

# Partial compositeness at LHC and on the Lattice



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GOAL: Explain the EW scale and the associated hierarchy by taking

- ▶ The **Higgs boson** to be a pseudo Nambu-Goldstone boson  
(**Composite Higgs model** [H. Georgi, D.B. Kaplan 1984])
- ▶ The **top quark** to mix with another heavy fermion  
(**Partial compositeness** [D.B. Kaplan 1991])
- We set out to classify the 4D gauge theories that could achieve this  
[D. Karateev and G.F. 1312.5330].
- In the meantime, [J. Barnard, T. Gherghetta and T. S. Ray 1311.6562]  
appeared, doing the  $Sp(4)$  case.
- For a more pedagogical intro, see [G. F. 1604.06467].

## General Remarks

- I) All composite Higgs models, except the minimal  $SO(5)/SO(4)$ , have additional pNGBs. Note that in the 4D gauge theory realizations, the most straightforwardly realized cosets are not of the above minimal type.
- II) 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 (still requiring some fine tuning, of course).

## Main Idea

Start with the Higgsless and massless Standard Model

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

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  $G_{\text{F}} \rightarrow H_{\text{F}}$  by fermion condensate  $\langle \psi\psi \rangle$  such that

$$\mathcal{L}_{\text{comp.}} + \mathcal{L}_{\text{SM}0} + \mathcal{L}_{\text{int.}} \longrightarrow \mathcal{L}_{\text{SM}} + \dots$$
$$\Lambda \sim 10 \text{ TeV}$$

( $\mathcal{L}_{\text{SM}} + \dots$  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.)

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

I will not discuss **such theory** and will concentrate on the physics below the  $\sim 10 \text{ TeV}$  scale, encoded in  $\mathcal{L}_{\text{comp.}}$  and  $\mathcal{L}_{\text{int.}}$ .

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 $\psi_\alpha$ Pseudoreal	$SU(4) / Sp(4)$
5 $\psi_\alpha$ 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  $SU(2)_L \times SU(2)_R$ :

- ▶ Ad of  $SU(4)_D \rightarrow (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + 2 \times (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
- ▶  $\mathbf{A}_2$  of  $Sp(4) \rightarrow (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
- ▶  $\mathbf{S}_2$  of  $SO(5) \rightarrow (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

For fermion masses, we also couple some **SM fermion** (mainly the **third quark family**) linearly to a  $G_{\text{HC}}$ -neutral fermionic bound state  $\mathcal{O}$ . This requires **additional hyper-fermions  $\chi$  carrying color**. Very schematically, in the UV:  $\mathcal{O}, \mathcal{O}' \dots = (\psi\chi\psi), (\psi\chi\psi)' \dots$

$$\mathcal{L}_{\text{int.}} \approx \frac{1}{\Lambda_{UV}^2} (y \bar{Q}_L(\psi\chi\psi) + y'(\psi\chi\psi)' t_R + \dots)$$

Going to the IR  $\Lambda_{UV} \rightarrow \Lambda$ , we get,

$$m_{\text{top}} \approx yy'v \left( \frac{\Lambda}{\Lambda_{UV}} \right)^{(2+\gamma_{\mathcal{O}})(2+\gamma_{\mathcal{O}'})}$$

We see that, to get the right top quark mass, we need  $\gamma_{\mathcal{O}}, \gamma_{\mathcal{O}'} \approx -2$  (since  $\Lambda \ll \Lambda_{UV}$ ). 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:  $(\Delta_{\mathcal{O}} = D_{\mathcal{O}} + \gamma_{\mathcal{O}} \approx 9/2 - 2 = 5/2 > 3/2)$ .

By the way, these fermionic bound states of two different hyperfermions are known as **Chimera Baryons**.

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And this is what a **Chimera** looks like.



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

## In summary, we require:

- ▶  $G_{\text{HC}}$  asymptotically free.
- ▶  $G_{\text{F}} \rightarrow H_{\text{F}} \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{\text{cus.}}} \supset G_{\text{SM}}$ .
- ▶ The MAC should not break neither  $G_{\text{HC}}$  nor  $G_{\text{cus.}}$ .
- ▶  $G_{\text{SM}}$  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  $G_{\text{SM}}$ .  
(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  $G_{\text{HC}}$  theory is outside the conformal window.

## With solutions:

$G_{\text{HC}}$	$\psi$	$\chi$	$G_{\text{F}}/H_{\text{F}}$
$SO(7)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\frac{SU(5)}{SO(5)} \frac{SU(6)}{SO(6)} U(1)$
$SO(9)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	
$SO(7)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$SO(9)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$Sp(4)$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$\frac{SU(5)}{SO(5)} \frac{SU(6)}{Sp(6)} U(1)$
$SU(4)$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \bar{\mathbf{F}})$	$\frac{SU(5)}{SO(5)} \frac{SU(3) \times SU(3)'}{SU(3)_D} U(1)$
$SO(10)$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	
$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$\frac{SU(4)}{Sp(4)} \frac{SU(6)}{SO(6)} U(1)$
$SO(11)$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	
$SO(10)$	$4 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$\frac{SU(4) \times SU(4)'}{SU(4)_D} \frac{SU(6)}{SO(6)} U(1)$
$SU(4)$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$6 \times \mathbf{A}_2$	
$SU(5)$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$	$\frac{SU(4) \times SU(4)'}{SU(4)_D} \frac{SU(3) \times SU(3)'}{SU(3)_D} U(1)$

## 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

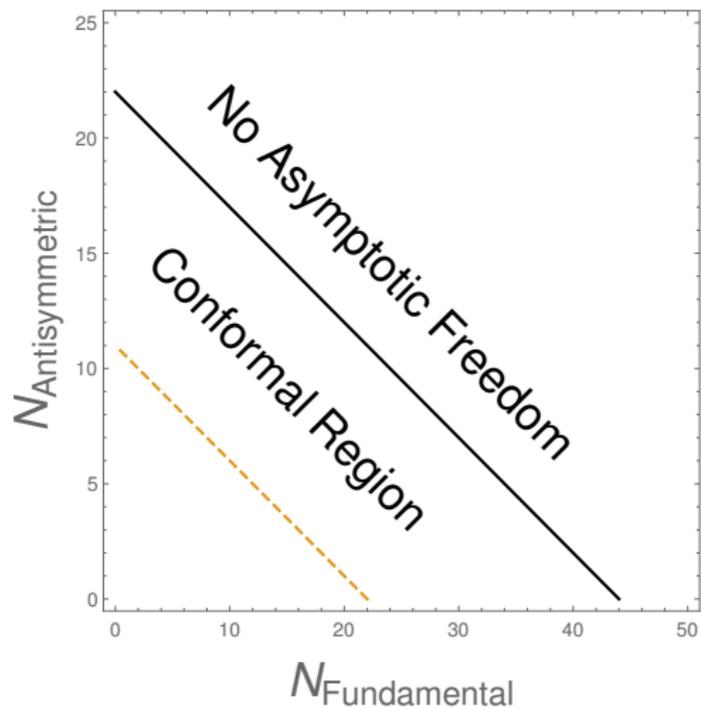
- ▶  $SU(4)$  with  $N_F$  Fundamentals and  $N_A$  Antisymmetric  
(possibly also  $SU(5)$ )
- ▶  $Sp(4)$  with  $N_F$  Fundamentals and  $N_A$  Antisymmetric
- ▶  $SO(N)$  with  $N_F$  Fundamentals and  $N_S$  Spin  
(with  $N = 7, 9, 10, 11$ )

Actually, since  $Sp(4) \approx SO(5)$  and  $SU(4) \approx SO(6)$ , with Fundamental  $\rightarrow$  Spin and Antisymmetric  $\rightarrow$  Fundamental, the last case subsumes the previous two.

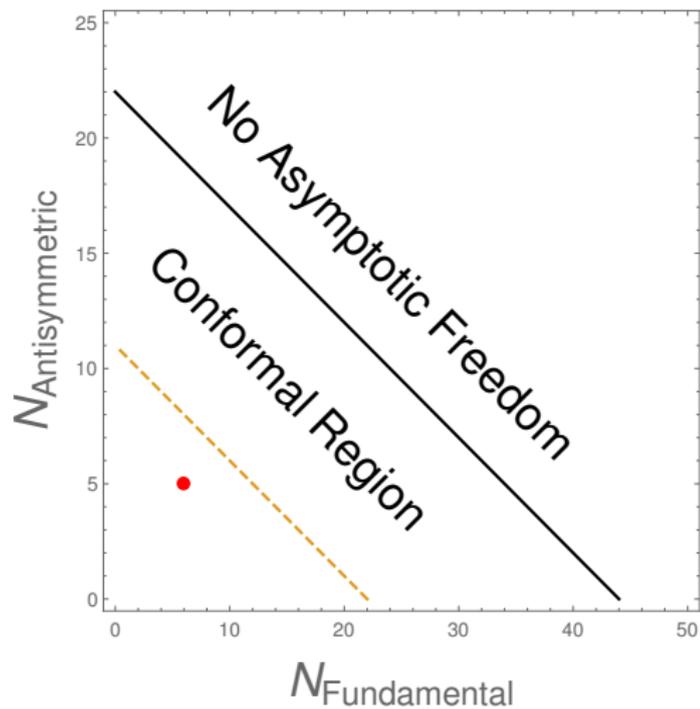
Some concrete questions that can be addressed are

- ▶ Where does the **boundary of the conformal window** start?
- ▶ For models **inside the conformal window**, what are the **anomalous dimensions** of the various composite operators?
- ▶ Taking the models **outside the conformal window**, (e.g. by removing some fermions), what are the **masses of the various resonances**?
- ▶ Can we estimate the **pNGB potential** and the **pre-Yukawa couplings** of top partners? (This last set of questions requires coupling to the SM)

## SU(4) case

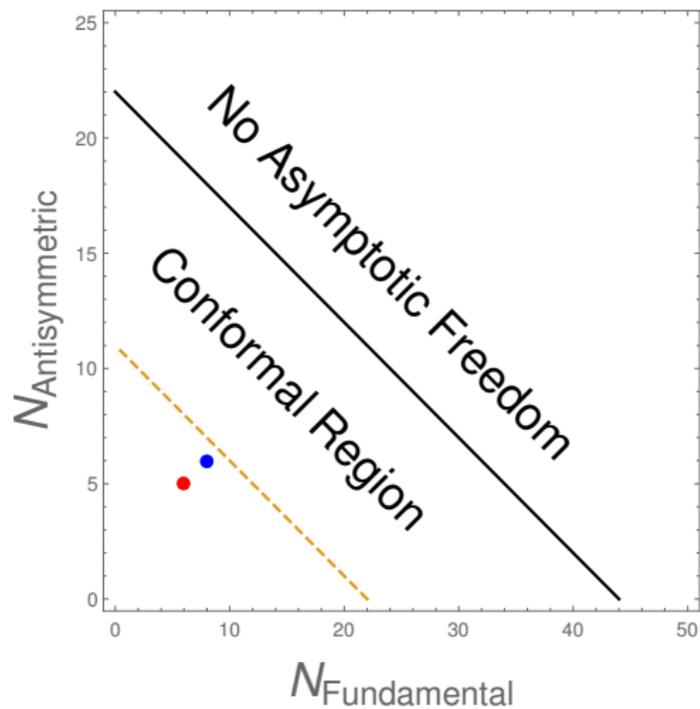


## SU(4) case



● = 1404.7137 (M6)

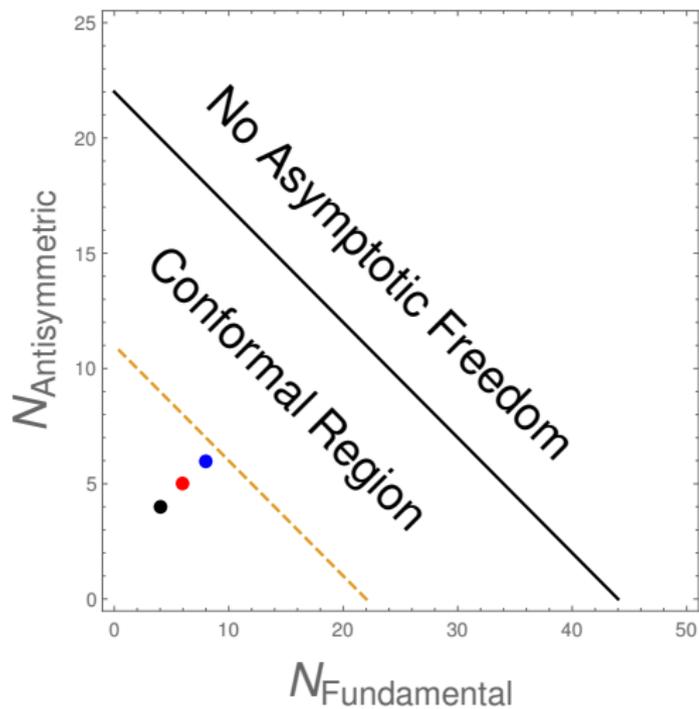
## SU(4) case



● = 1404.7137 (M6)

● = “swapped” (M11)

## SU(4) case

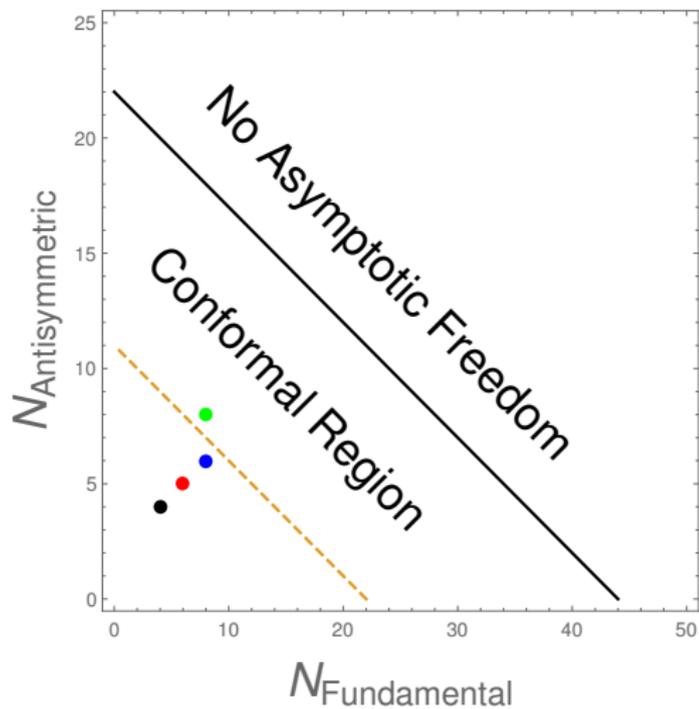


● = 1404.7137 (M6)

● = “swapped” (M11)

● = Lattice: Spectrum  
and pre-Yukawa  
1801.05809  
1812.02727

## SU(4) case



● = 1404.7137 (M6)

● = “swapped” (M11)

● = Lattice: Spectrum  
and pre-Yukawa  
1801.05809  
1812.02727

● = Lattice: Anomalous  
dimension  
2304.11729

The results so far are not encouraging for the **SU(4)** model.

Recall that the top partner matrix element, for some composite operator  $\mathcal{O}(x) \approx :\psi\chi\psi:(x)$  is defined, in analogy with proton decay, as

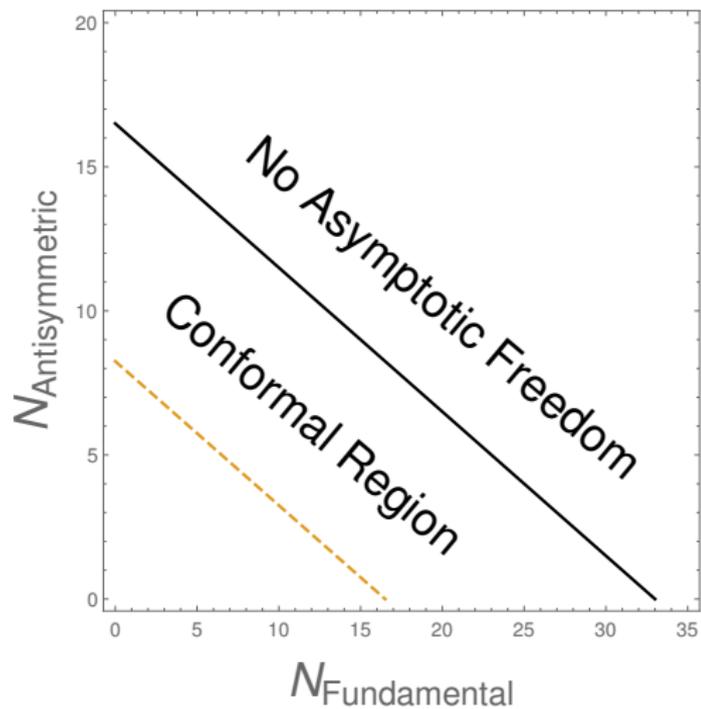
$$\langle \text{vac} | \mathcal{O}(0) | T, \sigma, \mathbf{0} \rangle = Z u_\sigma(\mathbf{0}),$$

with  $|T, \sigma, \mathbf{0}\rangle$  the top-partner at zero momentum. **Pre-Yukawa**  $\propto Z$

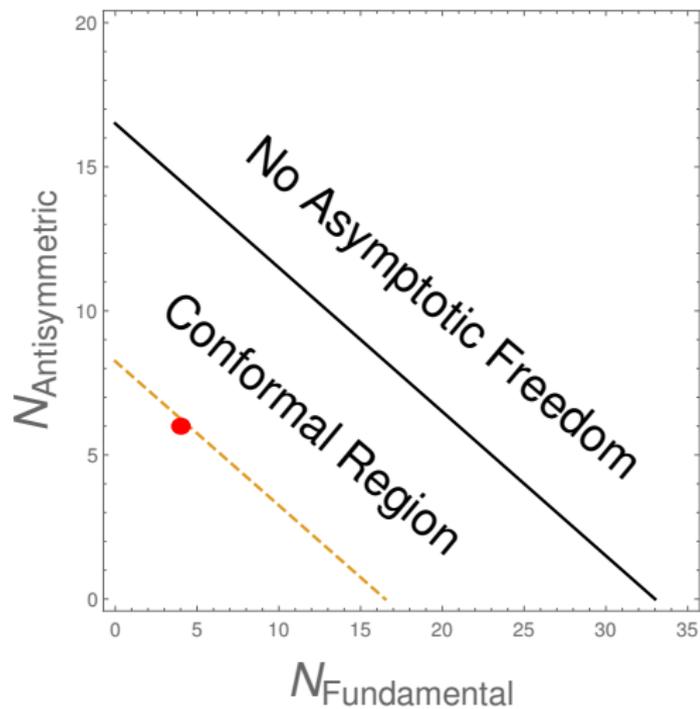
For the **• confining case** ( $N_F = 2 + 2$ , and  $N_A = 4$ ) [Ayyar, DeGrand, Hackett, Jay, Neil, Shamir and Svetitsky 1812.02727] find  $Z \approx 0.35 F_6^3$  in the chiral limit. (Compare with  $Z \approx 7 f_\pi^3$  in QCD.)

For the **• conformal case** ( $N_F = 4 + 4$ , and  $N_A = 8$ ) [Hasenfratz, Neil, Shamir, Svetitsky, and Witzel 2304.11729] find, for essentially the same operator, an anomalous dimension  $\gamma^* \approx -0.5$  (needed  $\gamma^* \approx -2$ ).

## Sp(4) case

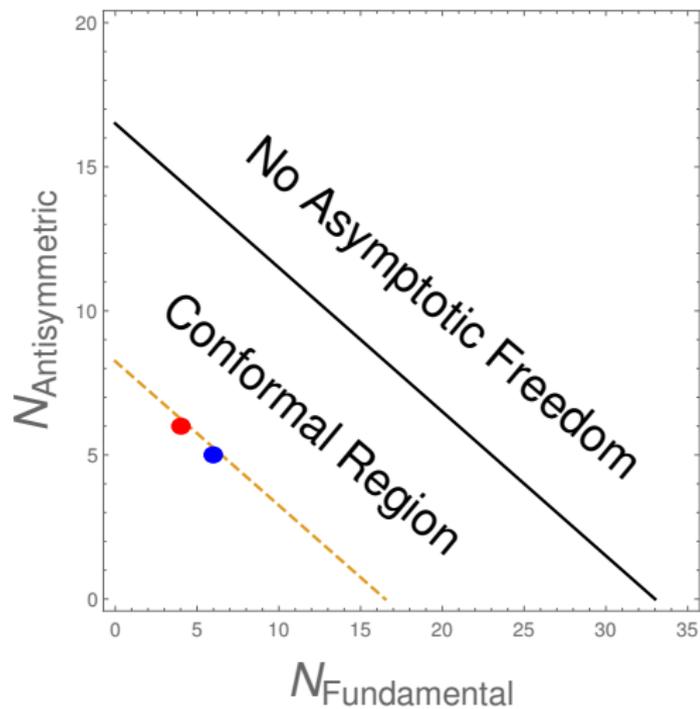


## Sp(4) case



● = 1311.6562 (M8)

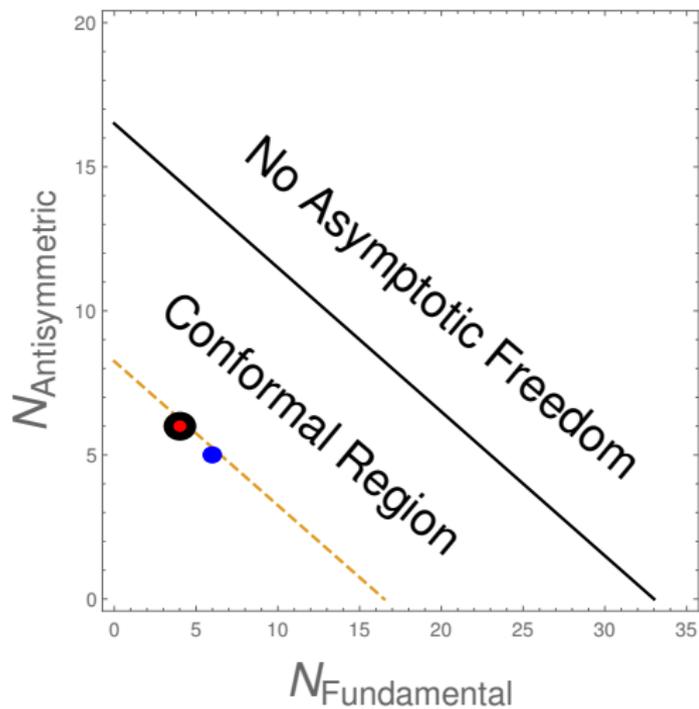
## Sp(4) case



● = 1311.6562 (M8)

● = "swapped" (M5)

## Sp(4) case

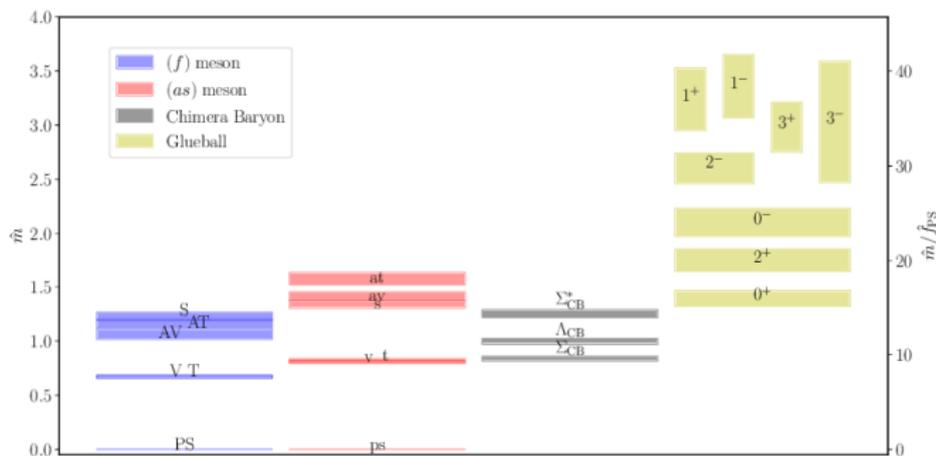


● = 1311.6562 (M8)

● = "swapped" (M5)

● = Lattice: Spectrum  
2311.14663  
2401.05637

For the **Sp(4)** model of [J. Barnard, T. Gherghetta and T. S. Ray 1311.6562] the spectrum has been computed with the right amount of fermions in [Bennett, Hong, Hsiao, Lee, Lin, Lucini, Piai, VDACCHINO 2311.14663 2401.05637]. (Caveats: Quenched, large bare masses.)



Observe that  $m_{\Sigma_{CB} \equiv 10} < m_{\Lambda_{CB} \equiv 5}$  under unbroken *flavor Sp(4)*.

## Phenomenology: An additional light ALP

Universal prediction: **There should be an ALP  $a$ .**

Consider the two global axial  $U(1)_\psi$  and  $U(1)_\chi$  symmetries rotating all  $\psi \rightarrow e^{i\alpha}\psi$  or all  $\chi \rightarrow e^{i\beta}\chi$ .



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  $a$  (light, possibly below 100 GeV), the orthogonal one to  $\eta'$  (heavy).

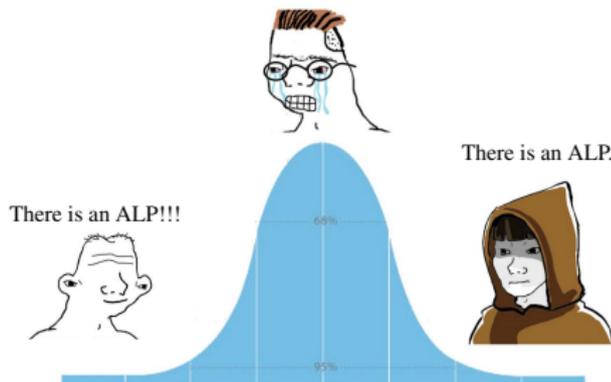
## To avoid misunderstandings:

$a$  has nothing to do with Dark Matter. (It decays promptly).

$a$  does not directly solve strong CP. (It has additional non-derivative couplings).

Still...

But it doesn't do anything!



The **coupling** to the vector bosons (e.g. gluon)

$$\frac{K_g \alpha_s}{4\pi f_a} a G_{\mu\nu}^A \tilde{G}^{A\mu\nu}$$

can be computed from the ABJ anomaly of the  $\chi$  current and the (non-anomalous) SM fermion loops.

The **coupling** to the fermions (e.g. top quark)

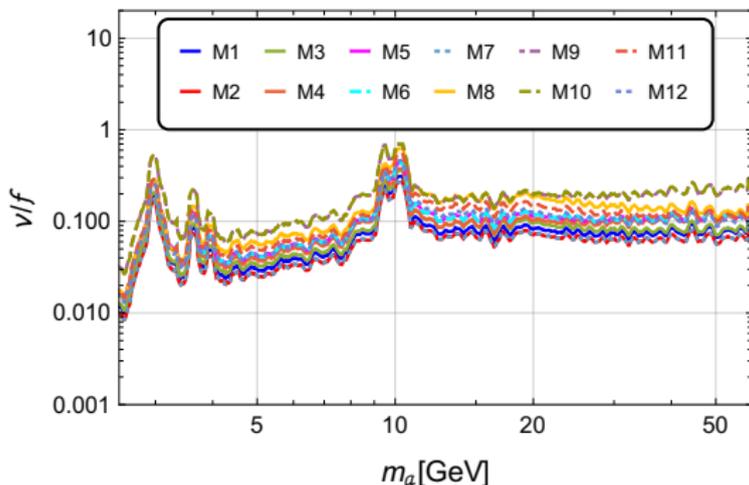
$$i \frac{C_t m_t}{f_a} a \bar{t} \gamma^5 t$$

are more model dependent but can be estimated by a spurion analysis.

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 gotten from the underlying theory and one is left with two continuous parameters  $f_a$  and  $m_a$  to describe the model.

In the mass range between 3 and 50 GeV, the strongest bounds are from  $pp \rightarrow a \rightarrow \mu^+ \mu^-$  [Buarque Franzosi, Cacciapaglia, Cid Vidal, G.F., Flacke, and Vázquez Sierra 2106.12615]



Uses results from [LHCb 1710.02867, 2007.03923, BaBar 1210.0287, CMS 1206.6326, 912.04776]

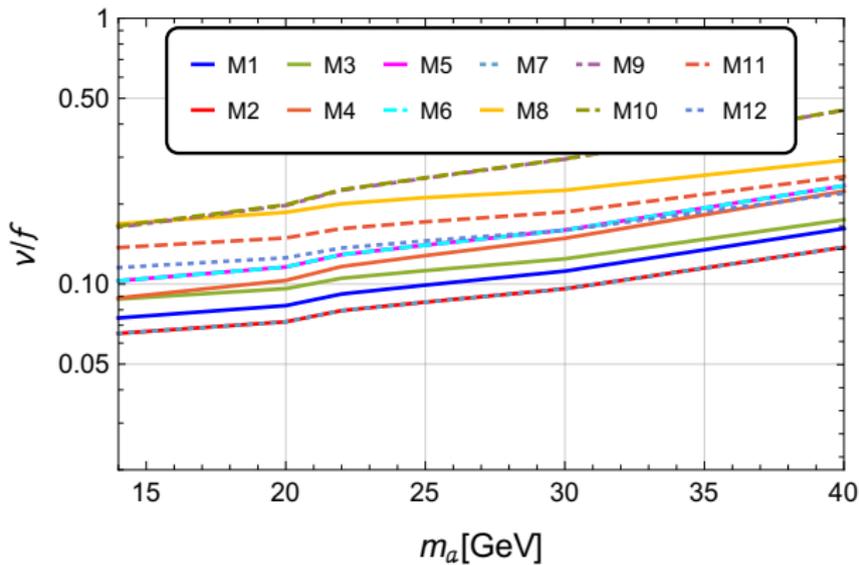
## How about the $pp \rightarrow a \rightarrow \tau^+ \tau^-$ channel?

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

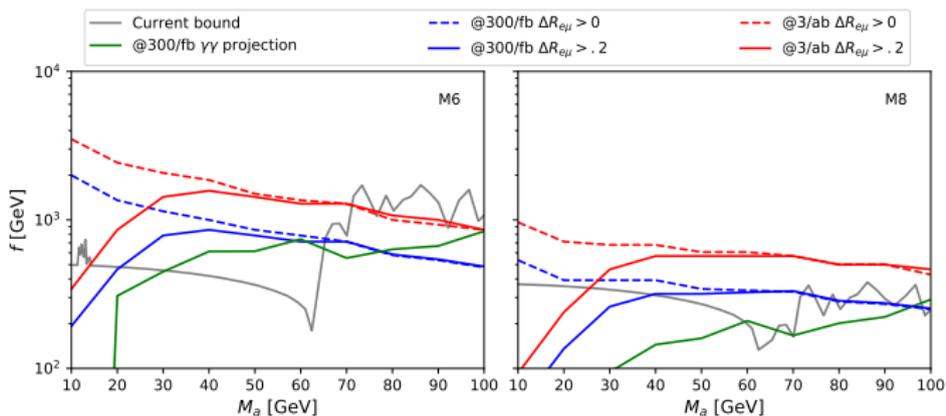
Two general statements from our analysis

- ▶ 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  $2 \times \text{BR}(\tau \rightarrow e + 2\nu) \times \text{BR}(\tau \rightarrow \mu + 2\nu) = 0.062$

Projected bounds at 90% C.L. on  $v/f$  as a function of  $m_a$  for the **di-tau channel** for the 12 models at **LHCb** with  $\mathcal{L} = 15/\text{fb}$ . [Buarque Franzosi *et al.* 2106.12615]



Projected bounds at 95% C.L. on  $f$  as a function of  $m_a$  for the **di-tau channel** for M6 and M8 at **CMS** with  $\mathcal{L} = 300/\text{fb}, 3/\text{ab}$  [Yellow Report (Group 3) 1812.07831].



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.

- ▶ The minimal **EW cosets** in this context are  $SU(4)/Sp(4)$ ,  $SU(5)/SO(5)$ , and  $SU(4) \times SU(4)' / SU(4)_D$ . ( $\Rightarrow$  **more scalars.**)
- ▶ **Top partners** arise as fermionic trilinears. Not all fermions need have a partner.
- ▶ The **Lattice** is starting to give crucial information on these models.
- ▶ An **ALP** is always present and represents an important target for the **HL-LHC** program. (E.g. **di-tau** channel.)

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Thank you for your attention!