New Ideas in Randall-Sundrum Models

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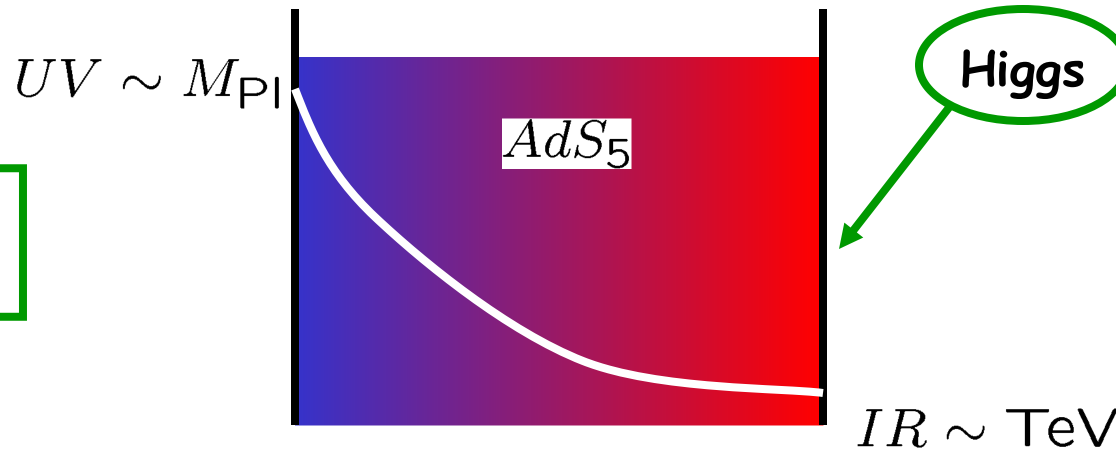
Randall-Sundrum for a theorist

A dream come true !!



- Solid motivation:

  Solution to the gauge hierarchy problem

- Suggestive theory of flavor:

  Fermion masses hierarchical with FCNC naturally absent for light fermions

- Insight on strongly coupled theories: AdS/CFT

Randall-Sundrum for an experimentalist

Hold your horses, boy!!

- The devil is in the details:
  - Strong Z and W mixing with their KK modes: T too large
  - Large flavor violation for heavy fermions ... maybe too large?
- Bounds from EW precision observables sends new physics at the verge (or well beyond it) of LHC reach
- But:
  - New ideas protect EW precision observables, allowing KK modes with masses $M_{KK} \sim 1-4$ TeV

Outline

- Fields in models with extra dimensions
- Phenomenology of Randall-Sundrum:
  - Masses
  - Couplings
- Bounds on the KK scale
  - Gauge boson mixing: T parameter
  - Heavy fermions: Zbb coupling
  - Light fermion coupling to KK gauge bosons: S parameter
- New Ideas: Custodial protection of T and Zbb
- How far can we get?
  - One-loop corrections to T and Zbb
- Global fit to Electroweak precision observables
- Phenomenology
- Conclusions

Fields in Extra Dimensions

- Fields living in higher dimensional compact spaces can be decomposed in normal (Kaluza-Klein) modes:

$$\phi(x, y) = \sum_{n=0}^{\infty} f_n(y)\phi_n(x), \text{ with } \partial_\mu \partial^\mu \phi_n = m_n^2 \phi_n$$

- (Quantized) momentum in the extra dimension corresponds to 4D mass for the Kaluza-Klein modes:

$$[\partial_y^2 + m_n^2] f_n = 0 \quad + \text{b.c.} \quad \Rightarrow \quad m_n \sim \frac{1}{L}$$

- Interactions are given by overlaps of the wave functions:

$$\mathcal{L} = \int \mathrm{d}y\, \phi\, \bar{\psi}\, \psi' = \sum_{nmr} \left[\int \mathrm{d}y\, f_n^{\phi} f_m^{\psi} f_r^{\psi'} \right] \phi_n\, \bar{\psi}_m\, \psi'_r$$

Phenomenology of RS: masses

- Goal: Study phenomenology → masses and couplings

- Boundary conditions:
  - $(++)$: Massless zero mode

    Chiral fermions

    Unbroken gauge symmetries

  - $(--), (-+), (+-)$: No zero mode

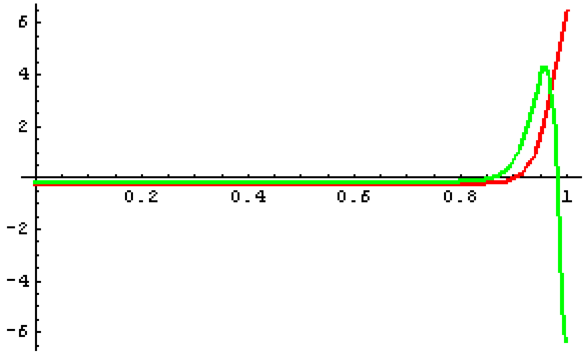
    Broken gauge symmetries

- In Randall-Sundrum the Kaluza-Klein scale is given by:

$$M_{KK} \sim \tilde{k} \equiv k\, e^{-kL} \sim \text{TeV}$$

Spectrum: couplings

- Light KK modes are localized towards the IR brane with small, almost constant, tails toward the UV brane

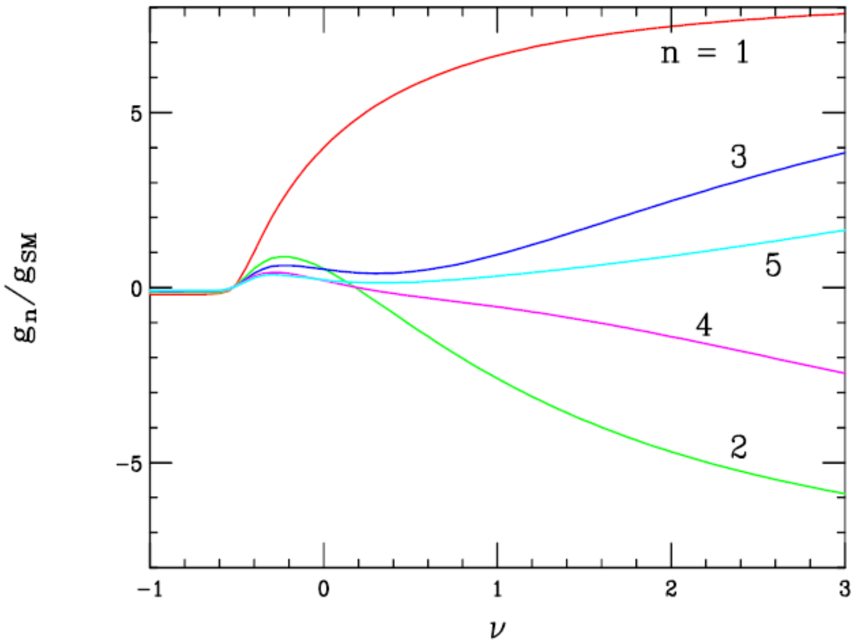


Strong KK coupling to the Higgs

- Gauge boson zero modes are flat (4D gauge invariance)
- Fermion zero modes can be (exponentially) localized anywhere:
  - Light fermions far from the IR (Higgs)
  - Third generation near the IR: Important effects

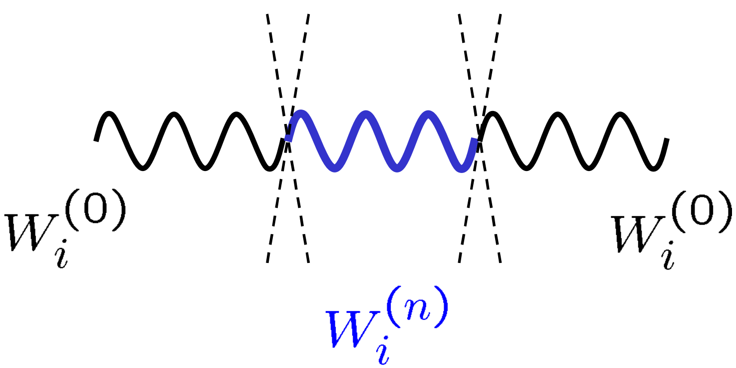
Spectrum: couplings (continued)

- Fermion zero mode couplings to the gauge boson KK modes depend on the fermion localization:
  - Constant for light fermions (near the UV brane)
  - Zero for delocalized fermions
  - Highly enhanced for heavy fermions (near IR brane)



The bads of the old RS: T parameter

Gauge KK modes are localized near the IR brane → Large mixing with the Z and W zero modes through the Higgs → Large T parameter



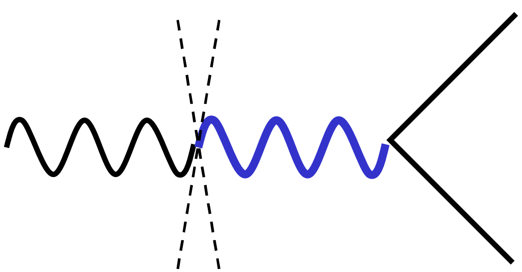
$$M_{KK} \gtrsim 5 - 10\,\text{TeV}$$

The bads of the old RS: Zbb coupling

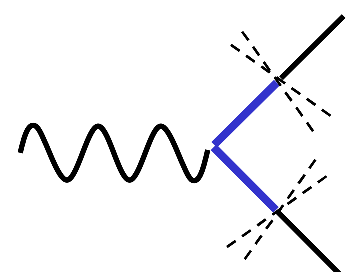
Top (bottom) zero modes are localized near the IR brane

Large gauge and Yukawa couplings to GB and fermion KK modes

Large anomalous Zbb coupling



$$M_{KK} \gtrsim 7-8\,\text{TeV}$$



The bads of the old RS: S parameter

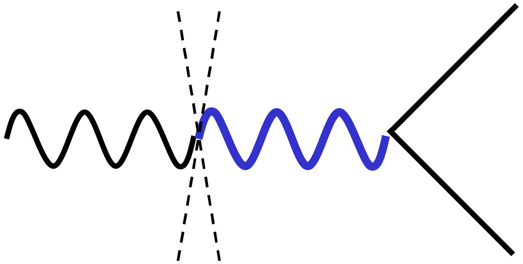
Light fermions are localized near the UV brane

→

Constant (non-zero) couplings to Gauge Boson KK modes

→

Can be reabsorbed into a (moderate) S parameter



light fermions

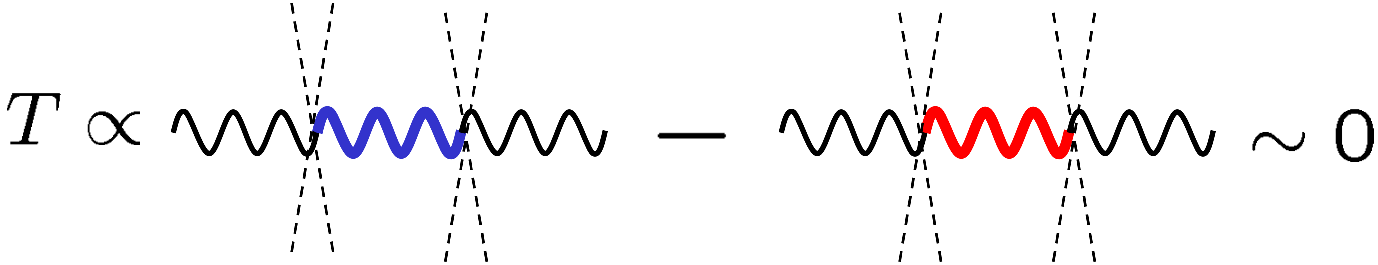
$$M_{KK} \gtrsim 3 - 4 \, \text{TeV}$$

New Ideas: custodial symmetry

- The T parameter is protected in the SM (at tree level) by a global $SU(2)_R$ custodial symmetry
- Custodial protection of Randall-Sundrum:

  Agashe, Delgado, May, Sundrum JHEP (03)

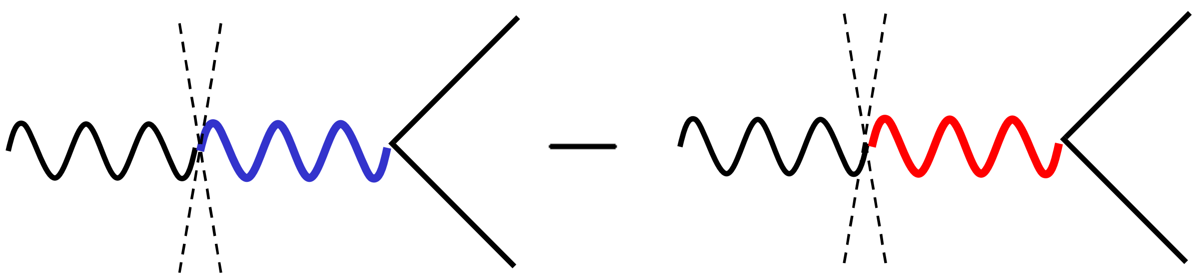
  - Bulk Gauge Symmetry: $SU(2)_L \times SU(2)_R \times U(1)_X$
  - Broken by boundary conditions (-,+) to the SM on the UV brane



What about Zbb?

- New KK modes [SU(2)$_R$ gauge bosons and new fermions] also affect the anomalous coupling of the b quark to the Z
- The correction depends on the fermion quantum numbers:
  - The simplest choice doesn't work: large Zbb corrections
  - If we have $T_3^L(b_L) = T_3^R(b_L)$ then Zbb coupling is protected by the custodial symmetry:

$$\delta g_{b_L} \propto$$



$$\sim 0$$

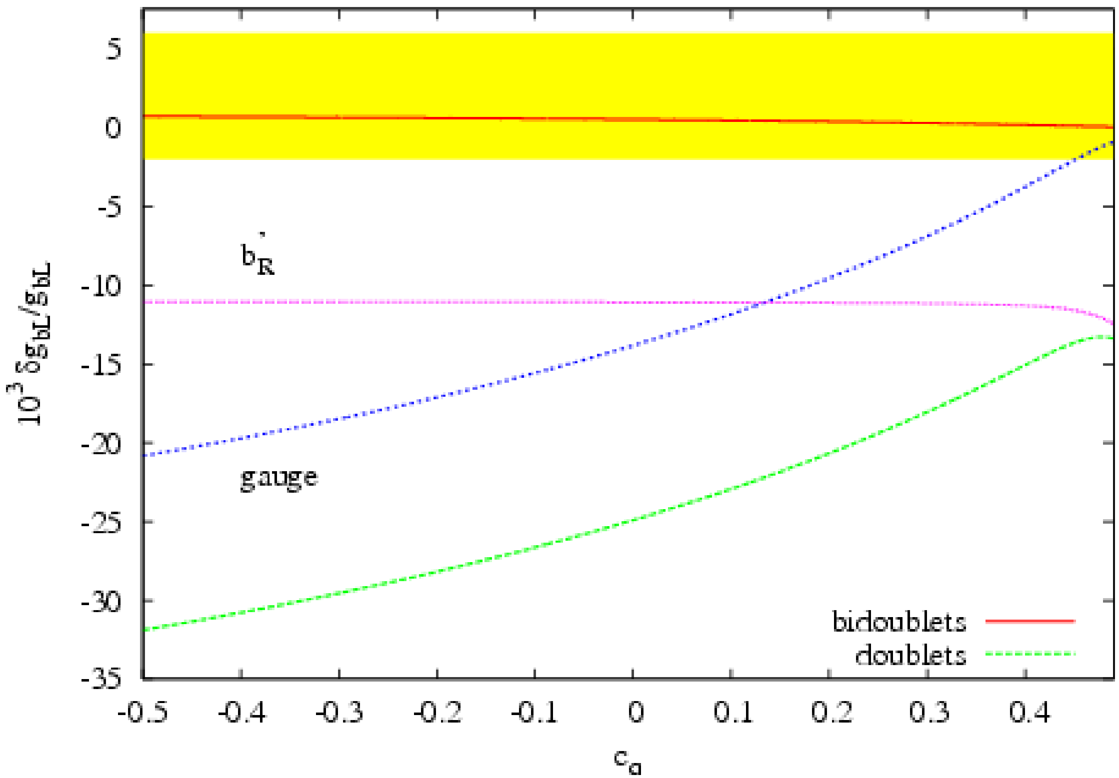
$$T_3^L(b_L) = T_3^R(b_L)$$

Mixing with fermion KK modes affecting Zbb naturally reduced

Agashe, Contino, Da Rold, Pomarol ph/0605341

What about Zbb?

$$M_{KK} \approx 3.75\ \text{TeV}$$



Custodial protection of T and Zbb is crucial to have light KK excitations

Fermion Quantum Numbers

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

The simplest option is bidoublets under $SU(2)_L \times SU(2)_R$

$$SU(2)_R \longleftrightarrow \qquad\qquad U(1)_Q$$

$$SU(2)_L \updownarrow \begin{pmatrix} \chi^u_L(-+) & t_L(+,+) \\ \chi^d_L(-+) & b_L(+,+) \end{pmatrix}_X \sim (2,2)_{2/3} \sim \begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix}$$

The Higgs is also a bidoublet with $Q_X = 0$

$$t_R(+,+) \sim (1,1)_{2/3}$$

How low can we get?

- Tree level corrections to the T parameter and Zbb anomalous coupling are tiny (no constraints)
- The S parameter forces

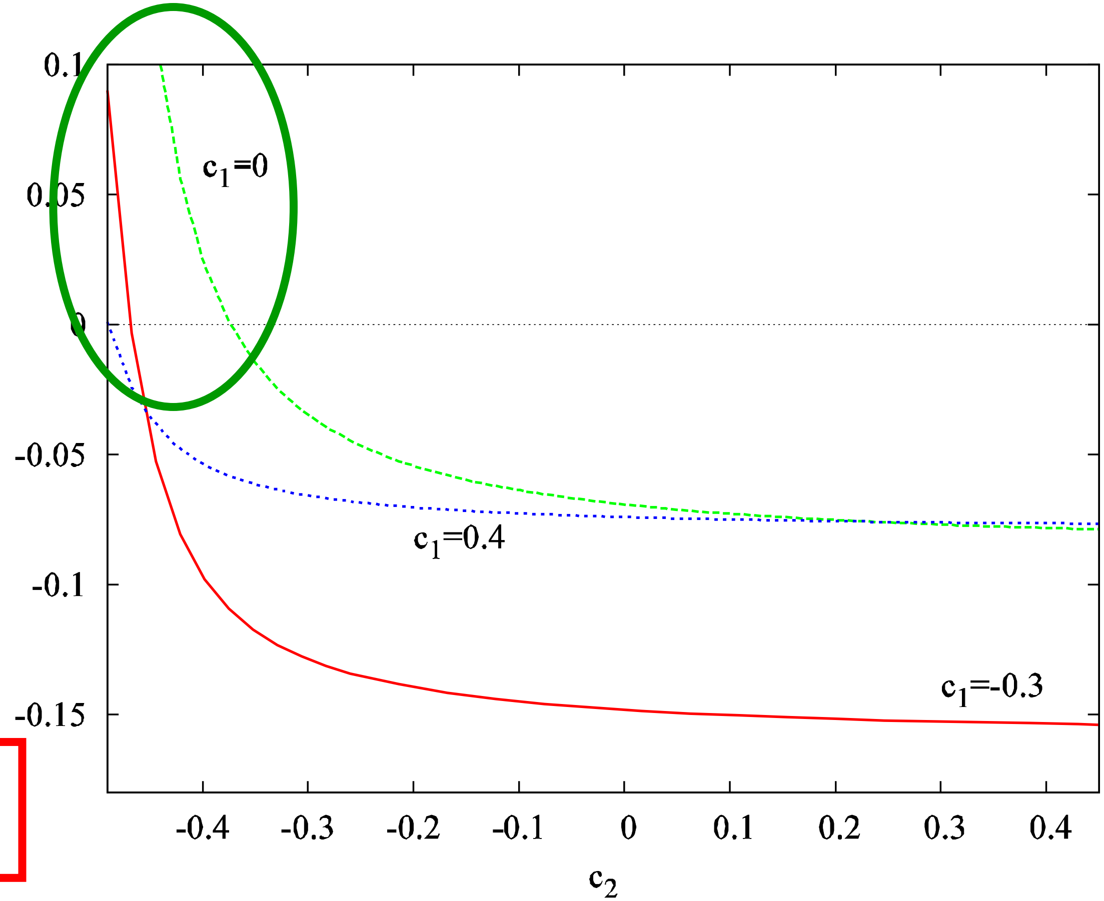
$$\tilde{K} \gtrsim 1.2\,\text{TeV} \Rightarrow M_{KK} \gtrsim 3\,\text{TeV}$$

- However, one-loop corrections can be important:
  - Bidoublets contribute negatively to T
  - Singlets contribute positively to T (need light singlets)
- Light fermion KK modes with strong couplings induce large one loop corrections to the Zbb coupling

T parameter at one loop

Light, strongly coupled $t_R^{(1)}$

Large corrections to Zbb coupling



UV ← singlet localization → IR

Global Fit to Electroweak Observables

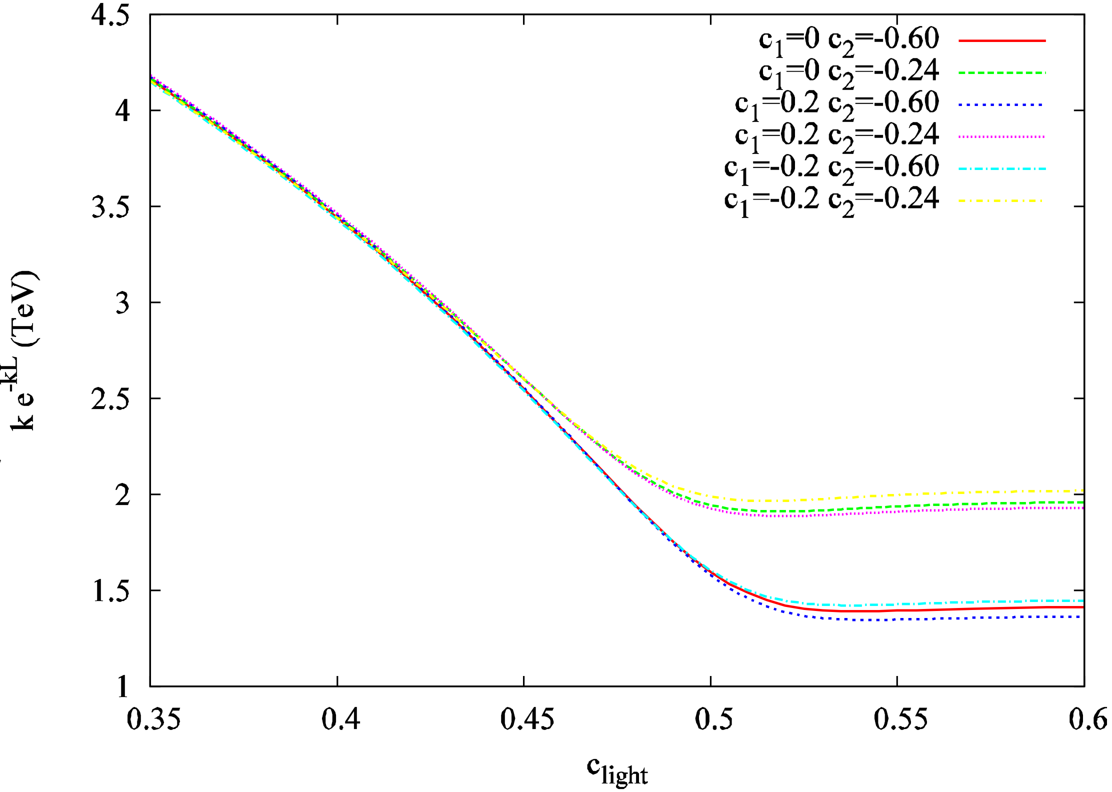
Han, Skiba PRD(05); Han PRD(06)

- We have performed a global fit to all relevant electroweak precision observables including:
  - All tree-level effects at leading order in $\mathcal{O}(v^2/\tilde{k}^2)$
  - Leading one loop effects: S and T parameters and Zbb
- We compute the χ^2 as a function of the localization parameter of the fermion zero modes: t_L, t_R, b_R, q_{light}
- Zbb coupling and the S parameter are the most restrictive observables when the light fermions are near the UV brane
- Loss of universality when light fermions near the IR brane

Result of the global fit

$\tilde{k} \gtrsim 1.5$ TeV

$M_{KK}(\text{gauge}) \gtrsim 3.75$ TeV



IR ← light families → UV

Example of model that saturates the bound:

$$c_{t_L} = 0, \quad c_{t_R} = -0.48, \quad c_{b_R} = c_{\text{light}} = -0.6, \quad M_u = 3.1$$

Phenomenology

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

$$M_{\chi_2^u} = M_{q_1} = M_{q'^d} \approx 510 \text{ GeV} .$$

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

$$M_{q_2} \approx 530 \text{ GeV} , \qquad M_{u_2} \approx 850 \text{ GeV} .$$

  - Heavier modes with masses $\gtrsim 2\,\text{TeV}$
- Top mixing with vector-like quarks induces anomalous couplings

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

Conclusions

- New ideas based on custodial symmetry get the Randall-Sundrum model back in the game for the LHC
- One loop effects are important: Tension between the T parameter and Zbb coupling
- Realistic models with $M_{KK}^{\rm gauge} \sim 3.75\,{\rm TeV}$ 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: $M_{KK} \sim 0.5 - 4\,{\rm TeV}$
  - Anomalous top couplings: up to 10-20% corrections
- Future work:
  - Collider phenomenology
  - Flavor Physics