Aspects of composite Higgs phenomenology

Duccio Pappadopulo
weak force $\gg$ gravity $\iff M_W \ll M_P$

\[ c \Lambda_{UV}^2 H^\dagger H \]

\[ \Lambda_{UV} \sim M_P \Rightarrow c \sim 10^{-32} \]
Higgs compositeness as a solution

The UV - IR hierarchy is generated by dimensional transmutation.

A light scalar can be accidentally present (light dilaton) or related by symmetry to the longitudinal W and Z (PGB Higgs).
Two objections

No sign of compositeness so far

First things we expect to see in weakly coupled models are new particles. Not in this case: heavy physics but strongly coupled. Indirect signals should come first. Cure: model building + fine-tuning

No compelling single model

Can be a virtue as it forces to understand generic features first.
Transverse gauge fields and light fermions are external to the strongly interacting sector.

Couplings of SM fields break global symmetry $G$ and generate a potential for $H$ which determines the vacuum of the theory.
coupling to vector resonances

 composite “Yukawa”
(can be naturally smaller due to chiral symmetries)

\[ f : \text{sigma-model scale, expansion parameter for Higgs (goldstones) self interactions} \]

\[ F \left( \frac{\pi}{f} \right) \]

\[ m_\rho \sim g_\rho f \]

\[ m_\Psi \sim g_\Psi f \]
$m_h \ll \Lambda_{IR}$ by Goldstone symmetry

The strong dynamics breaks some global symmetry of the UV theory delivering a set of Goldstone fields

**Unitarity** (compact cosets)

+ **Custodial symmetry**

<table>
<thead>
<tr>
<th>$G$</th>
<th>$H$</th>
<th>$N_G$</th>
<th>NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(5)</td>
<td>SO(4)</td>
<td>4</td>
<td>$4 = (2, 2)$</td>
</tr>
<tr>
<td>SO(6)</td>
<td>SO(5)</td>
<td>5</td>
<td>$5 = (1, 1) + (2, 2)$</td>
</tr>
<tr>
<td>SO(6)</td>
<td>SO(4) $\times$ SO(2)</td>
<td>8</td>
<td>$4_+^2 + 4_-^2 = 2 \times (2, 2)$</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(6)</td>
<td>6</td>
<td>$6 = 2 \times (1, 1) + (2, 2)$</td>
</tr>
<tr>
<td>SO(7)</td>
<td>G$_2$</td>
<td>7</td>
<td>$7 = (1, 3) + (2, 2)$</td>
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<tr>
<td>SO(7)</td>
<td>SO(5) $\times$ SO(2)</td>
<td>10</td>
<td>$10_0 = (3, 1) + (1, 3) + (2, 2)$</td>
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<tr>
<td>SO(7)</td>
<td>[SO(3)]$^3$</td>
<td>12</td>
<td>$(2, 2, 3) = 3 \times (2, 2)$</td>
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<tr>
<td>Sp(6)</td>
<td>Sp(4) $\times$ SU(2)</td>
<td>8</td>
<td>$(4, 2) = 2 \times (2, 2), (2, 2) + 2 \times (2, 1)$</td>
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<tr>
<td>SU(5)</td>
<td>SU(4) $\times$ U(1)</td>
<td>8</td>
<td>$4_{-5} + 4_{+5} = 2 \times (2, 2)$</td>
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<tr>
<td>SU(5)</td>
<td>SO(5)</td>
<td>14</td>
<td>$14 = (3, 3) + (2, 2) + (1, 1)$</td>
</tr>
</tbody>
</table>

Mrazek et al '11
The symmetry structures fixes Higgs self interactions at low energy.

\[
\mathcal{L} = \frac{f^2}{2} (D_\mu \phi)^T (D^\mu \phi) = \frac{1}{2} (\partial_\mu h)^2 + \frac{f^2}{2} \text{Tr}[(D_\mu \Sigma)^T (D^\mu \Sigma)] \sin^2 \left( \theta + \frac{h(x)}{f} \right) \\
= \frac{1}{2} (\partial_\mu h)^2 + \left( m_W^2 W^+ W^- + \frac{m_Z^2}{2} Z^2 \right) \left( 1 + 2\sqrt{1 - \frac{\xi h}{v}} + (1 - 2\xi) \frac{h^2}{v^2} + \ldots \right)
\]

\[
m_W^2 = \frac{g^2 f^2}{4} \sin^2 \theta
\]

\[
\xi = \frac{v^2}{f^2} = \sin^2 \theta
\]

Higgs coupling to fermions is model dependent (see later)
The misalignment angle is determined dynamically

\[ V(h) \sim \frac{m^4}{g^2} \frac{g'^2}{16\pi^2} F \left( \frac{h}{f} \right) \Rightarrow \frac{v}{f} \approx 1 \]

G-breaking interactions (top mass,...)

unless fine tuning

\[ \star \]

unless complicated model building (see little Higgs models)

Small v/f (large f) decouples new physics and allow to live with the bounds from EW physics

\[ \sin \theta = 0 \quad : \text{unbroken EW} \]

\[ \sin \theta = 1 \quad : \text{technicolor limit} \]
Infrared logs: 

\[ W_3 \xrightarrow{\rho} v \xrightarrow{v} B \quad \Rightarrow \quad \hat{S} \sim \frac{m_W^2}{m_\rho} \sim \frac{g^2}{g_\rho^2} \frac{v^2}{f^2} \]

+ Infrared logs:

\[ \Delta \hat{S} : \quad \Delta \hat{T} : \]

The bound on \( \xi \) cannot be relaxed assuming the existence of non-oblique NP contribution to the Z\( b\bar{b} \) vertex (curing AFB and R\( b \) anomalies)
Higgs sector
(strongly coupled)

SM gauge bosons

SM fermions
Yukawa

plain small N technicolor: $f = v$, $g_\rho \sim 4\pi$, $m_\rho \sim 4\pi v$

$$\frac{4\pi}{\Lambda_F^{d_H-1}} QU \mathcal{O}_H \rightarrow 4\pi \left( \frac{m_\rho}{\Lambda_F} \right)^{d_H-1} QU H$$

$$\Lambda_F \sim 4\pi v \left( \frac{4\pi v}{m_t} \right)^{\frac{1}{d_H-1}}$$

You could in principle cure the flavor problem with very large $f$: requires too much tuning.

Flavor violation

$$\frac{y_s y_d(\Lambda_F)}{\Lambda_F^2} (s^c d)^2$$

$$d_H \sim 3 \Rightarrow \Lambda_{\text{eff}} \approx 10^4 \text{ TeV}$$

still too small

Caveat emptor...

Luty, Okui ('04) but also Rattazzi, Rychkov, Tonni, Vichi ('08) ...
One way out: **partial compositeness**

![Diagram](Q \lambda O_Q)

\[
\lambda_Q Q O_Q + \lambda_U U O_U \Rightarrow y_t \sim \frac{\lambda_Q \lambda_U}{g_Y} \equiv g_Y \epsilon_Q \epsilon_U
\]

\(\epsilon \equiv \frac{\lambda}{g_Y} \) : measures the mixing between elementary and composite states.*

\[
\lambda = \lambda_{UV} \left( \frac{\Lambda_{IR}}{\Lambda_{UV}} \right)^{5/2-d_O}
\]

Maybe ad hoc \(d = 5/2\) decouples the UV flavor problem completely without reintroducing a hierarchy problem. \(d > 5/2\) explains Yukawa hierarchies.

*(weak gauging of a global symmetry of the strong sector automatically implement PC in the gauge sector)*
Flavor violation at the IR scale is controlled by the mixing selection rules (differs from FN, to be thought as a non compact $U(1)$)

$\Delta F = 2$  
\[ \Delta S = 2 : \quad m_\rho \gtrsim 10 \text{ TeV} \frac{g_\rho}{g_\Psi} \Rightarrow \frac{v^2}{f^2} \lesssim 0.02 \left( \frac{g_\Psi}{5} \right)^2 \]
\[ m_\Psi \gtrsim 2 \text{ TeV} \frac{1}{\epsilon_R} \frac{3}{g_\Psi} \]

$\Delta F = 1$  
\[ \epsilon_i \epsilon_j g_\Psi \frac{v}{m_\rho^2} \frac{g_\rho^2}{16 \pi^2} \bar{f}_i \sigma(eF) f_j \]
\[ b \to s, \quad \frac{\epsilon'}{\epsilon} : \quad m_\rho \gtrsim 10 \div 15 \text{ TeV} \frac{g_\rho}{4\pi} \Rightarrow \frac{v^2}{f^2} \lesssim 0.04 \]

$\Delta F = 0$  
\[ \epsilon_i \epsilon_j \frac{g_\rho^2}{m_\rho^2} \bar{f}_i \gamma^\mu f_j iH^\dagger D_\mu H \]
\[ B_s \to \mu^+ \mu^- : \quad \frac{v^2}{f^2} \lesssim 0.4 \left( \frac{g_\Psi}{5} \right)^2 \]

$\Delta F = 0$  
\[ d_n : \quad m_\rho \gtrsim 30 \div 50 \text{ TeV} \frac{g_\rho}{4\pi} \Rightarrow \frac{v^2}{f^2} \lesssim 0.008 \]

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Huber '03  
Davidson, Isidori, Uhlig '07  
Keren-Zur, Lodone, DP, Rattazzi, Vecchi '12
The constraints are much worse in the lepton sector

\[ BR(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12} \Rightarrow m_\rho \gtrsim 150 \text{ TeV} \frac{g_\rho}{4\pi} \]

(with a choice of the mixings which minimizes the constraints)

In general one may want to give up complete explanation of the flavor structure and assume the existence of appropriate flavor symmetries.

\[ MFV, \ U(2)^3 \ldots \]
MFV and PC

\[ \lambda^Q Q^i O^i_Q + \lambda^U U^i O^j_U + \lambda^D D^i O^j_D \]

U(3) symmetry in the strong sector broken by right-handed mixing. Realizes MFV.

No FCNC (but assume CP)

- quark compositeness: \( m_\Psi > 1 \text{ TeV} \frac{1}{\epsilon_R^2} \frac{3}{g_\Psi} \)
- quark-lepton universality: \( m_\Psi > 5 \text{ TeV} \frac{1}{\epsilon_R} \)

\[ \lambda^Q_{ij} Q^i O^{j}_{Q_u} + \lambda^Q_{ij} Q^i O^{j}_{Q_d} + \lambda^U U^i O^j_U + \lambda^D D^i O^j_D \]

U(3)xU(3) symmetry in the strong sector broken by left-handed mixing. Realizes MFV.

epsK:

- quark compositeness: \( m_\Psi > 1 \text{ TeV} \frac{1}{\epsilon_R^2} \frac{3}{g_\Psi} \)
- quark compositeness: \( m_\Psi > 11 \text{ TeV} \frac{2}{\epsilon_R} \frac{g_\Psi}{3} \)

Bounds can be relaxed below the TeV with LHComp and more elaborated flavor structures: U(2)xU(2)xU(2).
The Higgs potential and tuning
The potential is dominated by the top quark sector.

\[ V(h) = \frac{N_C m^4_\Psi}{16\pi^2} \times \left[ \frac{\lambda^2}{g^2_\Psi} f_1 \left( \frac{h}{f} \right) + \frac{\lambda^4}{g^4_\Psi} f_2 \left( \frac{h}{f} \right) + \frac{g^2_\Psi}{16\pi^2} \times \ldots \right] \]

\[ f_1 \left( \frac{h}{f} \right) = a_1 I_1 \left( \frac{h}{f} \right) + a_2 I_2 \left( \frac{h}{f} \right) + \ldots \quad \text{sum of simple trigonometric functions} \]

The explicit form of the trigonometric invariants is fixed by symmetry (for the normalization you need a complete model)

\[ \bar{q}^\alpha_L \left( \lambda_L \right)_\alpha I \mathcal{O}^I_L + \bar{t}_R \left( \lambda_R \right)_I \mathcal{O}^I_R \]

All that matter are the SO(5) representations of \( \mathcal{O}_L \) and \( \mathcal{O}_R \)

(This choice also determines Higgs-fermion couplings)
The potential is dominated by the top quark sector.

Assume singlet top-right

1.3. PARTIAL COMPOSITENESS

1 loop:

2 loops:

\[ V(\pi_s) = V_1(1 \text{ loop}) + V_2(2 \text{ loop}) + \ldots \]

\[ y_t = \lambda_L \epsilon_R \]

\[ V(h) = \frac{N_C y_t^2}{16\pi^2} \frac{m_{\psi}^2}{\epsilon_R^2} \left( a h^2 + b \frac{h^4}{f^2} + \ldots \right) \]

\[ FT = \left( \frac{450 \text{ GeV}}{m_{\psi}} \right)^2 \left( \frac{3}{g_{\psi}} \right)^2 \epsilon_R^2 \]

stolen without permission from R.Rattazzi
Natural EWSB requires light top partners.

Light Higgs requires them to be not too strongly coupled.
A non generic spectrum (~ SUSY)

$g_\Psi < g_\rho$

EW vector resonances

Fermionic resonances

Top partners

2 – 3 TeV

0.7 – 1 TeV
Extra dimensional realizations

EW vector resonances

Fermionic resonances

Top partners

$g_\Psi \sim g_\rho$

Agashe, Contino, Pomarol
... 
DP, Torre, Thamm '13
Is it possible to study the resonances which are typical of composite Higgs models (EW resonances, heavy gluons, top partners) avoiding to pick a specific model?

\[ \Psi' \]

\[ \Psi \]

\[ \Psi \]

\[ \Delta m \gg m_\Psi \]

 Allows to develop a quantitatively valid EFT description of the lowest lying resonance (quantum numbers, few couplings).

The light state is lighter because more weakly coupled \( g_\Psi < g_{\Psi'} \)

Makes it possible to have a lighter resonance without lowering the cutoff.

(“Partial UV completion”)

In the limit \( \Delta m \sim m_\Psi \) still have a valid qualitative description.

Contino, Marzocca, DP, Rattazzi '11 (Effect of vector resonances on WW scattering)
Application to the study of top partners

Assumptions: PGB higgs + partial compositeness + fully composite R-handed top

**Inputs:**
- SO(5) quantum numbers of the operator mixing with **L-handed top**
- SO(4) quantum numbers of the light state

\[
t_L : \quad 4 = \left(\begin{array}{c} 2 \\ 2 \end{array}\right) \quad \quad \quad 5 = 4 \oplus 1 \quad \quad \quad 10 = 4 \oplus 6 \quad \quad \quad 14 = 9 \oplus 4 \oplus 1
\]

\[
\mathcal{L} \sim \bar{\Psi}(i \not{\! D} - M)\Psi + i c_1 \bar{\Psi} \phi \pi t_R + y_1 f_{qL} f_1(\pi) \Psi_R + y_2 f_{qL} f_2(\pi) t_R
\]

- Affects single production
- Affect the spectrum

\[
\Psi = \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}
\]

\[
B \sim yv
\]

\[
T \sim yf
\]

\[
X_{2/3}, X_{5/3}
\]
Application to the study of top partners

Assumptions: PGB higgs + partial compositeness + fully composite R-handed top

**Inputs:** SO(5) quantum numbers of the operator mixing with L-handed top
SO(4) quantum numbers of the light state

\[ t_L : \quad 4 = (2, 1) \oplus (1, 2) \quad 5 = 4 \oplus 1 \quad 10 = 4 \oplus 6 \quad 14 = 9 \oplus 4 \oplus 1 \]

\[ \mathcal{L} \sim \bar{\Psi}(i \not{\partial} - M)\Psi + ic_1 \bar{\Psi} \phi \pi t_R + y_1 f q_L f_1(\pi) \Psi_R + y_2 f q_L f_2(\pi) t_R \]

Affects single production
Affect the spectrum
At small $y$, $B$ is lighter and contributes to the signal together with the $5/3$ quark. That's why the bound is stronger.

Bounds from:

\[ [\text{CMS}] \, b' \rightarrow W b : \, b + \ell \ell (SS)/\ell \ell \ell \ (5 \text{ fb}^{-1}[7 \text{ TeV}]) \, \quad X_{5/3}, \, B \]

\[ [\text{CMS}] \, t' \rightarrow W b : \, b b + \ell \ell (OS) + M_{\ell b} > 170 \text{ GeV} \ (5 \text{ fb}^{-1}[7 \text{ TeV}]) \, \quad \tilde{T} \]

Experimental searches are optimized for pair production. Single production dominates for heavy top partners.
Bosonic resonances

\[ \sim g_{\rho} \]

\[ \sim g_{\rho} \epsilon \]

\[ \sim g_{\rho} \epsilon^2 \]

coupling to elementary fields

composite-partially composite couplings (e.g. top)

Relevant for DY production

EW resonances

\[ \begin{array}{c}
\sim \frac{g_{W}^2}{g_{\rho}} \\
\end{array} \]

\[ m_\rho \text{ in TeV} \]

\[ \xi \]

\[ \begin{array}{c}
0 \quad 1 \quad 2 \quad 3 \quad 4 \\
10^{-2} \quad 10^{-1} \quad 10^0 \\
\end{array} \]

Not really probing strong coupling

Grojean et al. ('12)
Bosonic resonances

\[ \sim g_\rho \]

\[ \sim g_w \]

\[ \sim g_\rho \epsilon \]

\[ \sim g_\rho \epsilon^2 \]

\[ \sim \frac{g_w^2}{g_\rho} \]

coupling to elementary fields

\[ \sim g_\rho \epsilon \]

\[ \sim g_\rho \epsilon^2 \]

composite-partially composite couplings

(eg. top)

Relevant for DY production

Heavy gluon

A cut on the large Wb invariant mass allows to reduce the background. The channel is more sensitive than the tt final state.

\[ pp \rightarrow G^* \rightarrow \bar{T}t + \bar{B}b \rightarrow Wtb \rightarrow \ell b b j j E_T \]
Signals in Higgs physics
(aka Higgs phrenology)
The PGB Higgs and PC hypothesis imprint very specific signatures on Higgs couplings.

\[ \frac{c_H}{f^2} \partial_\mu |H|^2 \partial^\mu |H|^2 + \frac{c_H'}{f^4} |H|^2 \partial_\mu |H|^2 \partial^\mu |H|^2 + \ldots \]

\[ \frac{c_y}{f^2} y_f \bar{f} H f |H|^2 \]

\[ \frac{c_\gamma e^2}{16\pi^2 f^2} \frac{y_t^2}{g_\Psi^2} |H|^2 F^2 + \frac{c_g g_s^2}{16\pi^2 f^2} \frac{y_t^2}{g_\Psi^2} |H|^2 G^2 \]

Sub-leading at strong coupling

\[ \frac{ig}{16\pi^2 f^2} (D_\mu H)\dagger W^{\mu\nu} D_\nu H + \ldots \]

\[ \frac{g}{m_\rho^2} (H\dagger \sigma^a D_\mu H) D_\nu W^{a\mu\nu} + \ldots \]

Less relevant (angular distributions?)
\[ a = \sqrt{1 - \frac{v^2}{f^2}} \]

fixed by the coset

c depends on the fermion representations

\[ (\gamma\gamma) \quad m_\chi = 125.4 \pm 0.8 \text{ GeV} \]
\[ \mu = 0.78 \pm 0.27 \]

\[ (ZZ) \quad m_\chi = 125.8 \pm 0.5 \text{ GeV} \]

large deviations still allowed
The role of the SM Higgs boson:

The SM is singled out as the unique theory which can be extrapolated at weak coupling at arbitrarily high energies. For other parameter choices new states at high energy (weakly or strongly coupled).

\[ \propto a \]
\[ \propto b \]
\[ \propto b_3 \]
\[ \propto d_3 \]

\[ V_L \]
\[ \propto (a^2 - 1) \frac{E^2}{v^2} \]
\[ \propto (a^2 - b) \frac{E^2}{v^2} \]
\[ \propto (4ab^2 - 4a^3 - 3b_3) \frac{E^2}{v^3} \]

Similar effects for the fermions but delayed to higher energies.
Naive ratio between signal (s-wave amplitude) and ‘irreducible’ background (dominated by a Coulomb pole in the SM)

\[
\frac{\sigma_{\text{sig}}}{\sigma_{\text{bkg}}} \sim \frac{\hat{s}}{m_W^4} t_{\text{min}}
\]

Enough to have \( t_{\text{min}} \gtrsim m_W^2 \)?

\[ \text{NO} \quad \text{YES!} \]

Reduction of the rate to isolate the signal
**WW final state**  
Ballestrero et al ’09’11

Identification cuts +

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<tbody>
<tr>
<td>$</td>
<td>\Delta \eta</td>
<td>&gt; 4.5$</td>
</tr>
</tbody>
</table>

Parton level analysis including $\alpha_{EM}^6, \alpha_{EM}^4 \alpha_S^2, \alpha_{EM}^2 \alpha_S^4$ backgrounds.

Combining all channels $\sigma(pp \rightarrow jjX) = \xi^2 \sigma(pp \rightarrow jjX)_{\xi=1}$

<table>
<thead>
<tr>
<th></th>
<th>$\xi = 1$</th>
<th>$100 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow jjW(\ell\nu)V(jj)$</td>
<td>S</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>1100</td>
</tr>
<tr>
<td>$pp \rightarrow jjW^{\pm}(\ell^{\pm}\nu)W^{\pm}(\ell^{\pm}\nu)$</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>$pp \rightarrow jjZ(\ell^+\ell^-)Z(\nu\nu)$</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

**Double Higgs production**  
Contino et al ’10

Detection of double Higgs production is hampered by the more difficult final state. Heavy Higgs ($\sim 180$ GeV) was required to have sizable BR in VV.

The trileptonic channel is the cleanest

$$S_3 = pp \rightarrow hhjj \rightarrow l^+l^-l^\pm E_T + 4j$$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \eta_{jj}^{\text{ref}} \geq 4.5$</th>
<th>$m_{jj}^{\text{ref}} \geq 700$ GeV</th>
<th>$m_{jj,hl} \leq 160$ GeV</th>
</tr>
</thead>
</table>

LHC can only test the TC limit (before lumi. upgrade). No chance to measure the Higgs potential.

<table>
<thead>
<tr>
<th></th>
<th>3 leptons</th>
<th>2 leptons</th>
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<tbody>
<tr>
<td>$\xi = 1$</td>
<td>4.9</td>
<td>15.0</td>
</tr>
<tr>
<td>$\xi = 0.8$</td>
<td>3.3</td>
<td>10.1</td>
</tr>
<tr>
<td>$\xi = 0.5$</td>
<td>1.5</td>
<td>4.9</td>
</tr>
<tr>
<td>MCHM4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\xi = 0.8$</td>
<td>4.5</td>
<td>14.3</td>
</tr>
<tr>
<td>$\xi = 0.5$</td>
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<td>7.6</td>
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<tr>
<td>MCHM5</td>
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<td>$\xi = 0$</td>
<td>0.2</td>
<td>0.8</td>
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<tr>
<td>SM</td>
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<th>Event</th>
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<tbody>
<tr>
<td>$\xi = 1$</td>
<td>4.9</td>
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<td>26.6</td>
</tr>
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<tr>
<td>SM</td>
<td></td>
<td></td>
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Long term questions

$(t \to \infty ?)$
LHC is over and at most $\delta_{LHC} = O(10-20\%)$ deviation in Higgs couplings is observed. Maybe new particles discovered but with no clear role. Many relevant questions remain open.

**Weak or strong coupling?** Large effects due to heavy (invisible) physics suggest strong coupling.

$$
\delta = \begin{array}{c}
\text{Diagram 1} \\
\text{Diagram 2}
\end{array}
\sim \left(\frac{g_{NP} v}{m_{NP}}\right)^2
\rightarrow
\begin{array}{c}
g_{NP} \gtrsim \sqrt{\delta_{LHC} \frac{m_{NP}}{v}}
\end{array}

\text{Diagrams 3 and 4}
\sim \frac{E^2}{v^2}
\rightarrow
\begin{array}{c}
g_{NP}(E) \gtrsim \sqrt{\xi_{\text{obs}} \frac{E}{v}}
\end{array}

Bounding the effect from 4 derivative interactions allows to improve the bound

$$
A(2 \rightarrow 2) = \frac{s}{v^2} \left(1 + c \frac{s}{m_*^2}\right)
$$

$$
c < \epsilon \Rightarrow g_{NP}(E) \gtrsim \sqrt{\frac{\xi_{\text{obs}}}{\epsilon} \frac{E}{v}}
$$
**Does h belong to a doublet?** If so then $WW \to WW$ and $WW \to hh$ are equal up to higher order terms. No way to answer the question testing only single Higgs couplings. Need to measure $b$.

$$\Delta b = 2\Delta a^2 (1 + O(\Delta a^2))$$

$\Delta a^2 \sim 0.2$ requires % precision on $b$

If there are indications for a composite Higgs, **is this particle light due to Goldstone symmetry?** Check relation between $a$ and $b$. Look for triple Higgs production.

$$\Delta b = 2\Delta a^2$$

$\Delta b = \Delta a^2$: dilaton

**Triple Higgs production is suppressed for a PGB Higgs**

<table>
<thead>
<tr>
<th>Polarisation</th>
<th>Amplitude for PNGB</th>
<th>Amplitude for SILH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_L V_L \to hhh$</td>
<td>$g^2 v / f^2$</td>
<td>$\hat{s}v / f^4$</td>
</tr>
<tr>
<td>$V_L V_T \to hhh$</td>
<td>$\sqrt{\hat{s}g / f^2}$</td>
<td></td>
</tr>
<tr>
<td>$V_T V_T \to hhh$</td>
<td>$g^2 v / f^2$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>0</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNGB</td>
<td>0.32</td>
<td>0.46</td>
<td>0.71</td>
<td>1.47</td>
<td>2.41</td>
<td>4.13</td>
<td>0.30</td>
</tr>
<tr>
<td>SILH</td>
<td>0.32</td>
<td>0.71</td>
<td>0.87</td>
<td>7.56</td>
<td>42.89</td>
<td>407.9</td>
<td>7808</td>
</tr>
</tbody>
</table>

$e^+e^- \to \nu\bar{\nu}hhh \ @ 3 \text{ TeV}$
The final answer to these questions requires a high energy linear collider

**ILC (500GeV):**  
\( \Delta a^2 \gtrsim 0.5 \times 10^{-2} \)  
(1 ab\(^{-1}\))

**CLIC (3TeV):**  
\( \Delta b \gtrsim 1 \div 2 \times 10^{-2} \)  
\( \Delta d_3 \gtrsim 5 \times 10^{-2} \)  
(1 ab\(^{-1}\))
Conclusions

Figure nw
Summary of current constraints on $\xi = (v/f)^2$ and the mass of the lightest spin-1 resonance $m_\rho$ for SO(5)/SO(4) composite Higgs theories. See text.

Searches for direct production of spin-1 resonances at the LHC also set important constraints on the mass scale of a new strongly interacting dynamics $m_\rho$. The dominant resonance production channel is via Drell-Yan processes. Their cross section scales as $n^2/g_\rho^2$ since the couplings of the resonances to the SM are suppressed by $n/g_\rho$. CMS searches for $WZ$ resonances decaying leptonically currently put tight limits. While the experimental search excludes resonance masses up to $n_\rho$ TeV, we extend these limits to larger masses assuming a constant efficiency in detecting $WZ$ pairs. The limit on the production cross section $\sigma_{pp\rightarrow W\rho\rightarrow Z\rightarrow pp\ell\nu}$ excludes resonance masses up to $o_\rho$ TeV depending on $g_\rho$.

Tight limits are also set by $W$ resonances decaying directly into a lepton and neutrino. The situation of direct and indirect constraints is summarized in Fig. for the case of a generic SO(5)×SO(4) composite Higgs theory. This can be reasonably considered as a benchmark scenario, although the actual bounds will depend on the details of the strong dynamics and how it couples to the SM fermions. For simplicity we focus on the lightest spin-1 resonance of the strong sector, which we denote by $ρ$ and assume that it transforms as $a_ρ$ under $SU(5)_{L} \times SU(5)_{R}$ $\sim SO(5)_{d}$. For illustrative purposes, we fix $a_ρ = m_ρ/\sqrt{g_ρ}f$ so that the $ρ$ exchange unitarizes the $\pi\pi$ elastic scattering.

The fundamental free parameters of the new dynamics are then the mass of the spin-1 resonance $m_\rho$ and the strength of the Higgs interactions parametrized by $\xi = v/f^2$. The dark horizontal light purple bands of Fig. indicate the sensitivity on $\xi$ expected at the LHC from double single Higgs production with $5 fb^{-1}$ of integrated luminosity. The value shown...
Backup
In red dashed, the cross sections of pair production. In green and blue, the single production of the \( T \) in association with a \( b \) and of the \( X \) in association with a \( t \) respectively in model \( M1 \) and \( M4 \). The point chosen in the parameter space is \( \xi = 0.2, c_1 = 1, y_1 = 1 \). The values of \( c_2 \) is fixed at each value of \( M_\Psi \) in order to reproduce the top quark mass. All the single-production processes are parameterized in terms of universal coefficients \( \sigma_W^\pm t \) and \( \sigma_Z t \). Notice that a possible \( \sigma_Z b \) vanishes because flavor-changing neutral couplings are forbidden in the charge sector as explained in the previous section. As such, the single production of the \( B \) in association with a bottom quark does not take place. We have computed the coefficients \( \sigma_W^\pm t \) and \( \sigma_W^\pm b \) including the QCD corrections up to NLO using the MCFM code. To illustrate the results, we report in Table \( \sigma \) the single production cross section with coupling set to unity for different values of the heavy fermion mass and for the \( s \) and \( t \) TeV LHC. The values in the table correspond to the sum of the cross sections for producing the heavy fermion and its antiparticle on the left side we show the results for \( tB \) production on the right one we consider the case of \( b \). In our parametrization of eq, \( c_{\text{on}} \) and \( c_{\text{on}} p \) the cross sections in the table correspond respectively to \( \sigma_W^+ t f \) and \( \sigma_W^- t f \). We see that the production with the \( b \) is one order of magnitude larger than the one with the \( t \), this is not surprising because the \( t \) production has a higher kinematical threshold and therefore it is suppressed by the steep fall of the partonic luminosities. The values in the table do not yet correspond to the physical single production cross sections; they must still be multiplied by the appropriate couplings. The last coefficient function \( \sigma_Z t \) cannot be computed in MCFM and therefore to extract it, we used a LO cross section computed with MadGraph 5 in the model file produced with FeynRules package. To account for QCD corrections in this case, we used the \( \chi_f \) factors computed with MCFM for the \( tB \) production process. In order to quantify the importance of single production, we plot in figure \( \sigma \) the cross sections for the various production mechanisms in our models as a function of the mass of the partners and for a typical choice of parameters. We see that the single production rate can be very sizeable and that it dominates over the QCD pair production already at moderately high mass. This is again due to the more favorable lower kinematical threshold as carefully discussed in Ref. In order to quantify the importance of single production, we plot in figure \( \sigma \) the cross sections for the various production mechanisms in our models as a function of the mass of the partners and for a typical choice of parameters. We see that the single production rate can be very sizeable and that it dominates over the QCD pair production already at moderately high mass. This is again due to the more favorable lower kinematical threshold as carefully discussed in Ref. Let us finally discuss the decays of the top partners. The main channels are two-body decays to vector bosons and third-family quarks mediated by the couplings in eq. For the partners of charge \( n/\sigma \) and \( -m/\sigma \) also the decay to the Higgs boson is allowed and competitive with the others in some cases. This originates from the interactions of the partners with the Higgs reported.
Partial Compositness vs MFV

A full comparison between the two approaches requires the specification of a **coupling** and a **mass scale** to completely define the structure of flavor-violating higher dimensional operators.

Eg: in SUSY with gauge mediation universal soft masses are generated at M_{mess}, non-universality generated through running respect MFV.

Four-fermions operator at superpartner scale have the form

\[
\frac{g_s^2}{16\pi^2} \frac{g_s^2}{\bar{m}^2} \left( \bar{q}_L \frac{Y_U Y_U^\dagger}{16\pi^2} q_L \right)^2
\]

\[
\tilde{m}^2 = m_0^2 \frac{1}{M_{mess}}
\]

\[
\tilde{m}^2 = m_0^2(1 + c \frac{Y_U Y_U^\dagger}{(4\pi)^2} + ...)
\]

<table>
<thead>
<tr>
<th>Structure</th>
<th>MFV</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{d}_i L d_j L)</td>
<td>(V_{3i}^* V_{3j})</td>
<td>(V_{3i}^* V_{3j})</td>
</tr>
<tr>
<td>(\bar{d}_i R d_j R)</td>
<td>(y_i^d y_j^d V_{3i}^* V_{3j})</td>
<td>(\frac{y_i^d y_j^d}{V_{3i}^* V_{3j}})</td>
</tr>
<tr>
<td>(\bar{d}_i L d_j R)</td>
<td>(y_j^d V_{3i}^* V_{3j})</td>
<td>(\frac{y_j^d V_{3i}}{V_{3j}})</td>
</tr>
<tr>
<td>(\bar{d}_i R d_j L)</td>
<td>(V_{3j} )</td>
<td>(V_{3j})</td>
</tr>
</tbody>
</table>

Shows only the structure in flavor space other coupling constants have been suppressed