A Flavor Protection for Warped Higgsless Models

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based on arXiv:0904.2137

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Outline

Outline

The Randall-Sundrum Model

Motivation

It would be nice to use extra dimensions to explain small higgs VEV in a theory that

- does not have a very low cutoff,
- has experimental signatures.

$\longrightarrow$ **RS Model**

Setup

Let's build a warped 5D model that appears flat in 4D.

- Consider a finite interval along the 5$^{\text{th}}$ dimension (or orbifold a circle).
- We want to respect 4D Poincaré invariance:

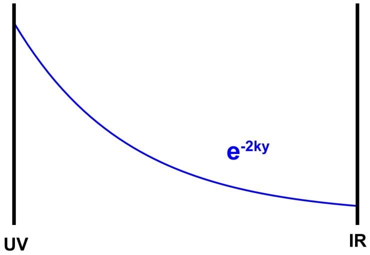
$$ds^2 = e^{-A(y)} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Solve Einstein Equations:

- *Warp factor* $A(y) = 2ky$.
- positive/negative tension brane at $y = 0/a$.
- $\Lambda_{\text{bulk}} < 0 \rightarrow$ (AdS).
- Tuning between brane tensions and Λ_{bulk}.

Features

- Due to warp factor, mass scale decreases exponentially from M_{Planck} at $y = 0$ to M_{IR} at $y = a$.
- Graviton zero mode localized near UV brane $\rightarrow$ normal gravity!
- KK modes near IR brane, with mass $\sim M_{\text{IR}} \rightarrow$ detectable!
- Higgs on IR brane $\rightarrow$ naturally small mass!
- Radius of extra dimension can be stabilized (Goldberger-Wise mechanism).



Keep in mind that this is an effective theory with a *position-dependent* cutoff.

Outline

AdS/CFT Duality

- We can perform a simple coordinate transformation to write the RS metric as

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx^\mu dx^\nu \eta_{\mu\nu} - dz^2\right)$$

where the UV and IR branes are now at $z = R = M_{\mathrm{Planck}}^{-1}$ and $z = R' = M_{\mathrm{IR}}^{-1}$.

- Ignore branes: this metric is scale-invariant.
- From the 4D point-of-view, moving along z simply rescales all lengths and energies $\rightarrow$ 4D CFT!

AdS/CFT Duality

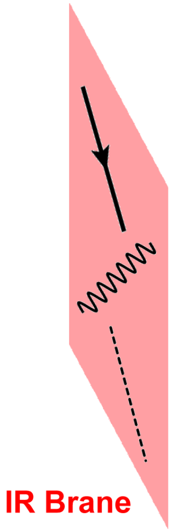
- A 4D CFT without gravity is the same as AdS_5 with gravity:

  Bulk of AdS $\leftrightarrow$ CFT.

- UV brane:
  - high-energy cutoff of CFT.
  - elementary states live near here.
- IR brane:
  - Theory slowly runs (walks) and at low energies suddenly becomes *confining*, breaking conformal invariance.
  - composite states live near here.
- This picture is very useful for model-building!

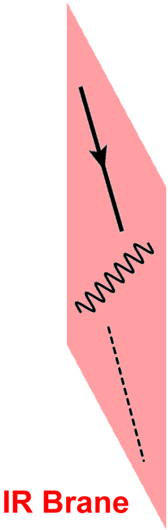
Outline

Standard Model Fields

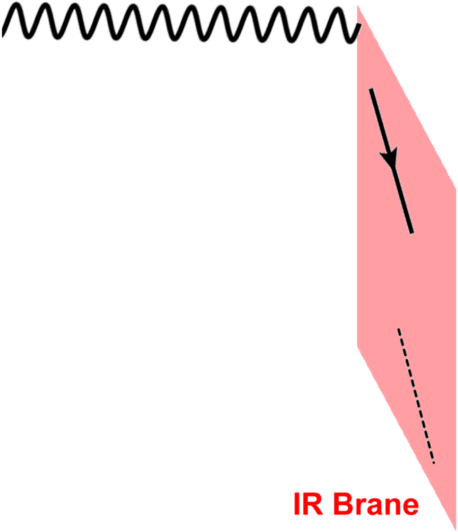


Standard Model Fields

$$\Lambda_F \sim \mathrm{TeV}$$



Standard Model Fields



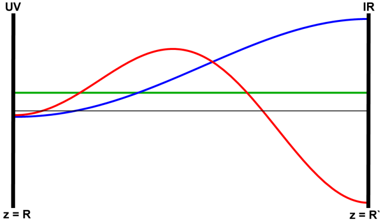
Gauge Fields in the Bulk

A Bit of Formalism

- Take 5D gauge theory and put it on an interval.
- Adding gauge fixing terms gives natural boundary conditions.

$$\partial_z A_\mu^a = 0 \qquad A_5^a = 0$$

- A_μ has zero mode: massless 4D gauge field.



Gauge Fields in the Bulk

Brane Terms

- VEV of brane scalar $\rightarrow$ brane-localized mass term for gauge fields. (Standard Higgs Mechanism!)
- If the VEV is small, ignore it when solving for 5D wave function. It is a small perturbation that:
  - gives 4D mass to zero mode
  - mixes KK modes on the brane (can often neglect)
- But if the VEV is not small, we need to incorporate it into boundary conditions:

$$\partial_z A_\mu \pm \frac{z_{\text{brane}}}{R} g_5^2 v^2 A_\mu = 0$$

"Breaking by Boundary Conditions" $\leftrightarrow$ make v "not small".

Gauge Fields in the Bulk

Simplest Implementation

Now let's put SM gauge fields into the RS model.

- $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$ by higgs on IR brane.
- This gives large correction to W/Z mass ratio unless we push the KK-scale to 10 TeV.
- Reason is that our model does not have the $O(4)$ global symmetry of SM higgs sector, which is broken spontaneously:

$$O(4) \sim SU(2)_L \times SU(2)_R \to SU(2)_D$$

- How can we incorporate that into RS model?

Gauge Fields in the Bulk

AdS/CFT and Custodial Symmetry

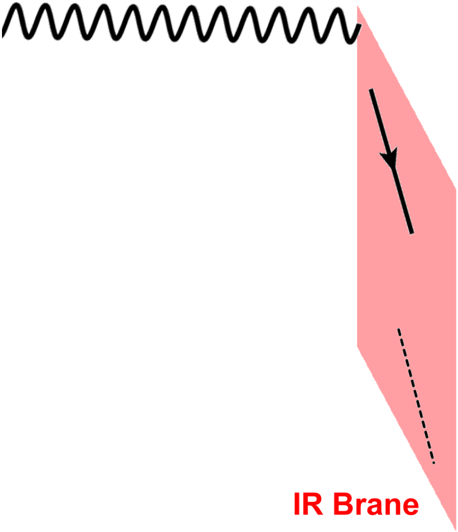
AdS		**CFT**
gauge fields in bulk	$\leftrightarrow$	symmetry (gauged by default)
bulk gauge symmetry broken on UV brane	$\leftrightarrow$	symmetry is global only
bulk gauge symmetry broken on IR	$\leftrightarrow$	strong dynamics also breaks gauge symmetry.

Hence our gauge symmetries should be

UV brane	Bulk	IR brane
$SU(2)_L \times U(1)_Y$	$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$	$SU(2)_D \times U(1)_{B-L}$

Now can have KK scale 3 TeV.

Standard Model Fields



Standard Model Fields

Standard Model Fields

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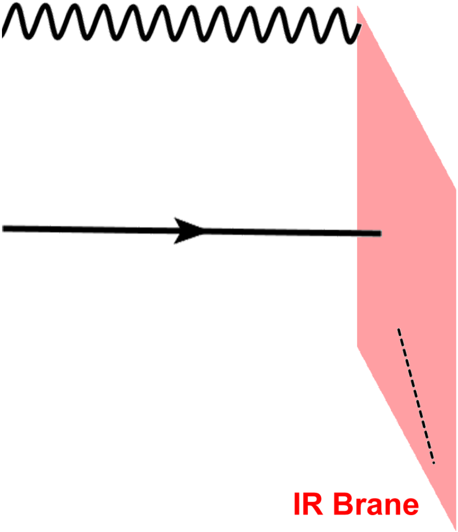
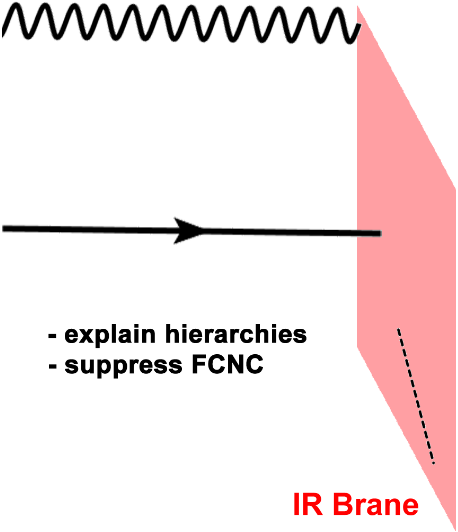
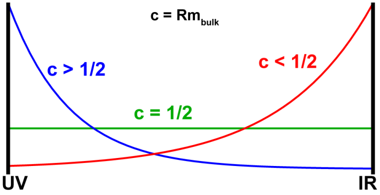


Standard Model Fields



Fermions in the Bulk

- The simplest 5D spinor is a 4D Dirac Spinor
- 4D Gauge boson couplings are overlap integrals.
- naturally get chiral BCs & zero modes.
- For the massless zero modes, bulk mass determines localization along the 5$^{\text{th}}$ dimension:



Flavor in SM

GIM Mechanism

- only Yukawa couplings Y_u, Y_d break flavor symmetry
- do biunitary transformation, rotate $u_{L,R}, d_{L,R}$
- all the mixing gets pushed into W couplings

$\Longrightarrow$ no tree-level FCNCs

But it would be nice to explain fermion mass and mixing hierarchies:

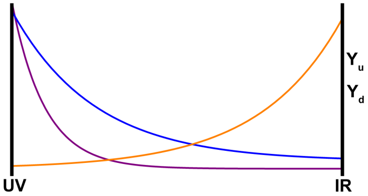
$$|V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \begin{array}{rcl} u, d, s & \sim & 10^{-3} - 10^{-2}\,\mathrm{GeV} \\ c, b & \sim & \mathrm{GeV} \\ t & \sim & 10^2\,\mathrm{GeV} \end{array}$$

$(\lambda \approx 0.2)$

Flavor in RS

Generating Hierarchies

- Anarchic IR Yukawa couplings to the higgs.
- Exponential fermion overlap with IR brane.
- Choose different bulk masses for the different quarks
  $\rightarrow$ effective 4D Yukawa matrices are hierarchical
  $\Longrightarrow$ quark mass and mixing hierarchies!.



Third generation close to IR, light quarks towards UV.

Flavor in RS

Suppressing FCNCs

- No flavor symmetry in RS, all 5D fermions are different.
- Gauge KK-modes are highly IR localized, so their coupling to fermions depends strongly on bulk mass

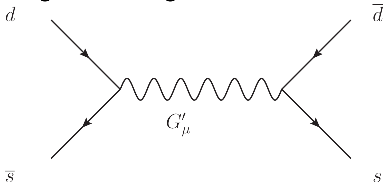
$\rightarrow$ Different for each generation in flavor basis.

$\rightarrow$ Flavor violating neutral couplings in mass basis!

Flavor in RS

Suppressing FCNCs

- Greatest contribution to tree-level FCNCs comes from KK-gluons, e.g.



$$\sim \quad \frac{g_{S*}}{M_G^2} f_s f_d f_s f_d$$

- fermion coupling to KK gluon depends on overlap with IR brane

$\longrightarrow$ exponential suppression $\Rightarrow$ RS-"GIM" Mechanism

Outline

Issues with the RS Model

This is all very nice, but...

- tends to give FCNCs that are too large, especially $K\overline{K}$-mixing.
- Little Hierarchy Problem: Why is the higgs VEV $\sim 1/100\ M_{\mathrm{KK}}$?

And more generally...what if there's no Higgs??

Outline

Solving the Little Hierarchy Problem

Solving the Little Hierarchy Problem

Solving the Little Hierarchy Problem

Let's see what happens if we increase the higgs VEV
while keeping the Z mass constant!

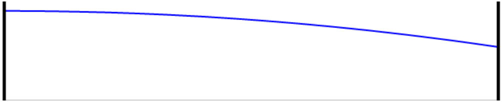
Reminder: gauge BCs with boundary scalar VEV are

$$\partial_z A_\mu \pm \frac{z_{\text{brane}}}{R} g_5^2 v^2 A_\mu = 0$$

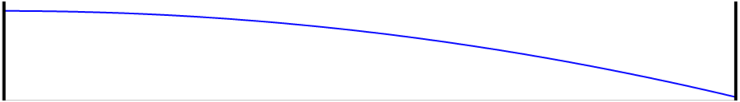
Increase VEV while keeping Z Mass Constant

$M_{\text{KK}} \sim 3\,\text{TeV}, \qquad v \approx 0.05 M_{\text{KK}}$:

$M_{\text{KK}} \sim 1.2\,\text{TeV}, \qquad v \approx 0.2 M_{\text{KK}}$:



$M_{\text{KK}} \sim 1\,\text{TeV}, \qquad v \approx M_{\text{KK}}$:



Solving the Little Hierarchy Problem

- Once $v \sim M_{\mathrm{KK}}$,

$$\partial_z A_\mu \pm \frac{z_{\mathrm{brane}}}{R} g_5^2 v^2 A_\mu = 0 \qquad \longrightarrow \qquad A_\mu = 0$$

- Let's decouple the higgs completely and see if we can build a model that works: $v \to \infty$.

Important Differences with $v \gtrsim M_{\mathrm{KK}}$:

- The size of the extra dimension generates W, Z masses
- $M_{\mathrm{KK}} \sim 1\,\mathrm{TeV}$
- No higgs at LHC

Ditch the Higgs!

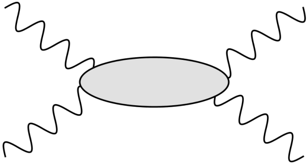
But what's it gonna cost us?

If we have no Higgs, we have to seriously worry about:

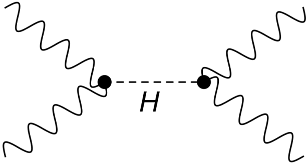
- Unitarization of longitudinal WW-scattering
- Low Cutoff
- Electroweak Precision

Unitarization of longitudinal *WW*-scattering

In the Standard Model, longitudinal *WW* scattering



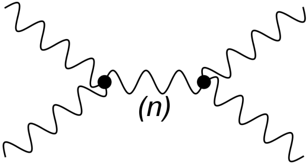
receives important contributions from higgs exchange



without which the amplitude would violate unitarity at $\sim 1\,\mathrm{TeV}$.

Unitarization of longitudinal WW-scattering

In the higgsless model, this amplitude is unitarized by gauge boson KK-exchange:



Important:

Cancellations which unitarize WW-scattering must happen below the cutoff scale.

Cutoff Scale

- RS is an effective theory with a position-dependent cut-off. It's worst near the IR-brane:

$$\Lambda_{\mathrm{cutoff}} \sim \frac{16\pi^2}{g_5^2}\frac{R}{R'}$$

- In higgsless theories, we can no longer freely determine R'.

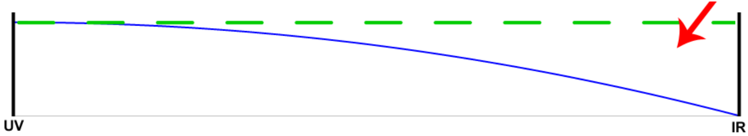
$$\rightarrow \qquad \Lambda_{\mathrm{cutoff}} \sim 5 - 10\,\mathrm{TeV}$$

- Can be dangerous for unitarization!

$\Rightarrow$ Decrease bulk curvature: $R^{-1} \rightarrow 10^8\,\mathrm{GeV}$

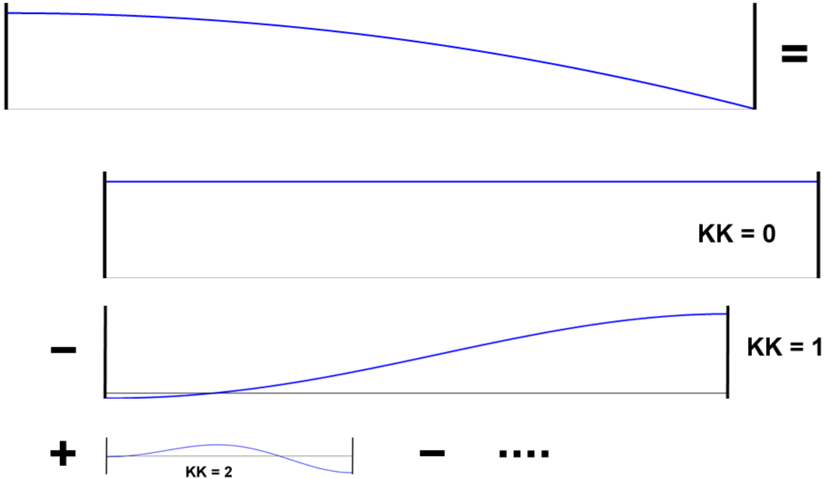
Electroweak Precision

- We can match m_W, m_Z and $\alpha_{\rm EM}$ to the SM. But what about the fermion couplings to the W, Z?
- The 5D profiles of the gauge bosons deviate significantly from flatness near the IR brane
  $\rightarrow$ coupling is now localization-dependent!



Electroweak Precision

Look at the 5D profile as a superposition of orthogonal KK modes using natural BCs.



Electroweak Precision

Important:

In higgsless models, fermion localization is no longer a free parameter. Fermions must be close to flat unless there are protective symmetries.

Outline

Brane Terms for Fermions

We can introduce brane mass and kinetic terms for the fermions.

- Must obey symmetry on brane.
- Mass terms on UV would make fermions very heavy
  $\rightarrow$ IR mass terms!
- However, the UV brane is nice because it is far away from coupling deviations near IR brane
  $\rightarrow$ might use UV kinetic terms to confine some fermions on the brane

These terms could arise from interactions with brane fields that have been integrated out.

Composite and Elementary Fermions

The UV kinetic terms could be **very** large.

That's OK!

Merely specifies which fraction of fermions lives on UV brane (elementary) and bulk (composite).

Flavor Protection

EWPD restricts fermion bulk masses $\rightarrow$ no more RS-GIM!

$\rightarrow$ Use global symmetries!

5D GIM Mechanism

- Impose $SU(3)_F$ flavor symmetries in bulk and IR brane.
- Only allow flavor violation on UV brane via kinetic terms, and only for RH fields.
- Can then use bulk symmetries to diagonalize UV terms

All the mixing is pushed into W-couplings.

Tree-level FCNCs are forbidden, just like SM GIM!

No explanation of hierarchies!

Outline

Simple Quark Models

The 5D GIM mechanism is rather restrictive. Can we build a quark model that still satisfies EWPD?

Some simple possibilities:

- Left-Right Symmetric Model
- Custodially Protected Model

Left-Right Symmetric Quark Model

The simplest potentially realistic model

		$SU(2)_L$	$SU(2)_R$	$X = B - L$
Q_L	$= \begin{pmatrix} u \\ d \end{pmatrix}_L$	$\square$	1	$\frac{1}{6}$
Q_R	$= \begin{pmatrix} u \\ d \end{pmatrix}_R$	1	$\square$	$\frac{1}{6}$

UV | bulk | IR

c_{Q_L}, c_{Q_R}

$\overline{u}^\alpha_R \sigma^\mu D_\mu K_u^{\alpha\beta} u^\beta_R$

$\overline{d}^\alpha_R \sigma^\mu D_\mu K_d^{\alpha\beta} d^\beta_R$

$\delta^{\alpha\beta} M_D \quad R' \overline{Q}^\alpha_L Q^\beta_R$

Left-Right Symmetric Quark Model

But this model doesn't work!

Large top mass
$\Rightarrow$ all quarks towards IR
$\Rightarrow$ wrong Z, W couplings

Tried to fix this with IR gauge kinetic terms
$\Rightarrow \Lambda_{\text{cutoff}} \rightarrow 1\,\text{TeV}$

The Heavy Top is a Real Problem

Custodially Protected Quark Model

$$\Psi_L = \begin{pmatrix} X_L & t_L \\ T_L & b_L \end{pmatrix} \sim (2,2)_{2/3} \qquad \Psi_R = \begin{pmatrix} X_R \\ T_R \\ b_R \end{pmatrix} \sim (1,3)_{1/3}$$

$$t_R \sim (1,1)_{2/3}$$

- b_L couplings independent of c_L bulk mass.
- On the IR brane, separate top and bottom Dirac Masses:

$$R' M_3 \overline{\Psi}_R \Psi_L^{\text{triplet}} \supset \overline{b}_R b_L \qquad M_1 \overline{t}_R \Psi_L^{\text{singlet}} \supset \overline{t}_R t_L$$

- The charge $5/3$ exotic X-quark has a mass of $\sim 0.5\,\mathrm{TeV}$.
- Top lives in both t and heavy T.

Custodially Protected Quark Model

$$\Psi_L = \begin{pmatrix} X_L & t_L \\ T_L & b_L \end{pmatrix} \sim (2,2)_{2/3} \qquad \Psi_R = \begin{pmatrix} X_R \\ T_R \\ b_R \end{pmatrix} \sim (1,3)_{1/3}$$

$$t_R \sim (1,1)_{2/3}$$

UV

bulk

IR

$$c_L, c_{d_R}, c_{u_R}$$

$$\overline{d}_R M_3 d_L$$

$$\overline{u}_R \begin{pmatrix} M_1^u & & \\ & M_1^c & \\ & & M_1^t \end{pmatrix} u_L$$

$$\overline{d}_R^\alpha \sigma^\mu D_\mu K_d^{\alpha\beta} d_R^\beta$$

Custodially Protected Quark Model

Nice features, but:

If we use this representation for all three generations with 5D GIM, we cannot match both b_r and u_ℓ^i couplings to SM.

- The 5D GIM mechanism is very restrictive!
- We have to compromise our flavor protection to match EWPD!

Outline

Higgsless NMFV Model: Setup

We need a hybrid approach to reconcile flavor protection with the third generation:

- Use
  - Q_L, Q_R rep for first two generations,
  - custodially protected rep for third generation.

  $\longrightarrow$ can get EWPD match!

- Enforce $SU(2)$ flavor symmetry between first two generations

  $\longrightarrow$ partial 5D GIM Mechanism suppresses 12 mixing

Higgsless NMFV Model: Setup

Bulk

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(2)_L \times U(1)_Y$ | $SU(2)_D \times U(1)_{B-L}$

$2 \times Q_L, Q_R \quad + \quad \Psi_L, \Psi_R, t_R$

$SU(3)_{Q_L}$ | $SU(2)_{Q_L} \times SU(2)_{Q_R}$ | $SU(2)_Q$

$K_u^{\alpha\beta}$

$K_d^{\alpha\beta}$

$c_{Q_L}, c_{Q_R} \qquad c_{\Psi_L}, c_{b_R}, c_{t_R}$

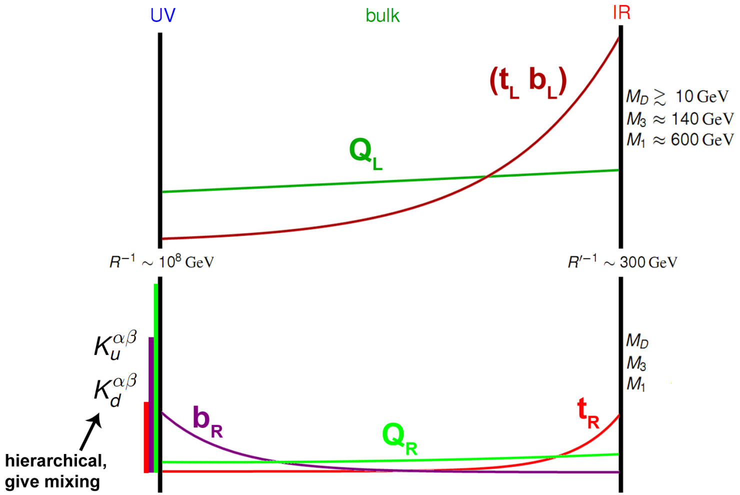
$M_D \overline{Q}_L Q_R$

$M_3 \overline{b}_L b_R \quad , \quad M_1 \overline{t}_L t_R$

UV | IR

Gauge Symmetry · Quarks · Flavor Symmetry

Impose Electroweak Precision Constraints



One can match EWPD with %-level tuning of bulk masses.

Outline

Flavor Protection

Flavor Basis

$$g_L = (g\Psi)_L \cdot \mathbb{1} + g_L^{\text{bulk}}$$
$$g_R = (g\Psi)_R \cdot (\mathbb{1} + f_R K f_R) + g_R^{\text{bulk}}$$

UV/elementary
bulk/composite

$$(\mathbb{1} + f_R K f_R) \to H(\mathbb{1} + f_R K f_R)H = \mathbb{1}$$

H is hermitian

4D diagonal mass matrix

$$M^{\text{mass}} = U_R^\dagger H\, M\, U_L = (HU_R)^\dagger\, M\, U_L$$

5D mass matrix from IR brane terms

$$g^{\text{mass}}_{Wu_L d_L} = U^\dagger_{Lu}\, g_{Wu_L d_L}\, U_{Ld}$$

W-coupling

Mass Basis

$$g_L^{\text{mass}} = (g\Psi)_L \cdot \mathbb{1} + U_L^\dagger g_L^{\text{bulk}} U_L$$
$$g_R^{\text{mass}} = (g\Psi)_R \cdot \mathbb{1} + M^{\text{mass}} U_L^\dagger M^{-1}\; g_R^{\text{bulk}}\; (M^\dagger)^{-1} U_L M^{\text{mass}\dagger}$$

Flavor Protection

For CKM-like mixing, the **off-diagonal** neutral couplings are

$$g^{\text{mass}}_{Ld,ij} \approx \left[g^{\text{bulk3}}_{Ld} - g^{\text{bulk1}}_{Ld}\right] U^{ji}_{Ld}$$

where $i < j$

$$g^{\text{mass}}_{Rd,ij} \approx \left[\frac{g^{\text{bulk3}}_{Rd}}{\rho_b^2 m_b^2} - \frac{g^{\text{bulk1}}_{Rd}}{\rho_c^2 m_c^2}\right] m^j_d m^i_d U^{ji}_{Ld}$$

and for $(i,j) = (1,2)$,

$$U^{ji}_{Ld} \rightarrow U^{32}_{Ld} U^{31}_{Ld}.$$

$\rho > 1$ sets how much larger than minimum to make the IR Dirac mass.

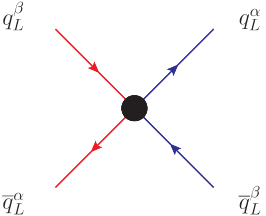
Flavor Protection Mechanisms:

- 12 mixing has to go through 3rd generation. Vital for K-mixing suppression.
- RS-GIM-like suppression for RH mixing due to UV localization of quarks.

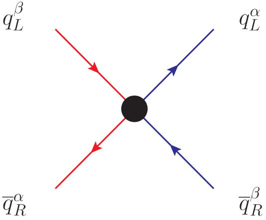
Outline

Compare to Experiment

In the effective Lagrangian, $\Delta F = 2$ FCNCs are parameterized by the C_1, C_4, C_5 operators:



$$\mathbf{C}_{1L}^{\alpha\beta\alpha\beta} \sim \left(\frac{\mathbf{g}_L^{\alpha\beta}}{\mathbf{m}_G}\right)^2 \sim \left(\frac{1}{\Lambda_1^{\alpha\beta}}\right)^2$$



$$\mathbf{C}_4^{\alpha\beta\alpha\beta} \sim \frac{\mathbf{g}_L^{\alpha\beta}\mathbf{g}_R^{\alpha\beta}}{\mathbf{m}_G^2} \sim \left(\frac{1}{\Lambda_4^{\alpha\beta}}\right)^2$$

Compare to Experiment

BSM Λ_4^K and $\Lambda_5^K > 200 \cdot 10^3\,\mathrm{TeV}$!

$\rightarrow$ Problem for RS-GIM.

In NMFV higgsless model, those operators $\propto g_{Rd}^{12} g_{Ld}^{12}$ are double-suppressed:

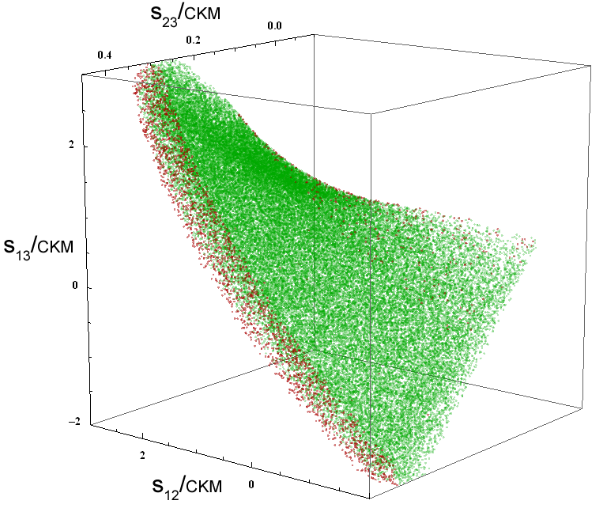
- flavor symmetry
- RS-GIM-like mechanism for RH couplings

$\longrightarrow$ Small enough in our model!

In NMFV higgsless model, all FCNCs are small enough if we push $\sim$ more than half the mixing into the up-sector.

Greatest mixing constraints come from C^1 operators, for which there is no RS-GIM-like mechanism.

Numerical Scan Over Down-Mixings U_{Ld}



Summary

The higgsless NMFV model could be a valid candidate for physics at the LHC.

- Uses custodially protected quark rep in 3^{rd} generation to satisfy EWP constraints with $O(1\%)$ tuning of bulk masses.
- UV-confinement of RH quarks and flavor symmetries suppress FCNCs below experimental bounds.
- Is perturbative up to $\sim 10\,\mathrm{TeV}$ and unitarizes before it becomes strongly coupled.

Signatures at LHC & next-gen Flavor Factories

- no Higgs
- G' at $700\,\mathrm{GeV}$
- exotic $5/3$-charged X-quark at $\sim 0.5\,\mathrm{TeV}$
- Non-zero correlated FCNCs

Next Step: Hopefully, full flavor Analysis by Andrzej Buras ☺.

References

- See-saw cartoon: www.mindreadersdictionary.com
- Please refer to the paper for citations.

Thank you to Johannes Heinonen for his helpful suggestions in preparing this talk.