$\Delta F = 2$ Observables and Fine-Tuning in a Custodially Protected Warped Extra Dimension

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based on: MB, Buras, Duling, Gori, Weiler, 0809.1073

$\Delta F = 2$ in Warped Extra Dimensions

many analyses in the existing literature

Burdman, hep-ph/0205329, hep-ph/0310144; Agashe, Perez, Soni, hep-ph/0408134; Moreau, Silva-Marcos, hep-ph/0602155; Chang, Kim, Song, hep-ph/0607313; Csaki, Falkowski, Weiler, 0804.1954; ...

What is new in BBDGW?

First complete analysis of $\Delta F = 2$ processes

- within the **custodially protected RS model**
- including simultaneously **all $\Delta F = 2$ operators**
- performing **RG-running at the NLO level**
- including both **strong and electroweak gauge boson** contributions
- considering **all interesting $\Delta F = 2$ observables simultaneously**
- analysing **fine-tuning** in flavour physics

Main Messages from BBDGW

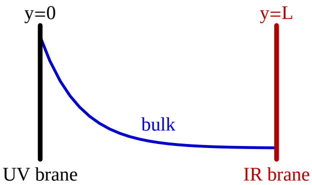
1. confirmation of **generic bound $\mathbf{M_{KK} \gtrsim 20\,TeV}$ from $\boldsymbol{\varepsilon_K}$**
   CSAKI, FALKOWSKI, WEILER, 0804.1954
2. also for $M_{KK} \gtrsim (2-3)\,\text{TeV}$ **agreement with $\boldsymbol{\varepsilon_K}$** possible **without relevant fine-tuning**
3. **$\mathbf{\Delta M_K}$ and $\boldsymbol{\varepsilon_K}$** are governed by **KK gluon contributions**
4. in **$\mathbf{B_{d,s} - \bar{B}_{d,s}}$ electroweak KK modes** equally important
5. **tree level down-type FCNCs through Z eliminated** by custodial protection of $Zb_L\hat{b}_L$ (both $\Delta F = 2$ and $\Delta F = 1$)
6. possible **tensions in the SM** $(\varepsilon_K, S_{\psi K_S}, \ldots)$ can be **solved**
7. **$\mathbf{S_{\psi\phi}}$ and $\mathbf{A^s_{SL}}$ can be large**

The basic RS Set-up

5D spacetime with **warped** metric:

RANDALL, SUNDRUM, HEP-PH/9905221

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2\,, \qquad 0 \leq y \leq L$$



- **fermions and gauge bosons** live in the bulk
- **Higgs** localised on IR brane

CHANG ET AL., HEP-PH/9912498
GROSSMAN, NEUBERT, HEP-PH/9912408
GHERGHETTA, POMAROL, HEP-PH/0003129

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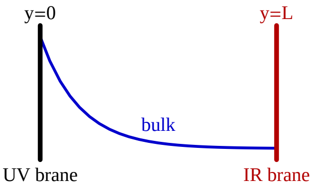

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- energy scales suppressed by **warp factor e^{-ky}**
  $\rightarrow$ **natural** explanation of **gauge hierarchy** problem
- **Kaluza-Klein (KK) excitations** live close to the IR brane

Constraints from EW Precision Tests

S parameter: $M_{KK} \gtrsim (2{-}3)\,\text{TeV}$ Agashe et al., hep-ph/0308036

T parameter:

- without protection: $M_{KK} \gtrsim 10\,\text{TeV}$
  (may be softened by heavy Higgs Casagrande et al., 0807.4937
  Barbieri et al., hep-ph/0603188, ...)
- with **custodially enlarged gauge symmetry** $\rightarrow$ ✓
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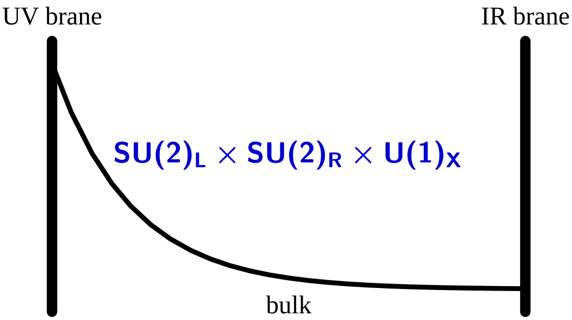
anomalous $Z b_L \bar{b}_L$ coupling: (exp.: $\lesssim 5 \cdot 10^{-3}$)

- corrections arise naturally at the $-(1-2)\%$ level
- protection by **discrete $SU(2)_L \leftrightarrow SU(2)_R$ symmetry** ✓
  $\longrightarrow$ enlarged fermion representations
  Agashe et al., hep-ph/0605341; Contino et al., hep-ph/0612048
  Carena et al., hep-ph/0607106

A Realistic Model in the Reach of LHC



$+ \ (L \leftrightarrow R)$-symmetric fermion representations

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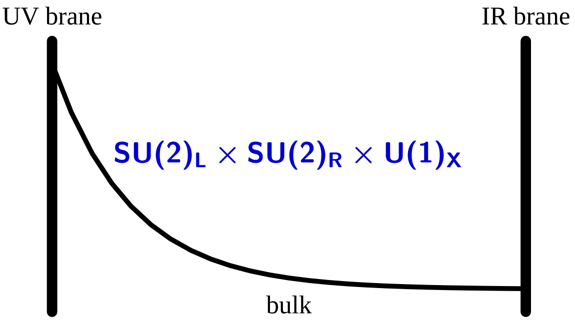
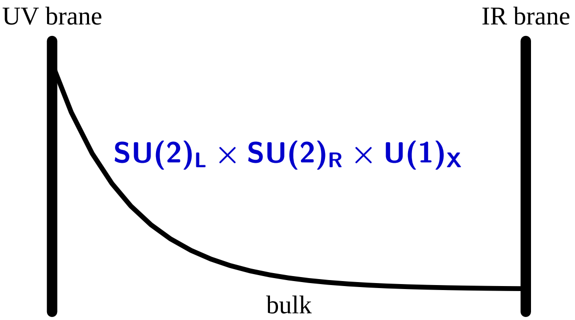


$SU(2)_R \times U(1)_X \to U(1)_Y$
by boundary conditions

$+$ $(L \leftrightarrow R)$-symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y$ in the absence of EWSB

A Realistic Model in the Reach of LHC



$\mathbf{SU(2)_R \times U(1)_X \rightarrow U(1)_Y}$
by boundary conditions

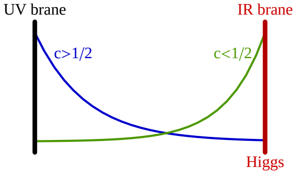
$\mathbf{SU(2)_L \times SU(2)_R \rightarrow SU(2)_V}$
by Higgs VEV

$+$ $(L \leftrightarrow R)$-symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$

zero mode profile depends strongly on bulk mass parameter **c**:

$$f^{(0)}(y,c) \propto e^{(\frac{1}{2}-c)ky}$$



$\mathbf{c} > \frac{1}{2}$: localisation around **UV brane**
$\mathbf{c} < \frac{1}{2}$: localisation around **IR brane**

Fermion Localisation and Yukawa Couplings

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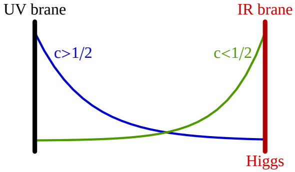

$\mathbf{c > \frac{1}{2}}$: localisation around **UV brane**
$\mathbf{c < \frac{1}{2}}$: localisation around **IR brane**

effective 4D Yukawa couplings: $$(\mathbf{Y_{u,d}})_{ij} = (\lambda_{u,d})_{ij}\, f_i^Q\, f_j^{u,d}$$

- $\lambda_{u,d} \sim \mathcal{O}(1)$ anarchic complex 3×3 matrix
- **hierarchical structure** can be naturally generated by exponential suppression of $\mathbf{f^{Q,u,d}}$ (fermion profile on IR brane)

Flavour Violation by KK Gauge Bosons

- **KK gauge bosons** localised close to **IR brane**: $g(y) \sim e^{ky}$
- couplings to SM fermions depend on their localisation
- **flavour eigenbasis:**

$$\bar{\psi}_i G_\mu \psi_i \sim -ig^{4\mathrm{D}} \gamma_\mu \sqrt{kL} (\mathbf{f}_i^{\psi})^2 + \text{const.}$$

flavour-diagonal, but non-universal!

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- rotation to **mass eigenbasis** via $\mathcal{D}_{L,R}$: (estimate for anarchic $\lambda_{u,d}$)

$$\bar{d}_L^i G_\mu d_L^j \sim -ig^{4\mathrm{D}} \gamma_\mu \sqrt{kL}\, \mathbf{f}_\mathbf{i}^\mathbf{Q}\, \mathbf{f}_\mathbf{j}^\mathbf{Q}$$
$$\bar{d}_R^i G_\mu d_R^j \sim -ig^{4\mathrm{D}} \gamma_\mu \sqrt{kL}\, \mathbf{f}_\mathbf{i}^\mathbf{d}\, \mathbf{f}_\mathbf{j}^\mathbf{d}$$

  - **tree level FCNCs arise!**
  - **protected by RS-GIM mechanism**

Agashe, Perez, Soni, hep-ph/0408134

Contributions to $\Delta F = 2$

- **KK gluons**

  Agashe, Perez, Soni, hep-ph/0408134
  Csaki, Falkowski, Weiler, 0804.1954; BBDGW

- **KK weak gauge bosons** $(Z_H, Z', A^{(1)})$ BBDGW

  subdominant in $K - \bar{K}$, but **competitive** in $B - \bar{B}$

- **Z boson** BBDGW

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  $\longrightarrow$ extends **custodial protection** to $\mathbf{Z d_L^i \bar{d}_L^j}$ couplings

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- generally: **new operators** are induced:

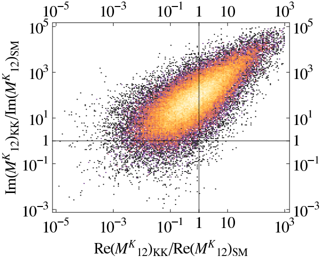
$$\mathcal{Q}_{LL} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_L d) \qquad \mathcal{Q}_{1LR} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma_\mu P_R d)$$

$$\mathcal{Q}_{RR} = (\bar{s}\gamma_\mu P_R d)(\bar{s}\gamma_\mu P_R d) \qquad \mathcal{Q}_{2LR} = (\bar{s} P_L d)(\bar{s} P_R d) \ ^{(*)}$$

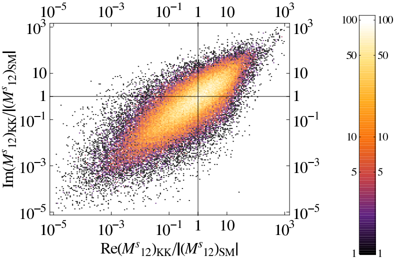
$^{(*)}$ KK gluons only

$\mathcal{Q}_{\mathbf{LR}}$: **QCD** ($K$ and B) **and chirally** (only K) **enhanced**!

$\mathrm{K}-\bar{\mathrm{K}}$ mixing:



$\mathrm{B_s}-\bar{\mathrm{B}}_\mathrm{s}$ mixing:



$$\mathrm{Re}(M_{12}^K)_{\mathrm{KK}} \sim \mathrm{Re}(M_{12}^K)_{\mathrm{SM}}$$
$$\mathrm{Im}(M_{12}^K)_{\mathrm{KK}} \sim 10^2\,\mathrm{Im}(M_{12}^K)_{\mathrm{SM}}$$

generally tension with ε_K

Csaki, Falkowski, Weiler

$$|(M_{12}^s)_{\mathrm{KK}}| \sim |(M_{12}^s)_{\mathrm{SM}}|$$
$$\mathrm{Arg}(M_{12}^s)_{\mathrm{KK}} \sim \mathcal{O}(1)$$

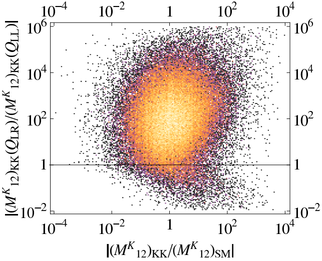
large $S_{\psi\phi}$ expected

BBDGW

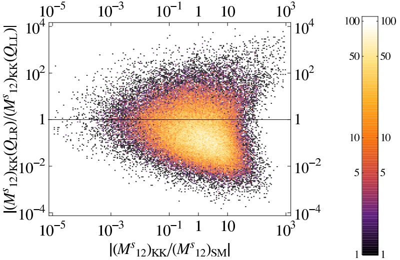
all results for $M_{\mathrm{KK}} \simeq 3\,\mathrm{TeV}$

Operator Competition in $\Delta F = 2$

$\mathrm{K} - \bar{\mathrm{K}}$ mixing:



$\mathrm{B_s} - \bar{\mathrm{B}}_\mathrm{s}$ mixing:



$\mathcal{Q}_{LR}$ dominates
by two orders of magnitude
KK gluons dominant

$\mathcal{Q}_{LL}$ and $\mathcal{Q}_{LR}$
are competitive
EW KK modes important

(no chiral LR enhancement in B system)

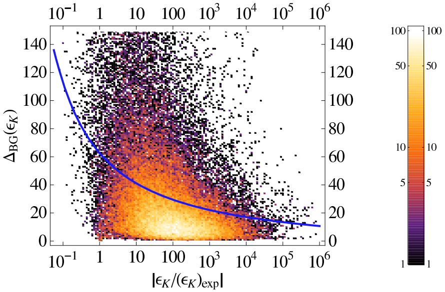
$\mathcal{Q}_{RR}$ contribution generally small

BBDGW

Required Fine-Tuning in ε_K

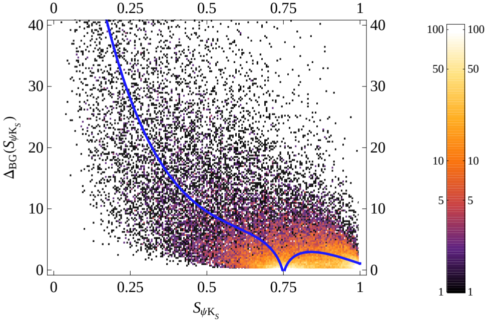
BBDGW

Barbieri-Giudice measure of fine-tuning:
sensitivity of observable to small variation of model parameters



- generically $\varepsilon_K \sim 10^2 (\varepsilon_K)_{exp}$
- required tuning generically increases with decreasing ε_K
- $\varepsilon_K \sim (\varepsilon_K)_{exp}$ **possible without significant tuning**

BBDGW

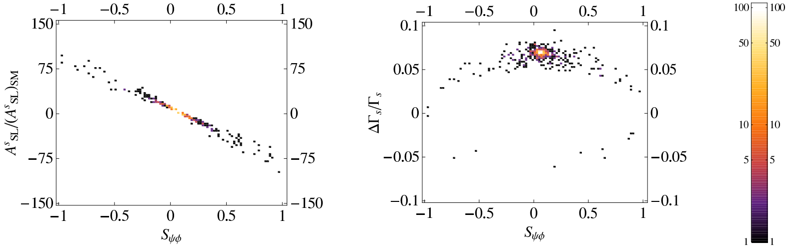


- generically $\mathbf{S_{\psi K_S} \sim (S_{\psi K_S})_{SM}}$ predicted
- **possible tension** between SM and data easily **resolved**

similar situation for other $\Delta F = 2$ observables

CP-Violation in $B_s - \bar{B}_s$ Mixing

after imposing existing $\Delta F = 2$ constraints: BBDGW



- full range $\mathbf{-1 < S_{\psi\phi} < 1}$ **possible**
  $\longrightarrow$ can explain recent CDF and DØ data
- strong **correlation with $\mathbf{A^s_{SL}}$** (see LIGETI ET AL., HEP-PH/0604112)
  $\longrightarrow A^s_{SL}/(A^s_{SL})_{SM} \sim 100$ possible
- $\Delta\Gamma_s/\Gamma_s$ can deviate significantly from SM prediction

Conclusions & Outlook

Our complete analysis of $\Delta F = 2$ processes in a custodially protected warped extra dimension showed:

- **$K - \bar{K}$** dominated by **$\mathcal{Q}_{LR}$, KK gluons**
- **$\mathcal{Q}_{LL}$ important for $B_{d,s} - \bar{B}_{d,s}$**, sizable **electroweak KK** contributions
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- ε_K constraint can be **fulfilled without significant tuning**
- simultaneous **agreement with all $\Delta F = 2$ data** can be obtained
- **large new physics effects in $S_{\psi\phi}$, A^s_{SL} and $\Delta\Gamma_s$** are possible

Implications for rare K and $B_{d,s}$ decays:

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Implications for rare K and $B_{d,s}$ decays: **coming soon!**

Back-up slides

Sources of Flavour Violation & Parameter Counting

Agashe, Perez, Soni, hep-ph/0408134

Flavour is violated by:

- **bulk mass terms c_Q, c_u, c_d**: 3 × 3 hermitian matrices — 3 × 6 real parameters, 3 × 3 complex phases
- **Yukawa couplings λ_u, λ_d**: 3 × 3 complex matrices — 2 × 9 real parameters, 2 × 9 complex phases

36 real parameters
27 complex phases

$U(3)^3$ flavour symmetry can be used to remove — − 9 real parameters, − 17 complex phases

physical flavour parameters: **27 real parameters**, **10 complex phases**

RS versus Froggatt-Nielsen

bulk fermions in RS

$$(Y_{u,d}^{\rm WED})_{ij} \propto (\lambda_{u,d})_{ij}\, e^{-kL(c_Q^i - c_{u,d}^j)}$$

self-similarity along y
bulk mass parameters $c^i_{Q,u,d}$
IR brane at $y = L$
warp factor e^{-kL}

Froggatt-Nielsen symmetry

$$(Y_{u,d}^{\rm FN})_{ij} \propto (\lambda_{u,d})_{ij}\, \epsilon^{a_i - b_j^{u,d}}$$

$U(1)_F$ symmetry
$U(1)_F$ charges $Q_F = a_i, b_i^{u,d}$
VEV of scalar Φ ($Q_F = 1$)
$\epsilon = \langle H\rangle / \langle \Phi \rangle \ll 1$

- **geometric interpretation of flavour symmetry**
- FN formulae for masses and flavour mixings can be applied
  $\rightarrow$ dependence on $\lambda_{u,d}$ and CP phases made explicit

BBDGW; Casagrande et al., 0807.4937

Explicit Expressions for Masses and Mixings

quark masses:

$$m_b = \frac{v}{\sqrt{2}} \lambda^d_{33}\, \mathbf{f^Q_3}\, \mathbf{f^d_3}$$

$$m_s = \frac{v}{\sqrt{2}} \frac{\lambda^d_{33}\lambda^d_{22} - \lambda^d_{23}\lambda^d_{32}}{\lambda^d_{33}}\, \mathbf{f^Q_2}\, \mathbf{f^d_2}$$

$$m_d = \frac{v}{\sqrt{2}} \frac{\det(\lambda^d)}{\lambda^d_{33}\lambda^d_{22} - \lambda^d_{23}\lambda^d_{32}}\, \mathbf{f^Q_1}\, \mathbf{f^d_1}$$

flavour mixing matrices (responsible for FCNCs):

$$(\mathcal{D}_L)_{ij} = \omega^d_{ij} \frac{\mathbf{f^Q_i}}{\mathbf{f^Q_j}} \qquad (\mathcal{D}_R)_{ij} = \rho^d_{ij} \frac{\mathbf{f^d_i}}{\mathbf{f^d_j}} \qquad (i < j)$$

($\omega^d_{ij}, \rho^d_{ij}$: functions of λ_d)

analogous formulae for the up-type quarks

New Flavour and CP Violating Effects

- $Z^{(0)}$ coupling becomes non-universal
  $\Rightarrow$ **tree level FCNC mediated by $\mathbf{Z^{(0)}}$ boson**

$$Z^{(0)}\bar{q}_i q_j \propto g F_i F_j \frac{v^2}{M_{KK}^2}$$

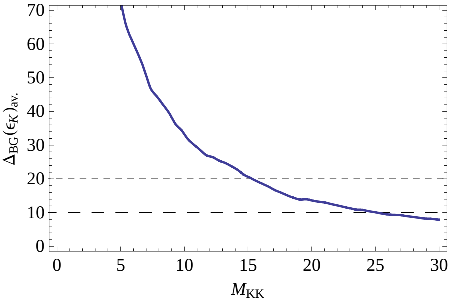
- **gauge KK modes** are localised at IR brane
  $\Rightarrow$ flavour universality is broken, FCNCs arise

$$Z^{(1)}\bar{q}_i q_j \propto g F_i F_j \qquad G^{(1)}\bar{q}_i q_j \propto g_s F_i F_j$$

- **loop contributions of new heavy particles**
- **9 new CP phases** in the mixing matrices $\mathcal{U}_{L,R}, \mathcal{D}_{L,R}$

Generic Bound on KK Scale

BBDGW



average required tuning in ε_K, depending on M_{KK}

$\rightarrow$ generic naturalness bound: $M_{KK} \simeq 20\,\text{TeV}$