Flavor Violation Tests of Warped/Composite SM

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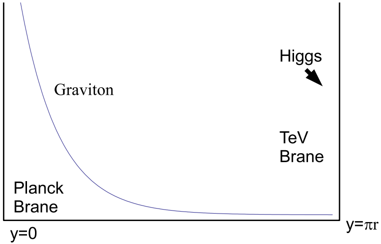
RS models

- Geometrical solution to the Planck -Electroweak hierarchy problem (Randall,Sundrum 99)

$$(ds)^2 = e^{-2ky} dx^\mu dx_\mu + (dy)^2 \qquad (0 \le y \le \pi r_c)$$

- $$\frac{< v >}{M_{Pl}} \sim e^{-k\pi r_c}$$

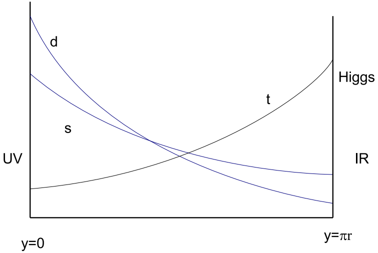


Fermions in the bulk

One can easily explain large hierarchies in the fermion masses by putting them in the bulk. The mass will be proportional to the overlap integral between the fermion profiles and Higgs field.

$$f(y) \propto e^{-cky}$$

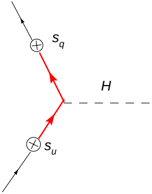
Small variation in the 5D mass parameter c will lead to the large hierarchies in the fermion masses.



- We want to study the phenomenology of the RS models, assuming that all the hierarchies in the fermion masses and mixings are generated by the warp factors, and all the Yukawa couplings are of the same order i.e. "anarchical".
- Instead of using specific $5D$ model we will use more economical description, namely "two site model"(Contino,Sundrum,Kramer,Son, 06), which is 4D effective field theory obtained by truncating RS model to the SM particles and their first KK excitations.
- Two-site model describes two sectors: composites of purely $4D$ strong dynamics and elementary fields (which are not part of the strong dynamics). These two sectors mix, with the resulting mass eigenstates being the SM particles and heavier partners, which correspond to the zero and KK modes of the $5D$ model.

Masses and mixings of the SM fermions

- The mass of the SM fermions in the Two Site model will be



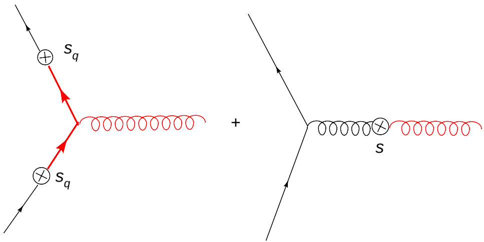
$$= \frac{Y_* v}{\sqrt{2}} s_q s_u$$

-

$$(D_L)_{ij}, (U_L)_{ij} \sim (V^{CKM})_{ij} \sim \frac{s_q^i}{s_q^j} \quad i < j$$

$$(D(U)_R)_{ij} \sim \frac{s_{d(u)}^i}{s_{d(u)}^j} \quad i < j$$

Interaction with vector bosons



$$= \rho^*_\mu g \left(-c_q^2 \tan\theta + s_q^2 \frac{1}{\tan\theta}\right),$$
$$g = g_* \sin\theta$$

Two site - 5D dictionary

- “Two Site”’ model captures robust features of the RS model, using fewer parameters
- “Two Site”-RS matching

$$
\begin{aligned}
s_{L,R} &\leftrightarrow f_{L,R} \\
\tan^2\theta &\leftrightarrow \frac{1}{k\pi r_c} \\
g_* &\leftrightarrow g_5\sqrt{k} \\
Y_* &\leftrightarrow Y_{KK} \\
\text{SM states} &\leftrightarrow \text{zero modes} \\
\text{heavy states} &\leftrightarrow \text{KK modes}
\end{aligned}
$$

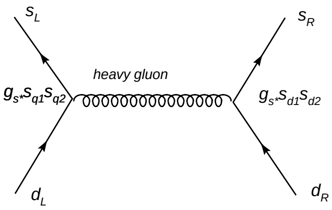
Flavor physics in the Two-site approach

- No flavor violation in elementary sector.
- Flavor anarchy in composite sector. (Composite site Yukawa couplings are of the same order and have no structure)
- Hierarchical mixing between elementary and composite sector generate hierarchical quark masses and CKM mixing angles.
- Flavor violation for first two generations are protected due to small mixing with composite sector. (RS-GIM)

Summary of the previous works on the flavor constraints in RS model

- The tree level flavor violation was studied in (Csaki,Falkowski,Weiler, JHEP 0809:008,2008; Blanke,Buras,Duling,Gori,Weiler arXiv:0809.1073 [hep-ph]; Casagrande, Goertz, Haisch, Neubert, Pfoh, JHEP 0810:094,2008)
- The strongest bound comes from ϵ_k parameter of the $K_0 - \bar{K}_0$ oscillation.
- $$M_{kk} \gtrsim 20\text{TeV}$$

  (i)Higgs exactly on IR brane
  (ii) QCD coupling matching at tree level
  (iii)Yukawa coupling from NDA, with 2 KK modes. .



- ϵ_k calculation from mass insertion

$$\Rightarrow C_{4K} \sim \frac{g_{*s}^2}{M_*^2} s_{q1}s_{q2}s_{d1}s_{d2} \sim \frac{g_{*s}^2}{M_*^2}\frac{2m_d m_s}{v^2 Y_*^2}$$

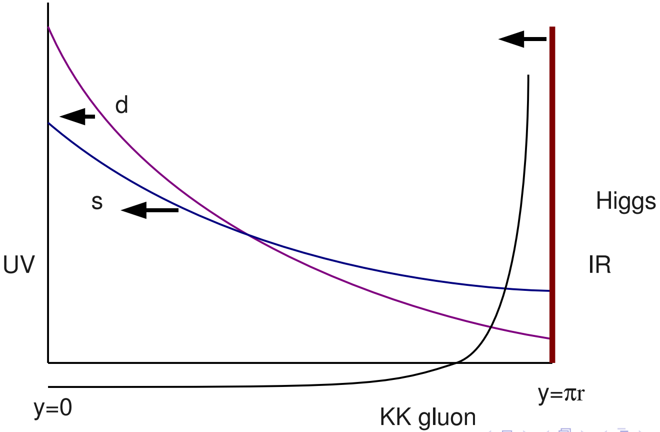
$$\mathcal{O}_4 = \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta, \qquad (1)$$

- Model independent bound: (UTfit Collaboration)

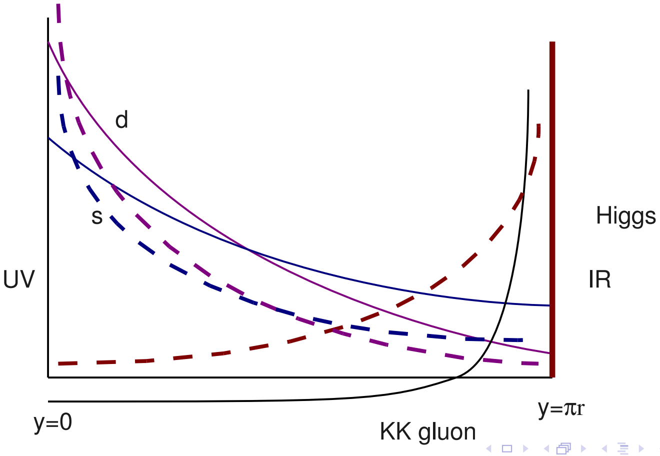
$$\text{Im}\, C_4 \lesssim \frac{1}{(\Lambda_F)^2}, \qquad \Lambda_F = 1.6 \times 10^5 \text{ TeV}$$

$$M_* \gtrsim \frac{11 g_{s*}}{Y_*^d} \text{ TeV}$$

Pushing Higgs in the Bulk



Pushing Higgs in the Bulk



Higgs field in RS models

- Higgs can be promoted to be 5D field (Cacciapaglia, Csaki, Marandella, Terning 06)

$$H_{5D} \sim e^{k(2+\beta)y}$$

  $\beta \to \infty$ corresponds to the brane Higgs
- $a = \frac{Y_0}{Y_{KK} f_q f_d}$
- a(Brane Higgs)$\sim$ 0.5, 0.5 $<$ a(Bulk Higgs)$<$ 1.5
- a (Two-Site)$= \frac{Y_{SM}}{Y_* s_q s_d} = \frac{Y_* s_q s_d}{Y_* s_q s_d} = 1$

ϵ_k bound for the bulk Higgs

$$M_* \gtrsim \frac{11 g_*}{a Y^d_{KK}} \text{ TeV} \tag{2}$$

- $g_* \sim 6$ tree level matching , $g_* \sim 3$ loop level matching with brane kinetic terms
- $a \sim 0.5$ brane Higgs, $a \sim 1$ Bulk Higgs
- Brane Higgs $Y_{KK} \lesssim \frac{4\pi}{N}$, bulk Higgs $Y_{KK} \lesssim \frac{4\pi}{\sqrt{N}}$
- $M_{KK} \gtrsim 3.7$ TeV

Rare decay $b \to s\gamma$

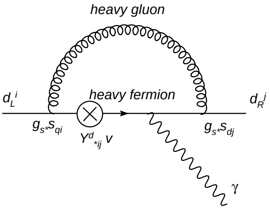
- Effective Hamiltonian

$$\mathcal{H}_{eff}(b \to s\gamma) = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} [C_7(\mu_b) Q_7 + C_7'(\mu_b) Q_7' + \ldots]$$

$$Q_7 = \frac{e}{8\pi^2} m_b \bar{b} \sigma^{\mu\nu} F_{\mu\nu} (1-\gamma_5) s; \quad Q_7' = \frac{e}{8\pi^2} m_b \bar{b} \sigma^{\mu\nu} F_{\mu\nu} (1+\gamma_5) s$$

- $C_7' \sim \frac{m_s}{m_b} C_7$ is negligible in SM.

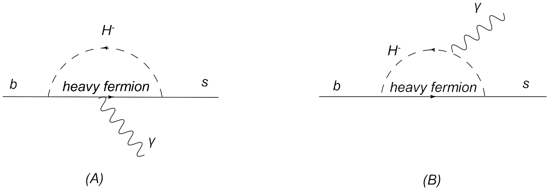
Heavy gluon contribution to $b \longrightarrow s\gamma$



- $$\propto s_{q_i} g_{s*}^2 Y^d_{*ij} s_{d_j}$$

  is aligned with the mass
- so the KK gluon can contribute only $O(\frac{v^3}{M_*^3})$ corrections

$b \longrightarrow s\gamma$



$$\propto s_{q_i} Y^d_{*ik} Y^d_{*kl} Y^d_{*lj} s_{d_j}$$

$b \to s\gamma$

- $$\begin{aligned} C_{7\,\text{estimate}}^{2-\text{site}}(m_*) &= -\frac{5}{48}\frac{(Y_*)^2}{(m_*)^2}\frac{\sqrt{2}}{G_F} \\ C'^{\,2-\text{site}}_{7\,\text{estimate}}(m_*) &= -\frac{5}{48}\frac{(Y_*)^2}{(m_*)^2}\frac{\sqrt{2}}{G_F}\frac{m_s}{m_b\lambda^4} \end{aligned} \quad (3)$$

- $$\frac{C'^{2-\text{site}}_7(m_*)}{C^{2-\text{site}}_7(m_*)} \sim 8$$

New physics contribution to the $b \to s\gamma$

- $$\Gamma^{\text{total}}(b \to s\gamma) \propto |C_7(\mu_b)|^2 + |C_7'(\mu_b)|^2$$
- $C_7^{\text{total}}(\mu_w) = C_7^{\text{SM}}(\mu_w) + C_7^{2-\text{site}}(\mu_w)$
- $\delta_7 \equiv C_7^{2-\text{site}}(m_*)/C_7^{SM}(\mu_w), \;\; \delta_7' \equiv C_7'^{\,2-\text{site}}(m_*)/C_7^{SM}(\mu_w)$
- $$\frac{\Gamma^{\text{total}}(b \to s\gamma)}{\Gamma^{SM}(b \to s\gamma)} \approx 1 + 0.68 Re(\delta_7) + 0.11|\delta_7'|^2$$

Constraints from $b \to s\gamma$

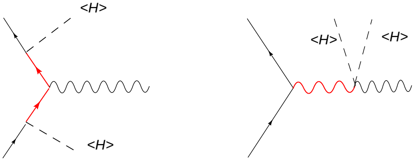
- $BR(b \to s\gamma) = (352 \pm 23 \pm 9) \times 10^{-6}$[HFAG]
- theoretical uncertainties $BR(b \to s\gamma) = (315 \pm 23) \times 10^{-6}$ [Huber:2007]
- 20% uncertainty is allowed
- $|\delta'_7| \lesssim 1.4$ and $\mathrm{Re}(\delta_7) \lesssim 0.3$.
- $$m_* \gtrsim (0.63) Y_* \text{ TeV}$$

Combining bounds

- $$m_* \gtrsim (0.63) Y_* \text{ TeV}$$
  $$M_* \gtrsim \frac{11 g_{s*}}{Y_*^d}$$
- setting $M_* = m_*$

$$\begin{aligned} M_* &\gtrsim 2.6\sqrt{g_{s*}} \text{ TeV} \quad \text{for} \quad Y_* \sim 4.2\sqrt{g_{s*}} \\ &\sim 4.5 \text{ TeV for } g_{s*} \sim 3 \\ &\sim 6.4 \text{ TeV for } g_{s*} \sim 6 \end{aligned}$$

$Z \to b\bar{b}$



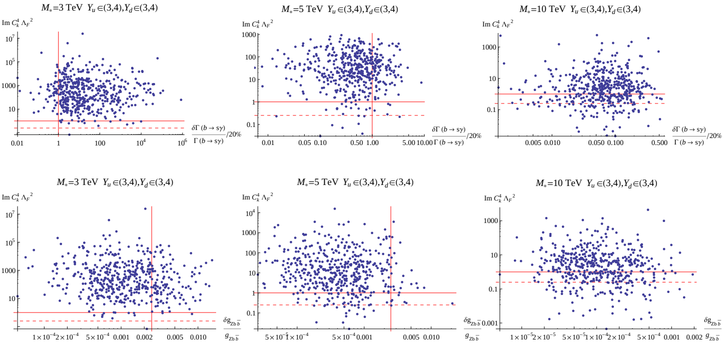
$$\frac{\delta g_{Z\bar{b}b}}{g_{Z\bar{b}b}} \approx \sum_{i=1}^{3} \left(\frac{Y_{*di3}}{Y_{*u33}}\right)^2 \left(\frac{m_t}{M_* s_{u3}}\right)^2 + \frac{1}{2}\left(\frac{m_t}{M_* s_{u3}}\right)^2 \left(\frac{g_{*2}}{Y_{*U33}}\right)^2$$

$$M_* \gtrsim 4.7 \quad \text{TeV}$$

Other flavor observables

- Constraints from $\Delta F = 2$ in the B,D sectors are weaker.
- Large time dependent CP asymmetry $S \sim \frac{C_7'(\mu_w)}{C_7(\mu_w)} \sim O(1)$, constraints are not strong.

Numerical Scan



Summary

- Two-site model provides an economical description of the RS models.
- Pushing Higgs in the bulk relaxes ϵ_K bound on the KK scale
- There is tension between ϵ_K and $b \to s\gamma$ constraints.
- O(5) TeV scale could be consistent with flavor physics bounds.
- We expect large new physics signals in many flavor observables.