K and B Physics in the Custodially Protected Randall-Sundrum Model

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Outline

based on: Albrecht, MB, Buras, Duling, Gemmler, 0903.2415
MB, Buras, Duling, Gori, Weiler, JHEP 03 (2009) 001 [0809.1073]
MB, Buras, Duling, Gemmler, Gori, JHEP 03 (2009) 108 [0812.3803]

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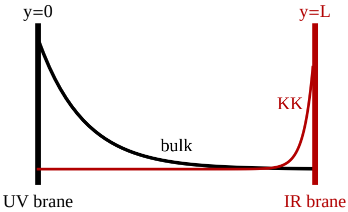
other related studies, see e. g.: Gedalia, Isidori, Perez
Casagrande, Goertz, Haisch, Neubert, Pfoh
Bauer, Casagrande, Grunder, Haisch, Neubert
Agashe, Perez, Soni
Csaki, Falkowski, Weiler
Huber; Huber, Shafi

The Randall-Sundrum Framework

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

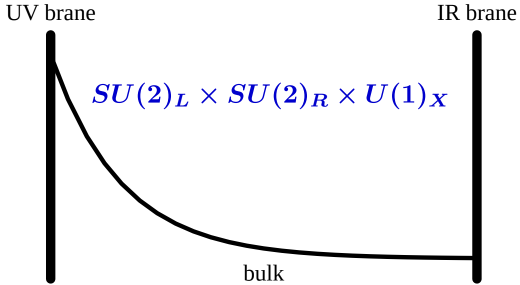
➢ energy scales suppressed by **warp factor** e^{-ky}
$\rightarrow$ **natural** explanation of **gauge hierarchy** problem

➢ **Kaluza-Klein (KK) excitations** live close to the IR brane

Protection of T parameter and $Zb_L\bar{b}_L$ coupling

AGASHE ET AL., HEP-PH/0308036; CSAKI ET AL., HEP-PH/0308038
AGASHE ET AL., HEP-PH/0605341

Extended electroweak symmetry structure:



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

$SU(2)_L \times SU(2)_R \to SU(2)_V$
by Higgs VEV

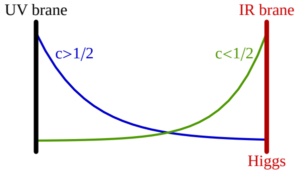
$+$ $(L \leftrightarrow R)$-symmetric fermion representations

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

Fermion Localisation and Yukawa Couplings

zero mode profile depends strongly on bulk mass parameter $\boldsymbol{c}$:

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



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

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

- **hierarchical structure** can be naturally generated by exponential suppression of $f^{Q,u,d}$ (fermion profile on IR brane)
- **light fermions** live close to the UV brane
  third generation localised closest to the IR brane

Grossman, Neubert, hep-ph/9912408
Arkani-Hamed, Grossman, hep-ph/9909411

Tree Level FCNCs & RS-GIM Mechanism

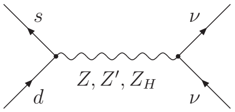
- different fermion localisation leads to **flavour non-universal couplings of KK gauge bosons**
- transmitted to Z **couplings** via EWSB
- **tree level FCNCs** arise through rotation to mass eigenbasis

$$\bar{d}^i_L G_\mu d^j_L \sim i g^{4\mathrm{D}} \gamma_\mu \sqrt{kL}\, f^Q_i\, f^Q_j$$
$$\bar{d}^i_R G_\mu d^j_R \sim i g^{4\mathrm{D}} \gamma_\mu \sqrt{kL}\, f^d_i\, f^d_j$$

- **RS-GIM mechanism**: suppression by flavour hierarchies

Agashe, Perez, Soni, hep-ph/0408134

- new contributions to **meson-antimeson mixing** and **rare K and B decays**



Detailed Study of K and B Physics Observables

Albrecht, MB, Buras, Duling, Gemmler, 0903.2415

theoretical framework & Feynman rules

MB, Buras, Duling, Gori, Weiler, JHEP 03 (2009) 001 [0809.1073]

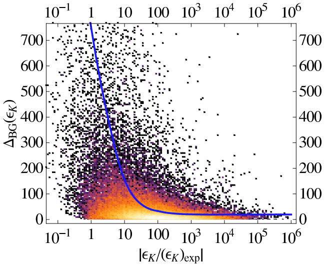
- calculation of new **strong** *and* **EW contributions to $\boldsymbol{\Delta F = 2}$**
- **simultaneous analysis** of all interesting $\Delta F = 2$ observables
- study of required **fine-tuning**

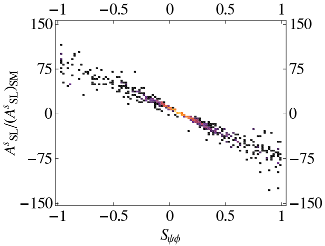
MB, Buras, Duling, Gemmler, Gori, JHEP 03 (2009) 108 [0812.3803]

- extension to include the **most prominent rare $\boldsymbol{K}$ and $\boldsymbol{B}$ decays** ($K \to \pi\nu\bar{\nu}$, $K_L \to \pi^0\ell^+\ell^-$, $K_L \to \mu^+\mu^-$, $B \to K^{(*)}\nu\bar{\nu}$, $B \to X_s\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$)
- quantification of **possible new physics effects**
- study of **correlations** among various observables
- comparison to LHT predictions (C. Tarantino's talk – TUM team, 06-09)

Messages from the $\Delta F = 2$ Sector

- large **contributions to left-right operators** by KK gluons
- **stringent constraint from ε_K**
  Csaki, Falkowski, Weiler, 0804.1954
- even for $M_{\text{KK}} \simeq \mathbf{2.5}$ **TeV**:
  all $\Delta F = 2$ data can be **fulfilled without significant fine-tuning**





★ distinction from LHT!

- **large CP-violating effects in $B_s - \bar{B}_s$** mixing are possible
- $-1 < S_{\psi\phi} < 1$ allowed
- sizable NP effects also in $A^s_{\rm SL}, \Delta\Gamma_s$

Pattern of New Physics Effects in Rare Decays

- $Zd_L^i\bar{d}_L^j$ **protected** by enlarged custodial symmetry

see also Buras, Duling, Gori, 0905.2318

- Z_H, Z' **contributions geometrically suppressed** $(\propto 1/(kL))$

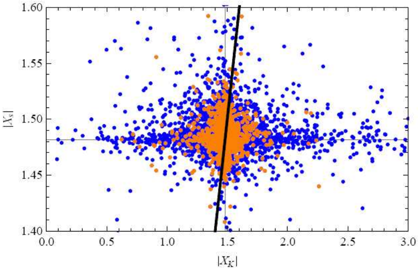
➢ rare decays dominated by Z **coupling to right-handed quarks**

flavour hierarchy weaker in right-handed down sector

➢ CKM hierarchy $1/\lambda_t^{(K)} \gg 1/\lambda_t^{(d)} \gg 1/\lambda_t^{(s)}$ only partly compensated

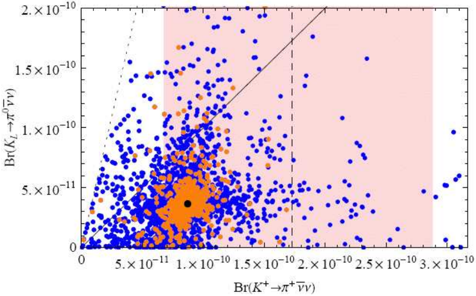
➢ **breakdown of universality:**

- large effects in K decays
- small effects in B decays



The $K \to \pi\nu\bar{\nu}$ System

★ distinction from LHT!



- **factor $2-3$ enhancements** possible
- **no visible correlation**
  - ➢ **test of operator structure in ε_K** MB, 0904.2528

The $K \to \pi\nu\bar{\nu}$ System

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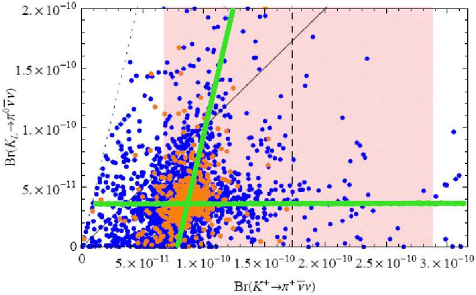

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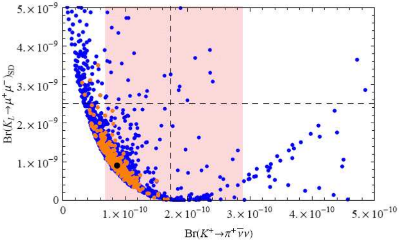
Other Useful Correlations in the K System

$K_L \to \mu^+\mu^-$ vs. $K^+ \to \pi^+\nu\bar\nu$

(CP-conserving)



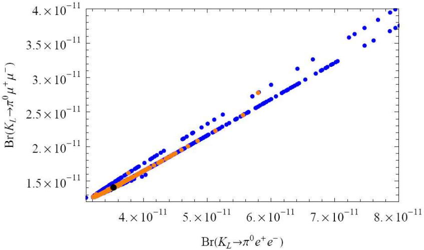
inverse correlation

➢ V+A structure of flavour violating coupling

★ distinction from LHT!

$K_L \to \pi^0\mu^+\mu^-$ vs. $K_L \to \pi^0 e^+e^-$

(CP-violating)



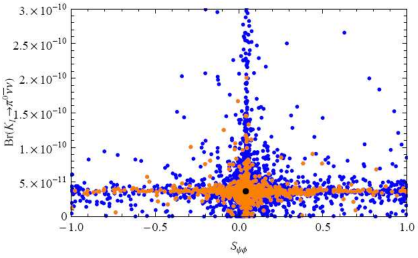
linear correlation

➢ no scalar operators

➢ universality of CP-phases

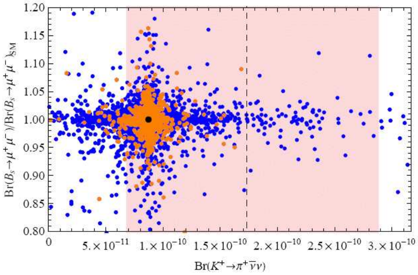
Isidori et al., hep-ph/0404127
Friot et al., hep-ph/0404136
Mescia et al., hep-ph/0606081

K vs. B Physics



large effects possible
in $S_{\psi\phi}$ and **rare K decays**,
but *not* **simultaneously**

- much **smaller effects** ($\sim 10\%$) in rare B **decays**
- difficult to measure
- **MFV relations strongly violated**



Main Messages from Flavour Phenomenology

Confronting $\Delta F = 2$ observables:

1. **generic strong constraint from ε_K** due to enhanced $\mathcal{Q}_{LR}$ contribution
2. but also for $M_{\text{KK}} \gtrsim (2-3)$ TeV **agreement with ε_K** possible **without relevant fine-tuning**
3. possible **tensions in the SM** $(\varepsilon_K, S_{\psi K_S}, \dots)$ can be **solved**
4. **$B_s - \bar{B}_s$ CP-violation can be large**

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

1. **dominant** contribution from **right-handed Z couplings**
2. **large effects in K decays**, smaller effects in $B_{s,d}$ decays
3. **correlations** allow for distinction from other NP models
4. sizable **violations of MFV** relations possible

Back-up slides

Main Virtues of Warped Extra Dimensions

1. warped extra dimensions with bulk fields provide a **simultaneous explanation** of gauge and flavour **hierarchies**
2. **custodially extended model** is consistent with EW precision data for $M_{\mathsf{KK}} \simeq \mathbf{(2-3)}$**TeV**
3. flavour exhibits a **Froggatt-Nielsen-like structure**:

- **effective 4D Yukawa couplings** obtained from **hierarchical bulk profiles** and $\mathcal{O}(1)$ **5D couplings**
- natural **explanation of mass and CKM hierarchy**
- new tree level FCNC effects strongly suppressed by **RS-GIM mechanism**

RS versus Froggatt-Nielsen

bulk fermions in RS

$$(Y^{\mathrm{RS}}_{u,d})_{ij} \propto (\lambda_{u,d})_{ij}\, e^{-kL(c^i_Q - c^j_{u,d})}$$

self-similarity along y

bulk mass parameters $c^i_{Q,u,d}$

IR brane at $y = L$

warp factor e^{-kL}

Froggatt-Nielsen symmetry

$$(Y^{\mathrm{FN}}_{u,d})_{ij} \propto (\lambda_{u,d})_{ij}\, \epsilon^{a_i - b^{u,d}_j}$$

$U(1)_F$ symmetry

$U(1)_F$ charges $Q_F = a_i, b^{u,d}_i$

VEV of scalar Φ $(Q_F = 1)$

$\epsilon = \langle\Phi\rangle/\Lambda \ll 1$

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

BBDGW; Casagrande et al., 0807.4937

Explicit Expressions for Masses and Mixings

quark masses:

$$\begin{aligned} m_b &= \frac{v}{\sqrt{2}} \lambda^d_{33}\, \boldsymbol{f_3^Q}\, \boldsymbol{f_3^d} \\ m_s &= \frac{v}{\sqrt{2}} \frac{\lambda^d_{33}\lambda^d_{22} - \lambda^d_{23}\lambda^d_{32}}{\lambda^d_{33}}\, \boldsymbol{f_2^Q}\, \boldsymbol{f_2^d} \\ m_d &= \frac{v}{\sqrt{2}} \frac{\det(\lambda^d)}{\lambda^d_{33}\lambda^d_{22} - \lambda^d_{23}\lambda^d_{32}}\, \boldsymbol{f_1^Q}\, \boldsymbol{f_1^d} \end{aligned}$$

flavour mixing matrices (responsible for FCNCs):

$$(\mathcal{D}_L)_{ij} = \omega^d_{ij} \frac{\boldsymbol{f_i^Q}}{\boldsymbol{f_j^Q}} \qquad (\mathcal{D}_R)_{ij} = \rho^d_{ij} \frac{\boldsymbol{f_i^d}}{\boldsymbol{f_j^d}} \qquad (i < j)$$

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

analogous formulae for the up-type quarks

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**

containing the SM 9+1 ones

Required Fermion Content (Quark Sector)

- Higgs transforms as $(\mathbf{2}, \mathbf{2})$
- due to P_{LR}.: $q_L \in (\mathbf{2}, \mathbf{2})$ with $T^3_L(b_L) = T^3_R(b_L) = -1/2$
- right-handed SM fields t_R, b_R are $SU(2)_L$ singlets
  ➢ possible gauge invariant Yukawa structures:

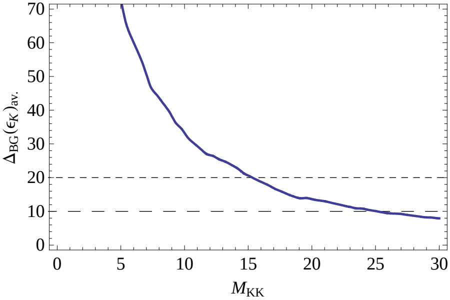
$$\overline{(\mathbf{2}, \mathbf{2})} \otimes (\mathbf{2}, \mathbf{2}) \otimes (\mathbf{1}, \mathbf{1}) \qquad \overline{(\mathbf{2}, \mathbf{2})} \otimes (\mathbf{1}, \mathbf{3}) \otimes (\mathbf{2}, \mathbf{2})$$

Contino et al., hep-ph/0612048, Carena et al., hep-ph/0607106

smoking gun signature:
$SU(2)_R$ partner of t_L: $\boldsymbol{Q = 5/3}$ **quarks with mass** $\lesssim 1$ **TeV**

Generic Bound on KK Scale

BBDGW



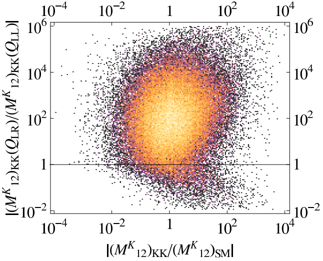
average required tuning in ε_K, depending on M_{KK}

➢ generic naturalness bound: $M_{\mathsf{KK}} \gtrsim 20\,\text{TeV}$

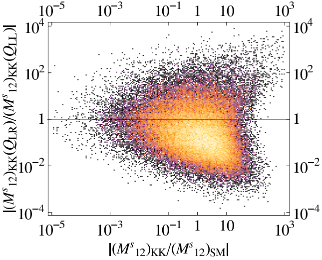
confirms Csaki, Falkowski, Weiler, 0804.1954

Operator Competition in $\Delta F = 2$

$K - \bar{K}$ mixing:



$B_s - \bar{B}_s$ 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

Anatomy of Z, Z_H, Z' Contributions

- **FCNC couplings to left-handed quarks:** BBDGG

$$\Delta_L(Z_H) : \Delta_L(Z') : \Delta_L(Z) \sim \mathcal{O}(1) : \mathcal{O}(10^{-1}) : \mathcal{O}(10^{-4})$$

Z and Z' coupling suppressed by custodial protection

- **FCNC couplings to right-handed quarks:**

$$\Delta_R(Z_H) : \Delta_R(Z') : \Delta_R(Z) \sim \mathcal{O}(1) : \mathcal{O}(1) : \mathcal{O}(10^{-2})$$

custodial protection not effective

- **propagators** $M_Z^2/M_{\text{KK}}^2 \sim \mathcal{O}(10^{-3})$ and **leptonic couplings** $\Delta^\ell_{L,R}(Z_H) : \Delta^\ell_{L,R}(Z') : \Delta^\ell_{L,R}(Z) \sim \mathcal{O}(10^{-1}) : \mathcal{O}(10^{-1}) : 1$

➢ **$\Delta F = 1$ rare decays dominated by $\Delta_R(Z)$**

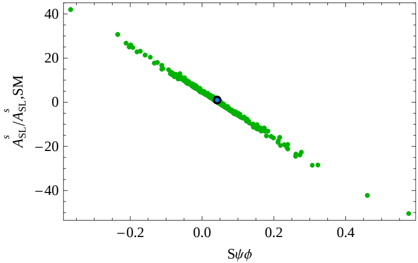
LHT: CP-Violation in $B_s - \bar{B}_s$ Mixing

BBPTUW, HEP-PH/0605214; BBRT, 0805.4393; BBDRT, 0906.5454

generally: LHT effects in B physics expected to be small

but: CP-violation in B_s extremely suppressed in the SM due to $\beta_s \simeq -1^\circ$

➢ **large LHT effects** possible

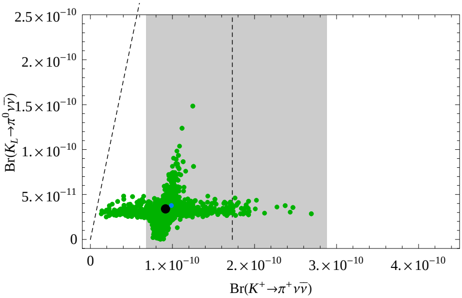


- $S_{\psi\phi} \sim 0.5$ possible
- naturally $S_{\psi\phi} \lesssim 0.2$
- strong correlation with A^s_{SL}

LIGETI ET AL., HEP-PH/0604112
MB ET AL., HEP-PH/0604057
GROSSMAN ET AL., 0904.0305
BIGI ET AL., 0904.1545

LHT: The $K \to \pi\nu\bar{\nu}$ System

BBDRT, 0906.5454



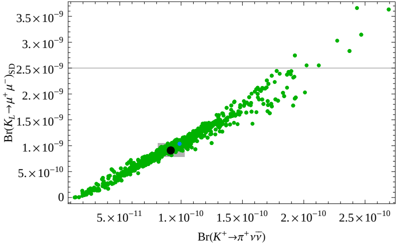
- **factor 2–3 enhancements** of $K \to \pi\nu\bar{\nu}$ possible
- **strict correlation** (two branches of possible points)
  - ➢ **equal CP-phases** in $K^0 - \bar{K}^0$ and $K \to \pi\nu\bar{\nu}$
  - ➢ **no new operators** in $K^0 - \bar{K}^0$ mixing

MB, 0904.2528

LHT: Correlations between Various Rare K Decays

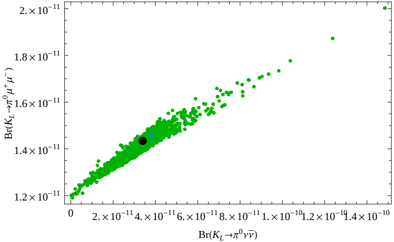
$K_L \to \mu^+\mu^-$ vs. $K^+ \to \pi^+\nu\bar{\nu}$

(CP-conserving)



$K_L \to \pi^0\mu^+\mu^-$ vs. $K_L \to \pi^0\nu\bar{\nu}$

(CP-violating)

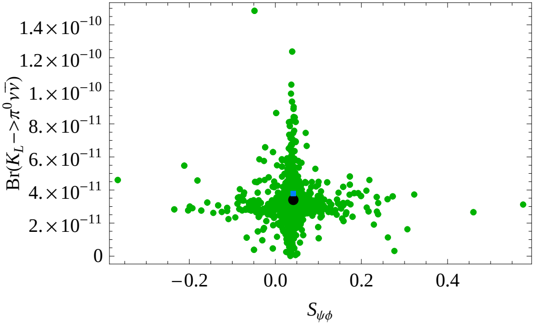


strong linear correlation in both cases — BBDRT, 0906.5454

- ➢ **V-A structure** of flavour violating coupling ($K_L \to \mu^+\mu^-$ vs. $K^+ \to \pi^+\nu\bar{\nu}$)
- ➢ **universality of CP-phases** ($K_L \to \pi^0\mu^+\mu^-$ vs. $K_L \to \pi^0\nu\bar{\nu}$)

LHT: K versus B Physics

BBDRT, 0906.5454



simultaneous large effects in $S_{\psi\phi}$ and rare K decays **unlikely**, but **not impossible**