EWSB sector of Higgs-less and Composite Higgs models

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Some contributors (surely forgot someone, sorry)
Weinberg; Susskind; Appelquist; CCWZ; Casalbuoni, De Curtis, Dominici, Dolce; Bagger et al; Csaki, Grojean, Pilo, Terning; Barbieri, Rattazzi, Pomarol...
Giorgi, Kaplan, Dimopoulos, Banks, Arkani-Hamed, Cohen, Katz, Nelson, Nomura, Pomarol, Sundrum, Contino, Agashe, Da Rold, Luty, Rattazzi, Carena, Wagner, Santiago, Ponton...
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Disclaimer
-no (warped) extra dimensions
-no Little Higgs
Terminology

- *Higgs-less models*
  
  = models without Higgs boson

  i.e. no CP-even scalar
  with significant coupling to $WW$

![Diagram showing a cross between W and h interactions](image-url)
EWSB sector
$W_\mu, B_\mu$

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$W_{\mu}, B_{\mu}$

$\psi_L, \psi_R$

EWSB sector

3 Goldstone bosons

$(W_L^\pm, Z_L)$
$W_\mu, B_\mu$

$\psi_L, \psi_R$

**EWSB sector**

3 Goldstone bosons

$(W_L^\pm, Z_L)$

Goldstones must be related by symmetry (to explain $\rho = 1.00 \ldots$)

$\Rightarrow$ Symmetry breaking pattern (at least)

$SO(4) \rightarrow SO(3)$

“custodial symmetry”
Minimal EWSB sector
(just Goldstones)

= nonlinear $SO(4)/SO(3)$ sigma-model for Goldstone interactions

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = \nu^2$$

$\nu = 174 \text{ GeV}$
Minimal EWSB sector

(just Goldstones)

= nonlinear $SO(4)/SO(3)$ sigma-model for Goldstone interactions

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = \nu^2$$

$\nu = 174 \text{ GeV}$

- not UV-complete
- $W_L W_L$ scattering violates perturbative unitarity:
SM - weakly coupled UV-completion

\[ L_{SM} = | \partial H |^2 + \lambda ( | H |^2 - v^2 )^2 \]

- Just 1 extra scalar (Higgs boson)
- Unitarizes $WW$ scattering
- Model valid up to arbitrary high energies
- Disfavored by naturalness
Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

\[ L_{TC} = \frac{1}{g^2} (F_{\mu\nu}^a)^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D\Psi^i \]
Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

\[ L_{TC} = \frac{1}{g^2} (F_{\mu\nu}^a)^2 + \sum_{i=1}^{N_f} \overline{\Psi}^i D\Psi^i \]

number of new fermions feeling the technicolor force
Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

\[ L_{TC} = \frac{1}{g^2} (F_{\mu\nu}^a)^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D\Psi^i \]

Chiral symmetry breaking:

\[ SU(N_f) \times SU(N_f) \rightarrow SU(N_f) \]

\[ \cong SO(4) \rightarrow SO(3) \quad \text{for} \quad N_f = 2 \]
Technicolor – strongly coupled UV-completion

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- EW scale neatly explained via dimensional transmutation
- no \textit{a priori} reason to expect a light scalar resonance (thus Higgs-less)
A basic question

Who unitarizes the $W_L W_L$ scattering in Higgs-less models?
Heavy vector resonances (techni-rho)

- After scalar, the only other way to restore unitarity (however, not fully perfect)
Heavy vector resonances (techni-rho)

- After scalar, the only other way to restore unitarity (however, not fully perfect)
- Mass, coupling, width relation:

\[ M_\rho = 0.5 \div 2 \text{ TeV} \quad \leftrightarrow \quad g_\rho \quad \leftrightarrow \quad \Gamma(\rho \rightarrow \pi\pi) = 4\% \left(\frac{M_\rho}{\text{TeV}}\right)^2 \]

50% for Higgs boson
Heavy vector resonances (techni-rho)

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50% for Higgs boson

can be detected in VBF at \( O(100) \, \text{fb}^{-1} \)

\( \rho^+ \to W^+Z \)

\( \rho^0 \to W^+W^- \)

unlike heavy Higgs, no \( ZZ \) decay
EW precision tests

cum grano salis

SM with $M_{h} = 120$ GeV
EW precision tests

cum grano salis

$T$

$S$

SM with $M_{h} = 120$ GeV

$S$ with $M_{h} = 1$ TeV

$\Delta T_{IR}, \Delta S_{IR}$
EW precision tests

cum grano salis

SM with $M_h = 120$ GeV

SM with $M_h = 1$ TeV

Higgs-less with $M_\rho = 1$ TeV

$\Delta T_{IR}, \Delta S_{IR}$

$\Delta S_{UV}$
Terminology

Composite Higgs model
= ‘pseudo-Goldstone Higgs’

= light CP-even scalar with SM-like couplings, mass protected by (approximate) spontaneously broken global symmetry

\[ W \xrightarrow{---} h = O(g_{SM}) \]
EWSB sector with composite Higgs

$W_\mu, B_\mu$

$\psi_L, \psi_R$

3 Goldstones $W_L^\pm, Z_L$

+ 1 Goldstone $h$
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grouped in a complex doublet of $SU(2)$
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$\Rightarrow$ Symmetry breaking pattern (at least) $SO(5) \rightarrow SO(4)$
EWSB sector with composite Higgs

\[ W_\mu, B_\mu \]
\[ \psi_L, \psi_R \]

3 Goldstones \[ W_L^\pm, Z_L \]

+ 1 Goldstone \[ h \]

\[ \Rightarrow \text{Symmetry breaking pattern (at least)} \]
\[ SO(5) \to SO(4) \]

Many non-minimal models are possible:
\[ SO(6) \to SO(5) \]
\[ SO(6) \to SO(4) \times SO(2) \]
\[ SO(7) \to SO(6) \]

\[ \Rightarrow \text{extended Higgs sectors} \]
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \quad \text{“Goldstone Higgs doublet”}$$

$SO(4) \supset SU(2)_w \times U(1)_y$
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \quad \Rightarrow \quad H$$

“Goldstone Higgs doublet”

$SO(4) \supset SU(2)_w \times U(1)_y$

EWSB via vacuum disalignment:

$$\Phi^T \Phi \equiv |H|^2 + \phi_5^2 = f^2$$

$$f = (\text{few}) \times v$$
Minimal Composite Higgs: $SO(5) / SO(4)$

\[ \Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \]

"Goldstone Higgs doublet"

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EWSB via vacuum disalignment:

\[ \Phi^T \Phi \equiv |H|^2 + \phi_5^2 = f^2 \]

\[ f = (\text{few}) \times v \]

moduli space of vacua

$\langle H \rangle = 0$ no EWSB

$|H|$
Minimal Composite Higgs: $SO(5)/SO(4)$

$$
\Phi = \begin{pmatrix}
\phi_1 \\
\phi_2 \\
\phi_3 \\
\phi_4 \\
\phi_5
\end{pmatrix}

H \quad \text{"Goldstone Higgs doublet"}

SO(4) \supset SU(2)_w \times U(1)_y

EWSB via vacuum disalignment:

$|H|$

$<H> = f$ too much EWSB

$<H>=0$ no EWSB

$\Phi^T \Phi \equiv |H|^2 + \phi_5^2 = f^2$

$f = (\text{few}) \times v$

moduli space of vacua
Minimal Composite Higgs: $SO(5)/SO(4)$

\[
\Phi = \begin{pmatrix}
\phi_1 \\
\phi_2 \\
\phi_3 \\
\phi_4 \\
\phi_5
\end{pmatrix}
\]

\[
H \quad \text{“Goldstone Higgs doublet”}
\]

$SO(4) \supset SU(2)_w \times U(1)_Y$

EWSB via vacuum disalignment:

\[
\Phi^T \Phi \equiv |H|^2 + \phi_5^2 = f^2
\]

\[
f = (\text{few}) \times \nu
\]

moduli space of vacua
Deviations in Higgs couplings

Consequence of nonlinear structure:

\[ O_H = \frac{c_H}{f^2} \partial(H^2)\partial(H^2) \]

\[ O_Y = \frac{c_Y}{f^2} H^2 (\bar{\psi}_L H \psi_R) \]

with model-dependent coefficients \( c_H, c_Y = O(1) \) [e.g. \( c_H = 1 \) for SO(5)/SO(4)]
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\[ W \]
\[ W \]
\[ \psi \]
\[ \psi \]
\[ h \]
\[ h \]
\[ g_{WWH} = \left( 1 - c_H \xi \right) g_{SM} \]

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

\[ g_{\psi\psi h} = \left( 1 - (c_H + c_Y) \xi \right) g_{SM} \]
Deviations in Higgs couplings

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

predicted positive, i.e. couplings reduced

Low, Rattazzi, Vichi
Incomplete unitarization

\[ W_L \sim \frac{s}{v^2} \]

\[ W_L \sim \frac{s}{f^2} \]

[presumably restored completely by super-heavy vectorial resonances with mass beyond LHC reach]
EW precision tests

\[ T \]

\[ S \]

Higgs-less
EW precision tests

Composite Higgs
$f = 500 \text{ GeV}$
EW precision tests

\[ \Delta T > 0 \] from “top partners” – extra vector-like quarks:

Carena, Ponton, Santiago, Wagner;
Barbieri, Bellazzini, S.R., Varagnolo;
Lodone; Gillioz; Pomarol, Serra;
Anastasiou, Furlan, Santiago
EWSB via vacuum disalignment

What causes it?

$W_\mu, B_\mu$

$\psi_L, \psi_R$

3 Goldstones $W_L^\pm, Z_L$

+ 1 Goldstone $h$

$SO(5) / SO(4)$

These couplings necessarily break global $SO(5)$, generate potential $V(h)$

In simplest models, $f/\nu$ hierarchy requires mild finetuning

$O(\nu^2 / f^2) \sim 10\%$
Summary of composite Higgs pheno

EWSB sector

► Lightish (100-200 GeV) SM-like Higgs boson

► \( \mathcal{O}(10-20\%) \) reductions in main Higgs boson couplings \( hWW, h\bar{t}t, h\bar{b}b, h\bar{\tau}\bar{\tau} \)

\[ \Rightarrow \text{changes in production cross sections and BR (including } h \to \gamma \gamma \text{)} \]

► In non-minimal models,
more pseudo-Goldstones \( \Rightarrow \) extended Higgs sector
[e.g. in SO(6)/SO(5) pseudo-scalar \( \eta \) which may appear in \( h \to \eta \eta \),
in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]
Summary of composite Higgs pheno

EWSB sector

- Lightish (100-200 GeV) SM-like Higgs boson
- $\mathcal{O}(10-20\%)$ reductions in main Higgs boson couplings $hWW, h\bar{t}t, hbb, h\bar{t}\bar{t}$

$\Rightarrow$ changes in production cross sections and BR (including $h \rightarrow \gamma\gamma$)

- In non-minimal models, more pseudo-Goldstones $\Rightarrow$ extended Higgs sector
  [e.g. in SO(6)/SO(5) pseudo-scalar $\eta$ which may appear in $h \rightarrow \eta\eta$
  in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]

100 fb$^{-1}$ stuff...

Bock, Lafaye, Plehn, Rauch, D. Zerwas, P. Zerwas
Summary of composite Higgs pheno

**EWSB sector**

- Lightish (100-200 GeV) SM-like Higgs boson

- $O(10-20\%)$ reductions in main Higgs boson couplings $hWW, h\bar{t}t, hbb, h\gamma\gamma$

  $\Rightarrow$ changes in production cross sections and BR (including $h \rightarrow \gamma\gamma$)

- In non-minimal models, more pseudo-Goldstones $\Rightarrow$ extended Higgs sector
  
  [e.g. in SO(6)/SO(5) pseudo-scalar $\eta$ which may appear in $h \rightarrow \eta\eta$, in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]

100 fb$^{-1}$ stuff...

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Extended quark sector ("top partners")... subject of another talk
Conclusions

- Higgs-less scenarios — keep in the back of your mind
  - need $O(100 \text{ fb}^{-1})$ to explore the likely mass region of vectorial resonances

- Composite Higgs is a more likely possibility
  - need $O(100 \text{ fb}^{-1})$ to test crucial predictions of nonlinear structure in EWSB sector