S · F · C · H

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Alessandro Strumia, talk at Invisibles 2016

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Scalarfriendly vs scalarphobic

Most theorists are scalarphobic: they believe that the Higgs must be replaced by natural wonderlands. The main expectation was weak-scale SUSY to purge the Higgs from quadratic divergences. But LHC data speak differently:

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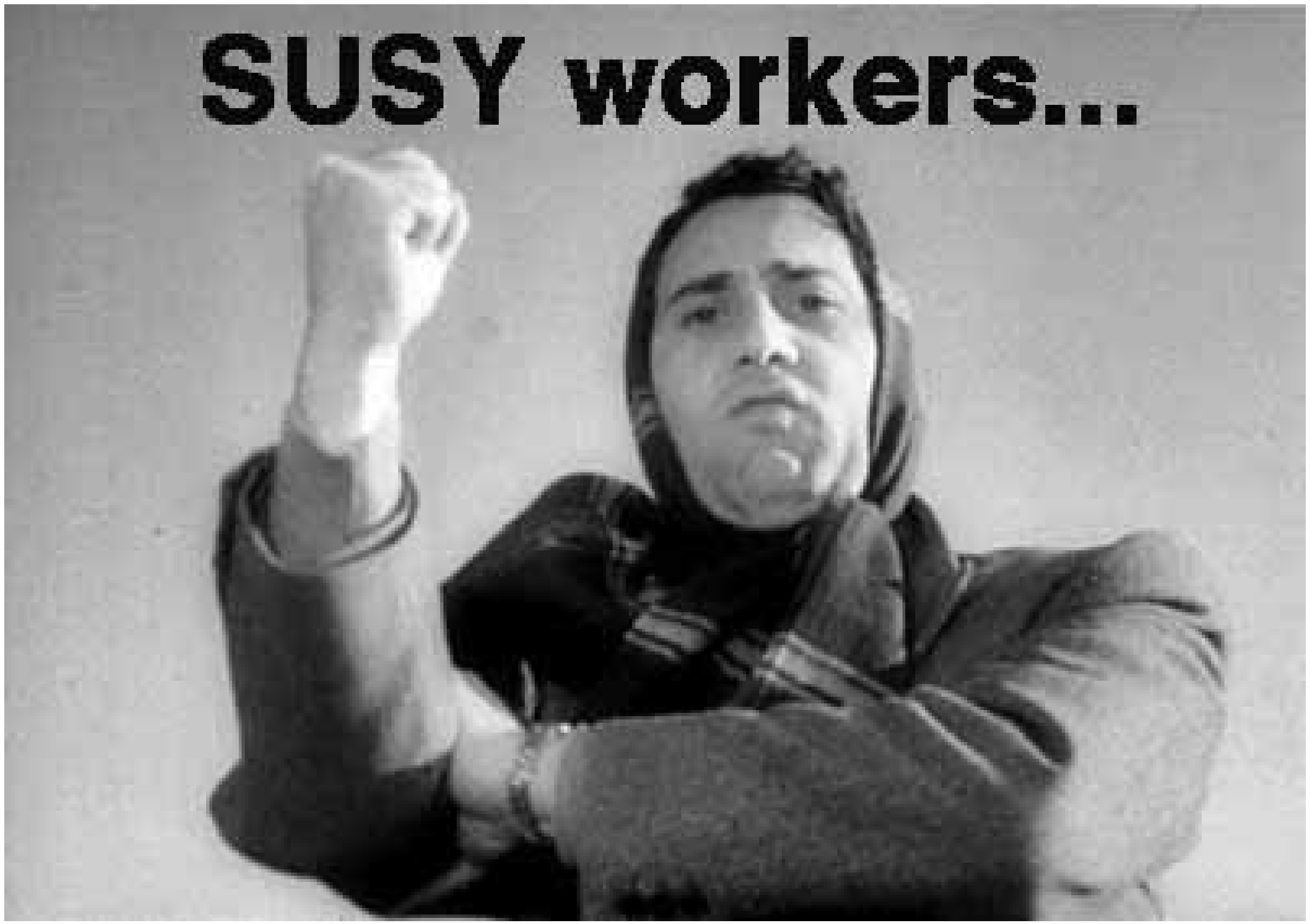


Scalarphobic compositeness

Many studies identified 3 pillars to make H composite of morally sane stuff:

1) H is a Goldstone boson of postulated global $G_{\rm gl} \to H_{\rm gl}$ e.g. SO(5) $\to$ SO(4).
2) SM fermions f get mass mixing with composite operators, $\mathscr{L} \ni f\mathcal{B}$.
3) Corrections to T and possibly $Zb\bar{b}$ suppressed imposing custodial symmetries.

1) roughly happens in QCD-like dynamics.
2) no theory $\Rightarrow$ degeneration into 'cosettology': abstract ad hoc bizarre $\mathscr{L}_{\rm eff}$.

Which mysterious dynamics can do this?

AdS/CFT? Warped extra dims? Data want something that mimics a scalar, $\dim \mathcal{H} \approx 1$. Naturalness wants $\dim \mathcal{H}^2 \approx 4$. Impossible.

If H is composite, what is it made of? Fermions are morally sane and cheap. But lattice tells $\dim(\mathcal{H} \sim \bar{\mathcal{F}}\mathcal{F}) \neq 1$ i.e. no Yukawa, U(3)^5.

Scalarfriendly Compositeness

Composite Higgs so far studied as a way to avoid scalars.

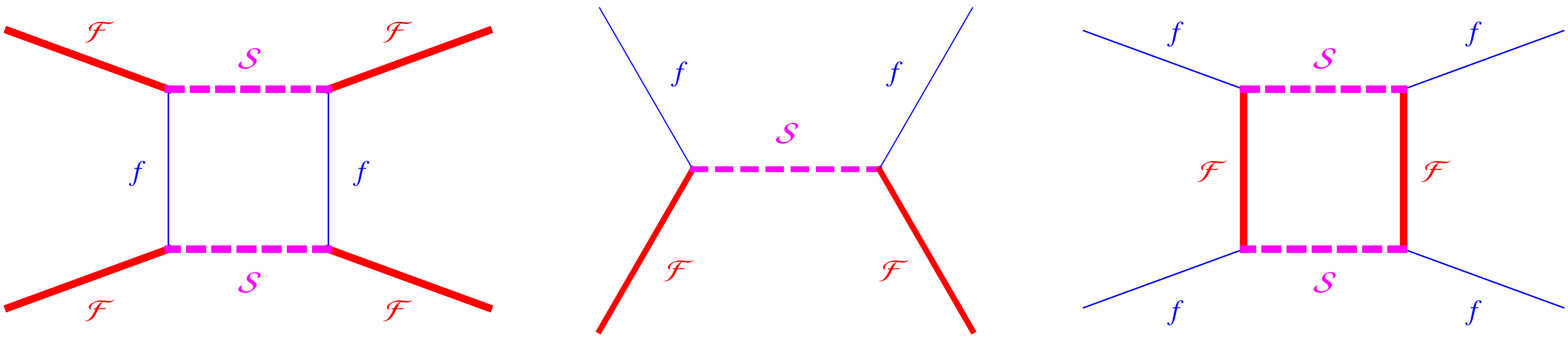
Power divergences give no physical effect.
Maybe theorists over-interpreted equations, as happened with the æther.

Let's explore if fundamental scalars allow composite Higgs... a Columbus egg.
If it looks like a scalar, smells like a scalar and couples like a scalar, it's probably a stupid elementary scalar. We don't need to reinvent the wheel.

The theory

Theory = (SM without H) + (extra $G_{\rm TC}$ = SU(N) or SO(N) or Sp(N)) + (vector-like TCfermions $\mathcal{F}$) + (TCscalars $\mathcal{S}$) + TCYukawas such that

(each SM fermion $f = L, E, Q, U, D$)×(some TC scalar $\mathcal{S}$)×(some TC fermion $\mathcal{F}$).



Higgs potential	SM fermion masses	Flavour violations
$\mathcal{F}^4 \sim H^2$	$f f \mathcal{F}\mathcal{F} \sim f f H$	f^4

Global symmetries

Vector-like $\mathcal{F}$ with $\Delta m \ll \Lambda_{\text{TC}}$ have accidental global symmetries. Condensates form if $\beta_{\text{TC}} \lesssim \frac{1}{3}\beta_{\text{TC}}|_{\text{gauge}}$ and respect G_{TC} and minimally break $G_{\text{gl}} \to H_{\text{gl}}$. Despite the presence of TC-scalars, the mass of $H \sim \mathcal{F}\mathcal{F}$ remains calculable.

Gauge group	Fermion bilinear condensate	Intact scalar symmetries
$\text{SU}(N)_{\text{TC}}$	$\text{SU}(N_F)_L \otimes \text{SU}(N_F)_R \to \text{SU}(N_F)$	$\text{U}(N_S)$
$\text{SO}(N)_{\text{TC}}$	$\text{SU}(N_F) \to \text{SO}(N_F)$	$\text{O}(N_S)$
$\text{Sp}(N)_{\text{TC}}$	$\text{SU}(N_F) \to \text{Sp}(N_F)$	$\text{Sp}(2N_S)$

Quasi-degenerate TCscalars similarly have accidental global symmetries, but
- $\langle \mathcal{S} \rangle$ and $\langle \mathcal{S}\mathcal{S} \rangle$ not fixed by general arguments. Lattice?
- They can break G_{TC}, giving H as elementary Goldstone boson.
- They can break G_{gl} giving more TCπ made of two TCscalars.
- The mass of $H \sim \mathcal{S}\mathcal{S}$ depends on $m_{\mathcal{S}}$.

Custodial symmetry for T

Composite H has $|H^\dagger D_\mu H|^2$ giving $\hat{T} \sim v^2/f_{\mathsf{TC}}^2 \lesssim 2\times 10^{-3}$: unnatural $f_{\mathsf{TC}} \gtrsim 5\,\mathsf{TeV}$.

Suppressed if $G_{\mathsf{gl}} \to H_{\mathsf{gl}} \supset \mathsf{SU}(2)_L \otimes \mathsf{SU}(2)_R \to \mathsf{SU}(2)$. Minimal realizations:

G_{TC}	$\mathsf{SU}(N)_{\mathsf{TC}}$	$\mathsf{SO}(N)_{\mathsf{TC}}$	$\mathsf{Sp}(N)_{\mathsf{TC}}$
$\mathcal{F}$	$\mathcal{F}_L \oplus \mathcal{F}_{E^c} \oplus \mathcal{F}_N$	$\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N$	$2_0 \oplus 1_{1/2} \oplus 1_{-1/2}$
$G_{\mathsf{gl}} \to H_{\mathsf{gl}}$	$\mathsf{SU}(4)_L \otimes \mathsf{SU}(4)_R \to \mathsf{SU}(4)$	$\mathsf{SU}(5) \to \mathsf{SO}(5)$	$\mathsf{SU}(4) \to \mathsf{Sp}(4)$
TCπ	$2(2,2) \oplus 1 \oplus 3_L \oplus 3_R$	$(1,1) \oplus (2,2) \oplus (3,3)$	$(2,2) \oplus (1,1)$
$\mathcal{S}$	$\mathcal{S}_L \oplus \mathcal{S}_{E^c} \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$
$G_{\mathsf{gl}} \to H_{\mathsf{gl}}$	$\mathsf{SU}(4) \to \mathsf{SU}(2)_L \otimes \mathsf{SU}(2)_R$	$\mathsf{SO}(5) \to \mathsf{SO}(4)$	$\mathsf{Sp}(6) \to \mathsf{Sp}(4) \otimes \mathsf{Sp}(2)$
if $\langle \mathcal{S}\mathcal{S} \rangle \propto$	diag $(0,0,1,1)$	diag $(0,0,0,0,1)$	$\varepsilon \otimes$ diag $(0,0,1)$
TCπ	$2 \times (2,2) \oplus (1,1)$	$(2,2)$	$2(2,2)$

$\mathcal{F}_L$ means TC-fermions with the same SM quantum numbers as SM L, etc.

One $(2,2)$ is ok. Two $(2,2)$ ok if vevs aligned.

Custodial symmetry for $Z \to b\bar{b}$

To get y_t, $Q = (t_L, b_L)$ must significantly mix with a composite $\mathcal{B}$ which can have crappy couplings to the Z, so $\delta g_{b_L} \sim y_Q^2 v^2/\Lambda_{\rm TC}^2 \lesssim$ few 10^{-3}: $\Lambda_{\rm TC} \gtrsim 5$ TeV.

Pomarol et al. showed how to implement extra custodial symmetries in $\mathscr{L}_{\rm eff}$: $\mathcal{B}$ must form a degenerate bidoublet of $\mathrm{SU}(2)_L \leftrightarrow \mathrm{SU}(2)_R$ ... bla bla...
... the cure is a theoretical perversion worse than the mild disease?

It is automatic in $\mathrm{SO}(N)_{\rm TC}$ with $\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N$ and $|m_L - m_{L^c}| \ll \Lambda_{\rm QCD}$. Adding $\mathcal{S}_{U^c}$ they couple to Q and U giving y_t, and $\mathcal{B} = \mathcal{F}\mathcal{S}$ make a protected bidoublet.

The 3 pillars of Fundamental Composite H

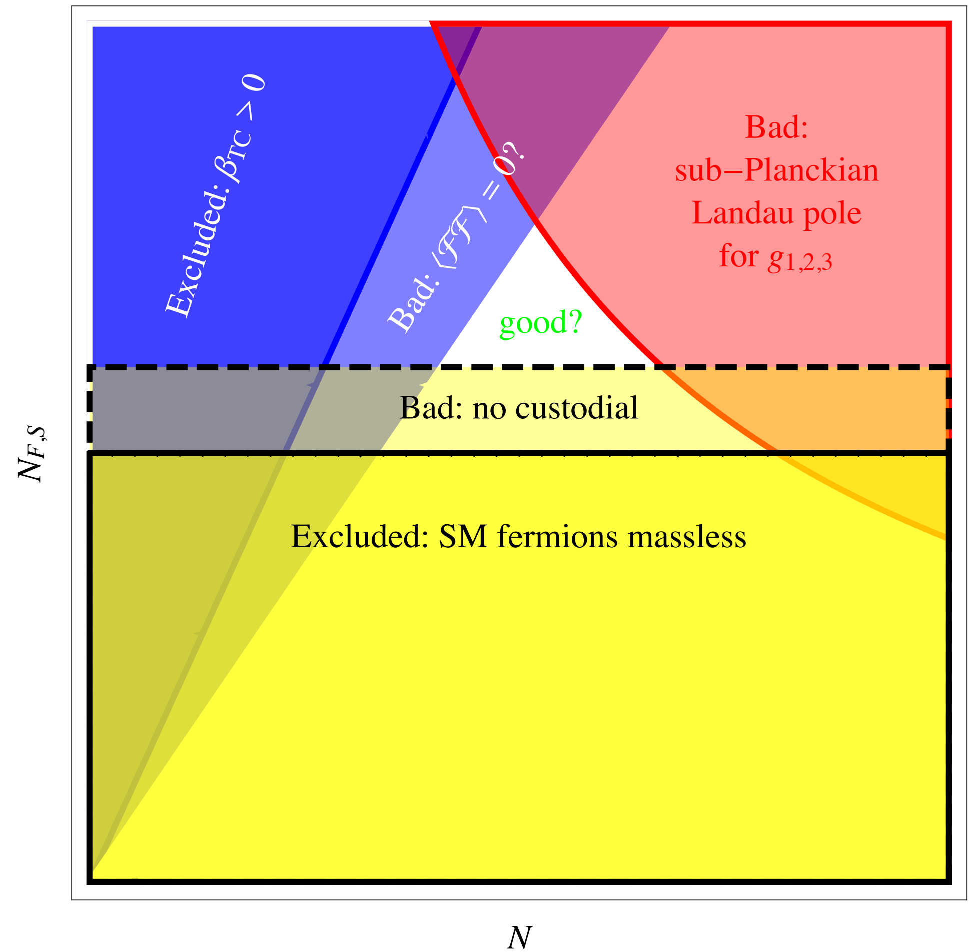
1) $G_{\rm TC}$ must be asymptotically free and form condensates:

$$N \gtrsim \begin{cases} \dfrac{3(4N_F+N_S)}{44} & \mathrm{SU}(N)_{\rm TC} \\ \dfrac{3(4N_F+N_S)}{44}+2 & \mathrm{SO}(N)_{\rm TC} \\ \dfrac{3(2N_F+N_S)}{22}-2 & \mathrm{Sp}(N)_{\rm TC} \end{cases}$$

2) No sub-Planckian Landau poles:

$$b_3 \lesssim 1.9\,, \qquad b_2 \lesssim 5.3\,, \qquad b_1 \lesssim 10$$

3) Each L, D, U, Q, E must get mass trough TC-Yukawas. And possibly custodial for T, maybe for $Zb\bar{b}$. Or for M_h.



These conditions might exclude all models

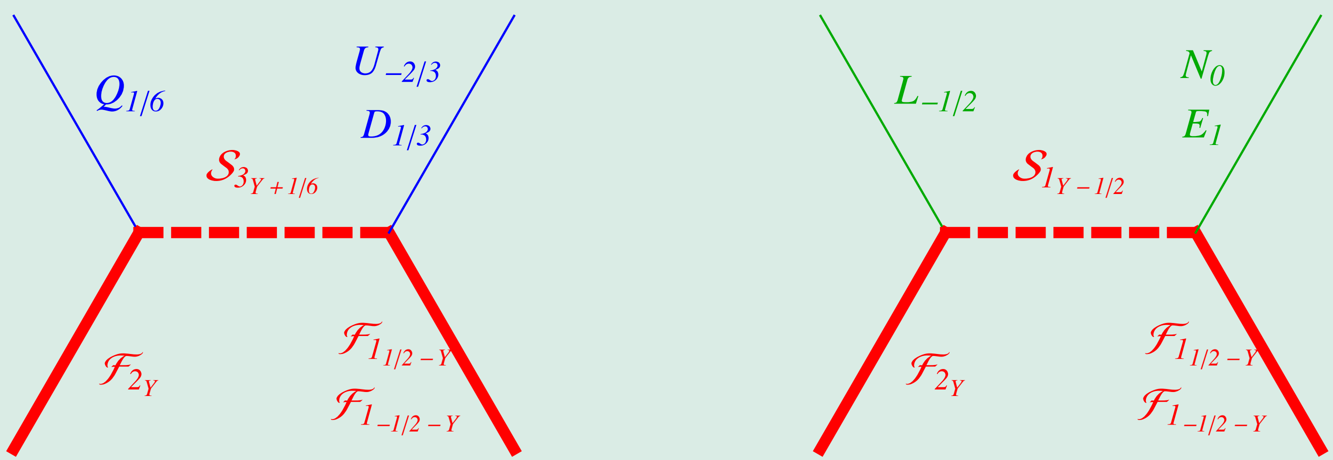
Do models exist?

Adding a TCfermion for each SM fermion is bad. More minimal $\sqrt{f}$ needed.

The good structure is SU(2)$_R$-like: same scalar coupled to U, D and to E, N

$$\mathscr{L}_Y \sim (Q\mathcal{F}\mathcal{S}_q^* + (\,U, D\,)\,\mathcal{F}^c\mathcal{S}_q) + (L\mathcal{F}\mathcal{S}_\ell^* + (\,E, N\,)\,\mathcal{F}^c\mathcal{S}_\ell)$$

SM-like miracle keeps fields minimal and implies custodial. For generic Y:



Model 1

Set $Y = -1/2$, get $\text{SU}(5)_{\text{GUT}}$ fragments $(\mathcal{F}_{L^c} \oplus \mathcal{F}_{E^c} \oplus \mathcal{F}_N) \oplus 3 \times (\mathcal{S}_{E^c} \oplus \mathcal{S}_{D^c})$ i.e.

name	spin	generations	$\text{SU}(3)_c$	$\text{SU}(2)_L$	$\text{U}(1)_Y$	G_{TC}
$\mathcal{F}_N$	1/2	N_{g_F}	1	1	0	N
$\mathcal{F}^c_N$	1/2	N_{g_F}	1	1	0	$\bar{N}$
$\mathcal{F}_L$	1/2	N_{g_F}	1	2	$-1/2$	N
$\mathcal{F}^c_L$	1/2	N_{g_F}	1	2	$+1/2$	$\bar{N}$
$\mathcal{F}_{E^c}$	1/2	N_{g_F}	1	1	-1	N
$\mathcal{F}^c_{E^c}$	1/2	N_{g_F}	1	1	$+1$	$\bar{N}$
$\mathcal{S}_{E^c}$	0	N_{g_S}	1	1	-1	N
$\mathcal{S}_{D^c}$	0	N_{g_S}	3	1	$-1/3$	N

$$\mathscr{L}_Y = y_L\ L\mathcal{F}_L\mathcal{S}^*_{E^c} + y_E\ E\mathcal{F}^c_N\mathcal{S}_{E^c} + (y_D\ D\mathcal{F}^c_N + y_U\ U\mathcal{F}^c_{E^c})\mathcal{S}_{D^c} + y_Q\ Q\mathcal{F}_L\mathcal{S}^*_{D^c} + \text{h.c.}$$

$$V = \lambda_E|S_{E^c}|^4 + \lambda_{ED}|S_{E^c}|^2\text{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}^\dagger_{D^c}) + \lambda_D\text{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}^\dagger_{D^c})^2 + \lambda'_D\text{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}^\dagger_{D^c}\mathcal{S}_{D^c}\mathcal{S}^\dagger_{D^c})$$

Model 1

β-functions ok for SU(2)$_{\rm TC}$ = Sp(2)$_{\rm TC}$ and SU(3)$_{\rm TC}$

For $N = 3$ no extra $\mathcal{F}\mathcal{F}\mathcal{S}, \mathcal{S}^3$ couplings are allowed

5 accidental U(1): B, L (like in the SM) + TCB ($\mathcal{F}_N^3$ as DM?) + 2 less relevant.

$$\mathrm{TC}\pi = 2 \times (1,1)_0 \oplus (1,3)_0 \oplus [(1,1)_1 \oplus 2 \times (1,2)_{-1/2} + \text{h.c.}]$$

If $\mathcal{S}$ heavy: $\mathcal{F}\mathcal{F}$ Higgs coupled to SM fermions.
If $\mathcal{F}$ heavy: $\mathcal{S}\mathcal{S}$ lepto-quarks coupled to $\bar{Q}\gamma_\mu L$, $\bar{D}\gamma_\mu E$.

T protected if $H \sim \mathcal{F}_L \bar{\mathcal{F}}_N$ has EW vev aligned with $H' \sim \mathcal{F}_L \bar{\mathcal{F}}_{E^c}$.

5 other models

Set $Y = 1/2$, get other SU(5)$_{\rm GUT}$ fragments $(\mathcal{F}_{L^c} \oplus \mathcal{F}_E \oplus \mathcal{F}_N) \oplus 3 \times (\mathcal{S}_N \oplus \mathcal{S}_{U^c})$.
β ok for $N = 3$ but extra terms $\mathcal{F}_N \mathcal{F}_N \mathcal{S}_N$ and S_N^3 break TCB and $\Delta L = 3$.

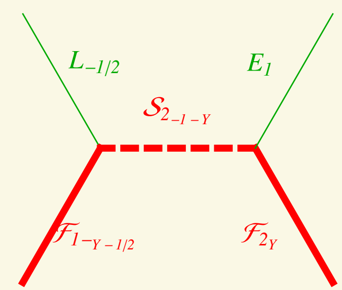
Set $Y = 0$, exotic TCparticles $(\mathcal{F}_{2_0} \oplus \mathcal{F}_{1_{\pm 1}}) \oplus 3(\mathcal{S}_{1_1} \oplus \mathcal{S}_{3_{1/6}})$; normal composites, reality allows Sp(2...14)$_{\rm TC}$ with minimal custodial SU(4) $\to$ Sp(4). TCB decay.

Model with scalar doublet:

$$(\mathcal{F}_L \oplus \mathcal{F}_{E^c} \oplus \mathcal{F}_N) \oplus 3 \times (\mathcal{S}_{L^c} \oplus \mathcal{S}_{D^c})$$

$$\mathscr{L}_Y = y_L \, L \mathcal{F}_N^c \mathcal{S}_{L^c} + y_E \, E \mathcal{F}_L \mathcal{S}_{L^c}^* + (y_D \, D \mathcal{F}_N^c + y_U \, U \mathcal{F}_{E^c}^c) \mathcal{S}_{D^c} + y_Q \, Q \mathcal{F}_L \mathcal{S}_{D^c}^* + \text{h.c.}$$

Lepto-quarks coupled to $\bar{D} \gamma_\mu L$ and $\bar{E} \gamma_\mu Q$.



Fully protected model: need SO(N) with $(\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N) \oplus 3 \times (\mathcal{S}_{U^c} \oplus \mathcal{S}_{D^c} \oplus \mathcal{S}_E)$.

$$\mathscr{L}_Y = y_L \, L \mathcal{F}_L \mathcal{S}_E + y_E \, E \mathcal{F}_N \mathcal{S}_E^* + y_D \, D \mathcal{F}_N \mathcal{S}_{D_c} + y_U \, U \mathcal{F}_N \mathcal{S}_{U_c} + (y_Q \, \mathcal{F}_{L^c} \mathcal{S}_{U_c}^* + y'_Q \, \mathcal{F}_L \mathcal{S}_{D_c}^*) Q + \text{h.c.}$$

β functions are bad, but not too bad for $N = 5$: $\beta_{\rm TC}$ negative but small, Landau pole for g_1 at 10^{14} GeV. $\mathbb{Z}_2$ keeps lightest TCB stable: $\mathcal{F}_L \mathcal{F}_{L^c} \mathcal{F}_N^3$ DM?

Scalar model: $3\mathcal{F}_N \oplus \mathcal{S}_L \oplus \mathcal{S}_{E^c} \oplus \mathcal{S}_{U^c} \oplus \mathcal{S}_{D^c} \oplus \mathcal{S}_Q$, ok for SU(2...9) and Sp(2...8).
TC$\pi \sim \mathcal{S}\mathcal{S}$ can contain custodially protected H if appropriate condensates.
Lightest DM stable at renormalizable level for $N \geq 5$.

The top Yukawa coupling

$y_t \sim y_Q y_U / g_{\mathrm{TC}}$ needs $y_Q \sim 1$, $y_U \sim g_{\mathrm{TC}}$: is this possible? Yes, the RGE are:

$$(4\pi^2)\frac{\partial g_{\mathrm{TC}}}{\partial \ln \mu} = b g_{\mathrm{TC}}^3, \qquad (4\pi^2)\frac{\partial y_f}{\partial \ln \mu} = f_f y_f^3 - f_g g_{\mathrm{TC}}^2 y_f,$$

where

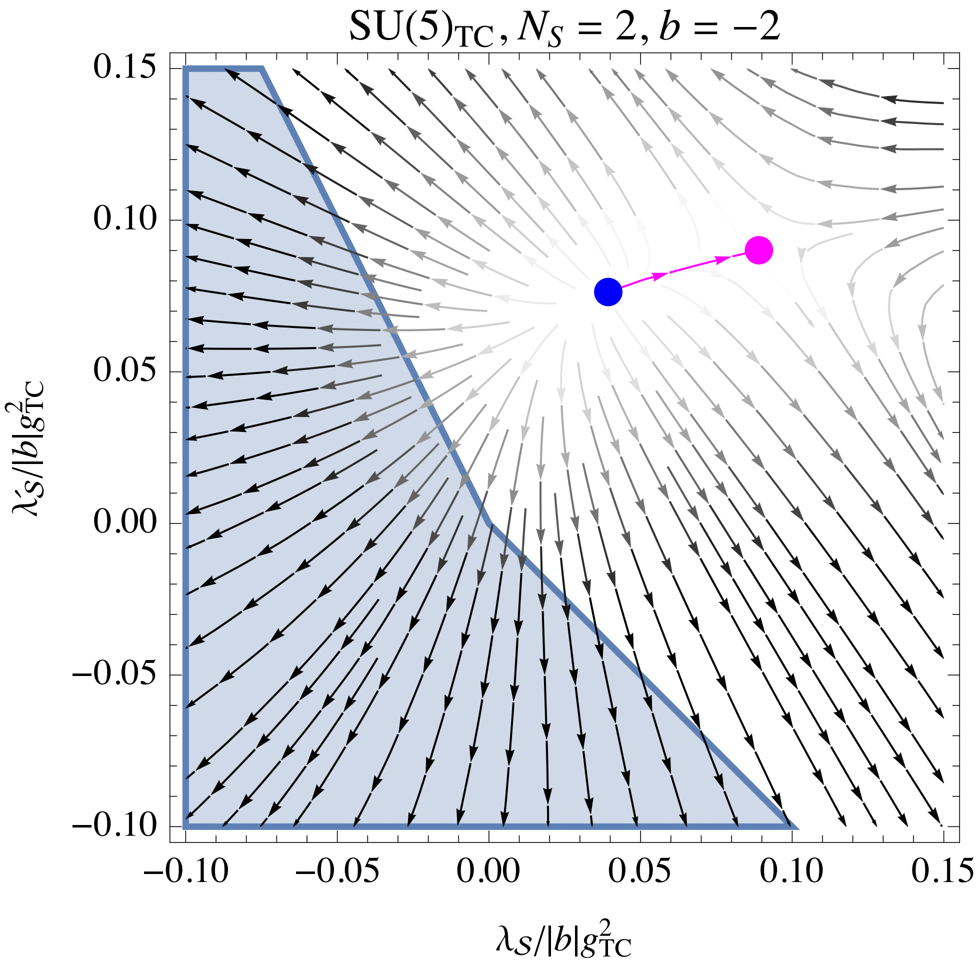
$$f_f = \frac{N + 2n_f + 1}{2}, \qquad f_g = 6C_N = 6\begin{cases} (N^2-1)/2N & \text{for } G_{\mathrm{TC}} = \mathrm{SU}(N) \\ (N-1)/2 & \text{for } G_{\mathrm{TC}} = \mathrm{SO}(N) \\ N(N+1)/4N & \text{for } G_{\mathrm{TC}} = \mathrm{Sp}(N) \end{cases}$$

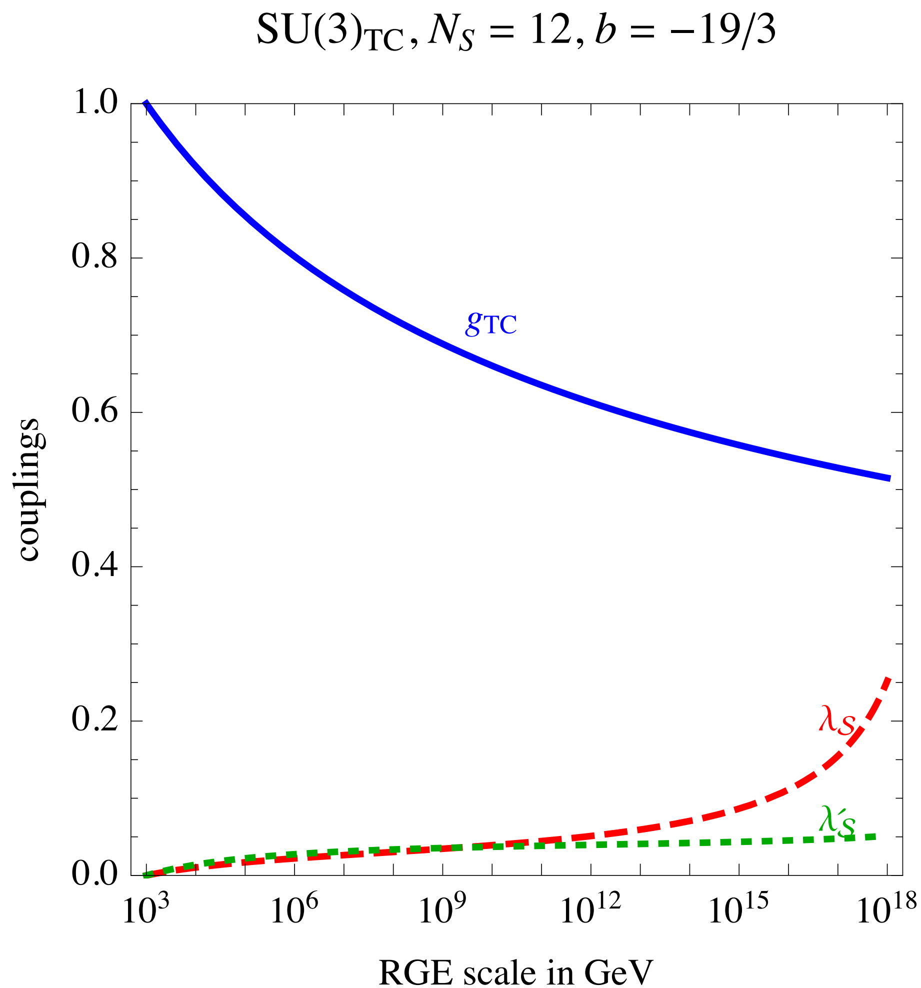
Quasi-fixed point: $y_f = g_{\mathrm{TC}}\sqrt{(f_g + b)/f_f} \sim g_{\mathrm{TC}}$.

Heavy top partners have $M \sim \Lambda_{\mathrm{TC}}$, up to TC-Yukawa repulsion.

The TCscalar quartics

$(4\pi)^2\beta_\lambda \sim +\lambda^2 + g^4_{\rm TC} - \lambda g^2_{\rm TC}$ means that $\lambda \sim \pm g^2_{\rm TC}$ can run big and negative.
Explicit computation finds IR fixed points with $\lambda \sim +g^2_{\rm TC}$.
Away from them, numerical runnings show that λ can remain small.





Lattice needed to know what happens

The Higgs potential

Computable! Use chiral Lagrangian techniques.

$$\mathcal{F}\mathcal{F} = f_{\rm TC}^2 \Lambda_{\rm TC} \mathcal{U}, \qquad \mathcal{U} = \exp \frac{2i\Pi}{f_{\rm TC}} \qquad \Lambda_{\rm TC} \sim g_{\rm TC} f_{\rm TC} \sim 4\pi f_{\rm TC}$$

3 contributions:

1. From TC-fermion masses (neglected in effective theories);
2. From SM gauge interactions;
3. From Yukawa interactions (at order $y_Q^2 y_U^2$, no y_U^2).

Result: one can tune a small M_h:

$$-M_h^2 \sim c_m \left(\sum m_{\mathcal{F}_i}\right) \Lambda_{\rm TC} + \left(c_g \frac{3(3g_2^2 + g_Y^2)}{64\pi^2} - c_y \frac{3y_t^2}{16\pi^2} \right) \Lambda_{\rm TC}^2$$

$$\lambda_H \sim \frac{c_y y_Q^2 y_U^2}{4(4\pi)^2} - \frac{c_g g_{\rm TC}^2 (3g_2^2 + g_Y^2)}{16(4\pi)^2} \sim \frac{y_t^2}{N}$$

The flavour of Higgs cousins

Spurionic structure similar to SM:

Coupling	Flavor symmetry of SM fermions					Flavor of TC-scalars	
	U(3)$_L$	U(3)$_E$	U(3)$_Q$	U(3)$_U$	U(3)$_D$	U(3)$_{\mathcal{S}_{E^c}}$	U(3)$_{\mathcal{S}_{D^c}}$
y_L	3	1	1	1	1	3	1
y_E	1	3	1	1	1	$\bar{3}$	1
y_Q	1	1	3	1	1	1	3
y_U	1	1	1	3	1	1	$\bar{3}$
y_D	1	1	1	1	3	1	$\bar{3}$
$m^2_{\mathcal{S}_E}$	1	1	1	1	1	$3 \otimes \bar{3}$	1
$m^2_{\mathcal{S}_D}$	1	1	1	1	1	1	$3 \otimes \bar{3}$
λ_E	1	1	1	1	1	$(3 \otimes \bar{3})^2$	1
$\lambda_{D,D'}$	1	1	1	1	1	1	$(3 \otimes \bar{3})^2$
λ_{ED}	1	1	1	1	1	$3 \otimes \bar{3}$	$3 \otimes \bar{3}$

Mixing matrices: (3 in y_f) + (2 in $m^2_{\mathcal{S}}$) + (more in quartics). SM Yukawas:

$$y_{ff'} \approx y_f \cdot \ell\left(\frac{f_{\mathrm{TC}}\Lambda_{\mathrm{TC}}}{m^2_{\mathcal{S}}}\right) \cdot y^T_{f'} \qquad \ell = \text{TC-loop function}$$

Dipoles

$$d_{LE}^{ij}(L_i\gamma_{\mu\nu}E_j)V_{\mu\nu}, \qquad \text{with} \qquad d_{LE} = \frac{g_{\rm SM}v}{g_{\rm TC}\Lambda_{\rm TC}^2} y_L \cdot \tilde{\ell}(\frac{\Lambda_{\rm TC}^2}{m_{\mathcal{S}}^2}) \cdot y_E^T$$

In general $\ell \neq \tilde{\ell}$ giving $d_e \sim e m_e/\Lambda_{\rm TC}^2$, 10^5 above the bound.

If $m_{\mathcal{S}}^2, \lambda \propto \mathbb{I}$ (e.g. zero) $d_{LE} \propto y_{LE}$ up to small corrections.

$$d_{LE} \sim \frac{g_{\rm SM}}{g_{\rm TC}} \frac{v}{\Lambda_{\rm TC}^2} y_L \cdot X \cdot y_E^T \qquad \text{with} \qquad X = \frac{(y_L^\dagger y_L)}{g_{\rm TC}^2}, \frac{(y_E^\dagger y_E)^T}{g_{\rm TC}^2}$$

$\Lambda_{\rm TC} \sim 1\,{\rm TeV}$ allowed. $\mu \to e\gamma$ and $h \to \tau\bar{\mu}$ are similarly suppressed.

Quark sector gives $d_{LE} \propto (y_L y_E^T) T$ with

$$\text{Im}\, T \sim \frac{1}{g_{\rm TC}^6} \text{Im Tr}\,[(y_Q^\dagger y_Q)^T (y_U^\dagger y_U)(y_D^\dagger y_D)] \sim \frac{y_t^2 y_b^2 V_{cb}^2}{g_{\rm TC}^2}$$

$$\text{Im}\ T = \frac{1}{g_{\rm TC}^{12}} \text{Im} Tr[(y_Q^\dagger y_Q)^2 (y_U^\dagger y_U)^{T2} (y_Q^\dagger y_Q)(y_U^\dagger y_U)^T] \sim \frac{y_t^4 y_c^2 V_{cb} V_{ub} V_{us}}{g_{\rm TC}^6}.$$

4–fermion operators

$$\sim \frac{(y_f^\dagger y_f)_{ij}(y_{f'}^\dagger y_{f'})_{i'j'}}{g_{\mathsf{TC}}^2 m_{\mathcal{S}}^2}(\bar{f}_i\gamma_\mu f'_{j'})(\bar{f}'_{i'}\gamma_\mu f_j) \qquad \text{for any } f, f' = \{L, E, Q, U, D\}.$$

E.g. $y_d y_s(\bar{s}_R d_L)(\bar{s}_L d_R)/\Lambda_{\mathsf{TC}}^2$: bound from ϵ_K satisfied.

Plus $(\bar{L}\gamma_\mu Q)(\bar{E}\gamma_\mu D)$ in the minimal model as characteristic of lepto-quarks.

TC-penguins: ok.

Extensions: GUT?

Example of disaster model. $\mathrm{SU}(5)_{\mathrm{GUT}}$ suggests

$$\mathcal{F}_{\bar{5}} \oplus \bar{\mathcal{F}}_1 \oplus 3\mathcal{S}_5$$

β-functions ok, each SM fermion has a Yukawa: $\bar{5}\mathcal{F}_1^c\mathcal{S}_5 + 10\,\mathcal{F}_{\bar{5}}\mathcal{S}_5^*$.
But up quarks remain massless, and B, L are violated (10 unifies Q, U).

"Subtract composite t_R". ????

Extensions: SUSY?

- A SUSY version would be conventionally natural
- TC-scalars = TC-fermions $\Rightarrow$ restricted flavor structure $y_{ifg}\Phi^i_{\mathsf{SM}}\Phi^f_{\mathsf{TC}}\Phi^g_{\mathsf{TC}}$.

I don't find any model with fully good β functions above m_{SUSY}.

Conclusions

Abandoning scalarphobia, one can build fundamental theories of composite Higgs that are almost as good as the SM.

PS

"We refrain from speculating whether it might explain the 750 GeV diphoton excess"