

# Models of partial compositeness in four dimensions

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(See also Avik Banerjee's talk)

- ▶ Pioneering papers:
  - **Composite Higgs:** D. B. Kaplan and H. Georgi, Phys. Lett. B 136 (1984) 183.
  - **Partial compositeness:** D. B. Kaplan, Nucl. Phys. B 365 (1991) 259.
- ▶ Our work: (trying to combine the two) 2302.11598, 2203.07270, 2202.00037, 2106.12615, 1907.05929, 1710.11142, 1610.06591, 1604.06467, 1404.7137, 1312.5330 *with various combinations of:* A. Banerjee, A. Belyaev, D. B. Franzosi, G. Cacciapaglia, H. Cai, X. Cid Vidal, A. Deandrea, T. Flacke, B. Fuks, D. Karateev, M. Kunkel, S. Moretti, L. Panizzi, A. Parolini, W. Porod, H. Serodio, C. Vázquez Sierra and members of the SHIFT collaboration.

## The story so far...

The Higgs boson is looking more and more Standard Model-like. However, some of us still expect new phenomena not far above the electro-weak scale.

The reason for this is the fact that the Higgs mass is not “*natural*” and I will unapologetically embrace this argument.

In this spirit, I will discuss some ideas on compositeness concentrating on 4D models in which the Higgs is realized as a (pseudo) Nambu-Goldstone boson and (at least) the top is partially composite.

I usually joke saying that *this idea is so old that it appears new*, but there are new ingredients, because we need to take into account the constraints coming from Higgs physics and the lattice.

## Plan

- ▶ Present the models, without too many technicalities (or too few).
- ▶ Discuss some recent lattice results (that already restrict the space of available models) and suggest possible future studies.
- ▶ Discuss a phenomenological feature common to all these models that is within reach for Run-3 of LHC.

So, what's the idea?

The idea is to start with the Higgsless (thus massless) Standard Model

$$\mathcal{L}_{\text{SM}0} = -\frac{1}{4} \sum_{F=GWB} F_{\mu\nu}^2 + i \sum_{\psi=QudLe} \bar{\psi} \not{D} \psi$$

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  $G_{\text{HC}}$  and global symmetry structure  $G_{\text{F}} \rightarrow H_{\text{F}}$  such that  $h \in G_{\text{F}}/H_{\text{F}}$  and

$$\mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM}0} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \cdots$$

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

Since we are taking the ultra-conservative approach:

*"Give me Naturalness or give me Death (a.k.a. Landscape)"*,  
in the construction of  $\mathcal{L}_{\text{comp}}$ , we are only going to use **fermions**,  
collectively denoted by  $\lambda$ , (the models under consideration require at  
least two types of fermion *irreps.*  $\lambda = \psi, \chi$ ), and hypercolor **gauge**  
**fields**  $G$ . Light scalars, including the Higgs, need to be realized as  
pNGBs.

Dropping all gauge, spinor, chirality and Lorentz indices:

|  | $G_{\text{SM}} (F)$ | $G_{\text{HC}} (G)$ |
|--|---------------------|---------------------|
| $f = (l, q) \text{ (SM)}$              | $R_{\text{SM}}$     |                     |
| $\lambda = (\psi, \chi) \text{ (BSM)}$ | $R_1$               | $R_2$               |

There are many physical requirements that need to be fulfilled by  $\mathcal{L}_{\text{comp}}$ . Some of them concern the physics at strong coupling and can only be “assumed” by wishful thinking and subsequently checked on the lattice or by observation.

Others are more symmetry/perturbatively based (and already select a restricted set of models):

- ▶ We need a Higgs pNGB (quantum nrs. of  $\lambda^2$ ) in the  $(2, 2)$  of  $SU(2)_L \times SU(2)_R$ .
- ▶ We need a top/bottom partner (quantum nrs. of  $\lambda^3$ ), to enhance the top quark mass, *but also to misalign the vacuum*. (See Avik’s talk.)
- ▶ We need Asymptotic Freedom so the theory flows to strong coupling from  $UV \rightarrow IR$ .

Taking  $f^2\lambda^2$ ,  $f\lambda^3$  and going to the IR:

$\lambda^3 \rightarrow a\Lambda_{\text{IR}}^3\Psi$  and  $\lambda^2 \rightarrow a'\Lambda_{\text{IR}}^2H$ , where  $a\Lambda_{\text{IR}}^3$  and  $a'\Lambda_{\text{IR}}^2$  are the overlap probability densities  $|\psi(0)|^2$  of the hyperfermions inside the composite fermions/bosons.  $\Psi$  and  $H$  are the interpolating fields.

To fix the ideas:

$$\Lambda_{\text{IR}} \approx 4\pi f_h \approx 10 \text{ TeV} \ll \Lambda_{\text{UV}} \approx 10^4 \text{ TeV}$$

We need to analyze the Higgs potential, in particular vacuum misalignment (more on this in Avik's talk), but also the Partial Compositeness term(s)

$$\mathcal{L} \approx a\Lambda_{\text{IR}} \left( \frac{\Lambda_{\text{IR}}}{\Lambda_{\text{UV}}} \right)^{2-\Delta_{\mathcal{O}}} f\Psi$$

We need (to be checked!)  $\Delta_{\mathcal{O}} \approx 2$  and  $a$  not too small.

The most promising models are those *just outside* the conformal window. These models can be easily brought into the conformal window from the strong coupling side by adding additional matter that decouples at the lower scale  $\Lambda_{\text{IR}}$



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**Time to show some concrete models:**  $\lambda = \psi, \chi$ .

We narrowed it down to a **list of twelve models** likely to be **just outside** the conformal window but with still enough matter to realize the mechanism of partial compositeness:  $[1604.06467, 1610.06591]$

| $G_{\text{HC}}$ | $\psi$  | $\chi$  | $G_{\text{F}}/H_{\text{F}}$  |
|-----------------|---|---|--|
| $SO(7)$         | $5 \times \mathbf{F}$                           | $6 \times \mathbf{Spin}$                        | $\frac{SU(5)}{SO(5)} \frac{SU(6)}{SO(6)} U(1)$                                 |
| $SO(9)$         | $5 \times \mathbf{F}$                           | $6 \times \mathbf{Spin}$                        |  |
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| $SO(9)$         | $5 \times \mathbf{Spin}$                        | $6 \times \mathbf{F}$                           |  |
| $Sp(4)$         | $5 \times \mathbf{A}_2$                         | $6 \times \mathbf{F}$                           | $\frac{SU(5)}{SO(5)} \frac{SU(6)}{Sp(6)} U(1)$                                 |
| $SU(4)$         | $5 \times \mathbf{A}_2$                         | $3 \times (\mathbf{F}, \bar{\mathbf{F}})$       | $\frac{SU(5)}{SO(5)} \frac{SU(3) \times SU(3)'}{SU(3)_D} U(1)$                 |
| $SO(10)$        | $5 \times \mathbf{F}$                           | $3 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$ |  |
| $Sp(4)$         | $4 \times \mathbf{F}$                           | $6 \times \mathbf{A}_2$                         | $\frac{SU(4)}{Sp(4)} \frac{SU(6)}{SO(6)} U(1)$                                 |
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| $SU(4)$         | $4 \times (\mathbf{F}, \bar{\mathbf{F}})$       | $6 \times \mathbf{A}_2$                         |  |
| $SU(5)$         | $4 \times (\mathbf{F}, \bar{\mathbf{F}})$       | $3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$   | $\frac{SU(4) \times SU(4)'}{SU(4)_D} \frac{SU(3) \times SU(3)'}{SU(3)_D} U(1)$ |

Models with hyper-color group  $SU(4)$  and  $Sp(4)$  are being studied by various lattice collaborations. [2304.11729, 1801.05809..., 2211.09581, 1904.08885..., 2304.01070, 2210.08154...]

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In particular, I want to emphasize the results of the recent lattice simulation [A. Hasenfratz, E. T. Neil, Y. Shamir, B. Svetitsky and O. Witzel, 2304.11729] in which they studied the model

$$\mathcal{M}^* \equiv (N_F = 4 + \bar{4}, N_{A_2} = 8)$$

with  $G_{\text{HC}} = SU(4)$ , 4 Dirac spinors in the fundamental, and 8 Majorana spinors in the antisymmetric.  $\mathcal{M}^*$  is conformal, but can “exit ” into the two previous models also with  $G_{\text{HC}} = SU(4)$ :

$$\mathcal{M}6 \equiv (N_F = 3 + \bar{3}, N_{A_2} = 5), \quad \mathcal{M}11 \equiv (N_F = 4 + \bar{4}, N_{A_2} = 6)$$



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They find:  $\Delta_{\mathcal{O}} \approx 0.5$

This result, together with a previous result by the same group [1812.02727], indicating that the overlap coefficient  $a$  is smaller than expected, disfavors the models based on  $G_{\text{HC}} = SU(4)$ .

Can one do something similar for  $G_{\text{HC}} = Sp(4)$ ? (Ongoing work in [2306.11649, 2304.01070, 2210.08154...])

$$\mathcal{M}^* \equiv (N_F = 8, N_{A_2} = 8)$$

with 4 Dirac spinors in the fundamental and 4 Dirac spinors in the antisymmetric can “exit” into

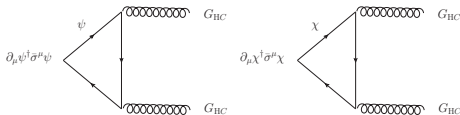
$$\mathcal{M}5 \equiv (N_F = 6, N_{A_2} = 5), \quad \mathcal{M}8 \equiv (N_F = 4, N_{A_2} = 6)$$

( $\mathcal{M}8$  originally proposed in [Barnard, Gherghetta, and Ray, 1311.6562])

Note: If  $(N_F = 4, N_{A_2} = 8)$  turned out to be conformal, it would be very useful for  $\mathcal{M}8$ .

No results are currently available for  $G_{\text{HC}} = SO(N)$  with spinorial irreps.

As far as LHC phenomenology goes, all these models have two global chiral symmetries  $U(1)_\psi$  and  $U(1)_\chi$  rotating  $\psi \rightarrow e^{i\alpha}\psi$  or  $\chi \rightarrow e^{i\beta}\chi$ .



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 an **ALP**  $a$  (light, typically below 100 GeV).

$$a = \cos \zeta a_\psi + \sin \zeta a_\chi$$

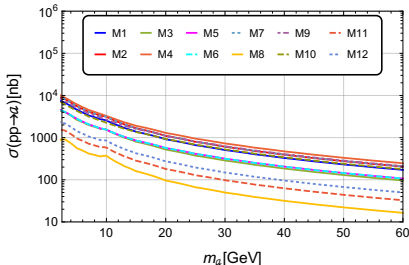
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - i \sum_{\psi} \frac{C_{\psi} m_{\psi}}{f} a \bar{\psi} \gamma^5 \psi$$

$$+ \frac{\alpha_s}{4\pi f} K_g a G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{\alpha}{4\pi f} K_{\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}.$$

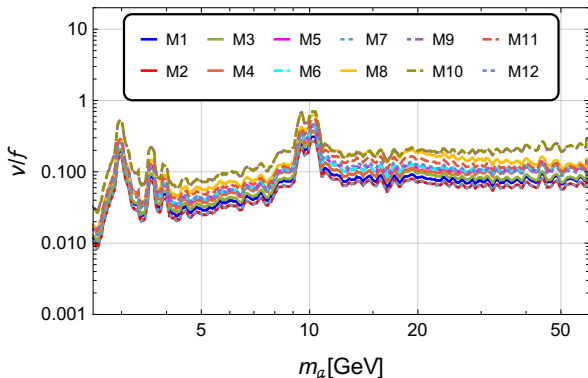
Where the coefficients  $K_g, K_{\gamma}, C_{\psi}$  are *calculable*, given the model.

The total production cross section for these models is significant.

In  $pp$  collisions at  $\sqrt{s} = 14 \text{ TeV}$  via ggF computed at NNLO with HIGLU for  $v/f = 1$  (it scales as  $(v/f)^2$ ).



The strongest bound to date are in the  $pp \rightarrow a \rightarrow \mu^+ \mu^-$  channel



Uses results from [LHCb 1710.02867, 2007.03923, BaBar 1210.0287, CMS 1206.6326, 1912.04776]

I want to conclude by advertising the  $pp \rightarrow a \rightarrow \tau\tau$  channel.

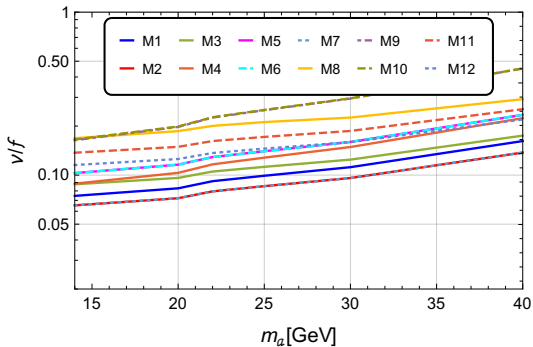
- The good new is that for generic coupling  $C_\mu = C_\tau$  the cross section is enhanced by  $m_\tau^2/m_\mu^2 = 283$ .
- The bad new is that you have to work with taus...

Two general statements from our analysis

- ▶ For a **hermetic detector** (ATLAS, CMS) the most promising production mode is  $pp \rightarrow aj$ , where the ALP acquires sufficient  $p_T$  by recoiling against a jet. For an **asymmetric detector** (LHCb)  $pp \rightarrow a$  suffices.
- ▶ In both cases the most sensitive decay channel is the **opposite flavor (and sign), OFOS** channel  $a \rightarrow \tau^+ \tau^- \rightarrow \mu^\pm e^\mp + 4\nu$  in spite of  $2 \times \text{BR}(\tau \rightarrow e + 2\nu) \times \text{BR}(\tau \rightarrow \mu + 2\nu) = 0.062$

## Di-tau at LHCb: [2106.12615]

(resonances)  $14 \text{ GeV} < m_a < 40 \text{ GeV}$  (depleted efficiency).

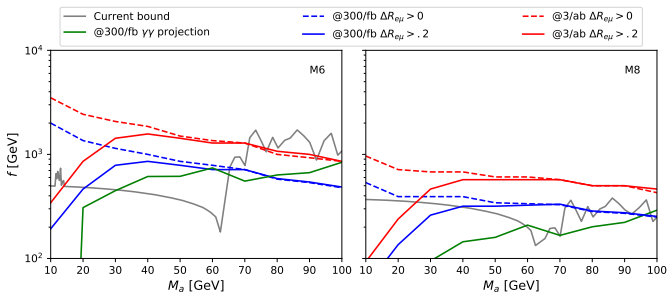


Projections for the bounds at 90% C.L. on  $v/f$  as a function of  $m_a$  for the di-tau channel for the 12 models at  $\mathcal{L} = 15/\text{fb}$ .

## Di-tau at ATLAS/CMS: [1812.07831]

Main difference is that we require a high- $p_T$  jet  $pp \rightarrow aj$ .

As before  $a \rightarrow e^\pm \mu^\mp + 4\nu$ .



The gray line is the convolution of the previous exclusion bounds.

The green line is the recast of the di-photon analysis [Mariotti *et al.* 1710.01743] for these models.

## CONCLUSIONS

- ▶ Realizing partial compositeness via ordinary 4D gauge theories provides a self contained concrete class of models to address the hierarchy problem.
- ▶ There are lots of open questions that go to the heart of strongly coupled theories, such as the range of the conformal window, anomalous dimensions, vacuum misalignment, and LEC.
- ▶ The di-tau channel is a challenging, but promising way to test the universal feature of these models (ALPs)
- ▶ The search for BSM at LHC is not dead!



Thank you for your attention!