Higgs FCNC's in Warped Extra Dimensions [a]

by

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at

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[a]Based on **PRD80**:035016('09) *A.Azatov, M.T., L.Zhu*

Outline

- Introduction
- Flavor “Anarchy”
- Higgs FCNC’s
- Conclusions

Introduction

Warped Extra Dimension's double motivation

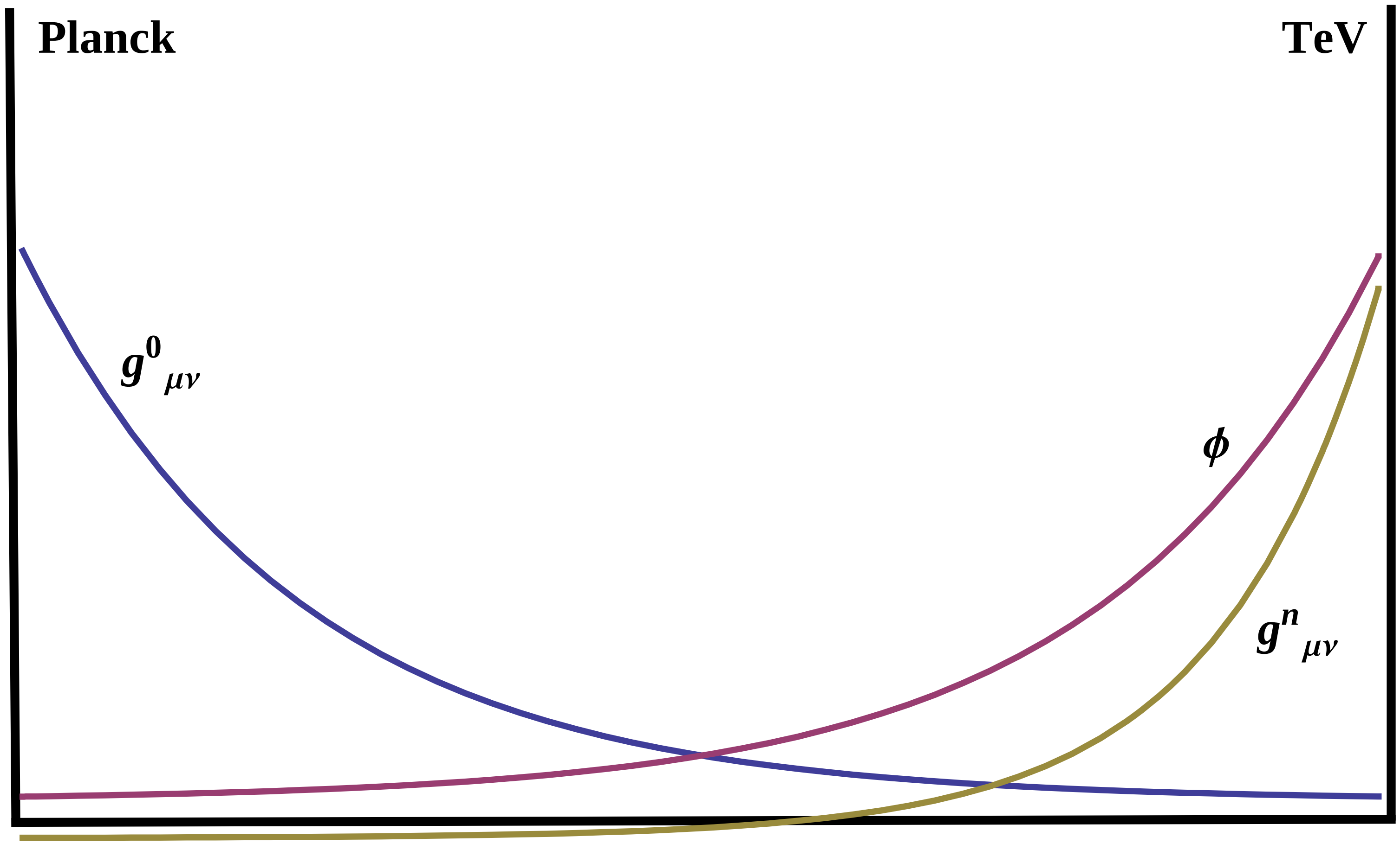
- Address Planck-TeV hierarchy [*Randall*,*Sundrum*](*RS*)
- Bulk SM with Fermion localization: Flavor hierarchies

[*Davoudiasl*,*Hewett*,*Rizzo*];[*Pomarol*,*Gherghetta*];[*Neubert*,*Grossman*];....

$$\text{RS Metric Background}: \quad ds^2 = e^{-2ky}\,\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

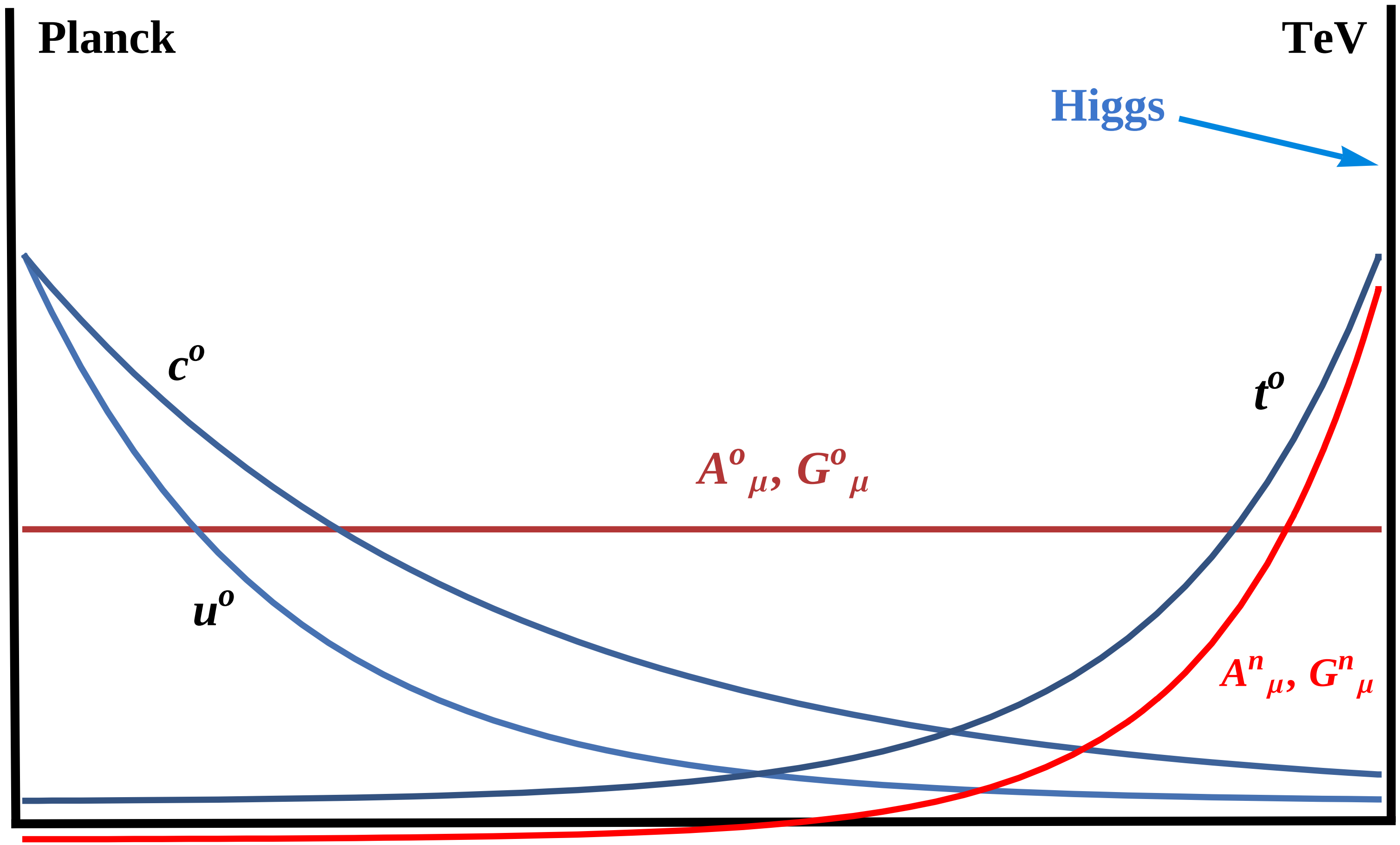
- Exponential factor "warps" down mass scales
- graviton localized near $y = 0$ Boundary (Planck or UV brane)
- Higgs localized near the other Boundary (TeV or IR brane)

Gravity Sector



RS Metric Background : $\quad ds^2 = e^{-2ky}\,\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

Matter in the Bulk



Precision Electroweak Constraints $M_{KK} > 3$ TeV

[Agashe,Delgado,May,Sundrum](03);[Agashe,Contino(06)]; [Carena,Ponton,Santiago,Wagner(06)(07)]

[Contino,DaRold,Pomarol(07)]..

Fermion localization: Flavor!

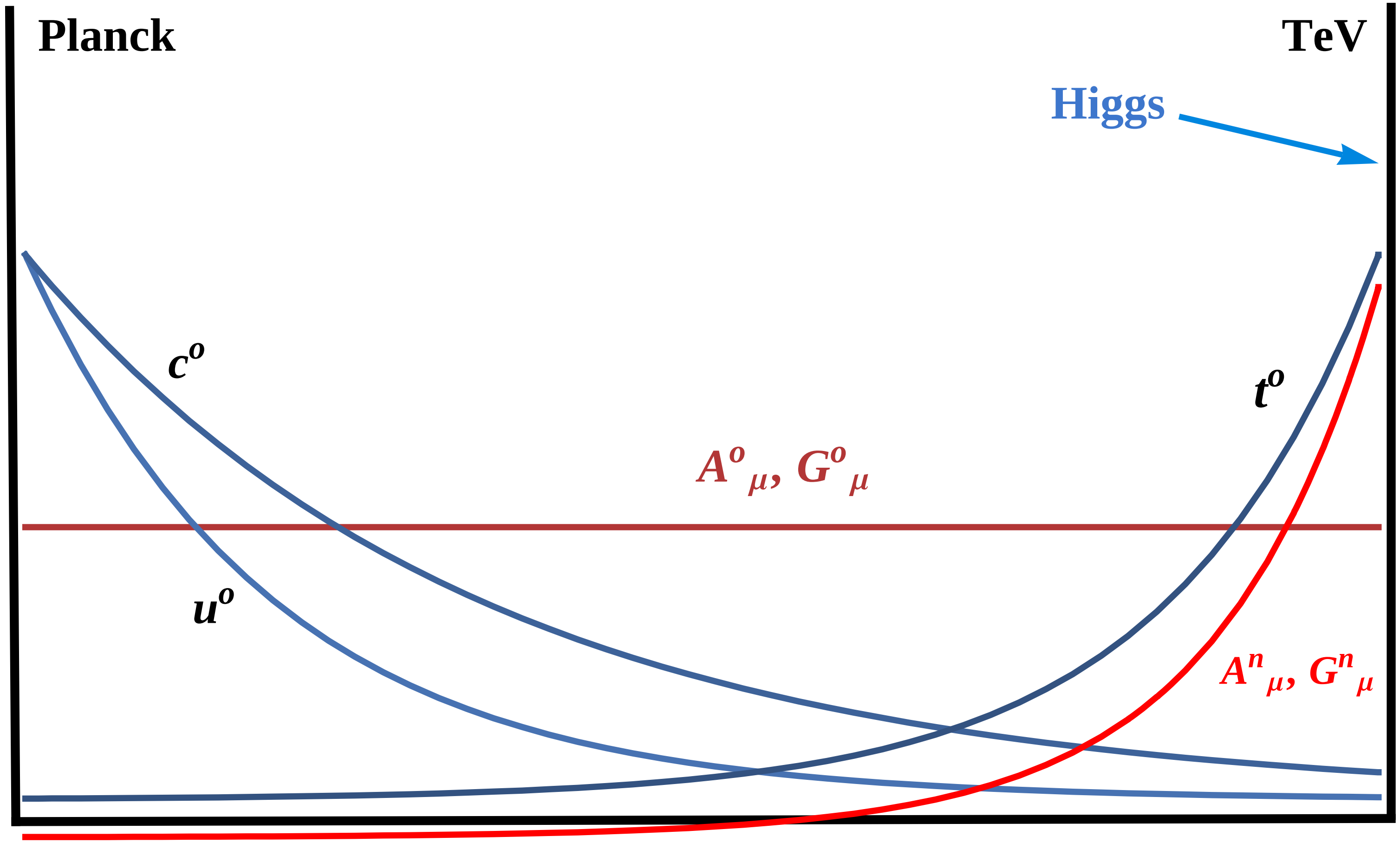
$$S = \int d^4x dy \sqrt{g} \left[\frac{i}{2} \left(\bar{Q}\Gamma^A \mathcal{D}_A Q - D_A \bar{Q} \Gamma^A Q \right) + \frac{i}{2} \left(\bar{U}\Gamma^A \mathcal{D}_A U - \mathcal{D}_A \bar{U} \Gamma^A U \right) \right.$$
$$\left. + c_Q \; k \; \bar{Q}Q + c_u \; k \; \bar{U}U \; + \; \left(Y \; \bar{Q}\mathcal{H}U + h.c. \right) \right]$$

- Massless Fermion mode profiles

$$Q_L^0(y) \quad \propto \quad e^{(1/2 - c_Q)ky}$$
$$U_R^0(y) \quad \propto \quad e^{(1/2 + c_u)ky}$$

In flat ED, SEVERE flavor problem $M_{KK} > 100 - 5000$ TeV [*Delgado,Pomarol,Quiros*]

Much milder in Warped case $M_{KK} > 5 - 40$ TeV [Csaki,Falkowski,Weiler]; [Agashe,Azatov,Zhu]



Planck
TeV
Higgs
c^o
u^o
t^o
$A^o{}_\mu, G^o{}_\mu$
$A^n{}_\mu, G^n{}_\mu$

Flavor Anarchy

- Fermion profiles $\Psi_i(y) \propto e^{(1/2-c_i)ky}$
- Let $f_i = \Psi_i(y_{TeV})$ ($\equiv$ profile at the TeV brane)
- SMALL hierarchy in c_i's $\Rightarrow$ LARGE hierachy in f_i's
- Fermion mass matrix from $Y_{ij}\ HQ_iU_j$

$$\mathbf{m_{ij}} = \frac{v}{2}\ f_{Qi} Y_{ij} f_{uj}$$

- 5D Yukawa Y_{ij} anarchic and $\mathcal{O}(1)$

  $\Rightarrow$ Mass matrices still hierachical

$$\mathbf{m_u} \sim \begin{pmatrix} f_{Q1}f_{u1} & f_{Q1}f_{u2} & f_{Q1}f_{u3} \\ f_{Q2}f_{u1} & f_{Q2}f_{u2} & f_{Q2}f_{u3} \\ f_{Q3}f_{u1} & f_{Q3}f_{u2} & f_{Q3}f_{u3} \end{pmatrix} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

- Diagonalize mass matrices:

$$
\begin{aligned}
U_{Q_u}\ \mathbf{m_u}\ W_u^\dagger &= \mathbf{m_u^{diag}} \\
U_{Q_d}\ \mathbf{m_d}\ W_d^\dagger &= \mathbf{m_d^{diag}}
\end{aligned}
$$

- SM Fermion physical masses hierarchical $m_{u_i} \sim v\ f_{Q_i} f_{u_i}$

$$
U_{Q_d}, U_{Q_u} \sim \begin{pmatrix} 1 & \frac{f_{Q1}}{f_{Q2}} & \frac{f_{Q1}}{f_{Q3}} \\ \frac{f_{Q1}}{f_{Q2}} & 1 & \frac{f_{Q2}}{f_{Q3}} \\ \frac{f_{Q1}}{f_{Q3}} & \frac{f_{Q2}}{f_{Q3}} & 1 \end{pmatrix}
$$

$$
W_u \sim \begin{pmatrix} 1 & \frac{f_{u1}}{f_{u2}} & \frac{f_{u1}}{f_{u3}} \\ \frac{f_{u1}}{f_{u2}} & 1 & \frac{f_{u2}}{f_{u3}} \\ \frac{f_{u1}}{f_{u3}} & \frac{f_{u2}}{f_{u3}} & 1 \end{pmatrix} \qquad W_d \sim \begin{pmatrix} 1 & \frac{f_{d1}}{f_{d2}} & \frac{f_{d1}}{f_{d3}} \\ \frac{f_{d1}}{f_{d2}} & 1 & \frac{f_{d2}}{f_{d3}} \\ \frac{f_{d1}}{f_{d3}} & \frac{f_{d2}}{f_{d3}} & 1 \end{pmatrix}
$$

- SM CKM matrix

$$V_{CKM} = U^\dagger_{Q_u} U_{Q_d} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \Rightarrow \ U_{Q_u} \sim U_{Q_d} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$W_u \sim \begin{pmatrix} 1 & \frac{m_u}{m_c}\frac{1}{\lambda} & \frac{m_u}{m_t}\frac{1}{\lambda^3} \\ \frac{m_u}{m_c}\frac{1}{\lambda} & 1 & \frac{m_c}{m_t}\frac{1}{\lambda^2} \\ \frac{m_u}{m_t}\frac{1}{\lambda^3} & \frac{m_c}{m_t}\frac{1}{\lambda^2} & 1 \end{pmatrix} \qquad W_d \sim \begin{pmatrix} 1 & \frac{m_d}{m_s}\frac{1}{\lambda} & \frac{m_d}{m_b}\frac{1}{\lambda^3} \\ \frac{m_d}{m_s}\frac{1}{\lambda} & 1 & \frac{m_s}{m_b}\frac{1}{\lambda^2} \\ \frac{m_d}{m_b}\frac{1}{\lambda^3} & \frac{m_s}{m_b}\frac{1}{\lambda^2} & 1 \end{pmatrix}$$

with $\lambda \sim .22$ cabibbo angle

Tree level Higgs FCNC's

Effective Theory Approach [Buchmuller,Wyler(86)], [delAguila,Perez-Victoria,Santiago(00)] [Agashe,Contino(09)]

Consider in 4D effective action, Dim 6 operators (down sector):

$$\lambda_{ij}\frac{H^2}{\Lambda^2}\ H\overline{Q}_{L_i}D_{R_j}$$

$\Rightarrow$ Corrections to mass matrix

$$v_4\left(y_{ij}+\lambda_{ij}\frac{v_4^2}{\Lambda^2}\right)$$

$\Rightarrow$ Correction to Higgs Yukawa couplings

$$\left(y_{ij}+3\lambda_{ij}\frac{v_4^2}{\Lambda^2}\right)\frac{h}{\sqrt{2}}\overline{Q}_{L_i}D_{R_j}$$

Tree level Higgs FCNC's

Effective Theory Approach [Buchmuller,Wyler(86)], [delAguila,Perez-Victoria,Santiago(00)]
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Consider in 4D effective action, Dim 6 operators (down sector):

$$\lambda_{ij}\frac{H^2}{\Lambda^2}\ H\overline{Q}_{L_i}D_{R_j} \qquad k^D_{ij}\frac{H^2}{\Lambda^2}\ \overline{D}_{R_i}\not\partial D_{R_j} \qquad k^Q_{ij}\frac{H^2}{\Lambda^2}\ \overline{Q}_{L_i}\not\partial Q_{L_j}$$

$\Rightarrow$ Corrections to mass matrix (also from canonical normalization)

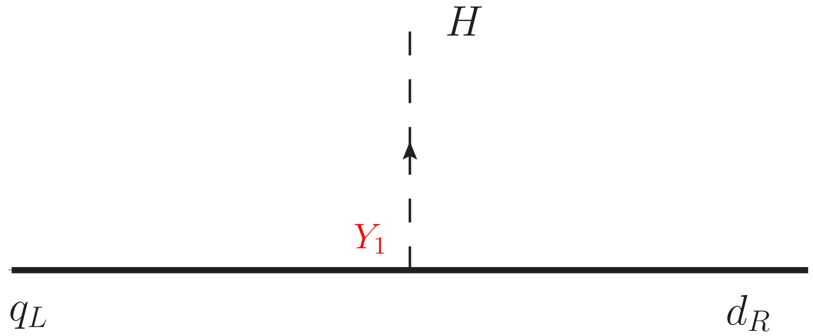
$$v_4\left(y_{ij}+\lambda_{ij}\frac{v_4^2}{\Lambda^2}\right)\overline{Q}_{L_i}D_{R_j} \quad \left(\delta_{ij}/2+k^D_{ij}\frac{v_4^2}{\Lambda^2}\right)\overline{D}_{R_i}\not\partial D_{R_j} \quad \left(\delta_{ij}/2+k^Q_{ij}\frac{v_4^2}{\Lambda^2}\right)\overline{Q}_{L_i}\not\partial Q_{L_j}$$

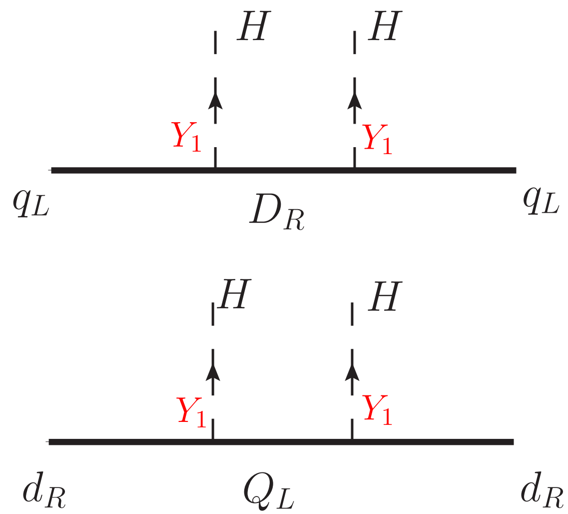
$\Rightarrow$ Correction to Higgs Yukawa couplings

$$\left(y_{ij}+3\lambda_{ij}\frac{v_4^2}{\Lambda^2}\right)\frac{h}{\sqrt{2}}\overline{Q}_{L_i}D_{R_j} \quad \left(2k^D_{ij}\frac{v}{\Lambda^2}\right)\frac{h}{\sqrt{2}}\overline{D}_{R_i}\not\partial D_{R_j} \quad \left(2k^Q_{ij}\frac{v_4}{\Lambda^2}\right)\frac{h}{\sqrt{2}}\overline{Q}_{L_i}\not\partial Q_{L_j}$$

Higgs FCNC's in RS

[Casagrande et.al.(08); Blanke et.al.(09); Buras et.al.(09)]





$$
\begin{aligned}
m_{SM}^d &\approx v\, f_Q Y_1 f_d \left(1 - f_Q^2 \frac{Y_1^2 v^2}{M_{KK}^2} - f_d^2 \frac{Y_1^2 v^2}{M_{KK}^2}\right) \\
Y_{SM}^d &\approx f_Q Y_1 f_d \left(1 - 2 f_Q^2 \frac{Y_1^2 v^2}{M_{KK}^2} - 2 f_d^2 \frac{Y_1^2 v^2}{M_{KK}^2}\right)
\end{aligned}
$$

$$
m_{SM}^d - Y_{SM}^d v \approx m_{SM}^d \frac{Y_1^2 v^2}{M_{KK}^2} \left(f_Q^2 + f_d^2\right)
$$

Higgs FCNC's in RS

[Agashe, Contino(09); Azatov,M.T.,Zhu(09)]

$$m_{SM}^d \approx v\, f_Q Y_1 f_d \left(1 - \frac{Y_1 Y_2 v^2}{M_{KK}^2}\right)$$

$$Y_{SM}^d \approx f_Q Y_1 f_d \left(1 - 3\frac{Y_1 Y_2 v^2}{M_{KK}^2}\right)$$

$$m_{SM}^d - Y_{SM}^d v \approx m_{SM}^d\, 2\frac{Y_1 Y_2 v^2}{M_{KK}^2}$$

Tree-level Higgs FCNC's!

Define : $$\mathcal{L}_{HFV} = a^d_{ij}\sqrt{\frac{m^d_i m^d_j}{v_4^2}} H \bar{d}^i_L d^j_R \; + h.c.$$

Solve perturbatively in $(Y \; v_4/M_{KK})$:

$$a^d_{ij} \sim \delta_{ij} - \bar{Y}^2 \frac{v_4^2}{M_{KK}^2} \begin{pmatrix} 1 & \lambda\sqrt{\frac{m_s}{m_d}} & \lambda^3\sqrt{\frac{m_b}{m_d}} \\ \frac{1}{\lambda}\sqrt{\frac{m_d}{m_s}} & 1 & \lambda^2\sqrt{\frac{m_b}{m_s}} \\ \frac{1}{\lambda^3}\sqrt{\frac{m_d}{m_b}} & \frac{1}{\lambda^2}\sqrt{\frac{m_s}{m_b}} & 1 \end{pmatrix}$$

$$a^u_{ij} \sim \delta_{ij} - \bar{Y}^2 \frac{v_4^2}{M_{KK}^2} \begin{pmatrix} 1 & \lambda\sqrt{\frac{m_c}{m_u}} & \lambda^3\sqrt{\frac{m_t}{m_u}} \\ \frac{1}{\lambda}\sqrt{\frac{m_u}{m_c}} & 1 & \lambda^2\sqrt{\frac{m_t}{m_c}} \\ \frac{1}{\lambda^3}\sqrt{\frac{m_u}{m_t}} & \frac{1}{\lambda^2}\sqrt{\frac{m_c}{m_t}} & 1 \end{pmatrix}$$

Tree level HIGGS exchange will induce $s_L d_R s_R d_L$ with coefficient

$$C_4 = a_{ds} a_{sd} m_d m_s \frac{1}{m_h^2 v_4^2} \quad \Rightarrow K - \bar{K} \text{ mixing and } \epsilon_K \text{ put tight bounds}$$

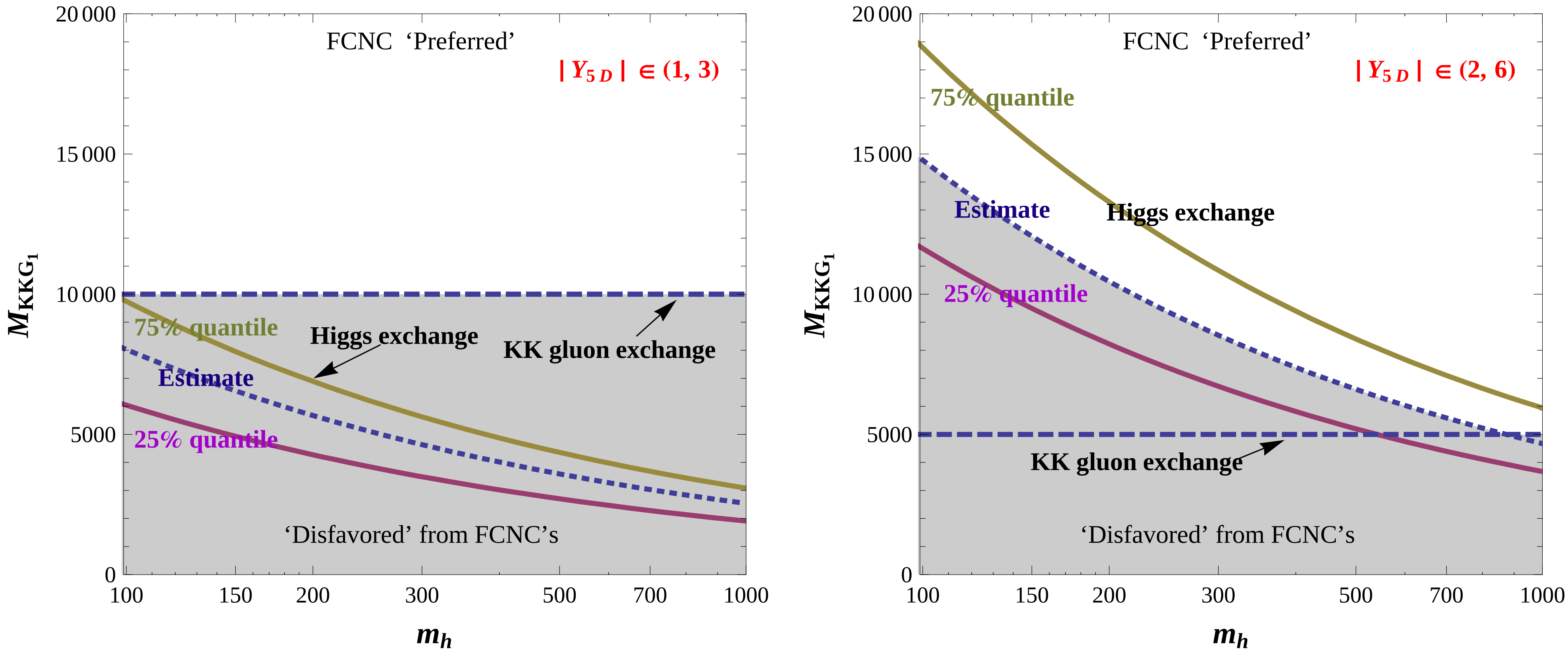


Figure 1: "Bounds" from ϵ_K in (m_h-M_{KK}) plane from Higgs exchange

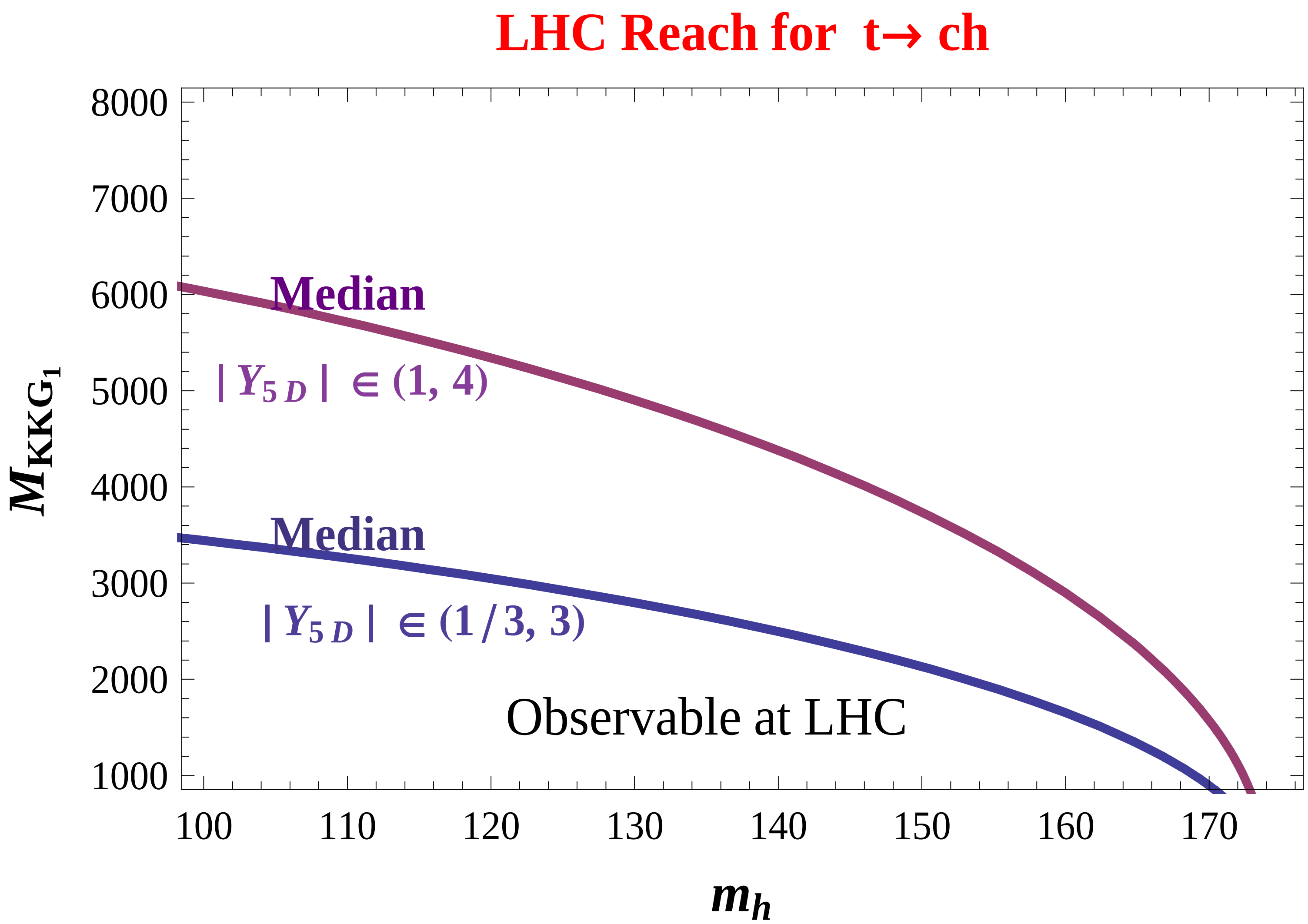


Figure 2: LHC observability $t \to ch$ in the plane (m_h, M_{KKG_1}). (using [Aguilar−Saavedra,Branco(00)] study)

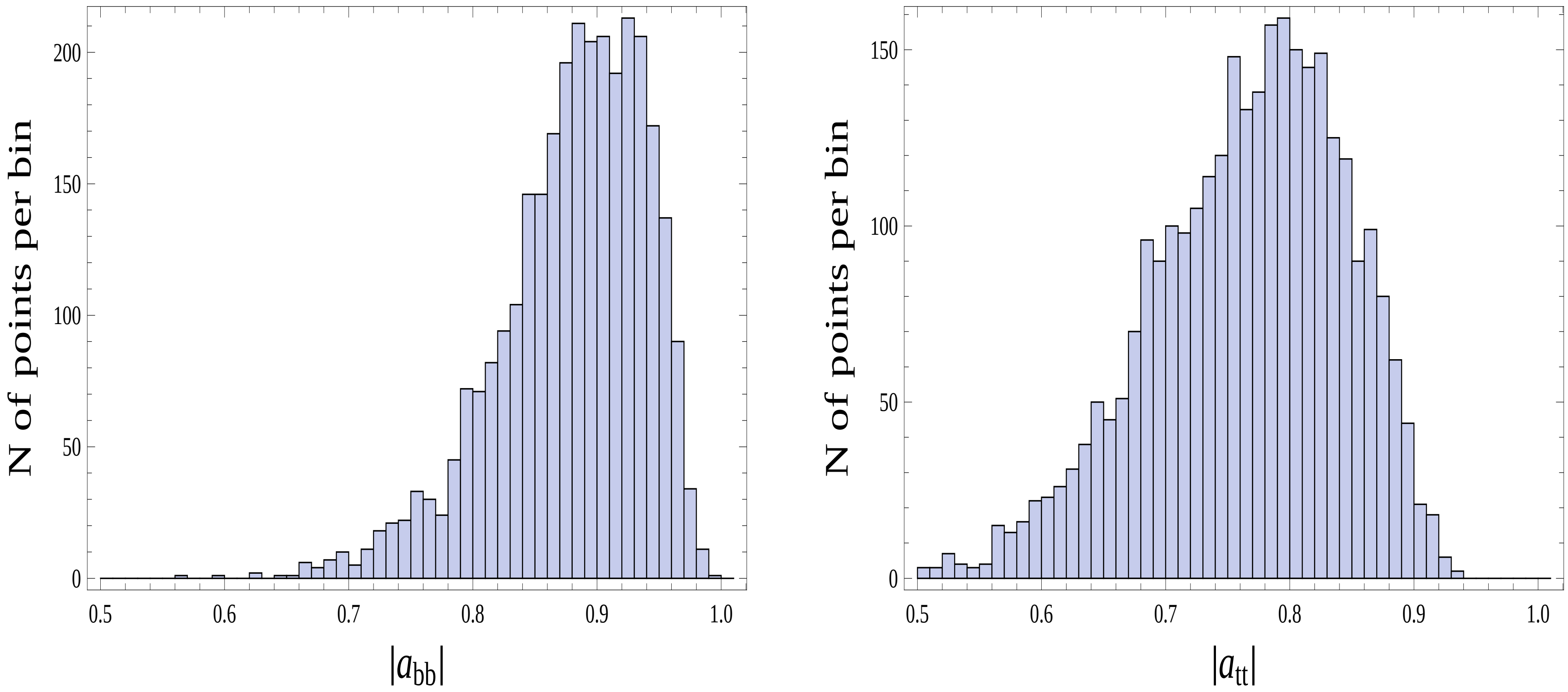


Figure 3: Distribution of a_{tt} and a_{bb}, in our numerical scan, with a fixed KK scale of $R'^{-1} = 1500$ GeV (KK gluon mass $M_{KKG} = 2.45 R'^{-1}$) and for 5D Yukawas $|Y_{5D}^{ij}| \in [0.3, 3]$.

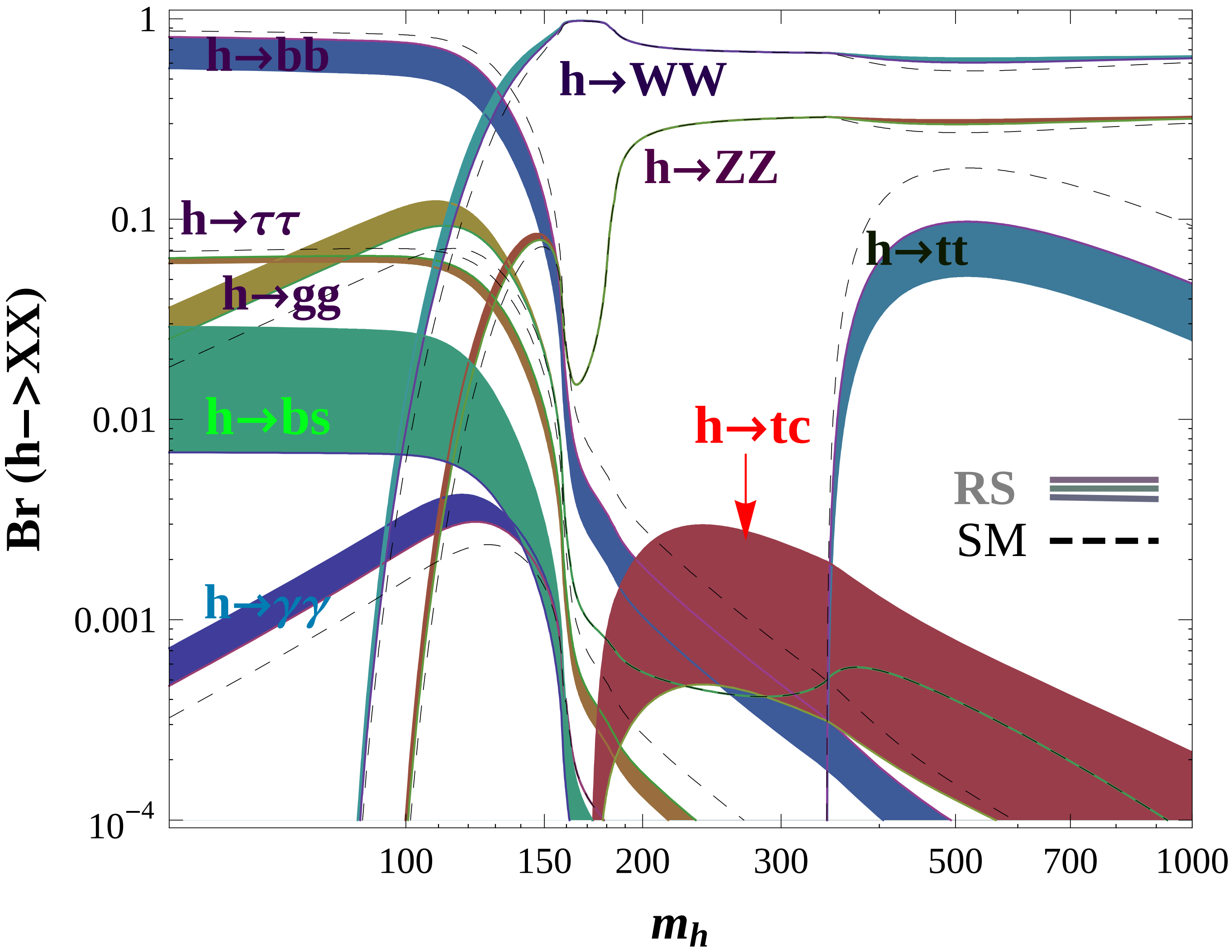


Figure 4: Higgs Branchings, for $\bar{Y} \sim 3$ and $1/R' = 1500$ GeV. $(KKG_1 \sim 3.5\text{TeV})$

Outlook

Maybe LHC discovers just one scalar and that's IT (maybe two with the radion..).

Is it the SM Higgs? (or a 2 Higgs doublet model?)
or is it an RS type scenario? (radion plus a Higgs?)

- Probing the couplings to fermions important.
- Higgs production may be significantly enhanced (work in progress)
- Probing the size of the Flavor structure also important.
- Flavor at LHC? ($t \rightarrow ch$?, $h \rightarrow$ t c ?)
- At Muon Collider, probe of diagonal and some off-diagonal yukawas..

Backup – Calculation

Down quark Action with a Bulk Higgs, in RS:

$$S = \int d^4x dz \sqrt{g} \Big[\frac{i}{2} \left(\bar{Q}\Gamma^A \mathcal{D}_A Q - D_A \bar{Q}\Gamma^A Q \right) + \frac{i}{2} \left(\bar{U}\Gamma^A \mathcal{D}_A U - \mathcal{D}_A \bar{U}\Gamma^A U \right)$$

$$+ \frac{c_Q}{R} \bar{Q}Q + \frac{c_U}{R} \bar{U}U \; + \; \left(Y \; \bar{Q}\mathcal{H}U + h.c. \right) \Big]$$

Decompose $Q = \begin{pmatrix} \mathcal{Q}_L \\ \mathcal{Q}_R \end{pmatrix}$ and $D = \begin{pmatrix} \mathcal{D}_L \\ \mathcal{D}_R \end{pmatrix}$ and perform a mixed KK expansion:

$$\begin{aligned} \mathcal{Q}_L(x,z) &= q_L(z)\, Q_L(x) + ... \\ \mathcal{Q}_R(x,z) &= q_R(z)\, D_R(x) + ... \\ \mathcal{D}_L(x,z) &= d_L(z)\, Q_L(x) + ... \\ \mathcal{D}_R(x,z) &= d_R(z)\, D_R(x) + ... \end{aligned}$$

$\Rightarrow$ Mixed profile equations

$$-m_d\ q_L - q'_R + \frac{c_q+2}{z} q_R + \left(\frac{R}{z}\right) v(z) Y_d\ d_R = 0$$

$$-m_d^*\ q_R + q'_L + \frac{c_q-2}{z} q_L + \left(\frac{R}{z}\right) v(z) Y_d\ d_L = 0$$

$$-m_d\ d_L - d'_R + \frac{c_d+2}{z} d_R + \left(\frac{R}{z}\right) v(z) Y_d^*\ q_R = 0$$

$$-m_d^*\ d_R + d'_L + \frac{c_d-2}{z} d_L + \left(\frac{R}{z}\right) v(z) Y_d^*\ q_L = 0$$

Massaging them we arrive at:

$$m_d = R^4 \int_R^{R'} dz \left(\frac{m_d}{z^4} (|d_L|^2 + |q_R|^2) + \frac{Rv(z)}{z^5} (Y_d\ d_R q_L^* - Y_d^*\ q_R d_L^*) \right)$$

4D Higgs Yukawa is : $\quad y_4^d = R^5 \int_R^{R'} dz \frac{h(z)}{z^5} (Y_d\ d_R q_L^* + Y_d^*\ q_R d_L^*)$

Misalignement between 4D fermion mass matrix and Yukawas!

$$\Delta^d \;=\; R^4 \int_R^{R'} dz \left(\frac{m_d}{z^4} (|d_L|^2 + |q_R|^2) - 2 Y_d^* \frac{R v(z)}{z^5} q_R d_L^* \right).$$