs sector which interacts with SM gauge bosons and matter through:

\[ [JHEP1511,201] \]
Full list of "minimal" CHM UV embeddings

<table>
<thead>
<tr>
<th>$G_{HC}$</th>
<th>$\psi$</th>
<th>$\chi$</th>
<th>Restrictions</th>
<th>$-g_\chi/g_\psi$</th>
<th>$Y_\chi$</th>
<th>Non Conformal</th>
<th>Model Name</th>
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<tbody>
<tr>
<td>Real</td>
<td>Real</td>
<td>SU(5)/SO(5) x SU(6)/SO(6)</td>
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<td></td>
<td></td>
<td></td>
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<td>$SO(N_{HC})$</td>
<td>$5 \times S_2$</td>
<td>$6 \times F$</td>
<td>$N_{HC} \geq 55$</td>
<td>$\frac{5(N_{HC}+2)}{6}$</td>
<td>1/3</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>$SO(N_{HC})$</td>
<td>$5 \times Ad$</td>
<td>$6 \times F$</td>
<td>$N_{HC} \geq 15$</td>
<td>$\frac{5(N_{HC}-2)}{6}$</td>
<td>1/3</td>
<td>/</td>
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<tr>
<td>$SO(N_{HC})$</td>
<td>$5 \times Spin$</td>
<td>$6 \times Spin$</td>
<td>$N_{HC} = 7, 9$</td>
<td>$\frac{5}{6}, \frac{5}{12}$</td>
<td>1/3</td>
<td>$N_{HC} = 7, 9$</td>
<td>M1, M2</td>
</tr>
<tr>
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<td>$5 \times Spin$</td>
<td>$6 \times F$</td>
<td>$N_{HC} = 7, 9$</td>
<td>$\frac{5}{6}, \frac{5}{3}$</td>
<td>2/3</td>
<td>$N_{HC} = 7, 9$</td>
<td>M3, M4</td>
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<tr>
<td>Real</td>
<td>Pseudo-Real</td>
<td>SU(5)/SO(5) x SU(6)/Sp(6)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$Sp(2N_{HC})$</td>
<td>$5 \times Ad$</td>
<td>$6 \times F$</td>
<td>$2N_{HC} \geq 12$</td>
<td>$\frac{5(N_{HC}+1)}{3}$</td>
<td>1/3</td>
<td>/</td>
<td></td>
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<tr>
<td>$Sp(2N_{HC})$</td>
<td>$5 \times A_2$</td>
<td>$6 \times F$</td>
<td>$2N_{HC} \geq 4$</td>
<td>$\frac{5(N_{HC}-1)}{3}$</td>
<td>1/3</td>
<td>$2N_{HC} = 4$</td>
<td>M5</td>
</tr>
<tr>
<td>$SO(N_{HC})$</td>
<td>$5 \times F$</td>
<td>$6 \times Spin$</td>
<td>$N_{HC} = 11, 13$</td>
<td>$\frac{5}{24}, \frac{5}{48}$</td>
<td>1/3</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Real</td>
<td>Complex</td>
<td>SU(5)/SO(5) x SU(3)^2/SU(3)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$SU(N_{HC})$</td>
<td>$5 \times A_2$</td>
<td>$3 \times (F, \bar{F})$</td>
<td>$N_{HC} = 4$</td>
<td>$\frac{5}{3}$</td>
<td>1/3</td>
<td>$N_{HC} = 4$</td>
<td>M6</td>
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<tr>
<td>$SO(N_{HC})$</td>
<td>$5 \times F$</td>
<td>$3 \times (Spin, Spin)$</td>
<td>$N_{HC} = 10, 14$</td>
<td>$\frac{5}{12}, \frac{5}{48}$</td>
<td>1/3</td>
<td>$N_{HC} = 10$</td>
<td>M7</td>
</tr>
<tr>
<td>Pseudo-Real</td>
<td>Real</td>
<td>SU(4)/Sp(4) x SU(6)/SO(6)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Sp(2N_{HC})$</td>
<td>$4 \times F$</td>
<td>$6 \times A_2$</td>
<td>$2N_{HC} \leq 36$</td>
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<td>$2N_{HC} = 4$</td>
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<td>$SO(N_{HC})$</td>
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<td>$6 \times F$</td>
<td>$N_{HC} = 11, 13$</td>
<td>$\frac{5}{3}, \frac{16}{3}$</td>
<td>2/3</td>
<td>$N_{HC} = 11$</td>
<td>M9</td>
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<td>Real</td>
<td>SU(4)^2/SU(4) x SU(6)/SO(6)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$SO(N_{HC})$</td>
<td>$4 \times Spin, Spin$</td>
<td>$6 \times F$</td>
<td>$N_{HC} = 10$</td>
<td>$\frac{5}{3}$</td>
<td>2/3</td>
<td>$N_{HC} = 10$</td>
<td>M10</td>
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<tr>
<td>$SU(N_{HC})$</td>
<td>$4 \times (F, \bar{F})$</td>
<td>$6 \times A_2$</td>
<td>$N_{HC} = 4$</td>
<td>$\frac{5}{3}$</td>
<td>2/3</td>
<td>$N_{HC} = 4$</td>
<td>M11</td>
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<tr>
<td>Complex</td>
<td>Complex</td>
<td>SU(4)^2/SU(4) x SU(3)^2/SU(3)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$SU(N_{HC})$</td>
<td>$4 \times (F, \bar{F})$</td>
<td>$3 \times (A_2, \bar{A}_2)$</td>
<td>$N_{HC} \geq 5$</td>
<td>$\frac{1}{3(N_{HC}-2)}$</td>
<td>2/3</td>
<td>$N_{HC} = 5$</td>
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<td>$4 \times (F, \bar{F})$</td>
<td>$3 \times (A_2, \bar{A}_2)$</td>
<td>$N_{HC} \geq 5$</td>
<td>$\frac{1}{3(N_{HC}+2)}$</td>
<td>2/3</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>
New PNGBs and their phenomenology

1. ALL models:
   $a$ and $\eta'$:(one HC anomaly free, one anomalous pseudo-scalar) which couple to SM gauge bosons through WZW couplings and to fermions with $m_f/f$.


2. ALL models:
   $\pi_8$: Color octet pseudo-scalar pNGB which couples to $gg, gy, gZ, tt$ [JHEP1701,094]

3. Depending on the embedding model: Additional colored and uncolored pNGBs

<table>
<thead>
<tr>
<th>Electro-weak coset</th>
<th>$SU(2)_L \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(5)/SO(5)$</td>
<td>$3_{\pm 1} + 3_0 + 2_{\pm 1/2} + 1_0$</td>
</tr>
<tr>
<td>$SU(4)/Sp(4)$</td>
<td>$2_{\pm 1/2} + 1_0$</td>
</tr>
<tr>
<td>$SU(4) \times SU(4)'/SU(4)_D$</td>
<td>$3_0 + 2_{\pm 1/2} + 2'<em>{\pm 1/2} + 1</em>{\pm 1} + 1_0 + 1'_0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color coset</th>
<th>$SU(3)_c \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SU(6)/SO(6)$</td>
<td>$8_0 + 6_{(-2/3 \text{ or } 4/3)} + 6_{(2/3 \text{ or } -4/3)}$</td>
</tr>
<tr>
<td>$SU(6)/Sp(6)$</td>
<td>$8_0 + 3_{2/3} + 3_{-2/3}$</td>
</tr>
<tr>
<td>$SU(3) \times SU(3)'/SU(3)_D$</td>
<td>$8_0$</td>
</tr>
</tbody>
</table>

[Agugliaro etal]

[JHEP1511,201]
Singlet pNGB summary and phenomenology

\[ \text{arXiv:1902.06890} \]

\( a \) and \( \eta' \): Arise from the SSB of \( U(1)_\chi \times U(1)_\psi \). One linear combination has a \( G_{HC} \) anomaly (\( \eta' \)) and is expected heavier. The orthogonal linear combination (\( a \)) is a pNGB. \( \Phi = \{a, \eta'\} \)

\[
\mathcal{L}_{\text{eff}} \supset \frac{1}{2} (\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m_\phi^2 \phi^2 \\
+ \frac{\phi}{16\pi^2 f_\psi} \left( g_s^2 K_{\Phi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + g^2 K_{W}^i W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g r^2 K_{B} B_{\mu\nu} \tilde{B}^{\mu\nu} \right) \\
- i \sum_f \frac{C_f^\phi m_f}{f_\psi} \phi \bar{\psi}_f \gamma^5 \psi_f \\
+ \frac{2v}{f_\psi^2} K_{\phi_h}^{\text{eff}} (\partial_\mu \phi)(\partial^\mu \phi) h + \frac{2m_Z}{f_\psi} K_{hZ}^{\text{eff}} (\partial_\mu \phi)(\partial^\mu h)
\]

- \( m_a \) must result from explicit breaking of the U(1)s. \( m_\eta \) also obtains mass from instantons.

- \( f_\psi \) (decay constant of the EW sector) results from chiral symmetry breaking.

- The WZW coefficients \( K^\Phi \) are determined by the quantum numbers of \( \chi, \psi \) (and \( (m_a, m_\eta) \)).

- The coefficients \( C_f^\phi \) are also fixed (depending on dominantly mixing top-partner).

- \( h\phi\phi \) and \( h\phi Z \) couplings are induced at 1-loop order.

- \( a \) and \( \eta' \) are produced in gluon fusion.

- The resonances are narrow.
### WZW coefficients

<table>
<thead>
<tr>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
<th>M10</th>
<th>M11</th>
<th>M12</th>
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<tr>
<td>$K^a_g$</td>
<td>-3.5</td>
<td>-3.6</td>
<td>-2.3</td>
<td>-5.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.7</td>
<td>-0.6</td>
<td>-8.4</td>
<td>-6.2</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>-1.8</td>
<td>-1.9</td>
<td>-1.3</td>
<td>-3.1</td>
<td>-1.8</td>
<td>-1.8</td>
<td>-1.9</td>
<td>-3.1</td>
<td>-4.8</td>
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<td>5.9</td>
<td>2.6</td>
<td>3.1</td>
<td>5.5</td>
<td>.68</td>
<td>4.6</td>
<td>3.7</td>
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<td>3.6</td>
<td>6.1</td>
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<td>7.1</td>
<td>6.8</td>
<td>1.7</td>
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<td>$K^a_B$</td>
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<td>-3.0</td>
<td>-8.8</td>
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<td>.81</td>
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<td>-18.</td>
<td>-13.</td>
<td>-1.8</td>
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<tr>
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<td>4.8</td>
<td>.09</td>
<td>-5.6</td>
<td>-2.8</td>
<td>.12</td>
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<tr>
<td>$K^{\eta'}_g$</td>
<td>5.4</td>
<td>5.9</td>
<td>1.8</td>
<td>3.9</td>
<td>5.4</td>
<td>5.1</td>
<td>6.6</td>
<td>.53</td>
<td>5.9</td>
<td>3.2</td>
<td>.68</td>
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<td>6.7</td>
<td>2.7</td>
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<td>8.9</td>
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<td>5.5</td>
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<td>16.</td>
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<tr>
<td>$f_\psi/f_\chi$</td>
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<td>.73</td>
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<td>1.9</td>
<td>.58</td>
<td>.38</td>
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<td>.52</td>
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<td>2.4</td>
<td>2.8</td>
<td>2.0</td>
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<td>2.8</td>
<td>1.2</td>
<td>1.5</td>
<td>3.1</td>
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</tbody>
</table>

**TABLE III.** Couplings of $\alpha$ and $\eta'$ to gauge bosons for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). The last two rows shows the numerical value of the decay constant ratios used in this work.
### Couplings to top

<table>
<thead>
<tr>
<th>$C^{a}_t$</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
<th>M10</th>
<th>M11</th>
<th>M12</th>
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<tbody>
<tr>
<td>$(\pm 2, 0)$</td>
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<td>±1.1</td>
<td>±.79</td>
<td>±.73</td>
<td>±1.1</td>
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<td>±1.1</td>
<td>±.68</td>
<td>±.58</td>
<td>±.46</td>
<td>±.54</td>
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<td>±1.2</td>
<td>±1.2</td>
<td>±1.1</td>
<td>±1.1</td>
<td>±1.2</td>
<td>±1.2</td>
<td>±1.2</td>
<td>±.92</td>
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<td>±.85</td>
<td>±.88</td>
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<td>$(0, \pm 2)$</td>
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<td>±.45</td>
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**TABLE IV.** Coupling of $a$ and $\eta'$ to the top, $C_t$, for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). For models with top partners in the form $\psi\chi\chi$ (see Table I), the two last rows should be intended (2, 4) and (2, −4).
FIG. 7. Representative Branching Ratios of $a$ in the decoupling limit for all models and for the six choices of top partner charges. We only show $gg$ (light and dark green), $\gamma\gamma$ (brown and red) and $\tau\tau$ (purple and lilac).
For a given model, we can combine bounds and sensitivities from resonance searches to get a bound on the compositeness scale $f$. 

[arXiv:1902.06890] [all other models in backup slides]
How can we search the gap at low mass? $\tau\tau$!

[EPJC 78 (2018) no.9, 724]

We studied di-tau channel in the low invariant mass regime ($pp \rightarrow j a \rightarrow j \tau_\mu \tau_e$) and designed a proposed search which promises good coverage of the pNGB low-mass regime.

Resulting projected reach for 300 fb$^{-1}$. 
Projected reach at HL-LHC

[arXiv:1902.06890]

[all other models in backup slides]
Colored PNGBs (the color octet $\Phi$)

Effective Lagrangian:

$$ \mathcal{L}_\Phi = \frac{1}{2} (D_\mu \Phi^a)^2 - \frac{1}{2} M_\Phi^2 \Phi^a + i \frac{C_t m_t}{f_\Phi} \Phi^a \, \bar{t} \gamma_5 \frac{\lambda^a}{2} t $$

where in the CH UV embeddings:

$$ \kappa_{g8} = \sqrt{2c_5} \, d_\chi, \hspace{1em} \kappa_{B8} = \sqrt{2c_5} \, 2Y_\chi \, d_\chi, \hspace{1em} C_{t8} = n_\chi \sqrt{2c_5}.$$

Phenomenology

- $\Phi$ is single-produced in gluon fusion or pair-produced through QCD.
- $\Phi$ decays to $gg$, $gy$, $gZ$, $tt$ with fully determined branching fractions into dibosons:
  - For $Y_\chi = 1/3$: $gg/gy/gZ = 1 / .05 / .015$, $Y_\chi = 2/3$: $gg/gy/gZ = 1 / .19 / .06$.
  - The resonance is narrow.
Channels with the strongest bound: gg (red), gɣ (cyan), tt (gray).
Contours give bounds on $\kappa_g/f_\Phi$ in TeV$^{-1}$.

For pair production, currently only searches for 4t and di-jet pairs are available. Other combinations of decays can yield better coverage at the LHC.

[PDF; in preparation]
X_{5/3} : Run II: M_X \geq 1.3 \text{ TeV}, \quad [\text{CMS PAS B2G-16-019, ATLAS: 1806.01762}]

T & B: Combined bounds on pair-produced top partners Run II

---

Other CH model signatures

Vector-like quarks (top- partners or quark partners) with charge 5/3, 2/3, -1/3, -4/3

---

[ATLAS-CONF-2018-032]
Top partners in CH UV embeddings

[JHEP 1806, 065]

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top/bottom and a pNGB are kinematically possible.
- With an underlying model specified, we showed how branching ratios of top partners to h/W/Z vs new pNGBs are related.
- Scanning through the different underlying models we looked for “common exotic” top partner decays and found several scenarios:
  1. decays of $T$ and $B$ to the singlet pseudo-scalar singlet $a$,
  2. decays of $T$ to the “exclusive pseudo-scalar” $\eta$,
  3. $X_{5/3} \rightarrow \bar{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t t$),
  4. $X_{5/3} \rightarrow t \phi^+$ and $X_{5/3} \rightarrow b \phi^{++}$.
- Decays of the pNGBs yield manifold novel multi-body decay modes and LHC signatures.
- Detailed pheno studies of several scenarios are under way.
Common exotic VLQ decays

Candidate 1: decays to the singlet pseudo-scalar singlet $a$

Effective Lagrangian(s):  \[ \text{[JHEP 1806, 065]} \]

\[
\mathcal{L}_T = \bar{T} (i \not{\partial} - M_T) T + \left( \kappa_{W,L}^T \frac{g}{\sqrt{2}} \bar{T} W^+ P_L b + \kappa_{Z,L}^T \frac{g}{2c_W} \bar{T} Z P_L t \right. \\
\left. - \kappa_{h,L}^T \frac{M_T}{v} \bar{T} h P_L t + i \kappa_{a,L}^T \bar{T} a P_L t + L \leftrightarrow R + \text{h.c.} \right),
\]

\[
\mathcal{L}_B = \bar{B} (i \not{\partial} - M_B) B + \left( \kappa_{W,L}^B \frac{g}{\sqrt{2}} \bar{B} W^- P_L t + \kappa_{Z,L}^B \frac{g}{2c_W} \bar{B} Z^+ P_L b \right. \\
\left. - \kappa_{h,L}^B \frac{M_B}{v} \bar{B} h P_L b + i \kappa_{a,L}^B \bar{B} a P_L b + L \leftrightarrow R + \text{h.c.} \right).
\]

\[
\mathcal{L} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2 a^2 - \sum_f \frac{iC_fm_f}{f_a} a \bar{\psi}_f \gamma^5 \psi_f \quad (1)
\]

\[
+ \frac{g_s^2 K_a}{16\pi^2 f_a} G_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a} W^{i\mu} \tilde{W}_{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}
\]
Common exotic VLQ decays

Benchmark parameters (obtained as eff. parameters from UV model):

Bm1: \( M_T = 1 \text{ TeV} \), \( \kappa_{Z,R}^T = -0.03 \), \( \kappa_{h,R}^T = 0.06 \), \( \kappa_{a,R}^T = -0.24 \), \( \kappa_{a,L}^T = -0.07 \);

Bm2: \( M_B = 1.38 \text{ TeV} \), \( \kappa_{W,L}^B = 0.02 \), \( \kappa_{W,R}^B = -0.08 \), \( \kappa_{a,L}^B = -0.25 \),

\( (2.3) \)

Branching ratios of quark partners to \( a \) in these benchmarks:
Common exotic VLQ decays

Examples of diagrams:

- T and B can be produced like “standard” top partners: QCD pair production or single production.

- New final states: MANY, depending on $m_a$ and single- or pair-production.
Conclusions

• Composite Higgs Models provide a viable solution to the hierarchy problem but they still provide many challenges and room for exploration in theory and model-building.

• EFT descriptions of composite Higgs models are only part of the story. UV embeddings need to be studied in more detail, and they lead to novel (as well as already well-known) BSM LHC signatures.

• We showed that additional pNGBs are present in CH UV embeddings (colored as well as uncolored ones) and studied constraints for the SM singlet and the color octet pNGB.

• Decays of top partners to $t/b + \text{pNGBs}$ rather than to $t/b + W/Z/h$ occur commonly in CH UV embeddings. These decays lead to many final states which are not targeted by current LHC searches, which need to be studied in more detail.

There is a lot to do!
Fundamental Composite Dynamics: Opportunities for Future Colliders and Cosmology

26 August 2019 to 6 September 2019
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

The main topics of the Scientific Program will be (1) the benchmark models for the electroweak sector of composite Higgs models and composite quark partners, (2) the composite models with dark matter candidates, (3) cosmological implications of phase-transitions in composite models, gravitational waves, baryogenesis, effects of the UV dynamics on cosmological evolution, (4) the prospects and opportunities for composite physics at HL-LHC and future hadron/ electron colliders (He-LHC, FCC, ILC, CLIC...), and finally (5) event-generators, simulation and recasting tools and methods for collider studies.

Starts 26 Aug 2019, 08:00
Ends 6 Sep 2019, 18:00
Europe/Berlin

Mainz Institute for Theoretical Physics,
Johannes Gutenberg University
02.430
Staudingerweg 9 / 2nd floor, 55128 Mainz

Organized by Giacomo Cacciapaglia (IPN Lyon), Thomas Flacke (IBS CTPU Daejeon), Benjamin Fuks (Univ. Sorbonne) and Krishnamoorthy Sridhar (Tata Institute Mumbai).

MITP supports equal opportunities in science.

https://indico.mitp.uni-mainz.de/event/185/
Backup
Chiral Lagrangian for the pNGBs

The pseudo-Goldstones are parameterized by the Goldstone boson matrices

\[ \Sigma_r = e^{i2\sqrt{2}c_5 \pi_r^a T_r^a / f_r} \cdot \Sigma_{0,r} \,, \quad \Phi_r = e^{ic_5 a_r / f_a} \, , \]

where \( r = \psi, \chi \), \( \pi^a \) are the non-abelian Goldstones, \( T^a \) are the corresponding broken generators, \( \Sigma_{0,r} \) is the EW preserving vacuum, and \( a \) are the U(1) Goldstones parameterized via the Goldstone boson matrices. (\( c_5 = \sqrt{2} \) for real reps and 1 otherwise).

The lowest order chiral Lagrangian is

\[ \mathcal{L}_{\text{Xpt}} = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2} \text{Tr}[(D_\mu \Sigma_r)\dagger(D^\mu \Sigma_r)] + f_a^2 \frac{1}{2c_5^2} (\partial_\mu \Phi_r)\dagger(\partial^\mu \Phi_r) \, . \]

where we chose the normalization such that \( m_W = \frac{g}{2} f_\psi \sin \theta \) where \( \theta \) is the vacuum misalignment angle.

In the large N limit, expect \( f_{a_r} = \sqrt{N_r} f_r \).

**Upshot:**
- The pNGBs are described in a non-linear sigma model.
- The different pNGBs can have different decay constants (ratios can be estimated, but in the end only calculated on the Lattice.)
1. The SM gauge group is weakly gauged, which explicitly breaks the global symmetry. This yields mass contributions for SM charged pNGBs. As the underlying fermions are SM charged, it also yields anomaly couplings of pNGBs to SM gauge bosons.

2. The elementary quarks (in particular tops) need to obtain masses. This can be achieved through linear mixing with composite fermionic operators (“top partners”), which explicitly break the global symmetries.

3. Mass terms for the underlying fermions explicitly break the global symmetries and give (correlated) mass contributions to all pseudo Goldstones.

Weak gauging and partial compositeness is commonly used in composite Higgs models to explain the generation of a potential for the Higgs (aka EW pNGBs). On the level of the underlying fermions, such mixing requires 4-fermion operators.

What are the implications of the above points for the SM singlet, and the color-octet pNGB?
Couplings of pNGBs to SM gauge bosons:

The underlying fermions are charged under the SM gauge fields, and thus ABJ anomalies induce couplings of the Goldstone bosons to the SM fields which are fully determined by the underlying quantum numbers.

Singlets: \( \mathcal{L}_{WZW} \supset \frac{\alpha_A}{8\pi} c_5 \frac{C^r_A}{f_{ar}} \delta^{ab} a_r \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A^b_{\alpha\beta} \),

where

<table>
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<th>( C^r_B )</th>
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<td>( d_\chi )</td>
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Non-abelian pNGBs: \( \mathcal{L}_{WZW} \supset \frac{\sqrt{\alpha_A \alpha_{A'}}}{4\sqrt{2\pi}} c_5 \frac{C^{r}_{AA'}}{f_r} c^{abc} \pi^a_r \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A^b_{\alpha\beta} \),

where

\[
C^{r}_{AA'} c^{abc} = d_r \text{Tr}[T^a_r \{ S^b, S^c \}]
\]

Upshot: - The couplings \( C^{r}_{A} \) of pNGBs to gauge bosons are fully fixed by the quantum numbers of \( \chi \) and \( \psi \).
- One model \( \Leftrightarrow \) one set of Branching ratios.
- Only unknown parameters are decay constants \( f_r \).
Couplings to tops and top mass: [JHEP1701,094]

We want to realize top masses through partial compositeness, i.e.

\[ \mathcal{L}_{\text{mix}} \supset y_L \bar{q}_L \Psi_{qL} + y_R \bar{\Psi}_{tR} t_R + h.c. \]

where \( \psi \) are the composite top partners, depending on the model either \( \psi \psi \chi \) or \( \psi \chi \chi \) bound states. The spurions \( y_{L,R} \) thus carry charges under the \( U(1)_{\chi,\psi} \).

The top mass in partial compositeness is proportional to \( y_L^* y_R \) and thus also has definite \( U(1)_{\chi,\psi} \) charges \( n_{\psi,\chi} \). For \( \psi \psi \chi \):

\[ y_L, y_R \sim (\pm 2, 1), (0, -1), \quad \Rightarrow m_{\text{top}} \sim (\pm 4, 2), (0, \pm 2), (\pm 2, 0), \]

The singlet-to-top coupling Lagrangian can be written as

\[ \mathcal{L}_{\text{top}} = m_{\text{top}} \Phi^{n_{\psi}}_{\psi} \Phi^{n_{\chi}}_{\chi} \bar{t}_L t_R + h.c. = m_{\text{top}} \bar{t} t + i c_5 \left( n_{\psi} \frac{a_{\psi}}{f_{a_{\psi}}} + n_{\chi} \frac{a_{\chi}}{f_{a_{\chi}}} \right) m_{\text{top}} \bar{t} \gamma^5 t + \ldots \]

NOTE:
- The term that generates the top mass also generates couplings of the pNGBs to tops.
- The possible top couplings depend on the model and top partner embedding, with a discrete set of choices.
- For the singlet pNGBs, the coupling never vanishes as in no case \( n_{\psi} = 0 = n_{\chi} \).
- The analogous argument yields zero coupling of \( \pi_8 \) to tops if \( n_{\chi} = 0 \).

Upshot: - pNGBs couple to top-pairs.
- there is a discrete set of possible couplings per model.
The SM singlet pNGBs cannot obtain mass through the weak gauging. To make them massive, we add mass terms for $\chi$ (and in principle $\psi$) which break the chiral symmetry. They yield mass terms

$$\mathcal{L}_m = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2} \Phi_r^2 \text{Tr}[X_r^\dagger \Sigma_r] + h.c. = \sum_{r=\psi,\chi} \frac{f_r^2}{4c_5^2} \left[ \cos \left( 2c_5 \frac{a_r}{f_{a_r}} \right) \text{ReTr}[X_r^\dagger \Sigma_r] - \sin \left( 2c_5 \frac{a_r}{f_{a_r}} \right) \text{ImTr}[X_r^\dagger \Sigma_r] \right].$$

The spurions $X_r$ are related to the fermion masses linearly

$$X_r = 2B_r m_r \quad r = \psi, \chi,$$

If $m_r$ is a common mass for all underlying fermions of species $r$, we get

$$m_{\pi_r}^2 = 2B_r \mu_r, \quad m_{a_r}^2 = 2N_r \frac{f_r^2}{f_{a_r}^2} B_r \mu_r = \xi_r m_{\pi_r}^2.$$

**Upshot:** - masses of singlet and non-abelian pNGBs are related.
- ratios can be estimated, but calculating them needs the Lattice
Singlets: masses and mixing

The states $a_{\psi, \chi}$ mix due to an anomaly w.r.t. the hyper color group which breaks $U(1)_\psi \times U(1)_\chi$ to $U(1)_a$.

The anomaly free and anomalous combinations are

$$\tilde{a} = \frac{q_\psi f_{a_\psi} a_\psi + q_\chi f_{a_\chi} a_\chi}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}}, \quad \tilde{\eta}' = \frac{q_\psi f_{a_\psi} a_\chi - q_\chi f_{a_\chi} a_\psi}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}}.$$  

The singlet mass terms (including contributions from underlying fermion masses) is thus

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{a_\chi}^2 a_\chi^2 + \frac{1}{2} m_{a_\psi}^2 a_\psi^2 + \frac{1}{2} M_A^2 (\cos \zeta a_\chi - \sin \zeta a_\psi)^2$$

where $\tan \zeta = \frac{q_\chi f_{a_\chi}}{q_\psi f_{a_\psi}}$, and $M_A$ is a mass contribution generated by instanton effects.

The masses of the pNGBs are

$$m_{a/\eta'}^2 = \frac{1}{2} \left( M_A^2 + m_{a_\chi}^2 + m_{a_\psi}^2 \pm \sqrt{M_A^4 + \Delta m_{a_\chi}^4 + 2M_A^2 \Delta m_{a_\chi}^2 \cos 2\zeta} \right)$$

and the interactions in the mass eigenbasis are obtained by rotating from the $a_{\psi, \chi}$ basis into the $a, \eta'$ basis with

$$\tan \alpha = \tan \zeta \left( 1 - \frac{\Delta m_{\eta'}^2 + \Delta m_a^2 - \sqrt{(\Delta m_{\eta'}^2 - \Delta m_a^2)^2 - 4\Delta m_{\eta'}^2 \Delta m_a^2 \tan^{-2} \zeta}}{2\Delta m_{\eta'}^2} \right)$$

Upshot: - The $\langle \chi \chi \rangle$ and $\langle \psi \psi \rangle$ pNGBs mix through an anomaly term and through their mass terms.
Production cross section for a pseudo-scalar

FIG. 1: Production cross section of a pseudo-scalar with coupling $\kappa_g/f = 1$ TeV from gluon fusion as a function of its mass $M_\sigma$ at LHC with $\sqrt{s} = 13$ TeV [JHEP1701, 094].

A. Phenomenology of the singlet pseudo-scalar PNGBs

The effective Lagrangian of a SM neutral pseudo-scalar interacting with SM gauge fields through anomaly terms is

$$ L = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - M_\sigma^2 \phi^2 + iC \bar{m}_t f_t \phi^5 + g_2^2 f_3 \phi W_3^\pm + g_2^2 f_3 \phi B_3^\pm, $$

which is characterized by five parameters: the mass $M_\sigma$, the ratio $\kappa_g/f$ (coefficient of the SU(3) term) which controls the production cross section, and the three ratios $C/f, B/f$ which dictate the branching ratios.

The dominant production channel for $\sigma$ is gluon fusion. Fig. 1 shows the production cross section from gluon fusion as a function of $M_\sigma$ for LHC at 8 and 13 TeV. In Fig. 1 we fixed $\kappa_g/f$ to 1 TeV (XXX to be decided). The production cross section scales like $(\kappa_g/f)^2$.

Decays to di-bosons through the WZW interactions or into $t \bar{t}$. The partial widths of $\sigma$ are given by [JHEP1701, 094]. Hugo: corrected decay to $tt$. For pseudo-scalar coupling goes with $1/2$.

The only other production channels are the vector boson fusion channels which however are negligible unless the ratios $C/f$ and/or $B/f$ do not only overcome the coupling suppression $g_2^2 f_3$ but also the suppression of vector boson PDFs as compared to the gluon PDF.
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**TABLE III.** Couplings of $a$ and $\eta'$ to gauge bosons for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). The last two rows shows the numerical value of the decay constant ratios used in this work.
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**TABLE IV.** Coupling of \( \alpha \) and \( \eta' \) to the top, \( C_{\ell} \), for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). For models with top partners in the form \( \psi \chi \chi \) (see Table I), the two last rows should be intended (2, 4) and (2, −4).
\[ K_{hZ}^{\phi \text{eff}} = \frac{3m_t^2}{32\pi^2 v m_Z} C_t^\phi \left[ 2(\kappa_t - \kappa_Z) B_0(\tau_{\phi/t}) - \kappa_t (B_0(\tau_{h/t}) - B_0(\tau_{\phi/t})) \\
+ (4 - \tau_{Z/t}) C_0(\tau_{\phi/t}, \tau_{h/t}, \tau_Z/t; 1) + (\tau_{\phi/t} + \tau_{h/t} - \tau_{Z/t}) C_1(\tau_{\phi/t}, \tau_{h/t}, \tau_Z/t; 1) \right] \]

\[ K_{\phi h}^{\text{eff}} = \frac{3\kappa_t}{8\pi^2} \left( \frac{C_t^\phi m_t}{v} \right)^2 \left[ B_0(\tau_{\phi/t}) + 2 C_0(\tau_{\phi/t}, \tau_{h/t}, \tau_{\phi/t}; 1) + \frac{1}{1 - 2\tau_{a/h}} (B_0(\tau_{h/t}) - B_0(\tau_{a/t})) \right] \]
SM singlet branching ratios

\[
\Gamma(\phi \to \text{had}) = \frac{\alpha_s^2(m_\phi) m_\phi^3}{8\pi^3 f_\psi^2} \left[ 1 + \frac{83}{4} \alpha_s(m_\phi) \right] \left| K_{gg}^\phi + C_t^\phi C_0(0, \tau_\phi/t, 0; 1) \right|^2
\]

\[
\Gamma(\phi \to \gamma\gamma) = \frac{\alpha^2 m_\phi^3}{64\pi^3 f_\psi^2} \left| K_{\gamma\gamma}^\phi + \frac{8}{3} C_t^\phi C_0(0, \tau_\phi/t, 0; 1) \right|^2
\]

\[
\Gamma(\phi \to WW) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_W/\phi)^{3/2}}{32\pi^3 f_\psi^2 s_W^4} \left| K_{WW}^\phi - \frac{3}{2} C_t^\phi C_{1+2}(\tau_W/t, \tau_\phi/t, \tau_W/t; \sqrt{\tau_b/t}) \right|^2
\]

\[
\Gamma(\phi \to Z\gamma) = \frac{\alpha^2 m_\phi^3 (1 - \tau_Z/\phi)^3}{32\pi^3 f_\psi^2 s_W^2 c_W^2} \left| K_{Z\gamma}^\phi + C_t^\phi \left( 1 - \frac{8}{3} s_W^2 \right) C_0(\tau_Z/f, \tau_\phi/t, 0; 1) \right|^2
\]

\[
\Gamma(\phi \to ZZ) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_Z/\phi)^{3/2}}{64\pi^3 f_\psi^2 s_W^4 c_W^4} \left| K_{ZZ}^\phi + C_t^\phi \left[ s_W^2 \left( \frac{8}{3} s_W^2 - 2 \right) C_0(\tau_Z/t, \tau_\phi/t, \tau_Z/t; 1) - \frac{3}{4} C_{1+2}(\tau_Z/t, \tau_\phi/t, \tau_Z/t; 1) \right] \right|^2
\]

\[
\Gamma(\phi \to hZ) = \frac{m_\phi^3}{16\pi f_\psi^2} \left| K_{hZ}^{\phi\text{eff}} \right|^2 \lambda(1, \tau_Z/\phi, \tau_h/\phi)^{3/2}
\]

\[
\Gamma(h \to \phi\phi) = \frac{v^2 m_h^3}{32\pi f_\psi^4} \left| K_{\phi\phi}^{\text{eff}} \right|^2 (1 - 2\tau_\phi/h)^2 \sqrt{1 - 4\tau_\phi/h}
\]
FIG. 7. Representative Branching Ratios of $a$ in the decoupling limit for all models and for the six choices of top partner charges. We only show $gg$ (light and dark green), $\gamma\gamma$ (brown and red) and $\tau\tau$ (purple and lilac).
NOTE: Low mass region has a “gap” between 15 - 65 GeV.
How can we search the gap at low mass? $\tau\tau$!

The gluon-fusion production cross section for light $a$ is large…

… and the $\tau\tau$ branching ratio is (for most models) not small.
How can we search the gap at low mass? $\tau\tau$!

Soft $\tau_{lep}$ or $\tau_{had}$ cannot be used to trigger on, but initial state radiation can boost the $gg \rightarrow a \rightarrow \tau\tau$ system (at the cost of production cross section, but we have enough).

As a very naive proof of principle analysis we look for a $j\ \tau_\mu\ \tau_e$ final state (jet + opposite sign, opposite flavor leptons) with cuts:

- $p_{T\mu} > 42$ GeV (for triggering)
- $p_{Te} > 10$ GeV
- $\Delta R_{\mu j} > 0.5, \Delta R_{ej} > 0.5$
- $\Delta R_{\mu e} < 1.0$
- no lower cut on $\Delta R_{\mu e}$!
- $m_{\mu e} > 100$ GeV

Main background:

- $Z/\gamma^* +$jets: 35 fb,
- $tt +$jets: 70 fb, $Wt +$jets: 7.4 fb, $VV +$jets: 13 fb.

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TABLE II: The values of $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1$ TeV and $m_a = 10 \cdots 100$ GeV for each of the models defined in Table I.
How can we search the gap at low mass? $\tau\tau$!

Note: This first proof of principle study is highly non-optimized.

- Cutting harder on $\Delta R_{\mu e}$ can substantially increase background suppression for the lighter mass range.
- We did not use any $\tau$ ID or triggers.
- We only used the OSOF lepton channel. $\tau_\mu \tau_\mu$, $\tau_\mu \tau_{\text{had}}$, $\tau_{\text{had}} \tau_{\text{had}}$ have larger branching ratios but require a more careful background analysis.
  [And needs tagging efficiencies for boosted $\tau_\mu \tau_{\text{had}}$, $\tau_{\text{had}} \tau_{\text{had}}$ systems which are beyond our capabilities, but possible for experimentalists.]

[arXiv:1710.11142]
How can we search the gap at low mass? \( \tau \tau \)!

Soft \( \tau_{\text{lep}} \) or \( \tau_{\text{had}} \) cannot be used to trigger on, but initial state radiation can boost the \( gg \rightarrow \) \( \tau \tau \) system (at the cost of production cross section, but we have enough).

As a very naive proof of principle analysis we look for a \( j \, \tau_{\mu} \, \tau_e \) final state (jet + opposite sign, opposite flavor leptons) with cuts:

- \( p_{T\mu} > 42 \) GeV (for triggering)
- \( p_{Te} > 10 \) GeV
- \( \Delta R_{\mu j} > 0.5, \Delta R_{ej} > 0.5, \)
- \( \Delta R_{\mu e} < 1.0 \)
- no lower cut on \( \Delta R_{\mu e} \)!
- \( m_{\mu e} > 100 \) GeV

Main background:

- \( Z/\gamma^*+\)jets: 35 fb,
- \( tt+\)jets: 70 fb, \( Wt+\)jets: 7.4 fb, \( VV+\)jets: 13 fb.

<table>
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<tr>
<th>( m_a ) (GeV)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
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TABLE II: The values of \( \sigma_{\text{prod.}} \times BR_{\tau \tau} \times \epsilon \) in fb for \( f_a = 1 \) TeV and \( m_a = 10 \ldots 100 \) GeV for each of the models defined in Table I. [EPJC 78 (2018) no.9, 724]
...are there other “common” top partner decays?

[JHEP 1806, 065]

• UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible.

• With an underlying model specified, we can relate top partner branching ratios to h/W/Z vs new pNGBs, as all relevant couplings arise from the Goldstone boson matrix.

• Scanning through the different underlying models we looked for “common exotic” top partner decays and found several scenarios.
Relating top partner couplings to Higgs and other pNGBs

Example: [JHEP 1806, 065]

For models with EW breaking pattern SU(4)/Sp(4), top-partners come in Sp(4) representations, e.g. 5 (for the t_L partner) and 1 (for the t_R partner).

$$5\text{-plet} \rightarrow \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}, \quad \begin{pmatrix} T \\ B \end{pmatrix}, \quad \tilde{T}_5; \quad \text{singlet} \rightarrow \tilde{T}_1$$

The “mass matrix” (pNGB interactions, expanded to leading order in s_θ=v/f) reads in the basis $\psi_t = \{t, T, X_{2/3}, \tilde{T}_1, \tilde{T}_5\}$

$$\bar{\psi}_t\begin{pmatrix}
0 & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5} \frac{a}{T_a} f s_\theta & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5} \frac{a}{T_a} f s_\theta & y_{1R} e^{i\xi_1} \frac{a}{T_a} f c_\theta & i y_{5R} c_\theta \eta \\
y_{5L} e^{i\xi_5} \frac{a}{T_a} f e^{2} & M_5 & 0 & 0 & 0 \\
y_{5L} e^{i\xi_5} \frac{a}{T_a} f s_{\theta/2} & 0 & M_5 & 0 & 0 \\
y_{1L} e^{i\xi_1} \frac{a}{T_a} f s_{\theta/2} & 0 & 0 & M_1 & 0 \\
-\frac{y_{5L}}{\sqrt{2}} s_\theta \eta & 0 & 0 & 0 & M_5
\end{pmatrix}\psi_t$$

Diagonalizing the mass matrix (and expanding in a and \eta) yields couplings of top and top partners to the pNGB in terms of the pre-Yukawas $y_{1,5}$.
Common exotic VLQ decays

Candidate 1: decays to the singlet pseudo-scalar singlet $a$

Effective Lagrangian(s):  [JHEP 1806, 065]

\[
\mathcal{L}_T = \mathcal{T} (i \bar{\psi} - M_T) T + \left( \kappa_{W,L}^T \frac{g}{\sqrt{2}} \mathcal{T} W^+ P_L b + \kappa_{Z,L}^T \frac{g}{2c_W} \mathcal{T} Z P_L t \\
- \kappa_{h,L}^T \frac{M_T}{v} \mathcal{T} h P_L t + i \kappa_{a,L}^T \mathcal{T} a P_L t + L \leftrightarrow R + \text{h.c.} \right),
\]

\[
\mathcal{L}_B = \mathcal{B} (i \bar{\psi} - M_B) B + \left( \kappa_{W,L}^B \frac{g}{\sqrt{2}} \mathcal{B} W^- P_L t + \kappa_{Z,L}^B \frac{g}{2c_W} \mathcal{B} Z^+ P_L b \\
- \kappa_{h,L}^B \frac{M_B}{v} \mathcal{B} h P_L b + i \kappa_{a,L}^B \mathcal{B} a P_L b + L \leftrightarrow R + \text{h.c.} \right).
\]

\[
\mathcal{L} = \frac{1}{2} (\partial^\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2 a^2 - \sum_f \frac{i C_f m_f}{f_a} a \bar{\psi}_f \gamma^5 \psi_f \quad (1)
\]

\[
+ \frac{g_s^2 K a}{16 \pi^2 f_a} G_{\mu \nu}^a G^{a \mu \nu} + \frac{g^2 K_a}{16 \pi^2 f_a} W^i_{\mu \nu} \tilde{W}^{i \mu \nu} + \frac{g'^2 K_a}{16 \pi^2 f_a} B_{\mu \nu} \tilde{B}^{\mu \nu}
\]
Common exotic VLQ decays

Benchmark parameters (obtained as eff. parameters from UV model):

\begin{align*}
\text{Bm1} : & \quad M_T = 1 \text{ TeV}, \quad \kappa^T_{Z,R} = -0.03, \quad \kappa^T_{h,R} = 0.06, \quad \kappa^T_{a,R} = -0.24, \quad \kappa^T_{a,L} = -0.07; \\
\text{Bm2} : & \quad M_B = 1.38 \text{ TeV}, \quad \kappa^B_{W,L} = 0.02, \quad \kappa^B_{W,R} = -0.08, \quad \kappa^B_{a,L} = -0.25, \quad \text{(2.3)}
\end{align*}

Branching ratios of quark partners to $a$ in these benchmarks:
Common exotic VLQ decays

Examples of diagrams:

- T and B can be produced like “standard” top partners: QCD pair production or single production.
- New final states: MANY, depending on $m_a$ and single- or pair-production.
**Common exotic VLQ decays**

**Candidate 2:** Decays of a top partner to the “exclusive pseudo-scalar” $\eta$. In models with SU(4)/Sp(4) breaking, one specific top partner couples only to the CP-odd SM singlet pNGB $\eta$. Both are odd under $\eta$-parity. $\eta$-parity is broken by EW anomaly couplings, and $\eta$ decays to WW, ZZ, $Z\gamma$.

Effective Lagrangian:

\[
\mathcal{L}_T = \bar{T} \left( i\gamma^\mu \partial_\mu - M_T \right) T - \left( iK_{\eta,L} \bar{T} \eta P_L t + L \leftrightarrow R + \text{h.c.} \right)
\]

\[
\mathcal{L}_\eta = \frac{1}{2} (\partial_\mu \eta)(\partial^\mu \eta) - \frac{1}{2} m_\eta^2 \eta^2 + \frac{g_2^2 K_\eta^\gamma}{16\pi^2 f_\eta} \eta G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_\eta} \eta W_{\mu\nu}^+ \tilde{W}_{-\mu\nu}^-
\]

\[
+ \frac{e^2 K_\eta^\gamma}{16\pi^2 f_\eta} \eta A_{\mu\nu} \tilde{A}^{\mu\nu} + \frac{g^2 c_W^2 K_Z^\gamma}{16\pi^2 f_\eta} \eta Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{egc_W K_Z^\gamma}{8\pi^2 f_\eta} \eta A_{\mu\nu} \tilde{Z}^{\mu\nu}
\]

[JHEP 1806, 065]
Common exotic VLQ decays

- The $\eta$-parity top partner is only QCD-pair produced.
- It decays 100% to $t\eta$.
- $\eta$ dominantly decays to $W^+ W^-$ or $Z\gamma$ (depending on its mass).
Common exotic VLQ decays

**Candidate 3**: $X_{5/3} \rightarrow \bar{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t t$)

In models with SU(6)/SO(6) breaking in the color sector.

Effective Lagrangian:

$$\mathcal{L}_{X_{5/3}}^{\pi_6} = \bar{X}_{5/3} \left( i \not{D} - M_{X_{5/3}} \right) X_{5/3}$$

$$+ \left( \kappa_{W,L}^{X} \frac{g}{\sqrt{2}} \bar{X}_{5/3} W^+ P_L t + i \kappa_{\pi_6,L}^{X} \bar{X}_{5/3} \pi_6 P_L b^c + L \leftrightarrow R + \text{h.c.} \right)$$

$$\mathcal{L}_{\pi_6} = |D_\mu \pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \left( i \kappa_{\pi_6,R}^{\pi_6} \bar{t}_6 (P_R t)^c + L \leftrightarrow R + \text{h.c.} \right)$$

**Benchmark parameters (obtained as eff. parameters from UV model):**

Bm3: $M_{X_{5/3}} = 1.3$ TeV, $\kappa_{W,L}^{X} = 0.03$, $\kappa_{W,R}^{X} = -0.11$, $\kappa_{\pi_6,L}^{X} = 1.95$, $\kappa_{tt,R}^{\pi_6} = -0.56$
Common exotic VLQ decays

Examples of diagrams:

- $X_{5/3}$ and $B$ can be produced in QCD pair production or single production.
- $\pi_6$ decays to $t\bar{t}$.
Common exotic VLQ decays

**Candidate 4: \( X_{5/3} \rightarrow t \phi^+ \) and \( X_{5/3} \rightarrow b \phi^{++} \)**

In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs.

Effective Lagrangian:

\[
\mathcal{L}_X^{5/3} = \overline{X}_{5/3} \left( i\tilde{\mathcal{D}} - M_{X_{5/3}} \right) X_{5/3} + \left( \kappa_{W,L}^X \frac{g}{\sqrt{2}} \overline{X}_{5/3} W^+ P_L t \\
+i\kappa_{\phi^+,L}^X \overline{X}_{5/3} \phi^+ P_L t + i\kappa_{\phi^{++},L}^X \overline{X}_{5/3} \phi^{++} P_L b + L \leftrightarrow R + \text{h.c.} \right)
\]

\[
\mathcal{L}_\phi = \sum_{\phi=\phi^+,\phi^{++}} \left( |D_\mu \phi|^2 - m_\phi^2 |\phi|^2 \right) + \left( \frac{egK^\phi_{W\gamma}}{8\pi^2 f_\phi} \phi^+ W^- \tilde{B}^{\mu\nu} + \frac{g^2 c_w K^\phi_{WZ}}{8\pi^2 f_\phi} \phi^+ W^- \tilde{B}^{\mu\nu} \\
+ \frac{g^2 K_{W}^\phi}{8\pi^2 f_\phi} \phi^{++} W^- \tilde{W}^{\mu\nu} + i\kappa_{tb,L}^\phi m_t \tilde{t} \phi^+ P_L b + L \leftrightarrow R + \text{h.c.} \right) . \tag{2.13}
\]
Common exotic VLQ decays

Benchmark parameters (obtained as eff. parameters from UV model):

\[ Bm4 : M_{X_{5/3}} = 1.3 \text{ TeV}, \quad \kappa_{W,L}^X = 0.03, \quad \kappa_{W,R}^X = 0.13, \quad \kappa_{\phi^+,L}^X = 0.49, \quad \kappa_{\phi^+,R}^X = 0.12, \quad \kappa_{\phi^{++},L}^X = -0.69, \quad \kappa_{tb,L}^\phi = 0.53, \]

Production of \( X_{5/3} \):
- Single- or pair-production.

Decays of the pNGBs:
- \( \phi^{++} \rightarrow W^+ W^+, \ W^+ \phi^+ \)
- \( \phi^+ \rightarrow tb, \ W^+ Z, \ W^+ \gamma \)

![Graph showing branching ratios](image-url)
Common exotic VLQ decays

Examples of processes: