Composite Higgs bosons

Gabriele Ferretti,
cHarged 2018, Uppsala

CHALMERS
UNIVERSITY OF TECHNOLOGY

Knut och Alice Wallenbergs Stiftelse

Stiftelsen
Lars Hiertas Minne

Picture credit: Andrew Friberg Wikimedia Commons

Based on

- `arXiv:1312.5330` G.F. and D. Karateev
- `arXiv:1404.7137` G.F.
- `arXiv:1604.06467` G.F.
- `arXiv:1610.06591` A. Belyaev, G. Cacciapaglia, H. Cai, G.F., T. Flacke, A. Parolini and H. Serodio
- `arXiv:1710.11142` G. Cacciapaglia, G.F., T. Flacke and H. Serodio
- Work in progress with the SHIFT collaboration (Stockholm-Uppsala-Göteborg)

Introduction

One of the few dynamical principles that can be used to explain the lightness of the Higgs boson is spontaneous symmetry breaking, in which the Higgs arises as a (pseudo)-Nambu-Goldstone boson (pNGB) [Georgi, Kaplan].

A true NGB field is invariant under shift symmetry $\phi \to \phi + \text{ const.}$ and thus cannot develop a potential.

This symmetry is only approximate for the Higgs field because of the SM couplings and a small potential is induced.

We know how to parameterize the most general Effective Field Theory (EFT) that describes this phenomenon. Just pick a global symmetry G broken to a subgroup H and use spurions to describe the couplings to the SM.

The simplest model giving rise to (only) the Higgs doublet and preserving custodial symmetry is based on $G/H = SO(5)/SO(4)$ and the vast majority of the literature on the subject focuses on this case. All other cosets give rise to additional pNGBs.

In fact, if one tries to realize this mechanism with a strongly coupled 4D gauge theory (hypercolor G_{HC}) with massless fermions, the three "basic" cosets are: (using Weyl notation)

4 $(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$
4 ψ_α Pseudoreal	$SU(4)/Sp(4) \equiv SO(6)/SO(5)$
5 ψ_α Real	$SU(5)/SO(5)$

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

- **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 $SO(5) \to (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

This well know fact, by itself, gives little information of the possible choice of hypercolor group and representation.

If we make the further assumption (partial compositeness [Kaplan]) that the mass of the top quark is generated by the mixing with a Vector-Like Quark (VLQ), we can try realizing such VLQs also as a bound state of the above gauge theory. (Schematically "ψ^3", although we need two different irreps.)

This puts more constraints on the gauge+matter content of the theory. With some additional assumptions, we can narrow it down to a handful of models.

The interest of these models resides mainly in the fact that many of the couplings of the effective field theory are computable from the underlying UV theory.

Example

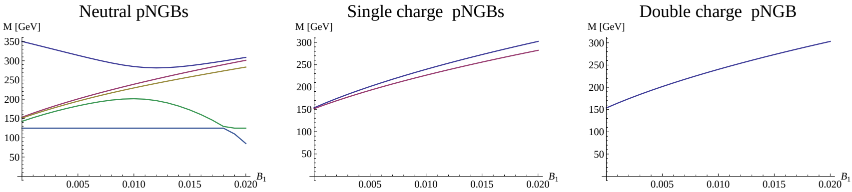
Hypercolor $G_{\rm HC} = SU(4)$ with

- $5\times\ \psi \in \mathbf{6}$ (real representation)
- $3\times\ (\chi, \tilde{\chi}) \in (\mathbf{4}, \bar{\mathbf{4}})$ (complex representation)

- EWSB coset: $SU(5)/SO(5)$ à la Dugan, Georgi, Kaplan but with misalignment driven by the top quark and not by an additional $U(1)$. pNGBs of type $\psi\psi$.
- Color: $SU(3)_{QCD} = SU(3)_D$ in $SU(3)\times SU(3)'/SU(3)_D$. Additional color octet pNGB of type $\chi\chi$.
- Top partners of type $\chi\psi\chi\ \tilde{\chi}\psi\tilde{\chi}$, .

Electro-weak Sector

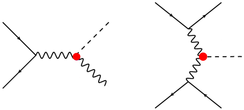
It is possible to find custodial vacua in which the spectrum looks like ($f = 800$ GeV):



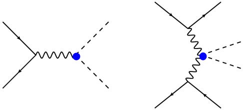
We considered a three parameter potential and fixed two relations to obtain $m_h = 125$ GeV and $v = 246$ GeV. This behavior is more generic than one would expect [1808.10175].

You recognize the custodial **5** and the custodial **3**.

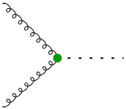
In this case the single production modes are associated production and VBF both via the anomalous coupling •



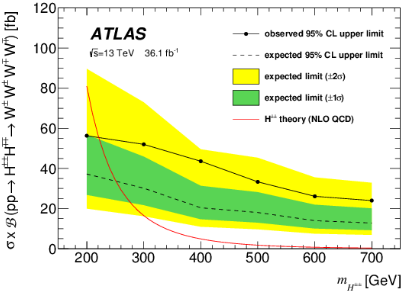
Pair production is driven by the renormalizable coupling •



For some neutral pNGBs there is also a coupling to gluons via top loops •.



Since the title of the workshop is c$H^{\pm}$arged, I will exaggerate and show the recent ATLAS search [1808.01899] on the pair production for the doubly c$H^{\pm\pm}$arged pNGB



The theory cross-section [1105.1925, hep-ph/0305288] is for a slightly different model, but the qualitative behavior is similar.

Note that in the current model we would expect BR$(H^{\pm\pm} \to W^{\pm}W^{\pm}) \approx 100\%$.

Additional pNGBs

We might have a better shot looking at those pNGBs that couple to gluons. In this model there are two such scalars of particular interest: a and η'. They are related to the two global $U(1)$ symmetries rotating all $\psi \to e^{i\alpha}\psi$ or all $\chi \to e^{i\beta}\chi$.

The linear combination free of $U(1)G_{\mathrm{HC}}G_{\mathrm{HC}}$ anomalies is associated to a (light), the orthogonal one to η' (heavy).

Importantly, the pNGB a could be in the 10-100 GeV range, where exclusions are much weaker.

Its production and decay are governed by the anomaly and by the coupling to the heavy SM-fermions

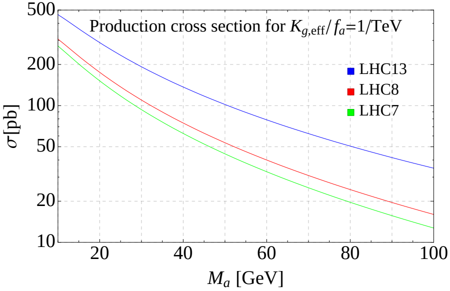
$$\begin{aligned}\mathcal{L} &= \frac{g_s^2 K_g}{16\pi^2 f_a} a G^A_{\mu\nu}\tilde{G}^{A\mu\nu} + \frac{g'^2 K_B}{16\pi^2 f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu} \\ &+ iC_b \frac{m_b}{f_a} a\,\bar{b}\gamma^5 b + iC_t \frac{m_t}{f_a} a\,\bar{t}\gamma^5 t + iC_\tau \frac{m_\tau}{f_a} a\,\bar{\tau}\gamma^5 \tau.\end{aligned}$$

The coefficients K_V and C_f are computable from the quantum numbers of the hyperfermions and of the spurions.

Assuming $m_a < 2m_t$ and integrating out the top ($K_g \to K_g^{\text{eff.}} = -4.9$ and $C_\tau = 1.5$ in the $G_{\text{HC}} = SU(4)$ model used as example.)

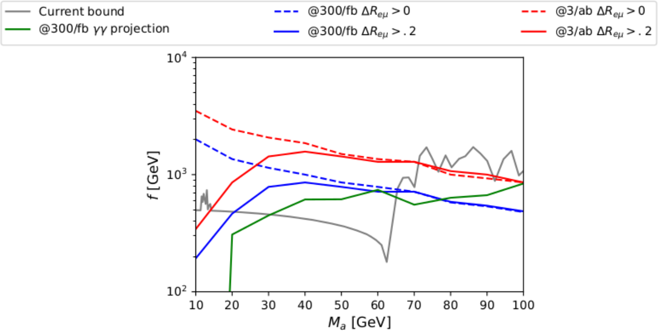
Note that a pNGB a with a mass between 10 and 100 GeV is not excluded by LEP since its coupling to the Z and W are much smaller than those of a Higgs boson of the same mass and thus is not produced by "alp-strahlung" or "vector boson fusion".

On the other hand, LHC has a much larger production cross-section e.g. via gluon fusion.



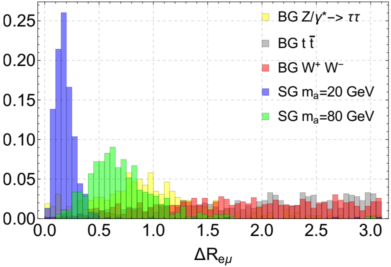
In [1710.11142] we estimated the reach at LHC-HL in the channel $a \to (\tau \to e\nu\bar{\nu})\,(\tau \to \mu\nu\bar{\nu})$ after 300 fb^{-1} and 3 ab^{-1}.

We also show the reach in the $a \to \gamma\gamma$ channel after 300 fb^{-1} using [1710.01743].



In all cases an ISR jet is required to boost the a to give the final products sufficient p_T to trigger on.

The di-tau signal seems promising in the low mass region. Looking, for instance, at the $\Delta R_{e\mu}$ distribution for signal and background:



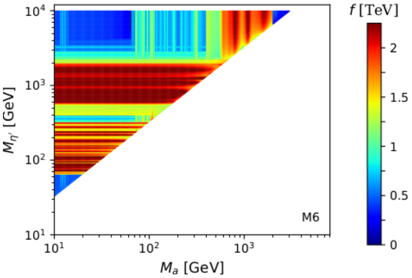
suggests to cut $\Delta R_{e\mu}^{\text{max.}} = 1$ and $\Delta R_{e\mu}^{\text{min.}}$ as low as possible (0.1?).

Further cuts used in the simulation:

$$p_{T\mu} > 50\ \text{GeV},\ \ p_{Te} > 10\ \text{GeV},\ \ \Delta R_{\mu j} = \Delta R_{ej} > 0.5,$$
$$p_{Tj} > 150\ \text{GeV},\ \ m_{e\mu} < 100\ \text{GeV}.$$

The S/B ratio is quite small in the OFOS channel, so it is important to reduce the systematic error as much as possible, or look at the τ_h channels. (Recently improved in CMS [1809.02816].)

One can also look at the combined reach involving both pNGBs. In some cases the heavy η' gives the strongest bound.



Heath map of the current exclusion in the $(M_a, M_{\eta'})$ mass plane. Note the unconstrained region in the upper-left corner.

Conclusions

- All composite Higgs models other than minimal $SO(5)/SO(4)$ contain additional pNGBs.
- Such pNGBs are becoming more and more attractive as a chance of seeing some on-shell new physics at LHC.
- Realizing these models via ordinary 4D gauge theories provides a concrete realization where some of the LEC can be computed.
- We presented just one example based on a $SU(4)$ hypercolor group.
- This model contains a double charged scalar with small producion cross section.
- Additional neutral pNGBs have larger production cross section (ggF) and can be probed, e.g. for low masses in the di-tau channel.