Gauge theories of partial compositeness, Scenarios for the Lattice and the LHC

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The LHC has now entered the phase where the potential for discovery is at its highest. In a few months (weeks?) we will know if the diphoton excess at 750 GeV is confirmed or excluded and, in the coming years, the experiments will probe deeply into the parameter space of many models of BSM physics.

Not surprisingly, this has led to a flurry of model-building activity and what I am going to tell you is one such idea based on `arXiv:1312.5330, 1404.7137, 1604.06467`.

These models can be described as "Gauge Theories of Partial Compositeness", although a more catchy name for this talk could be "Two irreps are better than one" as I will explain.

PLAN

The plan of this talk is threefold:

- Give an overview of the type of models being considered. (With apologies to some of you who have been sitting through this already!)
- Make concrete suggestions for lattice simulations that could test the viability of these models. (I know it's easier said than done, but there has been a demand for concrete proposals, and this is what I got.)
- Present some basic phenomenological aspects of these models. (More to come, in collaboration with Belyaev, Cacciapaglia, Cai, Parolini and Serodio.)

OVERVIEW

In a nutshell, we consider ordinary asymptotically free 4-dim gauge theories based on a simple group G_{HC} and with fermionic matter ψ and χ in two different irreps of G_{HC}.

These models have two main features:

- A naturally light Higgs boson arising as a pNGB.
- Top-partners (G_{HC} singlet of type $\psi\chi\psi$ or $\chi\psi\chi$), in the spirit of partial compositeness. (However, see also [Vecchi: 1506.00623].)

The added bonus is that it necessarily gives rise to a rich spectrum of possibilities that can be explored at LHC, mainly through additional neutral, EW and colored light scalar pNGBs.

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

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

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

$$\mathcal{L}_{\mathrm{comp.}} + \mathcal{L}_{\mathrm{SM0}} + \mathcal{L}_{\mathrm{int.}} \quad \underset{\Lambda = 5 \sim 10\ \mathrm{TeV}}{\longrightarrow} \quad \mathcal{L}_{\mathrm{SM}} + \cdots$$

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

Our goal is to find candidates for $\mathcal{L}_{\mathrm{comp.}}$ and $\mathcal{L}_{\mathrm{int.}}$ and to study their properties.

The interaction lagrangian $\mathcal{L}_{\text{int.}}$ typically contains a set of four-fermi interactions between hyperfermions and SM fermions, so the UV completion is only partial at this stage. However, we can imagine it being generated by integrating out d.o.f. from a theory $\mathcal{L}_{\text{UV}}$. (At a much higher scale to avoid flavor constraints.)

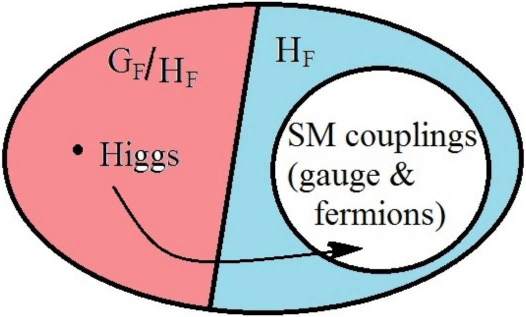
$$\begin{array}{ccc} \mathcal{L}_{\text{UV}} & \longrightarrow & \mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \cdots \\ \Lambda_{\text{UV}} > 10^4 \text{ TeV} & & \Lambda = 5 \sim 10 \text{ TeV} \end{array}$$

I will not attempt to construct such theory and will concentrate on the physics at the $5 \sim 10$ TeV scale, encoded in $\mathcal{L}_{\text{comp.}}$ and $\mathcal{L}_{\text{int.}}$

We need to accomplish two separate tasks:

- Give mass to the vector bosons.
- Give a mass to the fermions. (In particular the top quark.)

For the vector bosons, the picture we have in mind is that of the "Composite pNGB Higgs"



To preserve custodial symmetry and to be able to give the correct hypercharge to all SM fields, we need

- $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \subseteq H_F$
- Higgs $= (\mathbf{1}, \mathbf{2}, \mathbf{2})_0 \in G_F/H_F$

The three "basic" cosets one can realize with fermionic matter

For a set of n irreps of the hypercolor group:

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

(The $U(1)$ factors need to be studied separately because of possible ABJ anomalies.)

The first case is just like ordinary QCD: $\langle \tilde{\psi}^{\alpha a i} \psi_{\alpha a j} \rangle \propto \delta^i_j$ breaks $SU(n) \times SU(n)' \to SU(n)_D$
In the other two cases, a real/pseudo-real irrep of the hypercolor group possesses a symmetric/anti-symmetric invariant tensor $t^{ab} = \delta^{ab}/\epsilon^{ab}$ making the condensate $t^{ab} \langle \psi^{\alpha i}_a \psi^j_{\alpha b} \rangle$ also symmetric/anti-symmetric in i and j, breaking $SU(n) \to SO(n)$ or $Sp(n)$.

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

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

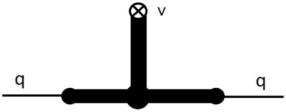
E.g. $SU(4)/SO(4)$ is not acceptable since the pNGB are only in the symmetric irrep $(\mathbf{3}, \mathbf{3})$ of $SO(4) = SU(2)_L \times SU(2)_R$ and thus we do not get the Higgs irrep $(\mathbf{2}, \mathbf{2})$.

pNGB content under $SU(2)_L \times SU(2)_R$: ($X = 0$ everywhere)

- **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, at least for the top quark we follow the road of "Partial Compositeness", coupling a SM fermion q linearly to a G_{HC}-neutral fermionic bound state, "$\mathcal{O} = \psi\chi\psi$ or $\chi\psi\chi$": $\frac{1}{\Lambda_{UV}^2} q\mathcal{O} =$ 

and mediating EWSB by the strong sector:



If the theory is conformal in the range $\Lambda_{UV} \to \Lambda$ with $\mathcal{O}$ of anomalous dimension γ we obtain, below the scale Λ, after the theory has left the conformal regime

$$m_q \approx v \left(\frac{\Lambda}{\Lambda_{\mathrm{UV}}}\right)^{2(2+\gamma)}$$

Looking at the (schematic) equation for the mass

$$m_q \approx v \left(\frac{\Lambda}{\Lambda_{\mathrm{UV}}} \right)^{2(2+\gamma)}$$

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

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

No new relevant operators are reintroduced in this case.

In many cases it is not possible to construct partners to all the SM fermions, so I suggest a compromise: Use “partial compositeness” for the top sector and the usual bilinear term for the lighter fermions.

What is non negotiable in this approach is the existence of at least two $\mathcal{O}$s hypercolor 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 (t_L, b_L) and t_R.)

In the composite sector they arise as Dirac fermions and only one chirality couples to the SM fields.

If one had scalars in the theory $\mathcal{L}_{\text{comp.}}$ one could make G_{HC} invariants of the right scaling dimension ($\Delta[\mathcal{O}] = 5/2$) by taking simply $\mathcal{O} = \psi\phi$ but, of course, this reintroduces the naturalness issue.

If some fermions are in the Adjoint of G_{HC}, one has also the option $\mathcal{O} = \psi\sigma^{\mu\nu}F_{\mu\nu}$ of naive dim. $\Delta[\mathcal{O}] = 7/2$ requiring only $\gamma \approx -1$, but it’s difficult (impossible ?) to get the right SM quantum numbers.

Since we want to obtain the top partners, we also need to embed the color group $SU(3)_c$ into the global symmetry of $\mathcal{L}_{\text{comp.}}$.
The minimal field content allowing an anomaly-free embedding of unbroken $SU(3)_c$ are

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

In summary, we require:

- G_{HC} asymptotically free.
- $G_{\mathrm{F}} \to H_{\mathrm{F}} \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\mathrm{cus.}}} \supset G_{\mathrm{SM}}$.
- The MAC should not break neither G_{HC} nor $G_{\mathrm{cus.}}$.
- G_{SM} free of 't Hooft anomalies. (We need to gauge it.)
- $G_{\mathrm{F}}/H_{\mathrm{F}} \ni (\mathbf{1}, \mathbf{2}, \mathbf{2})_0$ of $G_{\mathrm{cus.}}$. (The Higgs boson.)
- $\mathcal{O}$ hypercolor 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 (t_L, b_L) and t_R.)
- B or L symmetry.

In [G.F., Karateev: 1312.5330] we gave a list of solutions to the constraints, listing the allowed hypercolor groups $G_{\rm HC}$ and the irreps ψ and χ.

Two typical examples are [Barnard et al. 1311.6562], [G.F. 1404.7137]

	$\overbrace{Sp(4)}^{G_{\rm HC}}$	$SU(4)$	$SU(6)$	$U(1)'$
ψ	$\mathbf{4}$	$\mathbf{4}$	$\mathbf{1}$	3
χ	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{6}$	-1

(The columns $SU(4)$, $SU(6)$, $U(1)'$ are grouped under the brace $G_{\rm F}$.)

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

The list of solutions contains both conformal and confining models.

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$$\begin{array}{ccccc} & \Lambda_{\mathrm{UV}} & & \Lambda & \\ \mathrm{UV} & \multicolumn{3}{c}{\xrightarrow{\hspace{12em}}} & \mathrm{IR} \end{array}$$

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This is the list of theories that are likely to be *outside* the conformal window but still have enough matter to realize the mechanism of partial compositeness:

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

It is not possible to exactly identify the conformal region in non-supersymmetric gauge theories. However, one can use some heuristic arguments to get indications on their behavior and it turns out that most of the models are rather clear-cut cases.

$\beta(\alpha) = \beta_1 \alpha^2 + \beta_2 \alpha^3$. ($\beta_1 < 0$ always.) A formal solution α^* to $\beta(\alpha^*) = 0$ exists for $\beta_2 > 0$ and, if not to large, it can be trusted and the theory can be assumed to be in the weakly coupled conformal regime.

If $\beta_2 < 0$ or α^* is out of the perturbative regime, the model is likely to be confining.

In between there is a region, difficult to characterize precisely, where the theory is conformal but strongly coupled.

The models presented obey the heuristic bound [Ryttov, Sannino: 0906.0307] $11C(G) > 4\left(N_\psi T(\psi) + N_\chi T(\chi)\right)$ as well as the rigorous bounds from the *a*-theorem $a_{\mathrm{UV}} > a_{\mathrm{IR}}$.

POSSIBLE CONNECTIONS TO 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 $SU(5)$, $SU(6)$)
- $Sp(4)$ 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
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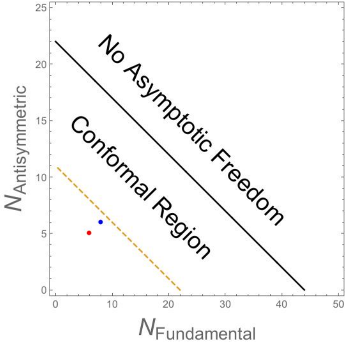

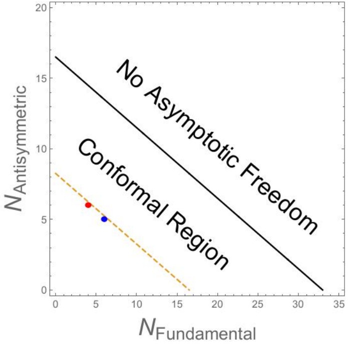

Focusing on $G_{\mathrm{HC}} = SU(4)$ with N_F Fundamentals and N_A Antisymmetric for definiteness, some concrete questions that could be addressed are

- Where does the boundary of conformal window start?
- For models inside the window, can we find an operator $\mathcal{O} \approx \psi\chi\psi$ (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 $\mathcal{O}$s?
- Can the mass be significantly lighter than the typical confinement scale Λ?
- Can we estimate the LEC in the pNGB potential?

None of these questions requires great numerical accuracy as a first step in the investigation.

PHENOMENOLOGY

- Electro-Weak sector: pNGBs associated to EWSB.
- Strong sector: Colored pNGBs and top partners.
- Two additional ALPs: Associated with $U(1)$ currents. Anomalous couplings to gluons.

Electro-Weak sector:

G/H	$H \to SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{S}_2 \to \mathbf{3}_{\pm 1}(\phi_\pm) + \mathbf{3}_0(\phi_0) + \mathbf{2}_{\pm 1/2}(H) + \mathbf{1}_0(\eta)$
$SU(4)/Sp(4)$	$\mathbf{A}_2 \to \mathbf{2}_{\pm 1/2}(H) + \mathbf{1}_0(\eta)$
$SU(4) \times SU(4)'/SU(4)_D$	$\mathbf{Ad} \to \mathbf{3}_0(\phi_0) + \mathbf{2}_{\pm 1/2}(H) + \mathbf{2'}_{\pm 1/2}(H') + \mathbf{1}_{\pm 1}(N_\pm) + \mathbf{1}_0(N_0) + \mathbf{1'}_0(\eta)$

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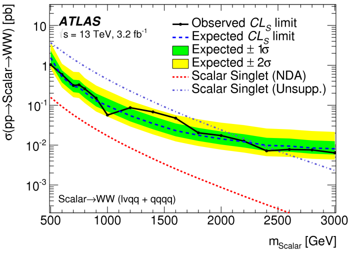
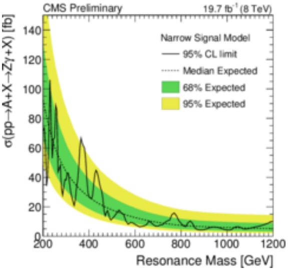
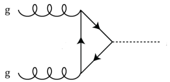
In the last weeks many diboson searches have been released by both ATLAS and CMS. Here is a couple on “non-diphoton” ones:





The models under study so far include a dim 5 coupling with gluons, giving rise to the fairly large cross-sections that can be excluded with the currently available data.



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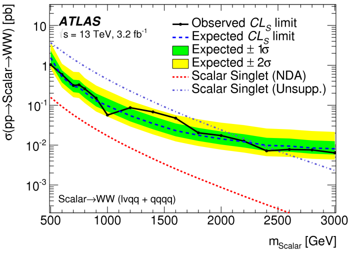
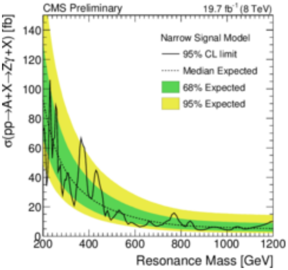
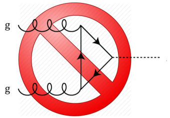
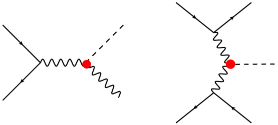




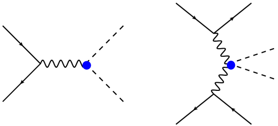
The EW bosons from the models in this talk do not have dim 5 gluon coupling, since the hyperquarks ψ involved are not colored. This leads to a lower cross-section and much weaker exclusion limits.



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



Pair production is instead driven by the renormalizable coupling •



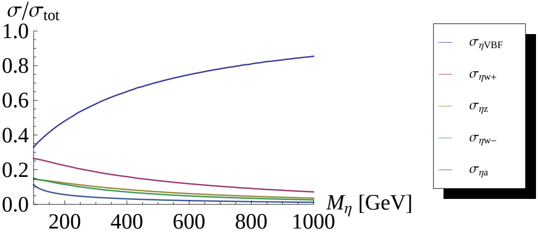
As an example, a particle present in both $SU(4) \times SU(4)'/SU(4)_D$ and $SU(4)/Sp(4)$ that does not mix with the other pNGB is the η

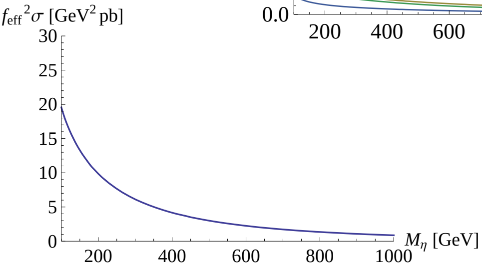
$$S_{\mathrm{WZW}} \supset \frac{\dim(\psi)}{16\pi^2 f} \mathrm{c}_\zeta \int \eta \left(\frac{g^2 - g'^2}{2} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + g g' F_{\mu\nu} \tilde{Z}^{\mu\nu} + g^2 W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right) \mathrm{d}^4 x.$$

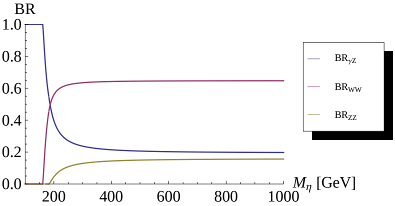
We can define $f_{\rm eff} = f/\dim(\psi)c_\zeta$

Unpublished work with A. Hallin and A. Padellaro

$$S_{WZW} \supset \frac{1}{16\pi^2 f_{\rm eff}} \int \eta \left(\frac{g^2 - g'^2}{2} Z_{\mu\nu}\tilde{Z}^{\mu\nu} + gg' F_{\mu\nu}\tilde{Z}^{\mu\nu} + g^2 W^+_{\mu\nu}\tilde{W}^{-\mu\nu} \right) d^4x.$$



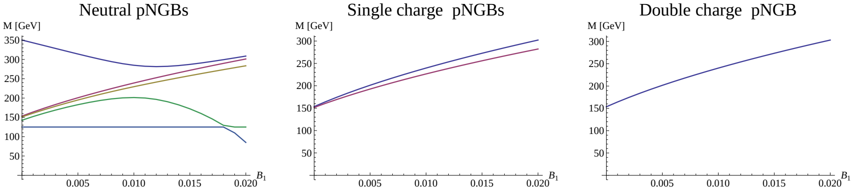




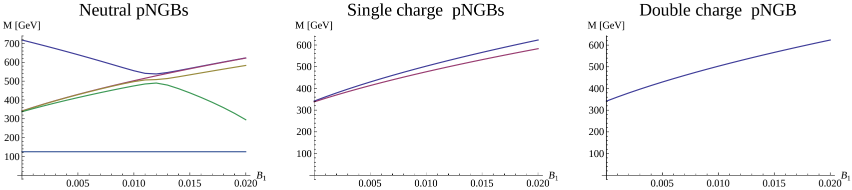
The pNGB potential, and associated mass matrix, is quite model dependent. Here I present, for illustration purpose, the spectrum arising from an effective potential induced by loops in the EW gauge fields, the top and possibly bare hyperquark masses.

The strategy is to consider a potential depending on three LEC.

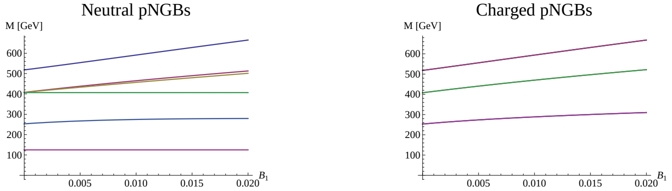
- One linear combination is traded to fix the Higgs vev $v = 246$ GeV. (Or, given f, the fine-tuning parameter).
- A second linear combination is traded for the Higgs mass $m_h = 125$ GeV.
- The third combination is varied and the dependence of the physical masses on it is plotted.



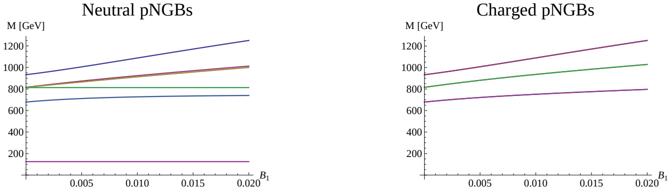
Example of spectrum for the $SU(5)/SO(5)$ model with $f = 800$ GeV



Same as above but with $f = 1600$ GeV



Now for the $SU(4) \times SU(4)'/SU(4)_D$ model with $f = 800$ GeV



Same as above but with $f = 1600$ GeV

Colored sector:

G/H	$H \to SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{S}_2 \to \mathbf{8}_0 + \mathbf{6}_{-2/3} + \overline{\mathbf{6}}_{2/3}$
	$\to \mathbf{8}_0 + \mathbf{6}_{4/3} + \overline{\mathbf{6}}_{-4/3}$
$SU(6)/Sp(6)$	$\mathbf{A}_2 \to \mathbf{8}_0 + \mathbf{3}_{2/3} + \overline{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{Ad} \to \mathbf{8}_0$

Colored sector:

G/H	$H \to SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{S}_2 \to \mathbf{8}_0 + \mathbf{6}_{-2/3} + \overline{\mathbf{6}}_{2/3}$
	$\to \mathbf{8}_0 + \mathbf{6}_{4/3} + \overline{\mathbf{6}}_{-4/3}$
$SU(6)/Sp(6)$	$\mathbf{A}_2 \to \mathbf{8}_0 + \mathbf{3}_{2/3} + \overline{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{Ad} \to \mathbf{8}_0$

Colored sector:

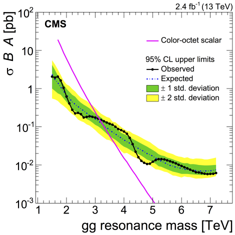
G/H	$H \to SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{S}_2 \to \mathbf{8}_0 + \mathbf{6}_{-2/3} + \overline{\mathbf{6}}_{2/3}$
	$\to \mathbf{8}_0 + \mathbf{6}_{4/3} + \overline{\mathbf{6}}_{-4/3}$
$SU(6)/Sp(6)$	$\mathbf{A}_2 \to \mathbf{8}_0 + \mathbf{3}_{2/3} + \overline{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{Ad} \to \mathbf{8}_0$

Colored sector:

G/H	$H \to SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{S}_2 \to \mathbf{8}_0 + \mathbf{6}_{-2/3} + \overline{\mathbf{6}}_{2/3}$
	$\to \mathbf{8}_0 + \mathbf{6}_{4/3} + \overline{\mathbf{6}}_{-4/3}$
$SU(6)/Sp(6)$	$\mathbf{A}_2 \to \mathbf{8}_0 + \mathbf{3}_{2/3} + \overline{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{Ad} \to \mathbf{8}_0$

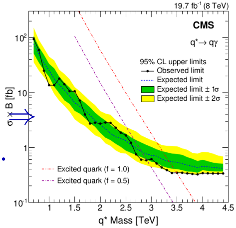
As well as the "usual" top and bottom partners and their friends of charges $\pm 5/3$ (possibly even $\pm 8/3$).

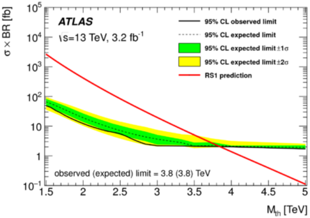
Here the experiments have already probed the multi TeV region. (The exclusion limit for these models is work in progress and will appear soon.)



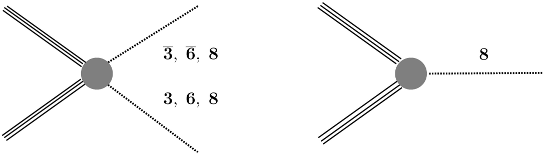
$\Leftarrow$ CMS dijet resonance search.
Relevant for all colored pNGBs.

ATLAS and CMS
$j\gamma$ resonance searches. $\Rightarrow$
Relevant for the octect.





These objects are pair produced with QCD cross-section values depending only on their mass. The octet can also be singly produced by the anomalous coupling via gluon fusion.



The decay modes are more interesting, since the sextet and triplet carry baryon number.

$$\text{Top partners } = \psi\chi\psi \quad \Rightarrow \quad \chi \text{ carries } B = 1/3$$
$$\text{Top partners } = \chi\psi\chi \quad \Rightarrow \quad \chi \text{ carries } B = 1/6$$

In some cases this leads to $\Delta B = 2$ eff. interactions inducing $n - \bar{n}$ oscillations and di-nucleon decay (but not proton decay).

Two additional ALPs:

There are two more scalars of interest: a and η'. They are related to the two global $U(1)$ symmetries rotating all $\psi \to e^{i\alpha}\psi$ or all $\chi \to e^{i\beta}\chi$.

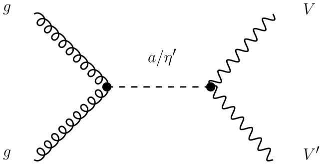
The linear combination free of $U(1)G_{\mathrm{HC}}G_{\mathrm{HC}}$ anomalies is associated to a, the orthogonal one to η'.

Their production and decay are governed by the anomaly, e.g. for a:

$$\mathcal{L} = \frac{g_s^2 k_s}{16\pi^2 f_a} a G^A_{\mu\nu}\tilde{G}^{A\mu\nu} + \frac{g'^2 k_B}{16\pi^2 f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 k_W}{16\pi^2 f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu},$$

with k coefficients computable from the quantum numbers of the hyperfermions.

Contrary to the pNGBs of the EW coset, the a (and η') have a color anomaly, allowing for the process $gg \to a \to \gamma\gamma$



For example one could try and use a to explain the current excess in the diphoton channel at 750 GeV (if confirmed!). (Such mass can be obtained e.g. by adding a small bare mass for the hyperfermions χ.)

This interpretation, combined with the bounds on other channels, allows to rule out some of the models. [Belyaev et. al. 1512.07242] [Belyaev et. al. in progress]

In fact, looking at the list shown before, only five models are consistent with such interpretation.

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

If you have bought the assumptions so far you are led to three favored low energy cosets.

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

CONCLUSIONS

- Realizing partial compositeness via ordinary 4D gauge theories with 2 irreps provides a self contained class of models to address the hierarchy problem.
- The minimal EW cosets in this context are $SU(4) \times SU(4)'/SU(4)_D$, $SU(5)/SO(5)$ and $SU(4)/Sp(4)$. All predict some additional scalars at the EW scale with low cross-section.
- Top partners arise as fermionic trilinears.
- An additional color octet scalar is always present, in some cases also triplets and sextets.
- Concrete questions about the strong dynamics can be addressed by the lattice.
- Multiple irreps lead to the existence of composite ALPs giving rise to diboson signals. (For example, identifying one as the 750 GeV candidate considerably narrows down the list and leads to further predictions.)