Higgs Flavor Violation in Warped Extra Dimension

Lijun Zhu

University of Maryland-College Park

05/11/2009

Work in progress with A. Azatov, M. Toharia.
For strong dynamics approach, see work in progress by K. Agashe and R. Contino.

Outline

Higgs boson in SM

Higgs boson in SM

- Higgs field gets VEV v, break EW symmetry.
- Higgs give masses to fermions through Yukawa couplings

$$\mathcal{L}_Y = y_f H \bar{f}_L f_R + h.c. \tag{1}$$

$$H \to \frac{1}{\sqrt{2}}(h + v) \tag{2}$$

- Fermion mass given by

$$m_f = \frac{y_f v}{\sqrt{2}} \Rightarrow y_f = \frac{m_f}{v/\sqrt{2}} \tag{3}$$

- Higgs Yukawa couplings aligned with SM fermion masses.

Drawbacks of SM Higgs

- Hierarchy between UV/Planck scale and EW scale not stabilized.
- Fermion masses parametrized by Yukawa couplings. Hierarchy of fermion masses not explained.
- CKM mixing matrix hierarchy not explained.

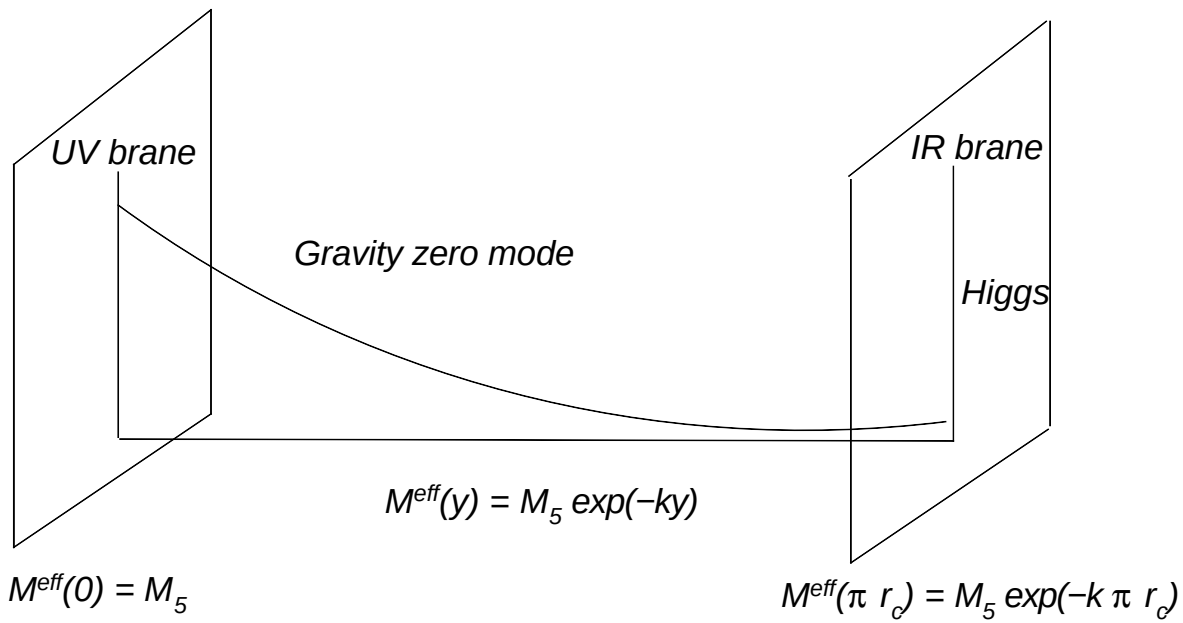
Warped Extra Dimension and Flavor Physics

Warped Extra Dimension

- Planck-weak hierarchy explained by "warp factor".[L. Randall and R. Sundrum 1999]

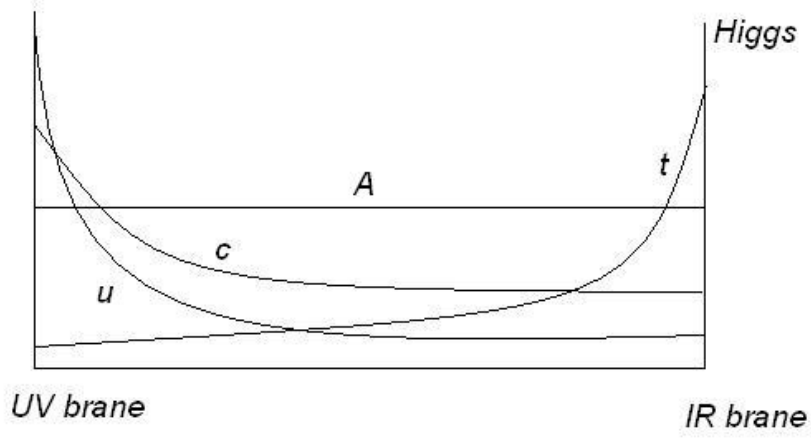
$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2; \quad y \in (0, \pi r_c) \tag{4}$$

k is the curvature scale $\sim M_{pl}$.



Flavor Structure of Warped Extra Dimension

- SM fermions and gauge fields propagate in the bulk.[T. Gherghetta , A. Pomarol, 2000]
- Explains the hierarchy of SM fermion masses through fermion wavefunctions $\chi(c; y) \propto e^{(\frac{1}{2}-c)ky}$, with $c = \frac{M_f^{5D}}{k}$.



$$f(c) \equiv \sqrt{\frac{1-2c}{1-\epsilon^{1-2c}}} = \begin{cases} \sqrt{2c-1}\epsilon^{c-1/2} \ (c > 1/2) \\ \sqrt{1-2c} \ (c < 1/2) \end{cases} ; \quad \epsilon = \frac{TeV}{k} \sim 10^{-15}$$

- Quark masses and mixing angles are set by the fermion wavefunctions.

$$m_{ij}^{u,d} \approx f(c_{q_i}) Y_{*ij}^{u,d} f(c_{d_j}) v \tag{5}$$

$$(U_L)_{ij} \sim (D_L)_{ij} \sim f(c_{q_i})/f(c_{q_j}) \quad (i<j) \tag{6}$$

$$(U_R)_{ij} \sim f(c_{-u_i})/f(-c_{u_j}); \quad (D_R)_{ij} \sim f(-c_{d_i})/f(-c_{d_j}) \quad (i<j) \tag{7}$$

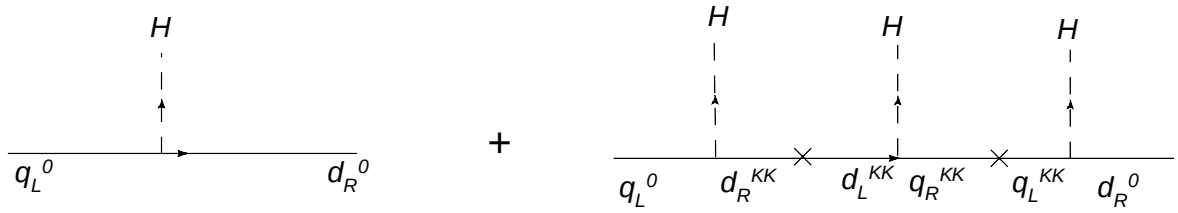
$$m_{diag,i}^{u,d} \sim f_{q_i} Y_*^{ij} f_{-d_i} v \tag{8}$$

- $5D$ Yukawa couplings are all of order 1 and have no structure (assumption of flavor anarchy).
- Hierarchy in SM fermion masses and CKM mixing angles can be obtained if $f(c_{q_1,u_1,d_1}) \ll f(c_{q_2,u_2,d_2}) \ll f(c_{q_3,u_3,d_3})$, which can be achieved with order one difference in c parameters.

Flavor Structure of Higgs Yukawa Couplings

Higgs Yukawa Couplings in Warped Extra Dimension (KK approach)

- Consider bulk Higgs localized near IR brane. Yukawa couplings receive corrections due to zero mode fermions mix with KK mode fermions.



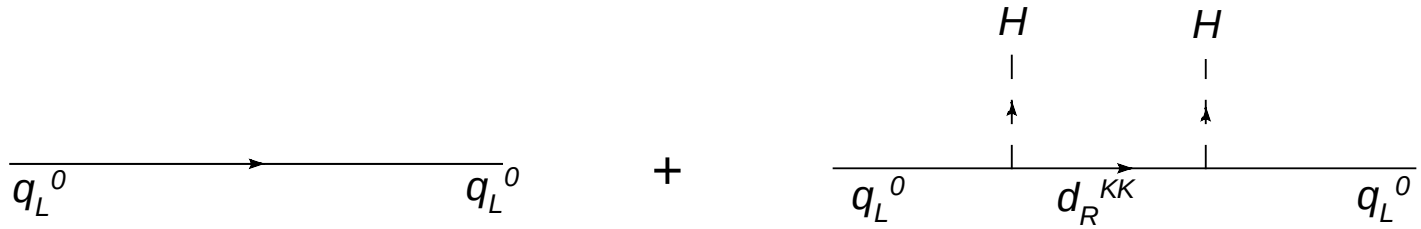
$$m_{SM} \approx Y_{00}v - Y_{0n}Y_{nm}Y_{m0}v\frac{v^2}{M_{KK}^2} \tag{9}$$

$$\approx f(c_q)Y_* f(-c_d)v - f(c_q)\frac{Y_*^2 v^2}{M_{KK}^2} f(-c_d)Y_* v$$

$$Y_{SM} \approx f(c_q)Y_* f(-c_d) - 3f(c_q)\frac{Y_*^2 v^2}{M_{KK}^2} f(-c_d)Y_* \tag{10}$$

$$\Rightarrow m_{SM} - Y_{SM}v \approx 2f(c_q)\frac{Y_*^2 v^2}{M_{KK}^2} f(-c_d)vY_* \tag{11}$$

Higgs Yukawa Couplings in Warped Extra Dimension



- Correction to kinetic term

$$\left(1 + Y_{d,0n} Y_{d,n0} \frac{H^2}{M_{KK}^2}\right) \bar{q}_L^{SM} i\partial q_L^{SM} \approx \left(1 + f(c_q)^2 \frac{(Y_* H)^2}{M_{KK}^2}\right) \bar{q}_L^{SM} i\partial q_L^{SM} \tag{12}$$

  Canonical normalization leads to

$$m_{SM} - Y_{SM} v \approx f(c_q)^3 \frac{Y_*^2 v^2}{M_{KK}^2} f(-c_d) v Y_* \tag{13}$$

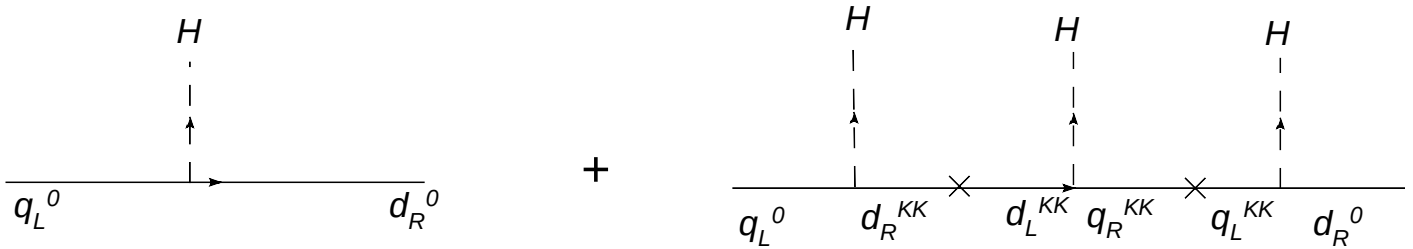
- Add them together, we get

$$m_{SM} - Y_{SM} v \approx f(c_q) \frac{Y_*^2 v^2}{M_{KK}^2} f(-c_d) v Y_* [2 + f(c_q)^2 + f(-c_d)^2] \tag{14}$$

$$\approx \frac{Y_*^2 v^2}{M_{KK}^2} [2 + f(c_q)^2 + f(-c_d)^2] m_{SM}$$

Higgs Yukawa Couplings in Warped Extra Dimension

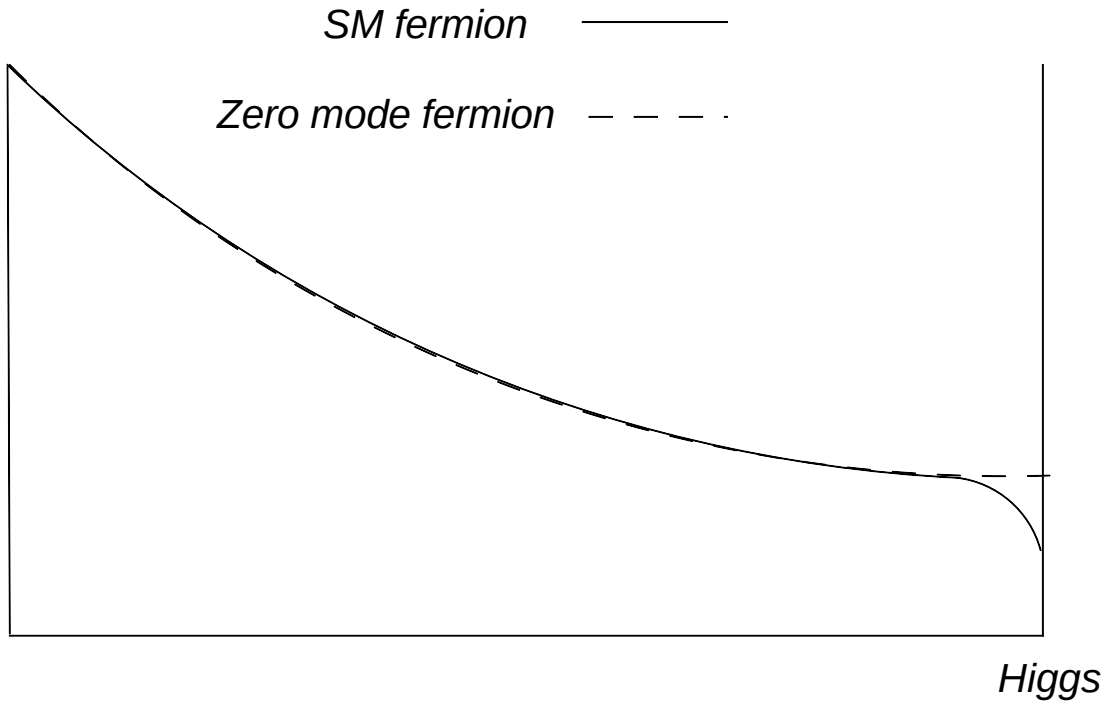
- A subtlety with exactly brane localized Higgs.



- Due to parity assignment (q_R (-,-), d_L (-,-)). The wavefunctions of q_R, d_L vanishes at IR brane, thus the coupling between q_R, d_L and Higgs vanishes.
- Need to regularize the Delta function and sum over infinite KK modes. It gives us a misalignment of the same order as the bulk Higgs case.

Higgs Yukawa Couplings in Warped Extra Dimension (5D Approach)

- Another way to see the source of this misalignment.



- Yukawa coupling determined by SM fermion wavefunction at IR brane.
- SM fermion masses sourced by Yukawa coupling with Higgs and also the "curvature" of wavefunction.

- 5D calculation shows

$$\Delta\hat{Y} = \frac{-2}{3}\begin{pmatrix} f_{q1} & & \\ & f_{q2} & \\ & & f_{q3} \end{pmatrix}\hat{Y}_*\hat{Y}_*^\dagger\hat{Y}_*\begin{pmatrix} f_{d1} & & \\ & f_{d2} & \\ & & f_{d3} \end{pmatrix}\left(\frac{v^2}{TeV^2}\right) \tag{15}$$

- After unitary transformation into mass eigenstate, flavor violating Yukawa couplings are generated.

$$\begin{aligned} \hat{Y}^{\text{off}}_{\alpha\beta} &= -(O^\dagger_{d_L}\Delta\hat{Y}O_{d_R})_{\alpha\beta} \\ &\sim \frac{2}{3}f(c_{q_\alpha})\bar{Y}^3_* f(c_{d_\beta})\frac{v^2}{TeV^2} \end{aligned} \tag{16}$$

- We can parameterize the flavor violating couplings as

$$\mathcal{L}_{HFV} = a^d_{ij}\sqrt{\frac{m^d_i m^d_j}{v^2}}H\bar{d}^i_L d^j_R + h.c. + (d \leftrightarrow u) \tag{17}$$

Higgs Yukawa Couplings in Warped Extra Dimension

- Sizes of $a^{u,d}_{\alpha\beta}$ can be estimated by using anarchy assumption

$$|a^d_{ij}| \sim \begin{pmatrix} 0.96 & 0.032 & 0.01 \\ 0.04 & 0.82 & 0.012 \\ 0.12 & 0.1 & 0.68 \end{pmatrix} \tag{18}$$

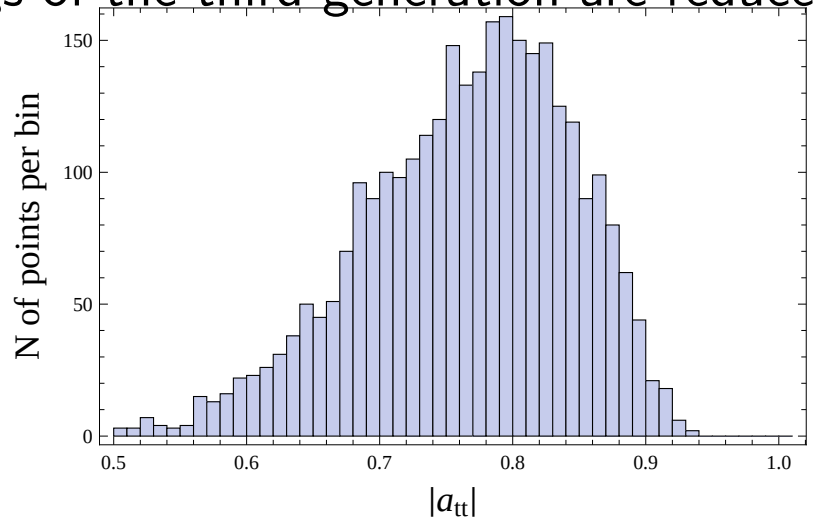
$$|a^u_{ij}| \sim \begin{pmatrix} 0.96 & 0.17 & 0.13 \\ 0.008 & 0.82 & 0.08 \\ 0.01 & 0.14 & 0.68 \end{pmatrix} \tag{19}$$

- Using $1/R' = 1.5$ TeV, $\bar{Y}_* = 2$.
- Numerical scan confirms this result.

Phenomenological Implications

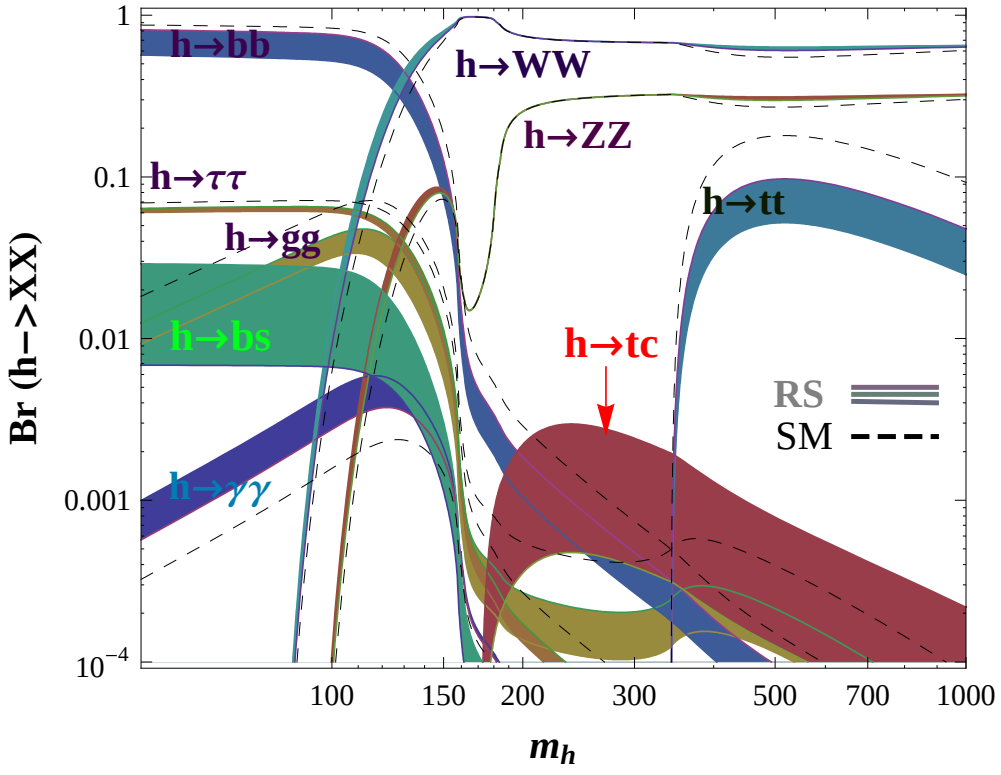
Phenomenological Implications

- Yukawa couplings of the third generation are reduced.



- Scan result for $1/R' = 1.5$ TeV, $Y_* \in [1/3, 3]$.
- Leads to reduced Higgs production at the LHC due to gluon fusion.

- Higgs decay branching ratios changed.



- Scan result with $1/R' = 1.5$ TeV, $Y_* \in [1, 4]$.

- Generate new contribution to $\Delta F = 2$ processes.

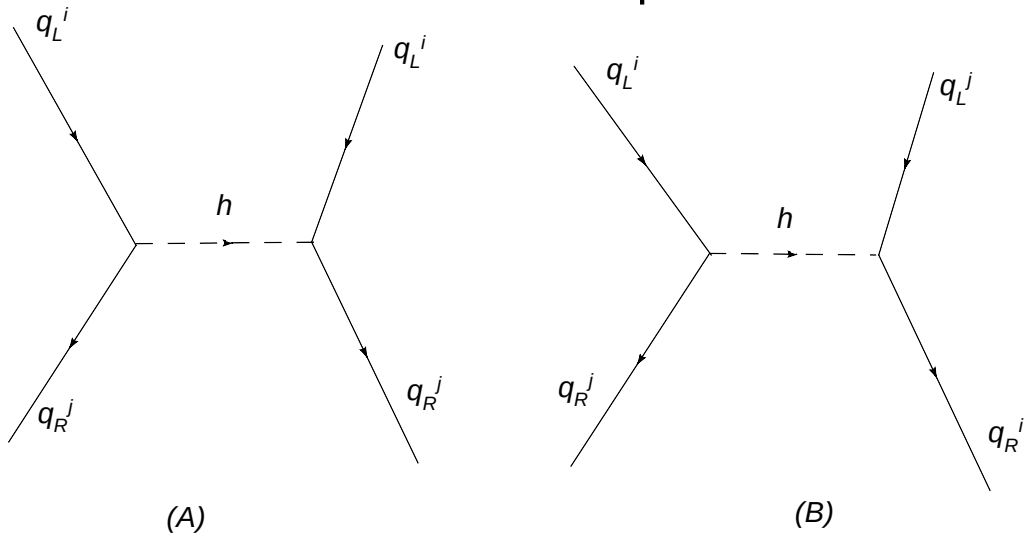
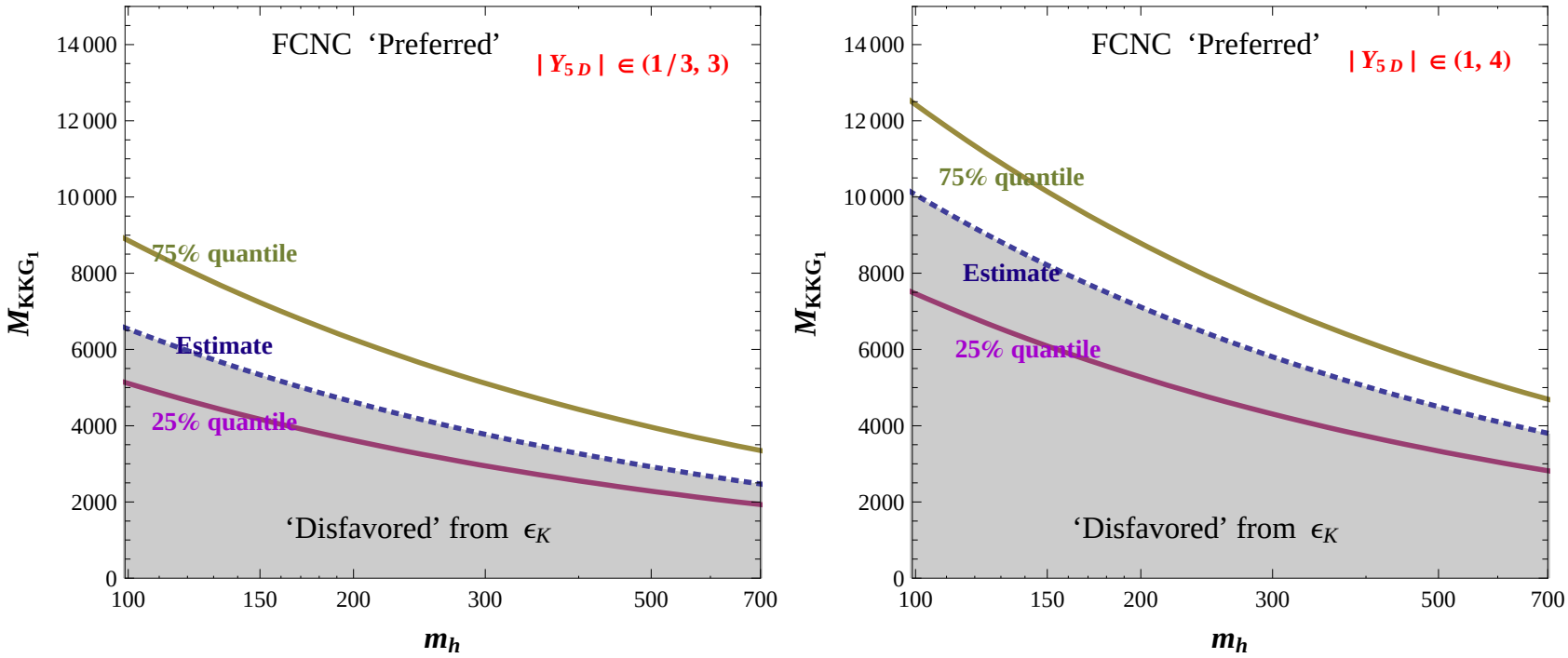


Figure: Contribution to $\Delta F = 2$ processes from Higgs exchange

- Bounds from ϵ_K. [UTfit 2008]

$$1.11 \left(\frac{350\ GeV}{m_h} \right)^2 \frac{\mathrm{Im}(a^d_{21} a^d_{12})}{(0.032 \times 0.04)^2} \leq 1 \qquad (20)$$

Assuming $1/R' = 1.5$ TeV, $\bar{Y}_* = 2$.



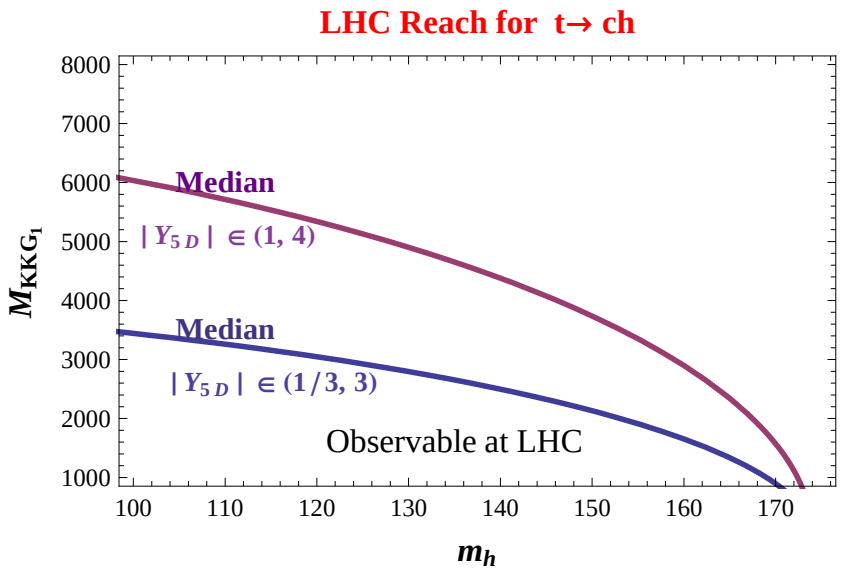
Bounds from ϵ_K in $M_{KKG} - m_h$ plane. Scanned over $Y_* \in [1/3, 3]$ and $Y_* \in [1, 4]$.

Signal at the LHC

- Rare top decay $t \to ch$. for $a^u_{23} = 0.08$ and $a^u_{32} = 0.14$, we get

$$Br(t \to ch) \sim 5 \times 10^{-5}. \tag{21}$$

- The sensitivity of LHC for this rare top decay is $Br(t \to ch) \geq 6.5 \times 10^{-5}$.[Aguilar-Saavedra, Branco 2000]



Conclusion

- In warped extra dimension with fermions propagating in the extra dimension and Higgs localized towards IR brane. Higgs Yukawa couplings and SM fermion masses are generally misaligned.
- This misalignment leads to flavor violating Yukawa couplings. And also changes the diagonal Yukawa couplngs.
- Yukawa couplings of the third generation are reduced. Leading to reduced Higgs production cross section and change Higgs decay branchings.
- Bounds from ϵ_K disfavor a light Higgs.
- Interesting rare top decay $t \longrightarrow ch$ can be probed at the LHC.