Fermionic UV Completions of Composite Higgs Models

SUSY2014, Manchester

Based on

arXiv:1312.5330

arXiv:1404.7137

PLAN

- Motivations for Partial Compositeness
- Classifying four-dimensional fermionic models
- The $SU(4)$ models in some details (misalignment, top partners, $Z \to b\bar{b}$)
- Conclusions

Note: I will give very few references throughout the talk in order to keep the presentation short and clean.

The pioneering work is that of Kaplan, Georgi and others in the 80's and early 90's.

One recent paper that is particularly close to the subject at hand is J. Barnard, T. Gherghetta and T. S. Ray `arXiv:1311.6562`.

The discovery of a 125 GeV Higgs boson, together with our expectations from effective field theory, points to the existence of new states and enlarged symmetries at the LHC scale.

Within the framework of purely four-dimensional theories, two options are available to stabilize the Higgs mass against a UV scale:

- (Broken) supersymmetry $\delta H = \epsilon\psi$
- (Broken) shift symmetry $\delta H = H + \epsilon$

If we want to stay in a four dimensional context and not not reintroduce fine tuning, the second option essentially requires that the Higgs arises as a composite state of fermionic UV theory.

The goal is to start with the Higgsless Standard Model.

$$\mathcal{L}_{SM0} = -\frac{1}{4} \sum_{V=G,W,B} F^2_{\mu\nu}(V) + i \sum_{\psi=QudLe} \bar{\psi} \, \not{D} \psi$$

and couple it to a theory $\mathcal{L}$ such that

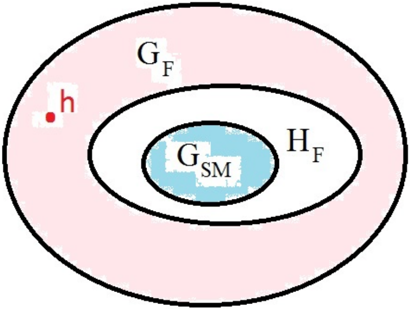
$$\mathcal{L}_{UV} \longrightarrow \mathcal{L} + \mathcal{L}_{SM0} + \mathcal{L}_{int.} \longrightarrow \mathcal{L}_{SM}$$

where $\mathcal{L}_{SM}$ is the usual SM, (plus possible extra light composites of $\mathcal{L}$ still allowed by the experimental constraints), and $\mathcal{L}_{int.}$ is the interaction between the composites of $\mathcal{L}$ and the SM fields.

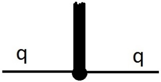
It is reasonably easy to give a mass to the W and Z bosons:

Let $G_F \to H_F$ be the pattern of global symmetry breaking of $\mathcal{L}$.
(The hyper-fermion condensate $\langle \Psi\Psi \rangle \neq 0$ does not break G_{SM} yet.)

Gauging a subgroup of H_F and coupling to the SM fermions turns the Nambu-Goldstone bosons (NGB) of G_F/H_F into pNGB, one of which ("the Higgs") is misaligned, condenses and breaks the EW group.



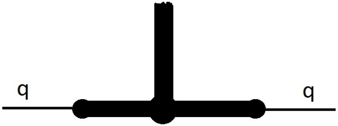
More challenging is to generate the fermion masses (particularly for the top quark) with a term bilinear is the SM fermions q of type:

$\frac{c}{\Lambda_{UV}^2} q^2 \Psi^2 =$ 

since, generically, $\Lambda_{UV} > 10^4$ TeV to avoid FCNC terms like $\frac{c'}{\Lambda_{UV}^2} q^4$.

A more promising avenue ("partial compositeness") is to have a mixing linear in q: $\frac{c}{\Lambda_{UV}^2} q \Psi^3 =$ 

and EWSB mediated by the strong sector:



Together with D. Karateev, we set out to classify the theories $\mathcal{L}$ obeying the following minimal group theory requirements:

- $G_F \to H_F \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{cus}} \supset G_{\text{SM}}$
- G_{SM} free of 't Hooft anomalies. (We need to gauge it.)
- $G_F/H_F \ni (\mathbf{1},\mathbf{2},\mathbf{2})_0$ of G_{cus}. (The Higgs boson.)
- ψ^3 hyper-color singlets $\in (\mathbf{3},\mathbf{2})_{1/6}$ and $(\mathbf{3},\mathbf{1})_{2/3}$ of G_{SM}. (The fermionic partners to the third family Q_L and t_R.)
- B and L symmetry. (No proton decay.)

We restricted the search to asymptotically free theories with a simple hyper-color group G_{HC} (still to be determined at this point).

Recall that (using two-component notation for the fermions)

$(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$\langle \tilde{\psi}\psi \rangle \neq 0 \Rightarrow SU(n) \times SU(n)/SU(n)$
ψ_α Pseudoreal	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/Sp(n)$
ψ_α Real	$\langle \psi\psi \rangle \neq 0 \Rightarrow SU(n)/SO(n)$

As far as the EW sector is concerned, the possible minimal custodial cosets are

4 ψ_α Pseudoreal	$SU(4)/Sp(4)$
5 ψ_α Real	$SU(5)/SO(5)$

Note that $Sp(4) \sim SO(5)$, so in all cases the composite states are classified by irreps of this algebra.

In our case, this is only one part of G_F/H_F since we also want to have colored objects (top partners). This requires adding additional hyper-fermions to the theory.
The minimal cosets allowing an anomaly-free embedding of unbroken $SU(3)_c$ are

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ Complex	$\langle \tilde{\chi}\chi \rangle \neq 0 \Rightarrow SU(3) \times SU(3)/SU(3)$
$6\ \chi_\alpha$ Pseudoreal	$\langle \chi\chi \rangle \neq 0 \Rightarrow SU(6)/Sp(6)$
$6\ \chi_\alpha$ Real	$\langle \chi\chi \rangle \neq 0 \Rightarrow SU(6)/SO(6)$

In this case one could also use bare masses avoiding extra pNGBs. (The $U(1)_X$ charge can be easily arranged by pairing it with the triality of the fields χ.)

Together with the remaining conditions, only a handful of solutions remain. The two prototypical ones being:

Model I

(Barnard, Gherghetta and Ray, `arXiv:1311.6562`)

	G_{HC}	G_F		
	$Sp(4)$	$SU(4)$	$SU(6)$	$U(1)'$
ψ	**4**	**4**	**1**	3
χ	**5**	**1**	**6**	-1

They split the six χ into three pairs $\chi\ \tilde{\chi}$ with a $SU(3)_c \times U(1)_X$ invariant mass and embed QCD in this way.
The model has composite scalars in the **3** and **6** of QCD.

I will focus instead on:

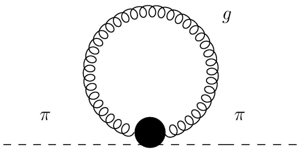
Model II

(G.F., arXiv:1404.7137)

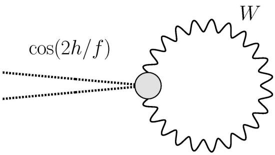
	G_{HC}	G_F				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
ψ	**6**	**5**	**1**	**1**	0	-1
χ	**4**	**1**	**3**	**1**	$-1/3$	$5/3$
$\tilde{\chi}$	$\bar{\mathbf{4}}$	**1**	**1**	$\bar{\mathbf{3}}$	$1/3$	$5/3$

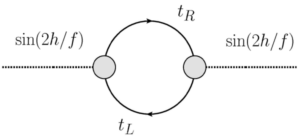
$\langle\psi\psi\rangle \neq 0$ enforces $SU(5) \to SO(5)$. After EWSB this giver rise to the usual Higgs, a doubly charged, two single-charge and four neutral pNGB, one of which totally G_{SM} neutral. One more G_{SM} neutral boson arises from breaking $U(1)'$ and lastly a color octet from $SU(3) \times SU(3)' \to SU(3)_c$. No leptoquarks or scalars in the **3** and **6** of QCD arise.

The colored pNGB octet gets a positive mass via the large contribution from gluons



whereas the coupling of the top quark favors the misalignment of the "right" Higgs boson





$$V(h) \propto \alpha \cos(2h/f) - \beta \sin^2(2h/f).$$

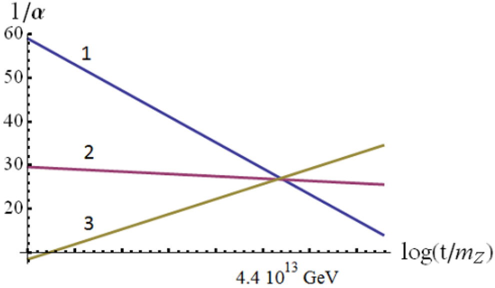
Without solving the strongly coupled theory we don't know how to compute reliably the coefficients α and β.

However we can make at least the following observation: With the same normalization $v = f\sin(\langle h\rangle/f) = 246$ GeV

$$\begin{aligned}
\text{For } SU(5)/SO(5): \quad & V(h) \propto \alpha\cos(2h/f) - \beta\sin^2(2h/f) \\
& \Rightarrow \xi \equiv (v/f)^2 \approx \frac{1}{4}(1-(\alpha/2\beta)^2) \\
\text{For } SO(5)/SO(4): \quad & V(h) \propto \alpha\cos(h/f) - \beta\sin^2(h/f) \\
& \Rightarrow \xi \equiv (v/f)^2 \approx (1-(\alpha/2\beta)^2)
\end{aligned}$$

The extra factor of $1/4$ helps keeping the S-parameter ($\propto \xi$) small with less fine-tuning required for α and β

There is an amusing coincidence when one looks at the impact of the extra fermions on the SM gauge couplings



But the scale is too low and one should expect new physics to arise before that anyway to give rise to the needed four-fermion couplings.

The top quark partners (both $(t, b)_L$ and t_R) can be found as fermionic resonances created by the composite operators

Object	$SO(5) \times SU(3)_c \times U(1)_X$
$\tilde{\chi}\psi\tilde{\chi}, \quad \bar{\chi}\psi\bar{\chi}, \quad 2 \times \bar{\chi}\bar{\psi}\tilde{\chi}$	$(\mathbf{5}, \mathbf{3})_{2/3}$
$\chi\psi\chi, \quad \bar{\tilde{\chi}}\psi\bar{\tilde{\chi}}, \quad 2 \times \bar{\tilde{\chi}}\bar{\psi}\chi$	$(\mathbf{5}, \bar{\mathbf{3}})_{-2/3}$

After EWSB we end up with one Dirac fermion B of charge $-1/3$, three $T_{i=1,2,3}$ of charge $2/3$, and one X of charge $5/3$.

The current ATLAS and CMS limits on these objects are $m \gtrsim 700\ \text{GeV}$.

All the relevant couplings can be worked out by applying the CCWZ techniques. (See paper.)

A positive feature of this model is that it does not give rise to large deviations from the $Z \to b\bar{b}$ decay rate.

This can be seen by noticing that the coupling of the B field to the Z boson turns out to be

$$\mathcal{L} \supset \frac{e}{s_w c_w}\left(-\frac{1}{2}+\frac{s_w^2}{3}\right)\bar{B}\gamma^{\mu}BZ_{\mu}$$

i.e. with the same coefficient as the SM b_L. This guarantees that no changes arise when rotating to the mass eigenbasis.

There are corrections to the (smaller) coupling to the b_R and to the t_L, t_R, but they are acceptable and might even be welcome in the light of the forward-backward asymmetry.

CONCLUSIONS

- Models of Partial Compositeness can provide an interesting alternative to SUSY in explaining the hierarchy problem.
- Looking for purely four dimensional UV completions can provide an interesting new angle justifying some classes of models.
- In `arXiv:1312.5330` we classified the various possibilities under a few extra simplifying assumptions such as G_{HC} simple.
- In `arXiv:1404.7137` we studied the spectrum, coupling and significant features of one of the most promising ones based on $G_{HC} = SU(4)$.
- We are all looking forward to the next LHC run to give us a hint on how to proceed in understanding the hierarchy problem (supersymmetry, compositenes, or...?).