New Physics Models

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“Particle Physics at the Energy Frontier of New Phenomena”

Weak Interactions and Neutrinos
Perugia, September 14-19 2009

Reasons for Going beyond the Standard Model

The SM describes present energy particle physics to **depressingly high precision**. However, it is assumed to be an **effective theory with a TeV scale cut-off** since it fails to address certain issues.

These include:

Gauge Coupling Unification

Flavour

Little Hierarchy

Baryon Asymmetry

Gauge Hierarchy

Dark Matter

...

Outline

The Littlest Higgs Model with T-Parity

LHT Literature

Flavor violation in the quark sector

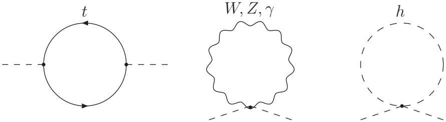
- Hubisz, Lee, Paz, hep-ph/0512169
- Blanke, Buras, Poschenrieder, Tarantino, Uhlig, Weiler, hep-ph/0605214
- Blanke, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig, Weiler, hep-ph/0609284, hep-ph/0610298
- Blanke, Buras, Recksiegel, Tarantino, Uhlig, hep-ph/0703254, 0704.3329
- Blanke, Buras, Recksiegel, Tarantino, 0805.4393
- Goto, Okada, Yamamoto, 0809.4753
- Blanke, Buras, BD, Recksiegel, Tarantino, 0906.5454

Lepton flavor violation

- Choudhury, Cornell, Deandrea, Gaur, Goyal, hep-ph/0612327
- Blanke, Buras, BD, Poschenrieder, Tarantino,hep-ph/0702136
- del Aguila, Illana, Jenkins, 0811.2891
- Blanke, Buras, BD, Recksiegel, Tarantino, 0906.5454

The Little Hierarchy Problem

- The Higgs mass is affected by **quadratically divergent** corrections



$\Rightarrow$ Needs to be stabilized not far beyond the TeV scale

- EWPT set very **stringent bounds** on the suppression scale of new effective operators

$$\Lambda \gtrsim (5 - 10)\ \mathrm{TeV}$$

$\Rightarrow$ Tension between predictions for the NP scale

...unless NP enters in a very delicate way

The Little Higgs Idea

Georgi, Pais '74; Georgi, Dimopoulos, Kaplan '84

Arkani-Hamed, Cohen, Georgi, hep-th/0104005, hep-ph/0105239

If

1. The Higgs arises as a pseudo-Goldstone (pNGB) boson of a spontaneously broken global symmetry $G \to H$
2. G is explicitly broken by weakly gauging of a subgroup $G' \subset G$ and by Yukawa couplings
3. The explicit breaking is arranged in a way that each coupling taken for itself does not break the full symmetry G (**collective symmetry breaking**)

Then

> The Higgs has a **small tree-level mass** and there are **no quadratically divergent mass corrections** at 1-loop level

The Littlest Higgs Model

Arkani-Hamed, Cohen, Katz, Nelson, (Gregoire, Wacker) hep-ph/0206021 (0206020)

Most **economic** implementation:

Littlest Higgs Model

2-stage SSB: $\Rightarrow$ **Particle content**:

$SU(5) \to SO(5)\,,$

$G' = [SU(2) \times U(1)]^2 \to [SU(2) \times U(1)]_V$

at scale $f \approx \mathcal{O}(1\mathrm{TeV})$

$[SU(2) \times U(1)]_V \to U(1)_{\text{em}}$

at scale v

SM

Heavy gauge bosons, $M \sim \mathcal{O}(f)$

$\boldsymbol{A_H,\, Z_H,\, W_H^\pm}$

Top partner **T**, $m_T \sim \mathcal{O}(f)$

Scalar triplet $\boldsymbol{\Phi}$, $M_\Phi \sim m_H \frac{f}{v}$

NLSM with eff. theory **cut-off** $\Lambda \sim 4\pi f \approx \mathcal{O}(10\mathrm{TeV})$

T-Parity

Csaki, Hubisz, Meade, Terning, hep-ph/0211124

Tree level exchange

- A_H, Z_H, $W_H^\pm$
- scalar triplet Φ

$\Rightarrow$ **Severe constraints** from EWPT

$\Downarrow$

$f \gtrsim 2 - 3\text{TeV}$

Introduce T-Parity

Cheng, Low, hep-ph/0308199, 0405243

- SM particles and T^+ are T-even
- heavy gauge bosons A_H, Z_H, $W_H^\pm$ as well as Φ are T-odd
- need to introduce **additional (vector-like) T-odd fermions** q_H, ℓ_H, ν_H, T^-

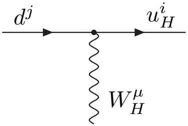
$\Rightarrow$ f can be as low as 500 GeV Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

$\Rightarrow$ A_H is a potential dark matter candidate Hill, Hill, arXiv:0705.0697

Krohn, Yavin, arXiv:0803.4202; Csaki, Heinonen, Perelstein, Spethmann, arXiv:0804.0622

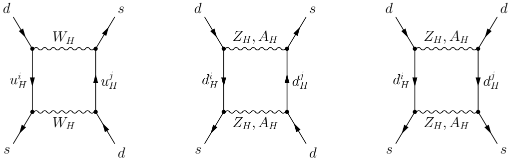
FCNCs

- **Mirror Fermions** interact with SM fermions and heavy gauge bosons
- Parameterization by mixing matrices V_{Hd}, V_{Hu}, $V_{H\ell}$, $V_{H\nu}$



$$\rightarrow \quad \frac{ig}{\sqrt{2}} (V_{Hd})_{ij} \gamma^\mu P_L$$

- Mixing matrices each have **3 angles** and **3 phases** (a priori arbitrary)
- New vertices enter in flavor processes such as $K^0 - \bar{K}^0$ mixing



- No tree level contributions
- No new operators
- **Large effects** possible

- Contributions from the T-even sector are small

Intermission: The Issue of Divergences

LH without T-parity

Buras, Poschenrieder, Uhlig, Bardeen, hep-ph/0607189

Z penguin contains left-over singularity

$\Rightarrow$ reflects **sensitivity to the UV completion**

Similar effect also encountered in LHT BBPRTUW, hep-ph/0610298

However:

Goto, Okada, Yamamoto, 0809.4753
del Aguila, Illana, Jenkins, 0811.2891

- additional contribution to Z penguin
- singularity exactly cancelled
- **FCNC amplitudes in LHT fully calculable!**

modified predictions for decays mediated by Z penguins
(e. g. $K \to \pi\nu\bar{\nu}$, $\mu \to eee$) ($\to$ **numerical update**) BBDRT, 0906.5454
but **no impact** on $P - \bar{P}$ mixing, $\mu \to e\gamma, \ldots$!

Naive Expectations for K and B Physics

BBPRTUW, hep-ph/0610298

relative size of LHT effects: $\propto \frac{1}{\lambda^i_{\text{CKM}}} \xi^i_{V_{Hd}}$

$$\frac{1}{\lambda_t^{(K)}} \simeq 2500 \quad \gg \quad \frac{1}{\lambda_t^{(d)}} \simeq 100 \quad > \quad \frac{1}{\lambda_t^{(s)}} \simeq 25$$

- **largest effects in K** physics observables
- **moderate effects in $B_{d,s}$** physics observables
- but pattern may be reversed by specific hierarchies in $\xi^i_{V_{Hd}}$

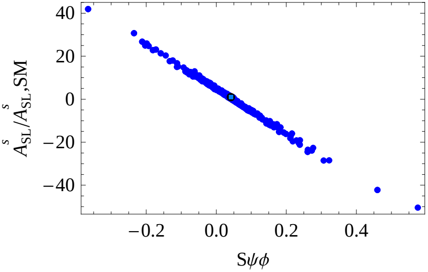
CP-Violation in B_s-$\bar{B}_s$ Mixing

BBPTUW, hep-ph/0605214; BBRT, 0805.4393; BBDRT, 0906.5454

ϵ_K **imposes a strong constraint** on the LHT parameter space, while generally LHT **effects in *B* physics expected to be small**

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

$\Rightarrow$ **large LHT effects** in B_s still possible!

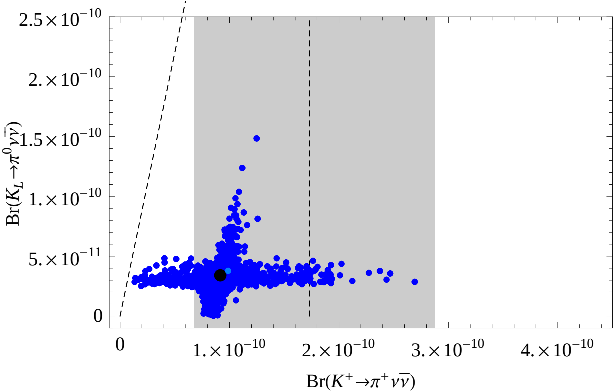


- $S_{\psi\phi} \sim 0.5$ possible
- naturally, $S_{\psi\phi} \lesssim 0.2$
- strong correlation with A^s_{SL}

Ligeti, Papucci, Perez, hep-ph/0604112

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

BBDRT, 0906.5454



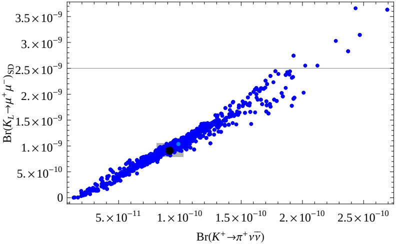
- **factor 2–3 enhancements** of $K \to \pi\nu\bar{\nu}$ possible
- **strict correlation** (two branches of possible points)

Blanke, 0904.2528

Correlations between Rare K Decays

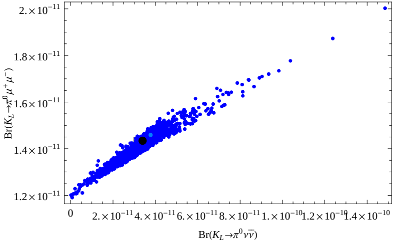
$K_L \to \mu^+\mu^-$ vs $K^+ \to \pi^+\nu\bar{\nu}$

(CP conserving)



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

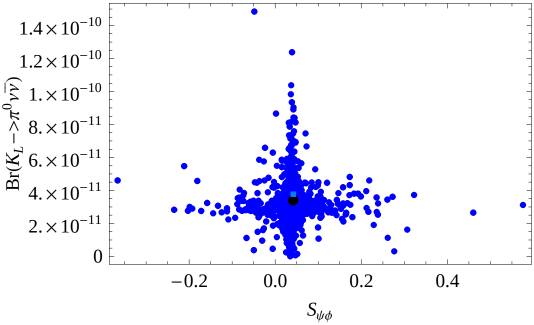
(CP violating)



Strong linear correlation in both cases

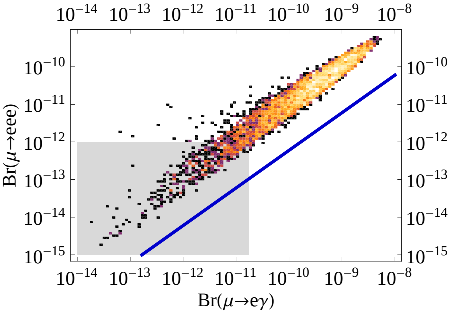
- **V-A structure** of flavor violating coupling ($K_L \to \mu^+\mu^-$ vs. $K^+ \to \pi^+\nu\bar{\nu}$)
- **universality of CP-phases** ($K_L \to \pi^0\mu^+\mu^-$ vs $K^+ \to \pi^+\nu\bar{\nu}$)

K Physics vs B Physics



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

Lepton Flavor Violation



Red/yellow points: **LHT**

Blue line: **MSSM**

- most points exceed experimental bounds

  del Aguila, Illana, Jenkins, 0811.2891

  $\Rightarrow \sim$ **10% fine-tuning** in mirror lepton parameters required
- **strong correlation** between $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$
- **dipole contribution** fully negligible unlike in the **MSSM**

Negligible dipole allows for a distinction from the **MSSM** through e.g.

$$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)} \approx \begin{cases} 0.02...1 & \textbf{(LHT)} \\ 6 \cdot 10^{-3} & \textbf{(MSSM)} \end{cases}$$

LHT Summary

The LHT...

- addresses the **little hierarchy problem**
- is an **effective theory** with an $\mathcal{O}(10\mathrm{TeV})$ cut-off
- offers a potential **dark matter candidate**

K and B physics

- **large effects** possible in $\boldsymbol{B_s}$ **CP-violation** and **rare K decays**
- **moderate effects** in most **B physics** observables
- specific **correlations** allow for **distinction from other NP frameworks** (CMFV, RS-Custodial, . . .)

Lepton flavor violation

- **large effects** expected in **LFV** μ **and** τ **decays**
- **ratios** of branching ratios very **different from SUSY**

The Custodially Protected Randall-Sundrum Model

RS Literature

Flavor violation in the quark sector

- Huber, hep-ph/0303183
- Agashe, Perez, Soni, hep-ph/0408134, 0406101
- Burdman, hep-ph/0205329, 0310144
- Csaki, Falkowski, Weiler, 0804.1954
- Agashe, Azatov, Zhu, 0810.1016
- Gedalia, Isidori, Perez, 0905.3264
- Moreau, Silva-Marcos, hep-ph/0602155
- Chang, Kim, Song, hep-ph/0607313
- Azatov, Toharia, Zhu, 0906.1990
- del Aguila, Santiago, hep-ph/0008143
- Djouadi, Moreau, Richard, hep-ph/0610173
- Albrecht, Blanke, Buras, BD, Gemmler, 0903.2415
- Blanke, Buras, BD, Gori, Weiler, 0809.1073
- Blanke, Buras, BD, Gemmler, Gori, 0812.3803
- Buras, BD, Gori, 0905.2318

RS Literature Cont'd

Lepton flavor violation

- Agashe, Blechman, Petriello, hep-ph/0606021
- Agashe, 0902.2400
- Iltan, 0708.3765

EWPT

- Csaki, Erlich, Terning, hep-ph/0203034
- Agashe, Delgado, May, Sundrum, hep-ph/0308036
- Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341
- Carena, Ponton, Santiago, Wagner, hep-ph/0701055
- Casagrande, Goertz, Haisch, Neubert, Pfoh, 0807.4937

Gauge Hierarchy and Flavor Problems

Gauge Hierarchy Problem

- Large Hierarchy between the electroweak and the Planck scale,

$$v/M_{Pl} \approx 10^{-16}$$

- Naturally, radiative corrections drag lower scales towards higher scales

The Flavor Problem

- Quark masses range over five orders of magnitude,

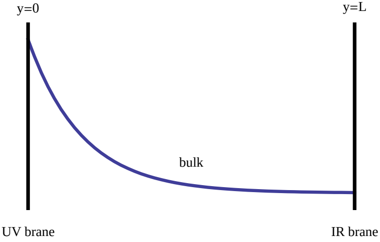
$$m_u \approx 5\mathrm{MeV} \text{ while } m_t \approx 172.5\mathrm{GeV}$$

- CKM matrix elements are vastly different,

$$|V_{ud}| \approx 1 \text{ while } |V_{us}| \simeq 0.226,\ |V_{cb}| \simeq 0.041,\ |V_{ub}| \simeq 0.0038$$

The Randall-Sundrum Setup

Randall, Sundrum, hep-ph/9905221



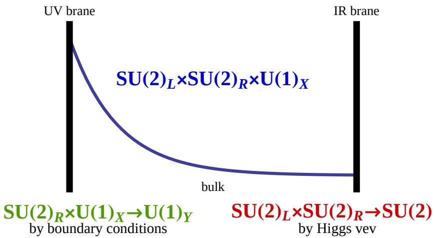
$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- RS Metric is a solution of the 5D Einstein equations
- Energy scales are “warped down” as one approaches the IR brane
- Localizing the Higgs at the IR brane and setting $kL \approx 36$ **naturally** explains the smallness of the EW scale!

Protection of $Zb_L\bar{b}_L$ and the T Parameter

Flavor constraints require force and matter fields to propagate into the bulk
$\Rightarrow$ **Severe constraints** from T and $Zb_L\bar{b}_L$

Csaki, Erlich, Terning, hep-ph/0203034



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

Agashe, Delgado, May, Sundrum, hep-ph/0308036

Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

T parameter and $Zb_L\bar{b}_L$ coupling are protected for $M_{KK} \gtrsim (2-3)\,\text{TeV}$

and

Low energy theory is $\boldsymbol{SU(2)_L \times U(1)_Y \to U(1)_{em}}$

Bulk Field Localization

Chang, Hisano, Nakano, Okada, Yamaguchi, hep-ph/9912498
Gherghetta, Pomarol, hep-ph/0003129; Grossman, Neubert, hep-ph/9912408

Force and matter fields can propagate into the 5th dimension

$\Longrightarrow$ Kaluza-Klein-tower of particles (n=0,1,2,...)

Gauge Bosons (before EWSB)

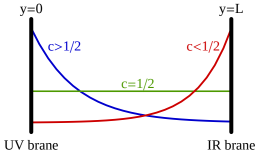
- n=0: flat
- n=1,2,...: peaked at the IR brane

$\Downarrow$

Address the **flavor problem** at the price of **tree-level FCNCs** $\Longleftarrow$

Fermions (before EWSB)

- n=0: **exponential localization**



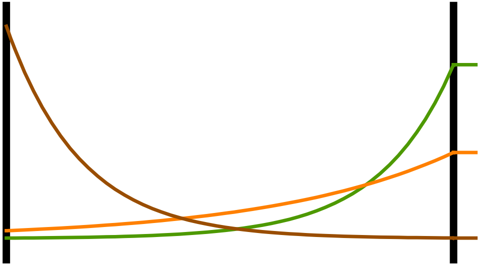
depends on $\mathcal{O}(1)$ parameters c_i (generation dependent)

- n=1,2,...: peaked at the IR brane

Origin of Mass Hierarchies

a.k.a. Geometrical Sequestering

Arkani-Hamed, Schmaltz, hep-ph/9903417



Effective Yukawa couplings: $(Y_{u,d})_{ij} = (\lambda_{u,d})_{ij} \, F_Q^i F_{u,d}^i$

Anarchic 5D Yukawas
+
Hierarchical brane values

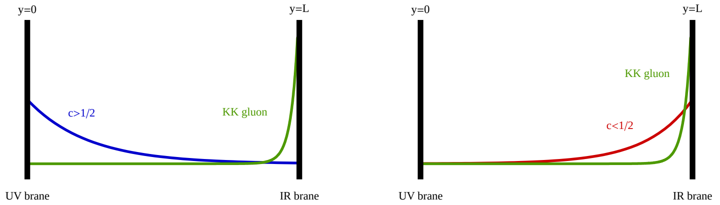
$\Rightarrow$ Hierarchical effective Yukawas

Impact on Flavor Physics

- 4D gauge couplings are determined by overlap integrals

$$\sim \frac{1}{L^{3/2}} \int_0^L dy\, f_{ferm}(y) f_{ferm}(y) f_{gauge}(y)$$

- Couplings of SM fermions to KK gauge bosons are **non-universal**

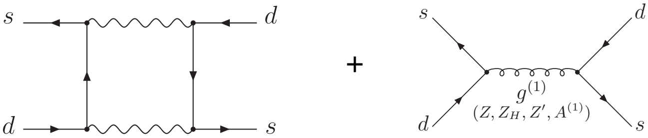


- When going to the quark mass eigenstate basis:

  Non-universalities $\Rightarrow$ **Flavor off-diagonal couplings**
- Analog of GIM mechanism is active: "**RS-GIM**"

Tree Level FCNCs Pt1

$\Delta F = 2$ processes



Main contribution from KK gluons, but for B observables also EW gauge bosons become relevant.

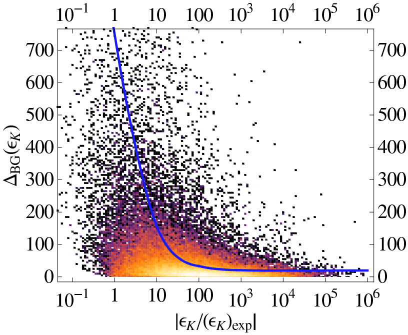
Induced operators:

- $Q_1^{VLL,VRR} = (\bar{s}\gamma_\mu P_{L,R} d)(\bar{s}\gamma^\mu P_{L,R} d)$
- $Q_1^{LR} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_R d)$
- $\boldsymbol{Q_2^{LR} = (\bar{s} P_L d)(\bar{s} P_R d)}$

K-$\bar{K}$ and B-$\bar{B}$ Mixing

Csaki, Falkowski, Weiler, 0804.1954

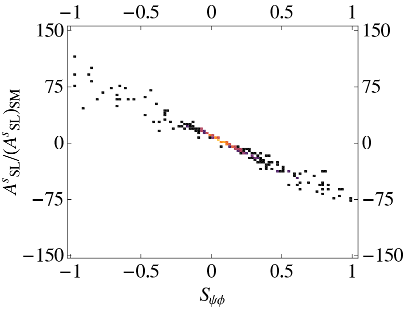
Blanke, Buras, BD, Gori, Weiler, 0809.1073



LR operators entering ϵ_K are chirally and QCD **enhanced**

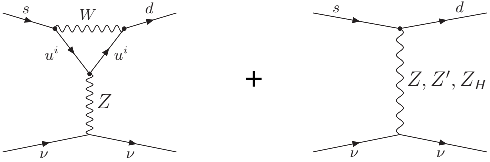
- Severe Bound on M_{KK}
  or
- Accidental cancellations necessary

Unaffected by the ϵ_K constraint, **large effects in the B system** are possible e.g. in $S_{\psi\phi}$, A^s_{SL} , $\Delta\Gamma_s/\Gamma_s$



Tree Level FCNCs Pt2

$\Delta F = 1$ processes



Due to the custodial symmetry it is not a priori clear which contribution (Z, Z_H or Z') is dominant (next slide)

Loop functions X, Y, Z become...

- complex
- flavor non-universal

Custodial Protection and EW Gauge Bosons

- Consider lightest EW gauge bosons

$Z^{(0)}, Z^{(1)}, Z_X^{(1)}$
gauge eigenstates

$\Rightarrow$

Z, Z_H, Z'
mass eigenstates

Csaki, Erlicher, Terning, hep-ph/0203034; Burdman, hep-ph/0205329

a priori, all three mass eigenstates have **flavor off-diagonal couplings**

- $Zb_L\bar{b}_L$ protected by custodial symmetry — Agashe, Contino, Pomarol

$\Rightarrow$ also $Zd_L^i\bar{d}_L^j$, $Zu_R^i\bar{u}_R^j$, $Z'd_L^i\bar{d}_L^j$, $Z'u_R^i\bar{u}_R^j$ couplings are protected!

Blanke, Buras, BD, Gori, Weiler; Buras, BD, Gori

- This protection is not spoilt by the impact of KK-fermions
- Eventually, this leads to the surprising fact that (in rare decays)

Couplings of Z to **right-handed** down-quarks dominate!

Estimate for NP effects in K and B Systems

With custodial protection: **Coupling of Z to RH quarks dominates**

- Hierarchy between meson systems in couplings is (roughly)
  $\Delta_R^{sd}(Z) : \Delta_R^{bd}(Z) : \Delta_R^{bs}(Z) \approx 1 : 5 : 10$
- Hierarchy between CKM factors:
  $\lambda_t^{(K)} : \lambda_t^{(d)} : \lambda_t^{(s)} \simeq 1 : 25 : 100$

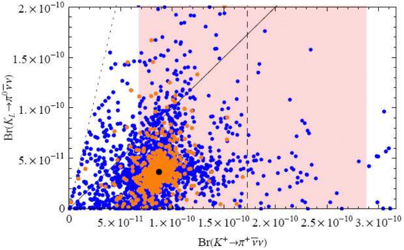
Size of NP effects expected to be **largest in the K system**, by factor 4 smaller in B_d system and by another factor of 2 smaller in the B_s system.

Without custodial protection: **Coupling of Z to LH quarks dominates**

- Hierarchy between meson systems in couplings is (roughly)
  $\Delta_L^{sd}(Z) : \Delta_L^{bd}(Z) : \Delta_L^{bs}(Z) \approx 1 : 15 : 100$

Size of NP effects expected to be **similar in the K and $B_{d,s}$ systems.**

Rare K Decays



Blanke, Buras, BD, Gemmler, Gori, 0812.3803

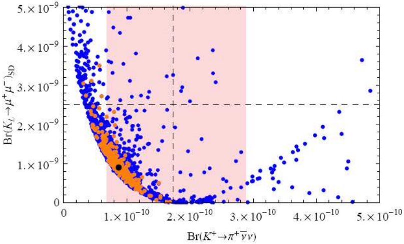
Enhancement by

- 100% for $Br(K^+ \to \pi^+\nu\bar{\nu})$
- 200% for $Br(K_L \to \pi^0\nu\bar{\nu})$

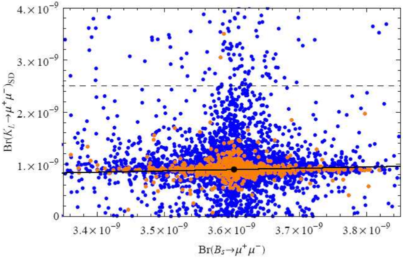
possible

RH Z couplings dominate

- NP enters $Br(K_L \to \mu^+\mu^-)_{\mathrm{SD}}$ and $Br(K_L \to \pi^0\nu\bar{\nu})$ with opposite sign
- **Inverse** correlation between Br's



K Physics vs B physics



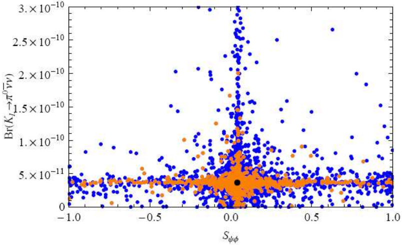
Smallness of $1/\lambda_{s,d}$ only partially compensated by $Zb_R\{\bar{d},\bar{s}\}_R$ couplings

Effects in rare B decays amount to at most 20%

Large effects in $\Delta S = 1$ and $\Delta B = 2$ processes are possible.

But:

Not simultaneously!



RS Summary

The custodially protected RS model...

- addresses the **gauge hierarchy problem**
- as well as the **flavor problem**

K and B mixing

- Constraints from $K^0 - \bar{K}^0$ mixing (ϵ_K, ΔM_K) can be satisfied
- **Large effects** in $B_s^0 - \bar{B}_s^0$ mixing ($S_{\psi\phi}$, A_{SL}^s, $\Delta\Gamma_s/\Gamma_s$) are possible

Rare K and B decays

- **Right-handed Z couplings** dominate $\Rightarrow$ **Specific correlations**
- For K branching ratios **enhancements by factors up to three**
- Small effects in B branching ratios

- Simultaneous large effects in rare K decays and $S_{\psi\phi}$ very unlikely

Problems (Un)Resolved

	LHT	RS-C	MSSM
Little Hierarchy Problem	🟢	🟢	🟢
Gauge Hierarchy Problem	🔴	🟢	🟢
Flavor Problem	🔴	🟢	🔴
Gauge Coupling Unification	🔴	🟢	🟢
Dark Matter Candidate	🟢	🔴	🟢

Anatomy of Flavor Effects

Altmannshofer, Buras, Gori, Paradisi, Straub, arXiv:0909.1333

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	●●●	●	●	●	●	●●●	?
ϵ_K	●	●●●	●●●	●	●	●●	●●●
$S_{\psi\phi}$	●●●	●●●	●●●	●	●	●●●	●●●
$S_{\phi K_S}$	●●●	●●	●	●●●	●●●	●	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	●	●	●	●●●	●●●	●	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	●	●	●	●●●	●●●	●●	?
$A_9(B \to K^*\mu^+\mu^-)$	●	●	●	●	●	●	?
$B \to K^{(*)}\nu\bar{\nu}$	●	●	●	●	●	●	●
$B_s \to \mu^+\mu^-$	●●●	●●●	●●●	●●●	●●●	●	●
$K^+ \to \pi^+\nu\bar{\nu}$	●	●	●	●	●	●●●	●●●
$K_L \to \pi^0\nu\bar{\nu}$	●	●	●	●	●	●●●	●●●
$\mu \to e\gamma$	●●●	●●●	●●●	●●●	●●●	●●●	●●●
d_n	●●●	●●●	●●●	●●	●●●	●	●●●
d_e	●●●	●●●	●●	●	●●●	●	●●●
$(g-2)_\mu$	●●●	●●●	●●	●●●	●●●	●	●●

Backup

Particle Content of the LHT Model

	T-even sector	T-odd sector
gauge bosons	$W_L^{\pm}$, Z_L, A_L gluons	$W_H^{\pm}$, Z_H, A_H
fermions	SM quarks top partner T_+ SM leptons	mirror quarks T_- mirror leptons
scalars	Higgs doublet H	scalar triplet Φ

LHT Maximal Values for LFV Branching Ratios

...after imposing all available constraints

BBDRT, 0906.5454

	$f = 1$ TeV	$f = 0.5$ TeV	SuperB
$\tau \to \ell\gamma$	$8 \cdot 10^{-10}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-9}$
$\tau \to \ell\ell\ell$	$1 \cdot 10^{-10}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-10}$
$\tau \to \ell\pi$	$4 \cdot 10^{-10}$	$2 \cdot 10^{-8}$	?
$\tau \to \ell\eta$	$2 \cdot 10^{-10}$	$1 \cdot 10^{-8}$	$5 \cdot 10^{-10}$
$\tau \to \ell\eta'$	$1 \cdot 10^{-10}$	$1 \cdot 10^{-8}$	?
...	...	...	...

For $f \lesssim 1$ TeV:

LHT effects may be observable at future facilities!

Correlations and Comparison with Supersymmetry

MSSM: dipole operator **dominates** in decays $\ell_i \to \ell_k \ell_k \ell_k$, $\ell_i \to \ell_j \ell_k \ell_k$

Ellis, Hisano, Raidal, Shimizu, hep-ph/0206110
Brignole, Rossi, hep-ph/0404211
Arganda, Herrero, hep-ph/0510405
Paradisi, hep-ph/0508054, hep-ph/0601100

$$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)} \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 2.7\right)$$

$$\frac{Br(\tau^- \to \ell^- e^+ e^-)}{Br(\tau \to \ell\gamma)} \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\tau^2}{m_e^2} - 2.7\right)$$

$$\frac{Br(\tau^- \to \ell^- \mu^+ \mu^-)}{Br(\tau \to \ell\gamma)} \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\tau^2}{m_\mu^2} - 2.7\right)$$

LHT: dipole operator **irrelevant**, decays dominated by Z^0-penguin and box diagrams

BBDPT, hep-ph/0702136

$\Rightarrow$ **Very different pattern!**

Ratios of LFV Branching Ratios

BBDRT, 0906.5454

	LHT	MSSM
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$ $\star$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$ $\star$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$

$\star$ can be significantly enhanced by Higgs contributions

Paradisi, hep-ph/0508054, hep-ph/0601100

Particle Content of the RS-C Model

Fermions

Charge +2/3					Charge -1/3			Charge +5/3		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$q_{L,R}^{u(2)}$	$u_{L,R}^{(2)}$	$U'^{(2)}$	$U''^{(2)}$	$\chi^{d(2)}$	$q_{L,R}^{d(2)}$	$D'^{(2)}$	$D_{L,R}^{(2)}$	$\chi^{u(2)}$	$\psi'^{(2)}$	$\psi''^{(2)}$
$q_{L,R}^{u(1)}$	$u_{L,R}^{(1)}$	$U'^{(1)}$	$U''^{(1)}$	$\chi^{d(1)}$	$q_{L,R}^{d(1)}$	$D'^{(1)}$	$D_{L,R}^{(1)}$	$\chi^{u(1)}$	$\psi'^{(1)}$	$\psi''^{(1)}$
$q_L^{u(0)}$	$u_R^{(0)}$	–	–	–	$q_L^{d(1)}$	–	$D_R^{(0)}$	–	–	–

Gauge bosons

$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$W_L^{\pm(2)}$	$Z^{(2)}$	$A^{(2)}$	$Z_X^{(2)}$	$W_R^{\pm(2)}$	$G^{(2)}$
$W_L^{\pm(1)}$	$Z^{(1)}$	$A^{(1)}$	$Z_X^{(1)}$	$W_R^{\pm(1)}$	$G^{(1)}$
$W_L^{\pm(0)}$	$Z^{(0)}$	$A^{(0)}$	–	–	$G^{(0)}$

Higgs sector

SM-like

Parameters in the Flavor Sector

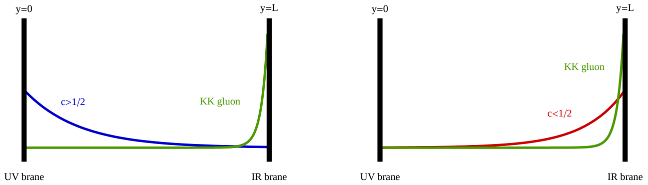
Agashe, Perez, Soni, hep-ph/0408134

Sources of flavor violation in the RS model are...

Hermitian 3×3 bulk mass matrices c_Q, c_u, c_d	3×6 real parameters 3×3 complex phases
Complex 3×3 Yukawa matrices λ_u, λ_d	2×9 real parameters 2×9 complex phases
	36 real parameters 27 complex phases
$U(3)^3$ flavor symmetry	-9 real parameters -17 complex phases
Physical flavor parameters (SM + RS)	**27 real parameters** **10 complex phases**

The RS-GIM Mechanism

- Both KK gauge and Higgs profiles are localized close to (or on) the IR brane
- This suggests that KK gauge couplings and quark masses are related



Small mass $\Longleftrightarrow$ small KK gauge coupling

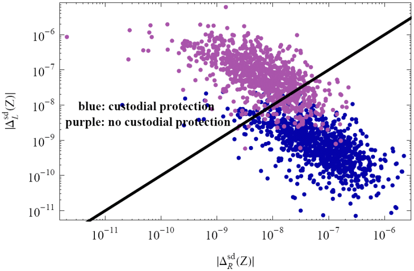
Large mass $\Longleftrightarrow$ large KK gauge coupling

- The flavor off-diagonal couplings are proportional to the mass splitting:

$$\Delta_{ij} \sim (m_i - m_j) U_{ij}$$

Off-diagonal Z Couplings: LH vs RH

Compare the situation with custodial protection (blue points) to the situation without custodial protection (purple points)



Blanke, Buras, BD, Gemmler, Gori

- With custodial protection: $\langle \Delta_R(Z) \rangle \sim \mathcal{O}(10^2) \langle \Delta_L(Z) \rangle$
- Without custodial protection: $\langle \Delta_R(Z) \rangle \sim \mathcal{O}(10^{-1}) \langle \Delta_L(Z) \rangle$

For Z' and active custodial protection: $\langle \Delta_R(Z') \rangle \sim \mathcal{O}(10^1) \langle \Delta_L(Z') \rangle$

Summary: Which Quantities are Protected?

- T-Parameter — Agashe, Delgado, May, Sundrum, hep-ph/0308036; Csaki, Grojean, Pilo, Terning, hep-ph/0308038
- $Zb_L\bar{b}_L$ — Agashe, Contino, DaRold, Pomarol, hep-ph/0605341
- $Zd^i_L\bar{d}^j_L$ — Blanke, Buras, BD, Gori, Weiler, arXiv:0809.1073; Blanke, Buras, BD, Gemmler, Gori, arXiv:0812.3803
- $Zu^i_R\bar{u}^j_R$ — Buras, BD, Gori, arXiv:0903.soon

Unprotected however are

$$Zd^i_R\bar{d}^j_R, \qquad Zu^i_L\bar{u}^j_L, \qquad W^+u^i_Ld^j_L, \qquad W^+u^i_Rd^j_R$$

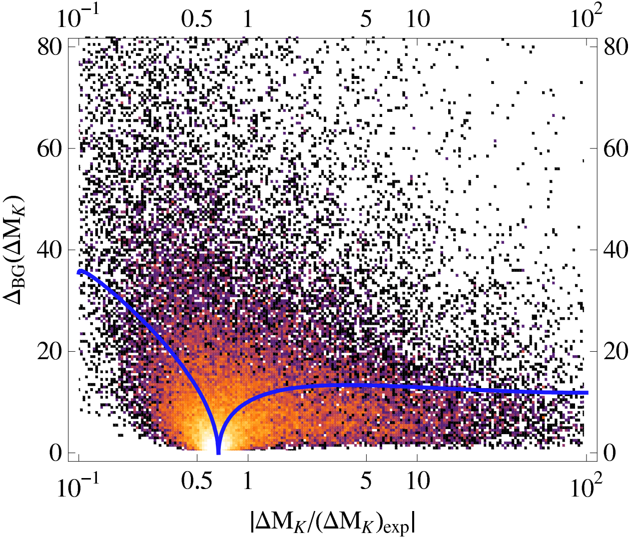
Froggat-Nielsen Equations

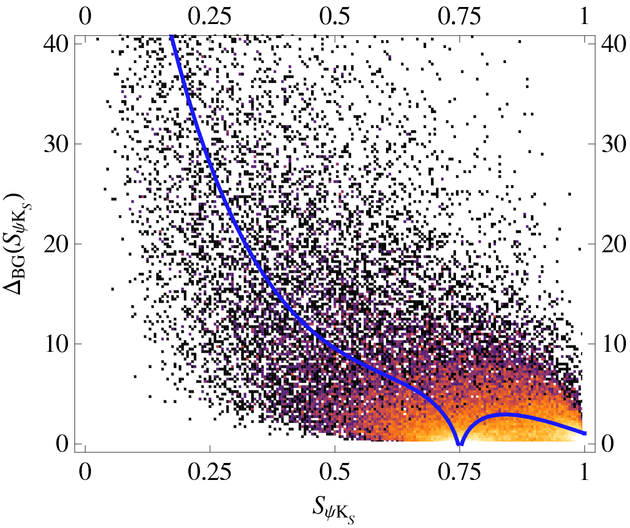
$$m_b = \frac{v}{\sqrt{2}} \lambda^d_{33} \frac{e^{kL}}{kL} f^Q_3 f^d_3$$

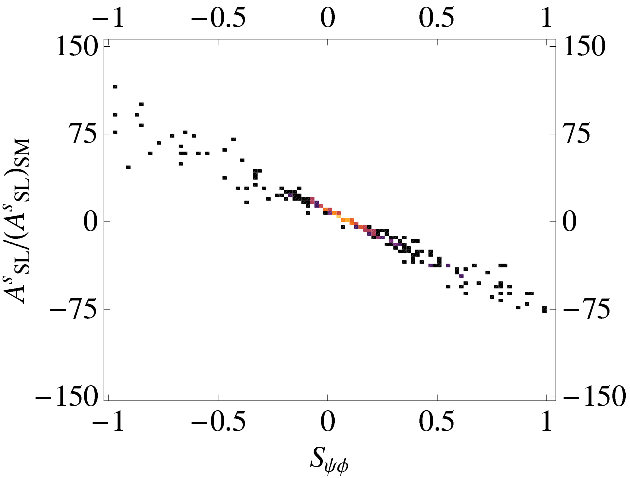
$$m_s = \frac{v}{\sqrt{2}} \frac{\lambda^d_{33}\lambda^d_{22} - \lambda^d_{23}\lambda^d_{32}}{\lambda^d_{33}} \frac{e^{kL}}{kL} f^Q_2 f^d_2$$

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

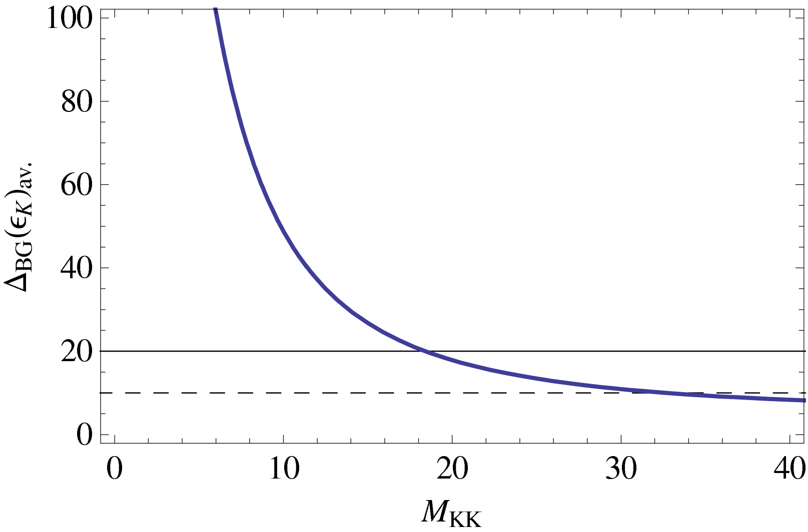
$$(\mathcal{D}_L)_{ij} = \begin{cases} \omega^d_{ij} \frac{f^Q_i}{f^Q_j} & (i < j) \\ 1 & (i = j) \\ \omega^d_{ij} \frac{f^Q_j}{f^Q_i} & (i > j) \end{cases} \qquad (\mathcal{D}_R)_{ij} = \begin{cases} \rho^d_{ij} \frac{f^d_i}{f^d_j} & (i < j) \\ 1 & (i = j) \\ \rho^d_{ij} \frac{f^d_j}{f^d_i} & (i > j) \end{cases}$$


10^-1
0.5
1
5
10
10^2
80
60
40
20
0
Δ_BG(ΔM_K)
|ΔM_K/(ΔM_K)_exp|


0
0.25
0.5
0.75
1
40
30
20
10
0
$\Delta_{BG}(S_{\psi K_S})$
$S_{\psi K_S}$



−1
−0.5
0
0.5
1
150
75
0
−75
−150
$A^s_{SL}/(A^s_{SL})_{SM}$
$S_{\psi\phi}$


$\Delta_{\text{BG}}(\epsilon_K)_{\text{av.}}$
100
80
60
40
20
0
0
10
20
30
40
M_{KK}