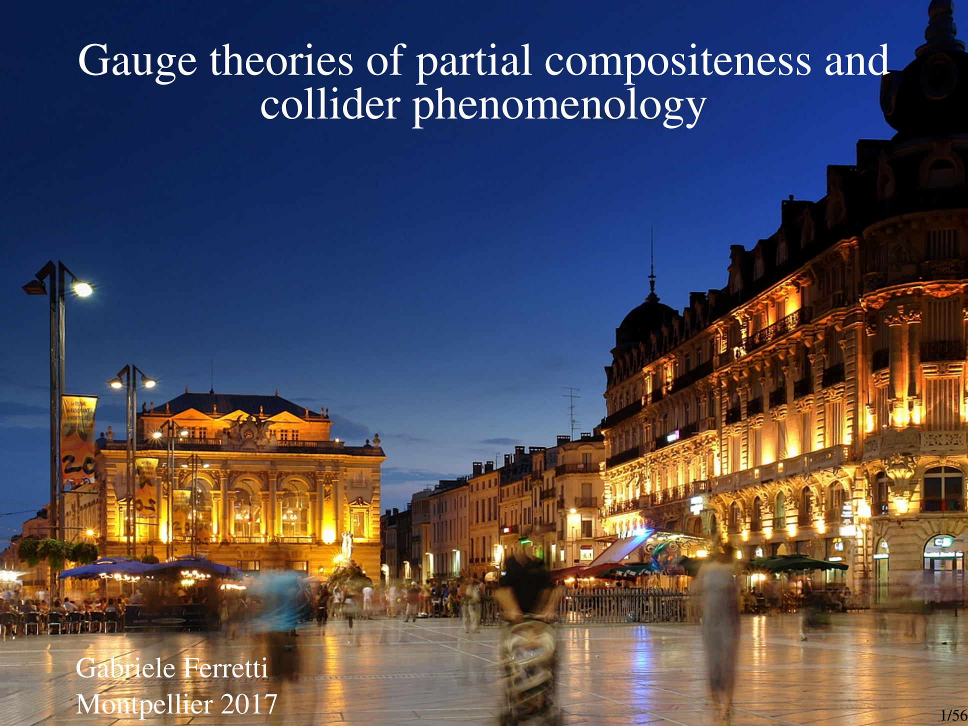
Gauge theories of partial compositeness and collider phenomenology



Gabriele Ferretti
Montpellier 2017

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.

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

- Give an overview of the main idea.
- Present the types of models being considered.
- Discuss few issues about strongly coupled dynamics that could be addressed on the lattice.
- Present some basic phenomenological aspects of these models and point out possible searches at LHC.

OVERVIEW

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

These models have two main features:

- A light Higgs boson arising as a pNGB from $\langle\psi\psi\rangle$.
- Top-partners ($G_{\rm HC}$ 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 additional light states that can be searched at LHC, mainly additional neutral / EW / colored light scalar pNGBs.

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

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

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

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

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

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 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.)

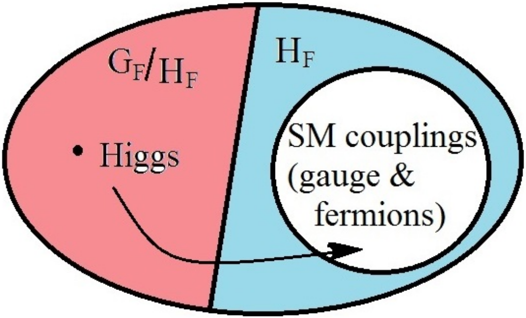
$$\begin{array}{ccc} \mathcal{L}_{\text{UV}} & \longrightarrow & \mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM0}} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \cdots \\ \Lambda_{\text{UV}} \sim 10^4 \text{ TeV} & & \Lambda \sim 10 \text{ TeV} \end{array}$$

I will not attempt to construct such theory and will concentrate on the physics below the ~ 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

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

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	$SU(5)/SO(5)$

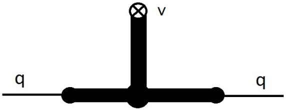
E.g. $SU(4)/SO(4)$ is not acceptable since the pNGB are only in the symmetric irrep $(\mathbf{3}, \mathbf{3})$ of $SO(4) = SU(2)_L \times SU(2)_R$ and thus we do not get the Higgs irrep $(\mathbf{2}, \mathbf{2})$.

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 $G_{\rm HC}$-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

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

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 necessarily 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, unless one uses supersymmetry.

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 is impossible to get all 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 choices of 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.
- $G_{\mathrm{F}} \to H_{\mathrm{F}} \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\text{cus.}}} \supset G_{\mathrm{SM}}$.
- 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. (To avoid rapid proton decay.)

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

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

	G_{HC}	G_{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_{HC}	G_{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 contained both conformal and confining models.

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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 $M_{\mathcal{O}}$.

Thus, in [1610.06591] we narrowed down the list to those which 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
$SO(7)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{SO(6)}U(1)$
$SO(9)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	
$SO(7)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$SO(9)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$Sp(4)$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{Sp(6)}U(1)$
$SU(4)$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$\frac{SU(5)}{SO(5)}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$
$SO(10)$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	
$Sp(4)$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$\frac{SU(4)}{Sp(4)}\frac{SU(6)}{SO(6)}U(1)$
$SO(11)$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$SO(10)$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(6)}{SO(6)}U(1)$
$SU(4)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	
$SU(5)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$

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.

POSSIBLE CONNECTIONS TO THE LATTICE

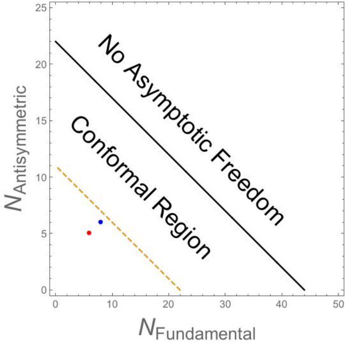
The first questions to be addressed concern the composite sector *in isolation*, before coupling to the SM. Then, the list of models reduces to

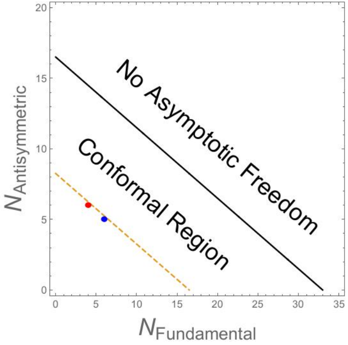
- $SU(4)$ with N_F Fundamentals and N_A Antisymmetric
  (possibly also $SU(5)$, $SU(6)$)
- $Sp(4)$ with N_F Fundamentals and N_A Antisymmetric
- $SO(N)$ with N_F Fundamentals and N_S Spin
  (with $N = 7, 9, 10, 11$)

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

$SU(4)$ case: • $= 1404.7137$
• = "swapped"

$Sp(4)$ case: • $= 1311.6562$
• = "swapped"





Some concrete questions that could be addressed are

- Where does the boundary of the 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?

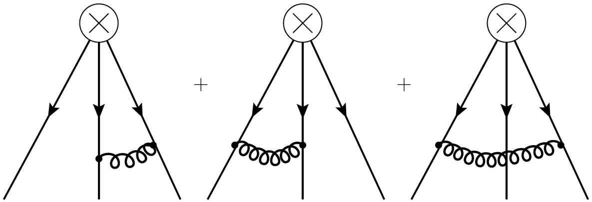
Is it realistic to expect large negative anomalous dimensions for top partners?

Consider three Weyl fermions X, Y and Z belonging to the irreps R_X, R_Y and R_Z such that $R_X \otimes R_Y \otimes R_Z$ or $R_X \otimes \bar{R}_Y \otimes \bar{R}_Z$ contains one (and only one) singlet.

At one loop

$$\gamma(g) = -\frac{g^2}{16\pi^2}\, a$$

(Since $m_t \approx v \left(\frac{\Lambda}{\Lambda_{\mathrm{UV}}}\right)^{2(2+\gamma^*)}$, $a \gg 1$ is "good".)



One finds ([G.F. unpublished], see also [DeGrand and Shamir, 1508.02581]).

Invariant	(s_L, s_R)	a
$XY^\dagger Z^\dagger$	$(1/2, 0)$	$-3C_X + 3C_Y + 3C_Z$
XYZ	$(1/2, 0)$	$C_X+C_Y+C_Z+4\sqrt{C_X^2+C_Y^2+C_Z^2-C_XC_Y-C_XC_Z-C_YC_Z}$
XYZ	$(1/2, 0)'$	$C_X+C_Y+C_Z-4\sqrt{C_X^2+C_Y^2+C_Z^2-C_XC_Y-C_XC_Z-C_YC_Z}$
$XY^\dagger Z^\dagger$	$(1/2, 1)$	$C_X - C_Y - C_Z$
XYZ	$(3/2, 0)$	$-C_X - C_Y - C_Z$

Where C_i are the second Casimirs of R_i. In the cases of interest two of the Casimirs are always the same (e.g. $C_X = C_Z$), so

$$C_X+C_Y+C_Z\pm 4\sqrt{C_X^2+C_Y^2+C_Z^2-C_XC_Y-C_XC_Z-C_YC_Z} = \begin{cases} -2C_X+5C_Y \\ 6C_X-3C_Y \end{cases}$$

Plugging in the numbers for the various models gives a:

	$(1/2,0)$	$(1/2,1)$	$(3/2,0)$
M1	27/8, 39/8, 9/2	-9/8, -3/2	-21/16
M2	15/2, 11/2, 6	-5/2, -2	-9/4
M3	27/8, 39/8, 9/2	-9/8, -3/2	-21/16
M4	15/2, 11/2, 6	-5/2, -2	-9/4
M5	3/2, 15/2, 6	-1/2, -2	-5/4
M6	15/4, 35/4, 15/2	-5/4, -5/2	-15/8
M7	81/8, 45/8, 27/4	-27/8, -9/4	-45/16
M8	3/2, 15/2, 6	-1/2, -2	-5/4
M9	105/8, 45/8, 15/2	-35/8, -5/2	-55/16
M10	81/8, 45/8, 27/4	-27/8, -9/4	-45/16
M11	15/4, 35/4, 15/2	-5/4, -5/2	-15/8
M12	18/5, 66/5, 54/5	-6/5, -18/5	-12/5

What to make of it?

- Independent on N_ψ, N_χ so I can go inside the conformal window.
- Agrees with [1508.02581]. Here $a \to \frac{1}{4}a$ for $G_{\mathrm{HC}} = SO(n)$.
- $a > 1$ (sometimes $a \gg 1$) for spin $1/2$ operators means that anomalous dimensions $-(g^{*2}/16\pi^2) \times \; a \approx -2$ for top partners are not unrealistic for a moderately strongly coupled conformal fixed point g^*. (To be checked case by case.)
- The higher spin operators show the opposite trend ($a < 0$).
- Notice however that the largest anomalous dimension occurs often for the color sextet, not the triplet.

PHENOMENOLOGY

- Electro-Weak sector: pNGBs associated to EWSB.
- Strong sector: Colored pNGBs and top partners.
- An additional light ALP: 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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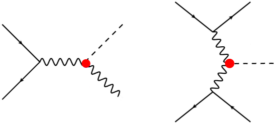
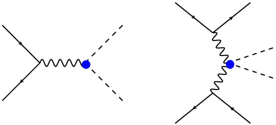
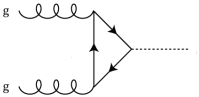
In this case the single production modes are associated production and VBF both via the anomalous coupling •



Pair production is instead driven by the renormalizable coupling •



There is also a model dependent coupling to gluons via tops.

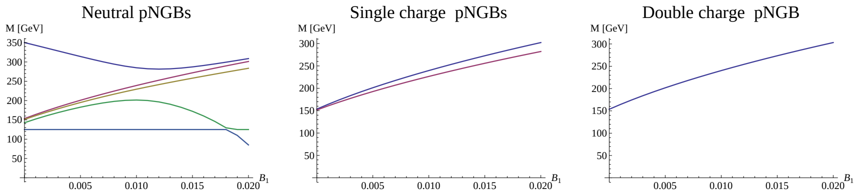


Mass spectrum

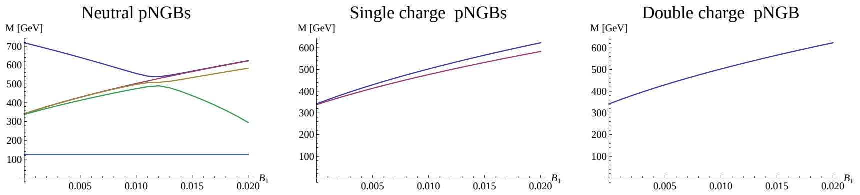
The pNGB potential, and associated mass matrix, is quite model dependent. Here I present, for illustration purpose, the spectrum arising from an effective potential induced by loops in the EW gauge fields, the top and possibly bare hyperquark masses.

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

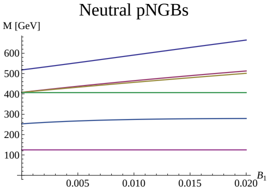
- One linear combination is traded to fix the Higgs vev $v = 246$ GeV. (Or, given f, the fine-tuning parameter).
- A second linear combination is traded for the Higgs mass $m_h = 125$ GeV.
- The third combination is varied and the dependence of the physical masses on it is plotted.

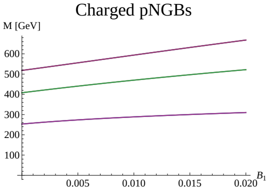


Example of spectrum for the $SU(5)/SO(5)$ model with $f = 800$ GeV

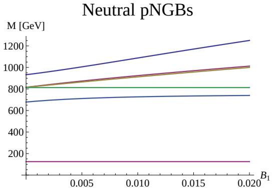


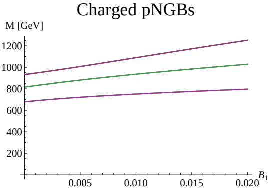
Same as above but with $f = 1600$ GeV





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 $\pm 5/3$.

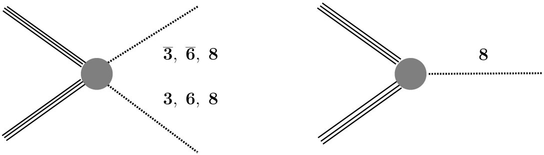
Colored sector:

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

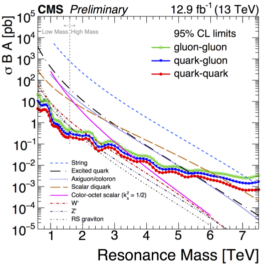
One feature common to all models is the presence of an octet $\mathbf{8}_0$.

These objects can be pair produced at LHC with QCD-type cross-sections depending only on their masses.

The octet can also be singly produced by the anomalous coupling via gluon fusion.

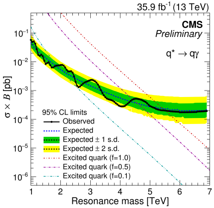


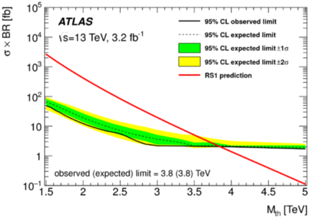
Here the experiments have already probed the multi TeV region for some (other) models.



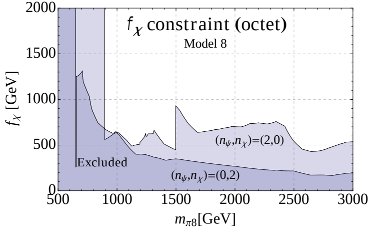
$\Leftarrow$ CMS dijet resonance search.
Relevant for all colored pNGBs.

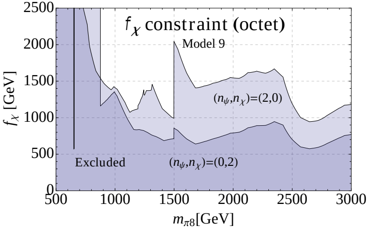
ATLAS and CMS
$j\gamma$ resonance searches. $\Rightarrow$
Relevant for the octet.





Combining all searches (up to and including ICHEP 2016) we obtained the following bounds for the octet for a couple of illustrative cases (M8 and M9).





The sextet and triplet are also interesting, since they carry baryon number and the coupling πqq 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 effective interactions inducing $n - \bar{n}$ oscillations and di-nucleon decay (but not proton decay).

An additional light ALP:

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 (light), the orthogonal one to η' (heavy).

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

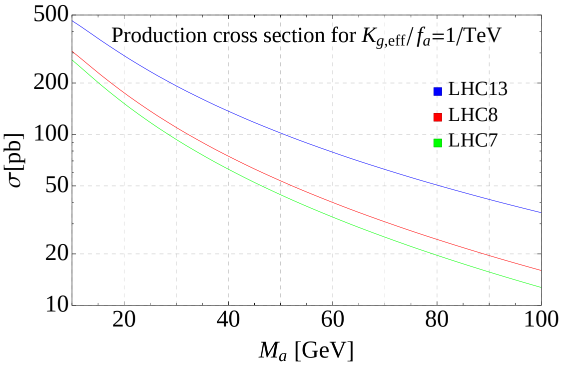
Its production and decay are governed by the anomaly and by the coupling to the heavy SM-fermions

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

with K_V and C_f coefficients computable from the quantum numbers of the hyperfermions. (See [1610.06591] and [1710.11142] including top loops.)

Such 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. (And also, to a lesser extent, various others processes involving heavy quarks.)



EXISTING BOUNDS

[Bauer, Neubert and Thamm, 1708.00443] have presented a comprehensive study of the current indirect limits for such objects. Our models easily fulfill all these bounds, basically due to the loop suppression of the anomaly coefficients. The only one relevant for these models is the contribution to the Higgs BSM decays [ATLAS and CMS 1606.02266].

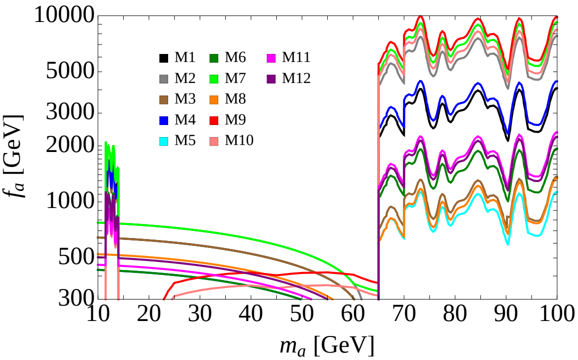
[Mariotti, Redigolo, Sala and Tobioka, 1710.01743] presented bounds from di-photon cross-section measurements [ATLAS 1211.1913, CMS 1704.03829, CMS 1405.7225]. When interpreted for our models they give some constraints in the low-mass region for a few models.

[ATLAS 1407.6583, CMS-PAS-HIG-17-013] are direct di-gamma searches constraining the $m_a > 65, 70$ GeV region.

[ATLAS-CONF-2011-020, CMS 1206.6326] provide constraints for $m_a < 14$ GeV from di-muon searches.

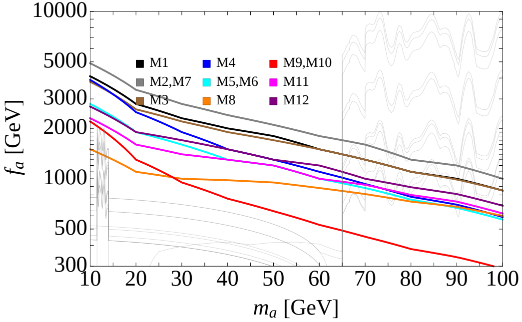
All these bounds are summarized as follows for the ALP in models M1 ... M12 (for fun we named it a Timid Composite Pseudo-scalar: TCP).

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
K_g	-7.2	-8.7	-6.3	-11.	-4.9	-4.9	-8.7	-1.6	-10.	-9.4	-3.3	-4.1
K_W	7.6	12.	8.7	12.	3.6	4.4	13.	1.9	5.6	5.6	3.3	4.6
K_B	2.8	5.9	-8.2	-17.	.40	1.1	7.3	-2.3	-22.	-19.	-5.5	-6.3
C_f	2.2	2.6	2.2	1.5	1.5	1.5	2.6	1.9	.70	.70	1.7	1.8
f_a/f_ψ	2.1	2.4	2.8	2.0	1.4	1.4	2.4	2.8	1.2	1.5	3.1	2.6



PROJECTED REACH

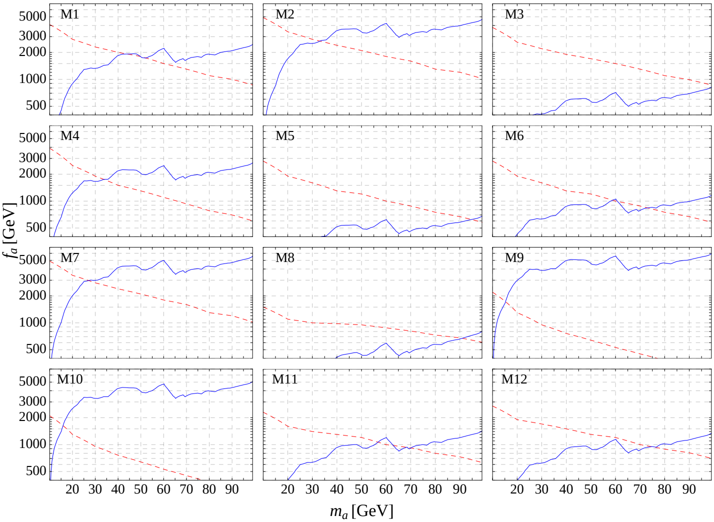
In [1710.01743] we estimated the reach in the channel $pp \to a \to (\tau \to e\nu\bar{\nu})\,(\tau \to \mu\nu\bar{\nu})$ after $300\ \mathrm{fb}^{-1}$ at 13 TeV.



One can also use [1710.01743] to estimate the reach in the $pp \to a \to \gamma\gamma$ channel.

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

There is a nice complementarity between the $\tau\tau$ and $\gamma\gamma$ channel in both energy range and type of models that would allow to probe this class of theories for f_a in the multi-TeV region.



CONCLUSIONS

- Realizing partial compositeness via ordinary 4D gauge theories with 2 irreps provides a self contained concrete 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 $SU(4)/Sp(4)$.
- Top partners arise as fermionic trilinears. In the simplest models, the remaining fermions do not have a partner and couple bi-linearly to the Higgs.
- An additional color octet scalar is always present, in some cases also triplets and sextets.
- Multiple irreps necessarily lead to the existence of a light timid composite pseudo-scalar a giving rise to potentially interesting signatures a LHC in the $\gamma\gamma$ or $\tau^+\tau^-$ channels.

META-CONCLUSIONS

- By the end of Run-II the LHC will have basically reached the upper limit of its discovery range. Given the current negative results it is becoming increasingly possible that no top-partner will be discovered, although I personally still want to wait a couple of years before loosing hope.
- If that scenario comes to pass, the focus will likely shift more and more on precision measurements, indirectly sensitive to particles out of the discovery range. However we should not forget light and weakly-coupled objects that occur in many BSM scenarios and require high luminosity and dedicated search strategies.
- Gauge theories of partial compositeness are one such scenario and, while nobody should take them too seriously, (I certainly don't), they do provide some concrete benchmark points and, with the help of the lattice, models where the LEC of the Higgs potential are calculable, despite being "incalculable" from the EFT point of view.