Flavor Physics in Warped Extra Dimensions

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Outline

1. Motivation
2. Brief Model Description
3. Selected Flavor Observables
   - ϵ_K
   - $S_{\psi\phi}$
   - $K \to \pi\nu\bar{\nu}$
4. Summary

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Two Ways to Look for New Physics

The high-energy frontier

Collider physics

- direct production of new particles
- determine the energy scale of NP

LHC, Tevatron

The high-precision frontier

Flavour physics

- new particles probed through quantum corrections
- determine the flavour structure of NP

(Super-) *B* factories, LHCb, Tevatron, EDM searches

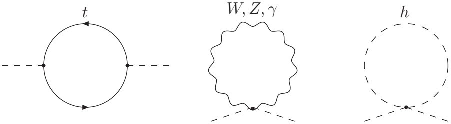
Why Do We Need NP I: Hierarchy Problem(s)

- The Planck scale is much larger than the EW scale:

$$\frac{v}{M_{\mathrm{Pl}}} \sim 10^{-16}$$

Is there a deeper reason for such a large hierarchy?

- The Higgs mass is unstable with respect to radiative corrections



Why does the Higgs mass not end up at the Planck scale?

What keeps the EW and Planck scales apart?

Why Do We Need NP II: the Flavor Puzzle

- The SM fermions have **vastly different masses**.
  In the quark sector alone they span five orders of magnitude:

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

- Also the elements of the CKM matrix are very different in size:

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

$\Rightarrow$ The underlying Yukawa matrices must have a **very special structure**

$$\begin{aligned} Y_D &\approx \left(10^{-5}, 0.0005, 0.026\right) \\ Y_U &\approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix} \end{aligned}$$

This looks unnatural. Is that an accident or is there a deeper reason?

NOT an Analogy

$\approx 10^5$

NOT an Analogy

 $\approx 10^5$ 

More fundamental theory:

 $\approx 10^{29}$  ,  $\approx 10^{24}$ 

A Possible Solution

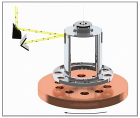
An **additional space dimension** could address both of these issues.

As for its motivation, there are two schools of thought:

- top-down approach: string theory (presumably) says so
- bottom-up approach: why not!

In any case, the extra dimension must be **compactified**, e.g. on a circle.

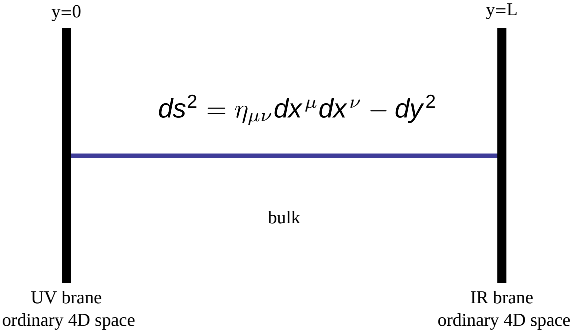
Experimential constraints on its size (torsion balance experiments) then are comparably weak:



- accelerator experiments
  $\Rightarrow 1/R > E_{\text{accelerators}} \sim \mathcal{O}(1TeV)$
- torsion balance experiments (Eötwash)
  $\Rightarrow 1/R \geq 60\mu m$

The Randall-Sundrum Setup

[Randall, Sundrum, hep-ph/9905221]

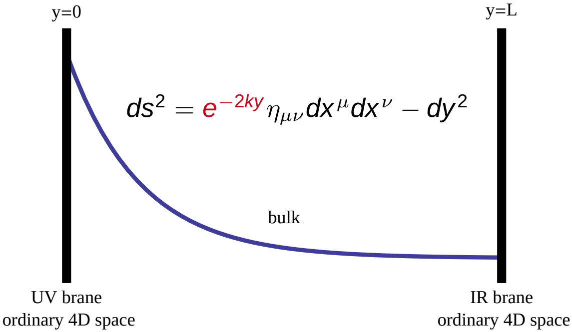


If “sensible” periodicity and boundary conditions are imposed,

a circle is **equivalent to an interval** with $L = \frac{2\pi R}{2}$

The Randall-Sundrum Setup

[Randall, Sundrum, hep-ph/9905221]



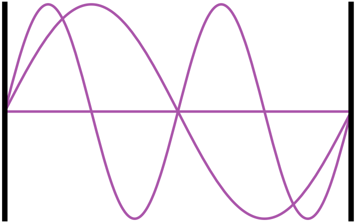
- RS Metric is a solution of the 5D Einstein equations
- Energy scales are “warped down” as one approaches the IR brane
- **Localizing the Higgs at the IR brane** and setting $kL \approx 36$ **naturally** explains the smallness of the EW scale!

Field Localization

Force and matter fields can propagate into the bulk.

For each field, equations of motion allow for infinitely many discrete solutions/profiles along the 5th dimension $\rightarrow$ Kaluza-Klein tower

In flat space:



$$\{sin(ny), cos(ny)\}$$

In warped space:

$$e^{rky}\left\{J_\alpha\left(\frac{m_n}{M_{KK}}ky\right), Y_\alpha\left(\frac{m_n}{M_{KK}}ky\right)\right\}$$

Only for appropriate boundary conditions massless zero-modes are present

Fermions

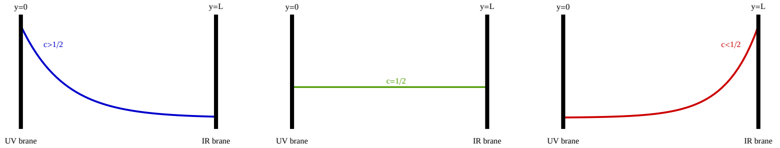
There are **no chiral fermions** in odd numbers of space-time dimensions.

4D chiral fermions can be obtained by introducing **three separate 5D fermions** per quark generation.

$$\boxed{Q_L^i \sim \mathbf{2},\ U_R^i \sim \mathbf{1},\ D_R^i \sim \mathbf{1}} \qquad i = 1, 2, 3$$

Bonus features:

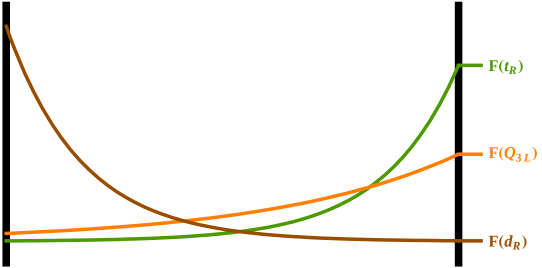
- all of these 5D fermions can have **individual 5D Dirac masses**
- these 5D Dirac masses ($c \equiv m_{\text{Dirac}}^{5D}/k$) exponentially influence the localization of their zero-modes



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

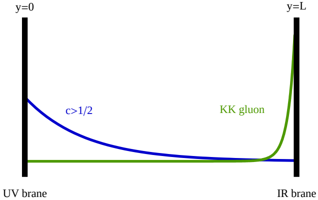
$\Rightarrow$ Hierarchical effective Yukawas

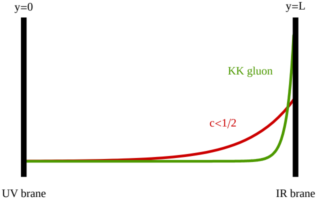
Flavor Changing Gauge Couplings

- 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**



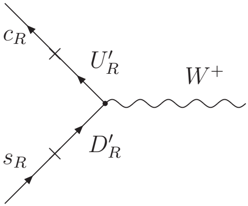


- When going to the quark mass eigenstate basis:

Non-universalities $\Rightarrow$ **Flavor off-diagonal couplings**

Fermion - KK Fermion Mixing

...is the only effect that generates **right-handed W couplings.**



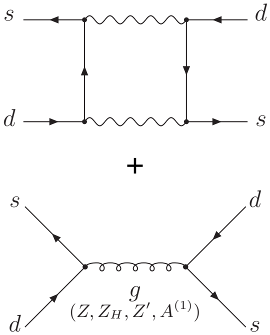
In the zero-mode approximation:

- SM Fermions mix with KK fermions of the same electric charge after EWSB
- KK fermions can have **different quantum numbers** and hence different gauge couplings
- In the mass eigenstate basis ⇒ flavor off-diagonal couplings

Summary of Flavor Effects

In the RS model with custodial protection we have

- flavor changing KK gauge boson couplings
- flavor changing Z couplings (has KK admixtures)
- a slightly non-unitary CKM matrix
- right-handed W couplings
- flavor changing Higgs couplings

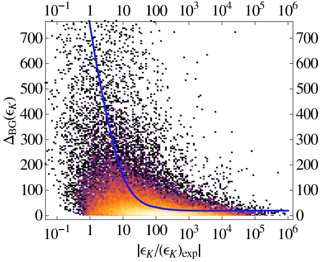


Q_1^{VLL}, Q_1^{VRR}, Q_1^{LR}

$Q_2^{LR} = (\bar{s}P_L d)(\bar{s}P_R d)$

strongly enhanced

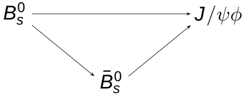
additional operator



- For $M_{KK} \simeq 2.45\mathrm{TeV}$, ϵ_K is by a factor ~ 100 too large
- Despite a generic bound $M_{KK} \geq 20\mathrm{TeV}$ one could get away with smaller values

Hot Topic: $S_{\psi\phi}$

$|J/\psi\phi\rangle \equiv |f\rangle$

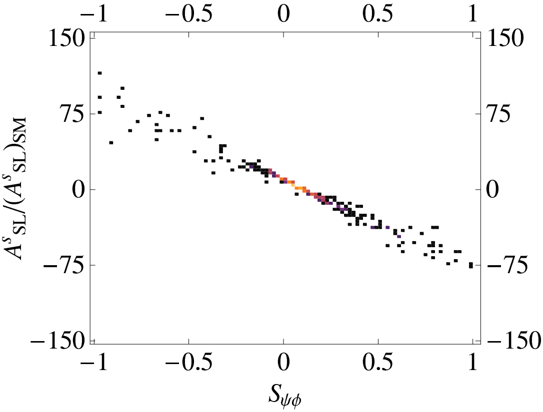


$$\begin{aligned}\mathcal{A}_{\mathrm{CP}}(t,f) &= \frac{\Gamma(B^0(t)\to f) - \Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f) + \Gamma(\bar{B}^0(t)\to f)} \\ &= \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(f)\cos(\Delta M \cdot t) \\ &+ \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(f)\sin(\Delta M \cdot t)\end{aligned}$$

$S_{\psi\phi} \equiv -\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}$ is a measure for the amount of CP violation in $B_s - \bar{B}_s$ mixing

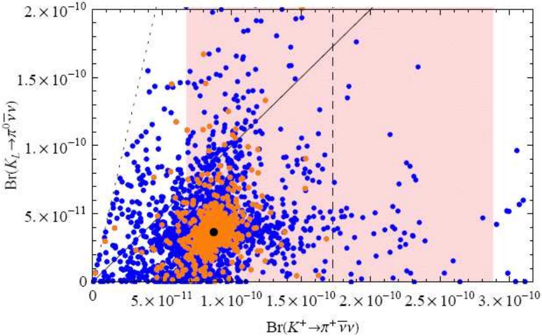
$S_{\psi\phi}$ is very suppressed in the SM $\Rightarrow$ **large relative NP effects** possible

Hot Topic: $S_{\psi\phi}$



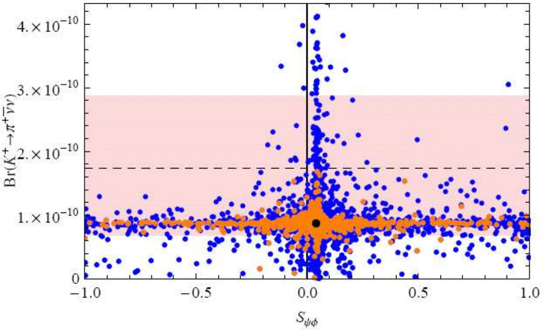
- $S_{\psi\phi}$ is potentially large in the RS model
- $S_{\psi\phi}$ will be measured at LHCb with high precision

Hot Topic: $K \to \pi\nu\bar{\nu}$



- Both branching ratios are potentially large
- For both there are experiments being built (NA62 at CERN and KOTO at KEK)
- In many models strong correlations exist $\to$ falsifiability

A Testable Signature: $K \rightarrow \pi\nu\bar{\nu}$ vs $S_{\psi\phi}$



- $Br(K \rightarrow \pi\nu\bar{\nu})$ and $S_{\psi\phi}$ can both recieve large enhancements
- This seems not to be the case simultaneously
- Reason for this behavior is understood
- Allows for falsifiability

Summary

- The RS-C model addresses the **gauge hierarchy problem** and **flavor puzzle**
- It has a number of interesting flavor effects

- ϵ_K **is generically too large** for low M_{KK} but the constraint can be satisfied
- $S_{\psi\phi}$ **can be strongly enhanced** beyond its SM value
- Enhancements in rare K decays are typically factors 2-3
- The RS-C model displays signatures that allow for its experimental verification/test/falsification