Top FCNC in Composite Higgs

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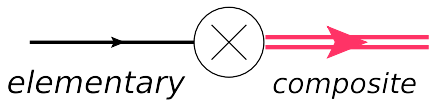
AA, G.Panico,G.Perez,Y.Soreq (see also the plenary talk by G. Perez on Wednesday)

Composite pseudo Nambu Goldstone Higgs

- Models, where Higgs is a composite state give a natural solution to the hierarchy problem
- Higgs can be made naturally light if it is Pseudo Nambu Goldstone Boson(PNGB) (*Georgi, Kaplan*)
- This scenario is realized in the warped extra dimensional models (*Randall,Sundrum*)with gauge-higgs unification, the Higgs boson arises as the 5th component of the 5D gauge field
- EWPT $\Delta\rho$ requires that the symmetry breaking structure should be $SU(2)_L \times SU(2)_R/SU(2)_V$
- The minimal construction with custodial symmetry is realized in $SO(5) \to SO(4)$(*Contino, Agashe, Pomarol*)

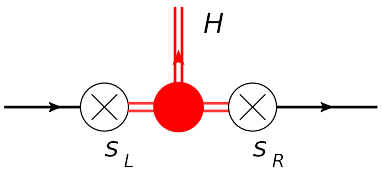
Fermions: partial compositeness *(Kaplan)*

- SM fermions mix only linearly with composite fermions



$$\Delta\mathcal{L} = \lambda \bar{q} O$$

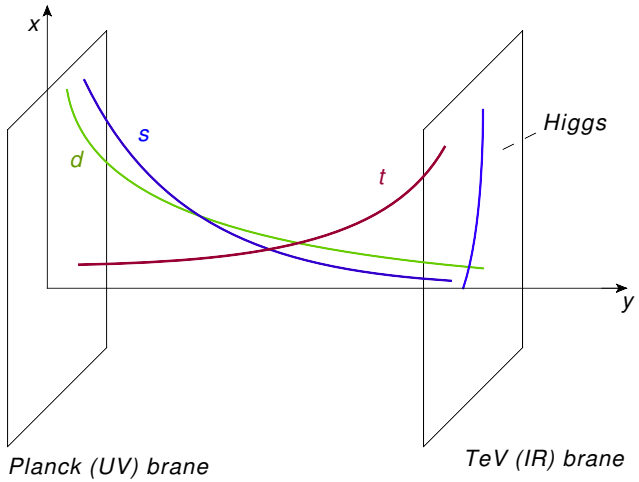
- Fermion mass generation



mixing at the low scale

$$s_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\gamma_{L,R}}, \quad m \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\gamma_L+\gamma_R}$$

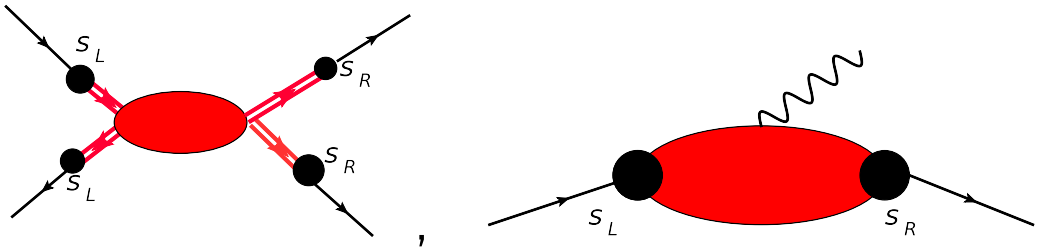
- 5D-Randall-Sundrum picture



$$s_{L,R} \Leftrightarrow f(\text{IR brane})$$

Flavor constraints on the models with partial compositeness

- Partial compositeness explains fermion mass hierarchy, and at the same time also suppresses FCNC (RS GIM (Csaki et al;Agashe et al)). The flavor violating effects are suppressed by the small masses of the light fermions



ϵ_K, $b \to s\gamma$, ϵ' require $M_* \gtrsim 10 - 20$ TeV

Agashe et al; Csaki et al;Blanke et al;Casagrande et al...

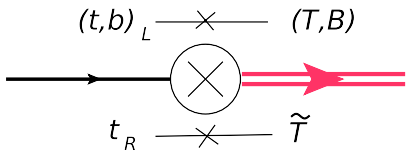
Top quark in Composite Higgs models

- Top quark is mixes strongly with the composite secotr, its coplings are the most sensitive probe of the new physics.
- The Higgs potential is generated by the top quark and top quark mixing parameters are strongly constrained by the Higgs mass *(Agashe et al;Pomarol et al;Panico et al;Marzocca et al; Redi et al;)*
- The same mixings control top Yukawa coupling and are top flavor violation, (for non PGB studies see *Agashe, Perez,Soni*)
- Is the "Higgs potential" related to the top FCNC??What we can say about partner of the light generations?

MCHM 5 model

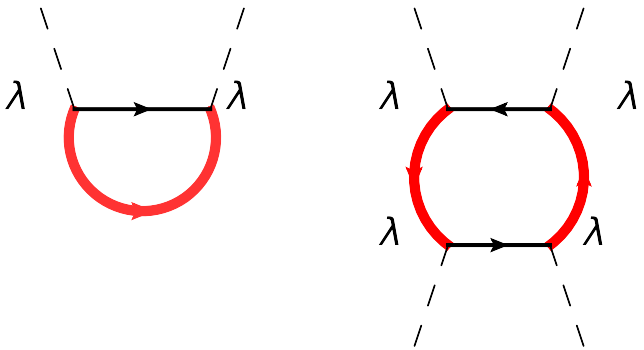
- Minimal model based on the $SO(5)/SO(4)$ coset where composite fermions appear as a multiplet of **5**
- SM mass generation

$$\mathbf{5}: \quad \mathcal{Q} = \frac{\mathbf{1}}{\sqrt{2}} \begin{pmatrix} T_{2/3} & \chi_{5/3} \\ B_{-1/3} & T'_{2/3} \end{pmatrix} \oplus \tilde{\mathbf{T}}_{\mathbf{2/3}}$$



$$\begin{aligned} \Delta\mathcal{L} &= \lambda_L^t \bar{q}_L P_q U(\pi) \mathcal{Q} + \lambda_R^T \bar{t}_R P_t U(\pi) \mathcal{Q} + M_1 \bar{\mathcal{Q}}_1 \mathcal{Q}_1 + M_4 \bar{\mathcal{Q}}_4 \mathcal{Q}_4 \\ m_t &\sim \frac{\lambda_L^t \lambda_R^t v}{f M_*} \end{aligned}$$

Higgs potential



- $V(h) = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$,
  $\xi = \sin^2 \frac{\langle h \rangle}{f} = -\frac{\alpha}{2\beta}$

$$\alpha^t_{L,R} \sim \frac{N_c}{16\pi^2}(\lambda^t_{L,R})^2 M_*^2, \;\; \beta \sim \frac{N_c}{16\pi^2}(\lambda^t_L \lambda^t_R)^2$$

$$\text{F.T.} \sim \frac{-2\beta\,\xi}{\alpha^t_{L,R}} \sim \frac{\min\left[(\lambda^t_R)^2, (\lambda^t_L)^2\right] v^2}{M_*^2 f^2} \sim \frac{m_t^2}{\max[\lambda_R^2, \lambda_L^2]}$$

Naturalness prefers both left handed and right handed tops are composite $\lambda_L \sim \lambda_R$.

Higgs potential: Effects of the partners of light quarks

$$V(h) = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$$

- In the anarchic models top mixes strongly with all the partners of the SM quarks

$$\alpha^t_{L,R} \sim \frac{N_c}{16\pi^2} (\lambda^t_{L,R})^\dagger M_* M_*^\dagger \lambda^t_{L,R}$$

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$$\text{F.T.} \sim \alpha^{-1}$$

Partners of the light quarks cannot be much heavier than the top partners

Interactions with the gauge bosons

- The most generic lagrangian consistent with the spontaneously broken symmeties can be written using the CCWZ formalism

$$U(\Pi) = e^{i\Pi}, \quad \Pi = \Pi^{\hat{a}} T^{\hat{a}}$$

and using the Maurer-Cartan forms

$$-iU^{\dagger} D_{\mu} U = d_{\mu}^{\hat{a}} T^{\hat{a}} + E_{\mu}^{a} T^{a} \equiv d_{\mu} + E_{\mu}$$

$$d_{\mu}^{\hat{a}} = A_{\mu}^{a} + \frac{\sqrt{2}}{f} (D_{\mu}\pi)^{a} + ..., \qquad E_{\mu}^{a} = A_{\mu}^{a} - \frac{i}{f^2} \left(\pi \overset{\leftrightarrow}{D}_{\mu} \pi \right)^{a} + ...$$

- Interaction with composite fermions

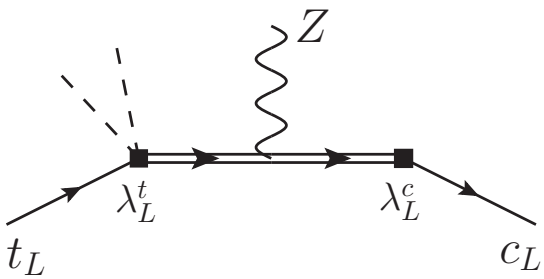
$$\mathcal{L} = \bar{\mathcal{Q}} \left(i\partial\!\!\!/ - E\!\!\!/ \right) \mathcal{Q} + \zeta \bar{\mathcal{Q}} d\!\!\!/ \mathcal{Q}$$

Flavor structure of the MCHM5

- Mass:

$$\left(m_u^{\mathrm{SM}}\right)^{ij} \simeq \frac{v\lambda_L^{ik}}{f}\left[\left(M_4^{-1}\right)^{kl} - \left(M_1^{-1}\right)^{kl}\right]\lambda_R^{lj}$$

- Couplings to Z: left handed quarks



$$\mathcal{O}_{LL}^{\Delta u=1} \sim \bar{q}_L^i \lambda_L^{il} U^\dagger \left[\left(M_4^\dagger M_4\right)^{-1}\hat{e}_\mu + \ldots\right]^{lk}\gamma^\mu U\lambda_L^{kj}q_L^j$$

$$g_{Z,L}^{FV} = -\frac{gv^2}{4c_W f^2}\left[\lambda_L\left(M_1^{-1}(M_1^{-1})^\dagger + M_4^{-1}(M_4^{-1})^\dagger\right)\lambda_L^\dagger\right]$$

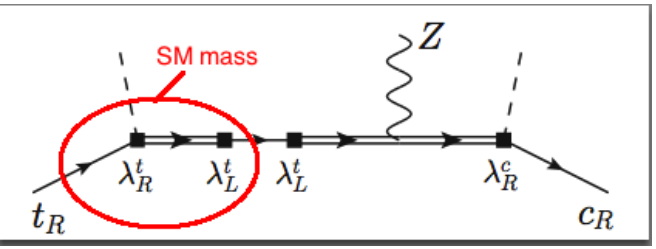
$$g_{tc,L} \sim \frac{g}{2c_W}\frac{v}{f}\frac{m_t V_{cb}}{M_*} \sim 7\times 10^{-4}\left(\frac{700}{f}\right)\left(\frac{700}{M_*}\right)$$

$$Br(t\to cZ) \sim 1.6\times 10^{-6}\left(\frac{700}{M}\right)^4$$

Flavor structure of the MCHM5: right handed quarks

- c_R is more composite than the c_L: $\frac{\lambda_R^c}{\lambda_L^c} \sim \frac{m_c}{m_t V_{cb}} \sim 2.6$, what about FCNC in right handed quark sector?
- Custodial symmetry protection for $Z\bar{b}b$ (*Agashe, Contino, Da Rold,Pomarol*) requires right handed SM top to be a singlet under under $P_{LR} \Rightarrow$ no flavor violation can be generated at the order $O(\lambda_R^2)$
- Flavor violation can appear only at the order $O(\lambda_R^2 \lambda_L^2)$, however in composite PNGB model prefer λ_L to be large (composite top left), so effect can still be very important.

Right handed quarks



$$\mathcal{O}_{RR}^{\Delta u=1} \sim \overline{q}_R \left\{ (m_u^{\rm SM})^\dagger \lambda_L^\dagger U^\dagger [(M_4 M_4^\dagger M_4)^{-1} \hat{d}_\mu + \ldots] U \lambda_R \right\} q_R$$

$$g_{Z,R}^{\rm SM} = -\frac{g v^2}{2\sqrt{2} c_W f^2} \left[m_u^{\rm SM\dagger} \lambda_L (M_4 M_4^\dagger M_4)^{-1} \lambda_R + h.c. \right]$$

$$g_{tc,R} \sim \frac{g}{2c_W} \frac{1}{M_*^2} \left(\frac{m_c m_t}{V_{cb}} \right) \sim 1.5 \times 10^{-3} \left(\frac{700}{M_*} \right)^2$$

$$BR(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*} \right)^4$$

Numerics

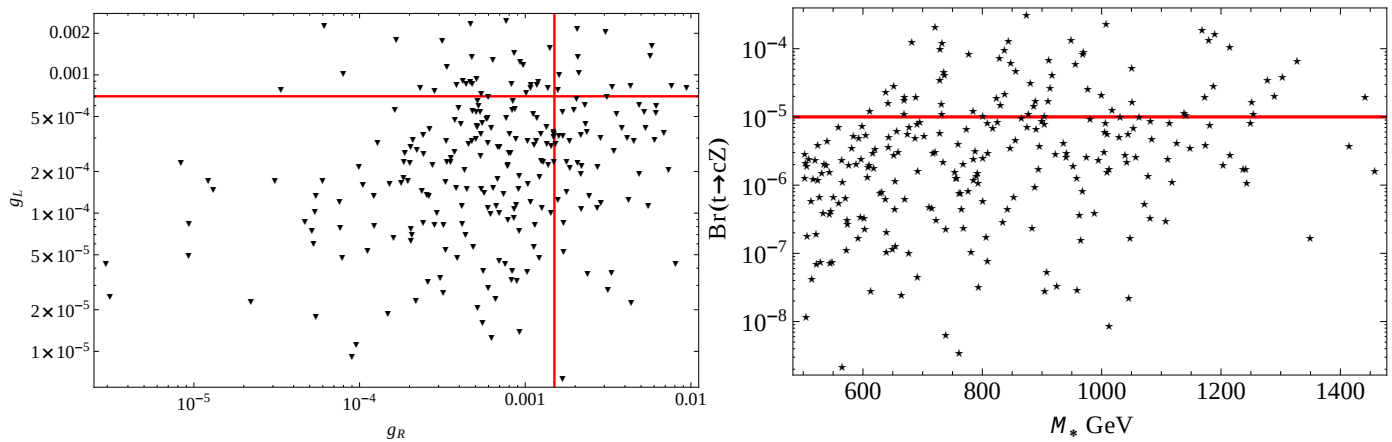


Figure: Scattered plots of the right handed and left handed top flavor violating coupling and the $Br(t \to ch)$ as a function of the mass of the lightest composite resonance.

Higgs FCNC

- At order $O(\lambda^2)$ only one spurion

$$\mathcal{L}_{SM} \simeq \bar{\psi}_R(\hat{\lambda}_R^\dagger)U^\dagger \left[M_4^{-1} - M_1^{-1}\right] U\hat{\lambda}_L\psi_L^I$$

  mass and Yukawa couplings are aligned *(Contino-Agashe)*
- Top quark mixes strongly with the composite sector and at $O(\lambda^4)$

$$O_1 \sim \bar{q}_L\lambda_L^\dagger U(M_4^{-2} - M_1^{-2})\lambda_L\hat{m}^{SM}q_R$$

-

$$Y_{t_R c_L} \sim \frac{m_t^2 V_{cb}}{fM_*} \sim 2\times 10^{-3}\left(\frac{700}{f}\right)\left(\frac{700}{M_*}\right)$$

$$Y_{t_L c_R} \sim \frac{m_t m_c}{fM_* V_{cb}} \sim 5\times 10^{-3}\left(\frac{700}{f}\right)\left(\frac{700}{M_*}\right)$$

$$Br(t\to ch) \sim 7\times 10^{-6}\left(\frac{700}{f}\right)^2\left(\frac{700}{M_*}\right)^2$$

Summary

- Top quark is a very sensitive new physics probe .
- Connection with the naturalness
  - Right handed top flavor violation is still dominant, even in the custodially protected models.
  - Partners of the light up quark c, u cannot be much heavier than the top quark.
- The composite Higgs models generically predict top flavor violation $t \to ch, t \to cZ$ in the range of the current and future LHC studies.

Current bounds and prospects for high luminosity LHC

- CMS-TOP-12-037 7 TeV+8 TeV
  $Br(t \to qz) < 5 \times 10^{-4}$
  CMS PAS HIG-13-034
  $Br(t \to ch) < 5.6 \times 10^{-3}$

- ATL-PHYS-PUB-2013-007 $3ab^{-1}$
  $Br(t \to qz) \lesssim 4 \times 10^{-5}$