Extended composite Higgs models

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

and **O. Matsedonskyi**. Based on *1703.10624 and 1705.03013*

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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

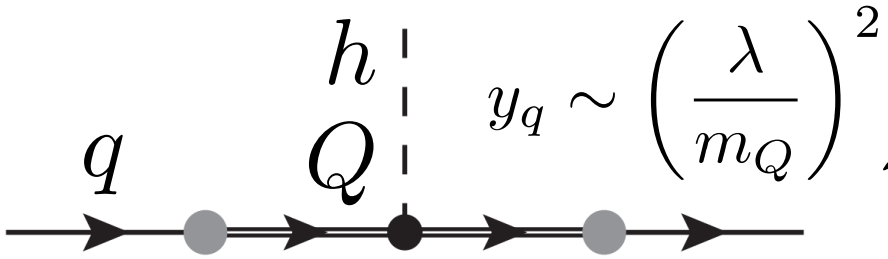
TeV scale

IR

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

parton condensate

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



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

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

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	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{\mathrm{SU}(2)\times\mathrm{SU}(2)}\,(\mathbf{r}_{\mathrm{SU}(2)\times\mathrm{U}(1)})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	11
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm\mathbf{1}/\mathbf{2}} + \mathbf{1}_{\mathbf{0}}$	10, 35
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	29, 47, 64
SU(4)	$[\mathrm{SU}(2)]^2 \times \mathrm{U}(1)$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm\mathbf{2}} = 2\cdot(\mathbf{2},\mathbf{2})$	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	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[\mathrm{SU}(2)]^3$	✓*	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	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\cdot(\mathbf{2},\mathbf{2})$	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
$[\mathrm{SU}(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_{\mathbf{0}} + \mathbf{2}_{\pm\mathbf{1}/\mathbf{2}} + \mathbf{3}_{\mathbf{0}}$	8
$[\mathrm{SO}(5)]^2$	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	$\mathbf{3}_{-\mathbf{1}/\mathbf{3}} + \bar{\mathbf{3}}_{+\mathbf{1}/\mathbf{3}} + \mathbf{1}_{\mathbf{0}} = 3\cdot\mathbf{1}_{\mathbf{0}} + \mathbf{2}_{\pm\mathbf{1}/\mathbf{2}}$	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
$[\mathrm{SO}(6)]^2$	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 *[Giudice, Grojean, Pomarol, Rattazzi, hep-ph/0703164]*

$$L \sim \frac{c_1}{f^2}[\partial_\mu(H^\dagger H)]^2 + \frac{c_2}{f^2}|H|^2|D_\mu H|^2$$
$$-\frac{c_3}{f^2}(H^\dagger H)^3 + \frac{c_4^{ij}}{f^2}(H^\dagger H\overline{\psi_L^i}H\psi_R^j) + \cdots$$

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$$-\frac{c_3}{f^2}(H^\dagger H)^3 + \frac{c_5^{ij}}{f}(S\overline{\psi_L^i}H\psi_R^j) + \cdots$$

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, *[Panico, Wulzer 1506.01961]*
- Operator coefficients of order one, up to selection rules
- It captures the features of many non-minimal CHMs

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

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

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

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

(Gripaios, Pomarol, Riva, Serra *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 $SO(6)/SO(5)$

(Gripaios, Pomarol, Riva, Serra *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 $SO(7)/G_2$

(MC *1210.6208;* Ballesteros, MC, Carmona *1704.07388*)

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

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

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

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.
- We end up with the minimal set of operators

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

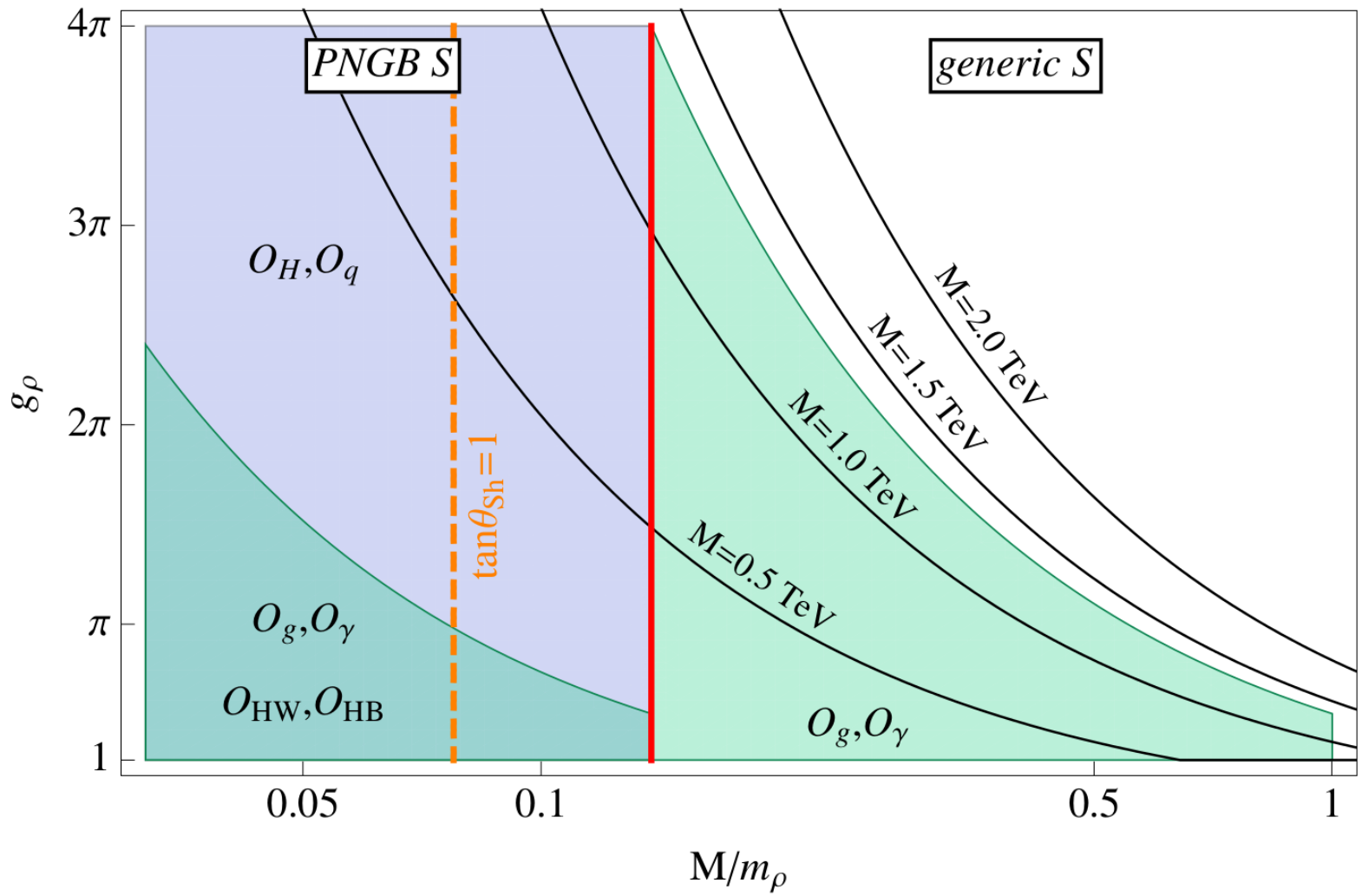
Estimated size of the dimension-5 operators

(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 Higgs physics

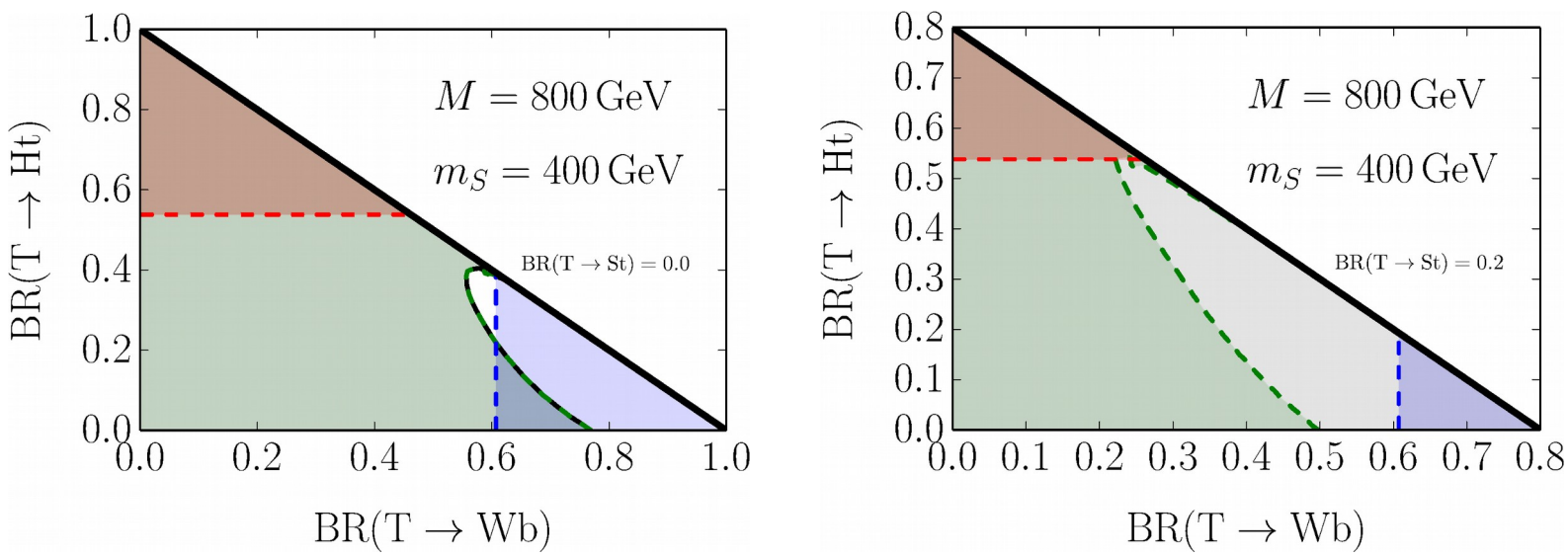
(cases beyond the PNGB one are also present)



Limits on new vector-like quarks

(MC *1705.03013;* see also Serra *1506.05110*)

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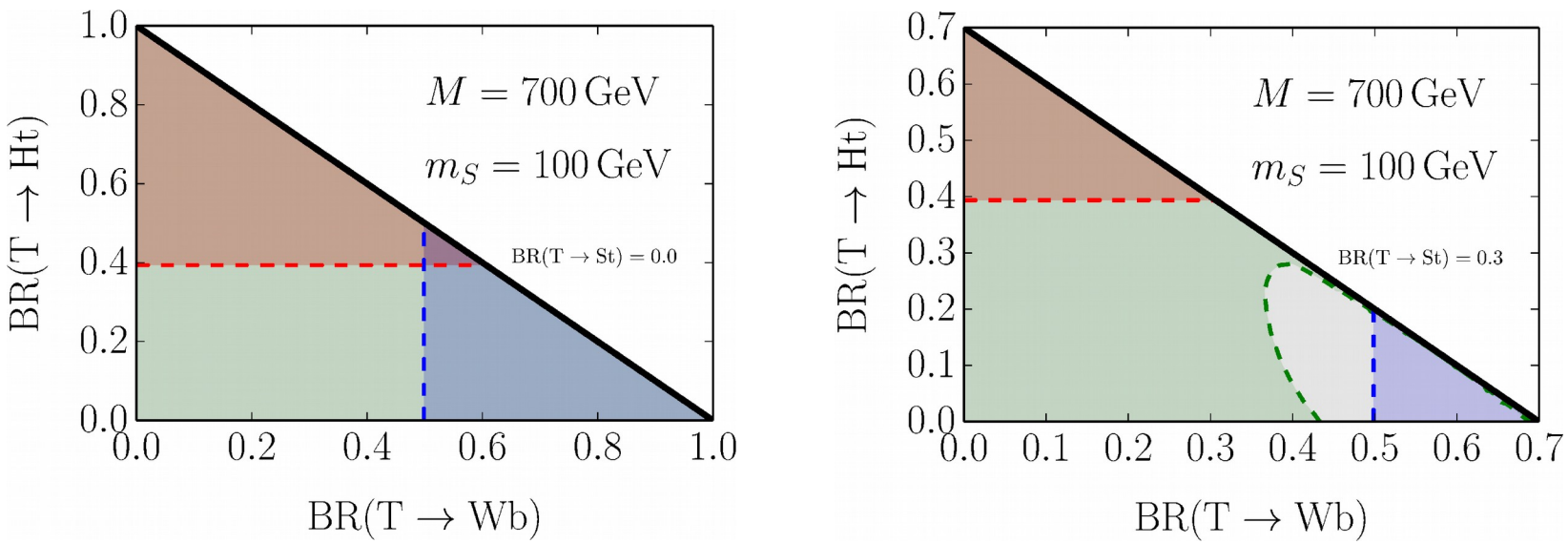
- Bounds can be automatically obtained using VLQ-limits, available at *http://github.com/mikaelchala/vlqlimits*



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
- VLQs are very different from what current analyses are searching for

Thank you very much

for your attention!

Backup