Recent developments in partial compositeness.

Gabriele Ferretti

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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,
- arXiv:1902.06890 G. Cacciapaglia, G.F, T. Flacke and H. Serodio,
- arXiv:1905.08273 D. Buarque Franzosi and G.F.,
- arXiv:1907.05929 R. Benbrik *et al.*

• Thanks to D. Karateev, A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini, H. Serodio, D. Buarque Franzosi and the SHIFT collaboration.

In a nutshell, Partial Compositeness is the attempt to explain the EW scale and the associated hierarchy by taking

- The Higgs boson to be a pseudo Nambu-Goldstone boson (explaining its lightness)
- The top quark to mix with another heavy fermion (explaining its heaviness)

PLAN:

- General Remarks
- Connections to Lattice Gauge Theory
- Phenomenology: Top partner decays and additional Alps

GENERAL REMARKS

There are various approaches to Partial Compositeness

- Just postulate the symmetry structure G/H and use CCWZ

$$\Sigma \equiv \mathrm{e}^{i\Pi/f} \to g\Sigma h^{-1}, \quad \Psi \to h\Psi, \quad q \to gq$$

- Restrict the choices (introducing model dependence) by focusing on the computability of the Higgs potential
    - Holography, multi-site deconstruction... (perturbative)
    - 4D gauge theory (lattice)

  In principle, the two approaches are dual to each other (at least at large N). In practice, one of the two sides is often “sharper” than the other.

I) All models except the minimal $SO(5)/SO(4)$ have additional pNGBs. Conditional to some sort of composite Higgs scenario being true, the existence of additional light scalars is generic.

Also, in the 4D gauge theory realizations, the most straightforwardly realized cosets are not of the above minimal type.

II) Problems with $\bar{Q}_L \mathcal{O} t_R$ led people to study $\bar{Q}_L \mathcal{O}'_R + \bar{\mathcal{O}}'_L t_R$.

In holography, it is natural to have partners for all SM fermions, but this need not be the case in strongly coupled gauge theories.

III) In the simplest models where the Higgs potential can be computed perturbatively, the mass of the top partner is required to be small. This can be somehow relaxed in more complex models and at strong coupling (still requiring some fine tuning, of course).

IV) In some phenomenological models, the t_R is a singlet of the full $SU(2)_L \times SU(2)_R$, thus allowing it to be chosen as fully composite if one desires (it fills the irrep.). However, from the gauge theory point of view, it is really hard to come up with chiral bound states of this type.

So... All of these caveats make it worthwhile to also consider plain 4D gauge theories as underlying models of partial compositeness, if anything, for the heuristic value of pointing at less investigated alternatives:

Perhaps there are additional pNGBs?
Perhaps not all SM fermions have partners?
Perhaps the partners are (a bit) heavier than expected?
Perhaps a fully composite t_R is less likely?

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 $\mathcal{L}_{\text{int.}}$

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

For a set of n hyper-fermions ψ in a irrep. 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, we couple a SM fermion q linearly to a $G_{\rm HC}$-neutral fermionic bound state, $\mathcal{O}$. This requires additional hyper-fermions χ carrying color, schematically $\mathcal{O} \approx \psi\chi\psi$ or $\chi\psi\chi$.

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

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

We see that, to get the right top quark mass, we need $\gamma \approx -2$ (since $\Lambda \ll \Lambda_{\rm UV}$). 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.

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

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

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ 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.
- $G_{\text{F}} \to H_{\text{F}} \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\text{cus.}}} \supset G_{\text{SM}}$.
- The MAC should not break neither G_{HC} nor $G_{\text{cus.}}$.
- G_{SM} free of 't Hooft anomalies. (We need to gauge it.)
- $G_{\text{F}}/H_{\text{F}} \ni (\mathbf{1}, \mathbf{2}, \mathbf{2})_0$ 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.)
- There is some amount of matter obeying the above requirements for which the G_{HC} theory is outside the conformal window.

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

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At Λ some fermions decouple reducing N_ψ, N_χ. The theory confines and breaks chiral symmetry. $\mathcal{O}$ creates a (light?) composite fermion $M_{\mathcal{O}}$.

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

<table>
<tr><th>G_{HC}</th><th>ψ</th><th>χ</th><th>$G_{\text{F}}/H_{\text{F}}$</th></tr>
<tr><td>$SO(7)$</td><td>$5\times\mathbf{F}$</td><td>$6\times\mathbf{Spin}$</td><td rowspan="4">$\frac{SU(5)}{SO(5)}\,\frac{SU(6)}{SO(6)}\,U(1)$</td></tr>
<tr><td>$SO(9)$</td><td>$5\times\mathbf{F}$</td><td>$6\times\mathbf{Spin}$</td></tr>
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<tr><td>$SU(4)$</td><td>$5\times\mathbf{A}_2$</td><td>$3\times(\mathbf{F},\overline{\mathbf{F}})$</td><td rowspan="2">$\frac{SU(5)}{SO(5)}\,\frac{SU(3)\times SU(3)'}{SU(3)_D}\,U(1)$</td></tr>
<tr><td>$SO(10)$</td><td>$5\times\mathbf{F}$</td><td>$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$</td></tr>
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<tr><td>$SO(11)$</td><td>$4\times\mathbf{Spin}$</td><td>$6\times\mathbf{F}$</td></tr>
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</table>

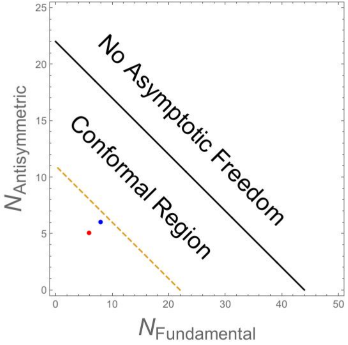
CONNECTIONS TO LATTICE GAUGE THEORY

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

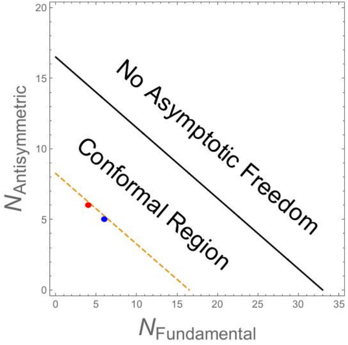
- $SU(4)$ with N_F Fundamentals and N_A Antisymmetric (possibly also $SU(5)$)
- $Sp(4)$ with N_F Fundamentals and N_A Antisymmetric
- $SO(N)$ with N_F Fundamentals and N_S Spin (with $N = 7, 9, 10, 11$)

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

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



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



Some concrete questions that can be addressed are

- Where does the boundary of the conformal window start?
- For models inside the window, can we find an operator $\mathcal{O} \approx \psi\chi\psi$ (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?
- Can we estimate the top Yukawa coupling?

Some of these questions have already started to be answered.

For $G_{\rm HC} = SU(4)$: USQCD collaboration

[Ayyar, DeGrand, Golterman, Hackett, Jay, Neil, Shamir, Svetitskly, 1710.00806, 1801.05809, 1812.02727]

For $G_{\rm HC} = Sp(4)$: SUNBIRD, HPC clusters at PNU and NCTU, CSD3 cluster

[Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino, 1710.07043, 1712.04220, 1811.00276, 1909.12662]

For $G_{\rm HC} = SO(N)$: Nothing of direct relevance to PC yet.

Just to put it in perspective, as of November 2019:

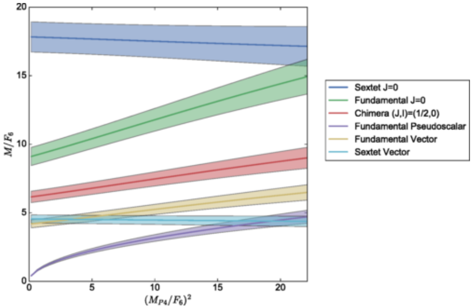
`f t SU and t lattice` 1357 hits

`f t Sp and t lattice` 6 hits

`f t SO and t lattice` 41 hits

$G_{\text{HC}} = SU(4)$ has been studied with (counting Weyl) $N_{\mathbf{6}} = 4$ (5 needed) and $N_{\mathbf{4}} = 4$ (6 needed).

For this theory there is clear evidence of confinement and "chiral" symmetry breaking with a mass spectrum [1801.05809]



The "chimera" states are the top-partners with a mass $m \approx 6.2\, F_6$ in the chiral limit (thus EWPT bounds on the pNGB decay constant F_6 puts them well out of reach of LHC). Both of the vector mesons (constructed with ψ or χ) are lighter.

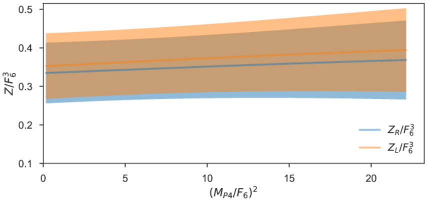
What is more worrisome is the recent computation of the baryon matrix element [1812.02727] (but without running!)

$$y_t = \left(\frac{g^2_{\rm EHC}}{\Lambda^2_{\rm EHC}}\right)^2 \frac{Z_L Z_R}{M_B F_6}$$

where

$$\langle {\rm vac}|\mathcal{O}^\alpha_{L,R}(0)|T,s,\mathbf{0}\rangle = Z_{L,R}u^\alpha(s,\mathbf{0})$$

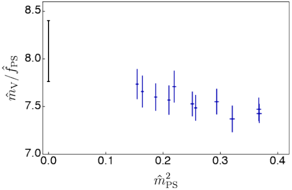
$|T,s,\mathbf{0}\rangle$ being the top-partner and the overlaps are found to be $Z_{L,R} \approx 0.35\, F_6^3$ in the chiral limit. (Compare with $Z \approx 7 f_\pi^3$ in QCD.)

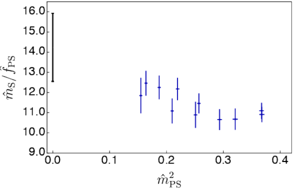


Thus $y_t \approx 0.02 \left(\frac{g^2_{\rm EHC}F_6^2}{\Lambda^2_{\rm EHC}}\right)^2$. Can large anomalous dimensions come to the rescue?

$G_{\mathrm{HC}} = Sp(4)$ has been studied with (conting Weyl) $N_{\mathbf{4}} = 4$ (4 needed) and any *quenched* $N_{\mathbf{5}}$ (6 needed) in [1811.00276]. or with only $N_{\mathbf{4}} = 4$ more recently [1909.12662] with better precision.

Also for this theory there is clear evidence of confinement and "chiral" symmetry breaking. The mass spectrum has been computed, so far only for the bosonic states. From





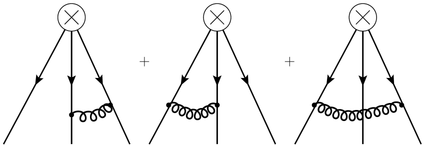
they estimate $M_V \approx 8.08 f_{PS}$ and $M_S \approx 14.2 f_{PS}$ in the chiral limit, (I only give central values), which unfortunately puts us outside the reach of LHC where $f_{PS} > 800$ GeV.
Similar results can be obtained for the $\chi \in \mathbf{5}$.

Is it realistic to expect large negative anomalous dimensions for top partners? Skepticism was expressed in [Pica and Sannino 1604.02572] but using QCD as a template. We did the computation for the actual theories at hand [Buarque Franzosi and G.F. 1905.08273].

Define:

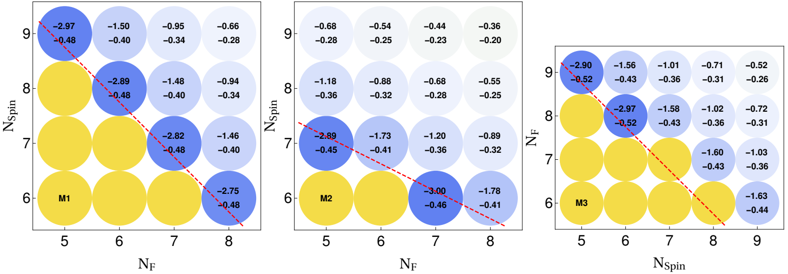
$$\gamma^* = \frac{\alpha_s^*}{4\pi}\, a \quad \text{where} \quad \beta(\alpha_s^*) = 0$$

Since $m_t \approx v \left(\frac{\Lambda}{\Lambda_{\mathrm{UV}}}\right)^{2(2+\gamma^*)}$, $a \ll 0$ is "good". (α_s^* depends of course on the model, the loops, N_ψ, N_χ and, for perturbation theory to be trusted, must be $< 4\pi$.)

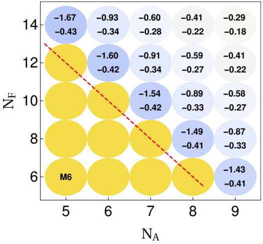


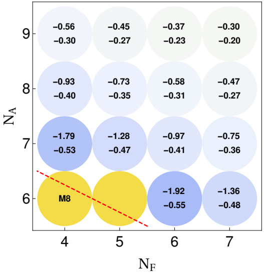
For a we find [1905.08273] (partial earlier results can be found in [DeGrand and Shamir, 1508.02581]).

	top-partners $(1/2,0)$	other $(1/2,0)$	$(1/2,1)$	$(3/2,0)$
M1	-27/8, - 9/2	-39/8	9/8, 3/2	33/8
M2	-11/2, -6	-15/2	5/2, 2	13/2
M3	-39/8, -9/2, -27/8		9/8, 3/2	33/8
M4	-11/2, -6, -15/2		5/2, 2	13/2
M5	-3/2, -6	-15/2	1/2, 2	9/2
M6	-15/4, -15/2	-35/4	5/4, 5/2	25/4
M7	-45/8, -27/4	-81/8	27/8, 9/4	63/8
M8	-15/2, -6, -3/2		1/2, 2	9/2
M9	-45/8, -15/2	-105/8	35/8, 5/2	75/8
M10	-45/8, -27/4, -81/8		27/8, 9/4	63/8
M11	-35/4, -15/2, -15/4		5/4, 5/2	25/4
M12	-66/5, -54/5, -18/5		6/5, 18/5	42/5
	-24/5, -36/5	-72/5	24/5 12/5	48/5



Models M1, M2 and M3 and their neighbours with N_X representing the number of Weyl fermions in the X representation. Yellow circles represent potentially *confining* models whereas blue circles represent models likely to be in the *conformal* window, with the estimated maximal and minimal value of γ^* displayed. The red dashed curve indicates the "conformal house" [0711.3745] prescription.





Ironically, models M6 and M8, which are the two most well studied, are those with the smallest anomalous dimensions (in absolute value). I don’t think we should read too much into it however, given the roughness of the approximation.

PHENOMENOLOGY

I just want to point to two recent developments

- Additional decay modes of top partners
- The presence of light(-ish) ALPs

Additional decay modes of top partners

The presence of additional pNGBs modifies the BR of top partners introducing additional decay channels to the usual three $T \to t\,Z$, $T \to t\,h$, $T \to b\,W$ [1506.05130, 1506.05110, 1803.11286, 1812.11286].

In particular, [G. Cacciapaglia, T. Flacke, M. Park and M. Zhang 1908.07524] studied $T \to t\,S,\ S \to g\,g$ and $T \to t\,S,\ S \to b\,\bar{b}$.

We [SHIFT collaboration 1907.05929] studied instead $T \to t\,S,\ S \to \gamma\,Z$ and $T \to t\,S,\ S \to \gamma\,\gamma$.

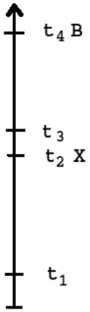
A concrete case (pointed out in [Bizot, Cacciapaglia and Flacke 1803.00021] as having a naturally large $T \to t\,S$ branching fraction) is the EFT with

- pNGBs $\Sigma \in SU(4)/Sp(4)$
- one fermionic partner $\Psi \in \mathbf{5}$ of $Sp(4)$
- spurions $Q_L,\ t_R \in \mathbf{6}$ of $SU(4)$. (Q_L fit of course into the bi-doublet of the $SU(2)_L \times SU(2)_R$ subgroup, while t_R is taken in the singlet of the $\mathbf{6} \to \mathbf{5} + \mathbf{1}$ decomposition of $SU(4) \to Sp(4)$.
- We assume $S \in \Sigma$ fermiophobic pseudoscalar with decays into di-boson only.

In this notation, the lagrangian becomes (ignoring the b mass).

$$\mathcal{L} = y_L f \,\mathrm{tr}\left(\bar{Q}_L \Sigma \Psi_R \Sigma^T\right) + y_R f \,\mathrm{tr}\left(\Sigma^* \bar{\Psi}_L \Sigma^\dagger t_R\right) - M \,\mathrm{tr}\left(\bar{\Psi}_L \Psi_R\right) + \text{ h.c.}$$
$$+ (S/v)(\alpha_2 \tilde{k}_W W_{\mu\nu} \tilde{W}^{\mu\nu} + \alpha_1 \tilde{k}_B B_{\mu\nu} \tilde{B}^{\mu\nu})$$

I spare you the singular-value decomposition of the top mass matrix and jump to the spectrum and the decay modes.



In this notation, the lagrangian becomes (ignoring the b mass).

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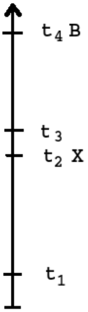

t_1 is the 173 GeV top with modified higgs couplings and no $\bar{t}_1 t_1 S$ coupling.

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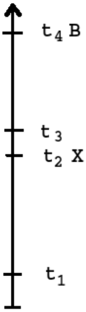


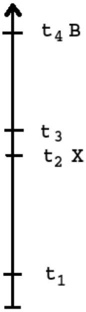
$t_2 \to t_1\, S$ and $X \to\ t_1\, W$ with 100% BR.

t_1 is the 173 GeV top with modified higgs couplings and no $\bar{t}_1 t_1 S$ coupling.

In this notation, the lagrangian becomes (ignoring the b mass).

$$
\begin{aligned}
\mathcal{L} \;=\; & y_L f \,\mathrm{tr}\left(\bar{Q}_L \Sigma \Psi_R \Sigma^T\right) + y_R f \,\mathrm{tr}\left(\Sigma^* \bar{\Psi}_L \Sigma^\dagger t_R\right) - M \mathrm{tr}\left(\bar{\Psi}_L \Psi_R\right) + \text{ h.c.} \\
& + (S/v)(\alpha_2 \tilde{k}_W W_{\mu\nu} \tilde{W}^{\mu\nu} + \alpha_1 \tilde{k}_B B_{\mu\nu} \tilde{B}^{\mu\nu})
\end{aligned}
$$

I spare you the singular-value decomposition of the top mass matrix and jump to the spectrum and the decay modes.



t_3 is $\mathcal{O}(v^2/f^2)$ heavier with all decay modes.
$t_2 \to t_1\, S$ and $X \to\; t_1\, W$ with 100% BR.

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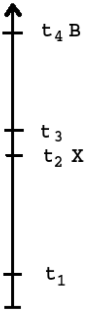


t_4 and B are heavier by $\sqrt{M^2 + y_L^2 f^2}/M$.

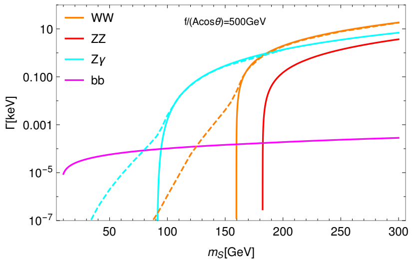
t_3 is $\mathcal{O}(v^2/f^2)$ heavier with all decay modes.

$t_2 \to t_1\, S$ and $X \to t_1\, W$ with 100% BR.

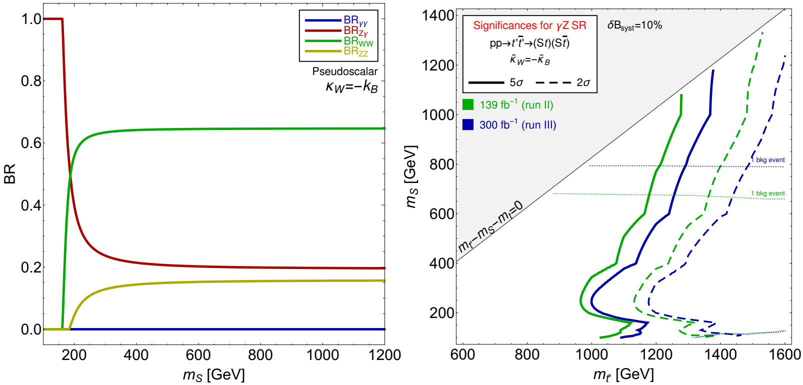
t_1 is the 173 GeV top with modified higgs couplings and no $\bar{t}_1 t_1 S$ coupling.

The current limit [ATLAS 1807.11883] on $m_{t_2} = m_X \equiv M$ is from searches for $X \to tW$. Double production gives $M > 1.2$ TeV. Single production via $C\,XWt$ becomes important for $C > 0.3$. For $C = 1$ the bound becomes $M > 1.64$ TeV.

Both can be improved by looking at the $t_2 \to t_1\,S$ channel, followed by S decay. (We published the study of pair production only.)

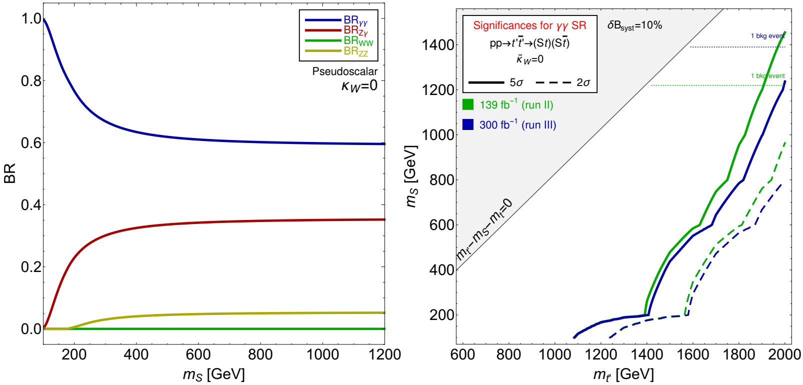


Note that both $S \to \gamma\,\gamma$ and $S \to \bar{t}\,t$ are suppressed in this model.



Left panel: BR of S resonance into EW bosons for the pseudoscalar case in the photophobic case ($\tilde{k}_B = -\tilde{k}_W$). Right panel: LHC reach for different LHC luminosities. [SHIFT collaboration 1907.05929]

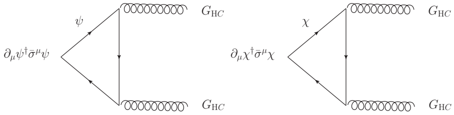
For the *W*-phobic case (not as well motivated!) we estimate the LHC reach using the more sensitive di-photon analysis.



Left panel: BR of *S* resonance into EW bosons for the pseudoscalar case in the *W*-phobic case ($\tilde{k}_W = 0$). Right panel: LHC reach for different LHC luminosities. [SHIFT collaboration 1907.05929]

An additional light ALP:

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



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

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

is associated to a (light, possibly below 100 GeV), the orthogonal one to η' (heavy).

The ratio $\tan\zeta = \frac{q_\chi f_{a_\chi}}{q_\psi f_{a_\psi}}$ allows to rotate from the unphysical a_ψ and a_χ fields to the (almost) mass eigenstates

$$a = \cos\zeta a_\psi + \sin\zeta a_\chi \quad \text{and} \quad \eta' = -\sin\zeta a_\psi + \cos\zeta a_\chi .$$

- The true mass eigenstates might require $\zeta \to \zeta + \delta\zeta$ if there are mass terms $\frac{1}{2}m_\psi^2 a_\psi^2 + \frac{1}{2}m_\chi^2 a_\chi^2$, coming from hyperquarks bare masses, in addition to the topological mass $\frac{1}{2}M^2(-\sin\zeta a_\psi + \cos\zeta a_\chi)^2$.
- f_{a_ψ} and f_{a_χ} are the "decay constants" for $U(1)_\psi$ and $U(1)_\chi$.

$$q_\psi \psi^\dagger \bar\sigma^\mu \psi + q_\chi \chi^\dagger \bar\sigma^\mu \chi \quad \propto \quad q_\psi f_{a_\psi} \partial^\mu a_\psi + q_\chi f_{a_\chi} \partial^\mu a_\chi$$

They can be related to the decay constants of the non-abelian part by a factor $\sqrt{N_\chi}$ and $\sqrt{N_\psi}$ in the large-N limit.

One can also define $f_a = \sqrt{\frac{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}{q_\psi^2 + q_\chi^2}}$

The charges also determine the couplings with the fermions (e.g. top quark) via a spurion analysis. E.g.

$$y_L \psi\chi\psi Q_L + y_R t_R^c \psi\chi\psi$$

means that $y_L,\ y_R$, and thus $m_t \propto y_L y_R$, carry $U(1)$ charges. So, the mass term must be dressed with powers of $e^{ia_\psi/f_{a_\psi}}$ and $e^{ia_\chi/f_{a_\chi}}$ leading to

$$\mathcal{L} \supset -m_t\, e^{-iC_t a/f_a}\, t_R^c t_L + \text{ h.c.} = -m_t \bar{t}t + i\frac{C_t m_t}{f_a}\, a\bar{t}\gamma^5 t + \mathcal{O}(a^2)$$

for some C_t that can be computed from the charges. This is a genuinely different coupling than the derivative one (even using the e.o.m. backwards) since it denotes an explicit breaking.

The coupling to the vector bosons (e.g. gluon) can be written as

$$\frac{g_s^2 K_g}{16\pi^2 f_a} a G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$

where K_g gets a contribution from the ABJ anomaly of the χ current and the (non-anomalous) SM fermion loops.

Finally, there are loop induced $h\,a\,a$ and $h\,a\,Z$ couplings as well.

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

EXISTING BOUNDS

[Bauer, Neubert and Thamm, 1708.00443] have presented a comprehensive study of the current indirect limits for such objects. 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].

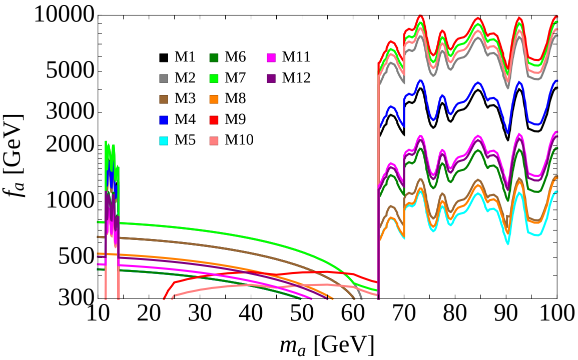
[ATLAS 1407.6583, CMS-PAS-HIG-17-013] are direct di-gamma searches constraining the $m_a > 65, 70$ GeV region.

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

[LHCb1710.02867] dark photon search re-casted for pseudo-scalars a la [Haisch, Kamenik, Malinauskas, Spira 1802.02156] may provide the strongest bounds between 10-60 GeV. (In progress.)

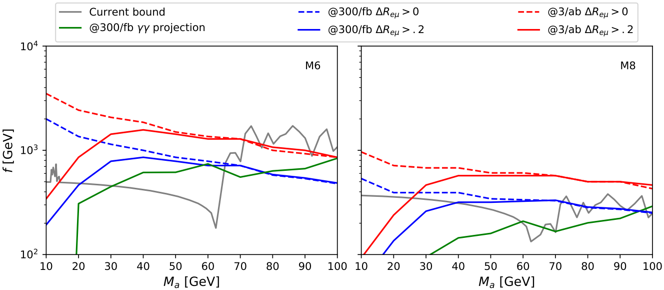
These bounds (except LHCb) are summarized as follows for the ALP in models M1 ... M12.

	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 HL-HE BSM Yellow Report [1812.07831] we estimated the reach in the channel $pp \to a \to (\tau \to e\nu\bar{\nu})\,(\tau \to \mu\nu\bar{\nu})$ for the two models (M6 and M8) that are being studied on the lattice.



One can also use [1710.01743] to estimate the reach in the $pp \to a \to \gamma\gamma$ channel, which turns out to be competitive for other models.

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

CONCLUSIONS

- Realizing partial compositeness via ordinary 4D gauge theories 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.
  - Additional decay modes of top partners are always present, in some cases dominate.
  - Multiple irreps necessarily lead to the existence of a light pseudo-scalar a giving rise to potentially interesting signatures at LHC in the $\tau^+\tau^-$, $\gamma\gamma$, $\mu^+\mu^-$ and $B\bar{B}$ channels.

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Thank you for your attention!