Gauge theories of partial compositeness, Scenarios for the LHC

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I am going to discuss work based on `arXiv:1312.5330` (with D. Karateev), `arXiv:1404.7137`, `arXiv:1604.06467`, unpublished work with A. Hallin and A. Padellaro, as well as a forthcoming paper with A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini and H. Serodio.

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

Given the audience (and my previous experiences) I will skip the intro on naturalness, which tends to consume half of the seminar.

I will instead jump right into the overview of the models.

After the overview I will discuss some of the phenomenological aspects of these models, of relevance for LHC.

Time permitting (but it won't) I will comment on some questions about the strongly coupled dynamics that could be addressed by lattice or the bootstrap.

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.

The added bonus is that they necessarily give 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

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

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

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

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

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

The interaction lagrangian $\mathcal{L}_{\text{int.}}$ typically arises as set of four-fermi interactions between hyperfermions and SM fermions (at a much higher scale to avoid flavor constraints), so the UV completion is only partial at this stage.

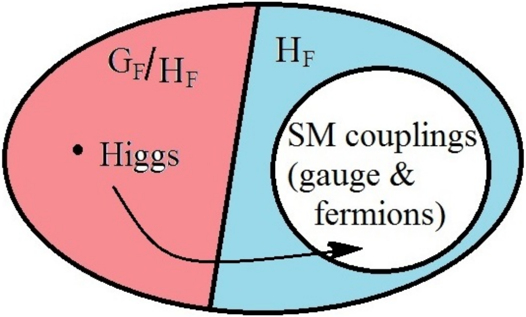
$$\mathcal{L}_{\text{UV}} \longrightarrow \mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \cdots$$

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

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

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

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	$SU(5)/SO(5)$

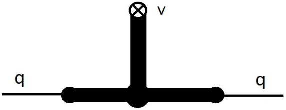
E.g. $SU(4)/SO(4)$ is not acceptable since the pNGB are only in the symmetric irrep $(\mathbf{3}, \mathbf{3})$ of $SO(4) = SU(2)_L \times SU(2)_R$ and thus we do not get the Higgs irrep $(\mathbf{2}, \mathbf{2})$.

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

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

we see that, to get the right top quark mass, we need $\gamma \approx -2$ (since $\Lambda \ll \Lambda_{\text{UV}}$). 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	$SU(6) \to SO(6) \supset SU(3)_c$

Since the top partners contain both types of fermions, one can use the "persistent mass condition" to argue that this global symmetry must also be realized in the Nambu-Goldstone mode.

In summary, we require:

- G_{HC} asymptotically free.
- $G_{\mathrm{F}} \to H_{\mathrm{F}} \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\text{cus.}}} \supset G_{\mathrm{SM}}$.
- The MAC should not break neither G_{HC} nor $G_{\text{cus.}}$.
- 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 $G_{\text{cus.}}$. (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]

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

	$G_{\rm HC}$	$G_{\rm F}$				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
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 original list of solutions contained both conformal and confining models.

My current philosophy is that the most promising models are those *outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter.

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$\Lambda_{\rm UV}$ CONFORMAL Λ CONFINING

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At Λ some fermions decouple: $N_\psi \to 4$, $N_\chi \to 6$ and the theory confines and breaks χS. $\mathcal{O}$ creates a (light?) composite fermion of mass $M_{\mathcal{O}}$.

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:

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

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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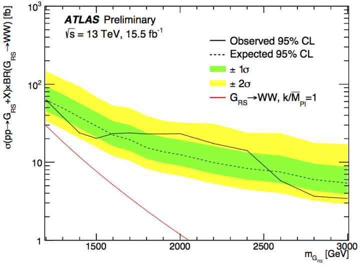
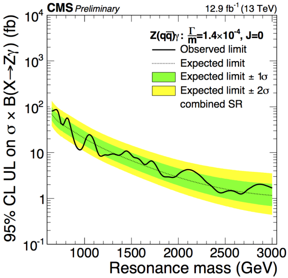
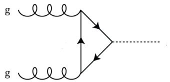
At ICHEP2016 many diboson searches have been presented by both ATLAS and CMS. Here is a couple on “non-diphoton” ones:





Many models studied 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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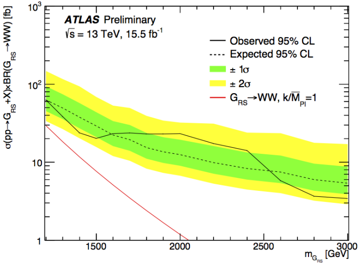
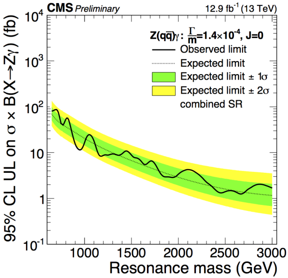
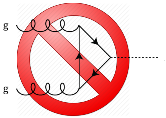
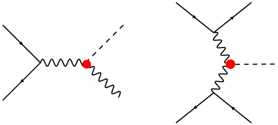




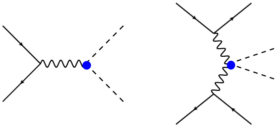
The EW bosons from the models in this talk do not have dim 5 gluon coupling, since the hyperquarks ψ involved are not colored. This leads to a lower cross-section and much weaker exclusion limits for those that don’t couple directly to the top.



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 •

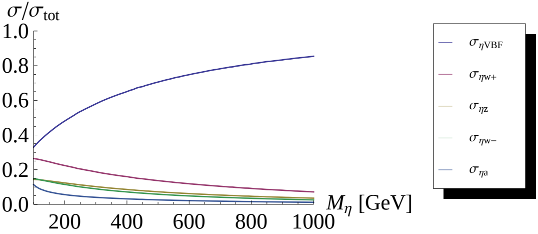


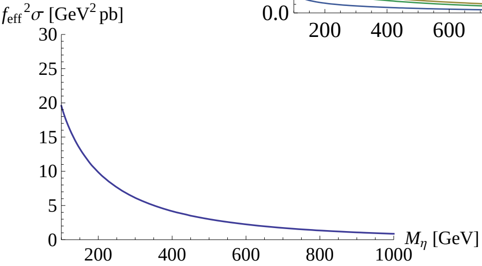
As an example, a particle present in both $SU(4) \times SU(4)'/SU(4)_D$ and $SU(4)/Sp(4)$ that does not mix with the other pNGB is the η

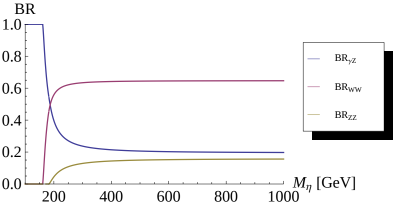
$$S_{\mathrm{WZW}} \supset \frac{\dim(\psi)}{16\pi^2 f} c_\zeta \int \eta \left(\frac{g^2 - g'^2}{2} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + g g' F_{\mu\nu} \tilde{Z}^{\mu\nu} + g^2 W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right) \mathrm{d}^4 x.$$

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

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



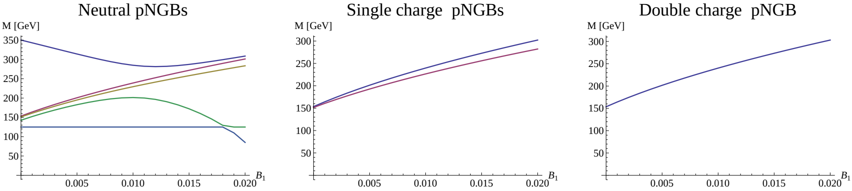




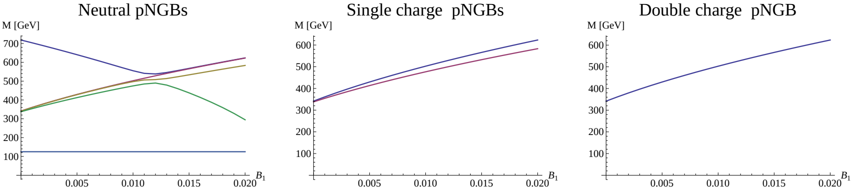
The pNGB potential, and associated mass matrix, is quite model dependent. Here I present, for illustration purpose, the spectrum arising from an effective potential induced by loops in the EW gauge fields, the top and possibly bare hyperquark masses.

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

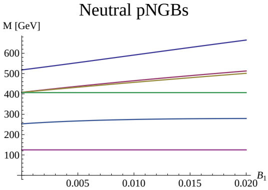
- One linear combination is traded to fix the Higgs vev $v = 246$ GeV. (Or, given f, the fine-tuning parameter).
- A second linear combination is traded for the Higgs mass $m_h = 125$ GeV.
- The third combination is varied and the dependence of the physical masses on it is plotted.

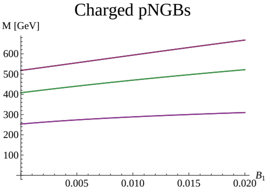


Example of spectrum for the $SU(5)/SO(5)$ model with $f = 800$ GeV

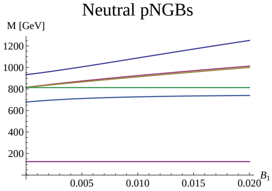


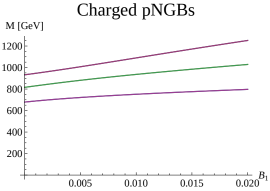
Same as above but with $f = 1600$ GeV





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

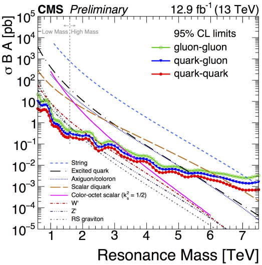
As well as the "usual" top and bottom partners and their friends of charges $\pm 5/3$ (possibly even $\pm 8/3$).

Colored sector:

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

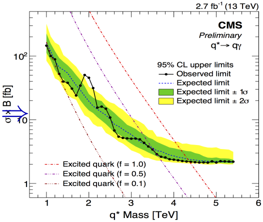
One feature common to all models is the presence of an octet $\mathbf{8}_0$. This octet decays in both di-jet and jet-gamma (jet-Z) channels, since χ carries a non-zero hypercharge.

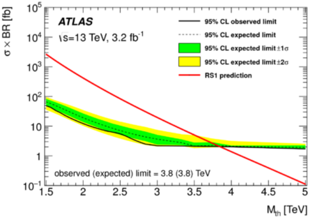
Here the experiments have already probed the multi TeV region.



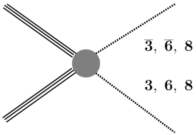
⇐ CMS dijet resonance search.
Relevant for all colored pNGBs.

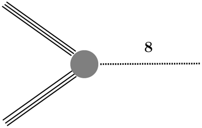
ATLAS and CMS
$j\gamma$ resonance searches. ⇒
Relevant for the octet.

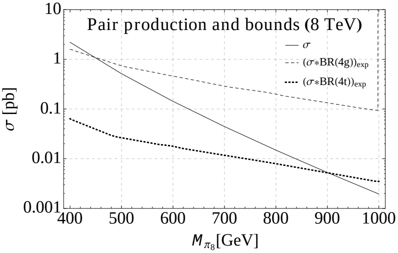


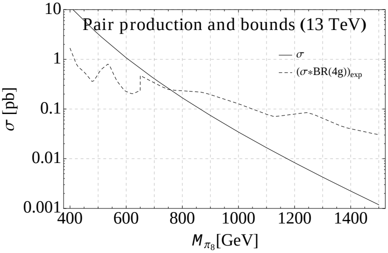


These objects are pair produced with QCD cross-section values depending only on their mass. The octet can also be singly produced by the anomalous coupling via gluon fusion.









Model independent bounds on the octet pair production.

The sextet and triplet are also interesting, since they carry baryon number and the decay $\pi \to qq$ can violate it.

$$T = \psi\chi\psi \;\Rightarrow\; B(\chi) = 1/3 \;\Rightarrow\; B(\pi) = \pm 2/3 \;\Rightarrow\; \Delta B = 0$$
$$T = \chi\psi\chi \;\Rightarrow\; B(\chi) = 1/6 \;\Rightarrow\; B(\pi) = \pm 1/3 \;\Rightarrow\; \Delta B = 1$$

In the second case this leads to $\Delta B = 2$ low energy 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 di-boson decay are governed by the anomaly, e.g. for a:

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

with k coefficients computable from the quantum numbers of the hyperfermions.
They also couple to the top quark:

$$\mathcal{L} \supset iC_t \frac{m_t}{f_a} a\bar{t}\gamma^5 t$$

The coupling with the top quark arises because in the UV we have the coupling between top and top-partners

$$\mathcal{L}_{mix} \supset y_L\, \bar{q}_L \Psi_{q_L} + y_R\, \bar{\Psi}_{t_R} t_R + \text{ h.c.}$$

The top-partners Ψ_{q_L} and Ψ_{t_R} are made of 3 fermions and carry charge under $U(1)_\psi$ and $U(1)_\chi$. We must then assign a charge to the pre-Yukawas $y_{L/R}$

$$y_L \to e^{i n_{L\psi} a_\psi / f} e^{i n_{L\chi} a_\chi / f} y_L, \quad y_R \to e^{i n_{R\psi} a_\psi / f} e^{i n_{R\chi} a_\chi / f} y_R$$

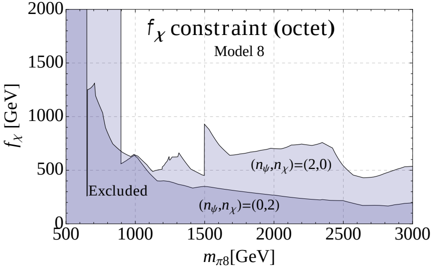
implying, after changing the basis and expanding to first order: ($m_{\text{top}} \propto y_L y_R$)

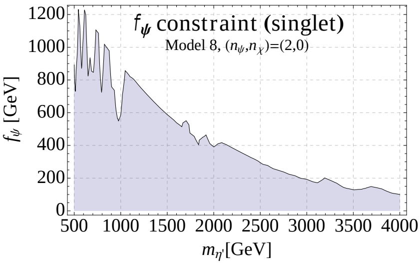
$$\mathcal{L}_{\text{top}} \supset i \frac{m_{\text{top}}}{f} \left(C_t^a a + C_t^{\eta'} \eta' \right) \bar{t} \gamma^5 t.$$

The (dimensionless) couplings k_s, k_B, k_W and C_t can be computed for the specific models under consideration. The remaining parameters are the resonance mass M_a and the decay constant f_a. (We make simplifying assumptions on the scaling of the various f's.)

In the absence of an excess... the strategy is that, for a given model and a given mass, the experimental exclusion limits allow to set a lower limit of the decay constant.

I show some of the results for the $Sp(4)$ model of [Barnard et al. 1311.6562]





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 but with very low production cross-section for those pNGBs not coupling to the top.
- Top partners arise as fermionic trilinears.
- An additional color octet scalar is always present, in some cases also triplets and sextets.
- Multiple irreps lead to the existence of additional composite $U(1)$ ALPs giving rise to potentially interesting di-boson/t-tbar signals.

Additional Slides

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 $a_{\rm UV} > a_{\rm IR}$.

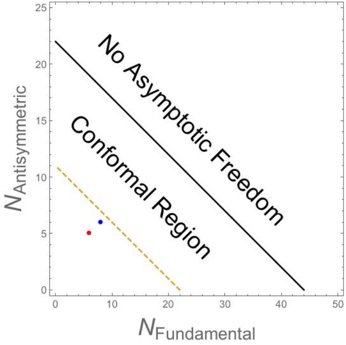
POSSIBLE CONNECTIONS TO THE LATTICE/BOOTSTRAP

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

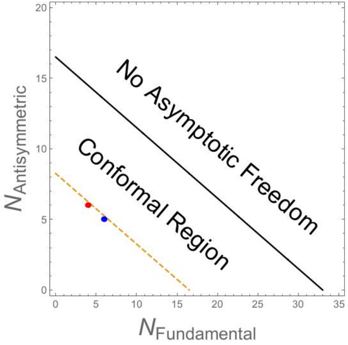
- $SU(4)$ with N_F Fundamentals and N_A Antisymmetric
  (possibly also $SU(5)$, $SU(6)$)
- $Sp(4)$ with N_F Fundamentals and N_A Antisymmetric
- $SO(N)$ with N_F Fundamentals and N_S Spin
  (with $N = 7, 9, 10, 11$)

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
$\bullet$ = "swapped"



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.