Composite Higgs Sketch

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Composite Sketch

if you see this suspect please call cern
Outline

• composite resonances in EWSB
• EFT for Higgs + spin-1 resonance
• sum rules and parameter space
• higgs rates: enhancement in gamma-gamma
• limits on vector resonances
• conclusions
Found the Higgs: what next?

E.g. what about the couplings?

Higgs effective lagrangian (w/ custodial sym.)

\[ \mathcal{L}_{eff} = a \left( \frac{m_Z^2}{v} Z_{\mu}^2 + \frac{2m_W^2}{v} W_{\mu}^2 \right) h + c_f \frac{m_f}{v} \bar{f} f h + c_{\gamma} \frac{\alpha}{\pi v} h F_{\mu\nu}^2 + c_{g} \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^2 \]

Strong dynamics \[ \mathcal{O}(1) \] change

Lower cut-off

\[ \Lambda \approx \frac{4\pi v}{\sqrt{1 - \alpha^2}} \ll \Lambda_{SM} \sim \infty \]
Examples

- **SM-Higgs**
  \[ a^2 = 1 \quad \Lambda = \infty \]

- **THDM**
  \[ a_{h_1}^2 + a_{h_2}^2 = 1 \quad \Lambda = \infty \]

- **pNGB**
  \[ a^2 = 1 - \frac{v^2}{f^2} \quad \Lambda = 4\pi f \]

- **Dilaton**
  \[ a^2 = \frac{v^2}{f^2} \quad \Lambda = \frac{4\pi v}{\sqrt{1 - v^2/f^2}} \]
Higgs + resonances

can we delay the onset of strong dynamics?

can we increase the cutoff?

- add new resonances coupled to the Pi’s
  (the first that go strong)

- enforce perturbative unitarity up to higher scales

familiar example: the SM Higgs

Higgsless: low cutoff

\[ \Lambda \sim 4\pi v \]

add the Higgs

\[ \Lambda = \infty \]
UV behavior and cutoff

\[
\left( V_\mu + \partial_\mu \pi + \frac{1}{6} [\pi, \partial_\mu \pi, \pi] + \ldots \right)^2 \rightarrow \frac{1}{6} \left[ (\pi \partial_\mu \pi)^2 - \pi^2 (\partial_\mu \pi)^2 \right]
\]

Equivalence theorem

\[
E \gg v \quad \Rightarrow \quad \Pi \sim \left( \frac{E}{v} \right)^2
\]

\[
\Lambda \sim 4\pi v
\]
UV-Moderators I

\[ 3 \times 3 = 1 + 3 + 5 \]

\[ (1 - a^2) \frac{s}{v^2} \]

\[ |D_\mu \Sigma|^2 \left( 1 + 2a \frac{h}{v} + b^2 \frac{h^2}{v^2} + \ldots \right) \]

Contino et al. 1002.1011 [hep-ph]
UV-Moderators II

$$3 \times 3 = 1 + 3 + 5$$

See e.g. 1202.1532 [hep-ph] and Falkowski's talk.
UV-Moderators III

$$3 \times 3 = 1 + 3 + 5$$

$$(1 - \frac{3}{4} \alpha^2) \frac{s}{v^2} + o(\log s)$$

$$- \frac{1}{4g_\rho^2} \rho_{\mu\nu}^2 + \frac{a_\rho^2}{2} v^2 \left[ \rho_{\mu}^2 + (\vec{\rho}_\mu \times \partial_\mu \vec{\pi}) \cdot \vec{\pi} + \frac{1}{2} (\vec{\pi} \times \partial_\mu \vec{\pi})^2 + \ldots \right]$$

more later...
Examples

\begin{itemize}
  \item QCD (vmd)
    \[ a_\rho^2 \approx 2 \]
    \[ \Lambda \sim m_\rho \]
  
  \item Higgsless
    \[ \sum_N \frac{3}{4} a_\rho^2 N = 1 \]
    \[ \Lambda \gg 4\pi v \]
\end{itemize}

\[ \Lambda_{NDA} \sim \Lambda_{unitary} \]
\[ \sqrt{s} \lesssim 2m_\rho \]
inelastic threshold
Higgs + Spin-1

one spin-1 below the cutoff (techni-rho, KK-W, ...)

\begin{align*}
\rho_\mu & \quad \text{as gauge vector} \quad \rho \longrightarrow h\rho h^\dagger - ih\partial_\mu h \\
\rho_L & \longrightarrow \partial\eta \\
\mathcal{L} & \notin \frac{\mathcal{O}}{m_\rho^\#} \\
\Sigma = e^{i\pi} & \longrightarrow e^{i\pi}(1 + \frac{h}{v}) \\
\text{easy (e.g. to implement on MC)}
\end{align*}
EXAMPLES

minimal setup

\[ \text{SO}(4) \cup \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{SU}(2)_\rho \]

more sites

\[ \text{SO}(4) \cup \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \cdots \rightarrow \text{SO}(4) \downarrow \text{SU}(2)_\rho \]

larger groups

\[ \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{SO}(5) \rightarrow \text{SO}(4) \]

\[ \sim \text{BESS model [Casalbuoni et al. `85]} \]

ex: extra Dim

\[ G \]

\[ H \]

ex: extra Dim

\[ SU(2)_L \times U(1)_Y \]

\[ H \]
spin-1: couples to the conserved custodial current

\[ g_\rho \rho_\mu^a J_C^{a \mu} = g_\rho \rho_\mu^a \varepsilon^{a bc} \rho_\mu^a \partial_\mu \pi^b \pi^c + \ldots \]
**Higgs + Vector**

**Higgs:** \( |D_\mu \Sigma|^2 \left( 1 + 2a \frac{h}{v} + \ldots \right) + c_t h t \bar{t} + \ldots \)

**Spin-1:**

\[
-\frac{1}{4g_\rho^2} \rho_{\mu\nu}^2 + \frac{a_\rho^2 v^2}{2} \left( \rho_\mu^a + \ldots \right)^2 \left[ 1 + 2c_\rho \frac{h}{v} + \ldots \right]
\]
SUM RULES

**elastic sum-rule**

\[
a^2 + \frac{3}{4} a^2_\rho = 1
\]

\[
\pi \to \pi \rho + \rho
\]

\[
\pi\pi \to \pi\pi
\]

\[
A(\pi\pi \to \pi\pi) \sim (1 - a^2 - \frac{3}{4} a^2_\rho) \frac{s}{v^2}
\]

**inelastic sum-rule**

\[
a = c_\rho
\]

\[
\pi \to \rho_L h
\]

\[
A(\rho_L \to \pi\pi) = i\epsilon^{abc} \frac{t - u}{2v^2} (a - c_\rho) a_\rho
\]

**2+3 parameters**

\[
a, \quad a_\rho, \quad m_\rho, \quad c_\rho, \quad c_{top}
\]
Models on a circle

\[ a_h^2 + \frac{3}{4} a_{\rho}^2 = 1 \]

sm-higgs
\[ \Lambda = \infty \]

weak 3-site
\[ \Lambda \sim m_H \lesssim 2m_{\rho} \quad \text{Integrate-out } H \]
\[ \Lambda \gg 2m_{\rho} \quad \text{Integrate-in } H \]

Higgsless XD
\[ \Lambda \sim 2m_{\rho} \]

(see Carcamo, Torre 1005.3809)

no change in \[ \pi \pi \rightarrow \pi \pi \]

parity-odd

gaugephobic

see Cacciapaglia et al. hep-ph/0611358
Models on a circle

\[ a_h^2 + \frac{3}{4} a_\rho^2 = 1 \]
INELASTIC CHANNELS

\[ m_h = 125 \text{ GeV}, a = 0.8 \]

\[ d^2 + 3a_0^2/4 = 1, b = d^2, c_\rho = a \]

\[ \Lambda \text{ [TeV]} \]

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

\[ \Lambda \text{ [TeV]} \]

\[ m_\rho \text{ [TeV]} \]
predictive:
3 parameters and several decay and production modes

\[ \frac{\Gamma}{\Gamma_{\text{SM}}} (h \rightarrow VV^*) = a^2 \]  
\[ \Gamma (h \rightarrow VV^*) = a^2 \]  
\[ \cdots \]

\[ \frac{\sigma}{\sigma_{\text{SM}}} (q\bar{q} \rightarrow hjj) = \frac{\sigma}{\sigma_{\text{SM}}} (q\bar{q} \rightarrow hW) = a^2 \]
\[ \frac{\sigma}{\sigma_{\text{SM}}} (gg \rightarrow h) \approx \frac{\sigma}{\sigma_{\text{SM}}} (gg \rightarrow h\bar{t}t) = c_t^2 \]
Higgs into gammas

\[ \frac{\Gamma}{\Gamma_{SM}(h\rightarrow\gamma\gamma)} \simeq \left[ 1 + \frac{9}{8} c_\rho + \frac{9}{7} (a - 1) - \frac{2}{7} (c_t - 1) \right]^2 \]
Boost into gammas

\[
\frac{\text{BR}}{\text{BR}_{\text{SM}}}(h \rightarrow \gamma\gamma) \simeq \frac{\left[1 + \frac{9}{8} \rho c + \frac{9}{7} (a - 1) - \frac{2}{7} (c_t - 1)\right]^2}{c_b^2 \text{BR}_{\text{SM}}(h \rightarrow b\bar{b}) + a^2 \text{BR}_{\text{SM}}(h \rightarrow VV^*) + \ldots}
\]

\[
\frac{\sigma}{\sigma_{\text{SM}}}(q\bar{q} \rightarrow hjj) \simeq a^2
\]

\[
\frac{\sigma}{\sigma_{\text{SM}}}(gg \rightarrow h) \simeq c_t^2
\]
Add Limits on $\rho^\pm$

\[ \Gamma_{\text{min}}/m_{\rho} \sim 0.04 \left( \frac{m_{\rho}}{1 \text{ TeV}} \right)^2 \]

\[ \sigma \sim 50 \text{ fb at 1 TeV} \]
Add Limits on Rho±

\[ \frac{\sigma/\sigma_{SM}(gg \to h) \times BR/BR_{SM}(h \to \gamma\gamma)}{\Lambda} \]

\[ c_t \approx c_\rho, \quad c_t = c_\rho = \frac{3}{4} \]

\[ a^2 = 1, \quad m_\rho = 1.5 \text{ TeV} \]

\[ m_h = 125 \text{ GeV}, \quad \Lambda = 3.5 \text{ TeV} \]

\[ a^2 + 3/4 a_\rho^2 = 1 \]
conclusions

- non standard higgs couplings -> new resonances below the cutoff
- Effective theory of Higgs + spin-1
- Elastic and inelastic sum rules to reduce the parameters
- smaller $h\rightarrowVV$ but larger $h\rightarrow2\gamma$s (even $x4\ SM$)
- CMS-bound on rho+- up to 900 GeV
Thank you!
BACKUP SLIDES
COUPLING TO FERMIONS
COUPLING TO FERMIONS

\[ g_{\rho \pm f f'} = g_{SM} \left( a_\rho \frac{m_W}{m_\rho} \right) \]

\[ g_{\rho \pm W \pm Z} = g_{SM} \left( a_\rho \frac{m_Z}{m_\rho} \right) \]

model independent
COUPLING TO FERMIONS

\[ g_{\rho \pm f f'} = g_{SM} \left( a_{\rho} \frac{m_W}{m_\rho} \right) \]

\[ g_{\rho \pm W \mp Z} = g_{SM} \left( a_{\rho} \frac{m_Z}{m_\rho} \right) \]

model independent

compositeness: model dependent

\[ g_{\rho f f}^{comp} \sim g_{\rho} \sin \theta^2 \]
S and T

cancellations? (axial vectors...)

tree-level contribution
$S$-PARAMETER

$m_h=125$ GeV, $\Lambda=3$ TeV

$LH$ 3rd gen. composite

$\Lambda \geq 3$ TeV

20.\%
Limits on ρ±

\[ \Gamma_{\text{min}} / m_\rho \sim 0.04 \left( \frac{m_\rho}{1 \text{ TeV}} \right)^2 \]

\[ \sigma \sim 50 \text{ fb at 1 TeV} \]

CMS Preliminary 2011

EXO-11-041

LH 3rd gen. composite

LH 3rd gen. fundamental

\[ m_h=125 \text{ GeV}, \Lambda=3.5 \text{ TeV}, a^2+3/4 a_\rho^2=1 \]
resonance production

Falkowski et al. 1108.1183 [hep-ph]
limits on \[ \text{rho} \rightarrow \text{WW} \text{ from } h \rightarrow \text{WW} \]

\[ G = \left( \frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}} \right) \left( \frac{g_{Z'WW}}{g_{Z'WW_{\text{max}}}} \right) \]

Eboli et al. 1112.0316 [hep-ph]

rho in DY; h in gluon and VB Fusion
h->WW optimal for SM couplings
rho->top pairs

composite top=large BR(rho->tt)

$\sigma \sim 50 \text{ fb at 1 TeV}$

limits~0.1-1 pb up to 3 TeV
More on the Inelastic

$m_h = 125\text{ GeV}, m_\rho = 1\text{ TeV}, a-c_\rho = 0$

$m_H = 2\text{ TeV}$
$\frac{a_T}{2} = \frac{a_T}{2} = 1$

$m_\rho = 1\text{ TeV}, a c_\rho - \frac{1}{4} = 0$

$a_0, a_1, a_2$