Composite Higgs models after Run 2

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Outline of this talk

1. Motivation
2. Composite Higgs
3. Higgs couplings and Recent Results
4. Conclusions

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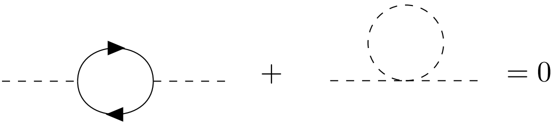
Motivation

- Hierarchy problem – loop corrections to the Higgs mass are quadratically divergent.
- Unless loops are naturally cut off, Higgs mass has a sensitive dependence on high energy scales.
- Extreme fine tuning between bare Higgs mass and loop contributions.

- Supersymmetry offers one solution to the hierarchy problem.
- Superpartners cancel out quadratic divergences:



- Generally speaking, the hierarchy problem points to TeV-scale new physics.

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- Loops are cut off at confinement scale $\sim \Lambda_{QCD}$.
- Λ_{QCD} is generated dynamically when QCD becomes strongly interacting.
- QCD condensate breaks chiral symmetry:

$$\langle \overline{q}_L q_R \rangle$$

$\rightarrow$ pions are pseudo-Goldstone bosons, natural "little" hierarchy between m_π and Λ_{QCD}.

Composite Higgs

- Higgs is a composite boson, arising from strong dynamics that confines at a scale f.
- The scale f is natural – it is generated dynamically.
- The Higgs is a Nambu-Goldstone boson, to keep a natural hierarchy between m_H and f.

Comparison to QCD

QCD	Composite Higgs
pNGBs: $\pi_0, \pi_\pm$	$H \ \ (+\,\phi_i \dots)$
fermionic resonances: p, n	$T, \tilde{T}$
$\langle \pi \rangle = 0$	$\langle H \rangle = \binom{0}{v} \rightarrow$ EWSB
no pion-fermion couplings	Yukawa terms: $\overline{\psi}_L H \psi_R$

Partial compositeness

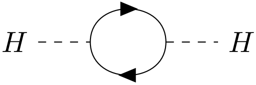
- SM fermions couple to the strong sector via mixing with composite partner fermions.

$$\mathcal{L}_{mix} \supset y_L f \bar{t}_L T_R + y_R f \bar{t}_R \tilde{T}_L + h.c.$$

$$\left|\tilde{t}\right\rangle = \cos\theta \left|t\right\rangle + \sin\theta \left|T\right\rangle$$

- *Partial compositeness* mechanism – allows one to generate large top Yukawa coupling, plus a natural quark mass hierarchy.

- Partner fermions must come in representations of the global symmetry $\mathcal{G}$.
- SM fermions do *not*.
- Partial compositeness breaks the symmetry explicitly.



Outline of this talk

Lots of models

To mention but a few:

- $SO(5)/SO(4)$
- $SU(4)/Sp(4)$
- $SU(5)/SO(5)$
- $SU(4) \times SU(4)/SU(4)$
- $SO(6)/SO(4) \times SO(2)$
- $SO(8)/SO(7)$
- $SO(9)/SO(8)$

Given one coset there are still many options for the partner fermion representations.

- In $SO(5)/SO(4)$ alone the options $\mathbf{4}, \mathbf{5}, \mathbf{10}, \mathbf{14}$ have been studied.
- Correct choice would depend on UV completion.

Effective theory for the pNGBs

- CCWZ formalism – toolkit for writing down pNGB effective theory
- Parameterise pNGBs with the matrix:

$$U = \exp(i\phi^a X^a / f)$$

  where X^a are the broken generators and f is the breaking scale.
- Non-linear transformations

$$U \to g\, U\, h^{-1}(\phi^a, g).$$

- Can form an object Σ out of contractions of U which has *linear* transformations.

Must construct an effective Lagrangian as a function of Σ and the fermion spurions, all of which are representations of the group $\mathcal{G}$.

- $SO(5)/SO(4)$

$$\Sigma = (0,0,0,\sin(h/f),\cos(h/f))^T$$

- $SU(4)/Sp(4)$

$$\Sigma = \begin{pmatrix} 0 & \cos(h/f) & -\sin(h/f) & 0 \\ -\cos(h/f) & 0 & 0 & \sin(h/f) \\ \sin(h/f) & 0 & 0 & \cos(h/f) \\ 0 & -\sin(h/f) & -\cos(h/f) & 0 \end{pmatrix}$$

- $SU(5)/SO(5)$

$$\Sigma = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos(h/f) & i\sin(h/f) \\ 0 & 0 & 0 & i\sin(h/f) & \cos(h/f) \end{pmatrix}$$

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If we expand around the Higgs VEV: $h \to \langle h \rangle + h$, we find

$$\mathcal{L}_{gauge} = \frac{1}{8} g^2 v^2 W_\mu^a W^{a\mu} + \frac{1}{4} g^2 v \sqrt{1-\xi}\, W_\mu^a W^{a\mu} h + \frac{1}{8} g^2 (1-2\xi) W_\mu^a W^{a\mu} h^2$$

where $\xi = v^2/f^2$.

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κ FORMALISM

- κ-factors describe the deviation from a Standard Model cross-section:

$$\kappa_i^2 = \sigma_i / \sigma_i^{SM}$$

- For instance decays of the Higgs to gauge bosons are modified by a factor of κ_V^2.
- In Composite Higgs κ_V is generically given by

$$\kappa_V = \sqrt{1 - \xi}.$$

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- T_L in $\mathbf{10}$ and T_R in $\mathbf{5}$:

$$\Sigma^T \overline{\Psi}_L^{\mathbf{10}} \Psi_R^{\mathbf{5}} \;\; \rightarrow \;\; \bar{t}_L t_R \sin(h/f)$$

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- T_L in $\mathbf{5}$ and T_R in $\mathbf{1}$:

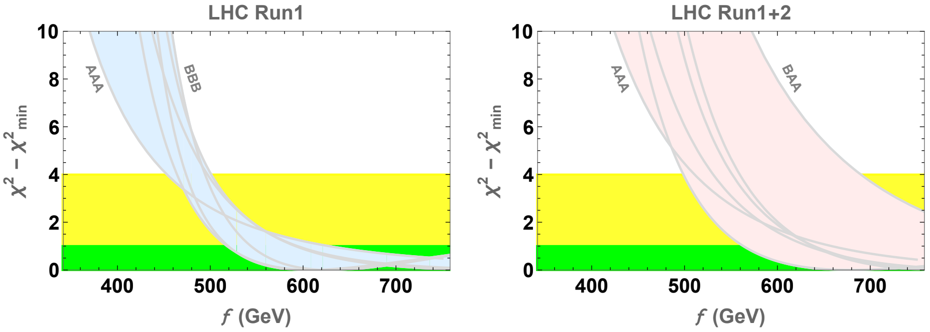
$$(\overline{\Psi}_L^{\mathbf{5}} \cdot \Sigma) \Psi_R^{\mathbf{1}} \;\; \rightarrow \;\; \bar{t}_L t_R \sin(h/f)$$

$$\sin(h/f) \rightarrow \kappa_F^A = \sqrt{1-\xi}$$
$$\sin(h/f)\cos(h/f) \rightarrow \kappa_F^B = \frac{1-2\xi}{\sqrt{1-\xi}}$$

- These structures are very generic.
- Different fermion species can be embedded in different representations, meaning that that κ_F for each species may be different.

Combined fit

We broadly categorise models according to the couplings of the top, bottom, and tau: $(\kappa_t^{A,B}, \kappa_b^{A,B}, \kappa_\tau^{A,B})$.



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- Couplings to SM particles are fairly generic across different models
- Robust limit on $f > 500$ GeV
- More data $\rightarrow$ more discrimination between models

Thanks for listening!