Compositeness above the Electroweak scale and a proposed test at LHCb.

Gabriele Ferretti, Cyberspace, Earth, August 2021*

* Also at Chalmers University, Gothenburg, Sweden.

The story so far...

The Higgs boson is nine years old but it's acting like an old person, being very conservative and not throwing any tantrums...

Still, many of us hope that it will grow into a revolutionary fighter that will lead us to break the shackles of the Standard Model!

The reason for this hope is, of course, the fact that its mass is not "*natural*" and I still unapologetically embrace this argument.

There are basically two *symmetry-based* ways to attack the problem:

- SUPERSYMMETRY $\delta h \approx \epsilon\psi$
- COMPOSITENESS $\delta h \approx h + a$

Supersymmetry is a weakly coupled theory with natural elementary scalars and its problem is that it predicts too much (there are many unwanted dim < 4 operators.)

Compositeness is a strongly coupled theory without elementary scalars that predicts too little (we lack the dim $= 4$ Yukawa operators.)

I will of course discuss compositeness (lest I be kicked out of this conference!) and concentrate on the subcase in which the Higgs is realized as a (pseudo) Nambu-Goldstone boson. (Lattice also hints at other possibilities that might be even more interesting, but I don't have anything to say about them.)

Contrary to other ideas in modern particle physics (Supersymmetry, Extra dimensions, Dilatons...) we *already know* that Nature does make use of the Nambu-Goldstone mechanism:

This is the picture of a pNGB scattering and creating another pNGB decaying into two more pNGBs, all swimming in a background of pNGBs...

Life was easy then.

Still...

That's a pretty dynamical mechanism you got there. It'd be a shame not to use it more often.

So, what's the idea?

The idea is to start with the Higgsless and massless Standard Model

$$\mathcal{L}_{\text{SM0}} = -\frac{1}{4} \sum_{F=GWB} F^2_{\mu\nu} + i \sum_{\psi=QudLe} \bar{\psi}\, \not{D}\psi$$

with gauge group $G_{\text{SM}} = SU(3) \times SU(2) \times U(1)$ and couple it to a theory $\mathcal{L}_{\text{comp.}}$ with hypercolor gauge group G_{HC} and global symmetry structure $G_{\text{F}} \to H_{\text{F}}$ such that $h \in G_{\text{F}}/H_{\text{F}}$ and

$$\mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}} \quad \longrightarrow \quad \mathcal{L}_{\text{SM}} + \cdots$$

($\mathcal{L}_{\text{SM}} + \cdots$ is the full SM plus possibly light extra matter from bound states of $\mathcal{L}_{\text{comp.}}$.)

To make the point even more explicit, at the cost of oversimplifying a bit, dropping couplings, gauge and Lorentz indices, mixing...

	G_{SM}	G_{HC}
q (SM)	R_1	x
ψ (BSM)	R_2	R_3
χ (BSM)	R_4	R_5

$$\mathcal{L}_{\text{int.}} \supset \frac{1}{\Lambda_{\text{UV}}^2}\left(q^2\psi\psi + q\psi\chi\psi \text{ (or } q\chi\psi\chi) + \cdots\right)$$

$$\to \left(\frac{\Lambda^2}{\Lambda_{\text{UV}}^2}\right)^{2+\gamma_\Phi} q^2\Phi + \left(\frac{\Lambda^2}{\Lambda_{\text{UV}}^2}\right)^{2+\gamma_\Psi} q\Psi + \cdots$$

Where $\Phi \approx \Lambda^{-2}\psi\psi$, $\Psi \approx \Lambda^{-2}\psi\chi\psi$ are the interpolating fields and γ_Φ, γ_Ψ their anomalous dimensions.

As far as the EW sector is concerned, the possible minimal custodial cosets of this type are generated by $\langle \tilde{\psi}^i \psi_j \rangle$ or $\langle \psi^i \psi^j \rangle$ for

$4\ (\psi, \tilde{\psi}) \in$ Complex irrep	$SU(4) \times SU(4)'/SU(4)_D$
$4\ \psi \in$ Pseudoreal irrep	$SU(4)/Sp(4)$
$5\ \psi \in$ Real irrep	$SU(5)/SO(5)$

E.g. $SU(4)/SO(4)$ is not acceptable since the pNGB are only in the symmetric irrep $(\mathbf{3}, \mathbf{3})$ of $SO(4) = SU(2)_L \times SU(2)_R$ and thus we do not get the Higgs irrep $(\mathbf{2}, \mathbf{2})$.

pNGB content under $SU(2)_L \times SU(2)_R$:

- $\mathbf{Ad}$ of $SU(4)_D \to (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + 2 \times (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
- $\mathbf{A}_2$ of $Sp(4) \to (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
- $\mathbf{S}_2$ of $SO(5) \to (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

As far as fermion masses are concerned, we couple a SM fermion q linearly to a G_{HC}-neutral fermionic bound state, Ψ. This requires additional hyper-fermions χ carrying color, schematically $\Psi \approx \psi\chi\psi$ or $\chi\psi\chi$.

We see that, to get the right top quark mass, we need $\gamma_\Psi \approx -2$ (since $\Lambda \ll \Lambda_{\mathrm{UV}}$). This requires the theory to be strongly coupled in the conformal range.

Notice however that $\gamma_\Psi \approx -2$ is still strictly above the unitarity bound for fermions: ($\Delta[\Psi] \approx 9/2 - 2 = 5/2 > 3/2$).

No new relevant operators are necessarily reintroduced in this case.

As an aside:

Since we have introduced a new set of hyper-fermions, we also need to embed the color group $SU(3)_c$ into the unbroken global symmetry of $\mathcal{L}_{\text{comp.}}$.

The choices of minimal field content allowing an anomaly-free embedding of unbroken $SU(3)_c$ are

$3\ (\chi, \tilde{\chi}) \in$ Complex irrep	$SU(3) \times SU(3)' \to SU(3)_D \equiv SU(3)_c$
$6\ \chi \in$ Pseudoreal irrep	$SU(6) \to Sp(6) \supset SU(3)_c$
$6\ \chi \in$ Real irrep	$SU(6) \to SO(6) \supset SU(3)_c$

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

UV $\longrightarrow$ IR

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

$$\text{UV} \quad \xrightarrow{\quad \Lambda_{\mathrm{UV}} \qquad\qquad\qquad\qquad\qquad\qquad \Lambda \quad} \quad \text{IR}$$

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

Λ_{UV} CONFORMAL Λ

UV $\longrightarrow$ IR

Here the theory is conformal.

G_{HC} with large enough N_ψ, N_χ.

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

$\Lambda_{\rm UV}$ CONFORMAL Λ

UV $\longrightarrow$ IR

Here the theory is conformal.
$G_{\rm HC}$ with large enough N_ψ, N_χ.
The CFT operator $\Psi \approx \psi\chi\psi$ acquires a (large?) negative anomalous dimension γ_Ψ.

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

Λ_{UV} CONFORMAL Λ CONFINING

UV $\longrightarrow$ IR

Here the theory is conformal. G_{HC} with large enough N_ψ, N_χ. The CFT operator $\Psi \approx \psi\chi\psi$ acquires a (large?) negative anomalous dimension γ_Ψ.

At Λ some fermions decouple reducing N_ψ, N_χ. The theory confines and breaks chiral symmetry.

The current philosophy is that one should start with models *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

Λ_{UV} CONFORMAL Λ CONFINING

UV $\longrightarrow$ IR

Here the theory is conformal. G_{HC} with large enough N_ψ, N_χ. The CFT operator $\Psi \approx \psi\chi\psi$ acquires a (large?) negative anomalous dimension γ_Ψ.

At Λ some fermions decouple reducing N_ψ, N_χ. The theory confines and breaks chiral symmetry.

Ψ creates a (light?) composite fermion M_Ψ.

We narrowed it down to a list of twelve models likely to be outside the conformal window but with still enough matter to realize the mechanism of partial compositeness: [1604.06467,1610.06591]

G_{HC}	ψ	χ	$G_{\text{F}}/H_{\text{F}}$
$SO(7)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\frac{SU(5)}{SO(5)}\,\frac{SU(6)}{SO(6)}\,U(1)$
$SO(9)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	
$SO(7)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$SO(9)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$Sp(4)$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$\frac{SU(5)}{SO(5)}\,\frac{SU(6)}{Sp(6)}\,U(1)$
$SU(4)$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$\frac{SU(5)}{SO(5)}\,\frac{SU(3)\times SU(3)'}{SU(3)_D}\,U(1)$
$SO(10)$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	
$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$\frac{SU(4)}{Sp(4)}\,\frac{SU(6)}{SO(6)}\,U(1)$
$SO(11)$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$SO(10)$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(6)}{SO(6)}\,U(1)$
$SU(4)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	
$SU(5)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\,\frac{SU(3)\times SU(3)'}{SU(3)_D}\,U(1)$

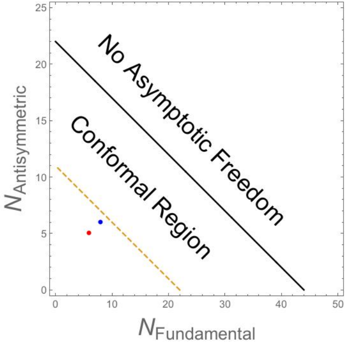
What's in it for the lattice?

The first questions to be addressed concern the composite sector *in isolation*, before coupling to the SM. Then, the list of models reduces to

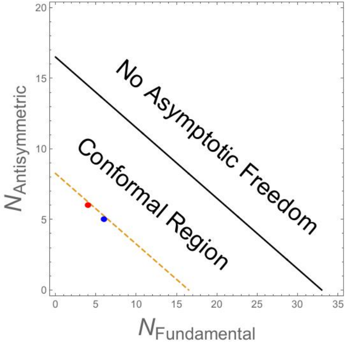
- $SU(4)$ with N_F Fundamentals and N_A Antisymmetric
  (possibly also $SU(5)$)
- $Sp(4)$ with N_F Fundamentals and N_A Antisymmetric
- $SO(N)$ with N_F Fundamentals and N_S Spin
  (with $N = 7, 9, 10, 11$)

In the first two cases, the hypercolor group is fixed and we scan over the two irreps:

$SU(4)$ case: $\bullet$ = 1404.7137
$\bullet$ = "swapped"



$Sp(4)$ case: $\bullet$ = 1311.6562
$\bullet$ = "swapped"



Some concrete questions that can be addressed are

- Where does the boundary of the conformal window start?
- For models inside the window, can we find an operator $\Psi \approx \psi\chi\psi$ (or $\chi\psi\chi$) of scaling dimension $\Delta \approx 5/2$?
- Does any of the four-fermi terms become relevant?
- Taking the models outside by removing some fermions, what is the mass of the composite fermionic resonances created by the remaining Ψs?
- Can the mass be significantly lighter than the typical confinement scale Λ?
- Can we estimate the LEC in the pNGB potential?
- Can we estimate the top Yukawa coupling?

Some of these questions have already started to be answered.

For $G_{\mathrm{HC}} = SU(4)$: [Ayyar, DeGrand, Golterman, Hackett, Jay, Neil, Shamir, Svetitskly, 1710.00806, 1801.05809, 1812.02727]

For $G_{\mathrm{HC}} = Sp(4)$: [Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino, 1710.07043, 1712.04220, 1811.00276, 1909.12662]

For $G_{\mathrm{HC}} = SO(N)$: Nothing of direct relevance to PC yet. (Anybody who likes spinorial irreps?)

Just for fun, an `iNSPIRE` search on June 2021:

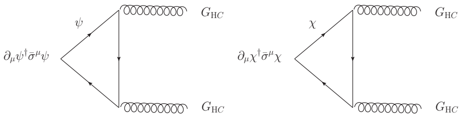
`f t SU and t lattice` 1321 hits

`f t Sp and t lattice` 6 hits

`f t SO and t lattice` 42 hits

An additional light ALP:

There are two global $U(1)_\psi$ and $U(1)_\chi$ symmetries rotating all $\psi \to e^{i\alpha}\psi$ or all $\chi \to e^{i\beta}\chi$.



The linear combination $q_\psi\psi^\dagger\bar\sigma^\mu\psi + q_\chi\chi^\dagger\bar\sigma^\mu\chi$ free of anomalies:

$$q_\psi N_\psi T(\psi) + q_\chi N_\chi T(\chi) = 0$$

is associated to a light ALP a.

The main point is that all the couplings C_ψ, K_g, K_γ can be computed from the underlying theory and one is left with two continuous parameters f_a and m_a to describe the model.

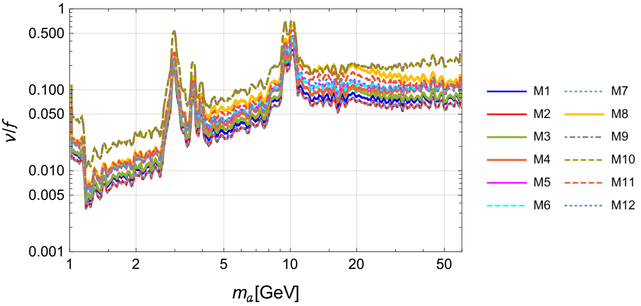
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 - i \sum_{\psi=QudLe} C_\psi \frac{m_\psi}{f_a} a\bar{\psi}\gamma^5\psi$$
$$+ \frac{a}{16\pi^2 f_a}\left(g_s^2 K_g G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + e^2 K_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

In [Buarque Franzosi, Cacciapaglia, Cid Vidal, Ferretti, Flacke and Vázquez Sierra, 2106.12615] we studied the reach of LHCb for such object.

Existing bounds

The [LHCb 2007.03923] search for pseudoscalars di-muon resonances in the 2HDM can be re-cast to provide bounds between 10-60 GeV by noting that both cross sections and widths scale like v/f in our models and $\sin\theta_H$ in the 2HDM.

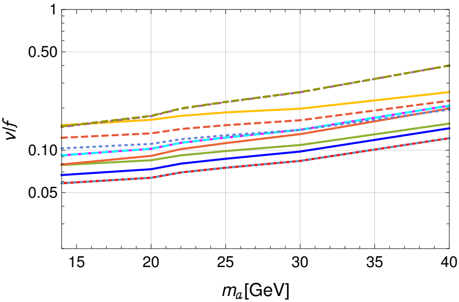
$$\frac{v}{f} = \sqrt{\frac{\sigma(pp \to a \to \mu^+\mu^-)_{\sin\theta_H=1}}{\sigma(pp \to a \to \mu^+\mu^-)_{v=f}}}\,\sin\theta_H$$



Proposed search $p\,p \to a \to \tau^+\,\tau^-$

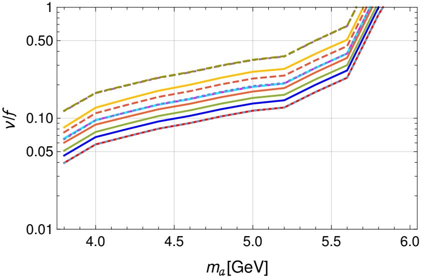
This channel "wins" over the muons by an enhanced Branching Ratio $\propto (m_\tau/m_\mu)^2 = 283$ but "loses" by the presence of neutrinos in the final states and usual difficulties with taus.

Combining the leptonic and three-prong hadronic τ decay channels we estimate a sensitivity comparable to that of the di-muon channel (mostly from opposite flavor leptonic decays $\tau\tau \to e\mu$). At 15 fb^{-1}:



Proposed search $p\,p \to a \to D^+ D^-$

This only works in a small mass window above the $D^+ D^-$ threshold where $a \to D^+ D^-$ exclusively has a large fragmentation function. We use the fact that the decay $D^\pm \to K^\mp \pi^\pm \pi^\pm$ (9.38% BR)* is fully reconstractable at LHCb, as long as all the decay products are within the geometric acceptance, and the resolution on the invariant mass $m(D^+ D^-)$ can reach ± 10 MeV. At $15\ \mathrm{fb}^{-1}$:



* Unfortunately there is no such channel for $b\,\bar{b}$.

CONCLUSIONS

- Realizing partial compositeness via ordinary 4D gauge theories provides a self contained concrete class of models to address the hierarchy problem.
- There are lots of open questions that go to the heart of strongly coupled theories, such as the range of the conformal window, anomalous dimensions and LEC.
- In the pNGB sector the models are fairly predictive, since many couplings can be computed from the underlying gauge theory.
- In particular, the presence of a ubiquitous light neutral pseudo-scalar a can be tested in various novel decay channels.

CONCLUSIONS

- Realizing partial compositeness via ordinary 4D gauge theories provides a self contained concrete class of models to address the hierarchy problem.
- There are lots of open questions that go to the heart of strongly coupled theories, such as the range of the conformal window, anomalous dimensions and LEC.
- In the pNGB sector the models are fairly predictive, since many couplings can be computed from the underlying gauge theory.
- In particular, the presence of a ubiquitous light neutral pseudo-scalar a can be tested in various novel decay channels.

Thank you for your attention!