Light KK modes in Custodially Symmetric Randall-Sundrum

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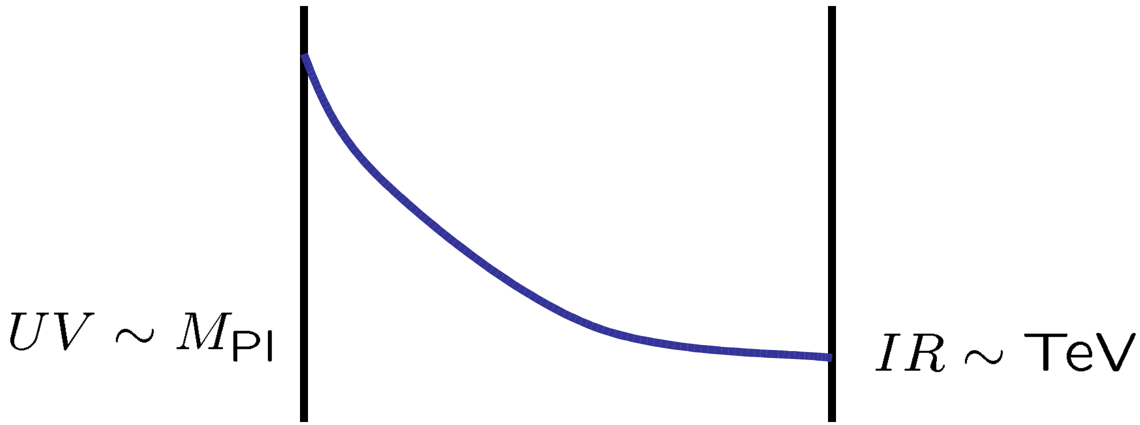
Motivation

- Randall-Sundrum like models offer a nice solution to the gauge hierarchy problem

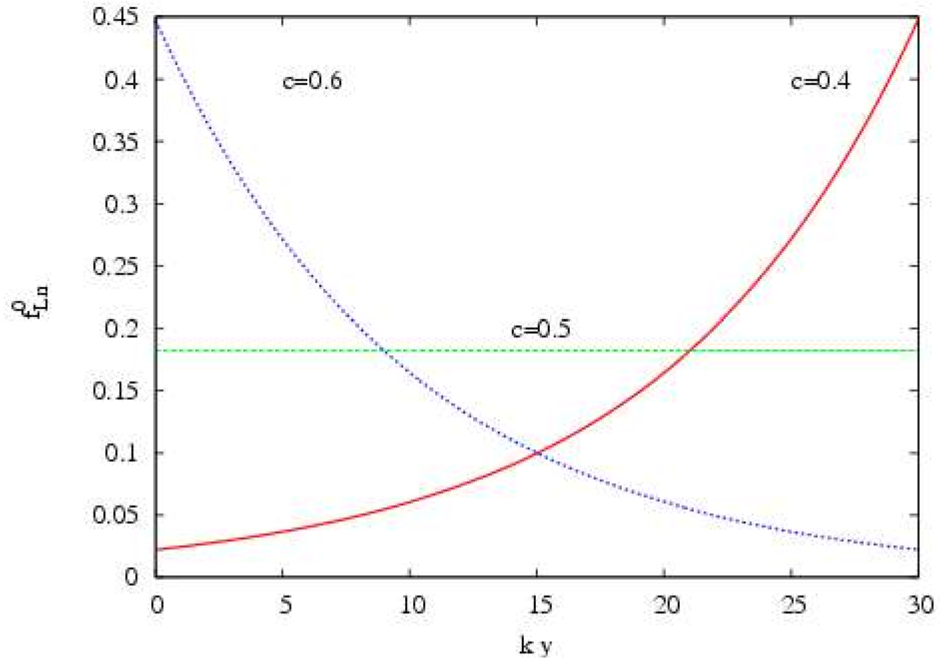


- Bulk fermions give a rationale for fermion mass hierarchies

Fermions in Randall-Sundrum

- Bulk fermions can have a mass term that determines the zero mode localization properties (and the mass of the first KK modes)

$$\mathcal{L}_m = c_\Psi k \bar{\Psi} \Psi$$



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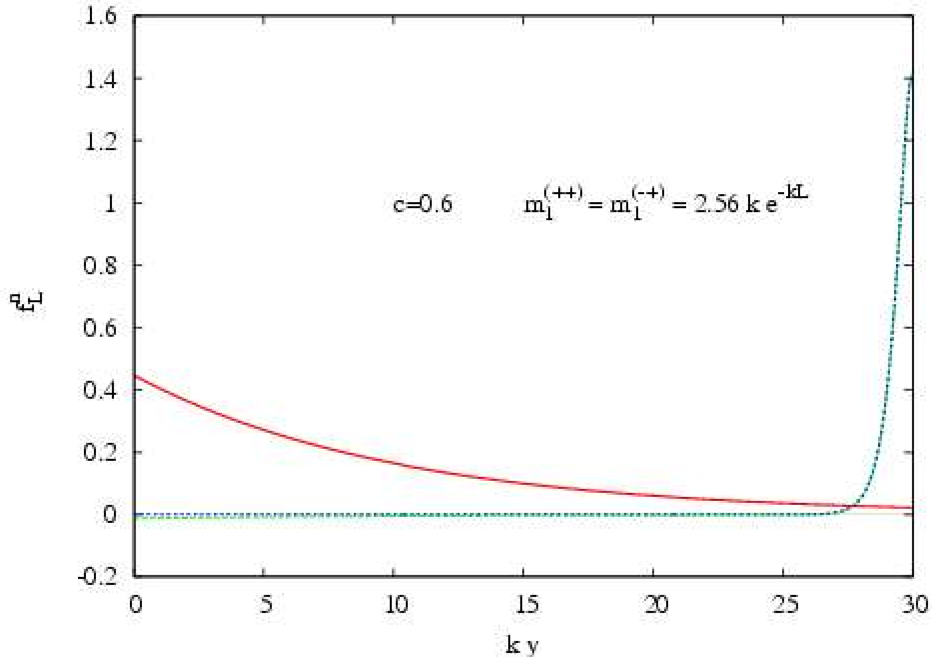
- Non-trivial $(-\,+)$ boundary conditions can produce ultralight KK modes (depending on the bulk mass)

Agashe, Servant JCAP (05)



$-\,+$ b.c.

~~zero mode~~

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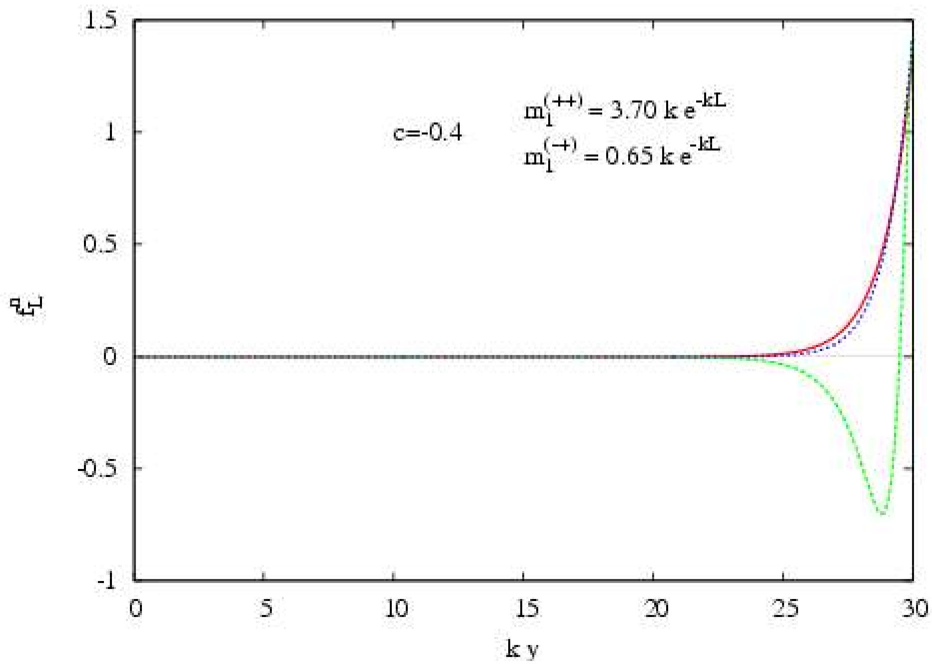

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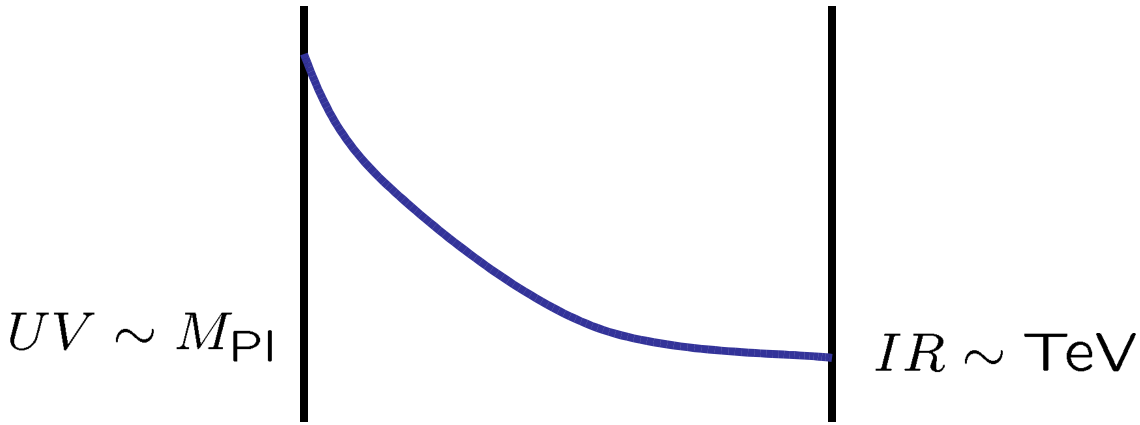


- Bulk fermions give a rationale for fermion mass hierarchies

- Large contributions to the T parameter and $Zb\bar{b}$ force the KK modes to be too heavy to be observable at the LHC unless custodial symmetry is implemented

Outline

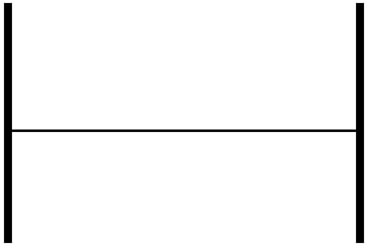
- Custodially symmetric Randall-Sundrum models
- Low energy effects of KK modes
- Custodial Symmetry at work: tree-level protection of T and Zbb
- One loop contribution to the oblique parameters
- Models of gauge-Higgs unification in warped space
- Realistic RS models with light KK modes: phenomenology
- Summary

$SU(2)_L$ x $SU(2)_R$ Randall-Sundrum Models

- Bulk gauge symmetry is $SU(2)_L \times SU(2)_R \times U(1)_X$ broken by boundary conditions on the UV brane

Agashe, Delgado, May, Sundrum JHEP (03)

$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$



$$W^{1,2,3}_{L\,\mu} \sim (+,+) \;, \qquad B_\mu \sim (+,+) \;,$$
$$W^{1,2}_{R\,\mu} \sim (-,+) \;, \qquad Z'_\mu \sim (-,+) \;,$$

where

$$B_\mu = \frac{g_{5\,X} W^3_{R\,\mu} + g_{5\,R} X_\mu}{\sqrt{g^2_{5\,R} + g^2_{5\,X}}} \;, \qquad Z'_\mu = \frac{g_{5\,R} W^3_{R\,\mu} - g_{5\,X} X_\mu}{\sqrt{g^2_{5\,R} + g^2_{5\,X}}} \;,$$

Low energy effects

- We can integrate out the gauge KK modes in terms of the 5D propagators, with the zero mode subtracted

Carena, Delgado, Pontón, Tait, Wagner PRD(03)

$$\tilde{G}^{++}_{p=0}(y,y') = \frac{1}{4k(kL)}\left\{\frac{1-e^{2kL}}{kL} + e^{2ky_<}(1-2ky_<) + e^{2ky_>}\left[1+2k(L-y_>)\right]\right\} ,$$

$$\tilde{G}^{-+}_{p=0}(y,y') = -\frac{1}{2k}\left[e^{2ky_<}-1\right] .$$

- We will define corrections in terms of convolutions

$$\delta^2_{++} = \frac{Lv^2}{2}\int_0^L dy dy' e^{-2ky} f_H(y)^2 \tilde{G}^{++}_{p=0}(y,y') e^{-2ky'} f_H(y')^2 .$$

$$G^{\psi}_{++} = \frac{v^2}{2}\int_0^L dy dy' |f^0_\psi(y)|^2 \tilde{G}^{++}_{p=0}(y,y') e^{-2ky'} f_H(y')^2 ,$$

Low energy effects

- The SM gauge boson masses are

$$m_Z^2 = \frac{e^2 v^2}{2 s^2 c^2}\left\{1 + \frac{e^2}{s^2 c^2}\left[\delta_{++}^2 + \left(\frac{g_R^2}{g_L^2} c^2 - s^2\right)\delta_{-+}^2\right] + \cdots\right\},$$

$$m_W^2 = \frac{e^2 v^2}{2 s^2}\left\{1 + \frac{e^2}{s^2}\left[\delta_{++}^2 + \frac{g_R^2}{g_L^2}\delta_{-+}^2\right] + \cdots\right\},$$

and their coupling to the SM fermions

$$J_Z^\mu = \bar{\psi}^0 \gamma^\mu \left(T_L^3 - s^2 Q\right)\psi^0 \left[1 + \frac{e^2}{s^2 c^2}\left(G_{++}^\psi - \frac{g_R^2/g_L^2\, c^2 T_R^3 + s^2 T_L^3 - s^2 Q}{T_L^3 - s^2 Q} G_{-+}^\psi\right)\right]$$

$$J_+^\mu = \left\{\bar{\psi}^0 \gamma^\mu T_L^+ \psi^0 \left[1 + \frac{e^2}{s^2} G_{++}^\psi\right] + \frac{g_R^2}{g_L^2}\frac{e^2}{s^2}\bar{\psi}^0 \gamma^\mu T_R^+ \psi^0 G_{-+}^\psi\right\}$$

Low energy effects

- If the light fermions are all near the UV brane we can cast the most important corrections in terms of effective oblique parameters

Carena, Delgado, Pontón, Tait, Wagner PRD(03)

$$S_{\text{eff}} = 32\pi G^{f}_{++},$$
$$T_{\text{eff}} = \frac{8\pi}{c^2} G^{f}_{++} - \frac{4\pi}{c^2}\left[\delta^2_{++} - \delta^2_{-+}\right] + \frac{2\pi v^2}{s^2} G^{\mu\mu}_{++},$$
$$U_{\text{eff}} = -8\pi v^2 G^{\mu\mu}_{++}.$$

$G^{\mu\mu}_{++}$ encodes the effects of gauge KK modes on μ decay. In practice these effects can be neglected.

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Carena, Delgado, Pontón, Tait, Wagner PRD(03)

$$\begin{aligned} S &= 32\pi G^{f}_{++}, \\ T &= \frac{8\pi}{c^2} G^{f}_{++} - \frac{4\pi}{c^2}\left[\delta^2_{++} - \delta^2_{-+}\right], \\ U &= 0, \end{aligned}$$

and the $Z\bar{b}_L b_L$ anomalous coupling

$$\frac{\delta g_{b_L}}{g_{b_L}} = \frac{e^2}{s^2 c^2}\left[G^{b_L}_{++} - \frac{c^2 T^3_R\, g^2_R/g^2_L + s^2 T^3_L - s^2 Q}{T^3_L - s^2 Q} G^{b_L}_{-+} - G^{f}_{++}\right]$$

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$$

- If light fermions are not near the UV brane, then there are extra corrections that can be non-universal and therefore cannot be absorbed into oblique effects (more on this latter)

Custodial symmetry at work: T and Zbb

- The relevant EW observables are then the S and T oblique parameters:

$$S = 32\pi G^f_{++}$$

Tend to cancel

$$T = \frac{8\pi}{c^2} G^f_{++} - \frac{4\pi}{c^2}\left[\delta^2_{++} - \delta^2_{-+}\right]$$

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and the $Z\bar{b}_L b_L$ anomalous coupling

$$\frac{\delta g_{b_L}}{g_{b_L}} = \frac{e^2}{s^2 c^2}\left[G^{b_L}_{++} - 0.09\, G^{b_L}_{-+} - G^{f}_{++}\right]$$

$$T^3_R(b_L) = 0$$

Bad cancellation

Custodial symmetry at work: T and Zbb

- The relevant EW observables are then the S and T oblique parameters:

$$S = 32\pi G^{f}_{++}$$

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$$\frac{\delta g_{b_L}}{g_{b_L}} = \frac{e^2}{s^2 c^2}\left[G^{b_L}_{++} - G^{b_L}_{-+} - G^{f}_{++}\right]$$

Good cancellation

$$T^3_R(b_L) = T^3_L(b_L)$$

$$(g_R = g_L)$$

$SU(2)_L \times SU(2)_R \times P_{LR}$ can protect $Zb\bar{b}$

Agashe, Contino, Da Rold, Pomarol ph/0605341

Quantum Numbers

$$T^3_R(b_L) = 0$$

$$\begin{pmatrix} t_L(+,+) \\ b_L(+,+) \end{pmatrix} \sim (2,1) \qquad \begin{pmatrix} t_R(+,+) \\ b'_R(-,+) \end{pmatrix}, \begin{pmatrix} t'_R(-,+) \\ b_R(+,+) \end{pmatrix} \sim (1,2)$$

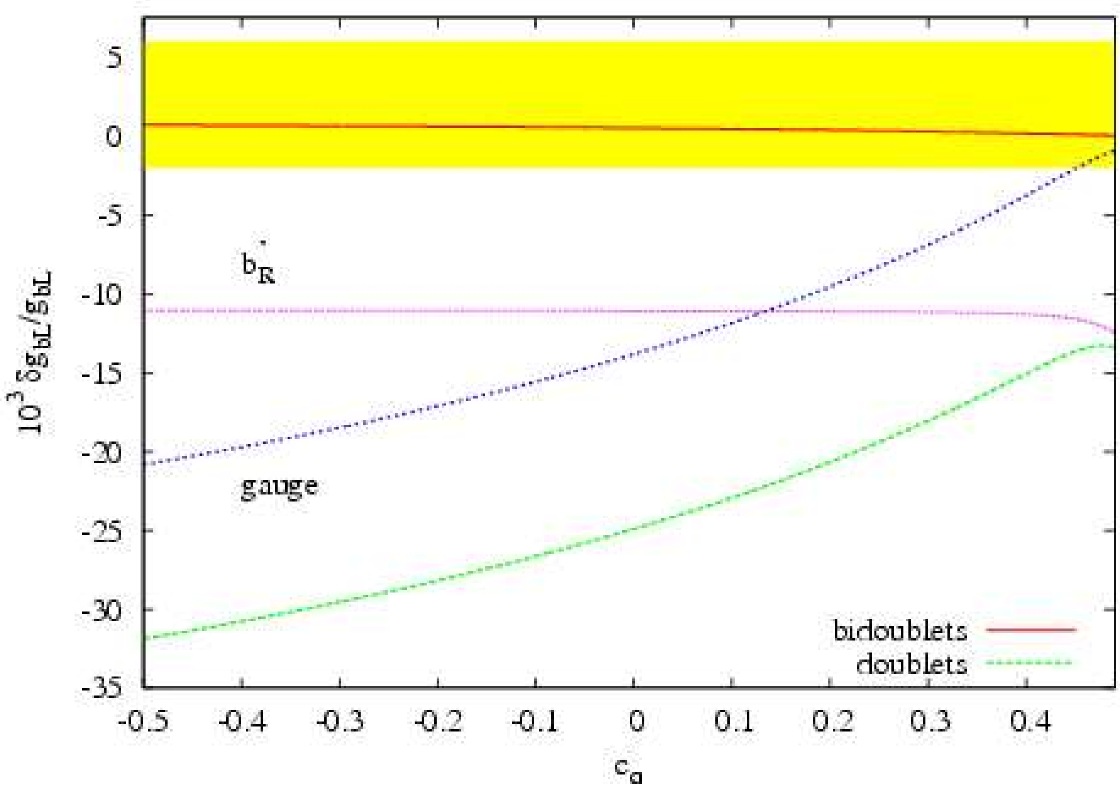
$$T^3_R(b_L) = T^3_L(b_L)$$
$$(g_R = g_L)$$

$$\begin{pmatrix} \chi^u_L(-+) & t_L(+,+) \\ \chi^d_L(-+) & b_L(+,+) \end{pmatrix} \sim (2,2)$$

$t_R(+,+) \sim (1,1)$ or

$$\begin{pmatrix} \psi'_R(-,+) \\ t'_R(-,+) \\ b'_R(-,+) \end{pmatrix} \sim (3,1) \oplus \begin{pmatrix} \psi''_R(-,+) \\ t_R(+,+) \\ b''_R(-,+) \end{pmatrix} \sim (1,3)$$

$M_{KK} \approx 3.75$ TeV



Custodial protection of Zbb (and therefore bidoublets) is crucial to have light KK excitations

Bidoublets and oblique corrections

- The new states give a one loop contribution to the T parameter that is finite due to the non-local breaking of EW and $SU(2)_R$
- Typical results for T (very sensitive to the parameters of the model and not necessarily small):
  - Bidoublets contribute negatively

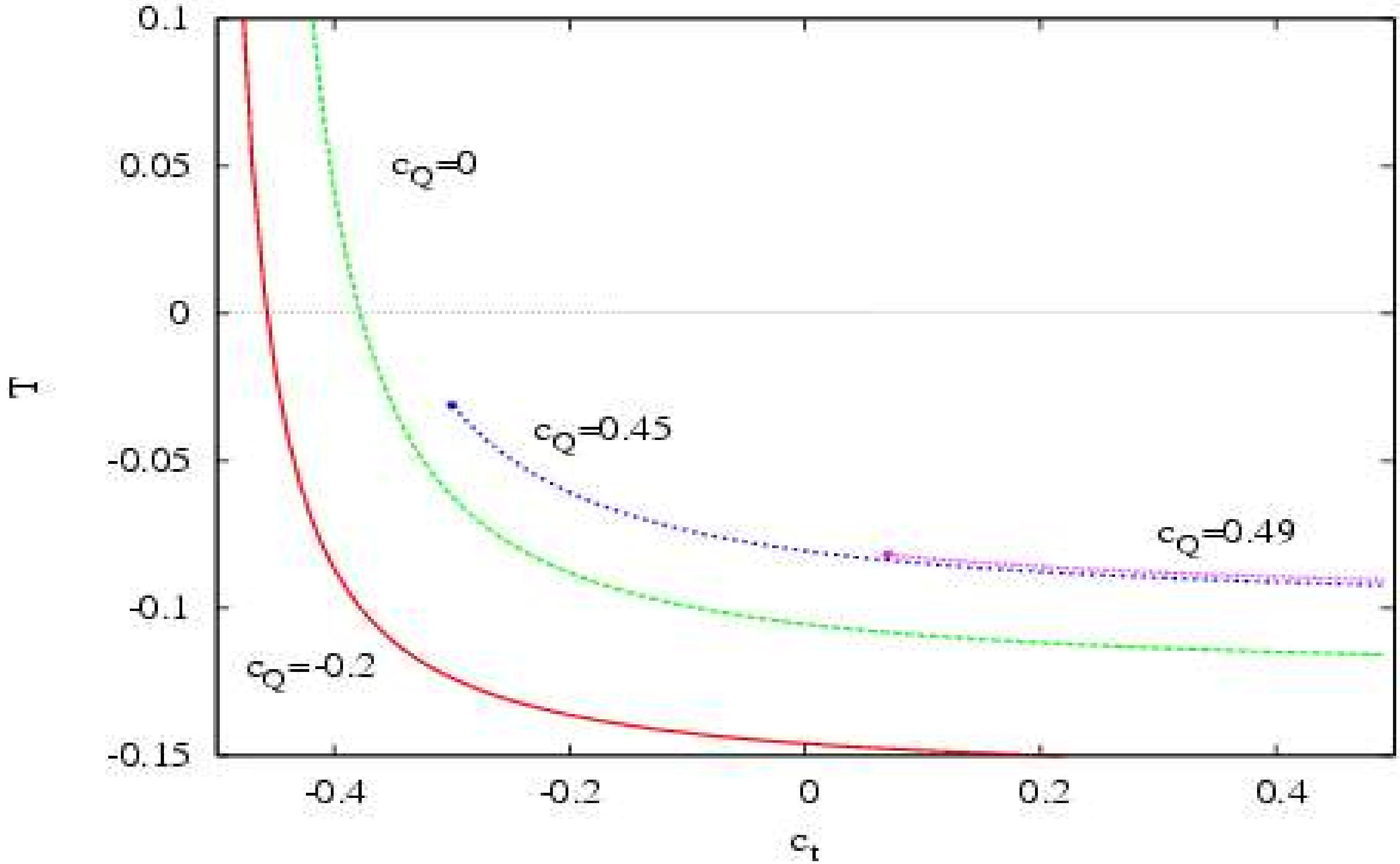
$$\Delta T = -T_{\text{top}} \frac{4 m^2_{\chi^d,t}}{M_q^2} \left[2(\eta_m + \eta_\lambda) \ln \frac{M_q^2}{m^2_{\text{top}}} - 5\eta_m - 3\eta_\lambda + \ldots \right]$$

  - Singlets and triplets contribute positively

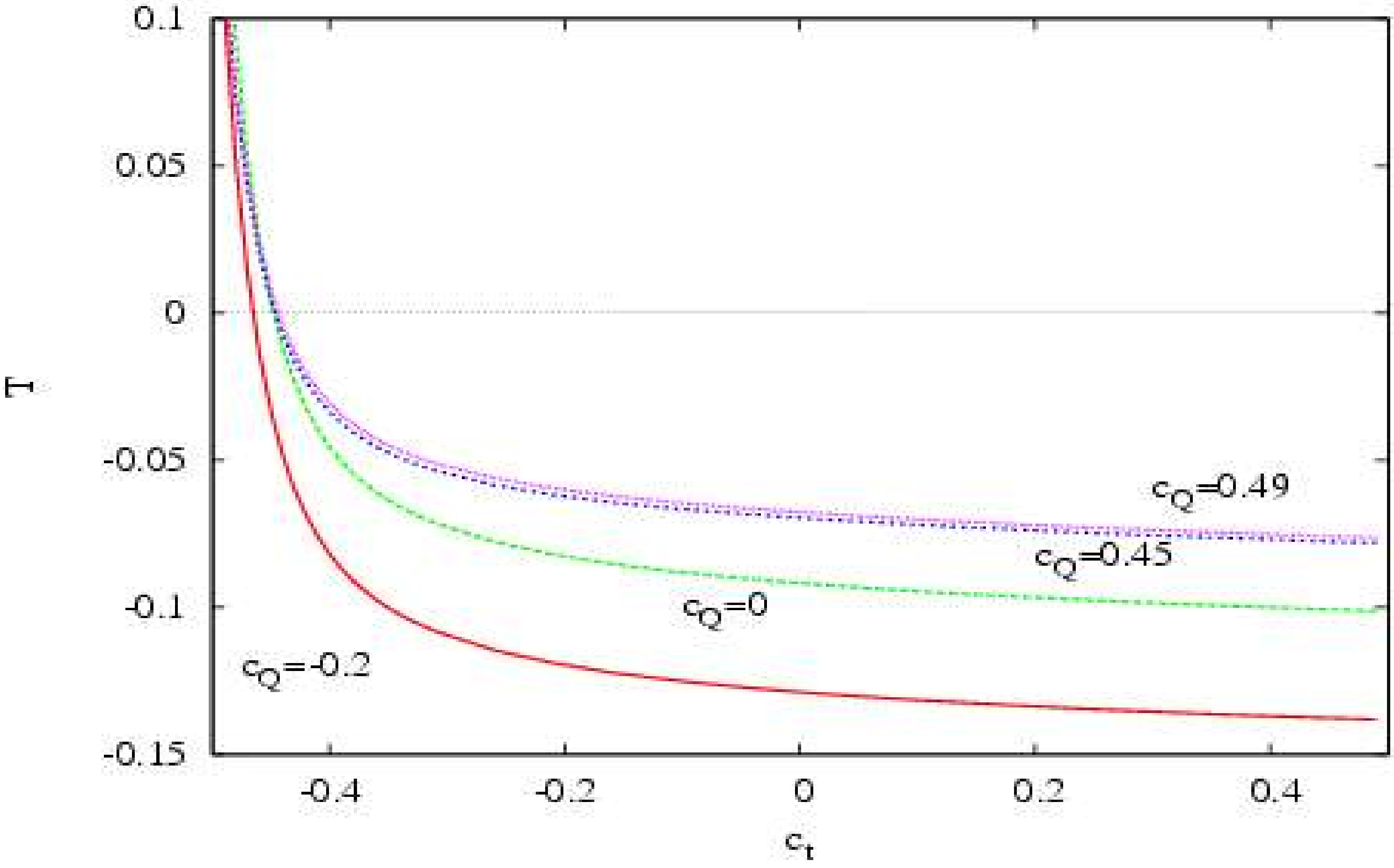
$$\Delta T = T_{\text{top}} \frac{2 m^2_{q_0^t,t}}{M_t^2} \left(\ln \frac{M_t^2}{m^2_{\text{top}}} - 1 + \frac{m^2_{q_0^t,t}}{2 m^2_{\text{top}}} \right) ,$$

- S is small and quite insensitive to the parameters of the model.

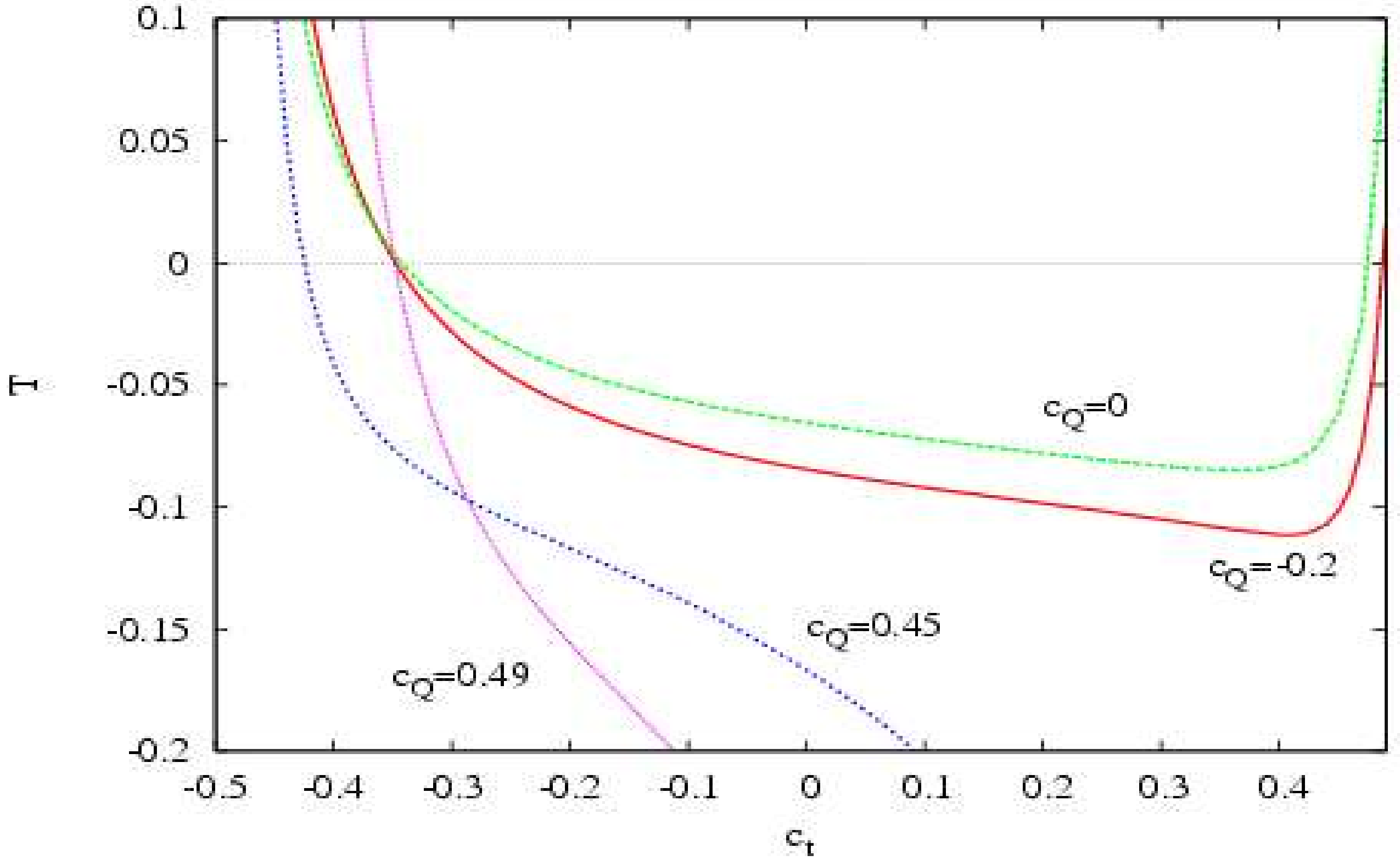
Brane Higgs $t_R \sim (1,1)$

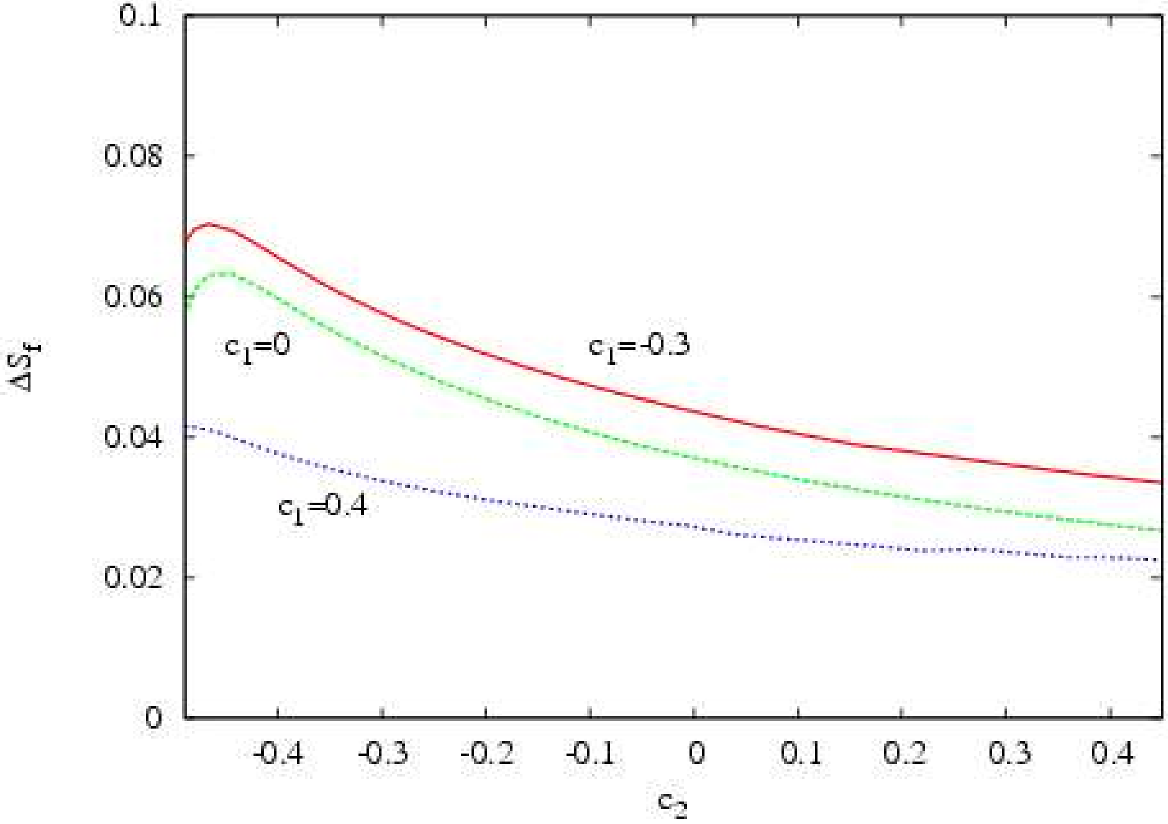


Bulk Higgs $t_R \sim (1,1)$



Bulk Higgs $t_R \sim (1,3)$

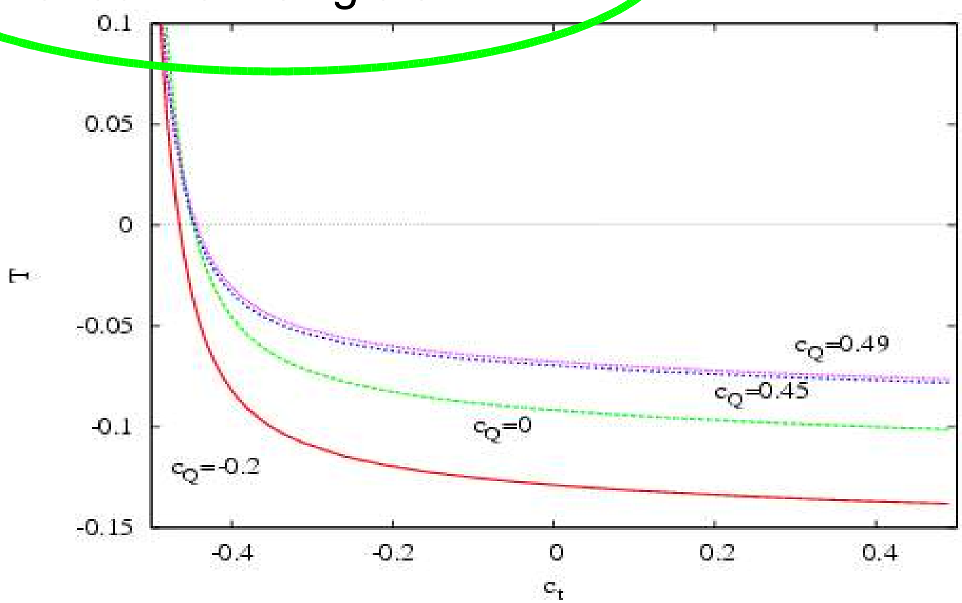




0.1
0.08
0.06
0.04
0.02
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
c_2
ΔS_f
c_1=0
c_1=-0.3
c_1=0.4

- There are regions of parameter space with a well-defined value of T:
  - Negative for t_R close to the IR brane, positive for t_R far from the IR brane (compatible with m_t)

$t_R^{(1)}$ light, λ^5 large ⇒ large effect from singlets



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Gauge-Higgs unification

Agashe, Contino, Pomarol NPB(05)

- We can enlarge the bulk symmetry to $SO(5)$ broken by boundary conditions to $SU(2)_L \times SU(2)_R$ on the IR brane and to the SM on the UV brane.
- The Higgs can arise then as the A_5 along the broken direction $SO(5)/SU(2)_L \times SU(2)_R$

$$A_5^{\hat{a}}(x,y) = a_H e^{2ky} A_5^{\hat{a}(0)}(x) + \ldots$$

- 5D gauge symmetry ensures that the Higgs potential is finite $\Longrightarrow$ Little hierarchy
- Yukawa couplings come from gauge couplings. Non-trivial flavor can be obtained by mixing at the boundary.

Gauge-Higgs unification

- Fermions must come in full representations of $SO(5)$

$$5 \sim (2,2) \oplus 1, \qquad 10 \sim (2,2) \oplus (3,1) \oplus (1,3)$$

- We focus on the simplest realistic choice of boundary conditions and quantum numbers

$$\xi_1 \sim Q_{1L} = \begin{pmatrix} \chi^u_{1L}(-,+) & q^u_L(+,+) \\ \chi^d_{1L}(-,+) & q^d_L(+,+) \end{pmatrix} \oplus u'_L(-,+)$$

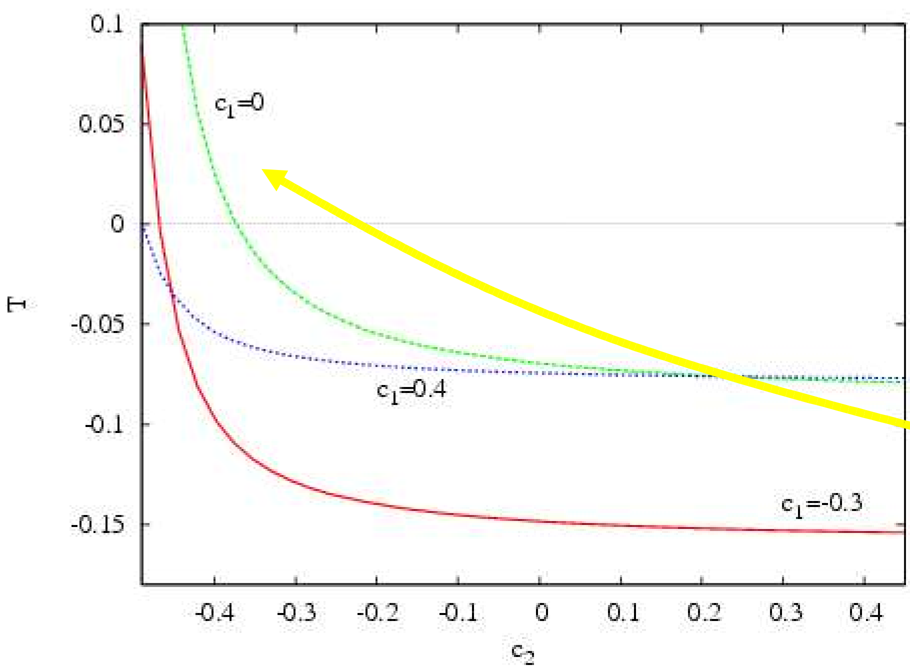
$$\xi_2 \sim Q_{2R} = \begin{pmatrix} \chi^u_{2R}(+,-) & q'^u_R(+,-) \\ \chi^d_{2R}(+,-) & q'^d_R(+,-) \end{pmatrix} \oplus u_R(+,+)$$

- With mixing

$$\mathcal{L}_m = \delta(y-L)[\widehat{M}_u \bar{u}'_L u_R + \text{h.c.}]$$

Gauge-Higgs unification

- Localized masses can make the light KK modes even lighter
  - Enhances the positive contribution of the singlet
  - Would enhance the negative contribution of the bidoublet
- The final result is similar to models with fundamental Higgs



t_R far from the IR brane forces $\widehat{M}_u$ to be larger (to generate m_t) and that makes $t_R^{(1)}$ lighter and therefore its positive contribution more important

- A realistic example:
  - For $c_2 \sim -0.5$ we can get any value of T, thus the bound comes from the S parameter.
  - For $m_H = 115\,\mathrm{GeV}$, the EW fit requires, at the two sigma level,

$$S \lesssim 0.3$$

  - This imposes a bound $\tilde{k} \equiv k e^{-kL} \gtrsim 1.2\,\mathrm{TeV} \Rightarrow M_{KK} \gtrsim 3\,\mathrm{TeV}$
- These values can be obtained with the following parameters

$$\left.\begin{aligned} \tilde{k} &= 1.2\,\mathrm{TeV} \\ c_1 &= 0 \\ c_2 &= -0.468 \\ \hat{M}_u &= 2.91 \end{aligned}\right\} \quad \Longrightarrow \quad \left\{\begin{aligned} & S \approx T \approx 0.3 \\ & \delta g_{b_L}/g_{b_L} \approx 0.8 \times 10^{-3} \\ & U \approx 0.005 \end{aligned}\right.$$

Phenomenology

- Fermionic spectrum:
  - Three light quarks (with charge 5/3, 2/3 and -1/3) that do not mix

$$M_{\chi_2^u} = M_{q_1} = M_{q'^d} \approx 470 \text{ GeV} .$$

  - Two charge 2/3 quarks that mix (strongly) with the top

$$M_{q_2} \approx 495 \text{ GeV} , \qquad M_{u_2} \approx 742 \text{ GeV} .$$

  - Heavier modes with masses $\gtrsim 1.9$ TeV

- Top mixing with vector-like quarks induces anomalous couplings

$$\frac{\delta g^L_{Ztt}}{g^L_{Ztt}} \sim -0.2 - 0.04 \qquad \frac{\delta g^L_{Wtb}}{g^L_{Wtb}} \sim -0.07 - 0.015$$

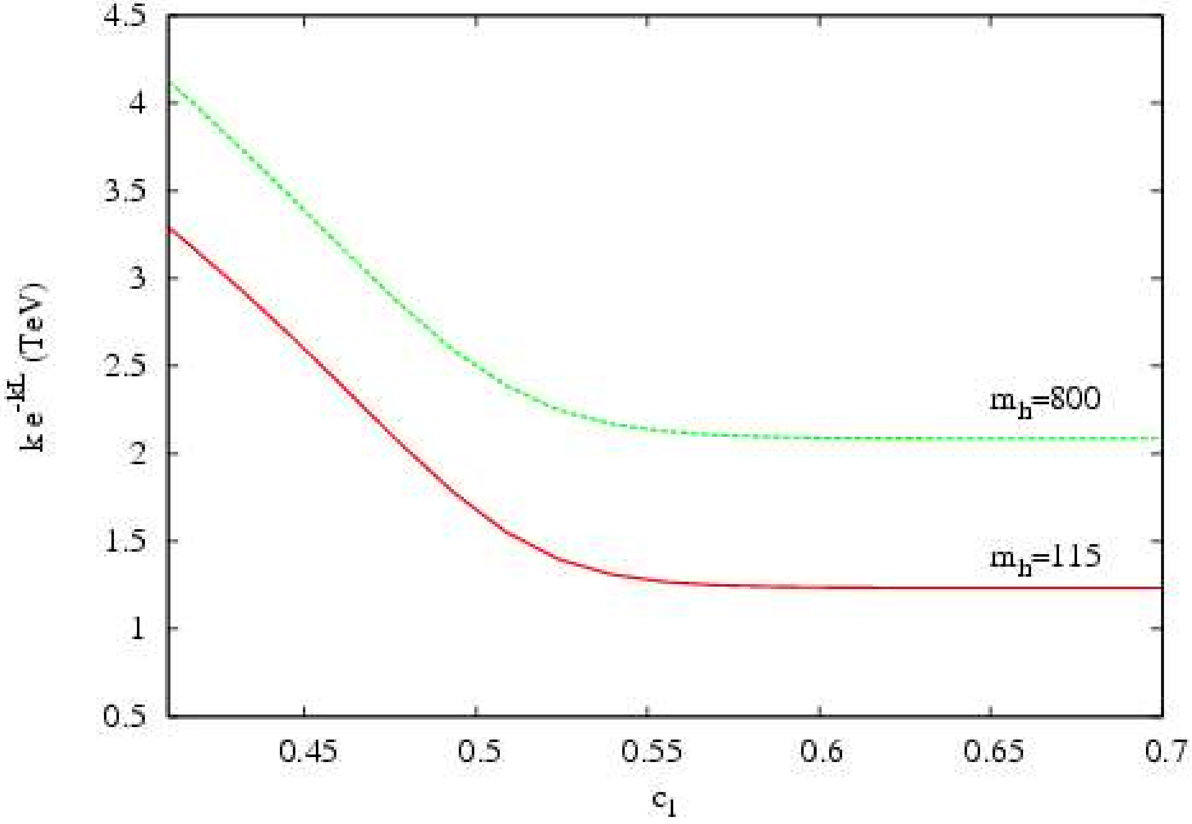
Moving the light generations

- The S,T analysis we have performed is valid when the light quarks and leptons are near the UV brane
- The couplings to the Z become non-universal if they get closer to the IR

$$\frac{\delta g_{f_L}}{g_{f_L}} = \frac{e^2}{s^2 c^2}\left[G^{f_L}_{++} - \frac{c^2 T^3_R + s^2 T^3_L - s^2 Q}{T^3_L - s^2 Q} G^{f_L}_{-+}\right]$$

- A global fit is necessary in that case

Han, Skiba PRD(05); Han PRD(06); Cacciapaglia, Csaki, Marandella, Strumia ph/0604111



4.5
4
3.5
3
2.5
2
1.5
1
0.5
0.45
0.5
0.55
0.6
0.65
0.7
$k\,e^{-kL}$ (TeV)
c_1
m_h=800
m_h=115

Conclusions

- Randall-Sundrum models with custodial symmetry can have small tree-level corrections to the T parameter and the $Zb\bar{b}$ coupling.
- One loop contributions to the T parameter are finite (therefore calculable) and generically large:
  - Bidoublets give a negative contribution
  - Singlets and triplets give a positive contribution
- Realistic models with $M_{KK}^{\text{gauge}} \sim 3$ TeV can be constructed and typically have light quarks that mix strongly with the top.
- Exciting phenomenology at the LHC
  - Light new fermions and gauge bosons
  - Anomalous top couplings