Top Quark Compositeness feasibility and implications

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Outline

Describe the composite top scenario in the framework of modern strongly-interacting theories of EWSB and give the main constraints and experimental signatures.

- Why the top ?
- Framework
- Feasibility
- Implications
- Conclusions

Why the top?

LEP → most fermions = point-like particles / not for the top

Why?

BSM sector responsible for EWSB + masses: (SM = without the Higgs)

✗ Weak coupling: fundamental Higgs + SUSY (naturalness),

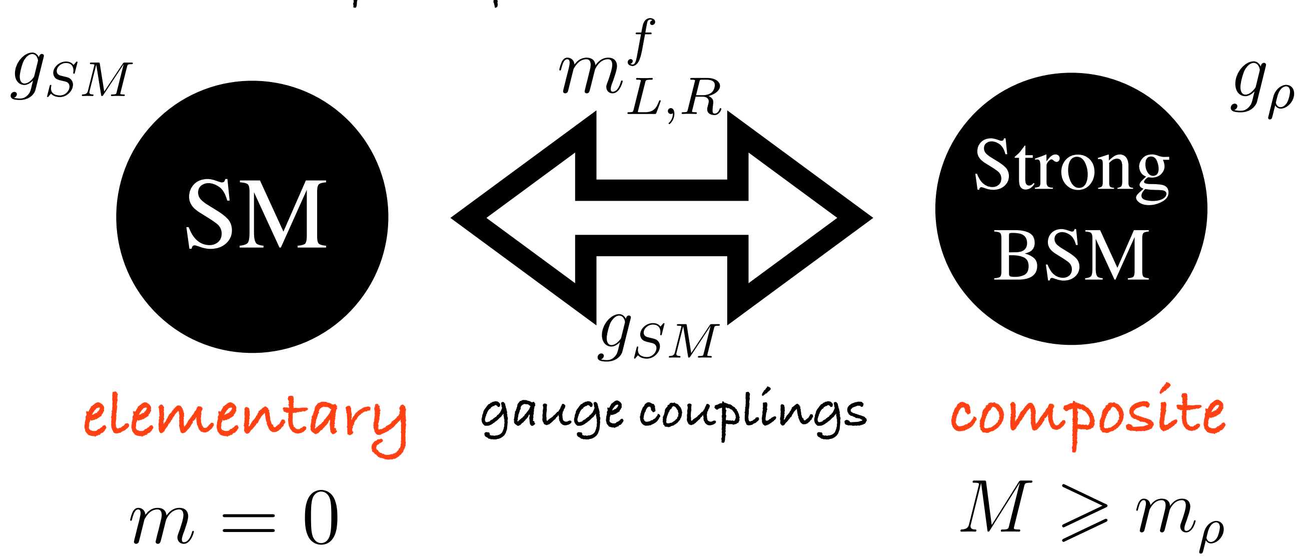
top is not special

✗ Strong coupling: Technicolor or Composite Higgs,

BSM physics (operators) couples to fermions proportionalty to mass

- Top quark the most sensitive fermion to the BSM sector.
- Top quark has properties of composite state.

Frame 1: BSM sector



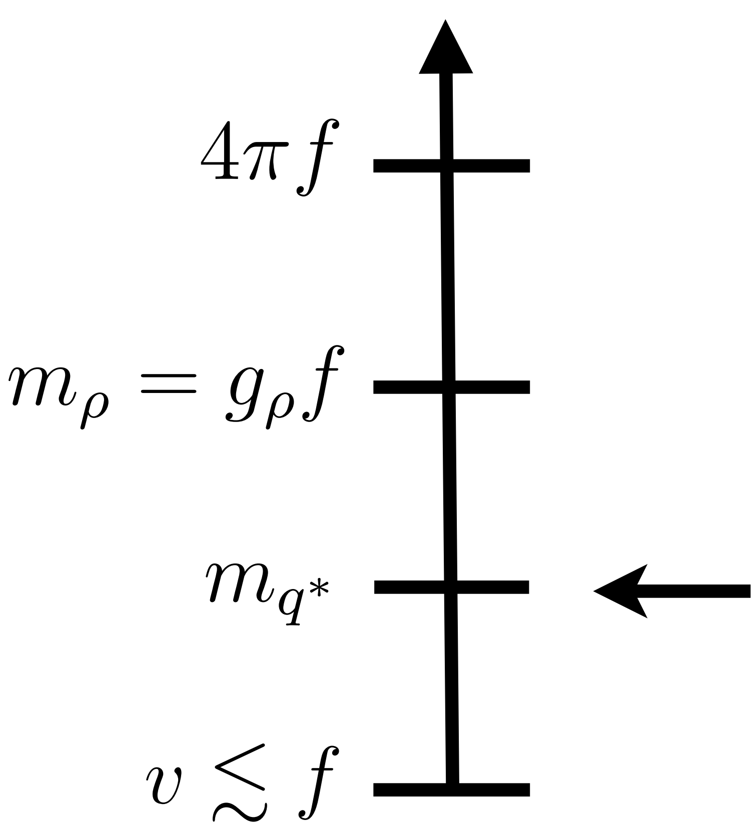
global symmetry $\mathcal{G} \longrightarrow \mathcal{H}$ residual global symmetry

↓

3 Nambu-Goldstone bosons Σ

(+n, PNGB)

Model independent analysis: strong sector characterized by



- m_ρ = mass of lightest bosonic resonances
- m_{q^*} = mass of lightest fermionic resonances
- f = global symmetry breaking scale (decay constant)

also, $g_\rho = \dfrac{m_\rho}{f}$ = coupling between resonances, $g_\rho \lesssim 4\pi$

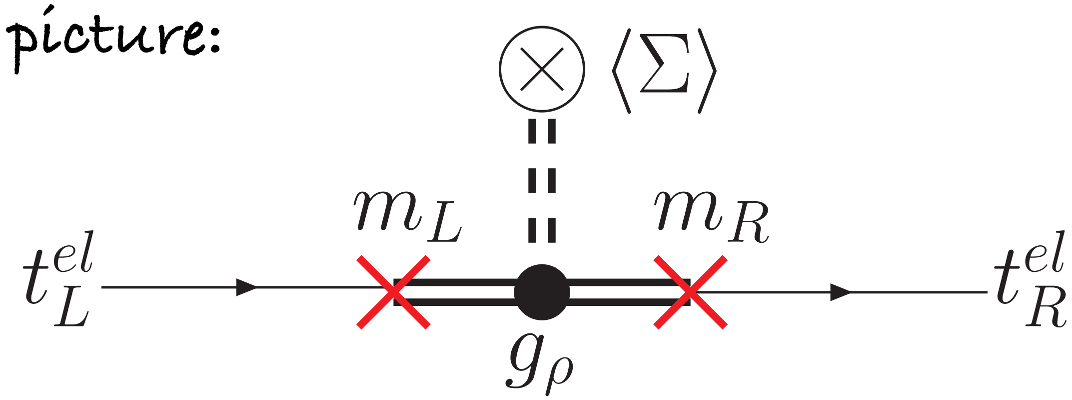
← inspired by holography – Warped Extra-D basic!

Higgsless: $v = f = 246$ GeV   SM: $f \gg v$

Frame 2: Partial Compositeness

SM fermions get their masses by mixing with resonances

- perturbative picture:



$$y_t \sim g_\rho \frac{m_L m_R}{M_Q M_T}$$

- non-perturbative picture:

$$\mathcal{L} = m_L\, \bar{q}_L^{\rm el} Q_R^q + m_R\, \bar{t}_R^{\rm el} T_L^t + M_Q \bar{Q}_L Q_R + M_T \bar{T}_R T_L + g_\rho \bar{Q}_L \Sigma T_R + \cdots$$

Q, T = BSM resonances

↓ diagonalization

massless states:

$$q_L = \cos\theta_L\, q_L^{\rm el} + \sin\theta_L\, Q_L^q\,, \quad \tan\theta_L = \frac{m_L}{M_Q}\,,$$

$$t_R = \cos\theta_R\, t_R^{\rm el} + \sin\theta_R\, T_R^t\,, \quad \tan\theta_R = \frac{m_R}{M_T}\,.$$

top Yukawa: $y_t = \sin\theta_L g_\rho \sin\theta_R$

Frame 3: Composite limit

extrema of partial compositeness

composite q_L: $\left\{ \begin{array}{c} \sin\theta_L \to 1 \\ m_L \to m_\rho \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} q_L \simeq Q_L^q \\ M_Q \ll m_L \end{array} \right\}$

if Q_L in higher representation (of global symmetry of strong sector):

$$q_L \in Q_L = (t_L, q_L^*)$$

top partners

before EWSB: $m_t = 0$ and $m_{q^*} \neq 0$ (but smaller than m_ρ)

$$\left\{ \begin{array}{c} \sin\theta_R \to y_t/g_\rho \\ m_R \to m_t \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} t_R \simeq t_R^{el} \\ M_T \to m_\rho \end{array} \right\}$$

3 scales: m_ρ, f, m_{q^*}

composite t_R: equivalent limit

Feasibility 1: Effective Lagrangian

How does the composite nature of the top modify the low energy theory?

$$m_\rho \gg (f, m_{q^*}) \gg E > m_t$$

"Chiral"-lagrangian for the top (low energy lagrangian)

2 rules: **x** extra composite state, $\frac{H}{f}, \frac{t}{f m_\rho^{1/2}}$ **x** extra derivative, $\frac{\partial}{m_\rho}$

$\frac{1}{f^2}$-operators (leading):

compo q_L

$$\frac{i c_L^{(1)}}{f^2} H^\dagger D_\mu H \bar{q}_L \gamma^\mu q_L + \frac{i c_L^{(3)}}{2f^2} H^\dagger \sigma^i D_\mu H \bar{q}_L \gamma^\mu \sigma^i q_L + h.c. + \frac{c_{4q}}{f^2} (\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) .$$

compo t_R

$$c_i = \mathcal{O}(1)$$

$$\frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R + \frac{c_{4t}}{f^2} (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$

compo H

$$\frac{c_T}{2f^2} |H^\dagger D_\mu H|^2 + \frac{c_S}{m_\rho^2} H^\dagger W_{\mu\nu} B^{\mu\nu} H + \cdots$$

Feasibility 2: EWPT and symmetries

from $\dfrac{1}{f^2}$ - operators:

✗ $\widehat{T} = \dfrac{g^2}{m_W^2}\left[\Pi_{W^+}(0) - \Pi_{W^3}(0)\right] = c_T \dfrac{v^2}{f^2} \lesssim 10^{-3}$ ⟶ strong bound on f

$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \xrightarrow[\langle\Sigma\rangle]{} \mathrm{SU}(2)_V \longrightarrow c_T = 0$$

$T = 0$ at tree-level

✗ $\dfrac{\delta g_{Zb_Lb_L}}{g_{Zb_Lb_L}} \simeq \left(c_L^{(1)} + c_L^{(3)}\right)\dfrac{v^2}{f^2} \lesssim 10^{-3}$ ⟶ strong bound on f

P_{LR} (interchanges $L \longleftrightarrow R$) ⟶ $c_L^{(3)} = -c_L^{(1)} \equiv c_L$

$b_L =$ eigenstate

$\delta g_{Zb_Lb_L} = 0$ at tree-level

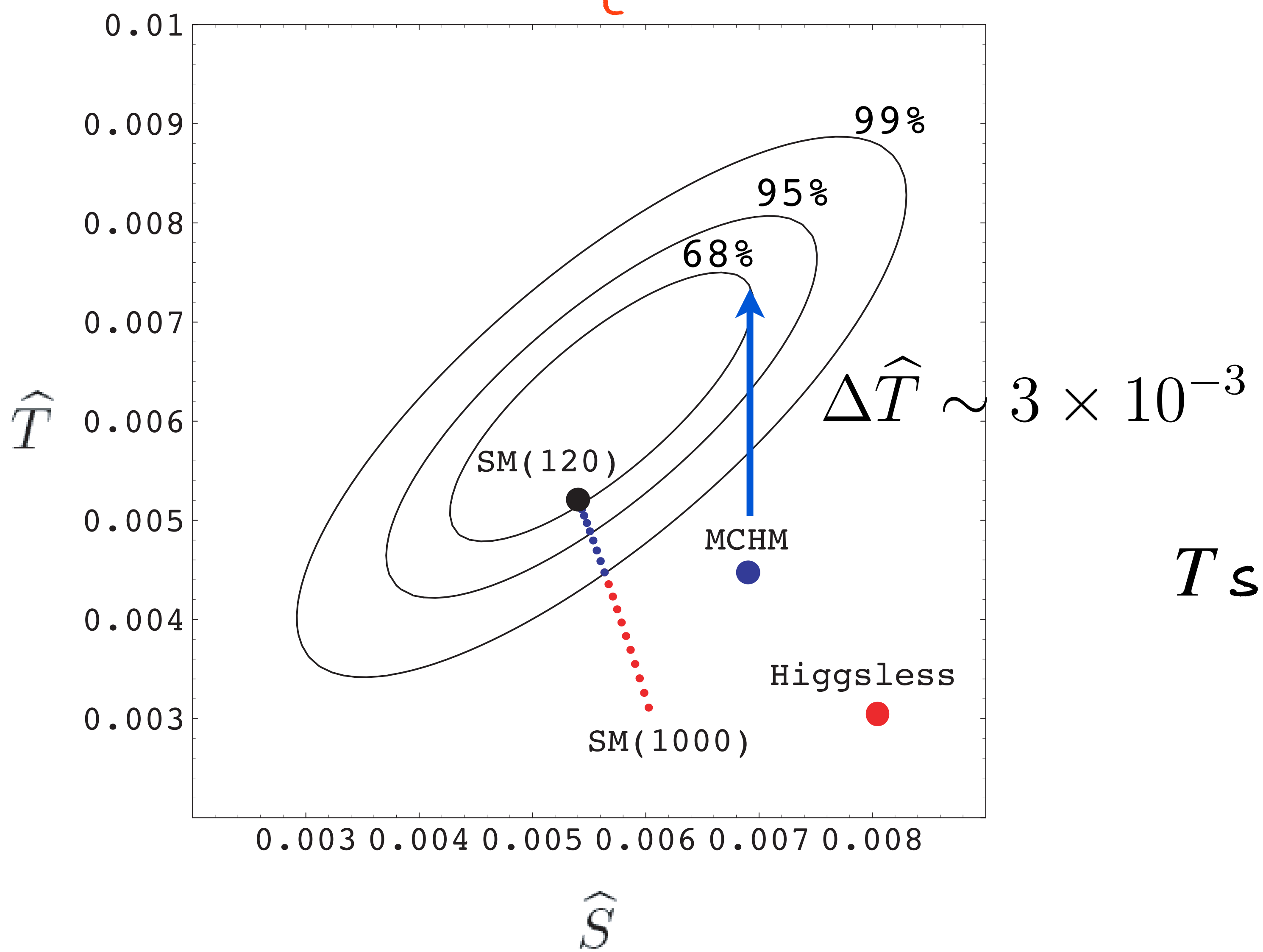
lucky we have these (accidental ?) symmetries !

Feasibility 3: EWPT and bounds

✗ $\widehat{S} = g^2 \Pi'_{W_3 B}(0) = 2 g^2 c_S \frac{v^2}{m_\rho^2} \lesssim 10^{-3}$ ⟶ bound on m_ρ

× if calculable, (AdS/CFT) $m_\rho \gtrsim 2.3$ TeV ⟶ ($g_\rho \sim 4.6$) $f \gtrsim 500$ GeV Reference

At the 0.1% level !



T sizable at one-loop?

Feasibility 4: Custodians

minimal global symmetries of BSM: $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_X$

$Q = T_L^3 + T_R^3 + X$

assignments for Q, T :

✗ b_L = eigenstate of P_{LR} $\quad T_L = T_R = 1/2, \quad T_L^3 = T_R^3 = -1/2$

✗ $g_\rho \bar{Q}_L \Sigma T_R \equiv (\mathbf{2}, R_q)_{X_q} (\mathbf{2}, \mathbf{2})_{\mathbf{0}} (\mathbf{1}, R_t)_{X_t}$ invariant

custodians of q_L

$q_L^* = \mathbf{2}_{\mathbf{7/6}} \Rightarrow Q = +\frac{5}{3}, +\frac{2}{3}$

custodians of t_R

$\mathbf{1}_{\mathbf{5/3}}, \mathbf{1}_{\mathbf{-1/3}}, \mathbf{3}_{\mathbf{2/3}} \Rightarrow Q = +\frac{5}{3}, +\frac{2}{3}, -\frac{1}{3}$

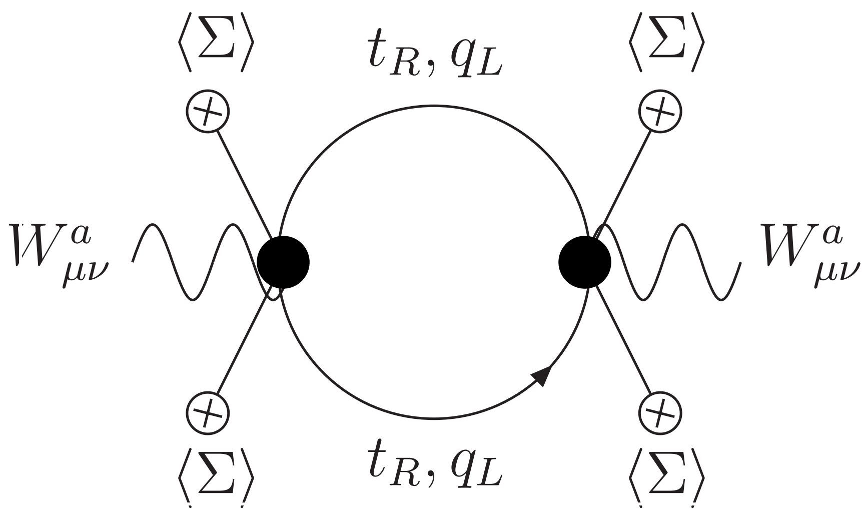
	Q	T
Case (a)	$(\mathbf{2}, \mathbf{2})_{\mathbf{2/3}}$	$(\mathbf{1}, \mathbf{1})_{\mathbf{2/3}}$
Case (b)	$(\mathbf{2}, \mathbf{2})_{\mathbf{2/3}}$	$(\mathbf{1}, \mathbf{3})_{\mathbf{2/3}} + (\mathbf{3}, \mathbf{1})_{\mathbf{2/3}}$

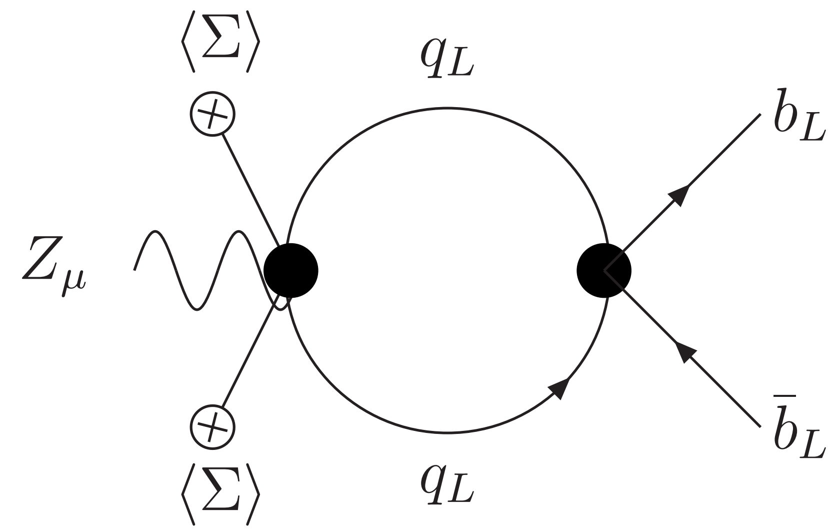
Note.- If larger low-energy symmetry, we embed (a) or (b) in some of its representations.

Feasibility 5: 1-loop estimates

Have we finished with EWPT?

NO. Low energy ($E < \Lambda$) one-loop (leading) estimates:





$$\widehat{T} \sim \frac{N_c}{16\pi^2} c^2_{L,R} \frac{v^2\Lambda^2}{f^4} \qquad \delta g_{Zb_Lb_L} \sim \frac{N_c}{16\pi^2} c_L c_{4q} \frac{v^2\Lambda^2}{f^4}$$

$$c^2_{L,R} \sim \left(\frac{m_{L,R}}{m_\rho}\right)^4 \qquad c_L c_{4q} \sim \left(\frac{m_L}{m_\rho}\right)^6$$

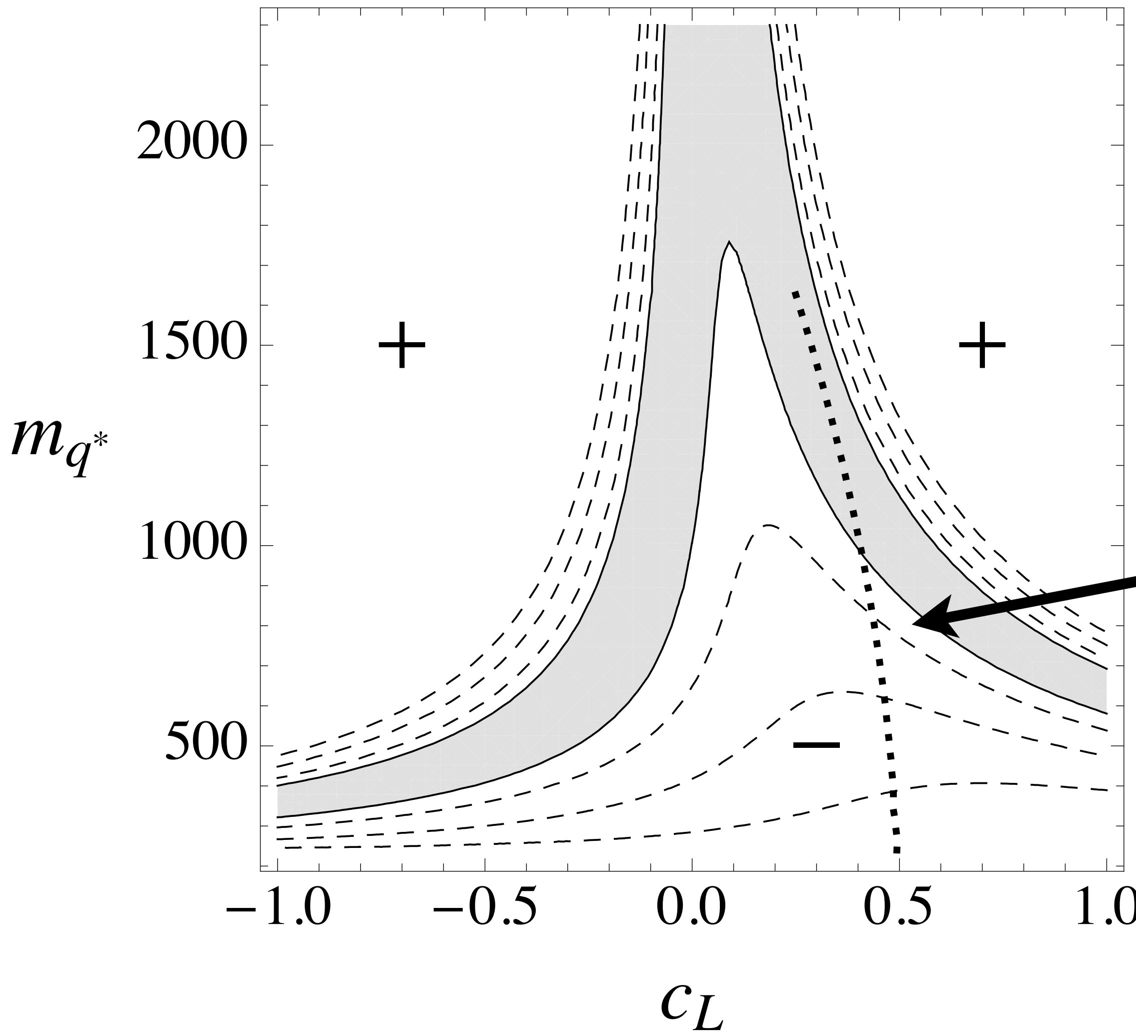
- generically: $\Lambda \sim m_\rho$ ⟶ $c_L, c_R, c_{4q} \neq 1$ ⟶ no large compositeness allowed
- composite limit: $\Lambda \sim m_{q^*}$ ⟶ large compositeness allowed

  $m_{q^*} \to 0$ ⟶ custodial symmetry recovered

Feasibility 6a: Composite q_L

Case (a):

T contour plot



$f = 500$ GeV
$m_\rho = 2.3$ TeV

from WED:

$$m_{q^*} \sim m_\rho \sqrt{1 - \frac{c}{\alpha}}$$

- ✗ large compositeness ⟷ light custodians
- ✗ softer bounds for $m_{q^*} \sim (500, 1000)$ GeV
- ✗ bounds from Zb_Lb_L can be hard (c_{4q} dependence)

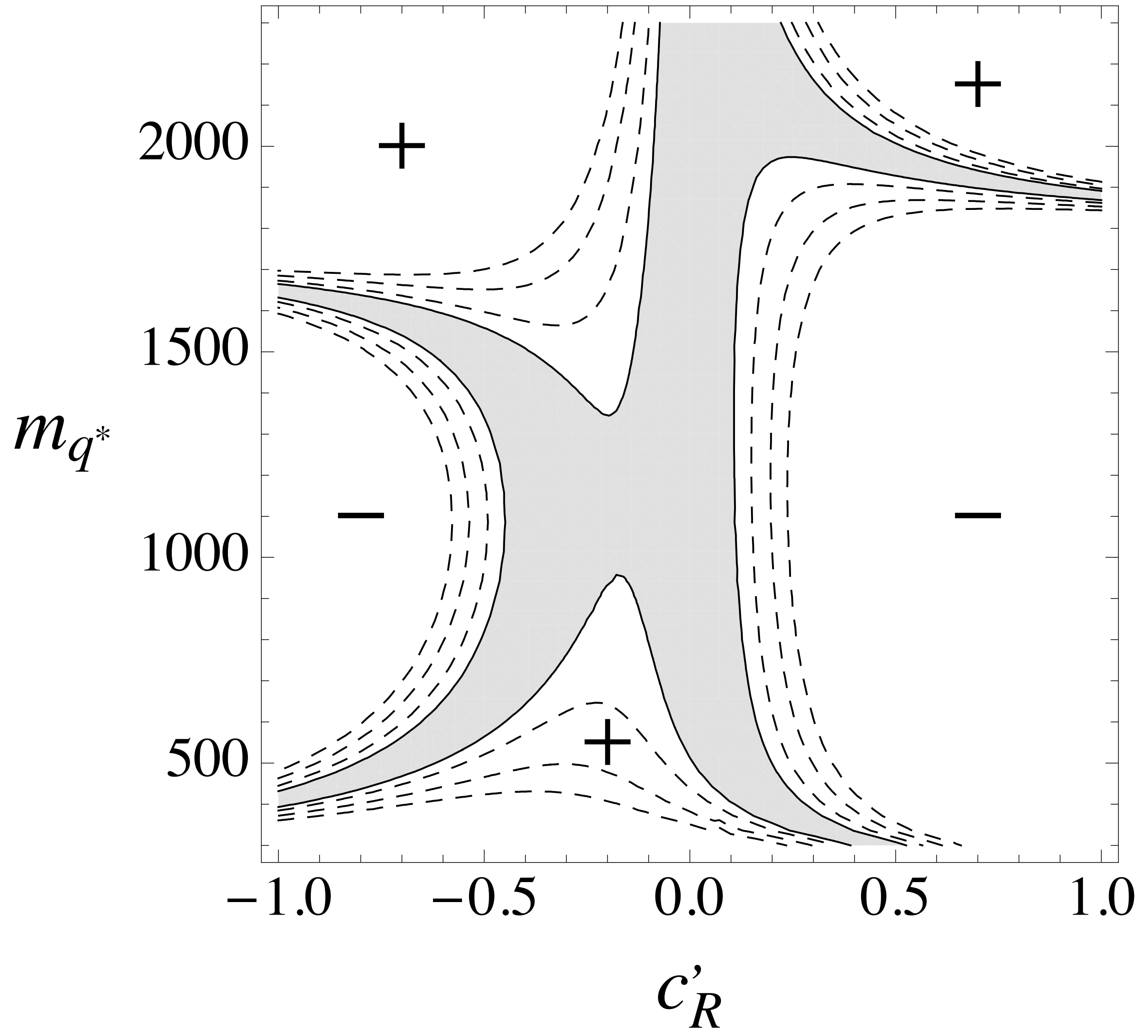
Case (b): allowed composite q_L parameter space very small

Feasibility 6b: Composite t_R

Case (a): no serious bounds on composite t_R parameter space

Case (b):

T contour plot



$f = 500$ GeV

$m_\rho = 2.3$ TeV

- ✗ softer bounds for negative c_R and $m_{q^*} \sim (500, 1500)$ GeV
- ✗ regions with positive T
- ✗ no strong bounds from Zb_Lb_L (no quadratic dependence on m_q)

Pheno 1: Effective Lagrangian

Model independent analysis of composite top consequences

$\frac{1}{f^2}$-operators (leading):

compo q_L

$$\frac{i c_L^{(1)}}{f^2} H^\dagger D_\mu H \bar{q}_L \gamma^\mu q_L + \frac{i c_L^{(3)}}{2 f^2} H^\dagger \sigma^i D_\mu H \bar{q}_L \gamma^\mu \sigma^i q_L + h.c. + \frac{c_{4q}}{f^2} (\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)\,.$$

compo t_R

$$c_i = \mathcal{O}(1)$$

$$\frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R + \frac{c_{4t}}{f^2} (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$

in our framework: $c_L^{(3)} \simeq -c_L^{(1)}$ and $c_R \simeq 0$

t_R = eigenstate of parity

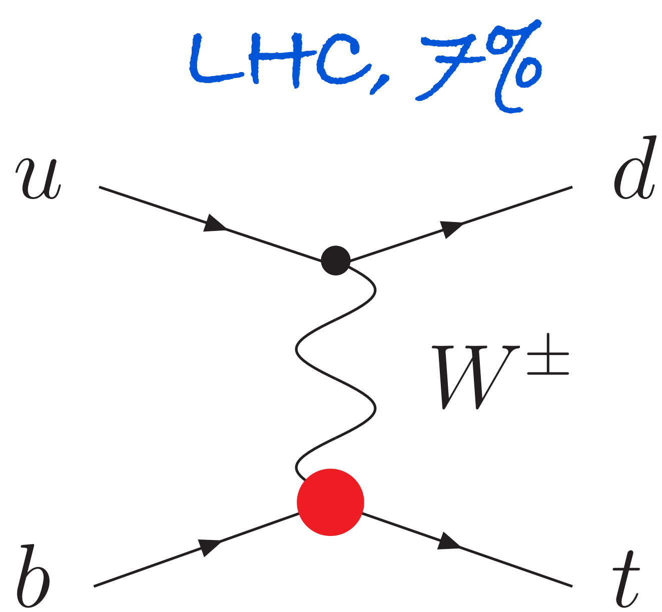
sym. protecting $Z t_R t_R$

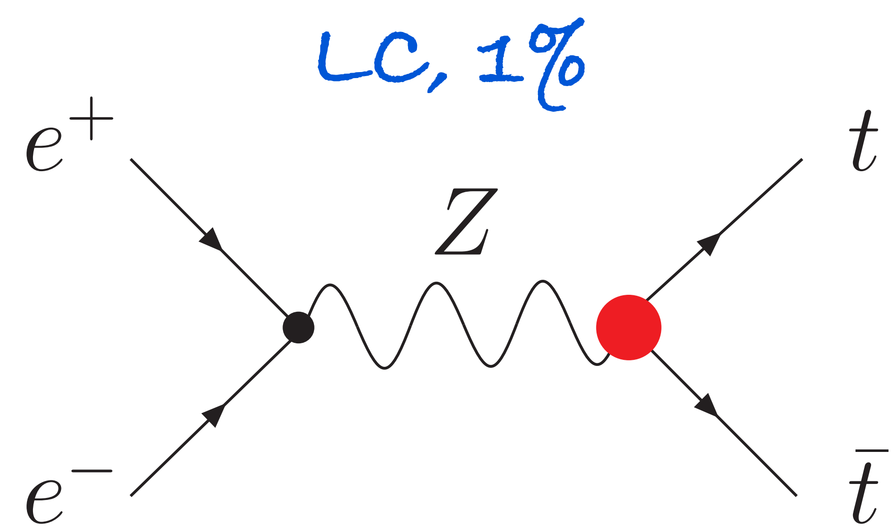
Pheno 2: Anomalous couplings

Modification of couplings top – SM gauge bosons

$$\frac{\delta g_{W t_L b_L}}{g_{W t_L b_L}} = c_L \frac{v^2}{f^2} \qquad \frac{\delta g_{Z t_L t_L}}{g_{Z t_L t_L}} \simeq 2 c_L \frac{v^2}{f^2} \qquad \frac{\delta g_{Z t_R t_R}}{g_{Z t_R t_R}} = \frac{3 c_R}{4 \sin^2\theta_W} \frac{v^2}{f^2}$$

$f = 500$ GeV ⟶ no strong enough present (direct) contraints





LHC: tops mainly pair produced and BR($t \to Wb$) ~ 1

Pheno 3: Four-top production

genuine effect!

c_{4q}, c_{4t} ⟶ strong tt, qq scattering

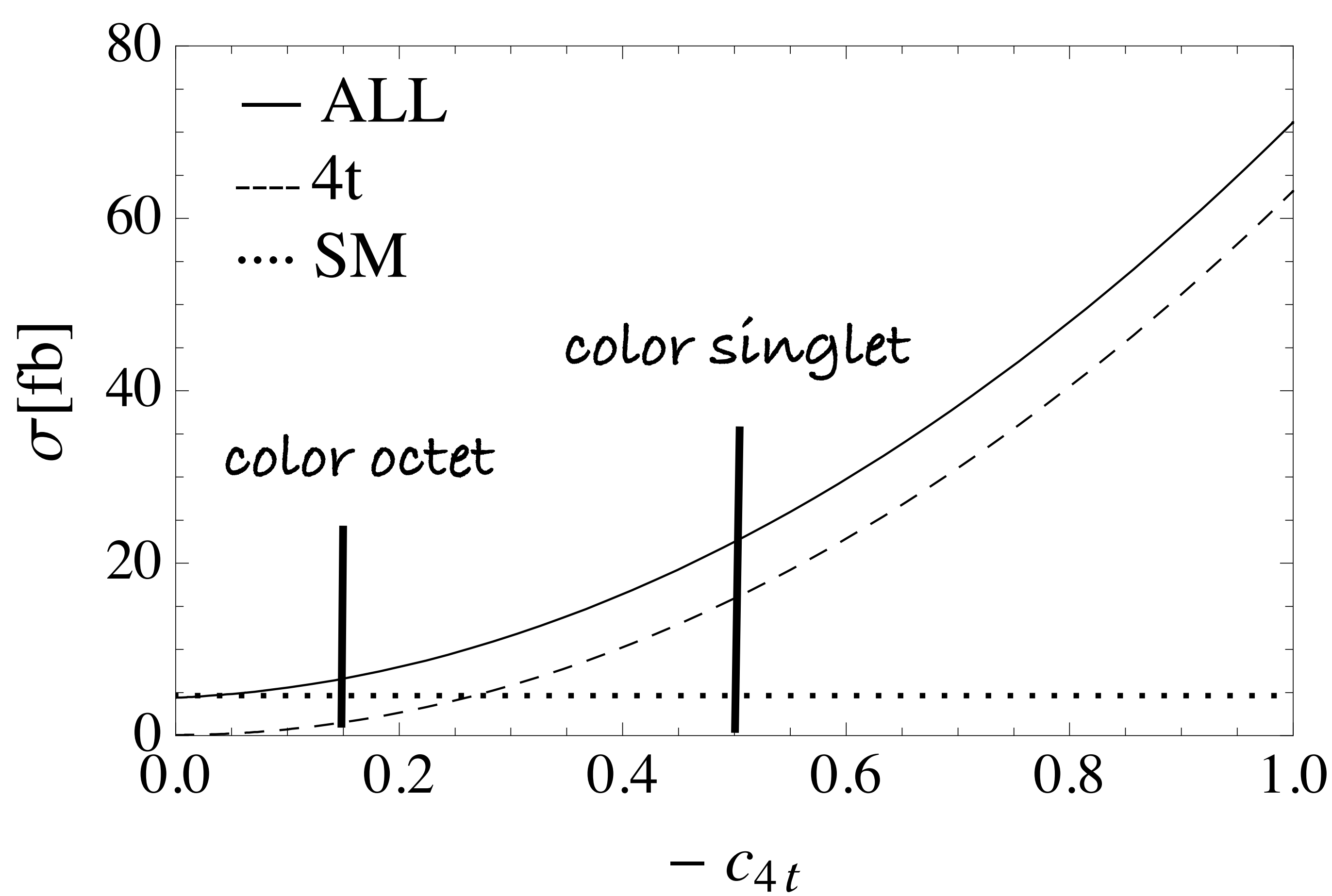
$$|\mathcal{A}[t\bar{t} \to t\bar{t}(b\bar{b})]|^2 \propto \frac{c_4^2}{f^4} u^2$$

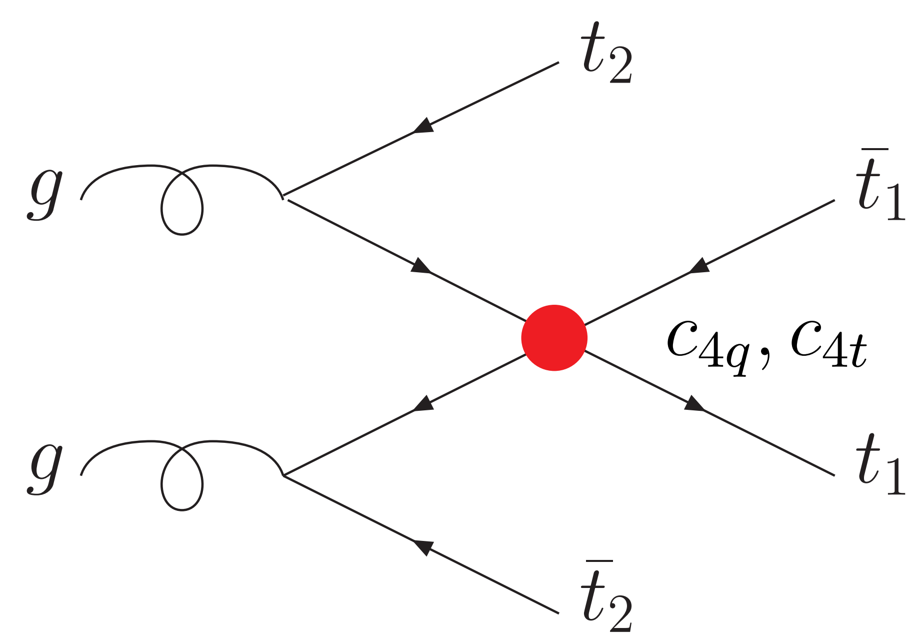
grows with energy

enhancement at the LHC!

$pp \to t\bar{t}t\bar{t}$

$pp \to t\bar{t}b\bar{b}$





$\sigma_{SM} \simeq 4.6$ fb

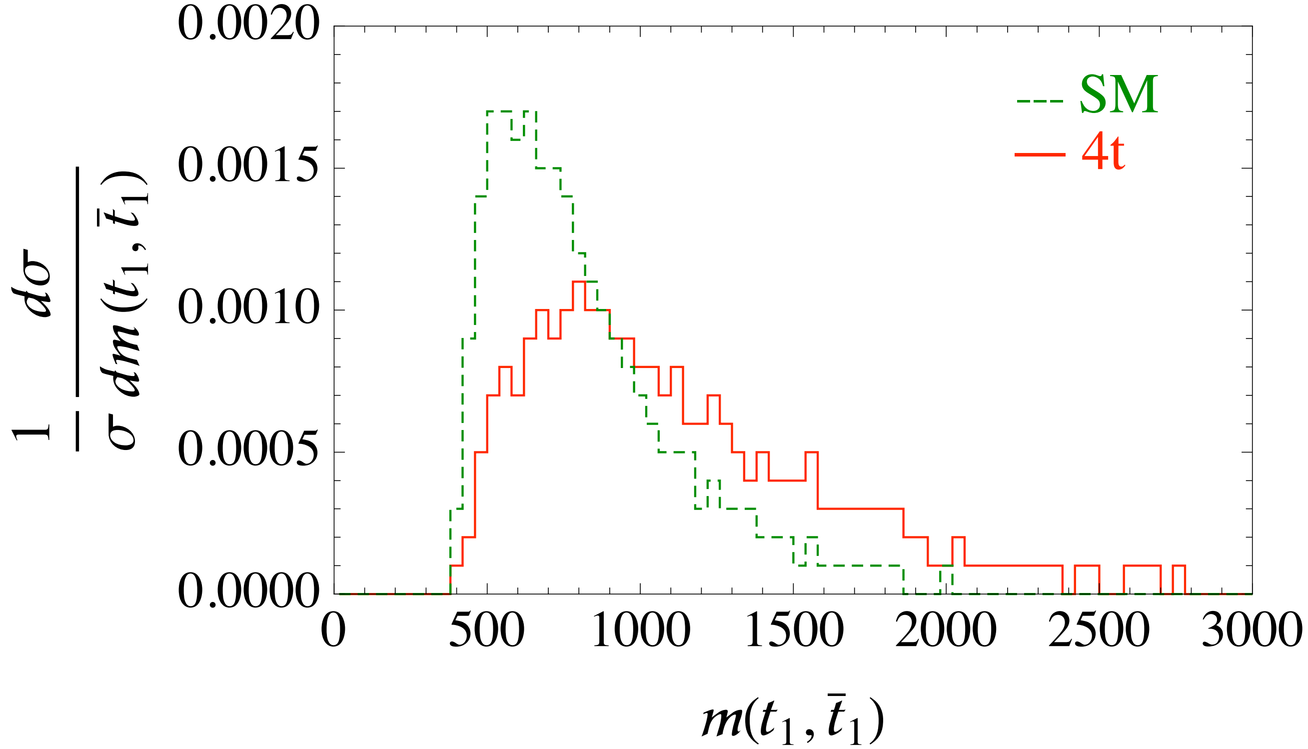
$\sigma_{octet} \simeq 1.8$ fb

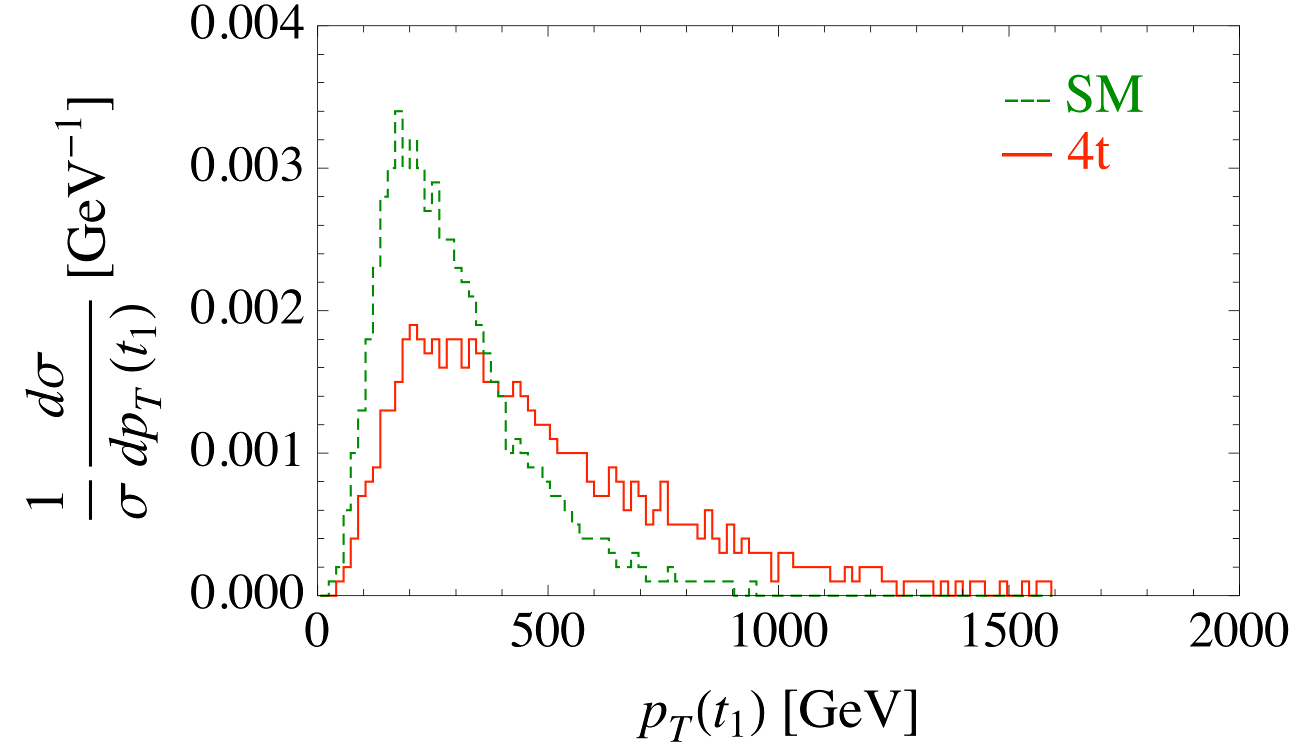
$\sigma_{singlet} \simeq 16$ fb

Pheno 4: Four-top production

2 tops (t_1) very energetic ($p_T(t_1) > p_T(t_2)$)

distributions:





cuts (reduce backgrounds) → 4t contribution dominates

detector analysis ?

- ✗ possible signal: $l^{\pm}l^{\pm}jj$ Lillie, Shu, Tait → $\sigma_{4t} > 45$ fb
- ✗ top reconstruction

Conclusions

The top quark is the most sensitive fermion to the strong sector responsible for EWSB and SM masses.

- Can one of the chiralities of the top be fully composite?

Present experimental bounds do not rule out this possibility.

Even we can get positive T contributions (mainly for c negative), needed in these models for agreement with EWPT.

- Can one test this possibility at the LHC?

  - four-top production enhancement = genuine (difficult but viable)
  - anomalous couplings

Also direct searches of top partners (Contino, Servant) and flavour transitions extra

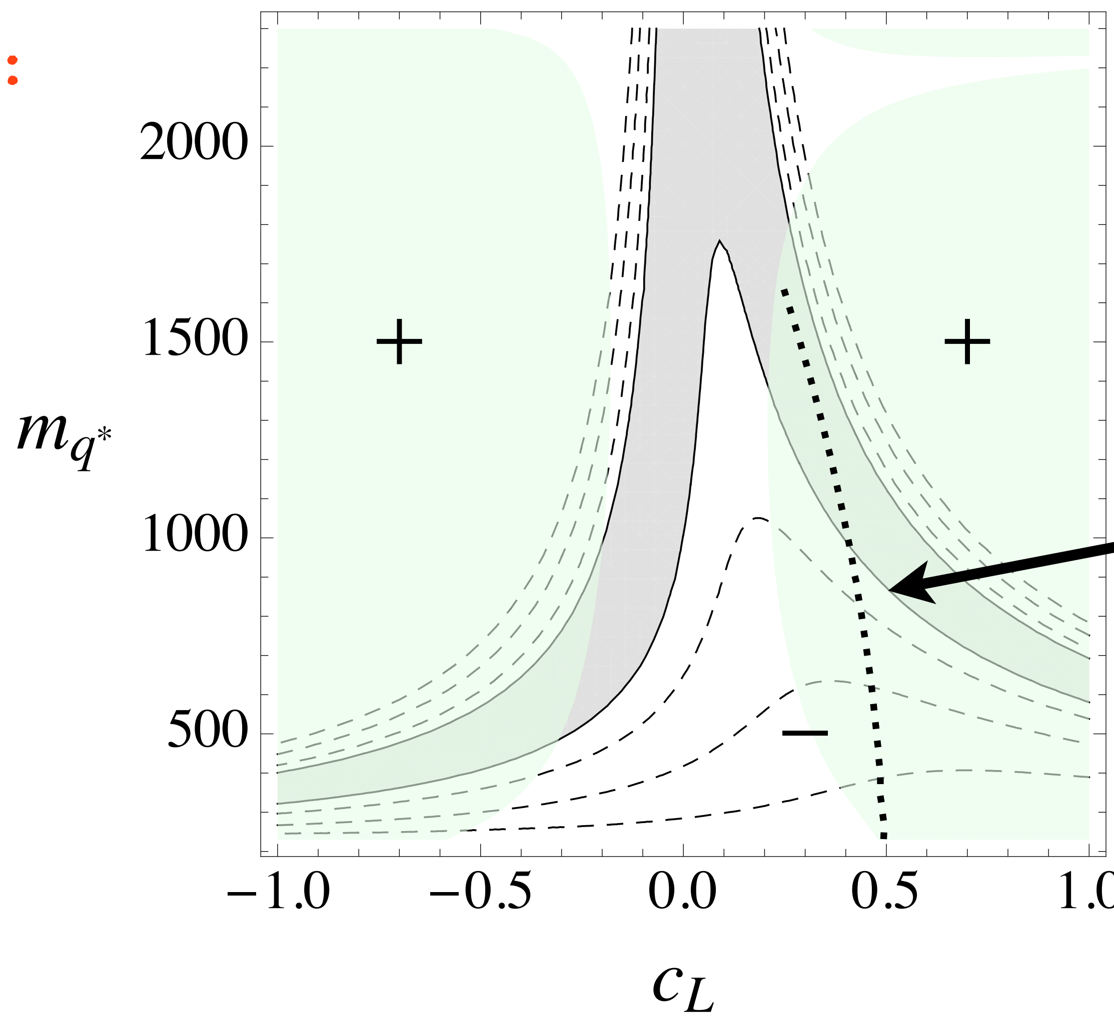
T and Zbb results

Composite q_L, case (a):

T contour plot

+

Zb_Lb_L excluded



$$\xi = \xi_R = \frac{1}{4}$$

$$m_\rho = 2.3 \text{ TeV}$$

$$c_{4q} = -c_L/3$$

from WED:

$$m_{q^*} \sim m_\rho \sqrt{1 - \frac{c}{\alpha}}$$

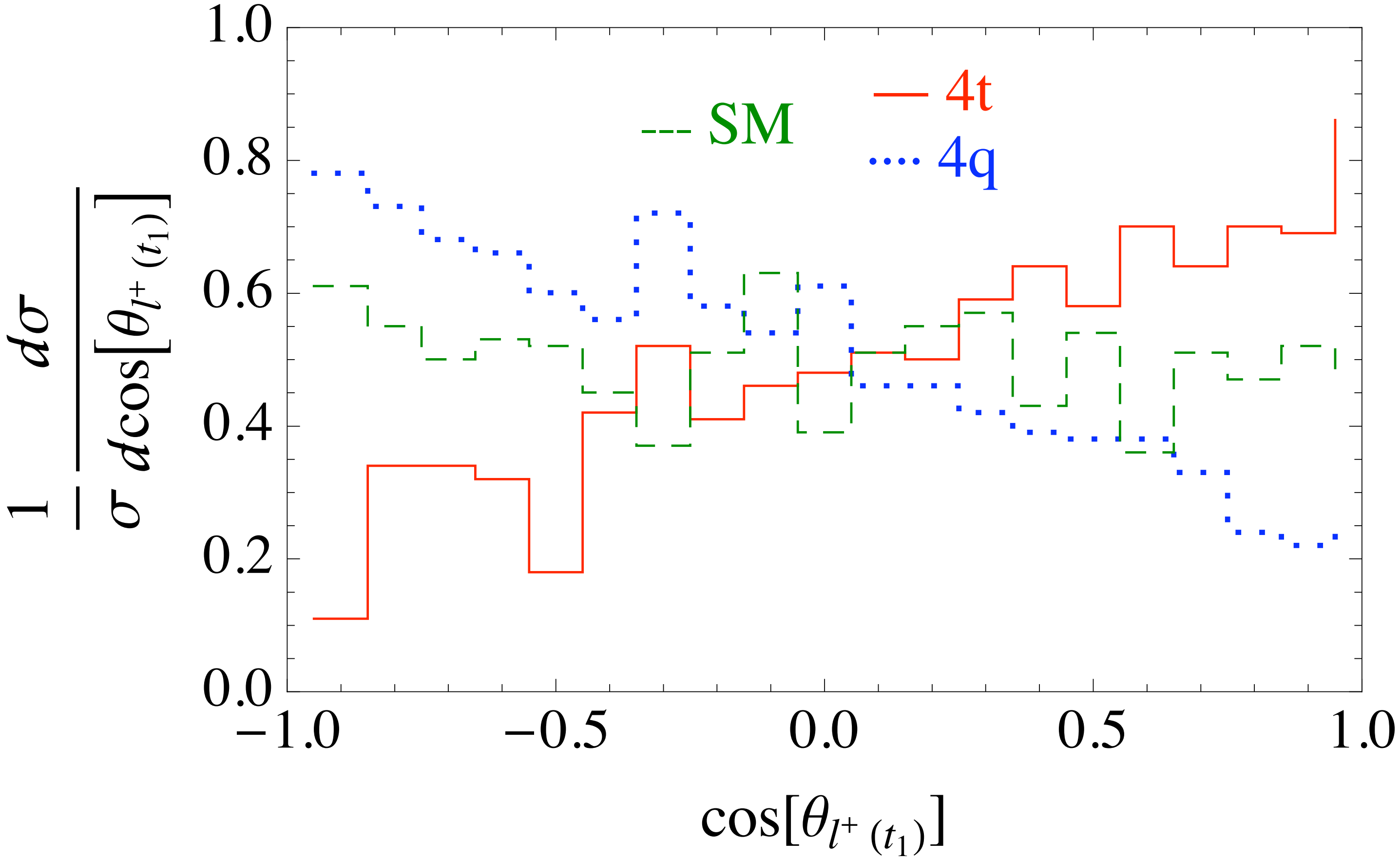
EFT results: $m_\rho \gg m_{q^*} \gg m_t$

$$\widehat{T} = \widehat{T}^{SM}_{top} \left[c_L^2 \xi^2 \left(2 \boxed{\frac{m_{q^*}^2}{m_t^2}} + 7 + 6 \log \frac{m_t^2}{m_{q^*}^2} \right) + c_L \xi \left(10 + 4 \log \frac{m_t^2}{m_{q^*}^2} \right) + \frac{m_t^2}{m_{q^*}^2} \left(\frac{22}{3} + 4 \log \frac{m_t^2}{m_{q^*}^2} \right) \right]$$

$$\delta g_{Zb_Lb_L} = -\delta g^{SM}_{b_L} 3 c_{4q} \xi \left[c_L \xi \left(4 \boxed{\frac{m_{q^*}^2}{m_t^2}} \log \frac{m_\rho^2}{m_{q^*}^2} + 4 \log \frac{m_t^2}{m_{q^*}^2} \right) + 2 \log \frac{m_t^2}{m_{q^*}^2} \right]$$

Four-top production

Can we distinguish between compo q_L or compo t_R in 4-top production?

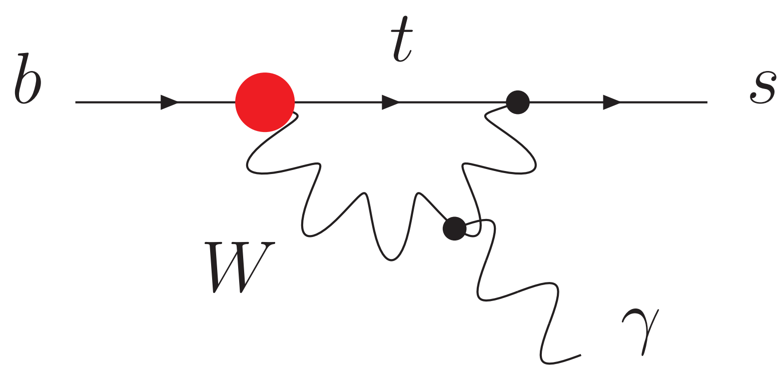


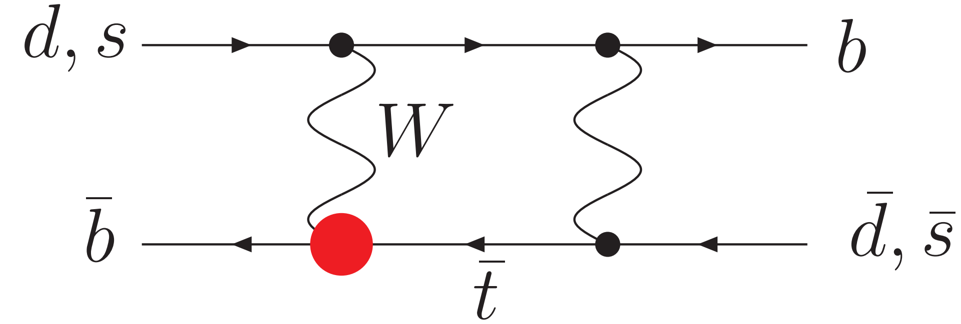
studying angular distributions of decay products (l^+)

Flavour constraints

Contraints on top compositeness from flavour physics?

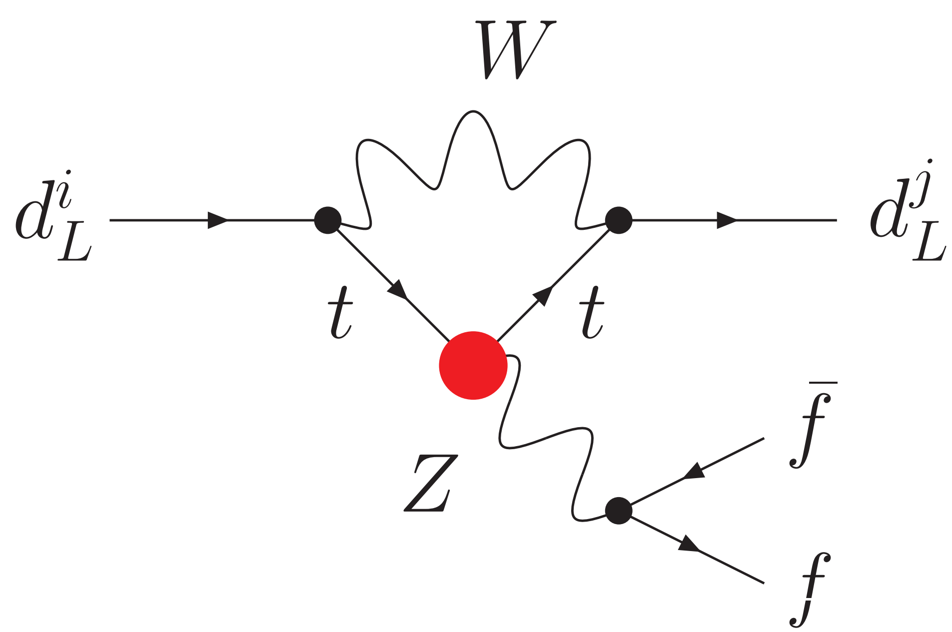
Wt_Lb_L coupling:





contraints at 15%

Ztt couplings:



mild constraints

flavour contraints = indirect (more model dependent)

generically = some extra flavor structure is needed