Flavor violation in Randall-Sundrum models

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Motivation

- SM hierarchy problem: $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
  - **Extra dimensions** (**Warped** (AdS), Flat)
  - Supersymmetry
  - Strong dynamics
  - Little Higgs
- AdS/CFT correspondence [Maldacena 97]
  - 5-D gravity theory in AdS $\underset{DUAL}{\longleftrightarrow}$ 4-D conformal field theory

Talk Outline

- Introduction to Warped-space (Randall-Sundrum) scenario
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
  - Fermion geography
- Flavor structure
- FCNC processes
- LHC processes

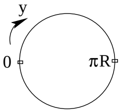
Warped Model

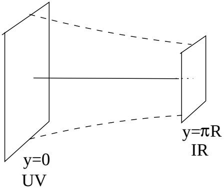
SM in background 5D warped AdS space [Randall, Sundrum 99]

$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

Z_2 orbifold fixed points:

- Planck (UV) Brane
- TeV (IR) Brane





R : radius of Ex. Dim.

k : AdS curvature scale ($k \lesssim M_{pl}$)

Hierarchy prob soln:

- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

Bulk Gauge Group

[Agashe, Delgado, May, Sundrum 03]

Bulk gauge group : $SU(3)_{QCD} \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- 8 gluons
- 3 neutral EW (W_L^3, W_R^3, X)
- 2 charged EW $(W_L^{\pm}, W_R^{\pm})$

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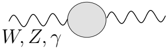
Gauge Symmetry breaking:

- By Boundary Condition (BC): $A_{-+}(x,y)$ BC: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \to U(1)_Y$
- By VEV of TeV brane Higgs Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

EW Precision Constraints



Precision Electroweak Constraints (S, T, $Zb\bar{b}$)

- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
  - T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced
- AdS bulk gauge symm $SU(2)_R$ $\Leftrightarrow$ CFT Custodial Symm
  [Agashe, Delgado, May, Sundrum 03]
  - T parameter - Protected
  - S parameter - $\frac{1}{k\pi R}$ for light bulk fermions
  - Problem: $Zb\bar{b}$ shifted
- 3rd gen quarks (2,2) [Agashe, Contino, DaRold, Pomarol 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{KK} \gtrsim 2 - 3$ TeV

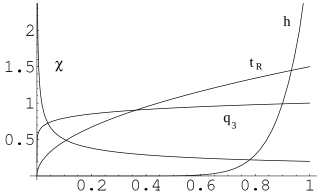
[Carena, Ponton, Santiago, Wagner 06,07] [Bouchart, Moreau-08] [Djouadi, Moreau, Richard 06]

Explaining SM mass hierarchy

Bulk Fermions explain SM mass hierarchy [Gherghetta, Pomarol 00][Grossman, Neubert 00]

$$\mathcal{S}^{(5)} \supset \int d^4x\, dy \;\left\{ c_\psi\, k\, \overline{\Psi}(x,y)\, \Psi(x,y) \right\}$$

Fermion bulk mass (c_ψ parameter) controls $f^\psi(y)$ localization



RS-GIM keeps FCNC under control

$$\frac{c}{\Lambda} \bar{\chi}^i \chi^j \bar{\chi}^k \chi^l \qquad \Lambda \gg TeV$$

Kaluza-Klein (KK) decomposition

Bulk fields $\Phi(x,y) = \{\Psi,\ A,\ ...\}$

$$\mathcal{S}^{(5)} = \int d^4x dy\ \mathcal{L}^{(5)} \quad ; \quad \mathcal{L}^{(5)} \supset \sqrt{|g|}\ \left\{ M_*^3 \mathcal{R}\ + c_\psi \Psi\Psi\ + g_5 \Psi\Psi\, A\ + \lambda_5\, \Psi_L \Psi_R\, H \right\}$$

KK expansion: $\Phi(x,y) = \sum_{n=0}^{\infty} f_{(n)}^{\phi}(y)\, \phi^{(n)}(x)$ with $\int dy\, f_{(n)}^{\phi} f_{(m)}^{\phi} = \delta_{nm}$

Bulk EOM give profiles $f_{(n)}^{\phi}(y)$; c_ψ controls $f^{\psi}(y)$ localization

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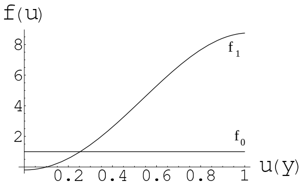

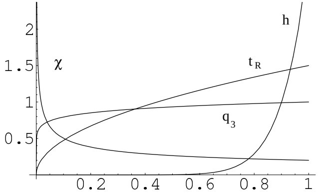

Integrate $\mathcal{S}^{(5)}$ over y $\longrightarrow$ **equivalent 4D theory**

$$\mathcal{S}^{(4)} = \int d^4x \sum\ m_n^2 \phi^{(n)}\phi^{(n)}\ +\ g_{4D}^{(nml)} \psi^{(n)}\psi^{(m)} A^{(l)}\ +\ \lambda_{4D}^{(nm)}\ \psi_L^{(n)}\psi_R^{(m)}\, H$$

$\phi^{(n)} \to$KK tower with mass m_n ; Denote $\phi^{(1)} \equiv \phi'$; $m_1 \equiv m_{KK} \sim$TeV

4-D KK couplings

$$\xi \equiv \sqrt{k\pi R} \approx 5$$

Compute overlap integral over y to get 4D couplings

- Yukawas: $\lambda_{4D}^{(nm)} = \lambda_{5D} \int dy\, f_n^{\psi_L}\, f_m^{\psi_R}\, f^H$
- Gauge couplings: $g_{4D}^{(nmk)} = g_{5D} \int dy\, f_n^{\psi}\, f_m^{\psi}\, f_k^A$

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Compare to SM couplings:

- ξ enhanced: $t_R t_R A'$, hhA', $\phi\phi A'$ (Equivalence Theorem $\Rightarrow$ $\phi \leftrightarrow A_L$)
- $1/\xi$ suppressed: $\psi_{light}\, \psi_{light}\, A'_{++}$ Note: $\psi_{light}\, \psi_{light}\, A'_{-+} = 0$
- SM strength: $t_L t_L A'$

Flavor structure

[Agashe, Perez, Soni, 04]

$$\mathcal{L} \supset \bar{\Psi}^i i\Gamma^\mu D_\mu \Psi^i + M_{ij}\bar{\Psi}^i\Psi^j + y^{5D}_{ij} H\bar{\Psi}^i\Psi^j + h.c.$$

- Basis choice: M_{ij} diagonal $\equiv M_i$
  - All flavor violation from y^{5D}_{ij}
  - KK decompose and go to mass basis
    - $\Longrightarrow g\,\bar{\Psi}^i_{(n)} W^{(k)}_\mu \Psi^j_{(m)}$ off-diagonal in flavor (due to non-degenerate f^i i.e. M^i)
- 5D fermion Ψ is vector-like
  - M_{ij} is independent of $\langle H \rangle = v$
  - But zero-mode made chiral (SM)

FCNC couplings

- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(0)}$: diagonal
- $\{A_{(0)}, g_{(0)}\}\,\psi_{(0)}\psi_{(0)}$: diagonal (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\,\psi_{(0)}\psi_{(0)}$: almost diagonal (non-diagonal due to EWSB effect)
- $h\,\psi_{(0)}\psi_{(0)}$: diagonal (only source of mass is $\langle h \rangle = v$)

- $h^{\mu\nu}_{(1)}\psi_{(0)}\psi_{(0)}$: off-diagonal
- $\{A_{(1)}, g_{(1)}\}\,\psi_{(0)}\psi_{(0)}$: off-diagonal (i=1,2 almost diagonal)
- $\{Z_{(1)}, Zx_{(1)}\}\,\psi_{(0)}\psi_{(0)}$: off-diagonal

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- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(1)}$: 0
- $\{A_{(0)}, g_{(0)}\}\,\psi_{(0)}\psi_{(1)}$: 0 (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\,\psi_{(0)}\psi_{(1)}$: off-diagonal (EWSB effect)
- $h\,\psi_{(0)}\psi_{(1)}$: off-diagonal (since M_ψ is extra source of mass)

$\psi_{(0)} \leftrightarrow \psi_{(1)}$ mixing due to EWSB

FCCC couplings

- $W^{\pm}_{L(0)} \psi^{i}_{(0)} \psi^{j}_{(0)}$: $g\, V^{ij}_{CKM}$
- $\left\{ W^{\pm}_{L(1)}, W^{\pm}_{R(1)} \right\} \psi_{(0)} \psi_{(0)}$: $g\, V_{100}\, [f_{W^{(1)}} f_{\psi} f_{\psi}]$
  - [...] suppressed for $i = 1, 2$; (Not suppr for b_L, t_L, t_R)
- $W^{\pm}_{L(0)} \psi_{(0)} \psi_{(1)}$: $g\, V_{001}\, \left[f_{W^{(1)}} f_{\psi} f_{\psi^{(1)}} \right]$

Example FCNC processes

- $K^0 \bar{K}^0$ mixing:
  - Tree-level FCNC vertex $g_{(1)} d\, s \propto V_L^{d\dagger} \begin{pmatrix} [g_{(1)} d\, d] & 0 \\ 0 & [g_{(1)} s\, s] \end{pmatrix} V_L^d$
- $b \to s\gamma$:
  - No tree-level contribution to helicity flip dipole operator
  - So 1-loop with $g_{(1)}\, b\, s_{(1)}$ OR $\phi^{\pm}\, b\, s_{(1)}$
- $b \to s\, \ell^+ \ell^-$, $b \to s\, s\, \bar{s}$, $K \to \pi \nu \bar{\nu}$:
  - Tree level FCNC vertex $Z\, s\, d$

Bound : $m_{KK} \gtrsim$ *few* TeV [Agashe et al][Buras et al][Neubert et al][Csaki et al]

Relaxed with flavor alignment : MFV, NMFV, flavor symmetries, ...
[Fitzpatrick et al][Agashe et al]

KK states at the LHC

- $h^{(1)}_{\mu\nu}$ (KK Graviton) $gg \to h^{(1)} \to t\bar{t}$

  $L = 300\ fb^{-1}$ LHC reach is about 2 TeV

  [Agashe, Davoudiasl, Perez, Soni 07]
  [Fitzpatrick, Kaplan, Randall, Wang 07]

- $g^{(1)}_{\mu}$ (KK Gluon) $q\bar{q} \to g^{(1)} \to t\bar{t}$

  $L = 100\ fb^{-1}$ LHC reach is 4 TeV

  [Agashe, Belyaev, Krupovnickas,Perez,Virzi 06]
  [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait 07]

- $Z^{(1)}_{\mu}$, $W^{(1)\pm}_{\mu}$ $(Z_{KK} \equiv Z'$, $W^{\pm}_{KK} \equiv W')$ $q\bar{q} \to Z', W' \to XX$

  $L = 300\ fb^{-1}$ LHC reach is 3 TeV

  [*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007 & 0810.1497]

- $\psi^{(1)}$ (KK Fermion)

  [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08][SG et al ongoing]

- Radion

Review: [Davoudiasl, SG, Ponton, Santiago, New J.Phys.12:075011,2010. arXiv:0908.1968 [hep-ph]]

Example LHC flavor changing processes

- Tree-level FCNC $t \longrightarrow c\,h$ OR $h \longrightarrow t\,c$ [Agashe, Contino 09]
  - $BR(t \longrightarrow c\,h) \sim 10^{-4}$
  - $BR(h \longrightarrow t\,c) \sim 5 \times 10^{-3}$
- Tree-level FCNC $BR(t \longrightarrow c\,Z) \sim 10^{-5}$ [Agashe, Perez, Soni 06]
- Loop FCNC $t \longrightarrow c\,\gamma$

Conclusions

- Warped models solve SM hierarchy and flavor problems
  - KK couplings to light fermions suppressed
  - KK couplings to t_R, t_L, b_L, A_L, h enhanced
  - Precision electroweak constraints imply $M_{KK} \gtrsim 2\ TeV$
- GaugeKK, fermionKK : *tree-level* flavor changing couplings
  - Precision flavor changing processes
  - High p_T flavor changing processes

BACKUP SLIDES

Fermion reps (Custodial protection for $Zb_L\overline{b_L}$)

Impose custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance [Agashe, Contino, DaRold, Pomarol 06]

Fermions:

- $Q_L = (2,2) = \begin{pmatrix} t_L & \zeta_L \\ b_L & T_L \end{pmatrix}$

  $t_R : (1,1)$ OR $(1,3) \oplus (3,1) = \begin{pmatrix} \chi'_R \\ t'_R \\ b'_R \end{pmatrix} \oplus \begin{pmatrix} \chi''_R \\ t''_R \\ b''_R \end{pmatrix}$; b_R : $(1,1)$ OR $(1,3) \oplus (3,1)$

- $Zb_L\overline{b_L}$ coupling protected! Note: Wt_Lb_L, Zt_Lt_L not protected, so expect shifts

New "exotic" fermions ζ_L, T_L, χ'_R, b'_R, ...

- No zero-mode. So $(-,+)$ BC $\Longrightarrow M_{\psi'} < M_{A'}$ [Agashe, Servant 04]
- Promising LHC signatures

Bulk EW Gauge Sector

Bulk EW Gauge group : $SU(2)_L \times SU(2)_R \times U(1)_X$

- Three neutral gauge bosons: (W_L^3, W_R^3, X)
- Two charged gauge bosons: $(W_L^\pm, W_R^\pm)$

Symmetry Breaking:

- By Boundary Condition (BC):
  $Z_X(-,+)$ means $Z_X|_{y=0} = 0\,;\ \partial_y Z_X\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$: $(W_L^3, W_R^3, X) \rightarrow (W_L^3, B, Z_X)$
    $A \rightarrow (+,+)\,;\ Z \rightarrow (+,+)\,;\ Z_X \rightarrow (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \rightarrow (-,+)$; $W_R^\pm \rightarrow (-,+)$
    - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+)$; $W_L^\pm \rightarrow (+,+)$

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  - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+)$; $W_L^\pm \rightarrow (+,+)$

- By VEV of TeV brane Higgs
  - $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$: $(W_L^3, B, Z_X) \rightarrow (A, Z, Z_X)$

Gauge KK States

Gauge Boson

- "Zero" modes: $A^{(0)}, Z^{(0)}$; $W_L^{(0)}$
- First KK modes: $A^{(1)}, Z^{(1)}, Z_X^{(1)} \longrightarrow Z'$; $W_L^{(1)}, W_R^{(1)}$

EWSB mixes : $Z^{(0)} \leftrightarrow Z^{(1)}$; $Z^{(0)} \leftrightarrow Z_X^{(1)}$; $Z^{(1)} \leftrightarrow Z_X^{(1)}$

$W_L^{(0)} \leftrightarrow W_L^{(1)}$; $W_L^{(0)} \leftrightarrow W_R^{(1)}$; $W_L^{(1)} \leftrightarrow W_R^{(1)}$

Mass eigenstates :

- "Zero" modes: A, Z ; $W^{\pm}$
- First KK modes: $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \longrightarrow Z'$; $\tilde{W}_{L_1}, \tilde{W}_{R_1} \longrightarrow W'^{\pm}$

Z' Overlap Integrals

Define: $\xi \equiv \sqrt{k\pi R} = 5.83$

Z' overlap with Higgs $\rightarrow \xi$
Z' overlap with fermions:

	Q^3_L	t_R	other fermions
$\mathcal{I}^+$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} \approx -0.2$
$\mathcal{I}^-$	$0.2\xi \approx 1.2$	$0.7\xi \approx 4.1$	0

Compared to SM

- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

$$\bar{\psi}_{L,R}\gamma^{\mu}\Big[eQ\mathcal{I}A_{1\,\mu} + g_Z\left(T^3_L - s^2_W T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T^3_R - s'^2 T_Y\right)\mathcal{I}Z_{X1\,\mu}\Big]\psi_{L,R}$$