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Flavor in Composite Higgs Models

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26/11/2015

1. Motivation

Address SM Hierarchy Problem: mechanism to protect Higgs mass.

$$\left(\frac{v}{\Lambda_{SM}}\right)^2 \begin{cases} \ll 1 \\ \lesssim 1 \end{cases}$$

- Naturalness $\Longrightarrow$ new physics at the TeV
- Environmental Selection
- Finite Naturalness, …
- Cosmological Relaxation
- ??

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- Naturalness $\Longrightarrow$ new physics at the TeV
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flavour robustness of

Introduction

Strong dynamics breaking EW symmetry.

Coupling to quarks:

- linear mixing (partial compositeness) $\bar{q}_L \mathcal{O}_{q_L} + \bar{u}_R \mathcal{O}_{q_R}$

- bilinear mixing (TC-like) $\bar{q}_L q_R \mathcal{O}$

Partial Compositeness

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \bar{\mathcal{O}} i \partial\!\!\!/ \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + \ldots + h.c.$$

$\mathcal{O} \in$ CFT

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}\log\mu} = \gamma\epsilon + \ldots , \qquad \gamma = \dim(\mathcal{O}) - 5/2$$

effective low energy description $\longrightarrow$

Partial Compositeness

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \bar{\mathcal{O}}(i\partial\!\!\!/ - m_M)\mathcal{O} + \epsilon \bar{\psi}\mathcal{O} + h.c.$$

$$\tan\phi = \frac{\epsilon}{m_M}$$

$$\text{light} = \psi\cos\phi + \mathcal{O}\sin\phi$$

$$\text{heavy} = -\psi\sin\phi + \mathcal{O}\cos\phi$$

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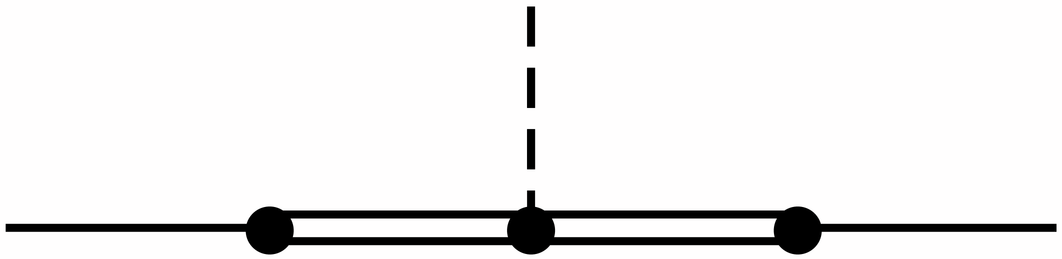

CHM

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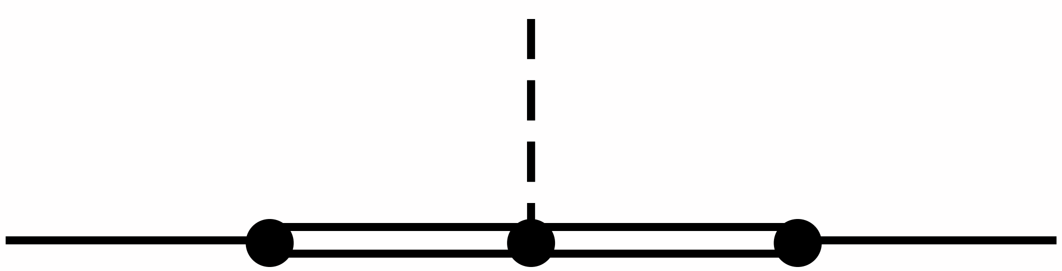
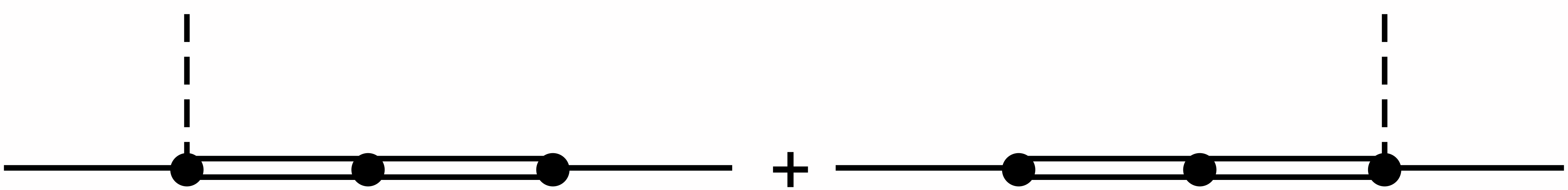


CHM



pNGB CHM

Partial Compositeness

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \bar{\mathcal{O}}(i\partial\!\!\!/ - m_M)\mathcal{O} + \epsilon \bar{\psi}\mathcal{O} + h.c.$$

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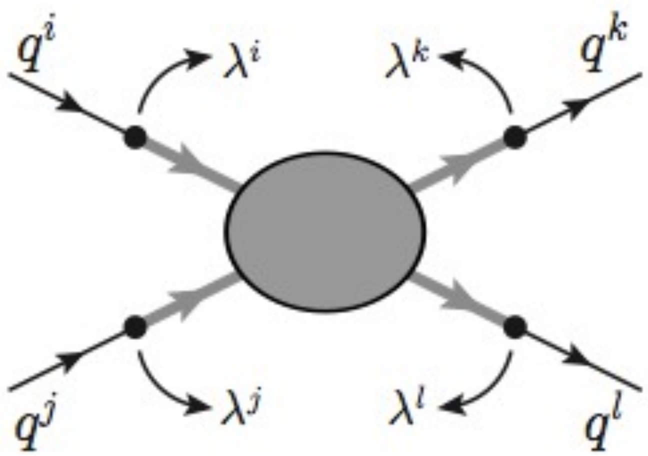
$$\text{light} = \psi\cos\phi + \mathcal{O}\sin\phi$$
$$\text{heavy} = -\psi\sin\phi + \mathcal{O}\cos\phi$$

- Flavor hierarchies
- GIM-like mechanism suppressing FCNC and ~~CP~~

Agashe, Perez, Soni	0408134
Cacciapaglia et al.	0709.1714
Redi, Weiler	1106.6357

Flavor constraints

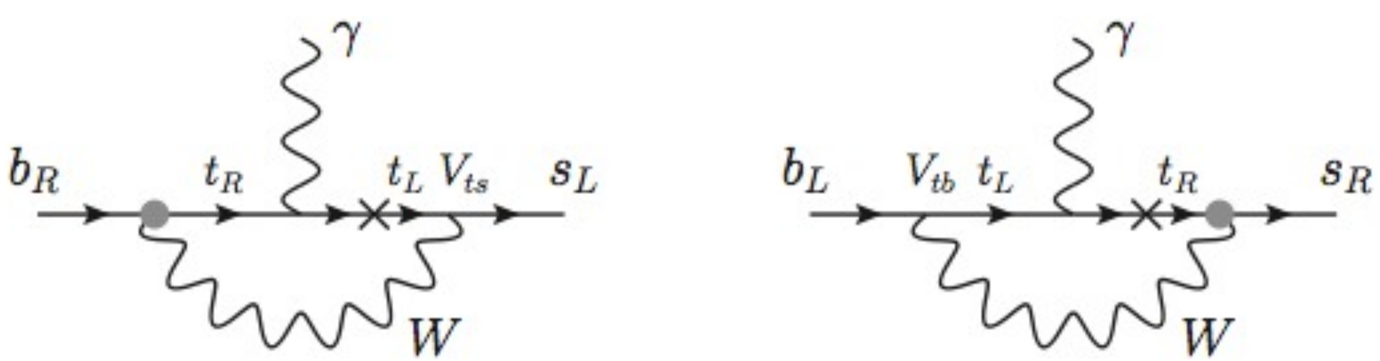
Panico Wulzer 1506.01961



$$m_* > O(1)\ \text{TeV}$$

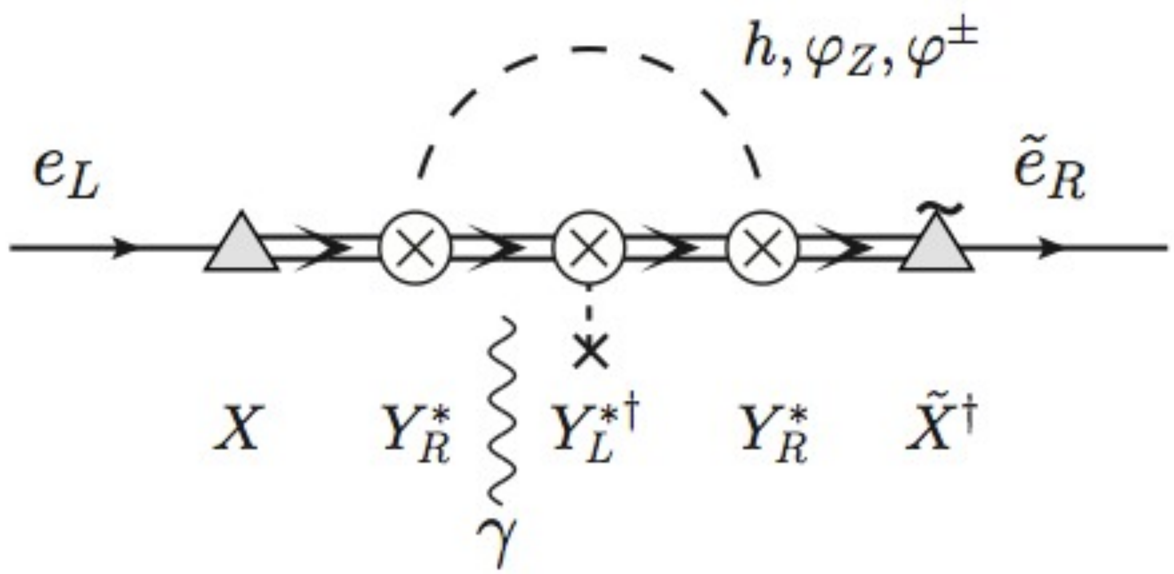
$$m_* > 10\ \text{TeV} \qquad \varepsilon_K$$

$$m_* > O(10)\ \text{TeV} \qquad \Delta F = 0$$



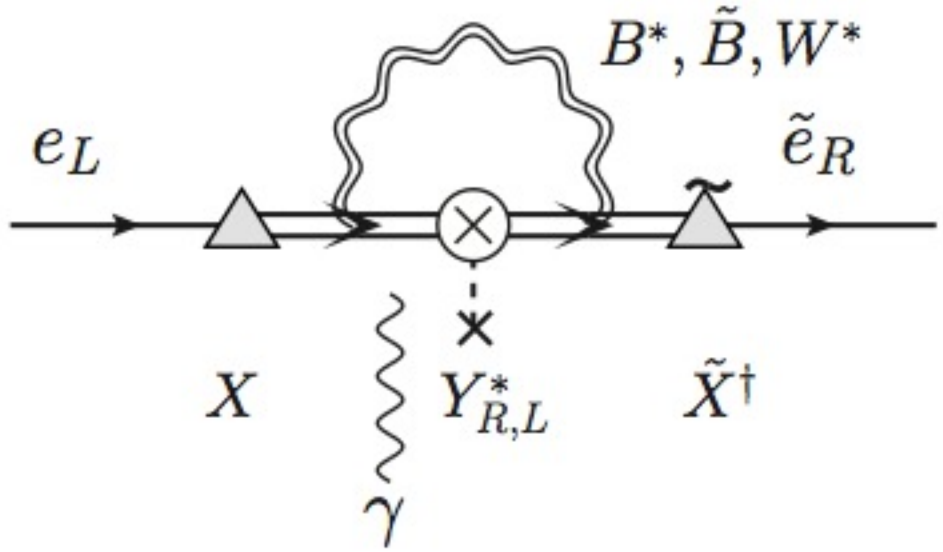
Flavor constraints: lepton sector

Feruglio et al   1509.03241



$m_* > O(10)$ TeV e EDM

$m_* > O(10)$ TeV $\mu \to e\gamma$



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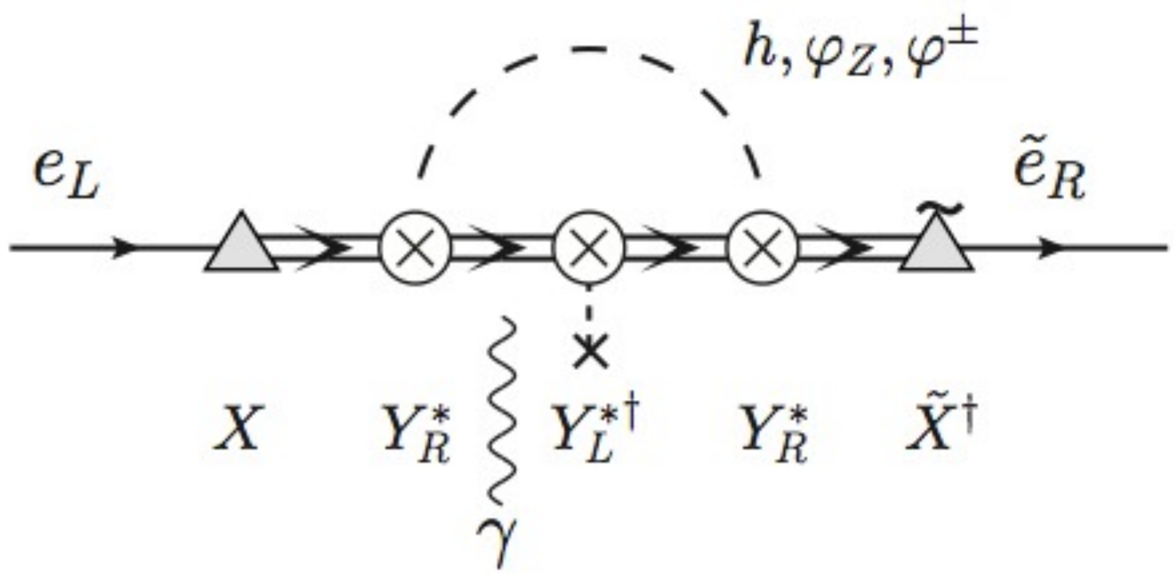
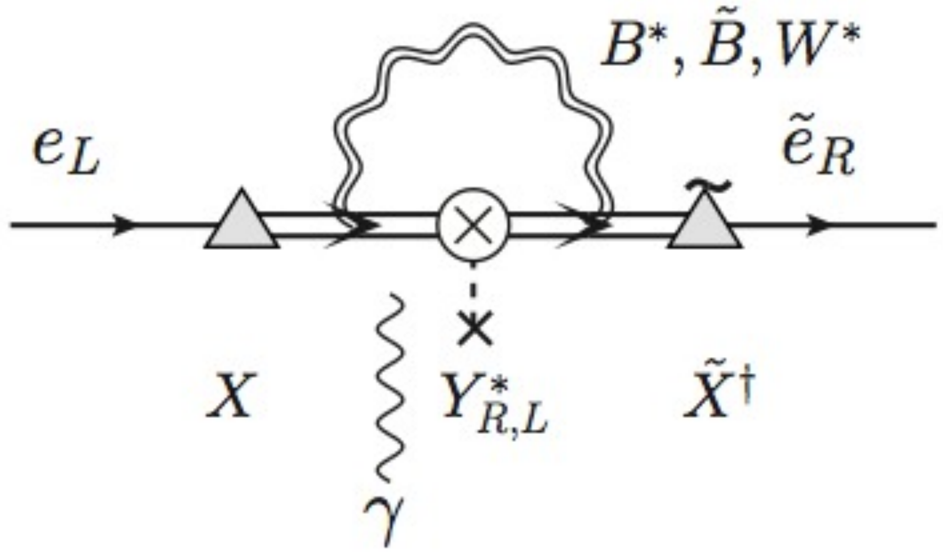


$m_* > O(10)$ TeV $\quad$ e EDM

$m_* > O(10)$ TeV $\quad$ $\mu \to e\gamma$



$Y_L^* = 0$ is a (stable) solution

An alternative model

Strong dynamics breaking EW symmetry.

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- bilinear mixing (TC-like) $\bar{q}_L q_R \mathcal{O}$

$$\bar{q}_L q_R \mathcal{O}$$

$$\Updownarrow$$

$$\bar{q}_L q_R \bar{q}_L q_R$$

An alternative model

1501.03818
JHEP 1506 (2015) 085
G. Cacciapaglia, H. Cai, T. Flacke, S. Lee, AP, H. Serodio

Mixed couplings:

- linear mixing for **top** (potentially bottom) $\bar{q}_L \mathcal{O}_{q_L} + \bar{u}_R \mathcal{O}_{q_R}$

- bilinear mixing for **other quarks** $\bar{q}_L q_R \mathcal{O}$

  (charm mass is compatible with $\Lambda_{UV} \lesssim 10^5 \text{ TeV}$)

Higgs as a pNGB

- $G/H, \quad \dim G/H \geq 4\,, \quad \mathrm{SO}(5)/\mathrm{SO}(4)$ ⇒ V(h)=0 at tree level

$$G = \mathrm{SO}(5) \times \mathrm{U}(1)_X$$

$$\downarrow$$

$$H = \mathrm{SO}(4) \times \mathrm{U}(1)_X$$

$$Y = T_{3R} + X$$

- $\mathrm{SU}(2) \times \mathrm{U}(1) \subseteq G_{SM} \subseteq H$ ⇒ V(h)≠0

  Partial compositeness (at least for the top)

The Model

$$\psi = \begin{pmatrix} Q \\ \tilde{T} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} i\ B - i\ X_{5/3} \\ B + X_{5/3} \\ i\ T + i\ X_{2/3} \\ -T + X_{2/3} \\ \sqrt{2}\ \tilde{T} \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{comp} =& i\overline{Q}_{L,R}\left(\not{D} + \not{E}\right) Q_{L,R} + i\overline{\tilde{T}}_{L,R}\not{D}\tilde{T}_{L,R} - M_4\left(\overline{Q}_L Q_R + \overline{Q}_R Q_L\right) \\ & - M_1\left(\overline{\tilde{T}}_L\tilde{T}_R + \overline{\tilde{T}}_R\tilde{T}_L\right) + ic_L\overline{Q}^i_L\gamma^\mu d^i_\mu\tilde{T}_L + ic_R\overline{Q}^i_R\gamma^\mu d^i_\mu\tilde{T}_R + \text{h.c.} \\ -\mathcal{L}_{mix} =& y_{L4,1} f\overline{q}^5_{3L} U\psi_R + y_{R4,1} f\overline{t}^5_R U\psi_L + \text{h.c.} \end{aligned}$$

$$\mathcal{L}_Y = \bar{q}_{L,\alpha}\lambda^u_{\alpha,\beta} u_{R,\beta}\ \mathcal{O}_u + \bar{\bar{q}}_{L,\alpha}\lambda^d_{\alpha,\beta} d_{R\beta}\ \mathcal{O}_d + h.c.$$

Up Sector Mass Matrix

$$\xi_\uparrow = \begin{pmatrix} u & c & t & T & X_{2/3} & \tilde{T} \end{pmatrix}^T \qquad v = s_\epsilon f \simeq 246 \text{ GeV}$$

$$M_{\rm up} = \begin{pmatrix} \tilde{m}[\epsilon]_{11} & \tilde{m}[\epsilon]_{12} & \tilde{m}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{21} & \tilde{m}[\epsilon]_{22} & \tilde{m}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{31} & \tilde{m}[\epsilon]_{32} & \tilde{m}[\epsilon]_{33} & f y_{L4} \cos^2 \frac{\epsilon}{2} & f y_{L4} \sin^2 \frac{\epsilon}{2} & -f \frac{y_{L1}}{\sqrt{2}} \sin\epsilon \\ 0 & 0 & f \frac{y_{R4}^*}{\sqrt{2}} \sin\epsilon & M_4 & 0 & 0 \\ 0 & 0 & -f \frac{y_{R4}^*}{\sqrt{2}} \sin\epsilon & 0 & M_4 & 0 \\ 0 & 0 & f y_{R1}^* \cos\epsilon & 0 & 0 & M_1 \end{pmatrix}$$

Up Sector Mass Matrix

$$U_{uL}^{\dagger} M_{\rm up} U_{uR} \simeq \begin{pmatrix} m_U & 0 \\ 0 & D_M \end{pmatrix} \qquad m_U = V_{uL} M_U V_{uR}^{\dagger}$$

$$m_U \simeq \frac{s_{2\epsilon}}{2}\, m_{\rm UV}^u + m_t \Pi\,, \quad \Pi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{uL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(\frac{m_c}{m_t}) & O(\frac{m_c}{m_t}) & 1 \end{pmatrix}$$

Up Sector Couplings

$$\Sigma_u \sim \begin{pmatrix} m_c^2 & m_c^2 & m_c m_t \\ m_c^2 & m_c^2 & m_c m_t \\ m_c m_t & m_c m_t & m_t^2 \end{pmatrix}$$

$$y_u \simeq \frac{m_U}{f s_{2\epsilon}/2}\left(1 - \frac{1}{2} s_{2\epsilon}^2\right) + B_u \,, \qquad B_u \sim \frac{\Sigma_u}{M_*^2}$$

$$\delta A_{NC}^{tL}\big|_{3\times 3} \simeq \frac{g}{c_W}\frac{\Sigma_u}{M_*^2}\,, \qquad \delta A_{NC}^{tR}\big|_{3\times 3} \simeq -\frac{g}{c_W}\frac{\Sigma_u}{M_*^2}$$

Flavor Preserving

$$\delta g_{Zt_L} \simeq -\frac{g}{c_W}\left(\frac{m_t}{M_*}\right)^2 \frac{(1-s_{\phi R}^2)^2}{2s_{\phi R}^2}, \quad \delta g_{Zt_R} \simeq -\frac{g}{c_W}\left(\frac{m_t}{M_*}\right)^2 \frac{(2-s_{\phi L}^2)}{2}$$

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$$\delta g_{Zt_L} \simeq -\frac{g}{c_W}\left(\frac{m_t}{M_*}\right)^2 \frac{\left(1-s_{\phi R}^2\right)^2}{2s_{\phi R}^2}, \quad \delta g_{Zt_R} \simeq -\frac{g}{c_W}\left(\frac{m_t}{M_*}\right)^2 \frac{\left(2-s_{\phi L}^2\right)}{2}$$

CKM unitarity: $$|\delta A_{CC}^L|^{1/2} \sim \left|\frac{m_t}{M_*}\frac{(1-s_{\phi R}^2)}{\sqrt{2}s_{\phi R}}\right| \lesssim 10^{-1}$$

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CKM unitarity:

$$|\delta A_{CC}^L|^{1/2} \sim \left| \frac{m_t}{M_*} \frac{\left(1-s_{\phi R}^2\right)}{\sqrt{2} s_{\phi R}} \right| \lesssim 10^{-1}$$

$$\delta g_{Zb_L} = 0\,, \qquad \delta g_{Zb_R} = -\frac{g s_{2\epsilon}^2}{8 c_W}\left(\frac{y_{L4} f m^d_{\mathrm{UV}33}}{M_4^2 + y_{4L}^2 f^2}\right)^2 \simeq -\frac{g}{2 c_W} s_{\phi L}^2 c_{\phi L}^2 \left(\frac{m_b}{M_*}\right)^2$$

Loop effects in Zbb couplings and S,T parameters: as in conventional CHM

Flavor Violating

Higgs mediated up FCNC

$$\frac{1}{m_H^2}\left(\frac{m_c}{M_*}\right)^4 \simeq \frac{10^{-12}}{\text{TeV}^2}\left(\frac{1\ \text{TeV}}{M_*}\right)^4$$

Z mediated up FCNC

$$\frac{g^2}{16 c_W^2 m_Z^2}\left(\frac{m_c}{M_*}\right)^4 \simeq \frac{10^{-11}}{\text{TeV}^2}\left(\frac{1\ \text{TeV}}{M_*}\right)^4$$

Z mediated down FCNC

$$\frac{10^{-4}}{\text{TeV}^2}\left[(V^*_{dL33}V_{dL31})^2 Q_1^{db} + (V^*_{dL33}V_{dL32})^2 Q_1^{sb} + (V^*_{dL32}V_{dL31})^2 Q_1^{ds}\right]$$

Flavor Violating: Top Couplings

LHC Run I

$$y_{tc,L} \simeq y_{tc,R} \sim \frac{m_c m_t}{f M_*} \simeq 10^{-4}$$

$$\mathcal{B}(t \to hc) < 6 \div 8 \times 10^{-3}$$

$$(\delta A^{tL,R}_{NC})_{32} \simeq \frac{g}{c_W} \frac{m_t m_c}{M_*^2} \simeq 10^{-4}$$

$$\mathcal{B}(t \to Zc) < 5 \times 10^{-4}$$

Flavor Violating Processes: heavy resonances

$$\mathcal{L} = \Phi(g_B \bar{Q} Q + g_S \bar{\tilde{T}} \tilde{T}) + \frac{1}{2} m_\Phi^2 \Phi^2$$

$$\mathcal{L} \simeq \left(\frac{\tilde{g}}{m_\Phi}\right)^2 \left(\frac{m_c}{m_t}\right)^4 \left(\frac{m_t}{M_*}\right)^2 \mathcal{Q}_4^{uc} \simeq \left(\frac{1\ \mathrm{TeV}}{M_*}\right)^2 \left(\frac{\tilde{g}}{m_\Phi/\mathrm{TeV}}\right)^2 \times \frac{10^{-10}}{\mathrm{TeV}^2} \mathcal{Q}_4^{uc}$$

$$\mathcal{L} \simeq \left(\frac{g_B s_{\phi L}^2 c_{\phi L}}{m_\Phi}\right)^2 \left(\frac{m_b}{M_*}\right)^2 \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds}\right]$$

$$\simeq \left(\frac{1\,\mathrm{TeV}}{M_*}\right)^2 \left(\frac{g_B}{m_\Phi/\mathrm{TeV}}\right)^2 \times \frac{10^{-5}}{\mathrm{TeV}^2} \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds}\right]$$

$$z_4^{d_\alpha d_\beta} = V_{dL3\alpha}^* V_{dL3\beta} \sum_{\gamma\delta} V_{dR\gamma\beta} V_{dR\delta\alpha}^*$$

Summary

+ vector resonances
+ Zbb, Zcc, …
+ CP and ~~CP~~
+ Higgs couplings
+ W FV couplings
+ UV four fermion operators (qq)(qq) $\Lambda_{UV} \lesssim 10^5$ TeV

Summary

- \+ vector resonances
- \+ Zbb, Zcc, …
- \+ CP and ~~CP~~
- \+ Higgs couplings
- \+ W FV couplings
- \+ UV four fermion operators (qq)(qq)

Up sector: OK

Down sector:

$$|V^*_{dL33}V_{dL13}| < 10^{-1}\,, \quad |V^*_{dL33}V_{dL23}| < 10^{-1/2}\,, \quad |V^*_{dL13}V_{dL23}| < 10^{-5/2}$$

$$|V_{dL13}| < 10^{-1}\,, \quad |V_{dL23}| < 10^{-1/2}\,,$$

$$|z_4^{db}| < 1 \div 10^{-2}\,, \quad |z_4^{sb}| < 1 \div 10^{-1/2}\,, \quad |z_4^{ds}| < 10^{-4} \div 10^{-6}\,,$$

$$|V^*_{dL33}V_{dL31}| < 10^{-1} \div 10^{-3}\,, \quad |V^*_{dL33}V_{dL32}| < 1 \div 10^{-2}\,,$$

$$|V^*_{dL32}V_{dL31}| < 10^{-3} \div 10^{-5}\,.$$

Summary

- \+ vector resonances
- \+ Zbb, Zcc, …
- \+ CP and ~~CP~~
- \+ Higgs couplings
- \+ W FV couplings
- \+ UV four fermion operators (qq)(qq)

Up sector: OK

Down sector:

$$V_{dL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_s}{m_b}) \\ O(1) & O(1) & O(\frac{m_s}{m_b}) \\ O(\frac{m_s}{m_b}) & O(\frac{m_s}{m_b}) & 1 \end{pmatrix}$$

Extensions

1. Different top partners, different cosets
2. Vector-like quarks
3. Different origin of bottom mass
4. Fully composite right top

Additional top partners

for instance $\mathbf{14} = \mathbf{1} + \mathbf{4} + \mathbf{9}$

$$\mathcal{L} \simeq -\frac{s^2_{\phi 9L} c^3_{\phi L}}{c^2_{\phi 9L}} \frac{\epsilon^2}{f} \, h \, \bar{b}_L \left(m^d_{\mathrm{UV}31} d_R + m^d_{\mathrm{UV}32} s_R + m^d_{\mathrm{UV}33} b_R \right)$$

$$\propto \begin{pmatrix} \bar{d}_L & \bar{s}_L & \bar{b}_L \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ m^d_{\mathrm{UV}31} & m^d_{\mathrm{UV}32} & m^d_{\mathrm{UV}33} \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

$$\mathcal{L} \simeq \frac{1}{m_H^2} \left(\frac{\epsilon m_b}{f} \right)^2 \left[z_4^{db} Q_4^{db} + z_4^{sb} Q_4^{sb} + z_4^{ds} Q_4^{ds} \right] \simeq \frac{10^{-4}}{\mathrm{TeV}^2} \left[z_4^{db} Q_4^{db} + z_4^{sb} Q_4^{sb} + z_4^{ds} Q_4^{ds} \right]$$

Bottom mass

Main motivation: dynamical explanation of structure of 3x3 down unitary transformation.

$$\mathcal{L} = y_R f\, \bar{\psi}_L U^t d_{3R}^{14} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \bar{B}_L b_R + h.c.$$

$$\mathrm{Tr}[\bar{Q}_{14} d_{3R}^{14}]$$

$$Q_{14} = U(Q_1 + Q_4 + Q_9)U^t$$

Bottom mass

Main motivation: dynamical explanation of structure of 3x3 down unitary transformation.

$$\mathcal{L} = y_R f\, \bar{\psi}_L U^t d^{14}_{3R} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \bar{B}_L b_R + h.c.$$

$$d^{14}_{3R} = \frac{b_R}{2\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & i & 0 \\ 0 & 0 & -i & 1 & 0 \\ 1 & -i & 0 & 0 & 0 \\ i & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\mathcal{L} = \bar{d}_{\alpha L} m^d_{\alpha\beta} d_{\beta R} + h.c.\,, \qquad m^d = m^d_{UV} \frac{s_{2\epsilon}}{2} + \Pi \frac{f y_R s_{\phi L}}{2} s_\epsilon$$

Conclusions

- Top partial compositeness and direct Yukawas
  (in pNGB composite Higgs models)

- Analysis of indirect bounds

- Generalizations
  - Additional partners
  - Bottom partial compositeness (without partners)
  - vector-like quarks
  - …

Thank You