Composite Higgs models

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in collaboration with **G. Durieux, C. Grojean, L. Lima,**

and O. Matsedonskyi. Based on *arXiv:1703.10624.*

The Standard Model is very strong, but it cannot explain all observations

Planck scale

valid up to

TeV scale

Composite Higgs models

(very good candidates for new physics)

- No hierarchy problem because the Higgs is a bound state,
- This is lighter than the new physics scale (presumably slightly above the TeV) because is a Goldstone of $\mathcal{G}/\mathcal{H}$,
- Fermion masses are induced by non-hierarchical couplings in the UV,

(almost) a high-energy copy of QCD

The composite Higgs paradigm

(a high-energy copy of QCD)

UV

GeV scale

IR

$$L \sim m_q \, \overline{q_L} q_R + SU(2)_L \times SU(2)_R$$

The composite Higgs paradigm

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TeV scale

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$$L \sim \lambda[\Lambda_{UV}]\overline{q_i}\mathcal{O}_F^{d_i} + \text{ new global}\,\mathcal{G}$$

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parton condensate

$$L \sim \lambda[\text{TeV}]\overline{q_i}Q^i$$

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$$\mathcal{H} \supset \mathcal{G}_{SM}$$

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$$h, S, \cdots \qquad \mathcal{H} \supset \mathcal{G}_{SM}$$

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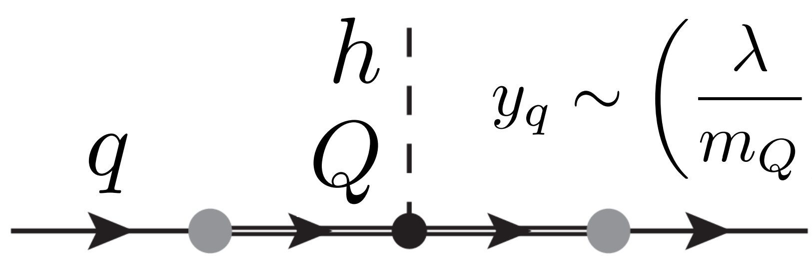

$$y_q \sim \left(\frac{\lambda}{m_Q}\right)^2$$

$$\mathcal{H} \supset \mathcal{G}_{SM}$$

Source of breaking: $L \sim \lambda[\mathrm{TeV}]\overline{q_i}Q^i$

(driven mainly by the top mixing)

- Sigma model Lagrangian + symmetry-breaking terms

$$-\frac{c_6}{f^2}(H^\dagger H)^3 + \frac{c_y^{ij}}{f^2}(H^\dagger H\overline{\psi_L^i}H\psi_R^j) + \cdots$$

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Non-minimal composite Higgs models

(even better candidates for new physics)

- No hierarchy problem because the Higgs is a bound state,
- This is lighter than the new physics scale (presumably slightly above the TeV) because is a Goldstone of $\mathcal{G}/\mathcal{H}$,
- Fermion masses are induced by non-hierarchical couplings in the UV,

provide dark matter candidates, explanation for baryon anti-baryon asymmetry, feasible UV completions...

Non-minimal composite Higgs models

(table taken from Bellazzini *et al*, 1401.2457)

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}$ $(\mathbf{r}_{SU(2)\times U(1)})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[SU(2)]^2 \times U(1)$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2 \cdot (\mathbf{2},\mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2 \cdot (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3 \cdot (\mathbf{2},\mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2 \cdot (\mathbf{2},\mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \cdot (\mathbf{2},\mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3 \cdot (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2 \cdot (\mathbf{2},\mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$	[34]
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3 \cdot \mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2 \cdot (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3 \cdot (\mathbf{1},\mathbf{1})$	[30, 47]
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2 \cdot (\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$	[36]

Source of breaking: $L \sim \lambda[\mathrm{TeV}]\overline{q_i}Q^i$

(driven mainly by the top mixing)

- Coefficients estimated via SILH formalism *[hep-ph/0703164]*

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$$-\frac{c_6}{f^2}(H^\dagger H)^3 + \frac{c_y^{ij}}{f^2}(H^\dagger H\overline{\psi_L^i}H\psi_R^j) + \cdots$$

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$$L \sim \frac{c_S^1}{2f^2}[\partial_\mu(S^2)]^2 + \frac{c_S^2}{2f^2}(S^\dagger\partial_\mu S)^2$$

$$-\frac{c_S^2}{f^2}(S^{2,3,\cdots}) + \frac{c_S^{ij}}{f}(S\overline{\psi_L^i}H\psi_R^j) + \cdots$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

- 1S1C $(f, g_\rho; m_\rho = g_\rho f)$ + dimensional analysis determines the scaling of the effective operators, *[1506.01961]*
- Operator coefficients of order one, up to selection rules
- It is actually an assumption, but is not an arbitrary one

$$m_\rho^2 f^2 \left[\frac{N_c y_t^2}{(4\pi)^2}\right]^{\#_{\not{L}}} \left[\frac{N_f g_\rho^2}{(4\pi)^2}\right]^{\#_L} \left[\frac{y_q \bar{q} q}{m_\rho^2 f}\right]^{\#_{\bar{q}q}} \left[\frac{g_A A}{m_\rho}\right]^{\#_A} \left[\frac{S}{f}\right]^{\#_S} \left[\frac{H}{f}\right]^{\#_H} \left[\frac{\partial_\mu}{m_\rho}\right]^{\#_\partial}$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

- There is *a priori* no reason for the mass of S to be tuned. It is then expected that

$$m_S^2 \sim m_\rho^2 \frac{N_c y_t^2}{(4\pi)^2} \sim \frac{f^2}{v^2} m_h^2 \sim (500\,\mathrm{GeV})^2$$
$$\ll m_\rho^2$$

Concrete expression in calculable composite Higgs models

$SO(6)/SO(5)$

- $t_R \sim 1$,
- $q_L \sim \mathbf{20}$
  $\sim 1 + \mathbf{5} + \mathbf{14}$

$SO(7)/G_2$

- $t_R \sim 1$,
- $q_L \sim \mathbf{35}$
  $\sim 1 + \mathbf{7} + \mathbf{27}$

The coset $SO(6)/SO(5)$

(first studied in *0902.1483*)

$$V \sim f^2\left[c_1 - \frac{7}{4}c_2\right]h^2 + (c_2 - c_1)h^4$$

$$-c_2 f^2 S^2 + (c_2 - c_1)h^2 S^2$$

The coset $SO(6)/SO(5)$

(first studied in *0902.1483*)

$$V \sim \frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda_h h^4$$

$$+\frac{1}{3}\lambda_h f^2(1-2\epsilon)S^2 + \frac{1}{4}\lambda_h h^2 S^2$$

The coset $SO(7)/G_2$

(first studied in *1210.6208*)

$$V \sim \frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{3}\lambda_h f^2 \Delta^2 + \frac{1}{8}\lambda_h h^2 \Delta^2 + \cdots$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

$\rho \sim$ few TeV

S

H

EW scale

Strong sector

Integrating out S,

$S|H|^2, S\overline{q}Hq$

$$(a+b)|H|^2\overline{q}Hq$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

$\rho \sim$ few TeV

S, generic but lighter

H

EW scale

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$S|H|^2, S\overline{q}Hq$

$$(a+b)|H|^2\overline{q}Hq$$

A basis for the EFT of H+S

(regarding S, we focus on dimension 5)

- Caveat: eliminating operator redundancies can break the power counting estimates:

$$\frac{1}{f}|D_\mu H|^2 S \;\rightarrow\; \frac{1}{2f}|H|^2\Box S - \frac{1}{2f}(H^\dagger \Box H S + \text{h.c})$$

A basis for the EFT of H+S

(regarding S, we focus on dimension 5)

- Caveat: eliminating operator redundancies can break the power counting estimates.

- The operators are related. One of them can be removed

$$\mathcal{O}_1 = \frac{1}{f}|D_\mu H|^2 S \qquad \mathcal{O}_2 = \frac{i}{f}(H^\dagger D_\mu H)\partial^\mu S + \text{h.c.} \qquad \mathcal{O}_3 = \frac{1}{f}\partial_\mu |H|^2 \partial^\mu S$$

$$\mathcal{O}_4 = \frac{1}{f}(H^\dagger \Box H) S + \text{h.c.} \qquad \mathcal{O}_5 = \frac{1}{f}|H|^2 \Box S$$

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- It can be removed in favor of $\partial_\mu S \, \overline{q}\gamma^\mu q$

$$\mathcal{O}_1 = \frac{1}{f}|D_\mu H|^2 S \qquad \mathcal{O}_2 = \frac{i}{f}(H^\dagger D_\mu H)\partial^\mu S + \text{h.c.} \qquad \mathcal{O}_3 = \frac{1}{f}\partial_\mu |H|^2 \partial^\mu S$$

$$\mathcal{O}_4 = \frac{1}{f}(H^\dagger \Box H) S + \text{h.c.} \qquad \mathcal{O}_5 = \frac{1}{f}|H|^2 \Box S$$

A basis for the EFT of H+S

(regarding S, we focus on dimension 5)

- Caveat: eliminating operator redundancies can break the power counting estimates.
- We end up with the minimal set of operators

$SX^2 \quad , \quad S^{2,4}$	$S\vert D_\mu H\vert^2 \quad , \quad S^{3,5}$
$S\bar{q}Hq \quad , \quad S^2\vert H\vert^2$	$S\vert H\vert^2 \quad , \quad S\vert H\vert^4 \quad , \quad S^3\vert H\vert^2$

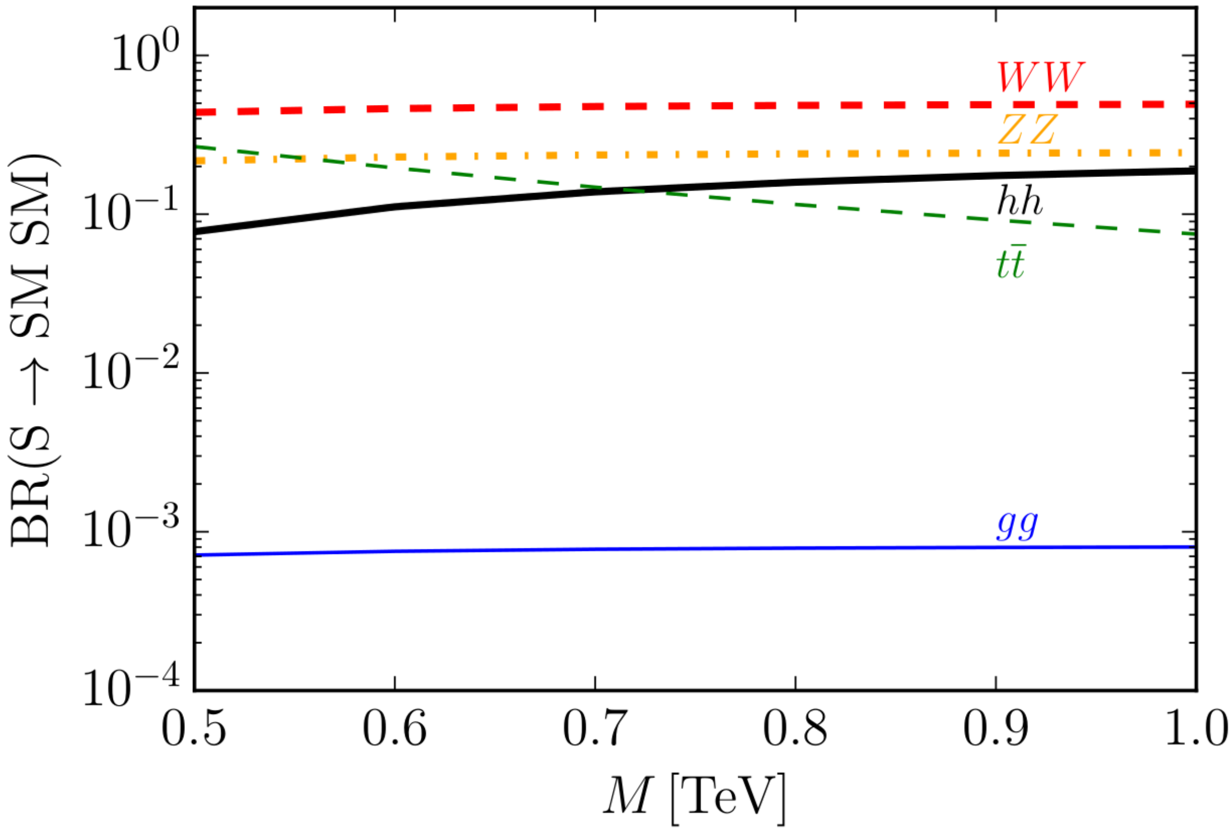
Estimated size of the dimension-5 operators

(cases beyond the PNGB one are also present)

	scalar		pseudo-scalar		
	generic	PNGB	generic	PNGB (PC)	PNGB (anom.)
$k_X\, SX^2$	$\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{g_X^2}{g_\rho^2}\frac{1}{f}$	$\frac{N_f^{(X)} g_X^2}{(4\pi)^2}\frac{1}{f}$
$k_q\, S\bar{q}Hq$	$y_q\frac{1}{f}$	$y_q\frac{1}{f}$	$iy_q\frac{1}{f}$	$iy_q\frac{1}{f}$	—
$k_H\, S\lvert D_\mu H\rvert^2$	$\frac{1}{f}$	—	—	—	—
$k_{H1}\, S\lvert H\rvert^2$, $k_{H2}\, S\lvert H\rvert^4/f^2$, $k_{H3}\, S^3\lvert H\rvert^2/f^2$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	—	—	—
$k_{H4}\, S^2\lvert H\rvert^2$	—	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$	$\frac{\tilde{N}_f g_\rho^2}{(4\pi)^2}\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f^2}$
$k_M\, S^2$, $k_4\, S^4/f^2$	m_ρ^2	$\frac{3y_t^2}{(4\pi)^2}m_\rho^2$	m_ρ^2	$\frac{3y_t^2}{(4\pi)^2}m_\rho^2$	$\frac{\tilde{N}_f g_\rho^2}{(4\pi)^2}m_\rho^2$
$k_3\, S^3$, $k_5\, S^5/f^2$	$\frac{m_\rho^2}{f}$	$\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{f}$	—	—	—

Impact on direct production of S

(PNGB scalar; the pseudoscalar goes to tt)



$$g_\rho = 4\pi$$

κ_i couplings set to 1

f and m_ρ are then fixed

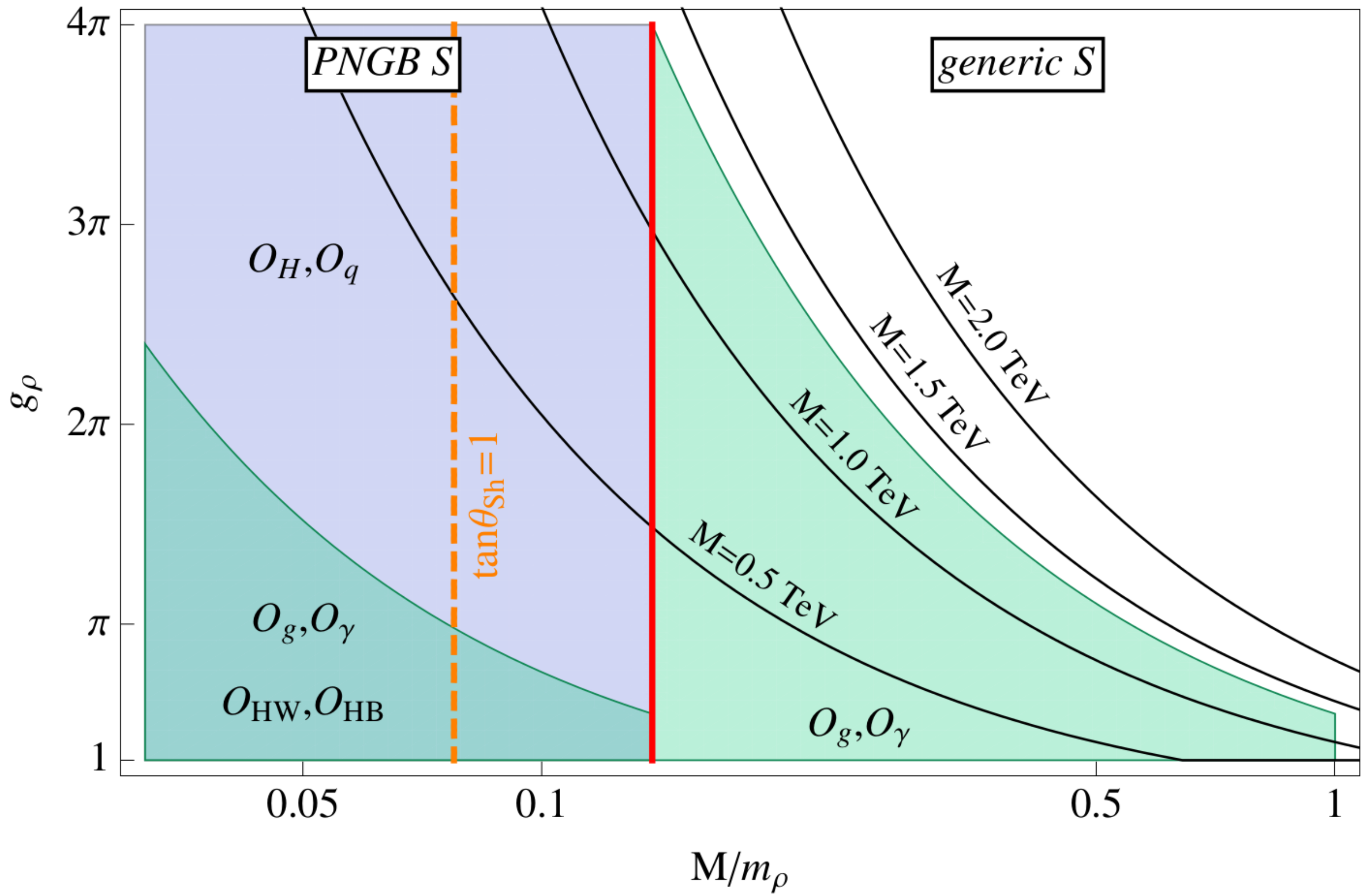
Impact on Higgs physics

(cases beyond the PNGB one are also present)

		effect of scalar S		compositeness effects [+MC]
		generic	PNGB	
$\mathcal{O}_g$	$\frac{g_S^2}{v^2}\lvert H\rvert^2 G_{\mu\nu}G^{\mu\nu}$	$k_g k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$k_g k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_g\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_\gamma$	$\frac{g'^2}{v^2}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$(k_W+k_B)k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$(k_W+k_B)k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_\gamma\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_W$	$\frac{ig}{2v^2}(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H)(D_\nu W^{\mu\nu})^i$	$4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_W\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_B$	$\frac{ig'}{2v^2}(H^\dagger\overleftrightarrow{D}_\mu H)(\partial_\nu B^{\mu\nu})$	$-4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$-4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_B\frac{1}{g_\rho^2}\xi$
$\mathcal{O}_{HW}$	$\frac{ig}{v^2}(D_\mu H)^\dagger\sigma^i(D_\nu H)W^{i\mu\nu}$	$-4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$-4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_{HW}\frac{1}{g_\rho^2}\xi\left[\frac{g_\rho^2}{(4\pi)^2}\right]$
$\mathcal{O}_{HB}$	$\frac{ig'}{v^2}(D_\mu H)^\dagger(D_\nu H)B^{\mu\nu}$	$4k_W k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$4k_W k_{H1}\frac{9y_t^4}{(4\pi)^4}\frac{1}{g_\rho^2}\frac{m_\rho^2}{M^2}\xi$	$c_{HB}\frac{1}{g_\rho^2}\xi\left[\frac{g_\rho^2}{(4\pi)^2}\right]$
$\mathcal{O}_q$	$\frac{1}{v^2}\bar{q}Hq\lvert H\rvert^2$	$y_q k_{H1}\left(k_q-\frac{k_H}{2}\right)\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$y_q k_{H1}k_q\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$c_q y_q\xi$
$\mathcal{O}_H$	$\frac{1}{2v^2}\partial_\mu\lvert H\rvert^2\partial^\mu\lvert H\rvert^2$	$k_{H1}\left(k_{H1}\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}-k_H\right)\frac{3y_t^2}{(4\pi)^2}\frac{m_\rho^2}{M^2}\xi$	$k_{H1}^2\frac{9y_t^4}{(4\pi)^4}\frac{m_\rho^4}{M^4}\xi$	$c_H\xi$

Impact on Higgs physics

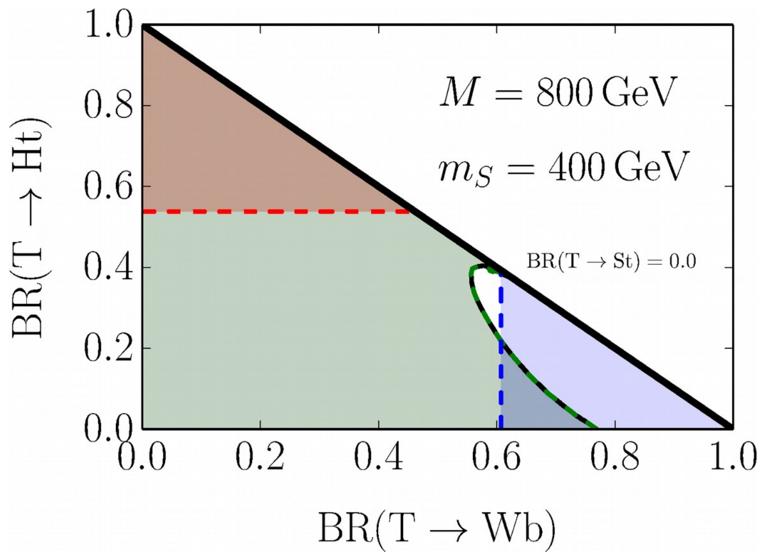
(cases beyond the PNGB one are also present)

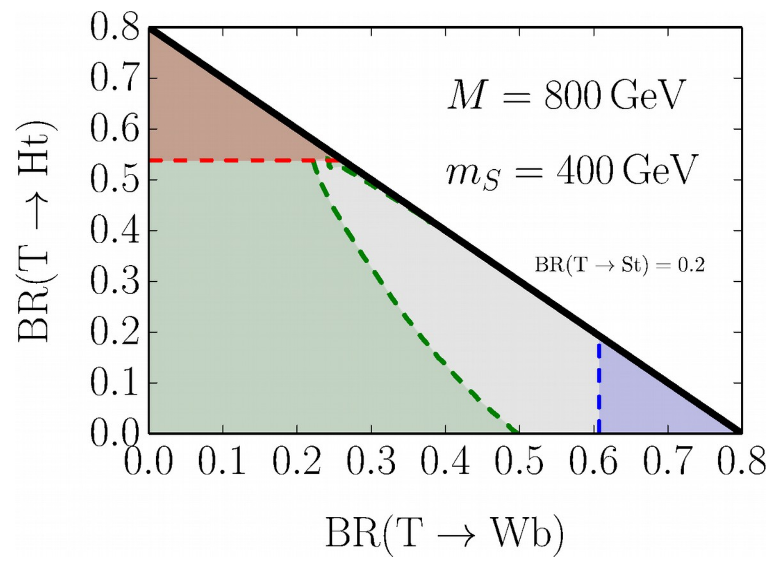


Limits on new vector-like quarks

(mainly QCD-produced top partners)

- Bounds considering all branching ratios (also elusive decays) in light of *1505.04306, ATLAS-2016-102, ATLAS-2016-104, ATLAS-2017-015, CMS-SUS-16-029*





Limits on new vector-like quarks

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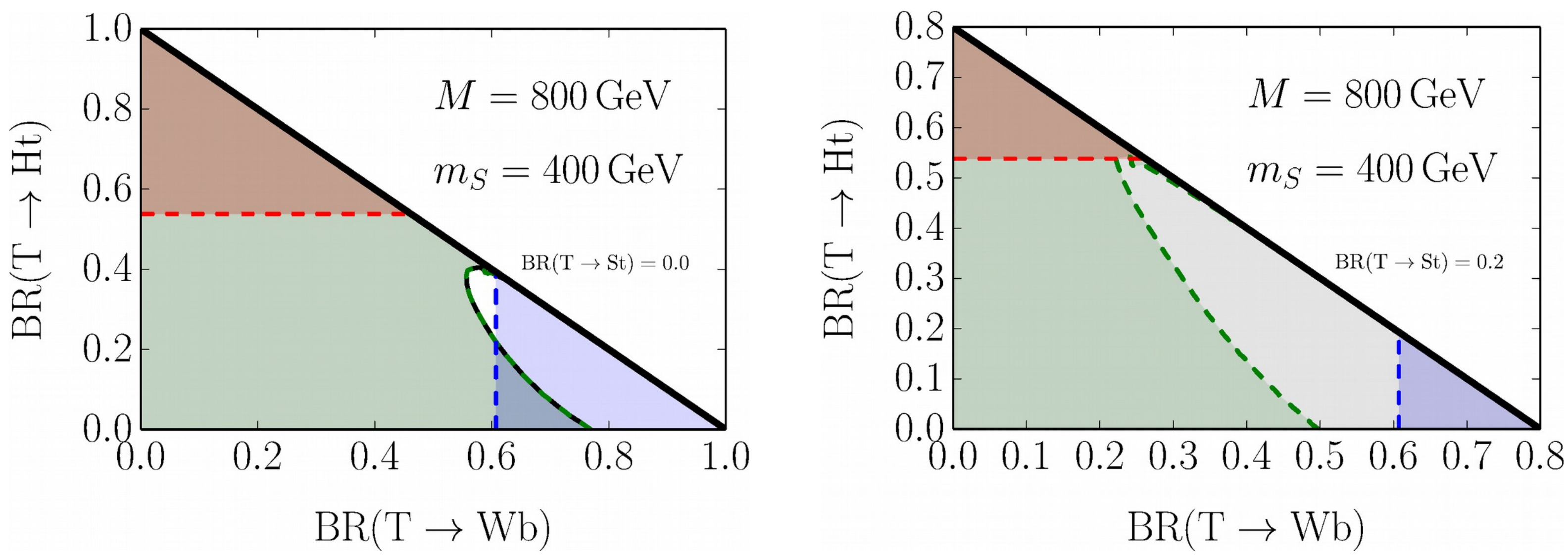
- Bounds can be automatically obtained using the VLQ-limits, available at *http://github.com/mikaelchala/vlqlimits*



Conclusions

- Non-minimal composite Higgs models are very good candidates for new physics
- Power counting estimates suggest that extra scalar singlets S are heavier than the Higgs boson
- We have worked out a basis of dimension-5 operators for S. Some redundant operators must be kept in order not to break the power counting
- The effects of S on Higgs physics can be larger than those coming from the strong sector

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- The effects of S on Higgs physics can be larger than those coming from the strong sector

Thank you very much for your attention!

Backup

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

- The form of the H+S potential can be obtained using the aforementioned power counting:

$$V \sim m_\rho^2 f^2 \frac{N_c y_t^2}{(4\pi)^2} \left[-\alpha \frac{|H|^2}{f^2} + \beta \frac{|H|^4}{f^4} \right]$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

- α and β have to be tuned in order to achieve the separation $v \ll f$. $\xi = v^2/f^2$ "measures" the tuning

$$V \sim m_\rho^2 f^2 \frac{N_c y_t^2}{(4\pi)^2} \left[-\alpha \frac{|H|^2}{f^2} + \beta \frac{|H|^4}{f^4} \right]$$

The EFT of next-to-minimal CHMs

(the scalar sector consists of H+S)

- α and β have to be tuned in order to achieve the separation $v \ll f$. $\xi = v^2/f^2$ "measures" the tuning

$$v = f\left(\frac{\alpha}{2\beta}\right)^{\frac{1}{2}} \,, \qquad m_h^2 \simeq \beta \frac{N_c y_t^2}{2\pi^2}\frac{v^2}{f^2} m_\rho^2$$

A basis for the EFT of H+S

(regarding S, we focus on dimension 5)

- Caveat: eliminating operator redundancies can break the power counting estimates.
- The reason is that the kinetic terms are not suppressed

$$\frac{y_t^2}{16\pi^2}\frac{m_\rho^2}{f}S|H|^2 \rightarrow \frac{1}{f}SH^\dagger\Box H \text{ or } \frac{1}{f}\Box S|H|^2$$

The composite Higgs paradigm

(a high-energy copy of QCD)

UV

GeV scale

IR

$$L \sim m_q \, \overline{q_L} q_R + SU(2)_L \times SU(2)_R$$

quark condensate

$$p, n, \Delta, \Sigma, \cdots$$

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(a high-energy copy of QCD)

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$$SU(2)_V$$

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quark condensate

$$p, n, \Delta, \Sigma, \cdots$$

$$\pi^0, \pi^\pm \qquad SU(2)_V$$