The Flavor Puzzle in the Randall-Sundrum model

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Outline

1. Motivations for WED:

- Addressing Gauge Hierarchy Problem
- Addressing the SM Flavor Problem
- Viable Model for the Electro-Weak Symmetry Breaking
- ...

2. Randall-Sundrum Scenario:

Theory

- The Model analyzed
- The NP Flavor Problem

Phenomenology

- K and B meson mixing
- Rare K and B decays

3. Conclusions

<u>Based on collaboration with:</u>

Monika Blanke, Andrzej Buras, Bjorn Duling, Katrin Gemmler, Andreas Weiler

Gauge Hierarchy Problem

The Problem: ...once that we extend the Standard Model

- Huge hierarchy between the fundamental gravity scale M_{pl} & the EW scale Λ_{EWSB}
- Tremendous fine-tuning required to keep $\Lambda_{EWSB} \sim 1$ TeV
- Even if $\Lambda_{EWSB} / M_{pl} \sim 10^{-16}$ is imposed at tree-level, loop corrections push $\Lambda_{EWSB} \sim M_{pl}$

Most popular solutions

- Supersymmetry
- Technicolour
- Large Extra Dimensions
- ...

New Physics at the TeV scale

The Hierarchy problem is not about big/small numbers

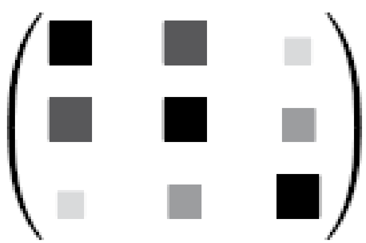
$= 10^{12}$

It is a problem of stability of a small number!

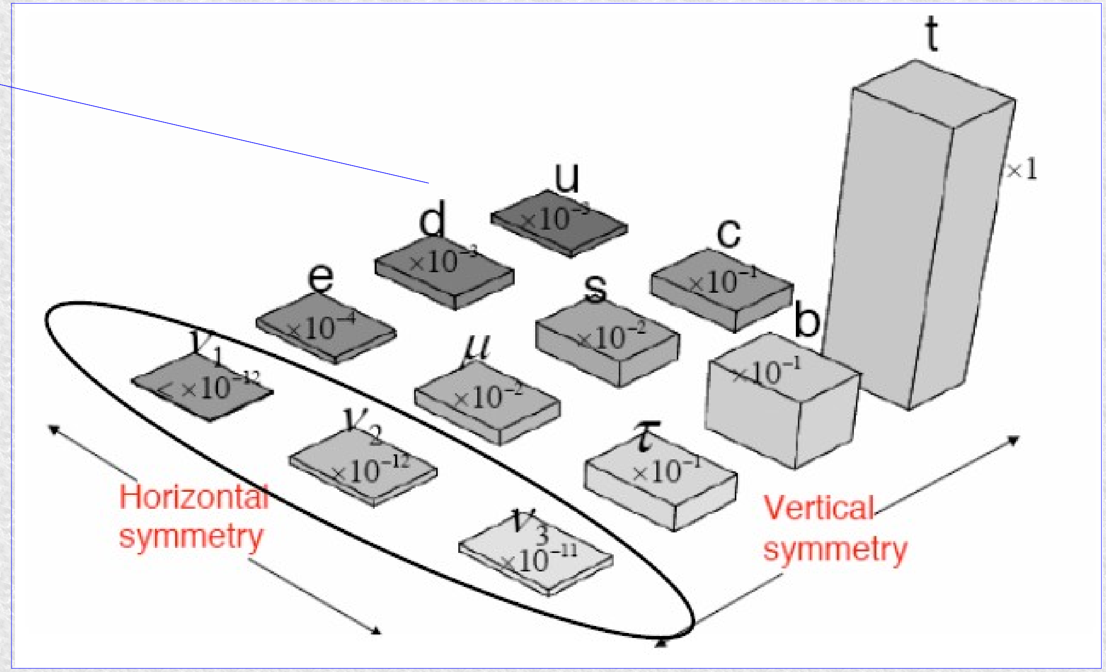
The SM Flavor Puzzle

$$Y_D = \mathrm{diag}(m_d, m_s, m_b)/v$$

$$Y_U = V^{\dagger}_{CKM}(m_u, m_c, m_t)/v$$

$V_{\mathrm{CKM}} =$ 

$+$



Compare to $g_s \sim 1,\ g \sim 0.6,\ g' \sim 0.3,\ \lambda_{Higgs} \sim 1$

SM Yukawa couplings have to exhibit an extremely hierarchical structure, **why?**

The Randall-Sundrum Set Up

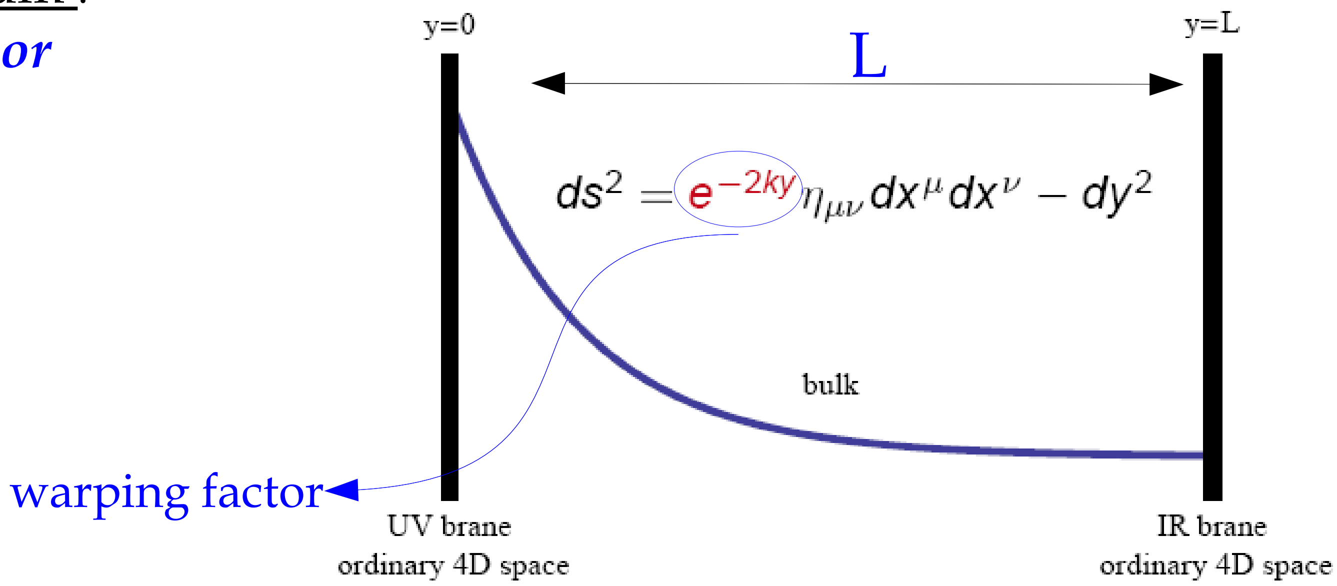
5 dimensions

1999, Randall, Sundrum :

warped metric tensor

hep-ph/9905221

Important feature:
L is relatively large



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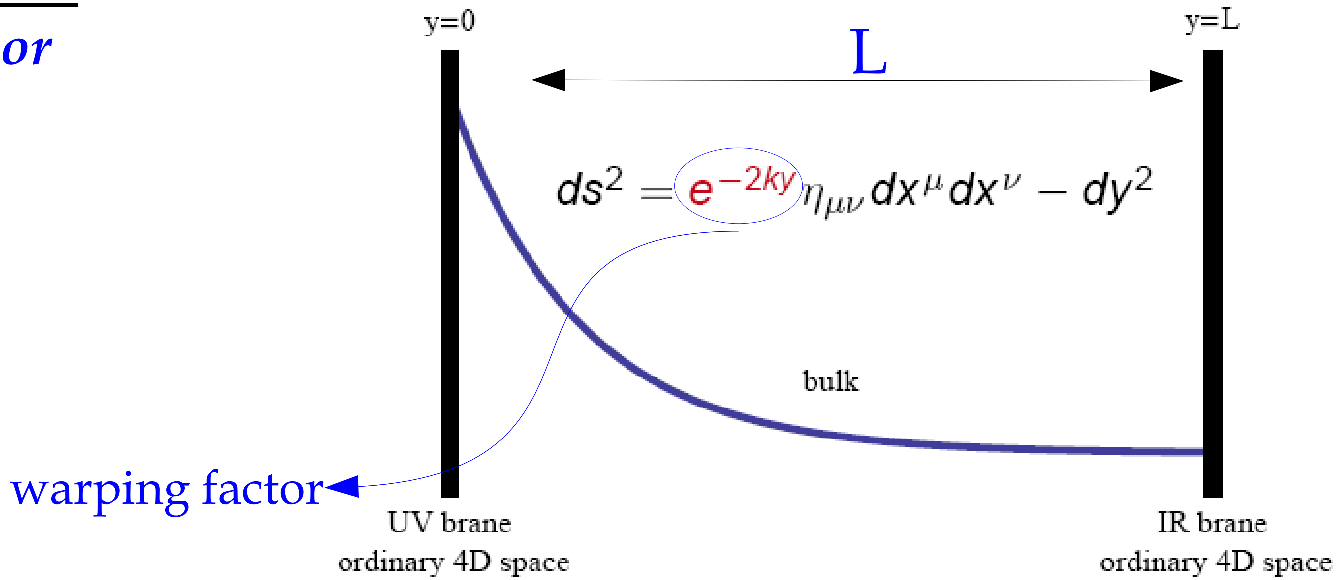

What about the impact of WED in particle physics?

The Higgs in the Fifth Dimension

$$\sqrt{-g} = e^{-k|y|}\,;\;\; g^{\mu\nu} = e^{2k|y|}\eta^{\mu\nu}$$

$$S = \int d^4x dy \sqrt{-g}\left(g^{\mu\nu}\partial_\mu H^\dagger \partial_\nu H - \lambda(H^2 - v_0^2)^2\right)\delta(y-L)$$

$$S = \int d^4x \left(\partial^\mu h^\dagger \partial_\mu h - \lambda(h^2 - v_0^2 e^{-2kL})^2\right) \equiv \int d^4x \left(\partial^\mu h^\dagger \partial_\mu h - \lambda(h^2 - v_{0\,IR}^2)\right)$$

Canonical normalization
$H \to e^{kL} h$

$v_{0\,IR}^2 = v_0^2 e^{-2kL}$

With $v_0 \sim \mathcal{O}(M_{pl})$ only a moderate hierarchy is required to obtain $v_{0\,IR} \sim \mathcal{O}(1\,TeV)$

$$kL \approx 30$$

Fundamental gravity scale still given by M_{pl}

$$f = ke^{-kL}$$

only free parameter coming from geometry

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Gauge Hierarchy Problem: OK!

$$f = k e^{-kL}$$

only free parameter coming from geometry

Origin of Mass Hierachies

- Each SM fermion multiplet belongs to a different 5D fermion field

- The Localization in the bulk is given by

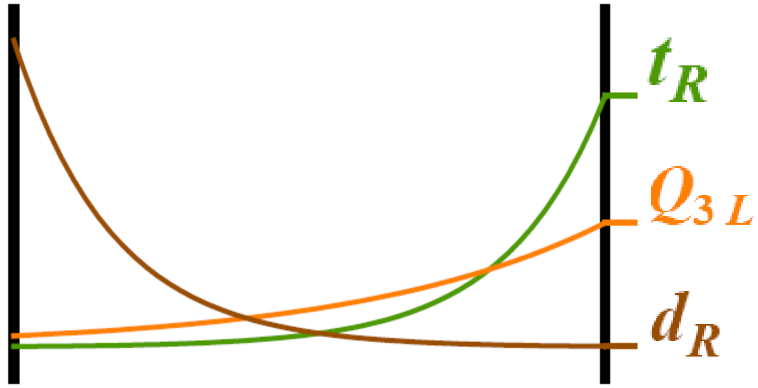
$$f^{(0)}(y,c) = \sqrt{\frac{(1-2c)\,kL}{e^{(1-2c)kL}-1}}\, e^{\left(\frac{1}{2}-c\right)ky}$$

Strong dependence on the bulk mass proper of the 5D fermion field

- 4D Yukawas in terms of shape functions:

$$Y_{ij} \propto \lambda_{ij}\, f_L^{(0)}(L,c^i)\, f_R^{(0)}(L,c^j)$$

5D Yukawas (assumed to be **anarchical** and O(1))



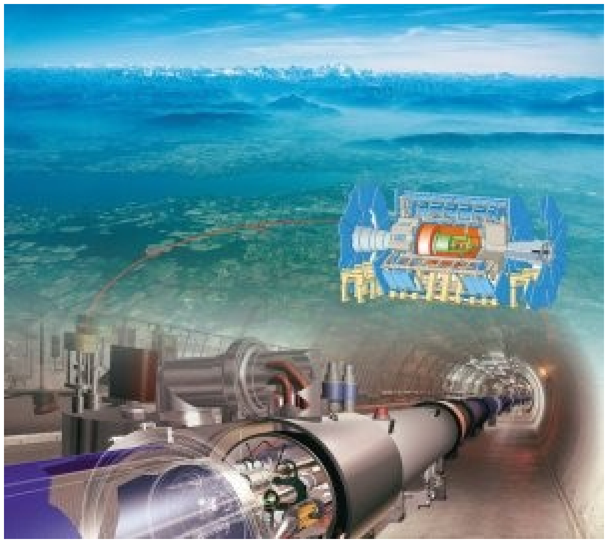
Arkani-Hamed, Schmaltz
hep-ph/9903417

- Result: slightly different bulk masses of O(1) lead to large hierarchies in Y_{ij}

Hierarchy of quark masses and mixings explained by a purely geometrical approach

Two Ways to Test the RS Model

The high-energy frontier



Collider Physics:

- Direct production of new particles
- Test of the NP scale f

Requirement for LHC, Tevatron:

$$f \sim \mathcal{O}(\text{TeV})$$

The high-precision frontier

Flavor Physics:

- New particles probed through quantum corrections
- Test of the flavor structure of the NP model

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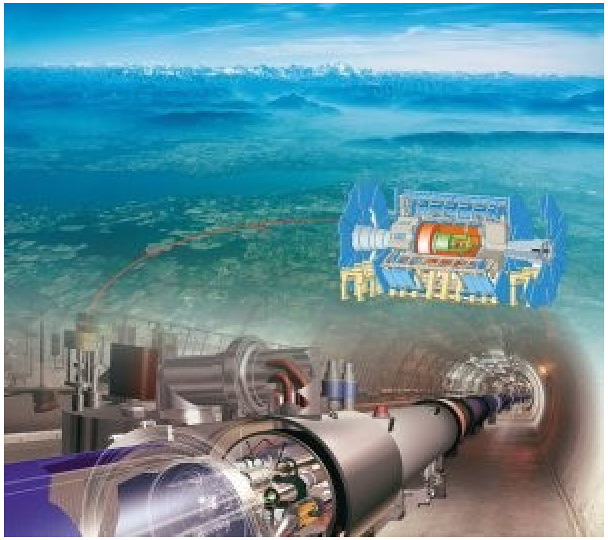

Collider Physics:

- Direct production of new particles
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Requirement for LHC, Tevatron:

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The high-precision frontier

We follow this approach

BUT

we fix a NP scale

$$f = 1\mathrm{TeV}$$

Flavor Physics:

- New particles probed through quantum corrections
- Test of the flavor structure of the NP model

The NP Flavor Puzzle

- The effects of New Physics at high energy scale Λ_{NP} can be represented by **higher dimensional operators** in the low energy effective theory

- Example for neutral meson mixing:

$$\frac{a_{ds}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu s_L)^2+\frac{a_{cu}}{\Lambda_{NP}^2}(\bar{c}_L\gamma_\mu u_L)^2+\frac{a_{db}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu b_L)^2+\frac{a_{sb}}{\Lambda_{NP}^2}(\bar{s}_L\gamma_\mu b_L)^2$$

$$\frac{\Delta M_d}{M_d}\sim\frac{f_B^2}{3}\frac{|a_{db}|}{\Lambda_{NP}^2}$$

- Assuming coefficients order one:

Mixing	$\Lambda_{NP}^{CPC}\geq$	$\Lambda_{NP}^{CPV}\geq$
$K-\bar{K}$	$1000\,TeV$	$20000\,TeV$
$D-\bar{D}$	$1000\,TeV$	$3000\,TeV$
$B_d-\bar{B}_d$	$400\,TeV$	$800\,TeV$
$B_s-\bar{B}_s$	$70\,TeV$	$70\,TeV$

- Fixing the cutoff to 1 TeV:

	$\lvert a_{ij}\rvert\leq$	$Im(a_{ij})\leq$
$K-\bar{K}$	8×10^{-7}	6×10^{-9}
$D-\bar{D}$	5×10^{-7}	1×10^{-7}
$B_d-\bar{B}_d$	5×10^{-6}	1×10^{-6}
$B_s-\bar{B}_s$	2×10^{-4}	2×10^{-4}

Nir et al.

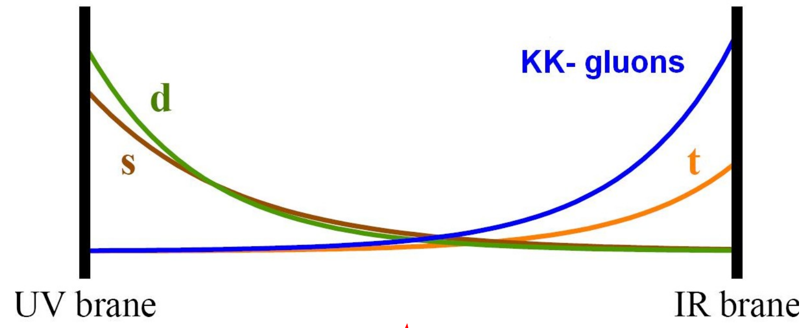
High energy scale much bigger than the EW scale ⟹ **Little Hierarchy Problem**

The Flavor Structure of New Physics should be **highly non generic**, to predict small Flavor Changing Neutral Currents (FCNCs)

Non Universality & FCNC at Tree Level (1)

- KK tower of heavy **gluons (gauge bosons)**

  ...that are all localized towards the IR brane



- Their couplings with SM fermions are non-universal

  ...because couplings to SM fermions depend on their localization

$$\Delta_{L,R} \propto \int_0^L dy\, e^{ky} \left[f^{(0)}_{L,R}(y, c^i_\Psi) \right]^2 g(y)$$

4D gauge couplings are determined by overlap integrals

Rotation to mass eigenstates:

non universalities → off-diagonal terms

FCNC at Tree Level mediated by the exchange of KK-gluons (KK-gauge bosons)

$$\Delta^{mass}_{L,R} \sim U^\dagger_{L,R} \begin{pmatrix} \clubsuit & & \\ & \heartsuit & \\ & & \spadesuit \end{pmatrix} U_{L,R}$$

Non universalities

The NP flavor problem seems to be particularly grave!!

RS-GIM Mechanism

How to protect the flavor changing observables from too large corrections?

- In the **SM**: unitarity of CKM matrix ⊕ equal masses for quarks

⇓

GIM mechanism (broken by the large top mass)

Agashe, Perez, Soni, hep-ph/0408134

- In **RS frameworks**: couplings of EW gauge bosons and SM fermions:

$$\Delta_{L,R} \propto \int_0^L dy\, e^{ky} \left[f^{(0)}_{L,R}(y, c^i_\Psi) \right]^2 g(y) \quad \Rightarrow \quad \Delta^{mass}_{L,R} \sim U^\dagger_{L,R} \begin{pmatrix} \clubsuit & & \\ & \heartsuit & \\ & & \spadesuit \end{pmatrix} U_{L,R}$$

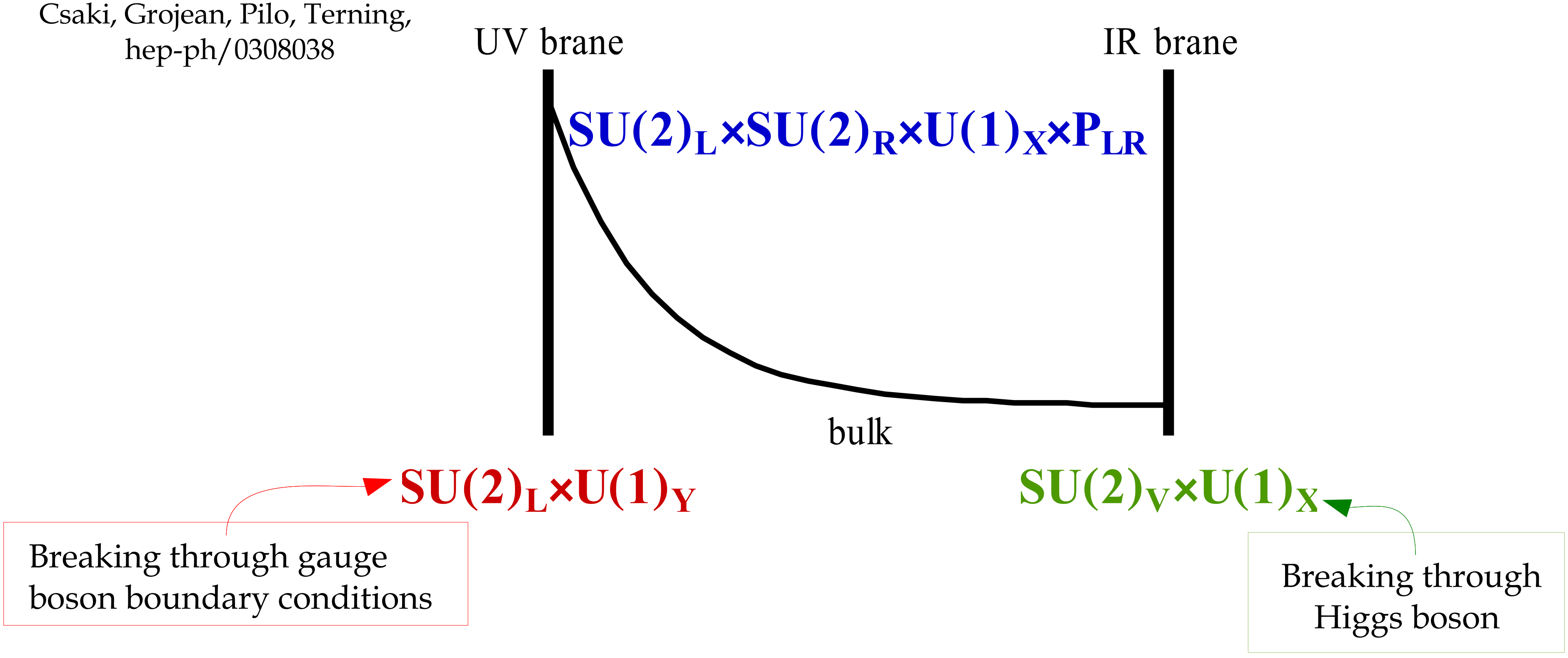
Flavor eigenstates — Mass eigenstates

- If $\clubsuit = \heartsuit = \spadesuit$ ⟶ No FCNCs at tree level
- Since $m_u \sim m_c$ and $m_d \sim m_s$ ⟶ $\clubsuit \sim \heartsuit$ ⟶ **Approximate RS-GIM mechanism**
- $m_t \gg m_u, m_c$ and $m_b \gg m_d, m_s$ ⟶ $\clubsuit, \heartsuit \neq \spadesuit$ ⟶ Breaking of RS-GIM mechanism if third generation involved

Protection of the observables involving the first two generations

The RS model with Custodial Protection

Csaki, Grojean, Pilo, Terning, hep-ph/0308038



With the enlarged gauge group in the bulk:

- Protection of the electroweak T parameter from too large NP corrections
- Protection of the coupling Zb_Lb_L ⟷ b_L is eigenvalue of P_{LR}

Protection Mechanism

Generalization of Agashe et al., hep-ph/0605341

Theorem: In theories with $SU(2)_L \times SU(2)_R \times P_{LR}$ gauge symmetry

if a fermion F has $T_L = T_R\,,\ T^3_L = T^3_R$ or $T^3_L = T^3_R = 0$

then

its coupling $ZF\bar{F}$ is **SM like**

- **In RS model:** relation not spoiled by the mixing with KK-fermions

Buras, Duling, SG, 0905.2318

- **Consequence for SM fermions:** all the $Zd^i_L\bar{d}^j_L$ and $Zu^i_R\bar{u}^j_R$ couplings are mainly SM like

Blanke, Buras, Duling, Gemmler, SG **0812.3803**

Expected small contributions of NP due to the breaking of the P_{LR} symmetry

Final Result: in spite of the FCNC at the tree level, flavor transition observables can be under control in the RS model with custodial protection

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Taking again the effective Hamiltonian of before...

$$\frac{a_{ds}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu s_L)^2 + \frac{a_{cu}}{\Lambda_{NP}^2}(\bar{c}_L\gamma_\mu u_L)^2 + \frac{a_{db}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu b_L)^2 + \frac{a_{sb}}{\Lambda_{NP}^2}(\bar{s}_L\gamma_\mu b_L)^2$$

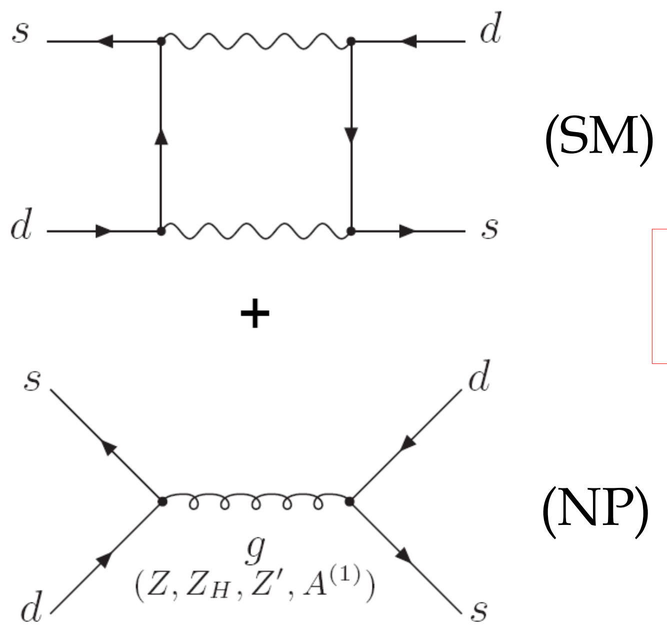
The theory predicts naturally small coefficients

→ Also a relatively low scale $f \approx \Lambda_{\rm NP} \sim \mathcal{O}(\rm TeV)$ can be acceptable

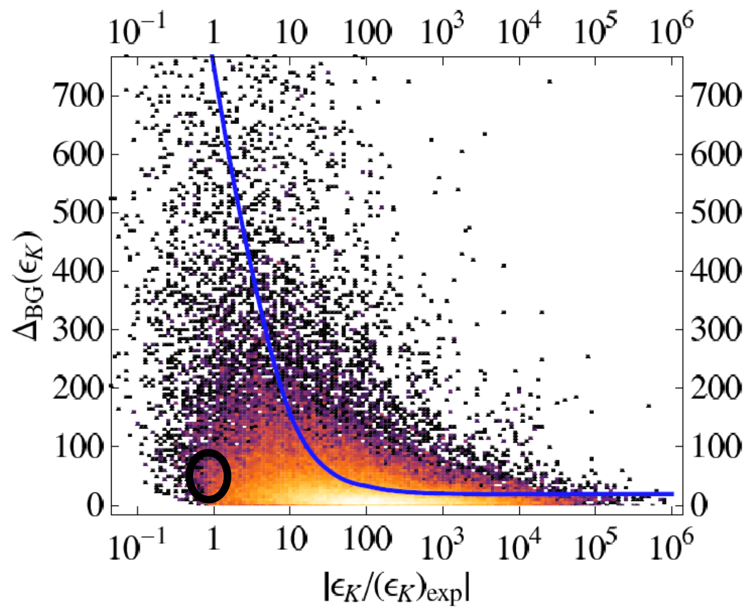
Still a Difficult Observable

ε_K : CP violating observable of the $K - \bar{K}$ system

Blanke, Buras, Duling, S.G., Weiler, 0809.1073



$f \sim 1\text{TeV}$



$$Q_1^{VLL} = (\bar{s}\gamma_\mu P_L d)\,(\bar{s}\gamma_\mu P_L d) \quad \text{(also in the SM)}$$

$$Q_1^{VRR} = (\bar{s}\gamma_\mu P_R d)\,(\bar{s}\gamma_\mu P_R d)$$

$$Q_1^{LR} = (\bar{s}\gamma_\mu P_L d)\,(\bar{s}\gamma_\mu P_R d)$$

$$Q_2^{LR} = (\bar{s} P_L d)(\bar{s} P_R d) \quad \text{(only for gluons)}$$

strongly enhanced

- Definiton of fine-tuning

$$\Delta_{BG}(Obs.) = max_i \frac{d\log(Obs.)}{d\log(x_i)}$$

- Generically $\varepsilon_K \sim 10^2\, \varepsilon_K^{\rm exp}$

- **Parameter sets with moderate fine tuning and $\varepsilon_K \sim \varepsilon_K^{\rm exp}$ exist**

Golden Channel for Flavor Physics

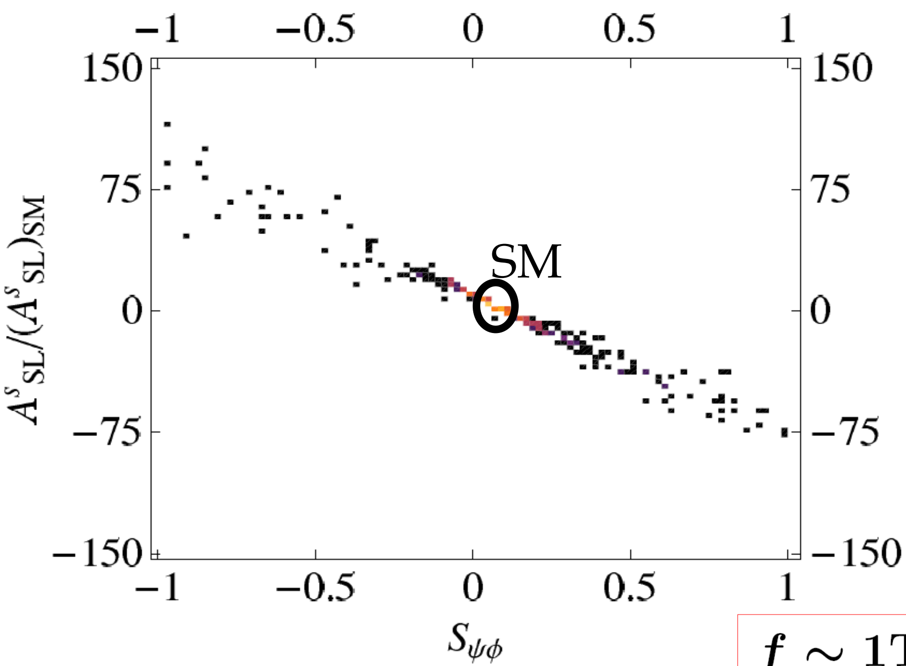
$S_{\psi\varphi}$: CP violating observable of the $B_s - \bar{B}_s$ system

- It is very suppressed in the SM: $(S_{\psi\phi})_{\rm SM} \sim 0.04$
- Large central value given by last experiments of CDF and D0: $(S_{\psi\phi})_{\rm exp} \sim 0.5$

~ 3σ of deviation

Blanke, Buras, Duling, S.G., Weiler, 0809.1073

Possible **large NP contributions**, being in agreement with the well measured ΔF=2 transitions



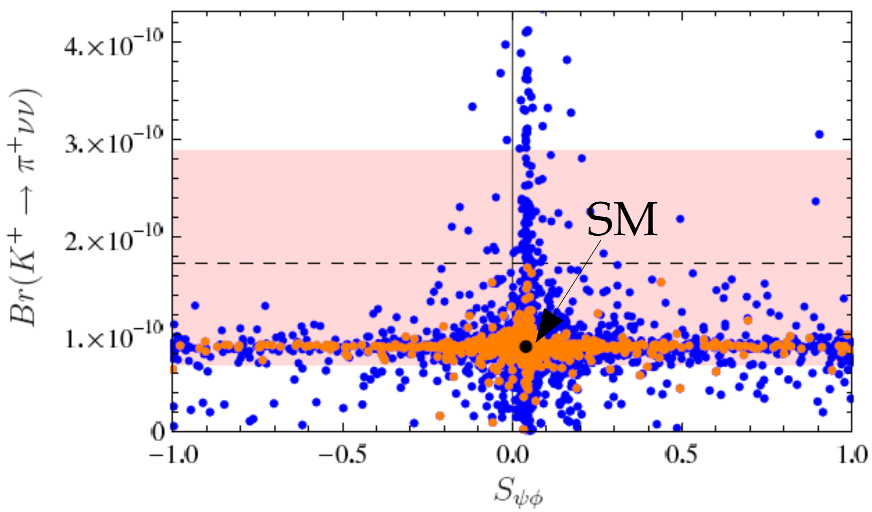
$f \sim 1\text{TeV}$

Waiting for the new results of LHCb...

Predictions of the Model for Flavor Transitions

Blanke, Buras, Duling,
Gemmler, SG, **0812.3803**

Study of the **footprints of the Randall-Sundrum Model** in flavor transitions



Rare K decays

Large NP contributions

BUT

Difficult to obtain simultaneously large deviations from the SM for both observables

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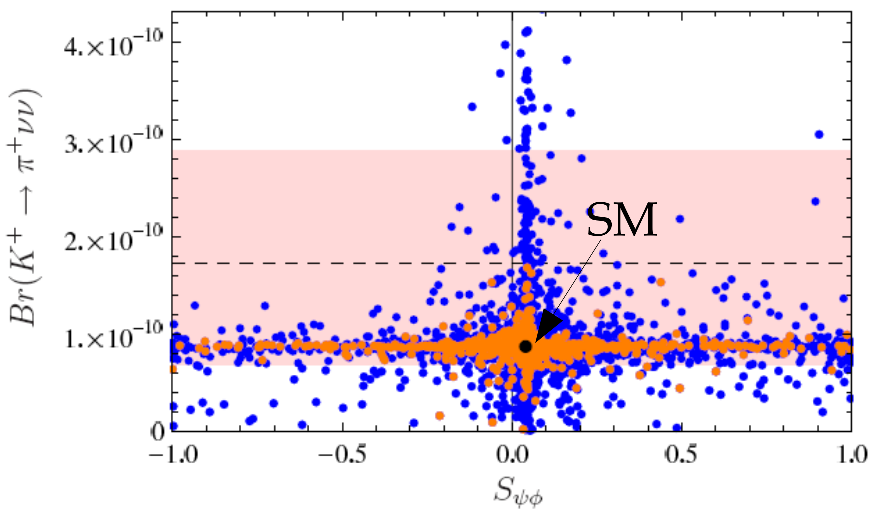

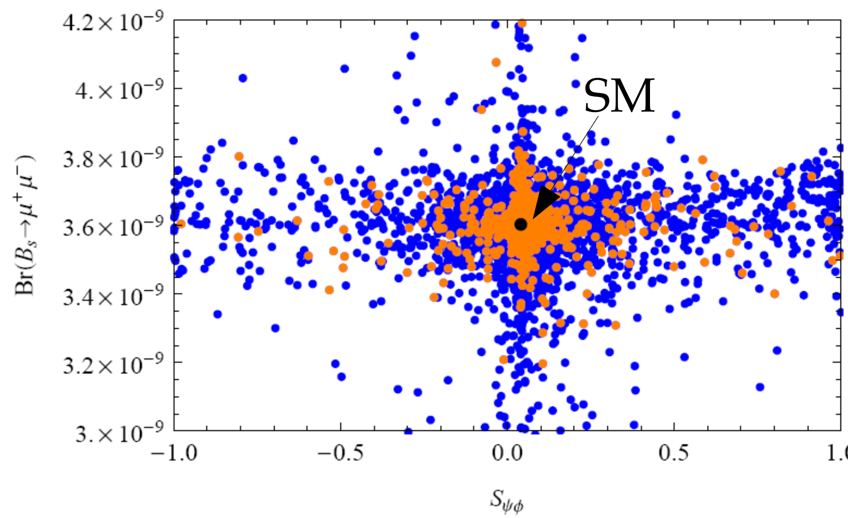

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Rare B decays

Small NP contributions

Two clear messages for future experiments!

Conclusions

- The RS model is an elegant way of addressing
  - The gauge hierarchy problem
  - The SM flavor problem

- In spite of FCNC at tree level, NP flavor problem is under control because of
  - RS-GIM mechanism
  - Protection mechanism (P_{LR} symmetry)

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Possibility of testing the model at the LHC

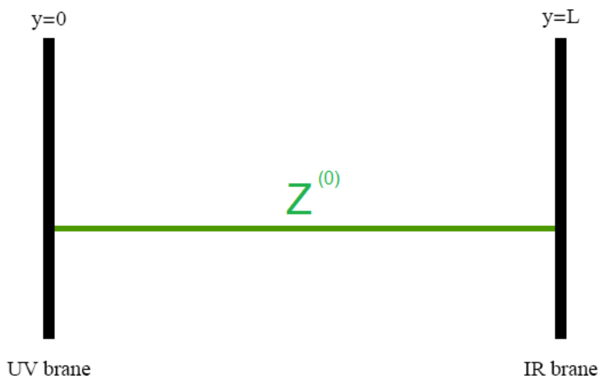
- The flavor phenomenology is interesting (f=1 TeV)

- ε_K is in general too large, but it can be fitted in particular regions of parameter space
- $S_{\psi\varphi}$ can be strongly enhanced
- Possible strong enhancements in rare K decay branching ratios but not simultaneously to $S_{\psi\varphi}$
- Small NP effects in rare B decays branching ratios

Non Universality & FCNC at Tree Level (2)

- Before EWSB the Z boson of the SM:

$$Z = Z^{(0)}$$



- After EWSB:

$$Z = aZ^{(0)} + bZ^{(1)} + cZ_X^{(1)}$$

KK gauge bosons

Shape function distorted
on the IR brane

FCNC at tree level for the Z boson of the SM

This effect is also present for **charged currents** but it is **subleading**.
In the SM flavor changing charged currents are already present at tree level.