Fermionic UV Completions of Composite Higgs Models

Montpellier, 2014

Based on

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PLAN

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  - Motivations for a (partial) UV completion
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  - Top partners sector
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INTRODUCTION

The discovery of a 125 GeV Higgs boson, together with our expectations from effective field theory, points to the existence of new states and enlarged symmetries near the LHC scale.

This is so because the SM Higgs suffers from additive renormalization and it is thus “UV sensitive”, requiring a fine-tuning of the lagrangian parameters.

If new physics is going to solve the problem, for this very reason it cannot lie much above the Higgs mass scale.

Quite generally, two options are available to stabilize scalar masses against a UV scale. Schematically:

- (Spontaneously broken) supersymmetry $\delta H = \epsilon\psi$
- (Explicitly broken) shift symmetry from SSB $\delta H = H + \epsilon$

The second option (the subject of this talk) has been mostly studied at the level of the effective lagrangian using the CCWZ formalism:

- Pick a coset G_F/H_F where the Higgs resides as a pNGB.
- Possibly also pick some fermions ψ in some irrep of H_F (the partners to the SM fermions).
- Couple to the SM.

The above scenario can be realized if the Higgs and the fermionic partners are composite objets. This however begs the question:

"Made of what?"

and motivates the search for a UV completion of this sector.

Further motivations:

- The effective cutoff scale is not *that* much larger than the LHC scale. (100 TeV collider anyone?)
- The UV completion can help pointing towards the most promising models.
- One can use lattice gauge theory to compute strong coupling quantities.

If we want to stay in a non-SUSY four-dimensional context, this essentially requires that the Higgs and the fermions arises as a composite state of a UV gauge theory with purely fermionic hyper-quarks.

The goal is to start with the Higgsless Standard Model.

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

and couple it to a fermionic gauge theory $\mathcal{L}_\Lambda$ such that

$$\mathcal{L}_\Lambda + \mathcal{L}_{SM0} + \mathcal{L}_{int.} \longrightarrow \mathcal{L}_{SM}.$$

where $\mathcal{L}_{SM}$ is the usual SM, (plus possible extra light composites of $\mathcal{L}_\Lambda$ still allowed by the experimental constraints), and $\mathcal{L}_{int.}$ is the interaction between the composites of $\mathcal{L}_\Lambda$ and the SM fields.

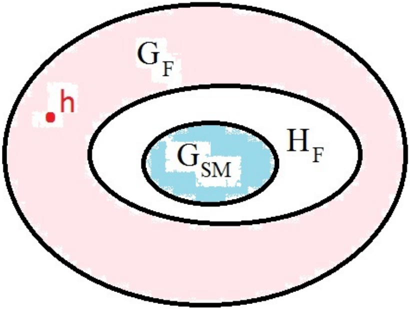
We will not address the origin of these interactions that presumably would come from a further UV completion at a much higher scale $\Lambda_{UV} \gg \Lambda$

$$\mathcal{L}_{\Lambda_{UV}} \longrightarrow \mathcal{L}_\Lambda + \mathcal{L}_{SM0} + \mathcal{L}_{int.}$$

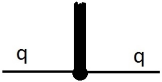
It is reasonably easy to give a mass to the W and Z bosons:

Let $G_F \to H_F$ be the pattern of global symmetry breaking of $\mathcal{L}_\Lambda$.
(The hyper-fermion condensate $\langle\psi\psi\rangle \neq 0$ does not break G_{SM} yet.)

Gauging a subgroup of H_F and coupling to the SM fermions turns the Nambu-Goldstone bosons (NGB) of G_F/H_F into pNGB, one of which ("the Higgs") is misaligned, condenses and breaks the EW group.



The fermionic masses are more challenging (particularly for the top quark).

First try a bilinear term 

(dropping group and Lorentz indices, $q =$ generic SM fermion, $\psi =$ generic hyper-fermion).
Starting at Λ_{UV} with terms like

$$\cdots + \frac{1}{\Lambda_{UV}^2}\psi\psi qq + \frac{1}{\Lambda_{UV}^2}qqqq$$

Generically $\Lambda_{UV} > 10^4$ TeV to avoid FCNC terms in $\frac{1}{\Lambda_{UV}^2}qqqq$.

Going down to the confinement scale Λ:

$$[\psi\psi]_{\Lambda_{UV}} = \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\gamma}[\psi\psi]_{\Lambda}$$

yields, after $H \propto [\psi\psi]_{\Lambda}$ acquires a vev $\langle H \rangle = v$

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

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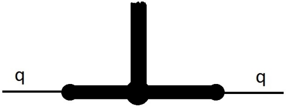
To get the top quark mass we need $\left(\frac{\Lambda}{\Lambda_{UV}}\right)^{2+\gamma} \approx 1$ and this can happen:

- if $\Lambda \approx \Lambda_{UV}$. But this reintroduces the fine-tuning since Λ_{UV} generically must be very large to suppress unwanted $qqqq$ interactions.
- if $\gamma \approx -2$. But this means that H is almost a free field and thus $H^\dagger H$ has scaling dimension ≈ 2, reintroducing the fine-tuning of the Higgs bilinear.

A better (?) way of doing it (known as partial compositeness) is to have a mixing linear in q: $\frac{1}{\Lambda_{UV}^2} q\psi\psi\psi =$ 

and EWSB mediated by the strong sector:



$$\text{In the UV:} \qquad \cdots + \frac{1}{\Lambda_{\mathrm{U}V}^2}\psi\psi\psi q + \frac{1}{\Lambda_{\mathrm{U}V}^2} qqqq$$

Going down to the confinement scale Λ one interpolates the *fermionic* field:

$$[\psi\psi\psi]_{\Lambda_{\mathrm{U}V}} = \left(\frac{\Lambda}{\Lambda_{\mathrm{U}V}}\right)^{\gamma'} [\psi\psi\psi]_{\Lambda}$$

yielding

$$m_q \approx \left(\frac{\Lambda}{M_T}\right)^2 \left(\frac{\Lambda}{\Lambda_{\mathrm{U}V}}\right)^{2(2+\gamma')} v$$

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To get the right top quark mass we still need $\Lambda \approx \Lambda_{\mathrm{U}V}$ or $\gamma' \approx -2$, but the second option is not fine tuned because it refers to $T \propto [\psi\psi\psi]_\Lambda$.

Also notice that $\gamma' \approx -2$ is still strictly above the unitarity bound for T contrary to $\gamma \approx -2$ for H which is at the free field limit.

Disclaimers:

- We have not been able to find fermionic partners for all SM fields and thus we provisionally propose to use partial compositeness only for the top quark sector ((t_L, b_L) and t_R) and to rely on the quadratic terms for the remaining fields.
- We have not proven that such large negative anomalous dimensions can be achieved. This is a non-perturbative statement on the evolution of the theory.
- We do not have a fully viable "extended" theory generating all the four-fermi couplings.

CLASSIFICATION

Together with D. Karateev, we set out to classify the theories based on hypercolor group $G_{\rm HC}$ obeying the following minimal requirements:

- $G_F \to H_F \supset \overbrace{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X}^{\text{custodial } G_{cus}} \supset G_{\rm SM}$
- The MAC should not break neither $G_{\rm HC}$ nor G_{cus}.
- G_{SM} free of 't Hooft anomalies. (We need to gauge it.)
- $G_F/H_F \ni (\mathbf{1},\mathbf{2},\mathbf{2})_0$ of G_{cus}. (The Higgs boson.)
- ψ^3 hyper-color 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 and L symmetry.

We restricted the search to asymptotically free theories with a simple hyper-color group G_{HC} (still to be determined at this point).

Recall that (using two-component notation for the fermions)

$(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$\langle\tilde{\psi}\psi\rangle \neq 0 \Rightarrow SU(n) \times SU(n)/SU(n)$
ψ_α Pseudoreal	$\langle\psi\psi\rangle \neq 0 \Rightarrow SU(n)/Sp(n)$
ψ_α Real	$\langle\psi\psi\rangle \neq 0 \Rightarrow SU(n)/SO(n)$

As far as the EW sector is concerned, the possible minimal custodial cosets 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	$SU(5)/SO(5)$

We will focus on the last two.

In our case, this is only one part of G_F/H_F since we also want to have colored objects (top partners). This requires adding additional hyper-fermions to the theory.
The minimal cosets allowing an anomaly-free embedding of unbroken $SU(3)_c$ are

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ Complex	$\langle\chi\tilde{\chi}\rangle \neq 0 \Rightarrow SU(3) \times SU(3)'/SU(3)_D$
$6\ \chi_\alpha$ Pseudoreal	$\langle\chi\chi\rangle \neq 0 \Rightarrow SU(6)/Sp(6)$
$6\ \chi_\alpha$ Real	$\langle\chi\chi\rangle \neq 0 \Rightarrow SU(6)/SO(6)$

In this case one could also use bare masses avoiding extra pNGBs. (The $U(1)_X$ charge can be easily arranged by pairing it with the triality of the fields χ.)

The QCD quantum numbers of the χs and their possible invariant mass terms are (writing only $SU(3)_c$ indices)

Complex case	$(\chi^{1,2,3}, \tilde{\chi}_{1,2,3}) \in (\mathbf{3}, \overline{\mathbf{3}})$
Pseudoreal case	$\chi^{1,2,3} \in \mathbf{3} \;\; \chi^{4,5,6} \in \overline{\mathbf{3}}$
Real case	$(\chi^1 + i\chi^4, \chi^2 + i\chi^5, \chi^3 + i\chi^6) \in \mathbf{3}$ $(\chi^1 - i\chi^4, \chi^2 - i\chi^5, \chi^3 - i\chi^6) \in \overline{\mathbf{3}}$

The mass terms invariant under $SU(3)_D$, $Sp(6)$ and $SO(6)$ respectively are

Complex case	$m(\chi^1\tilde{\chi}_1 + \chi^2\tilde{\chi}_2 + \chi^3\tilde{\chi}_3)$
Pseudoreal case	$m(\chi^1\chi^4 + \chi^2\chi^5 + \chi^3\chi^6)$
Real case	$m(\chi^1\chi^1 + \chi^2\chi^2 + \chi^3\chi^3 + \chi^4\chi^4 + \chi^5\chi^5 + \chi^6\chi^6)$

To give an idea of how the classification can be achieved, let us ask:

When is it possible to have $G_{HC} = SU(N_{HC})$?

We saw that ψ must be real (≥ 5 of them) or pseudoreal (≥ 4 of them). Trying to have χ also real or pseudoreal (≥ 6 of them in both cases) will not work because of asymptotic freedom:

The non-complex irreps with the smallest index are the adjoint **Ad** and the selfdual antisymmetric $\mathbf{A}_{N_{HC}/2}$ (for N_{HC} even). In all cases

$$-11 \times C(SU(N_{HC})) + 2 \times (4 \text{ or } 5)\, T(\psi) + 2 \times 6\, T(\chi) > 0$$

Trying now to have ≥ 3 pairs $(\chi, \tilde{\chi})$ in complex conjugate irreps, asymptotic freedom allows for the generic case

- $G_{\mathrm{HC}} = SU(N_{\mathrm{HC}})$ with $\psi \in \mathbf{Ad}$ and $(\chi, \tilde{\chi}) \in (\mathbf{F}, \bar{\mathbf{F}})$

and three special cases:

- $G_{\mathrm{HC}} = SU(4)$ with $\psi \in \mathbf{A}_2$ and $(\chi, \tilde{\chi}) \in (\mathbf{F}, \bar{\mathbf{F}})$ $(\star)$
- $G_{\mathrm{HC}} = SU(6)$ with $\psi \in \mathbf{A}_3$ and $(\chi, \tilde{\chi}) \in (\mathbf{F}, \bar{\mathbf{F}})$
- $G_{\mathrm{HC}} = SU(6)$ with $\psi \in \mathbf{A}_3$ and $(\chi, \tilde{\chi}) \in (\mathbf{A}_2, \bar{\mathbf{A}}_2)$

Only the first exceptional case $(\star)$ has acceptable top quark partners of type $\chi\psi\chi$ etc...

Note that the generic case has only color octets like $\tilde{\chi}\psi\chi$. The $SU(6)$ cases also don't work.
$SU(4)$ stands out as the unique unitary hypercolor group in this classification.

For completeness, the full list of solutions is

G_{HC}	ψ	χ or $(\chi, \tilde{\chi})$	Restrictions
$SU(N_{\mathrm{HC}})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\mathrm{HC}} = 4 \quad (\star)$
$Sp(2N_{\mathrm{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\mathrm{HC}} \geq 12$
$Sp(2N_{\mathrm{HC}})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\mathrm{HC}} \geq 4$
$Sp(2N_{\mathrm{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\mathrm{HC}} \leq 36$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} \geq 55$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} \geq 15$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\mathrm{HC}} = 7, 9, 11, 13$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} = 7, 9$
$SO(N_{\mathrm{HC}})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\mathrm{HC}} = 11, 13$
$SO(N_{\mathrm{HC}})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{\mathrm{HC}} = 10, 14$

THE $SU(4)$ MODEL IN SOME DETAIL

	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
	G_{HC}	G_F				
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 model is "non-chiral", thus hypercolor group is free of gauge anomalies G^3_{HC}.
- G_F is free of ABJ anomalies $G_F G^2_{\mathrm{HC}}$.
- $H_F = SO(5) \times SU(3)_c \times U(1)_X$ is free of 't Hooft anomalies H^3_F. Note that $G_{cus} \subset H_F \subset G_F$.

There are various ways to argue that the symmetry breaking pattern should be $G_F \to H_F$ leading to the coset

$$G_F/H_F = \left(\frac{SU(5)}{SO(5)}\right) \times \left(\frac{SU(3) \times SU(3)'}{SU(3)_c}\right) \times U(1)'$$

- All fermionic composite objects like $\chi\psi\chi$ can be made massive by giving a bare mass to ψ (which is in a real irrep of G_{HC}). This means that they are not available to cancel the 't Hooft anomaly associated to the G_F/H_F generators that must thus be broken.
- A (admittedly uncontrolled) computation of the NJL potential leads to a phase where $\psi\psi$ and $\chi\tilde{\chi}$ condense.
- The condensation of $\psi\psi$ and $\chi\tilde{\chi}$ can also be argued by standard MAC arguments. This also indicates that $f_{\psi\psi} \gtrsim f_{\chi\tilde{\chi}}$.

$$\begin{array}{ccccc} SO(5) \to SU(2)_L \times SU(2)_R \times U(1)_X & \to & SU(2)_L \times U(1)_Y \\ T_R^3 \quad + \quad X & = & Y \end{array}$$

The spectrum of light scalars thus comprises a Georgi-Machacek multiplet of the 14 NGB in $SU(5)/SO(5)$ (with $X = 0$) decomposing under $SO(5) \to SU(2)_L \times U(1)_Y$ as

$$\mathbf{14} \to \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1} \equiv (\eta, H, \Phi_0, \Phi_\pm)$$

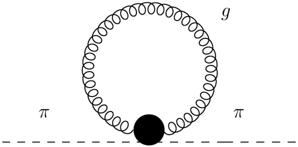
After EWSB this results in the usual Higgs particle, a doubly charged, two single-charge and four additional neutral particles.

One more G_{SM} neutral boson η' arises from breaking $U(1)'$.

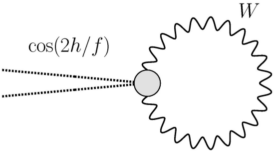
Finally there is a color octet Π^a arising from $SU(3) \times SU(3)' \to SU(3)_c$.

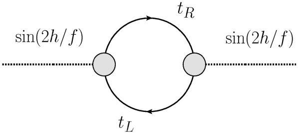
No leptoquarks or scalars in the **3** and **6** of QCD arise.

The colored pNGB octet gets a positive mass via the large contribution from gluons



whereas the coupling of the top quark favors the misalignment of the “right” Higgs boson





$$V(h) = \alpha \cos(2h/f) - \beta \sin^2(2h/f).$$

$$\langle \frac{\partial V}{\partial h} \rangle = 0 \Rightarrow \cos\left(\frac{2\langle h \rangle}{f}\right) = -\frac{\alpha}{2\beta}$$

$$m_h^2 = (125\ \mathrm{GeV})^2 = \langle \frac{\partial^2 V}{\partial h^2} \rangle = \frac{8\beta}{f^2} \sin^2\left(\frac{2\langle h \rangle}{f}\right) = \frac{8\beta}{f^2}\left(1 - \frac{\alpha^2}{4\beta^2}\right)$$

$$v^2 = (246\ \mathrm{GeV})^2 = f^2 \sin^2\left(\frac{2\langle h \rangle}{f}\right) = f^2\left(1 - \frac{\alpha^2}{4\beta^2}\right)$$

Apart from the usual tuning needed to get

$$S \propto \frac{v^2}{f^2} = \left(1 - \frac{\alpha^2}{4\beta^2}\right) \ll 1$$

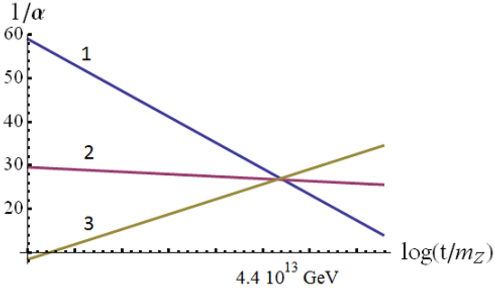
we still need to get β smaller than what one would expect from NDA

$$\frac{m_h^2}{v^2} = 0.26 = \frac{8\beta}{f^4} = 8 \times 3 \times \frac{y_t^2}{16\pi^2} \times \frac{\Lambda^2}{f^2}$$

Too big for $\Lambda \approx \frac{4\pi}{\sqrt{N_{\mathrm{HC}}}} f = 2\pi f$, but OK if $\Lambda \to M_T \gtrsim f$.

Before I move on to the fermionic sector, there is an amusing coincidence that I cannot resist showing...

When one looks at the impact of the extra fermions on the SM gauge couplings one finds:

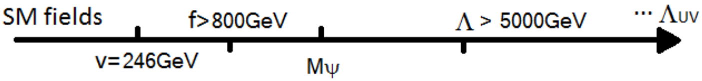


But the scale is too low and one should expect new physics to arise before that anyway to give rise to the needed four-fermion couplings.

The top quark partners (both $(t,b)_L$ and t_R) can be found as fermionic resonances created by the composite operators

Object	$SO(5)\times SU(3)_c\times U(1)_X$
$\tilde{\chi}\psi\tilde{\chi}, \quad \bar{\chi}\psi\bar{\chi}, \quad 2\times\bar{\chi}\bar{\psi}\tilde{\chi}$	$(\mathbf{5},\mathbf{3})_{2/3}$
$\chi\psi\chi, \quad \bar{\tilde{\chi}}\psi\bar{\tilde{\chi}}, \quad 2\times\bar{\tilde{\chi}}\bar{\psi}\chi$	$(\mathbf{5},\bar{\mathbf{3}})_{-2/3}$

It is reasonable to expect that these operators create the lightest fermionic particles. The extra assumption we need to make is that at least one of these resonances is significantly lighter than the typical mass scale Λ:



After EWSB we end up with one Dirac fermion B of charge $-1/3$, three $T_{i=1,2,3}$ of charge $2/3$, and one X of charge $5/3$.

$$
\begin{array}{cc}
SO(5) \times SU(3)_c \times U(1)_X & (\mathbf{5},\mathbf{3})_{2/3} \\
\downarrow & \downarrow \\
G_{\text{cus.}} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X & (\mathbf{3},\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{3},\mathbf{1},\mathbf{1})_{2/3} \\
\downarrow & \downarrow \\
G_{\text{SM}} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y & (\mathbf{3},\mathbf{2})_{7/6} + (\mathbf{3},\mathbf{2})_{1/6} + (\mathbf{3},\mathbf{1})_{2/3} \\
\downarrow & \downarrow \\
SU(3)_c \times U(1)_{\text{e.m.}} & \mathbf{3}_{5/3} + 3 \times \mathbf{3}_{2/3} + \mathbf{3}_{-1/3}
\end{array}
$$

The current ATLAS and CMS limits on these objects are $m \gtrsim 700\ \text{GeV}$.

All the relevant couplings can be worked out by applying the CCWZ techniques.

The top quark has three partners.

Their mass matrix turns out to be

$$\mathcal{M}_T = \begin{pmatrix} 0 & \frac{\lambda_q}{2} f(1+\cos(v/f)) & \frac{\lambda_q}{2} f(1-\cos(v/f)) & \frac{\lambda_q}{\sqrt{2}} f\sin(v/f) \\ \frac{\lambda_t}{\sqrt{2}} f\sin(v/f) & M & 0 & 0 \\ -\frac{\lambda_t}{\sqrt{2}} f\sin(v/f) & 0 & M & 0 \\ \lambda_t f\cos(v/f) & 0 & 0 & M \end{pmatrix}$$

whose lowest singular value is, to leading order in $v/f,\ v/M$

$$m_t \approx \frac{\sqrt{2} M f \lambda_q \lambda_t}{\sqrt{M^2+\lambda_q^2 f^2}\,\sqrt{M^2+\lambda_t^2 f^2}}\, v,$$

The bottom quark has one partner B and a bilinear μ_b coupling is needed to give a mass to both.

The mass matrix is

$$\mathcal{M}_B = \begin{pmatrix} \mu_b \sin(v/f)\cos(v/f) & \lambda_q f \\ 0 & M \end{pmatrix}$$

The mass of the b quark is, to lowest order in the Higgs vev,

$$m_b \approx \frac{\mu_b M}{f\sqrt{M^2 + \lambda_q^2 f^2}}\, v$$

A positive feature of this model is that it does not give rise to large deviations from the $Z \to b\bar{b}$ decay rate.

This can be seen by noticing that the coupling of the B field to the Z boson turns out to be

$$\mathcal{L} \supset \frac{e}{\mathrm{s_W c_W}} \left(-\frac{1}{2} + \frac{\mathrm{s_W^2}}{3} \right) \bar{B}\gamma^\mu B Z_\mu$$

i.e. with the same coefficient as the SM b_L. This guarantees that no changes arise when rotating to the mass eigenbasis.

There are corrections to the (smaller) coupling to the b_R and to the t_L, t_R, but they are acceptable and might even be welcome in the light of the forward-backward asymmetry.

CONCLUSIONS

- Models of Partial Compositeness can provide an interesting alternative to SUSY in explaining the hierarchy problem.
- Looking for purely four dimensional UV completions can provide an interesting angle justifying some classes of models and opening up the possibility of using the lattice for strong coupling computations.
- In `arXiv:1312.5330` we classified the various possibilities under a few extra simplifying assumptions such as G_{HC} simple.
- In `arXiv:1404.7137` we studied the spectrum, coupling and significant features of one of the most promising ones based on $G_{HC} = SU(4)$.

Open issues
(Some of them raised by the visits in Lyon and Montpellier)

- Find an extended sector generating the needed four-fermi couplings.
- Do some of these models have Dark Matter candidates?
- Can we justify the large anomalous dimension and small mass of the fermionic partners?
- It might just be possible to turn this into a UV completion of the "Littlest Higgs model." Here one needs to go to the non-minimal $SU(7)/SO(7)$ and this is still allowed by asymptotic freedom.
- Understand the conformal window.
- Have a closer look at the $SU(4) \times SU(4)'/SU(4)_D$ EW coset.
- The fate of the axions η and η'. Can we evade the experimental bounds?